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Abstract

A new method to simulate the daylight performance of fenestration systems and spaces is presented. This new method, named IDC (Integration of Directional Coefficients), allows the simulation of the daylight performance of fenestration systems and spaces of arbitrary complexity, under any sun, sky and ground conditions. The IDC method is based on the combination of scale model photometry and computer-based simulation. Physical scale models are used to experimentally determine a comprehensive set of "directional illuminance coefficients" at reference points of interest, which are then used in analytical, computer-based routines, to determine daylight factors or actual daylight illuminance values under any sun, sky and ground conditions.

The main advantage of the IDC method is its applicability to any optically complex environment. Moreover, the computer-based analytical routines are fast enough to allow for hourly simulation of the daylight performance over the course of an entire year. However, the method requires appropriate experimental facilities for the determination of the Directional Coefficients. The IDC method has been implemented and used successfully in inter-validation procedures with various daylight simulation computer programs. Currently, it is used to simulate the daylight performance of fenestration systems that incorporate optically complex components, such as Venetian blinds, optically treated light shelves and light pipes.

Introduction

Simulation of the daylight performance of fenestration systems and spaces is essential for appropriate consideration of luminous comfort and the estimation of potential energy savings through daylighting. There are two main approaches to simulating the daylight performance of fenestration systems and spaces: scale model photometry and computer-based simulation.

Scale model photometry involves measurements of light levels in a scale model under real or simulated sun, sky and ground conditions. The main advantage of this approach is the ability to model environments of arbitrary complexity, as accurately as the scale model represents the modeled environment. The main disadvantage of this approach is related to the need of the daylight source in the form of a sun, sky and ground environment. Measurements under real sky conditions, especially when the scale model is placed at the actual building site, may seem ideal. However, the lack of control with respect to the outdoor conditions and the position of the sun limit the applicability of this method to the time of the year and the outdoor conditions of the time of the measurements. This major problem has led to the development of sky simulation facilities, which are used to reproduce sky luminance distributions on the interior surface of hemispherical structures. However, such facilities are limited with respect to the number of the sky luminance distributions that they can model. Moreover, most facilities lack proper consideration of the sun and ground as sources of daylight.

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Computer-based simulation methods involve the implementation of radiation transfer algorithms, using an appropriate description of the environment to be modeled in terms of xyz coordinates, optical properties of surfaces and standardized sun, sky and ground luminance distributions. Currently there are many computer programs available for daylight analyses, with varying degrees of modeling capabilities and prediction accuracy (Windows and Daylighting 1990). The main advantage of computer-based simulation is the consideration of any time of the year and, depending on computation time requirements allowing hour-by-hour daylight analyses over the course of an entire year. The major disadvantage of computer-based simulations is the incorporation of assumptions about the geometry and the optical properties of the fenestration system and the interior and exterior surfaces. Moreover, the simulation of complex fenestration systems and spaces requires the employment of methods such as ray-tracing, whose computational time requirements may become prohibitive for comprehensive hour-by-hour daylight analyses.

The IDC Method

The method presented in this paper, named IDC (Integration of Directional Coefficients), is based on a hybrid approach, that is a combination of scale model photometry and computer-based simulation. Through scale model photometry, the IDC method allows the consideration of fenestration systems and spaces of arbitrary complexity, while through computer-based simulation it allows the consideration of the daylight performance at any time over the course of an entire year.

Scale Model Photometry

Scale model photometry is used to determine a comprehensive set of "directional illuminance coefficients," at any interior point of interest (e.g., workplane illuminance) using a scale model of the space and the fenestration system and a collimated beam of light. These coefficients are defined as:

$$C(\zeta,\vartheta)=\frac{E_i(\zeta,\vartheta)}{E_e^n(\zeta,\vartheta)} \quad (1),$$

where $E_i(\zeta,\vartheta)$ is the interior illuminance due to the collimated beam of light in the direction specified by (ζ,ϑ) and $E_e^n(\zeta,\vartheta)$ is the exterior illuminance due to and normal to the collimated beam of light in the direction specified by (ζ,ϑ) (Figures 1and 2).

