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Presented at the Workshop on Optical Property Measurement Techniques, Ispra, Italy, October 27–29, 1987

A Large Scanning Radiometer for Characterizing Fenestration Systems

K. Papamichael, J. Klems, and S. Selkowitz

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A LARGE SCANNING RADIOMETER FOR CHARACTERIZING FENESTRATION SYSTEMS

K.M. Papamichael, J.H. Klems and S. Selkowitz
Windows and Lighting Program
Applied Science Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720

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K. M. Papamichael, J. H. Klems and S. Selkowitz
Windows and Lighting Program
Center for Building Science
Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Summary

A large scanning radiometer for measuring the bidirectional transmittance and reflectance of fenestration systems and components is described. Examples of measured data obtained for simple non-specular samples using the radiometer are presented. A method of obtaining the overall bidirectional properties of systems by calculation from scanning radiometer measurements of components is suggested. Advantages and limitations of the method are discussed. The method appears promising.

1. INTRODUCTION

Fenestration systems affect building energy use in two ways. First, daylight admitted through the fenestration may reduce the need for electric lighting and hence reduce electricity usage. Second, the solar energy admitted may either reduce heating loads or increase air conditioning loads, depending on the season of the year and on other characteristics of the building, such as internal loads. To calculate the reduction of electric lighting needs, a detailed knowledge of the spatial distribution of daylight within the interior space is necessary in order to determine the illumination levels available for the particular visual tasks to be performed in the space. This requires knowledge of the angular distribution of the light admitted through the fenestration for any exterior sun/sky/ground conditions. While in principle determining the effect of solar heat gain also requires knowledge of the distribution of the energy within the space, since absorptivities and thermal capacities of surfaces may vary, in practice building simulation models utilize simplified calculations that require only the total amount of admitted solar energy.

For simple fenestration systems consisting of one or more layers of clear, tinted or coated glass, where the principal optical effects are absorption, unidirectional transmission and specular reflection, standard calculation procedures (1, 2) based on photometric measurements of material optical properties (3) are adequate to predict the transmission of the system. For these systems computer programs for calculating interior daylight levels also exist (4). However, in many cases layers such as blinds, louvres or drapes that are spatially inhomogeneous and/or diffusely transmitting or reflecting are used to control solar heat gain and daylighting levels. For these systems the standard procedures are not adequate.

At Lawrence Berkeley Laboratory we are establishing a methodology to predict accurately the luminous and thermal performance of fenestration systems incorporating optically complex components. This methodology is based on combining experimental procedures to determine detailed, angle-dependent, solar-optical properties of fenestration components and computational routines to determine the luminous and thermal performance of

fenestration systems using the detailed solar-optical properties of their components. We describe an apparatus for measuring the bidirectional solar-optical properties of fenestration components and systems, and present results from measurements of the bidirectional transmittance and reflectance of simple fenestration components. We also present and discuss the application of the measured solar-optical properties, completing the overall picture of the proposed methodology.

Since we have currently dealt only with the optical properties of fenestration components, we refer only to photometric quantities and symbols. However, our procedures also apply to the total solar spectrum.

2. BIDIRECTIONAL SOLAR-OPTICAL PROPERTIES OF FENESTRATION SYSTEMS

The bidirectional transmittance, $\tau(\theta_o,\phi_o;\theta_i,\phi_i)$, (or reflectance, $\rho(\theta_o,\phi_o;\theta_i,\phi_i)$) of a fenestration component or system is defined as the ratio of the transmitted (or reflected) flux collected over an element of solid angle surrounding the outgoing direction specified by the angles θ_o and ϕ_o to essentially collimated incident flux incoming from the direction specified by the angles θ_i and ϕ_i (figure 1):

$$\tau(\theta_o,\phi_o;\theta_i,\phi_i) = \frac{dL_o(\theta_o,\phi_o)}{dE_i(\theta_i,\phi_i)} \qquad [sr^{-1}], \tag{1}$$

where $dL_o(\theta_o,\phi_o)$ is the element of the outgoing (transmitted or reflected) luminance and $dE_i(\theta_i,\phi_i)$ is the element of the incident illuminance, normal to the incoming direction.[1]

The luminance of homogeneous layers due to transmitted or reflected radiation is a function of the outgoing direction alone (assuming uniform collimated incident flux). The luminance of inhomogeneous layers, however, is a function of both the outgoing direction and the position on the layer. In this case, we consider an average outgoing luminance over the entire fenestration layer (figure 2).

