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Paul J Littlefair

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Paul J Littlefair MA, PhD, MCIBSE, CEng
Building Research Establishment

PREDICTING HOURLY INTERNAL DAYLIGHT ILLUMINANCES FOR DYNAMIC BUILDING ENERGY MODELLING

by Paul J Littlefair

SUMMARY

Large computer programs which simulate the environmental performance of buildings are used in building research and increasingly in building design.

Daylighting has been shown to be an important element in design and particularly in passive solar design, and attempts have been made (ref 1) to include lighting and daylighting in such computer programs. The required calculations can be broken down into various stages. Basic hourly weather data are used to find external illuminances from which internal daylight illuminances are then derived. These are used to predict lighting use in the space and the consequent casual heat gains from luminaires.

This paper concentrates on the prediction of hourly internal illuminances, for which a number of algorithms exist. These algorithms are assessed, for the first time, using measured hourly average illuminances inside model rooms. A previous paper (ref 1) suggested a simple and versatile calculation method using the daylight factor coupled with vertical external illuminance. This method is shown to give good results for yearly lighting use, but is less good at following the detailed changes in illuminance as sky conditions and sun position alter. Other methods treat the sky as a linear combination of clear and overcast luminance distributions. These give good results in general, both for yearly lighting use and for predicting dynamic variations in daylight levels, provided horizontal or vertical illuminance or irradiance data are available. They are better at predicting the dynamic variations in daylight, although they are more computationally complex. Intermediate sky methods give comparable results but are even more difficult to use. None of the methods examined gave wholly satisfactory results, and further improvement and development using measured sky luminance data is desirable.

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1. INTRODUCTION

1.1 Background

The dynamic simulation of the environmental and energy performance of buildings is now an accepted technique in research, and is increasingly used in building design. Complex computer programs are available which can model, on an hourly basis, energy flows within buildings and the resulting environmental effects. Unfortunately these computer programs have in the past concentrated on heat flows, to the virtual exclusion of other types of energy usage even though these can contribute significantly to casual heat gains within a building, and to direct energy costs.

In many buildings the most important of these is lighting. In some types of non-domestic building, such as offices, 30-60% of the energy bill is used by lighting (ref 2). Moreover Crisp et al (ref 3) have identified substantial savings (typically around 20-40% of lighting use) that can be made by exploiting daylight in such buildings. Crisp et al further suggest that in passive solar design such positive use of daylighting can (in non-domestic buildings) be as important as the exploitation of solar heat gain. To a limited extent, building designers have begun to realise this, and some recent passive solar buildings have included lighting controls, and daylight related components such as light shelves or sunscoops (ref 4), and atria. Consequently there is now considerable interest in incorporating daylighting algorithms into energy modelling programs of the sort described above.

In doing so, it is important to realise that electric lighting contributes to the energy equation in two ways:-

(a) as an energy consumer in its own right;
(b) as a casual gain affecting the heat balance of the building.

Recent work at BRE (refs 5-7) has concentrated on aspect (a), obtaining a figure for lighting use over a whole year. The BRE Average Sky method (ref 6), for example, can give an excellent approximation to yearly lighting use under automatic control. However to properly model the effects of lighting as a casual gain, the dynamic simulation of variations in lighting use on an hourly basis is required. Casual gains are only useful at certain times of day and year. During the summer a combination of solar gain and casual gain can tip the balance towards overheating unless lights can be switched off in response to daylight. A good dynamic simulation should be able to analyse this sort of situation.

It follows, then, that for most basic energy applications the key quantity is the total lighting use over a year. But where the time distribution of casual gains becomes an issue, especially in summertime overheating studies, then adequate dynamic simulation of daylight and lighting use becomes important as well.

1.2 Introduction to the problem

The problem then becomes one of producing a load profile of the heat gain from electric lighting as daylight conditions change and lighting is switched on or off. This load profile has to be found from a limited range of available data; basic weather data from a meteorological tape, building geometry and reflectance data, and an occupancy profile.

The solution to this problem can be viewed as a five stage process:

(i) Obtain basic continuous meteorological data from a weather tape
(ii) Use these to calculate a sequence of external illuminance values
(iii) From these external illuminances, calculate internal daylight illuminance values
(iv) With these internal illuminances, plus a knowledge of occupancy and type of lighting control, calculate the resultant profile of electric lighting use
(v) Calculate the heat gain to the space resulting from this lighting use

The first two stages, namely the calculation of external illuminance values from basic weather data, are fairly well established. A weather tape will usually contain (refs 8, 9) measured or calculated values of direct and horizontal diffuse solar radiation. These can be converted into external illuminances by multiplying by an appropriate luminous efficacy. Full details are given in references 10 and 11.

In most computer programs the vertical irradiance in the plane of the window will be evaluated as part of the solar gain calculation procedure. Using luminous efficacy values this can be readily converted to a vertical illuminance which, since it is proportional to the amount of daylight entering the window, is an ideal starting point for interior daylighting calculations.

The remaining three stages of the calculation are more complex and less thoroughly researched. The interaction of internal daylight availability and electric lighting use is a key problem. As Baxter (ref 12) has shown, the choice of lighting control can have a considerable impact on building primary energy consumption and its variation with, for example, window area. One difficulty here is that most simulation programs work on an hourly time step whereas changes in daylight levels, and hence light switching patterns, often occur on a shorter timescale. Haves and Littlefair (ref 1) describe some work on these issues, including a treatment of manual switching based on Hunt's (refs 13, 14) behavioural model.

This paper is concerned however with stage three, the prediction of internal daylight illuminances from external values. Previous work on computer programs for calculating internal illuminances due to daylight (refs 15-17) has usually concentrated on the modelling of interreflected light. However this is only one aspect of the problem. What are perhaps more serious difficulties arise because daylight levels inside a room are not in general proportional to external illuminances (ref 18), but depend on the exact sky luminance distribution at the time. This is because a point in a room will receive direct light only from certain areas of the sky, and, while clear and overcast skies have been fairly well characterised, little is known about the luminance distributions of partly cloudy skies.

1.3 Purpose of this paper

The prediction of internal daylight illuminances is therefore a key stage in the integration of lighting into dynamic energy modelling programs. These internal illuminances will depend on the sky luminance distribution which will also need to be modelled on an hourly basis. A few attempts have been made to solve this problem (refs 1, 19, 20); however none of these has yet been rigorously tested against measured data under real skies.

The purpose of this paper is to provide such an assessment, using data from the continuous monitoring of daylight illuminances inside model rooms at Garston (ref 5). Hourly internal illuminances are calculated using a range of sky modelling assumptions, and these are compared with measured values from the model rooms.

2. METHOD

2.1 The experiment

The daylight measuring apparatus is illustrated in Figure 1. Essentially it consisted of five external photocells measuring the unobstructed illuminance on a horizontal plane and four vertical planes, and six horizontal photocells inside each of four model rooms. The rooms and vertical planes faced north, east, and west; each vertical photocell was screened from ground reflected light by a horizontal black honeycomb sheet.

Figure 2 illustrates a model room, which was painted black inside so that only the direct sky component of illuminance was recorded (externally reflected light was negligible). Because of this, the theoretical internal illuminances due to various types of sky luminance model can be calculated very accurately. Table 1 gives the CIE overcast sky daylight factor and uniform sky daylight factor at each point of measurement, including allowance for window glass transmission (ref 21). In this study, only readings from photocells 1, 3 and 5 in each room were used in the analysis.

TABLE 1 DAYLIGHT FACTORS IN THE MODEL ROOMS

PHOTOCELL NUMBER (SEE FIGURE 2)	OVERCAST SKY DAYLIGHT FACTOR (%)	UNIFORM SKY DAYLIGHT FACTOR (%)
1, 2	0.78	1.28
3	0.98	1.59
4	1.97	2.97
5	4.57	6.31
6	12.63	15.03

Figure 3 illustrates an additional photocell which was used to obtain the horizontal external diffuse illuminance. It was fitted with a manually aligned shade ring (ref 22) which blocked direct sunlight throughout the day. From the readings of this photocell and the other external photocells, values of horizontal diffuse, horizontal direct solar and vertical diffuse illuminances were derived, using the method outlined in reference 5.

The apparatus was situated on the roof of the Physics building at the Building Research Station near Watford (51.7°N, 0.4°W), in a position relatively free from external obstruction. The photocells were all connected to an amplifier and datalogger which enabled automatic recording of illuminance levels throughout the day. The total estimated experimental error for each photocell reading was 8%.

During normal working hours (8.30-17.30) each illuminance was recorded every minute. Readings began in February 1981 and continued for three years; the first time this range of illuminances had been measured over a long period. The data used in this paper were obtained during the period January 1983 - December 1983 inclusive. In all about 100,000 readings were made from each photocell during this period. Considerable effort was made to obtain a continuous record of illuminance, but occasionally readings had to be stopped or reduced in frequency for various reasons. For the purposes of this study, such minor gaps in the database did not matter since the aim was to obtain a specific set of data to compare the various predicted values with measured ones.

2.2 Statistical comparison of measured and predicted illuminances

The first stage in the statistical analysis was to take hourly averages of the measured illuminances. This was carried out for measurements made between 0900 and 1700 GMT. For simplicity, no allowance was made for BST in the calculations, since the aim was only to have a consistent database as mentioned above.

Readings were omitted from these averages if the photocell itself was faulty at the time, or if the external horizontal diffuse or global photocells were faulty, which made it impossible to calculate external diffuse illuminances.

The corresponding predicted illuminances were calculated for each hour and for each of the twelve photocell positions, using the various methods described in the next part of the paper. Then for each photocell and each month of the year, predicted and measured illuminances were statistically compared in three ways:

(i) a mean bias error, given by

$$100\% \qquad \frac{\text{Predicted - Measured}}{\text{Measured}} \qquad N$$

where N is the number of readings in the month. This can reveal whether the prediction method is systematically under- or over-estimating the measured internal illuminances.

(ii) a standard deviation, given by

$$100\% \qquad \frac{\text{Predicted - Measured}}{\text{Measured}}^{2} \; N$$

A high standard deviation indicates general inaccuracy in predicting the measured values. Both (i) and (ii) were calculated for each hour (between 0900 and 1700 GMT) as well as for an 0900 - 1700 working month. This allowed diurnal variations in the accuracy of the methods to be revealed. Values of (i) and (ii) were also calculated for sunny and cloudy conditions. An hour was defined as 'sunny' if the sunshine probability σ (calculated from illuminances as shown in the Appendix) was greater than 0.75, and as 'cloudy' if σ was less than 0.25.

(iii) A 'lighting use' for the month, calculated as the fraction of the 0900 - 1700 period a given illuminance (300, 500, 700 or 1000 lux) was exceeded. This effectively assumed photoelectric switching on an hourly basis. The aim here was not to provide a simulation of any real form of light switching, but to assess the probable impact of errors in sky luminance modelling on the prediction of lighting energy use inside the building.

By combining the monthly values of (i) and (ii), yearly values for each hour of the day and an 0900 - 1700 working year were calculated for each photocell position. Lighting use was also calculated for each photocell position for the full working year. Finally mean values of (i), (ii), (iii) for all photocells, both monthly and yearly, were calculated. The yearly values of these overall means are given in Tables 2-5.

In each case measurements of less than 10 lux or when the average solar altitude for the hour was less than 2°, were omitted from the illuminance comparisons. This was because of the large measurement errors (in percentage terms) at these low light levels. However these values were included in the lighting use calculations.

In interpreting the results of the statistical analysis it is important to remember the two main purposes of lighting simulation in a dynamic energy modelling program as outlined at the end of section 1.1. The first is to calculate lighting energy consumption over the whole year, and for this purpose a low yearly mean bias error and small error in lighting use is enough. The second aim, to provide a good dynamic simulation of casual gains due to lighting, will require in addition a low standard deviation and it is important that the method should not give large errors under particular weather conditions, or at particular times of day and year.

3. ASSESSMENT OF SKY MODELLING ALGORITHMS

3.1 Introduction

This part of the paper describes the sky modelling algorithms and how well they were able to predict the measured illuminances inside the model rooms. The detailed formulae which make up the algorithms are given in the Appendix. For ease of reference, the equations for each algorithm can be found in the part of the Appendix with the same decimal heading as the section of the main text which describes the algorithm.

