A Comparison of Photometric Modeling and Computer Simulation Techniques for Daylighting Prediction under Real Sky Conditions

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ABSTRACT

The importance of daylighting with respect to the thermal performance of building envelopes has been demonstrated. The two commonly used techniques for prediction of daylighting patterns are scale-model photometry and computer simulation. Comparative studies directed at development of a standard for the application of these techniques have been limited to artificial uniform sky conditions. In this study, photometric measurements for four fenestration types, made under real overcast skies and clear skies with sun, were compared with computer simulation results.

It was found that measures of daylight availability obtained at the experimental site differed widely from those predicted by equations for standard clear skies. Comparisons between scale-model photometry and simulation were therefore based on clear sky data collected at the test site. Generally good agreement was obtained for two window systems with relatively large and simple openings. There were larger discrepancies for a small window, both with and without shades. The increase in discrepancy with decreasing aperture size was consistent with the effects of factors that contribute to errors in scale model photometry and computer simulation.

INTRODUCTION

The importance of daylighting with respect to the thermal performance of building envelopes has been demonstrated (Jurovics 1982; Rundquist 1982; R. Johnson et al. 1984; C. Johnson et al. 1988). Substitution of daylight for electrical illumination can reduce electrical energy use for lighting and cooling, but may have complex effects on heat gains and losses across the building envelope. Window size and placement will affect both heat gain and loss as well as the effectiveness of the daylighting system in terms of illumination levels, penetration of light, and glare. To improve thermal and daylighting performance, some designers are employing more complex fenestration systems (Thomas et al. 1986; Heap et al. 1988; Love et al. 1988). The evaluation of these envelope designs requires increasingly sophisticated analytical tools and better knowledge of the performance of these tools.

The two most commonly used tools for analysis of the illumination performance of daylighting systems are computer simulation programs and scale-model photometry. In 1985, researchers at a national laboratory reported on a beginning effort to carry out a rigorous comparative evaluation of these tools (Spitzglas et al. 1985). The study was limited to consideration of uniform sky conditions (the photometric studies employed an artificial sky). Generally good agreement was obtained between the methods for side-lighting systems. The investigation of overcast and clear sky conditions, the subject of this paper, was concluded to be a necessary extension of this effort.

COMPARATIVE EVALUATION OF DAYLIGHTING ANALYSIS TOOLS

Discrimination of the Direct and Internally Reflected Components of Daylight

The Spitzglas et al. (1985, 42) paper noted that "the computational algorithms of most daylighting calculation programs treat the direct component of daylight (the flux initially entering the space

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through the windows) separately and differently from the way they treat the (internally) reflected component." Their experiments were therefore designed to distinguish between the direct and internally reflected contributions to interior light levels. This was achieved by taking two sets of measurements, one in a relatively high reflectance space (giving combined direct and reflected illuminances) and the other in a black interior in which conditions would be approached where only a direct component would exist. Measurements in the black model were corrected by subtracting estimates of the reflected component obtained using the numerical method, although these were often negligible. The difference between the total (white interior) and the direct (corrected black interior) values would yield a reflected component determined from measurements. The same approach was employed in this study. The authors also used the same daylighting simulation computer program since it represents the state of the art in digital simulation (Modest 1982, 1983; LBL 1985).

Factors Contributing to Error in Scale Model Photometry and Computer Simulation

Some factors contributing to error in scale model photometry are substantially under the control of the experimenter, including relative calibration of sensors and surface reflectances. Others are less readily mitigated; these are:

1. The size of the photocell. A photocell with an aperture 5/16 in (80 mm) in diameter placed in a 1:12 scale model measures illuminance on an area equivalent to 4 in (100 mm) across at full scale. Where illuminances are changing rapidly and by large degrees (close to a window without shading controls and at the "no sky" line, the boundary beyond which the photocell does not have a direct view of the sky), significant error may result.

2. Sensor leveling. In sidelit spaces, where much of the light striking a photocell does so at an oblique angle, small errors in leveling a photocell may produce large errors in illuminance measurements (Walsh 1961; Spitzglas et al. 1985). This error is more important the greater the contribution of the direct component to the overall illuminance at the point of interest.