Since the term $E_i(\zeta,\vartheta)$ includes the contribution of all inter-reflections, the fenestration system and the interior space are treated as a single optical system, whose behavior is described through the directional coefficients that relate its input, $E_e^n(\zeta,\vartheta)$, and output, $E_i(\zeta,\vartheta)$. The interior illuminance, then, due to a collimated beam of light in the direction specified by (ζ,ϑ) is determined by:

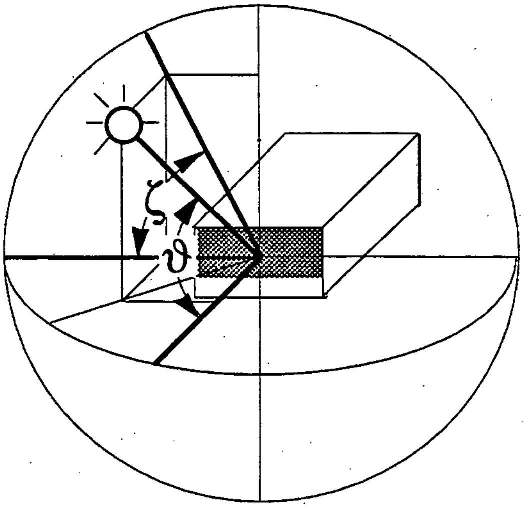

Figure 1. The ζ,ϑ coordinate system used to specify the incoming directions of radiation, relative to the fenestration system.

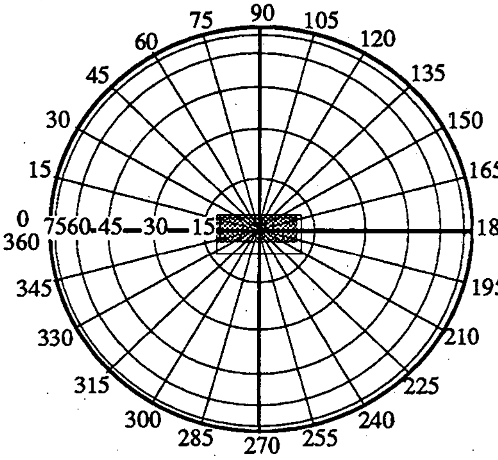

Figure 2. Projection of the ζ,ϑ angles on the window plane.

$$E_i(\zeta,\vartheta)=E_e^n(\zeta,\vartheta)\cdot C(\zeta,\vartheta) \quad (2).$$

The directional illuminance coefficients can then be used to determine the interior daylight illuminance due to radiation from the sun, or from a sky or ground element. Inclusion of these coefficients in integration over the luminance distribution of the sky and the ground can then be used to determine the interior daylight illuminance due to any sky and ground conditions, using analytical, computer-based routines.

Computer-Based Simulation

Two main sources of daylight are considered for the application of the directional illuminance coefficients: the sun, and the sky. Both are considered through the determination of Daylight Factors, which include not only the direct contribution of each source, but the contribution through reflection off the ground and through inter-reflections within the space.

The Sun Daylight Factor

The Sun Daylight Factor is defined as the ratio of the interior illuminance at a reference point due to direct (and inter-reflected direct) radiation from the sun, including the direct (and the inter-reflected direct) radiation from the ground due to direct radiation from the sun, to the exterior horizontal direct radiation from the sun:

$${}^{s}_{t}\mathrm{DF} = \frac{{}^{s}_{t}E_i}{{}^{s}E^h_e} \qquad (3),$$

where ${}^{s}_{t}E_i$ is the interior illuminance due to total radiation from the sun, and ${}^{s}E^h_e$ is the exterior horizontal illuminance due to radiation from the sun. Note that the Sun Daylight Factor is a function of the relative position of the sun to the window.