The algorithms fall into two main categories. Firstly there are those which use the daylight factor, in conjunction with either horizontal or vertical external illuminances. These have the advantage of being easily interfaced with existing daylight calculation methods. The daylight factor can be calculated using any one of a number of methods, or even measured inside a scale model building, and then input into the computer program.

The second group of algorithms is more sophisticated, relying on an explicit modelling of the sky luminance distribution as it changes with time. Most of these treat the sky as a linear combination of clear and overcast skies. They are more complex to program and time-consuming to run, but have greater potential for accurately modelling the dynamic variations in internal illuminance.

3.2 Daylight factor methods: horizontal illuminance

3.2.1 Horizontal diffuse illuminance x daylight factor

One of the simplest ways of calculating internal daylight illuminance, and one which has been used for some time (refs 23, 24) is to take the external horizontal diffuse illuminance and multiply it by the CIE overcast sky daylight factor. The first row of Table 2 gives the resulting yearly mean bias errors and standard deviations between measured values and those predicted using this method, plus a comparison of lighting use.

The results confirm the conclusions of previous assessments of this method (refs 5, 6, 25, 26). Because the CIE overcast sky has a relatively dark horizon, it tends to underestimate internal illuminances in side lit rooms, by 24% on average throughout the year. This effect is worst for the points at the back of the rooms, which receive their light from near the horizon. Moreover the CIE overcast sky cannot model the effects of orientation. Thus in the south facing room the method underestimates measured illuminances even more, by 40% on average. Under sunny conditions this problem is even worse.

3.2.2 Orientation factor method

For the calculation of yearly lighting use, Hunt (refs 13, 14) suggested improving the above method by multiplying the daylight factor by a single factor which depends on the orientation of the window. Moreover, since Hunt did not have access to a full set of illuminance data, he calculated diffuse illuminances by multiplying the external global illuminances by 0.6, the yearly average ratio of diffuse to global.

Table 2 shows that this revised method usually tends to underestimate measured illuminances, by around 40% on average. In practice this can easily be corrected for by omitting the factor 0.6 from Hunt's original equation, and then comparing this new equation with the measured illuminances.

The results are given in the bottom row of Table 2. As expected, the mean bias error for the whole year is now close to zero. But the analysis reveals significant inconsistencies in prediction which are responsible for the large standard deviations in Table 2. Under sunny conditions the method tends to overestimate internal illuminances in summer, and when the sun is not on the room facade. For sunny conditions in winter, however, it can considerably underestimate internal illuminances in rooms facing the sun. When the sky is cloudy slight underestimation also occurs, especially in the north facing room.

Thus, although it can give a good approximation to yearly lighting use (its original purpose), this method is not recommended for simulation of the dynamic variations in hourly daylight illuminances, in order to model the performance of photoelectrically controlled lighting installations. However it is of special interest because Hunt used it in setting up the BRE model of manual switching (refs 13, 14). Section 4 of the appendix describes the implications of the present study for simulating manual switching inside dynamic environmental modelling programs.

3.3 Daylight factor methods: vertical illuminance

3.3.1 Vertical total

Daylight factor methods using horizontal illuminance fail to model satisfactorily the time dependence of the relative orientation of sun and windows. Haves and Littlefair (ref 1) suggested that a method based on vertical external illuminance could overcome this problem. In most environmental modelling programs the irradiance on the external window wall is obtained as part of the solar gain calculation procedure. This can be converted into a vertical illuminance by multiplying by a luminous efficacy.

The ratio of internal horizontal illuminance to external vertical illuminance under an overcast sky can be found by dividing the daylight factor inside the room by the daylight factor on the external vertical

TABLE 2 AGREEMENT BETWEEN PREDICTED AND MEASURED ILLUMINANCES (AVERAGE FOR ALL PHOTOCELL POSITIONS), DURING 1983, HORIZONTAL ILLUMINANCE METHODS

	MEAN BIAS ERROR %			STANDARD DEVIATION %			LIGHTING USE, 500 LUX SWITCHING LEVEL (MEASURED) VALUE 0.63)
	ALL SKIES	SUNNY	CLOUDY	ALL SKIES	SUNNY	CLOUDY	
Horizontal diffuse illuminance x aylight factor	- 24	- 37	- 15	38	53	26	0.76
Orientation factor method (1), including factor of 0.6	- 40	- 22	- 48	51	54	50	0.79
Orientation factor method (2) without factor of 0.6	0	+ 30	- 14	53	87	26	0.64

surface. Haves and Littlefair proposed using this ratio, together with vertical total illuminances, to obtain internal horizontal illuminances.

The assessment of this method is summarised in the top row of Table 3. The method gives a close approximation to yearly lighting use overall. However it does slightly underestimate illuminances (and hence overestimates lighting use) inside the north facing room (by 17% on average) and overestimates illuminances (by 12% on average) inside the south facing room. Nevertheless for most measurement positions the yearly lighting use is predicted accurately.

The method is less good at simulating the dynamic variations in illuminance, however, especially under sunny conditions. For rooms facing the sun it tends to overestimate measured illuminances, except for some pockets of extreme underestimation when direct sunlight actualy reaches the measurement point. For rooms facing away from the sun the method tends to underestimate measured illuminances on sunny days. Under cloudy conditions the method performed much better; and thus it may be most suitable for relatively well daylit rooms, where the lights would be switched off anyway on sunny days and the inaccuracies of the prediction method would not matter.

It should be pointed out that the percentage errors reported are for the calculation of internal illuminances directly from vertical illuminance data. Where vertical data are not available the extra errors arising from their calculation from horizontal irradiances or illuminances need to be taken into account.

However this method should give better results in rooms with non-zero internal reflectances. This is because internally reflected light should be more nearly proportional to the vertical external illuminance on the window wall than the direct sky light which was all that was received inside the model rooms (ref 5).

In conclusion, then, this method is not as accurate as some, especially in predicting the dynamic variation of internal illuminances on sunny days. But under cloudy conditions it performs much better; and it adequately predicts lighting use over the whole year. Moreover because it is based on the daylight factor it is flexible and easy to incorporate into an environmental modelling program.

3.3.2 Vertical diffuse

In proposing the above method for use in environmental modelling programs, Haves and Littlefair (ref 1) also discussed whether the total or diffuse external illuminance should be used to generate internal illuminances. They chose to use the total illuminances, arguing that in real rooms with photoelectric controls the sensor is usually situated on the ceiling, and hence it can receive reflected sunlight if this enters the room. In the model rooms with their black surfaces and with the photocells in the working plane this argument is not necessary valid; the photocells will receive sunlight only at certain times of year.

Thus the analysis is described in the previous section was repeated, but this time the vertical diffuse external illuminance was used, multiplied by the same illuminance ratio as before. The results are given in Table 3.

This method tends to underestimate measured internal illuminances and hence overpredict lighting use. The underestimation is worst for sunny

TABLE 3 AGREEMENT BETWEEN PREDICTED AND MEASURED ILLUMINANCES (AVERAGE FOR ALL PHOTOCELL POSITIONS), DURING 1983, VERTICAL ILLUMINANCE METHODS

	MEAN BIAS ERROR %			STANDARD DEVIATION %			LIGHTING USE, 500 LUX SWITCHING LEVEL (MEASURED VALUE 0.63)
	ALL SKIES	SUNNY	CLOUDY	ALL SKIES	SUNNY	CLOUDY	
Vertical total illuminance x illuminance ratio	- 2	+ 9	- 9	37	61	16	0.62
Vertical diffuse illuminance x illuminance ratio	- 18	- 27	- 12	27	37	19	0.69
Vertical diffuse illuminance x illuminance ratio plus direct sun on point	- 14	- 22	- 8	25	29	22	0.68

conditions especially in winter, at the back of rooms, and in rooms facing the sun. Again there are some occasions of extreme underestimation when the sun could reach the measurement points.

3.3.3 Vertical diffuse plus direct sun

This last effect could be corrected for by adding in a direct solar component to the calculated illuminance on occasions when direct sunlight could reach the photocell positions. This was calculated by taking the external horizontal direct solar illuminance (found by subtracting diffuse from global) and multiplying it by the glass transmission and also by a geometrical factor which is the fraction of the hour that the sun could shine on the measurement point. Section 2 of the Appendix gives full details.

Table 3 shows that the incorporation of direct sunlight only makes a small difference to the average measured illuminances over the whole year, although it does have a large effect on the few occasions when sunlight could reach the measurement points. Overall, the method still tends to underestimate internal illuminances, especially in sunny conditions. However it does correct for some of the larger errors of the vertical total method (section 3.3.1) which occur when sunlight can enter the rooms.

For most purposes, especially those involving lighting use prediction over the year, it appears that the vertical total formula is the best one to use. The 'vertical diffuse plus direct sun' method would however be better at modelling changes in the visual appearance of the interior especially under sunny conditions.

Care should however be taken in modelling rooms where blinds or other shading devices are in operation. Research in Japan (ref 27) suggests that occupant use of venetian blinds is linked to direct sunlight on the facade. In this case it might be best to use the vertical diffuse method instead. At BRE a programme of research into venetian blind use has started, with the ultimate aim of producing an empirical model of occupant behaviour which could be inserted into environmental modelling programs.

3.4 Clear/overcast methods

3.4.1 Clear/overcast according to sunshine probability, no illuminance correction

In this section and the following ones we turn to methods which attempt to simulate changes in sky luminance distribution directly. As indicated in section 3.1, these methods are more complex to program and time-consuming to run, because it is necessary to recalculate the luminance distribution and its effects on internal illuminances for each hour of the year. In a practical computer algorithm it is necessary to adopt some mathematical technique to speed up calculation, such as the 'daylight coefficient' approach suggested by Tregenza (ref 28), or the precalculation of clear sky daylight factors for certain sun positions as proposed by Winkelmann and Selkowitz (ref 20). Because they involve approximations the use of these techniques may result in additional errors in the computation of internal illuminances. In the following analyses no such approximations were used and internal illuminances were always calculated using accurate numerical integration of the sky luminance distribution. This was feasible mainly because of the lack of an internally reflected component within the model rooms.

The first group of methods we shall examine involve treating the sky luminance distribution as a linear combination of clear and overcast skies. Methods of this type can be classified in two main ways:

(i) By the criterion used to determine what proportion of the sky is clear and what proportion overcast. This may be sunshine probability σ for the hour in question; thus when $\sigma = 1$ the sky is assumed clear, when $\sigma = 0$ it is assumed overcast, and when $\sigma = 0.5$ half clear and half overcast. Alternatively some function of cloud ratio can be used (ref 19); or fractional cloud cover, which was the approach used by Winkelmann and Selkowitz (ref 20). Unfortunately cloud cover data were not available for Garston and so this last method could not be analysed.

(ii) Methods also differ according to what form of external illuminance data are used in the calculation. These can be measured horizontal illuminances or vertical illuminances on the window wall. The simplest methods do not use illuminance data at all, relying on standard functions for clear and overcast sky illuminances. Winkelmann and Selkowitz (ref 20) propose a method of this sort for locations where no measured illuminance or irradiance data exist, but cloud cover data are available. A similar method is examined in this section; section 3.4.1 of the Appendix gives the mathematical details.

In this method the illuminances inside the model rooms due to clear and overcast skies are calculated using formulae based on solar position and the standard CIE luminance distributions. The predicted illuminance is then taken to be a linear combination of the clear and overcast illuminances according to sunshine probability. A predicted direct solar illuminance is also added in on occasions when the sun could shine on the measurement point.

The results are given in the top row of Table 4. It can be seen that the method considerably underestimates measured illuminances inside the model rooms, especially under sunny and partly cloudy conditions, and hence overpredicts lighting use. The results show that, as far as illuminance levels are concerned, the partly cloudy sky is not a linear combination of clear and overcast. This is not surprising as it is known (ref 29) that under partly cloudy skies the highest illuminances of all can occur.

3.4.2 Clear/overcast according to sunshine probability, Aydinli correction functions

One suggested solution which has been adopted for average skies is to use a correction function to boost the predicted illuminances. Aydinli (refs 30-32) has derived such functions (see Appendix A 3.4.2) to correct diffuse and direct solar data, based on radiation measurements in Hamburg; and reported good results in predicting month/hour average irradiances. Unfortunately as the second row in Table 4 shows, this approach does not work so well for correcting an hourly time series of illuminances. These illuminances are still underestimated, by 25% on average. The reason for this may be that hourly sunshine probabilities are often either 0 or 1 (when the diffuse correction function is equal to 1) while month/hour average sunshine probabilities are nearer the middle of the range, where the value of the correction function is larger.