3. Sensor placement. While it is not difficult to place photocell faces with sufficient accuracy for most conditions, small placement errors may produce significant measurement errors where light levels are changing rapidly and by large degrees (see number 1 above).

As with scale-model photometry, some factors contributing to error in computer simulation can easily be controlled, such as the number of iterations used in a numerical technique. The researcher faces greater difficulties in the case of

1. Surface element size. Within the limits of the computer program's features, the user may specify the size of surface elements. This has an effect on accuracy because the program determines values of illuminance only for the center point of the surface element and this values is taken to be the illuminance for the entire element. The smaller the grid element, the smaller will be the error introduced by this assumption. Increasing the number of grid elements increases memory requirements and computation time; the fineness of the "mesh" may also be limited by program capabilities.

   Large errors may occur with small apertures because sunlight or daylight striking parts of the few interior elements with a view of the sky will be ignored if they do not strike the center; likewise, the program may overestimate the illuminance on a surface element if the center has a view of the sun or sky but much of the element does not.

2. The representativeness of the daylight availability function. The computer program employs standard daylight availability functions. These are based on long-term averages typically measured at locations other than that at which the photometric measurements are being performed.

3. The representativeness of the sky luminance distribution function. See number 2, above. It is likely that errors due to this factor will increase as the size of the aperture decreases since small parts of the sky may diverge widely from average values (for instance, a small bright spot in an overcast sky).

Except as specifically noted above, these errors have no apparent bias in terms of over- or under-estimation of daylight levels.

The Test Space and the Test Fenestration Systems

While the Spitzglas et al. study dealt with both top- and side-lighting systems, this study was limited to sidelighting systems since a wider range of sky conditions were to be investigated. The proportions of the test space (18 ft window wall, 24 ft room depth, 8 ft ceiling) were chosen to correspond to common office dimensions and to provide a good test of daylight analysis tools in terms of determining direct and internally reflected components (hence, a room depth triple the ceiling height). The window wall width corresponds to that in a space currently being developed into a full-scale photometric measurement facility; it is the same as that used in a full-scale study of daylighting (Maitreya 1977) and can be divided into two equal modules typical of small individual offices.

The test fenestration systems (see Figure 1) were selected to:

1. test different capabilities of the simulation program (e.g., windows with and without frame effects);

2. correspond to window systems addressed in other studies of the thermal performance of building envelopes and typical of those found in real buildings; and/or

3. represent innovative approaches to daylighting.

Window system 1, an entirely glazed window wall, was the simplest system. It is equivalent to a transparent floor-to-ceiling curtain wall. Window systems 2 and 3 added the complexity of a 6 in (150 mm) deep window frame. Window system 2 meets the requirements of window-to-wall ratio and visible transmittance determined by Johnson et al. (1984) to be optimal in terms of energy use for a cold climate (Madison, WI) daylit building. Window system 3 represents the type of high window that might be used to obtain deeper daylight penetration, while window system 4 is the same window with interior and exterior "light shelves" added to provide shade from direct sun and to reflect direct sunlight onto the ceiling of the test space. In practice, a window such as type 3 or 4 would likely be used with a "view" window such as type 2; they were analyzed separately for convenience (since illuminances can be added, the combined effects of different window systems may easily be determined).

Daylight Availability

The determination of instantaneous interior illumination patterns provided by a given daylighting system may be divided into two distinct parts:

1. determination of the illumination arriving at the building envelope, and

2. determination of the behavior of the light as it passes through the envelope and the space of interest.

In the case of computer simulation, illumination from the sky is usually obtained from equations representing the sky luminance distribution. Standard luminance distributions for clear and overcast skies have been proposed by a number of researchers (CIE 1973; Gusev 1983; Robbins 1986). The computer program incorporates Kittler's equation for the luminance of a standard clear sky and the CIE standard overcast sky. Two modifications were made to the daylight availability code: a version was developed with the Gusev equation for clear sky (representing the sky luminance distribution of polluted atmospheres), and a version was developed so that measured daylight availability data (diffuse and direct horizontal illuminances and zenith luminance) could be used in the simulations.