Separating the direct and reflected-off-the-ground components of the interior illuminance in Equation 3, results in:

$${}^{s}_{t}\mathrm{DF} = \frac{{}^{s}_{d}E_i + {}^{s}_{g}E_i}{{}^{s}E^h_e} = \frac{{}^{s}_{d}E_i}{{}^{s}E^h_e} + \frac{{}^{s}_{g}E_i}{{}^{s}E^h_e} \qquad (4),$$

where ${}^{s}_{d}E_i$ is the interior illuminance due to direct radiation from the sun, including the interior inter-reflections, and ${}^{s}_{g}E_i$ is the interior illuminance due to reflected-off-the-ground radiation from the sun, including the interior inter-reflections.

The Sun Daylighting Factor has, then, two distinct components, the *direct* component of the Sun Daylight Factor, which is a function of the relative position of the sun to the window:

$${}^{s}_{d}\mathrm{DF} = \frac{{}^{s}_{d}E_i}{{}^{s}E^h_e} \qquad (5),$$

and the *ground* component of the Sun Daylight Factor, which is independent of the relative position of the sun to the window:

$${}^{s}_{g}\mathrm{DF} = \frac{{}^{s}_{g}E_i}{{}^{s}E^h_e} \qquad (6).$$

The exterior horizontal illuminance due to direct radiation from the sun can be also expressed as:

$${}^{s}E^h_e = {}^{s}E^n_e \cdot \cos\theta \qquad (7),$$

where θ is the incident angle of the direct solar radiation on a horizontal plane.

The direct component of the Sun Daylight Factor is then determined by substituting from Equations 1 and 7 into Equation 5:

$${}^{s}_{d}\mathrm{DF} = \frac{{}^{s}_{d}E^n_e \cdot C(\zeta,\vartheta)}{{}^{s}_{d}E^n_e \cdot \cos\theta} = \frac{C(\zeta,\vartheta)}{\cos\theta} \qquad (8).$$

The interior illuminance due to reflected-off-the-ground radiation from the sun is determined through integration of Equation 1 over the luminance distribution of the ground*:

$${}^{s}_{g}E_i = \int_{\zeta=180}^{360} \int_{\vartheta=0}^{90} L^s_g(\zeta,\vartheta) \cdot C(\zeta,\vartheta) \cdot \sin\vartheta \cdot d\zeta \cdot d\vartheta \qquad (9),$$

where $L^s_g(\zeta,\vartheta)$ is the ground luminance in the direction specified by (ζ,ϑ) due to direct radiation from the sun, and $C(\zeta,\vartheta)$ is the experimentally determined coefficient for the incoming direction specified by (ζ,ϑ). Equation 6, then, becomes:

$${}^{s}_{g}\mathrm{DF} = \frac{\int_{\zeta=180}^{360} \int_{\vartheta=0}^{90} L^s_g(\zeta,\vartheta) \cdot C(\zeta,\vartheta) \cdot \sin\vartheta \cdot d\zeta \cdot d\vartheta}{{}^{s}E^h_e} \qquad (10).$$

Considering uniform ground reflectance, the luminance of the ground due to radiation from the sun is:

$$L^s_g = \frac{{}^{s}E^h_e \cdot \rho_g}{\pi} \qquad (11).$$

where ρ_g is the uniform ground reflectance. Equation 10, then, becomes:

$${}^{s}_{g}\mathrm{DF} = \frac{\rho_g \cdot \int_{\zeta=180}^{360} \int_{\vartheta=0}^{90} C(\zeta,\vartheta) \cdot \sin\vartheta \cdot d\zeta \cdot d\vartheta}{\pi} \qquad (12).$$

The Sky Daylight Factor

In a similar way to the Sun Daylight Factor, the Sky Factor is defined as the ratio of the interior illuminance at a reference point due to direct (and inter-reflected direct) radiation from the sky, including the direct (and the inter-reflected direct) radiation from the ground due to direct radiation from the sky, to the exterior horizontal direct radiation from the sky, that is,

$${}^{k}_{t}\mathrm{DF} = \frac{{}^{k}_{t}E_i}{{}^{k}E^h_e} \qquad (13),$$

where ${}^{k}_{t}E_i$ is the interior illuminance due to total radiation from the sky, and ${}^{k}E^h_e$ is the exterior horizontal illuminance due to radiation from the sky. Note that the Sky Daylight Factor is a function of the relative position of the sun to the window. This is true only for sky luminance distributions that are functions of the sun's position, such as the CIE Clear Sky luminance distribution (CIE 1973), but not for sky luminance distributions that are independent of the sun position, such as the CIE Overcast luminance distribution (CIE 1970).