Thus as far as current methods are concerned, it appears that in estimating hourly internal illuminances some sort of hourly irradiance or illuminance

TABLE 4 AGREEMENT BETWEEN PREDICTED AND MEASURED ILLUMINANCES (AVERAGE FOR ALL PHOTOCELL POSITIONS), DURING 1983, CLEAR/OVERCAST SKY MODELS

		MEAN BIAS ERROR %			STANDARD DEVIATION %			LIGHTING USE, 500 LUX SWITCHING LEVEL (MEASURED VALUE 0.63)
Weighting factor	Illuminance date used	ALL SKIES	SUNNY	CLOUDY	ALL SKIES	SUNNY	CLOUDY	
Sunshine probability	None	- 33	- 34	- 25	54	44	58	0.76
Sunshine probability	Aydinli correction functions	- 25	- 30	- 21	48	40	56	0.73
Sunshine probability	Horizontal illuminance	0	+ 12	- 8	27	30	26	0.62
Cloud ratio function	Horizontal illuminance	- 10	- 9	- 10	28	28	27	0.67
Nebulosity index	Horizontal illuminance	- 2	0	- 5	27	24	29	0.64
Sunshine probability	Vertical illuminance	- 4	0	- 6	19	14	22	0.63
Nebulosity index	Vertical illuminance	- 5	- 4	- 5	19	13	22	0.64

data are required. Clear/overcast sky methods which do not use these hourly data (such as the first method proposed by Winkelmann and Selkowitz (ref 20)) are liable to underestimate internal illuminances. Further work would be required to produce a working method based on sunshine probability alone or cloud cover alone.

3.4.3 Clear/overcast according to sunshine probability, corrected using horizontal illuminance data

We now turn to methods which do use hourly external illuminance data, either measured or derived from irradiances on a weather tape. The same sky luminance distribution, a combination of clear and overcast skies weighted according to sunshine probability, is used as before. But this time the luminance distribution is weighted by a factor Z so that the external horizontal diffuse illuminance which would occur underneath such a sky is equal to the measured horizontal diffuse illuminance for the hour in question. Section A 3.4.3 of the Appendix shows how Z is calculated.

In effect this is a variant of the daylight factor method. We take the external horizontal diffuse illuminance and multiply it by a type of daylight factor to obtain internal illuminance. However in this method the 'daylight factor' is not calculated for a standard overcast sky, but for a sky which is a linear combination of clear and overcast in its luminance distribution. This type of approach was one of those suggested by Winkelmann and Selkowitz (ref 20) although they used cloud cover instead of sunshine probability to decide on the sky luminance distribution. In the analysis described here cloud cover data were not available and so sunshine probabilities had to be used.

The performance of this method is summarised in the third row of Table 4; the results are very encouraging. Over the whole working year the mean bias error averaged over all the photocell readings was only 0.5%; and at none of the measurement positions was the mean bias error greater than 10%. This meant that the lighting use at all the photocell positions was predicted very well in general.

For this purpose, then, it appears that the luminance distribution of the sky can be treated as a linear combination of clear and overcast, even though the absolute values of external illuminance under all skies should not be predicted in this way.

Nevertheless the method examined in this section is by no means perfect. Under cloudy conditions in summer it tends to underestimate measured illuminances (by 10-15% or so), in rooms which would have faced the sun had it been shining. Moreover under sunny conditions in summer it overestimated daylight levels inside rooms facing away from the sun, by an average of over 40% in July and August. So although this method usually gives good results, there is still some scope for improvement.

3.4.4 Clear/overcast according to Gillette's cloud ratio function, corrected using horizontal illuminance data

So far we have used only sunshine probability to determine whether a particular sky is clear of overcast. However it is not necessarily the best criterion to use, and other methods have been suggested. In this section we examine one put forward by Gillette (ref 19) which is based on cloud ratio, the ratio of diffuse to global irradiance on a horizontal plane. In this analysis we use the ratio of the two illuminances instead because irradiances were not available. To weight each sky as a linear combination of clear and overcast, Gillette used a function of cloud ratio which he called a 'sky phasing function'. This is given in equation A 33 of the Appendix. On an overcast day the cloud ratio (CR) will be 1, and hence the sky phasing function (SPF) will give zero clear sky. In principle the opposite (CR = 0 and SPF = 1) should occur on a clear day, but in practice cloud ratio never reaches 0, which is perhaps a weakness of Gillette's approach.

Illuminances were predicted using this method and compared with the measured values, and the results are given in the fourth row of Table 4. Unfortunately the method tended to underestimate the measured values, especially (by 20-30%) when the sun fell on the room facade, and also in winter. The exception was in summer for rooms facing away from the sun on sunny days. Then the method overestimated the measured values, by 20-25%. Thus overall it gave worse results than the sunshine probability method and is therefore not recommended.

3.4.5 Clear/overcast according to nebulosity index, corrected using horizontal illuminance

More recently Perraudeau (refs 33, 34) has investigated the problem of using cloud ratio to categorise sky type. He suggested a quantity called 'nebulosity index', which is given by $(1-CR)/(1-CR_T)$, where CR is the measured cloud ratio and CR_T is its theoretical value under a clear sky. The nebulosity index has the advantage of being exactly equal to 1 under standard clear sky conditions, and equal to 0 under overcast conditions.

The illuminance prediction method described in the previous two sections was repeated using nebulosity index as the criterion of sky type. The results (in the fifth row of Table 4) indicate good agreement with the measurements. In fact this method gives very similar results to the sunshine probability method in section 3.4.3. Over the whole year it predicts lighting use very well; for every photocell position mean bias errors were low, below 11%. Under sunny conditions it gives slightly better results than the sunshine probability method; for example for rooms facing away from the sun in July and August it overestimates by around 30% rather than 40%. However in summer it underestimates by 10-15% in rooms facing the sun position, for all weather conditions. Also in winter it gave a few very large errors at low solar altitudes.

Overall, then, there seems little to choose between the sunshine probability and nebulosity index methods. The nebulosity index method has the advantage that it can be carried out using hourly global and diffuse irradiance data alone; the other method requires hourly sunshine probabilities as well. Moreover in this analysis both nebulosity index and sunshine probabilities were derived from illuminance data, which could well have resulted in lower differences between measured and predicted internal illuminances. Using irradiances and sunshine probabilities could well decrease the performance of both methods. This would probably be worse for the sunshine probability method because of the inherent inaccuracy of the Campbell-Stokes sunshine recorder used to make the measurements (refs 35, 36).

3.4.6 Clear/overcast corrected using vertical illuminance

The methods just described all use horizontal external illuminance or irradiance data as the basis for predicting internal illuminances. However in some cases vertical external data (illuminances or irradiances) are also available. The analysis of the daylight factor methods (sections 3.2 and 3.3) suggests that using vertical data would improve prediction accuracy. Consequently the two best methods from the previous clear/overcast analyses (the sunshine probability and nebulosity index methods) were repeated using vertical diffuse illuminance on the window wall as the basic calculation data. In fact the methods are very similar to the 'vertical diffuse plus direct sun' method described in section 3.3.3. The vertical diffuse external illuminance is multiplied by an illuminance ratio to obtain internal illuminance as before. But this time instead of being an illuminance ratio for a purely overcast sky, it is a ratio for a sky whose luminance distribution is a linear combination of clear and overcast skies, according to the value of sunshine probability or nebulosity index for the hour in question. Section 3.4.6 of the Appendix gives the mathematical details.

These methods have been assessed in the same way as the others and the results are given in the last two rows of Table 4. Both methods tend to slightly underestimate measured illuminances on the whole; this effect is worst in winter and at the back of the model rooms. Nevertheless this underestimation hardly affects lighting use calculation at all. In fact these two methods were best of all at predicting 'lighting use' inside the model rooms. They were also the best at predicting the dynamic variations in daylight with standard deviations of less than 20% overall. Under sunny conditions the errors were especially low.

Again there was little to choose between sunshine probability and nebulosity index as criteria for determining the luminance distribution of the sky. The sunshine probability method gave slightly lower mean bias errors, although the discussion at the end of the last section has to be borne in mind.

Note that the improved prediction performance of these methods can only be realised if measured vertical illuminance or irradiance data are available. Using calculated vertical data will result in errors similar to, or worse than, those of the methods which use horizontal data.

3.5 Intermediate sky methods

3.5.1 Sky either clear or overcast or partly cloudy

So far we have looked at methods that are based on calculations for the two extremes of sky condition, clear and overcast. Partly cloudy skies between these two extremes have been assumed to be either a linear combination of clear and overcast, or to be approximated by one or the other.

Recently, however, a number of methods have been proposed that attempt to simulate directly the luminance distribution of these intermediate sky conditions. Two of them will be examined here. They differ according to the way the various skies are combined. The first assumes that at any one instant the sky is either clear or intermediate or overcast. The second, due to Nakamura and Oki (refs 37, 39) takes the sky as being a linear combination of the clear, intermediate and overcast luminance distributions.

The first method is based on equations included in the IES (North America) recommended practice for the calculation of daylight availability (ref 40). The CIE standard clear and overcast sky luminance distributions (refs 41-43) are used, together with a partly cloudy sky luminance distribution proposed by Pierpoint (ref 44). The IES recommended practice suggests two ways of deciding which distribution to use at any given time. The first used measured cloud cover data, which were not available for Garston. The second uses cloud ratio, the ratio of diffuse to global irradiance (illuminances were used here since irradiance data were unavailable). If the cloud ratio is less than 0.3 the sky can be assumed clear; if greater than 0.8 the overcast sky distribution is used. Otherwise the sky is assumed to be partly cloudy and Pierpoint's intermediate sky luminance distribution is used. In each case measured horizontal external illuminance data were used together with the appropriate luminance distribution to obtain internal illuminances.

The top row of Table 5 gives the results of using this model to predict the illuminances inside the model rooms. The method is shown to underestimate the measured illuminances, by 15% on average. This effect is worst for sunny conditions, and it appears that the use of cloud ratio to determine sky type may be part of the problem. The sky is only assumed clear if the cloud ratio is less than 0.3; this is quite a low value, especially if, as here, the cloud ratio is a ratio of illuminances. Thus under sunny conditions this method might use a partly cloudy distribution to model skies which are almost, or even entirely, clear. This seems to be what happened in the simulation of the illuminances inside the model rooms.

Consequently this method was repeated using an alternative criterion of sky type based on sunshine probability σ. If σ was greater than 0.75 the sky was assumed clear; for σ less than 0.25 the overcast sky was used; and for σ between 0.25 and 0.75 the partly cloudy sky luminance distribution was employed. As the second row of Table 5 shows, this alternative method did give better results in that it did not continuously underestimate internal illuminances. In fact it would predict yearly lighting use very well. Nevertheless there were a number of problems; under sunny conditions the method would considerably overestimate measured illuminances inside rooms facing away from the sun. Under cloudy and partly cloudy skies it would often underestimate internal illuminances. Overall it performed slightly less well than the corresponding clear/overcast method in section 3.4.3.

A problem with this method appears to be the sudden transitions which are assumed to occur between clear and intermediate, and intermediate and overcast skies. From the results it seems that a single luminance distribution, such as the IES 'partly cloudy', is not really capable of modelling what is in fact a range of sky conditions from almost clear to almost overcast.

3.5.2 Nakamura and Oki intermediate sky method

The next method is more sophisticated in that it treats the sky as a linear combination of clear, intermediate and overcast luminance distributions. It is based on the work of Nakamura and Oki (refs 37, 38) to characterise intermediate and hence average skies. Although their method was not originally intended as a means of obtaining an hourly time series of internal illuminances, its format is such that it can be used for that purpose.

The method analysed here is based on measured horizontal illuminance data together with a sky luminance distribution which is a linear combination of CIE standard clear, CIE standard overcast, and Nakamura and Oki's intermediate sky (ref 45). The proportions of each of the three skies are given by functions of sunshine probability (section A 3.5.2 of the Appendix) proposed by Nakamura and Oki (ref 46).

