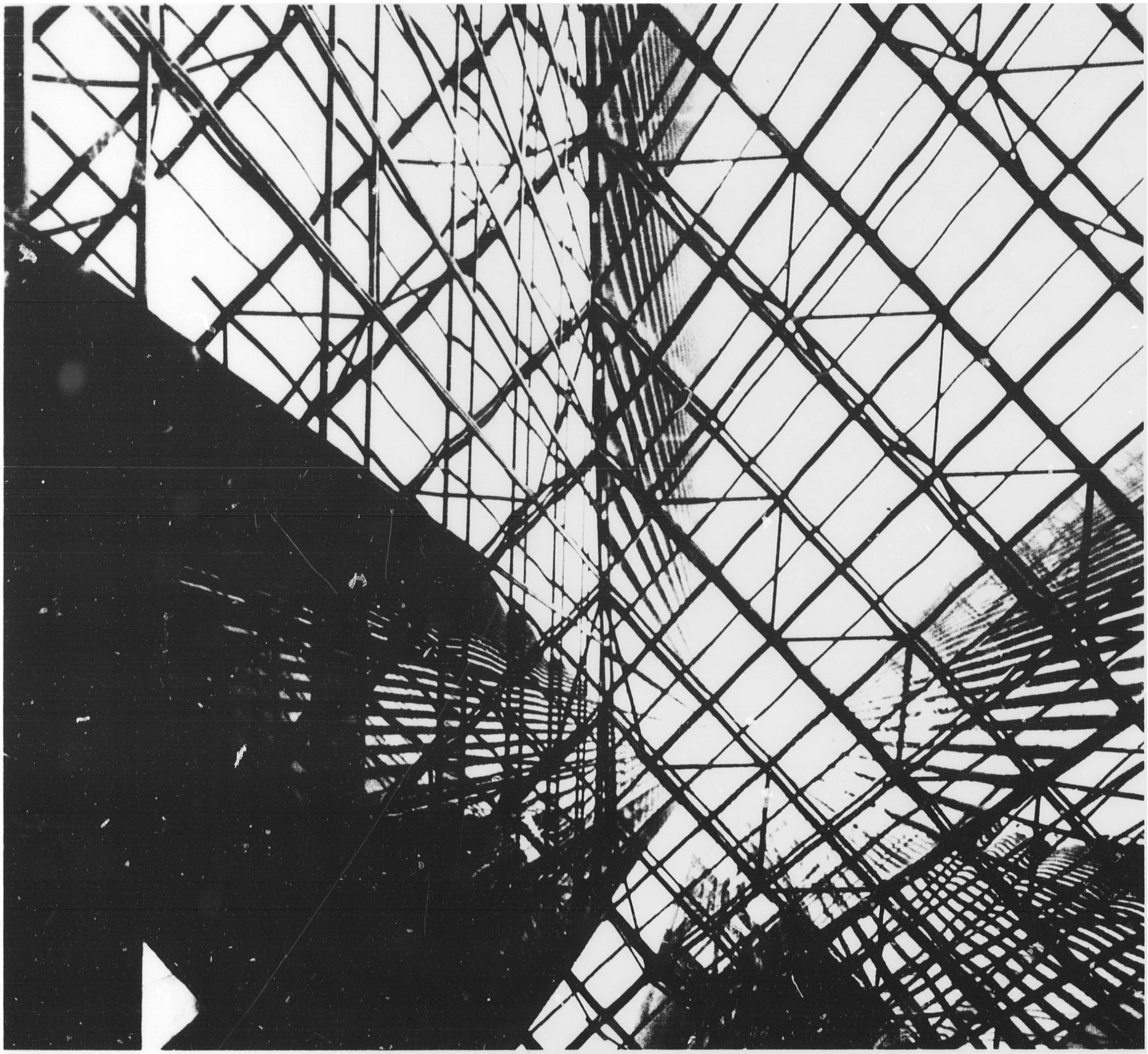

NBS BUILDING SCIENCE SERIES 152

A Daylighting Model for Building Energy Simulation

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

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NBS BUILDING SCIENCE SERIES 152

A Daylighting Model for Building Energy Simulation

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ABSTRACT

A computer model is outlined for estimating the annual energy performance of a daylighted building. The daylighting model is a system of FORTRAN subroutines designed for inclusion into larger building energy simulation programs such as DOE-2, BLAST, and NBSLD. Once incorporated into the main energy program, these subroutines will allow the existing program to account for the energy tradeoffs associated with natural illumination.

The daylighting model, DALITE, comprises three separate routines to do three separate functions. The first routine generates hourly sky luminances and sky illuminances as well as direct sun illuminance, taking solar radiation and sun position data as input. The second predicts interior daylight illumination at various points within a room due to any number of windows, skylights or clerestories. The last routine adjusts the electric lighting load (via photoelectric controls) in response to the available daylight. Unlike most other daylighting estimation techniques, this model is a dynamic model designed to study how conditions change with time. It has a further advantage in that it can be easily installed into most existing energy models written in FORTRAN 77.

Key Words: building computer simulation, building energy performance, clerestory performance, daylighting, lighting, skylight performance, window performance.

Cover: Daylight admitted through sloped glazing in a high-rise office complex.

PREFACE

This report is one of a series documenting NBS research and analysis efforts in developing energy and cost data to support the Department of Energy/National Bureau of Standards Measurements Program. The work reported in this document was performed under the Research Associate Program between the National Fenestration Council and the National Bureau of Standards. The Research Associate Program was partially supported by the U.S. Department of Energy under the Building Thermal Envelope Systems and Insulating Materials Program (contract no. ORNL/PO-22201).

ACKNOWLEDGMENTS

Don Vild, J. W. Griffith, and other members of the NFC Technical Committee gave valuable direction to the project, as did Dr. Tamami Kusuda, Group Leader of the Thermal Analysis Group, Building Physics Division, National Bureau of Standards, who guided the technical details. The sky measurement assistance of Stephen Treado, the computer assistance of John Bean, and the lighting consulting of Ted Hattenburg and Gary Yonemura, all of NBS, contributed significantly to the success of this project. To all, the author offers his deepest thanks.

Conversion Factors from English to Metric (SI) Units

Physical Quantity	To Convert From Customary Units	To SI Units	Multiply By
Length	ft	m	0.3048
Area	ft^2	m^2	0.0929
Energy	Btu	J	1055
Power	Btu/hr	W	0.2931
Illuminance	fc	lx	10.76
Irradiance	$Btu/hr \cdot ft^2$	W/m^2	3.155
Luminance	fL	nit (cd/m^2)	3.426

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Facing page: Daylighting from continuous skylights in an office mall

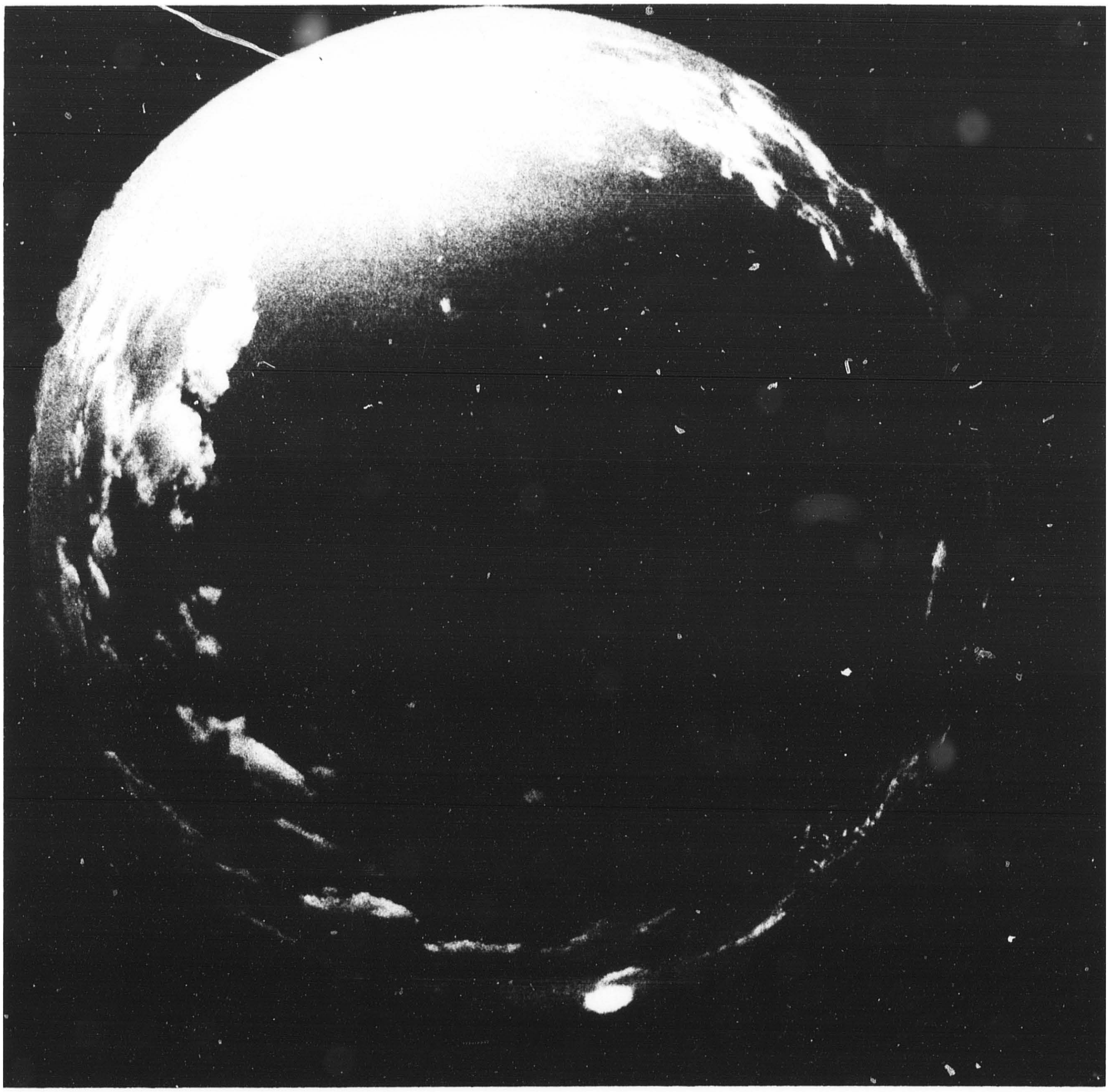
1. INTRODUCTION

With the renewed interest in energy conservation in general, and with daylighting in particular, many in the building profession have become interested in how daylighting impacts the energy performance of a building over time. This interest extends beyond simple daylighting design calculations by including the impact of daylighting strategies on the building lighting, heating, and cooling requirements. The goal has become annual energy consumption not illumination at one point in time. Only since the recent introduction of computers into the building industry, has it been possible to perform an annual energy analyses with any substantial degree of certainty. Today many computer programs exist for estimating energy use in buildings. Among the best known public domain programs are DOE-2 [1], BLAST [2], and NBSLD [3]; not to mention the host of proprietary programs currently in use [4]. These programs consider most of the major transient energy parameters in buildings. Some are more rigorous than others, and each has its strengths and weaknesses, but few have an integrated daylighting model sufficient for existing daylighting practice.

While there are also computer programs developed exclusively for daylighting analysis, these are designed for rigorous yet static design conditions and are normally too time consuming to be used repetitively for energy studies. In this category are such lighting programs as LUMEN II [5], SUPERLIGHT [6], and CEL-1 [7], which are useful programs for those interested in a careful evaluation of an illuminated space, but are much too rigorous for execution each daylight hour of the year. They also share in a common weakness as far as building energy simulation programs are concerned in that they study only standard sky conditions and are not designed to be responsive to changing weather conditions.

In the following pages, a daylighting model is offered which is specifically designed for use in large-scale building simulation programs. It has been prepared as a set of subroutines that can be incorporated into existing programs with a minimum of effort. The subroutines are short, concise, and computationally fast (normally causing under ten percent of the total CPU time for a full daylighting analysis). They should be compatible with most computer programs currently written in FORTRAN 77, and with only slight modifications could also be revised into FORTRAN IV. In fact, the daylighting algorithms are small enough to put into a micro-computer provided it has a FORTRAN compiler.

Facing page: The sky hemisphere under partly cloudy conditions



2. THE DALITE SUBPROGRAM

2.1 CAPABILITIES

The DALITE subprogram is unique in that it comes as a package, a group of small subroutines, which can be incorporated into most existing building simulation programs. Unlike most other daylighting models, its small packaged form enables it to be fully integrated into a larger building simulation program without requiring excessive computation time. In this way, hourly daylighting analyses can be done simulataneously with the thermal calculations, allowing an assessment of the overall energy impact of daylighting.

The DALITE package is streamlined to be computationally fast and computes only those elements that contribute significantly to the energy performance of the building. While being a simplified model, it is still flexible in its ability to simulate a range of fenestration scenerios - windows, skylights, clerestories, roof monitors, overhangs, sidefins, and almost any combination of these. The subprogram is also fairly even-handed in that it does not concentrate computation time on a few noncritical calculations at the expense of others. For instance, the interreflection model is flexible for use with both sidelighting and toplighting, yet avoids rigorous interflux calculations.

The sky subroutine deals with a continuous range of sky conditions, not just clear or overcast, and needs only the instantaneous solar radiation and sun position as input. From this internally generated availability data, another subroutine estimates the reflected light from surrounding buildings, light from the sky dome, reflected ground light, and internally reflected light. The direct beam illuminance, as a rhomboidal patch of sunlight on the workplane, is also simulated for each aperture that has sunlight falling on it. Thus, the package is capable of performing all critical daylighting/energy calculations, and utilizes information in the existing building simulation program to perform the daylighting analysis.

2.2 INCORPORATING THE SUBPROGRAM INTO AN ENERGY PROGRAM

Although the DALITE subprogram is a complete package and can be prepared as a stand-alone program, its intended purpose is for use as a subroutine package in other energy simulation programs. DALITE and its three subordinate subroutines should be executed as a part of the hourly building load calculations as shown in figure 2.1. From the programmer's point of view, incorporation requires only input/output preparation through a single two-dimensional array (see Appendix B). The instantaneous electric light load and heat-of-lights given as output can be fed into the hourly load compilaton along with the other thermal loads, which are totalled for each zone and sent on to the system and plant compilations to give the total annual energy (see Appendix C).

2.2.1 Subprogram Structure

The DALITE subprogram comprises a sky model (SKYLUM), an interior daylight model (RMLITE), and a lighting load model (LLOAD), each as a separate subroutine. Figure 2.2 illustrates the subroutine structure. DALITE is the master routine coordinating the data from the subroutines and prepares the input/output information. It acts as an interface between the individual components and the main energy program. DALITE is executed only once each daytime hour for any given room but the SKYLUM and RMLITE subroutines are executed, respectively, for each fenestration aperture and for each sensor position. LLOAD is executed once for each sensor each hour. To streamline the program further, the repetitive calculations in the RMLITE model are suppressed once the geometry coefficients have been computed and these coefficients are used each repeated hour, greatly increasing the speed of the program.

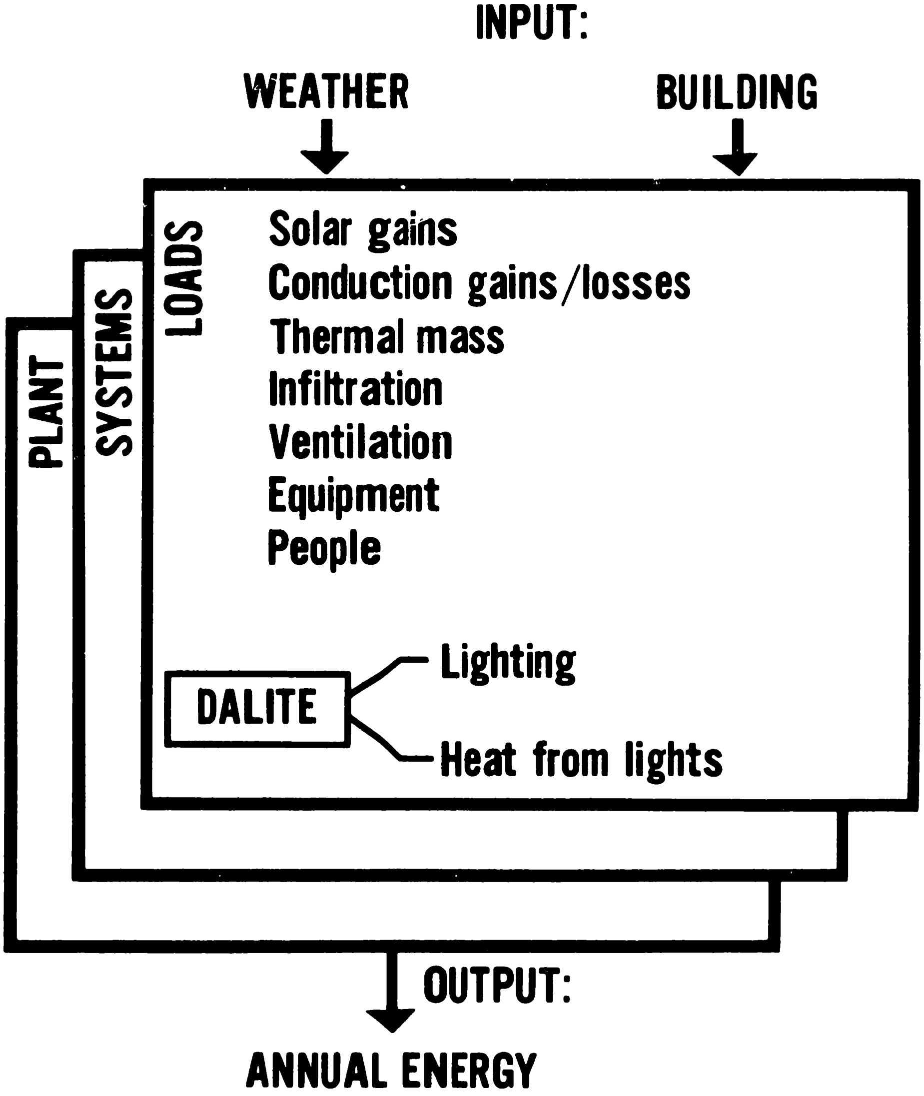


Figure 2.1 The DALITE program as a part of the total energy analysis process

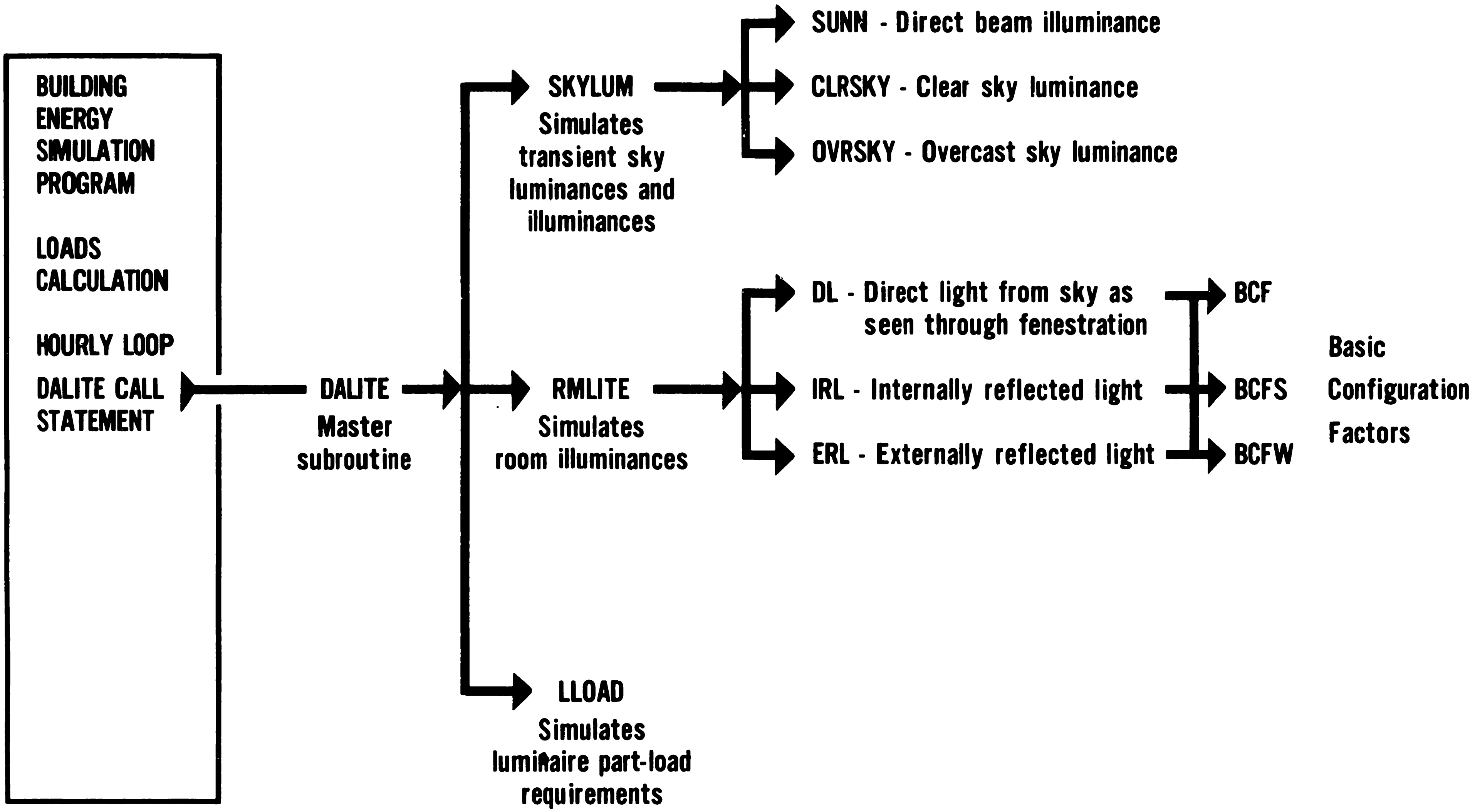


Figure 2.2 DALITE subroutine structure

2.2.2 Input/Output

Input is requested by the main energy program internally at two points during execution of the program: 1) during initialization when the main program is defining building information that remains constant throughout the analysis, and 2) during each repetitive execution when the sky and other conditions change (see Appendix C). A single array is used for storing input and output (I/O) information. The array is sized through parameter statements in the main program to accommodate an arbiturary number of fenestration apertures and dimmer/switch controls. In this way, for a larger (or smaller) capacity of either, adjustments can be made in the array size and the limits on the do-loops. Details of array element assignments are delineated in Appendix C.

2.2.3 Reference and Coordinate Systems

The DALITE routine has its own reference and coordinate systems which positions the building and the sun on the building site, positions the photo sensors in the room, and positions the fenestration on the walls or ceiling. Each reference system is briefly discussed below.

The coordinates of the building's orientation are shown in figure 2.3. Buildings oriented off the north/south axis (as shown) have an azimuth angle correction AZM, where AZM is in degrees clockwise from north. The sun angles SUNAZ and SUNALT are also input in degrees, and are the solar azimuth clockwise from north and solar altitude above the horizon, respectively.

Figures 2.4 and 2.5 illustrate the coordinates used to locate sensor positions and the fenestration. The coordinates of the room and the coordinates of each wall are always referenced to the lower left-hand corner of the plane. For example, to locate a window on a wall, the lower left-hand corner of the window is referenced to the lower left-hand corner of the wall as viewed externally. Skylights and clerestories are located on the ceiling in a similar way. It is important to note that coordinates of each surface, including the floor, are specified in either the height, width or length directions as represented in figure 2.6.

2.3 LIMITATIONS

As is characteristic of any prediction procedure, the daylighting model has limitations. Although the ceiling plane is allowed to be sloped, the room plan is otherwise assumed to be rectangular, meaning that the program cannot simulate interreflections in L-shaped or other non-rectangular geometries. A warning might be made here that when simulating room geometries with depth-to-height ratios greater than two or three to one, interreflected light should not be computed, since the validity of the assumptions used to determine interflected light is questionable at such room depths. There are also unique types of fenestration designs that cannot be sufficiently represented such as light shelves and domes. However, with wisdom in making the right assumptions these too can be done by approximation and should not be considered a severe weakness; most thermal models do not accurately account for such configurations either. When novel or complex fenestration designs are to be analyzed, a

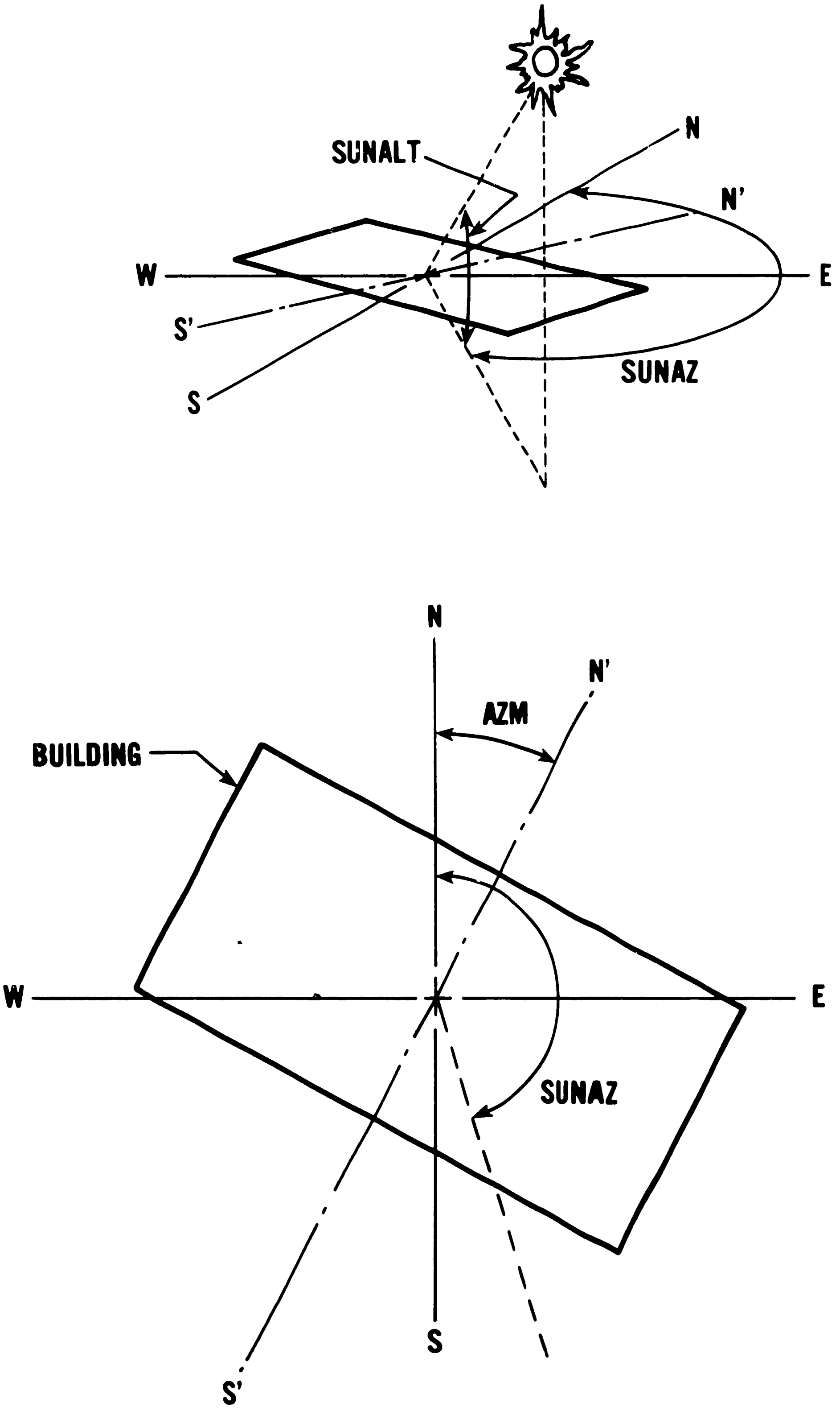


Figure 2.3 Building orientation coordinates

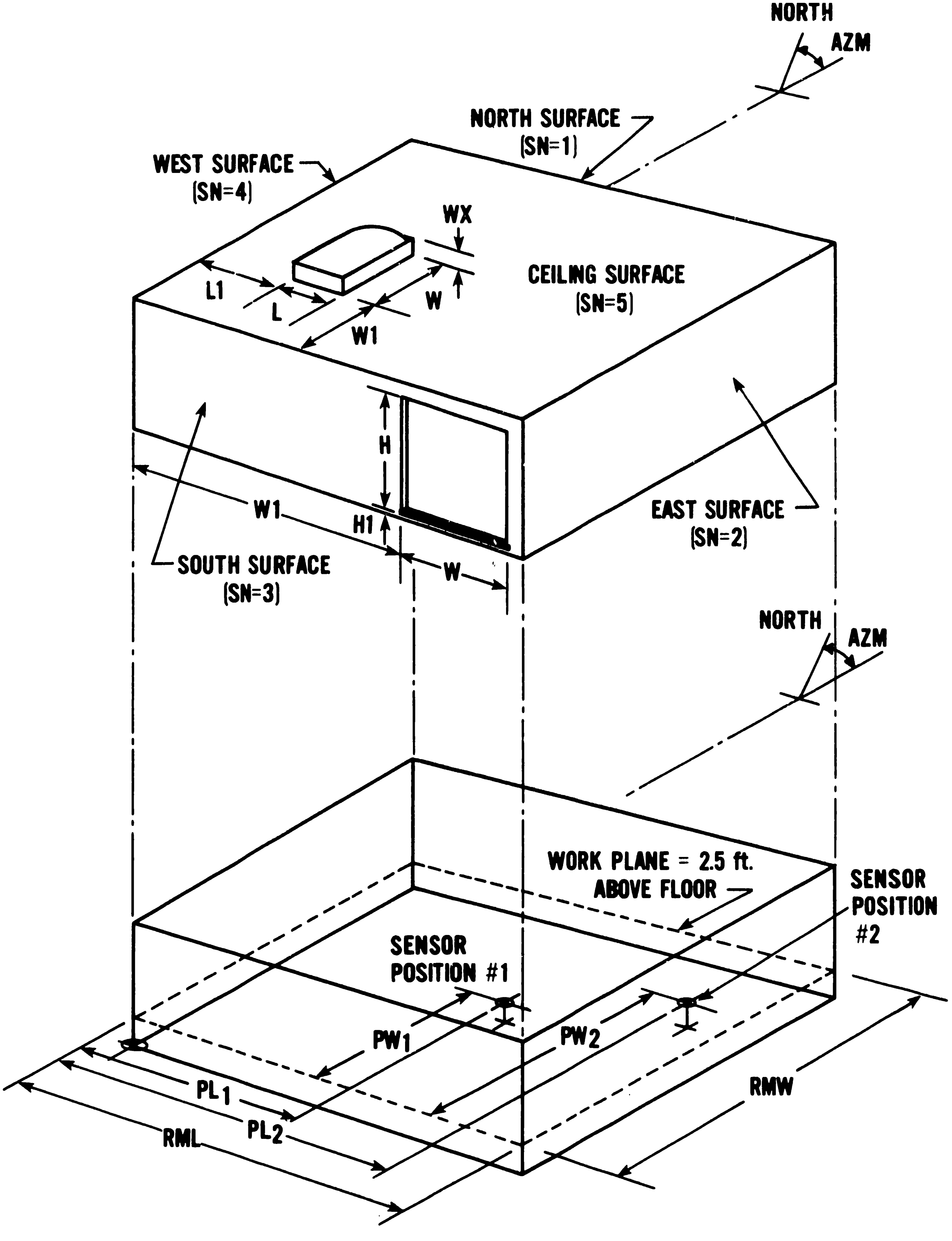


Figure 2.4 Room and fenestration coordinates

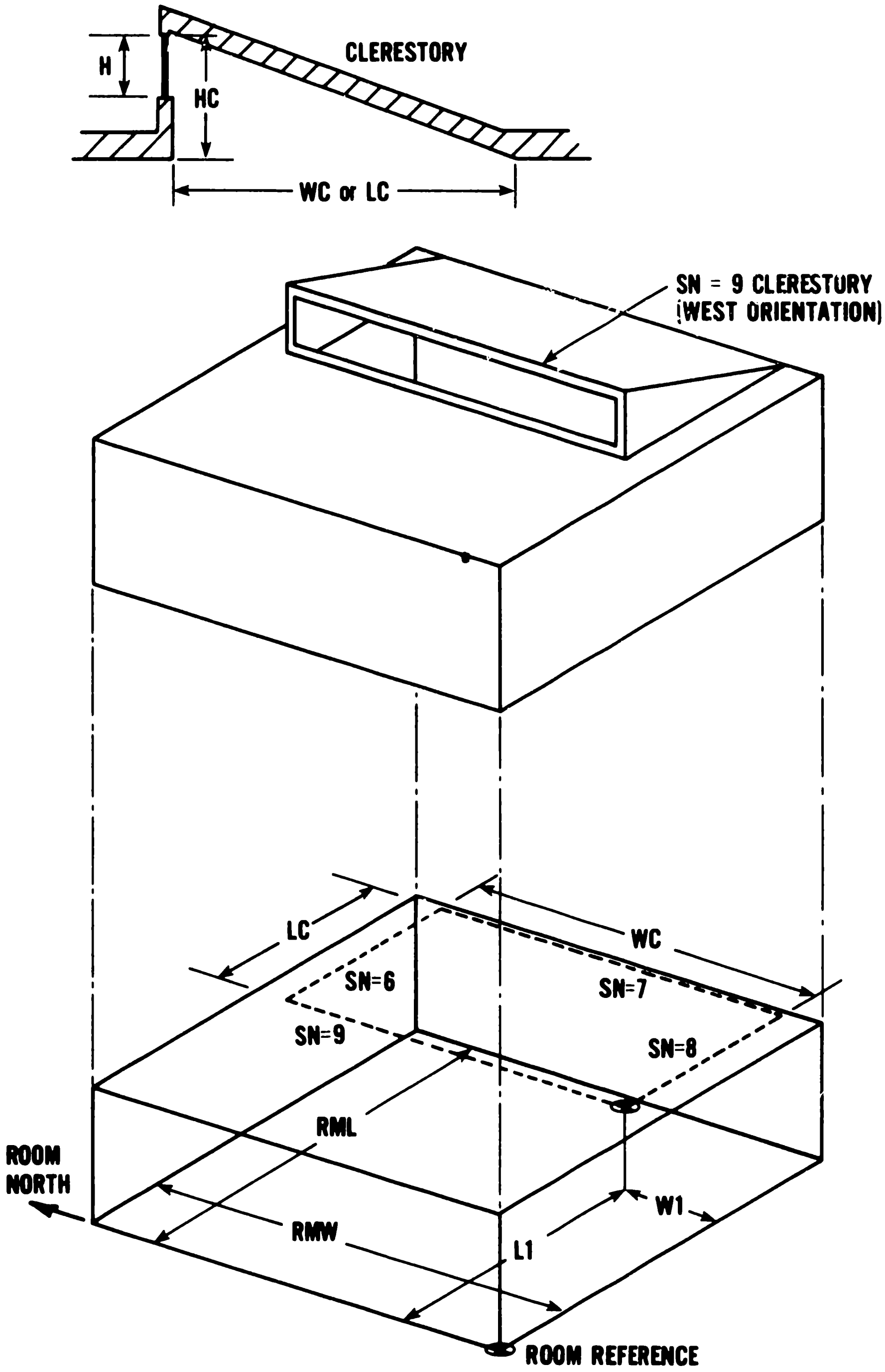
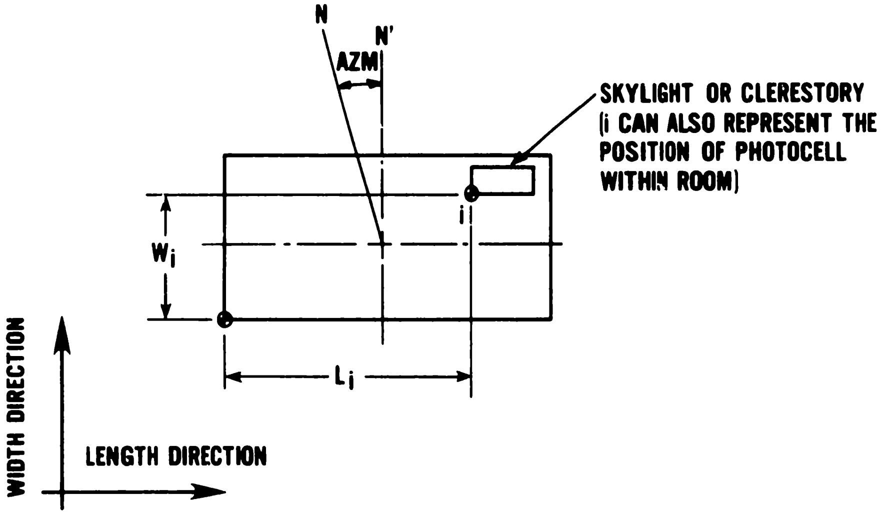
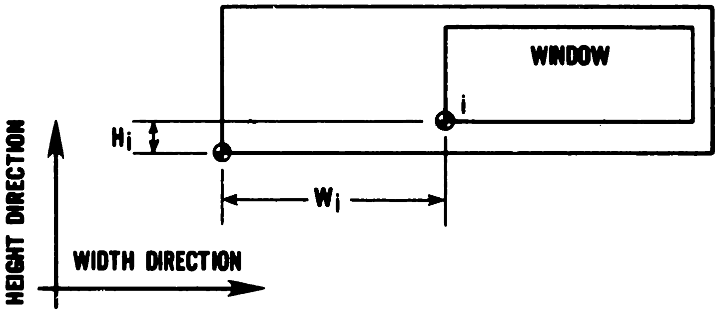


Figure 2.5 Fenestration coordinates for a clerestory



a) FOR CEILINGS AND FLOORS



b) FOR WALL SURFACES

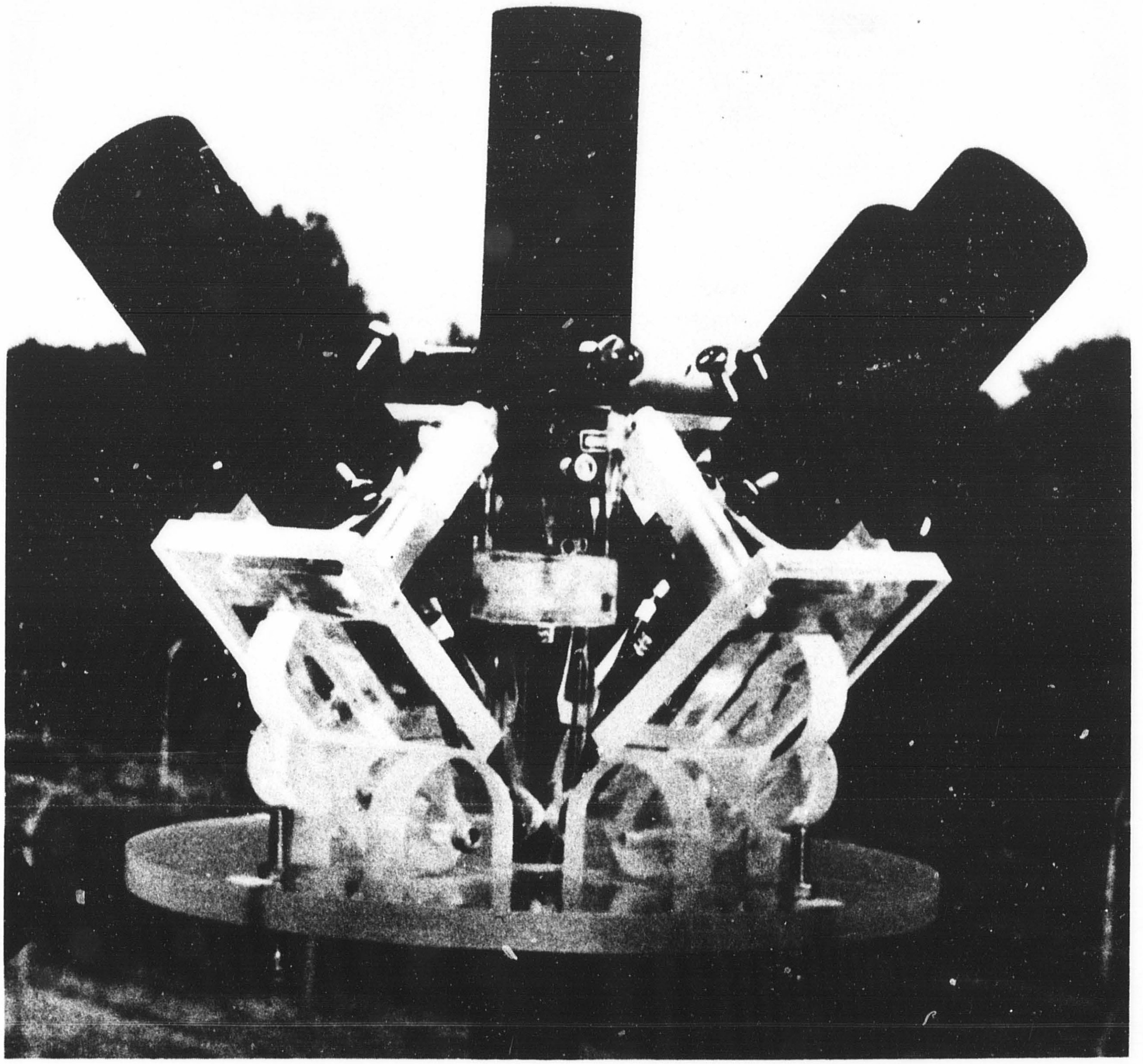
Figure 2.6 Surface coordinates

possible option is to determine the geometric daylight coefficients (see section 2.2.1) apart from the DALITE program using either physical models or manual calculations, and assuming these as constants, simulate the sky and building load interfacing using the remaining daylighting algorithms. Great flexibility can be achieved in this way, with the limits being only the extent at which such coefficients can be obtained.