Separating the direct and reflected-off-the-ground components of the interior illuminance in Equation 16, results in:

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* Equations refer to spaces with vertical windows. Integration limits would be different for sloped windows and skylights.

$${}^k_t\mathrm{DF} = \frac{{}^k_d E_i + {}^k_g E_i}{{}^k E_e^h} = \frac{{}^k_d E_i}{{}^k E_e^h} + \frac{{}^k_g E_i}{{}^k E_e^h} \qquad (14),$$

where ${}^k_d E_i$ is the interior illuminance due to direct radiation from the sky, including the interior inter-reflections, and ${}^k_g E_i$ is the interior illuminance due to reflected-off-the-ground radiation from the sky, including the interior inter-reflections.

The Sky Daylighting Factor has, then, two distinct components, the *direct* component of the Sky Daylight Factor, which is a function of the relative position of the sun to the window:

$${}^k_d\mathrm{DF} = \frac{{}^k_d E_i}{{}^k E_e^h} \qquad (15),$$

and the *ground* component of the Sky Daylight Factor, which is independent of the relative position of the sun to the window.

$${}^k_g\mathrm{DF} = \frac{{}^k_g E_i}{{}^k E_e^h} \qquad (16).$$

The interior illuminance due to direct radiation from the sky is determined through integration of Equation 1 over the luminance distribution of the sky:

$${}^k_d E_i = \int_{\zeta=0}^{180} \int_{\vartheta=0}^{90} L_k(\zeta,\vartheta)\cdot C(\zeta,\vartheta)\cdot \sin\vartheta\cdot d\zeta\cdot d\vartheta \qquad (17),$$

where $L_k(\zeta,\vartheta)$ is the sky luminance in the direction specified by (ζ,ϑ), and $C(\zeta,\vartheta)$ is the measured coefficient for the incoming direction specified by (ζ,ϑ).

The exterior horizontal illuminance due to direct radiation from the sky is determined through integration over the luminance distribution of the whole sky:

$${}^k E_e^h = \int_{\xi=0}^{360} \int_{\theta=0}^{90} L_k(\xi,\theta)\cdot \sin\theta\cdot\cos\theta\cdot d\xi\cdot d\theta \qquad (18),$$

where $L_k(\xi,\theta)$ is the sky luminance in the direction specified by (ξ,θ), which are now relative to the ground plane.

Substituting from Equations 17 and 18 into Equation 15 results in:

$${}^k_d\mathrm{DF} = \frac{\displaystyle\int_{\zeta=0}^{180} \int_{\vartheta=0}^{90} L_k(\zeta,\vartheta)\cdot C(\zeta,\vartheta)\cdot \sin\vartheta\cdot d\zeta\cdot d\vartheta}{\displaystyle\int_{\xi=0}^{360} \int_{\theta=0}^{90} L_k(\xi,\theta)\cdot \sin\theta\cdot\cos\theta\cdot d\xi\cdot d\theta} \qquad (19).$$

The luminance of the sky is usually expressed as a luminance distribution function relative to the luminance of the sky zenith:

$$L_k(\zeta,\vartheta) = L_z\cdot K(\zeta,\vartheta) \qquad (20).$$

where L_z is the luminance of the sky zenith, and $K(\zeta,\vartheta)$ is the luminance distribution function. Equation 19, then, becomes:

$${}^k_d\mathrm{DF} = \frac{\displaystyle\int_{\zeta=0}^{180} \int_{\vartheta=0}^{90} K(\zeta,\vartheta)\cdot C(\zeta,\vartheta)\sin\vartheta\cdot d\zeta\cdot d\vartheta}{\displaystyle\int_{\xi=0}^{360} \int_{\theta=0}^{90} K(\xi,\theta)\cdot \sin\theta\cdot\cos\theta\cdot d\xi\cdot d\theta} \qquad (21).$$

