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Determining Daylight Illuminance in Rooms Having Complex Fenestration Systems

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ABSTRACT

Traditional computational models predict daylight illuminance in a space by dividing window surfaces into discrete areas and then calculating the apparent luminance of each window element by multiplying the luminance of the natural light source in a given viewing direction by the window transmittance in that direction. This approach works well for conventional glazing materials but is incapable of modeling commonly used, but complex, window systems such, as those with specular reflective venetian blinds. We describe a new approach that combines measured luminance distributions for complex window systems with a flux transfer calculation within the space. This method resembles the calculation of illuminance from electric light fixtures where the candlepower distribution of the fixtures is measured and used as an input to the calculation. Based on the variable luminance characteristics of the window system, the SUPERLITE program calculates illuminance at the workplane over the entire space. The measurement techniques and mathematical implementation in the SUPERLITE program are described. This approach allows a wide range of complex window and shading systems to be evaluated without continuous changes in the computational program. A special apparatus for measuring the bidirectional transmittance of window systems has been built in conjunction with this approach. Sample results from the program are compared to measurements made in scale models in a sky simulator.

INTRODUCTION AND BACKGROUND

Accurate prediction of daylight illuminance and luminance distributions in interior spaces is usually performed either by experimental measurements (usually in scale models) or by computational methods using appropriate mathematical models. The experimental approach is versatile and can be very accurate, depending on the accuracy of the scale model. However, it is time consuming, inflexible, and may require a large investment in a photometric system. Results are limited to the specific sky conditions (real or simulated) under which the scale model is used. Moreover, examination of alternative designs or parametric studies requires a series of appropriate scale models or sophisticated adjustable ones. On the other hand, computational techniques in the form of computer programs offer speed and flexibility but are often limited in accuracy due to assumptions incorporated into the mathematical modeling. The major limitation of computational techniques is their inability to handle fenestration systems that incorporate shading devices, especially when the geometry and surface reflectance of these devices deviate from what conventional flux-exchange algorithms can handle.

Two fundamental issues surround the modeling of daylight illuminance in spaces with complex shading devices. The first is geometrical complexity. For example, eggcrate shading devices are composed of a number of daylight-

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admitting elements, each of which has four surfaces. Furthermore, most currently available vertical or horizontal movable louvers are made with a series of curved surfaces, while conventional daylight illumination models can model only flat surfaces. The second difficulty is the optical properties of shading device surfaces. The texture and finish of most louver types of shading devices results in a semi-specular surface. When combined with a curved geometry, such shading devices prohibit the adaptation of conventional analytical methods in determining their luminous performances.

SUPERLITE is a computer program for calculating daylight illuminance and luminance distributions in interior spaces (1,2,3). The modeling of the luminous performance of shading devices in SUPERLITE has been developed in three phases. In the first phase, shading devices were considered as the equivalent of one or more exterior surfaces. The major limitations of this approach are the restrictions in the number, shape, and type of the exterior surfaces the program can handle. Surfaces are assumed flat, with perfectly diffuse reflectance. Moreover, a large effort is required to prepare the appropriate input for the resulting surfaces. In the second phase, the program was modified to handle horizontal and vertical shading elements, using simple descriptions of their width, depth, and displacement between frames. This proved to be a considerable improvement for modeling overhangs, vertical and horizontal fins, and simple light shelves. However, surfaces are still assumed to be flat with perfectly diffuse reflectance, and the interreflections between the surfaces of the shading devices are ignored.

This paper describes the third phase of the development of the SUPERLITE computer program. During this phase, a new approach is taken towards the modeling of shading devices: the total fenestration system is treated as a luminous source of varying candlepower distribution. The candlepower distribution is determined from the bidirectional transmittance of the fenestration system (4,5). This approach offers the capability of determining the luminous performance of fenestration systems of arbitrary complexity in an accurate and consistent way.

NEW TECHNIQUES FOR MODELING COMPLEX SHADING DEVICES

Our new approach for modeling the luminous performance of shading systems of arbitrary complexity is based on using experimentally measured coefficients that describe the bidirectional transmittance of the shading system, that is, the fraction of the incoming luminous flux incident in direction (β_i,ψ_i) that is transmitted in each direction (β_o,ψ_o) (Figure 1). For a given sky condition a fenestration system can be interpreted as an optical black box or a light-emitting plane for which a candlepower distribution (analogous to that produced by a luminaire) can be calculated if the luminance distribution of the window-facing exterior hemisphere and the bidirectional transmittance of the fenestration system are known. The details of the geometry and the surface reflectance of shading devices, which ultimately determine the patterns of light transmission, are implicitly considered in the experimentally determined bidirectional transmittance.