Glare is not modeled explicitly, but this is intentional. DALITE seeks to simulate the photoelectric control response to changing daylighting conditions, not the user response to those conditions. While it is true that a relationship probably exists between the two, a valid correlation can only be assumed if building occupants respond to a glare problem by applying or adjusting a glare or sun control device, which in turn adjusts the effective transmittance of the fenestration. Since such adjustments are normally modeled as a part of the existing loads program, it is necessary only to replace the specified transmittance with an hourly adjusted value before the call statement to the DALITE subroutine is given.

Another possible limitation may be found in the model's assumption that the rooms are empty. Internal obstructions such as furniture and occupants are not considered as contributers in the lighting calculations even though they do contribute to the thermal latent and sensible loads. Since the daylighting model was developed as a streamlined program, such capabilities were not considered essential.

Facing page: Measuring the sky luminance at selected positions in the sky.



3. THE SKYLUM ROUTINE

3.1 CAPABILITIES

Since the weather data normally used in building energy programs do not include hourly exterior daylight, such values are generated internally from the available values of solar radiation and sun position. Total and diffuse solar radiation incident upon a horizontal surface, values that are normally computed within the larger existing programs, are used to determine the sky conditions. From this hourly information the sky luminances as seen through each window or skylight are calculated. The intensity of the direct sun and the total illuminance on a horizontal plane is also determined.

Obtaining hourly solar data in any form is a complex issue. For the relatively few locations in North America where hourly values of total horizontal and direct normal solar radiation are recorded, such data can be easily accessed. But for cities where only TRY (Test Reference Year) data are available, the hourly solar radiation must be generated internally using a calculation procedure such as developed by Liu and Jordan [8], Stevenson and Kimura [9], or others [10]. When the more common TRY weather tapes are used, the only hourly sky information provided is a visual (subjective) assessment of the cloud conditions, specified in terms of a cloud cover value and the type of cloud in four different layers. Even when TMY (Typical Meteorological Year) weather tapes or other solar data are used the data itself is normally incomplete and is interpolated for a complete hourly file. Therefore, due to the nature of the input data alone, the sky model carries a degree of uncertainty. The SKYLUM routine assumes that the following solar data are accessible by the time the DALITE subroutine is called: 1) sun altitudes and azimuth, 2) total horizontal solar radiation, and 3) the ratio of diffuse to total horizontal solar radiation. The instantaneous solar altitude and azimuth are used to determine the zenith clear sky luminance; the horizontal solar radiation is used to derive the horizontal illuminance and the overcast sky luminance; the ratio of the diffuse to total radiation (denoted as the cloud ratio, CR hereafter) is used to determine intermediate partly cloudy sky condition. This latter term is discussed in more detail below.

3.2 THE PHASING TECHNIQUE

To capture the variable nature of the sky as it changes with time, a continuous phasing technique is employed. Since skies are often neither perfectly clear nor perfectly overcast, a weighted averaging is done hourly between the two extremes based on the cloud ratio CR described above. The process requires an initial determination of the sky luminance as seen through the fenestration under the clear and overcast conditions, and a phasing technique is done between the two conditions to get the intermediate value actually used as shown in figure 3.1. The intermediate sky luminance at point P thus becomes,

$$L_p = \xi_{clr}(L_{p_{ovr}}) + \xi_{ovr}\,(L_{p_{ovr}})$$

or

$$L_p = \xi_{clr}(L_{p_{clr}}) + (1-\xi_{clr})(L_{p_{ovr}}) \qquad (3.1)$$

where,

ξ_{clr} = the clear sky fraction

ξ_{ovr} = the overcast sky fraction

$L_{p_{clr}}$ = the clear sky luminance

$L_{p_{ovr}}$ = the overcast sky luminance.

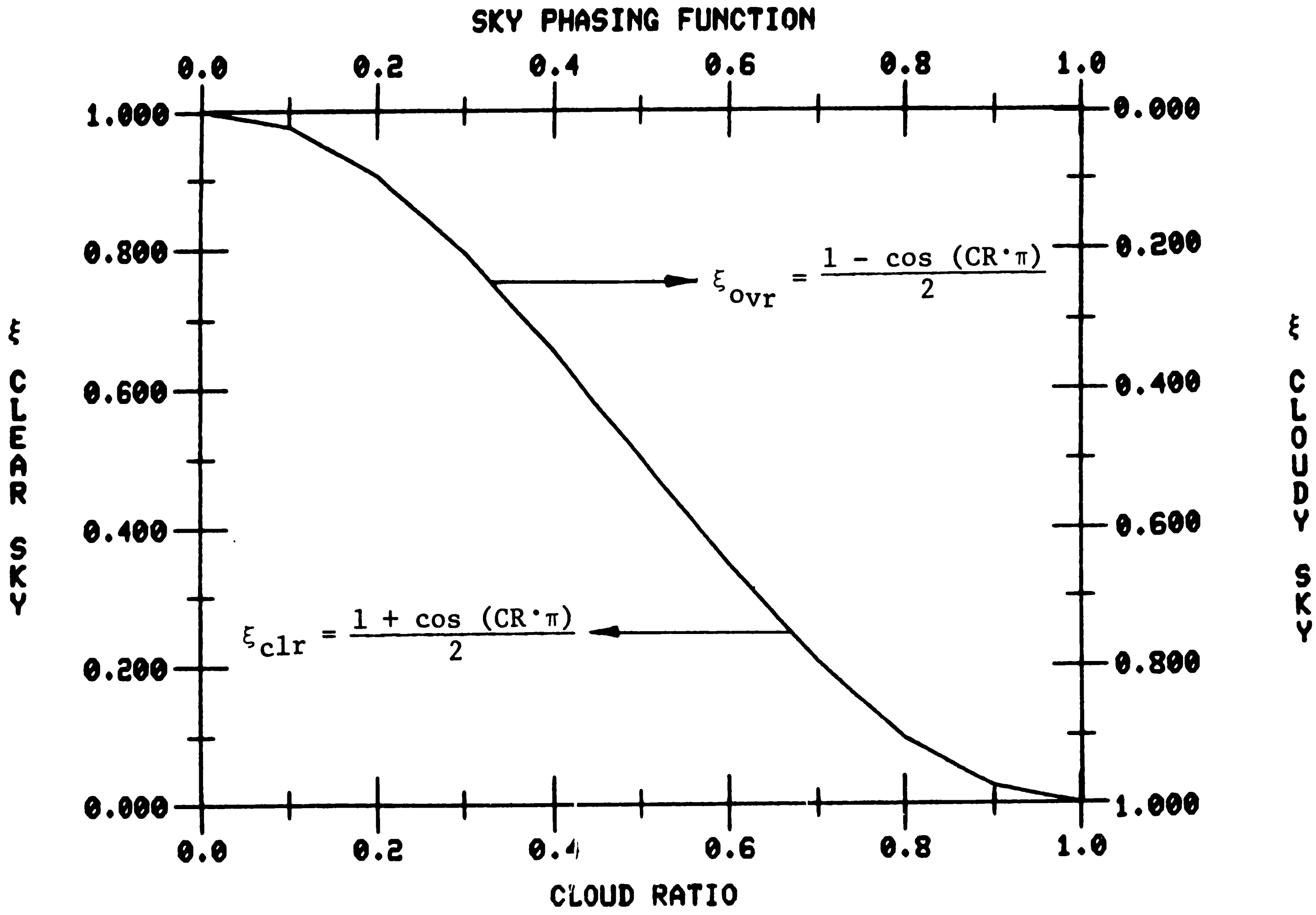


Figure 3.1 Curve used to obtain intermediate sky luminance as a function of cloud ratio

Due to the nature of the CR, a sinusoidal curve was used to interface between sky luminance values. This curve gives expressions for ξ_{clr} and ξ_{ovr} as,

$$\xi_{clr} = \frac{1 + \cos\ (CR*\pi)}{2} \tag{3.2}$$

and

$$\xi_{ovr} = \frac{1 - \cos\ (CR*\pi)}{2} \tag{3.3}$$

which provides the slightly biased weighted average in favor of either of the clear or overcast sky condition. It should be pointed out, however, that equations 3.2 and 3.3 do not generate the percentage of the sky in clouds, but rather estimate a weighted average luminance; the cosine curve is this weighting function. From sky measurements it has been noted that cloud ratios of about 0.20 and below are effectively clear skies with possibly only a slight haze present. Likewise, it appears that the blue sky is no longer present after the cloud ratio exceeds about 0.80. The cosine function is simply an attempt at capturing this natural bias toward the extremes.

3.3 THE ZENITH LUMINANCE AND LUMINANCE DISTRIBUTION

For the clear sky luminance at point P in the sky, Kittler's luminance distribution equation [11] is used,

$$L_{P\ clr} = L_{Z\ clr}\ \frac{(1-e^{-0.32/\sin\theta})\ (0.91 + 10e^{-3\psi} + 0.45\cos^2 \psi)}{0.274\ (0.91 + 10e^{-3(\pi/2-h)} + 0.45\ \sin^2 h)} \tag{3.4}$$

where the radian angles θ, ψ, and h are given in figure 3.2. The zenith sky luminance $L_{Z\ clr}$ for perfectly clear sky conditions is given by the equation

$$L_{Z\ clr} = a_o + a_1\ h^2 \qquad (k\ cd/m^2) \tag{3.5}$$

where,

h = the solar altitude in degrees
a_o, a_1 = atmospheric coefficients as found in table 1.

The coefficients a_o and a_1 are from Dogniaux [12] with the coefficients for the h^3 term excluded since their contribution is insignificant for this type of application. The values for the Ångström turbidity coefficient β and the precipitable water ω, while not normally available, can be approximated using the classification shown in table 1 (also from Dogniaux). Reference is made to Linke [13] and Nagel [14] for the relationship between β and ω and other atmospheric factors.

Figure 3.3 shows a plot of the NBS sky measurements [15] of clear sky zenith luminance along with curves for the upper and lower limits of equation 3.5.

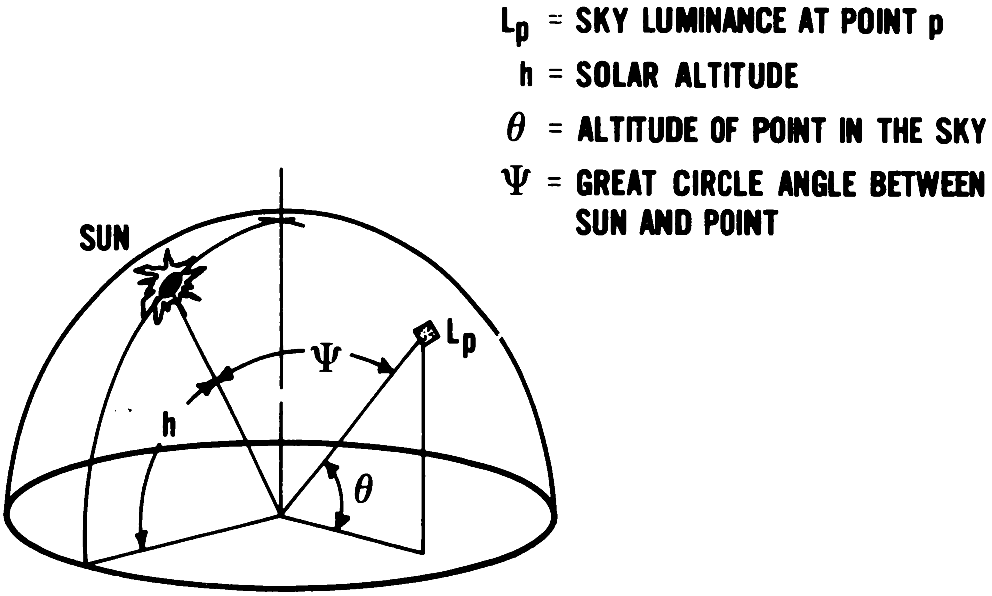


Figure 3.2 Sky dome with angles used in the sky luminance equations (angles in radians)

Table 1. Atmospheric Coefficients According to Dogniaux[12] (Excluding h^3 Term)

		Rural Region $\beta = 0.05$		Urban Region $\beta = 0.10$		Industrial Region $\beta = 0.20$	
		a_o	a_1	a_o	a_1	a_o	a_1
Dry Air (Desert Climate)	$\omega^* = 0.5$	0.9361	0.0020	1.0329	0.0024	1.1399	0.0030
	$\omega = 1.0$	0.9093	0.0018	1.0206	0.0022	1.1499	0.0028
	$\omega = 2.0$	0.8727	0.0014	1.0074	0.0019	1.1698	0.0025
	$\omega = 3.0$	0.8547	0.0012	1.0019	0.0017	1.1833	0.0023
	$\omega = 4.0$	0.8460	0.0011	0.999	0.0016	1.1899	0.0022
↓	$\omega = 5.0$	0.8410	0.0011	0.998	0.0016	1.1968	0.0021
Humid Air (Tropical Climate)							

* ω given in centimeters of water

The data is bias toward the lower curve, which is to be expected since the NBS measurement station is in a semi-rural area where the air tends to be somewhat humid. This is confirmed by measurements taken 60 years ago in the same area [16].

The overcast luminance distribution model is based on the simplified Moon and Spencer model [17],

$$L_{P\ ovr} = L_{Z\ ovr} \frac{(1 + 2 \sin \theta)}{3}. \tag{3.6}$$

If this equation is integrated across the sky dome to obtain horizontal illuminance E_{vt} from the overcast hemisphere, the resultant integration can be solved for the luminance at angle θ as,

$$L_\theta = \frac{3}{7\pi} E_{vt} (1 + 2 \sin \theta) \tag{3.7}$$

for which the zenith luminance becomes,

$$L_z = \frac{9}{7\pi} E_{vt} \tag{3.8}$$

Equations 3.6 and 3.8 are, therefore, combined to provide $L_{p\ ovr}$ as a direct function of E_{vt} under overcast conditions. This approach provides a substantially improved correlation with sky measurements (see chapter 6 on Validation) when compared to methods proposed by others.

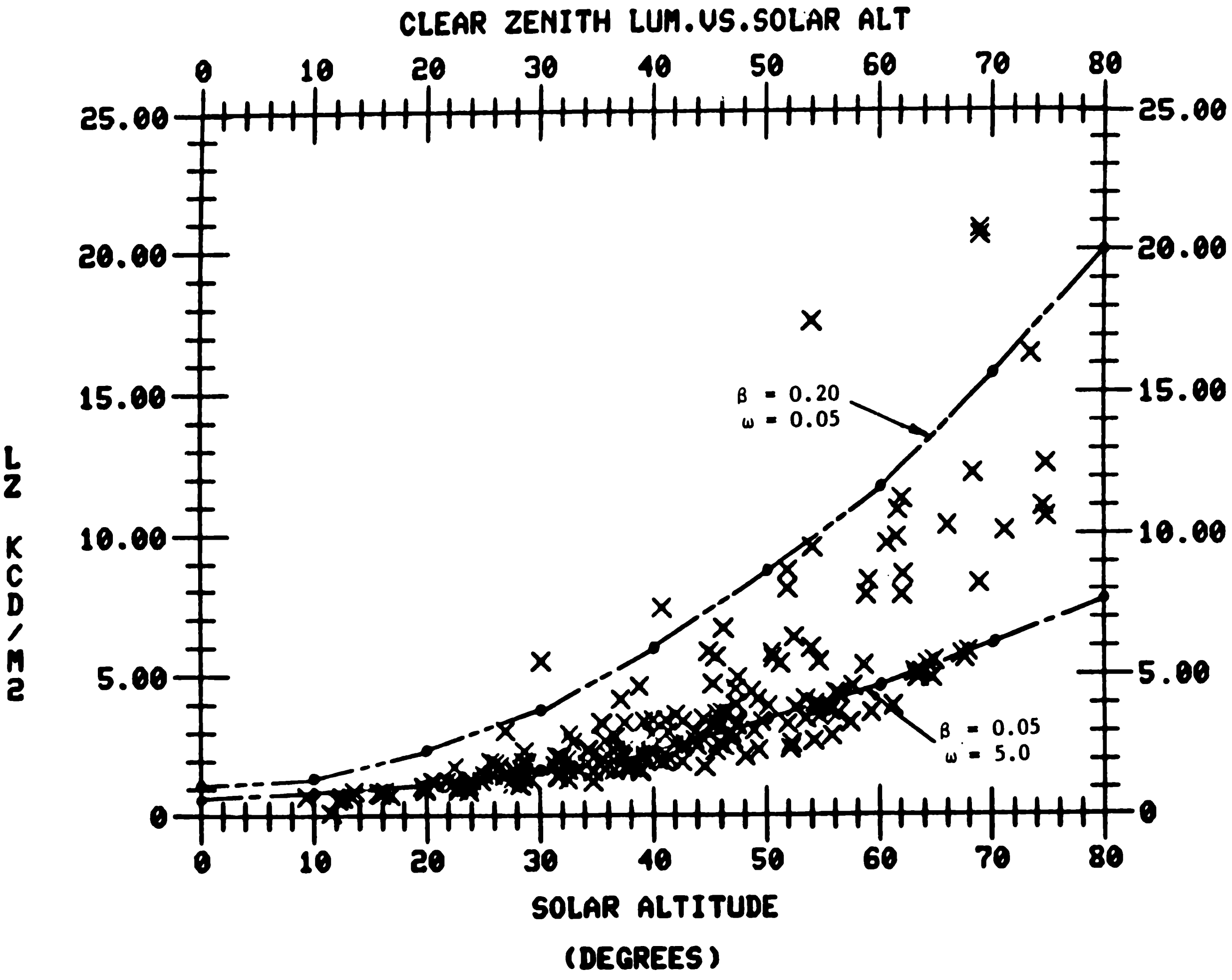


Figure 3.3 Clear sky zenith luminance as a function of solar altitude

3.4 PREDICTING HORIZONTAL ILLUMINANCE

Total and diffuse horizontal illuminance is obtained directly from knowledge of the total and diffuse solar radiation provided from the main program. Here a luminous efficacy approach is taken. Two equations are used,

$$E_{vd} = 111\ E_{ed} \tag{3.9}$$

and

$$E_{vt} = (93 + 18\ CR)E_{et} \tag{3.10}$$

where

E_{vd} = diffuse horizontal illuminance (lux);

E_{vt} = total (global) horizontal illuminance (lux);

E_{ed} = diffuse horizontal solar radiation (W/m^2);

E_{et} = total (global) horizontal solar radiation (W/m^2); and

$CR = \dfrac{E_{ed}}{E_{et}}$.

Equations 3.9 and 3.10 were also developed from the NBS measurements shown in figures 3.4 and 3.5. While it is possible to correlate E_{vt} with E_{et} using a single efficiacy value (figure 3.5), it is more useful to express E_{vt} also in terms of the cloud ratio, which gives a smooth, continuous transition into equation 3.8 for CR = 1.00 (where $E_{vd} = E_{vt}$) while also covering more of the range seen in figure 3.5.

3.5 PREDICTING DIRECT BEAM ILLUMINANCE

For predicting the intensity of the direct normal sunlight the following equation is used,

$$E_{DN} = E_{v\ SC}\left[1 + 0.033\cos\left(\frac{360\ x\ J}{365}\right)\right]e^{-a/\sin h} \tag{3.11}$$

where

E_{DN} = the direct normal beam illuminance;

$E_{v\ SC}$ = the solar illuminance constant;

J = the Julian date, from J=1 to J=365;

a = the atmospheric extinction coefficient; and

h = solar altitude.

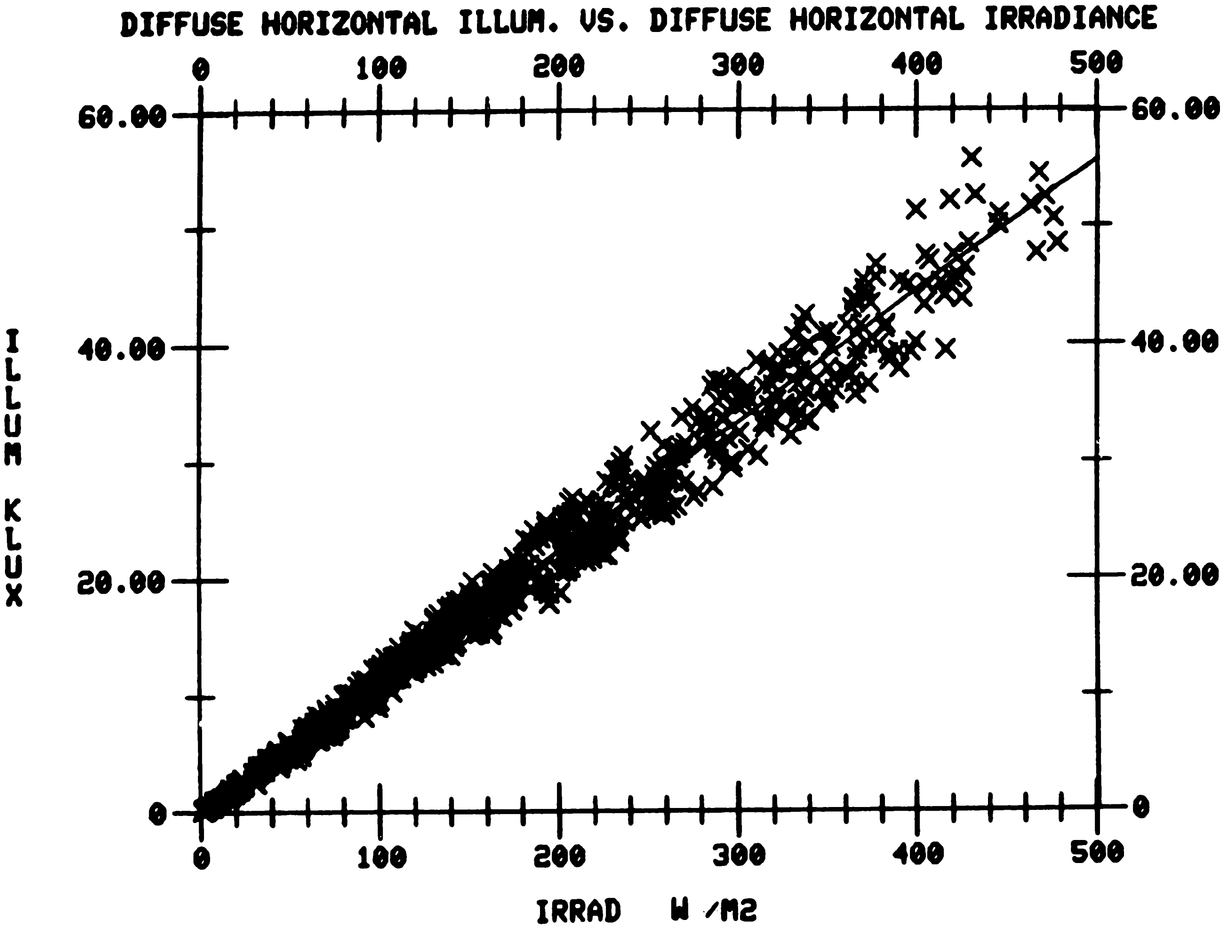


Figure 3.4 Diffuse illuminance as a function of diffuse solar radiation

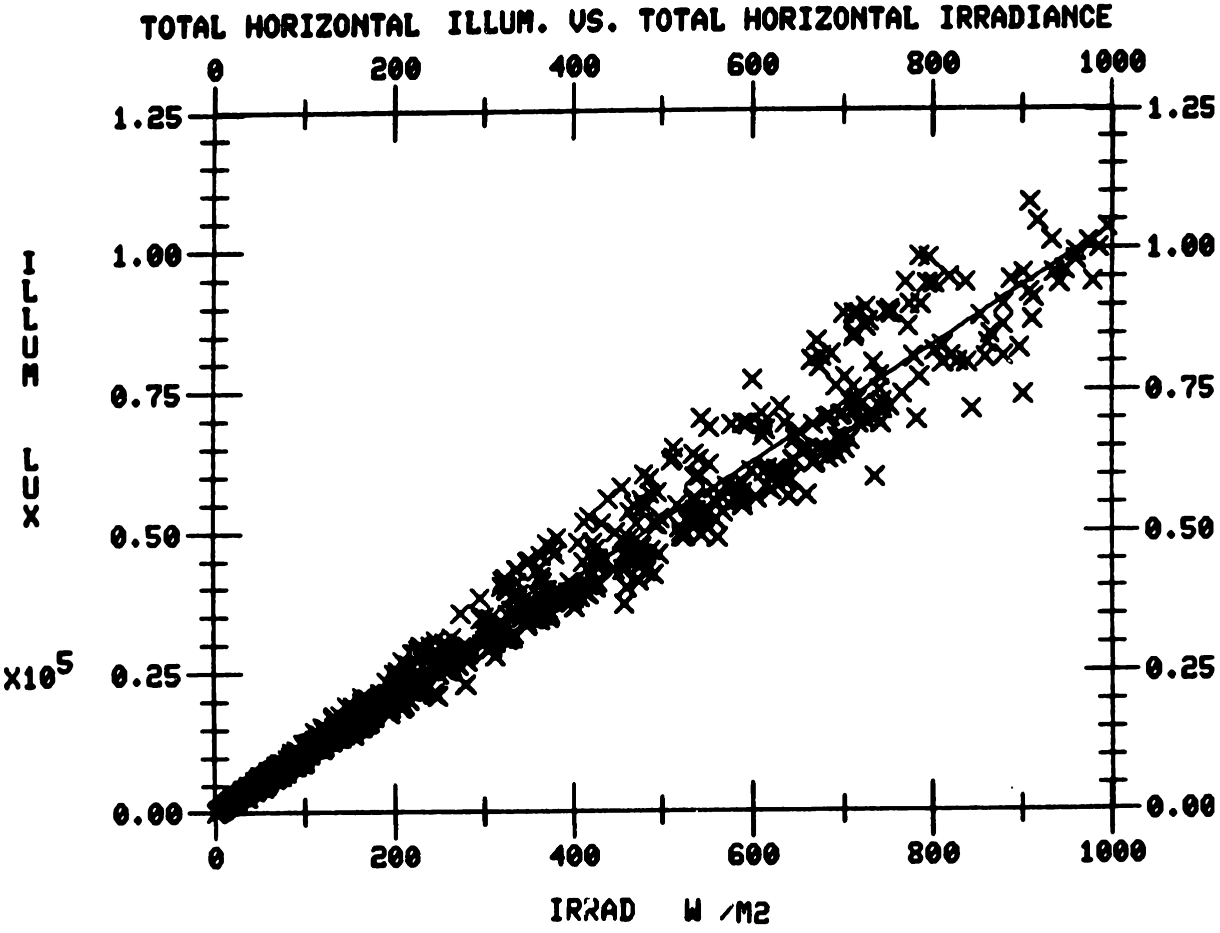


Figure 3.5 Total illuminance as a function of total solar radiation

The value for the mean extraterrestrial illuminance, $E_{v\ SC}$, was obtained by integrating the ASTM [18] standard spectral irradiance as follows:

$$E_{v\ SC} = K_M \int_{380}^{760} V_\lambda\ E_{e\lambda}\ d_\lambda \qquad (3.12)$$

where

K_M = the IES standard maximum spectral luminous efficiency, 683 lm/W [19];

V_λ = the IES standard spectral photopic eye response; and

$E_{e\lambda}$ = the ASTM standard spectral irradiance for the wavelength band, d_λ.

The resultant value,

$E_{v\ SC}$ = 127.5 klx

can be thought of as the daylighting equivalent of the solar constant, 1353 w/m^2. Measurements made both at NBS and elsewhere [20, 21] of the direct beam illuminance (figure 3.8) have been used to determine an average extinction coefficient for equation 3.7 of $a = 0.210$ for an unobstructed sun.

Others have measured the intensity of the direct beam with similar results [22]. Jones and Condit [20] extrapolated the Kimball and Hand data [16] to derive a zenith sun illuminance of 104.9 klx for the average condition between December and June sun. Moon [23] has also proposed a zenith value, which, when revised to agree with the currently recommended K_M, gives E_{DN} = 108.1 klx. From equation 3.7 the predicted mean illuminance is 105.3 klx, which agrees with Jones and Condit by within one percent and with Moon by within three percent. Similarly, Elvegard and Sjöstedt [24] fit a curve through their Swedish and Finnish data and reported a constant extinction coefficient of 0.231, a value that would cause the direct solar illuminance to be only slightly lower than predicted for equation 3.10.

The final form of the equation, therefore, for the instantaneous sun illuminance on a horizontal plane becomes,

$$E_{vs} = E_{DN} \cdot \sin h \cdot \xi_{clr} \qquad (3.13)$$

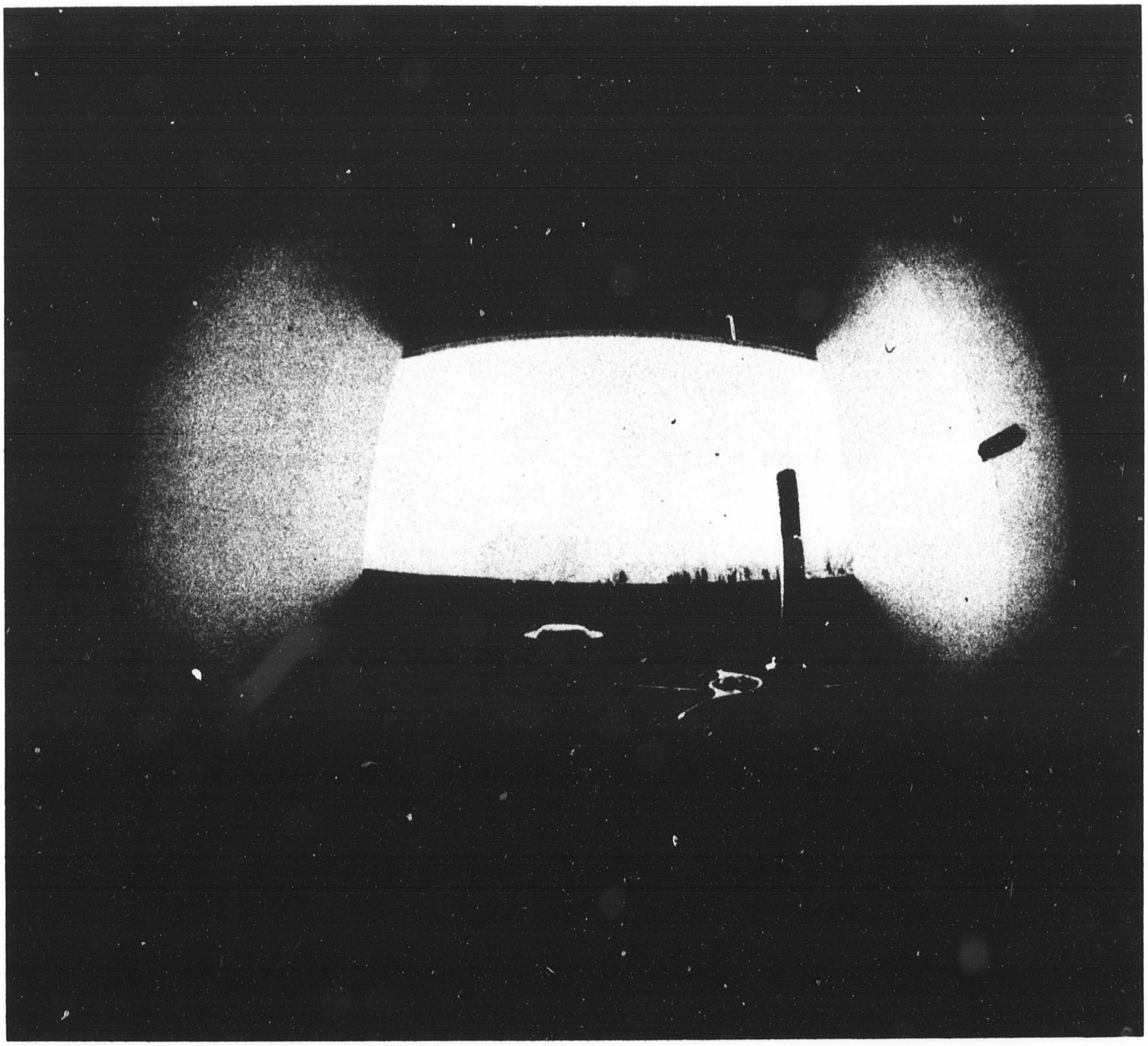
where,

E_{vs} = the horizontal solar illuminance;

ξ_{clr} = the clear sky fraction (see Section 3.2).

The sin h term corrects for the flux on the horizontal plane, and ξ_{clr} corrects for the loss in intensity due to partly cloudy conditions.

Facing page: *Measuring the interior daylight illuminance within a room.*



4. THE RMLITE ROUTINE

4.1 CAPABILITIES

RMLITE computes the interior illuminances on a horizontal workplane 0.76 m (2.5 ft) above the floor. The cumulative effect of multiple windows or skylights is recorded to give illuminances at user selected points within the room. It should be noted, however, that this routine is room specific and surface specific, meaning that the fenestration must be on one of the room surfaces, and that the illuminance positions must be within a defined room configuration. In some energy programs this might cause problems. For cases where the main energy program is not room specific, simplifications are possible in the RMLITE routine. This is discussed further under Subroutine Interfacing (Appendix C).

4.2 PREDICTING INTERIOR DAYLIGHT ILLUMINANCES

The interior daylight prediction technique is a simplified radiant flux procedure. The fenestration, room surfaces, and exterior surroundings are divided into sufficiently small surface elements where each element is either a primary or secondary source of light with a luminous exitance M*. In the most general case, the expression is:

$$E_P = \frac{1}{\pi} \int_f \int_m \frac{M \cos \theta \cos \psi}{D^2} \, df \, dm \qquad (4.1)$$

for the illuminance Ep from direct light sources above the workplane such as the portion of sky viewed through the fenestration (figure 4.1).

Equation 4.1 can also be used to compute the illuminances on the interior surfaces, which then become sources of secondary or reflected light. The more rigorous lighting computer programs generally make extensive use of radiant transfer [25] to obtain a much more refined solution, but such rigor is not necessary for this type of analysis.

Simplification can be done if the integration is made for generic types of geometric configurations. Using the integrated equations of Higbie [26], and more recently Pierpoint and Hopkins [27], a direct solution can be achieved for equation 4.1 provided the luminance of the surface is assumed uniform. Furthermore, subdividing the room and fenestration surfaces into a minimum number of surfaces further reduces the number of computations. Both strategies are used by the RMLITE routine and, as will be shown, provide a fast, yet in most cases sufficiently accurate daylighting algorithm.

4.3 PREDICTING ILLUMINANCES FROM PRIMARY LIGHT SOURCES

4.3.1 Diffuse Light From Vertical Windows

For the diffuse illuminance from the sky on a horizontal surface due to a vertical window, Higbie's perpendicular surface geometry equation is used,

$$E_P = \frac{L}{2} \left[\tan^{-1} \frac{m}{a} - \left(\frac{a}{\sqrt{a^2 + f^2}} \right) \tan^{-1} \left(\frac{m}{\sqrt{a^2 + f^2}} \right) \right] \qquad (4.2)$$

where,

E_p = workplane illuminance at point p;

L = centroid luminance of sky patch seen through opening mf; and

a,m,f = distances as shown in figure 4.2.a.