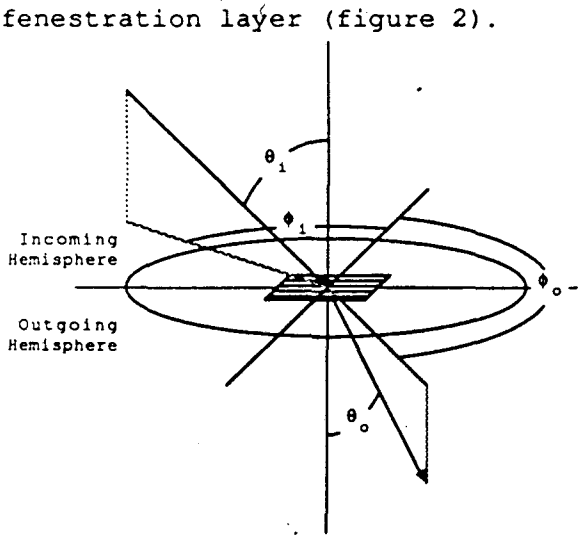

Figure 1. Definition of angles for bidirectional transmittance.

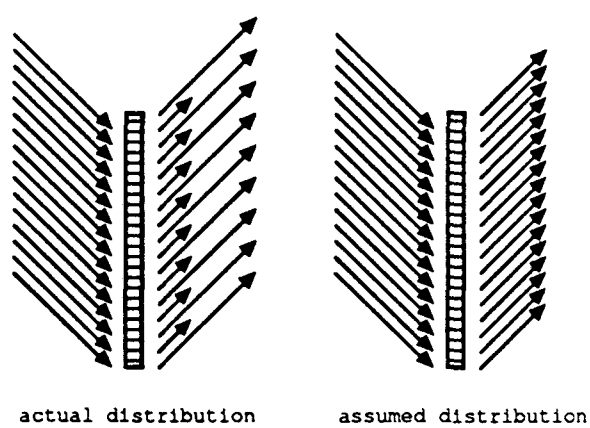

Figure 2. Consideration of an average luminance over the area of a sample.

[1] We use E_i as the illuminance in front of the sample normal to the incoming direction instead of incident on the sample, to cover devices that transmit or reflect radiation incoming at 90° incident angle, such as overhangs and awnings.

There are six solar-optical properties that fully characterize a fenestration layer: the bidirectional front and back transmittance and reflectance (τ^f, τ^b, ρ^f, ρ^b) and the directional front and back absorptance (α^f, α^b). For fenestration systems, however, information about the absorptance of each layer is also essential for determining the contribution of the absorbed radiation to the total solar heat gain through convection/conduction.

3. DETERMINATION OF BIDIRECTIONAL SOLAR-OPTICAL PROPERTIES

In order to determine the bidirectional solar-optical properties of fenestration components we have built a large scanning radiometer (figures 3 and 4). This radiometer, which was originally designed to measure candle-power distributions (5), consists of a fixed-position light source, a sample-holding plane with two rotational degrees of freedom, and a movable detector. The sample plane may be rotated about a vertical axis to adjust the angle of incidence, and about a horizontal axis to adjust the azimuth angle relative to a preferred direction on the device. The full incident hemisphere may be covered in this manner, although in most cases device symmetries will make measurements over the entire hemisphere unnecessary. The detector moves along a vertical semicircular track to cover an arc of 180°, and this track may be rotated about a vertical axis through a full revolution, enabling the detector to move over both the front and back hemispheres of the sample.

