# Daylight Simulation: Validation, Sky Models and Daylight Coefficients

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## Daylight Simulation: Validation, Sky Models and Daylight Coefficients

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## This thesis is dedicated to the memory of Professor Neil Bowman

Director of the Institute of Energy and Sustainable Development 1994 to 1999

#### Abstract

The application of lighting simulation techniques for daylight illuminance modelling in architectural spaces is described in this thesis. The prediction tool used for all the work described here is the *Radiance* lighting simulation system.

An overview of the features and capabilities of the *Radiance* system is presented. Daylight simulation using the *Radiance* system is described in some detail. The relation between physical quantities and the lighting simulation parameters is made clear in a series of progressively more complex examples. Effective use of the interreflection calculation is described.

The illuminance calculation is validated under real sky conditions for a full-size office space. The simulation model used sky luminance patterns that were based directly on measurements. Internal illuminance predictions are compared with measurements for 754 skies that cover a wide range of naturally occurring conditions. The processing of the sky luminance measurements for the lighting simulation is described. The accuracy of the illuminance predictions is shown to be, in the main, comparable with the accuracy of the model input data. There were a number of predictions with low accuracy. Evidence is presented to show that these result from imprecision in the model specification - such as, uncertainty of the circumsolar luminance - rather than the prediction algorithms themselves. Procedures to visualise and reduce illuminance and lighting-related data are presented.

The ability of sky models to reproduce measured sky luminance patterns for the purpose of predicting internal illuminance is investigated. Four sky models and two sky models blends are assessed. Predictions of internal illuminance using sky models/blends are compared against those using measured sky luminance patterns. The sky model blends and the Perez All-weather model are shown to perform comparably well. Illuminance predictions using measured skies however were invariably better than those using sky models/blends.

Several formulations of the daylight coefficient approach for predicting time varying illuminances are presented. *Radiance* is used to predict the daylight coefficients from which internal illuminances are derived. The form and magnitude of the daylight coefficients are related to the scene geometry and the discretisation scheme. Internal illuminances are derived for four daylight coefficient formulations based on the measured luminance patterns for the 754 skies. For the best of the formulations, the accuracy of the daylight coefficient derived illuminances is shown to be comparable to that using the standard *Radiance* calculation method.

The use of the daylight coefficient approach to both accurately and efficiently predict hourly internal daylight illuminance levels for an entire year is described. Daylight coefficients are invariant to building orientation for a fixed building configuration. This property of daylight coefficients is exploited to yield hourly internal illuminances for a full year as a function of building orientation. Visual data analysis techniques are used to display and process the massive number of derived illuminances.

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I declare that the content of the submission represents solely my own work.

John Mardaljevic, December 1999.

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## "Das licht! Das licht!"

Tristan und Isolde, Act II Richard Wagner



C h a pter

## Introduction

"Iread part of it all the way through"

SAM GOLDWYN

The goal of the work described in this thesis is the accurate simulation of hourly internal daylight illuminance levels for a full year under naturally occurring meteorological conditions. The prediction tool used for all the work described in this thesis was the *Radiance* lighting simulation system [Ward 98]. Chapter 2 is an introduction to daylight simulation using the *Radiance* system. This chapter was originally published in the book **Rendering with Radiance: the** Art and Science of Lighting Visualization.<sup>1</sup> This chapter introduces to the reader the fundamentals of using *Radiance* for exacting daylighting simulation work. The chapter covers a range of topics from daylight factor prediction for simple spaces to creating renderings of highly complex architectural designs. Throughout the chapter, a strong emphasis is placed on the relation between physical

<sup>1.</sup> Note that the originator of the *Radiance* system has been known variously as: Greg Ward, Greg Larson and Greg Ward Larson. Despite this, and several changes of employment, he has yet to escape recognition as the (effective) sole originator/creator of the *Radiance* system. As of late-1999, 'Greg Ward' is the name to use.

quantities and the lighting simulation parameters. The use of the ambient calculation for inter-reflected light, generally considered to be one of the more perplexing features of the *Radiance* system, is carefully described. The examples given in this chapter demonstrate how the performance of the ambient calculation can be optimized by judicious examination of the scene prior to attempting any simulations. This chapter was conceived as a 'tutorial' on daylight simulation for those already familiar with, at least, the basics of the *Radiance* system.<sup>2</sup> The chapters that follow are concerned with the validation of the illuminance calculation and the formulation, application and proving of techniques for daylight illuminance prediction.

The validation of the Radiance illuminance calculation under real sky conditions is described in Chapter 3 (Preparation) and Chapter 4 (Results). The validation dataset is based on simultaneous measurements of the internal illuminance in an office space and the luminance distribution of the sky.<sup>3</sup> The internal illuminance was recorded at six locations along the length of the office, and the sky luminance was measured at 145 points evenly distributed across the hemisphere. The validation dataset contains measurements - internal and external - for 754 unique skies that cover a wide range of naturally occurring conditions: from heavily overcast, through intermediate to clear. The sky brightness patterns used in the lighting simulation were based directly on the sky luminance measurements. A hypothesis regarding potentially unreliable photocell-sky combinations in the validation dataset is advanced. Chapter 4 begins with a summary presentation of the validation results. Thereafter, the validation results are subjected to a range of investigations. These analyses are gradually refined and evidence is presented to support the hypothesis advanced in Chapter 3. On the strength of this evidence, the photocell-sky combinations in the validation dataset are partitioned into 'reliable' and 'potentially unreliable'

<sup>2.</sup> For a practical introduction to Radiance, readers are directed to Chapters 1 to 4 of the book *Rendering with Radiance*.

<sup>3.</sup> Validation data were supplied by the Building Research Establishment.

sets based on the visibility of the circumsolar region from the photocell location. The accuracy of the illuminance predictions for the 'reliable' set is taken to be the intrinsic accuracy of the illuminance calculation.

The use of sky models for lighting simulation is investigated in Chapter 5. For this, the validation exercise was repeated but now the sky luminance patterns are based on sky models. The sensitivity of internal illuminance predictions to sky model type is evaluated. In all, four different sky model formulations and two sky model blends are assessed.

An implementation of the daylight coefficient approach for Radiance is described in Chapter 6. With the daylight coefficient approach, the internal illuminance for arbitrary sun and sky conditions can be evaluated by reusing pre-computed daylight coefficient values for a discretised sky. Five candidate daylight coefficient formulations for Radiance are examined. One of these is found to be potentially very inaccurate and it is eliminated from further consideration. The accuracy of the remaining formulations is tested using the validation dataset. Illuminance predictions for the office space are derived from daylight coefficients using the measured sky luminance patterns for all 754 skies in the validation dataset. The accuracy of daylight coefficient derived illuminance predictions are compared against measurements and those obtained using the standard Radiance calculation method. This chapter then shows how daylight coefficients can be used to predict the annual daylighting potential of an architectural space. A methodology for the efficient evaluation of annual daylighting potential as a function of building orientation is presented. Several possible applications for these new techniques are discussed. The thesis concludes with a list of suggestions for the practical application of the new techniques and recommendations for future work.

Familiarity with the *Radiance* system is a desirable, though not essential, prerequisite for critical reading of this thesis. It is hoped that many of the

findings described here will be of interest, to a greater or lesser degree, to all those concerned with daylight prediction.

# Chapter

# Daylight Simulation

This chapter presents an introduction to daylight simulation using the *Radiance* system. It originally appeared as one of the specialist application chapters in the book **Rendering with Radiance:** The Art and Science of Lighting Visualization (principle authors Greg Ward Larson and Rob Shakespeare) and was solely authored by John Mardaljevic. Conceived as a tutorial for daylight simulation, the chapter contains much essential information that is not available elsewhere. It explains how to accurately calculate illuminance values and render with daylight using four progressive case studies. Although presented as generalised examples, the techniques that are described were based directly on the studies that were carried out for the validation of the *Radiance* illuminance predictions (Chapter 3). The most important of the techniques described in this chapter is the optimization of the ambient calculation and how this relates to the scene geometry. Application of inter-reflected light is a required outcome.

Note that the format used here is largely the same as that used for the *Radiance* book. However, the section and figure numbering were changed to

be consistent with the rest of this thesis. Sections and figures in this chapter are referenced elsewhere in the thesis. The references within this chapter however, are made with respect to the book as published. The book **Rendering with Radiance: The Art and Science of Lighting** Visualization was published by Morgan Kaufmann (San Francisco) in 1998 and the chapter below is reproduced with permission. For a more comprehensive introduction to the features and capabilities of the *Radiance* lighting simulation system, see the article reproduced in the Appendix (C).

L he primary goal of daylighting analysis is the reliable evaluation of the potential of a design to provide useful levels of natural illumination. This chapter will explain how *Radiance* can be used to predict the daylighting performance of an architectural design.

It is expected that you will already be familiar with the fundamentals of the *Radiance* system, and that you have some knowledge of the way the command-line interface operates. The diffuse indirect calculation is particularly important for daylighting analysis, so a good understanding of the key features of this method is desirable. If you are specifically interested in daylighting but are new to *Radiance*, this chapter, together with the general introduction, could serve as a starting point for investigating the system.

Daylighting analysis can take many forms. A comprehensive survey of all the ways in which *Radiance* can be used to address these issues would require a book in itself. To limit the discussion to a single chapter, some compromises have to made. Rather than give cursory mention to a multiplicity of techniques, we will describe a set of key procedures in detail. These are presented in the form of case study examples. Some of the examples are straightforward descriptions of how to get from A to B. Others are expanded to demonstrate, for instance, the correspondence between analytical solutions and *Radiance* predictions, or accuracy criteria and efficiency. If you already know some daylighting, you may wish to skip the first few case studies.

The chapter begins with an overview of daylight monitoring, with little or no mention of *Radiance*. Next, there is a general discussion about evaluation techniques and how, in broad terms, these influence the *Radiance* modeling and simulation. The bulk of the chapter is taken up with case study examples.

The important *Radiance* programs for this chapter, that is, those for which you will learn how to make informed choices for critical parameter values, are **rtrace**, **rpict**, **mkillum**, **gensky**, and the script **dayfact**. It is expected that you have already formed, from the general introduction, some appreciation of the function and use of the rtrace, rpict, and mkillum programs. We will use a handful of other *Radiance* programs, such as **oconv** and **rcalc**, as a matter of course.

#### 2.1 Daylight: Monitoring, Sky Models, and Daylight Indoors

The source of all daylight is the sun. Scattering of sunlight in the atmosphere by air, water vapor, dust, and so on gives the sky the appearance of a self-luminous source of light. Here we are concerned only with daylight modeling for architectural purposes, so both the sky and the sun will be treated as light sources distant from the local scene. The brightness of the sun, or a point on the sky, will not be modified by scattering or absorption. In other words, the effects of participating media phenomena such as smog or haze on daylight will not be considered.<sup>1</sup>

The illumination produced by the sky depends on its luminance. Sky luminance varies according to a series of meteorological, seasonal, and geometric parameters that are difficult to specify. Characterizing the sun and sky for lighting simulation is equivalent to light source photometry for electric luminaires. Geometrically, the sky is simple to describe: the sky always has the same "shape" and "position." The brightness pattern of the sky, however, can be quite difficult to characterize for all but heavily overcast condi-

<sup>1.</sup> You are encouraged to investigate these effects at your leisure once you have grasped the requisite techniques.

tions. When clouds are present, the sky brightness distribution can change dramatically over very short time scales. For these reasons, it has been necessary to devise ideal sky brightness patterns known as *sky models*. These are used for the majority of daylight simulation applications. Sky models are used to generate sky brightness patterns from basic daylight quantities.

#### 2.1.1 Measuring Daylight

Continuous monitoring of the sky brightness began in earnest in the 1950s. There are now many locations in the industrialized world where 10 or more years of daylight data have been recorded and archived. The degree of monitoring varies from the most basic stations, which record integrated quantities averaged over time, to those that measure a comprehensive range of daylight metrics including the actual sky brightness distribution. They can be divided into classes as follows.

#### Basic

The longest time-series data from which daylight availability can be elucidated are the climatic or weather tapes [PO83]. These usually contain hourly integrated values of global and diffuse irradiance (Figure 2-1). Irradiance is a measure of the total energy flux (watts/meter<sup>2</sup>) incident on a surface. The visible part of the radiant energy, the illuminance (lumens/meter<sup>2</sup>), is calculated using a luminous efficacy model [Lit88]. Luminous efficacy, *K*, can be thought of simply as the ratio of illuminance to irradiance with units of lumens per watt:

$$K = \frac{683 \int S_{\lambda} v_{\lambda} d\lambda}{\int S_{\lambda} d\lambda}$$
(2-1)



Figure 2-1. Basic daylight components: (a) global horizontal (sky and sun), (b) diffuse horizontal (sky only), and (c) direct normal (sun only).

where  $S_{\lambda}$  is the spectral radiant flux in watts per unit wavelength interval at wavelength  $\lambda$  and  $V_{\lambda}$  is the relative spectral response of the eye at that wavelength. See Supplemental Information in Chapter 10 for a plot of this function. Equivalently, the ratio of luminance to radiance, which gives the same value, may be used.

This ratio is not constant and will vary with solar altitude, cloud cover, and sky turbidity. Furthermore, under the same sky conditions, the luminous efficacy for direct-beam radiation will be different from that for the diffuse component.

#### Intermediate

Monitoring of the visible component of irradiation, the illuminance, is nowadays more common. An intermediate-level monitoring station will measure global and diffuse illuminance together with the corresponding irradiance values. More comprehensive monitoring would include measurements of the direct components of solar illuminance and solar irradiance. These direct solar components are measured normal to the direction of the sun (Figure 2-1), so the instruments that record these quantities are mounted on sun-tracking motorized drives.

In addition, some stations record the illuminance incident on vertical surfaces facing north, south, east, and west. Here, the four vertical photocells are screened from groundreflected radiation and the illuminance recorded is that due to the sky only. Although the four vertical values can provide some indication of the azimuthal asymmetry in the brightness distribution, these are still integrated quantities.

#### Advanced

The finest level of detail is provided by stations that also measure the actual sky luminance distribution using a sky-scanning device. The number of measurements taken during each scan varies according to the instrument used. These data provide the measurements necessary to validate sky models. Measured sky brightness distributions may also be used directly in the lighting simulation [Mar95].

In addition to lighting quantities, many stations also record dry bulb temperature and relative humidity.

Basic daylight quantities provide the input to sky model generator programs. Global horizontal, diffuse horizontal, and direct normal are related as follows:

$$I_{gh} = I_{dh} + I_{dn} \sin\theta \tag{2-2}$$

where  $I_{gh}$  is the global horizontal irradiance,  $I_{dh}$  is the diffuse horizontal irradiance,  $I_{dn}$  is the direct normal irradiance, and  $\theta$  is the sun altitude. The same relation holds for illuminance quantities.

#### 2.1.2 Sky Models

The simplest sky model of them all is the Uniform Luminance Model, which describes a sky of constant brightness. It was intended to represent a heavily overcast sky. It has long been appreciated, however, that a densely overcast sky exhibits a relative gradation from darker horizon to brighter zenith; this was recorded as long ago as 1901. The Uniform Luminance Sky is therefore a poor representation of any actually occurring meteorological conditions and is generally not used for illuminance modeling.

The CIE Standard Overcast Sky, originally known as the Moon and Spencer Sky, was devised to better approximate the luminance distribution observed for overcast skies. Adopted as a standard by the CIE in 1955, this description is the one most frequently used for illuminance modeling. Normalized to the zenith luminance, it has the form

$$L_{\zeta} = \frac{L_{z}(1+2\cos\zeta)}{3}$$
 (2-3)

where  $L_{\zeta}$  is the luminance at an angle  $\zeta$  from the zenith and  $L_z$  is the zenith luminance. Comparisons with measured data have demonstrated the validity of the CIE Standard Overcast Sky model as a representation of dull sky conditions [KV93].

To describe the brightness distribution for clear sky conditions requires a considerably more complex mathematical representation. The complexity arises from a number of observed effects that are accounted for in the model. Among these are a bright circumsolar region, a sky luminance minimum that is at some point above the horizon, and a brightening of the sky near the horizon. The scales of these effects are related to the solar position and the relative magnitudes of the illumination produced by the sun and sky. Like the CIE overcast standard, the CIE clear sky model is normalized to zenith luminance and the sky luminance distribution is given by [CIE73]

$$L = L_{\zeta} \frac{(0.91 + 10e^{-3\theta} + 0.45\cos^2\theta)(1 - e^{(-0.32/\sin\gamma)})}{(0.91 + 10e^{-3(\pi/2 - \gamma_s)} + 0.45\sin^2\gamma_s)(1 - e^{-0.32})}$$
(2-4)

where  $\gamma$  is the sky point altitude,  $\gamma_s$  is the solar altitude, and  $\theta$  is the angle between the sun and the sky point. Note that the spectral distribution of skylight—its color—is not predicted by any of these models.

The overcast and clear CIE models are representations of extreme sky types—densely overcast or completely clear. Intermediate skies—that is, thin/moderate cloud cover and/ or hazy atmospheric conditions—are more likely occurrences than totally clear or over-cast skies for many geographical locations. Sky models generate continuous sky luminance distribution patterns. The discontinuous aspects of skylight—instantaneous cloud patterns—are not addressed.

#### 2.1.3 Daylight Indoors—The Components of Illuminance

It helps to characterize the daylight entering a space by its origin—sun or sky—and the path by which it has arrived—directly from the source or by reflection (Figure 2-2). These categories will be particularly useful later on, when we relate light exchanges by reflection to ambient parameter settings.

#### 2.2 Evaluation Techniques and Accuracy

Daylight simulation for interior spaces can be divided into two modes of evaluation:

- Quantitative, or numerical
- Qualitative, or visual

Quantitative data are usually presented in the form of line graphs, surface plots, or falsecolor maps, for example, of the distribution of illuminance across a plane. We use images to give an impression of what the finished building will look like, usually from several different viewpoints and under different lighting conditions. These modes are complementary rather than exclusive, and indeed often overlap. You may find that, even for purely numerical work, a few well-chosen images will facilitate the process of obtaining accurate predictions.



Figure 2-2. Components of daylight: (a) direct sun, (b) direct sky, (c) externally reflected, and (d) internally reflected.

For want of better criteria, we will distinguish between scenes that use the standard CIE overcast sky for illumination and the rest, which use any type of sky with sun. Overcast skies tend to be used for numerical work, which is aimed toward obtaining unambiguous quantities such as the daylight factor. Sunny sky conditions are particular to each sky, and the analysis under these circumstances will be more complex and less general than, say, a daylight factor evaluation. A few of the more common forms of analysis are described below for each of the two categories of illumination.

- 1. Standard CIE overcast sky conditions (daylight factor prediction)
- Analysis of an architectural design to ensure compliance with, say, a statutory minimum daylight provision
- Comparative evaluation of design options
- Prediction of the daylight factor reduction caused by introducing new external obstructions to the local environment, such as a proposed nearby building
- Visual impression of the scene accompanied by a false-color image of daylight factor (or illuminance values)
- 2. Skies with sun
- Visual impression at certain times of day/year
- · Solar penetration/shading studies, such as a "movie" sequence of images
- Effect of advanced glazing materials, such as a "movie" sequence and/or illuminance plots
- Glare evaluation, such as locating sources of glare in an image and predicting indices for visual comfort probability

These are just some of the possibilities. The daylight factor approach is a standard technique and warrants detailed description.



Figure 2-3. Internal and external horizontal illuminance.

#### 2.2.1 The Daylight Factor Approach

The daylight factor at any point is the ratio of the interior illuminance at that point to the global horizontal illuminance under CIE standard overcast sky conditions. The daylight factor (DF) is normally expressed as a percentage:

$$DF = \frac{E_{in}}{E_{out}} \cdot 100 \tag{2-5}$$

The interior illuminance is usually evaluated at workplane height (.Figure 2-3). Direct sunlight is, of course, excluded from the calculation. Because the overcast skies will generally be the dullest, the daylight factor method should be considered a "worst case" evaluation, primarily suited to calculating minimum values. Because the sky luminance does not vary with azimuth, the orientation of the scene about the *z*-axis has no effect on DF.

The conventional method to evaluate daylight factors, still very much in use, is from illuminance measurements taken inside scale models under artificial sky conditions. Unlike thermal, acoustic, or structural models, physical models for lighting do not require any scaling corrections. While a detailed physical model may indeed provide reliable results, such models can be very expensive to construct, especially if several design variants are to be evaluated. Increasingly, architects and design consultants are looking to computer simulation to offer an alternative solution approach.

Daylight factors are usually evaluated for uncluttered spaces. Since we are not interested in visual impression, the scene description usually accounts for only the important structural features of the space, and furniture and so on is not included.

Illuminance (and DF) are quantities that we derive from the irradiance predicted by the rtrace program. Often you will see that the irradiance values from the standard output of rtrace are converted directly to illuminance (or DF). Wherever in the text we refer to illu-

minance (or DF) prediction, we shall use the term to mean irradiance prediction followed by conversion to the appropriate units. The following section describes, in general terms, how the mode of analysis influences the setting of key *Radiance* parameters.

#### 2.2.2 Pictures, Numbers, and Accuracy

For a conventional office scene constructed with typical materials, an accurate (10%) illuminance prediction usually requires four or more ambient bounces [Mar95]. We will see later that some of the other ambient parameters can be set to fairly low-resolution values without compromising too much the accuracy of the illuminance calculation. As most users will already have discovered, however, coarse ambient parameter settings can give fast renderings but usually produce blotchy images.

So why is it that parameters that might result in blotchy images can nevertheless give accurate illuminance predictions? The answer becomes apparent when we consider the relative complexity of DF (illuminance) prediction and image generation. A screen-size image will comprise approximately one million pixels. Empty scenes look fairly boring, so we usually include tables, chairs, and so on, to make it look more like a real room. Depending on the view point, the image is likely to include several items of furniture. The more cluttered the scene from the view point, the harder the interreflection calculation has to work. This means more frequent sampling if we wish to avoid blotches, with the resulting computational overhead. Contrast this with an uncluttered space for DF evaluation. For an accurate prediction, it is essential that the first level of hemispherical sampling produce a good estimate of the irradiance gradient. DFs are usually evaluated at a relatively small number of points, say 50 to 500, across a plane. Furthermore, it is much easier to estimate irradiance gradients across one plane than across the hundreds of surfaces we are likely to see in the image (Figure 2-4). Because the first estimate is so





important for DF calculations, we usually set a high value for **-ad**, but relax the parameters that determine the density of the ambient calculation. This allows us to use a high value for **-ab** without the simulations becoming unmanageable.

As we turn our attention now to image generation, the experienced user will already be aware that the cost of computing images rises with each successive bounce. Do images need more than one or two ambient bounces? First, we should decide what information we want our image to contain. Do we really want highly accurate (10%)luminance values for every pixel in the image? One or two ambient bounces may give us pretty accurate luminance values, say, within 25%, for the majority of pixels in the scene, for example most of the wall, floor, and ceiling. But do we really want to crank up the number of ambient bounces to five or more just to add a little bit of luminance to each pixel, or possibly shade in what may be a tiny part of the scene? Given that sooner or later we will want to solve real-world problems, within real-world time constraints, the answer for the majority of us will be no.<sup>2</sup> The ambient calculation is one of the keystone features of Radiance and, used carefully, it can impart a tremendous impression of realism to a synthetic image. Note that it is the *directionality* of the ambient shading that lends this realism, for example the brightening of surfaces near a sun patch. This can be largely achieved with just one or two ambient bounces (possibly applied in conjunction with a mkillum-generated window). With increasing ambient bounces, the higher-level reflections tend toward a homogeneous and isotropic field of diffuse radiation. These higherlevel reflections add little that can be noticed on a monitor to the pixel luminance already achieved with, say, -ab = 2. For image generation, the higher-order reflections are therefore best approximated by the careful setting of a constant ambient value (-av). How to choose a value for the -av parameter will be demonstrated in the case study examples. Absolute accuracy is required for illuminance prediction, and the constant ambient value is usually set to zero for these calculations.

For image generation, the conversion of a window to a light source using the mkillum utility can significantly speed up the production of smooth renderings. The technique works well as long as the total number of secondary light sources is kept reasonably small. For illuminance calculations, however, where -ab > 2 is usually essential, the preprocessing of windows to secondary light sources is generally not recommended. Similarly, for those rare occasions when images need to be rendered using a high value for -ab, it may be best to avoid using secondary sources and rely on the ambient calculation.

#### 2.2.3 Color Specification

How we specify the colors of the objects in our scene is another consideration. Color will influence the photometric results owing to interactions between surfaces. Visually, we perceive this in renderings as "color bleed," whereby a surface takes on some of the hue of other, usually more strongly colored, surfaces. This can be a significant effect, not just for the surface materials, but also for the sky and the sun if they are given a nongray radiance. If the RGB color values of materials are known from spectrophotometer measurements, these should be used in the simulations. If this information is not available, then for purely quantitative work, you are urged to specify gray reflection, transmission, and emission properties for *all* the materials and sources. For visual

<sup>2.</sup> There will be exceptions; remember that these are recommendations, not rules.

impression, however, if color data are not available, you will have to make a few good guesses. The setting of spectral radiance values for colored skies will be addressed in Section 2.7.4, Sky Spectral Radiance Values.

Having covered some of the basics, we will now demonstrate, using a series of case study examples, how to apply *Radiance* to the solution of realistic daylighting problems.

#### 2.3 Case Study I: Creating the Luminous Environment

The sky and sun are, on an architectural scale, considered to be very distant from the local scene. In other words, the unobstructed view of the sky will be identical for all observers placed anywhere in the scene. The sky is therefore specified as a source solid angle rather than a dome of actual extent. From our local "flat Earth," the sky appears to be a luminous hemisphere. Thus, we model it as a source whose angle is 180 degrees, and we aim the center of the source directly upward, that is, toward the zenith.

Here we introduce a basic calculation technique fundamental to daylight prediction. The following example demonstrates the use of the rtrace program to determine the horizontal irradiance resulting from an unobstructed uniform sky.

#### 2.3.1 Example: Uniform Sky

The scene file, which we will call *sky\_uni.rad*, describes our entire scene, which is simply a hemispherical sky of unit radiance:

```
# uniform brightness sky (B=1)
void glow sky_glow
0
0
4 1 1 1 0
sky_glow source sky
0
0
4 4 0 0 1 180
```

By giving each of the spectral channels the same radiance (i.e., 1), we are defining a colorless, or "gray," sky. From this scene file, generate an octree, say

% oconv sky\_uni.rad > sky\_uni.oct

Now execute the rtrace program to determine the horizontal irradiance due to the uniform sky. A typical command might look like this:

% echo "0 0 0 0 1" | rtrace -h -I+ -w -ab 1 sky\_uni.oct

which writes to the standard output the simulated spectral (RGB) irradiance values:

#### 3.141593e+00 3.141593e+00 3.141593e+00

Because the Boolean irradiance switch is set to "on" (i.e., -I+), rtrace interprets the standard input as the measurement position (0 0 0) and orientation (0 0 1). In other words, rtrace will evaluate the irradiance at point 0 0 0 for a surface (an imaginary one) whose surface normal points upward (0 0 1). The output, therefore, is a triad of predicted values for spectral (RGB) horizontal irradiance. To convert the spectral irradiance triad to irradiance, use the following formula:<sup>3</sup>

<sup>3.</sup> The coefficients should match those specified in *src/common/color.h*.

$$I = 0.265I_R + 0.670I_G + 0.065I_R$$
(2-6)

Because the sum of the multiplying factors is 1, the achromatic irradiance equals 3.141593, which is of course the value for  $\pi$ . We will now compare this with an analytically derived result. For any hemisphere of radiance  $B(\theta, \phi)$  the horizontal irradiance is given by

$$I = \int_{0}^{2\pi \pi/2} \int_{0}^{2\pi/2} B(\theta, \phi) \sin \theta \cos \theta d\theta d\phi$$
 (2-7)

where for a uniform sky,  $B(\theta, \phi) = B$ , and Eq 2-7 simplifies to

$$I = B \int_{0}^{2\pi \pi/2} \int_{0}^{\pi/2} \sin \theta \cos \theta d\theta d\phi$$
(2-8)  
=  $\pi B$ 

which, for a sky of unit radiance, gives  $I = \pi$ . This value for irradiance is what the rtrace simulation predicted. Because the sky was of uniform brightness, all the samples return the same radiance, and we therefore get an exact answer. For any nonuniform sky, however, the prediction will never exactly match an analytically derived result. We see this in the next example. We shouldn't worry, though, because Monte Carlo–based algorithms were never intended to give exact solutions, but they can give very accurate ones.

#### 2.3.2 Example: CIE Overcast Sky

A more realistic example applies the same rtrace technique to a CIE standard overcast sky. Inserting the CIE overcast sky brightness distribution function (Eq 2-3) into Eq 2-7, and evaluating, gives

$$I = \int_{0}^{2\pi} \int_{0}^{\pi/2} B_{z} \left(\frac{1+2\sin\theta}{3}\right) \sin\theta\cos\theta d\theta d\phi$$
(2-9)  
=  $\frac{7}{9}\pi B_{z}$ 

where  $B_z$  is the zenith radiance. As with the uniform sky, the analytical result is exact. However, before we can repeat the above test with rtrace, we need to be able to create skies that have nonuniform brightness distributions. To do this, we select a predefined brightness function that corresponds to the CIE overcast description, then use this to vary the brightness of the glow material. This is achieved by using the gensky program, which can generate descriptions for several sky types. We will first look at how gensky can produce CIE overcast skies. To do this, we use the **-c** option to designate the type of sky we want, but we will also use the **-b** option so we can specify a zenith radiance for the sky. (The sun angles need to be declared also, but these will not be used by gensky for the CIE overcast, so any values can be supplied). The command

% gensky -ang 45 0 -c -b 1

writes the following to the standard output:

```
# gensky -ang 45 0 -c -b 1
# Ground ambient level: 0.8
void brightfunc skyfunc
2 skybr skybright.cal
0
3 2 1.00e+00 1.56e-01
```

The comment lines echo the gensky command and recommend a *ground ambient level*. We will discuss the significance of this value later; for the moment, we will restrict ourselves to the meaning of the rest of the output. The last line of the gensky output has three (real) arguments. These are the number 2, indicating the type of sky, the zenith radiance (1.00e+00), and the ground radiance (1.56e-01). The zenith radiance is what we expect, since we specified this as an input argument to gensky. The significance of the ground radiance we leave for later, because our simple scene, for now, will comprise only the sky.

The output from the gensky program provides a brightness function (skyfunc) that we can apply as a modifier to the glow material. The easiest way to include the modifier is to execute the gensky command in the description file. The contents of the file *sky\_ovc.rad* would then be as follows:

#### # CIE overcast sky (Bz = 1)

```
!gensky -ang 45 0 -c -b 1
skyfunc glow sky_glow
0
0
4 1 1 1 0
sky_glow source sky
0
0
4 0 0 1 180
```

The RGB radiance that the sky now assumes is skyfunc *multiplied* by the RGB radiance specified for glow, which here is unity for each of the channels because we want a gray (overcast) sky.

Now we create the octree for this scene, just as before:

% oconv sky\_ovc.rad > sky\_ovc.oct

and then calculate the horizontal irradiance using rtrace (pipe the output through rcalc to obtain the achromatic irradiance directly):

% rtrace -w -h -I+ -ab 1 sky\_ovc.oct < samp.inp | rcalc -e \ '\$1=\$1\*0.265+\$2\*0.670+\$3\*0.065'

which produces the value

2.434001

The exact theoretical value for irradiance from the CIE overcast sky is  $7_{\pi}B_z/9 = 2.443451$ , since  $B_z = 1$ . Our predicted value is in good agreement with this. Note also that rather than being supplied through the pipe by the echo command, the coordinates are now read from the file *samp.inp*.

## 2.3.3 Example: CIE Overcast Sky Defined by Its Horizontal Illuminance

The preceding example showed how to generate a brightness distribution based on the standard CIE overcast sky model. The absolute brightness of the sky, however, was normalized for the purposes of illustration. Furthermore, the input and output were in units of radiance or irradiance. Before we can tackle real-world problems, we need to be able to relate the more usual daylighting quantities of luminance and illuminance to the radiance and irradiance inputs required by gensky. Recall that although the *Radiance* system calculates in units of radiance/irradiance, we will use a constant value for the factor to convert these to luminance/illuminance, or vice versa.

Daylighting practitioners commonly describe a sky in terms of the diffuse horizontal illuminance that is produced by that sky. Recall that the CIE overcast model does not include the sun, so here the global horizontal illuminance will be the same as the diffuse horizontal illuminance. The CIE overcast sky can therefore be fully characterized by the horizontal illuminance, usually given in lux. A realistic horizontal illuminance for a (brightish) overcast sky is 10,000 lux. This is a convenient figure to work with; for example, a daylight factor of 5% corresponds to an illuminance of 500 lux. The gensky program gives us two ways in which we can generate a 10,000-lux CIE overcast sky. We can specify either the zenith radiance (**-b** option) or the horizontal (diffuse) irradiance (**-B** option). The second option is perhaps the more direct, and we shall use that for the next rtrace example

First, we need to modify the gensky command to produce a 10,000-lux sky. The irradiance that corresponds to this illuminance is  $10,000/179 = 55.866 \text{ w/m}^2$ . The line giving the gensky command should now look like this:

#### !gensky -ang 45 0 -c -B 55.866

The rest of the file remains as before. Let's now double-check that this sky is indeed what we specified. Run oconv as before, then execute a slightly modified rtrace command:

% rtrace -w -h -I+ -ab 1 sky\_uni.oct < samp.inp | rcalc -e \ '\$1=(\$1\*0.265+\$2\*0.670+\$3\*0.065)\*179'

The calculation returns the value

#### 9977.17002

which is pretty close to our starting value of 10,000 lux, in fact within 0.3%. Notice that the irradiance output is now multiplied by 179 to convert it to illuminance (lux). So far, the only ambient parameter that we've set for the simulation has been -ab; all the other parameters will use the default settings. Since this scene comprises only a glow source, the parameters that relate directly to the density of the irradiance gradient calculation (i.e., **-aa** and **-ar**) will have no effect. Before we go on to more complex (i.e., realistic scenes), we will first have a look at the sky we have generated. To view the sky, start the **rview** program:

#### % rview -vta -vp 0 0 0 -vd 0 0 1 -vu 0 1 0 -vh 180 -vv 180 sky\_ovc.oct

to give an angular fish-eye view of the entire sky. The view point will be useful later on, so save it in a file called *ang180.vf* using the rview command. A false-color image of the sky will show more clearly the CIE overcast sky luminance distribution:

#### Luminous Efficacy

This conversion factor is the *Radiance* system's own value for luminous efficacy and is fixed at  $K_R = 179$  lumens/watt (lm/w). This should not be confused with the more usual daylighting value, which can be anywhere between 50 and 150 lm/w depending on the type of sky or light considered.

% rpict -vf ang180.vf sky\_ovc.oct \ | falsecolor -s 4000 -l cd/m^2 > ovc\_lum.pic

The luminance scale in the **falsecolor** -s option was set too close to the approximate zenith luminance of the sky, found either from Eq 2-9 or by using the trace command in rview. The default label nits has been changed to the more familiar  $cd/m^2$ , which means the same thing. The false-color image shows what we expect to see from Eq 2-3: a brightness distribution depending only on altitude where the zenith luminance is three times that of the horizon.

#### 2.3.4 The Ground "Glow": An "Upside-Down" Sky

Although it might seem too self-evident to point out, we should remind ourselves that at the horizon the sky "meets" the ground. An actual ground plane of finite extent, say, a disc of radius r, will always fall short of an "infinite" horizon. For any given view toward the horizon, we can make the gap (a black void) between the edge of the ground and the sky appear smaller by using a larger r. However, we can never make them meet. Furthermore, there are good reasons not to introduce an actual ground plane of inordinately large size: the resolution of an ambient calculation will be dependent on the maximum dimension of the scene.

To get around this problem, we use an upside-down sky to represent a luminous ground. To do this, we apply the **skyfunc** modifier to a 180-degree glow source, where the direction vector is pointing downward. To include a glowing ground in our scene, add the following lines to the file *sky\_ovc.rad*:

```
skyfunc glow ground_glow
0
4 1 1 1 0
ground_glow source ground
0
4 0 0 -1 180
```

The glowing ground behaves differently from a glowing sky. Although the same modifier is used for both, *Radiance* can distinguish between the two by testing the z component of any ray's direction vector. Above the horizon, the sky-model brightness distribution is applied, but below the horizon, a constant brightness value is used.<sup>4</sup> Note that as with the sky, the ground brightness is achromatic. The radiance value that will be

<sup>4.</sup> In fact, a sharp-cutoff mixing function ensures a continuous transition from ground to sky. This operates only about the horizon, leaving most of the sky independent of the ground's brightness and vice versa.
used for the ground brightness was determined by the gensky program. It is based on two factors: the sky's (diffuse) horizontal irradiance and the "average ground reflectivity." The horizontal irradiance is either supplied as an argument to gensky or evaluated from the zenith radiance. The "average ground reflectivity" may also be supplied as a gensky argument (-g refl); otherwise, a default value of 0.2 is used (as will be the case for us). The value 0.2 (or 20%) is a typical value for ground plane reflectance. We can check the gensky-supplied value for ground radiance very easily using Eq 2-8, since the ground is in effect a luminous "hemisphere" of constant brightness. Execute the gensky command as it appears in the *scene* file:

#### % gensky -ang 45 0 -c -B 55.866

Recall that the last number of the gensky output for the CIE overcast sky is the ground radiance, which here is shown to be  $3.56e+00 \text{ w/m}^2$ . The illuminance from a hemisphere source of this brightness is  $\pi(3.56 \times 179) = 2001.9$  lux, which is 20% (or 0.2) of the horizontal illuminance due to the sky. We shouldn't worry too much about using an "upsidedown" sky for the ground, but we should be aware of the practicalities. Although the ground radiance is based on the sky's horizontal irradiance, putting something between the sky and the ground will not affect the brightness of either (Figure 2-5). In other words, no matter how built-up the model becomes, with nearby tall structures and so on, the ground radiance (where it is visible) will be the same as for an empty scene. By the same token, a single building is an obstruction. Therefore, all scenes should include a local ground plane that participates in the interreflection calculation. This will ensure that the ground plane brightness is a function of both the sky brightness and the local environment.

#### 2.3.5 Summary

The scene we have constructed thus far is a seamless luminous envelope. The brightness of this envelope is based on a combination of a mathematical sky model and a ground plane reflectance model. We can specify the absolute brightness of this environment using physically meaningful quantities. Environments of this type will contain the rooms, office spaces, and so on, for which we wish to predict daylight quantities.



Figure 2-5. The luminous "envelope" describes luminance as a function of incident direction.



Figure 2-6. Plan view of room.

## 2.4 Case Study II: Predicting Internal Illuminances

In this example, we demonstrate how to predict DF levels for a simple scene. We show how to automate the execution of the rtrace program and how this can be used to test for convergence in the ambient calculation. The section concludes with an introduction to the dayfact script.

#### 2.4.1 A Simple Space

The room we will use is 3 meters wide, 9 meters deep, and 2.7 meters high. These dimensions are typical of a deep-plan office module. The long dimension is aligned north-south; the room has a single south-facing window of width 2.6 meters and height 1.5 meters. The south wall is 0.2 meter thick and the window is set in the middle of this wall, so there are internal and external windowsills of depth 0.1 meter. The plan view of the room is shown in Figure 2-6. The room description is maintained in three scene files:

- room.rad—walls, floor, ceiling geometry
- mat\_gray.rad—material description for walls, floor, ceiling geometry
- window.rad—window geometry and material description

#### 2.4.2 Computing Daylight Factor Values

A typical analysis might begin by determining the daylight factor along the midpoint of the room. The file *samp1d.inp* contains the coordinates of the positions at which the DFs will be evaluated. Executing the rtrace command from a shell script is a convenient way to automate systematic explorations of parameter settings. The following script shows how to automate the DF calculation and test the sensitivity of the prediction to the number of ambient bounces. For this test, we cover the range -ab 1 to -ab 5.

#!/bin/csh -f

# loop through ab
foreach ab (1 2 3 4 5)

echo "Ambient bounces" \$ab

# Calculate DF



Figure 2-7. Daylight factor plots showing the effects of the -ab parameter. The top graph (a) uses fewer samples over the hemisphere, -ad 512 -as 0, than the bottom graph (b) which uses -ad 1024 -as 64.

rtrace -w -h -I+ -ab \$ab -aa 0.2 -ad 512 \ -as 0 -ar 128 scene.oct \ < samp1.inp | rcalc -e\ '\$1=(\$1\*0.265+\$2\*0.670+\$3\*0.065)\*179/10000\*100'

#### end

For all other parameter settings, the current rtrace defaults will, of course, be applied.<sup>5</sup> The predictions follow a characteristic pattern as shown in Figure 6.7: close to the window, the predictions for the range of -ab are relatively similar (17% to 20% at 0.5 meter). Farther away from the window, where interreflection becomes more important, they agree less (0.24% to 1.26% at 5 meters). We expect the predictions for -ab 5 to be greater than those for -ab 1, but sampling variance may mask that. We also expect the illumi-

<sup>5.</sup> Some of these are declared in the script to allow comparison later on. Default values occasionally change when a new version of *Radiance* is released.

nance, and therefore the DF, to gradually decrease away from the window. The DF curves in Figure 2-7(a) nevertheless confound our expectations: the predictions are simply not good enough to show a consistent pattern in the data. This is especially noticeable at the rear of the room, where the curves are very jagged.

You may be relieved to learn that we don't *always* have to work through a series of ab simulations before we can discover that one or more of the other ambient parameter settings was too coarse. We can, for many situations, use the -ab 1 as a diagnostic to help us make better choices for some of the other settings. Recall that for -ab 1, the illuminance predicted will be that due to the portion of sky that is directly visible from the point of calculation, that is, the direct sky component. This component is usually the major contributor to the total illuminance at that point. If we get the direct sky component (-ab 1) wrong, our predictions for the total illuminance (-ab > 1) will be also poor. For this space, we know that some sky should be visible from all the points for which we want to predict the DF. Examination of the data for -ab 1 reveals that for several points at the back of the room, the DF was predicted to be zero. This tells us that too few rays were spawned to guarantee adequate sampling of the window from all points in the DF plane. To remedy this, we should set -ad to a higher value, say 1024. We can further improve our estimates at -ab 1 by enabling the ambient supersampling option (-as) in the rtrace calculation. The value we set for -as is the number of extra rays that will be used to sample areas in the divided hemisphere that appear to have high variance. In other words, for this scene, additional rays will be used to sample around the window-assuming, of course, that the ambient division sampling picked up the window in the first instance.

We now repeat the DF predictions with -ad 1024 and -as 64. The ambient accuracy is the same as before, but the ambient resolution has been relaxed to -ar 16. These DF predictions look much better as shown in Figure 2-7(b). The curves are fairly smooth and the rank order is the same at all points along the DF plane. Which of these predictions, if any, are correct? Before we can answer this, we need to distinguish between *absolute* accuracy and *useful* accuracy. For daylighting purposes, it is important to obtain reliable predictions of the DF distribution in the critical range 10% to 0.5%. The recommended minimum DF for full daylighting is 5%, and the 1% value is generally considered to be a minimum below which the provision of daylight can be considered negligible. Thus, we need to be fairly certain of the DF down to the 1% level. There is little practical use in resolving the 0.1% DF boundary, or in distinguishing between the 0.02% and 0.05% levels. With this in mind, there is little to choose between the -ab 4 and -ab 5 curves. Would it be worthwhile predicting the DFs for -ab greater than 5? For this case, no. We can see from the curves that the difference between successive DF predictions for higher -ab gets smaller each time. Remember, the predictions will never be exact, so the DF curves for scenes like this will never be perfectly smooth. The basic tenets for setting the ambient parameters are

- 1. Set -ad high enough to capture the visible luminous features at the first bounce.
- 2. Give sufficient ambient bounces to redistribute the light.
- 3. Set the remaining ambient parameters to sufficiently high resolution to deliver *acceptably* smooth results.

#### 2.4.3 The Dayfact Script

The dayfact script is a user-friendly interface to the illuminance prediction capabilities of rtrace. The script essentially performs the same rtrace illuminance calculation shown above, but in addition it can create contour plots of

• Workplane illuminance

- Workplane daylight factors
- Potential savings resulting from daylight illumination based on a given lighting design level

The script works out the points in the DF plane based on user-supplied values for the plane origin and dimensions. It also determines the global horizontal illuminance directly from the gensky arguments. Try the script out using one of the ambient parameter combinations from the preceding example.

Dayfact is a handy utility to have, but because it hides some of the workings of rtrace, we do not recommend that you use it to investigate convergence and so on. Application-specific shell scripts are far better suited to exploring these aspects of the ambient calculation. The contour-level defaults built into dayfact may not be ideal for everyone and cannot be overridden. Users who do want *Radiance* contour images are urged to use the falsecolor script. Taking a dayfact-produced illuminance picture as input, falsecolor offers a great deal of user control over contour levels, color mapping, and so on. See the falsecolor manual page for details. Alternatively, you can import the illuminance prediction data into a proprietary software package that can produce contour, surface plots, and so on. The next example shows how additional objects, ground plane, and so on affect the ambient calculation, and shows how to account for them correctly.

## 2.5 Case Study III: Introducing Complexity

In this section, we add a ground plane and a nearby building to our simple scene. We model the ground plane as a disc of, say, radius 20 meters, centered on the origin. The diffuse reflectance for the disc material is the same as the ground plane reflectance used in the gensky command (0.2, or 20%). We can guess that the effect of the ground plane will be to slightly lower the DFs calculated in the preceding example, because, as we mentioned earlier in the chapter, we are replacing (locally) a ground glow of constant radiance with a material whose brightness now depends on the geometry and reflectance of nearby objects as well as the sky (Figure 2-8). In the vicinity of the room, the calculated ground plane radiance will be less than the ground glow radiance because the room obscures some of the ground plane's view of the sky. Rtrace now has to evaluate the ground plane brightness during the simulation; we should therefore consider the additional cost to the ambient calculation. This is best explained using a simplified ray





diagram to represent the ambient bounces (Figure 2-9). The ground component of internal illuminance is, in effect, "one bounce further away" with a ground plane than it is with a ground glow. The same will be true for nearby buildings that obscure the sky (glow)—the building facade brightness will have to be evaluated as part of the ambient calculation. To complete the modifications to the scene, we now add an external obstruction: a nearby building. We represent this using a box 9 meters square and 12 meters tall, which has a diffuse reflectance of 30%. The box is positioned so that it faces the room window and obscures much of the view of the sky from inside the room. The DF predictions are repeated as before, only now we increase the maximum -ab to 7.

The results for two ambient accuracy settings are shown in Figure 2-10. The DF curves in Figure 2-10(a) are surely unsound: the -ab 1 curve shows an *increase* in DF from 0.5 to 1 meter, and for higher -ab the DF at the rear of the room is *greater* than for the unobstructed case. Before we despair, let us examine the predictions obtained using the higher ambient accuracy in Figure 2-10(b). The DF curves now begin to make sense. Why the dramatic difference? This example was contrived to create the circumstances under which the irradiance interpolation algorithm would, for certain parameter combinations, perform relatively poorly. To appreciate why this has happened, we need to recognize that irradiance interpolation can occur across the points supplied to rtrace in the same way that it can across the surfaces (i.e., pixels) computed by rpict. In other words, hemispherical sampling (at the first level) will not necessarily be initiated from every point in the DF plane supplied to rtrace.