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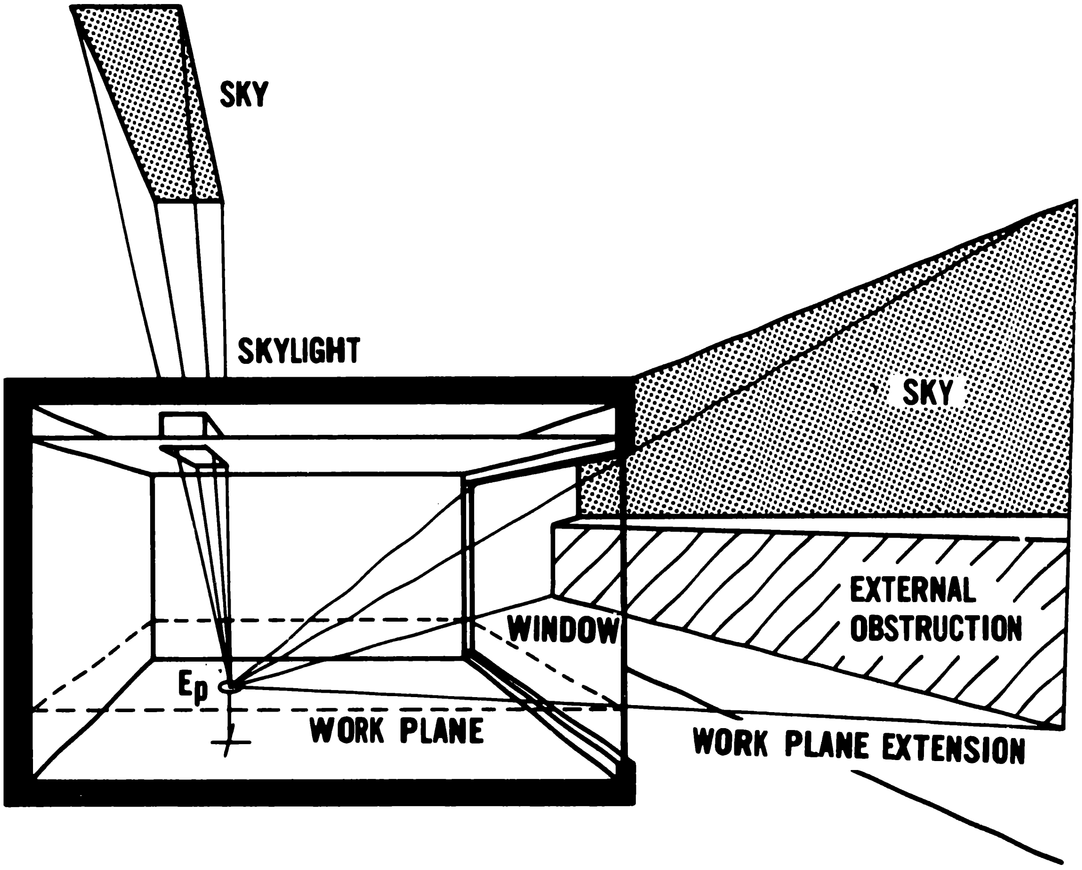
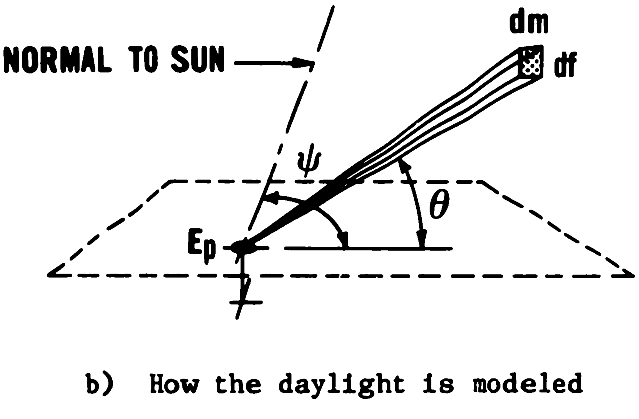
* Luminous exitance can be assumed equal to source luminance if an approximate lambertian surface is assumed; if so, $M = \pi L$, where L is the source luminance.



a) The daylight contributors to the illuminance at point p



b) How the daylight is modeled

Figure 4.1 Predicting the interior illuminance E_p at point p

E_P is given in lux when a, m, and f are in meters and L in nits (cd/m^2); E_P is in footcandles when a, m, and f are in feet and L in footlamberts. Lastly, superposition is used to locate this surface element anywhere on the wall.

4.3.2 Diffuse Light From Horizontal Skylights

For the diffuse illuminance from the sky on a horizontal surface due to a horizontal skylight, Higbie's parallel surface geometry equation is used,

$$E_P = \frac{L}{2} \left[\frac{f-a}{\sqrt{c^2 + (a-f)^2}} \tan^{-1} \left(\frac{m}{\sqrt{c^2 + (a-f)^2}} \right) \right] \tag{4.3}$$

where the geometry is shown in figure 4.2.b.

The skylight luminance L deserves a special note. For the skylight units with both transparent inner and outer glazing, L is the centroid sky luminance. However, when either outer or inner glazing is translucent, which is normally the case, L becomes the total exterior horizontal exterior illuminance E_{vt} (from sun and sky) multiplied by the net transmittance. The net transmittance includes the transmittance of both glazings, the dome effects, and the wall effects; it can be obtained from Appendix A [28].

4.3.3 Diffuse Light From Clerestories

The direct skylight admitted through the vertical glazing in a clerestory is treated as if coming from a remote vertical window (see 4.3.1), except that checks are made for those illuminance points along the workplane that would be obstructed from view of the clerestory fenestration (figure 4.3). The reflected light from roof and the sky onto the sloped clerestory ceiling is modeled using the Pierpoint and Hopkins equation,

$$\begin{aligned} E_P = \frac{L}{2} \Bigg[& \frac{x}{\sqrt{x^2 + z^2}} \tan^{-1} \frac{m\sqrt{x^2 + z^2}}{x^2 + y^2 + z^2 - ym} \\ & + \frac{f \cos \psi - x}{\sqrt{x^2 + z^2 + f^2 + 2fG}} \tan^{-1} \frac{m\sqrt{x^2 + z^2 + f^2 + 2fG}}{x^2 + y^2 + z^2 - ym + f^2 + 2fG} \\ & + \frac{y \cos \psi}{\sqrt{y^2 + H^2}} \tan^{-1} \frac{f\sqrt{y^2 + H^2}}{y^2 + H^2 + G^2 + fG} \\ & - \frac{(y - m) \cos \psi}{\sqrt{(y - m)^2 + H^2}} \tan^{-1} \frac{f\sqrt{(y - m)^2 + H^2}}{(y - m)^2 + H^2 + G^2 + fG} \Bigg] \end{aligned} \tag{4.4}$$

where,

$$G = z \sin \psi - x \cos \psi$$

and

$$H = z \cos \psi + x \sin \psi$$

The geometry is illustrated in figure 4.2.c. The luminance in this case is the centroid exitance of the surface, found by the product of the ceiling reflectance and the illuminance at the ceiling centroid.

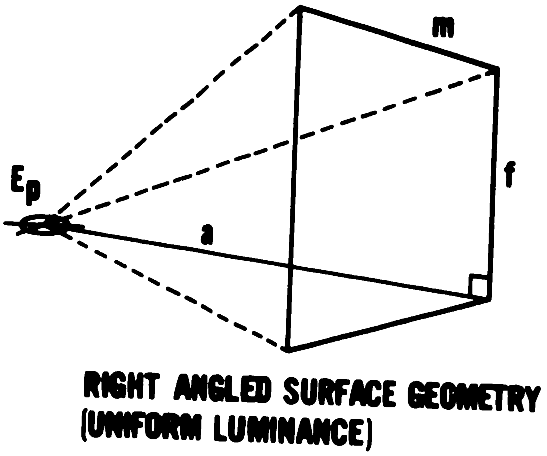


Figure 4.2.a

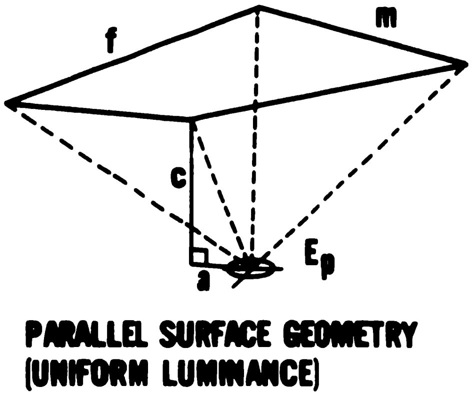


Figure 4.2.b

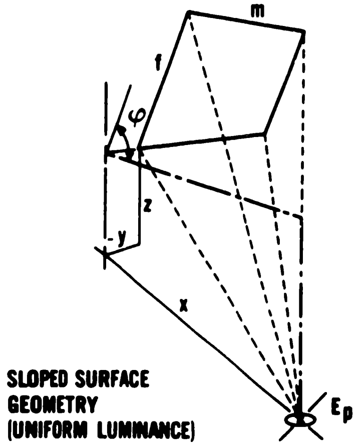


Figure 4.2.c

Figure 4.2 Geometric configurations for equations 4.2 - 4.4

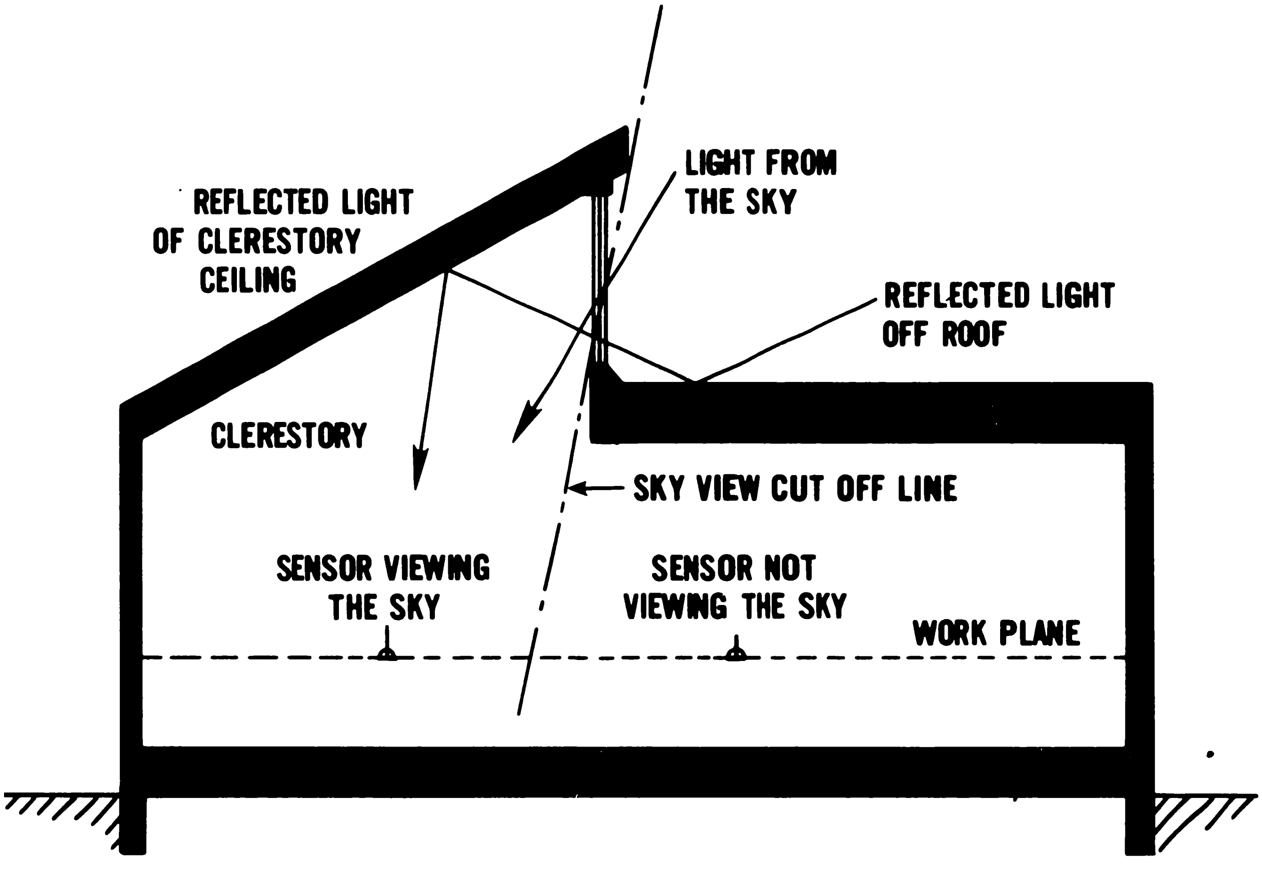


Figure 4.3 Clerestory illuminance technique

4.4 PREDICTING ILLUMINANCES FROM SECONDARY LIGHT SOURCES

4.4.1 Light From External Obstructions

External obstructions, such as surrounding buildings, are modeled as diffuse light sources with a uniform luminance. This luminance is obtained by multiplying the sky luminance for that obstructed region of the sky by the obstruction reflectance ρ_X. Geometrically, the obstructions are assumed to be simple vertical projections above the workplane running continuously in the horizontal direction (figure 4.4). It is possible to simulate external obstructions in a more rigorous way, yet because actual size and surface reflectance are rarely (if ever) known, it would be difficult to justify the increased complexity.

4.4.2 Light From the Ground

The ground reflected light is found by first obtaining the uniform ground luminance, which is the product of the total horizontal illuminance, E_{vt}, and the ground reflectance. Assuming that the ground surface is an infinite horizontal plane, the parallel surface equation is used to project ground light onto interior horizontal surfaces (the ceiling for example); the perpendicular surface equation is similarly used for vertical wall surfaces.

Light reflected off the roof onto the sloped clerestory ceiling surface is treated in like manner. Here the Pierpoint and Hopkins equation is used to obtain the illuminance at the center of the interior sloped surface due to the sky and the roof, which in turn, is then reflected into the room.

4.4.3 Light Interreflected Within Room

The multiple reflections and interreflections of light flux within a room is normally the most time consuming part of the most large lighting programs. Analytically, it is the most complex. Not only must equation 4.1 be applied for each incremental area within the room due to each source of light, but this must be done repetitively as these areas illuminate to become themselves sources of secondary light. Yet such an approach is necessary only if a rigorous solution is sought.

A simpler technique is to subdivide the room into only a few surfaces, such as the six enclosure surfaces. Obviously, averaging the luminance over these larger surfaces will be a less exact procedure. However, the fraction of the total illuminance due to interreflected light is normally quite low, thus, minimizing the impact on the total illuminance at a given point. Furthermore, due to uncertainties in the correct values for hemispherical-directional reflectance, and noting that internal obstructions on the walls and within the room normally exist, it is difficult to justify substantial time on the interflected light calculation.

In some ways the interreflected model used in RMLITE is similar to the split flux method [29, 30] which subdivides the room into two hemispherical elements, but overcomes one of its weaknesses by being more general and applicable to rooms with fenestration other than windows. The six surface model should also

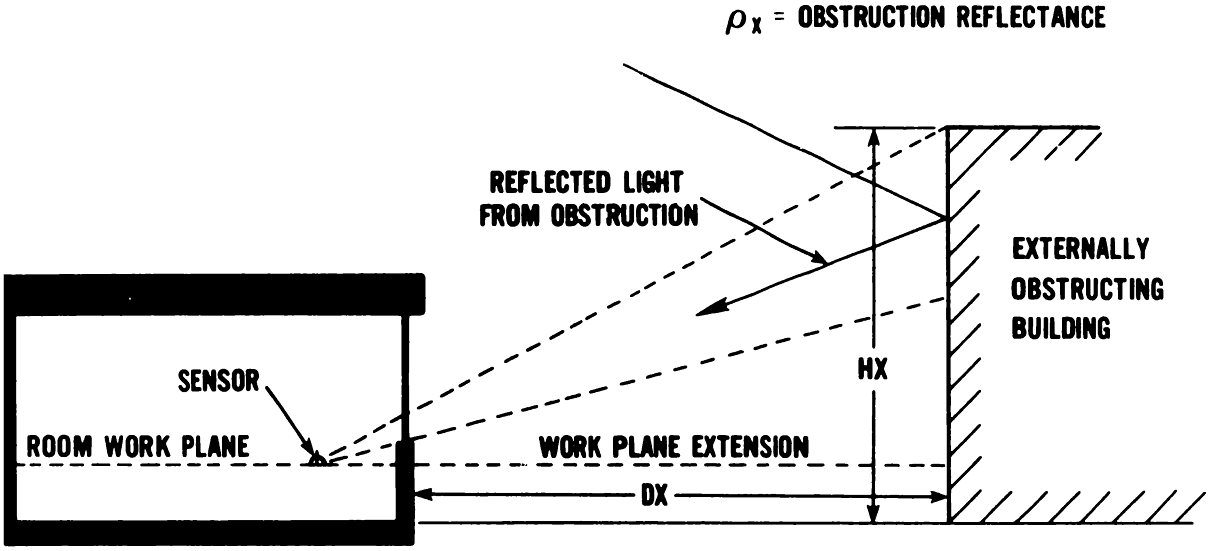


Figure 4.4 Light from external obstructing buildings

be slightly more accurate. Once the initial light flux is determined on each of the six surfaces, multiple interreflections are accounted for by assuming the room acts as an Ulbricht integrating sphere, an assumption that is valid for wall reflectances approaching the ceiling reflectance and room depths less than twice the ceiling height.

Dressler [31] found that if the wall surfaces act as diffuse lambertian reflectors, then the first reflected flux within the room can be expressed as,

$$\Sigma F_i = F_1\rho_1 + F_2\rho_2 + \ldots\ldots\ldots + F_n\rho_n \tag{4.5}$$

where F_n is the initial flux on surface n, ρ_n is its diffuse reflectance, and ΣF_i is the sum of the first reflected flux. The multiple reflected flux then becomes,

$$\Sigma F_i(1 + \rho_{ave} + \rho_{ave}^2 + \rho_{ave}^3 + \ldots.) = \frac{\Sigma F_i}{1-\rho_{ave}} \ . \tag{4.6}$$

Since the illuminance of the Ulbricht sphere is total flux over the total area, the interreflected illuminance becomes,

$$E_{ref} = \frac{(F_1\rho_1 + F_2\rho_2 + F_3\rho_3 + \ldots\ldots\ldots + F_n\rho_n) + F_s\rho_f}{(1-\rho_{ave})\ A_t} \tag{4.7}$$

where

F_n = E_n A_n (for each room surface)
F_s = E_s A_s (for the projected sunlight)
ρ_f = the reflectance of the floor
ρ_{ave} = the average reflectance of all surfaces
A_t = the total area of all surfaces
A_n = the area of surface n
A_s = the area of the sun patch rhomboid
E_n = the centroid illuminance of surface n
E_s = the sun patch illuminance from equation 3.13.

The initial centroid illuminance E_n for each surface is found by equations 4.2 through 4.4.

By letting n = 6 and solving equation 4.5, the inter-reflected daylight is obtained in a fraction of the time it would require other more rigorous models.

4.5 PREDICTING DIRECT SUNLIGHT

The model to determine the contribution of direct sunlight is fairly straightforward. The rhomboidal projection of the fenestration on the workplane is first determined and a check is made whether an illuminance point is within one of these patches of sunlight (figure 4.5). If so, the direct beam illuminance E_s is added to the existing workplane illuminance, after being corrected for glazing angle transmittance and cosine angle between the workplane and the sun.

4.6 MODELING GLAZING TRANSMITTANCE

There are two types of glazing transmittance used, the angular dependent transmittance, τ_D, for direct sunlight, and the hemispherical transmittance τ_d, for diffuse sky light. For flat fenestration the latter is assumed constant. The former, τ_D, varies with the angle between the surface normal and the sun angle, ψ, according to the expression [32],

$$\tau_\psi = 1.018\ \tau_o \cos \psi\ (1 + \sin^3 \psi) \qquad (4.8)$$

where τ_o is the visible transmittance value normally obtained from manufacturer's data.

For domed skylights, the curvature of the upper dome has been found to affect the transmittance of both the direct and diffuse daylight [33]. Although the aspect ratio of the dome, incident angle, and variations in thickness of the glazing material will cause variations in the direct transmittance, τ_D, the range is within approximately 10 percent of τ_o for solar altitudes above 20 degrees [28]. Thus, a single value is used for the direct transmittance. On the other hand, τ_d requires correction for well losses, which combine to give a single effective transmittance, τ_{eff}. While it is possible to incorporate all the transmittance correction factors into the computer model, it is far easier and probably more practical to allow this value to be computed externally (see Appendix A).

4.7 MODELING OVERHANGS AND SIDE FINS

Overhangs and side fins are accounted for by adjusting the effective window area according to the viewing obstruction angle. For overhangs, an effective window height is computed and used as if this were the actual height. Similarly, side fins adjust the window width to provide an effective window size as seen by point p. Since each correction is specific to the illuminance point under consideration, these adjustments are done for each point.

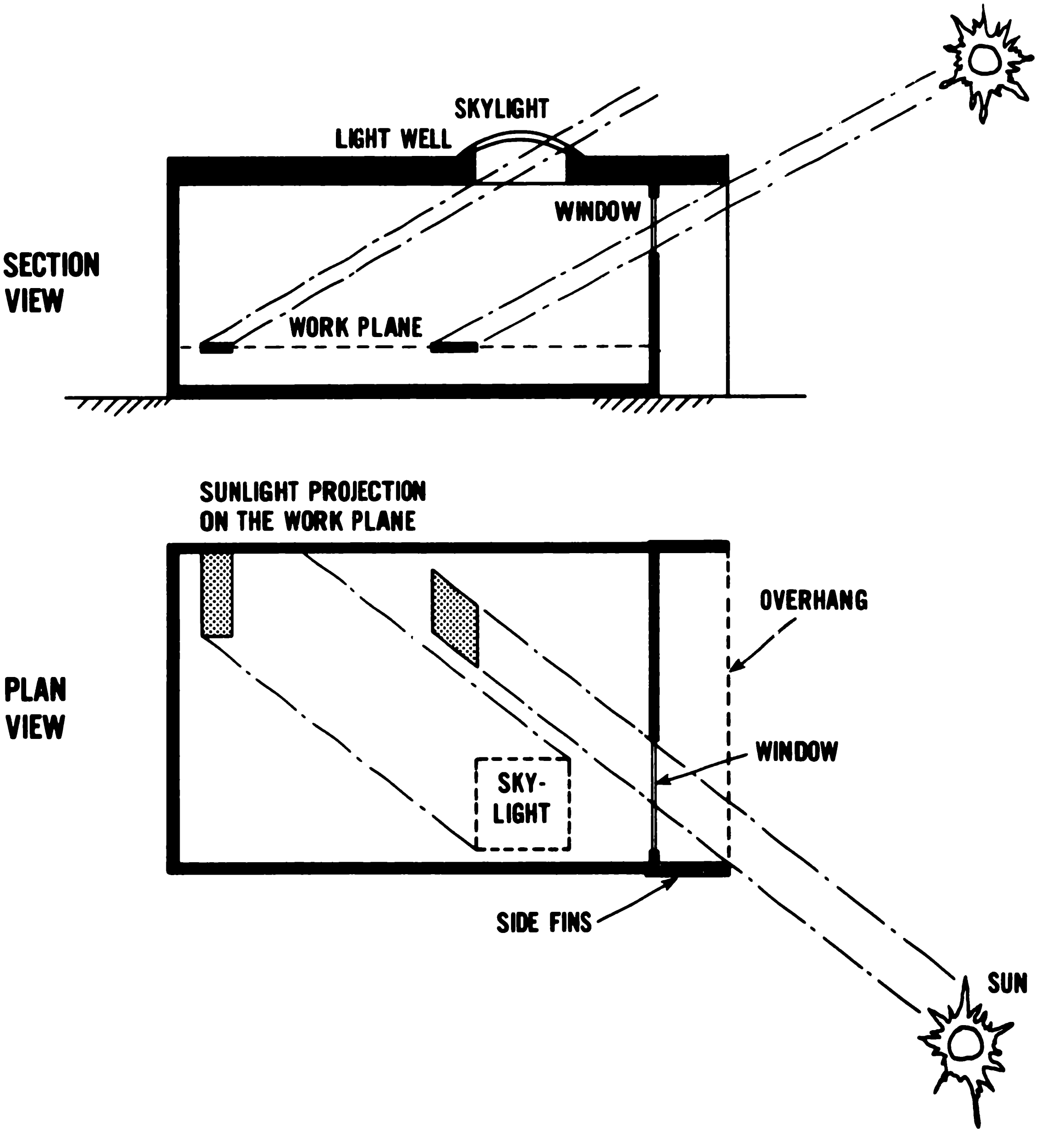


Figure 4.5 Sunlight projection within room

Facing page: Supplementing daylighting with incandescent sources to provide a constant illuminance level.

5. THE LLOAD ROUTINE

Once the illuminance is obtained at a point within the room, it is the lighting load routine LLOAD which developes an associated power load for use in the main building energy program. But a note should be made here. The daylight illuminance at a position on the workplane means nothing in terms of energy unless some type of control system recognizes this intensity and can respond by changing the power requirement of the lighting system. This is usually accomplished through the use of a photocell. The response strategy could be either switching or dimming; and the lighting system sensitive to this point illuminance could be a single luminaire, a bank of luminaires, or all the luminaires within the room. Since photocells are normally not located on the workplane, it is important to explain that the lighting system must be balanced once installed to meet a specified workplane illuminance and, therefore, the point where balancing is done becomes the illuminance point.

The LLOAD subroutine is not a lighting design tool but an analysis tool. Information must be supplied to the program stating the full lighting power load controlled by each photocell. On so doing, a completely general model is provided for modeling almost any type of lighting layout. Figure 5.1 will help explain this. Ambient and task lighting is shown where three illuminance points control three banks of general illumination, and one controls a task luminaire. As far as the daylighting model is concerned, the only important information necessary is the position directly below the photocell, the full connected power which will respond to the sensor, the setpoint illuminance, and the dimming strategy.

Four dimming strategies are offered. A simple on/off strategy shuts the connected power off once the setpoint illuminance is met by daylight. The second strategy, half-on/half-off step-down, shuts off half the connected power at half the prescribed illuminance, and the remainder after this illuminance is exceeded. The third strategy is a continuous dimming technique where the power is proportionally adjusted to follow a typical performance curve [34,35], but remains at the minimum power level when supplemental light is no longer necessary. The fourth is similar to the third except it allows the luminaires to shut off completely once the minimum power is reached. The continuous dimming strategies assume a simple linear relation between the percent supplemental light, $\%E_{sup}$, and the percent power required, $\%W_{req}$,

$$\%W_{req} = \xi\ (\%E_{sup}) + \chi \tag{5.1}$$

where ξ and χ are specified lighting control coefficients. If such coefficients are not available, the following default values are assumed for a generic system,

$\xi = 0.70$

$\chi = 0.30.$

Equation 5.1 is a simplified expression representing the generic curve for the dimming performance of a fluorescent ballast system (figure 5.2). For other types of lamp systems, such as high pressure sodium, appropriate values for ξ and χ can be substituted.

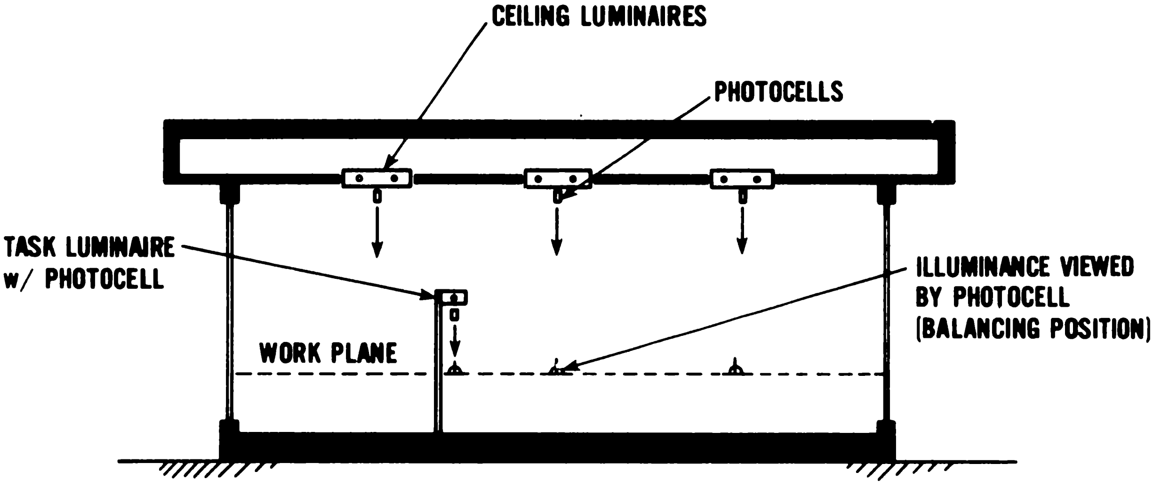


Figure 5.1 Task/ambient and general lighting layouts as viewed by program

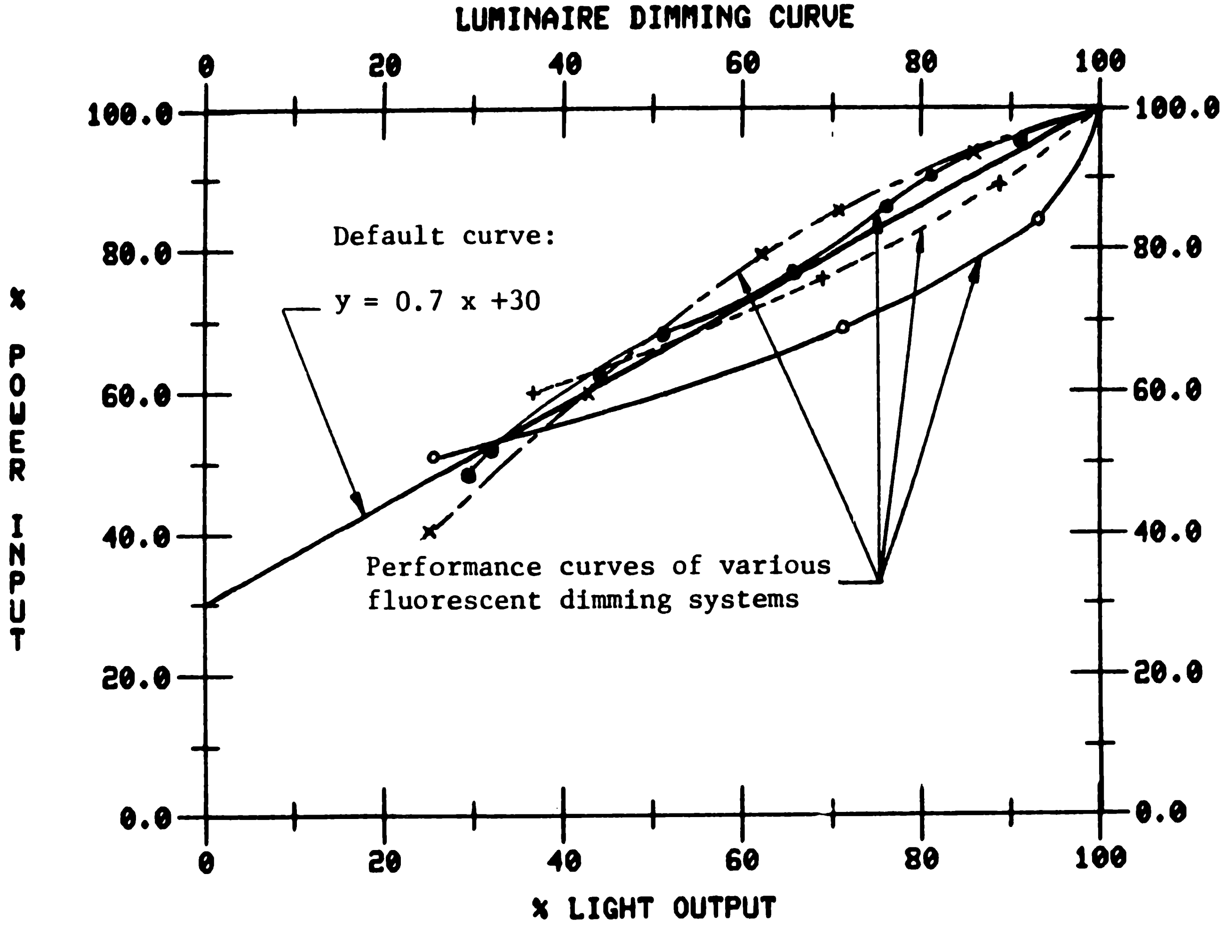
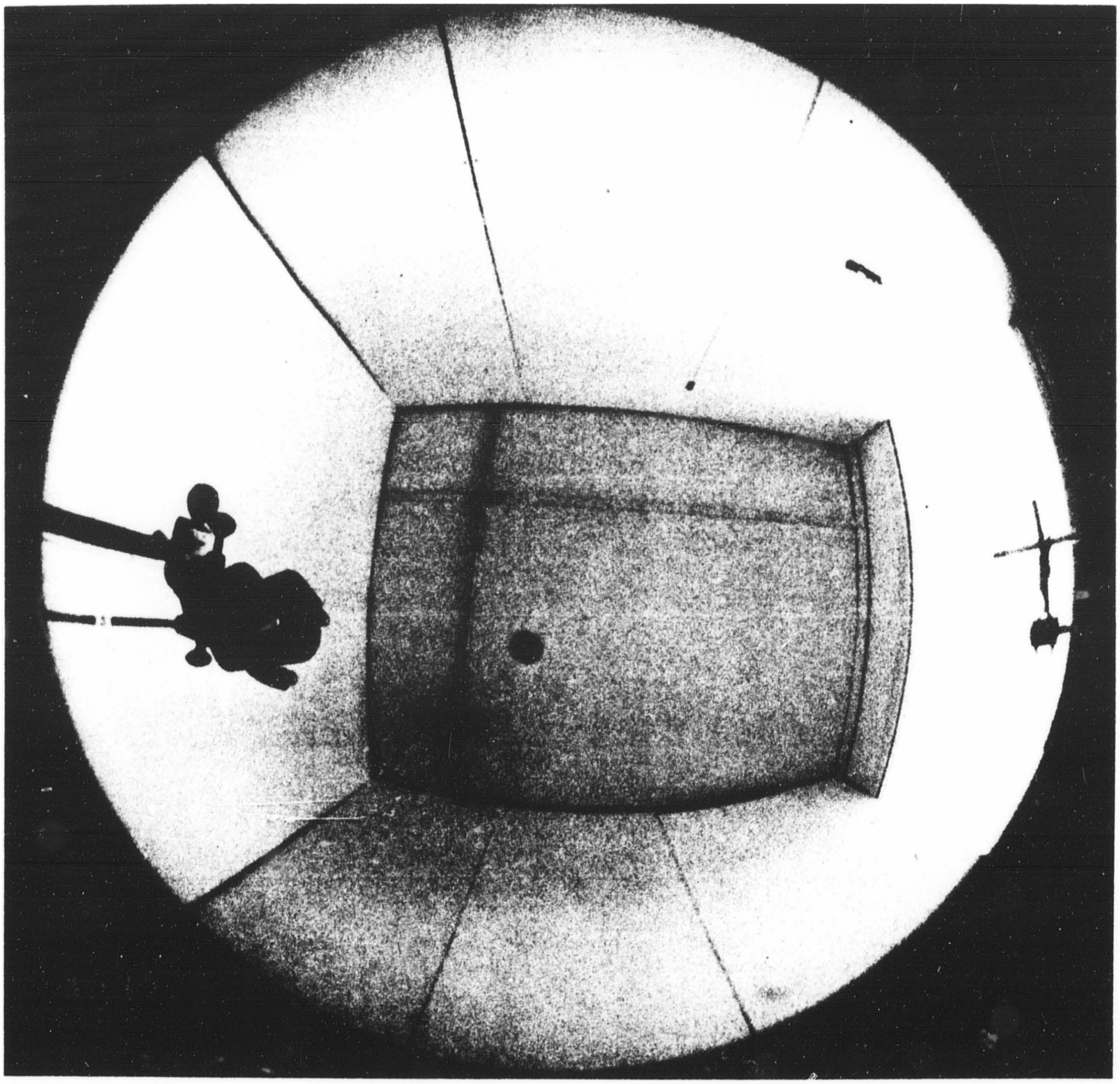


Figure 5.2 Dimming curve of lumminare dimming system used as default along with similar curves of various manufacturers



Caption: Validation measurements within a full scale room

6. VALIDATION

Inherent in any prediction technique is the need for validation against real-case conditions. Although it is sometimes possible to show a sufficient correlation by simply conducting a relative check with field measurements, such simplification can be very misleading. The case is particularly true with the validation of computer models. Some models simulate some conditions better than others, and as with all prediction techniques, the accuracy of the assumptions in the model and the accuracy of the input variables can often remain uncertain. Furthermore, daylighting measurements must be done with extreme care and should be based on a series of like measurements in order to assess the uncertainty of each measured quantity.

To control these characteric uncertainties, evaluating the accuracy of the DALITE model was done in stages, by first carefully establishing the test conditions for comparisons, and then by conducting step-by-step validation of each of the major algorithms used within the program. The sky model was compared against hourly measurements of sky luminance, sky illuminance, and solar radiation; the room illuminance model was compared against measurements made in two full-scale test rooms and in mock-up models; and the lighting load model was checked against laboratory tests of luminaire dimming and step-down performance. Where comparable measurements by others were available, a check with their data was also done. The result is an overall validation, showing both the strengths and weaknesses of the daylighting model.

6.1 VALIDATION OF THE SKY MODEL

SKYLUM, the subroutine that generates the hourly sky luminance, sky illuminance, and direct sun illuminance, was validated against sky measurements made at the National Bureau of Standards in Gaithersburg, MD (latitude 38° 5', longitude 77° 0'). The NBS data were from a series of days taken from more than two years of sky measurements. The reference sky data were selected from measurements known to be correct, and were chosen to provide good hourly data of clear skies, overcast skies, partly cloudy skies, summer conditions, winter conditions, and fall/spring conditions.

6.1.1 Validation of Sky Luminance

There are two basic parts to the sky luminance algorithm that need to be validated: the sky luminance distribution and the zenith luminance. Also, since a phasing technique is used to obtain intermediate sky condition based on the mix between the clear and overcast sky, both the validity of the phasing technique and the modeling of the clear and overcast skies must be substantiated.

The luminance distribution plots are illustrated in figures 6.1 and 6.2 of the clear and overcast skies respectively. Figure 6.1 shows the validity of the clear sky distribution model, particularly for sky regions away from the sun where the sky luminances are below 2,000 cd/m^2. It should be noted, however, that figure 6.1 is not a validation of the Kittler clear sky equation, but rather a comparison showing the ability this equation has in estimating the luminances in the real (not a standardized) clear sky. Likewise, figure 6.2 represents the correlation of the overcast luminance distribution with measured luminances. The four different symbols represent the 42 degree luminance at the four cardinal orientations. If the sky were perfectly uniform with respect to orientations, the symbols would coincide; and if the distribution matched the simulated distribution perfectly, the plot would fall on the solid line. Given the variableness in instantaneous sky conditions, both distribution models appear to perform reasonably well.