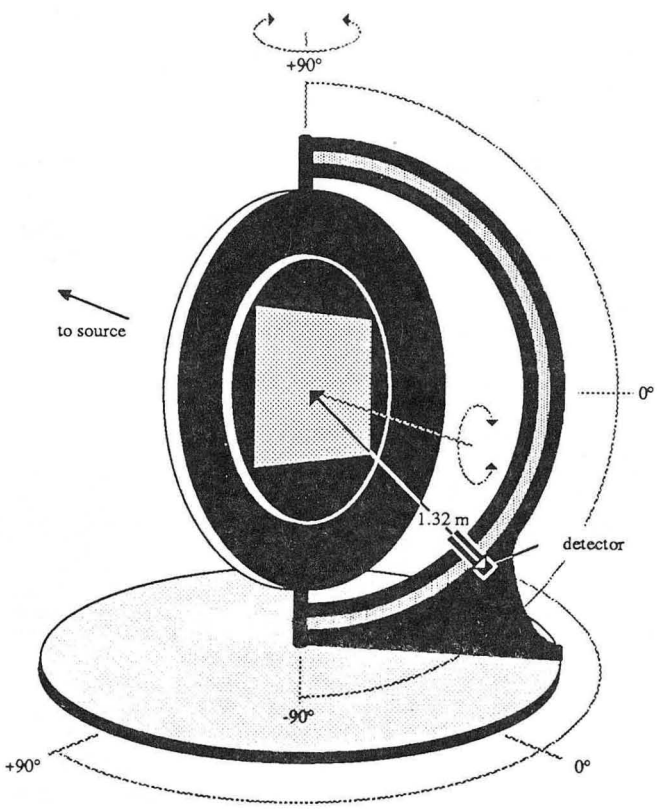

Figure 3. Schematic of the Scanning Radiometer, showing the possible rotations of the sample and the convention for the coordinates of the detector.

Figure 4. The Scanning Radiometer during early testing.

The movements of the scanning radiometer are driven by stepper motors under computer control. The detector is driven through its semicircular arc and 120 approximately equally-spaced data points are recorded. The detector arm is then rotated horizontally by a pre-set angle and the detector again sweeps through its arc. In this manner the entire outgoing hemisphere in a transmittance or reflectance measurement is scanned, and the computer steps the sample through a grid of incident angles and sample azimuths, scanning the outgoing hemisphere for each. Currently all of the rotation steps, with the exception of the semicircular vertical movement of the detector, are set at 15°; with this step size it takes about 20 minutes to scan a complete hemisphere, that is, to consider a single incoming direction.

The movable detector of the radiator is a photopically-corrected silicon sensor read by a computer-controlled digital voltmeter. Two additional fixed sensors are used, one to monitor the source intensity and one to record the illuminance in front of the sample, normal to the incoming direction. Data are read into a DEC LSI-11 computer and stored temporarily on a hard disc. At the completion of a measurement run data are transmitted to a VAX computer for analysis. Separate measurements of luminous noise are subtracted and the data points are interpolated to give values on a fixed grid in (θ_o, ϕ_o) coordinates. The average outgoing luminance is then calculated using the geometrical characteristics of the scanning radiometer, assuming that the area of the detector is very small with respect to the detector's distance from the sample and the area of the sample, as

$$\overline{L_o}(\theta_o, \phi_o) = \frac{E_S}{\int_A \frac{dA \cdot \cos\theta_A \cdot \cos\theta_S}{R^2}} \qquad [\text{lumens} \cdot m^{-2} \cdot sr^{-1}], \qquad (2)$$

where E_S is the illuminance recorded by the moving detector, A is the area of the sample, θ_A and θ_S are the angles between the propagation direction and the normal to the sample and the detector, respectively, and R is the distance from the detector to the sample elements. For small samples, where the angles angles, θ_A and θ_S, and the distance, R, do not change considerably over the area of the sample, equation 2 is simplified to:

$$\overline{L_o}(\theta_o, \phi_o) = \frac{E_S \cdot R^2}{A \cdot \cos\theta_o} \qquad [\text{lumens} \cdot m^{-2} \cdot sr^{-1}], \qquad (3)$$

where θ_o is the angle between the propagation direction and the normal to the sample at its center.

Since the detector accepts radiation from the entire area of the sample, the determined outgoing luminance is an average over the area of the sample, with respect to both position on the sample and direction within the solid angle subtended by the sample at the detector. We term this the "equivalent average luminance" of the sample.