Scale model photometry requires a real light source. Artificial skies reproduce theoretical sky luminance distribution with varying degrees of fidelity. They have the advantage of providing known, static, and reproducible sky conditions (Hopkinson 1966). However, it is difficult to reproduce complex sky luminance distributions such as those of the clear sky. On the other hand, real skies are continually varying; overcast and clear skies approaching standard conditions may occur rarely, depending on the geographic location and fluctuations in atmospheric conditions. Currently, the authors are developing facilities for photometric studies under both real and artificial skies. The authors tested only under real sky conditions since artificial lighting for clear and overcast sky distributions had not been completed at the time the real sky facility was completed. Testing under real skies allows evaluation of both daylight availability functions and algorithms for determining interior illumination.

A monitoring system was developed to simultaneously measure sky and model light levels and to record these values. Color and cosine corrected silicon photodiodes were used to measure illuminances; calibration factors were determined by the authors prior to testing. Diffuse and global illuminances (and irradiances) as well as the zenith luminance were recorded. The direct component was calculated by subtracting the diffuse values from the global using the techniques described by LeBaron et al. (1983) to correct for the effect of the shadow band. A data logger was programmed to record measurements every 10 seconds; every 30 seconds the most recent three readings were averaged and this value was stored in a hard disk file. The resolution of the data acquisition system was 1 microvolt, sufficient to detect light level changes of 1 footcandle (fc) (10 lux). Very few data acquisition systems have this order of sensitivity. The admissible range of input voltages was sufficient to measure illuminances from 0 to 13,000 fc (0 to 130,000 lux), the upper limit being posed by the limit of the calibration source.

Conditions for Scale-Model Photometry

The monitoring system employed for scale-model photometry is described above. Low-reflectance interiors were fabricated by painting plywood models with a flat black paint, yielding diffuse reflectances of 0.05. Flat white paint on plywood created diffuse reflectances of 0.83. The photocells were mounted in custom-made holders to provide the precise positioning required due to the rapid change of illuminances experienced near windows and the low incidence angle experienced at the rear of deep models. The photocells were positioned vertically so that measurements would correspond to standard work plane illuminances (30 in or 760 mm above the floor). The effect of the sensor holders was minimized by painting them to match the reflectances of the interiors in which they were placed.

The Spitzglas et al. study employed 0.1 in (20 mm) thick crescent-board material for the window wall to "avoid calculation problems related to modeling wall thickness for the window facade." In this study, 0.5 in (12.5 mm) plywood was used so that evaluations could be performed with and without edge effects (window type 1, a completely glazed window wall, had no frame and so avoided any window wall thickness effects).

In the earlier study, the windows of the models were "aimed toward the zenith of the sky simulator" to simplify ground plane and horizon effects (Spitzglas et al., 1985, 42). In this study, the windows were vertical and faced due south, overlooking a real ground plane; ground-reflected light was not measured (this capability was added for subsequent experiments employing full-scale photometry).

During photometric measurements, the 1:12 scale models were located indoors directly behind clear south-facing windows with visible transmittance of 0.83 and diffuse reflectance of approximately 0.05. Tests were conducted to ensure that differing distances between models and glazing did not affect illumination patterns (since the apertures of the models with the light shelves were necessarily set back from the glazing). The south-facing model test space permitted study of both sky and sun contributions to daylight. The view of the sky from the model space was free of exterior obstructions such as buildings, hills, and trees. Daylight levels in nominally identical models with simple window systems were measured simultaneously to evaluate the precision of the model and sensor holder construction; agreement within 2% was easily achieved.