The bidirectional transmission coefficient of a fenestration system is determined by:

$$C(\beta_i,\psi_i,\beta_o\psi_o) = \frac{L_m(\beta_i,\psi_i,\beta_o,\psi_o)}{I_m(\beta_i,\psi_i)} \tag{1}$$

where

$C\ (\beta_i,\psi_i,\beta_o,\psi_o)$ is the transmission coefficient for incoming direction (β_i,ψ_i) and outgoing direction (β_o,ψ_o) ,
$L_m\ (\beta_i,\psi_i,\beta_o,\psi_o)$ is the measured luminance of the fenestration system in direction (β_o,ψ_o), and
I_m is the measured illuminance from an elemental luminous source incident in direction (β_o,ψ_o).

The transmitted luminance distribution of a fenestration system due to the exterior hemisphere (sky, ground, exterior obstructions) is then calculated by:

$$L_c(\beta_o,\psi_o) = \int C(\beta_i,\psi_i\beta_o,\psi_o) \cdot L_e(\beta_i,\psi_i) \cdot \cos\theta_i \cdot d\omega_i \tag{2}$$

where

$L_c(\beta_o,\psi_o)$ is the luminance of the fenestration system in direction (β_o,ψ_o).
$L_e(\beta_i,\psi_i)$ is the luminance of the exterior-hemisphere (sky or ground) element in direction (β_i,ψ_i).
θ_i is the incident angle of the incoming radiation from the exterior-hemisphere (sky or ground) element,
$C\ (\beta_i,\psi_i,\beta_o,\psi_o)$ is the transmission coefficient for incident direction (β_i,ψ_i) and transmitted direction $(\beta_o,\psi o)$, and
$d\omega_i$ is the solid angle subtended by the exterior-hemisphere (sky or ground) element.

For the purposes of converting the set of the discrete measured transmission coefficients into functional form, a new set of algorithms can be used to generate mathematical functions such as associated Legendre polynomials that describe the bidirectional transmittance of fenestration systems.

VALIDATION OF THE COMPUTER ALGORITHMS

For the purposes of validating the new computer algorithms, we performed two different tests using fenestrations having theoretical candlepower distributions that could also be modeled using the previous computational algorithms of SUPERLITE.

For the first test we considered a perfectly diffusing glass. Interior daylight illuminance levels were then calculated and compared using (1) the theoretical bidirectional transmittance of perfectly diffusing glass modeled as a shading device with the new set of algorithms and (2) the diffuse glazing calculation option of the previous algorithms of SUPERLITE. Results showed excellent agreement (Figure 2).

The second test was based on the additive property of light. We again produced two candlepower distributions that combined to give the distribution of perfectly diffusing glass (see Figure 3). Because the sum of the two candlepower distributions of Figure 3 (a) and (b), becomes (c), it is expected that the sum of indoor illuminance levels calculated first by using (a) and then by using (b) should be identical to the illuminance level calculated under candlepower condition (c). Figure (4) verifies this; the sum of the results from (a) and (b) are almost identical to the results from (c).

In the previous cases, we used only candlepower distributions that gave uniform or part of a uniform luminance profile. For the third test we considered a glazing layer with bidirectional transmittances identical to the luminance distribution of the CIE overcast sky. We generated the candlepower distribution of a vertical window with no glazing under the CIE overcast sky condition (see Figure 5a). In this case, the candlepower distribution is theoretically calculated as:

$$L_c(\beta_o,\psi_o) = \frac{1+2\cos\beta_i}{3 \cdot E_v} \tag{3}$$

where

β_i = angle from the zenith, and
E_v = illuminance on vertical plane from the CIE overcast sky.

The overcast sky vertical illuminance can be calculated as a double integral over half of the hemisphere as:

$$E_v = \frac{8 + 3\pi}{18} L_z \tag{4}$$

We compared results from two cases, one room whose window was modeled as a surface having the calculated candlepower distribution, and another modeled as non-glazed window. The calculated indoor illuminances from those two cases were again in excellent agreement (Figure 5-b). These and similar additional comparisons proved that the basic computational approach was viable as implemented.