Examples of results obtained with the scanning radiometer are shown in figures 5, 6 and 7. Figure 5 shows the transmitted distribution through a diffusive sample for an incident angle of 0°. The data are shown in terms of the detector coordinate angles, prior to their transformation into (θ_o, ϕ_o) coordinates. This graph displays the entire 120-point scan in the sensor altitude, hence the narrow line spacing in that dimension. As expected, the data show a broad peak centered about the incident direction. Figure 6 shows the reflected distribution from the same sample for an incident angle of 45°. The data in this plot have been interpolated in the neighborhood of -30° sensor azimuth, where the sensor arm shadows the

sample. The data here indicate a combination of specular and diffuse reflection. Figure 7 shows the transmitted distribution through a white, slatted, venetian-blind-like sample with the slats fully open and an incident angle of 60° (which corresponds to a sensor azimuth of -60° and a sensor altitude of 0°). The incident plane is perpendicular to the slat direction. Here we can clearly see the outgoing distribution resulting from one reflection off the slats (high peak at 30° sensor azimuth) and from two reflections (smaller peak at -45° sensor azimuth).

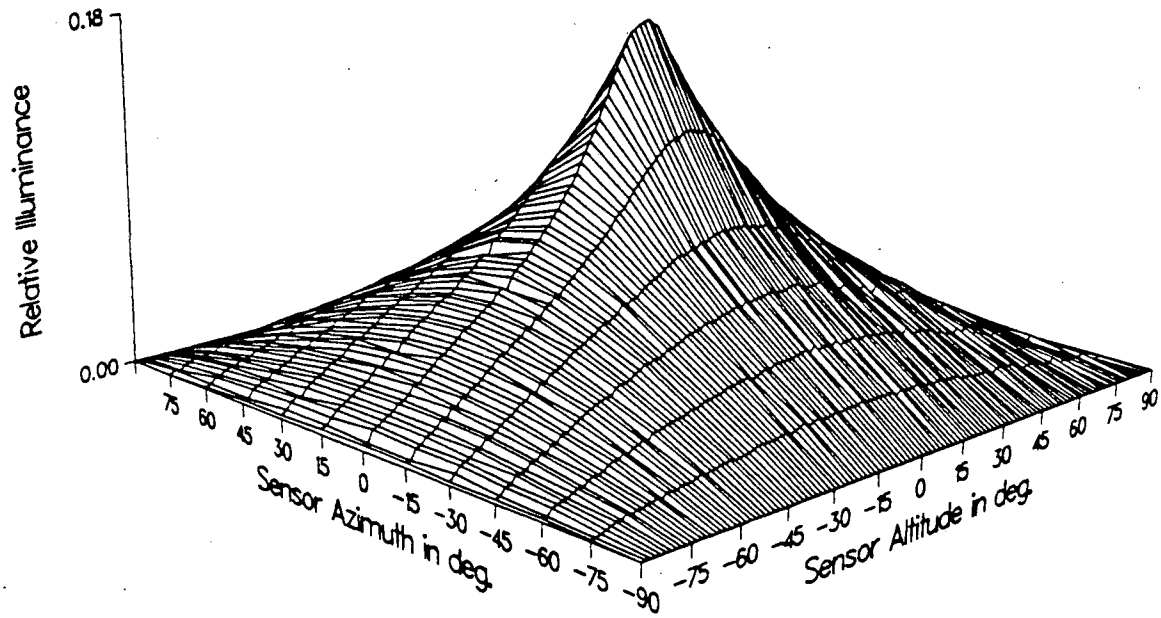

Figure 5. Transmitted distribution through a diffusive sample for 0° incident angle.