In the Spitzglas et al. study, the data collection system monitored 28 sensors placed in a continuous file along the center line of the sidelit models. The faces of the photocells were mounted flush with the "floors" of the models to minimize interference with visible flux distributions. At the time the measurements for this study were conducted, 12 sensors were available for model measurements (6 for each of the black and the white models) after the sensors required for monitoring of sky conditions had been allocated. Three sensors were placed at the "max," "mid," and "min" positions (see Figure 2) for determination of illuminances as provided by the Recommended practice of daylighting (IES 1978). The other sensors were spaced around these locations at regular intervals.

To review the primary illumination-related characteristics of the model monitoring station: pairs of 1:12 scale models had interior reflectances of 0.05 for the black model and 0.83 for the white model. The model apertures were oriented to the south behind clear glazing with visible transmittance of 0.83 and diffuse reflectance of 0.05.

Conditions for Computer Simulation Studies

Spitzglas et el. noted the importance of grid density and the number of iterations in obtaining results approaching smooth integration and full convergence. They used a 1 ft square (0.3 by 0.3 m) grid for windows and a 2 ft square (0.66 by 0.66 m) for interior surfaces, and the same values were used in this study. In the case of the low-reflectance models, one iteration was sufficient to give values that did not differ from those obtained after five iterations. However, two or more iterations were always used as a precaution. For the high reflectance spaces, detectable differences in results were obtained as the number of iterations was increased to 13; there were no detectable differences in results when the number of iterations was varied from 13 to 20, so the former number was used. Since the standard version of the computer program will only print up to 12 grid values along a given axis, the output code was modified to provide up to 40 grid values along any working plane axis. This made it possible to match computed and measured data precisely. Calculation results were rounded to the nearest footcandle (10 lux) since this was the resolution of the measurement system.

Measured values of reflectances and window transmittance, summarized at the end of the preceding section, were used for calculation of daylight levels together with the default ground reflectance of 20%. While a ground reflectance of this order would have a negligible effect on spaces with small apertures (i.e., window types 3 and 4), calculations were also carried out with the ground reflectance set at 0.15 for window types 1 and 2 to assess the impact of the ground reflectance estimate on the relative differences.

Features of the modified versions of the computer program are summarized in Table 1, together with the required daylight-availability-related user-supplied data required by the standard and modified versions.

RESULTS AND DISCUSSION

In the Spitzglas et al. paper, photometric and simulation results were compared by applying the following formula to direct component results:

$$\text{Relative Difference} = \frac{(\text{Measured Value} - \text{Calculated Value})}{\text{Measured Value}} \cdot 100\% \qquad (1)$$

where

Measured Value was either the corrected black model value, in the case of direct component comparisons, or the difference between the white model values and corrected black model values, in the case of reflected component comparisons.

Calculated Value was the corresponding direct or reflected component determined by the numerical method.

The reflected components were similarly compared, except that the "measured value" for the models was obtained by subtracting measurements for the low-reflectance models from corresponding measurements for the high-reflectance models.

The relative difference method of comparison presents some difficulties. In this study, cases occurred where the measured values were zero (e.g., for most of the measurement positions in the black space with window type 4 under overcast sky); the relative difference was then taken to be 0% to avoid problems with division.

Even with a monitoring system resolution of 1 fc (10 lux), small differences in light levels can produce large relative differences at low light levels experienced under real sky experimental conditions despite the fact that absolute differences between measured and computed values are a few footcandles or less. This accounts for the much of the large variation in relative differences for direct components seen far from the window wall in Figures 3, 5, and 7, as well as the similar variations in standard deviation in Figures 10 and 12. Since more sensitive data acquisition systems are not readily available, a possible solution would be to use photocells with a larger detection area at the rear of low-reflectance models.

Clear Sky with Sun

Initial results showed wide deviations between the calculated and actual daylight availability data (direct horizontal illuminance, diffuse horizontal illuminance, and zenith luminance). The Kittler sky function is very sensitive to atmospheric turbidity as determined by two factors: the total water content of the air and the turbidity coefficient. The initial values used were the appropriate monthly averages for the sites nearest Ann Arbor as provided by the manual for the computer program. These values were adjusted until a computed zenith luminance matching the measured zenith luminance was obtained. However, the corresponding computed direct and diffuse horizontal illuminances still differed widely from those obtained from the sky monitoring station. Diffuse horizontal illuminances were overestimated by as much as 50%, while direct horizontal illuminances were underestimated by as much as 15%. The Gusev sky version of the program was found to give similar results to the Kittler sky function under the very clear atmospheric conditions being experienced during the measurement period. This indicates the need for further work on sky luminance and daylight availability functions. In order to provide satisfactory test conditions for the program, the version employing measured daylight availability data was used for the clear sky comparisons.