The interior illuminance due to reflected-off-the-ground radiation from the sky is determined through integration of Equation 1 over the luminance distribution of the ground:

$${}^k_g E_i = \int_{\zeta=180}^{360} \int_{\vartheta=0}^{90} L_g^k(\zeta,\vartheta)\cdot C(\zeta,\vartheta)\cdot \sin\vartheta\cdot d\zeta\cdot d\vartheta \qquad (22),$$

where $L_g^s(\zeta,\vartheta)$ is the ground luminance in the direction specified by (ζ,ϑ) due to direct radiation from the sky, and $C(\zeta,\vartheta)$ is the experimentally determined coefficient for the incoming direction specified by (ζ,ϑ). Equation 16, then, becomes:

$${}^k_g\mathrm{DF} = \frac{\displaystyle\int_{\zeta=180}^{360} \int_{\vartheta=0}^{90} L_g^k(\zeta,\vartheta)\cdot C(\zeta,\vartheta)\cdot \sin\vartheta\cdot d\zeta\cdot d\vartheta}{{}^k E_e^h} \qquad (23),$$

Considering uniform ground reflectance, the luminance of the ground due to radiation from the sky is:

$$L_g^k = \frac{{}^k E_e^h\cdot \rho_g}{\pi} \qquad (24),$$

where ρ_g is the uniform ground reflectance. Equation 23, then ,becomes:

$${}^k_g\mathrm{DF} = \frac{\rho_g\cdot \displaystyle\int_{\zeta=180}^{360} \int_{\vartheta=0}^{90} C(\zeta,\vartheta)\cdot \sin\vartheta\cdot d\zeta\cdot d\vartheta}{\pi} \qquad (25).$$

The ground components of the Sun Daylight Factor (Equation 12) and the Sky Daylight Factor (Equation 25) are, then, identical.

Implementation and Inter-validation

The IDC method has been implemented using a scanning radiometer (Papamichael et al. 1987, 1988) for the determination of the directional coefficients and a computer program named SSG (Sun Sky Ground) for the implementation of the analytical routines. This IDC implementation has been used in inter-validation procedures with three computer-based simulation methods: the daylighting algorithms of the DOE-2 energy analysis computer program (Building Energy Simulation Group 1984a, 1984b), the SUPERLITE daylight analysis computer program (Modest 1982; Windows and Daylighting Group 1985, 1993) and the RADIANCE ray-tracing computer program (Ward 1990).

A daylight analysis was performed using a 1/2 inch to 1 foot scale model of a 20 feet wide by 30 feet deep space, with a ceiling height of 10 feet, having a 20 feet wide by 7 feet high window, with a 3 feet sill height. The window had single clear glass of 0.9 visible transmittance and 0.09 visible reflectance, while the reflectance of the interior surfaces were 0.44 for the walls, 0.21 for the floor, and 0.76 for the ceiling. Directional workplane illuminance coefficients were determined for six reference points, at 5 feet increments along the centerline of the space starting at 2.5 feet from the window wall, at a height of 2.5 feet. The incoming directions of radiation were considered at 15 degrees increments for the ζ and ϑ angles (Figures 3 and 4). The SSG computer program was then used to simulate the daylight performance of the modeled space for the CIE overcast and 30 CIE clear sky luminance distributions, considering uniform ground reflectance of 0.0 and 0.5.

The same space was then modeled using DOE-2, SUPERLITE and RADIANCE. The results from these computer programs were then compared to those derived using the IDC method (Figures 5 through 9).

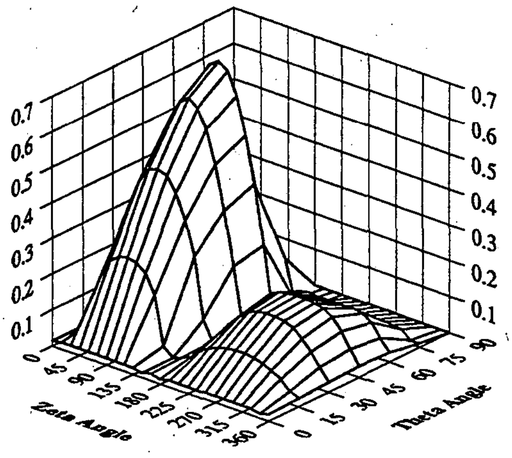

Figure 3. Directional Illuminance Coefficients for reference point at 2.5 feet from clear glass window.