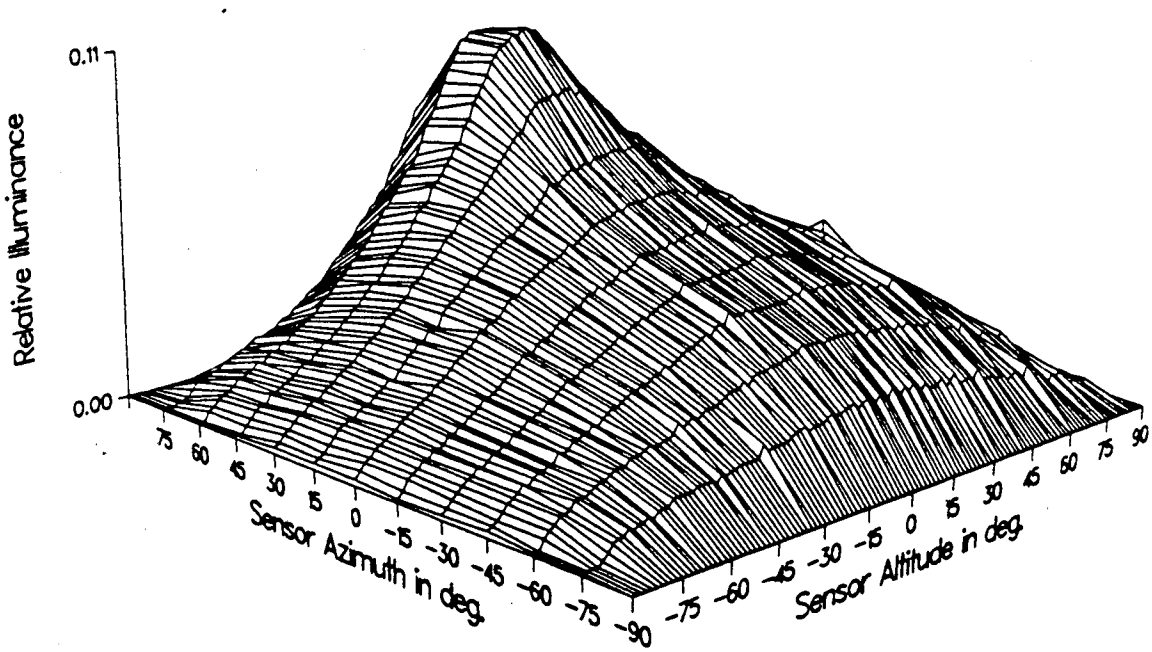

Figure 6. Reflected distribution from a diffusive sample for 45° incident angle.