Measurements were made with the sun at about 47° altitude and 34° west of south. Under these conditions, direct sun was penetrating all window types, but the working plane was screened by the interior light shelf in model type 4. For window 1, the sensor nearest the window wall intercepted direct sunlight.

The results show good agreement between the measured and calculated values for window types 1 and 2 for both direct and reflected components (see Figures 3 and 4 respectively). The one exception was the 33% relative difference 19 ft from the window wall for window type 2 (see Figure 3); this corresponds to an absolute difference of only 2 fc (20 lux) and occurred for reasons discussed above. Variations in the ground reflectance had little impact on the results in the range tested. This shows that, for large apertures, both the direct and reflected illumination resulting from direct sun as well as clear sky can be handled well by numerical methods, and that a thick (0.5 ft or 0.15 m) window frame can be modelled accurately using numerical methods.

While good agreement was obtained for the direct component for window types 3 and 4, making allowance for measurement difficulties discussed above (see Figure 5), large deviations occurred in the determination of the internally reflected component (see Figure 6). This could not be attributed to measurement difficulties, since the illuminances were well above the monitoring system threshold. Sources of error for scale model photometry and computer simulation were discussed earlier in the paper.

In the case of window 3, initial calculated work plane illuminances did not show a peak although direct sun was visibly penetrating the window. With a finer grid, the small sun patch was detected. The element size used for the floor, the first surface the sunlight would strike, was decreased to 18 in square (450 by 450 mm); this increased calculated working plane illuminances by as much as 60% and reduced the relative difference to the values plotted here. Further reduction of the element size was not undertaken since it would have required additional modification of the program. As was mentioned above, a finer numerical mesh significantly improves estimation of the sky and sun "seen" by critical interior surfaces.

The relative differences in the direct component for window type 4 vary between complete agreement on no direct component (for the four positions nearest the window) to 100% or more for the two positions furthest from the window. However, the measured values at the rear positions were only 4 fc (40 lux) and the absolute differences were only 9 and 4 fc (90 and 40 lux).

Overcast Sky

The relative differences for overcast skies were determined using daylight factors rather than absolute illuminances. Measured daylight factors were taken as the averages for 30 minute periods when the sky was heavily overcast as determined by the ratio of the diffuse to global illuminance. Measurements were only used from periods when the ratio of the diffuse to global illuminance was 0.92 or higher and relatively constant (standard deviation of no more than 1%). Since the monitoring system recorded values for each sensor every 10 seconds, 180 samples were obtained over each 30 minute measurement period.

Daylight factors of less than 0.25%, corresponding to interior illuminances of 1.25 to 5 fc (12.5 to 25 lux) under typical diffuse horizontal illuminances of 500 to 1000 fc (5000 to 10,000 lux) for heavily overcast skies, since these values were at the low end of the measurement capability of the monitoring system. The values obtained for the initial set of measurements under overcast skies may be found in Figures 7 and 8. The poorest agreement occurred in estimating the reflected component for the light shelf aperture; while both methods concurred on the effectively nonexistent direct component, the numerical method estimated the reflected component at 21% to 67% higher than the model photometry did.

Tregenza (1980) has shown that measured values for the nominally constant daylight factor can vary widely under real overcast sky conditions. Our results are consistent with his conclusion that the least variation in daylight factors occurs for measurement positions with a relatively large sky view. Measurements were carried out for four different overcast periods for window type 1 to assess the stability of the daylight factor (both direct and reflected components). The percent standard deviations for all measurement positions were relatively constant over all measurement periods for the reflected component (see Figure 9), and of the same order as the relative differences. The percent standard deviations were slightly more variable for the direct component for measurement positions in the front half of the model and varied enormously in the rear half (see Figure 10); these variations occurred with very small absolute illuminances (on the order of 1 to 5 fc or 10 to 50 lux).