As the third row of Table 5 indicates, this method gives good results overall. The mean bias errors are relatively low and so lighting use over a whole year would be predicted very well. Some problems occur on cloudy and partly cloudy days when the method tends to underestimate measured illuminances, especially in rooms facing away from the solar position. In

TABLE 5 AGREEMENT BETWEEN PREDICTED AND MEASURED ILLUMINANCES (AVERAGE FOR ALL PHOTOCELL POSITIONS), DURING 1983, INTERMEDIATE SKY MODELS

METHOD	CRITERION FOR SKY TYPE	MEAN BIAS ERROR %			STANDARD DEVIATION %			LIGHTING USE, 500 LUX SWITCHING LEVEL (MEASURED VALUE 0.63)
		ALL SKIES	SUNNY	CLOUDY	ALL SKIES	SUNNY	CLOUDY	
Either clear or intermediate or overcast (IES)	Cloud ratio	- 15	- 22	- 11	29	29	28	0.68
As above	Sunshine probability	- 5	+ 14	- 11	28	31	28	0.63
Nakamura and Oki	Function of sunshine probability	- 5	+ 3	- 4	27	27	27	0.64

summer it can also overestimate measured illuminances on sunny days in rooms facing away from the sun.

In general the performance of this method was very similar to that of the clear/overcast sky methods described in sections 3.4.3 and 3.4.5. Its major disadvantage is that it is more difficult and complex to use. However it does have the potential for further development; it may be that use of a different intermediate sky distribution, or an alternative means of selecting the proportion of each type of sky, could give significantly better results.

4. CONCLUSIONS

This paper has examined various methods for predicting hourly internal daylight illuminances for use in large environmental modelling computer programs. Daylight factor methods are the simplest and most versatile; of these the best appears to be that described by Haves and Littlefair (ref 1), which uses vertical total illuminance on the external window wall as the starting point for calculations. It gives good results for yearly lighting use, but like other daylight factor methods is less good at predicting the dynamic variations in daylight illuminance as sky conditions and sun position alter.

Methods which attempt to explicitly model changes in sky luminance distribution are more complex to program but have greater potential for simulating these dynamic variations. Some form of illuminance or irradiance data (from a weather tape) are required; horizontal (global/direct and diffuse) are suitable, but if measured vertical data are available these give better results. Vertical data would be especially useful for modelling rooms with light surfaces and a high internally reflected component, because this is almost proportional to the vertical illuminance on the window wall. Of the luminance distribution methods most are based on a linear combination of clear and overcast skies. These give acceptable results both in modelling changes in internal illuminance, and in predicting yearly lighting use. Current intermediate sky methods give very similar levels of accuracy, and hence are probably not worth the extra computational complexity involved.

None of the methods tested was by any means perfect, however. Further development of the sky luminance models would require long term monitoring of sky luminance distribution. Fortunately such monitoring, in the UK and elsewhere, is planned as part of International Daylight Measurement Year in 1991 (ref 47). The resulting data should enable new luminance models to be derived which will approach the limits of accuracy for this type of calculation. Moreover the measurements of vertical illuminance at a number of UK sites, planned for 1991, should provide a better starting point for calculations if they can be included in weather data tapes.

However the calculation of internal illuminances is only one stage in the process of predicting artificial lighting use and its environmental effects. Further work is required especially in the area of lighting controls and their interactions with daylight. These interactions often occur on a short timescale, while this paper has only analysed the prediction of hourly illuminances. Work at BRE has also begun in another relatively unexplored area namely the prediction of venetian blind use in buildings. The use of such manually controlled shading devices (refs 48, 49) can have a large effect on daylighting and solar gains inside buildings, but only crude assumptions about occupant use of blinds have been employed so far in environmental modelling programs.

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GLOSSARY

CR	cloud ratio
CR_T	theoretical cloud ratio for clear sky
d	CIE overcast sky daylight factor
E	internal illuminance
E_{cl}	internal clear sky illuminance
E_{clh}	external horizontal diffuse clear sky illuminance
E_{clv}	external vertical diffuse clear sky illuminance
E_d	internal diffuse illuminance
E_{dh}	external horizontal diffuse illuminance
E_{dv}	external vertical diffuse illuminance
E_{esh}	external horizontal direct solar irradiance (W/m^2)
E_{esn}	external direct solar irradiance (W/m^2) on the normal plane
E_{gh}	external horizontal global illuminance
E_{gv}	external vertical total illuminance
E_{oc}	internal overcast sky illuminance
E_{och}	external horizontal overcast sky illuminance
E_{ocv}	external vertical overcast sky illuminance
E_{pc}	internal partly cloudy sky illuminance
E_{pch}	external horizontal partly cloudy sky illuminance
E_s	internal direct solar illuminance
E_{sh}	external horizontal direct solar illuminance
f	fraction of hour sun could shine on point in room
f_h	fraction of hour sun is in correct altitude range to illuminate point in room
f_p	fraction of hour sun is in correct azimuth range to illuminate point in room
L_{cl}	clear sky luminance (cd/m^2)
L_{pc}	partly cloudy sky luminance (cd/m^2)
L_{zcl}	clear sky zenith luminance (cd/m^2)
L_{zpc}	partly cloudy sky zenith luminance (cd/m^2)
N	nebulosity index
P_{cl}	proportion of clear sky in sky luminance distribution
P_{oc}	proportion of overcast sky in sky luminance distribution
r_o	orientation factor
R_H	correction function for diffuse illuminance, due to Aydinli
R_S	correction function for direct solar illuminance, due to Aydinli
t	solar time (hours from noon)
Z_h	correction factor for horizontal diffuse illuminance
Z_v	correction factor for vertical diffuse illuminance
α	azimuth of sky element
α_1	azimuth of left hand edge of window
α_2	azimuth of right hand edge of window
α_n	azimuth of normal to window aperture
α_s	solar azimuth

γ	altitude of sky element
γ_n	altitude of window head, measured normal to window
γ_s	solar altitude
γ_t	altitude of window head, measured obliquely to window
δ_s	solar declination
θ	angle between sun and element of sky
ξ	sky phasing function due to Gillette
σ	sunshine probability (hourly, fractional)
τ	glass transmission factor
ϕ	latitude

NB All illuminances are expressed in lux: angles are in radians unless otherwise stated.

APPENDIX EQUATIONS USED IN THE CALCULATIONS

A1 CALCULATION OF SUNSHINE PROBABILITY

During 1983 no direct measurements of sunshine duration were made at Garston. Sunshine probability for each hour was therefore calculated from the illuminance measurements in the following way.

First the direct solar illuminance E_{sh} on a horizontal plane was calculated:

$$E_{sh} = E_{gh} - E_{dh} \qquad \text{... (A1)}$$

Here E_{gh} is the global horizontal illuminance and E_{dh} the diffuse horizontal illuminance, corrected for the effects of the shade ring as described in reference 5.

From E_{sh} the corresponding direct horizontal irradiance E_{esh} was calculated using the luminous efficacy formula in reference 11:

$$E_{esh} = E_{sh}/(51.8 + 1.646\ \gamma_s - 0.01513\ \gamma_s^2) \qquad \text{... (A2)}$$

where γ_s is the solar altitude in degrees.

Then the direct normal irradiance E_{esn} can be calculated using the formula

$$E_{esn} = E_{esh}/\sin \gamma_s \qquad \text{... (A3)}$$

To avoid large errors at low solar altitudes, if γ_s was less than 2° then E_{esn} was set equal to 0.

Finally the sunshine probability σ was calculated as the fraction of the hour that E_{esn} exceeded 120 W/m^2, the threshold for bright sunshine adopted by the WMO (ref 50).

A2. PREDICTION OF HOURLY AVERAGE DIRECT SOLAR ILLUMINANCES IN ROOMS

For some of the daylight algorithms described in the text, it is necessary to predict the direct sun illuminance at a point indoors. Here we are concerned with direct light only, not reflected light which was not significant in the model rooms.

To calculate the internal direct solar illuminance at a given instant in time is quite easy. We check if the sun can shine on the point in the room in question. If so, then the direct solar illuminance is equal to the corresponding external solar illuminance, multiplied where necessary by an appropriate glass transmission factor. Otherwise the direct solar illuminance on the point is zero.

However to calculate the hourly average of this illuminance is less simple because the sun will not remain stationary for the whole hour. In a number of cases the sun will only be shining on the point for a fraction of the hour, even under clear conditions. This effect can be allowed for in the following way. We assume that during the hour the sun's altitude changes from $\gamma_s - \frac{1}{2}\, d\gamma_s/_{dt}$ to $\gamma_s + \frac{1}{2}\, d\gamma_s/_{dt}$, where γ_s is the altitude at the middle of the hour and $d\gamma_s/_{dt}$ is its rate of change with time (t is measured in hours here). Similarly its azimuth will change from $\alpha_s - \frac{1}{2}\, d\,\alpha_s/_{dt}$ to $\alpha_s + \frac{1}{2}\, d\alpha_s/_{dt}$, where α_s is the azimuth (in radians clockwise from due north) at the middle of the hour, and $d\alpha_s/_{dt}$ is its rate of change.

From references 51, 52

$$\sin \gamma_s = \cos \Phi \cos \delta_s \cos \frac{\pi t}{12} + \sin \Phi \sin \delta_s \qquad \ldots \text{(A4)}$$

where Φ is latitude and δ_s the solar declination. t is the solar time (hours from noon).

All angles are in radians.

$$\therefore \cos \gamma_s \frac{d\gamma_s}{dt} = -\frac{\pi}{12} \cos \Phi \cos \delta_s \sin \frac{\pi t}{12}$$

$$\frac{d\gamma_s}{dt} = -\frac{\pi}{12} \quad \frac{\cos \Phi \cos \delta_s \sin {}^{\pi t}/_{12}}{\cos \gamma_s} \qquad \ldots \text{(A5)}$$

From reference 52

$$\cos \alpha_s = \frac{\sin \delta_s - \sin \gamma_s \sin \Phi}{\cos \gamma_s \cos \Phi} \qquad \ldots \text{(A6)}$$

$$-\sin \alpha_s \frac{d\alpha_s}{dt} = \frac{(-\cos^2 \gamma_s \cos \Phi \sin \Phi) + \cos \Phi \sin \gamma_s (\sin \delta_s - \sin \gamma_s \sin \Phi)}{\cos^2 \gamma_s \cos^2 \Phi} \frac{d\gamma_s}{dt}$$

$$= \frac{-\cos^2 \gamma_s \sin \Phi + \sin \gamma_s \sin \delta_s - \sin^2 \gamma_s \sin \Phi}{\cos \gamma_s \cos \Phi} \frac{d\gamma_s}{dt}$$

$$-\sin \alpha_s \frac{d\alpha_s}{dt} = \frac{\sin \gamma_s \sin \delta_s - \sin \Phi}{\cos^2 \gamma_s \cos \Phi} \times -\frac{\pi}{12} \frac{\cos \Phi \cos \delta_s \sin {}^{\pi t}/_{12}}{\cos \gamma_s}$$

$$= \frac{-\pi}{12} \frac{(\sin \gamma_s \sin \delta_s - \sin \Phi) \cos \delta_s \sin \pi t/_{12}}{\cos^3 \gamma_s}$$

From reference 51

$$\sin \alpha_s = \pm \frac{\cos \delta_s \sin {}^{\pi t}/_{12}}{\cos \gamma_s} \qquad \ldots \text{(A7)}$$

$$\therefore \frac{d\alpha_s}{dt} = \frac{\pi}{12} \frac{\sin\gamma_s \sin \delta_s - \sin\phi}{\cos^2\gamma_s}$$

Since α_s is always increasing throughout the day, we can write

$$\frac{d\alpha_s}{dt} = \left| \frac{\pi}{12} \frac{\sin\gamma_s \sin \sigma_s - \sin\phi}{\cos^2\gamma_s} \right| \qquad \ldots .$$

Equations A5 and A7 can be combined to give the simpler expression

$$\frac{d\gamma_s}{dt} = \mp \frac{\pi}{12} \cos\phi \sin \alpha_s \qquad \ldots \text{(A9)}$$

During the daytime, if $\alpha_s < \Pi$, γ_s will be increasing and sin α_s is positive. If $\alpha_s > \Pi$ (sin α_s negative) γ_s will be decreasing. Thus

$$\frac{d\gamma_s}{dt} = \frac{\Pi}{12} \cos \Phi \sin \alpha_s \qquad \ldots \text{(A9)}$$

These equations can be used together with a knowledge of window geometry to calculate f, the fraction of a given hour that the sun is visible through a window. In this note we take the simple example of a large rectangular window with its base in the working plane.