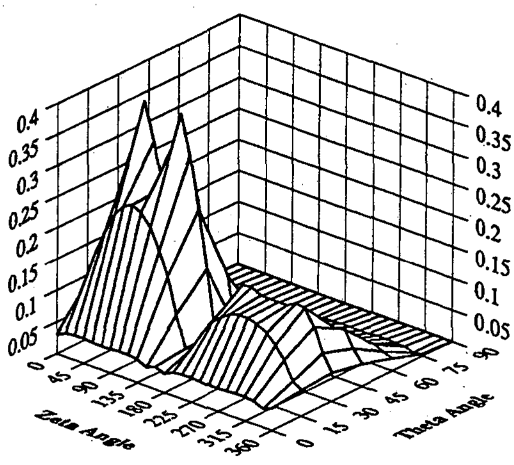

Figure 4. Directional Illuminance Coefficients for reference point at 12.5 feet from clear glass window.

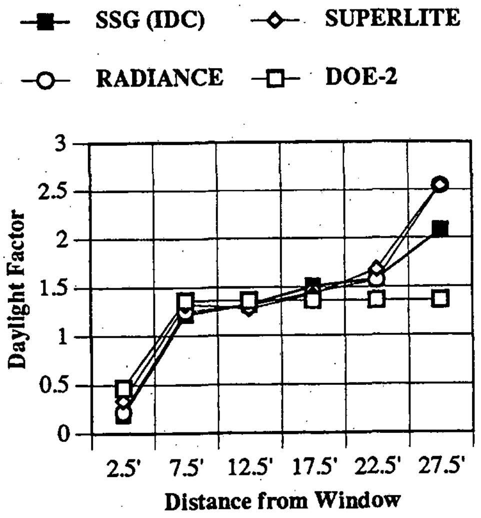

Figure 5. Sun Daylight Factors for sun at ζ=15 degrees and ϑ=15 degrees.

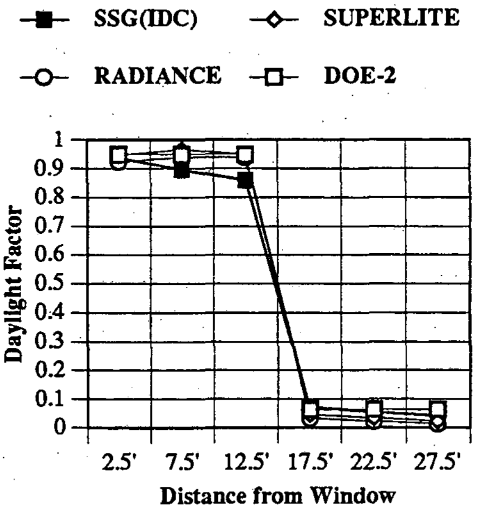

Figure 6. Sun Daylight Factors for sun at ζ=60 degrees and ϑ=50 degrees.

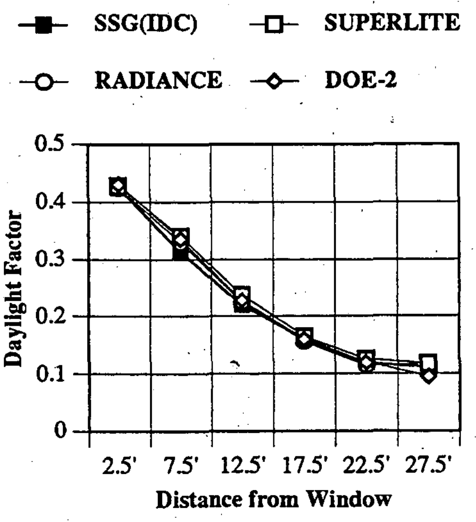

Figure 7. CIE Clear Sky Daylight Factors for sun at ζ=15 degrees and ϑ=15 degrees.