The zenith luminance correlations shown in figures 6.3 and 6.4 plot the sky model's ability to predict the sky luminance at the zenith, which is normally the reference value used to obtain absolute luminances once the luminance distribution is known. Figure 6.3 compares the validity of the clear sky zenith equation while also revealing the stability in the sky conditions. In a similar way, a general agreement is also illustrated in figure 6.4, but with an expected increase in scatter due in part to the variability of the overcast sky.

6.1.2 Validation of Exterior Horizontal Illuminance

A comparison of calculated exterior horizontal illuminance is shown against comparable measurements in figure 6.5. The data represents a substantial set of measurements for a wide range of sky conditions and cloud type and shows a good linear agreement. The correlation shows agreement both in the clear summer months (above 60,000 lux) as well as the winter months (below 60,000 lux).

6.1.3 Validation of Direct Beam Illuminance

Figure 6.6 is used to validate the direct beam illuminance algorithm. The sunlight algorithm for the winter solstice (Julian date = 321) and summer solstice is compared against measurements made both at NBS and elsewhere within the United States. [36]. Unfortunately, much of the data recorded elsewhere was not separated by season, and it appears as though there is a slight seasonal dependence, but this is only a second order affect for lower solar angles. The equation is seen to capture the seasonal variation and exhibits a good fit to the measured data.

6.2 VALIDATION OF THE ROOM ILLUMINANCE MODEL

The interior daylight illuminance model was validated using measurements from two full-scale test rooms and two scale-model test rooms. Because the interior prediction routine incorporates all the other subroutines, this validation represents the overall performance of the daylighting program. Furthermore, since the collective set of subroutines can simulate many daylighting scenerios, it was desirable to evaluate several room, fenestration, and sky conditions.

The physical characteristics of the four test rooms used in the validation work are given in figures 6.7 and 6.8. The four rooms provide measurement data for rooms of different dimensions, wall reflectances, and fenestration types and orientations. Although not all possible combinations were explored, the ones illustrated appear representative; scale model measurements facing east and west and with different glazing areas show similar results. The two scale-models (test room No. 1 and No. 2) and one of the full-scale rooms (test room No. 3) had workplane illuminance recorded each hour along with the other hourly measurements of sky luminance, sky illuminance, and horizontal solar radiation. The fourth test room was instrumented in a slightly different way, with independent measurements taken every five minutes and catalogued according to depth from the fenestration. These latter measurements could be compared to determine the amount of relative uncertainty in the daylighting measurements. Hourly profiles of both calculated and measured illuminance in the scale models are shown in figures 6.9, 6.10, and 6.11 representing the overcast, partly cloudy, and clear sky conditions respectively. All three figures show good agreement for all sky conditions, particularly under the clear and overcast sky. Figure 6.11 also shows the successful modeling of the direct sunlight. In a similar way, hourly values are compared for the full-scale room No. 3, but with a full range of sky conditions (cloud ratios) in figure 6.12.

The measurements performed in test room No. 4 were done separately from the others. Special care was taken to obtain precision measurements of instantaneous room and sky conditions and to provide exact input information for the prediction routine. In this way a band of the uncertainty in the data can be noted. Figure 6.13 is an overall comparison plot of all the measurements (excluding the clerestory measurements) for room No. 4 and shows that, in general, the daylight program tends to overpredict slightly at deeper room depths and to underpredict slightly near the fenestration; however, given the uncertainty of each measured quantity, the correlation is still quite good.

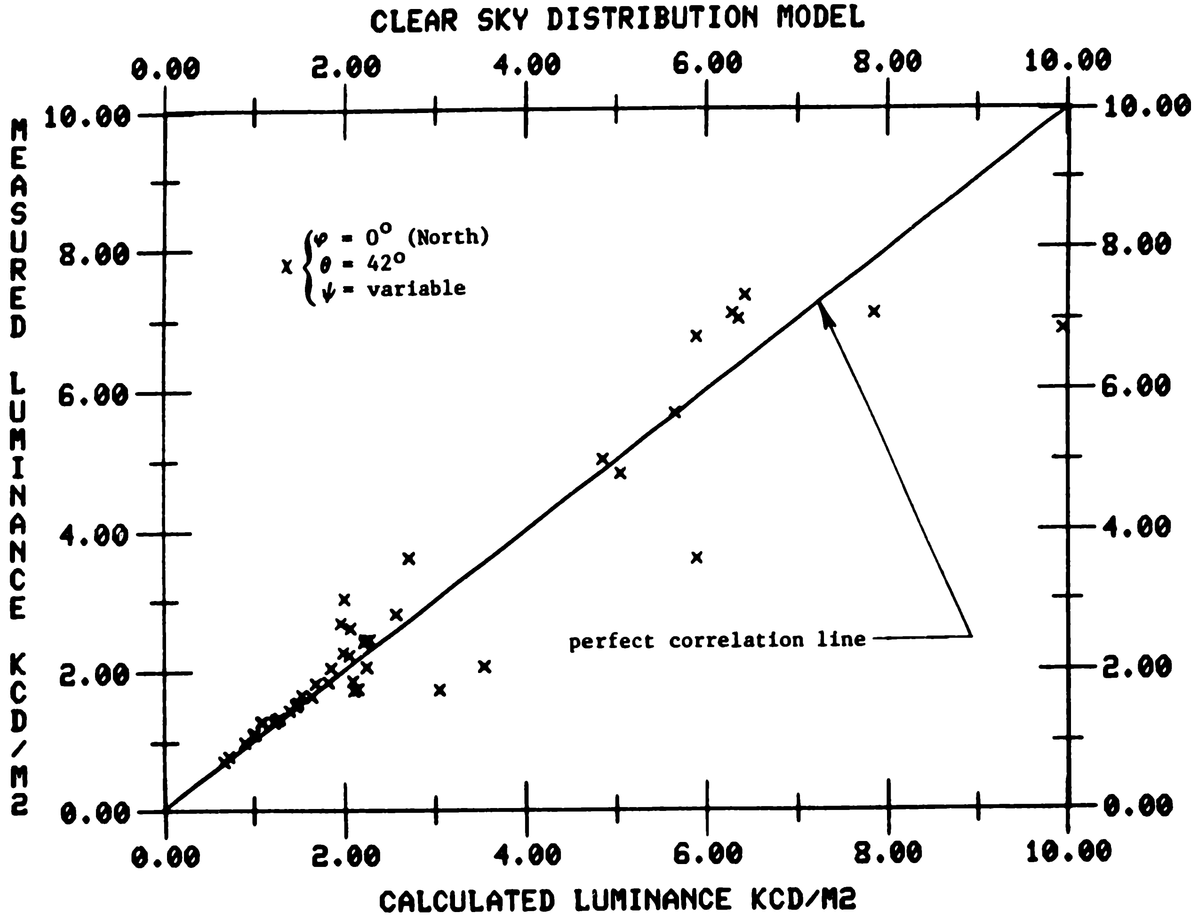


Figure 6.1 Measured sky luminance versus calculated luminance using the clear sky distribution model

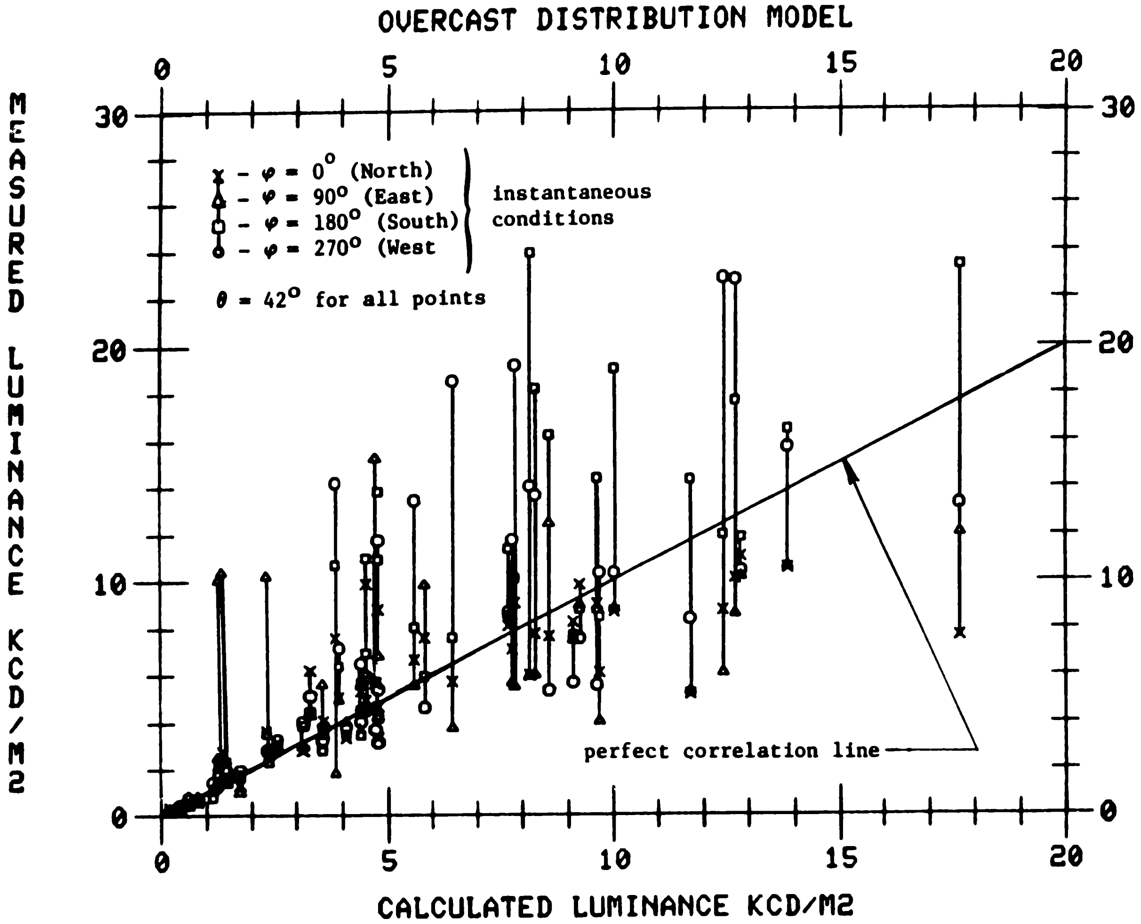


Figure 6.2 Measured sky luminance verses calculated luminance using the overcast sky distribution model

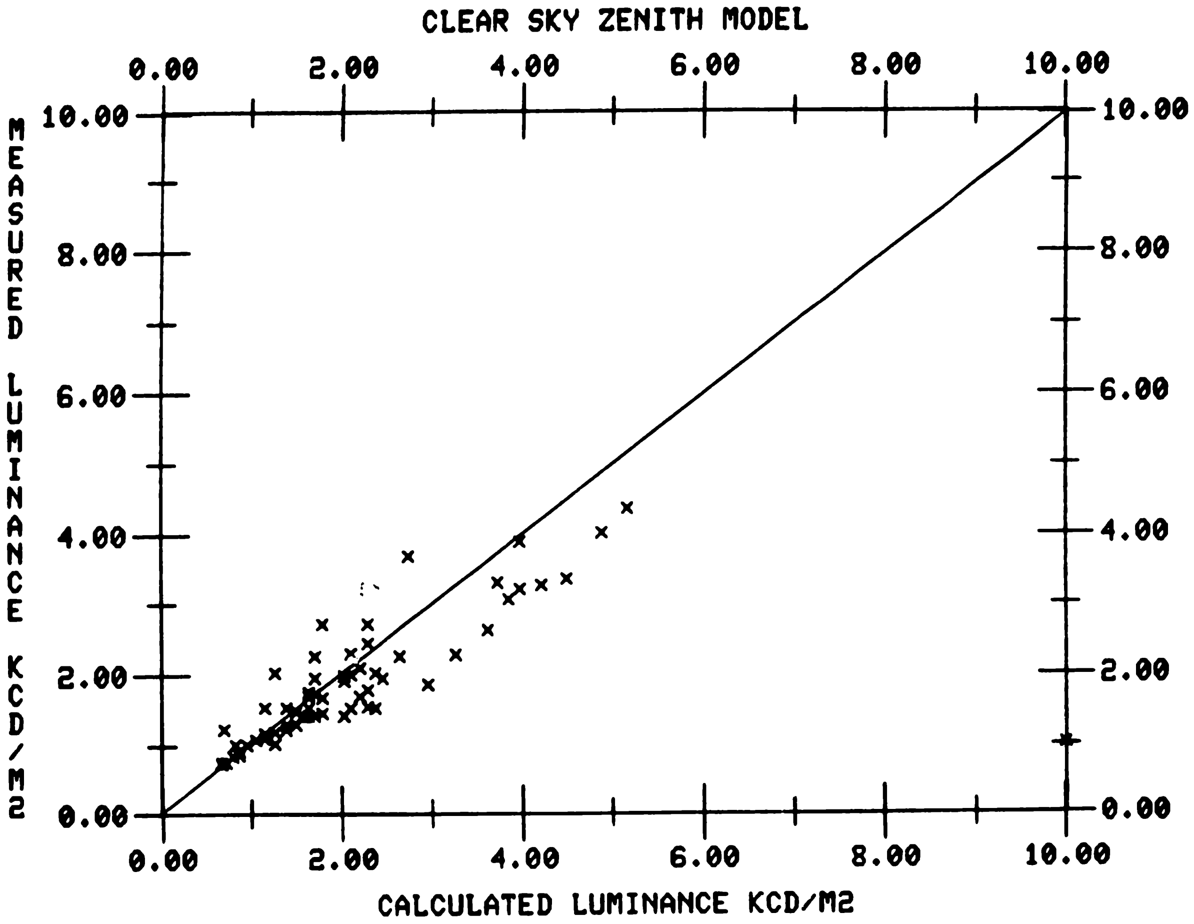


Figure 6.3 Measured zenith sky luminance verses calculated luminance using the clear sky zenith model

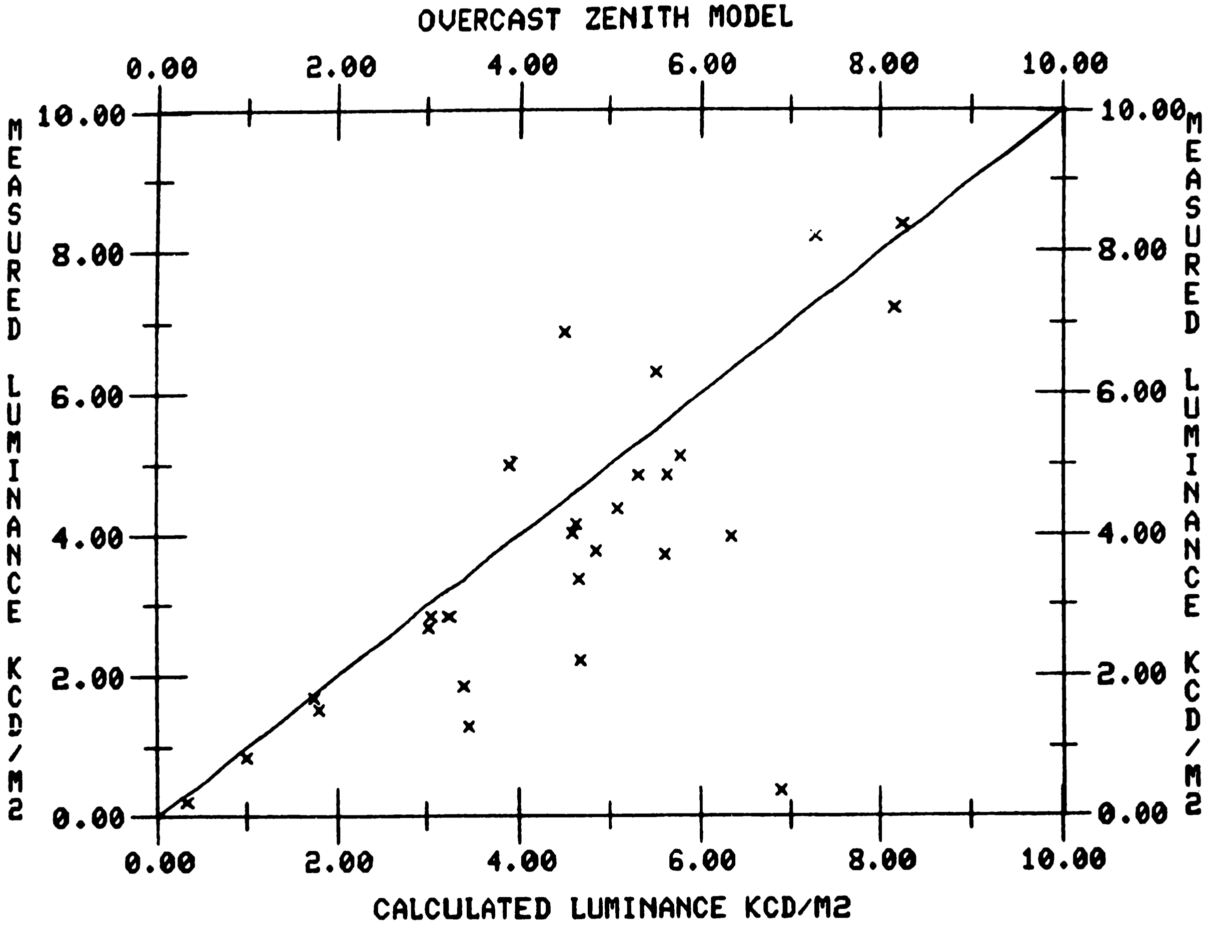


Figure 6.4 Measured zenith sky luminance verses calculated luminance using the overcast sky zenith model

#8

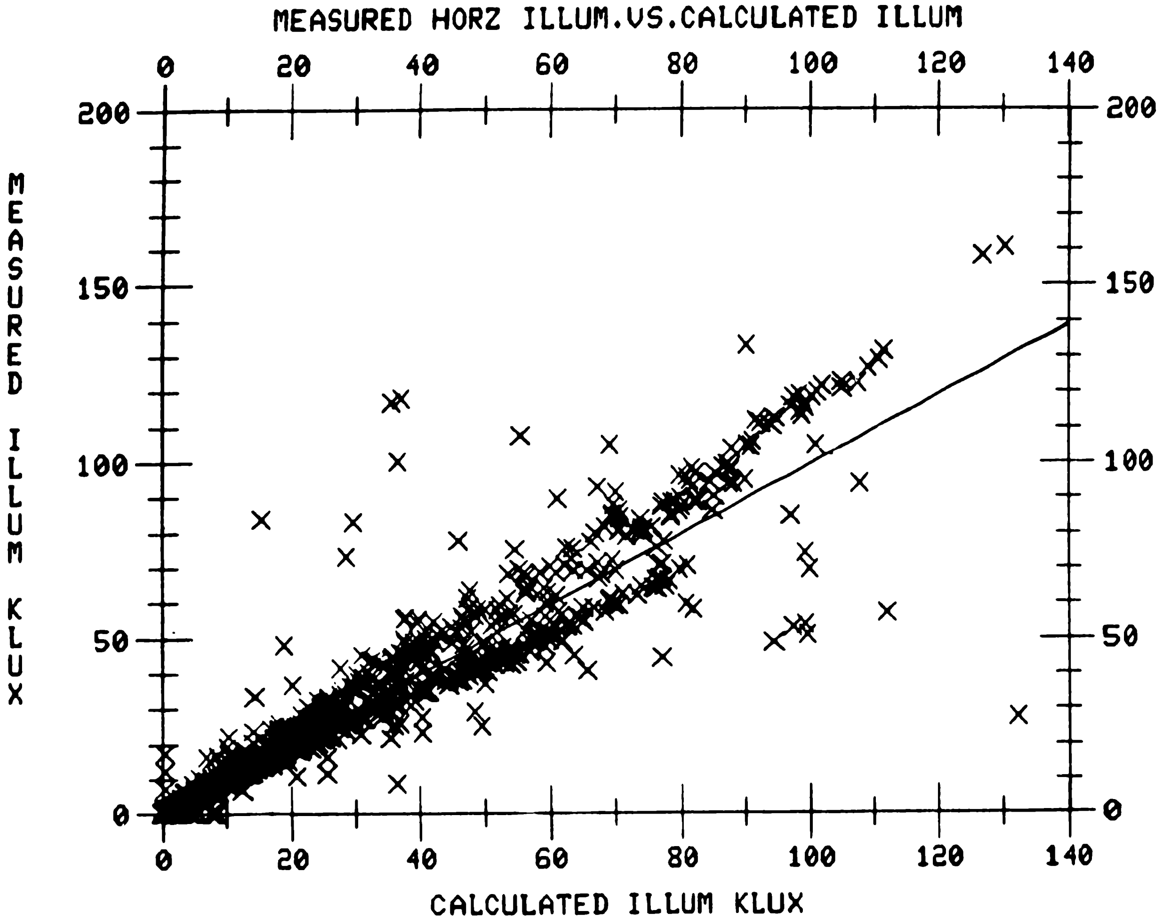


Figure 6.5 Measured horizontal illuminance verses calculated illuminance using the sky illuminance model for all sky types

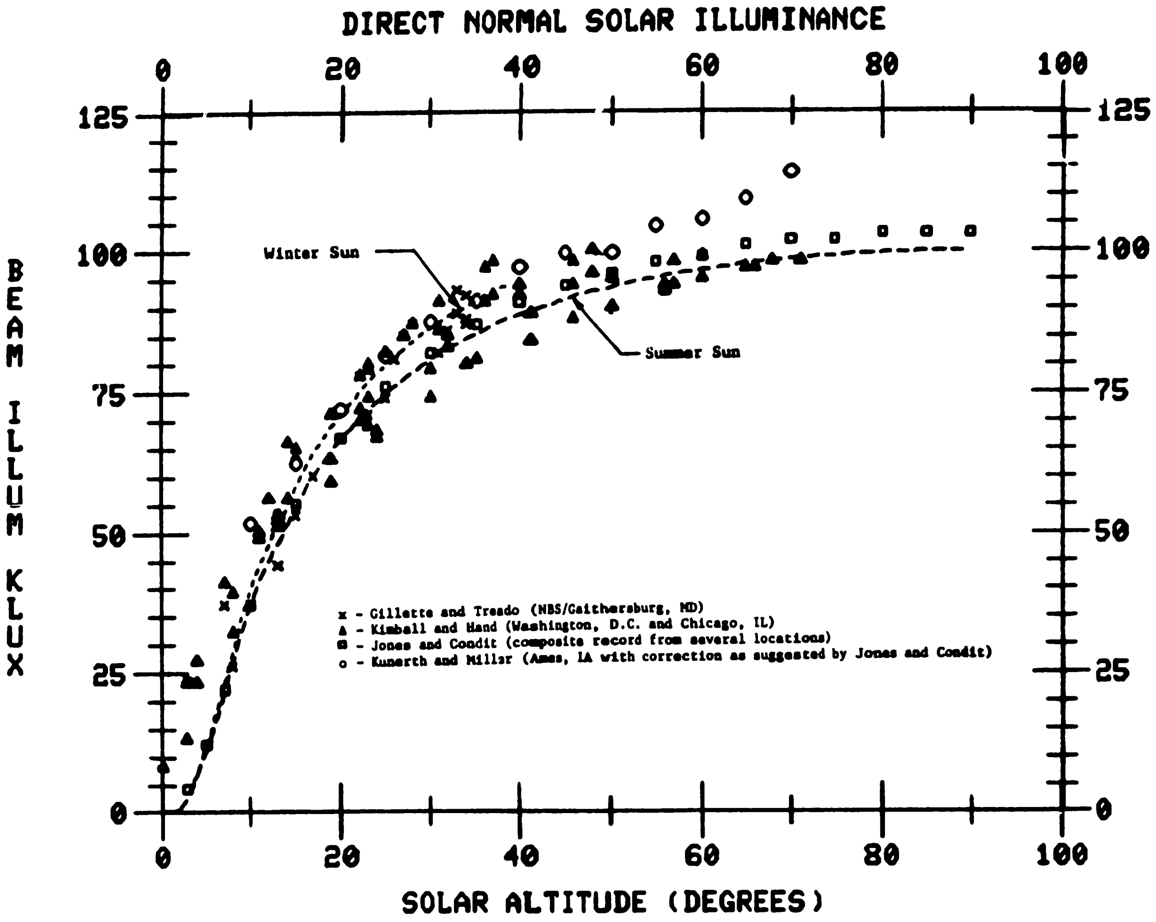
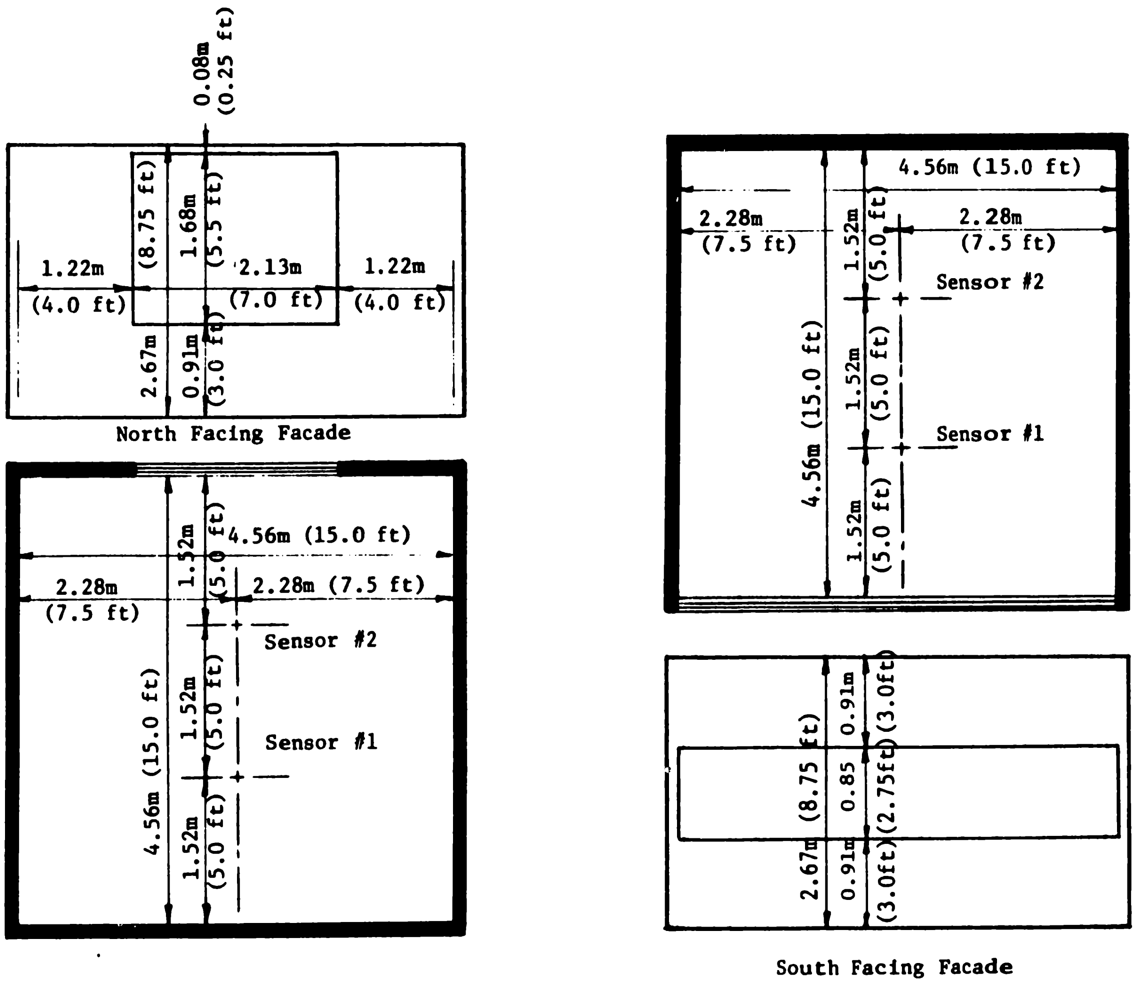


Figure 6.6 Comparison of measured sunlight illuminance with predicted illuminance of direct sunlight



Test Room No. 1

Test Room No. 2

For Both Rooms:

$\rho_f = 0.40$

$\rho_c = 0.80$

$\rho_w = 0.30$

$\rho_g = 0.00$

$\tau = 0.82$

Model Scale: 1.0 inch = 1.0 ft

Figure 6.7 Description of scale model test rooms

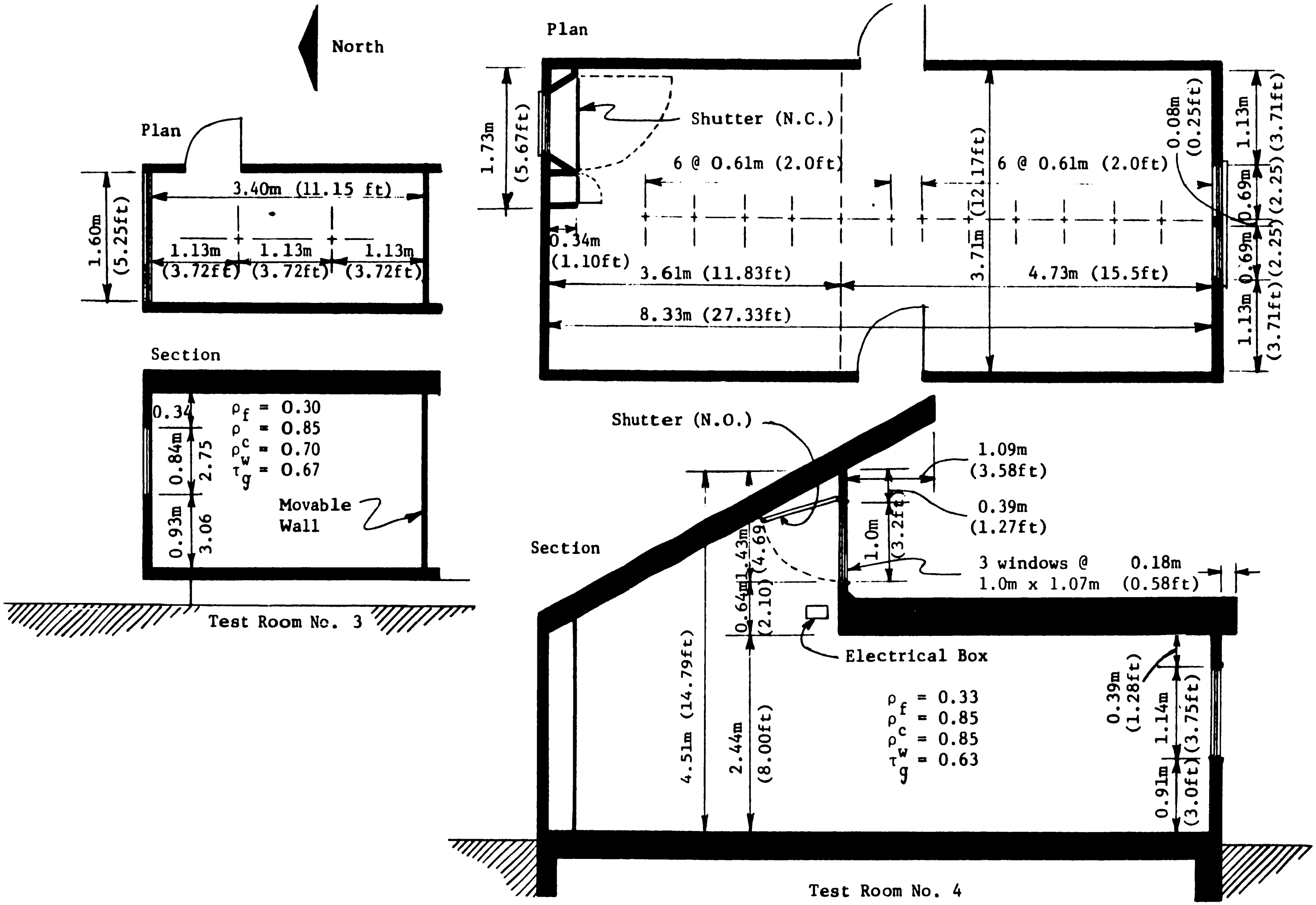


Figure 6.8 Description of full scale test rooms

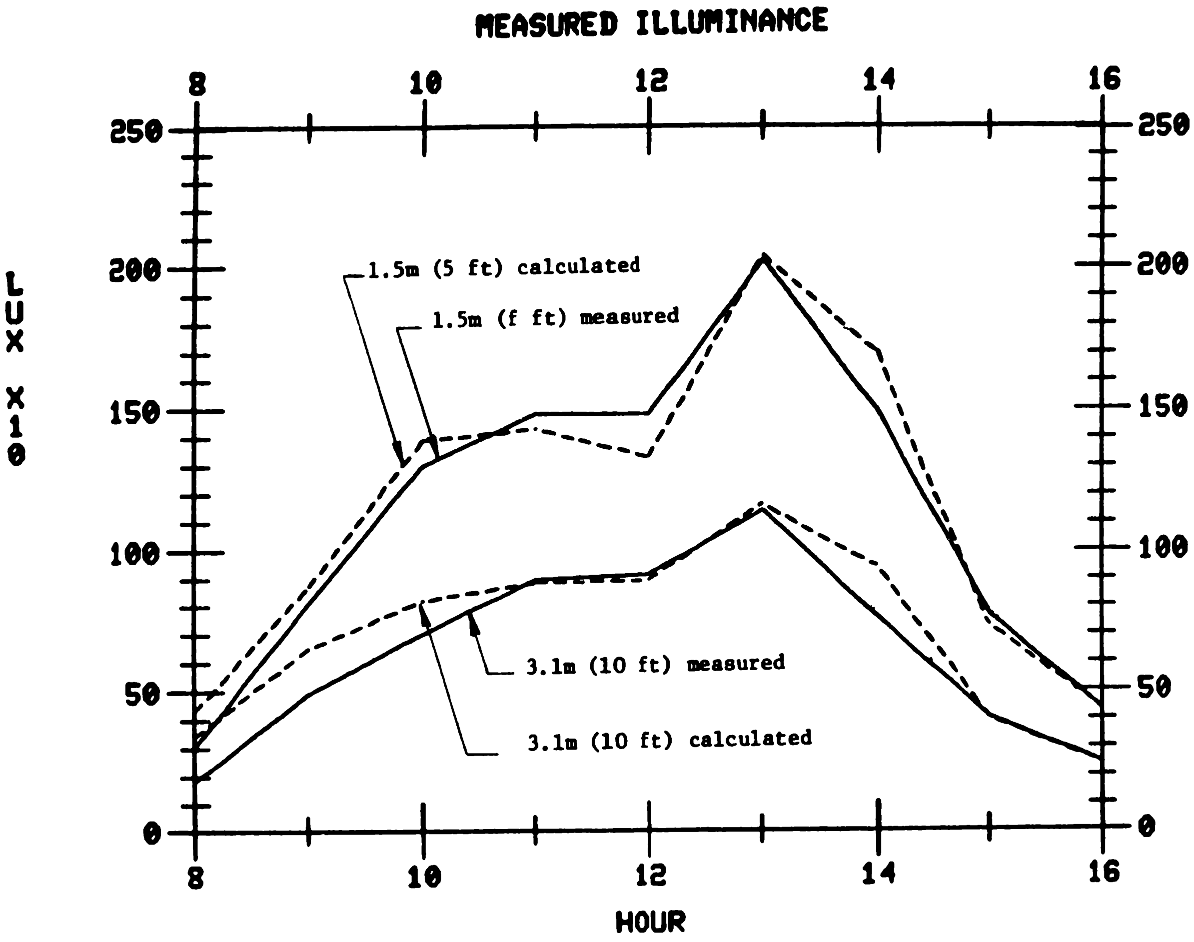


Figure 6.9 Hourly interior daylight illumination for an overcast day in room no. 1 (north fenestration)

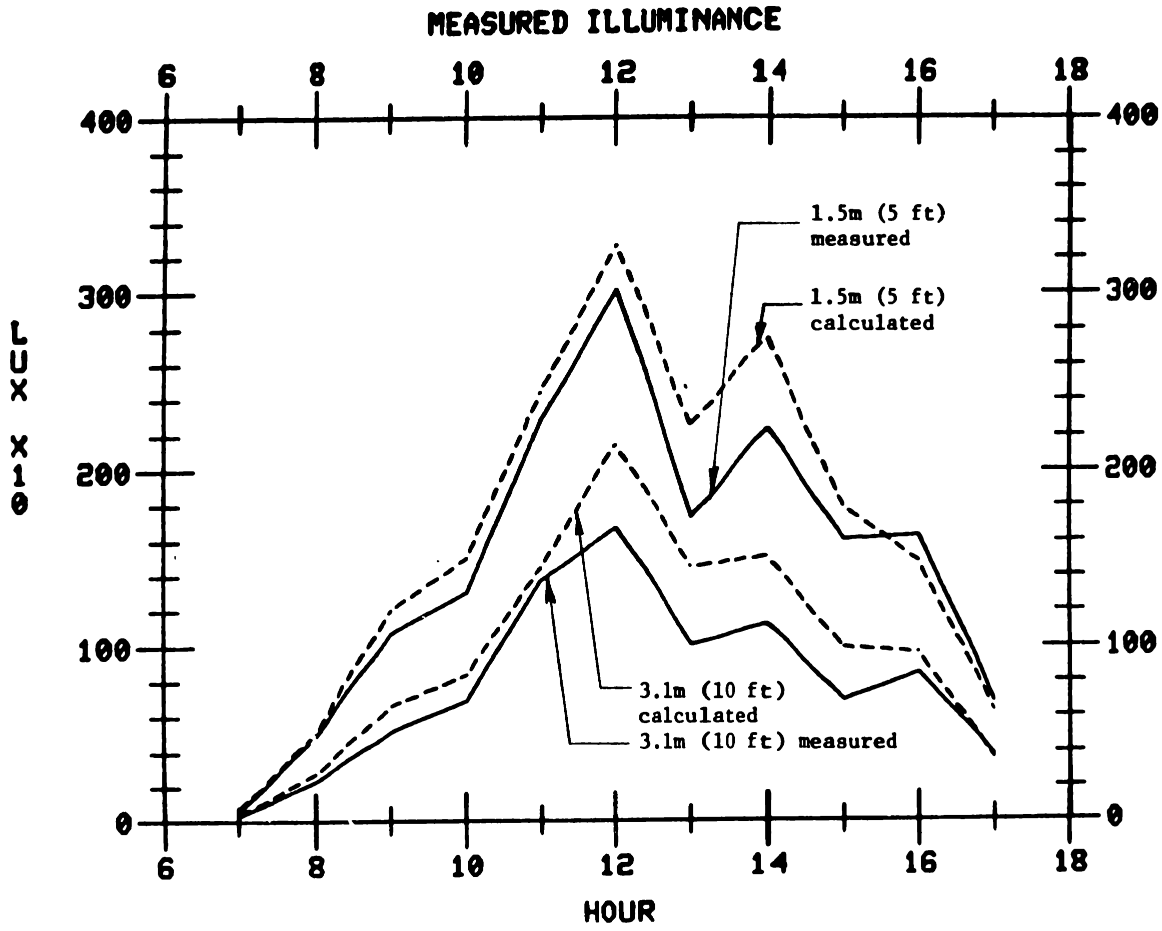


Figure 6.10 Hourly interior daylight illumination for a partly cloudy day in room no. 1 (north fenestration)