First of all we calculate the fraction of the hour f_h that the sun is below the window head. Figure A1 illustrates an example. It shows a view from the reference point P. The horizontal line is the window head, whose altitude γ_t (seen from P) is given by

$$\tan \gamma_t = \tan\gamma_n \cos (\alpha_n - \alpha_s)$$

Here γ_n is the altitude of the window head measured in the vertical plane through P and perpendicular to the window, and α_n is the azimuth angle of this plane. The sloping line in Figure A1 is the solar orbit during the hour. In the case shown, the solar orbit starts above the window head, then the sun becomes visible later in the hour.

There are in fact three separate cases to be considered:

(i) $\gamma_t \geq \gamma_s + \left| \frac{1}{2}\, d\gamma_s/dt \right|$

In this case the whole of the sun's path is visible throughout the hour, and $f_h = 1$.

(ii) $\gamma_t \leq \gamma_s - \left|\tfrac{1}{2}\, d\gamma_s/dt\right|$

Here none of the solar orbit is visible, and $f_h = 0$.

(iii) $\gamma_s - \left|\tfrac{1}{2}\, d\gamma_s/dt\right| \leq \gamma_t \leq \gamma_s + \left|\tfrac{1}{2}\, d\gamma_s/dt\right|$

This is the intermediate case shown in Figure A1. The sun will be visible for a fraction of hour

$$f_h = \frac{\gamma_t - \left(\gamma_s - \left|\tfrac{1}{2}\, d\gamma_s/dt\right|\right)}{\left|d\gamma_s/dt\right|} \qquad \ldots \text{(A10)}$$

So far we have considered only variations in altitude. Using similar principles it is possible to calculate the fraction of the hour f_p for which the sun lies between the two azimuths α_1 and α_2 ($\alpha_2 > \alpha_1$). Here there are five possible cases:

(i) $\alpha_s + \tfrac{1}{2}\, d\alpha_s/dt \leq \alpha_1$

The sun is invisible throughout and $f_p = 0$.

(ii) $\alpha_1 - \tfrac{1}{2} \frac{d\alpha_s}{dt} \leq \alpha_s \leq \alpha_1 + \tfrac{1}{2} \frac{d\alpha_s}{dt}$

Here the solar orbit for the hour intersects the left hand side of the window. The sun is visible for a fraction of hour

$$f_p = \frac{\alpha_s - (\alpha_1 - \tfrac{1}{2}\, d\alpha_s/dt)}{d\alpha_s/dt} \qquad \ldots \text{(A11)}$$

(iii) $\alpha_1 + \tfrac{1}{2} \frac{d\alpha_s}{dt} \leq \alpha_s \leq \alpha_2 - \tfrac{1}{2} \frac{d\alpha_s}{dt}$

The solar orbit is visible throughout the hour and $f_p = 1$.

(iv) $\alpha_2 - \tfrac{1}{2} \frac{d\alpha_s}{dt} \leq \alpha_s \leq \alpha_2 + \tfrac{1}{2} \frac{d\alpha_s}{dt}$

The solar orbit intersects the right hand side of the window. The sun is visible for a fraction of hour

$$f_p = \frac{\alpha_2 + \tfrac{1}{2} \frac{d\alpha_s}{dt} - \alpha_s}{\frac{d\alpha_s}{dt}} \qquad \ldots \text{(A12)}$$

(v) $\alpha_2 + \tfrac{1}{2} \frac{d\alpha_s}{dt} \leq \alpha_s$

The sun is invisible throughout and $f_p = 0$.

Having obtained f_p and f_h, we now combine them to obtain f, the fraction of hour the sun's orbit is visible through the window. Clearly if either of f_p or f_h is zero then the sun will be blocked for the whole hour, and f will also be zero. If $f_p = 1$ then the sun is not occluded by the sides of the window at all and f will equal f_h. Similarly if $f_h = 1$ then f will equal f_p Figure A2 illustrates these cases; each of the sloping arrows represents a possible solar orbit segment for the hour in question. The general rule is that f equals the minimum of f_h and f_p.

Problems occur when both f_p and f_h lie between 0 and 1. The four distinct cases when this can happen are all illustrated in Figure A3. In cases A and B both window head and side obscure the sun for the same part of the hour.

Thus, as before, f will equal the minimum of f_h and f_p. The only exception to this general rule occurs in cases C and D illustrated, either at the left hand side of the window in the morning, or the right hand side of the window in the afternoon. In these cases the side and head of the window obscure the sun in different parts of the hour. f is equal to $f_h + f_p - 1$, or zero, whichever is the greater.

Having found f we can then obtain the internal direct solar illuminance E_s (not including internal or external reflections) using the formula:

$$E_s = f \times E_{sh} \times \tau \qquad \ldots \text{(A13)}$$

where τ is the glass transmission and E_{sh} is the external direct solar illuminance on a horizontal plane. Note the implicit assumption that the sun is shining steadily throughout the hour; in fact this assumption can be a source of error in practice. If the weather data is in hourly form no other assumption is practical, since only hourly average direct illuminance is normally recorded.

A3 SKY MODELLING ALGORITHMS - FORMULAE

A 3.1 INTRODUCTION

This part of the Appendix contains the equations used in the sky modelling algorithms described in the main text.

A 3.2 Daylight factor methods: horizontal illuminance

A 3.2.1 Horizontal diffuse illuminance x daylight factor

$$E = E_{dh} \times d \qquad \ldots \text{(A14)}$$

Throughout the Appendix E is the final predicted internal illuminance. E_{dh} is the external horizontal diffuse illuminance (corrected for light blocked by the shade ring (ref 5)) and d is the CIE overcast sky daylight factor, expressed as a fraction. Values of d were calculated using Seshadri's formula (refs 53, 54) multiplied by a glass transmission coefficient (ref 21). They are given in Table 1 of the main text.

A 3.2.2 Orientation factor method

Hunt's equation is the first one analysed:

$$E = E_{gh} \times 0.6 \times d \times r_o \qquad \ldots \text{(A15)}$$

Here E_{gh} is the external horizontal global illuminance. r_o is the orientation factor from reference 13; 0.77 for north, 1.04 for east, 1.20 for south and 1.00 for west facing rooms. The factor 0.6 represents the average yearly ratio of diffuse to global illuminance. This factor is omitted from the second equation to be analysed:

$$E = E_{gh} \times d \times r_o \qquad \ldots \text{(A16)}$$

A 3.3 Daylight factor methods: vertical illuminance

A 3.3.1 Vertical total

The equation used is a simplification of that proposed by Littlefair and Haves (ref 1):

$$E = E_{gv} \times d \;/\; 0.396 \qquad \ldots \text{(A17)}$$

where E_{gv} is the measured vertical total illuminance on the external window wall (which excluded ground reflected light). The factor 0.396 is the CIE overcast sky daylight factor on the vertical window wall.

A 3.3.2 Vertical diffuse

Equation A17 is used, but E_{gv} is replaced by E_{dv}, the measured vertical diffuse illuminance on the external window wall. Thus

$$E = E_{dv} \times d \;/\; 0.396 \qquad \ldots \text{(A18)}$$

A 3.3.3 Vertical diffuse plus direct sun

Where direct sun cannot reach the measurement point equation A18 is used, but where it can the modified equation

$$E = E_{dv} \times d \;/\; 0.396 + E_s \qquad \ldots \text{(A19)}$$

is applied. E_s is the direct solar illuminance (equation A13) on the measurement point. Its calculation is explained in section A2.

A 3.4 Clear/overcast methods

A 3.4.1 Clear/overcast according to sunshine probability, no illuminance correction

The basic equation used is

$$E = \sigma E_{cl} + (1 - \sigma) E_{oc} + \sigma E_s \qquad \ldots \text{(A20)}$$

where σ is the sunshine probability calculated according to section A1.

E_{cl} is the clear sky internal illuminance calculated using the formula

$$E_{cl} = L_{zcl} \int_{\alpha_1}^{\alpha_2} \int_{o}^{\gamma_t} \tau \quad \frac{L_{cl}}{L_{zcl}} (\gamma, \alpha) \cos \gamma \sin \gamma \, d\gamma \, d\alpha \qquad \text{... (A21)}$$

In this equation α_2 and α_1 are the azimuths subtended by the sides of the window at the measurement point P. γ_t is given by

$$\tan \gamma_t = \tan \gamma_n \cos \alpha$$

where γ_n is the altitude subtended by the window head at P. τ is the glass transmission as given in ref 21. The clear sky relative luminance distribution at altitude γ and azimuth α $L_{cl} (\gamma, \alpha) / L_{zcl}$ is the standard CIE distribution originally developed by Kittler (ref 41). L_{zcl}, the clear sky zenith luminance is given by Kittler's formula (ref 43).

$$L_{zcl} = 300 + 3000 \tan \gamma_s \quad cd/m^2 \qquad \text{... (A22)}$$

where γ_s is the solar altitude.

E_{oc}, the overcast sky internal illuminance, is calculated from

$$E_{oc} = E_{och} \times d \qquad \text{... (A23)}$$

where E_{och}, the overcast sky horizontal illuminance is given by (ref 43)

$$E_{och} = 300 + 21000 \sin \gamma_s \qquad \text{... (A24)}$$

d the daylight factor is calculated as outlined in section A 3.2.1.

Finally E_s, the direct solar illuminance, is calculated from equation A13 (section A1):

$$E_s = f \times E_{sh} \times \tau$$

Here E_{sh}, the external horizontal solar illuminance, is not derived from measured data but is found using Kittler's formula (ref 43)

$$E_{sh} = \frac{125{,}000 \sin \gamma}{1 + 0.45 \operatorname{cosec} \gamma} \quad \text{lux} \qquad \text{... (A25)}$$

This equation was chosen because it avoids the use of Linke turbidity factor which is often contained within formulae for solar irradiance and illuminance (refs 20, 30). In a situation where measured irradiance data are unavailable, Linke turbidity factors will not be available either.

A 3.4.2 Clear/overcast according to sunshine probability, Aydinli correction functions

The basic equation examined in this section is

$$E = R_H \left(\sigma E_{cl} + (1-\sigma) E_{oc}\right) + R_s \sigma E_s \qquad \text{... (A26)}$$

which is the same as equation A20 but with the Aydinli correction functions R_H and R_S. These are given by (refs 30-32)

$$R_H = 1 + 2.54\,\sigma - 2.98\,\sigma^2 + 0.444\,\sigma^3 \qquad \ldots \text{(A27)}$$
$$R_S = 1.48 - 4.066\,\sigma + 6.92\,\sigma^2 - 3.34\,\sigma^3 \qquad \ldots \text{(A28)}$$

A 3.4.3 Clear/overcast according to sunshine probability, corrected using horizontal illuminance data

Again a modification of equation A20 is used:

$$E = Z_h \left(\sigma\, E_{cl} + (1-\sigma)\, E_{oc}\right) + E_s \qquad \ldots \text{(A29)}$$

In this equation E_{cl} and E_{oc} are calculated as before (equations A21 and A23). E_s is found using equation A13 but this time E_{sh} is derived from the measured horizontal external illuminance data, according to equation A1.

Z_h is a correction factor based on the measured external horizontal diffuse illuminance E_{dh}:

$$Z_h = \frac{E_{dh}}{\sigma\, E_{clh} + (1-\sigma)\, E_{och}} \qquad \ldots \text{(A30)}$$

For this equation E_{och}, the standard overcast sky horizontal diffuse illuminance was given by equation A24. E_{clh}, the standard clear sky diffuse illuminance was calculated using the equation (refs 30, 31)

$$E_{clh} = L_{zcl}\,(6.9731 + 4.2496.10^{-2}\,\gamma_s - 8.5375.10^{-4}\,\gamma_s^{2}$$
$$- 8.6088.10^{-5}\gamma_s^{3} + 1.9848.10^{-6}\,\gamma_s^{4} - 1.6222.10^{-8}\,\gamma_s^{5}$$
$$+ 4.7823.10^{-11}\gamma_s^{6}) \qquad \ldots \text{(A31)}$$

where γ_s is the solar altitude in degrees, and L_{zcl}, the clear sky zenith luminance, is given in equation A22.