VALIDATION OF THE NEW APPROACH WITH MEASURED DATA

To test our new approach, we built a simple system to measure $L(\beta_i,\psi_i,\beta_o,\psi_o)$ of a shading device, when the device was illuminated with a collimated beam incident at angle (β_i,ψ_i). The luminance distribution was measured at a limited set of discrete locations by scanning the shading device over the hemispherical field of transmitted flux using a moving sensor. These measured luminance data were converted into bidirectional transmission coefficients as shown in Equation 1. We then calculated interior daylight illuminance values using SUPERLITE with the experimentally determined bidirectional transmission coefficients for a slat-type shading device. These illuminance values were compared to illuminance values measured from a scale model having the same slat-type device. In this case we considered the sun at a specific position on the sky hemisphere as the only source of daylight. Due to the mechanical limitation of the photometric setup used for the purposes of this paper, we could measure the candlepower distribution of the hemisphere only in the portion where the zenith angle is greater than 65°. Thus, we extrapolated measured data to supplement the missing data (see Figure 6 (a) for the measured and extrapolated candlepower data).

The calculated results were in good, but not excellent, agreement with measured ones. The deviation between two results was noticable especially at the points near the window. This was mainly due to the lack of a complete set of the candlepower distribution data of the window, requiring us to use extrapolated data for some directions.

CONCLUSIONS

Initial results of validation tests using measured photometric data for a slat-type shading system are promising. The comparison between measured and calculated daylight illuminance levels in interior spaces suggests that the achievable level of accuracy using SUPERLITE to calculate indoor illuminance values depends on the available detail about the bidirectional properties of complete fenestration systems.

We intend to use the automated scanning radiometer to generate a library of detailed bidirectional properties of many shading systems. The bidirectional properties of multilayer fenestration systems (glazing plus one or more shading systems) can be calculated if the layer-by-layer properties are known [5]. We can then use SUPERLITE to simulate the hourly, seasonal, or annual luminous performance of multilayer fenestration systems of arbitrary complexity. These data can thus be used in conjunction with a future building energy analysis tool such as DOE-2 to simulate the effects of daylight in components and total building energy consumption and demand. We believe that the application of this approach, combining the power and versatility of experimentally determined bidirectional optical properties and the flexibility and speed of advanced simulation techniques, will encourage proper evaluation of daylight design strategies and thus better use of daylight in buildings in future.

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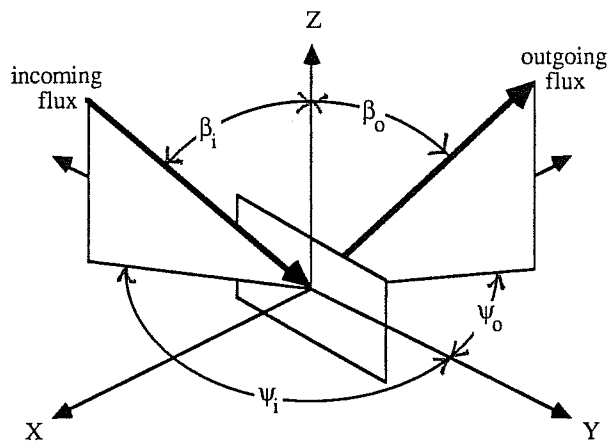
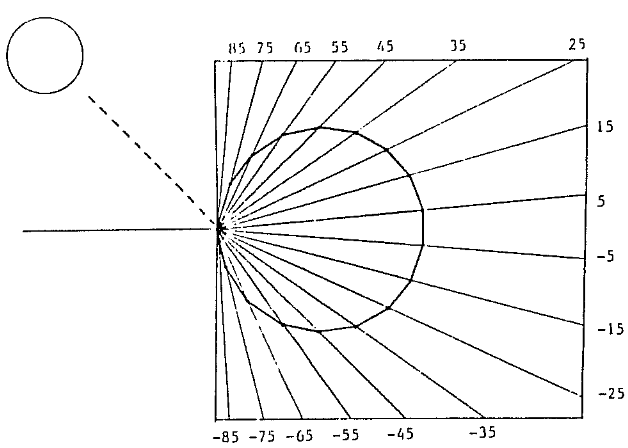
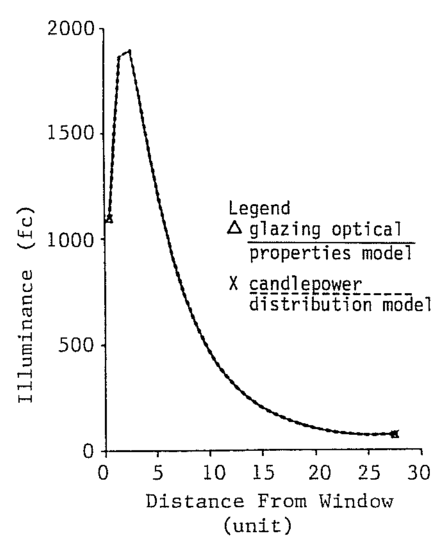