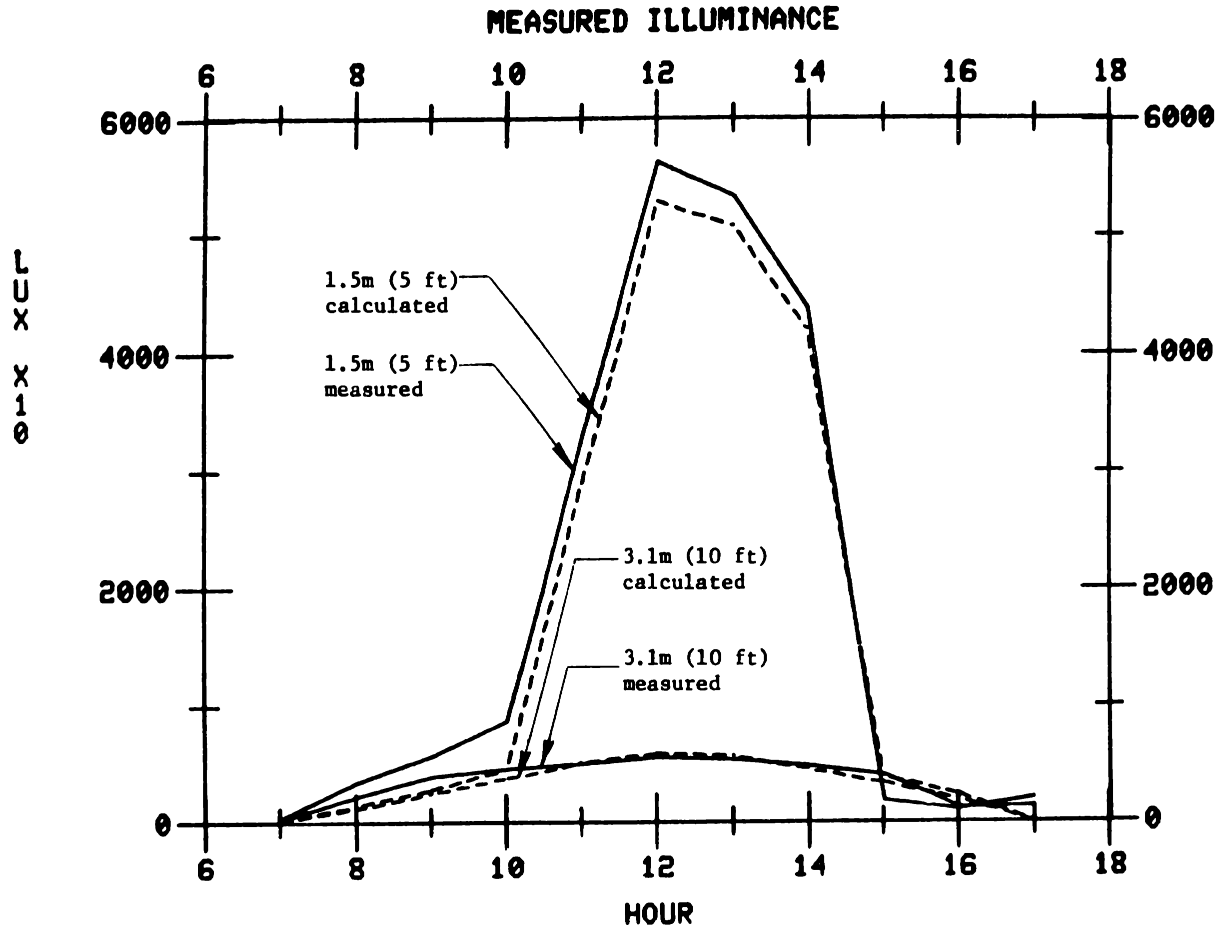


Figure 6.11 Hourly interior daylight illumination for a clear day in room no. 2 (north fenestration)

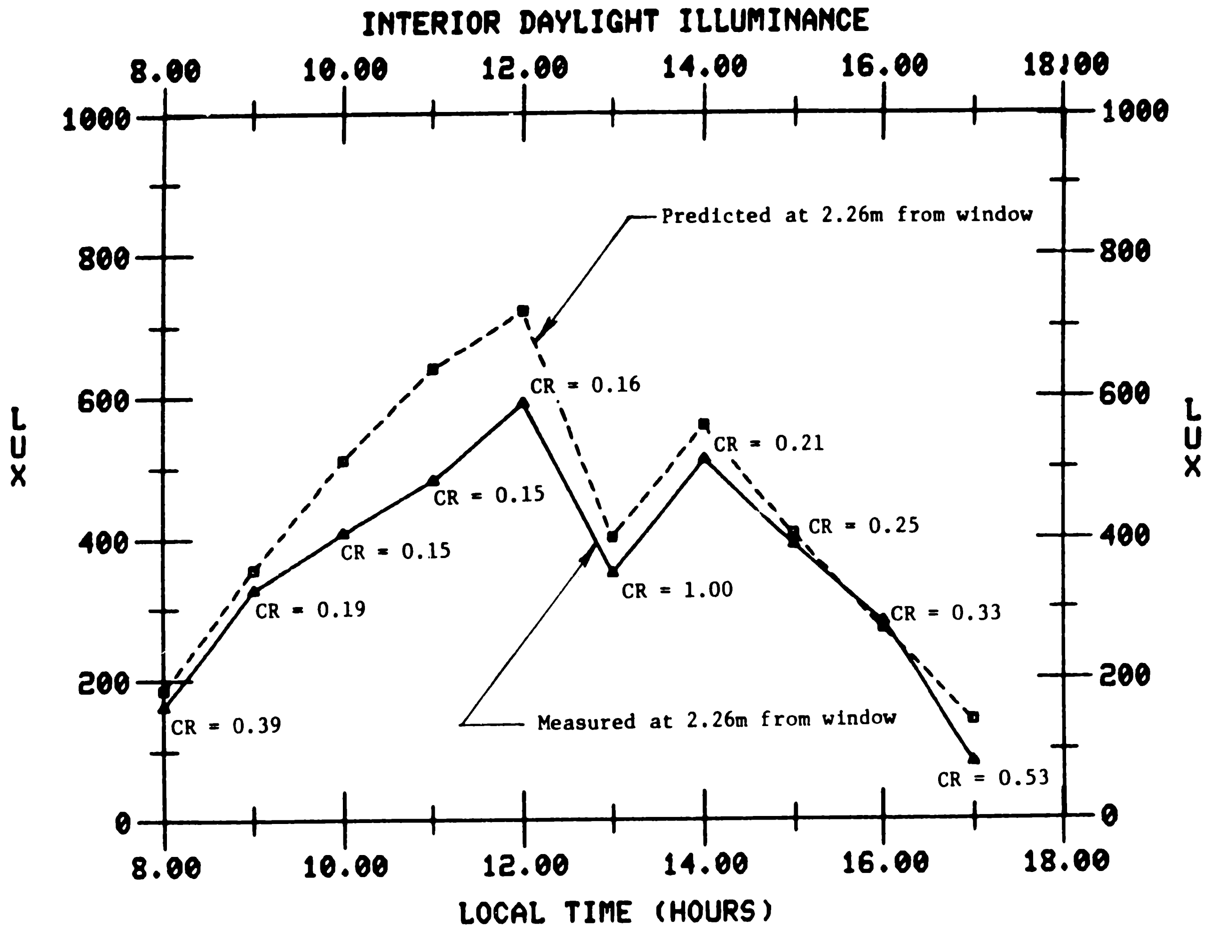


Figure 6.12 Hourly interior daylight illumination for several sky conditions in room no. 3 (north fenestration)

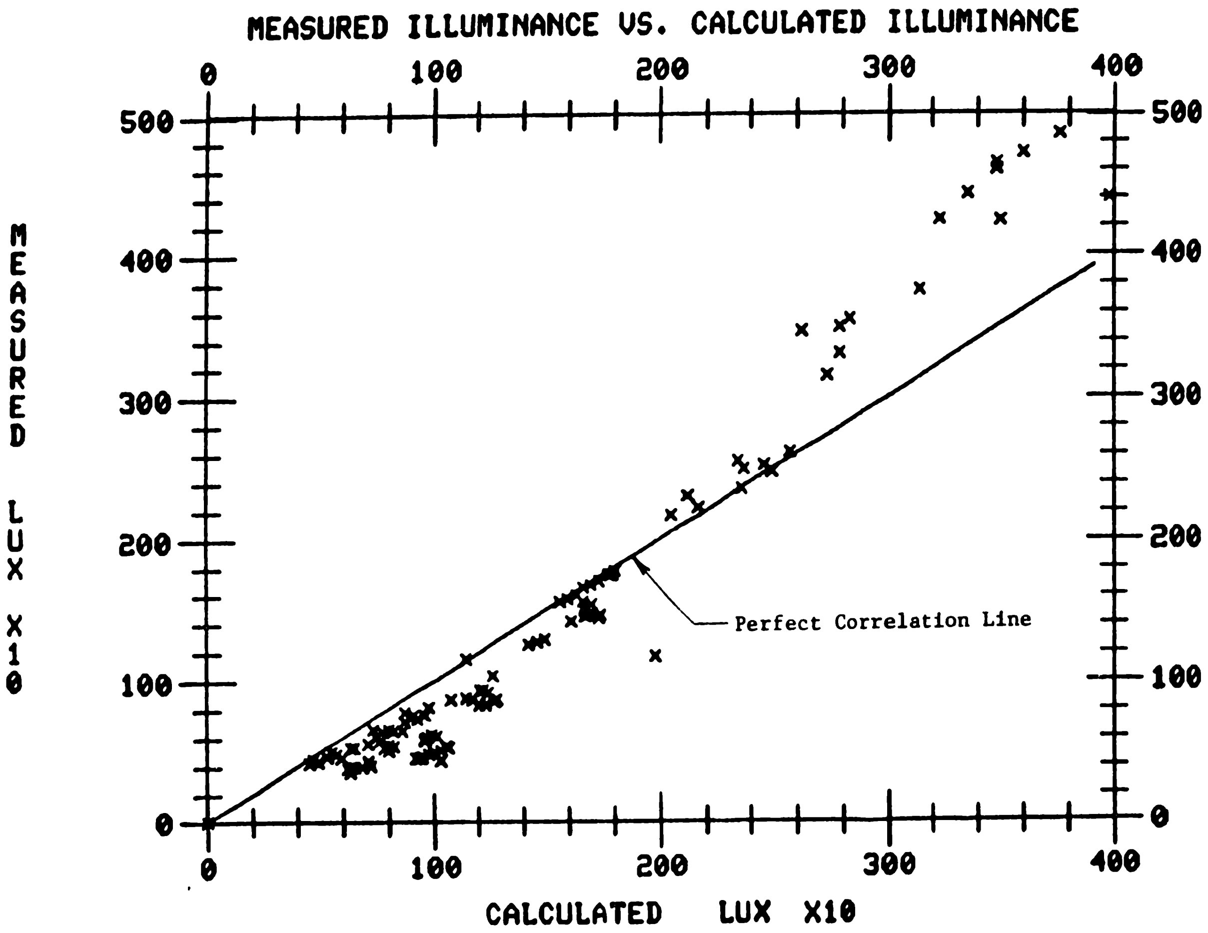
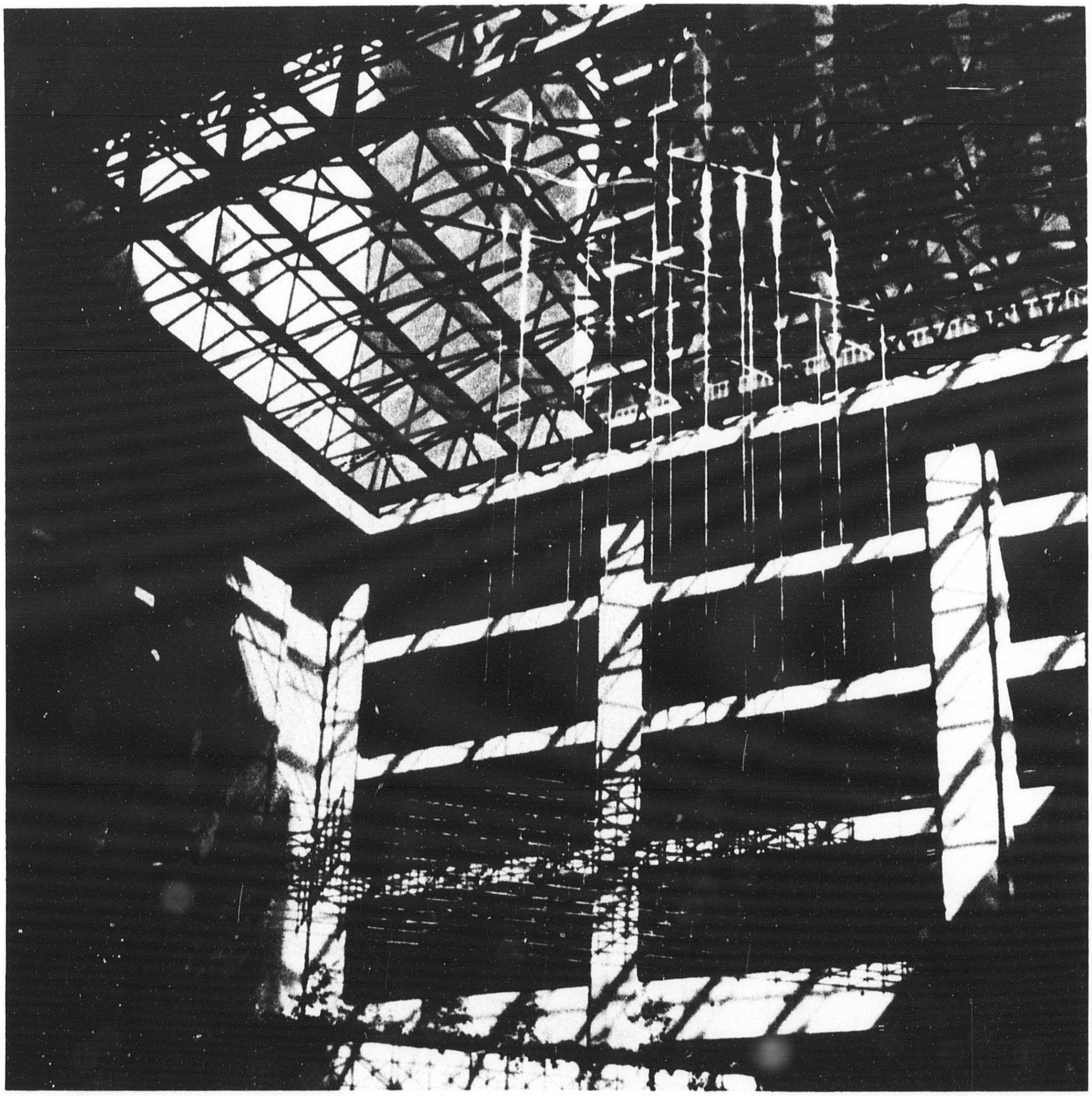


Figure 6.13 Collective plot of measured versus calculated interior illumination in room no. 4 (for south facing windows only)

Facing page: Sunlight penetration from an atrium in an office complex.



7. CONCLUSIONS

A small computer model has been developed for inclusion into larger building energy simulation programs for studying the hourly energy impact of daylighting in buildings. The model is computationally fast in computer time, yet can accommodate a variety of fenestration designs and electric light dimming strategies. The model uses solar radiation and sun position data for estimating outdoor daylighting conditions, and these data are currently available in the existing hourly energy simulation programs. Although the model is streamlined for its particular application, it still simulates field conditions reasonably well, usually well within 30 percent including uncertainties in both the sky and room prediction models. It should easily fit into most building energy programs written in Fortran 77. With its modular structure, revisions and expansions to the original model can be accomplished easily. Its modular design also lends itself to micro and mini-computer applications either as part of a small-scale energy simulation model, or as a stand alone daylighting program.

Other strengths of the DALITE model include the streamlined simulation of skylights, sloping clerestores, and vertical windows, and the capability to simulate a full range of sky conditions. Validation efforts have shown the program to perform well when compared against actual daylighting measurements under real sky conditions for a variety of room and sky senerios.

The limits of the DALITE modle include the restriction to rectangular room geometries and simplified fenestration appendages such as overhangs and side fins. While exterior louvers can be modeled as multiple minute overhangs, this technique is not always best. Further research work is therefore suggested in modeling exterior appendages, particularly with respect to specular reflections.

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where,

h = the well height
w = the well width
l = the well length

By computing the appropriate factors and solving equation A.1, the effective transmittances for diffuse and direct light can be provided for input into the skylight algorithm.

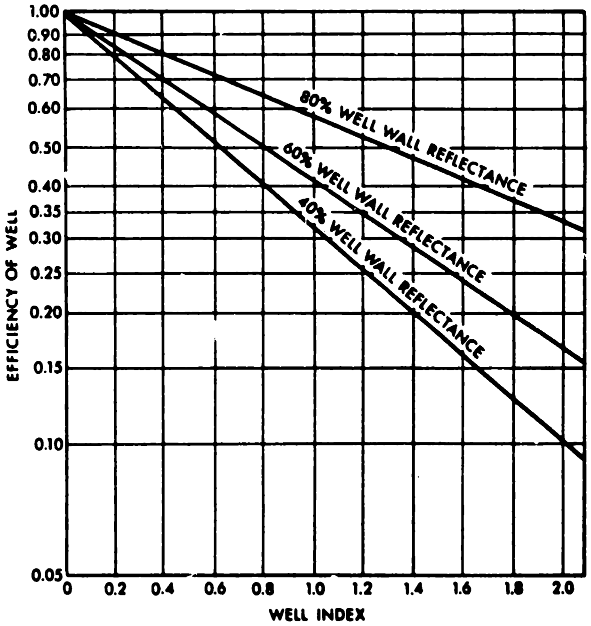

Figure A.1 Well efficiency η_W as a function of a well index and well reflectance

(from the 1981 Reference Volume of the I.E.S. Lighting Handbook, p. 9-86, used with permission)

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APPENDIX B: DESCRIPTION OF VARIABLES

The following is a listing of all the important variables used within the DALITE program, including both I/O variables "seen" by the user and variables used internally. It should be noted that although it is possible to adapt the program for use in computer models that use SI units, the I/O is here given in English units for compatibility in most of the existing energy programs currently available. A conversion table to SI unit is given on page vi.

A = total surface area of interior room surfaces (square feet)

AZM = azimuth angle of the building off the cardinal axis, clockwise from north (degrees)

AZS = difference in azimuth angle between the surface perpendicular and the azimuth of the sun (degrees)

ANG = solar profile angle from horizon (radians)

ANGL1 = azimuth angle sensor makes with right edge of window (degrees)

ANGL2 = azimuth angle sensor makes with left edge of window (degrees)

ANGL3 = ANGL1 referenced to true north (degrees)

ANGL4 = ANGL2 referenced to true north (degrees)

AW = distance from ceiling to top of window (feet)

BCF = Basic Configuration Factor - general sloping case

BCFS = Basic Configuration Factor - parallel surface (skylight) case

BCFW = Basic Configuration Factor - perpendicular window case

BETA = atmospheric turbidity coefficiency (β)

CC = length of sloped clerestory ceiling (feet)

CHI(χ) = constant offset dimmer control coefficient (default is 0.30)

CR = cloud ratio; ration of diffuse to total horizontal solar radiation.

CRL = ceiling reflected light coefficient.

CNFLX = ceiling flux coefficient; for reflected light off clerestory

DAYLT = daylight illuminance array for "n" number of sensors (footcandles)

DAYLTE = daylight illuminance of sensor under consideration (footcandles)

DILL = maintained design illuminance at the photocell (footcandles)

DIM = dimmer type:

1 - on/off switch or relay
2 - two level step-down; half off at half load, full off at full load.
3 - continuous dimming
4 - continuous dimming with shut-off

DP = depth of photocell from fenestration; for skylights & clerestories, distance from bottom of fenestration to workplane (feet)

DS1 = horizontal depth of sun's projection within room due to upper edge of window - see figure B2 (feet)

DS2 = horizontal depth of sun's projection within room due to lower edge of window - see figure B2 (feet)

DW = depth of skylight well (feet)

DX = distance of external obstructing building from fenestration surface (feet)

EX = extraterrestrial illuminance of the sun (footcandles)

FLUX1 = first reflected flux coefficient for surface containing the fenestration

FLUX2 = first reflected flux coefficient for left surface with respect to fenestration

FLUX3 = first reflected flux coefficient for surface opposite fenestration

FLUX4 = first reflected coefficient for right surface with respect to fenestration

FLUX5 = first reflected flux coefficient for the ceiling

FP = fin projection from the fenestration (feet), two fins are assumed on either side of fenestration

GAMMA = angular great circle distance between the sun and the specified point in the sky (radians)

GRDLIT = exterior horizontal illuminance incident on the ground (footcandles)

GRL = ground reflected coefficient

H = height of fenestration (feet)

H1 = height distance from fenestration to bottom of wall surface (feet)

H2 = height distance as shown in figure B.3 (feet)

H3 = height distance as shown in figure B.3 (feet)

H4 = height distance as shown in figure B.3 (feet)

H5 = height distance as shown in figure B.3 (feet)

HH = height distance as shown in figure B.3 (feet)

HH1 = height distance as shown in figure B.3 (feet)

HH2 = height distance as shown in figure B.3 (feet)

HH3 = height distance as shown in figure B.3 (feet)

HH4 = height distance as shown in figure B.3 (feet)

HH5 = height distance as shown in figure B.3 (feet)

HX = height of external obstruction above the workplane (feet)

HC = height of clerestory projection above ceiling plane (feet)
HC is negative if clerestory is sloped, positive if roof monitor ($\phi=0$)

HHC = the distance from the top of the clerestory fenestration to the clerestory ceiling (feet)

JUL = Julian date from 1 (January 1) to 365 (December 1)

L = length of skylight (feet)

L1 = length distance from room reference to skylight reference (feet)

L2 = length distance as shown in figure B.4 (feet)

L3 = length distance as shown in figure B.4 (feet)

LC = distance from room reference to clerestory reference in length direction (feet)

LLOAD = incremental instantaneous lighting load due to single phototcell and single aperature (kilowatts)

LLOADN = the instantaneous lighting load associated with photocell "n" (kilowatts)

LLOADX = the hourly sum of all photo-controlled lighting loads per room (kilowatts)

LOAD = full connected lighting load associated with each photocell, including ballast losses (kilowatts)

LS1 = length distance from room reference to near edge of sunlight patch from skylight on workplane (feet)

LS2 = length distance from room reference to far edge of sunlight patch from skylight on workplane (feet)

M = mullion correction factor; the fractional loss in transmittance due to mullions and glazing bars

NA = number of aperatures within room

NL = number of luminare switch/dimmers within room

OMEGA = atmospheric water vapor content in centimeters of water (ω)

OP = horizontal overhang projection from the fenestration (feet)

PHASE = percentage of clear sky luminance and sun illuminance available

PHI = in the SUNN subroutine the vertical profile angle of the sun-see figure B.2 (radians); in the DL subroutine the slope of the clerestory from the horizontal (radians)

PL = position of photocell along the length direction from the room reference (feet)

PSI = complement angle of PHI; the slope of the clerestory from the zenith (radians)

PSL = percentage of supplemental light necessary (decimal)

PW = position of photocell along the width direction from the room reference (feet)

RAVE = average reflectance of all interior room services (decimal)

RCN = reflectance of the ceiling (decimal)

RFL = reflectance of the floor (decimal)

RG = reflectance of the ground immediately outside the fenestration (decimal)

RL = apparent room length as seen by the particular fenestration (feet)

RHM = room height (feet)

RML = interior room size in length direction (feet)

RMN = room number (just an identifier)

RMW = interior room size in width direction (feet)

RRF = roof reflectance immediately outside clerestory (decimal)

RRL = roof reflected light coefficient

RW = apparent room width as seen by the particular fenestration (feet)

RWL = reflectance of the interior wall surfaces (decimal)

RX = average reflectance of external obstruction (decimal)

SIDLIT = total exterior vertical illuminance on window surface (footcandles)

SKYLIT = sky illuminance at fenestration centroid (footlamberts)

SN = surface number of fenestration:

1 - if north facing
2 - if east facing
3 - if south facing
4 - if west facing
5 - if ceiling/roof
6 - if clerestory north facing
7 - if clerestory east facing
8 - if clerestory south facing
9 - if clerestory west facing

SNL = sunlight coefficient

SRD = diffuse horizontal solar radiation (Btu/S.F-hr.)

SRT = total horizontal solar radiation (Btu/S.F-hr.)

SUMFLX = sum of the interior surface flux coefficients

SUNALT = solar altitude above horizon (degrees)

SUNAZ = solar azimuth clockwise from north (degrees)

SUNBM = solar beam illuminance direct normal (footcandles)

SUNFLX = sun flux coefficient

SUNLIT = the horizontal illuminance due to beam sunlight (footcandles)

SURFAZ = azimuth angle from surface normal clockwise to true north (degrees)

T = average visible transmittance of glazing (including a maintenance factor)

THETA = altitude angle between the window centroid and the photocell (degrees)

TNX = angular visible transmittance, accounting for angle of incidence

W = width of fenestration (feet)

W1 = width distance of window or skylight from surface reference (feet)

W2 = width distance as shown in figure B.3 (feet)

W3 = width distance as shown in figure B.3 (feet)

W4 = width distance as shown in figure B.3 (feet)

W5 = width distance as shown in figure B.3 (feet)

W6 = width distance as shown in figure B.3 (feet)

W7 = width distance as shown in figure B.3 (feet)

WA = window area (square feet)

WC = width of clerestory opening (feet)

WC1 = width distance of clerestory opening from room reference (feet)

W1NAZ = viewing azimuth angle between photocell position (at work plane) and window/skylight centroid; clockwise from north (degrees)

WP = width distance of photocell with respect to surface reference - see figure B.3 (feet)

WS1 = width distance of near edge of skylight sun projection from room reference at workplane (feet)

WS2 = width distance of far edge of skylight sun projection

WX = depth of skylight well from ceiling to fenestration (feet)

XDL = direct skylight coefficient

XI(ξ) = linear dimmer control coefficient

XIRL = internally reflected light coefficient

XERL = externally reflected light coefficient

ZLUM = zenith sky luminance (footlamberts)

ZLITE (42, 12)

	1	2	3	4	5	6	7	8	9	10	11	12	
1	RMH	RML	RMW	AZM	RCN	RWL	RFL	RG	RX	NA	NL	RMN	]-Room Information
2	SUNALT	SUNAZ	SRD	SRT	β	ω		JUL					]-Sky Information
3	W	H	H1	W1	±T	M	HX	DX	SN	OP	AW	FP	]-For Window
4	W	L	L1	W1	±T	M	HX	DX	SN				]-For Skylight
5	W	H	H1	W1	±T	M	WC1	LC1	SN	WC	LC	±HC	]-For Clerestory
6													
7													
8													
9													
10													For 30 Apertures
.													
.													
.													
.													
32													
33	PW	PL	DILL	DIM	LOAD	ξ	χ			(DAYLTE)	(LOADX)	(GRDLIT)	
34													
35													
36													
37													For 10 Photocells
38													
39													
40													
41													
42													

Figure B.1 Input/output array

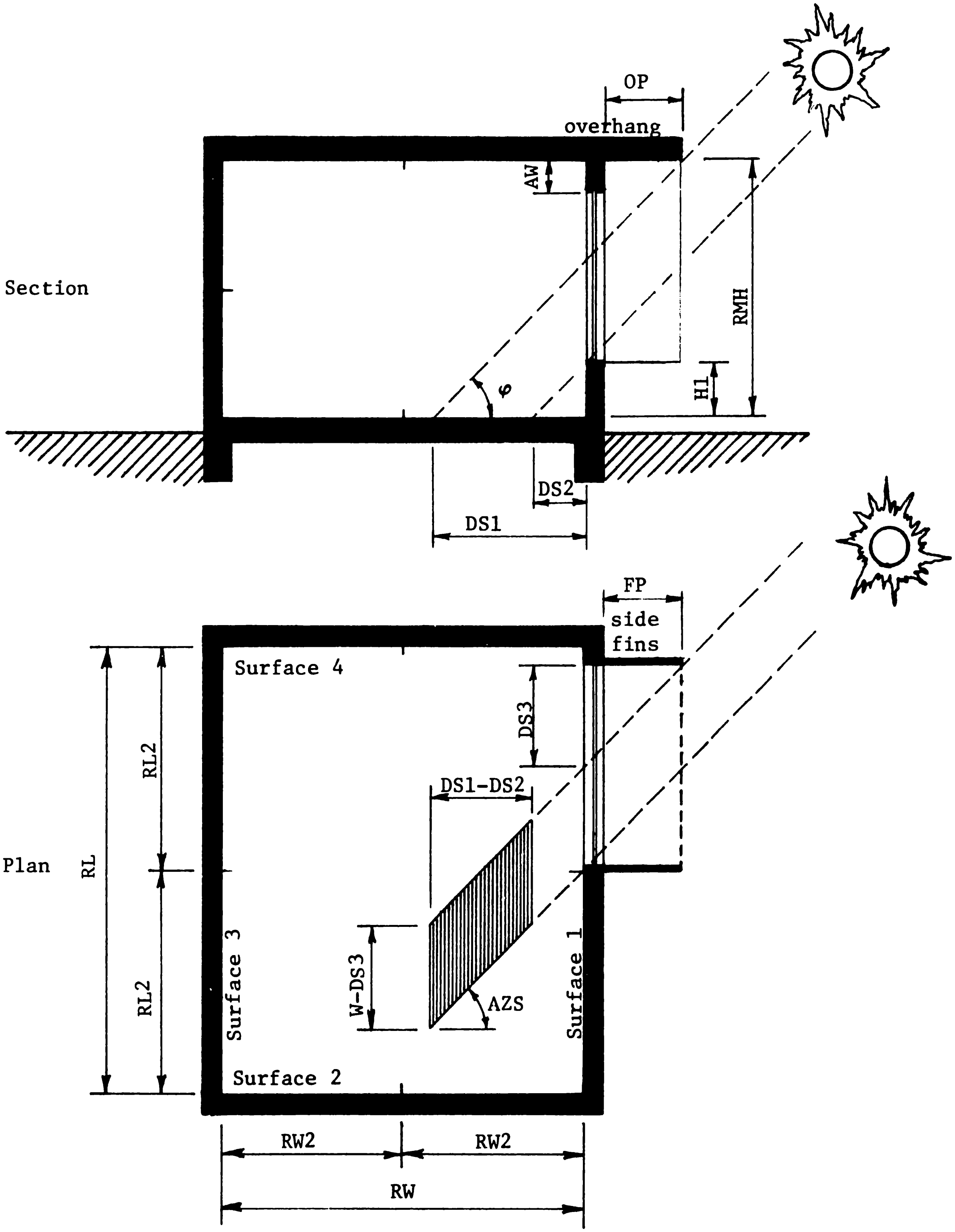

Figure B.2 Room coordinates defined with respect to glasing surface in IRL subroutine