To understand the possible outcomes, we need to examine in more detail the way the simulation progresses. Hemispherical sampling at the first level will always be initiated from the first point supplied to rtrace provided that  $-ab \ge 1$ . From the rays spawned at the first point, the ambient calculation will predict the way the indirect irradiance is changing about that point—this is the indirect irradiance gradient. The calculation also evaluates an estimation of error associated with the prediction for the irradiance gradient. These quantities, together with the ambient accuracy parameter, are used to determine a "radius of validity" for the gradient estimate. If the next point supplied to rtrace is within this radius, the indirect irradiance is evaluated from the gradient estimate and not from further hemispherical sampling. In other words, the value is obtained by a form of interpolation rather than by actual sampling. This is a somewhat abridged description of the way the ambient calculation operates; see Chapter 12 for a detailed explanation.





Factors that influence the scale over which interpolation may occur are

- Ambient accuracy (-aa)
- Ambient resolution (-ar)
- Maximum scene dimension

The minimum possible spacing between hemispherical sampling points is the maximum scene dimension multiplied by the ambient accuracy divided by the ambient resolution. We can confirm that the bad results for -aa 0.2 arose from interpolation by plotting on the abscissa of both graphs the points in the DF plane from which hemispherical sampling was initiated ( $\Delta$  markers). For -aa 0.1, sampling was initiated from all the points supplied to rtrace; for -aa 0.2, it was from every other point. Note that a doubling of the value for ambient resolution (i.e., from 16 to 32) would *not* necessarily have effected the same cure. This is because the -ar parameter acts as a limiting device. If you are already running up against the -ar limit, increasing the setting will result in a higher density of sampling. If the limit has not been reached, then increasing -ar should have no effect. It should now be apparent why the ground plane size should be chosen with care. This is usually the largest surface in any scene, and its size will directly affect the sampling density for any given -aa and -ar. As a rule of thumb, the ground plane should be at least twice the maximum extent (horizontal or vertical) of the scene contents.<sup>6</sup>

We urge you to develop this exploration of the ambient calculation one or two stages further. Add or change, one at a time, features of the scene and investigate the effect that this has on the convergence characteristics of the ambient calculation. Try to anticipate the effect of changes in scene composition and/or parameter combination. The *Radiance* ambient calculation may appear difficult to control the first few times. However, by carrying out a handful of exploratory tests, you will begin to develop an almost intuitive sense of how to manage the simulation to good effect.

## 2.6 DF Prediction: Tricks of the Trade

Here are a few hints on how to accelerate the modeling and evaluation process.

## 2.6.1 Appropriate Complexity

For illuminance (DF) prediction, it is not normally necessary to model nearby external obstructions in fine detail. Most building facades can be modeled using a single material whose reflectance is an area-weighted average of the reflectances of the major facade elements. It may be necessary to pay attention to surface finish, especially when the adjacent building is clad in mirrored glazing.

Where visual realism is not intended, the scale of modeling complexity should generally be commensurate with the scale of the effect of the modeled structures on internal light levels. A good example of putting this principle into practice might be a DF analysis for an office module in an atrium building (Figure 2-11). Nesting of a moderately detailed scene description in a simpler structure should not compromise the accuracy of the DF predictions, but it can produce significant savings in modeling time.



Figure 2-11. Nesting of a detailed office module in a coarsely modeled atrium building.

<sup>6.</sup> The dimensions of a scene can be obtained using the getbbox program.

## 2.6.2 Views from the DF Plane

It often helps to visualize the scene from one or more view points along the DF plane. Choose a point in the DF plane, say, near the window, and generate a view looking directly upward—use the interactive previewer rview. Set the view type to hemispherical (**h**) and the view angles to 180 degrees. As the image resolution gradually improves, you will see a hemispherical projection view of the sky through the window. Set -av to some value to reveal the other surfaces. This makes it easier to understand the image, but what we are really interested in is the view of the sky. Compare the views with and without the external obstruction (Figure 2-12). The impact of the nearby building on internal light levels can be roughly estimated just from these images. Since the building obscures about half the view of the sky, the DF values will be approximately halved. This is a worst-case guess—it will, of course, depend on the facade reflectance. Examining a scene in this way will help you to appreciate the luminous environment "from a light meter's point of view."

## 2.6.3 The Ambient Exclude/Include Options

It is possible to limit the number of surfaces that participate directly in the indirect irradiance calculation. By limiting the scope of the ambient calculation, we can make significant savings in simulation time. This is achieved by telling rtrace not to include certain named material modifiers in the indirect calculation. Instead, the named materials will receive the constant ambient-value approximation. There is a complementary option called ambient include. With this option, only the named materials participate in the indirect calculation; the rest receive constant ambient-value approximation. We should take care to exclude only those materials that play no major part in the illumination of the space. The rtrace manual page explains how the options are enabled.

## 2.7 Case Study IV: Creating Skies with Sun

There are two *Radiance* sky generator programs. The "official" program, which is part of the standard *Radiance* release, is called gensky; it offers a selection of sky model types based on CIE standards. The other program is called **gendaylit**; it is one of the many *Radiance* extension programs, that is, it is not part of the standard release but is freely available to all users. We will discuss this program briefly near the end of this section.



Figure 2-12. Two views from the daylight factor plane: unobstructed view (a), and view with nearby building (b).

#### 2.7.1 Gensky

In addition to the standard CIE overcast model, the *Radiance* sky generator program can produce sun descriptions and sky brightness distributions that correspond to either the CIE clear or intermediate skies. The gensky program has several modes of operation, and unless you are careful, you can end up using a sky generated from default geographical parameters that are not appropriate to the intended location. Try the command

#### % gensky -defaults

to check what the current defaults are. Furthermore, if you do not explicitly specify parameters in the gensky command that are related to absolute sky and sun brightness, these quantities will be evaluated using standard functions. These quantities also may not be entirely suitable for your location.

The only way to be certain of the sky and sun brightness is to supply them as gensky arguments. The sky brightness can be specified in terms of either the zenith radiance (**-b** option) or the horizontal diffuse irradiance (**-B** option). The sun brightness is either given directly (**-r** option) or evaluated from the horizontal direct irradiance (**-R** option). Most users will want to generate sun and skies based on either measured or yardstick values for global horizontal and diffuse horizontal illuminance. For example, say we want to generate a sun and intermediate sky description from these measured quantities: a global horizontal illuminance of 66,110 lux and a diffuse horizontal illuminance of 41,881 lux. The sun position was recorded as altitude 49.6 degrees and azimuth 222.5 degrees. The altitude is the angle in degrees above the horizon and the azimuth is measured as degrees east of north. Note that this azimuth convention is different from the one used in *Radiance*, which is degrees west of south, so we need to subtract 180 degrees from the measured azimuth value. From the illuminance quantities, we need to deduce the correct gensky arguments for the -B and -R options—they are the easiest to figure out from what we have.

horizontal diffuse irradiance = 
$$\frac{\text{horizontal diffuse illuminance}}{\text{luminous efficacy}}$$
 (2-10)  
233.97 =  $\frac{41881}{179}$   
nd

and

horizontal direct irradiance = 
$$\frac{\text{hor. global ill. - hor. diffuse ill.}}{\text{luminous efficacy}}$$
  
135.35 =  $\frac{(66110 + 41881)}{179}$ 

Thus, our gensky command, executed in a scene file, would look like this:

# Intermediate sky with sun
# Igh=66,110 lux, Idh=41,881 lux.

!gensky -ang 49.6 42.5 +i -B 233.97 -R 135.35

```
skyfunc glow sky_glow
0
4 0.986 0.986 1.205 0
sky_glow source sky
0
0
4 0 0 1 180
```

Remember that the material and surface specifications for the sky should follow the gensky command. This sky has a small blue excess specified for the glow material (see below). You may wish to generate a sun position based on an actual time of day, in which case the site latitude, longitude, and standard meridian need to be known. The following example demonstrates how to set these values. See also the gensky manual pages for the full list of options.

## 2.7.2 Time of Day Image Sequence

The progression of the solar beam in a space can be shown by images generated for different times of day. The creation of these can be automated by treating the gensky (or gendaylit) time parameters as shell variables. Here we show how to generate a dawn-todusk sequence of images. The location is Athens; the date is July 1. The geographical coordinates of Athens are 37.97 degrees N and 23.5 degrees E, but the site meridian on which local time is based is at longitude 30.0 degrees E, that is, two hours ahead of the time at the Greenwich meridian. The gensky command for an intermediate sky at noon on this day is

```
% gensky 7 1 12 +i -a 37.97 -o -23.50 -m -30
```

Note that negative angles are used for degrees east of Greenwich (or south of the equator). Experienced shell programmers all have their own styles and are likely to do things slightly differently. The example below illustrates just one of the many ways to automate scene and picture file creation.

```
#!/bin/csh -f
```

```
#
# Set month, day and geographical coordinates
#
set mon = 07
set month = July
set day = 01
set coord = (-a 37.97 -0 -23.50 -m -30)
set ab = 2
set ad = 512
set as = 128
set ar = 64
set ar = 64
set aa = 0.3
```

foreach hr (05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20)

```
set skypar = ($mon $day $hr +i $coord)

set gambv = `gensky $skypar | rcalc -i '# Ground ambient\level: ${ga}' -e '$1=ga'`

if ($gambv == 0) goto SKYDARK

set inamb = `rcalc -n -e '$1='''$gambv'''/2'`

set inamb = ($inamb $inamb $inamb)
```

set ambpar = (-ab \$ab -ad \$ad -as \$as -ar \$ar -aa \$aa -av \$inamb)

oconv -i scene.oct '\!gensky '''\$skypar'' sky.rad > hr.oct

rpict -vf view.vf \$ambpar \ -x 1024 -y 1024 hr.oct \ | pfilt -1 -e 0.06 -x /3 -y /3 \ | pcompos-00 \!psign '''\$month''' '''\$day''' '''\$hr'''h00' 0 0>\$month\$day\$hr.pic

rm hr.oct

#### SKYDARK:

#### end

We do not intend this book to be a treatise on shell programming, so we will describe this script purely in functional terms—what it does, rather than why we do it in this way. First, we define shell variables for the month (number and name), the day, and the geographical coordinates. We then define most of the ambient parameter shell variables. The foreach line starts the loop; here we cycle through all the hours listed in the parentheses. Next, we group all the gensky parameters into one shell variable: skypar. The four lines that follow are used to set a shell variable for the constant ambient value. The value itself is based on the ground ambient value, which is extracted from the gensky output; that is why we execute gensky here. This scene was very open, so the constant ambient value was set to half the ground ambient value: a rough estimate, but adequate for this task. Included here is a test for night (that is, zero-brightness) skies. Next, just to be neat, we group all the ambient parameters to one shell variable. Then we make the scene octree. There is no need to recreate the entire octree when we are changing only the sun and sky. So to maximize efficiency, we use the include option of oconv to specify a previously created scene octree. This octree contains everything but the sun and sky. You will notice that the gensky command is executed inline with oconv. The file sky.rad contains the material and source descriptions for the sky and ground glow materials. Remember that this always follows the gensky command or output. The rendering command looks a little daunting, but it is really quite straightforward. For each pass of this command,

- 1. A picture is generated; maximum dimension is 1024 pixels.
- 2. The picture is filtered down to one third the original size and the exposure is set.
- 3. A picture label based on the settings of the shell variables for month, day, and hour is created.
- 4. The label is added to the filtered image.

This could be achieved in four separate steps, each producing its own output, three of which would be discarded. By using the UNIX pipe, however, we avoid the intermediary output, creating only what we want to keep.

On completion, we are left with a sequence of images showing the illumination of the scene at various times of day. These could be combined into a single picture, or even used as the basis for an animation. The script could easily be changed to cycle through other parameters, say, month, day, building orientation, and so on.

On the CD-ROM, we have included an example animation sequence showing a daylit interior throughout the hours of a day. The exposure of the images was computed to correspond to human visual response using the new pcond program.

### 2.7.3 Gendaylit

Another *Radiance* sky generator program, gendaylit, (written by Jean-Jacques Delavnay) produces a description based on the Perez All-Weather model [PSM93]. With this model, the generator program determines the sky conditions (overcast, intermediate, clear, and so on) based on the input parameters. You are therefore spared having to choose a particular sky type. For this reason, it is perhaps the best sky model to use with a time series of measured illuminance data, for instance, for an automated set of simulations. The gendaylit program source code is included on the CD-ROM; its use is described in the accompanying manual page.

### 2.7.4 Sky Spectral Radiance Values

Spectral radiance values for nongray skies should be calculated so that they do not affect the overall sky luminosity. To ensure that this is the case, the following condition should hold:

$$1 = 0.275L_R + 0.670L_G + 0.065L_R$$
(2-11)

where  $L_R$ ,  $L_G$ , and  $L_B$  are the RGB radiance values for the sky glow material. The same should be true for the ground as well.

## 2.8 Rendering Scenes Illuminated by Sunny Skies

So far, the emphasis has been on illuminance prediction and how to obtain highly accurate values. A lighting designer will have no problem interpreting these data, but this is only part of the story. The majority of people can only really appreciate an architectural design once they have seen the finished building. If you want to know in advance what it will look like, you need to visualize it somehow. The capabilities of the *Radiance* system make it particularly well suited to the rendering of architectural scenes under daylight illumination.

Recall that when we render a scene, we are not striving for absolute accuracy in the prediction of luminance for every pixel in the image. In fact, the accuracy criteria we employ for judging images include many subjective elements. With this in mind, we demonstrate in this section a few different approaches to image synthesis. You will by now be aware that it is impossible to recommend a single set of rendering parameters that can guarantee an efficient solution for every conceivable design type. It should, however, be possible to anticipate from the actual design and lighting conditions the best approach to solving the problem.

### 2.8.1 A Note about the Rad Program

This chapter is really intended for those users who will eventually want to carry out exacting quantitative work and/or produce high-quality renderings of daylightilluminated scenes. For either of these tasks, it helps to gain a detailed understanding of how key features of the *Radiance* system work. A more direct route to producing renderings, however, is to use the **rad** program. This "executive control" program will automatically determine many of the parameter values based on a few intuitive variable settings. Rad will also construct a "rendering pipeline" for you. This could include fairly complex operations, such as a mkillum preprocess of windows. The rad program, therefore, screens you from many of the intricacies of the rendering process; it has greatly improved the overall usability of the *Radiance* system. Try out the rad program and see if suits your needs—its use is described in Part I, Tutorials (Chapters 1 through 3). Sooner or later, though, and particularly for research applications, you will want to exercise complete control over all aspects of the simulation. The sections that follow will show how this can be achieved.

#### 2.8.2 The Simple Space Lit by a Sunny Sky

Recreate the simple room scene octree using the intermediate sky description. In-clude the ground plane but leave out the external obstruction. Use the rview interactive renderer to view the scene from somewhere at the back of the room, looking toward the window at about eye-level height. All that you will see at first is the sky through the window and the sun patch on the floor/wall. Initiate the inter-reflection calculation by setting the number of ambient bounces to 1. Restart the image with the command new.<sup>7</sup>

You now begin to see more of the room, but it will appear blotchy because the default ambient parameter settings for rview are fairly coarse. At this stage in the chapter, we should be able to anticipate the pattern of light transfer in this scene for ambient bounce settings of 0 and 1. A pair of simplified ray diagrams illustrate some of the light transfers we can expect (Figure 2-13). With the ambient calculation switched off, we see the sky (glow) through the window and whatever sun patches are directly visible from the view point. With the interreflection calculation switched on, several other routes to the eye (that is, the camera) become possible via hemispherical sampling. Three of these are illustrated in the second diagram of the figure. Each one shows how a distinct component of internal illumination might be evaluated during the simulation. The point in the ray path where hemispherical sampling was initiated is marked by a shaded semicircle. The illumination components and the source origin are

- 1. The ceiling illuminated by the sun patch inside the room (solid rays)
- 2. The ceiling illuminated by the sun patch outside on the ground plane (dotted rays)
- 3. The floor inside the room illuminated by the sky glow (dashed rays)

It is important to appreciate the element of chance at work whenever hemispherical sampling is used. If the number of initial sampling rays (-ad) were set too small, the calculation might, for example, "miss" the sun patch even though it was "visible" from the point at which the rays were spawned. By the same token, an unrepresentative chance "hit" of a small sun patch by one of the sampling rays can produce a gross overestimate for indirect irradiance. In a rendering, the artifacts associated with ambient undersampling are all too apparent—bright and dark blotches. To avoid this, we need to set a sufficiently high value for the number of initial sampling rays.

Hemispherical sampling is generally too expensive to initiate at every surface visible from the eyepoint (that is, from every pixel). The calculation needs good indirect irradiance estimates from sampling at a limited number of locations. We then rely on the irradiance interpolation algorithm to estimate the in-between, or missing, values. To

<sup>7.</sup> Note that further increases in the -ab value from within rview will not show up in the onscreen rendering (even after issuing a **new** command) because the cached values will be reused and they were computed with only a single bounce.



Figure 2-13. Possible light transfers for ambient bounces equal to 0 (a), and 1 (b).

generate a fairly smooth rendering for the sunlit space, accounting for the first level of interreflection, we would need to set moderately high resolution values for the ambient parameters. To approximate the effect of the higher-level reflections, we should set a value for the -av parameter. In a later section (Visualizing a Highly Detailed Atrium Scene), we show how to obtain a good estimate for this parameter using rview. A rough guess, however, would be something in the range of 1/50 to 1/200 of the ground ambient value (obtained by executing the gensky command).<sup>8</sup> You may decide that -ab 1 is insufficient to model the major light transfers, and that -ab 2 is needed. In fact, this is almost certainly the case, because by using only one ambient bounce, we fail to account for the externally reflected component of *sky light*. This is likely to result in significant underestimation of the ceiling luminance near the window, since this part of the room has a good "view" of the (external) ground plane.

#### 2.8.3 The Mkillum Approach

We can somewhat reduce the element of chance in our calculations for important light transfers by treating the window opening in a special way. The *Radiance* system allows you to select known sources of light (windows, skylights, and so on) and precompute light output distributions for them. They are then moved from the indirect (stochastic) calculation to the direct (deterministic) calculation. The program we use for this task is

<sup>8.</sup> This range in percentage terms, 2% to 0.5%, corresponds approximately to the daylight factor about the middle of the room.

called mkillum. To illustrate the effectiveness of this approach, consider hemispherical sampling spawned at the rear wall of the room and also at the window plane. At the rear wall, the window subtends a solid angle that accounts for about 5% of the hemispherical "view" normal to the wall surface. Therefore, only about 5 in every 100 rays spawned from this point will directly sample the luminous environment through the window— even though we know the window to be the only "source" of illumination. The same sampling strategy at the window plane, however, will cause about half the rays to sample the sky and the remainder to sample the ground. This is how mkillum works; you direct the program to determine a light output distribution for the window based on the sampling of incident radiation and the glazing transmission properties. In any subsequent calculation or rendering, the glazing elements are treated as "secondary light sources." Note that mkillum can account only for the diffuse component of light that passes through the glazing; the direct and specular components are unaffected.

Mkillum parameters can be specified in the scene description file, but on first encountering the technique, you may prefer to control all aspects of the calculation from the command line. In this case, you must keep the window description, materials, and surfaces in a separate file. To create a scene octree with the modified window description usually requires three stages:

- 1. Prepare scene octree in the normal way.
- 2. Use mkillum to compute the light output distribution of named glazing elements, usually one or more polygons. On completion, the program will have created new window description(s) using a special light source material called *illum*. In addition, there will be data files, one for each illum surface, that contain the material's light output distribution.
- 3. Recreate the scene octree, replacing the original window description with the modified light source window.

The commands might be as follows:

```
% oconv room.rad window.rad sky.rad out.rad > scene.oct
% mkillum [rtrace options] scene.oct < window.rad > mkiwin.rad
% oconv room.rad mkiwin.rad sky.rad out.rad > mkiscene.oct
```

What rtrace settings you use will depend on which light transfers you think need to be modeled, and on the complexity of the external scene. A series of simplified ray diagrams<sup>9</sup> (Figure 2-14) shows what ab settings will account for these components of diffuse radiation incident at the window:

- The diffuse component of light from the glow sky (b)
- The diffuse component of the first-order reflection of solar radiation from outside surfaces, for example the ground plane (c)
- The diffuse component of the first-order reflection of sky radiation from outside surfaces, for example the ground plane (d)

For the majority of scenes, setting –ab 2 is usually sufficient to account for most of the diffuse light transfer paths to a window

Ordinary *Radiance* light sources are opaque; if this were the case with the illum window, we would not be able to see through it. To avoid this, the illum sources have a dual nature. When treated in the direct component calculation, they behave like ordinary light sources, but when viewed directly, they revert to the original material description.

<sup>9.</sup> Here we ignore the fact that *Radiance* actually traces rays backward from the eye, and instead adopt the more intuitive convention that rays emanate from luminous sources.

The mkillum approach requires a certain amount of user expertise to be implemented effectively for all but the simplest of cases. We therefore hope that if you are interested, you will take some time to familiarize yourself with the technique. The "Drafting Office" example in the *obj/virtual* subdirectory is a good place to start. The scene, devised by Greg Ward Larson, demonstrates fairly advanced use of the mkillum approach.

## 2.9 Visualizing a Highly Detailed Atrium Scene

Every design will present its own set of problems. With an ambitious project, even the experienced *Radiance* user is likely to chance upon one or more unforeseen difficulties. While these are undeniably frustrating at times, the possibility of discovering new techniques with *Radiance* usually serves to inspire the user—discovery is, after all, part of the fun. The visualization and analysis of a design known as the Foggo Atrium was one such project.

The IESD Center at De Montfort University, UK, was invited to participate in a casestudies design project for low-energy urban offices. The proposed design, by the architectural firm Peter Foggo Associates, was for a building that avoided air conditioning and made maximum use of daylight. The floor plan of the five-story building was fairly deep: 16.5 meters and 15 meters (upper two stories). The design would incorporate a linear atrium to provide core illumination. The lighting analysis brief called for both daylight factor prediction and visualization of the scene. The daylight factors were required to assess the effectiveness of external facade shading devices, and of the atrium as a provider of illumination. The images, on the other hand, were conceived to create a strong visual impression of what the design might look like.



Figure 2-14. The direct solar component (a) is not accounted for by mkillum because it is part of the *Radiance* direct calculation. The direct sky component (b) is accounted for by mkillum, as is the indirect solar component (c), and the indirect sky component (d). A synthetic image of the atrium, (Figure 2-15), shows the degree of complexity that was achieved for this model. The entire *Radiance* scene description was created from the command line. This task was not as horrendous as it might first appear. Once a basic office module had been worked up, it was easy to generate much of the structure using the repeated-transformation option in **xform**. In fact, the scene description consists of hierarchies of repeated transforms at various scales—for example, ceiling lights, a single office module, a row of office modules, and so on. For the daylight factors, however, a fully detailed office module was nested in a simple atrium model using the technique described in the section called DF Prediction: Tricks of the Trade.

## 2.9.1 Ambient Calculation Parameter Values

Having created the scene description, how do we go about selecting values for the ambient parameters? First, we need to decide what light transfers are needed to produce the major illumination components for the rendering we have in mind. This will depend to some degree on how we choose to illuminate the model, and on the view parameters. For open scenes, it is invariably the case that some direct solar illumination greatly enhances the impact of the rendering. Overcast-sky illumination looks dull and dreary in renderings and in real life. So we opt for a sunny sky description, in this case a CIE clear sky with sun. From what we know of the model geometry and orientation, we can decide on a viewpoint and make a good guess at the solar altitude and azimuth positions. A visual check with rview will tell us whether or not we have chosen well.



Figure 2-15. A daylight simulation of an atrium designed by Foggo Architects, U.K. (Model courtesy of John Mardaljevic)

This atrium has numerous facade windows and many roof glazing elements. With so many potential sources of light, it would be very inefficient to calculate their contribution in the deterministic domain. Preprocessing of glazing elements to secondary light sources is therefore not advised for this type of building. Consequently, we will rely exclusively on the ambient calculation to model the interreflection.

The following sections show, step by step, how to make informed choices for ambient parameter values *before you begin any batch rendering*. Trial and error can be an instructive process. However, when, as here, the number of possibilities is nearly infinite, we need to drastically reduce the options before we do any exploring.

#### Setting -ab

Having settled on a view point and a sun position, we then set the ambient calculation parameters. The most important of these is, of course, the number of ambient bounces. We could go for a low-cost rendering and set -ab 0, but the final result, we know, would not be very convincing. At one ambient bounce, the sky and sun patch become potential sources of indirect illumination. At two ambient bounces, we have the potential to calculate indirect illumination for surfaces that have no direct line of sight to either sky or sun patch. This should be sufficient to give most of the surfaces that we can see a *calculated* diffuse irradiance. We approximate the effect of subsequent ambient bounces with a constant ambient value.

#### Setting -av and -aw

The constant ambient value option serves two functions. The first is to participate in the interreflection calculation, where it approximates the contribution of the higher-order reflections (see Chapter 12 for a description of the way this approximation is calculated). The other function is as sole provider of indirect illumination to surfaces excluded from the ambient calculation (see the Ambient Exclude/Include Options section, below). It usually pays to spend a moment or two to determine a "good" value for this parameter. With simple models, a value can sometimes be arrived at by analytical means. For the majority of scenes, however, it is more likely that you will need to base the estimate on calculated values. Here, we demonstrate how rview can be used to make a reasonable estimate for a constant ambient value. Where in the scene should we determine this value? The average radiance in the middle of the office floor at level 2 will be very different from the average radiance at the top of the elevator shaft. We decide by anticipating where in the scene the ambient calculation will expend the greatest effort. This is most likely to be for the office ceilings, many of which are visible from our viewpoint. Consequently, a "good" ambient value for the office spaces is what we should determine. This can be achieved in the following way:

- 1. Start the previewer rview with the irradiance option (-i) enabled, -ab 1, and maybe ad set to higher than the default.
- 2. Wait a while for some detail to appear, then select a region in shade to refine (frame option). In this case, a bit of the ceiling at level 2 would be suitable.
- 3. After some further refinement, pick out and display the irradiance evaluated at a surface on the ceiling (use the trace option). We call this value *I*.
- 4. Recall that a uniform radiance that produces an irradiance, *I*, is simply  $I/\pi$ . (See Eq 2-8.)

Try this value  $(I/\pi)$  with the ambient bounces set to zero. Does it give similar indirect illumination for the same surface? If yes, this is the value to use.

The ambient weight parameter -aw, if enabled (i.e., -aw > 0), will modify the default ambient value in a moving average as new indirect irradiances are computed. This may produce more accurate renderings for scenes where the luminance extremes, and therefore the indirect contributions, are not too great. However, this is rarely the case for renderings with daylight, and it is usually safest to disable this option, setting -aw 0.

#### Setting -ad and -as

Having decided on values for -ab and -av, how do we go about setting the remaining ambient parameters? The sun patches on the floor and structure of the atrium will be significant sources of indirect illumination. To capture these potential sources, we should use a relatively large number of ambient divisions, in this case -ad 1024. Ambient super-sampling should therefore be set to about one half or one quarter of this value.

#### Setting -aa and -ar

Our view of the atrium will reveal an enormous amount of fine-scale detail, for example the numerous ceiling lights and acoustic baffles. None of these objects is seen really close up, but we still want to calculate values for them rather than use a constant ambient approximation. Otherwise, we would not see, in the shading, the local illumination effect of the sun patch. Exact shading for each and every surface, however, is not really necessary; moderate irradiance interpolation errors over the scale size of a ceiling fixture should not be too conspicuous in the final image. Thus, a moderately accurate value should suffice. For this rendering, -aa 0.3 was used.

Having settled on a value for -aa, we can base the ambient resolution on a minimum separation for indirect irradiance values in the cache. In other words, for distances less than this minimum, the calculation will always resort to interpolation, rather than initiate more sampling, regardless of the error estimate associated with that interpolation. This prevents the calculation from expending massive effort resolving irradiance gradients over negligible scales. Strictly speaking, this distance gives the scale at which the interpolation accuracy *begins* to deteriorate from the -aa setting. How do we decide on a magnitude for this scale? It often helps to evaluate this scale for a range of -ar and then to choose the value that gives the best compromise between speed and accuracy. The scene dimension,  $D_{max}$ , is found from the scene octree using the -d option of **getinfo**. For this atrium, it was 99.2 meters. The minimum separation for cached irradiances,  $S_{min}$ , is given by

$$S_{min} = \frac{D_{max} \times -aa}{-ar}$$
(2-12)

For -aa 0.3, the  $S_{min}$  for a range of -ar are given in Table 2-1. The third column gives the approximate relative cost of the calculation based on a minimum ambient resolution of 32. From these values, we can make a reasonably informed choice for -ar and anticipate the trade-off between accuracy and speed. For the minimum -ar listed, the potential exists for poor irradiance interpolation over scales of about 1 meter. These could be quite conspicuous from our view point, whereas (potentially) inaccurate shading over scales smaller than about 0.25 meter is far less likely to impair image quality. Higher resolution is of course possible, but at some cost. With this in mind, an ambient resolution of 128 seems a reasonable compromise.

S <sub>min</sub> [m]	-ar	Relative cost
0.93	32	1
0.47	64	4
0.23	128	16
0.12	256	64

#### Table 2-1. Minimum separation and relative computational cost for a range of -ar settings.

#### Ambient Exclude/Include Options

Having set the parameters that control the computation of indirect irradiance, we should decide whether we want to exclude any materials from this calculation. Excluded materials will use the ambient value approximation directly, rather than a calculated indirect irradiance. Depending on the scene, we can make significant savings in rendering time by applying this option. How do we decide what to leave out? Exclusion criteria could be any of the following:

- Surfaces not visible from our view point (and unimportant in terms of light transfer)
- High-detail areas (the -ar parameter may already impose a partial restriction here)
- Surfaces that have a small diffuse reflectance (say, less than 5%)
- Surfaces that will appear very small in the final image
- "Sticks"—surfaces that will appear as thin lines in the final image

Some of the surfaces of the Foggo Atrium model that did not participate in the rendering ambient calculation (and the reasons for their exclusion) were

- 1. External facade detail including light shelf surfaces (not visible)
- 2. Window frames (sticks)
- 3. Windowsills (small)
- 4. Atrium roof vent slats (detail and small)
- 5. Atrium roof glazing bars (sticks)
- 6. Black handrail supports (low diffuse reflectance)

As we can see from the final image, Figure 2-15, these exclusions hardly detract from the quality of the rendering.

Note: It is easier to apply this technique if you segregate the materials into include and exclude types when you first construct the scene. In CAD terms, it helps to build up the model, layer by layer, with these requirements in mind.

## Ambient File Use and the "Overture" Calculation

For a daylight rendering, the lion's share of the computation is invariably taken up by the ambient calculation. It makes sense, therefore, to save the cached indirect irradiance values to a file so they can be reused for later renderings. With a well-populated ambient file, it can be surprising how little time additional renderings take to complete, especially when there is significant overlap between views. There are rules that have to be observed when reusing ambient files. The most important of these rules is that you must always set the same combination of ambient parameters for every rendering that uses the ambient file. There is a special exception to this (see below). Also, the ambient exclude (or include) list should not change after the ambient file has been created.

Interpolation accuracy can be improved if the "presentation" (i.e., large) image is rendered using an already partially populated ambient file. The creation of the initial ambient file is known as an "overture" calculation. The ambient parameters values for the "overture" calculation should be those we have made the case for above. We use the same view parameters that are intended for the "presentation" image, but we generate the ambient file for a small picture size, no larger than, say, 64 by 64 pixels. We then reuse the ambient file to render a larger "presentation" image. The overall cost of the rendering will not be much greater than that of a one-pass approach, but the results can be significantly better.

Having created the ambient file with the "overture" calculation, you can, with caution, relax *some* of the ambient parameters for the larger renderings. The parameter revisions could be one or both of the following:

- Reduce -ad and -as by about 50%
- Slightly increase -aa (i.e., by 0.05 or 0.10)

The other ambient parameter settings should not be changed. If you do decide to change any of the -ad, -as, or -aa settings after the "overture" calculation, you should be aware that the modifications will not be reflected in the header of the ambient file. Thus, you need to track both the picture and the ambient file headers to obtain a complete record of the parameter settings for an image.

#### 2.9.2 Batch Rendering

The ambient parameter values are set and we are ready to make the first rendering. Starting with the "overture" calculation, we generate a small image and save the ambient file. The "presentation" image we have in mind is a rendering at approximately the resolution of the monitor display: about 1000 pixels square. We rarely show images at the resolution at which they were rendered; alias artifacts always look unpleasant and greatly detract from the impression of realism. The highest quality is achieved by creating the rendering at two or three times the eventual size, then scaling it down using the **pfilt** program. We could go directly from the "overture" calculation to an (unfiltered) presentation image about 3000 pixels square. This is quite a leap and may take some time to render. In this case, we might prefer to reassure ourselves with an intermediate-sized image, say, 500 pixels square. This should provide sufficient detail for us to appraise the effectiveness of the ambient calculation. For certain scenes with multiple ambient bounces, you may find that it is the "overture" calculation that takes the longest, and that subsequent renderings, regardless of size, are completed relatively quickly. In this case, don't be too concerned if the "overture" calculation seems to be taking a long time to generate a small image.

Rendering time can be like kitchen cupboard space—it doesn't matter what you *need*, you always fill up what's *available*. It makes sense, therefore, to batch-render a series of images, say, overnight or over the weekend. Automate the rendering from shell scripts and keep track of the progress by setting the -e and -t options of rpict.

#### A Critical Appraisal of the Atrium Rendering

The viewpoint and lighting were chosen to create a striking impression rather than to show a typical view. The low view point was deliberately chosen to reveal specular reflections from the "terrazzo" floor and the nearby water feature. This effect is perhaps too exaggerated, and the floor itself has something of the appearance of calm water in a murky pool. It is in fact the uniformity of the floor that is the problem, rather than the specular component. If the floor had been divided up into slabs or tiles, and these given slightly different material properties, the final result would be much more convincing. If each tile had a small random component applied to its surface normal, giving us a slightly uneven floor, the rendering would be better still. These issues are related to material properties and to the way the model was constructed; what about the contribution of the indirect calculation? In terms of overall impression, the diffuse shading looks pretty good. The indirect illumination effect of the sun patch is readily apparent, and the shading on the underside of the walkways between the elevator shafts is particularly realistic. At a finer level of detail, even individual ceiling fixtures don't look too bad, though there does appear to be some erroneously bright shading at the very smallest scales. Errors of this proportion were anticipated when we set the -aa and -ar parameters. On larger scales, we can see no evidence of light blotches, so our -ad and -as parameters were adequate for this scene.

#### 2.9.3 Summary

From the limitless number of conceivable ambient parameter combinations, we have arrived at a set of values that we hope will either give acceptable results immediately or require only minor amendment. For each parameter, we have shown how the choice is influenced by the building design, the illumination, and the view point. The same approach could be applied to many architectural rendering problems.

However thoughtful our selection of ambient parameter values, we are unlikely to hit on the ideal combination that delivers the best compromise between speed and accuracy. Even if we stumbled across this magic combination, how would we know? Unless we tried out zillions of other combinations, we never would. Thus, we shouldn't worry about this too much. It is important, though, to have good ballpark values to begin with. Thereafter, we should be able to anticipate the effect, to a greater or lesser degree, of any subsequent parameter modifications. After all, our goal is to provide workable solutions to real-world problems.

## 2.10 Conclusion

Accurate simulation of the quantity and distribution of daylight in an architectural space is now a realistic prospect. The *Radiance* system can be used to predict illumination levels and visual appearance under daylight conditions for virtually any building design. In this chapter, we have looked at just some of the ways in which *Radiance* can be applied to solving daylight problems. We hope that daylight designers will find the techniques of value and use them to solve their own lighting problems. More important, we hope that the majority will be inspired to take a closer look at the system and the possibilities it offers. Chapter

3

## Validation I: Preparation

"Entirely by ironic coincidence, on the day I wrote this I received a postcard from an art gallery which somehow got my name on its mailing list. It was to announce a new one-man show entitled **Primus corpus: DNA License**. A Sample of the artist's work was included. It consisted of a small plastic bag stamped 'Universal Notice - Only One -Original Human' containing some hair trimmings. Anyone struck dumb by this achievement is unlikely, I daresay, to be among the admirers of this chapter."

#### NORMAN LEVITT (IN PROMETHEUS BEDEVILLED)

**R**ecent advances in computer graphics techniques allow, in principle, the modelling of realistic architectural scenes for visualisation and illuminance prediction [Sillon 94, Ward 94]. Validation studies of these new programs have, to date, been of restricted value, one reason being that comparison against scale models measured in artificial skies are made using necessarily idealised sky brightness distributions [Selkowitz 82]. Also, where illuminance predictions have been compared with measurements taken in real rooms under real sky conditions [Bellia 94], the sky brightness distribution used by the program was based on a theoretical sky model generated from bulk values e.g. global and diffuse horizontal illuminance. Differences between the real sky luminance distribution and that used in the program are not known. It is therefore impossible to determine where the errors arise; in the basic algorithms or the representation of the sky.

This chapter describes the preparation for a validation study that offers a considerable advance on previous work. In this study, illuminance predictions were compared with measurements taken in full size office spaces under real sky conditions. The simulation program used model sky luminance patterns that were based directly on measured sky brightness distributions. The uncertainties in model representation, that had limited the findings of earlier studies, were greatly reduced for this validation. It was possible therefore, to make a reliable evaluation of the absolute accuracy of the program under naturally occurring daylight conditions.

Section 3.1 describes the composition of the validation dataset. That section also discusses to what degree the validation dataset is representative of the full range of naturally occurring sky conditions for the UK. The lighting simulation models for both the luminous environment (sun and sky) and the office space are described in Section 3.2. The processing of the sky luminance measurements to a form compatible with the simulation program is also described. The section ends with a hypothesis concerning potentially unreliable sky-photocell combinations. In Section 3.3 the lighting simulation itself is described. That section includes a methodology for the setting and optimization of the ambient calculation parameters. The results of the validation are presented and analysed in Chapter 4.

## 3.1 The validation dataset

The first steps towards constructing a definitive world atlas of daylight availability were made when the Commission Internationale de l'Eclairage (CIE) organised the International Daylight Measurement Programme (IDMP). A major objective of the programme was to collect long-duration time-series data for a range of daylight parameters, including, at the stations designated 'research class', measurement of the actual sky brightness distribution together with integrated quantities. The IDMP has coordinated the activities of 15 such 'research class' monitoring stations around the globe, the majority of which attempted to achieve continuous monitoring over a period of a year or more. One of the two UK 'research class' stations was at the Building Research Establishment (BRE), Garston, UK.

In conjunction with the sky monitoring programme, the BRE conducted an evaluation study of the light redistribution properties of five innovative glazing systems against standard clear glazing. The sky monitoring apparatus were positioned on the roof directly above the experimental rooms. Room illuminance and sky luminance measurements were recorded within seconds of each other. From matched samples of data from these two measurement programmes, a database for the validation of lighting simulation programs was constructed. This is referred to herein as the BRE-IDMP validation dataset.

### 3.1.1 Measured quantities and site details

The site details for the BRE station were as follows<sup>1</sup>.

Station Location:	Latitude: 51°43' N
	Longitude: 0°22' W
Height above sea level:	80m
Operation:	Started <sup>2</sup> on July 16, 1992,
	ended on July 1, 1993.

The external quantities monitored and the measuring instruments used were as follows:

• Illuminances

Global horizontal: Diffuse horizontal: North vertical: East vertical: South vertical: West vertical: Direct normal: LMT BAP 30 FCT Eppley, Solar Tracker

<sup>1.</sup> Information obtained from IDMP web-server http://idmp.entpe.fr/

<sup>2.</sup> Measurements were made available from earlier in 1992.

Irradiances

South vertical:Kipp & Zonen CM 5West vertical:Kipp & Zonen CM 5Direct normal:Eppley, Solar Tracker	Diffuse norizontal:Kipp &North vertical:Kipp &East vertical:Kipp &South vertical:Kipp &West vertical:Kipp &Direct normal:Eppley	2 Zonen CM11 2 Zonen CM 5 2 Zonen CM 5 2 Zonen CM 5 2 Zonen CM 5 7 Solar Tracker
----------------------------------------------------------------------------------------------------	---------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------

• Others

Sky luminance: Dry Bulb Temperature: Relative Humidity: PRC Krochmann Sky Scanner (15 mn) Vaisala HMP 132Y Vaisala HMP 132Y

The instrumentation layout on the roof of the BRE office block (Building 9) and the obstructions to the view above the horizon are shown in Figure 3-1.



Figure 3-1. Instrumentation layout and obstructions to view above horizon

### 3.1.2 Internal conditions: illuminance measurements

Two full-size mock offices, adjacent to each other and with south-facing glazing were set up by the BRE on the top storey of Building 9, Figure 3-2.



Figure 3-2. Building 9 with inset showing test offices

Room dimensions were almost identical; 9 metres deep, 3 metres wide and 2.7 metres high. The rooms were left unfurnished, though the surface reflectances were chosen to correspond to a typical office. The window of one office was adapted so that an innovative daylighting system could be installed, the other had conventional single glazing, Figure 3-3.



Figure 3-3. Photographs of the BRE office rooms (a) single glazing and (b) innovative glazing

Six illuminance cells positioned at work plane height (0.7m), regularly spaced along the centre line of each room, were used to monitor the illuminance distribution in the room, Figure 3-4.

The innovative glazing systems used in the BRE study were: diffuse and mirror finish light shelf, 3M prismatic film, Siemens prismatic glazing and Okalux mirrored louvre. Each system was evaluated for a period of about six weeks close to an equinox (23 September, 21 March) and again for two shorter periods during summer and winter months [Aizlewood 93]. The innovative glazing systems were installed in turn in one of the two office spaces. The other mock office had conventional single glazing throughout the entire monitoring period.



Figure 3-4. The BRE test cell

#### File formats

The internal illuminance data were obtained as ascii files, one for each day of monitoring. The illuminance measurements for the two mock offices were supplied as 5 minute averages of 1 minute data. For these files, each record contained 16 entries: time, 6 illuminance measurements (innovative glazing office), 6 illuminance measurements (single glazing office), and sun position. A sample is shown in Table 3-1.

Hour	Min.	lllum innov P_ce	inanc vative II 1 - 6	e mea glazi S	asuren ng offi	nents ce	for		lllum singl P_ce	inanc e-glaz II 1 - 6	e mea ed off	suren lice	nents	for		Alt.	Azi.
12	45	21259	19495	3514	2259	1724	1592	] [	19374	20454	18787	3814	1751	1709	][	18.7	195.3
12	50	20904	18689	3561	2367	1733	1594		17990	20335	18441	9499	1749	1698		18.4	196.5
12	55	20725	18803	3677	2547	1785	1620		19332	20843	18675	5240	1784	1726		18.2	197.8
13	0	21238	17485	3716	3585	1780	1604		19102	20056	12508	19291	1796	1727		18.0	199.0
13	5	21006	15742	3756	11969	1776	1598		18842	19560	7461	18953	1816	1733		17.7	200.2
13	10	20644	16832	3854	15513	1773	1579		18805	19219	18513	18569	1826	1728		17.4	201.4
13	15	20780	15221	3923	15623	1758	1566		18682	18852	18325	18213	1818	1711		17.1	202.6

Table 3-1. Sample from file for day 318\_92.csv

#### 3.1.3 External conditions: monitoring the sky and sun

The instrument used to measure the sky brightness distribution was a PRC Krochmann sky scanner, Figure 3-5. The sky scanner measured the sky luminance distribution every 15 minutes during daylight hours. Each scan consisted of 150 readings according to the pattern recommended by the CIE [Perez 91] and took approximately 25 seconds to complete. Of the 150 measurements taken, 145 were for unique positions on the sky vault (the zenith luminance was recorded 6 times during each scan). The scanner acceptance angle was 11° giving a sky coverage of ~68% [Tregenza 87], Figure 3-6. The scanner did not measure the sky luminance at the position closest to the sun, and a scan could contain one or more occurrences of 'out of range' measurements.

#### File formats

The global quantities file contained the basic illuminance and irradiance data together with a few environmental parameters. These quantities were five minute averages of one minute data. Each record in the file contained 22 entries, Table 3-2. An example few lines from a global quantities file is given in Table 3-3.



Figure 3-5. Krochmann PRC sky scanner positioned on the roof of the BRE lighting laboratory building and detail



Figure 3-0. Sky scalinel measurement pattern
----------------------------------------------

Quantity	Units
Error code	-
GMT	hr., min.
Horizontal global illuminance	lux
Horizontal diffuse illuminance	lux
Vertical total illuminances (north, east, south, west)	lux
Direct normal solar illuminance	lux
Zenith luminance	cd/m <sup>2</sup>
Dry bulb temperature	°C
Relative humidity	%
Horizontal global irradiance	W/m <sup>2</sup>
Horizontal diffuse irradiance	W/m <sup>2</sup>
Vertical total irradiances (north, east, south, west)	W/m <sup>2</sup>
Direct normal solar irradiances	W/m <sup>2</sup>
Solar altitude (above horizon)	deg. ( ° )
Solar azimuth (clockwise from due north)	deg. ( ° )

Table 3-2. Global quantities file

SkyLog: V 3.0 (c) Copyright Cambridge Consultants (SE) Ltd. 1991												
SL318_9	2.ILR											
	1992.											
	318.											
	Time		Horiz	Diff	VertN	VertE	VertS	VertW	Direct	Zenth	T/AI	Hu/Az
0	10	10	26564	10750	5070	31229	62109	5914	48233	1592	4.1	100.0
			254.27	84.56	37.78	298.31	624.20	44.54	495.19		17.0	156.6
0	10	15	27179	10863	5107	30366	63406	6019	49067	1617	4.2	100.0
			260.58	85.63	38.01	289.57	635.44	45.37	501.16		17.3	157.8

Table 3-3. Sample from global quantities file sl319\_92.alr

The measured sky luminance distribution data were instantaneous values recorded at 15 minute intervals. Each record contained 155 entries: an error flag, the time of observation, sun position, 144 measurements of the sky luminance distribution, and six measurements of the zenith luminance (see Figure 3-6 for a graphic of the measurement pattern). A sample file showing the measurements taken at 13h00 for day 102 in year 1992 is given in Table 3-4.

32713										Flag
102	92	13	00	45.5	201.4					Day, year, hr., min., altitude, azimuth
24444	22900	23438	19435	14154	12554	9607	8512	7313	6258	150 measurements
5912	5393	5395	5345	5108	5237	5248	4942	5077	5241	of the sky luminance
5541	6138	6887	8088	10016	11831	15468	18043	21404	26991	
30099	27793	30696	24041	16433	14122	10613	9126	7689	6594	
5819	5665	5459	5368	5343	5241	5267	4948	5081	5226	
5619	6254	7098	8484	10755	12614	17844	20959	25620	36961	
42601	41862	30333	21104	14797	10499	8020	6461	5522	5001	
5083	4834	4775	4889	4494	4866	5433	6307	7851	10320	
13690	20758	31728	41523	99999	40227	33260	21457	15445	10945	No measurement at
8079	7073	5684	5492	4682	5119	4469	4653	4669	4781	the sun position
5283	6267	8413	10468	14618	21543	31644	51516	99998	33055	Out-of-range
25636	15314	10124	7482	6419	5091	4665	4830	5828	6108	
5566	8138	10582	15487	21929	31264	36910	27183	14230	9113	
7699	5319	5984	6809	6482	10328	15479	19513	20161	12472	
9634	8309	8060	14219	12571	9242	12078	10854	10238	13932	Six zenith measurements

Table 3-4. Measured data for case 102\_92\_13h00

# 3.1.4 Comparison of the validation dataset composition with the Kew TRY

Data files comprising 27 days monitoring from the year 1992 were provided by the BRE. The days supplied were pseudo-randomly scattered throughout the year, Figure 3-7. Due to the presence of a large tree east of the site -



Figure 3-7. Distribution of validation dataset samples from the year 1992

which can cause shadowing on the windows of the mock-office (Figure 3-1) - all illuminance levels measured with the solar azimuth at less than 160° were removed from data by the BRE as part of their quality assurance procedures. The distribution in sun azimuth and altitude for the validation dataset is given as a two dimensional frequency histogram, Figure 3-8. The bin width for the altitude and the azimuth angles was 5° because this was roughly commensurate with the 15 minute timestep for the scanner measurements. For comparison, the distribution in sun position that would occur for an entire year (at 15 minute intervals) at the validation site is given also. The absolute numbers are of course very different: for one year (at 15

minute intervals) there were 17,635 occurrences of the sun altitude greater than 0°, as opposed to 754 entries in the validation dataset. However, to reveal any bias that may exist for the sun positions in the validation database, each frequency map was normalised to maximum = 1 (see legend Figure 3-8). The distribution plots show that most of the actually occurring sun positions (for sun azimuth  $\geq 160^{\circ}$ ) were represented to a greater or lesser degree in the validation database. There is an arc of empty bins in the distribution that was due to the lack of samples from around either day 70 or day 290. At this stage, there is no reason to believe that this deficiency will have any significant bearing on the outcome of the validation.