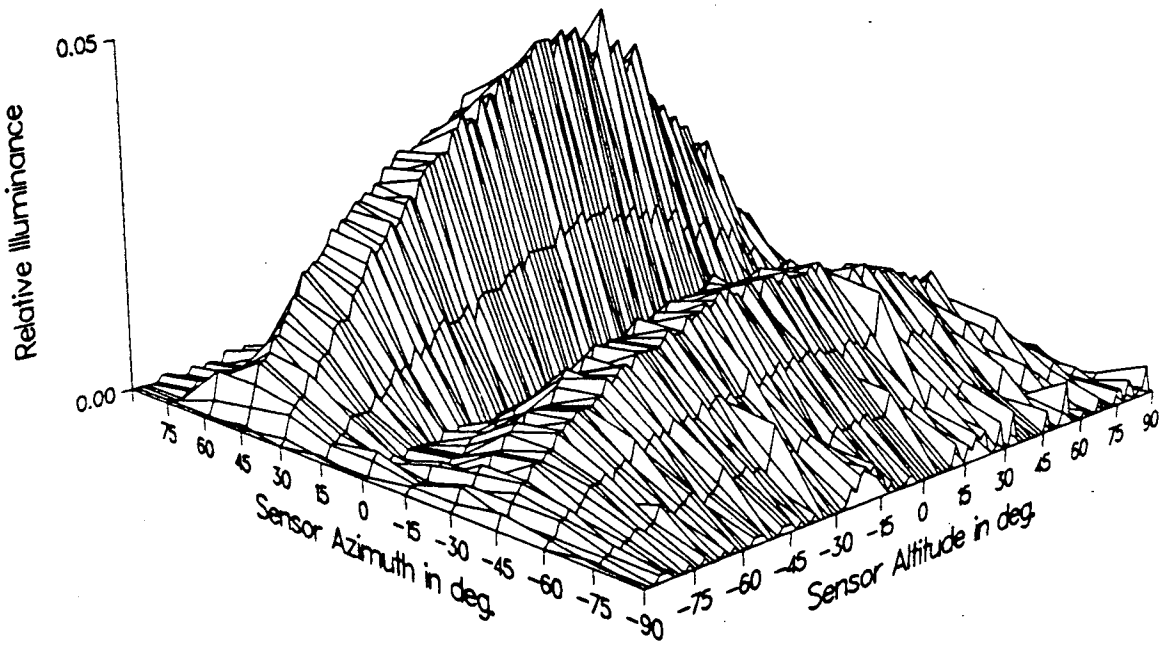

Figure 7. Transmitted distribution through a white slat-type sample for 60° incident angle on a plane perpendicular to the slat direction.

4. APPLICATION OF BIDIRECTIONAL SOLAR-OPTICAL PROPERTIES

Once the bidirectional solar-optical properties of fenestration layers are determined, they are organized into matrices, where the rows and columns correspond to the outgoing and incoming directions, respectively. The solar-optical properties of any combination of layers are then calculated using matrix operations (6).

If we consider a pair of adjacent layers, i and j, and for the moment neglect interreflections between them, then for a given illuminance E_i on layer i, normal to the incoming direction, the total illuminance incident at a particular point on layer j is

$$E_j = E_i \cdot \int_{\Omega_i} \tau_i^f(\theta_o, \phi_o; \theta_i, \phi_i) \cdot d\Omega_{ij} \qquad [\text{lumens} \cdot \text{m}^{-2}], \tag{4}$$

where τ_i^f is the front bidirectional transmittance of layer i, $d\Omega_{ij}$ is the solid angle subtended at the point on j by an element of area on i, and the integral is taken over the layer i. If the integral in equation 4 is approximated by a sum over finite elements of solid angle, then the equation may be rewritten in matrix form as

$$E_j = \Omega_i \cdot \tau_i^f \cdot E_i \qquad [\text{lumens} \cdot \text{m}^{-2}], \tag{5}$$

where Ω_i is a diagonal matrix of the solid angle elements and represents the propagation from layer i to the point on layer j. If multiple reflections between the layers are now included equation 5 becomes

$$E_j = (1 - \Omega_i \cdot \rho_i^b \cdot \Omega_i \cdot \rho_j^f)^{-1} \cdot \Omega_i \cdot \tau_i^f \cdot E_i \qquad [\text{lumens} \cdot \text{m}^{-2}], \tag{6}$$

where the $\rho_i{}^b$ and $\rho_j{}^f$ are the respective front and back bidirectional reflectances of the layers. For a two-layer fenestration system the overall front transmittance would then be given by

$$\tau^f = \tau_j^f \cdot (1 - \Omega_i \cdot \rho_i^b \cdot \Omega_i \cdot \rho_j^f)^{-1} \cdot \Omega_i \cdot \tau_i^f \qquad [\text{sr}^{-1}]. \tag{7}$$

Systems consisting of more than two layers are more complicated in that reflections from subsequent layers incident on the back of layer j must be included, but these do not change the essential point that the system properties may be calculated from the individual layer bidirectional properties through a series of matrix operations.

A computer program, named "TRA", has been developed to perform the above-described matrix operations for a two-layer fenestration system. It is used to compute the bidirectional solar-optical properties of the fenestration system, as well as the directional-hemispherical properties of the two layers and of the system, including the directional absorptance of each layer as part of the fenestration system.

The bidirectional optical properties are then used by a daylight analysis computer model (7, 8) which calculates appropriate illuminance coefficients for a large number of sky luminance distributions to determine electric lighting requirements and luminous comfort. The directional-hemispherical solar properties are used in integration over a large number of sky luminance distributions to determine average transmittance and absorptance for radiation that is direct, diffuse from the sky and diffuse from the ground. These average values are then used by a thermal analysis computer program (2) to determine solar heat gain coefficients. The daylight illuminance and the solar heat gain coefficients are in turn used by an energy analysis computer model (9, 10), to calculate energy use patterns for every hour of the year. The experimental and computational process (figure 8) includes validation stages using our integrating sphere (11), our sky simulator (12) and our Mobile Window Thermal Test (MoWiTT) facility (13).