Figure 1. The angles β_i,ψ_i and β_o,ψ_o, which describe the directions of the incoming and outgoing radiation.



a) Candlepower distribution of perfectly diffusing glass



b) Indoor illuminance

Figure 2. Part a shows the candlepower distribution of perfectly diffusing glass. Part b shows a comparison of interior illuminance levels for perfectly diffusive glass calculated with the new candlepower distribution model and the old glazing properties algorithms of SUPERLITE.

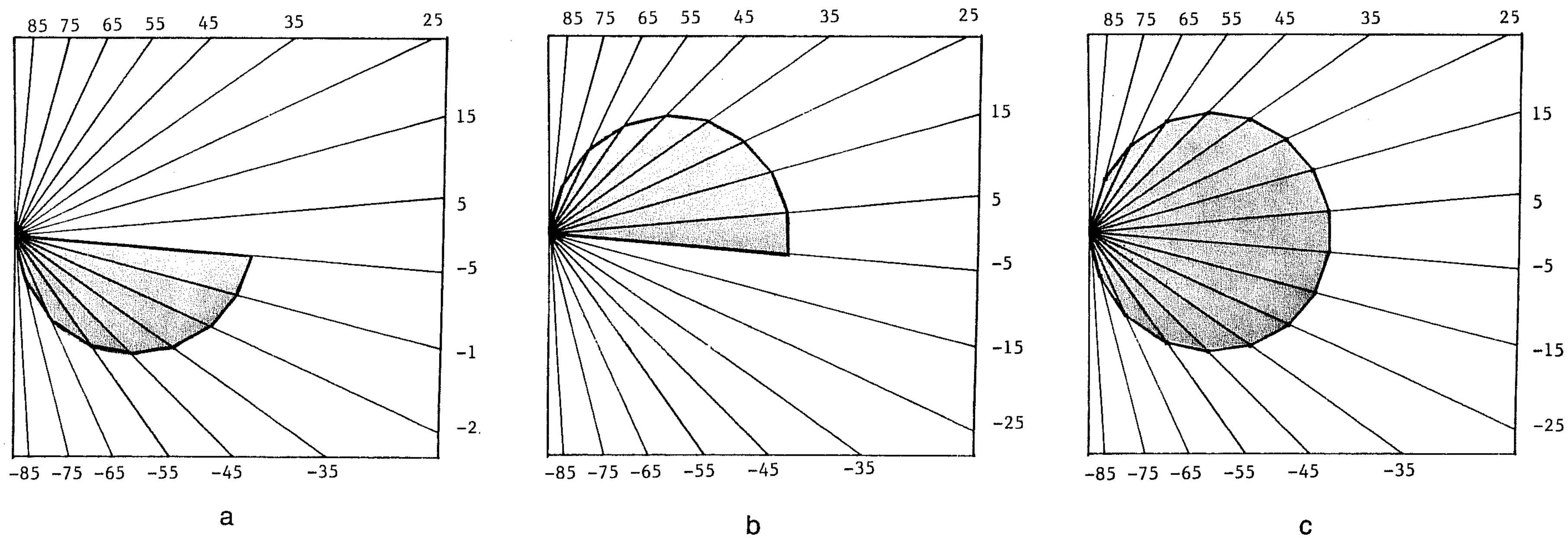


Figure 3. Complementary candlepower distributions of simulated shading device (diffusing glass).