Figure 3-8. Distribution in azimuth and altitude for validation database and entire year

Just how representative these 754 skies were of the full range of naturally occurring sky conditions (clear, overcast etc.) in the UK can be judged from Figure 3-9. Here, the distribution in the sky clearness index for the



Figure 3-9. Distribution in clearness index compared to TRY

validation dataset and for a standard test reference year (TRY) are compared. The TRY data were recorded at Kew which is close to the validation site. The TRY time-series contains hourly measurements of the diffuse sky irradiance and the direct normal solar irradiance<sup>3</sup> for one year. The distribution in sky types for the validation dataset was broadly similar to that for the TRY. In the validation data, heavily overcast skies (bin 1) were somewhat over-represented whilst the very clearest skies were underrepresented. The clearness index,  $\varepsilon$ , is given by [Perez 90]:

<sup>3.</sup> Irradiances were converted to illuminances using a constant value for luminous efficacy.
$$\varepsilon = \frac{\left[\left(\frac{E_{dh} + E_{dn}}{E_{dn}}\right) + 1.041Z^3\right]}{1 + 1.041Z^3}$$
(3-1)

where  $E_{dh}$ ,  $E_{dn}$  and Z are the diffuse horizontal illuminance, the direct normal illuminance and solar zenith angle respectively.

#### 3.1.5 Scope of the validation

The fixtures in the innovative glazings room were cycled throughout the monitoring period. So it was the clear glazing office that was exposed to the largest number of skies. Accordingly, the all-skies (754) validation exercise was carried out using this window type. Note that clear glazing is used for the majority of existing and new buildings in the UK. In a limited study, the diffuse and specular light shelves were modelled (see below). The other three innovative glazings - Okalux mirrored louvre, Siemens prismatic glazing and 3M prismatic film - were excluded from the validation because the optical transmission properties of these materials had not been measured. The *Radiance* program has the capability to model in detail the bidirectional reflection transmission distribution function (BRTDF) of a material, and it would be possible to extend the validation to include these materials if and when the BRTDF data becomes available.

# 3.2 The lighting simulation models

#### 3.2.1 The office model

Geometrically, the office model created for the simulations was a very close representation of the experimental office. The dimensions of the clear glazed office room were measured by hand to an accuracy of ~1cm, and the space was described in the model as a collection of rectangular polygons. Particular attention was paid to the window bars and glazing panes which were measured to an accuracy of ~0.2cm and modelled as discrete elements. The illuminance meters themselves were not modelled, rather the horizontal illuminance at that point was calculated. All opaque surfaces

were modelled in the first instance as achromatic diffuse reflectors, although it is apparent from the photograph of the room that the paint used for the walls has a small specular component (Figure 3-3). The reflectances used in the model were the average of the values measured at the beginning and end of the monitoring period: walls 0.83, ceiling 0.80 and carpet 0.095 [Aizlewood 93]. Window transmittance was that for standard single glazing. A glazing maintenance factor of 5% was incorporated into the transmittance.<sup>4</sup> A rectangular ground plane of size 9 x 10m and reflectivity 0.15, was placed at ground level in front of the glazed facade of the office. This was the only non-luminous external object in the model. A line drawing created directly from the *Radiance* scene description for the single-glazed office room is shown in Figure 3-10.



Figure 3-10. Line drawing and rendering of office scene description

<sup>4.</sup> Private communication - M. Aizlewood, BRE.

The experimental rooms were on the third storey of Building 9, whereas the ground plane in the model was placed at the same level as the office floor. The justification for this is as follows. The 3D model, necessarily, had to be an incomplete description of reality, and it was decided at an early stage that it should be as simple as possible.<sup>5</sup> For light transfers from the ground plane into the office, the 'view' of the ground plane from the ceiling just inside the office window is a major factor. In this respect, a small ground plane at the same level as the office floor functions in much the same way as a larger ground plane with the office placed above it, Figure 3-11.



Figure 3-11. Simplified ground plane model

Furthermore, there are good reasons to prevent the maximum scene dimension from getting too large (see Section 2.5).

In the first published results of this work [Mardaljevic 95], a circular ground plane of radius 30 metres and centred on the room was used. With this ground plane, it was discovered that the inter-reflection calculation

<sup>5.</sup> Ockham's Razor, a principle urging the use of the most economical and least complex assumptions, is, in its original phrasing, particularly apt: "Entities should be not multiplied unnecessarily".

expended some effort in predicting the luminance of the external walls and adjacent ground plane. The luminance of the (external) side and rear walls however had negligible effect on the internal illuminance. Therefore the circular plane was replaced with a 'front-facing' rectangular ground plane.

In the limited study, two of the five innovative glazing fixtures were also modelled. These were internally mounted diffuse and specular (mirror) finish light shelves. Both shelves were the same size: full room width, 1.00 metre deep and fixed at a height of 2.08m. The diffuse finish light shelf was coated with a paint similar to that used on the ceiling and so was a assigned a reflectivity of 0.80. The upper surface of the specular shelf, in reality a polished aluminium sheet, was modelled as a mirror having a reflectivity of 0.90. Some uncertainty exists here: specular light shelf reflectivity was not directly measured and the value used in the model was based on typical value for this material.

# 3.2.2 The sun and sky models - generic form in the simulation

For lighting simulation, a model scene is constructed using various 'surface primitive' types (e.g. sphere, polygon, ring) and the illumination is provided by making one or more of these entities self-luminous. For the validation scene, there were two sources of (daylight) illumination - the sun and the sky. These were represented in the model using a special type of surface called **source**. A source is not really a surface, but a solid angle. And as such, a sun or sky described using source is effectively infinitely distant from the rest of the (finite) model scene. The source primitive has the basic format

```
mod source id
0
0
4 xdir ydir zdir angle
```

The arguments **xdir**, **ydir** and **zdir** give the direction to the centre of the source and **angle** is the number of degrees subtended by its 'disk'. A

schematic illustrating the extent and orientation of the source angles for the sky and sun is given in Figure 3-12.



Figure 3-12. Sky and sun source geometry (not to scale)

### 3.2.3 Modelling the sky and sun

The model sky and sun, when based on measured quantities, can have a representation that is subtly different from what one might expect, given the operational characteristics of the measuring instruments themselves. This difference is demonstrated in the following example in which a model sun is based on a measurement for the direct normal illuminance,  $E_{dn}$ . The model description requires a value for the brightness of the solar disc which is:

$$L_{sun} = \frac{E_{dn}}{\pi \sin^2 \left(\frac{\Theta_{sun}}{2}\right)}$$
(3-2)

The solar disc angle,  $\Theta_{sun}$ , is usually taken to be 0.5° even though the acceptance angle of the measuring instrument was much larger: 6° for the Eppley solar tracker. In *Radiance*, the rationale for this is related in part to the program's hybrid deterministic/stochastic sampling approach. In this,

small concentrated sources of light (i.e. the sun) are sampled deterministically whereas large diffuse sources of light (i.e. the sky) are sampled stochastically [Ward 98]. The material type that is specified for a light source decides the domain in which its contribution to illuminance is calculated: type **light** in the deterministic domain and type **glow** in the stochastic domain, Figure 3-13. Note from this illustration that, (i) a single ray is used to sample the sun (solar penumbras are therefore not calculated), and (ii) any direct light source that is intercepted by an indirect ray returns zero.



Figure 3-13. Hybrid deterministic/stochastic sampling of the light sources for the sun and the sky

Now, the sun luminance could be defined as a 0.5° or a 6° solar disc and, for either angle, the resulting direct normal illuminance will be the same. This is because a single ray is aimed towards the source centre regardless of source angle. The prediction of diffuse horizontal illuminance however, will not be exactly the same for both cases: with a larger (direct) light source, there is an increased probability that indirect sampling rays will intercept it and return zero.<sup>6</sup> If this happens, the indirect illuminance will be underpredicted, albeit by a small amount. Given that the direct calculation is insensitive to the size of the source for the sun, it makes good sense to use a small solar disc. Although the sun source size could be arbitrarily small, convention has it that the actual size used is  $0.5^{\circ}$  - small enough to not interfere significantly with accuracy of the indirect calculation.

### 3.2.4 The brightdata format

The brightness of the sky source solid angle may, at its simplest be constant, it may take its form from a mathematical function or sky model (see Section 2.3.2), or it may be based on discrete data values - that is, measured sky luminance patterns. To use measured sky luminance data in a *Radiance* simulation, the data values need to be applied as a pattern modifier to a constant (e.g. unit) brightness sky. This can be done using either the colordata or brightdata pattern types.

The definition for the two pattern types is as follows<sup>7</sup>:

Colordata uses an interpolated data map to modify a material's color. The map is ndimensional, and is stored in three auxiliary files, one for each color. The coordinates used to look up and interpolate the data are defined in another auxiliary file. The interpolated data values are modified by functions of one or three variables. If the functions are of one variable, then they are passed the corresponding color component (red or green or blue). If the functions are of three variables, then they are passed the original red, green, and blue values as parameters.

<sup>6.</sup> The probability is related to the source angle, for the 6° disc this is ~150 x that for the 0.5° disc.

<sup>7.</sup> Taken from the *Radiance* documentation for Version 3.1.

Brightdata is like colordata, except monochromatic.

```
mod brightdata id
3+n+
    func datafile
    funcfile x1 x2 .. xn transform
0
m A1 A2 .. Am
```

So there is just one auxiliary data file for the monochromatic form. The monochromatic brightdata pattern type was used to model the measured skies. The effect of the modifier is illustrated in Figure 3-14. To use



Figure 3-14. Application of brightdata pattern type

measured values with the brightdata modifier, the data must be in a regular grid form - regardless of the projection mapping of the data values, i.e. onto a plane or onto an arbitrary curved surface (e.g. hemisphere). This is so that the bi-linear interpolation scheme in *Radiance* can work effectively. The sky luminance measurements - which were (approximately) evenly distributed across the hemisphere - had therefore, to be mapped to a regular grid. In the regular grid, the spatial increment in either dimension is arbitrary, but it must be constant across the dimension. This means that there must be for a hemisphere - the same number of azimuth data values at all altitudes. Thus the zenith region will be more 'crowded' with data values than the horizon. In fact, although the zenith is a point, it requires the same number of azimuth data values as the row of minimum altitude. The minimum azimuth increment for the scanner measurements was  $12^{\circ}$  (for altitudes  $6^{\circ}$  and  $18^{\circ}$ ), whereas the altitude increment was  $12^{\circ}$  (i.e. constant) across the range. The regular array increments for both dimensions were therefore set to  $12^{\circ}$ . This ensured that resolution of the regular grid was commensurate with the resolution offered by the irregular measurement grid. The mapping of the measurement grid to the regular grid is illustrated in Figure 3-15.



Figure 3-15. Sky luminance data - measured and brightdata-format grids

Example code showing how the regular grid was used to create a *Radiance* model sky that was based on measured values is given below, Table 3-5. To the right of the code is a brief description explaining the function of each block, except for the **brightdata** block which functions as follows:

- **noneg** interpolation should not be allowed to give a negative result;
- 102\_92\_13h00.dat the file name for the (regular) array of sky brightness values;
- . dot character signifies that additional function files are not needed;
- Asin(Dz)/DEGREE effect transformation between z-direction vector and altitude (degrees); and,

```
Comment line
# Example measured sky/sun Radiance file
void light solar
                                                               Declare material (light) for
                                                               sun and sun R,G,B
0
                                                               radiance values - void
0
3
    3.05528e+06 3.05528e+06 3.05528e+06
                                                               indicates no previous
                                                               modifier
                                                               Apply modifier for sun
solar source sun
                                                               material to a surface
0
                                                               (source) and define
0
4
                      -0.652586
                                                               surface orientation (sun
       -0.255746
                                        0.713250 0.5
                                                               position x,y,z vector) and
                                                               opening angle (0.5°)
                                                               See main text
void brightdata skylumdat
5 noneg 102_92_13h00.dat . Asin(Dz)/DEGREE \
mod(atan2(Dx,Dy)/DEGREE-201.4,360)
0
0
skylumdat glow sky_glow
                                                               Apply sky brightness data
                                                               modifier to sky material
0
                                                               (glow), and set (un-
0
4 1 1 1 0
                                                               modified) sky radiance
                                                               R,G,B to 1
                                                               Apply modifier for sky
sky_glow source sky
                                                               material to a surface
0
0
                                                               (source) and define
4 0 0 1 180
                                                               surface orientation
                                                               (upwards) and opening
                                                               angle (180°)
```

Table 3-5. Code example sun/sky input file

 mod(atan2(Dx, Dy)/DEGREE-201.4, 360) - effect transformation between x and y direction vectors and azimuth (degrees) and account for 'offset' angle of the data (each row begins at the sun azimuth, here 201.4°).

The auxiliary data file for this example (**102\_92\_13h00.dat**) is given in Table 3-6. These data were processed from the original measured data given as an example in an earlier section (Table 3-4 on page 52). Note that there are 31 data values for each row of fixed altitude - the first at 0° and the last

2						n-dimensions	
6 90 8						Altitude start, e num. of increm	end and ents
0 360 31						Azimuth start, e	end and ents
136.559	150,788	119.575	100,799	86.4134	66.0950	_	6°
55.9553	45.1844	38.4749	34.2905	30.9553	29.2793		
28.3631	27.6089	29.3184	29.2570	28.5363	29.8603		
30,1397	30,1285	33.0279	34,9609	40.8547	47.5531		
53.6704	70.1341	79.0726	108.575	130.939	127.933		
136.559							
168 151	206 486	143 128	117 089	99 6871	70 4693	<u> </u>	10°
60 0838	47 3966	39 6536	34 9385	31 3911	29 1955	fuc	10
28 3855	27 6425	29 4246	29 2793	29 8492	29 9888	alti	
30 4972	31 6480	32 5084	36 8380	42 9553	50 9832	l at a	
59 2905	78 8939	91 8045	134 307	171 486	155 268	far	
168.151	10.0000	51.0040	104.007	171.400	100.200	suc	
237 00/	236 086	203 288	151 130	106 084	76 4804		20°
60 6619	48 9486	39 7924	34 0338	30 3520	27 7962	Ö	30
25 4683	25 8452	27 /20/	26 6760	26 7622	28.0178	ð	
28 1867	23.0432	30 8492	34 8234	40 8592	49 4719	ц ц	
62 5644	82 6648	109 953	145 591	198 390	238 857	ac	
237.994	02.0040	103.500	140.001	150.050	200.007	e -	
282 588	207 3/0	223 550	146 622	112 400	81 6648	Q	100
61 7909	297.349 51 2652	42 0207	33 3626	20 5140	27 1163	∽ ∣	42
26 1060	26 2172	25 6294	24 0665	29.3140	26.0186	5	
20.1009	20.2172	23.0304	24.9003	12 5023	10 9655	nts	
65 8157	86 28/0	110 102	160 183	202 608	235 063	ue u	
282.588	00.2045	110.152	100.100	202.000	200.000	rer	
195 356	187 484	165 442	132 729	105 939	86 5196	ino –	54°
68 6423	55 6800	48 1407	38 8632	31 0950	31 9863	Ę	54
34 5964	33 5086	30 1922	26 9832	25 9508	26 2149		
27 5053	31 2501	35 8603	38 9974	43 9113	52 8805	azi.	
65.1501	85.5531	119.297	153.836	178.786	192.466	0 7	
195.356						ace	
206 201	174 311	127 900	97 2256	88 8061	86 4749	- de	ee°
77 7/16	64 4761	51 5400	<i>4</i> 1 7282	36 2123	35 7056	<u>&gt;</u>	00
37 4289	38 0035	36 3338	33 /302	30.2123	20 05/3	eu	
31 5555	37 3313	43 0112	46 2249	48 8764	53 8903	ě	
63 4782	79 4972	103 670	134 485	170 005	200 370	.⊆	
206.201	10.4012	100.010	1011100		2001010	31)	
112 631	111 850	106 802	98 8772	80 3515	70 /358	©	70°
70 1500	61 8362	54 6998	48 9937	45 0279	43 0180	j ši	10
12 5980	43 3012	44 7060	46.3307	48 1200	40.0100	alt	
51 2366	52 6092	53 8212	54 9422	56 4584	58 9768	0 0	
63 1449	69 6760	78 9307	89 5837	99 9183	108 205	Ŭ	
112.631	00.0700		00.0007	00.0100		dia	
64 1667	64 1667	64 1667	64 1667	64 1667	64 1667		00°
64 1667	64 1667	64 1667	64 1667	64 1667	64.1667		30 (700:16)
64 1667	64 1667	64 1667	64 1667	64 1667	64 1667		(zenith)
64 1667	64 1667	64 1667	64 1667	64 1667	64 1667		
64,1667	64,1667	64,1667	64,1667	64,1667	64,1667		
64,1667							

Table 3-6. Data file for sky 102\_92\_13h00 (radiance values)

at 360° are, of course, identical. This is to ensure continuity across the azimuth range for the *Radiance* bi-linear interpolation scheme. How the mapping from the measured to the regular grid was achieved is described below.

## 3.2.5 Pre-process of the sky luminance measurements

The PRC Krochmann scanner began each sky scan, and each subsequent row of fixed altitude measurements, at the solar azimuth position. The measurement pattern, though regular, possessed therefore a rotation offset about the zenith axis which was different for each scan. For each row, measurements were taken as the scanner rotated 'anti-clockwise', i.e.  $N \rightarrow W \rightarrow S \rightarrow E$ , Figure 3-16(a). For the simulation however, the brightdata pattern type expects the data file to read 'clockwise', i.e.  $N \rightarrow E \rightarrow S \rightarrow W$ , Figure 3-16(b). This was another factor that needed to be taken into account in preparing the measurements for use in the simulation.



Figure 3-16. Comparison of the measurement pattern (a) with the brightdata format grid (b)

The processing of the scanner measurements for simulation involved the following procedures:

- 1. The azimuth order of the measured data was reversed.
- 2. The data were then interpolated to the regular grid pattern and normalised (this stage included the estimation of the out-of-range measurements).
- 3. The files containing the sky description and the auxiliary data (in *Radiance* format) were written to disk.

For this, a 1-dimensional interpolation scheme was applied across each reversed-order row (i.e. fixed altitude) of in-range scanner measurements.<sup>8</sup> To ensure continuity across the full 360° in azimuth, the row vector was concatenated with itself, and mapped to an extended range of azimuth values, Figure 3-17.

Following interpolation, the sky luminance distribution was normalized to the diffuse horizontal illuminance,  $E_{dh}$ , which was obtained from measurements of the global horizontal illuminance,  $E_{gh}$ , and the direct normal illuminance  $E_{dn}$ :

$$E_{dh} = E_{gh} - E_{dn} \sin \gamma_s \tag{3-3}$$

where  $\gamma_s$  is the sun altitude. This derived value is considered more reliable than using the shadow-band corrected measurement for diffuse horizontal illuminance.<sup>9</sup>

<sup>8.</sup> A 2-dimensional interpolation in spherical co-ordinates (i.e. a surface fit) is, potentially, a more accurate technique for estimating missing values, because this fit takes into account all neighbouring in-range data. However, the additional complexity was not considered warranted for this application.

<sup>9.</sup> Private communication - P. Littlefair, BRE.



Figure 3-17. Interpolation across concatenated vector

Each (interpolated) sky luminance measurement  $L_j^u$  was then normalized to  $L_j^n$  using the normalization factor  $f_{norm}$ :

$$f_{norm} = \begin{pmatrix} E_{dh} \\ \frac{145}{\sum_{i=1}^{145} L_i \Omega_i \sin \gamma_i} \end{pmatrix}$$

$$L_j^n = L_j^u f_{norm}$$
(3-4)

Where  $L_i$ ,  $\Omega_i$  and  $\gamma_i$  are, respectively, for 'rectangular' patch *i*, the luminance, the solid angle and the altitude of the patch centre, Figure 3-18. The solid angle of the rectangular patch for each row in the measurement pattern is given in Table 3-7.



Figure 3-18. Rectangular and circular patch geometry

Row	Altitude	Number of patches per row	Azimuth increment	Solid angle subtended by 'rectangular' patch (sr)
1	6°	30	12°	0.0435
2	18°	30	12°	0.0416
3	30°	24	15°	0.0474
4	42°	24	15°	0.0407
5	54°	18	20°	0.0429
6	66°	12	30°	0.0445
7	78°	6	60°	0.0455
8	90°	1	360°	0.0344 <sup>a</sup>

#### Table 3-7. Pattern of rectangular patches

a. 'Polar cap', not 'rectangle'.

A sky luminance interpolation/visualisation software tool was created to examine and display the processed luminance distribution for the skies in the validation database. The tool functions either interactively or in batch mode and it displays to either X-windows or PostScript devices. The display for a sky contains the following information:

- Seven plots of the luminance versus azimuth (at fixed altitude) for measured and interpolated sky luminance - both normalized to E<sub>dh</sub>. The sun azimuth is marked with a dashed vertical line.
- A plot showing the scatter in the six zenith luminance measurements with a horizontal line to indicate the mean.
- A false-colour map of the array of interpolated-normalized sky luminance values. The sun position is at the intersection of the dashed lines.
- A projection of the false-colour map onto a hemisphere. This gives an 'external view' of the sky luminance distribution. The view direction is from the sun position to the hemisphere origin.
- A legend showing the mapping of colour to luminance.

Example output for three skies are shown in Figure 3-19 to Figure 3-21. For sky 093\_92\_13h15 (Figure 3-19), the estimate for the 'missing' scanner measurement at the sun position is likely to be reliable since this sky exhibits fairly overcast conditions. For clear and intermediate skies (e.g.  $125_92_13h15$ , Figure 3-20), the estimate will be less reliable because it is impossible to accurately reconstruct potentially large luminance gradients when the highest luminance value is missing. The medium-tension cubic-spline algorithm used for the interpolation does allow for estimates greater than the peak measurement in a row (see plot for Scan alt. = 54°, Figure 3-20). Whilst this may be more realistic than a linear interpolation - which can never exceed the neighbouring values - it cannot be regarded as a truly reliable estimate.



Figure 3-19. Sky 093\_92\_13h15



Figure 3-20. Sky 125\_92\_13h15



Figure 3-21. Sky 273\_92\_12h15

It is possible therefore that, for clear sky conditions, the sky luminance at the sun position is under-estimated by the interpolation scheme. This, when it occurs, will affect all the other sky luminance measurements, because the normalization factor (Eq 3-4) is then set to a high value to compensate. Under-estimation of the circumsolar sky luminance may lead to under-prediction of some vertical illuminances - principally the south and west orientations that most often 'saw' the solar disc. Note also that a patch of circumsolar sky, when visible, is likely to contribute proportionately more to the total illuminance on a vertical plane than a horizontal plane, Figure 3-22.



Figure 3-22. Horizontal and vertical illuminances

#### 3.2.6 Deficiencies in the model sky representation

The BRE sky scanner measurements, although as accurate as any comparable dataset, may contain deficiencies that limit the potential accuracy of the illuminance predictions. The principal shortcoming in the measured data was the uncertainty of the sky luminance about the solar position, for both the average across the region and the luminance gradient across it. As discussed in the previous section, these quantities cannot be reliably estimated using interpolation, particularly for clear sky conditions. The effect that this uncertainty may have on the model representation of the sky is illustrated using a (schematic) plot of sky luminance versus azimuth taken at the solar altitude and centred on the sun position, Figure 3-23. For



Figure 3-23. Schematic for sky luminance versus angle

this schematic plot, an idealised clear sky luminance is shown. This luminance is symmetric about the solar position and, to simplify the exposition, the sun altitude was taken to be equal to the scanner altitude. The relationship between the circular regions A and C, the annulus region B (in Figure 3-23) and the operational characteristics of the measurement instruments is shown in Figure 3-24. Due to the symmetry,  $A_1$  and  $A_2$  are identical, as are  $B_1$  and  $B_2$ .



Figure 3-24. Sky scanner (a) and solar tracker (b) acceptance angles (not to scale)

The regions  $A_1$  and  $A_2$  show the sky patches closest to the sun that were measured by the sky scanner. For each (in-range) measurement, the recorded value was the average luminance within the sky scanner's 11° acceptance angle. Similarly, for region C, the (derived) measurement of luminance was the average luminance within the solar tracking instrument's 6° acceptance angle. The sky luminance across the annulus region ( $B_1$  and  $B_2$ ) was not measured because the scanner did not record at the sun position. For clear sky conditions, the relation between the (likely) actually occurring sky luminance distribution and the measuredinterpolated quantities is summarised in Table 3-8.

Another feature of the interpolation procedure described in Section 3.2.5 is that the sky luminance peak, for clear skies, may not coincide with the solar position. This can be seen in Figure 3-21 where the measured-interpolated peak occurred at (scanner) altitude 42° and not at altitude 30° which was closest to the sun altitude. This displacement of the interpolated sky

Region	Average luminance	Estimate of luminance gradient across region (clear sky conditions)
$A_1$ and $A_2$ (sky patches on either side of sun position)	Measured by sky scanner (11° acceptance angle)	Likely to be small or moderate
$B_1$ and $B_2$	Not measured - estimated from interpolation of neighbouring values $A_1$ and $A_2$	Potentially significant
C	Evaluated from measurement of direct normal illuminance (6° acceptance angle)	Likely to be quite large

Table 3-8. Likely luminance gradients across regions

luminance peak from the sun position can be appreciated better from the maps and plots shown in Figure 3-25.



Figure 3-25. False colour maps and profiles of the circumsolar luminance for a measuredinterpolated sky and a Perez model sky for case 188\_92\_13h30

For this illustration, renderings for a 60° by 60° region centred on the sun position were generated for sky 188\_92\_13h30 using a luminance distribution based on the scanner data ('Measured') and the Perez-All-Weather model ('Perez'). Each sky was normalized to the same diffuse horizontal illuminance. An angular fish-eye projection was used to generate the renderings from which these maps were derived. In this projection, the distance from the centre of the image is proportional to the angle from the central view direction.

Sky 188\_92\_13h30 had one of the highest sky clearness indices in the validation sample, and their is no evidence of cloud structure from the measured luminance distribution. It can be reasonably expected therefore that the sky luminance peak should be coincident with the sun position. This was not the case however with the measured-interpolated sky. Here, the interpolation algorithm could not reproduce the luminance peak at the sun position. In contrast, the Perez model predicted an approximately symmetrical luminance distribution centred on the sun position. The luminance gradient in each map can be gauged from the overlaid contours. Below each map is a plot of the luminance profile and luminance gradient across the sun position for the dashed line shown in the maps.<sup>10</sup> Here it can be seen that, across the sun position, there is marked difference between the measured-interpolated sky and the Perez model sky, in both the magnitude and gradient of the luminance profile. It is not intended that any inference regarding the accuracy of the Perez model should be drawn from this illustration.

# 3.2.7 A hypothesis concerning potentially unreliable photocell-sky combinations

In this section, a class of potential sources of imprecision in the model representation and program operation are identified. These sources of

<sup>10.</sup> Pixel sampling effects are responsible for the small peaks etc. in the luminance gradient plots.

imprecision are distinct in origin, and yet strongly inter-related in effect. Any one of these could be the cause of occasional gross over or underprediction in internal illuminance. The class are referred to here as 'source visibility related errors' (SVRE). The reason for this name will become apparent in the discussion that follows. The class comprises four separate types of error: three are related to imprecision in the model representation and one to the operational mode of the lighting simulation program. A description of the four types, their cause, their principal effects and an assessment of the scope for improving or fixing the errors are given in Table 3-9.

Туре	Description	Cause	Principal effect	Scope for improvement/fix
A	Imprecision in the geometrical specification of the office model, i.e. inaccurate placement of window bars	Finite resolution of measurement accuracy for linear dimensions - hand measurement by ruler	Photocell actually in shade may be predicted to be in sun, or vice-versa	Repeat measurements using better accuracy techniques <sup>a</sup>
в	Uncertainty in the sky luminance distribution about the solar position	Operational characteristics and finite resolution of the sky scanner and solar tracker	Direct component of illuminance resulting from circumsolar region maybe in error	None <sup>b</sup>
С	Single-ray light source sampling of sun	Default operational mode of <i>Radiance</i> sampling	Solar penumbra not computed in simulation	Multiple-ray light source sampling is possible
D	Point source representation of photocell in model	Default calculation mode	Partial shading - and therefore partial response - of the photocell is not modelled	An array of calculation points could instead be used

Table 3-9. Source visibility related errors - type, circumstance and effect

a. In practice this could prove to be a significant task, requiring digital photogrammetry etc.

b. For existing validation set.

Improving on or fixing the type C and D errors would be relatively straightforward, The type A error would be more difficult to improve on; in practice this could be a significant task, requiring digital photogrammetry etc. The type B error however, would still be a major source of inaccuracy, and so remedial action to correct the type A, C and D errors was not considered justified. Note that the potential for inaccuracy in the illuminance predictions resulting from all four error types - acting independently or in combination - is greatest for sunny conditions when the circumsolar region (and sun) 'come into view' from the photocell position.

It is proposed that:

- 1. The four error types have the potential to affect only certain photocellsky combinations.
- 2. The photocell-sky combinations at-risk are those where the photocell can 'see' all or some of the circumsolar region.
- 3. Illuminance predictions from the at-risk combinations may contain gross errors which are due to imprecision in the model representation rather than the underlying accuracy of the program.
- 4. If these at-risk cases are identified and treated separately, then a true assessment of the absolute accuracy of the program can be made.

These propositions form the hypothesis concerning potentially unreliable photocell-sky combinations. In Chapter 4, the error characteristics of the illuminance predictions are analysed, and evidence to support the hypothesis is presented.

# 3.3 The lighting simulation - preparation

# 3.3.1 Simulation parameter settings and accuracy

The potential accuracy of the illuminance calculation may not be realised if the simulation parameters are not set correctly. The key simulation parameters for daylight illuminance calculations are those which control the depth (i.e. number of reflections) and resolution of the inter-reflection calculation. In the *Radiance* system these are referred to as the ambient parameters.<sup>11</sup> The inter-reflection calculation, in *Radiance*, progresses recursively. Rays are spawned at the evaluation point(s) to sample the luminous environment, when a ray intersects with a material surface, additional rays may be spawned and so on. In this scheme, each level of sampling is equivalent to one (diffuse) reflection of light.

The computational cost of an illuminance calculation (and rendering) is very sensitive to the setting of the key ambient parameters. For the work described here and in later sections, it was necessary to carry out many thousands of lighting simulations. For this to be achieved on what is now considered to be a relatively low powered workstation<sup>12</sup> each simulation, ideally, needed to take no longer than a few minutes. A preliminary to the validation simulations was a parameter optimization study where the sensitivity of the accuracy and the simulation time to variation in six ambient parameters was investigated. These parameters were:

- **ad** the number of ambient divisions
- **as** the number of ambient super samples
- **ar** the ambient resolution
- **aa** the ambient accuracy
- **ab** the number of ambient bounces
- **av** the constant ambient approximation

The large number of parameters requiring investigation presented a problem: even if the range and the number of values for each parameter was restricted to say five, the total number of possible combinations would be large (i.e.  $5^6 \approx 15.6 \times 10^3$ ). An additional complication is that, at low resolution, Monte-carlo calculations can give seemingly accurate predictions through 'chance hits' rather than from reliable convergence. 'Chance hits', when the occur, are by their nature unreliable - a small change in parameter value in either direction can give very different results.

<sup>11.</sup> In computer graphics, light not received directly from a source of illumination is usually referred to as the 'ambient component'.

<sup>12.</sup> Sun SPARC station 2.

And, a chance accurate prediction for one luminous environment may not necessarily be repeated for another. This is illustrated in the following example where the direct sky component (expressed as daylight factor) at a point in the room was predicted using a wide range of ambient divisions (i.e. initial sampling rays). Genuine convergence in the predicted value is apparent for ad > 128. Note however that for ad = 2 and 4, these samples produce 'chance hits' which result in predictions that are close to the converged value, Figure 3-26.



Figure 3-26. Predicted sky component (daylight factor) versus number of ambient divisions

As a result, it was not sufficient to select one parameter combination, which happened to give an accurate result for one sky, and hope that the success would be repeated for the entire validation sample. Instead, what was needed was a robust parameter selection method which ensured that an accurate result, when achieved, was relatively insensitive to moderate changes in any of the parameter settings. And also that the prediction was not highly sensitive to any particular sky and sun conditions. This goal was achieved by examining the trend in the accuracy of the predictions as a single parameter was varied, with the other parameters held constant. This was done for each parameter in turn.

A positive ambient value can be used to approximate the contribution of higher order reflections in a rendering or illuminance calculation. If ab is set to zero, the ambient value is used directly to approximate the (essentially) infinite number of light reflections that can occur. For ab > 0, the ambient value is the remainder contribution at the final (calculated) reflection. It is clear however that for all normal spaces under varying natural illumination conditions, an appropriate ambient value is both time (that is, illumination) and position dependant: it will be greatest near to the windows and least at the back of the room. A constant ambient approximation can, at best, be appropriate for only a limited range of sky conditions and for only a small fraction of the workplane surface in a typically glazed space - such as that used in this validation study, Figure 3-27. It is not reliable therefore to use



Figure 3-27. Constant ambient value approximation

the (constant) ambient approximation when high accuracy predictions are needed.<sup>13</sup> For the parameter optimization exercise that is described below, the ambient value was set to zero and the total light contribution due to inter-reflection was calculated explicitly. This parameter was therefore eliminated from the optimization exercise. As a consequence, it was necessary to carefully examine the convergence characteristics when increasing the ab parameter. If this parameter is not set sufficiently high, the calculation is likely to consistently under-predict illuminance regardless of the resolution of the other ambient parameters.

## 3.3.2 Optimization methodology

The methodology for the optimization was as follows. One clear sky case and one overcast sky case were selected at random from the validation data. For the clear sky case the internal illuminance was predicted using a balanced set of high resolution parameters (with av=0). If the simulation did not complete within 1hr. of CPU time, it was terminated and the simulation was restarted with one or more of the parameters relaxed.<sup>14</sup> Once an accurate prediction was achieved using 1 hr. or less CPU time, the simulation was repeated for the overcast sky to ensure that equivalently accurate predictions were obtained. There was an element of luck here, the few cases that were chosen at random for the initial tests all yielded accurate illuminance predictions at each of the photocell locations.<sup>15</sup> The results presented in Section 4.5 however show that this would not have been the case for all of the skies in the validation data.

The high resolution ambient parameter settings which gave an accurate result were called the 'slow-basecase' combination. The next stage was to examine the trend in results as, one at a time, a parameter was varied from

<sup>13.</sup> This is not usually the case for renderings. See "Setting -av and -aw" on page 38.

<sup>14.</sup> Initial tests using 'guesstimate' parameter combinations showed that accurate results could be achieved using 1hr or less CPU time.

<sup>15.</sup> Fortunately, the skies randomly selected for this preliminary exercise did not contain occurrences of photocell - sun position combinations that proved to be unreliable (see discussion on SVRE Section 3.2.7).

a very low resolution value to its (high resolution) 'slow basecase' setting. Where possible, the increments were chosen to cause an approximate doubling in the complexity (and therefore computational cost) of the calculation. For example, the number of ambient divisions was increased from 2, 4, 8, 16, 32, and so on. The trend in CPU usage was compared alongside the trend in the accuracy of the predictions. The hypothesis governing this approach was based on the assumption that, for each parameter, a value could be found which gave accurate results quickly, and which were stable to moderate changes in parameter value. Albeit, in combination with, in each case, the 'slow basecase' settings. The individual parameter values determined in this way were collected together to form a new combination called the 'fast basecase'. The illuminance predictions were repeated using this fast combination of parameters. The final stage in the optimization was to 'fine-tune' the 'fast basecase' parameters by incrementing them - one at a time - to higher resolution values, trading off gains in accuracy against increases in CPU time. This resulted in the final 'basecase' set of parameters that was used for most of the lighting simulation work described in this and later chapters.

Flexible optimization criteria were employed at various stages, and the process was steered to some degree by the intuitive sense for predicting outcome that a user often develops from working with a complex simulation model. An example set of plots from the optimization exercise are shown in Figure 3-28. In this test, the number of ambient divisions (ad) was the parameter that was varied (from 16, 32, 64, etc. to 4096), the others were held constant. For each value of ad tested, the illuminance (measured and predicted) is shown versus distance from the window. Below each illuminance plot there is a bar graph showing the relative error in the illuminance prediction at each photocell location. The graph titled 'Convergence', plots the average of the relative errors (absolute values) for the six illuminance predictions versus the processor (CPU) time used for each of the ad values tested. Here, the fastest simulation (ad=16) took only



Figure 3-28. Results for ambient divisions excursion

a few seconds but produced large errors, whereas the slowest (ad=4096) took ~1000 secs and gave very accurate predictions. The last plot shows how the number of ambient locations (that is, points were an indirect irradiance gradient was calculated) was related to the CPU usage. Each series of simulations for an excursion was initiated from custom C-shell scripts, which in turn were initiated from an 'executive' script that controlled the entire simulation sequence. The optimization exercise was therefore highly automated, and much of the available processor time was used to thoroughly investigate the convergence characteristics of the illuminance calculation.

For reasons of brevity, the majority of the simulation data resulting from the optimization study (dozens of sets of plots) have not been included in this thesis. For a practical guide to how to set the ambient parameter values, see the author's chapter in Rendering with *Radiance* (Chapter 2 in this thesis).

The 'basecase' parameters that were determined using the optimization methodology described above are listed in Table 3-10. With this parameter combination, each simulation used approximately 5 minutes CPU time. The total CPU time for one pass of the validation data was therefore approximately 2.6 days. The 'slow basecase' parameter combination in comparison, would have required about 1 month CPU time.

Parameter	Value
ad	2048
ab	7
ar	2
as	32
aa	0.10

Table 3-10. 'Basecase' parameter values (av=0)

# 3.3.3 Ambient calculation - progression and convergence characteristics

The progression of the ambient calculation can be appreciated from the renderings shown in Figure 3-29. For these images, a red marker was added



Figure 3-29. Recursive progression of ambient calculation; levels 1 to 6

to the model at those places in the scene where an indirect irradiance value was calculated. These locations were extracted from the ambient file which resulted from a seven bounce simulation for case  $102_92_13h00$ . For ab = 1 (level 1), there were six points from which indirect irradiance sampling was initiated. These were the six photocell locations.<sup>16</sup> At these points, hemispherical sampling rays were spawned. Some of these rays will sample

<sup>16.</sup> It is not necessarily the case that the number of initial sampling points will always equal the number of calculation points - See "Case Study III: Introducing Complexity" on page 24.

the sky luminance through the glazing. Most however will intersect with opaque surfaces, and from some of these points the next level of sampling was initiated. These are the red markers for 'Level 2', which of course, are all above the (horizontal) plane of the photocells. For this illustration, the number of initial sampling rays was 2048. But the number of sampling points at higher levels is much lower than this because most of the spawned rays use nearby cached values, that is, already determined indirect irradiance values. The number of sampling points at each level is given in Table 3-11. This caching and reusing of indirect irradiance values is one of the keystone features of the *Radiance* program. Without this and other optimizations, the total number of rays spawned would grow geometrically and soon become unmanageable.

Level	Number of sampling points
1	6
2	87
3	199
4	202
5	188
6	151

Table 3-11. Number of points at each level where hemispherical sampling was initiated

The convergence characteristics of the illuminance calculation for one case  $(121_92_14h15)$  are shown in Figure 3-30. Here, the RER in the illuminance prediction at each photocell is shown for ambient bounces equal to 1, 2, 3, 4, 5, 6 and 7. It can be seen here that inter-reflection is generally more important at the back of the room where ab > 5 is required to achieve a |RER| < 10%.

#### 3.3.4 Automation of the simulations

A scheme for the management and automation of a large number of simulations needs to be both efficient and extensible. Efficient, because the sequence of simulations should ideally be executed with minimal user



Figure 3-30. Convergence characteristics of the illuminance calculation

intervention, and extensible so that no practical limit is placed on the range or scope of the investigation(s). Moreover, for the purposes of validation, it is advantageous to maintain the measurements and the predictions in a common format.

As demonstrated in Section 3.2.5, the sky luminance measurements needed to be reformed to be compatible with the *Radiance* brightdata format. This was achieved using a set of procedures and functions written in IDL. For the initial tests and parameter optimization (Section 3.3.2) just a couple of skies were prepared using the IDL programs, and all the simulations were initiated from (UNIX) shell scripts. Having settled on a basecase set of ambient parameter values, a scheme was conceived to manage both the execution of the simulations and the updating of the results dataset. Furthermore, the same program environment would be
used for the analysis and the plotting of all the results. The IDL environment was selected for this task.<sup>17</sup>

Prior to the simulations, it was necessary to prepare the validation data and convert it to IDL variables. The first stage was to create a single 2D floating-point array which contained all of the relevant matched entries in the validation data files.<sup>18</sup> In total, the BRE supplied 81 ascii data files (27 days, and 3 types). The sky luminance distribution was recorded every 15 minutes, but the other measurements were given as 5 minute averages of 1 minute data. It was necessary therefore to 'time-align' the measurements: readings taken at the same instant were identified and formed into a row vector for insertion into the array. Each row vector of the array therefore contained all the (unique) entries in the measured data that were taken at the same instant. Some of the measured quantities were of type integer, these were converted to floating-point. The 5 minute data was maintained in a separate array structure.

The array of measured quantities was of size  $754 \times 178$ , that is, 178 measured quantities (and identifiers) taken at 754 instants. The contents of a row vector are given in Table 3-12. The simulation results for each

Index	0-1	2-3	4-5	6-12	13-15	16-165	166-171	172-177
Quantity	day year	solar azimuth altitude	hour minutes	glb.horiz. glb. diff. vertical N,E,S&W dir.norm.	zen.lum. temp. humid.	150 sky luminance meas.	innov. office illuminance	single glazed office illuminance

Table 3-12. Measured quantities by vector index

<sup>17.</sup> IDL is a high-level, interpretive programming language with powerful data analysis and visual display features. IDL variables, procedures, operators and functions operate on scalar, vector and array data with no change in notation or meaning. Additionally, IDL can communicate with the UNIX operating system. It is relatively straightforward therefore to execute shell scripts etc. from within a IDL program.

<sup>18.</sup> Irradiance quantities in the ALR files were excluded.

individual sky were concatenated to the validation array thereby increasing the number of columns in the array. For example, the first quantities to be predicted for all 754 skies were the global horizontal illuminance and the four vertical illuminances. These five predicted quantities were - for each sky - concatenated to the row vector for that sky. The array size was then increased to 754 x 183. The index numbers for these predicted quantities were, Table 3-13.

Index	178	179	180	181	182
Quantity	glb.horiz.	vertical N	vertical E	vertical S	vertical W

Table 3-13. Vector index for first predicted quantities

At the time of completion of this thesis, the validation array had grown to size 754 x 405: that is, 227 lighting and lighting-related quantities - for each sky - were predicted using *Radiance*. The quantities added to the validation array at various stages included the following:

- Internal and external illuminances using measured sky luminance distributions (Chapter 4).
- Visibility tests and components of internal illuminance (Chapter 4).
- Internal illuminance predictions using sky model generated luminance distributions (Chapter 5).
- Internal illuminance predictions derived using daylight coefficients (Chapter 6).

A full description of the contents of the validation array is given in Table A-2.

In Chapter 4, the sensitivity of the relative error in the internal illuminance predictions to several measured and predicted quantities is analysed. This process was greatly facilitated by maintaining all the measurements and predictions in a simple common format. As the range and scope of the validation grew, so did the size of the validation array. Because the validation array grew by concatenation of the row vectors, backwards compatibility with analysis programs was preserved: already existing programs could use the newly updated validation array without modification.

Each sequence of 754 (or more) *Radiance* simulations was initiated from an 'executive' IDL program, specially written for the task. Although each executive program was different they all shared a basic program structure, Figure 3-31.

# **3.4 Conclusion**

The preparatory work for the validation of the *Radiance* lighting simulation program has been described. Each stage in the processing of measured sky luminance distributions has been presented and example file formats etc. given. A hypothesis concerning potentially unreliable photocell-sky combinations was formulated in Section 3.2.7. This hypothesis is tested in Chapter 4.



Figure 3-31. Structure of the 'executive' program

# Chapter

# Validation II: Results and Analysis

"And so we see that the poetry fades out of the problem, and by the time the serious application of the exact science begins we are left with only pointer readings."

EDDINGTON

 $T_{\rm his}$  chapter presents the results for the validation of the Radiance illuminance calculation. Predictions for external and internal illuminances are compared first with measurements. Next, the error characteristics of the internal illuminance predictions are analysed in detail, and the hypothesis concerning the source visibility related errors is tested. The preparatory work for the validation was described in the previous chapter.

# 4.1 External illuminance predictions

The first test of the validation exercise was a comparison of predictions for external illuminances with measurements. Global horizontal illuminance and the four vertical illuminances were measured independently of the sky luminance distribution. The comparison therefore served as a first stage 'quality assurance' test. Plainly, any major discrepancies here would indicate that there were gross errors in either the validation data and/or the processing of the sky luminance measurements - the intrinsic accuracy of the *Radiance* illuminance calculation for this relatively trivial task is not an issue.<sup>1</sup> In the absence of input data errors, it was to be expected that the external illuminance could be predicted to a reasonably high degree of accuracy. The ambient parameter combination used to predict the external quantities is given in Table 4-1. The *Radiance* scene for these simulations contained only the sky description - the office model was not required and so it was excluded. Surfaces across which irradiance interpolation may occur were therefore not present in the scene, and so the simulation was insensitive to the value of the **ar** and **aa** ambient parameters. The ambient value (**av**) was of course set to zero. The *Radiance* simulations for this test were managed using the automation scheme outlined in Section 3.3.4.

Parameter	Value
ad	1024
as	256
ab	1

Table 4-1. Ambient parameters for external illuminance predictions

#### 4.1.1 Results and discussion

The relative error in the illuminance predictions for the global horizontal and the four total vertical quantities are shown as frequency histograms in Figure 4-1. In each case, the bin size was 1% and the distribution was normalised to total = 1. As expected, the relative errors in the predictions for global horizontal illuminance were very low.<sup>2</sup> They were not however exact: the peak of the distribution was in the range -1.5% to -0.5% and the MBE was -0.7%. This slight negative bias was despite the fact that the (model) sky luminance distribution was normalised to the diffuse horizontal illuminance.<sup>3</sup> For the total vertical quantities the predictions were as

<sup>1.</sup> See example Section 2.3.3.

<sup>2.</sup> The relative error (RER), the mean bias error (MBE) and the root mean square error (RMSE) are defined Appendix A.



Figure 4-1. Predictions for total vertical illuminances

follows. Vertical north showed a positive bias (MBE = 4.3%) and moderate scatter (RMSE = 9.5%). The distributions in the RERs for vertical south and west were nearly identical - MBEs were 1.2% and 1.5% and RMSEs were 5.8% and 5.7% for south and west respectively. The distribution in RER for vertical east was bimodal with a negative and a positive peak at (approx.) - 5% and 5%. The MBE for this orientation was very small (-0.4%), but the scatter (RMSE = 7.4%) was larger than that for vertical south and west.