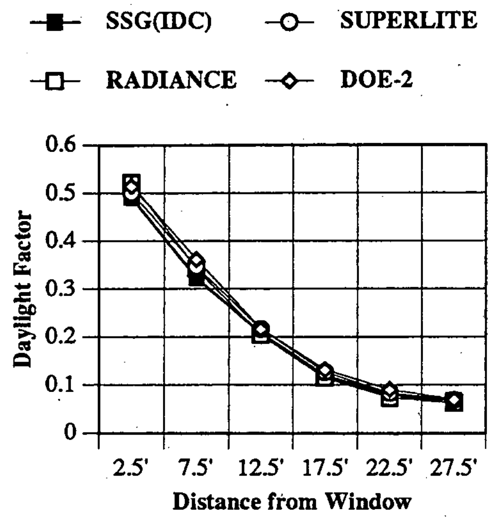

Figure 8. CIE Clear Sky Daylight Factors for sun at $\zeta=60$ degrees and $\vartheta=50$ degrees.

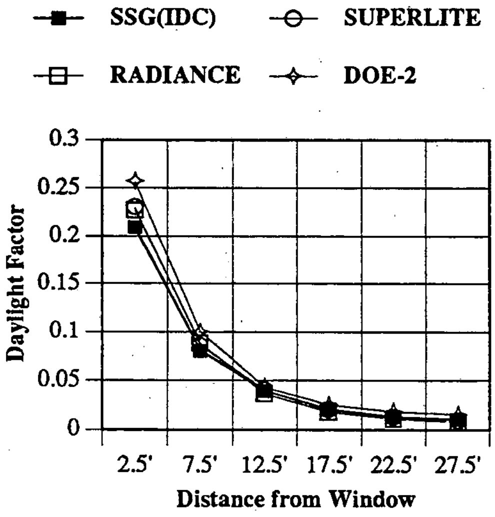

Figure 9. CIE Overcast Sky Daylight Factors.

The IDC method is currently used to determine the hour-by-hour daylight performance of optically complex fenestration systems, such as Venetian blinds, light shelves and light pipes (Figures 10 through 13). Multiple SSG runs are used to determine a comprehensive set of Sun and Sky Daylight Factors, for sun positions on 15° increments with respect to solar azimuth and altitude. These daylight factors are then used with the DOE-2 energy analysis program to determine hour-by-hour daylight performance over the course of an entire year, through interpolation.

Discussion

The IDC method was developed as a response to the need for hourly daylight analyses over the course of an entire year of optically complex fenestration systems. So far, the method has been proven very powerful and efficient. The SSG algorithms are simple and fast, thus suitable for hourly daylight analyses. However, the experimental procedures for the determination of directional coefficients may be time consuming without an appropriate experimental setup like the scanning radiometer used for this

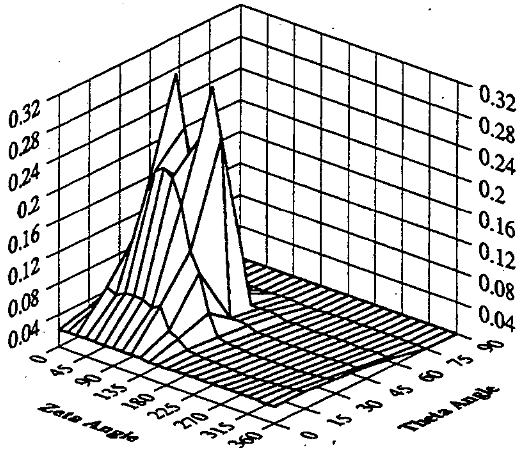

Figure 10. Directional Illuminance Coefficients for reference point at 12.5 feet from Venetian blinds at 45 degrees upward position.