5. DISCUSSION

This approach represents a new step towards the simulation of the luminous and thermal performance of fenestration systems that incorporate optically complex components. Although the approach requires significant effort and computational power, we believe that it contributes greatly to the proper assessment of the luminous and thermal performance of complex fenestration systems, which cannot be achieved otherwise. The determination of the properties of fenestration systems from the properties of their components through computation contributes towards reducing the effort and information requirements of lengthy measurement procedures for the large number of fenestration systems which may result from combinations and permutations of even a small number of components. Moreover, this approach offers essential information on the absorbed radiation by layer, which is otherwise unobtainable. However, the validity of the underlying assumptions and the utility of the approach are as yet untried, and a thorough validation of the procedure is necessary.

A key assumption is the concept of equivalent average luminance, expressed in the statement that the spatial variations in optical properties may be averaged over the device dimensions without changing the resulting lighting or heat gain calculations. This is a reasonable assumption for fenestration systems, since absorption of solar energy at surfaces is itself a spatial averaging process, and since good lighting design will allow spatially irregular light fluxes to reach a visually

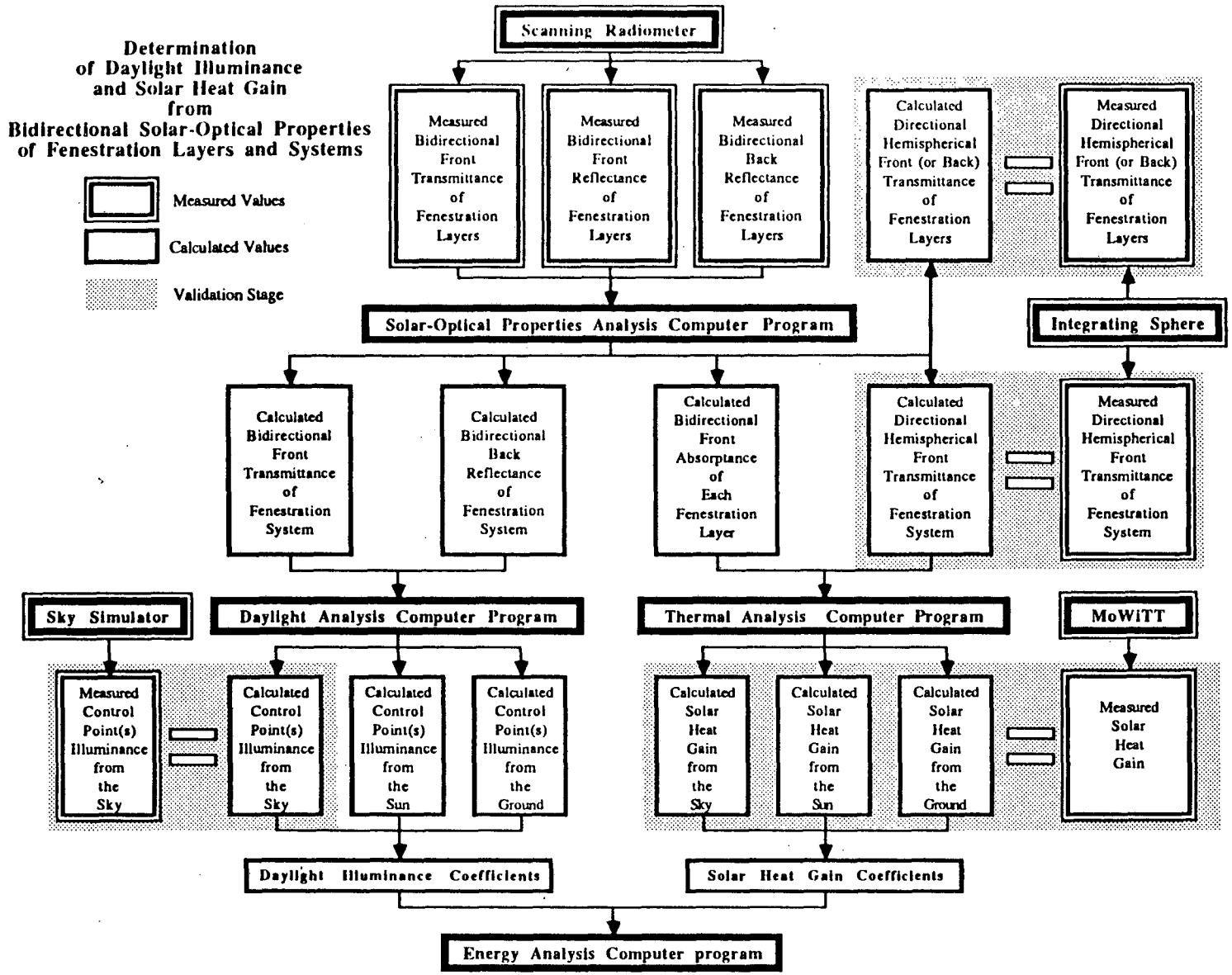

Figure 8. Overall scheme for producing and using bidirectional solar-optical properties of fenestration systems. The lower third of the figure indicates plannes usesof the properties in simulation programs and for simplified application guidelines.

important surface only after at least one diffuse reflection, which similarly averages out the spatial variation. However, to extend this assumption to the individual layers is a much stronger statement. While there are clearly systems that violate this assumption, one purpose of our work is to determine whether it holds for a usefully large class of fenestration systems.

A second assumption is that the angular resolution of the scanning radiometer is sufficient for a usefully large class of shading devices. The angular resolution is limited by the sample size, the detector size, and the sample-detector distance. For our apparatus, the latter was dictated by cost considerations. It is very difficult to determine *a priori* the angular resolution necessary. Only tests of the method for a variety of realistic components and systems will answer this question.