Some of the features of these RER distributions can be attributed to underestimation of the circumsolar sky luminance. Recall that the circumsolar sky luminance was not measured by the scanner and so it had to be estimated using interpolation (Section 3.2.5). As described in that section, the interpolation could not reliably reproduce the high luminances of the sky about the circumsolar region (for non-overcast days). Furthermore, when this occurs, the normalisation will then reset the other sky luminances to a slightly higher value to offset the under-prediction in the circumsolar luminance (see Figure 3-23 on page 76). This effect may be manifest in the predictions for the vertical illuminances as follows. For those

<sup>3.</sup> This results from the finite-element approximation used for the normalisation.

instances when the sky was clear and the sun was in the south, underprediction of the sky component (i.e. circumsolar sky luminance) of illuminance for vertical south will be associated with over-prediction of the sky component of illuminance for vertical north. When this situation occurs, it is likely to show up in the RERs as an over-prediction for vertical north, but not necessarily as an under-prediction for vertical south. This is because the (total) vertical south illuminance has, for the scenario described above, components of sky and (direct) sun illuminance. Whereas the (total) vertical north illuminance is that due to the sky only. The propensity for the under-prediction of the (total) vertical south illuminance was greatest for clear sky conditions. But for these instances, the direct sun component of the total vertical south illuminance was large - thereby minimising the effect of the (proposed) under-estimation of the circumsolar sky luminance. This effect is seen in some of the plots below where the RER in the predictions for the four total vertical illuminances is shown alongside a time-series of the measured four total vertical illuminances, with direct normal illuminance also, Figure 4-2 - Figure 4-5. The days when it was most apparent were 102\_92, 125\_92, 127\_92 and 128\_92 (all Figure 4-2). This effect may also be the reason for the small negative bias in the RER distribution for vS and the larger positive bias in the RER distribution for vN (Figure 4-1).

There were other patterns in the RER time-series plots for vertical illuminance that cannot be explained in terms of under-estimation of the circumsolar luminance. However, they clearly have some relation to the angle between the sun and the vertical plane surface normal. For example, there were distinct 'blips' in the RER time-series that were associated with sun azimuth angles of (approx.) 180° and 270°. At these azimuths, the sun 'switches' from just illuminating one vertical plane, e.g. east, to just illuminating the 'opposite' plane, i.e. west. For example, the east-west switch is associated with noticeable 'blips' at times (approx.) 137\_92\_12h00 and 318\_92\_12h00. The 'blips' associated with the north-south switch



Figure 4-2. Vertical illuminance RER time-series



Figure 4-3. Vertical illuminance RER time-series



Figure 4-4. Vertical illuminance RER time-series



Figure 4-5. Vertical illuminance RER time-series

appear even more pronounced, e.g. 128\_92\_17h00, 137\_92\_17h00 and 188\_92\_17h00. Note also that for all the clear sky days, the pattern in the RER time-series exhibits sinusoidal-like features: 102\_92 and 128\_92 (Figure 4-2); 137\_92 and 188\_92 (Figure 4-3); 318\_92 (Figure 4-4) and 363\_92 and 364\_92 (Figure 4-5). These patterns are very distinct, and because they only occur for clear skies it is highly likely that they are related in some way to the sun position.

# 4.2 Internal illuminance predictions

#### 4.2.1 Individual cases

Internal illuminance predictions for a handful of skies were obtained prior to carrying out the simulations for all the 754 skies in the validation dataset. This was to demonstrate that the modelling approach was sound and also to carry out a limited test for two of the innovative glazing types. Detailed comparisons between measurement and predictions are presented for four cases: two for ordinary glazing, one for the diffuse light shelf and one for the mirror light shelf. Table 4-2 gives a brief description of the measured skies and the glazing type modelled for the office.

Day-time-year	Solar altitude	Solar azimuth	Sky type	Innov. glazing fixture
102_92_13h00	45.5	201.4	Sunny - intermediate	-
121_92_14h15	44.3	230.1	Dull - overcast	-
137_92_12h00	57.7	181.8	Sunny - intermediate	Diffuse light shelf
318_92_12h00	19.8	184.0	Sunny - intermediate	Mirror light shelf

Table 4-2. Summary of sky conditions and glazing type

The results for the four cases are given in Figure 4-6 and Figure 4-7. Each of the figures shows the following:

- a plot of the measured and predicted illuminance at the six photocell locations (logarithmic scaling);
- a histogram of the relative error in the predictions; and,
- a wire-line surface plot of the (model) sky luminance distribution with a perspective-aligned contour plot of same.

The predictions for all the skies, glazing fixtures and photocell locations show good agreement with measurement. For all 24 (6 x 4) illuminance predictions, the mean error was 5.6% with a standard deviation of 3.4%. In only 3 occurrences is the agreement worse than 10%, and then never greater than 13%. Illuminances from 50 lux to 27,000 lux were accurately predicted under very different sky conditions and for different glazing fixtures.



Figure 4-6. Clear glazing - 102\_92\_13h00 and 121\_92\_14h15



Figure 4-7. Diffuse light shelf - 137\_92\_12h00 and mirror light shelf - 318\_92\_12h00

The room illuminance measurements were accurate to within  $\pm 5\%$ [Aizlewood 93] and the sky luminance/illuminance data were accurate to within ±10%.<sup>4</sup> Percentage uncertainties in other input parameters, e.g. surface reflectivities, were less than that for the monitoring instruments. For the inter-reflection part of the lighting simulation, random errors are an inherent feature of a Monte-Carlo approach since a limited number of rays are used to sample a continuous luminous environment. Also, systematic under prediction might result from modelling what is effectively an infinite number of reflections with a restricted number of ambient bounces. However, using the basecase set of ambient parameters (Section 3.3.2), these errors were reduced to a negligible level. Compared to the uncertainties associated with the monitored data, the agreement between measurement and prediction for these four cases must be considered to be very good; errors resulting from the simulation model, random or systematic, are not significant compared to the errors in the input parameters. Note that there was an element of luck in the selection of these four cases; errors of the type proposed in Section 3.2.7 (see Table 3-9) were either absent or negligible in effect.

Following the initial specification of an overcast and a sunny sky day for the clear glazing cases, and clear skies for the two light shelf cases, the days were chosen at random. For the clear sky cases, times around noon were selected to ensure that there was solar penetration into the office space. The complex luminance patterns that can result under these conditions are illustrated in Figure 4-8. Here a rendering of the office space with the mirror light shelf at time 318\_92\_12h00 is shown as a 'normal' image and a false colour luminance map. For this case, the predicted field-of-view luminance ranges from ~500 to 40,000 cd/m<sup>2</sup>. The internal illuminance predictions for this case were good (Figure 4-7), so it is reasonable to assume that the predicted field-of-view luminance was correspondingly accurate. These sky conditions were likely to be more demanding of the illuminance calculation

<sup>4.</sup> Private communication - P. Littlefair, BRE.



Figure 4-8. Rendering and luminance map for room with mirror light shelf 318\_92\_12h00 than cases with overcast skies where the luminance range and gradients are generally much smaller.

## 4.2.2 All 754 skies

Having demonstrated for a test sample that accurate prediction of illuminance was achievable, the next stage was to repeat the simulations for all the 754 skies in the validation dataset. Recall that for the office with innovative glazings, the five different glazing types were cycled throughout the period of monitoring. Furthermore, only two of these - the diffuse and mirror light shelves - could be modelled using 'normal' materials. The ordinary glazing office therefore was exposed to the greatest number of skies; that is, 754. Consequently, this office configuration was used for the all-skies validation. The *Radiance* simulations for this were carried out using the automation procedure described in Section 3.3.4.

The internal illuminance predictions at the six photocell locations for the 754 skies are presented in four groups of summary plots. The first group is a set of six scatter plots of the predicted versus measured illuminances at each photocell, Figure 4-9. The measured internal illuminances range from



Figure 4-9. Predicted vs measured illuminance scatter plot

~10 lux to ~50,000 lux (logarithmic scaling is used). These plots show that the majority of the predictions were at least reasonably accurate: the points are mostly straddling the equality line. However, it can be seen that inaccurate predictions - both over and under - were more likely at high illuminances. That is, for bright clear sky conditions rather than for dull skies.

The second group of plots shows the distribution in the relative error for the illuminance predictions at each photocell, Figure 4-10. The RERs were aggregated into 5% bins, over the range -102.5% to +102.5% and the distribution was normalized to total = 1. Marked on each histogram is the 0% line (solid) and the  $\pm 10\%$  lines (dashed). Each histogram is annotated with the photocell number, the overall mean bias error (MBE) and the root mean square error (RMSE). Each of the distributions, with the exception of p\_cell 3, is fairly symmetric about the 0% line, and the main body of the



Figure 4-10. Frequency distribution in RER - all skies

distribution is contained within the range  $\pm 17.5\%$ . From p\_cell 1 at the front of the room to p\_cell 6 at the rear, there is a reduction in the kurtosis (or 'peakiness'), of the distribution. High RERs, that is greater than  $\pm 50\%$ , occur more frequently nearer the window than at the back of the room - this is revealed in the trend of decreasing RMSE from p\_cell 1 to p\_cell 6. All the photocells, with the exception of number 6, show a positive mean bias error. This was probably caused by a small number of large over predictions except for p\_cell 3 where the main body of the distribution is off-centre with a positive bias.<sup>5</sup>

The third set of plots shows the relative error (RER) in the illuminance predictions versus scan number, Figure 4-11. The RER at each photocell is marked by a black square ( $\blacksquare$ ) on a vertical line which indicates the range in the RER at the six photocells for that scan. The RER plot range is limited to ±50%, and RER values outside this range were reset to the nearest range limit, i.e. +50% or -50%. Small downward pointing arrows mark the day boundaries between the scans. For nearly all the scans, there were at least

<sup>5.</sup> Over prediction can give (positive) RERs > 100%, but the RER limit for under prediction is - 100%.



Figure 4-11. Relative error versus scan number

one or two photocell predictions (out of each group of six) that gave a RER within  $\pm 10\%$ . The pattern in the RER for the internal illuminance predictions does appear to contain something of the sinusoidal character that was identified in the vertical illuminance predictions (Figure 4-2 - Figure 4-5), also there were conspicuous clusters of high RERs that were

associated with particular days (e.g. scans 712 to 753, days 363 and 364 respectively).

The final plot in this series shows the distribution in the absolute relative error for all the predictions aggregated into 10% bins, Figure 4-12. The last



Figure 4-12. Number (per bin) versus |RER|

bin (100 - Inf.) contains all the (absolute) RERs greater than 100%. Each bar of the histogram is annotated with the percentage of the total sample in that bin, e.g. 63.8% of the internal illuminance predictions were within  $\pm 10\%$  of the measured value.

The difference in the overall character of the RERs at each photocell suggested that there might be different origins for the cause of the errors. One of the reasons for this suspicion was that there were many occasions when, for a particular scan, the illuminance at the back of the room was accurately calculated and at the front of the room the errors were very large. This finding alone gives reason to suspect that factors other than errors resulting from the underlying simulation algorithms were present in the results - since the predictions would at first sight appear to be more accurate where the simulation was expending greatest effort.<sup>6</sup>

# 4.3 Error characteristics related to positional factors

This stage of the analysis examines the relationship between positional factors (e.g. the sun position) and the error characteristics of the illuminance predictions.

## 4.3.1 Sun angle relative to glazing normal

The first of these examines the relation between the sun angle to the glazing normal and the relative error in the illuminance prediction. For these plots, the angle between the sun and the glazing normal ( $\beta$ ) is mapped to a compass rose diagram on which the glazing normal and glazing plane are marked. This mapping gives the opportunity to distinguish between the angles that lie to the east of the glazing normal ( $\beta_1$ ) and those that lie to the west of the glazing normal ( $\beta_2$ ), Figure 4-13. The magnitude of the RER is given by distance from the origin. A logarithmic scaling was used and circles that encompass the 1%, 10% and 100% RER regions are drawn. At the origin, the RER is 0.1%; RERs smaller than this were plotted here. Separate groups are shown for positive and negative<sup>7</sup> RERs. In the first group, the RER as a function of  $\beta$  is given for each photocell, Figure 4-14. In the second group, the MBE and RMSE are given for the RERs put into bins of angle  $\beta$  that are of size 10°, Figure 4-15.

Most conspicuous in these two figures is the very low occurrence of negative RERs for p\_cell 3. This is consistent with the distribution given in Figure 4-10. It might be expected that a small error in the relative position of the sun and the building orientation could result in significant RERs when, on clear sky days, the sun was near to grazing incidence to the glazing plane. This

<sup>6.</sup> The illuminance at the back of a room is mainly composed of inter-reflected light which is more difficult to model accurately than direct illumination.

<sup>7.</sup> For negative RERs, the absolute value is plotted.



Figure 4-13. Illustration for sun incidence angle plots

does not seem to be the case here: there does not appear to be any significant clustering of high (~100%) RERs when the sun lies near the plane of the glazing ( $\beta \approx 90^{\circ}$ ). The highest (>100%) RERs are all positive and are mostly confined to an arc that is approximately centred on the glazing normal. Furthermore, this arc diminishes in angular extent from p\_cell 1 to p\_cell 6. This pattern is also apparent in the negative RER plots (close to 100%).

#### 4.3.2 Errors related to the sun angle distribution

Here, the previous analysis is extended and the RERs, now binned, are given in terms of the MBE and the RMSE for each bin as a function of the azimuth and altitude angles of the sun, Figure 4-16. A consistent pattern in the error distribution, i.e. one that persists for all six photocells, could indicate that external structures (or obstructions) significant for light transport were not accounted for in the building model. This does not seem to be the case here, although it should be noted that some of these bins have



Figure 4-14. Relative error versus angle between sun position and glazing normal



Figure 4-15. Relative error versus angle between sun position and glazing normal



Figure 4-16. MBE and RMSE as a function of binned sun position

very low occupancy. What is clear however is that bins with large RMSEs (>40%) occur across a wide range of azimuth and altitude values at the front of the office (p\_cell 1), and over a very narrow range at the back (p\_cell 6). And of course, from p\_cell 1 the "view" of the window is much greater than that from p\_cell 6. This suggests that the accuracy of the predictions are related in some way to the photocell's "view" of the window. If confirmed, this would lend support to the hypothesis regarding source visibility related errors proposed in Section 3.2.7. In the following section, the relation is examined more closely.

# 4.3.3 High RERs related to the "view" from the photocell location

In Section 2.6.2 it was shown how renderings "from a light meter's point of view" can be used to understand the luminous environment with regard to illuminance (daylight factor) prediction. That approach was used here to relate the occurrence of high RERs to the photocell "view" of the office. Hemispherical fish-eye view renderings of the office - as seen from each of the photocell locations - were generated using *Radiance*.<sup>8</sup> The sun position for all the predictions where the absolute RER was 50% (i.e. very high) were superposed on each respective rendering (+ mark), Figure 4-17. A label on each rendering gives the number of points plotted, which decreases gradually from 68 at p\_cell 1 to only 5 at p\_cell 6. Almost all the sun positions are located on the glazing (that is, visible from the photocell), or just off the glazing. As a key, renderings for p\_cell 1 and p\_cell 6 with all 754 sun positions marked are shown in Figure 4-18. These findings further strengthen the hypothesis that certain sun position - photocell combinations yield unreliable predictions.

<sup>8.</sup> These renderings were laterally (i.e. East - West) inverted so that, for example, sun positions to the West appear to the left, in keeping with previous figures. Note also that, the hemispherical view for these images contains a cosine weighting of the (hemisphere) projected

solid angle. For illumination therefore, equal areas of equal luminance (in the projected view) contribute equally to the total horizontal illuminance at the view point.



Figure 4-17. Photocell view of sun position



Figure 4-18. Key renderings for sun positions

It could be that significant errors in the illuminance prediction may have resulted from small geometric/orientation differences between the simulation model and reality: since misalignment of just one millimetre can produce large errors when there are shadows cast on - or near to - the photocell by the window frame bars (i.e. Type A errors, Table 3-9). The office glazing had several window bars, and although they were measured individually to an accuracy of ~2mm, positional errors of 1-2cm relative to the overall scale of the room were possible. It was reasonable to assume therefore that at least some of the high RERs were due to a mis-match between the modelled geometry and that of the actual office. Given all of the uncertainties, it is virtually impossible to conclusively attribute any one specific high RER to positional misalignment alone. Indeed, the potential for misalignment errors proving significant were largest when the sky was clear, and so shadows were cast by the frame bars. However, these were also exactly the conditions when the uncertainty of the brightness distribution about the solar position could also lead to large errors.

#### 4.3.4 Effect of frame bar shadowing

It was possible to find considerable evidence to support that frame bar shadowing was not the sole cause of large RERs. This was achieved by generating a 'movie' sequence of renderings that showed, for a continuous period in the validation data, the frame bar shadows about the photocell location. The photocells (that is, calculation points) were located at a height of 0.7m above the office floor. Due to projection displacement, the frame bar shadowing on the floor would be very different from that in the (horizontal) plane of the photocell. To make the shadows in the plane of the photocell visible, a white disc (radius 0.1m) was added to the simulation model scene description at each of the photocell locations. A black sphere (radius 0.01m) was added at the centre of the disc to mark the photocell location. The images were generated for a viewpoint at a height of 2m (from the floor) directly above the photocell. An image from one of the generated sequences is shown in Figure 4-19. The labels indicate the dimensions of the disc and



Figure 4-19. Illustration for photocell renderings (127\_92\_12h00 p\_cell 2)

the marker sphere, and the regions of the scene that were (predicted to be) in sun or shade. Each rendering has a label that shows the 'time stamp' and the relative error in the illuminance prediction. Image sequences were generated for three continuous periods of clear sky conditions: photocell 1 for day 102\_92 (Figure 4-20); photocell 2 for day 127\_92 (Figure 4-21); and photocell 2 for day 318\_92 (Figure 4-22).

The first of these image sequences (Figure 4-20) clearly shows the traverse of frame bar shadows across the photocell. Note that, for some of these times, the RERs were very large i.e. > 50% (dashed-line box). It is quite plausible therefore that misalignment was the cause of high RERs for some instances. The other two image sequences (Figure 4-21 and Figure 4-22) also show occasions where a frame bar shadow was (predicted to be) near to the photocell position. Note here however that there does not appear to be a consistent pattern in the relationship between frame bar shadowing



Figure 4-20. Photocell 1 - day 102\_92



Figure 4-21. Photocell 2 - day 127\_92



Figure 4-22. Photocell 2 - day 318\_92

and the RER for the illuminance prediction. There were several instances where the white disc was either fully in shade or fully in sun, and yet the RERs for these occasions were nevertheless very large (e.g. 11h15 and 12h45 in Figure 4-22). It is unlikely that the magnitude of the geometric mis-alignments would be sufficiently large such that the images would show the white disc fully in shade when an actual disc would have been fully in sun - or vice versa. This suggests that geometric mis-alignment alone is insufficient to explain many of the occurrences of high RERs.

The likelihood that a shadow from a glazing frame bar has traversed the disc in the 15 minute interval between the frames can be roughly estimated as follows. Taking the window mid-point (M) as the "fulcrum", the horizontal  $(\Phi_h)$  and vertical  $(\Phi_v)$  angles subtended by a shadow-disc at M can be easily calculated from the vector geometry illustrated in Figure 4-23. The



Figure 4-23. Vector geometry

horizontal and vertical angles subtended by the shadow-disc at all six photocell locations are given in Table 4-3. Also given is the equivalent

	Horizontal displacement			Vertical displacement		
P_cell	Angle $\Phi_{h}$	t <sub>equiv</sub> [mins]		Angle $\Phi_{v}$ [°]	t <sub>equiv</sub> [mins]	
1	8.7	34.7		5.3	21.1	
2	4.3	17.1		1.3	5.1	
3	2.8	11.1		0.5	2.2	
4	2.0	8.2		0.3	1.2	
5	1.6	6.5		0.2	0.7	
6	1.3	5.3		0.1	0.5	

Table 4-3. Approximate horizontal and vertical angles subtended by shadow discs at glazingmid-point

transit time of the sun - moving at 15° hour<sup>-1</sup> - to traverse the angles.<sup>9</sup> For times around midday when the sun is about its zenith, the sun's angular

motion is largely composed of a change in azimuth angle, i.e. horizontal. At these times, the change in altitude (i.e. vertical angle) is relatively small and, for the purpose of this illustration, can be ignored. In which case, the approximate time needed for a shadow of the window mid-point (i.e. frame bar) to traverse the shadow-disc is ~35 mins for p\_cell 1 and ~17 mins for p\_cell 2. For example, the (largely horizontal) transition of a frame-shadow is captured in images 14h15 to 14h45 (Figure 4-20). A transition time of ~30 mins is indicated which is consistent with the value given in Table 4-3. It can be fairly confidently asserted therefore that, for the sequences given in Figure 4-20 and Figure 4-21, the traversal of all the frame-bar shadows has been captured in the images. Additional tests using a lower position for M (more realistic for low-altitude winter sun) indicate that this was the case for the sequence in Figure 4-22 also.

## 4.4 Errors related to illuminance components

It was shown in Section 4.3.3 that the majority of the high (> 50%) RER predictions occurred when the sun, and therefore the circumsolar region, was visible from the photocell location. It might also be possible to associate these high error cases with the relative contributions that the components of illuminance (direct sky etc.) made to the total illuminance. If established, a relation could serve to identify "at risk" cases in the validation data. Note that, although a strong *relation* between circumsolar visibility and inaccurate predictions is clearly present in Figure 4-17, the inaccurate predictions were selected *a priori* and superpositioned over the renderings. That, in itself, does not constitute a test. For the tests described below, the relations examined were between the error in prediction and:

- the fraction of the (predicted) illuminance from inter-reflected light only; and,
- the fraction of the (predicted) illuminance due to the direct sky component.

<sup>9.</sup> The vertical angle is, of course, hypothetical.

#### 4.4.1 Components of illuminance

With Radiance it is a relatively straightforward task to manipulate the scene description and/or the calculation parameters to determine, in one or more steps, any conceivable component of illuminance, e.g. externally reflected light from the sky only. For the purpose of these tests, the total predicted illuminance  $(E_p)$  can be taken to be the sum of three distinct illuminance components: the direct sun illuminance  $(E_{sun})$ , the direct sky illuminance  $(E_{sky})$  and the illuminance due to inter-reflection  $(E_{int})$ , e.g.

$$E_p = E_{sun} + E_{sky} + E_{int}$$

The last component is all the light that arrives at the calculation point following one or more reflections, from either internal or external surfaces, Figure 4-24. For any given sun and sky description, the direct sun and



Figure 4-24. Illuminance components

direct sky components can be evaluated with relative ease and certainty. That is, certainty with respect to the *model* description. The simulation of inter-reflected light is considerably more demanding, and, so one might expect, this is where the potential for errors are greatest. To test this, the relation between the relative proportions of the predicted components of illuminance and the RER were examined.

In the first instance, it was the total illuminance at each photocell that was predicted. The proportion of the total (predicted) illuminance that was due to (a) the sky component, and (b) the direct sun component could thereafter be computed fairly rapidly since neither case required a (recursive) interreflection calculation. The illuminance predictions for all 754 were recomputed<sup>10</sup> - with the inter-reflection calculation switched off - for the office model with:

1. a model sun description only; and,

2. a model sky description only.

The sum of the two components subtracted from the total predicted illuminance yielded the (predicted) illuminance that was due to interreflected light only:

$$E_{int} = E_{tot} - (E_{sun} + E_{skv})$$

The sky was visible through the glazing from all photocell locations so each photocell received some direct sky illuminance, but only occasionally did a photocell receive direct sun light. All photocells received, of course, interreflected light.

#### 4.4.2 Errors versus fraction of illuminance component

In order to make comparison between cases, the absolute fractional error (AFE) in the illuminance prediction,  $|(E_p - E_m)|/E_m$ , was plotted against the magnitude of the predicted illuminance component expressed as a fraction of the total predicted illuminance. This was done (for each photocell) for the inter-reflected component  $E_{int}$  (Figure 4-25) and for the sky component  $E_{sky}$ 

 $<sup>10.\,</sup>$  The simulations were carried out using the automation scheme described in Figure 3-31 on page 95.


Figure 4-25. Fraction inter-reflected component by photocell

(Figure 4-26). The number distribution of the points along the ordinate and abscissa axes was plotted on the top and right-hand edge of each plot (a bin size of 0.01 was used).

Looking first at the inter-reflected component, the difference in the scatter of the points between the photocells is most obviously apparent. At the back of the room (p\_cell 6), the points are mostly clustered in the range  $E_{int}/E_p = 0.8$  to 0.95, and for this cluster the AFE was fairly low - most of the points were in the range AFE = 0 to 0.2 (i.e. relative errors in the range ±20%). Turning now to the absolute fractional error for inter-reflected light - points and distribution - at p\_cell 1, there were large errors across the range of  $E_{int}/E_p$ . In contrast, at p\_cell 6 there were only a few instances where the AFE was greater than 0.3. Since there were only relatively few instances where a photocell received some direct sun light, the  $E_{sky}/E_p$ plots for the sky component appear similar to a lateral inversion of the interreflected component plots.



Figure 4-26. Fraction sky component by photocell

For Figure 4-27, the AFE data shown in Figure 4-25 & Figure 4-26 have been aggregated into bins of width 0.1 for each of the fractional components, and the mean absolute fractional error (MAFE) for the predictions in each bin are shown as a histogram. The bold vertical line on each of the histogram bars indicates one standard deviation from the MAFE. Below each of the MAFE component histograms for  $E_{int}/E_p$  and  $E_{skv}/E_p$  is a plot showing the number of points in each of the bins. Because each photocell prediction was considered individually, there were  $754 \times 6 = 4524$ predictions in total. For low fractions of the inter-reflected component (0 to 0.2), the MAFE was large, as was the scatter in the predictions. This range accounts for only a relatively small number of predictions from the entire sample. For  $E_{int}/E_p > 0.2$ , the MAFE drops sharply to ~0.1 and remains fairly steady, but the standard deviation gradually diminishes with increasing  $E_{int}/E_p$ . The range  $0.6 \le E_{int}/E_p \le 0.9$  account for over half of all the predictions. The MAFE as a function of (binned)  $E_{sky}/E_p$  shows a similar



Figure 4-27. Mean absolute fractional error as a function of binned fractional component of illuminance

trend to that for  $E_{int}/E_p$ , only here the peak of the number distribution is in the range  $0.1 \le E_{skv}/E_p \le 0.4$ .

From either of these plots it is possible to determine a discriminator that could be used to partition the photocell-sky combinations so that one population contained mostly accurate predictions. For example, predictions where either  $E_{int}/E_p \ge 0.4$  or where  $E_{sky}/E_p \ge 0.3$  would function as fairly robust discriminators. There are shortcomings however in using either of these ratios as discriminators for filtering out un-reliable predictions. Firstly, a mechanism has not yet been proposed that might explain the relation. And secondly, the application of either discriminator may unduly bias the validation sample to a limited range of sky types - thus compromising the generality of the validation. Using  $E_{sky}/E_p \ge 0.3$  does indeed bias the sample to predominantly overcast skies, whereas applying  $E_{int}/E_p \ge 0.4$  preserves a wider range of sky conditions and rejects fewer cases from the total number of photocell-sky combinations. This is shown in Figure 4-28 where the effect of applying the discriminator on the sky type is shown. For example, applying  $E_{int}/E_p \ge 0.4$  removes less than 0.2 (i.e.



Figure 4-28. Fraction of total per bin

20%) of the skies from any of the sky clearness index bins. Whereas, using  $E_{sky}/E_p \ge 0.3$  removes from the sample more than half of skies with a clearness index bin greater than 3.

#### 4.4.3 Summary

To summarise the findings discussed above:

1. Skies where  $E_{int}/E_p \ge 0.4$  are associated with accurate (MAFE < 0.2) illuminance predictions. These cases make up ~82% of the total sample and they cover a wide range of sky conditions.

2. Skies where  $E_{sky}/E_p \ge 0.3$  are also associated with accurate illuminance predictions. These cases make up ~53% of the total sample, but the clear sky conditions are under-represented in preference to overcast sky conditions.

In other words, illuminance predictions with a significant inter-reflected component  $(E_{int}/E_p \ge 0.4)$  tended to be accurate regardless of the sky type. Whereas, illuminance predictions with a significant direct-sky component  $(E_{sky}/E_p \ge 0.3)$  tended to be accurate mainly for overcast conditions.

### 4.5 Partition of the validation dataset

The findings described in the previous sections are summarized as follows:

- 1. For the majority of cases (2885, or 64% of the total), the internal illuminance was predicted to a high degree of accuracy ( $\pm 10\%$ ).
- 2. There were a small number (184, or 4% of the total) of conspicuously inaccurate predictions where the IRER1 > 50%. However, it was rarely the case that, for any one sky, the accuracy was this poor for all six photocells.
- 3. The high RER predictions were strongly associated with visibility (total or partial) of the circumsolar region from the photocell location.
- 4. Positional/geometric errors in the model description were unlikely to be the sole cause of most of the high RER predictions.
- 5. Accurate predictions, for all sky types, were associated with a significant (predicted) component of inter-reflected illuminance, i.e.  $E_{int}/E_p \ge 0.4$ .

Taken together, these findings support the hypothesis given in Section 3.2.7 that there exists in the validation dataset a class of errors that are related to imprecision in the model geometry and/or the sky description. That hypothesis is tested by partitioning each of the illuminance predictions using visibility of the circumsolar region as the discriminator. Predictions

for those photocells that did not 'see' the circumsolar region are then compared with the predictions for those that did 'see' the circumsolar region. The test and the results using the partitioned illuminance predictions are described below.

#### 4.5.1 Test for circumsolar region visibility

The extent of the circumsolar region for the test should be large enough to reduce, or possibly eliminate, all four types of source visibility related errors outlined in Table 3-9. Referred to here as the circumsolar exclusion region (CER), it should not be made too large so that many predictions (that is, photocell-sky combinations) are excluded un-necessarily. The largest luminance gradients around the circumsolar region will be for clear skies at the transition between the sky and the  $(0.5^{\circ})$  solar disc. Recall that the average luminance across a 6° circumsolar region was measured (indirectly) by the solar tracker. It is not possible to disaggregate with any certainty the sun luminance (magnitude) from the sky luminance (magnitude and distribution) within this region. Around the 6° circumsolar region, the sky luminance was estimated using interpolation. The full extent of uncertainty in the sun and sky luminance therefore covers a region that is at least 11° across.<sup>11</sup> The sky luminance gradients in this larger region however are likely to be much smaller than those within the 6° disc. For this reason, the angular extent of the CER was chosen to be, in the first instance,  $6^{\circ}$ . The visibility test for the CER was carried out for each of the 4,524 photocell-sky combinations in the validation dataset. This was achieved by using, for each of the 754 skies, a 6° unit-brightness 'sun' centred on the sun position. The  $6^{\circ}$  'sun' (that is, the CER) was the only luminous source in the model. To test for visibility of the CER, a ray bundle was aimed at the CER from each of the six photocells. A description of the generation and aiming of the ray bundle follows.

<sup>11.</sup> There were occasions when more than one scanner measurement around the solar position was "out-of-range".

For a disc, centre (0,1,0), normal (0,1,0) which subtends an angle of 6° at the origin, the (x,z) co-ordinates of ~1000 points randomly distributed across the disc were generated. The (x,y,z) co-ordinates of the origin and these points gave normalized direction vectors. These vectors formed the basic ray bundle for visibility testing. To test for visibility of the CER, a scene description of the office model with the CER at the sun position was generated. The transformation of the bundle centre (i.e. unit vector [0,1,0]) to the sun position was applied to all the vectors in the ray bundle. The vector list for the ray bundle was then replicated 6 fold, and the co-ordinates of the photocells were added to the list. Thus, a list of ray origin and direction vectors was formed for use with the rtrace program, Figure 4-29. If, from one photocell, all the rays aimed towards the CER returned zero luminance, then from that photocell, the CER was not visible. If however, one or more of the rays returned a non-zero luminance, the CER was visible, and the degree of visibility was calculated from the number of non-zero luminance rays. The CER visibility was determined for each of the 754 unique sun positions in the validation dataset. Once again, this test was carried out using the automation scheme described in Figure 3-31.

#### 4.5.2 Results for the partitioned data

The illuminance predictions at each of the six photocells for the 754 skies were partitioned into sets designated as either 'reliable' or 'potentially unreliable' depending on the visibility of the circumsolar region from each of the photocell positions. The RERs for the 'reliable' and the 'potentially unreliable' sets were aggregated into frequency distribution histograms. The RER bin size was 5% and the number in each distribution was normalised. Each histogram is annotated with the photocell number, the number of predictions in the sample, the overall mean bias error (MBE) and the root mean square error (RMSE).

Considering first the predictions from the 'reliable' photocell-scan combinations, i.e. where the CER was not visible (CS6-VIS) Figure 4-30(a).



Figure 4-29. Generating ray bundles to test for visibility of circumsolar disc

Here, each of the distributions, with the exception of p\_cell 3, appears fairly symmetric about the 0% line, and, as with the un-filtered data, the main body of the distribution is contained within the range  $\pm 17.5\%$ . For all p\_cells, with the exception of number 3, the MBE is very low, and the RMSEs are never greater than 17%. This is a significant improvement over the un-filtered data (Figure 4-10).

The predictions from the 'potentially unreliable' (CS6+VIS) photocell-scan combinations are very different, Figure 4-31(b). Note that not only are the MBEs much larger than for the 'reliable' data, but they are all positive. This is because over prediction can give (positive) RERs » 100%, but the RER



Figure 4-30. RER histograms for 'reliable' data



Figure 4-31. RER histograms for 'potentially unreliable' data

limit for under prediction is -100%. Significant over prediction in illuminance can occur when a photocell was predicted to be in sun when in reality it was in shade. The smallest of differences in geometry between the model and the actual office could cause this. The small inset histogram for each photocell shows the distribution in the fraction of the 6° CER disc that was visible for each photocell. For example, at the back of the room (p\_cell 6) the photocell never 'saw' more than about half of the CER disc.

The overall effectiveness of the partition can be better appreciated from the plots in Figure 4-32. For the upper plot (a), the absolute relative error - for all the photocells together - was aggregated into bins of size 10%. The 'reliable' (CS6°-VIS ■) and 'potentially unreliable' (CS6°+VIS ■) sets are plotted alongside, and their sum<sup>12</sup> is given by the box that bounds each pair. The last bin (100 - Inf.) is for all absolute RERs greater than 100%. The lower plot (b) gives the number of 'reliable' and 'potentially unreliable' samples as a fraction of the total number. For example, there were nearly 3,000 cases where the absolute relative error was in the range 0 - 10%, of which nearly 400 (i.e. ~0.15 of the total) were classed as 'potentially unreliable' because the CER was visible from the photocell. For |RERs| > 40%, the greater part of the total number are classed as 'potentially unreliable', and for |RERs| > 90%, all of the cases are classed as 'potentially unreliable'. It is clear from the Figure 4-32 however that many accurate illuminance predictions are also classed as 'potentially unreliable'.

One might speculate that it is possible to include the most heavily overcast skies - where large luminance gradients about the solar position are unlikely - as 'reliable' even though the (dull) circumsolar region was visible to the photocell. To test this premise, the partitioned sets were stratified by sky clearness index bin and the MBE and RMSE for each new set evaluated, Figure 4-33. For both MBE and RMSE, the accuracy for the 'reliable' set is

<sup>12.</sup> The sum is identical to Figure 4-12 given in Section 4.2.2.



Figure 4-32. Partitioned dataset

always better than for the 'potentially unreliable'. As might be expected, the difference is less for the overcast skies (bin 1), but it is nevertheless significant. So the premise is considered to be false.

In the last of the plots for this section, the RER at each photocell is plotted together with the time-series of global horizontal, diffuse horizontal and vertical South illuminances. A pair of plots are given for each of the 27 days. They are grouped together in Figure 4-34 to Figure 4-37. Here, the relative



Figure 4-33. MBE and RMSE stratified by clearness index

error at each photocell is marked at the time of the measurement by a shaded square. The 'reliable' photocell-scan combinations are shaded magenta ( ) and the 'potentially unreliable' combinations are shaded cyan ( ). RERs less than -50% or greater than 50% are plotted at -50% and 50% respectively. The illuminance predictions were made every 15 minutes, which was the sampling frequency of the sky scanner. The three external illuminances values however are plotted at 5 minute intervals, which was the interval at which these quantities were obtained. Note that for heavily overcast skies, the lines for the global horizontal and diffuse horizontal illuminances are superposed.



Figure 4-34. Illuminance RER time-series



Figure 4-35. Illuminance RER time-series



Figure 4-36. Illuminance RER time-series



Figure 4-37. Illuminance RER time-series

From the plots in these figures, the following features are observed:

- The RERs were generally much lower for overcast skies than for nonovercast skies.
- The majority of instances when an RER was outside of the range ±25% occurred for non-overcast skies.
- When these occurred, most were identified as 'potentially unreliable'.
- There is evidence to suggest that the occasional poor accuracy from 'reliable' data might be related to rapidly varying sky conditions. This is suggested by occasional large variation in the 5 min. external quantities time-series, e.g. for periods on days 129\_92 and 273\_92.

• Something of the sinusoidal character discerned in the plots for external quantities on clear-sky days (Figure 4-2 - Figure 4-5) is apparent in the pattern of the internal RERs for the same period.

The findings for this section are summarised below.

#### 4.5.3 Summary

The partition of the validation data into 'reliable' and 'potentially unreliable' sets, based on visibility of the (6°) CER, has been demonstrated and considerable evidence has been presented to support the hypothesis given in Section 3.2.7. Based on that evidence, it is proposed that intrinsic accuracy of the *Radiance* illuminance calculation is indicated by the characteristics of the 'reliable' set, and that the characteristics of the 'potentially unreliable' set are largely dominated by one or more of the source visibility related errors listed in Table 3-9. There were however, some cases where 'reliable' data resulted in poor accuracy predictions. In the following sections, attempts to further reduce or eliminate these instances are described and evaluated.

The positive bias in the illuminance predictions at p\_cell 3 was not greatly improved by partition of the validation dataset, even though the scatter was much reduced. This suggests that this photocell suffered from a calibration error, or similar fault, during all, or most, of the measurement period for this dataset. The experimenters have acknowledged that this is a possibility.<sup>13</sup>

# 4.6 The ambient parameter resolution revisited

Thus far, the analysis of the error characteristics for the illuminance predictions has concentrated on identifying potentially unreliable photocellsky combinations, and then eliminating them from the overall assessment of the accuracy of the calculation. But what of the *Radiance* illuminance calculation itself - might it be possible to obtain higher accuracy predictions

<sup>13.</sup> Private communication - M. Aizlewood, BRE.

by increasing the resolution of one or more of the simulation parameters? Also, is there the potential to achieve comparable accuracy to the basecase simulations using lower resolution parameters in a computationally less demanding (that is, faster) calculation?

Given the high dimensionality of the parameter space for the ambient calculation, it was not practicable to repeat for the entire validation sample the process that was used to select the basecase parameter set (Section 3.3). Instead, the illuminance predictions for the entire validation sample were repeated using two new sets of ambient parameter combinations. One set, called lo-amb, of much lower resolution than the basecase set. The other, called hi-amb, of much higher resolution than the basecase set. The new parameter combinations that were used - including the basecase set for comparison - are given in Table 4-4. The change from the basecase to the

Parameter	Hi-amb	Lo-amb	Basecase	
ad	4096	1024	2048	
ab	7	7	7	
ar	4	1	2	
as	64	16	32	
aa	0.05	0.2	0.10	

Table 4-4. Ambient parameter settings (av=0)

hi-amb set was effectively a doubling of the resolution of each parameter. Similarly, the change from the basecase to the lo-amb values was a halving of the resolution. The ambient bounces parameter (**ab**) was fixed because without a sufficient number of levels of inter-reflection, the calculation could never converge to an accurate value - regardless of the resolution of the other ambient parameters.

#### 4.6.1 Low ambient parameter resolution

The results from the lo-amb simulations are given as histogram plots of the (binned) predicted relative error, Figure 4-38. As with the predictions that were obtained using the basecase set (Figure 4-30), all photocell-sky

combinations where the 6° circumsolar disc was visible have been eliminated from the sample.



Figure 4-38. Lo-amb results

Most readily apparent in Figure 4-38 is the very poor accuracy for the illuminance predictions at photocells 2 and 4. For the other photocells however, the overall predictions were only slightly worse than those obtained using the basecase parameter set. The pattern in the relative error distribution across the photocells indicates that, for this parameter combination, the irradiance interpolation algorithm has performed very poorly. Errors of this type were described in Section 2.5 on page 24. When these errors occur, the predictions can be very sensitive to the order of the calculation points that are passed to the **rtrace** program. To demonstrate this, the low-amb simulations were repeated, but now the photocell points were passed in *reverse* order, Figure 4-39. The illuminance predictions for this scenario are shown in Figure 4-40. The accuracy shown here is significantly poorer than that for the same parameter combination with the points in the default order (Figure 4-38). This is because the entire interreflection calculation depends - to a greater or lesser degree - on the first



Figure 4-39. Photocell points reversed



Figure 4-40. Lo-amb results with calculation points reversed

estimates of the indirect irradiance gradient. The gradient is first estimated from the sampling rays that are spawned from the *first* point of calculation,

which here, was the first photocell location in the list of positions supplied to **rtrace** in the simulation shell script. For the default order, it was p\_cell 1 nearest the window. When the points were reversed, it was p\_cell 6 at the back of the room. The same number of initial sampling rays were used for both sets of (low resolution parameter) simulations. It is clear however, that the number of the spawned rays that sampled the window area was much greater from p\_cell 1 than from p\_cell 6. In fact, since the indirect hemispherical sampling has a cosine weighting in the distribution, the probability that a ray samples the glazing can be determined from hemispherical projection renderings<sup>14</sup> of the office from the photocell locations (see Figure 4-17 on page 119). In the rendering of the hemispherical 'view' from p\_cell 1, the glazing occupies ~16% of the total (circular) field of view. The glazing therefore is sampled by  $\sim 16\%$  of the rays spawned from p\_cell 1. From p\_cell 6 however, the 'view' of the glazing is much smaller: only about 0.3% of the total (circular) field of view. The probability that the glazing will be sampled by rays spawned from each of the photocell locations is given in Table 4-5.

Photocell	1	2	3	4	5	6
Probability that glazing is sampled	1	1/2.5	1/6	1/13	1/26	1/50

Table 4-5. Glazing sampling probability at photocell locations normalised to 1 at p\_cell 1

#### 4.6.2 High ambient parameter resolution

The high resolution ambient parameter combination resulted in barely significant improvement over the basecase set, Figure 4-41. Only at p\_cell 1 was the improvement marked to any degree: from MBE = 7.1% (basecase) to -2.4% (hi-amb). For p\_cells 2 to 5, the change in either MBE or RMSE was never greater than 1.2%. At p\_cell 6, the MBE shifted from -2.5% (basecase) to 3% (hi-amb) - a change of 5.5%, but hardly important. That this should

<sup>14.</sup> This projection has the same cosine weighting that was used for the sampling distribution. Therefore, equal areas in the rendering are sampled by, on average, equal numbers of rays.



Figure 4-41. Hi-amb results

be the case, even though the high resolution calculation spawned  $\sim 10x$  more sampling rays than the basecase calculation, suggests that each of the simulations had, for practical purposes, converged to a final value with the basecase parameter set.

#### 4.6.3 Summary

The results for this section are summarised schematically in Figure 4-42. The abscissa line represents an idealised continuous variation in the resolution of the ambient parameter combination - actually a variation in 4 dimensional parameter space (**ab** was constant). From the three point plot, the trajectory of the line from point B to point H can be fairly certainly estimated: an increase in the resolution of any of the four parameters would have resulted in a prediction that offered no significant improvement over the basecase, whilst taking longer to compute.

Would it be worthwhile to investigate the (4D) parameter space that lies between the points L and B? Given the scope of the problem - many possible combinations of 4 parameters - and that the absolute best that could be



Figure 4-42. Accuracy versus parameter resolution

achieved would be less than a factor 10 increase in computational speed, the answer offered is no. The advances in the speed of computers shows no sign of abating, and the present generation of processors are 10x or more faster than the machine that was used for the bulk of the validation work described here. What of the need though to evaluate an annual profile for internal illuminance, say at an hourly time-step? For this, the internal illuminance due to 4000 or so unique skies and sun configurations would need to be computed. Presented with this magnitude of individual illuminance predictions, it could be argued that the potential for quicker simulations should be investigated. It may not however be necessary to perform the computationally demanding part of the calculation more than a few hundred times - regardless of the number of unique sky/sun configurations that, thereafter, need to be evaluated. A technique that achieves this is described in Chapter 6.

# 4.7 The circumsolar exclusion region revisited

The application of the rejection criterion for potentially unreliable photocellsky combinations - visibility of a 6° circumsolar disc - elicited a marked improvement in the assessment of the overall accuracy of the illuminance predictions (Section 4.5). The original hypothesis appears therefore to be vindicated on the basis of this improvement and the supporting evidence. A CER diameter of 6° was chosen because this was the acceptance angle of the instrument that measured the direct normal illuminance. A CER of smaller diameter might reasonably be expected to be less successful at identifying unreliable photocell-sky combinations in the validation data. But would a larger diameter CER pick-out additional unreliable photocell-sky combinations? Also, is there evidence to indicate that uncertainty in the circumsolar sky luminance may exist over regions greater than 6° for some skies? The following section describes a rendering-based analysis that compares the measured and modelled sky luminance distributions for an overcast and a clear sky. Differences between measured and modelled sky luminances are quantified.

#### 4.7.1 Luminance gradients in the circumsolar region

Comparison between the scanner-measured sky luminance and the resulting continuous sky luminance distribution is not straightforward. One quantity that can be obtained is the difference between the measured sky luminance and the luminance of those patches of the continuous sky that are coincident with the scanner measurement pattern. For this, a series of renderings for a 40° by 40° region centred on the sun position were generated for one overcast day (121\_92) and one clear sky day (318\_92). Each rendering was false-coloured to show the sky luminance; below horizon 'sky' is shaded gray.

First, the clear sky day, Figure 4-43. The upper sequence shows the continuous sky luminance distribution that was used in the *Radiance* simulations for times 12h00 to 14h45 for day 318\_92. The lower sequence

shows the measured sky luminance (circular patches) overlaid onto the continuous model sky. Recall that to transform from the scanner measurements to the *Radiance* continuous sky brightness distribution, two interpolation mechanisms were applied. Firstly, the scanner measurements were interpolated to a regular array compatible with the brightdata format (Section 3.2.5 on page 67). Then, *Radiance* used its own bi-linear interpolation to estimate in-between (i.e. continuous) values from the brightdata array. Note that for most of the instances in the sequence, the (continuous) circumsolar sky luminance has a diamond-like shape. This pattern is a characteristic artifact of a bi-linear interpolation about a peak value.

It is apparent from the sequence showing the scanner measurements that there is often significant difference between the luminance of the continuous model sky and the measured patches. This is to be expected because the scanner measured an average sky luminance across an 11° field. Indeed, it would be highly un-realistic to model the measured sky as 11° patches of constant luminance (where measured) with some, say, interpolated value for the regions not covered by the scanner. What the difference between the measured and modelled sky luminance distributions does give however is some indication of the degree of uncertainty in the distribution. The continuously modelled sky reproduces the likely form of a clear-sky circumsolar region, at least approximately. But the actual sky luminance values within each measurement patch - and in between cannot be said to describe the conditions as they occurred at the time. Compare this with the rendering sequence for an overcast sky, Figure 4-44. For these sky conditions, it was likely that there was little significant difference between the measured and modelled sky luminance distributions.