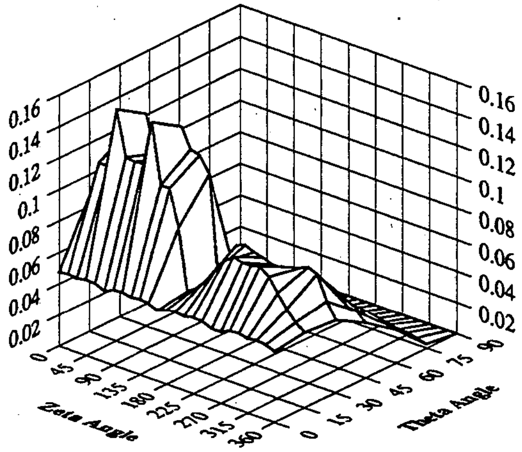

Figure 11. Directional Illuminance Coefficients for reference point at 12.5 feet from Venetian blinds at fully open position.

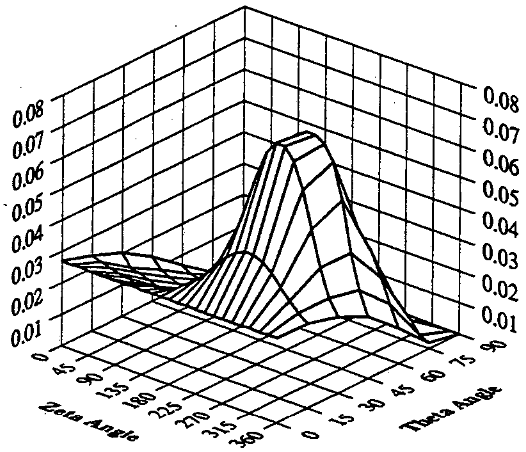

Figure 12. Directional Illuminance Coefficients for reference point at 12.5 feet from Venetian blinds at 45 degrees downward position.

implementation, or other approaches that allow accurate angular control of the incoming direction of radiation to the scale model.

In addition to scale model representation and photometry issues, the accuracy of the IDC method depends on the density of the incoming directions of radiation considered for the determination of the directional coefficients. This density affects mainly the direct component of the Sun Daylight Factor, which may vary significantly with small variations in the incoming direction of radiation. Plans for the immediate future include experimentation to quantify these effects on single-time daylight performance, as well as on daily, monthly and annual performance.

Future research and development plans include further inter-validation between the IDC method and the RADIANCE ray-tracing computer program, considering optically complex fenestration systems and spaces.

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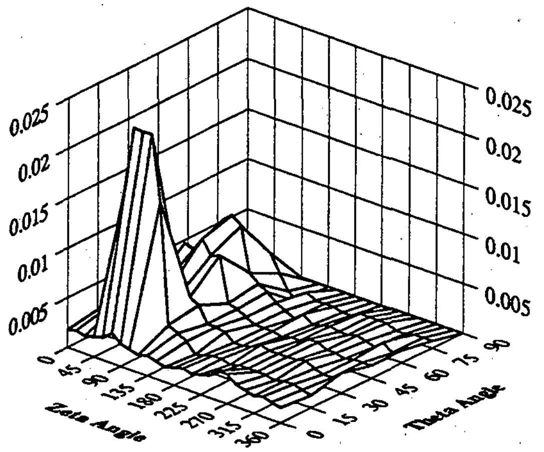

Figure 12. Directional Illuminance Coefficients for reference point at 12.5 feet from an optically treated light shelf design.

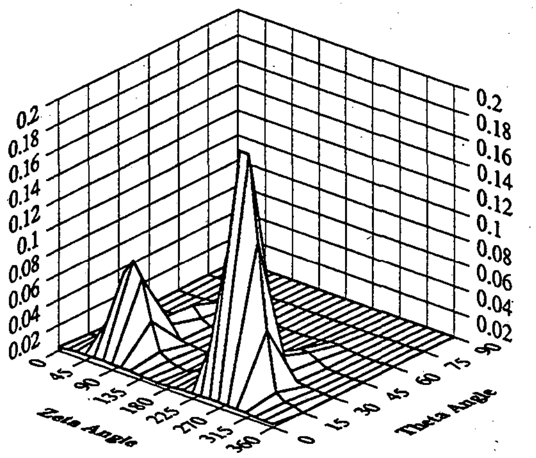

Figure 13. Directional Illuminance Coefficients for reference point at 27.5 feet from a light pipe design.

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