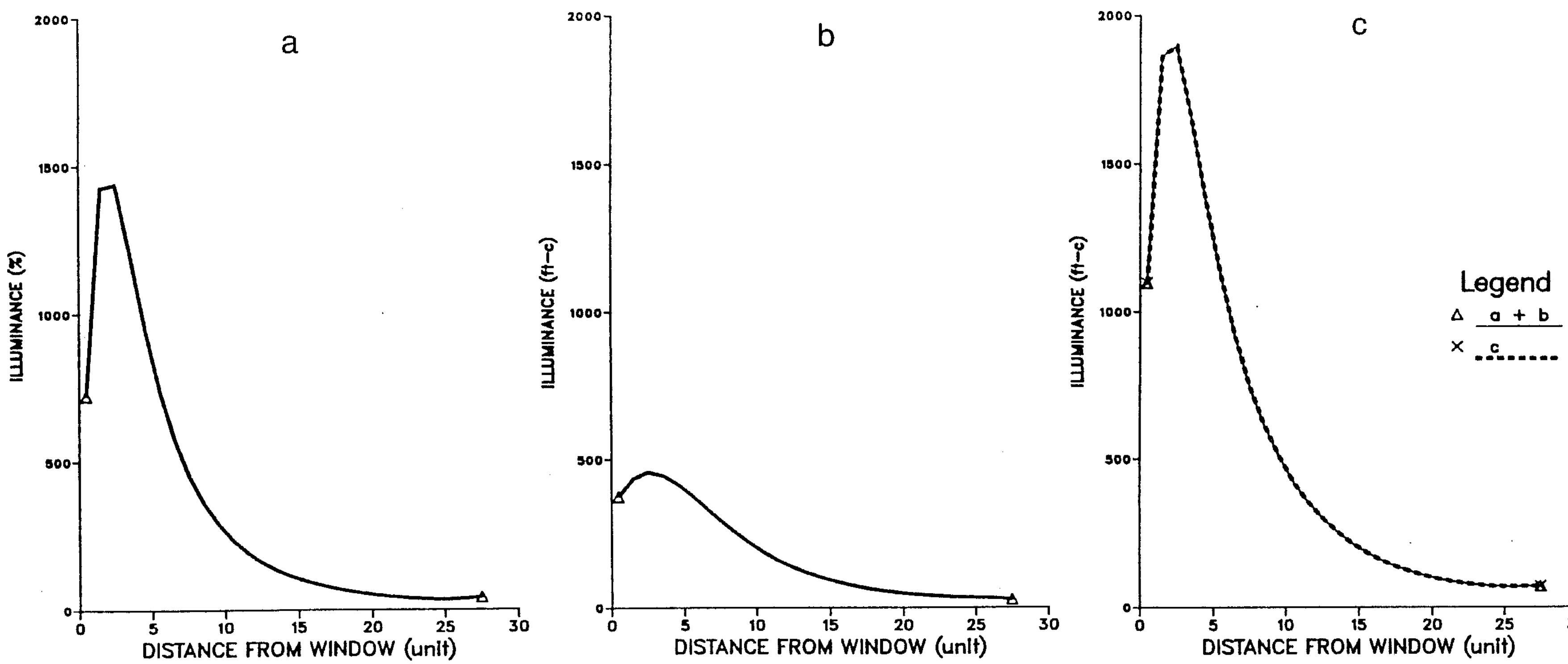
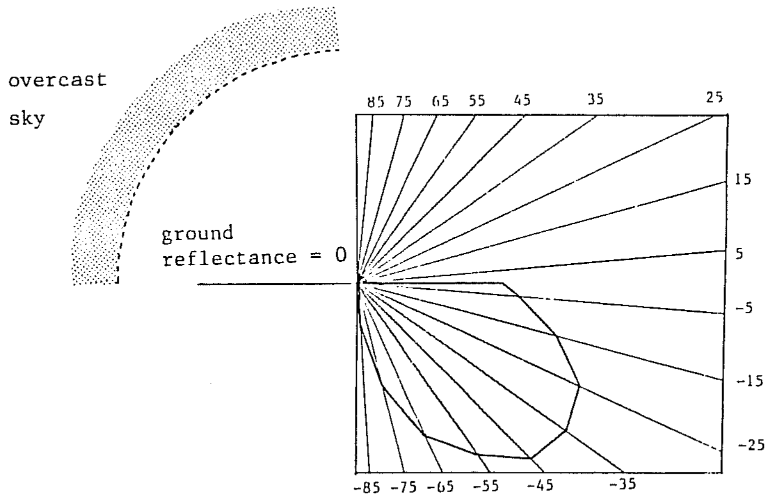
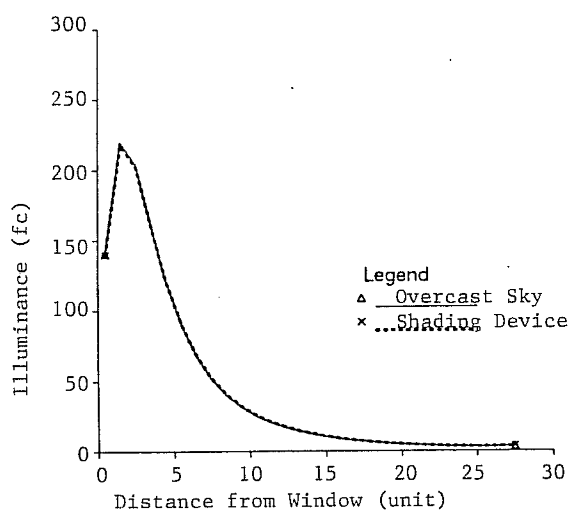