A simple numerical comparison between the measured and modelled  $40^{\circ}$  by  $40^{\circ}$  circumsolar regions was achieved by using the non-zero luminance values in the scanner image to identify the coincident pixels in the



Figure 4-43. Renderings of model and measured skies for day 318\_92



Figure 4-44. Renderings of model and measured skies for day 121\_92

continuous sky renderings. In this way, the mean bias difference (MBD) and the root mean square difference (RMSD) between the coincident scannerpixels and the continuous-pixels for each of the 40° by 40° renderings was obtained, Table 4-6. The RMSD should be taken as giving some indication of the uncertainty in the luminance distribution in the 40° by 40° extended circumsolar region. The MBD for the clear sky day was always positive and ranged from 3% to 10%. This is consistent with normalization of the model luminance sky when the circumsolar sky is under-estimated (Section 3.2.6). The RMSD between coincident pixels for the clear sky day was quite large: 49% to 103%. Both the MBD and RMSD were very much lower for the overcast sky day. This limited examination suggests that uncertainty in the circumsolar sky luminance distribution may, for clear skies, extend over regions larger than the 6° CER. In the next section, the sensitivity of the overall errors for internal illuminance prediction to the CER angle is examined.

Time	Clear sk	Clear sky 318_92		Overcast sky 121_92		
	MBD%	RMSD%	МВ	D%	RMSD%	
12h00	6.8	51.3		2.0	22.3	
12h15	6.9	48.6		1.6	11.5	
12h30	4.9	45.0		0.2	8.6	
12h45	5.0	62.2		0.7	5.4	
13h00	4.4	73.3		0.2	4.0	
13h15	4.2	78.9		-0.1	3.8	
13h30	3.0	53.0		0.5	4.5	
13h45	3.1	60.3		0.3	4.5	
14h00	5.5	60.0		0.2	5.6	
14h15	7.0	51.7		-0.3	4.3	
14h30	9.7	103.0		0.1	6.0	
14h45	10.0	96.0		0.4	3.4	

 Table 4-6. Difference between measured (patch) luminances and equivalent patches from continuous sky luminances

#### 4.7.2 Errors as a function of CER angle

A modified form of the visibility test described in Section 4.5.1 was repeated for a number of CER angles covering the range 0.2° to 16°. The diameters 0.2° to 2° were in 0.2° steps, and the 2° to 16° range was covered in 2° steps. In preference to presenting another 16 histograms plots<sup>15</sup> (one for each additional CER angle), a more concise presentation was devised. The results for each photocell are shown in Figure 4-45. Plotted on the graphs, in a vertical line at each CER angle tested, are the RERs where the CER was not visible from the photocell. From each of the RER distributions, the following quantities were derived and plotted to show their variation with CER angle:

- the mean bias error;
- the room mean square error;
- the maximum and minimum RERs; and,
- the 2nd and 98th percentile values for the RERs.

Immediately apparent in these plots is the improvement in the overall accuracy over the complete sample results (CER =  $0^{\circ}$ ) at the first non-zero CER angle  $(0.2^{\circ})$ . This is to expected since the main effect here is the removal of large positive RERs which would occur when a photocell in shade was predicted to receive direct sunlight - as might happen if there was misalignment between model and reality. This effect is of course independent of the disc diameter. Surprising perhaps, is the relative insensitivity of the overall MBE and scatter (i.e. standard deviation) to the CER angle, for photocells 3 to 6. Recall that for the complete sample, the MBE was always skewed to the positive because of the occurrences of RER » 100%. With these eliminated  $(CER > 0^{\circ}).$ any subsequent improvements with progressively increasing disc diameters do not figure too greatly in the MBE because they affect a relatively small number of cases: the majority of the predictions were, in any case, good.

<sup>15.</sup> That is, of the type shown in Figure 4-30.



Figure 4-45. Sensitivity of errors to CER angle

A conspicuous feature of the plots, for all 6 photocells, is the variation of the maximum positive and negative RERs. After removal of the highest positive RERs (CER =  $0.2^{\circ}$ ), the maximum positive RER thereafter remains constant for all CER angles. This insensitivity means that the maximum positive RERs were not related to uncertainties in the either the luminance gradient

across the circumsolar discs or their absolute brightness. In contrast, the maximum negative RER shows gradual improvement with increasing disc diameter - this is so for all photocells (except p\_cell 6), though not to the same degree. This is consistent with under-prediction of the circumsolar sky luminance (Section 3.2.6).

Finally, these results are further reduced to an overall summary plot that shows, for the entire sample, the fraction of the sample that is within the RER limits of  $\pm 10\%$ ,  $\pm 15\%$  and  $\pm 20\%$  for all the CER angles tested, Figure 4-46. Also shown, is the fraction of the total sample remaining at each CER angle. For example, for the entire sample (CER = 0°), approximately 0.64 (that is 64%) of the total number of predictions are within  $\pm 10\%$  of the measured value. And about 0.88 (that is 88%) of the predictions are within  $\pm 20\%$  of the measured value. In view of the fact that p\_cell 3 may have suffered from a calibration error (Section 4.5.3), the results for the total sample minus the measurements at p\_cell 3 are shown also. Eliminating these measurements elicits a marked improvement for all three RER ranges, and at all CER angles. The change from CER = 0° to CER = 0.2° elicited the greatest 'step' improvement. Successive increases in the CER angle resulted in only marginal increase in the fractions of the total within the RER ranges, at the expense of reducing the sample size.

#### 4.7.3 Summary

This study has shown the results are less sensitive to the size of the CER than may have been expected. Indeed, what emerges as most significant is the elimination of all cases where the photocell could 'see' the sun, i.e. for all CER > 0°. Sensitivity to CER angle was greatest for p\_cell 1 which, of course, had the greatest 'view' of the sky. The insensitivity of the 2nd and 98th percentile lines to changes in CER angle indicates that, although outliers may be affected, the overall RER distribution was largely unchanged. Only for p\_cell 1 did the 2nd percentile line show any significant variation with CER angle.



Figure 4-46. Fractions versus CDOA

# 4.8 Conclusion

This validation study had demonstrated that the *Radiance* system has the potential to accurately predict daylight illumination levels under naturally occurring conditions for a wide range of sky types. The relative error for the majority of the predictions was commensurate with the precision of the measuring instruments themselves. Where the relative errors were high, the majority of those instances were reliably attributed to factors related to model representation rather than the prediction algorithms themselves. These findings gave considerable support to the hypothesis regarding source visibility related errors (SVRE) that was formulated in Chapter 3. For the small number of high relative error predictions that could not be attributed to SVRE, it was not possible to find a single cause or relation to

model parameters. It is suggested that these might be due to any one of a number of *other* causes related to model representation, rather than the underlying accuracy of the *Radiance* program itself.

These could be any one or more of the following:

- The limited geometrical extent of the building model (Section 3.2.1).
- The uncertainty of the sky brightness distribution away from the CER

   small bright clouds could cause significant variation in sky
   luminance at scales smaller that the 11° acceptance angle of the
   scanner.
- Marked changes in the sky brightness distribution during the sky scan this can occur on bright days with fast moving patchy clouds.
- Marked variation in the values and character of the external ground reflectance due to rain or snow.
- Marked variation in the window transmission characteristics caused by dirt, heavy showers etc.

Accurate illuminance predictions were achieved using, in the main, fairly coarse ambient parameter settings. It is reasonable to assume therefore that comparable accuracy could also be attained for buildings of greater complexity than the BRE office, e.g. an office space adjacent to an atrium, Figure 4-47(a). There are, of course, qualifications to this assertion. Firstly, complex buildings are likely to require longer simulation times. Predicting the daylight illuminance levels for a very deep-plan space, such as the example given in Figure 4-47(b), is possible, if computationally very demanding. But note that for most practical daylighting purposes, useful levels of illumination are generally achieved after two or three diffuse light reflections; thereafter the higher order reflections add little to the overall total. For the very deep-plan space therefore, there is likely be little practical use in predicting what will be negligible levels of daylight illumination.



Figure 4-47. 'Complex buildings'

The modelling of so-called advanced glazing materials, such as prismatics (Figure 4-47c), pose other problems. To model these materials with any certainty, their optical properties must be adequately represented in the simulation. This generally means that the material's bi-directional transmission distribution function (BTDF) must be known and characterised in some way. The *Radiance* system has the capability to model advanced glazing materials based on empirical BTDFs. These quantities are only just being measured and their use in *Radiance* is not

straightforward. Even 'common or garden' venetian blinds can prove difficult to model because light transmission here depends on several reflections occurring over very small scales between the slats, Figure 4-47(d).

For overcast skies - where the circumsolar luminance is not an issue - the accuracy of the illuminance predictions must be considered to be very good. Accordingly, daylight factor predictions using the CIE overcast sky will have comparable accuracy. For all non-overcast skies however, the illuminance predictions for all those occasions when the circumsolar region is visible from the point of calculation must be considered to be potentially inaccurate. This is likely to be the case for any illuminance predictions resulting from sky luminance patterns that are based on scanner measurements comparable to those used for this study.

In the main, for the vast majority of practitioners, a daylight illumination analysis will be one based on daylight factors (Section 2.2.1). The daylight factor approach assumes a CIE overcast sky, i.e. no sun and no azimuthal anisotropy in the sky luminance. The daylight factor approach is based on a fixed ratio between the internal and the external illuminance. It has long been appreciated however that the ratio of internal to external illuminance varies greatly under real skies [Tregenza 83]. Thus the daylight factor approach can offer only a limited measure of the actually occurring daylight illumination levels. A more accurate evaluation of daylight provision would take into account all of the illuminance components - direct sun, direct sky and inter-reflected - resulting from a wide range of sky types that can be demonstrated to be representative of the naturally occurring climatic conditions for the appropriate locale. Techniques to achieve this goal are described, applied and tested in the following chapters.

# Chapter

Sky Models for Lighting Simulation

"It's cloudy... and then there's a sun"

Elspeth

The validation results presented in Chapter 4 have shown that the *Radiance* system can predict internal illuminance to a high degree of accuracy for a wide range of naturally occurring sky conditions. Measured sky brightness data is however, at this point in time, very limited. Long timeseries data exist for only a few sites in the world, largely collected as part of the International Daylight Measurement Year.<sup>1</sup> For the majority of lighting scientists and practitioners, non-overcast sky luminance distributions for their locale will have to be derived from measurements of integrated quantities, e.g. irradiance data from weather tapes. This necessitates the use of a theoretical model to generate the sky luminance distribution.

In this Chapter, the performance of a range of sky models is evaluated in terms of their ability to reproduce a sky luminance patterns for the purpose

<sup>1.</sup> See IDMP website: http://idmp.entpe.fr/ for a list of the stations.
of illuminance prediction. Performance criteria were based on the error characteristics for predictions of the four total vertical illuminances, and internal illuminances at the six photocell locations in the BRE office (Figure 3-4). Four 'pure' sky models and two sky model blends were evaluated. Sky models and how they are used in *Radiance* was first introduced in Chapter 2 (see Section 2.1.2, 2.3.3, 2.7.1 and 2.7.3).

# 5.1 Introduction

Sky models generate continuous sky luminance patterns. The discontinuous aspects of skylight - instantaneous cloud patterns - are not addressed. Attempts have been made to devise a theoretical framework which provides for the inclusion of discontinuous brightness features (that is, clouds) on a continuous luminance distribution [Perez 93b]. Here Perez et al investigated the possibility of parameterising the magnitude and spatial distribution of discontinuous features based on indices for the sky clearness and sky brightness. The method can be applied to any continuous sky brightness distribution model and may be a way of reconstructing some of the random aspects of daylight from measurements of integrated quantities. It is not, of course, expected to reproduce actual sky brightness configurations observed at a particular instant.

Differences that may arise between measured and modelled sky luminance patterns can result from one or both of the following:

- 1. The model was unable to reproduce the underlying continuous luminance pattern of the measured sky.
- 2. The underlying luminance pattern of the measured sky may have been accurately reproduced, but the model did not account for the random-discontinuous features that were present in the measurements.

Evidently, the role of sky model validation is to evaluate the performance of theoretical models based on the first of these causes.<sup>2</sup> Preliminary

comparisons between various sky models and measured sky luminance patterns have recently been reported [Ineichen 94][Littlefair 94].

## 5.1.1 Real and model skies

Some of the differences, and similarities, between measured and modelled sky luminance patterns are demonstrated in the following examples. The luminance patterns of four measured skies are presented alongside luminance patterns generated by a sky model. The four skies were selected from the BRE-IDMP validation dataset (Section 3.1) to demonstrate something of the diversity in naturally occurring conditions. They cover the range from heavily overcast, through two intermediate skies, to clear sky conditions. The inputs to the sky model generator program were measurements of the direct normal and the diffuse horizontal illuminance recorded at the same time as the scan. The sun description used in both the measured and the theoretical representations was the same for any one sky. The measured and modelled skies are labelled Lumscan and Skymodel respectively. The measured sky luminance patterns were based on the 145 readings taken by the Krochmann sky scanner (Section 3.1.3). The luminance measurements were interpolated to a regular grid compatible with the Radiance brightdata format (Section 3.2.4). The model sky description was generated using the gendaylit program (Section 2.7.3). This program creates a luminance distribution based on the Perez 'All-Weather' model [Perez 93]. A summary of the specification for the measured and modelled skies is given in Table 5-1.

For these illustrations, the sky brightness distribution is shown as a luminance surface. The height of the surface (z-axis) is proportional to the sky point luminance. *Radiance* was used to generate the 'views' of the measured and modelled skies from which the luminance surfaces were

<sup>2.</sup> It should be noted that what is considered to be a continuous or discontinuous feature may depend on the angular resolution of the sky scanner. For example, a sky with cirrus of cirrocumulus formations could be recorded as having a very uneven luminance distribution if the scanner managed to resolve the finescale luminance patterns of the cloudlets.

	Lumscan	Skymodel	
Sky luminance	Based on measured data	Based on Perez All- weather model	
Input parameters	145 measurements of sky luminance	Diffuse horizontal illuminance <sup>a</sup>	
<i>Radiance</i> pattern type	brightdata	brightfunc	
Luminance at sky point (i.e. pixel	Interpolated from data map	Evaluated from continuous function	

Table 5-1. Measured distribution and sky model specification

a. Evaluated from direct normal illuminance and global horizontal illuminance (Section 3.2.5).

derived. Luminance surfaces for the four measured and modelled skies are shown in Figure 5-1 and Figure 5-2. The sky point luminance at the horizon is indicated by the height of the surface's cylindrical 'skirt' (dashed line). The luminance surface is based on an angular fish-eye view of the sky. For this projection, the radial distance (seen here in perspective) from the centre of the surface in the x-y plane is proportional to the zenith angle. For each figure, the same scaling and rotation were applied to the luminance surfaces. Each figure includes the sun position marked on an altitudeazimuth polar plot, and the relative error in the prediction for global horizontal and the four vertical illuminances.

For the modelled sky, the sky point luminance was determined directly from the equation for the sky model. For the measured sky however, the sky point luminance invariably resulted from a bi-linear interpolation of the brightdata datamap. This can be seen in the luminance surfaces for the measured skies: a local high luminance value is shown as a peak rather than as a patch of constant luminance.<sup>3</sup> The four comparisons below are purely illustrative. It is *not* intended that any judgement be drawn on the accuracy of the Perez model from these four cases alone.

<sup>3.</sup> The scanner measured the average sky luminance across a 'cone' 11° wide (Figure 3-6).

### Densely Overcast Sky (326\_92\_11h00)

The measured and modelled luminance patterns are characteristic of those observed for heavily overcast skies - very little azimuthal asymmetry with the zenith luminance greater than that at the horizon, Figure 5-1 (a). The variation in sky luminance with altitude, however, are noticeably different. The luminance scanner recorded a larger luminance ratio from zenith to horizon than that predicted by the model. The lower ratio for the model - indicated by a higher horizon luminance - was the cause of the over-prediction for the vertical illuminances.

### Overcast-Intermediate Sky (183\_92\_10h30)

Cloud cover for this sky was thinner than for the densely overcast sky, Figure 5-1 (b). There was a small component of direct solar radiation, and the maximum sky luminance was at the sun position. Unevenness in the luminance pattern was recorded by the scanner but, of course, does not feature in the distribution generated by the sky model. The vertical illuminance predictions of the Skymodel show the greatest error (overprediction) for the two surfaces that were illuminated by the sun (i.e. East and South).

### Clear-Intermediate Sky 129\_92\_11h00

The luminance pattern for this sky was dominated by the bright region centred on the sun position, Figure 5-2 (a). However, a fair amount of unevenness resulting from bright patches of cloud was also present in the measurements. These conspicuous cloud patterns were the likely cause of the poor model predictions for the North and West facing vertical illuminances.

### Clear Sky 102\_92\_13h30

The clear sky luminance pattern measured by the scanner does show some slight unevenness, but the form is very similar to that seen in the model sky, Figure 5-2 (b). Both Lumscan and Skymodel exhibit features typical of clear



Figure 5-1. Overcast (a) and overcast-intermediate (b) skies

sky conditions - brightening at the horizon and a region of minimum sky brightness about 90° away from the sun across the zenith. The model sky however performed poorly for all the vertical orientations. In the absence of conspicuous unevenness in the measured pattern, it is probable that the



Figure 5-2. Intermediate-clear (a) and clear (b) skies

model was unable to accurately reproduce the underlying luminance pattern for this sky.

## 5.1.2 Summary

The four measured skies shown above illustrate something of the range in sky luminance patterns that occur in the UK. From heavily overcast, through intermediate to clear sky conditions, the underlying luminance pattern becomes increasingly anisotropic and dominated by the circumsolar region. Qualitatively, the Perez model representations show similarity with the underlying pattern for the measured skies, even though the vertical illuminances predicted using the model sky were often inaccurate (IRER1 > 10%). As previously stated, these were illustrative examples only. In the sections that follow, the sky model formulations available with the standard *Radiance* release are evaluated using all of the 754 skies in the validation dataset.

# 5.2 Radiance generator programs for sky models

The *Radiance* standard release includes the sky model generator program **gensky**. This utility program will produce *Radiance* format sky luminance distributions for four sky model types, with the option to create a sun description for the non-overcast sky models. Another sky model generator program is **gendaylit** (discussed above). This program is not part of the standard release, and so it is not updated with each release of *Radiance*. However, like *Radiance*, it is freely available and it gives the user access to the Perez All-weather model which is not supported by **gensky**.

## 5.2.1 The models supported by gensky

The gensky program can produce sky luminance distributions based on:

- the uniform luminance model;
- the CIE overcast sky model;
- the CIE clear sky model; and,
- the Matsuura intermediate sky model.

The absolute luminance of any of these sky luminance patterns is controlled by supplying the program with either the zenith luminance or the diffuse horizontal illuminance.<sup>4</sup> The clear and intermediate sky models allow the option to automatically create a description of the sun. In which case, the solar luminance is either directly supplied to the program or calculated from horizontal direct illuminance. The sun position can either be defined by altitude and azimuth or calculated by gensky from the time and uniform geographical coordinates. The luminance model is unrepresentative of any naturally occurring sky conditions and is therefore excluded from any further consideration.<sup>5</sup> The gensky input parameter specification for the remaining three models is described below.

#### The CIE overcast sky model

The overcast model takes the standard CIE form for this type of sky (see Eq 2-3, Section 2.1.2). The generator command is executed as:

### % gensky -ang $\gamma$ (180 - $\alpha$ ) -c -B $I_d$

Where the altitude and azimuth<sup>6</sup> are, respectively,  $\gamma$  and  $\alpha$ , and  $I_d$  is the diffuse horizontal irradiance, which is calculated from global horizontal illuminance,  $E_{gh}$ , and direct normal illuminance,  $E_{dn}$  using:

$$I_d = \frac{E_{gh} - E_{dn} \sin\gamma}{K_R}$$
(5-1)

where  $K_R$  is the Radiance luminous efficacy factor (179 lm/W). The solar component, however, is not generated automatically. A Radiance description for the sun must be specified manually or generated by another program.

<sup>4.</sup> Actually, as with all *Radiance* programs and descriptions, it is the radiance and/or irradiance that must be specified. See Section 2.3.3.

<sup>5.</sup> The uniform luminance model is useful however for 'Rights to Light' and other specialist applications.

<sup>6.</sup> Note, the *Radiance* convention has the azimuth as degrees West of South, rather than degrees East of North.

The description for the sun is:

```
void light solar
0
0
3 Rs Gs Bs
solar source sun
0
0
4 x y z 0.5
```

where **Rs**, **Gs** and **Bs** are, respectively, the red, green and blue spectral radiance values for the sun. The source angle for the sun is  $0.5^{\circ}$ , and it is centred on the direction vector  $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ . In this work, the sun was modelled as an achromatic source and the solar radiance,  $B_{sun}$  (= **Rs** = **Gs** = **Bs**), was evaluated from the direct normal illuminance,  $E_{dn}$  using:

$$B_{sun} = \frac{E_{dn}}{\Delta \omega_s K_R}$$
(5-2)

where  $\Delta \omega_s$  was the solid angle subtended by the (0.5°) solar disc. The vector components are computed from the sun altitude and azimuth values. The **gensky** output with the added solar component forms the CIE overcast sky with sun description.

#### The CIE clear sky model

For the CIE clear sky model, the sky and sun description can be both generated using the **gensky** command. The equation for this sky was given in Eq 2-4, Section 2.1.2. The brightness parameters supplied to **gensky** are diffuse horizontal irradiance and solar radiance. The command used is:

```
% gensky -ang \gamma (180 - \alpha) +s -B I_d -b B_{sun}
```

#### The "Matsuura intermediate sky" model

This formulation is based on a model that was proposed by Matsuura to describe sky conditions that have a higher turbidity than the CIE clear sky model.<sup>7</sup> At the time that the Matsuura model was implemented into the

<sup>7.</sup> Private communication - G. Ward, LBL.

**gensky** program, it was not recognised as a CIE standard.<sup>8</sup> Hereafter, it is referred to as the intermediate sky model. This model takes the form:

$$L(\gamma, \theta) = \frac{L_z \cdot a \cdot b}{2.326}$$
(5-3)

where

$$a = [1.35 \sin(5.631 - 3.59\xi) + 3.12]\sin(4.396 - 2.6\xi_s) + 6.37 - \xi$$
  

$$b = EXP\{-0.563\theta[(2.629 - \xi)(1.562 - \xi_s) + 0.812]\}$$
  

$$L_z = \text{zenith luminance}$$
  

$$\xi = \pi/2 - \gamma$$
  

$$\xi_s = \pi/2 - \gamma_s$$
  

$$\theta = \text{angle from sun to sky point}$$
  

$$\gamma = \text{sky point altitude}$$
  

$$\gamma_s = \text{sun altitude}$$

The zenith luminance (actually, radiance) is normalised to the diffuse horizontal irradiance.

In comparison to the CIE clear sky model, the intermediate formulation generally predicts lower luminance for the circumsolar region and slightly higher zenith luminances. Additionally, horizon brightening which can be a prominent feature of the clear sky model, is generally absent. This is discernible in Figure 5-3 which shows plots of the sky luminance versus altitude together with false-colour luminance maps for the clear, intermediate and overcast models. The sky point luminance along an arc from  $\gamma = 0^{\circ}$  (due North), across the zenith to  $\gamma = 0^{\circ}$  (due South) is plotted on the graph (dashed line on the false-colour maps). Each sky model was normalised to the same diffuse horizontal illuminance (30,000 lux). The sun

<sup>8.</sup> At the time that this thesis was near completion, the CIE announced that an official standard for intermediate skies had been agreed. It is not known if this official formulation is the same as the Matsuura model used here.

altitude and azimuth were  $45^{\circ}$  and  $180^{\circ}$  respectively, though the sun itself was not modelled.



Figure 5-3. Luminance profile and maps for narrow-range sky models

#### 5.2.2 The gendaylit program

The **gendaylit** sky model generator produces a *Radiance* description based on the Perez All-weather model [Perez, 93].<sup>9</sup> This model takes the form:

$$L(\gamma, \theta) = L_z \left[ 1 + a \text{EXP}\left(\frac{b}{\sin\gamma}\right) \right] \left[ 1 + c \text{EXP}(\theta d) + e \sin^2 \theta \right]$$
(5-4)

Where a, b, c, d and e are adjustable coefficients which depend on solar altitude  $\gamma$ , sky clearness  $\varepsilon$  and sky brightness  $\Delta$ . The five coefficients a, ..., eare continuous in terms of  $\Delta$  and  $\gamma$ , and discrete in terms of  $\varepsilon$ . In other words, the parameters which depend on  $\varepsilon$  are values held in a look-up table of model coefficients. The model coefficients were derived via least squares fitting of a large data base of ~16,000 sky scans that were recorded at Berkeley (California, USA) between June 1985 and December 1986. Each sky scan recorded 186 measurements of the sky luminance. The **gendaylit** program will evaluate the coefficients a, ..., e from diffuse horizontal and direct normal illuminance. In keeping with the conventions of the *Radiance* system, **gendaylit** uses a value of 179 lm/W for luminous efficacy ( $K_R$ ). The key feature of the Perez model is the potential to generate many sky types, from overcast through to clear, from only the magnitudes of the input parameters. This is in contrast with the different formulations in **gensky** which have to be selected manually by the user.

## 5.3 Evaluation I: 'Pure' sky models

The illuminance predictions for the validation exercise described in Chapter 3 and Chapter 4 were repeated with the sky luminance patterns now provided by sky models. Illuminance predictions for the skies in the validation dataset were obtained for the following sky models (all with sun):

- the CIE standard overcast sky model;
- the Matsuura Intermediate sky model;.

<sup>9.</sup> The **gendaylit** program was written by Jean-Jaques Delauney, FhG-ISE, Freiburg, Germany.

- the CIE clear sky model; and,
- the Perez All-weather sky model.

The first three of the above are 'narrow-range' models. These were formulated to reproduce luminance patterns for specific sky conditions. As their names suggest, these sky conditions are: densely overcast with no sun; hazy, thin cloud with sun (intermediate) and clear, sunny sky conditions without clouds. Only the Perez All-weather model was designed to generate luminance patterns for a wide range of sky conditions. These four are, nevertheless, called here 'pure' sky models because they are distinct formulations. For brevity, the models are referred to occasionally simply as overcast, intermediate, clear and Perez.

Any one of the narrow-range models will be incapable of reproducing the full range of sky conditions in the validation dataset. That notwithstanding, the predictions for the narrow-range models serve two purposes. The first is illustrative: just how well do the narrow-range models perform when applied routinely to all the skies of the validation dataset? The second, and more significant purpose, is to generate the basic data from which the illuminance *effect* of a sky model blend may be synthesised (this is examined in Section 5.4). The absolute performance of the narrow-range models should *not* be inferred from the comparison that follows.

## 5.3.1 Automation of the simulations

For each of the sky models in turn, external and internal illuminance predictions were obtained for each of the 754 skies in the validation dataset. Each sequence of simulations was initiated from an 'executive' IDL program similar to the one described in Figure 3-31. The input parameters for the sky model programs were derived from measurements of the global horizontal illuminance, the direct normal illuminance and the sun position. The 'executive' program spawned shell scripts that contained commands for the following operations:

- 1. Generate *Radiance* format skies using **gensky** or **gendaylit** (input parameters were read from temporary files created by the 'executive' program).
- 2. Create Radiance octree for the sun and sky description.
- 3. Execute **rtrace** to calculate the external illuminances and write to temporary file.
- 4. Add sun and sky description to the (frozen) octree for the BRE office scene.
- 5. Execute **rtrace** to calculate the internal illuminances at the six photocell locations and write to temporary file.

Altogether, there were 3,016 (= 754 x 4) executions of **rtrace** for the external illuminances and the same number again for the internal illuminances. The basecase set of ambient parameters was used for all the simulations for the internal illuminance (Section 3.3.2). The input parameters to the generator programs and the measured quantities from which they were derived are listed in Table 5-2.

Model ty	уре	CIE overcast	CIE clear	Intermediate	Perez 'All- Weather'
Generat	or program	gensky	gensky	gensky	gendaylit
ent	Input	$I_{dh}$	$I_{dh}$	$I_{dh}$	$E_{dh}$
Sky compone	Derived from	${E_{gh}, E_{dn}, \gamma, \over K_{R}}$	${E_{gh}, E_{dn}, \gamma, \over K_{R}}$	${E_{gh}, E_{dn}, \gamma, \over K_{R}}$	$E_{\sf gh}, E_{\sf dn}, \gamma$
ent	Input	B <sub>sun</sub> <sup>a</sup>	B <sub>sun</sub>	B <sub>sun</sub>	$E_{dn}$
Sun compone	Derived from	$E_{dn}, K_{R}$	$E_{dn}, K_{R}$	$E_{dn}, K_{R}$	-

#### Table 5-2. Sky generator program parameters

a. Sun description added by routine in 'executive' program.

## 5.3.2 External illuminance predictions

The first stage of the comparison is a presentation of the relative error in the illuminance predictions for the four vertical illuminances. The relative errors for each orientation are shown as frequency histograms. Each histogram is annotated with the overall MBE and RMSE for the sample. The results were as follows.

#### CIE Overcast sky model

The distributions showed a low (< 10%) overall bias in predictions for vertical North (VN) and vertical East (vE), Figure 5-4. Illuminances for the vertical South (vS) and vertical West (vW) orientations, however, tended to be under-predicted. The MBE for vS and vW was -15% and -19% respectively. The overall accuracy indicated by the RMSEs was in the range 22% to 28%.



Figure 5-4. CIE overcast sky model

### CIE Clear sky model

This model performed fairly poorly for all but the vE orientations, Figure 5-5. The general tendency was to overpredict vertical illuminances, particularly for the vS and vW orientations where the MBEs were 52% and 58% respectively. The RMSEs were correspondingly very large; in the range 30% (vE) to 94% (vW).



Figure 5-5. CIE clear sky model

### Matsuura Intermediate sky model

The performance of the intermediate sky is, in character, similar to that for the clear sky, Figure 5-6. However the bias in the predictions for the intermediate sky was always lower than for the clear sky, and the accuracy greater. Note also that the MBEs for vN and vE were marginally negative (-7% and -13%), whereas with the clear sky model they were markedly positive (24% and 18%).

### Perez All-weather model

As is immediately apparent from the distributions, the Perez model performed reasonably well for all vertical orientations, Figure 5-7. For only one orientation (vN) was the MBE greater than 10%, and then only marginally (11%). The MBE was positive for all orientations. The RMSE values were in the range 17% to 42%. The high RMSEs for vS and vW were



Figure 5-6. Intermediate sky model



Figure 5-7. Perez all-weather model

caused by a small number of outliers where the RER was greater than 100%. It should be noted that there were 41 skies for which the Perez model description could either not be generated (outside parameter range) or

which produced negative vertical illuminances. These were eliminated from the analysis for this model leaving 713 skies. The negative vertical illuminances resulted from distortions in the sky luminance distribution that can occur unexpectedly for certain combinations of input parameters. These parameter combinations were present in the data collected by the BRE but they were not encountered in the Berkeley data that were used to derive the model.<sup>10</sup> This effect was noted by Littlefair and an adjustment to the model to prevent this distortion was advised by Perez [see Littlefair 94]. A routine examination of the gendaylit code showed this fix to be present. This suggests that either the fix (or some other part of the model) was incorrectly coded, or that there are still some parameter combinations that result in distortion, regardless of the fix. The presence of a distortion was taken to be a negative value for any of the predicted vertical illuminances. The actual luminance distribution for the sky was not examined. So the possibility remains that some of the other skies may yet have exhibited some distortion. If a distortion did result, but was not sufficient to give a negative vertical illuminance, it would simply be manifest as an underprediction, and so would not be identified as an erroneous sample. In which case, the error metrics for this model may, to some degree, be contaminated.

## 5.3.3 Analysis of RERs for vertical illuminance predictions

The sky model MBEs and RMSEs for each of the orientations are shown as a histogram chart in Figure 5-8. The results for the measured skies (Lumscan) are included for comparison (taken from Figure 4-1). In terms of bias for the vertical orientations, Perez performed best of the models for vE, vS and vW. Only for vN did the overcast model produce a lower bias than the Perez, and then only marginally. A striking feature of the histogram plots is the similarity in rank order of vN with vE, and of vS with vW. This is apparent for both the MBE and the RMSE. The poor performance of the clear sky model is most apparent for the vS and vW orientations.

<sup>10.</sup> Private communication - P. Littlefair, BRE.



Figure 5-8. Sky models MBE and RMSE

In terms of producing the lowest overall bias for the average (absolute) MBE, the Perez model performed the best, Table 5-3. Next was the overcast, closely followed by the intermediate model. The performance of the clear sky model was markedly worse than the other three. The overall performance of the narrow-range models can be largely attributed to two factors: the characteristic luminance patterns of the sky models; and, the composition of the validation dataset.

	Overcast	Clear	Intermediate	Perez
Avg( MBE )	11.9%	38.0%	14.1%	6.7%
Avg(RMSE)	25.0%	62.4%	34.8%	28.7%

Table 5-3. Vertical illuminance: average |MBE| and RMSE

#### RERs related to sky model luminance patterns

The luminance patterns for the overcast, intermediate and clear sky models posses characteristic features. Some aspects of the RER distributions for vertical illuminance may be explained in terms of these distinctive features. The plot of model sky point luminance versus altitude (Figure 5-3) is used to illustrate how systematic biases in the prediction of vertical illuminance might arise. Recall that for Figure 5-3, each of the skies were normalised to the same diffuse horizontal illuminance, and the solar altitude and azimuth were 45° and 180° (due South). Consider the following possibilities for the prediction of the vertical South illuminance ( $E_S$ ).

- 1. That the actual sky conditions were consistent with the overcast sky representation. In this event it would be expected that the overcast sky model give a reasonably accurate prediction for  $E_S$ . The clear sky model would however, for the same conditions, generate a luminance distribution with a relatively intense peak at the solar position. This is despite the fact that the actual solar luminance (derived from measurement for a heavily overcast sky) was likely to be less than the clear sky model luminance at the solar position. It is apparent then that, for the scenario described above, the clear sky representation would always overpredict  $E_S$  when actual overcast conditions prevailed. Similarly, the intermediate sky would also overpredict  $E_S$ , but to a lesser degree.
- 2. That the actual sky conditions were consistent with the clear (or intermediate) sky model (sun position as above). Now it is the overcast sky model which gives a poor representation. Since one would expect

some sky brightening about the solar position for actually occurring clear (or intermediate) conditions, the overcast model would then systematically under-predict  $E_S$  for this scenario.

There are limits to generalisations elucidated from a relatively small number of specific cases. For example, a bright circumsolar region (when present in the validation dataset) was not always at altitude 45° and due South. However, for this dataset, the sun position was 'visible' from the vertical South plane for most of the skies (Figure 3-8). Also, the illuminance is, of course, the cosine (zenith angle) weighted integral of luminance over a hemisphere, not just an arc.<sup>11</sup> With these qualifications kept in mind, the two examples above nevertheless offer some insight. And indeed, the relative sizes of the vertical South MBEs for the overcast and clear skies are consistent with the mechanisms outlined above. For the overcast model, the MBE was -15.1%. Whereas, the clear sky model produced a significantly larger (absolute) MBE of +52.1%. The relative difference of these biases may, in part, be explained by considering also the contribution of direct solar radiation to vertical South illuminance. The clear sky model was a poor representation when the actual conditions were overcast, i.e. when solar radiation was negligible and the sky was the sole contributor to illuminance. In contrast, the overcast model was a poor representation when the actual conditions were clear/intermediate, i.e. when solar radiation was likely to be significant. So although the overcast sky produced less vertical South illuminance than would a clear sky, the solar contribution to  $E_S$  was the same for both - the same sun description was used for all the models. Thus, the systematic bias that resulted from modelling actual clear skies with overcast, was less than that from modelling actual overcast conditions with clear skies.

<sup>11.</sup> Actually, a half-hemisphere for vertical illuminances, where the photocells are shaded from ground luminance.

#### RERs related to composition of the validation dataset

The 754 skies in the validation dataset contain a large number of overcast skies. Approximately 60% of the skies have a clearness index that falls in to clearness bin number 1, Figure 3-9. It is not surprising therefore that, overall, the overcast sky model performed moderately well. The bias in the distribution of the sun azimuth angle is another factor to consider. Recall that operational factors limited the collection of room illuminance data to after 10:30h (see Section 3.1.4). This means that, for the sample as a whole, only a relatively small number of vE measurements included a component for direct solar radiation. Whereas, the vS and vW planes were often illuminated by direct solar radiation (when present). This bias was the likely reason for the similarity between the distributions for vN and vE, and also between vS and vW. The vN and vE photocells rarely recorded a direct solar contribution, whereas the vS and vW photocells often did. If the distribution in solar azimuth was symmetrical about the N-S line (and without a bias in altitude), the vE and vW RER distributions would then be broadly similar. This would be the case for any of the sky models.

## 5.3.4 Internal illuminance predictions

The overall sky model MBEs and RMSEs for the prediction of internal illuminance at the six photocell locations are presented as histogram plots in Figure 5-9. For comparison, the results for the measured skies (Lumscan) are shown also (taken from Figure 4-10). These are the results for the entire sample.<sup>12</sup> As one might expect for an office with near-to South facing glazing, the rank order in MBE for the sky models at each photocell is very similar to that for the vertical South illuminance (Figure 5-8). Overall the Perez model gave the lowest bias, closely followed by the overcast model. The clear and intermediate models both performed poorly, though the clear sky model was the worst by a significant margin. The overcast model had a tendency to underpredict internal illuminance. This is in contrast to the

<sup>12.</sup> That is, all photocell-sky combinations for all 754 skies (713 for the Perez model).

other models which all exhibited a tendency to overpredict internal illuminance, to a greater or lesser degree. The RMSEs for the overcast sky model were, for most photocell locations, markedly lower than for the other three models. The MBE and RMSE for the Lumscan predictions was



Figure 5-9. Internal illuminance: sky models MBE and RMSE

generally lower than for any of the sky models. Though it is likely that the MBE and RMSE for Lumscan and all the sky models are dominated by

	Overcast	Clear	Intermediate	Perez
Avg( MBE )	18.8	92.2	34.9	12.7
Avg(RMSE)	32.8	155.8	69.1	62.5

source visibility related errors (Section 3.2.7). The average (absolute) MBE and RMSE across the six photocells are given in Table 5-4.

Table 5-4. Internal illuminance: average |MBE| and RMSE

#### Model sky performance based on a percentile analysis

It was demonstrated in Chapter 4 that the BRE-IDMP data contained many of potentially unreliable photocell-sky occurrences combinations (Section 4.5). These were referred to as source visibility related errors (SVRE) and they were identified as resulting from one or more of four error types (Table 3-9). As things stand, there is little scope to correct for any one of these errors with any certainty. Furthermore, because each can have a similar effect on the predictions, it was not possible to dis-aggregate the effect of one error type from the rest. Recall that one of these SVREs (Type B, Table 3-9) resulted from the uncertainty of the sky luminance distribution about the solar position; the sky scanner could not resolve the circumsolar luminance gradients. Sky models for non-overcast skies on the other hand, are designed to reproduce the circumsolar sky luminance.

The partition of the validation dataset, based on visibility of a 6° circumsolar exclusion region (CER), eliminated most (possibly all) of the SVRE and elicited a marked improvement in the assessment of the intrinsic accuracy of the illuminance predictions. To do the same for the sky model predictions would remove from the validation dataset those cases where the CER was visible from the photocell. This would have the unfortunate effect of eliminating from the comparison those instances where the illuminance predictions were most sensitive to luminance gradients about the circumsolar region. And indeed those *might* be the instances where the sky model accurately reproduced conditions that the scanner could not

measure. To assess the sky model performance without *a priori* partitioning of the validation data requires a comparison test that is based on something other than MBE and RMSE, because these can be heavily biased by a few outliers. This was achieved using a percentiles-based comparison.

For this, the percentage of the predictions that had a relative error within the range  $\pm R$  were plotted as a function of *R*. These plots are referred to here as percentile-RER plots. The results for the four sky models are shown in Figure 5-10. For comparison, the results for the measured skies are shown



Figure 5-10. Sky model percentiles-RER comparison

also (Lumscan). In addition to showing the percentile lines for all (4,524) photocell-sky combinations for each model, percentiles for each of the partitioned data sets are given also. This figure is to be read as follows: for all photocell-sky combinations (solid lines), ~64% of the illuminance predictions using the measured skies (Lumscan, magenta line) were within  $\pm 10\%$  of the measured value (marked by  $\rightarrow$  on graph). Using the same skies, of those instances where the 6° CER was not visible from the photocell (CS6 -VIS dotted line), ~66% of those predictions were within ±10% of the measured value. Similarly, for just those instances where the 6° CER was visible (CS6 +VIS dashed line), ~51% of the predictions were within ±10% of the measured value. The rank order, best first, for all cases (solid lines) at the ±10% RER line (y-axis) is Lumscan, Perez, Overcast, Intermediate and Clear. For all but the Overcast, the CS6-VIS set had a marginally greater percentage within the RER range  $\pm 10\%$ , and the CS6+VIS had a smaller percentage within the RER range  $\pm 10\%$ . The rank order of the three sets (All, CS6-VIS and CS6+VIS) for each of the sky models is maintained across the range of (absolute) RER, except for the Overcast.

Confounding expectation, the rank order, best first, for the Overcast model at the  $\pm 10\%$  line is CS6+VIS, then All, then CS6-VIS. The cause for this is revealed in Figure 5-11. These plots are similar to those given in Figure 4-



Figure 5-11. RER time-series for overcast (with sun) model - CS6-VIS(■) and CS6+VIS(■)

34 to Figure 4-37, only here the relative error for the predictions using the Overcast model are shown. The instances where a photocell did not 'see' the circumsolar region (CS6-VIS) are shaded magenta (■), and where it did (CS6+VIS) are shaded cyan (). For days such as 344\_92, the Overcast model performed well regardless of the visibility or otherwise of the CER, because of course there was negligible sun. For clear sky days however (102\_92), the CS6-VIS and CS6+VIS sets can have very different RER characteristics. For those cases where the CER was not visible ( $\Box$ ), there was consistent under-prediction. This is expected because the maximum luminance for the Overcast sky is at the zenith, rather than at the circumsolar position which was mostly in the South for this day (see Figure 5-3). This was so even when the circumsolar region was not directly visible. Where the CER was visible (), there was significant underprediction, over-prediction and a run of very accurate values. The accurate values result from those occasions when a photocell was, correctly predicted, to be directly illuminated by the sun. When this happened, the illumination from the sky had a relatively marginal effect - though note how these (mostly) accurate predictions all share a small negative bias. The under-prediction may result when a photocell predicted to be in shade, was actually in sun. And vice-versa for over-prediction. It is generally the case that the extremes in the RER are greater for the CS6+VIS set than those for the CS6-VIS set. This explains the peculiar behaviour of the three percentile lines for the Overcast model.

It may well have been the case that, for a number of skies, the circumsolar region was better reproduced by one or more of the non-overcast sky models than by the measured-interpolated distributions described in Chapter 3. If so, the analysis described above was insufficient to reveal this. It may have been worthwhile to repeat the percentiles analysis using only clear skies had a much larger sample of non-overcast skies been available.

# 5.4 Evaluation II: Sky model blends

Three of the four sky models evaluated above were devised to be applicable to a limited range of possible sky conditions, that is, overcast, intermediate and clear. It is only the Perez model that was specifically formulated to represent all (or at least the majority) of naturally occurring skies. It is not surprising therefore that the one model designed with 'wide-range' applicability performed better than the other three 'narrow-range' models. However, wider application of the 'narrow-range' models might be achieved by blending the luminance patterns of two or more of them in response to meteorological conditions. This would produce a sky luminance pattern which is a blend of the component model patterns. The following sections describes the formulation and testing of two sky model blends.

## 5.4.1 Model sky blends: ex post facto synthesis

The common practice for blending skies is to combine an overcast luminance pattern with one or more non-overcast patterns according to some rule [Littlefair 94]. A number of ways of achieving this are currently in use. For the investigation described here, just two simple sky model blends are evaluated in terms of their ability to reproduce sky conditions for the purpose of internal illuminance prediction. The 754 skies in the BRE-IDMP dataset were sufficient for the validation work described in Chapter 3 and Chapter 4. This number of skies however is too small to warrant an exhaustive examination of complex sky models blends, since certain sky conditions were represented by a relatively small number of measurements (see Figure 3-9). Accordingly, the sky model blends used here are each a composite of an overcast luminance pattern and just one non-overcast luminance pattern.

An optimum sky model blending function for the validation dataset was determined for each of the sky model blends. The effect of a composite sky was synthesised by combining the existing illuminance predictions for the narrow-range sky models. Proceeding in this way, any arbitrary blending of the sky models can be investigated without calling for additional illuminance predictions.

The illuminance predictions for the overcast, intermediate and clear models were re-used to synthesise the illuminance effect of an overcast-intermediate blend and an overcast-clear blend. The theoretical basis for this is described below using the clear overcast blend as an example. In terms of sky luminance, the resultant sky point luminance for a clear-overcast blend  $L_{co}$  would be:

$$L_{co} = f_{cl} L_{cl} + f_{ov} L_{ov}$$
(5-5)

Where  $L_{cl}$  and  $L_{ov}$  are, respectively, the sky point luminances for the clear and overcast models. The weighting given to the components are  $f_{cl}$  for the clear sky, and  $f_{ov}$  for the overcast. The applied weighting was constant across the sky vault. Therefore, the resultant diffuse horizontal illuminance from a sky will vary in proportion to the weighting factor, e.g. for clear sky:

$$\int_{2\pi} f_{cl} L_{cl}(\gamma, \alpha) \sin \gamma \, d\Omega = f_{cl} \int_{2\pi} L_{cl}(\gamma, \alpha) \sin \gamma \, d\Omega = f_{cl} E_{cl}^{dh}$$
(5-6)

where  $f_{cl}E_{cl}^{dh}$  is the diffuse horizontal illuminance for the clear sky distribution  $L_{cl}(\gamma,\alpha)$  weighted by  $f_{cl}$ . Recall that the luminance for all the models skies was normalised to the diffuse horizontal illuminance, so that  $E^{dh} = E_{cl}^{dh} = E_{ov}^{dh}$ . Therefore, setting  $f_{ov} = 1 - f_{cl}$ , normalises the composite sky to diffuse horizontal illuminance also. Thus,

$$L_{co} = f_{cl}L_{cl} + (1 - f_{cl})L_{ov}$$
(5-7)

and

$$E^{dh} = f_{cl} E^{dh} + (1 - f_{cl}) E^{dh}$$
(5-8)

The illuminance predicted using the pure sky models was the total illuminance; the component illuminances from the sun and sky were not calculated separately.<sup>13</sup> For all the sky models however, the illuminance from the sun was the same; they all shared the same description for the

sun. Therefore, blending the clear and overcast total illuminances is equivalent to blending the sky components (Eq 5-8), and then adding the sun component  $E^{sun}$ :

$$f_{cl}(E^{sun} + E^{dh}) + (1 - f_{cl})(E^{sun} + E^{dh}) = E^{sun} + f_{cl}E^{dh} + (1 - f_{cl})E^{dh}$$
(5-9)

The luminance patterns for the three narrow-range models and the two sky blends are given in Figure 5-12. This figure shows luminance surfaces for the intermediate, the overcast and the clear sky models, all normalised to the same horizontal diffuse illuminance. Below, are two "half-and-half" blends for an intermediate-overcast blend and a clear-overcast blend, i.e.  $f_{in} = f_{ov} = f_{cl} = 0.5$ . Both of the sky model blends would produce the same diffuse horizontal illuminance as the 'pure' sky luminance patterns. The same scaling and rotation were used to display each luminance surface.

Although the blended luminance surface shows what a particular composite pattern would look like, in the analysis that follows, they were never actually generated. To recap, their illuminance effect was synthesised from the existing illuminance predictions for the narrow range models.