When the data for the four 30 minute measurement periods were combined, the percent standard deviation in the reflected component daylight factor was about double the average for the individual measurement periods (see Figure 11). A much greater change occurred for the rear four measurement positions in the black model (see Figure 12). This shows that there is much less consistency in the daylight factor over a range of overcast conditions than there is for individual overcast periods. Fortunately, the daylight components that are most critical in determining the aggregate daylight factor (the direct and reflected components at the front of the room and the reflected component at the rear of the room) appear to be the most stable.

CONCLUSION

It was found that daylight availability metrics estimated with existing clear sky equations did not match very well with measured data for the periods during which tests were conducted. Hence, all comparisons were conducted with measured daylight availability data used in the computer simulations. Under these conditions, good agreement was obtained between calculated and measured direct and reflected components of daylight for simple, unshaded windows under clear and overcast skies with the exception of small direct components accounting for a very small fraction of overall work plane illuminances.

Under clear skies with the sun at the position for which the test was conducted, the calculation procedure estimated a much lower value for the reflected component than was measured for the small window with and without a light shelf. Under overcast skies, good agreement was obtained for the reflected component with the small window. The calculation procedure estimated a much higher value for the light shelf system than was measured in the models. These larger discrepancies for smaller apertures are consistent with the factors identified above as contributing to errors in scale-model photometry and computer simulation. In particular, illuminances determined by the calculation procedure for small windows were found to be highly sensitive to the element size chosen for interior surfaces initially struck by daylight.

Future Research

The authors have added a laboratory for full-scale photometric studies to the experimental system. Data has been collected for a number of fenestration systems under a wide range of sky and sun conditions. This will permit considerably more rigorous evaluation of factors contributing to error in scale-model photometry and in computer simulation.

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TABLE 1

Features of the Standard and Modified Versions of the Computer Simulation Program

PROGRAM FEATURE	PROGRAM VERSION Standard	 Modified 1	 Modified 2	 Modified 3
Determination of Direct Horizontal Illuminance	1	1	1	measured
Determination of Zenith Luminance	2	2	2	measured
Sky Luminance Distribution (as function of zenith luminance)	Kittler	Kittler	Gusev	measured diffuse horizontal illuminance used
Data for Determination of Amospheric Turbidity	3,4	3,4	3,4	not required
Maximum Number of Work Plane Illuminance Points to Output	12	40	40	40

Notes:

1. see ASHRAE 1985.
2. Liebelt's equation as adapted by Karayel et al. 1984
3. thickness of condensible water in the atmosphere to be analyzed (user specified)
4. Angstrom atmospheric turbidity coefficient (user specified)