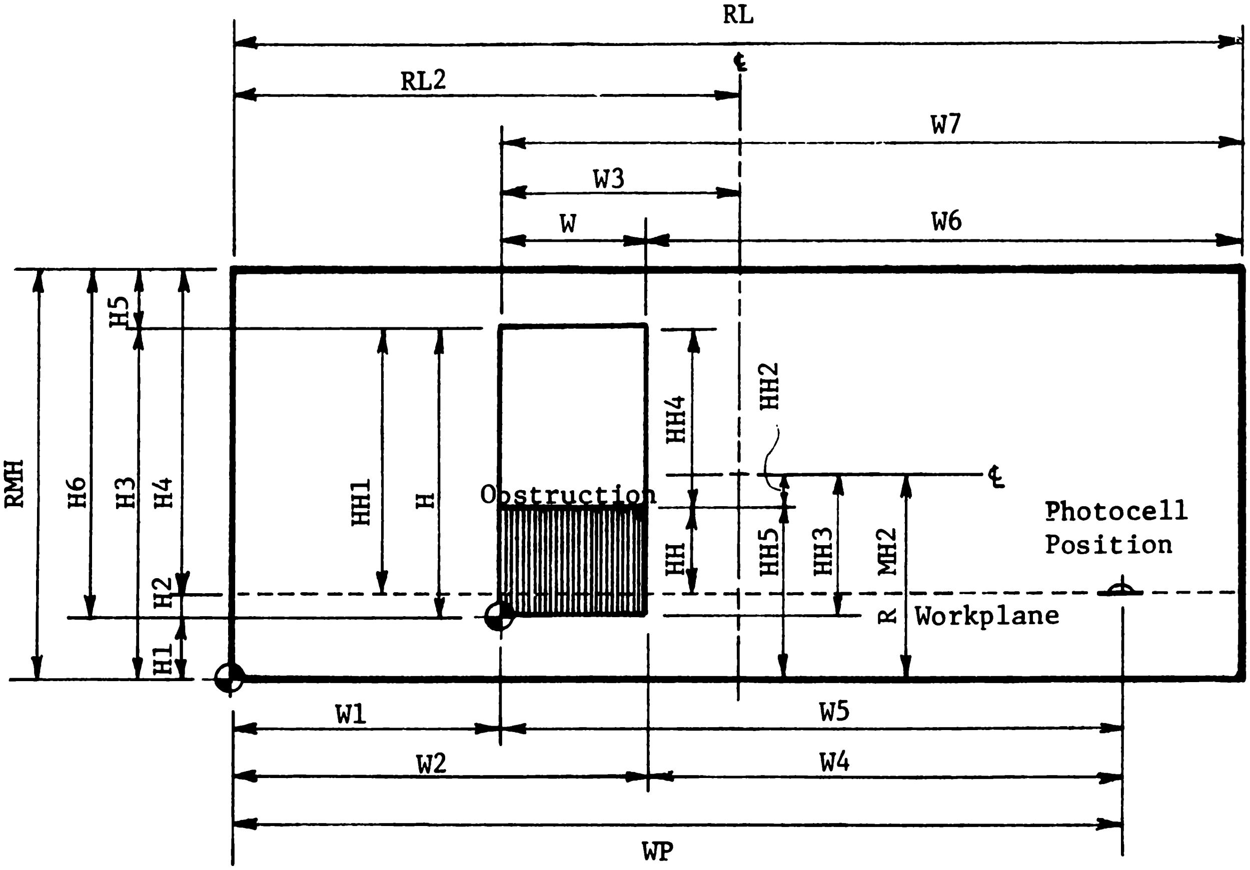

Figure B.3 Wall surface dimensions used internally in the DALITE program

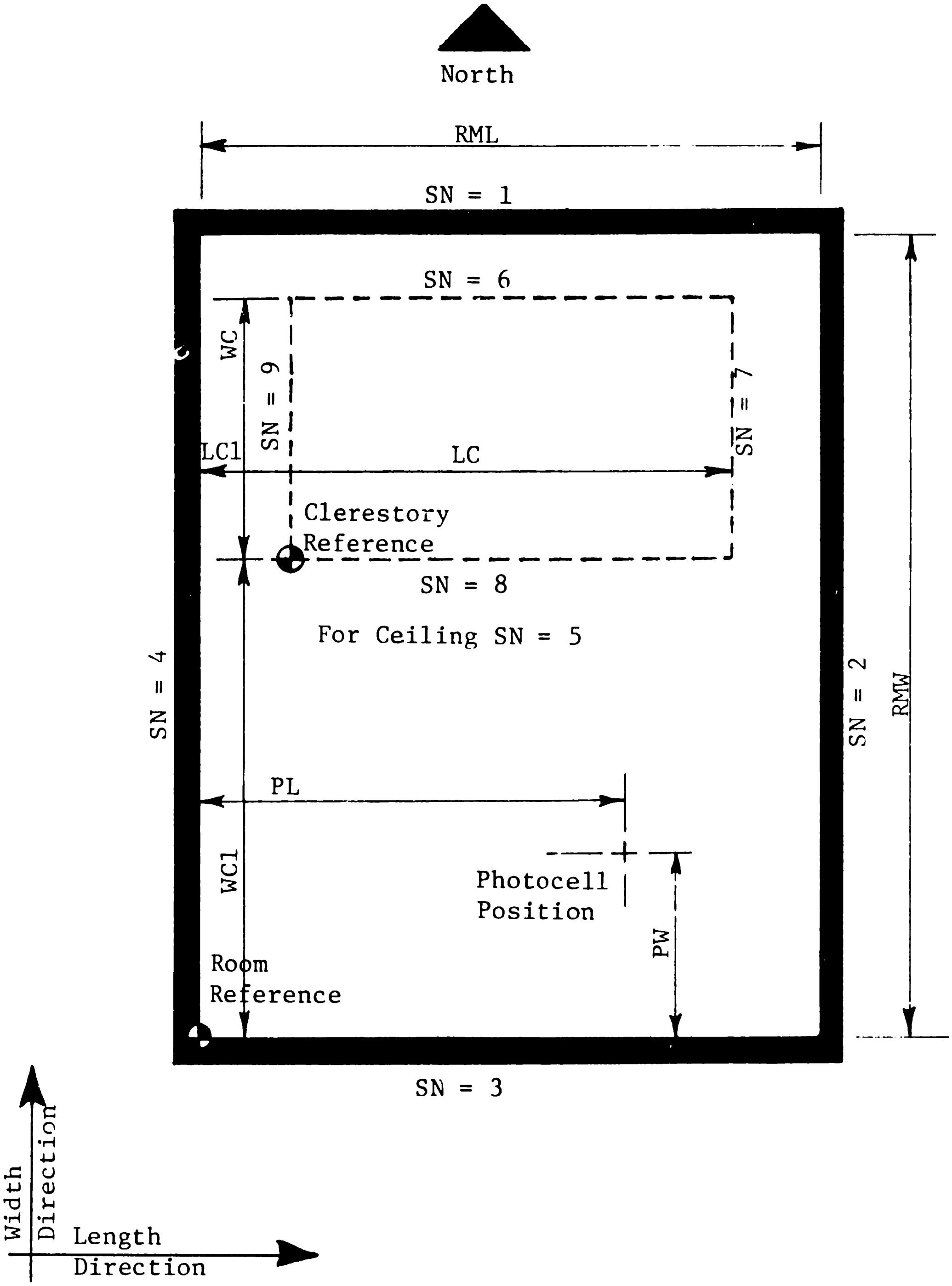

Figure B.4 Surface numbering sequence and clerestory reference variables

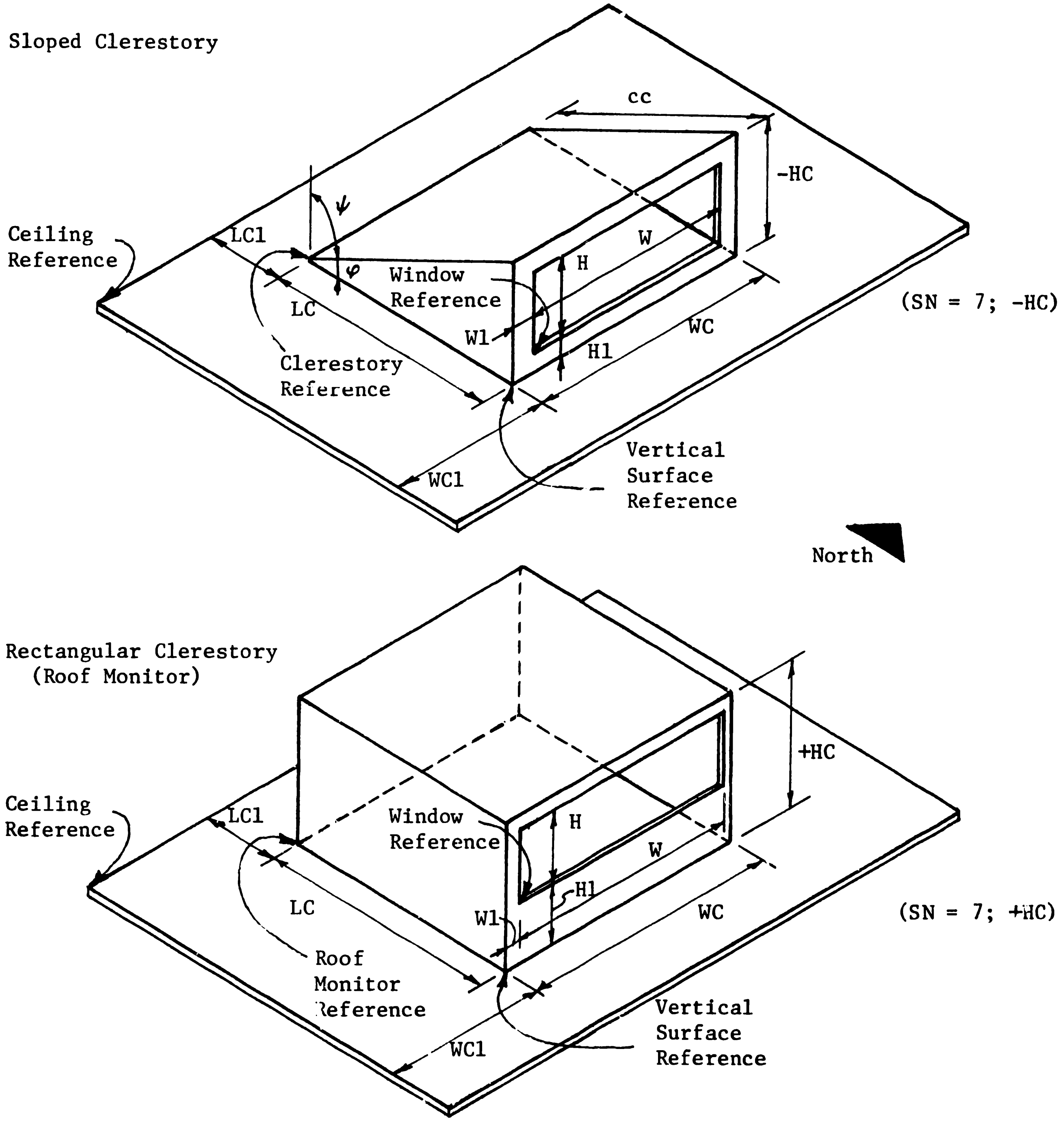

Figure B.5 Clerestory coordinates

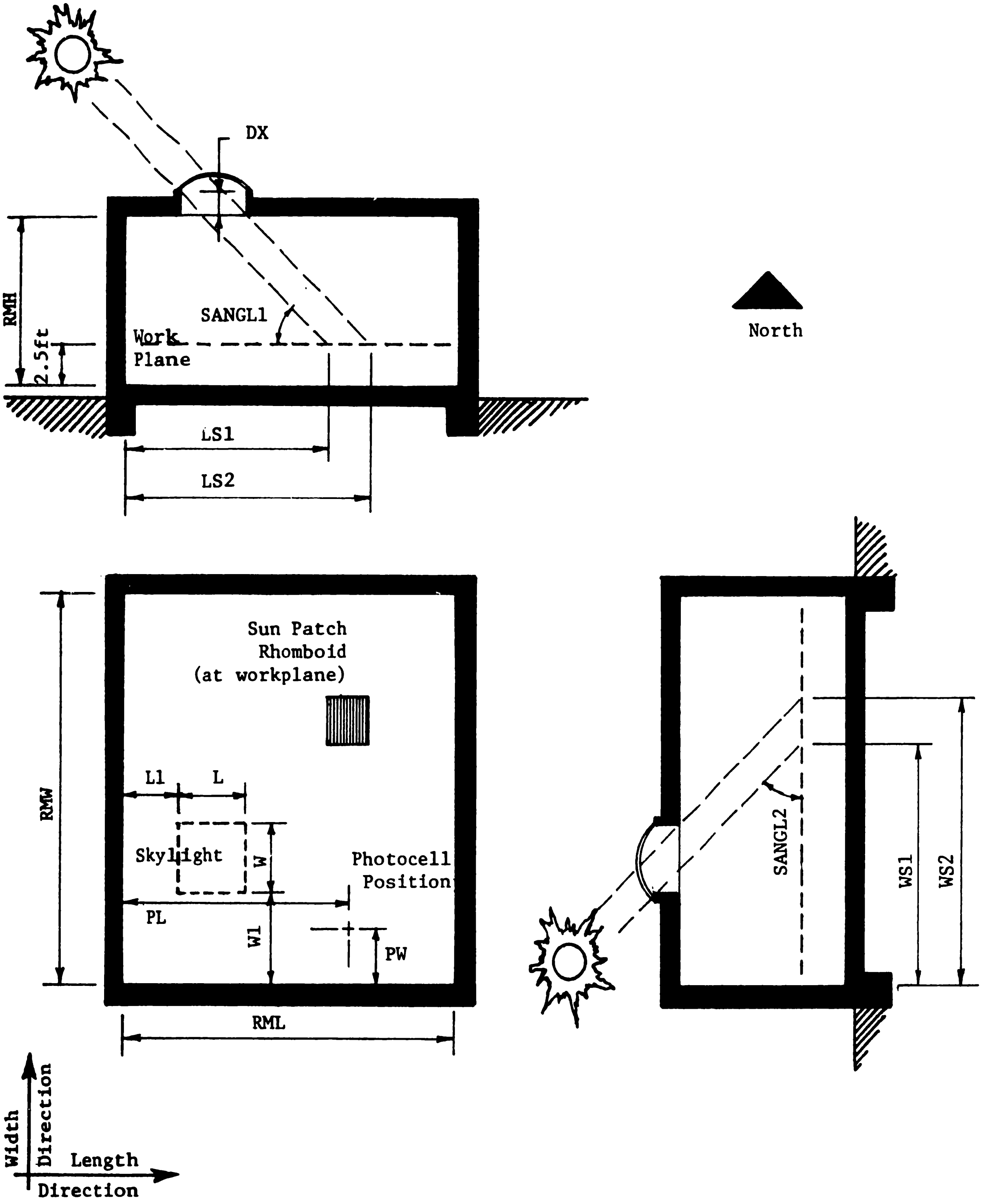

Figure B.6 Sun projection variables for skylights

APPENDIX C: SUBROUTINE INTERFACING

Interfacing the DALITE subroutines with an existing FORTRAN program is accomplished by changes at two locations in the main program. The first is at initialization. Here the common block for the two input/output arrays and the dimensioning of the other internal arrays are assigned (figure C.1). Here also READ statements are given, following the array declarations, where the building and component characteristics are defined for the daylighting I/O array along with the other building characteristic assignments. Such READ statements may be provided either through a pre-processor or through various statements within the main program. At this point the room, aperature, and photocell information is assigned within the ZLITE array (see figure B.1) where it will be called later by the various daylighting subroutines during execution.

The second revision is done inside the hourly (or other time step) loop. Here input assignments are given for each hourly set of sky conditions preceeding the CALL statement for the daylighting analysis. Daylighting output information is then passed from the DALITE subroutine to the main program via the ZLITE array, where it is used as a part of the hourly load compiliation.

The adjusted electric load (WLAMP) and the exterior horizontal illuminance (FCDAY) are the normal output values. However, illuminance at each sensor position is also accessible from the array DAYLT (n), n being the sensor number. Further output information, such as wall luminances, luminance ratios, and the like can also be obtained, but program revisions would be necessary; normally such data would be too exhaustive to include in an energy simulation, and was therefore not specified as part of the normal output.

Since the daylighting interreflection routine is room-specific and models a rectangular room geometry, a few revisions may be necessary for programs that do not prescribe set room dimensions or for cases where the assumption of a rectangular room is invalid. Two options are possible. The first is to approximate an equivalent (or effective) room height, width, and depth for the enclosed volume. The second option is to leave out the room geometry and surface reflections altogether, which would avoid the calculation of any interreflected light. This latter option is a good one when there is substantial uncertainty in the room configuration; this option is conservative, yet not excessively so since interreflected light is normally a small fraction of the total.

```
       ●
       ●
```

Array declarations

```
        PARAMETER NNN=30
        PARAMETER LLL=10
        PARAMETER MMM=LLL+NNN+2
        DIMENSION COEF(NNN,LLL),SURFAZ(9),WINAZ(NNN,LLL),
       *THETA(NNN,LLL),WP(NNN,LLL),DP(NNN,LLL)
        COMMON /DD/ZLITE(MMM,12),DAYLT(LLL)
       ●
       ●
       ●
       ●
C
C       READ DAYLIGHTING INPUT DATA
C
        READ(5,1460)          (ZLITE(1,J),J=5,11)

        ITEST=0
        READ (5,1466)(ZLITE(II,K),K=1,12)

        LN=ZLITE(1,11)+32
        READ (5,1460)((ZLITE(I,J),J=1,7),I=33,LN)
```

Hourly loop for thermal loads

Solar loads are done here within the main program

```
       ●
       ●
       ●
       ●
       ●
C
C      DAYLIGHTING CALCULATIONS
C
       WLAMP=0                    ●INIT FOR NON-DAYLIGHT.
       ZLITE(33,12)=QSOL(NK)*0.2931*111.      ●FC
       DO 722 I=33,42
722    WLAMP=WLAMP+ZLITE(I,5)
       IF(QLITX(NK,JJ).EQ.0.) GO TO 725
       IF(SALT(NK).LE.0.) GO TO 725
       IF((ZLITE(33,1).EQ.0.).OR.(ZLITE(33,4).EQ.0.))GO TO 725
       WLAMP=0.                   ●INIT FOR DAYLIGHTING CALCS
```

Hourly initialization of solar loads

```
       ZLITE(1,1) =HT
       ZLITE(1,2) =L
       ZLITE(1,3) =W
       ZLITE(1,4) =IROT
       ZLITE(1,12)=IJKLMN         ●ROOM NUMBER
       ZLITE(2,1)=SALT(NK)        ●SOLAR ALTITUDE (DEGREES)
       ZLITE(2,2)=180+SAZM(NK)●SOLAR AZIMUTH  (DEGREES)
       ZLITE(2,3)=XIDFHC          ●DIFFUSE SOLAR HORIZONTAL
       ZLITE(2,4)=QSOL(NK)        ●TOTAL SOLAR HORIZONTAL
       ZLITE(2,8)=ND              ●JULIAN DATE
       ITEST=ITEST+1              ●LOOP COUNTER TEST
       NA =NNN                    ●NUMBER OF APERTURES(MAX)
       NL =LLL                    ●NUMBER OF LUMINAIRE CONTROLS(MAX)
C
       CALL DALITE(COEF,SURFAZ,WINAZ,THETA,WP,DP,NA,NL,ITEST)
C
       DO 724 I=33,42
       WLAMP=WLAMP+ZLITE(I,11)      ●ADJUSTED LIGHT LOAD (KW)
 724   CONTINUF
       FCDAY(NK)=ZLITE(33,12)  ●EXTERIOR HORZ. ILLUMINANCE (FC)
725    QLITE(NK)=((QLITY*AG)+(WLAMP*1000))*(QLITX(NK,JJ)*3.412*NOFLR)
```

Continuation of thermal loads

```
       ●
       ●
       ●
       ●
       ●
       ●
```

Figure C.1 Program interfacing

Variable Name	Variable* Specification	Variable Limits
RMH	REAL	None
RML	REAL	None
AZM	REAL	Minimum = 0.; Maximum = 360.
RCN	REAL	Must be decimal fraction less then 1.00
RWL	REAL	Must be decimal fraction less then 1.00
RFL	REAL	Must be decimal fraction less then 1.00
RG	REAL	Must be decimal fraction less then 1.00
RX	REAL	Must be decimal fraction less then 1.00
NA	REAL (Assigned)	Limit is number used in NNN parameter statement
NL	REAL (Assigned)	Limit is number used in LLL parameter statement
RMN	REAL	NONE
SUNALT	REAL	IF SUNALT < 5., SUNLIGHT = 0.
SUNAZ	REAL	NONE
SRD	REAL	SRD must be < SRT
SRT	REAL	NONE
BETA(β)	REAL	Allowable values for β are 0.05,0.10, & 0.20
OMEGA(ω)	REAL	Allowable values for ω are 1.0, 2.0, 3.0 4.0, & 5.0
JUL	REAL (Assigned)	Minimum = 0.; Maximum = 365.

* Format is arbitrary and depends only on the format specified in the READ statement of the main program.

Figure C.2 Input variable specifications for room and sky data

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Variable Name	Variable* Specification	Variable Limits
W	REAL	None
H	REAL	None
L	REAL (Assigned)	None
H1	REAL	None
L1	REAL (Assigned)	None
W1	REAL	None
T	REAL	Must be decimal fraction less then 1.00
M	REAL	Must be decimal fraction less then 1.00
HX	REAL	None
WC1	REAL	None
DX	REAL	None
SN	REAL	Minimum = 1.; Maximum = 9.
OP	REAL	NONE
WC	REAL	Must be > W + W1
AW	REAL	NONE
LC	REAL (Assigned)	NONE
FP	REAL	NONE
HC	REAL	Must be > H + H1
PW	REAL	If PW = 0., DAYLIGHT contribution is assumed zero.
PL	REAL	NONE
DILL	REAL	NONE
DIM	REAL	Allowable values are 1., 2., 3., & 4.
LOAD	REAL (Assigned)	NONE
XI	REAL	Must be decimal fraction less than 1.00
CHI	REAL	Must be decimal fraction less than 1.00

* Format is arbitrary and depends only on the format specified in the READ statement of the main program.

Figure C.3 Input variable specifications for fenestration data

Variable Name	Variable* Specification	Variable Limits
DAYLTE	REAL	None
LOADX	REAL (Assigned)	None
GRDLIT	REAL	None
DAYLT(n)	REAL	None

* Format is arbitrary and depends only on the format specified in the READ and WRITE statements of the main program.

Figure C.4 Output variable specifications

APPENDIX D: SAMPLE RUN

SAMPLE RUN OF A BUILDING DAYLIGHTED WITH CLERESTORIES

Location: Washington, D.C. Latitute = 38° 5'N Longitude = 77° 0'W

Fenestration: Three north facing clerestories

Lighting Control: Five banks of fluorescent luminaires at 1.25 KW each continuous dimming (50 fc minimum illuminance)

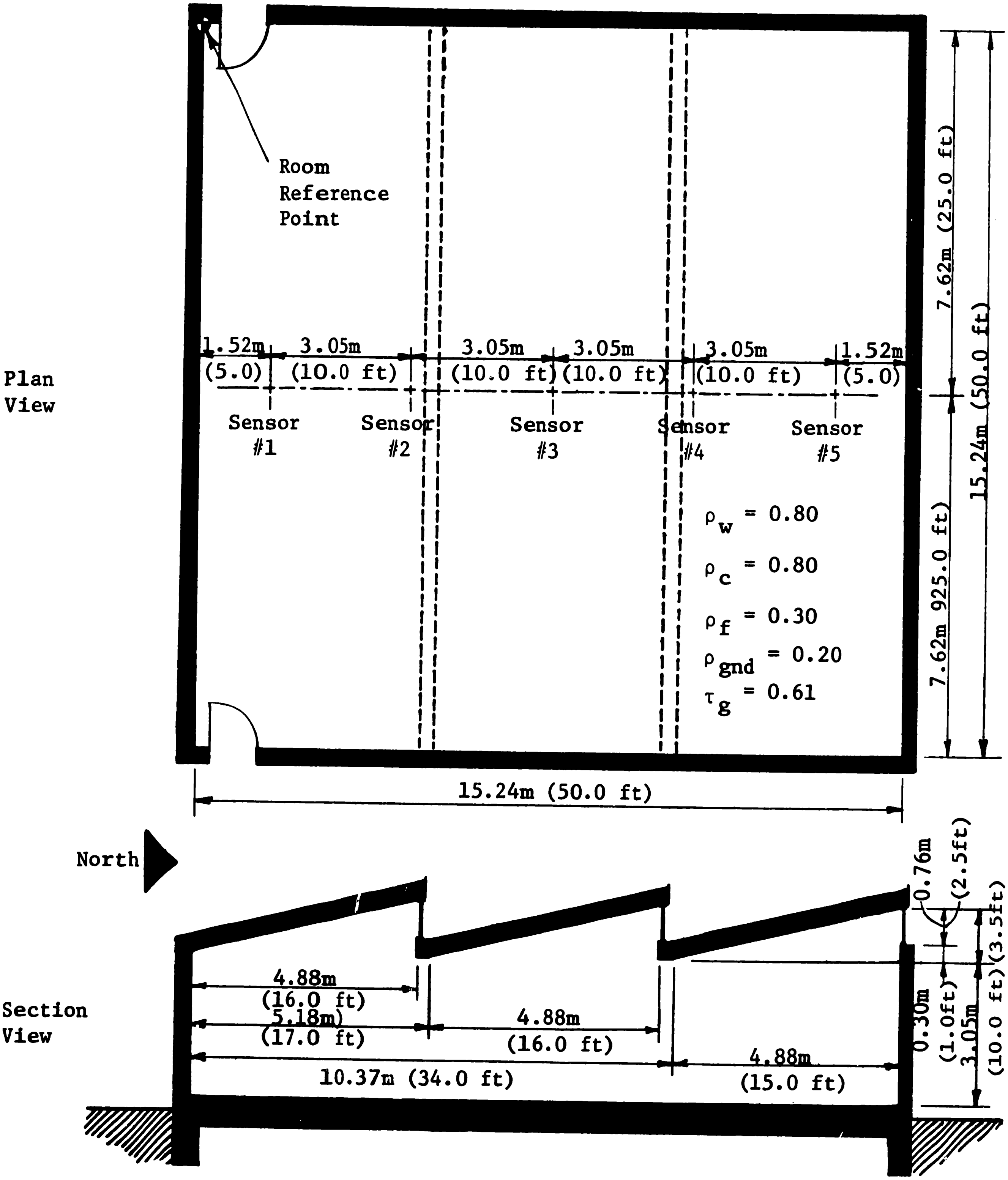
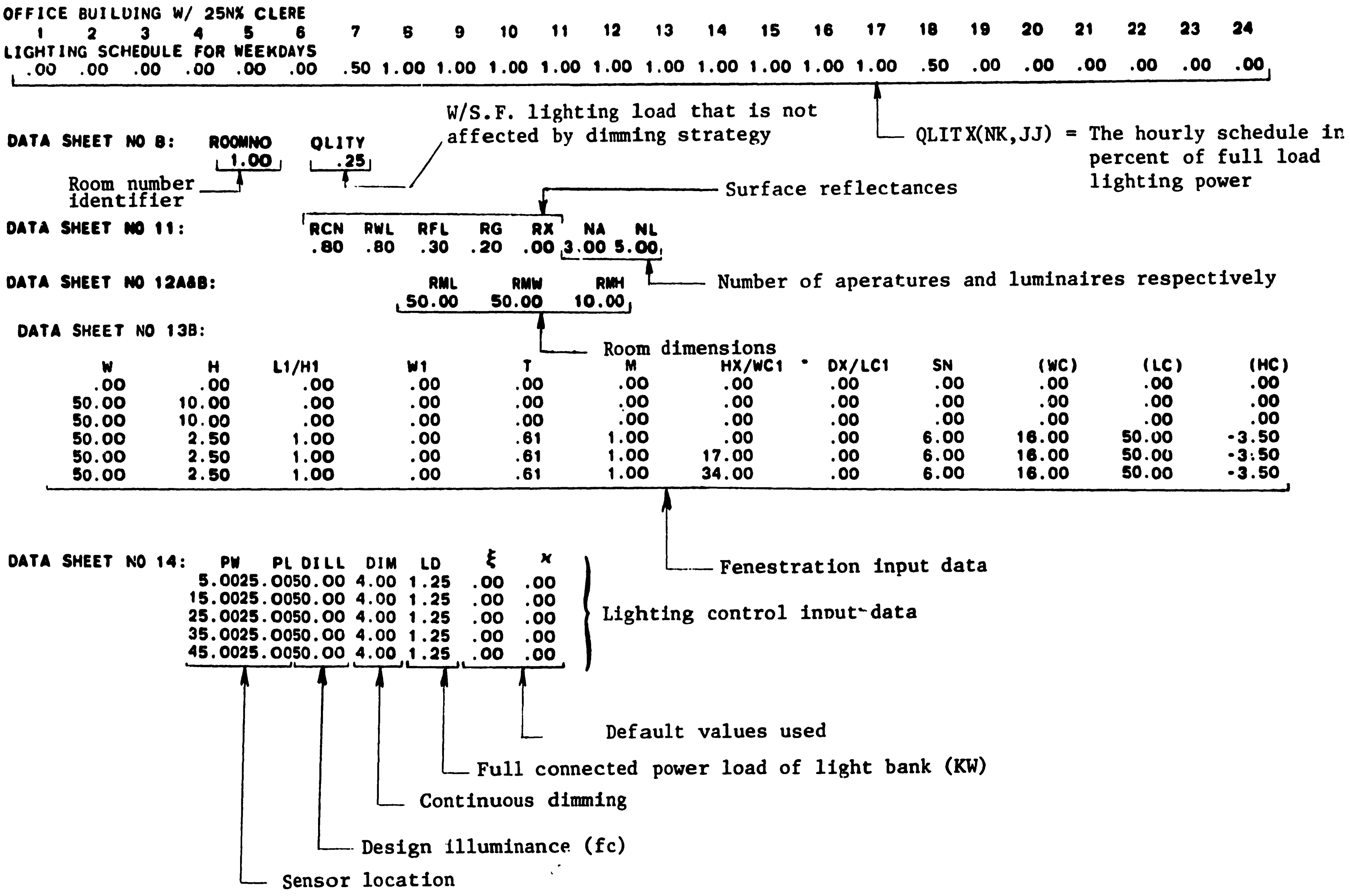


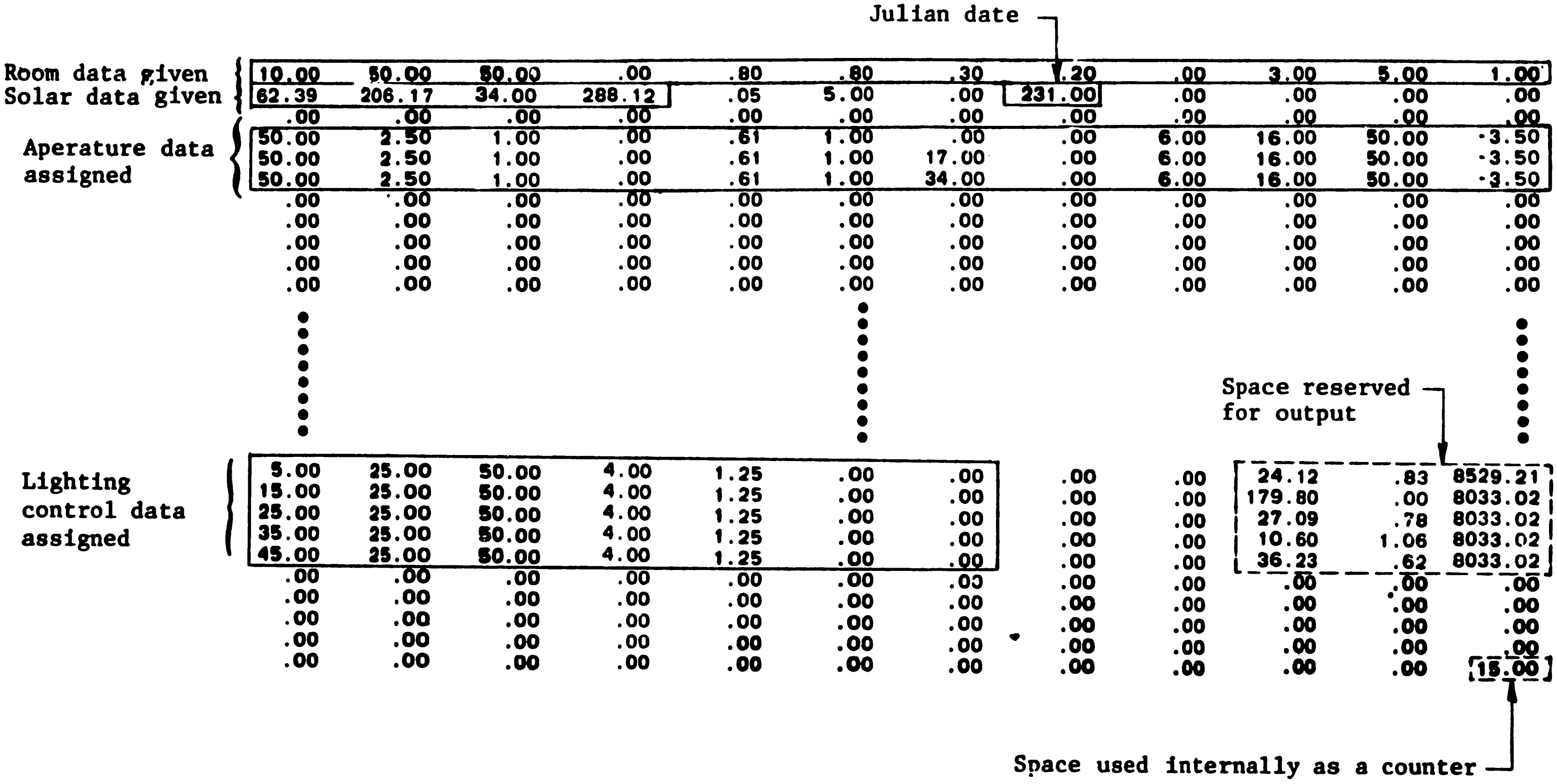
Figure D.1 Sample Building



```
OFFICE BUILDING W/ 25N% CLERE
  1    2    3    4    5    6     7    8    9    10   11   12   13   14   15   16   17    18   19   20   21   22   23   24
LIGHTING SCHEDULE FOR WEEKDAYS
 .00  .00  .00  .00  .00  .00   .50 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00  .50  .00  .00  .00  .00  .00  .00

DATA SHEET NO 8:    ROOMNO    QLITY
                     1.00      .25

DATA SHEET NO 11:             RCN  RWL  RFL  RG   RX   NA   NL
                              .80  .80  .30  .20  .00 3.00 5.00

DATA SHEET NO 12A&B:                RML     RMW     RMH
                                   50.00   50.00   10.00

 DATA SHEET NO 13B:
       W         H       L1/H1       W1       T        M       HX/WC1 *  DX/LC1    SN      (WC)     (LC)     (HC)
      .00       .00       .00       .00      .00      .00       .00       .00      .00      .00      .00      .00
    50.00     10.00       .00       .00      .00      .00       .00       .00      .00      .00      .00      .00
    50.00     10.00       .00       .00      .00      .00       .00       .00      .00      .00      .00      .00
    50.00      2.50      1.00       .00      .61     1.00       .00       .00     6.00    16.00    50.00    -3.50
    50.00      2.50      1.00       .00      .61     1.00     17.00       .00     6.00    16.00    50.00    -3:50
    50.00      2.50      1.00       .00      .61     1.00     34.00       .00     6.00    16.00    50.00    -3.50

DATA SHEET NO 14:  PW   PL DILL  DIM  LD    ξ    x
                  5.0025.0050.00 4.00 1.25  .00  .00
                 15.0025.0050.00 4.00 1.25  .00  .00
                 25.0025.0050.00 4.00 1.25  .00  .00
                 35.0025.0050.00 4.00 1.25  .00  .00
                 45.0025.0050.00 4.00 1.25  .00  .00
```

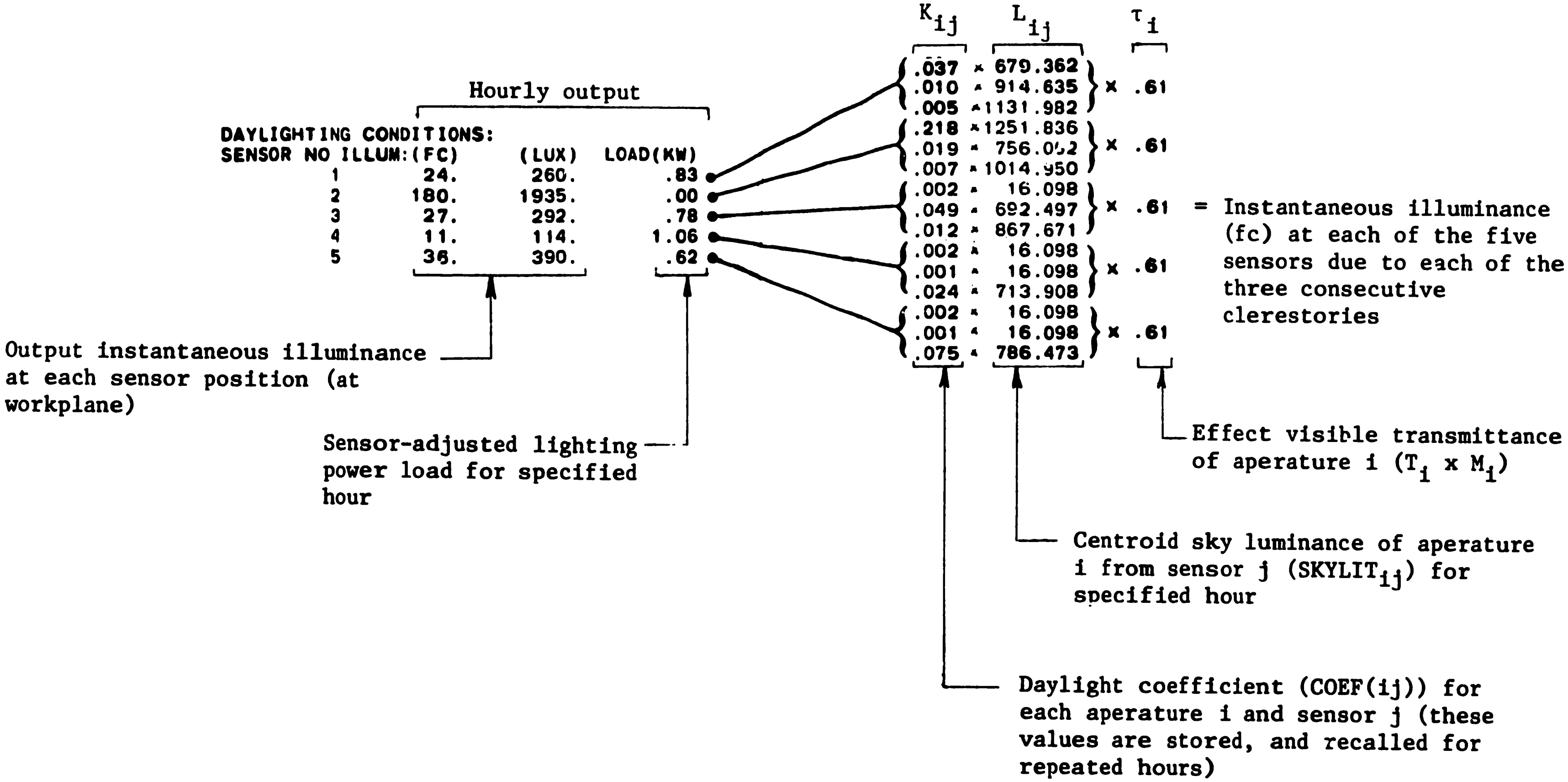
Figure D.2 Input from main energy simulation program

ZLITE array input for sample problem: snapshot for a specified hour



```
 10.00    50.00    50.00      .00      .80      .80      .30      .20      .00     3.00     5.00     1.00
 62.39   206.17    34.00   288.12      .05     5.00      .00   231.00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
 50.00     2.50     1.00      .00      .61     1.00      .00      .00     6.00    16.00    50.00    -3.50
 50.00     2.50     1.00      .00      .61     1.00    17.00      .00     6.00    16.00    50.00    -3.50
 50.00     2.50     1.00      .00      .61     1.00    34.00      .00     6.00    16.00    50.00    -3.50
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
     .                                          .                                                    .
     .                                          .                                                    .
     .                                          .                                                    .
  5.00    25.00    50.00     4.00     1.25      .00      .00      .00      .00    24.12      .83  8529.21
 15.00    25.00    50.00     4.00     1.25      .00      .00      .00      .00   179.80      .00  8033.02
 25.00    25.00    50.00     4.00     1.25      .00      .00      .00      .00    27.09      .78  8033.02
 35.00    25.00    50.00     4.00     1.25      .00      .00      .00      .00    10.60     1.06  8033.02
 45.00    25.00    50.00     4.00     1.25      .00      .00      .00      .00    36.23      .62  8033.02
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00
   .00      .00      .00      .00      .00      .00      .00      .00      .00      .00      .00    15.00
```

Figure D.3 DALITE input snapshot for a specified hour



```
DAYLIGHTING CONDITIONS:
SENSOR NO ILLUM:(FC)      (LUX)  LOAD(KW)
    1         24.       260.       .83
    2        180.      1935.       .00
    3         27.       292.       .78
    4         11.       114.      1.06
    5         36.       390.       .62
```

Figure D.4 DALITE output snapshot for a specified hour

Daylighting output

Hourly electric load after dimming (including 0.25 W/S.F. equipment constant load)

Snapshot hour values

Hourly exterior horizontal illuminance

```
   ROOM NAME= OFFICE BUILDING W/ 25N% CLERE          WITH DAYLIGHT
MONTH DAY          MHR      QLMAX     CLDAY      HLDAY        DBA          ELEC
  8    21           16     -27189.   -276697.      0.          81.9          51.5
HR DBOUT     WBOUT      DBIN      RHIN      TMRT     PMV        PPD  CLO    VEL     QLS       QLL     QLITE DAYLIGHT    SUN  ELECTRIC PEOPLE
     F         F          F         F         F                              M/S   BTU/HR    BTU/HR   BTU/HR    FC   BTU/HR/FT2 KWH   BTU/HR
 1 76.34     70.39     79.85     67.40     79.97      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
 2 75.44     70.13     79.42     68.35     79.59      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
 3 74.72     69.93     79.06     69.16     79.27      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
 4 74.18     69.77     78.70     70.00     78.93      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
 5 74.00     69.72     78.49     70.46     78.70      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
 6 74.36     69.82     78.64     70.13     78.81      .00        .00  .00    .0        0.        0.        0.       0.      7.   .0000     0.
 7 75.26     70.08     78.00     60.00     78.75      .00        .00  .00    .0    -8563.    -3892.     7587.    1963.     68.  2.5354  2136.
 8 76.88     70.55     78.00     60.00     79.36      .00        .00  .00    .0 -14872.    -5628.    14400.    3853.    136.  4.8443  4400.
 9 79.22     71.21     78.00     60.00     79.55      .00        .00  .00    .0 -15359.    -5628.    13634.    5552.    198.  4.6196  4400.
10 81.92     71.96     78.00     60.00     79.91      .00        .00  .00    .0 -16573.    -5628.    13234.    6911.    247.  4.5027  4400.
11 84.98     72.79     78.00     60.00     80.25      .00        .00  .00    .0 -17969.    -5628.    13269.    7819.    280.  4.5127  4400.
12 87.86     73.57     78.00     60.00     80.57      .00        .00  .00    .0 -19352.    -5628.    13417.    8203.    294.  4.5562  4400.
13 90.02     74.14     78.00     60.00     80.83      .00        .00  .00    .0 -20286.    -5628.    13338.    8033.    288.  4.5331  4400.
14 91.46     74.51     78.00     60.00     81.02      .00        .00  .00    .0 -20911.    -5628.    13207.    7322.    262.  4.4945  4400.
15 92.00     74.65     78.00     60.00     81.12      .00        .00  .00    .0 -21348.    -5628.    13422.    6128.    219.  4.5576  4400.
16 91.46     74.51     78.00     60.00     81.12      .00        .00  .00    .0 -21561.    -5628.    14080.    4545.    161.  4.7503  4400.
17 90.20     74.19     78.00     60.00     81.00      .00        .00  .00    .0 -21415.    -5628.    14890.    2707.     95.  4.9878  4400.
18 88.22     73.66     78.00     60.00     80.49      .00        .00  .00    .0 -14485.    -3828.     7944.     825.     28.  2.6401  2200.
19 85.88     73.04     81.97     62.91     82.19      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
20 83.54     72.40     81.68     63.50     81.34      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
21 81.56     71.86     81.57     63.72     81.43      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
22 79.76     71.36     80.96     65.01     80.88      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
23 78.32     70.95     80.65     65.67     80.67      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
24 77.24     70.65     80.19     66.65     80.26      .00        .00  .00    .0        0.        0.        0.       0.      0.   .0000     0.
```

Hourly temperatures

Hourly sensible and latent loads

Hourly heat load from lights and equipment

Incident horizontal solar

Hourly loads from people

Figure D.5 Main program output for a day showing the daylighting impact on the building loads

APPENDIX E: PROGRAM LISTING

A FORTRAN 77 listing of the DALITE program is given on the following pages. The listing is subdivided into four sections and includes a diagrammatic representation preceding each. The code is the UNIVAC version of FORTRAN 77.