A 3.4.4 Clear/overcast according to Gillette's cloud ratio function, corrected using horizontal illuminance data

Equation A29 is modified to give

$$E = Z_h \left(\xi\, E_{cl} + (1-\xi)\, E_{oc}\right) + E_s \qquad \ldots \text{(A32)}$$

where sunshine probability σ is replaced by Gillette's function (ref 19) of cloud ratio CR:

$$\xi = \frac{1 + \cos\,(\pi\, CR)}{2} \qquad \ldots \text{(A33)}$$

CR is given by the ratio of horizontal diffuse to global illuminance:

$$CR = E_{dh} / E_{gh} \qquad \ldots \text{(A34)}$$

Note that CR is here given as an illuminance ratio, whereas it would normally be an irradiance ratio. Unfortunately measured irradiance data were not available.

In equation A32, correction factor Z_h now becomes (compare equation A30)

In equation A32, correction factor Z_h now becomes (compare equation A30)

$$Z_h = \frac{E_{dh}}{\xi \, E_{clh} + (1-\xi) \, E_{och}} \qquad \ldots \text{(A35)}$$

where E_{clh} and E_{och} are given in equations A31 and A24 respectively.

A 3.4.5 Clear/overcast according to nebulosity index, corrected using horizontal illuminance data

Equation A32 is altered to become

$$E = Z_h \left(N \, E_{cl} + (1-N) \, E_{oc}\right) + E_s \qquad \ldots \text{(A36)}$$

where N is Perraudeau's nebulosity index (refs 33, 34) given by

$$N = \frac{1 - CR}{1 - CR_T} \qquad \ldots \text{(A37)}$$

Here CR is the measured cloud ratio (equation A34) and CR_T is the theoretical value for a completely clear sky. (Note that N should equal 1 for a clear sky, and should be 0 for an overcast day when the cloud ratio is 1).

In reference 34 Perraudeau derives a function for CR_T from equations by Perrin de Brichambaut (ref 55). However the resulting function exhibits odd behaviour at low solar altitudes, tending to infinity at sunrise and sunset. In this study CR_T was calculated from modification of equation A34:

$$CR_T = \frac{E_{clh}}{E_{clh} + E_{sh}} \qquad \ldots \text{(A38)}$$

where E_{clh}, the theoretical clear sky diffuse illuminance, is given by equation A31, and E_{sh}, the solar illuminance on a horizontal plane for a clear day, is given by equation A25. Equation A38 has the advantage of never giving a value greater than 1.

In equation A36, correction factor Z_h is now given by (see equation A35)

$$Z_h = \frac{E_{dh}}{NE_{clh} + (1-N) \, E_{och}} \qquad \ldots \text{(A39)}$$

A 3.4.6 Clear/overcast corrected using vertical illuminance

The first method uses sunshine probability σ and its basic equation is

$$E_{in} = Z_v \left(\sigma \, E_{cl} + (1-\sigma) \, E_{oc}\right) + E_s \qquad \ldots \text{(A40)}$$

This is the same as equation A29, except that Z_h has been replaced by Z_v, a correction factor for vertical illuminance, given by

$$Z_v = \frac{E_{dv}}{\sigma \, E_{clv} + (1-\sigma) \, E_{ocv}} \qquad \ldots \text{(A41)}$$

Thus Z_v is the ratio of the vertical diffuse illuminance (on the window wall) calculated from measured data E_{dv}, and the corresponding vertical illuminance under the given luminance distribution. E_{clv}, the clear sky vertical illuminance, was found using Gaussian integration of the CIE cler sky luminance distribution (ref 41). E_{ocv} is given by

$$E_{ocv} = 0.396\ E_{och} \qquad \text{... (A42)}$$

where E_{och}, the standard overcast sky horizontal illuminance is as given in equation A24.

The second method is very similar except that sunshine probability is replaced by nebulosity index N (equation A37). Equation A40 becomes

$$E = Z_v \left(N\ E_{cl} + (1-N)\ E_{oc}\right) + E_s \qquad \text{... (A43)}$$

and Z_v is now given by

$$Z_v = \frac{E_{dv}}{NE_{clv} + (1-N)\ E_{ocv}} \qquad \text{... (A44)}$$

A 3.5 Intermediate sky methods

A 3.5.1 Sky either clear or overcast or partly cloudy

Internal illuminance E is given by

$$E = E_d + E_s \qquad \text{... (A45)}$$

where the solar illuminance E_s is calculated from measured data as in equation A13.

Three different formulae are used to find E_d, depending on the value of cloud ratio CR (see equation A34):

(i) If $CR < 0.3$ $E_d = E_{cl}$ (clear sky)
(ii) If $0.3 \leq CR \leq 0.8$ $E_d = E_{pc}$ (partly cloudy)
(iii) If $CR > 0.8$ $E_d = E_{oc}$ (overcast)

E_{cl} is calculated using equation A21, except that Kittler's formula is not used for the clear sky zenith luminance L_{zcl}. Instead L_{zcl} is found from the measured external diffuse illuminance E_{dh} using the clear sky equation (refs 30, 31)

$$L_{zcl} = E_{dh}/(6.9731 + 4.2496.10^{-2}\ \gamma_s - 8.5375.10^{-4}\ \gamma_s^{2} - 8.6088.10^{-5}\gamma_s^{3} + 1.9848.10^{-6}\ \gamma_s^{4} - 1.6222.10^{-8}\ \gamma_s^{5} + 4.7823.10^{11}\ \gamma_s^{6}) \qquad \text{... (A46)}$$

This equation is a simple inversion of equation A31, with solar altitude γ_s in degrees.

For partly cloudy skies E_{pc} is found in a similar way, except that instead of the CIE clear sky luminance distribution the partly cloudy distribution due to Pierpoint (refs 40, 44) is used:

$$L_{pc} = L_{zpc} \frac{(0.526 + 5 \exp(-1.5\,\theta))\,(1-\exp(-0.8/\sin\gamma))}{(0.526 + 5 \exp(-1.5\,(\pi/2-\gamma_s))\,(1-\exp(-0.8))} \quad \ldots \text{(A47)}$$

In this equation, the solar altitude γ_s, the altitude of the sky element γ and its angle from the sun θ are all expressed in radians. The partly cloudy sky zenith luminance L_{zpc} was again found from the horizontal diffuse illuminance E_{dh}, the ratio of the two being found by numerical integration of the luminance distribution in equation A47.

Finally E_{oc} was found using equation A14.

In the second method described in this section, the alternative criterion of sky type was as follows:

(i) If sunshine probability $\sigma > 0.75$ $E_d = E_{cl}$ (clear sky)
(ii) If $0.25 \leq \sigma \leq 0.75$ $E_d = E_{oc}$ (partly cloudy)
(iii) If $\sigma < 0.25$ $E_d = E_{oc}$ (overcast)
E_{cl}, E_{pc} and E_{oc} are calculated in the same way as before.

A 3.5.2 Nakamura and Oki intermediate sky method

The basic equation is

$$E = Z_h \left[P_{cl} E_{cl} + P_{oc} E_{oc} + (1 - P_{cl} - P_{oc}) E_{pc} \right] + E_s \quad \ldots \text{(A48)}$$

In this equation E_s the direct solar illuminance is found from measured data using equation A13. E_{cl}, the clear sky internal illuminance is calculated using equation A21, although instead of equation A22 to find clear sky zenith luminance L_{zcl}, the equation of Nakamura et al (ref 37) is used:

$$L_{zcl} = 4470 \tan^{1.13} \gamma_s + 140 \qquad \text{cd/m}^2 \quad \ldots \text{(A49)}$$

E_{pc}, the corresponding partly cloudy sky illuminance is found in a similar way from the Nakamura and Oki intermediate sky luminance distribution (refs 38, 45)

$$L_{pc} = L_{zpc} \frac{0.43 \left[\gamma + 4.799 + 1.35 \left(\sin(3.59\,\gamma - 0.09) + 2.31\right) \sin(2.6\gamma_s + 0.316)\right]}{0.988 \left[\sin(2.6\,\gamma_s + 0.316) + 2.772\right]}$$

$$\times \frac{\exp\left[-0.563 \left((\gamma + 1.059)(\gamma_s - 0.008) + 0.812\right) \theta\right]}{\exp\left[-1.481 (\gamma_s + 0.301)(1.571 - \gamma_s)\right]} \quad \ldots \text{(A50)}$$

In equation A50 the altitude γ of an element of sky, its angular distance from the sun θ and the solar altitude γ_s are all expressed in radians. The intermediate sky zenith luminance L_{zpc} is given by (ref 38)

$$L_{zpc} = 0.47\ (4470 \tan^{1.13} \gamma_s + 140) + 0.66\ (15000 \sin^{1.68} \gamma_s + 70)\ \text{cd/m}^2 \qquad \ldots\ (A51)$$

In equation A48 E_{oc} the overcast sky internal illuminance is given by equation A14

$$E_{oc} = E_{och} \times d$$

where d is the CIE overcast sky daylight factor, expressed as a fraction, and the external diffuse illuminance E_{och} is given by (ref 37)

$$E_{och} = 70 + 15000 \sin^{1.68} \gamma_s \qquad \ldots\ (A52)$$

The proportions of clear and overcast skies P_{cl} and P_{oc} in equation A48 are functions of sunshine probability σ (refs 38, 46):

$$P_{cl} = \frac{0.05689}{1.054 - \sigma} - 0.05397 \qquad \ldots\ (A53)$$

$$P_{oc} = \frac{0.78629}{0.551 + \sigma} - 0.50694 \qquad \ldots\ (A54)$$

The final term in equation A48 is Z_h, a correction factor based on the measured horizontal diffuse illuminance E_{dh}:

$$Z_h = \frac{E_{dh}}{P_{cl}\ E_{clh} + P_{oc}\ E_{och} + (1 - P_{cl} - P_{oc})\ E_{pch}} \qquad \ldots\ (A55)$$

In this equation E_{clh}, the standard clear sky diffuse illuminance on a horizontal plane, was given by equations A31 and A49. The corresponding partly cloudy sky illuminance E_{pch} was found by integrating the luminance distribution in equation A50.

A4 AN ASSESSMENT OF A METHOD TO PREDICT MANUAL SWITCHING IN DYNAMIC ENERGY MODELLING PROGRAMS

Section 3.2.2 of the main text outlines the 'orientation factor' method of calculating internal illuminances, due to Hunt (refs 13, 14). External horizontal global illuminance data are used as the starting point, multiplied by a factor of 0.6 to convert to diffuse. Then internal illuminances are calculated by multiplying by the daylight factor, and by an orientation factor (see Appendix A 3.2.2).

This method is of particular interest because Hunt used it in setting up the BRE model of manual switching (refs 13, 14). He calculated internal illuminances using the method and correlated these calculated values with the observed switching probabilities inside the rooms studied.

More recently, Haves and Littlefair (ref 1) have included this correlation equation in a set of lighting algorithms for SERI-RES, the first time manually switched lighting has been simulated inside a dynamic energy modelling program. For manual switching they used Hunt's original method of calculating internal illuminances, stating that 'the use of another method would destroy the internal consistency of the model'.

The middle row of Table 2 shows that this method is in fact relatively poor at predicting internal illuminances. In particular it usually tends to underestimate internal illuminances, by around 40% on average. However a consistent underestimation would not cause errors in the prediction of lighting use if illuminances calculated in this way were used to generate manual switching probabilities. This is because the correlation function itself (used by Hunt), was based on calculated illuminances which would have underestimated the actual illuminances inside the rooms where switching was taking place.

To take a numerical example: suppose Hunt had measured a 50% probability of switching on the lights in a room where the actual minimum internal daylight illuminance was 100 lux. However the calculation method used by Hunt would have indicated an internal illuminance of 60 lux (40% less) and it would have been this lower value that was used in generating the correlation function. Now suppose we want to use the correlation function to generate the switching probability in another room with the same daylight conditions. To obtain the correct switching probability of 50%, it would be necessary not to use the measured internal illuminance of 100 lux, but to use the value of 60 lux calculated by the same method used to generate the internal illuminances in the original empirical correlation.