#### 5.4.2 The blending functions

The weighting factor for the non-overcast sky  $f_{cl}$  (or  $f_{in}$ ) should depend in some way on the clearness of the sky.<sup>14</sup> Evidently, the more overcast the actual sky conditions the smaller  $f_{cl}$  should be. For fully overcast skies,  $f_{cl}$ should equal zero. Conversely, for progressively clearer skies,  $f_{cl}$  should tend to unity. The factor  $f_{cl}$  therefore should be some function  $f(\varepsilon)$  of the sky clearness index  $\varepsilon$  (Eq 3-1) over a mixing range bounded by lower and upper values for  $\varepsilon$ . Within the mixing range, the effect of a linear and a power-law blending function was examined. The illuminances synthesised

<sup>13.</sup> These, or any other illuminance components, could of course be calculated separately if desired (see Section 4.4).

<sup>14.</sup> The clear-overcast blend is used to illustrate the linear and power-law blends. The blending function equations for the intermediate-overcast blend are essentially the same, and for brevity, they are not reproduced.



Figure 5-12. Example composite skies

from the narrow-range model predictions using linear and power-law  $f(\varepsilon)$  were compared against measured data. The optimization for  $f(\varepsilon)$  was as follows. The parameter (linear) or parameter combination (power-law) that resulted in a minimum RMSE for the synthesised predictions of vertical illuminance was selected as the optimum  $f(\varepsilon)$ . Since the goal was the comparison of predictions for internal illuminance with measurement, it could be argued that either:

- 1. the RMSE for predictions of vertical South should be minimised since the room has approximately South facing glazing; or, taking this reasoning one step further,
- 2. the RMSEs for internal illuminance should be minimised.

Both these approaches were rejected because they limit the generality of the  $f(\varepsilon)$  to either a specific orientation (1) or a specific orientation *and* an actual room configuration (2). Nevertheless, it remains the case that any mixing function elucidated from this one dataset will be both site and sample specific to a greater or lesser degree.

#### Linear mixing function

The form used for this, the simpler of the two combinations, was a straightforward linear mix based on clearness index  $\varepsilon$ , where the fraction of the total due to the clear sky is

$$f_{cl} = \begin{pmatrix} \frac{\varepsilon - \varepsilon_l}{\varepsilon_{ul} - \varepsilon_l} \end{pmatrix} \qquad \varepsilon \le \varepsilon_{ul}$$

$$1 \qquad \varepsilon > \varepsilon_{ul}$$
(5-10)

The lower bound clearness index  $\varepsilon_l$  was always equal to 1 and  $\varepsilon_{ul}$  was the upper bound, Figure 5-13 (a).



Figure 5-13. Linear and power-law blending functions

The vertical illuminance RMSEs versus  $\varepsilon_{ul}$  are shown in Figure 5-14 for clear-overcast and intermediate-overcast linear blends. The average RMSE versus  $\varepsilon_{ul}$  is also shown. Each of the curves show a single stationary (minimum) point. The minimum of the average RMSE is taken to be the

optimum value. The minima for all the curves are also marked in Figure 5-14. The optimum (that is, average RMSE minima) values for  $\varepsilon_{ul}$  were 1.41 for the clear-overcast blend and 1.10 for the intermediate-overcast blend. For both of the blends, the curves show marked insensitivity to increasing  $\varepsilon_{ul}$  beyond the stationary point.



Figure 5-14. Plots of RMSEs for linear blends

#### Power-law mixing function

This form uses a parabola-like function for the mixing range:

$$f_{cl} = \frac{1 - \left\{1 - \left(\frac{\varepsilon - \varepsilon_l}{\varepsilon_{up} - \varepsilon_l}\right)\right\}^n}{1} \qquad \varepsilon \le \varepsilon_{up}$$
(5-11)

Where, for n > 1, the transition from pure overcast to pure clear sky with increasing  $\varepsilon$  is more gradual, and, arguably, more physically realistic than for the linear combination, Figure 5-13 (b). For n = 1, the power-law form reduces to the linear form. The average RMSE (for the four vertical illuminances) was evaluated for all the parameter combinations covering the range  $1 \le \varepsilon_{up} \le 2$  and  $1 \le n \le 3$ . The average RMSE for the clear-overcast and intermediate-overcast blends are shown as false-colour maps, Figure 5-15. Also shown on each map is the trajectory of the RMSE minima for each value of *n* (gray line). The minimum of these minima is marked by



Figure 5-15. Maps of RMSEs for power-law blend

a gray box. The inset plot is of the RMSE minima versus n. Although the optimum is indicated at n = 3 for both blends, the difference in minima between n = 3 and n = 1 (linear form) is very slight indeed. Accordingly, there is little to choose between the linear blend and the (arguably) more physically realistic n = 3 power-law blend for either of the blend models. Invoking Ockham's Razor once again, the simpler linear blend model is used for both models to synthesise the illuminance effect of composite sky models. The results using the linear blend models are described in the following section.

## 5.4.3 Illuminance predictions for sky blends

The relative errors in the predictions for vertical illuminance are presented as frequency histograms. The results for the clear-overcast and the intermediate-overcast blends are shown in Figure 5-16 and Figure 5-17, respectively. As expected, both blend models offer a significant improvement in performance over the any of the narrow-range models alone (see Figure 5-4, Figure 5-5 and Figure 5-6). The MBEs and RMSEs for the sky blends are compared against those for the Perez models and the measured skies (Lumscan) in Figure 5-18. It is worth noting that, of the two blends, the clear-overcast blend performed better for the South and West orientations, whilst the intermediate-overcast blend performed better for



Figure 5-16. Clear + overcast sky composite



Figure 5-17. Intermediate + overcast sky composite



Figure 5-18. Sky models and composites MBE and RMSE

the North and East orientations. Recall that the azimuth angle for the sun position was contained within the range 160° to 310° (Figure 3-8). Only occasionally, therefore, did direct sun make a contribution to the illuminance for the North and East orientations. It would appear to be the case then, that the clear-overcast blend performed best for orientations South and West where direct sun was often a major contributor to total illuminance. Whilst the intermediate-overcast blend performed best for orientations North and East where direct sun was rarely a significant contributor to total illuminance. This observation may be evidence,
admittedly slight, that a three component model - overcast, intermediate and clear - would perform better than either of the two-component models considered here. As stated previously, it was felt that the number of skies in the BRE-IDMP validation dataset did not warrant testing the configuration of sky blends based on more than two component skies.

#### Percentile plots for the sky blends

The percentiles analysis (Section 5.3.4) was repeated, but now the narrowrange models (overcast, intermediate and clear) are replaced by the two sky model blends, Figure 5-19. The Lumscan and Perez results are shown once again for comparison. At the  $\pm 10\%$  RER line (y-axis), the percentage of the complete sample of skies that achieved this accuracy was: Lumscan, ~63%; clear-overcast blend, ~39%; intermediate-overcast blend, ~34% and Perez, ~30%. The percentile lines (All, CS6-VIS and CS6+VIS) for the measured skies (Lumscan) were markedly better than the corresponding lines for the two blend models up to IRERI ~100% where they converge. Note that the rank order in performance for the percentile lines up to IRERI = 50% is the same as the rank order in RMSE for the prediction of vertical South illuminance (Figure 5-18).

It should also be noted that the clear-overcast blend performed better than the intermediate-overcast blend, if only marginally, even though the luminance distribution of the composite form is somewhat unrealistic.<sup>15</sup> It is likely therefore that the slightly better performance of the clear-overcast blend over the intermediate-overcast blend resulted from a number of sunny sky conditions where the contribution of the overcast sky was zero for both blends. Evidence that this was indeed the case is given in the timeseries RER plots for two clear sky days, Figure 5-20. For both of these days, the clear-overcast blend resulted in more accurate illuminance predictions than the intermediate-overcast blend for most of the skies.

<sup>15.</sup> The half-and-half clear-overcast sky has pronounced horizon brightening and a relatively low circumsolar luminance (see example in Figure 5-12). Yet, horizon brightening is generally associated with clear sky conditions when the circumsolar luminance is large.



Figure 5-19. Percentile sky blends

#### Time-series plots for the clear-overcast blend and Perez

With time-series plots it is possible to determine patterns in the RER for predictions of internal illuminance that are difficult to discern from summary metrics. It is practical to show results for only two cases per plot, any more and the plots are too cluttered. Although it would be instructive to show time-series plots for the two blend models, the Perez model, and, for comparison, Lumscan, it would require a large number of plots and lead to



Figure 5-20. Time-series RER for clear-overcast (=) and intermediate-overcast (=) blends

some repetition. For brevity, just one set of time-series plots for all skies in the validation dataset are shown in this chapter.

The two blend models performed identically for overcast conditions because, of course, they both used the same overcast sky model. Also, the Lumscan results were presented in the previous chapter. Accordingly, the two cases shown here are the best performing model - the clear-overcast blend - and the Perez model. The relative error in the illuminance predictions for these two models is shown alongside the corresponding time-series for global horizontal, diffuse horizontal and vertical South illuminance in Figure 5-21 to Figure 5-24. The format for these plots is the same as that used in Chapter 4, only here all the predictions for both models are shown.



Figure 5-21. Time-series RER for clear-overcast blend (■) and Perez(■)



Figure 5-22. Time-series RER for clear-overcast blend (■) and Perez(■)



Figure 5-23. Time-series RER for clear-overcast blend (■) and Perez(■)



Figure 5-24. Time-series RER for clear-overcast blend (■) and Perez(■)

The following are noted:

- For clear sky days 102\_92, 128\_92 and 137\_92, the clear-overcast blend generally performed better than the Perez model which tended to under-predict illuminances.
- There was a general tendency for the Perez model to overpredict illuminances for overcast skies (e.g. 121\_92, 265\_92 and 311\_92).
- Clear sky conditions in winter (318\_92, 363\_92 and 364\_92) resulted in RERs for both models very similar to that achieved using measured sky luminance distributions (see Figure 4-36 and Figure 4-37 for the Lumscan RERs).

• For several of the overcast days, both models performed relatively poorly compared to the measured skies (e.g. 093\_92, 131\_92, 183\_92 and 196\_92). Here it was very likely that, although overcast, these skies contained 'lumpy' sky luminance patterns. Measured by the scanner, these 'lumpy' patterns could not, of course, be reproduced by either of the sky models.

The time-series plots have revealed consistent differences in performance for the two models. It would appear that the low zenith-to-horizon luminance ratio noted in Figure 5-1(a) is a feature of the Perez model for overcast skies, and was the cause of the regular over-prediction for these conditions. There was also some tendency for the Perez model to regularly under-predict for clear sky conditions, though this was not always the case throughout the entire day.

### 5.5 Conclusion

The results presented here have demonstrated how sky models can be evaluated based on predictions for internal illuminance. Four 'pure' sky models and two sky model blends were examined. Illuminance predictions for the sky model blends were synthesised from the illuminance predictions for the narrow-range 'pure' sky models.

Routine application of the narrow-range models for all 754 skies resulted in poor performance overall. The two blend models and the Perez model performed reasonably well, with the clear-overcast blend marginally the best of the three, and the Perez model marginally the worst. It is not possible to generalise these findings without further work because, of course, the sky model blends were 'tuned' to the validation dataset whereas the Perez model was not. It has already been noted that the Perez model is also site specific to some degree (Section 5.2.2). Nevertheless, the blend models and the Perez model could be applied with reasonable confidence to, say the Kew TRY since this has a similar composition to the validation dataset (Section 3.1.4).

The internal illuminances (predicted and measured) were generally more sensitive to the luminance of the visible part of the sky rather than the much larger part of the sky that was not 'seen'. Thus, the results presented here have demonstrated more the ability of the sky model/blend to reproduce luminance patterns for those parts of the sky that were visible from the photocell locations, than for the sky in total. Which is, of course, as it should be if the purpose of the sky model is to provide daylight illumination for internal spaces.

This investigation is, as far as the author is aware, the first comparison of sky model performance against measured sky luminance patterns that was based on predictions of internal illuminance. The breadth of the analysis was commensurate with the number of skies in the validation dataset. A larger sample, particularly for clear sky conditions, would have allowed a more thorough investigation. Accordingly, conclusions drawn for the performance of these sky models/blends needs to be made with caution.

A more comprehensive evaluation of sky model performance, based on internal illuminances, should examine the effects of glazing orientation. Also, more than 754 skies needs to be used. But how many skies should be considered a representative sample? The answer will depend, to a degree, on the intended use for the sky model. For daylight illumination, one goal is the prediction of time-varying internal illuminances using realistic models for the sky and the sun conditions. This could be carried out in conjunction with dynamic thermal analysis, using the same period and timestep as the thermal simulation [Clarke 98]. This invariably means a simulation period of a full year at a timestep of one hour with meteorological conditions derived from test reference year data.

Any analysis that is based on a TRY time-series would be computationally very demanding; approximately 4,000 unique skies (i.e. daylight hours in the year) would need to be modelled for each case. Using the 'standard calculation', that is modelling the illuminance effect of each individual sky for thousands of unique skies, could take days or even weeks of computer processor time. A potentially more efficient approach to predicting the internal illuminance for a large number of unique sky and sun configurations - measured or modelled - is described in the following chapter.

# Chapter 6

# Daylight Coefficients: Formulation, Validation and Application

"Funding for this work... would be nice."

GREG WARD (RE: MGF)

This chapter describes how time varying daylight illumination can be both accurately and efficiently predicted for arbitrary sky and sun conditions. The prediction technique is based on the daylight coefficient approach. The accuracy of the daylight coefficient derived illuminance predictions is verified using the BRE-IDMP validation dataset. The chapter concludes with a series of examples that demonstrate how daylight coefficients can be used to predict the daylight illumination for an entire year on an hourly basis.

### 6.1 Introduction

The seasonal and daily variations in daylight follow a typical pattern, Figure 6-1. These two contour plots show calculated means of global and diffuse horizontal illuminance based on ten years of measurements taken at Kew, UK [Hunt 79]. The dashed lines indicate the start and finish of the normal working day; 09:00 to 17:30 hrs. LAT is the local apparent time which approximates to GMT for this location. The cumulative diffuse illuminance availability can be shown as the percentage of the working year for which a given diffuse illuminance is exceeded, Figure 6-2.



Figure 6-1. Global and diffuse illuminance availability (klux)

#### 6.1.1 The daylight factor approach to annual estimates

The daylight factor approach is invariably used to assess the potential of a design to provide useful levels of daylight illumination. The approach - described in Section 2.2.1 - uses the CIE standard overcast sky, irrespective of the prevailing climatic conditions for the locale of the proposed design. And of course, the contribution of sunlight to internal illuminance is not modelled using this approach. Applying a simple technique, cumulative internal illuminance availability can be calculated from daylight factor values and charts of cumulative diffuse sky illuminance. This gives a first order approximation to annual daylighting provision from which supplementary lighting requirements can be estimated.



Figure 6-2. Cumulative diffuse illuminance

#### **Example**

Suppose that the minimum required internal illuminance at a point in an office is 500 lux, and that a daylight factor evaluation using the CIE standard overcast sky (equation, scale-model or simulation) predicts a

daylight factor value of 3.3%. The minimum diffuse sky illuminance which provides an average internal illuminance of 500 lux, is therefore

$$\frac{500 \times 100}{3.3} = 15,000 \text{ lux}$$

It can be determined from Figure 6-2 that a diffuse sky illuminance of 15 klux is exceeded for about 55% of the normal working time.

The CIE standard overcast sky is likely to be a reasonable approximation to some of the duller skies in the cumulative distribution. However, it was demonstrated in the previous chapter that internal illuminance predictions are very sensitive to the sky model type (Section 5.3). Furthermore, only about 40% of the skies in the Kew TRY can be classed as heavily overcast (Figure 3-9). To predict annual daylighting provision with any certainty therefore, predictions need to be based on the full range of naturally occurring sky conditions. Furthermore, the sky models that are used need to be reasonable representations of the naturally occurring sky luminance distributions.<sup>1</sup>

As noted above, the daylight factor method does not account for direct sunlight. It is therefore highly inappropriate for building designs where the redistribution of direct beam radiation to provide diffuse illuminance is a significant feature of the daylighting system. As is the case with designs that make use of light shelves or mirrored louvres.

### 6.1.2 Annual daylight provision based on varying sky conditions

Luminance distributions that do not conform to the CIE overcast standard have generally been used for specialist studies designed to address specific issues, e.g. solar penetration or shading for particular times of the day or year. Typically, only a few cases are modelled and the results have little

<sup>1.</sup> Or even an annual time-series of measured sky luminance distributions. But since several years data are needed to synthesise a 'statistically average' year, it is unlikely that such a dataset will emerge for some time.

relevance to the long term daylighting potential of a space. A true measure of the long-term daylighting potential for a building must account for the internal illuminances produced by *all* the skies measured at or near the intended site over a monitoring period of, ideally, a full year or more. Such an evaluation would typically adopt the following procedure [Littlefair 92]:

- Obtain basic climate data from a weather tape, usually global and diffuse irradiance.
- Convert the irradiance data to external horizontal illuminances using a luminous efficacy model.
- Generate a sky luminance distribution using a sky model.
- Use the sky luminance distribution to calculate internal illuminances.
- Determine the artificial lighting requirements using a lighting control algorithm.
- Calculate the resultant heat gains produced by the lighting (if the lighting simulation is to be part of an integrated buildings energy analysis program).

If measurements were obtained as hourly integrated values, as is generally the case with weather tapes, a normal working year would contain data for approximately 3,500 skies. With the latest generation multi-processor workstations, modelling several thousand individual cases is a tractable, though still rather time consuming, task. A more efficient solution method might be the daylight coefficient approach [Tregenza 83]. This technique eliminates the need to perform the most computationally demanding part of the simulation - the inter-reflection calculation - for every individual case, i.e. ~3,500 skies for a full year. The daylight coefficient approach requires that the sky be broken into many patches. The internal illuminance at a point that results from a patch of unit-luminance sky is computed and cached. This is done for each patch of sky. It is then possible, in principle, to determine the internal illuminance for an arbitrary sky luminance distribution (and sun luminance/position) using relatively simple (i.e. quick) arithmetic operations on matrices. The computational expense of a daylight coefficient calculation for a sky with N patches is comparable to that for N standard calculations. Provided therefore that the number of patches is less than the number of skies that need to be modelled, the technique has the potential to be computationally more efficient than treating each sky individually.

## 6.2 Daylight coefficients: Fundamentals, prediction and analysis

There is more than one way to calculate daylight coefficients using *Radiance*. The first approach, described below, is called the 'Naive Method', or NM. As will be demonstrated, the Naive Method is the most straightforward way to predict DCs with *Radiance*. Preliminary tests however indicated that, with this approach, the derived internal illuminances were likely to contain significant errors. This led to the formulation of a second approach called the 'Refined Method' (RM), which was designed to overcome the imprecision of the Naive Method. For the RM, two different sky discretisation resolutions and their consequences were examined: they are referred to as the 'Default' and 'Finescale' discretisation schemes. These lead to the possibility of several variants of the final daylight coefficient (DC) formulation for the Refined Method. The two methods (NM and RM) are described below, and the daylight coefficients calculated using both are presented and analysed. There is then a simple comparison test that demonstrates the weakness of the Naive Method.

#### **6.2.1 Fundamentals**

If  $\Delta E_{\gamma\alpha}$  is the total illuminance produced at a point in a room by a small element of sky at altitude  $\gamma$  and azimuth  $\alpha$ , then the daylight coefficient is defined as

$$D_{\gamma\alpha} = \frac{\Delta E_{\gamma\alpha}}{L_{\gamma\alpha} \Delta S_{\gamma\alpha}}$$
(6-1)

where  $L_{\gamma\alpha}$  is the luminance of the element of sky and  $\Delta S_{\gamma\alpha}$  is the solid angle of the patch of sky, Figure 6-3.



Figure 6-3. Daylight coefficient basics

The magnitude of the daylight coefficient  $D_{\gamma\alpha}$  will depend on the physical characteristics of the room and the external environment, e.g. room geometry, surface reflectances, glazing transmissivity, outside obstructions and reflections etc. It is, however, independent of the distribution of luminance across the sky vault, since  $\Delta E_{\gamma\alpha}$  varies in proportion to  $L_{\gamma\alpha}$ . The total illuminance *E* produced at the point in the room is then calculated from:

$$E = \int_{0}^{2\pi} \int_{0}^{\pi/2} D_{\gamma\alpha} L_{\gamma\alpha} \cos \gamma \, d\gamma \, d\alpha$$
 (6-2)

It is possible to determine a functional form for daylight coefficients (DCs) for idealised scenes, such as an unobstructed horizontal surface [Tregenza 83]. However, some form of finite element calculation is needed for even the simplest realistic scene.

If the sky were divided into n angular zones, then for numerical evaluation, Eq 6-2 can be formulated as:

$$E = \sum_{p=1}^{n} D_p S_p L_p$$
 (6-3)

This gives the illuminance as sum of *n* products of *D*, *S* and *L*, for each patch of sky *p*. The *n* values of *D*, *S* and *L* can therefore be treated as vectors e.g.  $\mathbf{D} = \begin{bmatrix} D_1, D_2, \dots, D_n \end{bmatrix}$ . The formulation may be expanded to account for *m* points in the room. The array of daylight coefficients then becomes a *m* x *n* matrix. The internal illuminances will then be described by a column vector **E** containing *m* elements. Similarly, another column vector, **c**, can be formed from the *n* products of angular size and luminance. This gives the compact matrix formulation

$$\mathbf{E} = \mathbf{D} \times \mathbf{c} \tag{6-4}$$

or in expanded form,

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & \dots & D_{1n} \\ D_{21} & D_{22} & \dots & D_{2n} \\ \vdots & \vdots & & \\ D_{m1} & D_{m2} & & D_{mn} \end{bmatrix} \times \begin{bmatrix} S_1 & L_1 \\ S_2 & L_2 \\ \vdots & \vdots \\ \vdots & \vdots \\ \vdots & \vdots \\ S_n & L_n \end{bmatrix}$$
(6-5)

This is what may be called the standard daylight coefficient formulation as presented in the original paper [Tregenza 83]. That paper includes a theoretical discussion which describes, in general terms, how individual components of the daylight coefficient matrix (DCM) may be evaluated. The components account separately for the externally reflected light, the direct light and the internally reflected light. A later paper, also theoretical, describes how DCs might be used for the practical computation of internal illuminances [Littlefair, 92]. That paper includes several recommendations for a practical implementation of the daylight coefficient approach. Some of these were found useful for the work described below, others were not. The final form of the most successful DC implementation described below was dictated in part by *Radiance's* own, unique calculation algorithms.

#### 6.2.2 Overview of the discretisation schemes

At the onset, it was the intention to test the accuracy of the DC derived illuminances using the BRE-IDMP validation dataset. Accordingly, the discretisation schemes employed had to have some correspondence to the sampling pattern of the PRC Krochmann sky scanner. The discretisation schemes made use of different shaped patches and of different resolutions. One of these was based on a sub-division of the sky vault that gave complete sky coverage for the sky hemisphere. Here, each patch was bounded by lower and upper values for altitude and azimuth. These segments of sky, although part of a hemisphere, are referred to for brevity as 'rectangular' patches. The other type of discretisation used solid angles which are referred to as 'circular' patches. The underlying pattern for both patch types was identical to the sampling pattern of the Krochmann sky scanner. That is, 145 patches arranged in the same fashion as the scanner pattern, Figure 6-4.

The 145 patch scheme is referred to as the 'Default' discretisation. The effect of a patch scheme that replaced each of 145 'circular' patches with four individual 'circular' patches was also examined. This scheme used 580 patches and is referred to as the 'Finescale' discretisation. The ordering and numbering scheme for the 'Default' discretisation, complete with the altitude and azimuth for each patch centre, is shown in Figure 6-5. The 145 elements are numbered 1 to 145, and count 'clockwise' from North i.e.  $N \rightarrow E \rightarrow S \rightarrow W$ . The orientation of the BRE office description relative to the discretised sky is shown at the base of Figure 6-5.



Figure 6-4. DC patch schemes based on scanner measurement pattern

#### 6.2.3 The 'Naive Method'

The 'Naive Method' was based closely on the standard formulation given in Section 6.2.1. For the prediction of the DCs, each luminous sky patch was modelled using a source angle type **light**. These are the 'circular' patches described in the previous section. These patches do not, of course, offer complete sky coverage. Note that it is not possible to specify a 'rectangular' source angle in *Radiance* in a straightforward way (this is discussed in later sections). The source angle type **light** is sampled with a single ray, which, in the usual mode of use, is directed to the source centre, Figure 6-6.

Thus, the direct component (from the photocell to the source) was calculated using a single ray directed to the source centre.<sup>2</sup> For the indirect component, many sampling rays were used. But here also, for every final light transfer from a surface to the source, a single ray was directed to the

<sup>2.</sup> Recall that Radiance uses backwards ray tracing.



Figure 6-5. Patch ID and building orientation



Figure 6-6. The naive formulation

source centre. So, the daylight coefficient for each *patch* was calculated using rays that sampled only the *point* at the patch centre.

The daylight coefficient for the 'circular' patch *p* therefore is:

$$D_p = \frac{\Delta E_{p(c)}}{L_{p(c)} \Delta S_{p(c)}}$$
(6-6)

The subscript in parentheses denotes the patch shape, e.g. (c) for 'circular' and (r) for 'rectangular'. Using this method, the total internal illuminance  $E_{tot}$  due to a sky and sun of arbitrary luminance is calculated as the sum of the sky  $(E_{sky})$  and sun  $(E_{sun})$  illuminance components:

$$E_{sky} = \sum_{p=1}^{n} D_p \Delta S_{p(r)} L_{p(r)}^{sky}$$
(6-7)

Note that 'rectangular' patches are now used because the sum of the individual patch solid angles must be equal to the solid angle for a hemisphere:

$$2\pi = \sum_{p=1}^{n} \Delta S_{p(r)}$$
(6-8)

In other words - for each patch in turn - the illumination effect of a 'rectangular' patch of sky of uniform luminance is derived using the DC value predicted for one point at the patch centre. The sun component of the illuminance is given by:

$$E_{sun} = D_{\beta} S^{sun} L^{sun}$$
(6-9)

where  $D_{\beta}$  is the vector of daylight coefficients for the patch nearest to the sun position, and  $S^{sun}L^{sun}$  is the product of the solid angle and luminance of the sun. The total illuminance therefore is:

$$E_{tot} = E_{skv} + E_{sun} \tag{6-10}$$

#### DC calculation with Radiance

The patch configuration for the Naive Method was equivalent to a sky with 145 'suns', each of source angle 11°. The ambient parameter combination used to predict daylight coefficients for the NM was the same as the 'basecase' set used for the validation of the standard calculation (Section 3.3.2). With the NM, a patch of sky is, in effect, identical to a sun description in the standard calculation. Both are described using the source material **light**, for which single-ray sampling is employed. The source angle therefore has no effect (Section 3.2.3). It was shown in Section 4.5.2 that, source visibility related errors notwithstanding, the internal illuminance for clear sky days (e.g. 102\_92, 129\_92, 137\_92, etc.) was accurately predicted. For these conditions, the sun was the dominant source of illumination. Thus, there was no reason to suspect that the 'basecase' parameter combination would perform any less well for the prediction of daylight coefficients using the Naive Method.<sup>3</sup>

The DCs were predicted using an automated scheme similar to that described in Section 3.3.4. The 145 individual source description files were generated by an IDL procedure and the sequence of simulations was

<sup>3.</sup> Note also that for the standard calculation there was a sun and a sky, whereas with each DC patch calculation (NM) there was only a 'sun'.

managed by an 'executive' C-shell script. Using the same ambient parameter combination as the standard calculation, the simulation time for the DC prediction was about the same as that needed for 145 skies. The magnitude and the pattern of the DCs predicted at each photocell is discussed below.

#### Naive Method DCs: Results and Analysis

The DCs predicted at each photocell are given in Figure 6-7. The magnitude is shown using false colours and the individual patches can be matched to a patch number using the key given in Figure 6-5. The DCs for the total illumination (Direct+Indirect) cover a wide range: from 1.695e-05 to 0.6473. The pattern in total DCs at each photocell can be related somewhat to the building geometry. For p\_cell 1, which was nearest the window, the DCs are generally larger than for all the other p\_cells. The change in the pattern of the high-value DCs (> 0.2, yellow shading) from p\_cell 1 to p\_cell 6 suggests a decrease in the number of patches that were directly visible.<sup>4</sup> The patterns however are not quite what one might expect: the decrease in the number of high-value DC patches from p\_cell 1 to p\_cell 2 seems rather too large. Furthermore, both p\_cells 2 and 3 have the same number - three - of high value DCs, even though the p\_cell further away from the window should 'see' fewer patches. These observations are the result of single-ray light source sampling: the source's contribution to direct illuminance was calculated on the basis of total source visibility, or total source occlusion. As a consequence, depending on the position of the calculation point, the direct sky component could be significantly overestimated, or actually predicted to be zero.

To clarify that this was indeed the case, the DCs were re-calculated for the direct component-only. They are shown alongside the total (i.e. Direct+Indirect) DCs in Figure 6-7. A cross (+) marks a zero value. The range in the direct DCs was much narrower: from 0.0854 to 0.618 (for DCs > 0).

<sup>4.</sup> Compare this pattern with the photocell 'view' renderings in Figure 4-17 on page 119.

<sup>6.2</sup> Daylight coefficients: Fundamentals, prediction and analysis



#### Figure 6-7. Predicted DCs for the NM

Note that the mapping of the magnitude of the predicted DC to colour uses a logarithmic scale

The effects suggested by the total DCs are more readily apparent in the direct-only DCs. In particular, note that there are only three non-zero DCs at p\_cell2 and six at p\_cell3 (which was further away from the window).

To better understand the effect of single-ray light source sampling, a rendering was created using a special sky description that contained all 145 sky patches. The centre of each 11° 'white' source was marked by adding a much smaller 'red' source  $(1.5^\circ)$  to the sky description. The rendering in Figure 6-7 shows a view of this special sky from p\_cell 1; the pattern of sky patch visibility/occlusion is related to a (magnified) plot of the predicted DCs. Note how the direct only DC is predicted to be zero when the patch centre is occluded, even though much of the rest of the patch may be visible. It seems likely therefore that, from p\_cell 2, the centres of several sky patches were also occluded by glazing frame bars. Note also that, when a source centre was visible from two or more p\_cells, the predicted direct DC was the same for all the p\_cells. This is because the ray direction to any one patch was identical for all p\_cell locations. For all the p\_cells that 'see' a particular patch centre, the reduction in the ray luminance due to glazing transmittance (from L to  $L_g$ ), and therefore the daylight coefficient value, will be identical, Figure 6-8. In contrast, sampling across the source would reveal that it was, say, partially occluded from both positions, though to different degrees (Figure 6-8). Accordingly, direct DCs should have a unique value based on the degree of visibility. This cannot happen when the DC for a patch is predicted using a single point.

Can Radiance be persuaded to sample the source material **light** with more than one ray? In principle, yes. Although the method is not straightforward.<sup>5</sup> An alternative approach would be to change the source material to **glow** and predict the direct contribution using *Radiance's* indirect calculation, i.e. by hemispherical sampling. With a large number of

<sup>5.</sup> It involves repeating the direct DC prediction for each patch many times with 'jittering' enabled for the source calculation. With this, rays are randomly distributed over the source. Though with the source material **light**, it would still be one ray per source, hence the need for a large number of individual simulations.



Figure 6-8. Identical DC values for the same patch positions

hemispherical rays, one can be assured that the **glow** source is adequately sampled. This could be demonstrated with convergence tests. However, the technique is very wasteful of sampling rays because an entire hemisphere of rays are spawned to find a relatively small source. And, more importantly, the potential for inaccuracy remains because all the patches taken together do not provide complete sky coverage, Figure 6-9. This rendering shows the 'view' of the sky patches from p\_cell 6. Note that the two source centres - counted as visible for the NM direct DCs (p\_cell 6 in Figure 6-7) - would both have been counted as fully occluded had the horizontal frame bar been placed a little higher. Both of these issues are addressed in the later sections that describe the 'Refined Method' for calculating DCs.

#### The Sun Component

Another potential problem with the Naive Method arises when the DCs are used to calculate the illumination from the sun. Significant errors may arise



Figure 6-9. Incomplete sky coverage with 'circular' sources

when there is a large difference between the actual sun position and the centre of the nearest patch. This is referred to here as the sun displacement angle (SDA), Figure 6-10. With a patch discretisation based on the scanner



Figure 6-10. Sun displacement angle

pattern (Figure 6-5), the SDA can be as large as  $7^{\circ}$ . The greater the SDA, the greater the likelihood that a point is evaluated to be in shade when it was actually illuminated by the sun - or vice-versa. So it is the direct component of illumination from the sun than can be in error the greatest. The indirect component ensues from one or more reflections, and so it is less directional in nature than the direct component. Consequently, the indirect component is generally much less sensitive to the SDA.<sup>6</sup>

Whatever the resolution of the DC patch scheme, there will always be errors in the direct source calculation due to displacement of the sun position. However, these errors could be reduced arbitrarily by using a large number of sources for the *direct sun component only*. For a direct light source calculation, the computational expense is tiny so many thousands of sources could be modelled. The indirect sun component would then be calculated separately using a much smaller number of sources. The separation of the calculation for the direct and indirect sun illuminance components is the first step towards a potentially more accurate and generalised DC scheme. This new scheme, the Refined Method, is described in the following sections.

#### 6.2.4 The 'Default Refined Method'

The potential for imprecision in the direct calculation with the Naive Method could be reduced by increasing the number of individual light sources. In other words, using many points to better approximate the effect of a patch. There is no theoretical limit to the number, or size, of light sources that could be used. However, a simulation would have to be carried out for every source. A more elegant route to achieving the same ends might be to carry out the calculation using 'aimed rays' rather than the irradiance calculation, which has been shown to be prone to light source visibility errors.

<sup>6.</sup> An exception may be when the sun is just in front of the glazing plane and the SDA is such that the nearest DC patch is just behind, or vice versa.

#### Aimed Rays

The 'aimed rays' approach requires only one sky vault description, so it eliminates the need to generate hundreds (or thousands) of individual source descriptions. This is possible because source sampling with 'aimed rays' can be precisely controlled by the user. The 'aimed rays' approach is in fact very simple. The **rtrace** program was used to compute the luminance of rays 'aimed' from each photocell location. To do this, **rtrace** was supplied with a list of the ray's origin and direction vectors. The direction vector part of the list is formed from the co-ordinates of an arbitrary number of points evenly distributed over a unit hemisphere. This list was repeated six-fold and 'laminated' to the ray-origin co-ordinates, i.e. the photocell locations. For each ray in the list, **rtrace** computed a luminance value, Figure 6-11.



Figure 6-11. 'Aimed' rays

The illuminance at a photocell due to any region of (unit luminance) sky can be determined from the individual ray values for all the rays that intersect with the region of sky. The illuminance due to sky patch p is

$$\Delta E_p = \sum_{r \in T} L_r \cos \theta_r \Delta S_r$$
(6-11)

where  $L_r$  is the ray luminance,  $\theta_r$  is the ray zenith angle and  $\Delta S_r$  is the solid angle associated with the ray. *T* is the set of rays *r* that, in an unobstructed scene, intersect with the patch *p*. The solid angle associated with each ray  $\Delta S_r = 2\pi/N_r$ , where  $N_r$  was the number of rays evenly distributed over the hemisphere. The set *T* consists of elements *r* such that, for a rectangular patch of extent  $\Delta \alpha$  by  $\Delta \gamma$  centred on  $(\alpha, \gamma)$ , the set is given by:

$$T = \{r: (\gamma - \Delta \gamma/2) \le \gamma_r < (\gamma + \Delta \gamma/2), (\alpha - \Delta \alpha/2) \le \alpha_r < (\alpha + \Delta \alpha/2)\}$$
(6-12)

or for a 'polar-cap' patch:

$$T = \left\{ r: (\pi/2 - \Delta \gamma_z) \le \gamma_r \right\}$$
(6-13)

The DCM for the direct component of illumination was determined using the 'aimed' rays method described above, Figure 6-12(a). A total of 100,366 rays, evenly distributed across the hemisphere, were aimed from each photocell location. Each 'rectangular' patch was sampled by approximately 650 rays (i.e. 100,366/145). The direct DC was computed using Eq 6-1 and Eq 6-11:

$$D_p = \frac{\sum_{r \in T} L_r \cos \theta_r \Delta S_r}{L_p \Delta S_p} = \frac{\sum_{r \in T} L_r \cos \theta_r}{L_p}$$
(6-14)

because

$$\sum_{r \in T} \Delta S_r = \Delta S_p \tag{6-15}$$

Note that the individual rays could also be used to construct a direct DCM for all the 100,366 points evenly distributed across the hemisphere e.g.

$$D_r = \frac{L_r \cos\theta_r \Delta S_r}{L_p \Delta S_r} = \frac{L_r \cos\theta_r}{L_p}$$
(6-16)

A finely discretised direct DCM could be used in a generalised DC implementation to calculate the direct component of illumination from the sun.<sup>7</sup> A generalised implementation of the DC approach, demonstrated in a later section, includes a discussion on the resolution of the direct sun DCM.



Figure 6-12. The refined formulation

Many rays are used to sample each 'rectangular' patch for the direct component. The indirect component is evaluated using the same light sources as the NM.

The DCM for the indirect component was calculated using the same technique as the Naive Method. The total and direct components for the NM were given in Figure 6-7. The indirect component therefore is simply the total minus the direct component, Figure 6-12(b). By using the NM for the indirect component, will not the DCM for this component be prone to the same errors that were identified for the direct component? Yes, however

<sup>7.</sup> With so many points distributed over the hemisphere, the sun displacement angle - the angle between the actual sun position and the nearest point on the sky vault - would be tiny. Although, for practical purposes, a DCM of size 100,366 by 6 is likely to prove unnecessarily large.

single-ray light source sampling errors are likely to be less of a problem here precisely because the indirect component is calculated using *many* rays from many different ray origins.<sup>8</sup> Furthermore, as discussed earlier with respect to the sun displacement angle, the indirect component is less directional in nature than the direct component. Thus the difference between a point and patch indirect DC is not likely to be so significant.

#### Default Refined Method DCs: Results and Analysis

The DCMs for the direct and indirect components are given in Figure 6-13. As with the total DCMs calculated using the Naive Method (Figure 6-7), these DCs exhibit a large range in magnitude: from 1.69e-5 to 0.46. For the direct DCs, it is apparent that the Refined Method has taken account of the partial occlusion of the (rectangular) sky patches. The pattern in the (non-zero) direct DCs has a coarse likeness to the image of the glazing as it would be seen in a (hemispherical fish-eye) view from the photocell location.<sup>9</sup> The direct DCs cover approximately 2 orders of magnitude: from 0.006 to 0.46.

The patterns for the indirect DCs, since they result from one or more reflections and do not include a direct component, are more complex. They also cover a larger range; approximately 4 orders of magnitude (1.69E-05 to 0.23). Because they were computed using a large number of reflections, all the indirect DCs have a magnitude greater than zero. The lowest altitude patches 'behind' the office, i.e. patch numbers 26-30 and 1-10 (see Figure 6-5 for key), had the smallest indirect DCs because illumination from these patches required several reflections to reach a photocell location. The

<sup>8.</sup> An approach to calculate the indirect component from 'rectangular' patches of sky was also evaluated. For this it was necessary to use a **glow** source hemisphere in conjunction with a *Radiance* **cal** file to modify the luminous output of the sky according to the azimuth and altitude of 'intersecting' rays. In this way, a 'rectangular' patch of sky could be made luminous, and the rest of the hemisphere set to zero. Whatever benefits there may have been in terms of complete sky coverage and many-rays sampling, they were not realised because the calculation was extremely inefficient. This was because the calculation now had to 'find' the source of (indirect) illumination - the sky patch - using Monte-Carlo sampling. In doing so, most of the (hemispherical) sampling rays were wasted because all but a small patch of the hemisphere had zero luminance.

<sup>9.</sup> See Figure 4-17 for renderings of the photocell's 'view of the glazing.



Figure 6-13. Calculated daylight coefficients for the default Refined Method

largest indirect DCs are where a photocell received, from a patch of sky, the greatest indirect illumination. The direct DCs were dependent on the visibility of the sky patch, whereas the indirect DCs were dependent on the view of those surfaces in the office that were strongly illuminated by a sky patch. The largest indirect DCs were those predicted for patches 17 and 18, for the photocell at the *back* of the office. This may at first seem counter intuitive, since it is quite rightly taken that illumination at the back of a room will always be less than at the front. Indirect DCs however, do not have an obvious relation to total illuminance.

Visualisation techniques can be used to help understand difficult illumination problems (Section 2.6.2). The complex relation between the patch position, the photocell location and the magnitude of the predicted indirect DC can be appreciated by considering, for a few cases, the photocell's 'view' of the illuminated scene. A pair of renderings generated from the viewpoint of p\_cells 5 and 6 shows each photocell's view of the luminous environment when illuminated by 'circular' patch #17, Figure 6-14. The images were generated using only the direct light source calculation. It was necessary therefore to apply a small constant ambient value to make the non-directly illuminated room surfaces visible. In both renderings, the same room surfaces as seen from slightly different viewpoints are visible. These surfaces are:

- Ceiling in shade colour dark gray.
- Walls and window frames in shade colour medium gray.
- North wall strong illumination colour white (top on image).
- West wall 'low' illumination colour light gray (right of image).

The light source in this projection is just visible through the South facing window.<sup>10</sup> The centre of the 'circular' light source #17 was at altitude  $6^{\circ}$  and

<sup>10.</sup> Although the light source appears as a disc in the image, all surface-to-source light transfer is modelled using a single ray aimed towards the source centre.



**Figure 6-14. Photocell hemispherical views for scene illuminated by patch# 17** *These renderings have been laterally inverted West - East to relate to the compass orientated DC plots.* 

azimuth 192°. The outgoing surface normal from the glazing has an azimuth of 196°. Light from the source therefore 'shines' down the length of the room, illuminating the North wall at close to normal incidence. The luminance of the directly illuminated part of the North wall was ~10 times that of the West wall where the source angle of incidence was close to grazing i.e. just  $< 90^{\circ}$ , Figure 6-14. It is readily apparent from the renderings that p\_cell 5 'sees' much less of the bright rear wall than does p\_cell 6. The hemispherical view used for these fish-eye images contains a cosine weighting of the (hemisphere) projected solid angle. For illumination therefore, equal areas of equal luminance (in the field of view) contribute equally to the total illuminance at the viewpoint. As a consequence, the indirect DC for patch #17 was greater at p\_cell 6 than at p\_cell 5. For a multiple-reflection indirect calculation, most if not all of the internal surfaces will attain some non-zero luminance value. It was the first reflection however, from the photocell to the source that provided the greatest contribution to the indirect illuminance. Note also from these renderings the effect of single-ray lightsource sampling - no penumbras. As a consequence, the East wall was not
illuminated by the light source, even though the edge of the circular source (patch) was just visible from the wall surface.<sup>11</sup>

#### The two methods: a simple test

The potential for error associated with the Naive Method is revealed in the following tests. The direct component of illuminance from a uniform luminance sky was derived from daylight coefficients predicted using both the Naive and Refined methods. These were compared against the illuminance predicted using the standard calculation for the same sky. The results are shown in Figure 6-15(a).



Figure 6-15. NM and RM comparison test

Inset rendering shows the 'view' from  $p_{cell} 2$  of the NM sky patches. The centres of only three patches are visible ( $\bigcirc$ ), resulting in marked under-prediction of the direct component.

<sup>11.</sup> Consider, the angle of incidence of the source centre to the (internal) East wall was  $94^{\circ}$ , and so not visible. However a tiny segment of the  $11^{\circ}$  source-angle, just  $1.5^{\circ}$ , was visible from the East wall.

For this test, the accuracy of the standard calculation was not an issue, the illuminance values predicted using this method should, for the purpose of comparison, be considered correct.<sup>12</sup> Thus, the relative error in the DC derived predictions is shown with respect to the standard calculation. For the direct component, it is clear that the NM performed poorly with erratic behaviour across the six photocells. The relative errors range from about - 55% (p\_cell 2) to about +55% (p\_cell 4). The Refined Method predictions however are barely distinguishable from those for the standard calculation.

The standard calculation was repeated to predict the total illumination from the uniform sky. The results from the validation of the standard calculation (Chapter 4) showed that, when the circumsolar luminance was not an issue, the internal illuminance was predicted to a high degree of accuracy. Thus for a uniform luminance sky, the standard calculation predictions are considered to be correct. The total illuminances (i.e. direct plus indirect component) derived using each Method were compared against predictions using the standard calculation, Figure 6-15(b). Here, the errors for the NM were less than for the direct-only component. But nevertheless significant, particularly for p\_cell2 where the relative error was about -30%. These two tests offer only indications of the degree of inaccuracy that might be expected using the Naive Method because, of course, real skies have nonuniform luminance distributions. The test however was sufficient to demonstrate that the Refined Method was a superior technique.

# 6.2.5 The 'Finescale Refined Method'

It was suggested in Section 6.2.4 that imprecision resulting from single ray light source sampling is likely to be much less significant for the indirect component than for the direct. This assertion is now re-examined following the investigation of the cause for the high-value indirect DC for patch# 17 at p\_cell 6 (Figure 6-13 and Figure 6-14). It was shown that, for this patch-

<sup>12.</sup> The reliability of the standard illuminance was ensured by increasing the number of hemispherical sampling rays until satisfactory convergence had been achieved at all photocell locations.

photocell combination, the indirect DC was in fact highly directional in nature. Thus, small displacements in the patch centre could have resulted in marked changes for the magnitude of the indirect DC. It is conceivable therefore that, at the Default discretisation ( $N_{patch} = 145$ ), the indirect DCM may contain imprecisions resulting from single-ray light-source sampling. Albeit for only a small number of patches. To test if this was a significant effect, the indirect DCM was evaluated using a finer discretisation. Called the 'Finescale' discretisation, this scheme used four evenly spaced 5° light source solid angles (i.e. patches) for each patch of the Default scheme, Figure 6-16. This gave a total of 580 patches for the 'Finescale' indirect DCM, and so it required four times longer to compute than the 'Default' indirect DCM.



Figure 6-16. Four 'finescale' patches for each 'default' patch

#### Finescale Refined Method DCs: Results and Analysis

The intention here is to discover significant differences, if any, between the Finescale and Default discretisations for the indirect DCM. And, if significant differences are found, to anticipate their consequences for illuminance prediction. The method for doing this was as follows. If there was little variation in the DCs within each group of four finescale patches, it was assumed that they would have a similar illumination effect to the single default patch. This was a reasonable assumption for the patch configurations considered here. Indirect DCs can be highly sensitive to the source's angle of incidence on the principal internal surfaces (i.e. walls, floor and ceiling). This is apparent from Figure 6-14 where a small clockwise shift in azimuth for patch 17 would switch the illumination from the West wall to the East wall.

What follows is a three stage graphical analysis. Results are shown for photocells 1 and 6 only to reduce the number of plots, Figure 6-17. Firstly, the two plots at the top show the indirect DCMs at the two photocell locations. In terms of shade and pattern, the DCMs for the 'Finescale' scheme appear very similar to those for the 'Default' (Figure 6-13). It is possible however to discern variation in the magnitude of the indirect DC within some groups of four from shade alone. The difference in DCs within each group of four is better revealed as a coefficient of variation. These are the two plots in the middle of Figure 6-17. The coefficient of variation (CoV), for any group of four patches, is simply the variance of the group divided by the mean, i.e.

$$CoV = \left(\frac{\sum_{j=1}^{4} \left(DC_{j} - \overline{DC}\right)^{2}}{4 - 1}\right) / \overline{DC}$$
(6-17)

Here the range in CoV varies from low (0 to 0.05), indicated by a blue shade, to high (> 0.25), indicated by pink. Below these are plots of the normalised coefficient of variation (NCoV) which will be discussed later.



#### Figure 6-17. Indirect DCMs for the finescale discretisation at p\_cells 1 and 6

The top two plots show the magnitude of the indirect DCs for the 580 patches. The middle two plots show the coefficient of variation (CoV) within each group of four patches. The bottom two plots show the normalised coefficient of variation (NCoV).