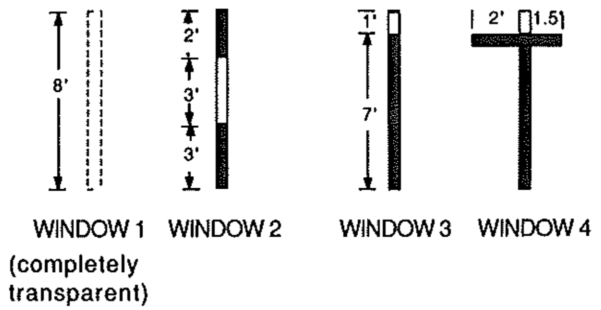

Figure 1. The four test window systems

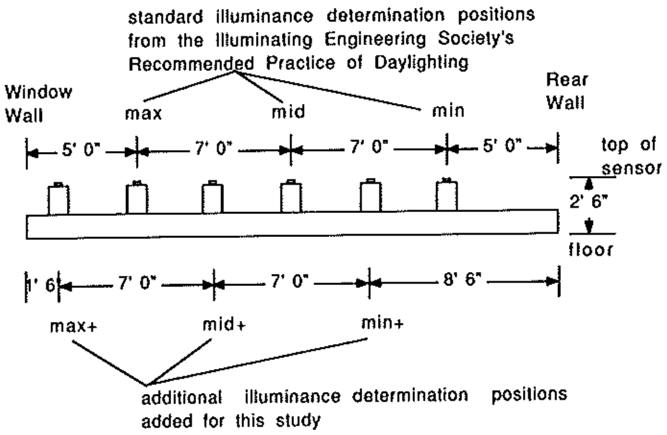

Figure 2. Photocell locations in the test space

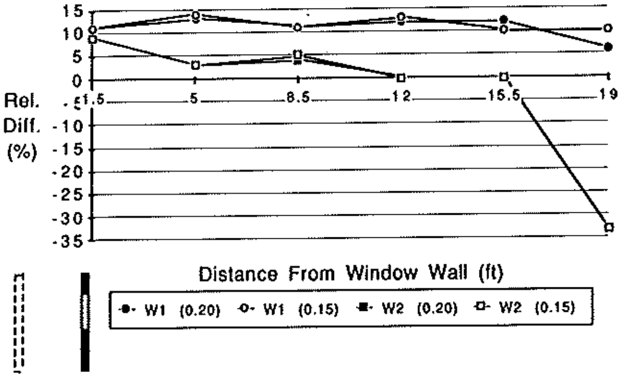

Figure 3. The relative difference between direct components for window types 1 and 2 under clear sky with sun (ground reflectances of 0.20 and 0.15)

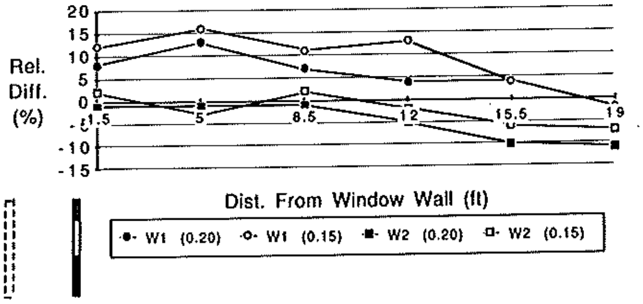

Figure 4. The relative difference between reflected components for window types 1 and 2 under clear sky with sun (ground reflectances of 0.20 and 0.15)

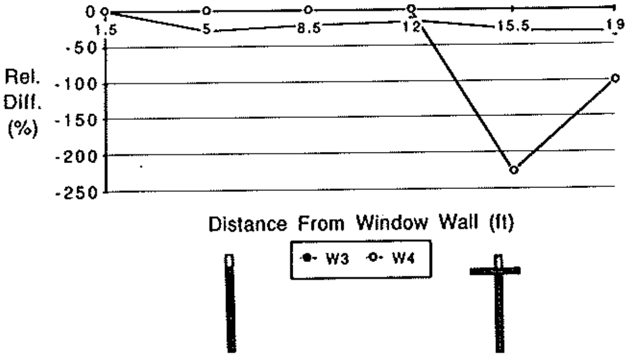

Figure 5. The relative difference between direct components for window types 3 and 4 under clear sky with sun

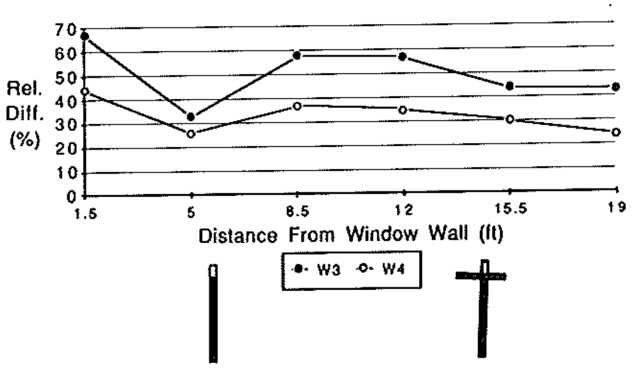

Figure 6. The relative difference between reflected components for window types 3 and 4 under clear sky with sun