It follows, then, that in assessing the suitability of this method for calculating illuminances for manual switching prediction purposes, we can ignore the 40% underestimation that occurs on average, since this will cancel out when the correlation function is applied. To compare the predictions of the method with measured illuminances, can easily be done by omitting the factor 0.6 from Hunt's original equation. This has been done and section 3.2.2 and Table 2 show the comparison of these new predicted illuminances with measured values. As expected, the mean bias error for the whole year is now close to zero. However this method is relatively poor at modelling the dynamic variations of daylight illuminances with sky condition and especially with time of day.

Manual switching occurs at certain times of day, principally in the early morning. The analysis showed that illuminances in the east facing room were understimated by an average of 20% between 0900 and 1000 GMT, while those in the west facing room were overestimated by an average of 25%. These errors would result in errors in lighting use prediction of around 10% of full lighting load if manual switching occurred solely at this time. Of course in a building with both an east facing and an equivalent west facing facade the two errors would cancel out to a large extent.

These errors arise because the orientation factor is a single figure for each room, regardless of time of day, weather conditions or solar altitude. Thus it is not capable of accounting for the dynamic variation in sky luminance distribution, which is an especially important issue for lighting algorithms in environmental modelling programs.

There are three main options for the integration of manual switching into dynamic environmental models. The first is to adopt the Haves and Littlefair approach (ref 1) and accept the orientation factor method, despite its possible inaccuracies in prediction for certain orientations and at certain times of day and year, in order to maintain the internal consistency of the manual switching model; bearing in mind that manual switching is itself subject to behavioural variations and hence is not entirely predictable.

For the simple hand calculation of yearly lighting use with manual switching the current, orientation factor based approach, as outlined in references 14 and 56, definitely seems to be best as more complex methods would not be easy to use.

However, in large computer programs there are other possibilities. The second option, and perhaps the ideal one in principle, would be to rework the Hunt studies of manual switching using measured internal illuminances, or at least a more accurate illuminance prediction model. However this would be difficult and time-consuming to carry out in practice.

The third option is to use a more accurate illuminance prediction model inside the computer program, coupled with Hunt's original correlation curve (ref 14). However, as described above, this would destroy the internal consistency of the model since the original correlation curve was derived using the orientation factor method. If this third option was adopted it would probably be best to multiply the accurately calculated illuminances by 0.6 before calculating the switching probability, because the illuminances in the original correlation curve were underestimated to that extent on average.

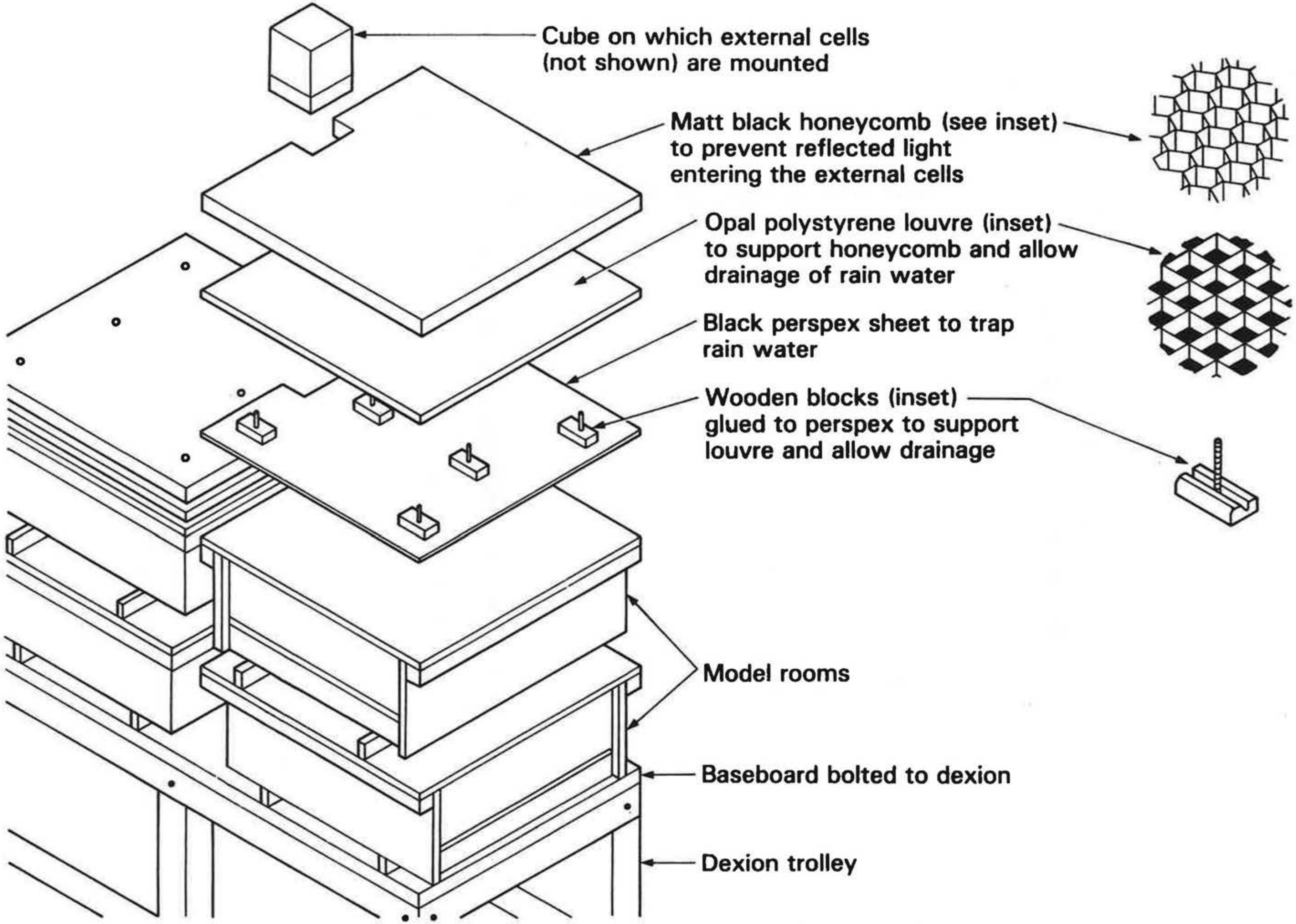
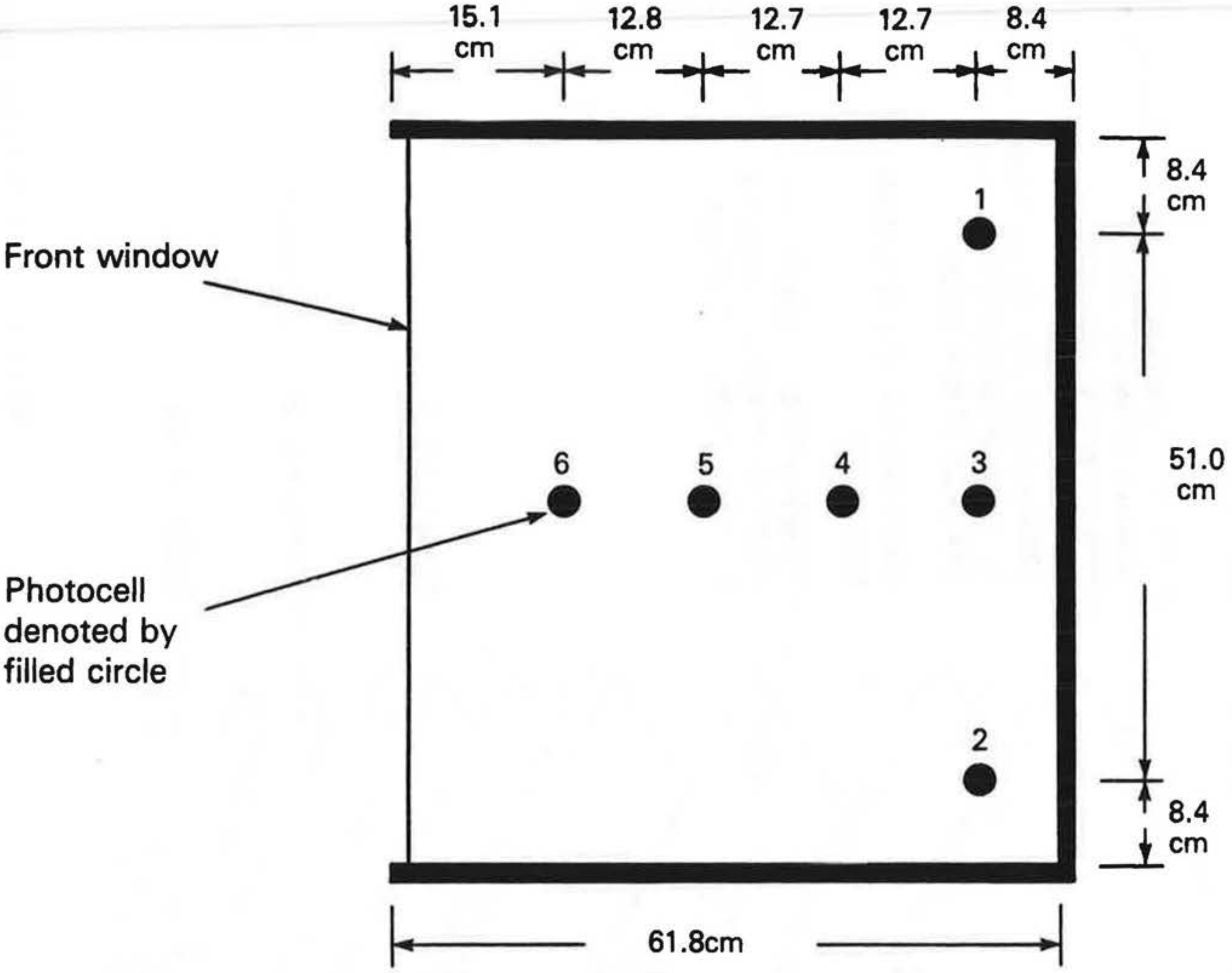


Figure 1 Apparatus used for illuminance measurements.



Height of room = 25.5cm
Sill/cell height = 6.7cm
Window height = 18.8cm

Figure 2 Plan of scale model room used for daylight measurements

25 3044/33 P. Littlefair

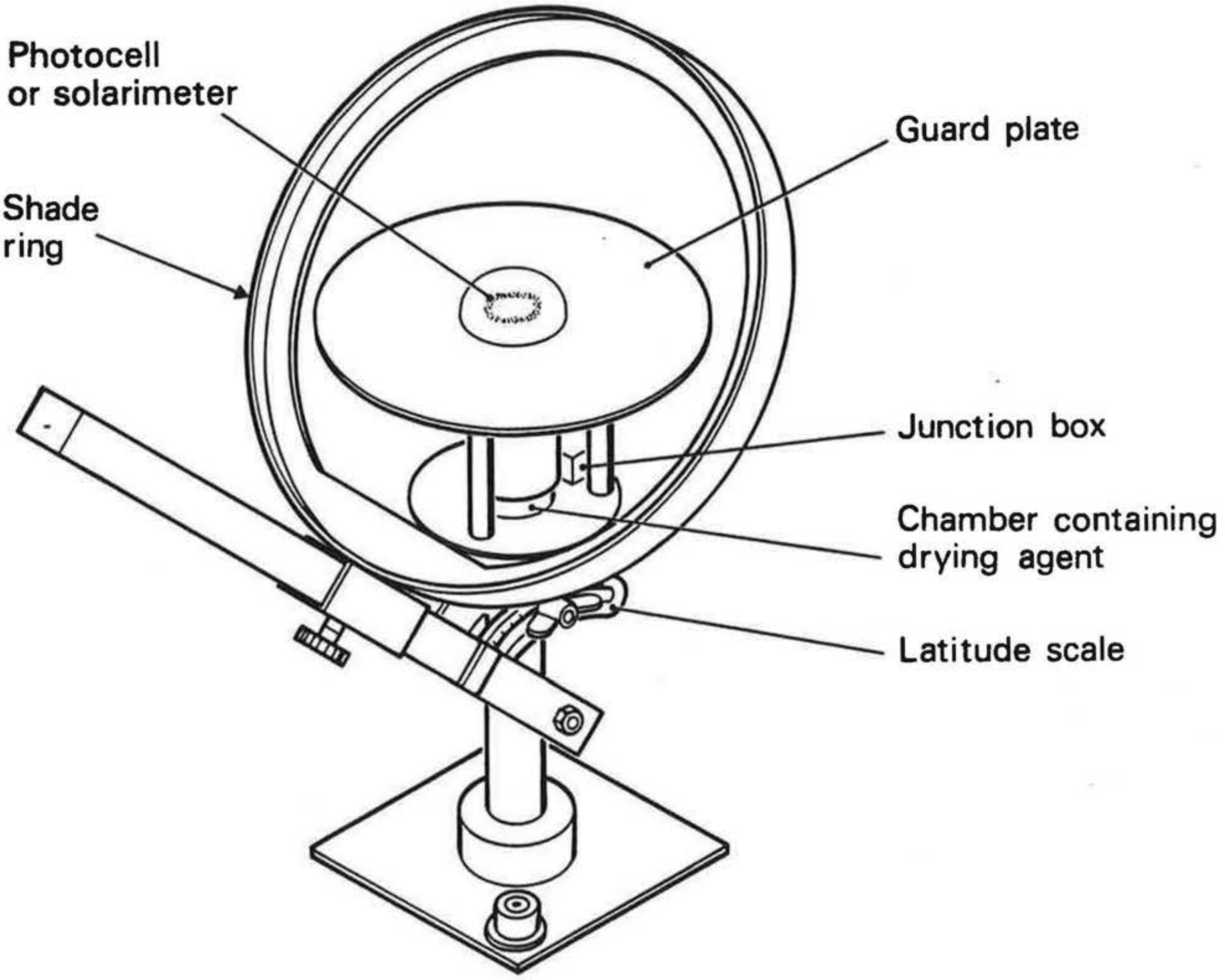


Figure 3 Photocell or solarimeter fitted with shade ring for external diffuse illuminance measurements