Returning now to the patterns in the CoV. These patterns can be related to the scene geometry. Re-plotting the CoV graphic for p\_cell 6 alongside a schematic of the room shows this more clearly, Figure 6-18.



Figure 6-18. Relationship between the building configuration and the spatial pattern in the coefficient of variation for p\_cell 6

Three distinct regions of high (pink) CoV are delineated. They are labelled as follows:

- Wf showing patches which are, from the photocell viewpoint, visible through the window, or just outside the field of view.
- Gw here the stripling of pink (i.e. high) CoV values shows those patches which have a near grazing incidence to the office window.
- Bh this indicates the arc of patches that were "behind" the officeroom and just above the horizon.

The appearance of these three regions of high CoV can be explained by considering what effect a small displacement in source position has on the resulting indirect illuminance at the rear of the room. Consider first the patches in the region marked Wf. Recall the view from p\_cell 6 as shown in Figure 6-14. In that image, the scene was illuminated by sky patch #17 - one of those patches which when subdivided appears here in region Wf. It is clear from this view that small ( $\sim 5^{\circ}$ ) displacements in source position have a significant effect on scene illumination.

The high CoV patches within the region Gw clearly show a relationship with the plane of the glazing. This is to be expected since small displacements in source position will have a twofold effect on room illumination. At close to grazing incidence, say  $10^{\circ}$ , a change to  $5^{\circ}$  will greatly reduce both the projected area of illumination inside the room and the transmission of light through the glazing.

Those patches behind the office-room, region Bh, cannot illuminate the space directly - at least one reflection of light from the ground plane "up" into the room is required. So it is the luminance of the ground plane, lit by a source patch, that determines the resulting illuminance inside the space. Therefore, for patches (within a group of four) just above the horizon, two will be at altitude 3°, and two at 9°. The ground plane luminance due to the higher altitude patches will be  $(\sin 9^\circ / \sin 3^\circ) \approx 3$  times brighter than for the lower altitude patches. Thus the patches at higher altitude will yield a higher indirect DC - see Figure 6-17 for verification of this.

Returning now to the plots of the NCoV (bottom of Figure 6-17). The NCoV is the CoV multiplied by a normalisation factor:

$$NCoV = CoV \times \overline{DC} / \overline{DC}_{max}$$
 (6-18)

where  $\overline{DC}_{max}$  was the maximum of the 145 values of  $\overline{DC}$  at each photocell. A high NCoV (pink) therefore discloses those sectors where both the CoV was high *and* where the mean indirect DC was large. Although there was a high CoV in the group of four DCs for both p\_cell1 and p\_cell6, only for patches 17 and 18 at p\_cell6 was the NCoV comparably large. This suggests that, if there is a difference in the derived illuminance predictions between the Default and Finescale discretisations, the difference will be more

<sup>6.2</sup> Daylight coefficients: Fundamentals, prediction and analysis

noticeable at p\_cell6 than at p\_cell1, and it will be due to those patches that had a high NCoV.

# 6.3 Validation of DC derived illuminances

# 6.3.1 DC formulation for validation

The illuminance at a photocell location, *E*, was evaluated as the sum of four illuminance components:

$$E = E^{d} + E^{i} + E^{sd} + E^{si}$$
(6-19)

Where  $E^{d}$  and  $E^{i}$  are, respectively, the direct and indirect components of illuminance due to the sky. Similarly,  $E^{sd}$  and  $E^{si}$  are the direct and indirect components of illuminance due to the sun. The illuminance components  $E^{d}$ ,  $E^{i}$  and  $E^{si}$  were derived from the DCMs computed using variants of the 'Refined Method', Figure 6-19. For the purpose of validation, the direct sun component was determined using the standard calculation. The DC derived illuminance predictions were partitioned in the same way as for the standard calculation (Section 4.5). Accordingly, all the instances where the sun was visible from the photocell location (i.e.  $E^{sd} > 0$ ) were classed as potentially unreliable and eliminated. Thus the validation results were insensitive to the magnitude of the direct sun component and any value could have been used. The way the direct sun illuminance should be calculated in a generalised DC scheme is discussed later.

The direct components of illuminance account for window and room configuration, external obstructions and glazing transmittance. The indirect quantities account for the inter-reflected light components, which for both cases, sun and sky, include internal and external reflections. In contrast to the scheme described by Littlefair [92], the illuminance components used here are defined by type - direct or indirect - and luminous origin - sun or sky. All the external obstructions and reflections etc. are absorbed in these four categories.



Figure 6-19. The four components of illumination

### The components of illumination due to skylight

The illumination from skylight was derived from  $(m \ge n)$  daylight coefficient matrices for:

- the direct sky component  $\mathbf{D}^d$  (Refined Method), and
- the indirect sky component  $\mathbf{D}^{i}$  (Naive Method).

Where m was the number of points in the office (i.e. photocell locations) and n was the number of sky patches.

The skylight only illumination (no sun) is the sum of the direct and the indirect illumination

$$\mathbf{E}^{sky} = \mathbf{E}^d + \mathbf{E}^i \tag{6-20}$$

where

$$\mathbf{E}^d = \mathbf{D}^d \times \mathbf{c} \tag{6-21}$$

and

$$\mathbf{E}^{i} = \mathbf{D}^{i} \times \mathbf{c}$$
 (6-22)

Giving the illuminance vector for skylight in terms of DCMs as

$$\mathbf{E}^{sky} = (\mathbf{D}^d \times \mathbf{c}) + (\mathbf{D}^i \times \mathbf{c})$$
  
=  $(\mathbf{D}^d + \mathbf{D}^i) \times \mathbf{c}$  (6-23)

The *n* element column vector  $\mathbf{c}$  is formed from the product of the solid angle and the luminance for the sky patches.

#### The solar components of illumination

As noted above, the direct component of illuminance due to the sun,  $\mathbf{E}^{sd}$ , was determined using the standard calculation - although the outcome of the validation is insensitive to this value. The indirect component of illumination from sunlight,  $\mathbf{E}^{si}$ , was evaluated using part of the daylight coefficient matrix for indirect sky illumination,  $\mathbf{D}^{i}$ , such that

$$\mathbf{E}^{si} = \mathbf{D}^{i}_{\beta} S^{sun} L^{sun}$$
(6-24)

Where  $\mathbf{D}_{\beta}^{i}$  is column  $\beta$  of the  $(m \ge n)$  matrix  $\mathbf{D}^{i}$  for the (indirect) patch nearest to the sun position.<sup>13</sup> The scalars  $S^{sun}$  and  $L^{sun}$  are, respectively, the solid angle and the luminance of the sun.

<sup>13.</sup> For any given sun position, the angle between the sun and every indirect patch was calculated, and the nearest indirect patch to the solar position, represented by the index  $\beta$ , was identified.

The total illuminance due to the sun is the sum of the direct and the indirect components

$$\mathbf{E}^{sun} = \mathbf{E}^{sd} + \mathbf{E}^{si}$$
(6-25)

which, in terms of the column vector extracted from the DCM for the indirect sky component, is:

$$\mathbf{E}^{sun} = \mathbf{E}^{sd} + \mathbf{D}_{B}^{i} S^{sun} L^{sun}$$
(6-26)

#### Total illuminance in terms of DCMs

The m element vector for the internal illuminance, **E**, is

$$\mathbf{E} = (\mathbf{D}^{d} \times \mathbf{c}) + (\mathbf{D}^{i} \times \mathbf{c}) + \mathbf{E}^{sd} + \mathbf{D}_{\beta}^{i} S^{sun} L^{sun}$$
(6-27)

This is the 'kernel' form of the daylight coefficient equation that was used for this study. Variants of this equation are described in the following section.

#### 6.3.2 Variants of the daylight coefficient formulation

The Default and Finescale indirect DCMs are referred to, respectively as,  $\mathbf{D}^{i145}$  and  $\mathbf{D}^{i580}$ . Likewise, the vector,  $\mathbf{c}$ , formed from the product of sky patch solid angle and luminance, contains 145 elements in the Default scheme ( $\mathbf{c}^{145}$ ) and 580 elements for the Finescale discretisation ( $\mathbf{c}^{580}$ ). The direct sky component DCM  $\mathbf{D}^{d}$  was the same for all variants i.e. n = 145. The equations for the four variants are given below.

#### Variant 1

This is simply the default formulation.

$$\mathbf{E} = (\mathbf{D}^{d} \times \mathbf{c}^{145}) + (\mathbf{D}^{i145} \times \mathbf{c}^{145}) + \mathbf{E}^{sd} + \mathbf{D}_{\beta}^{i145} S^{sun} L^{sun}$$
  
=  $(\mathbf{D}^{d} + \mathbf{D}^{i145}) \times \mathbf{c}^{145} + \mathbf{E}^{sd} + \mathbf{D}_{\beta}^{i145} S^{sun} L^{sun}$  (6-28)

#### Variant 2

This formulation used the Finescale discretisation to evaluate the indirect component of illumination from the sky.

$$\mathbf{E} = (\mathbf{D}^{d} \times \mathbf{c}^{145}) + (\mathbf{D}^{i580} \times \mathbf{c}^{580}) + \mathbf{E}^{sd} + \mathbf{D}_{\beta}^{i145} S^{sun} L^{sun}$$
(6-29)

#### Variant 3

Here the Finescale discretisation was used to evaluate the indirect component of illumination from the sun.

$$\mathbf{E} = (\mathbf{D}^{d} \times \mathbf{c}^{145}) + (\mathbf{D}^{i145} \times \mathbf{c}^{145}) + \mathbf{E}^{sd} + \mathbf{D}_{\beta}^{i580} S^{sun} L^{sun}$$
  
=  $(\mathbf{D}^{d} + \mathbf{D}^{i145}) \times \mathbf{c}^{145} + \mathbf{E}^{sd} + \mathbf{D}_{\beta}^{i580} S^{sun} L^{sun}$  (6-30)

#### Variant 4

This last variant used the Finescale discretisation to calculate the indirect component of both the sun and the sky illumination.

$$\mathbf{E} = (\mathbf{D}^{d} \times \mathbf{c}^{145}) + (\mathbf{D}^{i580} \times \mathbf{c}^{580}) + \mathbf{E}^{sd} + \mathbf{D}_{\beta}^{i580} S^{sun} L^{sun}$$
(6-31)

The variants are summarised in Table 6-1.

	Sky component		Sun Component	
Variant	Direct	Indirect	Direct	Indirect (sky)
1	Refined Method (aimed rays)	Default	Standard calculation	Default
2		Finescale		Default
3		Default		Finescale
4		Finescale		Finescale

Table 6-1. DC Variants

#### 6.3.3 Pre-process of the sky luminance measurements

The conversion of the sky luminance data to a suitable format for the standard calculation was described in Section 3.2.5. The conversion for the validation of the DC derived illuminances required a similar process, except that in this instance, the pattern for the interpolated sky luminance data was identical to the pattern for the measurement. The daylight coefficient

implementation required a sky vault discretisation that was based on a fixed-orientation pattern, whereas the orientation for the measured pattern was variable, Figure 6-20. Apart from these differences, the interpolation of



Figure 6-20. Comparison of scanner measurement pattern with DC patch scheme

the measurement pattern to the DC pattern and normalisation of the sky luminance used the techniques described in Section 3.2.5. An example of a measured and interpolated sky for use with daylight coefficients is given in Figure 6-21. This same sky (125\_92\_13h15) was given as an example of the interpolation applied for the standard calculation (Figure 3-20). The differences between that interpolation and the one shown in Figure 6-21 are slight; in both cases it is likely that the circumsolar sky luminance was underestimated.



Figure 6-21. Sky 125\_92\_13h15

### 6.3.4 Results

Illuminance predictions for the 754 skies in the BRE-IDMP validation dataset were derived using the four DC variants (Eq 6-28 to Eq 6-31). As with the standard calculation, the predictions were partitioned into 'reliable' and 'unreliable' sets according to the visibility of the 6° circumsolar region (Section 4.5). Only those photocell-scan combinations classed as reliable were used for comparison with measurements and the predictions using the standard calculation.

The overall mean bias error (MBE) and root mean square errors (RMSE) for the illuminance predictions at each photocell for the standard calculation and the four variants of the daylight coefficient implementation are shown in Figure 6-22. The number of reliable photocell-scan combinations is marked at each photocell position, i.e.  $N_{scan} = 688$  for photocell 4.

The illuminance predictions from the standard calculation were generally better than those for any of the DC variants, particularly in terms of MBE for those photocells at the back of the room. The differences from the measurements were however not that great, and the MBEs for DC variants 2 and 4 were always less than 10% for all photocells.<sup>14</sup> The differences in prediction between the four DC variants were significant only at the back of the room (p\_cells 5 and 6). It was suggested in Section 6.2.5 that this was likely to be the case. Even so, the differences were not that large. Variant 2 performed marginally better than Variant 3. This suggests that, for the skies in the validation dataset, the indirect sky component was more sensitive to the change in patch discretisation (Default to Finescale) than the indirect sun component. Variant 4 performed the best, but the improvement over Variant 2 was only marginal.

<sup>14.</sup> With the exception of photocell 3, which may contain a calibration error (Section 4.5.3).





#### Time-series plots for DC variant 4 and the standard calculation

The relative error in the illuminance prediction for daylight coefficient variant 4 (DCV4) and the standard calculation is shown with the corresponding time-series for global horizontal, diffuse horizontal and vertical South illuminance in Figure 6-23 to Figure 6-26. These plots use the same format as in earlier chapters. Only those photocell-scan combinations that were classed as reliable are shown. The relative error in DCV4 predictions is marked by blue ( ) square, and the standard calculation by a red ( ) square. There are 27 pairs of plots in the figures: one for each day in the validation dataset.



Figure 6-23. Comparison standard calculation and DC variant 4



Figure 6-24. Comparison standard calculation and DC variant 4



Figure 6-25. Comparison standard calculation and DC variant 4



Figure 6-26. Comparison standard calculation and DC variant 4

From these plots, the following observations are made:

- 1. The RERs for DCV4 were generally good (i.e. RER < 10%).
- 2. The RERs for DCV4 were comparable to those obtained using the standard calculation.
- 3. For both DCV4 and the standard calculation, some RERs were noticeably large (> 20%) for clear sky conditions from day 273\_92 onwards.
- 4. For overcast conditions late in the year, e.g. days 265\_92, 266\_92 and 269\_92 (Figure 6-25), DCV4 tended to overpredict slightly in both absolute terms, and relative to the standard calculation.

The difference in performance between any of the DC variants and the standard calculation was discernible. Though for most practical purposes, the differences are not considered to be important.

# 6.3.5 Summary

The daylight coefficient approach has been successfully implemented using the *Radiance* system as the calculation 'engine'. The validation of the daylight coefficient derived illuminance predictions was carried out using the same rigorous procedures as for the standard calculation. The error characteristics for the daylight coefficient derived illuminances have been demonstrated to be comparable to those for the standard calculation. In the following section, a generalised daylight coefficient approach is described and demonstrated.

# 6.4 DC Based daylighting analysis: The way ahead

# 6.4.1 Background

Daylight modelling in the UK has traditionally been based on the convention of a Standard Overcast Sky for three reasons:<sup>15</sup>

- If the natural lighting is sufficient on an overcast day it is likely to be more than adequate when the sun is shining.
- A densely overcast sky looks the same whichever direction (in plan) one faces north, south, east or west. The effect of the orientation vanishes from the calculation.
- Given the overall luminance profile of the Standard Overcast Sky, the illuminance at any given point indoors must be directly proportional to the simultaneous outdoor illuminance under the unobstructed overcast sky vault, whether the sky itself is bright or dull.

<sup>15.</sup> Taken from the CIBSE virtual conference pages - http://www.virtual-conference.com/ cibse97/conference/papers/e-html/DAYFAC.HTM

It is fair to say that the approach has gained favour largely because of its simplicity rather than its intrinsic accuracy. The assumption of a CIE Standard Overcast Sky transforms what is in reality a time-varying scenario - a succession of unique sky and sun conditions - into one that is static. The penalty of simplicity however is a considerable loss in realism. It is impossible to reproduce using an overcast sky the naturally occurring variations in the quantity, the character (e.g. diffuse, direct) and the distribution of internal daylight levels.

It has long been appreciated that the ratio of internal to external illuminance varies greatly under real skies [Tregenza 83], but the significance of this has yet to be accurately quantified. For this to be achieved, realistic measures of the true long-term daylighting performance for buildings must be made. The assessment period should ideally be a full year so that the seasonal variation in daylight is captured (Figure 6-1). And the timestep at which the evaluation is carried out should be small enough to capture the observed short-term variation in daylight. The most readily available sources of data that matches these requirements are climatic or weather tapes (see Section 2.1.1). These data contain hourly integrated values for a full year. Standardised weather tapes, known as Test Reference Years, are usually based on several years data so that the effect of 'exceptional' years is minimised. The use of daylight coefficients to predict long-term daylighting performance based on Test Reference Year data is described and demonstrated in the sections that follow.

### 6.4.2 A system to predict time-varying illuminances

The DC Variant 1 implementation (Section 6.3.2) was generalised so that illuminances for all four components could be derived from daylight coefficients.<sup>16</sup> In the generalised scheme, the direct sun illuminance was derived from a direct component DCM for 5010 points evenly distributed

<sup>16.</sup> Because these are demonstration examples, the simplest DC variant was used. In practice, DCV4 would be the best one to use.

over the hemisphere. Following the procedure outlined by Littlefair (see Section 6.1.2), the basic climate data used for the all examples that follow were obtained from the Kew84 Test Reference Year. The building model for these examples was the BRE office so the daylight coefficients calculated for the validation were re-used. Only the direct DCM for the 5010 points needed to be calculated anew - a relatively trivial task taking only a few seconds to compute.The internal illuminance therefore was calculated using Eq 6-28 with the direct sun component  $\mathbf{E}^{sd}$  now derived from daylight coefficients:

$$\mathbf{E} = (\mathbf{D}^{d} \times \mathbf{c}^{145}) + (\mathbf{D}^{i145} \times \mathbf{c}^{145}) + \mathbf{D}_{\beta}^{d5010} S^{sun} L^{sun} + \mathbf{D}_{\beta}^{i145} S^{sun} L^{sun}$$
(6-32)

The vector  $\mathbf{D}_{\beta}^{d5010}$  is column  $\beta$  of the DCM  $\mathbf{D}^{d5010}$  for the point on the hemisphere nearest to the actually occurring sun position. The procedure for deriving the illuminances was as follows:

- Load TRY data then the following operations were carried out for each hour of the TRY where the global irradiance  $(I_{gh})$  was greater than zero.
- Convert irradiances to illuminances using a luminous efficacy model.
- Generate the sun position from the geographical location and timestamp of the TRY data.
- Generate the sky luminance at the 145 patch centres on the sky vault.
- For the indirect DCM ( $\mathbf{D}^{i145}$ ), locate the patch nearest to the sun position. This is for the indirect component of illuminance from the sun.
- For the direct sun DCM ( $\mathbf{D}^{d5010}$ ), locate the point nearest to the sun position. This is for the direct component of illuminance from the sun.
- Compute the illuminance components using Eq 6-32.

For the Kew TRY, there were 4,406 hours (i.e. unique values) where  $I_{gh} > 0$ . The internal illuminance at the six photocell locations of the BRE office was derived from daylight coefficients for all these hours. A number of these illuminances were either too small to be of practical use and/or they occurred outside of normal working hours. The computational overhead of calculating them however was slight. The mean displacement between the 4,406 calculated sun positions and the nearest point on the hemisphere (for the direct sun component) was  $0.77^\circ$ , with a standard deviation of  $0.28^\circ$ . The maximum displacement of the sun position was  $1.41^\circ$ .

The move from a static daylight factor analysis to one based on hourly illuminance values for an entire year necessitates a substantial leap in complexity, for both data analysis/reduction and interpretation. For example, the BRE office has six calculation points (i.e. photocell locations), resulting in a total of  $6 \ge 26,500$  derived illuminance predictions. It is a quite straightforward matter to reduce a time-series of illuminance values to a handful of summary metrics. For example, the percentage of the working year for which a target illuminance, say 500 lux, is achieved at each of the calculation points. Summary metrics are useful as ultimate indicators of performance, but significant and/or instructive features of the original dataset may be lost. For the work described here, a gradual 'sifting' of the data is preferable. To this end, a hierarchical approach to data reduction - involving visualisation - was employed. The formats used to present/ analyse the data were:

- MAP is a false-colour map (365 x 24) of the 'raw' hourly values for the year, e.g. illuminances derived from DCs.
- FRQ is a frequency histogram of the incidence (i.e. number of hours) of binned values. It is derived from the 'raw' hourly values, but it can be set to include only those data that fulfil arbitrary criteria. For example, only those illuminances that occur during working hours.
- CML is a curve of the cumulative total usually calculated using the same criteria as the frequency histogram.

When applied to daylighting quantities, these formats are referred to collectively as 'annual daylighting profiles' (ADPs).

# XDAPS

As the suite of programs and scripts that were created for each individual analysis grew, it became desirable to generalise the function of key routines so that they could be re-used for different applications/analyses. From this emerged the "e $\underline{X}$ tensible  $\underline{D}A$ ylight  $\underline{P}$ rediction  $\underline{S}$ ystem" (XDAPS). The system is an evolving toolkit of data analysis/visualisation procedures written in the IDL programming language and the UNIX C-shell. The individual programs carry out a range of tasks including:

- Generation of *Radiance* format source descriptions and ray vector coordinates for the DC simulations.
- Management of the DC simulations.
- Transformations from Cartesian to spherical co-ordinates (polar and altitude-azimuth).
- Calculation of sun position from time and geographical location.
- Luminous efficacy models.
- Generation and normalisation of sky luminance distributions from sky models and sky model blends.
- Derivation of hourly-annual illuminances from daylight coefficients using Test Reference Year irradiance time-series.
- Analysis and visualisation (with hardcopy) of hourly-annual illuminances, e.g. false-colour maps (365 x 24 arrays) of illuminances, frequency histograms and cumulative values.
- Parametric analyses of hourly-annual illuminances as a function of building orientation.

Most of the above tasks are handled by IDL procedures; UNIX scripts are used to manage the *Radiance* simulations that predict the DC coefficients. The system offers an effective software environment to rapidly prototype analysis scenarios.<sup>17</sup> Using a moderately powered computer (Sparc Ultra 10), XDAPS can derive internal illuminance predictions for the BRE office at

a rate of ~100 skies per second using pre-calculated coefficients. That processing time includes the generation and normalisation of sky luminance distributions from TRY data. It takes therefore ~40 seconds to derive the illuminances for the daylight hours for one year.

# 6.4.3 Example 1: Introduction to ADPs

The procedure to derive illuminance ADPs for the BRE office is described in this section. For this example, the glazing normal was set to exactly due South. The hourly sky and sun conditions were derived from the irradiance data of the Kew TRY. The diffuse horizontal and direct normal irradiances for this TRY are shown using the MAP format in Figure 6-27. Positive irradiances between > 0 and 500 Wm-2 are shaded blue-through-yellow. Zero values are shaded gray. With this format, one can easily appreciate the significant features of the data for the entire year. Most obvious is the daily and seasonal variation for both irradiances. The hour-by-hour variation in the irradiances is also apparent, particularly so for direct normal irradiance. To give the basic quantities needed for the generation of the sky and sun luminances, the irradiances were converted to illuminances using a constant value for luminous efficacy of 120 lm/W.<sup>18</sup>

The sky and sun conditions were generated from the external illuminances and the (calculated) sun position using the intermediate-overcast sky model blend described in Section 5.4.<sup>19</sup> The sky model mixing function  $f_{in}$  for the Kew TRY (Section 5.4.2) is given in Figure 6-28. The majority of the skies, 60%, were given the intermediate sky description (blue ), 24% were given the CIE overcast sky description (red ). The remainder, 16%, used an

<sup>17.</sup> **XDAPS** is used for research and testing within the IESD - it is not intended for general use.

<sup>18.</sup> Luminous efficacy was not an issue for this work, so a simple model was used. More complex efficacy models could be used, if desired, without adding significantly to the computational effort.

<sup>19.</sup> For the test described in Chapter 5, the clear-overcast blend performed marginally better than the intermediate-overcast blend. However it was noted that in Section 5.4.3 that the clear-overcast blend may result in composite luminance patterns that are unrealistic. For this reason, the intermediate-overcast blend is used here.



Figure 6-27. Key TRY time series maps

overcast-intermediate blend, the relative proportions for which depended on the sky clearness index (green and transitional shades).

Using the procedure outlined in Section 6.4.2, internal illuminances at the six photocell locations in the BRE office were derived from DCMs. To reduce the number of plots, the ADPs at just one of the photocell locations (p\_cell 3) are shown in Figure 6-29. The first of the ADPs, the MAP format at the top of the figure, gives an overview of the hourly illuminance predictions for the whole year. Note that the highest illuminances,  $\geq 2500$  lux, occur around noon for the winter months. Next, the FRQ format ADP, shows the number of hours that a (binned) illuminance occurred during the working day, i.e. 09h00 to 18h00. The binsize used for this plot was 50 lux. The last of profiles, CML, shows the cumulative illuminance expressed as a



Figure 6-28. Sky model mixing function

percentage of the working year. For example, the illuminance levels: 100, 200, 500 and 1000 lux were attained for (approx.) 90, 80, 65 and 40% of the working year, respectively, at p\_cell3.

Recall that the internal illuminance was computed as four distinct illuminance components (Eq 6-32). The MAP format ADPs for the individual illuminance components are shown in Figure 6-30. The high illuminances identified in the MAP for the total illuminance (Figure 6-29) were, of course, due to direct illumination by the sun. For daylighting evaluation, it may well prove useful to analyse both the relative proportions and the magnitude of the illuminance components, e.g. for the ability of a light shelf to redirect sunlight compared to ordinary glazing. The next ADP example shows how a fundamental property of DCs can be exploited to yield an immense quantity of daylighting performance information.



Figure 6-29. DC derived illuminances for p\_cell 3 (south glazing)

# 6.4.4 Example 2: Parametric evaluation of ADPs

For a fixed building configuration, the daylight coefficient matrix is invariant to the building orientation. In other words, once the DCMs have been evaluated, internal illuminances can be derived for arbitrary building orientations by simply applying a rotational transformation to the generated sky-point and sun luminances, Figure 6-31. Consequently, it is a relatively



Figure 6-30. DC derived illuminance components

trivial matter to automate the derivation of internal illuminances for a range of arbitrary building orientations. The procedure used for the previous example was modified to predict ADPs for all building orientations in steps of  $30^\circ$ , i.e. 12 orientations in total. The predictions are presented as a series of 'ADP-roses', one each for the MAP, FRQ and CML formats. In the first instance, predictions for just one calculation point (p\_cell3) are shown to limit the number of graphs. The first of these is the MAP-rose, Figure 6-32. The orientation of each MAP in the figure indicates the orientation of the glazing normal for the office model. The sensitivity of daylight illumination to orientation is readily apparent. The anisotropic nature of the sky luminance distributions (and sun conditions) that were used for many of the individual skies is echoed in the patterns of internal illuminance. Note the large difference in overall magnitude for illuminances between the North and South orientations, and the difference in the patterns for illuminance between the East and West orientations. Of course, none of these effects could be reproduced using the standard daylight factor approach. Proceeding as with the first ADP example, the next stage is the 'FRQ-rose',



#### Figure 6-31. Rotation-invariant nature of the DCM

The effect of arbitrary building rotation  $\alpha_b$  is achieved by transforming the azimuth of the sun by  $-\alpha_b$ . Illustration shows building rotated 60° West of South and the noonday sun location.

showing the binned occurrence of predicted illuminances as a function of building orientation, Figure 6-33. And then the cumulative totals 'CML-rose' in Figure 6-34. As in Figure 6-29, the cumulative availability of four 'target' illuminances - 100, 200, 500 and 1,000 lux - for each building orientation is marked on the curves.

The cumulative availability of the 'target' illuminances for all six photocells as a function of building orientation is shown in a highly compact form in Figure 6-35. This type of plot is referred to here as the 'target' illuminance or TI-rose. For this example, a total of 317,232 (= 4406 x 12 x 6) illuminance predictions were derived from just the one set of DCMs. In fact, because the four illuminance components were computed separately, the total number of internal illuminance predictions was ~1.2 million.



Figure 6-32. 'MAP-rose' for p\_cell3

# 6.4.5 Example 3: ADPs and the daylight factor method

Daylight coefficient derived cumulative illuminances for one year could be compared with cumulative estimates based on daylight factor values (Section 6.1.1). Provided of course that the same TRY was used for both analyses. A straightforward comparison between a DC derived cumulative illuminance and one based on daylight factors is problematic because they are not identical quantities. The daylight factor approach to annual



Figure 6-33. 'FRQ-rose' for p\_cell3

estimates considers only the *diffuse* illuminance availability (Figure 6-2). One could argue therefore that results from this simple approach should only be compared with the DC derived illuminance for the sky component, i.e. just two of the four components shown in Figure 6-30. Whilst this might be considered as comparing like-with-like, the sky only illuminance is in reality a somewhat abstract quantity of qualified physical significance. This is so because, for real buildings, it is almost impossible to exclude the



Figure 6-34. 'CML-rose' for p\_cell3

illumination effects of sunlight - particularly indirect - for a fixed building/ glazing design. Indeed, from the MAPs shown in Figure 6-30 it is clear that, for this orientation at least, the indirect sun illuminance was a significant (if erratic) contributor to the total annual illuminance.

As noted previously, the ratio of internal to external illuminance varies greatly under real skies [Tregenza 83]. This ratio is called here the 'Total Daylight Factor' (TDF) because it is based on the total internal illuminance,



Figure 6-35. 'TI-rose' for all photocells

i.e. direct and indirect for both sky and sun. The hourly TDFs at p\_cell 2 in the BRE office were derived from the illuminance predictions shown in Figure 6-32 and the Kew TRY. The distribution in TDFs as a function of glazing orientation is shown in Figure 6-36. This distribution provides a



Figure 6-36. Frequency distribution of predicted TDFs as a function of glazing orientation

measure of the deviation between the TDFs and the standard daylight factor (SDF) based on the CIE Standard Overcast Sky. The most prominent feature of the distributions is the peak centred on TDF = 4.75%. The peak is of
similar size - approx. 800 hours (i.e. skies) - for all the glazing orientations. For the TDFs that were counted in this bin, the corresponding illuminances were derived from DCs using the overcast sky description. This TDF therefore is the standard daylight factor (SDF) as it would be calculated using traditional techniques.

The deviation between the TDFs and the SDF is examined in more detail in Figure 6-37. Three glazing orientations from Figure 6-36 are used for illustration - North, East and South. The luminance distributions for an overcast and an intermediate sky are included as shaded surfaces at the bottom of the figure. These two skies were normalised to give the same diffuse horizontal illuminance, and they are shown using identical scaling. The difference in the distribution of TDFs as a function of glazing orientation is explained as follows. Consider first those irradiance values in the Kew TRY that resulted in overcast sky conditions with no significant sun component (using the sky blending rule described in Section 5.4.2). For these instances in the TRY, the sky luminance distribution used to derive internal illuminances was that of the CIE standard overcast sky. Thus, for these skies, the ratio of internal illuminance to external illuminance was a constant: identical to the standard daylight factor. The CIE overcast sky is, of course, symmetric about the z-axis, so these TDFs were the same for all orientations. Next, consider those instances where the sky conditions were determined to be largely non-overcast (i.e. intermediate). For these, the maximum sky luminance was concentrated about the sun position, which for the most part was in the South. Also, there was the contribution of mainly indirect - sunlight. The luminance of the sky in the North is, for the non-overcast (i.e. intermediate) model, lower than that for an equivalent (i.e. same diffuse horizontal illuminance) overcast sky (around midday), see Figure 6-37. Relative to the SDF therefore, TDFs for non-overcast (i.e. intermediate) skies were lower for a North glazing orientation and higher for the South glazing orientation. For the East (and West) glazing orientations, the distribution was a mixture of those for the North and South. The East



Figure 6-37. Examination of TDF distributions for three orientations

Example overcast and intermediate skies produce the same (diffuse) horizontal illuminance

orientation was just as likely to have the sun with a bright circumsolar region 'in front of' the glazing in the morning as it was to have the lower luminance sky, opposite the sun, 'in front of' the glazing in the evening.

The numbers in the TDF distribution will be sensitive to the sky model(s) used, but the general observations are likely to remain the same. This is because they are a consequence of the fundamental difference between the Standard Overcast Sky (peak luminance at the zenith) and the non-overcast models (peak luminance at the sun position). Furthermore, since evidence has been presented to the effect that the overcast-intermediate blend offers plausible representation of naturally occurring sky conditions a (Section 5.4), a reasonable conclusion from this exercise is that actually occurring TDFs are likely to vary significantly from the (static) SDF value as shown in Figure 6-36. This observation in itself is nothing new [Tregenza 83]. The significance of the analysis presented here is that it is now possible to quantify the discrepancy to a high degree of precision - controversy regarding sky models notwithstanding. The analysis does not have to make use of sky models, the luminance distribution could equally be based on actual measurements, as it was for the validation. Accordingly, it was not the intention here to suggest that the overcast-intermediate sky model that was used to derive the TDFs is the 'best' sky model combination to use for the Kew TRY, or any other Test Reference Year. Rather, this example has demonstrated one aspect of a new schema for the investigation and, importantly, validation of daylight prediction techniques.

### 6.4.6 Implementation and application issues

In this section, issues relating to the practical and research use of the daylight coefficient approach are discussed.

### Variable Building or Glazing Configurations

Any change to a building that alters the passage of daylight into a space creates, in effect, a new building configuration. Ideally, each unique building configuration would require its own unique set of DCMs. Changes to the building configuration can be effected by any of the following:

- user-operated venetian blinds;
- a motorised shading screen that automatically responds to illumination levels; and,
- responsive glazing systems e.g. photochromic (passive) or electrochromic (active).<sup>20</sup>

For a continuously variable property, such as the angle and/or extent of a motorised shading screen, the full range of variation would have to be modelled as a limited number of incremental changes in building configuration. If the number of discrete configurations is large, then the potential advantage of DCs over the standard calculation may be diminished or even eliminated.

### Sub-hourly Predictions and Lighting Controls

With a daylight coefficient approach, the prediction of internal illuminances at a sub-hourly timestep is a tractable problem. The issues to consider are the nature of the variability in the meteorological conditions and how they relate to internal illuminance. If the intention is to account for the internal illuminance resulting from small changes in the sun position, then the timestep for the analysis needs to be commensurate with that aim. For example, at the hourly timestep of typical TRYs, the sun moves 15° every timestep. Modelling this with a hi-res direct DCM for 5010 points on the hemisphere gives a mean sun displacement angle for the year of less than 1°, which is more than adequate.<sup>21</sup> At a timestep of 5 minutes, the sun moves approximately 1.2° every timestep, which is close to the typical sun

<sup>20.</sup> If it is only the glazing transmissivity that changes, and the change is applied equally to all the glazing elements, then it may be possible to model this scenario with just one set of DCMs by adjusting the internal illuminance levels in response to the glazing transmissivity.

<sup>21.</sup> The typical sun displacement angle is about half the angular spacing of the points across the hemisphere. For 5000 points the angular spacing is about  $2^{\circ}$ .

displacement angle for the 5010 point DCM. Is there any advantage in modelling the sun position to a higher degree of accuracy, regardless of the timestep used? The answer is - almost certainly no. There is little practical value in resolving internal illuminance levels at very fine *spatial* scales. However, there is value in obtaining illuminance levels at very fine *temporal* scales. Here it is the short-term variability of internal illuminance levels in response to rapidly changing sky and sun brightness conditions that is the issue, rather than variability which is due solely to the changing sun position.

Everyday experience informs us that sky and sun brightness conditions change at timescales much shorter than the hourly timestep of TRYs. Whilst the evaluation of daylight illumination based on ADPs offers a significant advance over the standard daylight factor approach, the modelling of daylight responsive systems needs to be carried out at the timescale at which the systems are likely to respond. This is particularly important for the modelling of lighting control systems which are intended to respond to changes in daylight illumination levels. With a DC based approach, the prediction of daylight illuminance levels at a timestep as short as even 1 minute, for long time periods, is a practical possibility. Thus, the long-term behaviour of arbitrary lighting control algorithms can be predicted.

### Luminous Efficacy and Sky Model Performance

The sky luminance distributions used in the derivation of ADPs will generally be based on basic irradiance quantities, such as the Kew TRY (examples Section 6.4.3 to Section 6.4.5). Thus, the ADPs that are derived will be sensitive to the luminous efficacy models and the sky models that are used. Luminous efficacy is known to vary depending on several factors including sky conditions (e.g. clear, overcast) and source type (i.e. direct sun or diffuse sky) [Littlefair 88].

For sky models, there are several types that are currently in use. Testing of these models has only recently taken place with the availability of measured sky luminance distributions [Ineichen 94][Littlefair 94]. The validation has generally been based on the ability of the models to reproduce measured sky luminances. Another approach to validation is to examine the effect of sky model type on *internal illuminance*. Based on the work described in this thesis, it is now possible to accurately - and efficiently - predict the sensitivity of internal illuminance to both luminous efficacy and sky model type. Making full use of each set of DCMs, it is possible to efficiently investigate the effects of building orientation and different climatic zones over an analysis period of a full year at an hour (or better) timestep. The potential to generate such a wealth of reliable internal illuminance data from a relatively small number of lighting simulations is unprecedented.

### Design Guides

The rotation-invariant nature of DCMs means that, once the DCM has been computed, the sensitivity of daylight illumination to building orientation can be determined at minimal expense (Section 6.4.4). Furthermore, illuminances can be derived from DCMs using arbitrary Test Reference Years for any geographical locale. For example, it would be a relatively trivial matter to reproduce the TI-rose analysis (Figure 6-35) for a wide range of prevailing climatic conditions covering Europe, or even further afield. The daylight part of design guides - such as the LT method [Baker 94] - could be significantly improved if these techniques were to replace the daylight factor based methods used for the original analyses.

### DC derived ADPs: End-User Software

The following questions concerning implementation of the DC approach need to addressed if it is to gain wider acceptance. Firstly, is it practicable to embed the daylight coefficient scheme in end-user software? Secondly, to what degree can the intricacies of the technique be hidden from a prospective (i.e. non-expert) user?

If it is practicable for a non-expert user to calculate daylight factors accurately using *Radiance*, then daylight coefficients should not prove to be

too difficult. The main problem - for either daylight factor or daylight coefficient calculation - is the setting of the ambient parameters (Section 3.3.2). If this can be achieved reliably, then automation of the prediction of DCMs is a relatively straightforward matter which can be largely hidden from the user. It is possible to provide some general guidance for the setting of the ambient parameters. However, optimum values for the parameters are largely scene dependant, so some insight and/or experimentation is usually needed to achieve the best effect.

These issues notwithstanding, the IESD have produced a *Radiance*-based software tool to predict time varying illuminances called the Dynamic Lighting System [EPSRC 97]. The work described in this chapter formed the basis of the 'calculation engine' for the Dynamic Lighting System (DLS). At the time of writing, the DLS was about to be released for beta-testing. It is hoped that the daylight coefficient approach described here will be incorporated into other *Radiance*-based software packages.

### DC derived ADPs: A Benchmark for Evaluating Simpler Methods

Sufficient evidence has been presented in this chapter to demonstrate that daylight coefficient based analyses offer a major advance over established techniques. The uncertainties, such as they are, are those relating to luminous efficacy and sky models, and not with the DC approach itself. It seems reasonable therefore to propose that DC based ADPs become the benchmark against which predictions for long-term daylighting performance using simpler techniques are compared. Making comparisons however, is unlikely to be straightforward. Largely because it is dissimilar quantities that will be under consideration (see Section 6.4.5). It likely that a new set of daylighting metrics will need to be formulated before these issues can be resolved. What form these metrics may take is discussed below.

### **Refinement of ADPs**

The ADPs that have been described thus far need to be refined before they can be of practical use to lighting designers. The fundamental inadequacy of the ADPs, as described above, is that each point of calculation is treated independently. What is needed is a class of measures, based on the hourly illuminance predictions, that account for the entirety of the space. For example, a quantity of key importance for daylighting is the uniformity of illumination across the work plane. It would be a trivial matter to calculate, for each hour, the uniformity ratio for a space based on the hourly illuminance predictions at each calculation point. The uniformity ratio on its own however is less than ideal because it does not give any indication of useful levels of illumination. A more helpful measure would make account of both uniformity and absolute illuminance levels. A term for these hypothesised measures is offered: 'Total Daylighting Performance Metrics' (TDPMs). Note that TDPMs could be formulated to account for both absolute and relative levels of any (or all) of the four illuminance components.<sup>22</sup> By treating the sun illuminance components separately, the performance of an innovative glazing system could be assessed in terms of both shading and re-direction of solar beam radiation.

To be truly comprehensive, TDPMs would need to make account of field-ofview luminances also. This could be the luminance for points across the principal wall surfaces, and perhaps across the glazing also. Luminance TDPMs would be calculated for the same period and timestep as the illuminances. How luminance TDPMs might be formulated is described in a paper presented by the author at the 1998 National Lighting Conference [Mardaljevic 98]. Aside from a few suggestions as to what quantities TDPMs might make account of, the formulation of TDPMs is likely to be a significant task and beyond the scope of this thesis.

<sup>22.</sup> If they are based on illuminances derived using the Radiance DC formulation.

### 6.5 Conclusion

The accurate and efficient prediction of hourly internal illuminances for a full year is now a practical possibility using daylight coefficients. This chapter has demonstrated how the Radiance lighting simulation system can be used to predict the daylight coefficients from which internal daylight illuminances are derived. Several variants of the daylight coefficient implementation were investigated. The magnitude and form of the daylight coefficient matrices were related to the building configuration and the discretisation scheme. The accuracy of the derived illuminance predictions was verified using the BRE-IDMP validation dataset. The daylight coefficient implementation was then generalised so that hourly daylight illuminances could be predicted from Test Reference Year time-series data. Hourly illuminance predictions for a full year were presented using three different formats demonstrating a progressive reduction of the data. The rotation invariant nature of the DCM was made use of in an example that predicted the annual daylighting profile as a function of building orientation. A range of implementation and application issues were discussed.

Chapter

### Conclusion

"These are the only ones of which the news has come to Ha'vard, And there may be many others, but they haven't been discavard."

TOM LEHRER

### 7.1 Summary

The accurate prediction of daylight illuminance using lighting simulation was the goal for this thesis. The foundation for the work was the validation of the *Radiance* illuminance calculation under real sky conditions. This work would not have been possible without the BRE-IDMP validation dataset. This dataset is believed to be the only one in the world that has simultaneous measurements of the sky luminance distribution and internal illuminance. As such, it must be considered the 'gold-standard' dataset for the validation of lighting simulation programs.

The validation exercise described in Chapter 3 and Chapter 4 confirmed that *Radiance* can accurately predict internal daylight illuminance under a wide range of naturally occurring conditions. The accuracy of the illuminance predictions was shown to be, in the main, comparable with the accuracy of the model input data. There were a number of predictions with low accuracy. Evidence was presented to show that these invariably resulted from imprecision in the model specification - such as, uncertainty of the circumsolar luminance - rather than the prediction algorithms themselves. On the basis of these results, Radiance can be used with confidence to accurately predict internal illuminance under standard overcast sky conditions (i.e. daylight factors) for 'traditional', that is, ordinary glazed, buildings. This covers the overwhelming majority of existing and new commercial building designs. Buildings more complex than the BRE office, e.g. atria, should not present difficulties provided that the ambient calculation is used effectively (see Section 4.8). This invariably means some convergence testing along the lines described in Section 2.4 and Section 2.5 will be required. Following the procedures outlined in these sections, less-than-expert Radiance users should be able to produce reliable daylight factor predictions for the majority of current building designs. Accurate illuminance predictions under non-overcast skies were also demonstrated in the validation. Though these needed to be identified and separated from the potentially unreliable predictions based on visibility of the circumsolar region.

The ability of sky models to reproduce sky luminance patterns for the purpose of predicting internal illuminance was investigated in Chapter 5. Four sky models and two sky models blends were assessed. Three of the sky models were designed to be applicable to a narrow range of sky conditions, i.e. overcast, intermediate and clear. Only the Perez model was designed to reproduce a wide range of sky conditions. The sky model blends were composites of an overcast and a non-overcast narrow-range model, i.e. the intermediate-overcast blend and the clear-overcast blend. For each of these, the weighting factor was a function of the sky clearness index. The configuration of each blend was based on the minimisation of RMSEs for the vertical illuminances.

Predictions of internal illuminance using sky models and sky model blends were compared against those using measured sky luminance patterns for all 754 skies in the validation dataset. Routine application of the narrowrange models resulted in large MBEs and RMSEs for internal illuminance because of the, occasionally very large, differences between the measured and modelled sky luminance patterns. The Perez model and the sky model blends performed comparably well. Illuminance predictions using measured skies, however, were markedly better than those using sky models/blends.

An implementation of the daylight coefficient approach for *Radiance* was described in Chapter 6. Five candidate daylight coefficient formulations for *Radiance* were described and examined. The form and magnitude of the daylight coefficients were related to the scene geometry and the discretisation scheme. One of the formulations (the 'naive method') was found to introduce large systematic biases in the illuminance predictions. The 'naive method' was eliminated from further testing. The accuracy of the remaining daylight coefficient formulations was verified using the validation dataset. Illuminance predictions for the office space were derived from daylight coefficients using the measured sky luminance patterns for all 754 skies. This was done for each of the formulations. The accuracy of daylight coefficient derived illuminance predictions for the best of the formulations was comparable to that using the standard *Radiance* calculation method. The performance of the other three formulations was only marginally worse than that of the best.

As given in Chapter 6, the daylight coefficient approach should be considered equivalent in accuracy to the standard calculation, and accordingly very accurate in absolute terms.<sup>1</sup> This being so, the daylight coefficient approach offers the potential to significantly advance the practice of daylight illuminance prediction. From a relatively small number of precomputed daylight coefficients, the internal illuminance for many thousands of arbitrary sun and sky conditions can be speedily computed.

<sup>1.</sup> Issues regarding visibility of the circumsolar region notwithstanding.

For the first time therefore, the computation of internal illuminance based on hourly (or better) sky/sun conditions for a full year is a practical possibility. Examples for how this might be carried out were described in Section 6.4. Techniques to visualise and reduce the voluminous illuminance data were presented.

### 7.2 Suggestions for further work

Is there a need for additional validation work on Radiance of the type described in Chapter 3 and Chapter 4? For building designs using 'traditional' materials, further testing of the Radiance system is not urgently required. The modelling of so called 'advanced glazing materials' (e.g. prismatic films, mirrored louvres) however presents many difficulties for Radiance and, indeed, any other lighting simulation program. The transmission properties of advanced glazings materials need to be represented in some way in the simulation. This can either be as a function or as an interpolated data map of values, both of which will need to be based on measurements. Both the measurement and modelling of these materials is very complex. Validation of some kind is needed if the results of a lighting simulation for these materials are to be used with any confidence. Three advanced glazings materials were installed for short periods in the BRE office rooms (Section 3.1.2). The validation described in Chapter 3 and Chapter 4 could be repeated for these materials if the original samples, or identical copies, are still available for measurement. Otherwise, a new validation dataset for these and other materials will be required.

It would be instructive to compare the accuracy of *Radiance* illuminance predictions with alternative simulation programs for both overcast and nonovercast sky conditions. For this it would be preferable to use the BRE-IDMP validation dataset (Section 3.1) since this is currently the best available. As noted in Chapter 3, for previous studies using non-overcast skies it was impossible to determine if the sky luminance pattern used in the model was the same as that occurring at the time of measurement. As far as the author is aware, the validation described in this thesis is the only one to date that has used measured sky luminance patterns and simultaneous internal illuminance measurements.