E.1 The DALITE subroutine

E.2 The SKYLUM subroutine

E.3 The RMLITE subroutine

E.4 The LLOAD subroutine

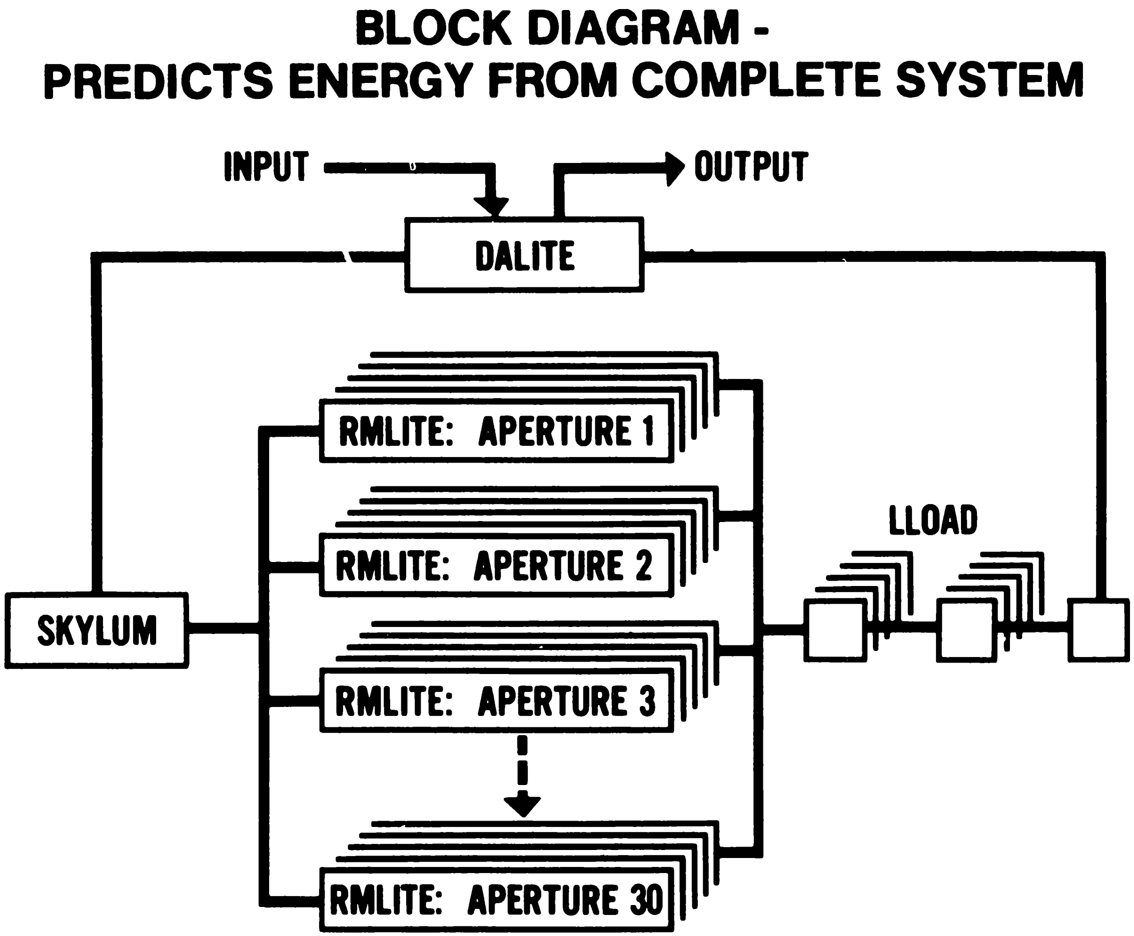


Figure E.1 Block diagram for predicting hourly daylight and its associated adjusted electric lighting energy

```
Q$Q$Q$*GARY(1).DALITE(16)
      SUBROUTINE DALITE(COEF,SURFAZ,WINAZ,THETA,WP,DP,NA,NL,ITEST)
C
C     ANALIZES THE HOURLY DAYLIGHTING CONDITIONS AND
C     CALCULATES HOURLY ELECTRIC LIGHTING ENERGY REQUIREMENTS.
C     THESE DALIGHTING ALGORITHMS WERE DEVELOPED BY GARY GILLETTE.
C
C
C     NOTE: ALL DISTANCES ARE IN FEET AND ALL ANGLES IN DEGREES.
C
C           ROOM VARIABLES:
C
C     RMH   =ROOM HEIGHT (FT)
C     RML   =ROOM LENGTH (FT)
C     RMW   =ROOM WIDTH (FT)
C     AZM   =CLOCKWISE AZIMUTH OF ROOM FROM NORTH
C     RCN   =CEILING REFLECTANCE
C     RWL   =WALL REFLECTANCE
C     RFL   =FLOOR REFLECTANCE
C     RRF   =ROOF REFLECTANCE (IMMEDIATELY OUTSIDE CLERESTORY)
C     RG    =GROUND REFLECTANCE
C     RX    =EXTERNAL OBSTRUCTION REFLECTANCE
C     NA    =NUMBER OF APERTURES IN ROOM
C     NL    =NUMBER OF BANKS OF LUMINAIRES CONNECTED TO A
C            LIGHTING CONTROL DEVICE
C     RMN   =ROOM NUMBER
C
C           SKY VARIABLES:
C
C     SUNALT=SUN ALTITUDE ABOVE THE HORIZONTAL
C     SUNAZ =SUN AZIMUTH CLOCKWISE FROM NORTH
C     SRD   =SOLAR RADIATION DIFFUSE HORZ.(BTU/SF-HR)
C     SRT   =SOLAR RADIATION TOTAL ON HORZ.(BTU/SF-HR)
C     CR    =CLOUD RATIO, DIFFUSE/TOTAL SOLAR RADIATION
C     ZLUM  =ZENITH SKY LUMINANCE
C
C           WINDOW VARIABLES:
C
C     W     =WIDTH OF WINDOW
C     H     =HEIGTH OF WINDOW
C     H1    =HEIGTH OF WINDOW SILL FROM FLOOR
C     W1    =WIDTH OF WINDOW'S LEFT EDGE FROM WALL'S LEFT EDGE
C     T     =VISIBLE TRANSMITTANCE
C     M     =CORRECTION FOR MULLIONS
C     HX    =HEIGHT OF EXTERNAL OBSTRUCTION
C     DX    =DISTANCE OF EXTERNAL OBSTRUCTION FROM ROOM
C     SN    =WALL SURFACE ASSOCIATED WITH APERTURE
C            1-NORTH SURFACE
C            2-EAST  SURFACE
C            3-SOUTH SURFACE
C            4-WEST  SURFACE
C     OP    =HORIZONTAL OVERHANG PROJECTION (FEET)
C     AW    =DISTANCE FROM CEILING TO TOP OF WINDOW (FEET)
C     FP    =FIN PROJECTION FROM FENESTRATION (FEET)
C
C           SKYLIGHT VARIABLES:
C
C     W     =WIDTH OF SKYLIGHT
```

```
C     L    =LENGTH OF SKYLIGHT
C     L1   =DISTANCE (IN LENGHT DIRECTION) OF SKYLIGHT FROM
C           ROOM REFERENCE
C     W1   =DISTANCE (IN WIDTH DIRECTION) OF SKYLIGHT FROM
C           ROOM REFERENCE
C     T    =EFFECTIVE VISIBLE TRANSMITTANCE OF SKYLIGHT W/ WELL
C           (ENTER NEGATIVE VALUE IF TRANSLUCENT)
C     M    =CORRECTION FOR MULLIONS
C     WX   =WELL EXTENTION(DEPTH OF SKYLIGHT WELL)
C     RX   =WELL REFLECTANCE
C     SN   =5 FOR CEILING SURFACE
C
C          CLERESTORY (AND ROOF MONITOR) VARIABLES:
C     WC   =WIDTH OF CLERESTORY OPENING
C     LC   =LENGTH OF CLERESTORY OPENING
C     HC(-) =TOTAL HEIGTH OF SLOPED CLERESTORY (ABOVE CEILING PLANE)
C     HC(+) =TOTAL HEIGHT OF SQUARE MONITOR CLERESTORY (ABOVE CEILING PLANE)
C     W    =WIDTH OF WINDOW IN CLERESTORY
C     H    =HEIGHT OF WINDOW IN CLERESTORY
C     H1   =HEIGHT OF CLERESTORY WINDOW SILL FROM CEILING
C     W1   =WIDTH OF CLERESTORY WINDOW'S LEFT EDGE FROM CLERESTORY
C           WALL
C     LC1  =DISTANCE(IN LENGTH DIRECTION) OF CLERESTORY
C           FROM ROOM REFERENCE
C     WC1  =DISTANCE(IN WIDTH DIRECTION) OF CLERESTORY
C           FROM ROOM  REFERENCE
C     T    =VISIBLE TRANSMITTANCE OF GLAZING
C     M    =CORRECTION FOR MULLIONS
C     SN   =6 FOR CLERESTORY/MONITOR NORTH SURFACE
C           7 FOR CLERESTORY/MONITOR EAST SURFACE
C           8 FOR CLERESTORY/MONITOR SOUTH SURFACE
C           9 FOR CLERESTORY/MONITOR WEST SURFACE
C
C          DIMMER VARIABLES:
C
C     PW   =WIDTH DISTANCE OF SENSOR POINT FROM SOUTH WALL (FT)
C     PL   =LENGTH DISTANCE OF SENSOR POINT FROM WEST WALL (FT)
C     DILL =DESIGN ILLUMINANCE (FC)
C     DIM  =DIMMER SYSTEM (ON/OFF=1,STEP-DOWN=2,CONT DIMMING W/MIN=3,
C          DIMMING W/OFF=4)
C     LOAD =CONNECTED LIGHT LOAD ASSOCIATED WITH SENSOR (KW)
C     CHI  =CONSTANT (MIN) OFFSET DIM CONTROL COEFFICIENT(DEFAULT=0.30)
C     XI   =LINEAR DIM CONTROL COEFFICIENT(DEFAULT=0.30)
C
      PARAMETER MMM=42
      PARAMETER NNL=10
      REAL LOAD,LLOAD,LLOADX,LLOADN,L,LC,L1,L2,M
      COMMON /DD/ZLITE(MMM,12),DAYLT(NNL)
      DIMENSION COEF(NA,NL),SURFAZ(*),WINAZ(NA,NL),THETA(NA,NL),
     *WP(NA,NL),DP(NA,NL)
      PI=3.14159
      IF(ZLITE(2,4).LE.0.)GO TO 90  @CHECKS IF IT IS DAY OR NIGHT
      RMH=ZLITE(1,1)
      RML=ZLITE(1,2)
      RMW=ZLITE(1,3)
      AZM=ZLITE(1,4)
      DO 30 I=1,NL
      DAYLT(I)=0.
```

```
   30 CONTINUE
      GRDLIT=0.
      LLOADX=0.
      NN=NA+3
      NST=ZLITE(1,11)+32
C
      DO 70 K=NN,NST  @FOR EACH OF NL POSSIBLE FIXTURE BANKS
C
      IF(ZLITE(K,1).EQ.0.)GO TO 70
      PW  =ZLITE(K,1)
      PL  =ZLITE(K,2)
      DILL=ZLITE(K,3)
      DIM =ZLITE(K,4)
      LOAD=ZLITE(K,5)
      N =K-32
      MST=MMM-NNL
C
      DO 60 J=3,MST  @FOR EACH OF NA POSSIBLE APERTURES
C
      IF(ZLITE(J,9).LE.0.)GO TO 60
      T =ZLITE(J,5)
      M =ZLITE(J,6)
      SN=ZLITE(J,9)
      ISN=SN
      IF(SN.GE.6)SURFAZ(ISN)=90.*(SN-6)+AZM
      IF(SN.LT.6)SURFAZ(ISN)=90.*(SN-1)+AZM
      IF(ITEST.GT.1)GO TO 50    @IF COEFFICIENTS ALREADY OBTAINED
C
C     CALCULATE DAYLIGHT GEOMETRY COEFFICIENTS
C     THESE COEFICIENTS ARE CALCULATED INITIALLY AND STORED
C     FOR HOURLY USE
C
      IF((ZLITE(J,9).EQ.0.).OR.(ZLITE(J,5).EQ.0.))GO TO 60
      W =ZLITE(J,1)
      W1=ZLITE(J,4)
C
C     DEFINE LOCAL COORDINATES (THESE ARE DISTANCES AS SEEN BY
C     THE FENESTRATION,OR ANGLES AS VIEWED THROUGH THE FENESTRATION)
C
C     WINAZ(J,N) =FENESTRATION AZIMUTH ANGLE @ CENTRIOD
C     THETA(J,N) =FENESTRATION ALTITUDE ANGLE @ CENTROID
C     SURFAZ(ISN)=WALL SURFACE AZIMUTH (DEGREES FROM NORTH)
C
C     COORDINATES FOR ROOM SURFACE 1
C
      IF(SN.EQ.1)THEN
        WP(J,N)=RML-PL
        DP(J,N)=RMW-PW
        RW=RMW
        RL=RML
        IF(W1.GE.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)-ATAN((W1-WP(J,N)+.5*W)/
     *DP(J,N))*57.3
        IF(W1.LT.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)+ATAN((WP(J,N)-W1-.5*W)/
     *DP(J,N))*57.3
C
C     COORDINATES FOR ROOM SURFACE 2
C
      ELSE IF (SN.EQ.2) THEN
```

```
        WP(J,N)=PW
        DP(J,N)=RML-PL
        RW=RML
        RL=RMW
        IF(W1.GE.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)-ATAN((W1-WP(J,N)+.5*W)/
     *DP(J,N))*57.3
        IF(W1.LT.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)+ATAN((WP(J,N)-W1-.5*W)/
     *DP(J,N))*57.3
C
C      COORDINATES FOR ROOM SURFACE 3
C
       ELSE IF (SN.EQ.3) THEN
        WP(J,N)=PL
        DP(J,N)=PW
        RW=RMW
        RL=RML
        IF(W1.GE.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)-ATAN((W1-WP(J,N)+.5*W)/
     *DP(J,N))*57.3
        IF(W1.LT.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)+ATAN((WP(J,N)-W1-.5*W)/
     *DP(J,N))*57.3
C
C      COORDINATES FOR ROOM SURFACE 4
C
       ELSE IF (SN.EQ.4) THEN
        WP(J,N)=RMW-PW
        DP(J,N)=PL
        RW=RML
        RL=RMW
        IF(W1.GE.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)-ATAN((W1-WP(J,N)+.5*W)/
     *DP(J,N))*57.3
        IF(W1.LT.WP(J,N))WINAZ(J,N)=SURFAZ(ISN)+ATAN((WP(J,N)-W1-.5*W)/
     *DP(J,N))*57.3
C
C      COORDINATES FOR CEILING SURFACE 5
C
       ELSE IF (SN.EQ.5) THEN
        L =ZLITE(J,2)
        L1=ZLITE(J,3)
        DP(J,N)=RMH-2.5
        L2=L1-PL
        W2=W1-PW
        IF((L2.GT.0.).AND.(W2.LT.0.))AZM=AZM+90.   @IN DEGREES
        IF((L2.LT.0.).AND.(W2.LT.0.))AZM=AZM+180.  @IN DEGREES
        IF((L2.LT.0.).AND.(W2.GT.0.))AZM=AZM+270.  @IN DEGREES
        IF(AZM.LE.360.)AZM=0.
        IF(L1.LT.PL)L2=PL-L-L1
        IF(W1.LT.PW)W2=PW-W-W1
        IF(W2+W/2.EQ.0.)THEN
        WINAZ(J,N)=AZM
        ELSE
        WINAZ(J,N)=ATAN((L2+L/2)/(W2+W/2))*57.3+AZM @IN DEGREES
        END IF
        IF((L2+L/2.EQ.0.).AND.(W2+W/2.EQ.0.))THEN
        THETA(J,N)=90.
        ELSE
        THETA(J,N)=ATAN(DP(J,N)/SQRT((L2+L/2)**2+(W2+W/2)**2))*57.3  @IN DEGREES
        END IF
C
```

```
C      COORDINATES FOR CLERESTORY SURFACE 6
C
       ELSE IF (SN.EQ.6) THEN
         H1=ZLITE(J,3)
         LC=ZLITE(J,11)
         LC1=ZLITE(J,8)
         WC=ZLITE(J,10)
         WC1=ZLITE(J,7)
         DP(J,N)=RMH-2.5+H1
         WP(J,N)=RML-PL
         RW=RMW
         RL=RML
         IF((WC1+WC).LT.PW)WINAZ(J,N)=SURFAZ(ISN)   @NOTE:DSF=0.
         IF(LC1.GE.PL)WINAZ(J,N)=SURFAZ(ISN)+ATAN((LC1-PL+.5*LC)/
      *  (WC1+WC-PW))*57.3
         IF(LC1.LT.PL)WINAZ(J,N)=SURFAZ(ISN)-ATAN((PL-LC1-.5*LC)/
      *  (WC1+WC-PW))*57.3
C
C      COORDINATES FOR CLERESTORY SURFACE 7
C
       ELSE IF (SN.EQ.7) THEN
         H1=ZLITE(J,3)
         LC=ZLITE(J,11)
         LC1=ZLITE(J,8)
         WC=ZLITE(J,10)
         WC1=ZLITE(J,7)
         DP(J,N)=RMH-2.5+H1
         WP(J,N)=PW
         RW=RML
         RL=RMW
         IF(((LC1+LC).GE.PL).AND.(WC1.GE.PW))WINAZ(J,N)=SURFAZ(ISN)-
      *  ATAN((WC1-PW+.5*W)/(LC1+LC-PL))*57.3
         IF(((LC1+LC).GE.PL).AND.(WC1.LT.PW))WINAZ(J,N)=SURFAZ(ISN)+
      *  ATAN((PW-WC1-.5*W)/(LC1+LC-PL))*57.3
         IF((LC1+LC).LT.PL)WINAZ(J,N)=SURFAZ(ISN)   @NOTE:DSF=0.
C
C      COORDINATES FOR CLERESTORY SURFACE 8
C
       ELSE IF (SN.EQ.8) THEN
         H1=ZLITE(J,3)
         LC=ZLITE(J,11)
         LC1=ZLITE(J,8)
         WC=ZLITE(J,10)
         WC1=ZLITE(J,7)
         DP(J,N)=RMH-2.5+H1
         WP(J,N)=PL
         RW=RMW
         RL=RML
         IF(WC1.GT.PW)WINAZ(J,N)=SURFAZ(ISN)   @NOTE:DSF=0.
         IF(LC1.GE.PL)WINAZ(J,N)=SURFAZ(ISN)-ATAN((LC1-PL+.5*LC)/
      *  (WC1+WC-PW))*57.3
         IF(LC1.LT.PL)WINAZ(J,N)=SURFAZ(ISN)+ATAN((PL-LC1-.5*LC)/
      *(WC1+WC-PW))*57.3
C
C      COORDINATES FOR CLERESTORY SURFACE 9
C
       ELSE IF (SN.EQ.9) THEN
         H1=ZLITE(J,3)
```

```
        LC=ZLITE(J,11)
        LC1=ZLITE(J,8)
        WC=ZLITE(J,10)
        WC1=ZLITE(J,7)
        DP(J,N)=RMH-2.5+H1
        WP(J,N)=RMW-PW
        RW=RML
        RL=RMW
        IF((LC1+LC).LT.PL)WINAZ(J,N)=SURFAZ(ISN)   @NOTE:DSF=0.
        IF(((LC1+LC).GE.PL).AND.(WC1.GE.PW))WINAZ(J,N)=SURFAZ(ISN)+
     *  ATAN((WC1-PW+.5*W)/(LC1+LC-PL))*57.3
        IF(((LC1+LC).GE.PL).AND.(WC1.LT.PW))WINAZ(J,N)=SURFAZ(ISN)-
     *  ATAN((PW-WC1-.5*W)/(LC1+LC-PL))*57.3
      END IF
   50 CONTINUE
C
C     CALCULATE ANGULAR CORRECTION OF GLAZING TRANSMITTANCE
C     (CORRECTS FOR SUNLIGHT GRAZING ANGLE)
C
      SUNALT=ZLITE(2,1)  @IN DEGREES
      SUNAZ =ZLITE(2,2)  @IN DEGREES
      IF(SUNAZ.GT.360.)SUNAZ=SUNAZ-360.
      AZ=ABS(SUNAZ-WINAZ(J,N))
      IF (AZ.GT.90.)THEN
      ANG=0.
      ELSE
      ANG=ATAN(SQRT(TAN(SUNALT*PI/180.)**2+SIN(AZ*PI/180.)**2)
     */COS(AZ*PI/180.))
      END IF
      TNX=1.018*T*COS(ANG)*(1.+SIN(ANG)**3)
C
C     CALCULATE SKY LUMINANCE AS SEEN THROUGH THE FENESTRATION
C
      CALL SKYLUM(SURFAZ(ISN),WINAZ(J,N),THETA(J,N),PL,PW,WP(J,N),
     *DP(J,N),J,SKYLIT,SUNLIT,GRDLIT,SIDLIT)
      IF(ITEST.GT.1)GO TO 55
C
C     CALCULATE ROOM ILLUMINANCE AT SENSOR LOCATION
C
      CALL RMLITE(WP(J,N),DP(J,N),PL,PW,RW,RL,J,SKYLIT,SUNLIT,
     *GRDLIT,XLITE)
      COEF(J,N)=XLITE
   55 CONTINUE
      IF((T.LT.0).AND.(SN.EQ.5))DAYLTE=COEF(J,N)*GRDLIT*ABS(T)*M
      IF((T.LT.0).AND.(SN.NE.5))DAYLTE=COEF(J,N)*SIDLIT*ABS(T)*M
      IF(T.GT.0)DAYLTE=SUNLIT*TNX*M+COEF(J,N)*T*M*SKYLIT
      IF(T.EQ.0)DAYLTE=0.
      DAYLT(N)=DAYLT(N)+DAYLTE
   60 CONTINUE
C
C     CALCULATE ADJUSTED LIGHTING LOAD
C
      DAYLTE=DAYLT(N)
      XI=0.70
      CHI =0.30
      IF(ZLITE(K,6).GT.0.)XI=ZLITE(K,6)
      IF(ZLITE(K,7).GT.0.) CHI=ZLITE(K,7)
      LLOADN=LLOAD(DAYLTE,DILL,DIM,LOAD,XI,CHI)

      ZLITE(K,10)=DAYLTE
      ZLITE(K,11)=LLOADN
      ZLITE(K,12)=GRDLIT
   70 CONTINUE
   90 RETURN
      END
```

BLOCK DIAGRAM - PREDICTS SKY CONDITIONS

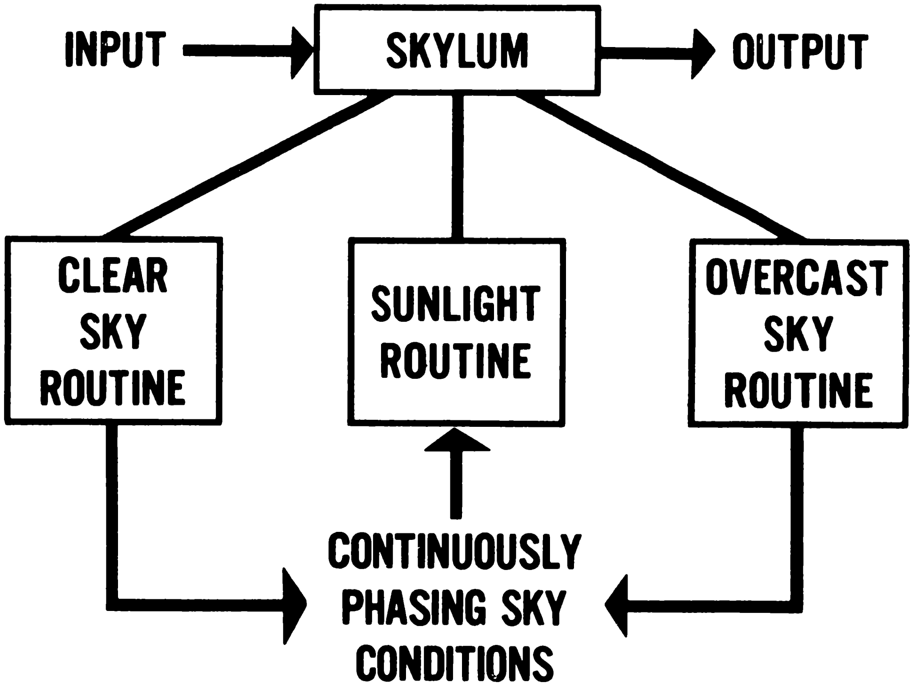


Figure E.2 Block diagram for predicting sky conditions

```
Q$Q$Q$*GARY(1).SKYLUM(31)
      SUBROUTINE SKYLUM(SURFAZ,WINAZ,THETA,PL,PW,WP,DP,J,SKYLIT,
     *SUNLIT,GRDLIT,SIDLIT)
C
C     TO CALCULATE THE  SKY LUMINANCE AS SEEN THRU A WINDOW/SKYLIGHT
C
C     SUNALT=SOLAR ALTITUDE ANGLE (DEGREES ABOVE HORIZON)
C     SUNAZ =SOLAR AZIMUTH ANGLE (DEGREES CLOCKWISE FROM NORTH)
C     BETA  =HAZINESS FACTOR:RURAL=0.05 URBAN=0.10 INDUSTRIAL=0.20
C     WINAZ =VEIWING WINDOW AZIMUTH ANGLE @ CENTER AS SEEN BY
C            POINT ON W0RK PLANE (DEGREES CLOCKWISE FROM NORTH)
C     THETA =VEIWING WINDOW ALTITUDE ANGLE @ CENTER AS SEEN BY
C            POINT ON WORK PLANE (INPUT IN DEGREES ABOVE HORIZON)
C     CR    =CLOUD RATIO,DIFFUSE/TOTAL SOLAR RADIATION
C            (CLOUD COVER/10. COULD BE USED IN LIU OF CR,BUT W/ SOME
C            LOSS OF ACCRURACY)
C     SRT   =TOTAL SOLAR RADIATION,HORIZONTAL(BTU/HR/SF)
C     SRD   =DIFFUSE SOLAR RADIATION,HORIZONTAL(BTU/HR/SF)
C     SKYLUM=SKY LUMINANCE @ WINDOW CENTROID (FOOTLAMBERTS)
C     CLRSKY=CLEAR SKY LUMINANCE @ WINDOW OR SKYLIGHT CENTROID
C     OVRSKY=OVERCAST SKY LUMINANCE @ WINDOW OR SKYLIGHT CENTROID
C     SUNLIT=DIRECT  SUN ILLUMINANCE ON THE HORIZONTAL
C     SUNBM =DIRECT BEAM ILLUMINANCE AT NORMAL INCIDENCE
C
      COMMON/DD/ZLITE(42,12),DAYLT(10)
      REAL  L,L1,LC,LC1
      RMH   =ZLITE(1,1)
      AZM   =ZLITE(1,4)
      SUNALT=ZLITE(2,1)
      SUNAZ =ZLITE(2,2)
      SRD   =ZLITE(2,3)
      SRT   =ZLITE(2,4)
      BETA  =ZLITE(2,5)
      OMEGA =ZLITE(2,6)
      JUL   =ZLITE(2,8)
      SN    =ZLITE(J,9)
      PI    =3.14159
      IF(SUNAZ.GT.360.)SUNAZ=SUNAZ-360.
      IF(SN.EQ.5)THEN   @FOR HORIZONTAL SKYLIGHTS
          X=0.
          H =0.
          H1=0.
          W =ZLITE(J,1)
          L =ZLITE(J,2)
          L1=ZLITE(J,3)
          W1=ZLITE(J,4)
          HX=ZLITE(J,7)
          DX=ZLITE(J,8)
          OP=ZLITE(J,10)
          THETA=THETA*PI/180.
          HWP  =0.
      ELSE IF(SN.LT.5)THEN    @FOR VERTICAL WINDOWS
          X=0.
          L =0.
          L1=0.
          W =ZLITE(J,1)
          H =ZLITE(J,2)
          H1=ZLITE(J,3)
```

```
              W1=ZLITE(J,4)
              HX=ZLITE(J,7)
              DX=ZLITE(J,8)
              OP=ZLITE(J,10)
              AW=ZLITE(J,11)
              HWP=H+H1-2.5
              HH=HX*(DP/(DP+DX))
              THETA=ATAN((HWP-(HWP-HH)/2)/DP)    @IN RADIANS
          ELSE IF(SN.GT.5)THEN               @FOR CLERESTORIES
              W =ZLITE(J,1)
              H =ZLITE(J,2)
              H1=ZLITE(J,3)
              W1=ZLITE(J,4)
              WC1=ZLITE(J,7)
              LC1=ZLITE(J,8)
              WC=ZLITE(J,10)
              LC=ZLITE(J,11)
              HC=ZLITE(J,12)
              OP=0.
              AW=DP
              IF(SN.EQ.6)X=WC+WC1-PW
              IF(SN.EQ.7)X=LC+LC1-PL
              IF(SN.EQ.8)X=PW-WC1
              IF(SN.EQ.9)X=PL-LC1
              HWP=RMH+H1+H/2-2.5
              THETA=ATAN(HWP/X)   @IN RADIANS
          END IF
          IF(SRT.EQ.0.)GO TO 20
          IF(THETA.LT.0.)THETA=0.
C
C     CALCULATE INTERMEDIATE CLOUD-MODIFIED SKY LUMINANCE
C
      CR    =SRD/SRT
      PHASE =(1.+COS(PI*CR))/2.
      SKYLIT=CLRSKY(SUNALT,SUNAZ,WINAZ,THETA,BETA,OMEGA)*PHASE
     *+OVRSKY(SRD,THETA)*(1.-PHASE)
C
C     CALCULATE SUNLIGHT PRESENT AT SENSOR POSITION
C
      IF(SUNALT.LT.5)THEN
      SUNBM=0.  @CONTROLS PROBLEM DUE TO LOW SUN ANGLES
      ELSE
      SUNBM=SUNN(SUNALT,SUNAZ,AZM,H,H1,W,W1,L,L1,OP,AW,WP,
     *PL,PW,DP,DX,SN,JUL,X)*PHASE
      SUNLIT=SUNBM*SIN(SUNALT*PI/180.)
      END IF
C
C     CALCULATE OUTDOOR HORIZONTAL & VERTICAL ILLUMINATION
C
      AZ=ABS(SURFAZ-SUNAZ)
      GRDLIT=(93.+18.*CR)*SRT*.2931  @ILLUMINANCE ON GROUND(FC)
      IF(AZ.GE.90.)SIDLIT=.5*111.*SRD*.2931  @(FC)
      IF(AZ.LT.90.)SIDLIT=(.5*111.*SRD*.2931)
     *+(SUNBM*COTAN(SUNALT*PI/180.))  @ILLUMINANCE ON VERTICAL(FC)
   20 RETURN
      END
```

```
Q$Q$Q$*GARY(1).SUNN(9)
      FUNCTION SUNN(SUNALT,SUNAZ,AZM,H,H1,W,W1,L,L1,OP,AW,WP,
     *PL,PW,DP,DX,SN,JUL,X)
C
C      SUBROUTINE TO CALCULATE THE DIRECT SUN CONDITIONS
C
C     SUNAZ =SUN'S AZIMUTH (DEGREES CLOCKWISE FROM NORTH)
C     SUNALT=SUN'S ALTITUDE  (DEGREES ABOVE HORIZON)
C     JUL   =JULIAN DATE(JAN 1=1,DEC 31=365)
C     AZM   =CLOCKWISE AZIMUTH COORDINATES OF WALL OFF N-S AXIS
C     EX    =EXTRATERRESTRIAL ILLUMINANCE NORMAL TO SUN (FOOT-CANDLES)
C     SUNN  =DIRECT SUNLIGHT ILLUMINANCE NORMAL TO SUN (FOOT-CANDLES)
C
      REAL L,L1,LS1,LS2
      PI    =3.14159
      SUNN  =0.0
      IF(SN.GT.5)DP=X
      EX=11840.*(1.+.033*COS(.99*JUL*PI/180)) @EXTRATERRESTRIAL ILLUMINANCE (FC)
C
C     ALGORITHM TO DETERMINE THE SOLAR DISC ILLUMINANCE
C     PROJECTED ON THE WORKPLANE FROM A VERTICAL WINDOW OR CLERESTORY
C
      ANGL1=ABS(ATAN((W+W1-WP)/DP)*180./PI)
      ANGL2=ABS(ATAN((W1-WP)/DP)*180./PI)
      IF((SN.EQ.1).OR.(SN.EQ.6))THEN
        GO TO 60
      ELSE IF((SN.EQ.2).OR.(SN.EQ.7))THEN
        IF(SUNAZ.GT.(180.+AZM))GO TO 60
        DS1=(H+H1+AW)/TAN((SUNALT*PI/180.)/
     *  COS(ABS(SUNAZ-90.-AZM)*PI/180.))-OP
        ANGL3=90.+AZM-ANGL1
        ANGL4=90.+AZM+ANGL2
      ELSE IF((SN.EQ.3).OR.(SN.EQ.8))THEN
        IF((SUNAZ.LT.(90.+AZM)).OR.(SUNAZ.GT.(270.+AZM)))GO TO 60
        DS1=(H+H1+AW)/TAN((SUNALT*PI/180.)/
     *  COS(ABS(SUNAZ-180.-AZM)*PI/180.))-OP
        ANGL3=180.+AZM-ANGL1
        ANGL4=180.+AZM+ANGL2
      ELSE IF((SN.EQ.4).OR.(SN.EQ.9))THEN
        IF(SUNAZ.LT.(180.+AZM))GO TO 60
        DS1=(H+H1+AW)/TAN((SUNALT*PI/180.)/
     *  COS(ABS(SUNAZ-270.-AZM)*PI/180.))-OP
        ANGL3=270.+AZM-ANGL1
        ANGL4=270.+AZM+ANGL2
      ELSE
        GO TO 50          @FOR(SN.EQ.5)
      END IF
      IF((SUNAZ.LT.ANGL3).OR.(SUNAZ.GT.ANGL4))GO TO 60
      DS2=0.              @INITIALIZE
      IF(SN.LT.5)DS2=(DS1+OP)*H1/(H1+H+AW)
      IF(SN.GT.5)DS2=DS1*(H1+AW)/(H+H1+AW)
      IF((DP.GT.DS1).OR.(DP.LT.DS2))GO TO 60
      SUNN=EX*EXP(-.21/SIN(SUNALT*PI/180.))
      GO TO 60
C
C     ALGORITHM TO DETERMINE THE SOLAR DISC ILLUMINANCE
C     PROJECTED ON THE WORKPLANE FROM A HORIZONTAL SKYLIGHT
C
```

```
50 SANGL1=SUNALT+(90.-SUNALT)*ABS(COS(SUNAZ*PI/180.))
   IF((SANGL1.EQ.90.).OR.(SANGL1.EQ.270.))THEN
     LS1=L1
   ELSE
     IF(SUNAZ.LE.180.)LS1=L1-(DP+DX)/TAN(SANGL1*PI/180.)
     IF(SUNAZ.GT.180.)LS1=L1+(DP+DX)/TAN(SANGL1*PI/180.)
   END IF
   LS2=LS1+L
   IF((PL.LT.LS1).OR.(PL.GT.LS2))GO TO 60
   SUNN=EX*EXP(-.21/SIN(SUNALT*PI/180.))
   SANGL2=SUNALT+(90.-SUNALT)*ABS(SIN(SUNAZ*PI/180.))
   IF(SANGL2.EQ.90.)WS1=W1
   IF(SANGL2.NE.90.)WS1=W1+(DP+DX)/TAN(SANGL2*PI/180.)
   WS2=WS1+W
   IF((PW.LT.WS1).OR.(PW.GT.WS2))SUNN=0.
60 CONTINUE
   RETURN
   END
```

```
QSQSQS*GARY(1).CLRSKY(25)
      FUNCTION CLRSKY(SUNALT,SUNAZ,WINAZ,THETA,BETA,OMEGA)
C
C     SUBROUTINE TO CALCULATE THE  CLEAR SKY LUMINANCE AT THE
C     CENTROID OF THE WINDOW/SKYLIGHT
C
C           (INPUT VALUES FOR CLRSKY ARE CONVERTED TO RADIANS BELOW)
C     SUNALT=SOLAR ALTITUDE IN DEGREES ABOVE HORIZON
C     ZLUM  =ZENITH SKY LUMINANCE (FOOTLAMBERTS)
C     AZ    =AZIMUTH ANGLE BETWEEN SUN AND VIEW POINT OF GLAZING
C     THETA =ALTITUDE ANGLE OF GLAZING VIEW POINT
C     GAMA  =SOLID ANGLE BETWEEN SUN AND GLAZING VIEW POINT
C     OMEGA =ATMOSPHERIC MOISTURE COEFFICIENT
C     BETA  =ATMOSPHERIC TURBIDITY COEFFICIENT
C
      DIMENSION A0(6,3),A1(6,3)
      DATA(A0(J,1),J=1,6)/0.9361,0.9093,0.8727,0.8547,0.8460,0.8410/
      DATA(A0(J,2),J=1,6)/1.0329,1.0206,1.0074,1.0019,0.9990,0.9980/
      DATA(A0(J,3),J=1,6)/1.1399,1.1499,1.1698,1.1833,1.1899,1.1968/
      DATA(A1(J,1),J=1,6)/0.0020,0.0018,0.0014,0.0012,0.0011,0.0011/
      DATA(A1(J,2),J=1,6)/0.0024,0.0022,0.0019,0.0017,0.0016,0.0016/
      DATA(A1(J,3),J=1,6)/0.0030,0.0028,0.0025,0.0023,0.0022,0.0021/
      PI=3.14159
      IF(BETA.LE.0.05)IBETA=1
      IF((BETA.GT.0.05).AND.(BETA.LE.0.10))IBETA=2
      IF(BETA.GT.0.10)IBETA=3
      IF(OMEGA.LE.0.5)IOMEGA=1
      IF((OMEGA.GT.0.5).AND.(OMEGA.LE.1.0))IOMEGA=2
      IF((OMEGA.GT.1.0).AND.(OMEGA.LE.2.0))IOMEGA=3
      IF((OMEGA.GT.2.0).AND.(OMEGA.LE.3.0))IOMEGA=4
      IF((OMEGA.GT.3.0).AND.(OMEGA.LE.4.0))IOMEGA=5
      IF(OMEGA.GT.4.0)IOMEGA=6
      SALT =SUNALT*PI/180.  @IN RADIANS
      ZLUM =(A0(IOMEGA,IBETA)+A1(IOMEGA,IBETA)*SUNALT**2)*291.9
      AZ   =ABS((SUNAZ-WINAZ)*PI/180.)  @IN RADIANS
      GAMA =ACOS(SIN(THETA)*SIN(SALT)+COS(THETA)*COS(SALT)*COS(AZ))
      CLRSKY=ZLUM*(0.910+10.*EXP(-3*GAMA)+0.45*COS(GAMA)*COS(GAMA))*
     *(1.-EXP(-0.32/SIN(THETA)))/(0.27385*(0.91+10.*EXP(-3*(1.57-SALT))
     *+0.45*SIN(SALT)*SIN(SALT)))
      RETURN
      END
```

```
Q$Q$Q$*GARY(1).OVRSKY(17)
      FUNCTION OVRSKY(SRD,THETA)
C
C     SUBROUTINE TO CALCULATE THE  OVERCAST SKY LUMINANCE AT THE
C     CENTROID OF THE WINDOW/SKYLIGHT
C
C     ZLUM  =ZENITH SKY LUMINANCE (FOOTLAMBERTS)
C     OVRSKY=OVERCAST SKY LUMINANCE OF APERTURE MIDPOINT
C     THETA =ALTITUDE ANGLE STUDY POINT MAKES WITH APERTURE MIDPOINT
C
      PI=3.14159
C
C     CALCULATE ZENITH LUMINANCE
C
      ZLUM=(111.*SRD*0.2931)*9/7
C
C     CALCULATE OVERCAST SKY LUMINANCE AT WINDOW VIEW ANGLE
      OVRSKY=ZLUM*((1.+2.*SIN(THETA))/3.)
      RETURN
      END
```