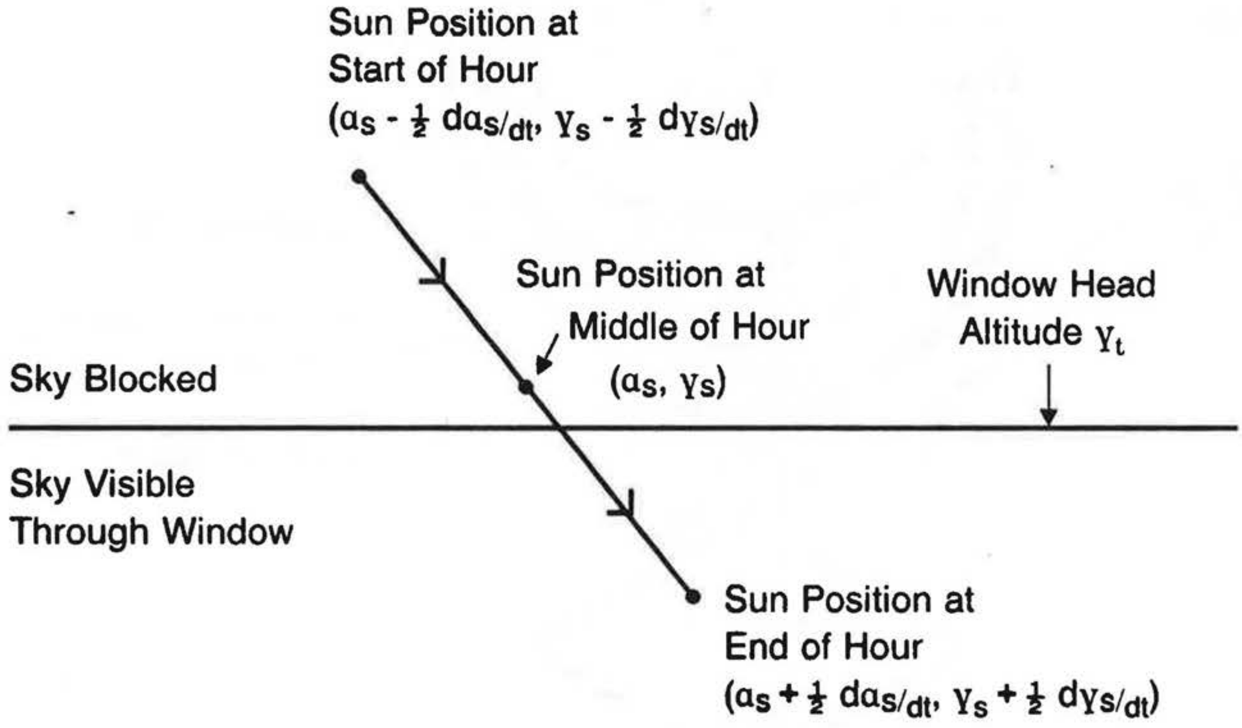


Figure A1 View (from inside) of part of the solar orbit as it intersects the window head.

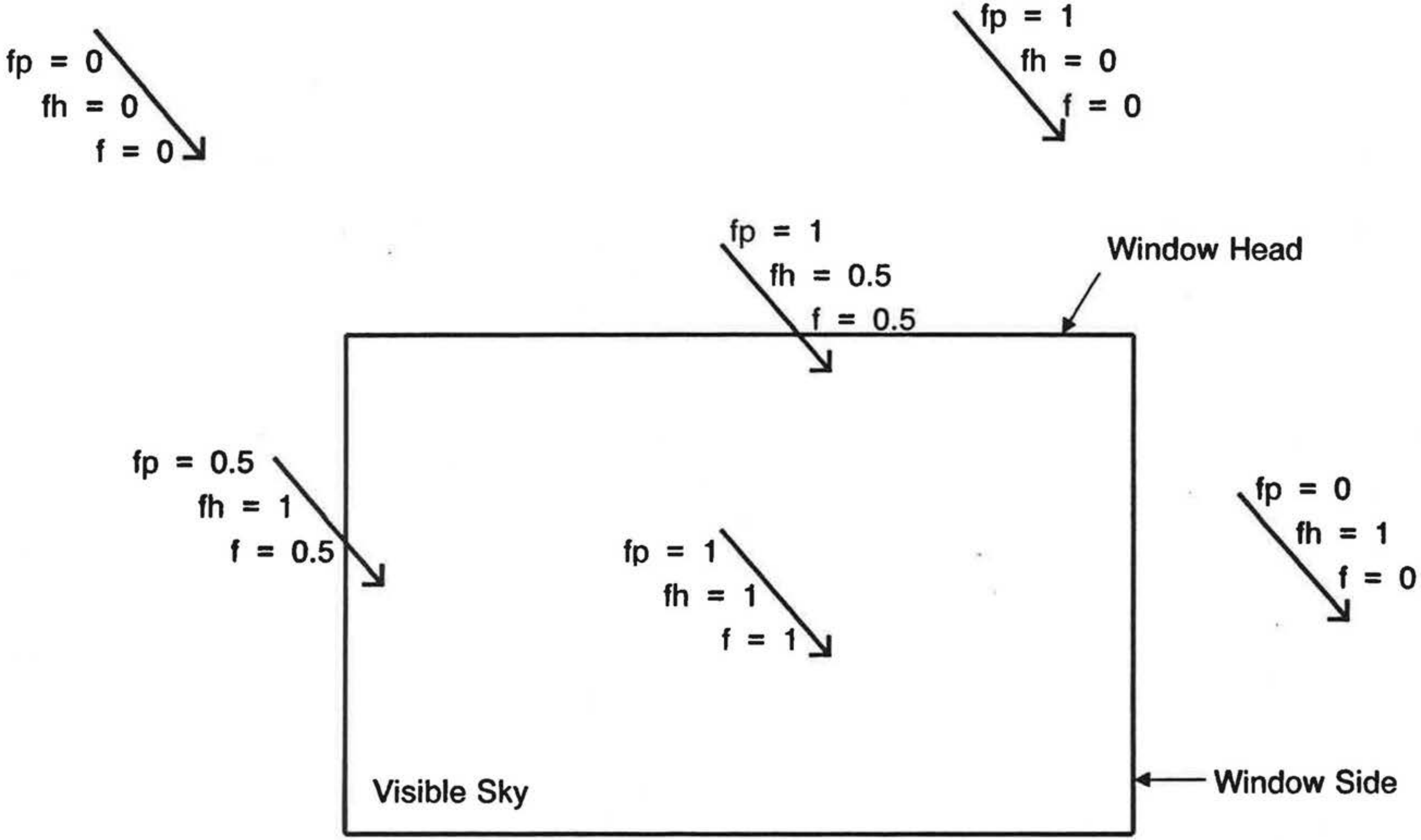


Figure A2 Possible solar orbit segments viewed from inside a room with a rectangular window.

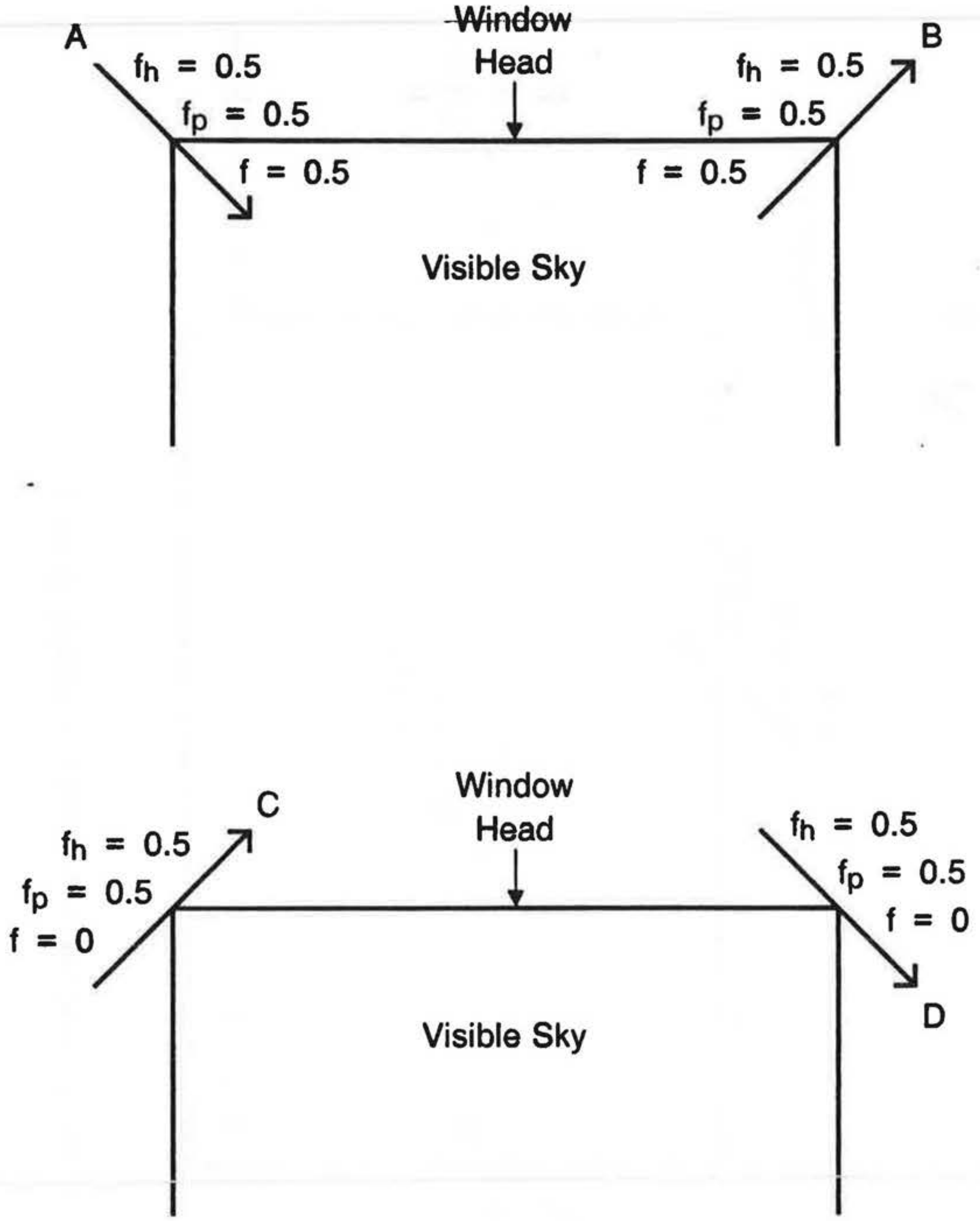


Figure A3 Possible solar orbit segments intersecting the corners of a window (viewed from inside the room).