A third assumption is that the computation power necessary to carry out the matrix calculations remains reasonable. This hinges strongly on the degree of angular accuracy necessary. With the current 15° angular grids the bidirectional matrices contain 145 X 145 elements, and as is well-known, computation time goes up very rapidly with matrix size. For systems of more than two layers, multiple reflections between non-adjacent layers will cause the calculation time to rise faster than linearly with the number of layers. Also, simple storage, indexing and accessing of the measured properties becomes a problem with the volume of information used by this method. However, a simplifying circumstance is that most of the layers in any fenestration system will be glazings, for which the matrices are diagonal. It is likely that even the most complex fenestrations will not have more than 3 or 4 optically complex layers, and many will have only one.

In carrying out the proposed approach to characterizing fenestration systems we will investigate all of the above issues. Moreover, several validation procedures will be followed (figure 8). Two of these are directly related to determining the solar-optical properties of fenestration systems. The first validation procedure is based on comparing the directional-hemispherical transmittance obtained by integration of measured bidirectional transmittance over the output hemisphere, with that measured directly using our large integrating sphere (11). This comparison has so far been carried out only for the transmittance of a uniform diffusing sample. For an incident angle of 45° the directional-hemispherical transmittance was calculated to be 0.51 and a somewhat crude measurement with the integrating sphere yielded a value of 0.47. The difference is within the estimated experimental error of the sphere measurement. The second validation procedure (not shown in figure 8) is based on comparing measured bidirectional properties of fenestration systems, using the scanning radiometer, with those calculated using the TRA computer program from measured layer properties.

6. CONCLUSIONS

We have succeeded in constructing and operating a large scanning radiometer capable of producing rapidly and economically optical data for optically complex fenestration components, which are otherwise unobtainable. While the data presented here are preliminary and calibration and extension to the radiometric regime are still to be completed, the facility already represents a unique measurement capability.

The method of characterizing layers by their equivalent average luminance and combining separately measured properties by calculation has the potential for solving an otherwise difficult combinatorial problem in characterizing fenestration systems. While the range of applicability of this method is still to be determined, it is clearly useful for the large class of fenestration systems consisting of a single geometrically complex shading device in combination with several glazing layers, with or without tints or coatings. We believe that it has considerable promise.

7. ACKNOWLEDGEMENTS

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