Figure 4. Parts a, b, and c show calculated indoor illuminance levels using the complementary candlepower distributions shown in Figure 3a, b, and c, respectively.



a) Candlepower distribution of clear glass window under overcast sky



b) Indoor illuminance

Figure 5. Comparison showing excellent agreement of interior illuminance values for: 1) a theoretical fenestration system having a candlepower distribution equal to the luminance distribution of the CIE overcast sky calculated with the new algorithms of SUPERLITE, and 2) a clear glass window under the CIE overcast sky.

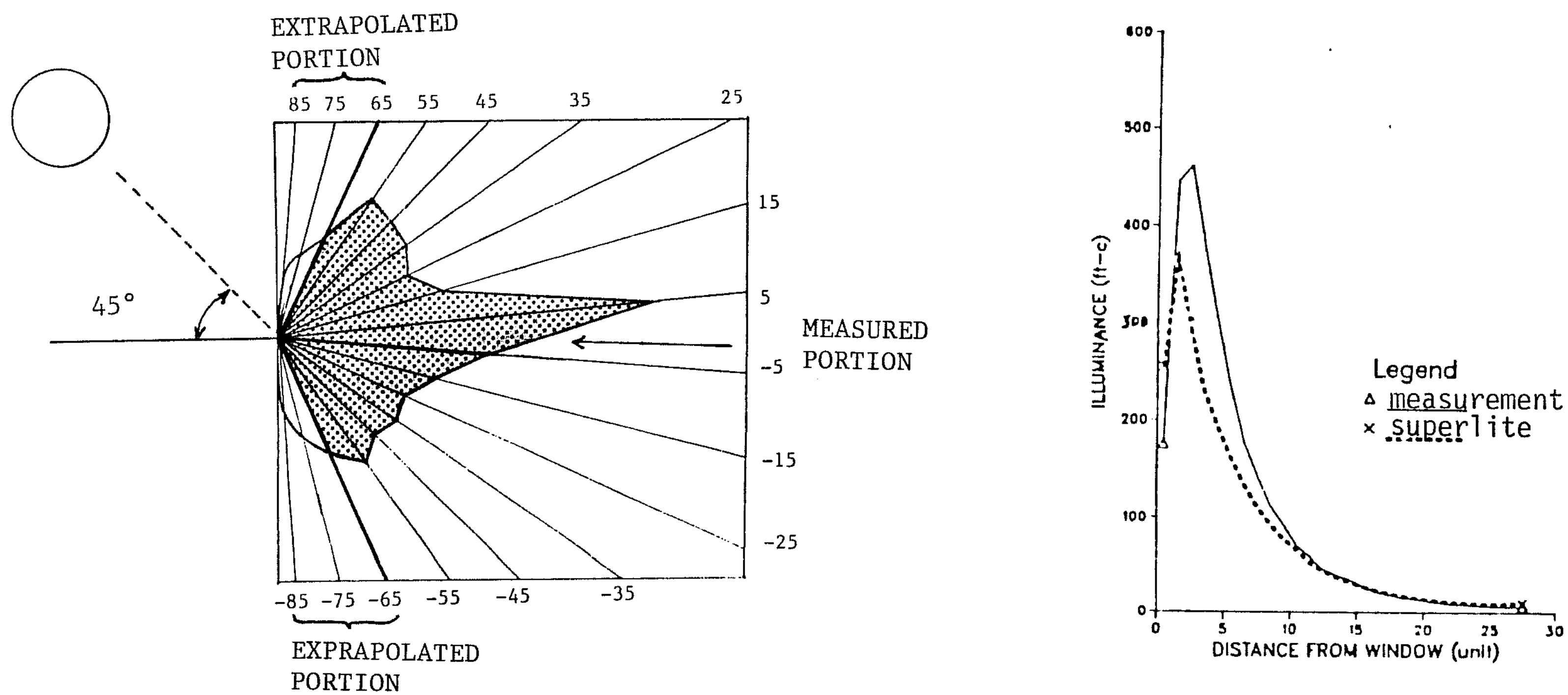


Figure 6. Comparison of measured and calculated indoor illuminance using measured candlepower distribution.