BLOCK DIAGRAM - PREDICTS ROOM CONDITIONS

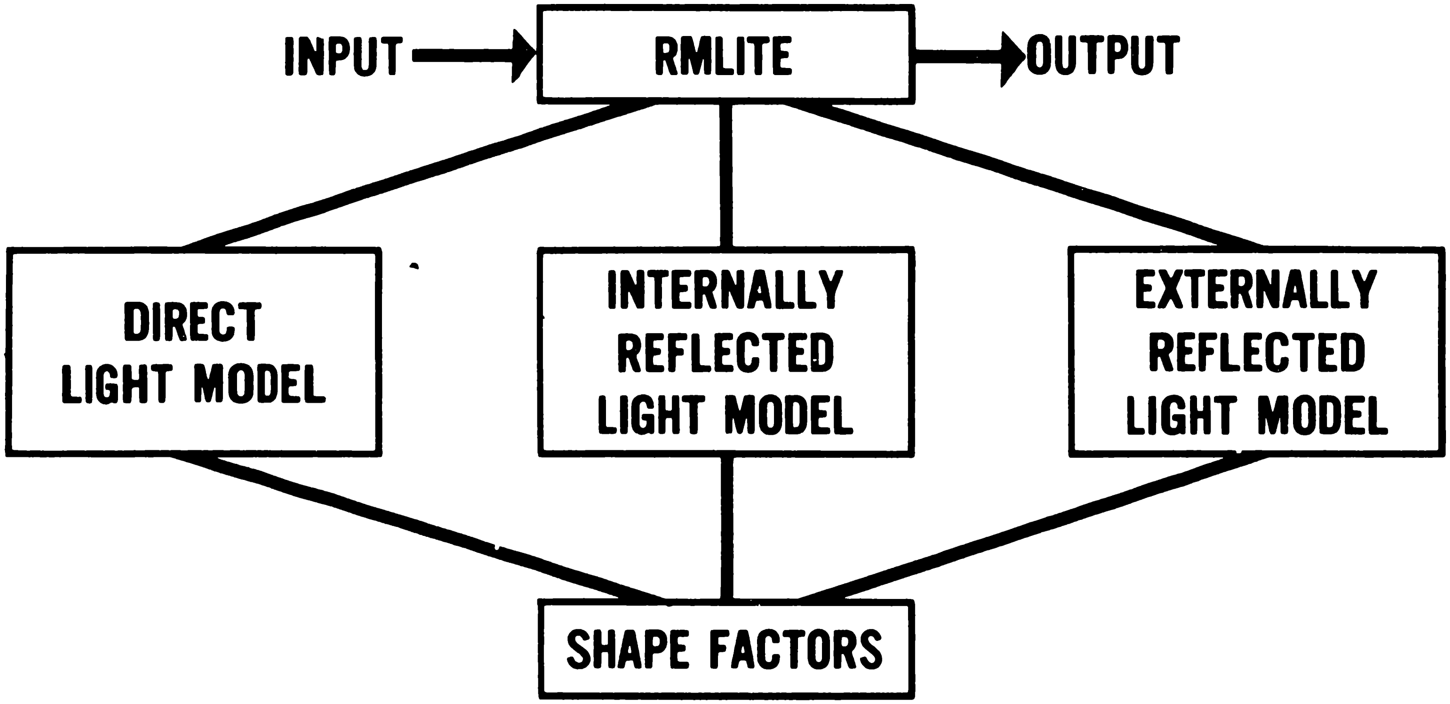


Figure E.3 Block diagram for predicting room daylight conditions

```
Q$QSQ$*GARY(1).RMLITE(36)
      SUBROUTINE RMLITE(WP,DP,PL,PW,RW,RL,J,
     *SKYLIT,SUNLIT,GRDLIT,XLITE)
C
C        THIS ROUTINE CALCULATES THE COMBINED ILLUMINANCE COEFFICIENTS
C        USED TO OBTAIN TOTAL WORKPLANE ILLUMINANCE.
C
C     DP    =DEPTH OF THE REFERENCE POINT FROM THE APERTURE SURFACE(FEET).
C     T     =TRASMISSION COEFFICIENT OF WINDOW OR SKYLIGHT
C             (NEGATIVE IF TRANSLUCENT)
C     WA    =WINDOW OR SKYLIGHT AREA, SQ. FT.
C     A     =ROOM INTERNAL SURFACE AREA
C     RX    =REFLECTANCE OF EXTERNAL OBSTRUCTION OR SKYLIGHT WELL
C     RFW   =AVERAGE REFLECTANCE FACTOR OF THE LOWER HALF OF THE ROOM
C     RCW   =AVERAGE REFLECTANCE FACTOR OF THE UPPER  HALF OF THE ROOM
C     RAVE  =AVERAGE REFLECTANCE OF THE ENTIRE ROOM
C     W     =WINDOW OR SKYLIGHT WIDTH, FT.
C     L     =SKYLIGHT LENGTH, FT.
C     H     =WINDOW HEIGHT, FT.
C     HL    =PROJECTED HEIGHT OF OBSTRUCTION ON WINDOW
C     HX    =HEIGHT OF OBSTRUCTION FROM WORK PLANE
C     DX    =DISTANCE OF OBSTRUCTION FROM WINDOW
C     WX    =SKYLIGHT WELL DEPTH
C     RMH   =ROOM HEIGHT
C     RML   =ROOM LENGTH
C     RMW   =ROOM WIDTH
C     RW    =APPARENT ROOM WIDTH (USED IN INTER-REFLECTION MODEL)
C     RL    =APPARENT ROOM LENGTH (USED IN INTER-REFLECTION MODEL)
C     WP    =DISTANCE FROM CORNER OF ROOM TO PERP. REFERENCE LINE
C     H1    =SILL HEIGHT ABOVE FLOOR
C     W1    =DISTANCE FROM LEFT MOST CORNER OF WINDOW OR SKYLIGHT
C             TO LEFT MOST CORNER OF WALL SURFACE(IN "WIDTH" DIRECTION)
C     L1    =DISTANCE LEFT MOST CORNER OF SKYLIGHT TO LEFT MOST
C             CORNER OF WALL SURFACE(IN  LENGTH DIRECTION)
C     M     =CORRECTION FOR GLAZING MULLIONS
C     T     =COMBINED EFFECTIVE TRANSMITTANCE OF THE GLAZING
C     TNX   =ANGULAR DEPENDENT TRANSMITTANCE
C     RG    =GROUND REFLECTANCE
C     JUL   =JULIAN DATE
C     DAYLTE=INTERIOR DAYLIGHT ILLUMINATION
C     XDL     =DIRECT LIGHT FROM THE SKY
C     XERL    =EXTERNALLY REFLECTED LIGHT (FROM OBSTRUCTING BUILDINGS)
C     RRL   =ROOF REFLECTED LIGHT ENTERING CLERISTORY
C     XIRL    =INTERNALLY REFLECTED LIGHT (FROM ROOM SURFACES)
C     SKYLIT=SKY LUMINANCE @APERTURE CENTROID(AVERAGE APERTURE LUMINANCE)
C     SUNLIT=HORIZONTAL ILLUMINANCE FROM THE DIRECT SUN
C     GRDLIT=TOTAL HORIZONTAL GROUND ILLUMINATION(SKY&SUN)
C     SIDLIT=VERTICAL SURFACE ILLUMINANCE(SKY ONLY)
C     GRL   =GROUND REFLECTED LIGHT COEFFICIENT
C     SNL   =SUNLIGHT COEFFICIENT
C
      COMMON/DD/ZLITE(42,12),DAYLT(10)
      REAL M,L,L1,LC,LC1
      PI=3.14159265
      RMH   =ZLITE(1,1)
      RML   =ZLITE(1,2)
      RMW   =ZLITE(1,3)
      RCN   =ZLITE(1,5)
```

```
      RWL   =ZLITE(1,6)
      RFL   =ZLITE(1,7)
      RG    =ZLITE(1,8)
      RX    =ZLITE(1,9)
      SUNALT=ZLITE(2,1)
      JUL   =ZLITE(2,8)
      T     =ZLITE(J,5)
      M     =ZLITE(J,6)
      SN    =ZLITE(J,9)
      OP    =ZLITE(J,10)
      AW    =ZLITE(J,11)
      FP    =ZLITE(J,12)
C
C     FOR THE FOUR ROOM SURFACES
C
      IF(SN.LT.5)THEN
        W=ZLITE(J,1)
        H=ZLITE(J,2)
        H1=ZLITE(J,3)
        W1=ZLITE(J,4)
        HX=ZLITE(J,7)
        DX=ZLITE(J,8)
        WA=W*H
        HH=HX*DP/(DP+DX)
        HL=HH-H1+2.5
        HH1=H+H1-2.5
        IF(HL.GT.H)HH=H
C
C     FOR CEILING SURFACE
C
      ELSE IF(SN.EQ.5)THEN
        W=ZLITE(J,1)
        L=ZLITE(J,2)
        L1=ZLITE(J,3)
        W1=ZLITE(J,4)
        HX=ZLITE(J,7)
        DX=ZLITE(J,8)
        H =L
        HL=0.
C
C     FOR CLERESTORY SURFACES
C
      ELSE IF(SN.GT.5)THEN
        W =ZLITE(J,1)
        H =ZLITE(J,2)
        H1=ZLITE(J,3)
        W1=ZLITE(J,4)
        WC1=ZLITE(J,7)
        LC1=ZLITE(J,8)
        WC=ZLITE(J,10)
        LC=ZLITE(J,11)
        HC=ZLITE(J,12)
        HH=0.
        HH1=0.
        HL=0.
      END IF
      XDL=0.
C
```

```
C     PREPARE VARIABLES FOR INTERREFLECTION SUBROUTINE
C
      A=2.*((RML*RMH)+(RML*RMW)+(RMH*RMW))
      ACN= RMW*RML
      AWL=(RL*RMH)+2*(RW*RMH)
      RAVE=(AWL*RWL+ACN*RFL+ACN*RCN+(W*H)*.15+(RL*RMH-W*H)*RWL)
     */(AWL+ACN+ACN+RL*RMH)
      IF(SN.GT.4)GO TO 10
C
C     CALCULATE CORRECTION FOR EXTERIOR FINS & OVERHANGS
C
      IF(HL.GE.H)GO TO 20
      IF((OP.GT.0.).AND.(ATAN(AW/OP).LT.ATAN(HH1/DP)))HH1=DP*(HH1+AW)/
     *(OP+DP)          @CORRECTION FOR OVERHANG
      IF(FP.GT.0.)W=W-(FP*W/2/(DP+FP))    @CORRECTION FOR SIDE FINS
C                                        @ASSUMES WINDOW CENTRIOD REPRESENTATIVE
   10 CONTINUE
C
C     CALCULATE THE DIRECT LIGHT CONFIGURATION COEFFICIENT BETWEEN THE
C     FENESTRATION AND A POINT IN THE ROOM.
C
C
      CALL DL(XDL,CRL,RRL,HH1,HH,W,WP,DP,PL,PW,GRDLIT,J)
C
C     CALCULATE THE EXTERNALLY REFLECTED LIGHT
C
      IF(SN.GE.5)XERL=0.
   20 IF(SN.LT.5)XERL=ERL(W,H,W1,H1,HH,WP,DP)*RX     @EXTERNAL REF LIGHT
C
C     CALCULATE THE SUNLIGHT INTENSITY ENTERING ROOM
C     & THE GROUND LIGHT AS COEFFICIENTS
C
      IF(SUNALT.LT.5.)THEN
      SNL=0.  @CONTROLS PROBLEMS DUE TO LOW SUN ANGLES
      ELSE
      SNL=SUNLIT/(ABS(T)*M*SKYLIT)
      IF((SN.GE.6).AND.(XDL.EQ.CRL))SNL=SUNLIT/GRDLIT
      END IF
      GRL=GRDLIT/(ABS(T)*M*SKYLIT)
C
C     CALCULATE INTERNALLY REFLECTED LIGHT
C
      CALL IRL(J,HH,RL,RW,RAVE,A,GRL,SNL,CRL,XIRL)  @INTERNAL REF LIGHT
C
C     CALCULATE DAYLIGHT ILLUMINANCE
C     NOTE: NEGATIVE TRANSMITANCE MEANS TRANSLUCENT GLAZING
C
      IF((SN.GE.6).AND.(XDL.EQ.CRL))T=1.0
      XRRL=RRL/(T*M*SKYLIT)
      IF((T.LT.0).AND.(SN.EQ.5))XLITE=XDL+XIRL
      IF((T.LT.0).AND.(SN.NE.5))XLITE=XDL+XIRL-XERL
      IF((SN.GE.6).AND.(XDL.EQ.CRL))XLITE=XIRL
      IF((T.GT.0).AND.(T.NE.1))XLITE=XDL+XERL+XIRL+XRRL
      IF(T.EQ.0.)DAYLTE=0.
      RETURN
      END
```

```
Q$Q$Q$*GARY(1).DL(19)
      SUBROUTINE DL(XDL,CRL,RRL,HH1,HH,W,WP,DP,PL,PW,GRDLIT,J)
C
C     DL  =DIRECT LIGHT FROM SKY ON  A POINT IN THE ROOM.
C        THIS ROUTINE CALCULATES POINT ILLUMINANCE COEFFICIENTS
C        OF THE DIRECT SKY COMPONENT FOR WINDOWS,HORIZONTAL SKYLIGHTS,
C        AND  CLERESTORIES.
C
      COMMON /DD/ZLITE(42,12),DAYLT(10)
      REAL L,L1,L2,L3,LC,LC1,LC2
      PI =3.14159265
      PI2=PI/2
      H  =ZLITE(J,2)
      H1 =ZLITE(J,3)
      W1 =ZLITE(J,4)
      SN =ZLITE(J,9)
      RCN=ZLITE(1,5)
      RG =ZLITE(1,8)
      XDL=0.   @INITIALIZE
      CRL=0.   @INITIALIZE
      ZERO=0.
      IF(SN.GE.5)GO TO 30
C
C     WINDOW ROUTINE
C
      H2 =2.5-H1
      H2A=ABS(H2)
      W4 =WP-W1-W
      W5 =WP-W1
      IF(HH.GE.HH1)GO TO 40
      IF(HH.EQ.0.)THEN
        IF(H2.LE.0.)XDL=BCF(W,H,DP,W5,H2A,PI2)
        IF(H2.GT.0.)XDL=BCF(W,HH1,DP,W5,ZERO,PI2)
      ELSE
        HH4=H-HH
        HH6=HH-H2
        XDL=BCF(W,HH4,DP,W4,HH6,PI2)
      END IF
      GO TO 40
   30 CONTINUE
C
C     MODEL DIRECT LIGHT FROM TOPLIGHTING(OVERHEAD FENESTRATION)
C
      WC1=ZLITE(J,7)
      LC1=ZLITE(J,8)
      WC =ZLITE(J,10)
      LC =ZLITE(J,11)
      HC =ZLITE(J,12)
      IF(HC.GT.0.)PSI=90.  @ROOF MONITOR CHECK
      HC=ABS(HC)
      X  =PL-LC1
      Y  =PW-WC1
      ZZ =DP
      IF(SN.EQ.5)THEN
C
C     SKYLIGHT ROUTINE
C
C     ASSUMES USE OF EFFECTIVE TRANS FOR LIGHT WELL EFFECTS
```

```
C
      A =0.
      L =ZLITE(J,2)
      L1=ZLITE(J,3)
      WX=ZLITE(J,8)
      ZZ=DP+WX
      W2=W1-PW
      L2=L1-PL
      IF(W2.GE.0.)THEN
        W3=W2+W
      ELSE
        W3=ABS(W2)
        W2=ABS(W2)-W
      END IF
      IF(L2.GE.0.)THEN
        L3=L2+L
        IF(L2.EQ.0)L3=L
      ELSE
        L3=ABS(L2)
        L2=ABS(L2)-L
      END IF
      IF(W3.LE.W)THEN
        W2=W-W3
        W3=W
        IF(L3.LE.L)THEN
          L2=L-L3
          L3=L
          XDL=BCFS(W3,L3,ZZ,A)+BCFS(W3,L2,ZZ,A)
     *       +BCFS(W2,L3,ZZ,A)+BCFS(W2,L2,ZZ,A)
        ELSE
        L2=L2+((WX*L2)/DP)
          XDL=BCFS(W3,L3,ZZ,A)-BCFS(W3,L2,ZZ,A)
     *       +BCFS(W2,L3,ZZ,A)-BCFS(W2,L2,ZZ,A)
        END IF
      ELSE
        W2=W2+((WX*W2)/DP)
        IF(L3.LE.L)THEN
          L2=L-L3
          L3=L
          XDL=BCFS(W3,L3,ZZ,L2)-BCFS(W2,L3,ZZ,L2)
        ELSE
          L2=L2+((WX*L2)/DP)
          XDL=BCFS(W3,L3,ZZ,A)-BCFS(W2,L3,ZZ,A)
     *       -BCFS(W3,L2,ZZ,A)+BCFS(W2,L2,ZZ,A)
        END IF
      END IF
C
C     CLERESTORY ROUTINE (INCLUDING ROOF MONITORS)
C
      ELSE IF((SN.EQ.6).OR.(SN.EQ.8))THEN
      XX =Y
      IF(SN.EQ.8)XX=WC-Y
      YY =X-W1
      IF(SN.EQ.8)YY=W+W1-X
      CC =SQRT(WC**2+HC**2)
      IF(PSI.EQ.90.)CC=WC
      CC2=CC/2
      LC2=LC/2
```

```
      WC2=WC/2
C
C     CALCULATE ROOF REFLECTED LIGHT: RRL
C
      IF(PSI.EQ.90.)THEN
        PHI=0.
        A  =HC
        ZZ =DP+HC
      ELSE
        A =WC2*SIN(PHI)
      END IF
      B1=CC2*SIN(PHI)
      B2=H-B1
      C =SQRT(WC2**2+A**2)
      RRL=BCF(LC,B2,C,LC2,A,PHI)*RG*GRDLIT
     **BCF(LC,CC,XX,YY,ZZ,PHI)*RCN
      IF(PSI.EQ.90)GO TO 10
C
C     CALCULATE CEILING REFLECTED LIGHT: CRL
C
      XX =WC-Y
      HHC=HC-H-H1
      CRL=BCF(LC,CC,XX,YY,ZZ,PHI)*BCF(W,H,CC2,LC2,HHC,PSI)*RCN
   10 CONTINUE
C
C     CALCULATE DIRECT LIGHT: XDL
C
      XX =WC-Y
      IF(SN.EQ.8)XX =Y
      XDL=BCF(W,H,XX,YY,DP,PI2)+CRL
      IF((SN.EQ.6).AND.(Y.GT.WC))XDL=CRL
      IF((SN.EQ.8).AND.(Y.LT.0.))XDL=CRL
C
      ELSE IF((SN.EQ.7).OR.(SN.EQ.9))THEN
      XX =X
      IF(SN.EQ.9)XX =LC-X
      YY =Y
      CC =SQRT(LC**2+HC**2)
      IF(PSI.EQ.90)CC=LC
      CC2=CC/2
      LC2=LC/2
      WC2=WC/2
C
C     CALCULATE ROOF REFLECTED LIGHT: RRL
C
      PHI=ATAN(HC/LC)
      PSI=PI/2-PHI
      IF(PSI.EQ.90.)THEN
        PHI=0.
        A  =HC
        ZZ =DP+HC
      ELSE
        A=LC2*SIN(PHI)
      END IF
      B1=CC2*SIN(PHI)
      B2=H-B1
      C =SQRT(LC2**2+A**2)
      RRL=BCF(WC,B2,C,WC2,A,PHI)*RG*GRDLIT
```

```
     **BCF(WC,CC,XX,YY,ZZ,PHI)*RCN
      IF(PSI.EQ.90.)GO TO 20
C
C     CALCULATE CEILING REFLECTED LIGHT: CRL
C
      HHC=HC-H-H1
      CRL=BCF(WC,CC,XX,YY,DP,PHI)*BCF(W,H,CC2,WC2,HHC,PSI)*RCN
   20 CONTINUE
C
C     CALCULATE DIRECT LIGHT: XDL
      XDL=BCF(W,H,XX,YY,Z,PI2)+CRL
      XX =LC-X
      IF(SN.EQ.9)XX =X
      IF((SN.EQ.7).AND.(X.GT.LC))XDL=CRL
      IF((SN.EQ.9).AND.(X.LT.0.))XDL=CRL
      END IF
   40 RETURN
      END
```

```
Q$Q$Q$*GARY(1).IRL(50)
      SUBROUTINE IRL(J,HH,RL,RW,RAVE,A,GRL,SNL,CRL,XIRL)
C
C     COMPUTES THE INTER-REFLECTED LIGHT (FROM THE ROOM SURFACES)
C
C     RMH  =ROOM HEIGHT
C     RW   =APPARENT ROOM WIDTH (AS SEEN BY THE FENESTRATION)
C     RL   =APPARENT ROOM LENGTH (AS SEEN BY THE FENESTRATION)
C     RWL  =REFLECTANCE OF WALL
C     RCN  =REFLECTANCE OF CEILING
C     RFL  =REFLECTANCE OF FLOOR
C     XIRL =INTERNALLY REFLECTED LIGHT COEFFICIENT
C     GRL  =GROUND REFLECTED LIGHT COEFFICIENT
C     SNL  =SUNLIGHT COEFFICIENT
C
      REAL LC,LC1
      COMMON /DD/ZLITE(42,12),DAYLT(10)
      RMH   =ZLITE(1,1)
      RCN   =ZLITE(1,5)
      RWL   =ZLITE(1,6)
      RFL   =ZLITE(1,7)
      RG    =ZLITE(1,8)
      RX    =ZLITE(1,9)
      SUNALT=ZLITE(2,1)
      SUNAZ =ZLITE(2,2)
      W     =ZLITE(J,1)
      H     =ZLITE(J,2)
      H1    =ZLITE(J,3)
      W1    =ZLITE(J,4)
      SN    =ZLITE(J,9)
      PI  =3.14159
      PI2 =PI/2
      KOUNT=1
      ZLITE(42,12)=ZLITE(42,12)+KOUNT
C
C     FOR INTER-REFLECTIONS FROM TOPLIGHTING(SKYLIGHTS & CLERESTORIES)
C
C     NOTE:LIGHT WELL & CLERESTORY CAVITY REFLECTED LIGHT
C          IS COMPUTED IN DL SUBROUTINE
C
      IF(SN.EQ.5)SURFAZ=ZLITE(1,4)
      IF(SN.GT.5)SURFAZ=90.*(SN-6)+ZLITE(1,4)
C
C     INTERNAL REFLECTIONS FROM SKYLIGHT
C
      IF(SN.EQ.5)THEN
      FLUX1=0.
      FLUX2=0.
      FLUX3=0.
      FLUX4=0.
      FLUX5=W*H*GRL          @FLUX FROM SKYLIGHT
      SUNFLX=SNL*W*H*RFL     @FLUX FROM THE SUN
C
C     INTERNAL REFLECTIONS FROM CLERESTORY
C
      ELSE IF(SN.GT.5)THEN
      WC1=ZLITE(J,7)
      LC1=ZLITE(J,8)
```

```
      WC =ZLITE(J,10)
      LC =ZLITE(J,11)
      IF(SN.EQ.6)THEN
        XX=WC1+WC
        YY=LC1+LC-W1-W
      ELSE IF(SN.EQ.7)THEN
        XX=LC1+LC
        YY=WC1+W1
      ELSE IF(SN.EQ.8)THEN
        XX=RW-WC1
        YY=LC1+W1
      ELSE IF(SN.EQ.9)THEN
        XX=RW-LC1
        YY=WC1-W1-W
      END IF
      ZZ=RMH/2+H1
      FLUX1=0.
      FLUX2=0.
      BCF3 =BCF(W,H,XX,YY,ZZ,PI2)     @FLUX FROM BACK(OPPOSITE) WALL
      FLUX3=BCF3*RL*RMH*RWL
      FLUX4=0.
      FLUX5=0.
      SUNFLX=SNL*W*H*RWL  @FLUX FROM THE SUN
      CNFLX=CRL*LC*WC*RCN
C
      ELSE IF(SN.LT.5)THEN
      FP    =ZLITE(J,10)
      AW    =ZLITE(J,11)
C
C     FOR INTER-REFLECTIONS FROM SIDELIGHTING
C
      RL2  =RL/2
      RH2  =RMH/2
      RW2  =RW/2
      HH1  =H+H1-2.5
      HH2  =RMH/2-HH-2.5
      HH3  =RMH/2-H1
      HH4  =H-(HH3-HH2)
      HH5  =RMH/2-HH2
      H2   =2.5-H1
      H3   =H1+H
      H4   =RMH-H1-H2
      H5   =RMH-H1-H
      H6   =RMH-H1
      W2   =W1+W
      W3   =RL2-W1
      W6   =RL-W2
      W7   =RL-W1
      ZERO =0.
      SURAZ=90.*(SN-1)+ZLITE(1,4)
C
C     CALCULATE INTERNALLY REFLECTED FLUX FROM THE SUNLIGHT
C
      AZS=ABS(SUNAZ-SURAZ)
      IF(AZS.GE.90.)THEN
        SUNFLX=0.
      ELSE
        PHI=(SUNALT*PI/180.)/COS(AZS*PI/180.)
```

```
        IF(AW.LT.(FP*TAN(PHI)))DS1=RMH/TAN(PHI)-FP
        IF(AW.GE.(FP*TAN(PHI)))DS1=(RMH-AW)/TAN(PHI)-FP
        DS2=H1/TAN(PHI)
        DS3=FP*(TAN(AZS*PI/180.))
        IF(DS3.GT.0.)W=W-DS3
        SUNFLX=SNL*W*(DS1-DS2)*RFL   @FLUX FROM THE SUN
      END IF
C
C     CALCULATE FLUX FROM CEILING
C
      BCFCN=BCF(W,H,RW2,W3,H5,PI2)
      CNFLX=BCFCN*RW*RL*RCN*RG*GRL
C
C     CALCULATE FLUX FOR EACH WALL SURFACE
C
      SUMFLX=ZLITE(33,9)
      IF(ZLITE(42,12).GT.KOUNT)GO TO 10
C
C     WINDOW WALL SURFACE 1
C
      FLUX1=0      @SINCE WINDOW WALL HAS LITTLE REFLECTED LIGHT
C
C     LEFT SIDE SURFACE 2
C
      IF(RX.EQ.0.)BCF2=BCF(H,W,RW2,HH3,W1,PI2)
      IF(RX.GT.0.)BCF2=BCF(HH4,W,RW2,HH2,W1,PI2)
     *                +BCF(HH1,W,RW2,HH3,W1,PI2)*RX
      FLUX2=BCF2*RMH*RW*RWL
C
C     BACK WALL SURFACE 3
C
      IF(RX.EQ.0.)BCF3=BCF(W,H,HH3,W3,RW,ZERO)
      IF(RX.GT.0.)BCF3=BCF(W,HH4,HH2,W3,RW,ZERO)
     *                +BCF(W,HH1,HH3,W3,RW,ZERO)*RX
      FLUX3=BCF3*RMH*RL*RWL
C
C     RIGHT SURFACE 4
C
      IF(RX.EQ.0.)BCF4=BCF(H,W,RW2,HH3,W6,PI2)
      IF(RX.GT.0.)BCF4=BCF(HH4,W,RW2,HH2,W6,PI2)
     *                +BCF(HH1,W,RW2,HH3,W6,PI2)*RX
      FLUX4=BCF4*RMH*RW*RWL
C
C     FLOOR SURFACE 5
C
      IF(RX.EQ.0.)BCF5=BCF(W,H,RW2,W3,H1,PI2)
      IF(RX.GT.0.)BCF5=BCF(W,HH4,RW2,W3,HH5,PI2)
     *                +BCF(W,HH1,RW2,W3,H1,PI2)*RX
      FLUX5=BCF5*RW*RL*RFL
C
C
      END IF
C
C     COMPUTES MULTIPLE INTER-REFLECTIONS (ASSUMING ULBRICHT SPHERE)
C
      SUMFLX=(FLUX1+FLUX2+FLUX3+FLUX4+FLUX5)
     */A/(1-RAVE)
   10 IF(SN.LT.5)ZLITE(33,9)=SUMFLX
```

```
      XIRL=SUMFLX+((CNFLX+SUNFLX)/A/(1-RAVE))
      RETURN
      END
```

```
QSQSQ$*GARY(1).ERL(31)
                  FUNCTION ERL(W,H,W1,H1,HH,WP,DP)
            C
            C      ERL     = EXTERNALLY REFLECTED LIGHT FROM SURROUNDING BLDGS
            C
                  HWP=H1+H
                  W4 =WP-W1
                  W5 =W4-W
                  H2 =H1-2.5
                  H2A=ABS(H2)
                  W5A=ABS(W5)
                  W4A=ABS(W4)
                  IF(W5.GT.0) GO TO 1
                  IF(W5.LT.0) GO TO 2
                  ERL=BCFW(W,HH,DP)-BCFW(W,H2A,DP)
                  GO TO 3
                1 ERL=BCFW(W4,HH,DP)-BCFW(W1,HH,DP)-BCFW(W4,H2A,DP)+BCFW(W1,H2A,DP)
                  GO TO 3
                2 IF(W4.LT.0.)ERL=BCFW(W5A,HH,DP)-BCFW(W5A,H2A,DP)-BCFW(W4A,HH,DP)
                 *+BCFW(W4A,H2A.DP)
                  ERL=BCFW(W4,HH,DP)+BCFW(W5A,HH,DP)-BCFW(W4,H2A,DP)
                 *-BCFW(W5A,H2A,DP)
                3 RETURN
                  END
  END PRT

@PRT,S GARY.BCF,.BCFS,.BCFW,.LLOAD
```

```
Q$Q$Q$*GARY(1).BCF(6)
      FUNCTION BCF(M,F,X,Y,Z,PHI)
C
C     BCF=BASIC CONFIGURATION FACTOR (PIERPOINT/HOPKINS EQUATION)
C     M F=SURFACE WIDTH & HEIGTH RESPECTIVELY(IN FEET)
C     XYZ=X,Y,&Z COORDINATES TO SURFACE'S LOWER LEFT CORNER(IN FEET)
C     PHI=SURFACE DECLINATION ANGLE (IN RADIANS)
C
      REAL M
      PI =3.14159265
      G  =Z*SIN(PHI)-X*COS(PHI)
      H  =Z*COS(PHI)+X*SIN(PHI)
      A  =SQRT(X**2+Z**2)
      A1 =A**2+Y**2-Y*M
      B  =SQRT(X**2+Z**2+F**2+2*F*G)
      B1 =B**2+Y**2-Y*M
      C  =SQRT(Y**2+H**2)
      D  =SQRT((Y-M)**2+H**2)
      E1 =0.0
      E2 =0.0
C     DIVIDE CHECK
      IF(A1.EQ.0.) A1 =0.0001
      IF(B1.EQ.0.) B1 =0.0001
      IF(A1.LE.0.) E1 =PI
      IF(B1.LE.0.) E2 =PI
C
      BCF=(X/A*(ATAN(M*A/(A1))+E1)
     *+(F*COS(PHI)-X)/B*(ATAN(M*B/(B1))+E2)
     *+Y*COS(PHI)/C*ATAN(F*C/(C**2+G**2+F*G))
     *-(Y-M)*COS(PHI)/D*ATAN(F*D/(D**2+G**2+F*G)))/2/PI
      RETURN
      END
```

BLOCK DIAGRAM -
PREDICTS LIGHTING ENERGY

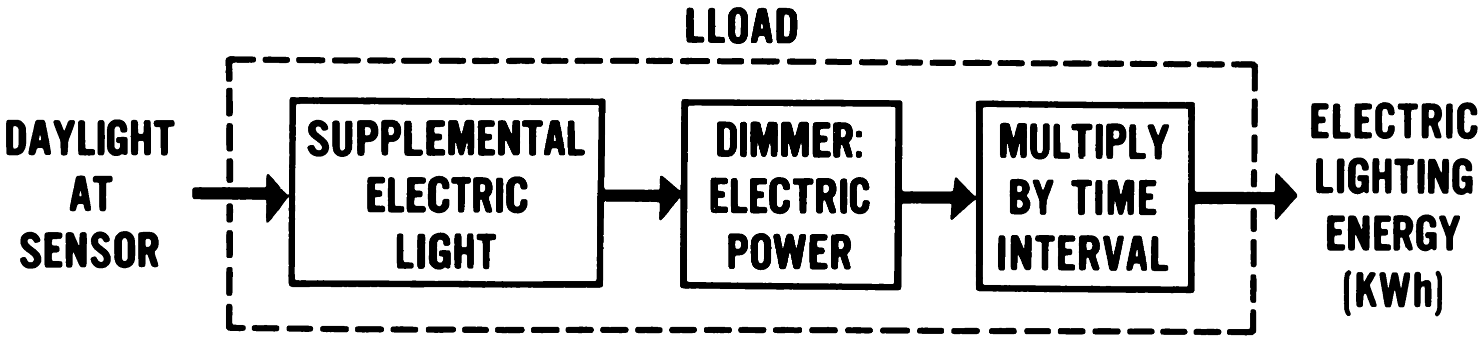


Figure 4. Block diagram for predicting electric lighting load

```
Q$Q$Q$*GARY(1).BCFS(8)
      FUNCTION BCFS(W,L,DP,A)
C
C     BCFS =BASIC CONFIGURATION FACTOR BETWEEN A HORIZONTAL SKYLIGHT AND
C           A HORIZONTAL WORKPLANE
C
C     W    =WIDTH OF SKYLIGHT
C     L    =LENGTH OF SKYLIGHT
C     A     =SHIFTED DISTANCE OF POINT ALONG REFERENCE EDGE
C           (NOTE: LENGTHS ARE HORIZONTAL DISTANCES IN THE DIRECTION OF
C            THE ROOM'S LENGTH(RML). THE WIDTHS ARE IN THE DIRECTION OF THE
C            ROOM'S WIDTH(RMW) )
C     DP   =DISTANCE FROM WORK PLANE TO BOTTOM OF SKYLIGHT
C
      REAL L
      PI=3.14159265
      B =SQRT(DP*DP+L*L)
      C =SQRT(DP*DP+A*A)
      D =SQRT(DP*DP+(A-L)**2)
      E =SQRT(DP*DP+W*W)
C     IF(A.GT.0.)BCFS=(A/C*ATAN(W/C)+W/E*ATAN(L*E/
C    *SQRT(A*A+DP*DP+W*W-A*L))+(L-A)/D*ATAN(W/D))/2./PI
      BCFS=(L/B*ATAN(W/B)+W/E*ATAN(L/E))/2./PI
      RETURN
      END
```

```
QSQSQS*GARY(1).BCFW(6)
      FUNCTION BCFW(W,H,D)
C
C     BCFW=BASIC CONFIGURATION FACTOR FOR A WINDOW
C     (HIGBIE'S EQUATION FOR HORIZ. ILLUMINATION FROM VERTICAL WINDOW)
C
      PI=3.14159265
      A=SQRT(D*D+H*H)
      BCFW=(ATAN(W/D)-D/A*ATAN(W/A))/2./PI
      RETURN
      END
```

```
Q$Q$Q$*GARY(1).LLOAD(8)
      FUNCTION LLOAD(DAYLTE,DILL,DIM,LOAD,XI,CHI)
C
C     LLOAD =LIGHTING LOAD(HOURLY KW)
C
C     DAYLTE=DAYLIGHT ILLUMINANCE AT SENSOR
C     DILL  =DESIGN ILLUMINANCE(FOOTCANDLES) REQUIRED AT SENSOR LOCATION
C     DIM   =DIMMING STRATEGY,EITHER 1(ON/OFF),2(STEP DOWN),3(CONTINOUS),
C            OR 4(CONTINUOUS W/ OFF)
C     LOAD  =POWER LOAD(BEFORE DIMMING) ASSOCIATED WITH SENSOR LOCATION
C     XI    =LINEAR DIMMING COEFFICIENT
C     CHI   =CONSTANT DIMMING COEFFICIENT
C
      REAL LOAD,LLOAD
      PSL=(DILL-DAYLTE)/DILL   @DETERMINES PERCENT SUPPLEMENTAL LIGHT NEEDED
      IF(PSL.GT.0.00) GO TO 1
      IF(DIM.EQ.3)LLOAD=CHI*LOAD
      LLOAD=0.0
      GO TO 4
C
C     ON/OFF SWITCHING
C
    1 IF(DIM.GT.1.0) GO TO 2
      LLOAD=LOAD
      GO TO 4
C
C     TWO LEVEL STEP-DOWN SWITCHING
C
    2 IF(DIM.GT.2.0) GO TO 3
      IF(PSL.GT.0.5) LLOAD=LOAD
      IF(PSL.LE.0.5)LLOAD=LOAD*0.5
      GO TO 4
C
C     CONTINUOUS DIMMING
C     (FLUORESCENT DIMMING IS DEFAULT)
C
    3 LLOAD=(CHI+XI*PSL)*LOAD
    4 RETURN
      END
 END PRT

@SEND IBM001
```

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A computer model is outlined for estimating the annual energy performance of a daylighted building. The daylighting model is a system of FORTRAN subroutines designed for inclusion into larger building energy simulation programs such as DOE-2, BLAST, and NBSLD. Once incorporated into the main energy program, these subroutines will allow the existing program to account for the energy tradeoffs associated with natural illumination.

The daylighting model, DALITE, comprises three separate routines to do three separate functions. The first routine generates hourly sky luminances and sky illuminances as well as direct sun illuminance, taking solar radiation and sun position data as input. The second predicts interior daylight illumination at various points within a room due to any number of windows, skylights or clerestories. The last routine adjusts the electric lighting load (via photoelectric controls) in response to the available daylight. Unlike other daylighting estimation techniques, this model is a dynamic model designed to study how conditions change with time. It has a further advantage in that it can be easily installed into most existing models written in FORTRAN 77.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

building computer simulation; building energy performance; clerestory performance; daylighting; skylight performance, window performance.

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