Two "new generation" artificial sky simulators have recently been constructed in the UK (UWCC, Cardiff and UCL, London). These are designed specifically to reproduce non-overcast sky conditions for scale models. However, recent studies have questioned the accuracy of scale models for illumination prediction [Cannon 97]. Scale model illuminances under real overcast sky conditions were found to be ~60% greater than those measured in the actual building. Whereas under real clear skies, the scale model illuminances were 100% to 250% greater than those measured in the building (Figure 8 in Cannon 97). Those errors were largely attributed to construction of the scale model and uncertainty in the positioning of the photocell where there were steep illuminance gradients. It should be possible to reproduce the validation described in this thesis using a scale model of the BRE office in one of the sky simulators. This would offer controlled/repeatable sky conditions for scale model evaluation. The measured sky luminance patterns would need be recreated in the sky simulator. The illuminance predictions would be prone to the same source visibility related errors that affected the simulations, and the potentially unreliable predictions would need to be identified. It should be noted that the new sky simulators use an array of discrete light sources to simulate sky luminance patterns. It is possible that configurations with incomplete coverage - i.e. dark gaps between the light sources - may introduce errors related to the discontinuous nature of the sky luminance patterns. It remains to be seen if the accuracy of scale model illuminance predictions under non-overcast sky conditions (real or sky simulator) can rival that demonstrated for lighting simulation in this thesis.

The evaluation of sky models based on predictions for internal illuminance is an area where further research is needed. The work described in Chapter 5 could be expanded in several ways. Ideally, additional sky model types and blends should be assessed in subsequent studies using a larger number of measured skies. The effects of building orientation and prevailing meteorological conditions should also be examined. For future sky model studies, daylight coefficient based approaches are likely to be computationally more efficient than the techniques described in Chapter 5.

Performance evaluation of buildings at the design stage is necessary to achieve the twin goals of energy efficiency and occupant comfort. Analysis of the heating/cooling requirements for a proposed design is routinely carried out using dynamic thermal simulation (DTS). With DTS, the response of the building to time-varying meteorological parameters (and plant operation) is modelled. DTS is an established technique offering a considerable advance over earlier (non-dynamic) approaches based on static U-values. Currently, lighting analysis is - conceptually - far less sophisticated than dynamic thermal simulation. Daylight provision is invariably appraised using the daylight factor approach (Chapter 2). To make a parallel with thermal modelling - lighting modelling is presently at the static (or "U-value") stage of development. The practical implementation of the daylight coefficient approach (Chapter 6) makes it possible to evaluate daylighting of buildings in a way which is, at least conceptually, on a par with dynamic thermal analysis. It is not yet clear how a daylighting evaluation based on hourly (or better) predictions of illuminance for an entire year would proceed, or indeed of what value the analysis would be to a designer/architect. The sheer wealth of information provided by the Radiance daylight coefficient formulation poses problems. Not only are there about four thousand illuminance values to consider for each of the calculation points<sup>2</sup>, there are four components of illuminance. One could argue that there is value in treating at least some of the illuminance components separately.<sup>3</sup>

<sup>2.</sup> For an hourly test reference year.

<sup>3.</sup> It is often the case that direct sun illuminances are preferred less by occupants than equivalent diffuse illuminances, especially when computers are in use.

Evidently, there is considerable work to be done to develop a schema to interpret and apply the results of a daylight coefficient based evaluation. Allied to this is the investigation of the sky models mentioned earlier, since these will be used to generate luminance patterns based on TRYs. The daylight factor approach, whatever its shortcomings, is an established, one might even say entrenched, technique. It is important therefore to critically assess what advantages a daylight coefficient based evaluation may offer. It is hoped that this work will be carried out in the not-too-distant future.

### The Radiance lighting simulation system

Does the Radiance system itself need to be further enhanced? It is the opinion of this author that, with the current release (version 3.1), the Radiance lighting simulation system is effectively 'complete'. This assertion may surprise, and some, might pose the question: "How can the system be 'complete' when 'usability' is still an issue?" But completeness and usability are not the same thing. The absence of a graphical user interface (GUI) for Radiance is often perceived, by newcomers at least, to be an enormous deficiency. Comments such as: "Surely there will be a user-friendly GUI for Radiance sooner or later", are not uncommon. However, not only is this unlikely ever to happen, the desire for one is based on a misconception. The standard (UNIX) version of Radiance has been effectively applied to many different lighting problems precisely because it is based on the UNIX toolbox approach. It is worth noting that, for all of this author's work, standard versions of Radiance were used; not a single line of source code was changed. The originator of the Radiance system (Greg Ward), did not anticipate many of the uses to which it has been put. Rather, he ensured that the toolkit of individual programs could be configured, in almost any combination, to solve highly specific problems efficiently. For this reason, a 'fully-featured' GUI for Radiance is something of a pipe-dream. All of the non-UNIX versions of Radiance offer, to a greater or lesser degree, some access to the core Radiance programs. However, in making a few straightforward tasks easier, they make others virtually impossible.

Potential users need to be aware of what can and, more importantly, cannot be achieved using the non-UNIX versions.

Another usability concern relates to the 'correct' setting of the simulation parameters. To date, none of the 'user-friendly' (that is, non-UNIX) versions have addressed this problem, other than repeating the recommendations that are supplied with the UNIX version. In this respect, the 'user-friendly' versions do not offer any advantage over the UNIX version. It is in this area, more than others perhaps, that 'usability' issues need to be addressed.

Creating a building model in *Radiance* format is not always a straightforward task. Translator programs for a few CAD formats are included with the standard UNIX release, and several others are available. However, it is often the case that not all of the primitives for any one CAD system can be translated to *Radiance* format. For this reason, it is perhaps best to construct a CAD model using only those primitives that do convert. Creation of the model is of course unrelated to the version of *Radiance* being used. The PC version of *Radiance* known as 'Desktop', currently in development, may provide an efficient way to create building models for lighting simulation.<sup>4</sup> This version aims to integrate *Radiance* with the popular CAD package AutoCAD. If Desktop does not however offer an equivalent to the scripting functionality found in UNIX *Radiance*, it is unlikely to supplant the original (UNIX) version.

In conclusion, it is proposed that there is a greater need to apply *Radiance* to existing and emerging lighting problems than there is to tinker with or modify *Radiance* itself.

<sup>4.</sup> The *Radiance Desktop* website: http://radsite.lbl.gov/radiance/desktop.html.

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# A p p e n dix

### Validation data

### A.1 Equations

The relative error (RER) in a prediction is given as:

$$RER = 100 \times \left(\frac{Predicted - Measured}{Measured}\right)$$
(A-1)

The mean bias error (MBE) for N predictions is given as:

$$MBE = 100 \times \left(\frac{1}{N}\right) \sum_{i=1}^{N} \left(\frac{Predicted_i - Measured_i}{Measured_i}\right)$$
(A-2)

The root mean square error (RMSE) for N predictions is given as:

$$RMSE = 100 \times \sqrt{\left(\frac{1}{N}\right) \sum_{i=1}^{N} \left(\frac{Predicted_i - Measured_i}{Measured_i}\right)^2}$$
(A-3)

### A.2 Scanid

The scan ID is given in Table A-1.

#	ID	#	ID	#	ID	#	ID
0	093_92_11h15	1	093_92_11h30	2	093_92_11h45	3	093_92_12h0
4	093_92_12h15	5	093_92_12h30	6	093_92_12h45	7	093_92_13h00
8	093_92_13h15	9	093_92_13h30	10	093_92_13h45	11	093_92_14h00
12	093_92_14h15	13	093_92_14h30	14	093_92_14h45	15	093_92_15h00
16	093_92_15h15	17	093_92_15h30	18	093_92_15h45	19	093_92_16h00
20	093_92_16h15	21	093_92_16h30	22	093_92_16h45	23	093_92_17h00
24	093_92_17h15	25	093_92_17h30	26	093_92_17h45	27	093_92_18h00
28	093_92_18h15	29	102_92_11h15	30	102_92_11h30	31	102_92_11h45
32	102_92_12h00	33	102_92_12h15	34	102_92_12h30	35	102_92_12h45
36	102_92_13h00	37	102_92_13h15	38	102_92_13h30	39	102_92_13h45
40	102_92_14h00	41	102_92_14h15	42	102_92_14h30	43	102_92_14h45
44	102_92_15h00	45	102_92_15h15	46	102_92_15h30	47	102_92_15h45
48	102_92_16h00	49	102_92_16h15	50	102_92_16h30	51	102_92_16h45
52	102_92_17h00	53	102_92_17h15	54	102_92_17h30	55	102_92_17h45
56	102_92_18h00	57	102_92_18h15	58	102_92_18h30	59	121_92_11h15
60	121_92_11h0	61	121_92_11h45	62	121_92_12h00	63	121_92_12h15
64	121_92_12h30	65	121_92_12h45	66	121_92_13h00	67	121_92_13h15
68	121_92_13h30	69	121_92_13h45	70	121_92_14h00	71	121_92_14h15
72	121_92_14h30	73	121_92_14h45	74	121_92_15h00	75	121_92_15h15
76	121_92_15h30	77	121_92_15h45	78	121_92_16h00	79	121_92_16h15
80	121_92_16h30	81	121_92_16h45	82	121_92_17h00	83	121_92_17h15
84	121_92_17h30	85	121_92_17h45	86	121_92_18h00	87	121_92_18h15
88	121_92_18h30	89	121_92_18h45	90	125_92_11h15	91	125_92_11h30
92	125_92_11h45	93	125_92_12h00	94	125_92_12h15	95	125_92_12h30
96	125_92_12h45	97	125_92_13h00	98	125_92_13h15	99	125_92_13h30
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104	125_92_14h45	105	125_92_15h00	106	125_92_15h15	107	125_92_15h30
108	125_92_15h45	109	125_92_16h00	110	125_92_16h15	111	125_92_16h30
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116	125_92_17h45	117	125_92_18h00	118	125_92_18h15	119	125_92_18h30
120	125_92_18h45	121	125_92_19h00	122	125_92_19h15	123	126_92_11h15
124	126_92_11h30	125	126_92_11h45	126	126_92_12h00	127	126_92_12h15
128	126_92_12h30	129	126_92_12h45	130	126_92_13h00	131	126_92_13h15
132	126_92_13h30	133	126_92_13h45	134	126_92_14h00	135	126_92_14h15

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140	126_92_15h30	141	126_92_15h45	142	126_92_16h00	143	126_92_16h15
144	126_92_16h30	145	126_92_16h45	146	126_92_17h00	147	126_92_17h15
148	126_92_17h30	149	126_92_17h45	150	126_92_18h00	151	126_92_18h15
152	126_92_18h30	153	126_92_18h45	154	126_92_19h00	155	126_92_19h15
156	127_92_11h15	157	127_92_11h30	158	127_92_11h45	159	127_92_12h00
160	127_92_12h15	161	127_92_12h30	162	127_92_12h45	163	127_92_13h00
164	127_92_13h15	165	127_92_13h30	166	127_92_13h45	167	127_92_14h00
168	127_92_14h15	169	127_92_14h30	170	127_92_14h45	171	127_92_15h00
172	127_92_15h15	173	127_92_15h30	174	127_92_15h45	175	127_92_16h00
176	127_92_16h15	177	127_92_16h30	178	127_92_16h45	179	127_92_17h00
180	127_92_17h15	181	127_92_17h30	182	127_92_17h45	183	127_92_18h00
184	127_92_18h15	185	127_92_18h30	186	127_92_18h45	187	127_92_19h00
188	127_92_19h15	189	128_92_11h15	190	128_92_11h30	191	128_92_11h45
192	128_92_12h00	193	128_92_12h15	194	128_92_12h30	195	128_92_12h45
196	128_92_13h00	197	128_92_13h15	198	128_92_13h30	199	128_92_13h45
200	128_92_14h00	201	128_92_14h15	202	128_92_14h30	203	128_92_14h45
204	128_92_15h00	205	128_92_15h15	206	128_92_15h30	207	128_92_15h45
208	128_92_16h00	209	128_92_16h15	210	128_92_16h30	211	128_92_16h45
212	128_92_17h00	213	128_92_17h15	214	128_92_17h30	215	128_92_17h45
216	128_92_18h00	217	128_92_18h15	218	128_92_18h30	219	128_92_18h45
220	128_92_19h00	221	129_92_11h15	222	129_92_11h30	223	129_92_11h45
224	129_92_12h00	225	129_92_12h15	226	129_92_12h30	227	129_92_12h45
228	129_92_13h00	229	129_92_13h15	230	129_92_13h30	231	129_92_13h45
232	129_92_14h00	233	129_92_14h15	234	129_92_14h30	235	129_92_14h45
236	129_92_15h00	237	129_92_15h15	238	129_92_15h30	239	129_92_15h45
240	129_92_16h00	241	129_92_16h15	242	129_92_16h30	243	129_92_16h45
244	129_92_17h00	245	129_92_17h15	246	129_92_17h30	247	129_92_17h45
248	129_92_18h00	249	129_92_18h15	250	129_92_18h30	251	129_92_18h45
252	129_92_19h00	253	129_92_19h15	254	130_92_11h15	255	130_92_11h30
256	130_92_11h45	257	130_92_12h00	258	130_92_12h15	259	130_92_12h30
260	130_92_12h45	261	130_92_13h00	262	130_92_13h15	263	130_92_13h30
264	130_92_13h45	265	130_92_14h00	266	130_92_14h15	267	130_92_14h30
268	130_92_14h45	269	130_92_15h00	270	130_92_15h15	271	130_92_15h30

#	ID	#	ID	#	ID	#	ID
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276	130_92_16h45	277	130_92_17h00	278	130_92_17h15	279	130_92_17h30
280	130_92_17h45	281	130_92_18h00	282	130_92_18h15	283	130_92_18h30
284	130_92_18h45	285	130_92_19h00	286	131_92_11h15	287	131_92_11h30
288	131_92_11h45	289	131_92_12h00	290	131_92_12h15	291	131_92_12h30
292	131_92_12h45	293	131_92_13h00	294	131_92_13h15	295	131_92_13h30
296	131_92_13h45	297	131_92_14h00	298	131_92_14h15	299	131_92_14h30
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308	131_92_16h45	309	131_92_17h00	310	131_92_17h15	311	131_92_17h30
312	131_92_17h45	313	131_92_18h00	314	131_92_18h15	315	131_92_18h30
316	131_92_18h45	317	131_92_19h00	318	131_92_19h15	319	137_92_11h15
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328	137_92_13h30	329	137_92_13h45	330	137_92_14h00	331	137_92_14h15
332	137_92_14h30	333	137_92_14h45	334	137_92_15h00	335	137_92_15h15
336	137_92_15h30	337	137_92_15h45	338	137_92_16h00	339	137_92_16h15
340	137_92_16h30	341	137_92_16h45	342	137_92_17h00	343	137_92_17h15
344	137_92_17h30	345	137_92_17h45	346	137_92_18h00	347	137_92_18h15
348	137_92_18h30	349	137_92_18h45	350	137_92_19h00	351	137_92_19h15
352	137_92_19h30	353	175_92_11h30	354	175_92_11h45	355	175_92_12h00
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360	175_92_13h15	361	175_92_13h30	362	175_92_13h45	363	175_92_14h00
364	175_92_14h15	365	175_92_14h30	366	175_92_14h45	367	175_92_15h00
368	175_92_15h15	369	175_92_15h45	370	175_92_16h00	371	175_92_16h15
372	175_92_16h30	373	175_92_16h45	374	175_92_17h00	375	175_92_17h15
376	175_92_17h30	377	175_92_17h45	378	175_92_18h00	379	175_92_18h15
380	175_92_18h30	381	175_92_18h45	382	175_92_19h00	383	175_92_19h15
384	175_92_19h30	385	175_92_19h45	386	175_92_20h00	387	182_92_11h30
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392	182_92_12h45	393	182_92_13h00	394	182_92_13h15	395	182_92_13h30
396	182_92_13h45	397	182_92_14h00	398	182_92_14h15	399	182_92_14h30
400	182_92_14h45	401	182_92_15h00	402	182_92_15h15	403	182_92_15h30
404	182_92_15h45	405	182_92_16h00	406	182_92_16h15	407	182_92_16h30

#	ID	#	ID	#	ID	#	ID
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412	182_92_17h45	413	182_92_18h00	414	182_92_18h15	415	182_92_18h30
416	182_92_18h45	417	182_92_19h00	418	182_92_19h15	419	182_92_19h30
420	182_92_19h45	421	183_92_11h30	422	183_92_11h45	423	183_92_12h00
424	183_92_12h15	425	183_92_12h30	426	183_92_12h45	427	183_92_13h00
428	183_92_13h15	429	183_92_13h30	430	183_92_13h45	431	183_92_14h00
432	183_92_14h15	433	183_92_14h30	434	183_92_14h45	435	183_92_15h00
436	183_92_15h15	437	183_92_15h30	438	183_92_15h45	439	183_92_16h00
440	183_92_16h15	441	183_92_16h30	442	183_92_16h45	443	183_92_17h00
444	183_92_17h15	445	183_92_17h30	446	183_92_17h45	447	183_92_18h00
448	183_92_18h15	449	183_92_18h30	450	183_92_18h45	451	183_92_19h00
452	188_92_11h30	453	188_92_11h45	454	188_92_12h00	455	188_92_12h15
456	188_92_12h30	457	188_92_12h45	458	188_92_13h00	459	188_92_13h15
460	188_92_13h30	461	188_92_13h45	462	188_92_14h00	463	188_92_14h15
464	188_92_14h30	465	188_92_14h45	466	188_92_15h00	467	188_92_15h15
468	188_92_15h30	469	188_92_15h45	470	188_92_16h00	471	188_92_16h15
472	188_92_16h30	473	188_92_16h45	474	188_92_17h00	475	188_92_17h15
476	188_92_17h30	477	188_92_17h45	478	188_92_18h00	479	188_92_18h15
480	188_92_18h30	481	188_92_18h45	482	188_92_19h00	483	188_92_19h15
484	188_92_19h30	485	188_92_19h45	486	188_92_20h00	487	196_92_11h30
488	196_92_11h45	489	196_92_12h00	490	196_92_12h15	491	196_92_14h30
492	196_92_14h45	493	196_92_15h00	494	196_92_15h15	495	196_92_15h30
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504	196_92_17h45	505	196_92_18h30	506	196_92_18h45	507	196_92_19h00
508	196_92_19h15	509	196_92_19h30	510	196_92_19h45	511	265_92_11h00
512	265_92_11h15	513	265_92_11h30	514	265_92_11h45	515	265_92_12h00
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520	265_92_13h15	521	265_92_13h30	522	265_92_13h45	523	265_92_14h00
524	265_92_14h15	525	265_92_14h30	526	265_92_14h45	527	265_92_15h00
528	265_92_15h15	529	265_92_15h30	530	265_92_15h45	531	265_92_16h00
532	265_92_16h15	533	265_92_16h30	534	265_92_16h45	535	265_92_17h00
536	265_92_17h15	537	265_92_17h30	538	266_92_11h00	539	266_92_11h15
540	266_92_11h30	541	266_92_11h45	542	266_92_12h00	543	266_92_12h15

#	ID	#	ID	#	ID	#	ID
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548	266_92_13h45	549	266_92_14h00	550	266_92_14h15	551	266_92_14h30
552	266_92_14h45	553	266_92_15h00	554	266_92_15h15	555	266_92_15h30
556	266_92_15h45	557	266_92_16h00	558	266_92_16h15	559	269_92_11h00
560	269_92_11h15	561	269_92_11h30	562	269_92_11h45	563	269_92_12h00
564	269_92_12h15	565	269_92_12h30	566	269_92_12h45	567	269_92_13h00
568	269_92_13h15	569	269_92_13h30	570	269_92_13h45	571	269_92_14h00
572	269_92_14h15	573	269_92_14h30	574	269_92_14h45	575	269_92_15h00
576	269_92_15h15	577	269_92_15h30	578	269_92_15h45	579	269_92_16h00
580	269_92_16h15	581	269_92_16h30	582	269_92_16h45	583	269_92_17h00
584	273_92_10h45	585	273_92_11h00	586	273_92_11h15	587	273_92_11h30
588	273_92_11h45	589	273_92_12h00	590	273_92_12h15	591	273_92_12h30
592	273_92_12h45	593	273_92_13h00	594	273_92_13h15	595	273_92_13h30
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600	273_92_14h45	601	273_92_15h00	602	273_92_15h15	603	273_92_15h30
604	273_92_15h45	605	273_92_16h00	606	273_92_16h15	607	273_92_16h30
608	273_92_16h45	609	273_92_17h00	610	273_92_17h15	611	273_92_17h30
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616	311_92_11h30	617	311_92_11h45	618	311_92_12h00	619	311_92_12h15
620	311_92_12h30	621	311_92_12h45	622	311_92_13h00	623	311_92_13h15
624	311_92_13h30	625	311_92_13h45	626	311_92_14h00	627	311_92_14h15
628	311_92_14h30	629	311_92_14h45	630	311_92_15h00	631	311_92_15h15
632	311_92_15h30	633	311_92_15h45	634	311_92_16h00	635	311_92_16h15
636	318_92_10h30	637	318_92_10h45	638	318_92_11h00	639	318_92_11h15
640	318_92_11h30	641	318_92_11h45	642	318_92_12h00	643	318_92_12h15
644	318_92_12h30	645	318_92_12h45	646	318_92_13h00	647	318_92_13h15
648	318_92_13h30	649	318_92_13h45	650	318_92_14h00	651	318_92_14h15
652	318_92_14h30	653	318_92_14h45	654	318_92_15h00	655	318_92_15h15
656	318_92_15h30	657	318_92_15h45	658	318_92_16h00	659	326_92_10h30
660	326_92_10h45	661	326_92_11h00	662	326_92_11h15	663	326_92_11h30
664	326_92_11h45	665	326_92_12h00	666	326_92_12h15	667	326_92_12h30
668	326_92_12h45	669	326_92_13h00	670	326_92_13h15	671	326_92_13h30
672	326_92_13h45	673	326_92_14h00	674	326_92_14h15	675	326_92_14h30

Table A-1. Scan ID

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684	343_92_12h15	685	343_92_12h30	686	343_92_12h45	687	343_92_13h00
688	343_92_13h15	689	343_92_13h30	690	343_92_13h45	691	343_92_14h00
692	343_92_14h15	693	343_92_14h30	694	343_92_14h45	695	343_92_15h00
696	343_92_15h15	697	344_92_10h30	698	344_92_11h45	699	344_92_12h00
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704	344_92_13h15	705	344_92_13h30	706	344_92_13h45	707	344_92_14h00
708	344_92_14h15	709	344_92_14h30	710	344_92_14h45	711	344_92_15h00
712	363_92_10h45	713	363_92_11h00	714	363_92_11h15	715	363_92_11h30
716	363_92_11h45	717	363_92_12h00	718	363_92_12h15	719	363_92_12h30
720	363_92_12h45	721	363_92_13h00	722	363_92_13h15	723	363_92_13h30
724	363_92_13h45	725	363_92_14h00	726	363_92_14h15	727	363_92_14h30
728	363_92_14h45	729	363_92_15h00	730	363_92_15h15	731	363_92_15h30
732	363_92_15h45	733	364_92_10h45	734	364_92_11h00	735	364_92_11h15
736	364_92_11h30	737	364_92_11h45	738	364_92_12h00	739	364_92_12h15
740	364_92_12h30	741	364_92_12h45	742	364_92_13h00	743	364_92_13h15
744	364_92_13h30	745	364_92_13h45	746	364_92_14h00	747	364_92_14h15
748	364_92_14h30	749	364_92_14h45	750	364_92_15h00	751	364_92_15h15
752	364_92_15h30	753	364_92_15h45				

Table A-1. Scan ID

### A.3 Composition of the validation array

Below are row index values for all the predicted quantities, Table A-2.

Index	178-188		189-199		200-210		211-221	
Param	glb.horiz. vertical N,E,S& W	single glazed office illuminan ce	glb.horiz. vertical N,E,S& W	single glazed office illuminan ce	glb.horiz. vertical N,E,S&W	single glazed office illuminanc e	glb.horiz. vertical N,E,S&W	single glazed office illuminanc e
Notes	Scanner s	ky	Perez sky	model	Intermediate	e sky model	Overcast (w model	ith sun) sky

Index	222-232		233-243		244-254		255-260 <sup>a</sup>
Param	glb.horiz. vertical N,E,S& W	single glazed office illuminan ce	glb.horiz. vertical N,E,S& W	single glazed office illuminan ce	glb.horiz. vertical N,E,S&W	single glazed office illuminanc e	Fraction of 6° circumsolar disc (CD) visible at p_cell location
Notes	Clear sky	model	Direct sun componen	Direct sun component only		omponent er sky	-

Index	261-284	285-386	387-392	393-398
Param	single glazed office illuminance derived from daylight coefficients - variants 1 - 4	Fraction of circumsolar disc (CD) visible at p_cell location	single glazed office illuminance	single glazed office illuminance
Notes	-	For CD angles: 0.2°,0.4°, 0.6°, 0.8°, 1.0°, 1.2°, 1.4°, 1.6°, 1.8°, 2°, 4°, 6°, 8°, 10°, 12°, 14°, 16°.	Scanner sky - hi-res ambient calc.	Scanner sky - lo-res ambient calc.

Index	399-404
Param	single glazed office illuminance
Notes	Scanner sky - lo-res ambient calc. with points reveresed

### Table A-2. Predicted quanities by vector index

a. Although repeated at a later stage (see indices 285-386), this entry was kept to maintain backwards compatability with existing analysis programs.

The composition of the measured quantities (and identifiers) was given in Table 3-12. The file size of the validation array was - in its final updated form - 1.22Mb. This is a relatively small amount of data and the same approach could have been used un-modified on much larger data sets. For example, a full year's data at 15 minute timestep contains (approximately) 17,500 (daylight) entries. For this number of daylight entries, the validation array would have dimensions 17500 x 404 and file size (approximately) 28Mb. Which is small enough to be loaded directly into physical memory and explored interactively.

# Appendix B

### Published work

### **B.1** List of related publications

Mardaljevic, J. *The Radiance lighting simulation system* Building Performance (BEPAC) Issue 2, 6-17 (1999)

Mardaljevic, J. Notes on (1) Daylighting Applications, (2) Advanced Daylighting Calculations and (3) Validation Studies in *Rendering with Radiance: A Practical Tool for Global Illumination* ACM SIGGRAPH 98 Course Notes CD-ROM (Orlando, 1998)

Mardaljevic, J. Daylight simulation - In Rendering with Radiance: The Art and Science of Lighting Visualization (G. Ward Larson & R. Shakespeare) San Francisco: Morgan Kaufmann (1998)

Mardaljevic, J. and Lomas, K. A Simulation Based Method to Evaluate the Probability of Daylight Glare Over Long Time Periods and its Application National Lighting Conference, Lancaster, UK (1998)

Mardaljevic, J. Validation of lighting simulation program: a study using measured sky brightness distributions Lux Europa 97 proc. 555-569 (Amsterdam, 1997)

Mardaljevic, J. Validation of a lighting simulation program under real sky conditions Lighting Res. Technol. 27(4) 181-188 (1995)

Mardaljevic, J. Daylighting models in *Realistic Input for Realistic Images* ACM SIGGRAPH 95 Course Notes CD-ROM (Los Angeles, 1995)

Mardaljevic, J. and Lomas, K. *Creating the right image* Building Services The CIBSE Journal 15 (3) 28-30 (1993)

## A p p e n d ix

### The Radiance system

### **BEPAC** Article

This article originally appeared in **Building Performance**, Issue 2, winter 1998/9 (**BEPAC**). It is reproduced here in its original form with permission. Note that the numbering scheme does not follow that for the rest of the thesis. Sections and figures in this chapter are not referenced elsewhere in this thesis.



### The Radiance lighting simulation system

The Radiance system is a professional toolkit for lighting simulation. It can be used to model daylight and electric lighting in almost any environment and to almost any level of complexity, and it is used worldwide by both researchers and practitioners to solve a huge range of lighting problems. Radiance has been rigorously validated and proven to be highly accurate. Furthermore, the software (UNIX version) is freely available. Sounds (almost) too good to be true. Should all lighting designers be using Radiance? If not all, then who and why? In this major article, *John Mardaljevic*<sup>1</sup> considers these questions and addresses some of the myths and misunderstandings about the Radiance system.

Look carefully at the images in the centre of these pages. One is a photograph of the Computer Labs at MIT, the other a Radiance rendering. But which is which? Most people need at least a second glance to distinguish between the rendering and the photograph. (If you aren't sure, the answer is at the end of the article.) But even if you *can* tell the difference the rendering is impressive.

There are three reasons why this Radiance rendering looks like the real thing. Firstly, the model geometry seems to be a very full and exact representation of the real scene. Secondly, the luminaire photometry and materials specification were closely based on actual measured properties. Lastly, the simulation software has predicted the field of view luminance using a physically accurate model of light transport. This is what Radiance does.

### What is Radiance?

Radiance (UNIX version) consists of over 50 tools (i.e. programs), many of which cannot be found anywhere else. These were developed over the course of 10 years, with funding from the US Department of Energy and the Swiss Federal government, primarily by Greg Ward Larson. They do everything from object modelling to point calculation, rendering, image processing, and display. The system was originally developed as a

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research tool to explore advanced rendering techniques for lighting design. It has evolved

simulate light behaviour in complicated environments, which means two things:



### Real or rendering ? ...

over the years into a highly sophisticated lighting visualization system, which is both challenging and rewarding to learn. Radiance is unique in its ability to accurately correct numerical results, and renderings that are indistinguishable from photographs. There is simply no other physically based rendering system, free or otherwise, with as much power and flexibility as Radiance. There are a few core Radiance programs that everyone will use, several that most will use, and many more that only a few will use. The most advanced users may even combine programs to create new functionality specific to their needs. Most users fall into one of the following categories:

• Computer graphics enthusiasts

People who want the most realistic rendering software available and/or are working with a relatively small budget. *Researchers* 

- Research students and university staff who want source-level access to advanced techniques in rendering and global illumination, or a basis for comparison to their own rendering algorithms.
- Designers

Architects, illumination engineers, and other designers who need accurate tools for predicting light levels and visual appearance in novel situations and who have the time and energy to invest in a sophisticated rendering system.

• Students

Computer graphics and design students using Radiance as part of their coursework in rendering or CAD modelling.

For the majority of BEPAC members, the categories of interest will be *Designers* and possibly *Industry professionals*.Note the caveat: "... and who have the time and energy to invest in a sophisticated rendering system."

Newcomers to Radiance have found the complexities of the system rather daunting. Although the original (UNIX) version of the software is free, the system has to be learnt, and any small to medium-size practice needs to consider the cost implications of this. It is not easy for a practice to judge the cost effectiveness of a new and complex simulation tool. A manager may decide that, for todays work, the practice cannot afford to make the learning investment in this particular tool. In the future however, clients are increasingly likely to expect high-guality visualisation and daylight prediction as partand-parcel of a comprehensive design analysis. More and more practices will feel the need to develop this expertise in-house so that they can offer a complete environmental or specialist lighting design evaluation

This article will try to give an overview of the Radiance system and its application, without resorting too much to technical



### .... rendering or real?

### Industry professionals

Professionals working in the arts, entertainment, and litigation who need rendering tools with the latest in local and global illumination methods to obtain results of the highest quality and veracity. details. It will also attempt to address the "usability" issues — real and imagined — associated with this simulation package. To this end, testimonies from new and experienced users working in commercial practices are included also.

#### What makes Radiance unique?

What claim can a simulation package have for uniqueness when, on close inspection, the majority seem to be more similar that different? Radiance has, arguably, more claim than most for the following reasons:

- 1 Its singular flexibility. This is largely because the system is based on the UNIX toolbox model (see page 13).
- 2 The algorithms used to predict the transport of light are not found in any other lighting simulation system or package.
- 3 The development history of the software. In the nine years since the first release, Radiance has benefited enormously from user feedback: most of the enhancements made to the system were the outcome of real or perceived user requirements.

### When and for what should Radiance be used?

The placing and size of windows on a building facade greatly affects internal conditions. At the design stage, the provision for natural lighting is invariably assessed in terms of the predicted daylight factor (DF). The CIBSE Windows design guide, or a simple PC program such as DAYLIGHT, will provide a reasonably accurate estimate for the average DF in simple rectangular-shaped spaces. Both the design guide and the DAYLIGHT program are intended for non-expert users, be they architects or engineers. So the application of Radiance for this task could be perceived as overkill.

Is there any advantage to using Radiance for simple DF calculations? There might be, provided that the user has sufficient knowledge of the system. For example, creating the geometry for a simple space can take less than 15 minutes, and the simulation time could be anything from a minute or two to several hours depending on the accuracy required. But note that even a quick simulation will give reasonably accurate predictions. Furthermore, it is possible to carry out fully automated parametric studies using custom scripts: almost any material or object property can be manipulated in a script. For example, the DF distribution could be calculated as a function of the proximity of a nearby obstruction using a simple script.

For complex spaces, the design guide and simple programs may give estimates that are wide of the mark. Complex here means a space that has one or more of the following attributes:

- non-rectangular shape;
- non-standard glazing, eg diffusing material;
- non-vertical and/or irregular glazing arrangement;
- internal/external obstructions and/or light redirecting devices, eg light shelf;
  spaces adjacent to light wells or atria.

For any of these, a lighting simulation (such as Radiance) or a scale model study may be required. The designer may, for a daylight factor evaluation, see little to choose between a scale model and a Radiance simulation. If the requirements go beyond daylight factors to include visualisation, then simulation may become the preferred option. This is largely because of the relative ease with which buildings complexity can be introduced (at any scale), especially if the building description already exists in a suitable 3D CAD form.

With physically-based lighting simulation, visualisation takes on a new meaning: the Radiance image file is a pixel map of spectral (i.e. with colour) luminance (or illuminance) values in a high-dynamicrange, floating point data format (see below). The image on the computer screen is just one way of "looking" at the data, albeit the most convenient and intuitive way. The information contained in the image (and scene) files could also be used, say, to locate glare sources. In place of a luminance map (i.e."normal image"), a rendering could show the illuminance, as lux or davlight factor, on all the surfaces in the field of view, (a very useful technique to assess the illumination for art galleries and exhibition spaces). It is also possible to overlay illuminance (as contour lines) over a normal image.

The sections that follow show how Radiance can be used to solve a wide range of lighting design problems. Ranging from the possibly mundane (DF calculation) to the positively offbeat (tallow candle lighting), not to mention outer space, these images are testament to the power and flexibility of the Radiance system.

### Radiance renderings: information content and display

The pixels of a Radiance rendering are real numbers corresponding to the physical quantity of radiance (recorded as watts/ steradian/m<sup>2</sup>). The visible part of radiance is luminance; the two quantities are interchangeable using a conversion factor. Each Radiance rendering also has a header that contains information on the generating commands, view options, exposure adjustments etc.

It is important to note that, while Radiance can accurately predict real-world luminances, all display devices without exception - VDUs, projectors and so on have a very limited range of luminance output. Otherwise, we could get a suntan from a display of a rendering of the sun! To overcome this limitation, the "exposure" of the finished rendering has to be adjusted for display. For example, say that the rendering was for a room with a window to a bright daylit outdoor scene. The exposure (of the finished rendering) could be adjusted to reveal either low-luminance internal detail at the expense of "burning-out" the view through the window, or show the view outside but now with a darkened room where all shadow detail is hidden. Alternatively, some compromise exposure could be sought. (In principle, this approach is identical to what a photographer must do to record the same scene: expose the limited-range film for either the dark inside or the bright outside.)

This was the situation until the advent of Radiance version 3.1; the new release includes a powerful image conditioning program called pcond. The role of pcond is to compress the dynamic range of the rendering such that both dark and bright regions are visible in the displayed image. Pcond uses a variety of mathematical techniques to determine an appropriate exposure and (optionally) simulate loss of acuity and veiling glare, loss of focus, and loss of colour sensitivity. Renderings conditioned with pcond can result in displayed images that preserve the visibility of high dynamic range scenes, across the luminance range. In other words, the visual response evoked is close to that which would be experienced for an equivalent real-world scene.

For this article however, the images chosen were those that would reproduce (reasonably) well in monochrome. The original images were converted to grayscale and, for most, the contrast was adjusted to compensate for the loss of colour information. Links to the websites that have the original colour images are given where available.

### **Example applications I: workaday**

### Daylight factor prediction

Daylight factors were calculated at the work plane height across floor-plans for levels 1 and 3 of the atrium model shown in **Figure 1**, using a simplified version of the atrium model to reduce simulation time. The office cells containing the floor plans were modelled in detail, as was the atrium roof. But the rest of the structure was modelled as planar surfaces with bulk reflective properties. The predicted DFs are shown in **Figure 2**.

### Visualisation - Interiors

The office model shown in Figure 3 was used to assess the visual impact of external bronze grilles. The realistic carpet pattern was achieved using a pair of "procedural functions" that modified the carpet material's reflectance. One function produced the regular carpet weave pattern; the other added random larger-scale patches of slight darkening to mimic uneven brushing/wear of the carpet tufts. A similar technique was used to create the water pools for the atrium model (Figure 1): a procedural function was used to perturb the surface normal across the single flat sheet of glass material that served as the water surface. Thoughtful application of these and similar functions can produce very realistic looking materials, and also add a great deal of "visual interest" for very little modelling effort.

The new Engineering Building at De Montfort University Leicester has already been noted for its uses of a passive ventilation strategy. The building also contains some innovative daylighting features, notably light shelves in the computer rooms. These are intended to reduce glare and to redistribute natural light more evenly across the space. A rendering of the view along the length of the computer room is shown in **Figure 4**. The wall to the right shows the light shelf at eye level covering most of the length of the wall. This model was used to predict the daylight factor distribution for the space.

#### Visualisation - exteriors

Radiance has been used to assess the lighting schemes for several huge building projects. The two examples here are both in Hong-Kong. The first is a proposed lighting scheme for the entrance to the passenger lobby at Cathay Pacific's Headquarters, **Figure 5**. The other example is a rendering of the Tsing Ma suspension bridge, **Figure 6**. This model had thousands of accurately depicted light sources and required considerable computer power to render. For more examples of exterior lighting, see http://appia.tvc.indiana.edu/~tvc/gallery.html

### Shading analysis

The movement of shadow patterns over a site can be assessed from a sequence of



Figure 1: Rendering of an atrium designed by Peter Foggo Associates, with water and (below)

Figure 2: Predicted daylight factors in the Foggo atrium



Atrium



Figure 3: A model used to assess the visual impact of external bronze grills — note the weave in the carpet



Figure 4: A model of the computer room in the Queen's Building at De Montfort University used to predict DFs and assess the effect of light shelves



Figure 5: The passenger lobby entrance at Cathay Pacific HQ, Hong Kong



Figure 6: Tsing Ma suspension bridge, Hong Kong — with thousands of separate light sources and water

image pairs like **Figures 7** and **8**, created by Ove Arup & Partners. One of the images (**Figure 7**) is generated for a high viewpoint above the site, the other (**Figure 8**) shows the view of the site from the sun position.



Figure 7





### Glare analysis

The *findglare* program is used to locate potential glare sources in the field of view. In each of the three renderings shown in **Figure 9**, regions of high luminance have been identified and marked with an ellipse. The point luminance across several room surfaces has been marked also.

### Rights to light

Here Radiance was used to determine the minimum separation between an existing building and a proposed cold store, **Figure 10**. The criterion used was based on the percentage of the working plane predicted to have a sky factor of less than 0.2%. In terms of lighting, this is a trivial problem to solve:





As-is light shelf

**Conventional light shelf** 



Figure 9: Glare analysis for three design variants

inter-reflection is not an issue. Nevertheless, Radiance was an ideal tool for this job because the scene geometry - specifically the position of the proposed building - could be manipulated using scripts, making it a simple matter to automate a parametric study.

#### Student architecture

Architecture students at the ETH in Zurich regularly use Radiance to render their coursework designs; **Figure 11** is an example. The students have access to a tailored solution in which designs, created using Microstation CAD, are converted to Radiance format via a VRML intermediary. The complexities of Radiance are largely hidden from the users, and they are able to create renderings which although not always "perfect" are nonetheless a major improvement over the best that can be had using 3-D Studio. For more examples, see the CAAD website: http://caad.arch.ethz.ch/teaching/ radgallery/

### **Example applications II: exotic**

### Historical building simulation

Radiance has been used to re-create the lighting conditions in historical theatres as it was actually experienced by performers and the audience, as shown in **Figures 12** and **13**. The model light sources were based on photometric measurements of an actual tallow candle with a period-type rag wick. The information that resulted from this form of building simulation gave valuable insight into aspects of period performance since this would have been influenced by the quantity and distribution of the lighting.

#### Space shuttle

The Graphics Research and Analysis Facility (GRAF) is an integral part of the Flight Crew Support Division (FCSD) at NASA. GRAF uses high performance computer graphics workstations interfacing with various graphics software modules to address human engineering issues in spacecraft design and analysis. One of these is Radiance, which GRAF uses to produce realistic images of complex environments. Measured data is used to develop models of shuttle and station artificial lights. Natural lighting, such as sun and earth shine, can also be incorporated into the lighting analyses. By incorporating the measured reflectances for each material into the lighting model, an accurate calculation of the amount of light entering a camera can be made. Then, using this calculated light distribution with the



Figure 10



Figure 11



Figure 12: Simulation of tallow-candle lighting in a historical theatre

and (below)

Figure 13: A contemporary engraving of the same theatre



GRAF's model of the shuttle cameras, camera images can be simulated accurately. Figures 14 and 15 show some of the results. You can visit GRAF at http://www-sa.jsc.nasa.gov/FCSD/ CrewStationBranch/GRAF/graf4.html

### Theatre lighting - modern

The Theatre Computer Visualization Centre at Indiana University have developed an interface that integrates the positioning and control of virtual theatre lighting systems with Radiance. With this, they can explore complex stage lighting scenarios using visualisation, as Figures 16 and 17 show, and so refine the lighting design for a production in advance of any actual rehearsals. The stage lighting photometry can be very accurately described in the Radiance models. Effects such as beam focus, colour filters, colour changes due to lamp dimming, shutters, template patterns etc. can all be realistically portrayed. For the 'rock-n-roll' image (Figure 18 (next page) — actually a still from an animation), stage fog was modelled using the Radiance mist material. For more images, visit http:// appia.tcvc.indiana.edu/~tcvc/.

### Emergency lighting - US Navy cruiser

The effectiveness of an emergency lighting system for a US Navy cruiser was assessed using visualisation - stills and animation. **Figures 19** and **20** (next page) show the view under normal and emergency lighting.

### Example applications III: research

Here, research is taken to mean any exploratory work using Radiance that is not addressing a specific lighting problem. Taking a wider meaning, many of the previously described applications would rightly be counted as research also.

### Daylighting research at the Institute of Energy and Sustainable Development, DMU

A great deal of Radiance-based daylighting research has been carried out at the IESD since Radiance was first used here in 1991. Firstly, Radiance illuminance predictions were rigorously validated using measurements taken in full-size office spaces under real sky conditions. For this work, Radiance used sky luminance patterns based directly on measured sky brightness distributions. The results from the validation proved that Radiance can predict internal illuminance to a high degree of accuracy for a large sample of skies which cover a wide range of naturally occurring sky conditions. As far as the author is aware, this validation



Figures 14: Simulation of an image from a camera on the space shuttle

and (below)

Figure 15: Another simulated shuttle photograph





Figure 16: Exploring a complex lighting scheme for a theatre production

and (below) Figure 17: A simulated scene




Figure 18: A still from an animation, with Radiance mist



Figure 19: Normal lighting in a USN warship and (below) Figure 20: Emergency lighting





Figure 21: Renderings of a pine forest at four magnifications

study is the only one to date that has made use of measured sky brightness distributions and simultaneous internal illuminance measurements.

Next, Radiance was used to compare the absolute and relative performance of sky models. The validation exercise was repeated using sky models to generate the sky luminance distribution. This study compared the sensitivity of internal illuminance predictions to sky model type. Four sky models and two sky model composites were examined.

Guided by the results from these projects, the next task was to develop a methodology for predicting the annual daylighting potential of a space. This takes into account the varying internal illumination from sky and sun throughout the year. An explicit evaluation of the daylighting potential provided by a design would account for the internal illuminances produced by all the skies measured at or near the intended site over a monitoring period of a year or more.

If measurements were obtained as hourly values, the data for a normal working year would contain approximately 3,500 skies. With the latest generation workstations, modelling several thousand cases is a tractable, though still rather time consuming task. A more efficient solution is to use the daylight coefficient approach. This technique eliminates the need to perform the most computationallydemanding part of the simulation — the inter-reflection calculation — for every individual case. The davlight coefficient approach requires that the sky be broken into many patches, and the internal illuminance at a point from every patch of unit sky brightness be individually determined and cached. (The daylight coefficient approach was described in more detail in Building Performance issue 1, pp 21-2) . Thus, an internal illuminance prediction resulting from any sky brightness distribution can be obtained by appropriate scaling of the contribution from each patch.

A formulation for Radiance was devised, implemented and validated. The accuracy of the daylight coefficient derived illuminance predictions were found to be comparable to those for the individually modelled skies. This research formed the basis for the Dynamic Lighting System (DLS), a Radiancebased system to predict time varying illuminances. The DLS incorporates several artificial lighting control models so that luminaires are responsive to the varying daylight level predictions. The program calculates annual totals for lighting demand and energy use. Following initial testing, usability issues are being addressed and the system will be released early in 1999. This software will be made freely available. For news and updates of the DLS, visit IESD's Web site http://www.iesd.dmu.ac.uk/dls/ and for information on daylighting research at the Institute visit the author's homepage http:// www.iesd.dmu.ac.uk/~jm/.

# Daylight Europe

The overall aim of the Daylight-Europe (DL-E) project is to generate daylighting design guidelines for architects and engineers The basic method was to evaluate and exemplify the daylighting behaviour of 60 European buildings which typify the range of design types and climatic contexts. To this end, the techniques of monitoring, simulation and post occupancy evaluation were employed. The role of simulation was to ensure, firstly, that daylight utilisation was not being achieved at the expense of other performance parameters (such as thermal comfort or heating energy consumption) and, secondly, to determine the effects of design and climate parameter variations in order to generalise the results from the case studies. Radiance was used for all the lighting simulation work; Figure 9 (page 10) is an example.

#### **Computer graphics**

Radiance is being used by graphics researchers as a testbed to try out other algorithms and parallel computing implementations, and also to investigate the perceptual equivalence of a rendered scene to a real scene.

#### **Creating a Radiance model**

How one creates a Radiance scene description for a design is largely a matter of choice. One of the basic precepts of Radiance is that scene geometry can be taken from almost any source. It is hardly surprising therefore that there are a wide range of CAD to Radiance converters available, including:

- archicad2rad: converts from ArchiCAD RIB exports to Radiance (for Macintosh)
- arch2rad: converts from Architrion Text Format to Radiance
- *arris2rad*: converts ARRIS Integra files to Radiance
- *dem2rad*:converts from Digital Elevation Maps to gensurf input
- ies2rad: converts from the IES standard

luminaire file format to Radiance *mgf2rad*:converts from the Materials and

- Geometry Format to Radiance • *nff2rad*: converts from Eric Haines's
- Neutral File Format to Radiance *obj2rad*: converts from Wavefront's .obj format to Radiance
- radout: converts ACAD R12 to Radiance (ADS-C add-on utility)
- *rad2mgf*: converts from Radiance to the Materials and Geometry Format
- stratastudio: converts Macintosh Strata-Studio files to Radiance
- *thf2rad*: converts from the GDS Things File format to Radiance
- *tmesh2rad*: converts a basic trianglemesh to Radiance
- torad: converts from DXF to Radiance (AutoLISP routine must be loaded from within AutoCAD)

What is perhaps surprising is that a number of users opt to create very complex models using only the scripting capabilities built into Radiance. The atrium model shown in **Figure 1** contains over 50,000 polygons and was generated by the author entirely without the aid of CAD. The majority of practitioners however seem to prefer a pragmatic approach — a mixture of CAD and Radiance scripting.

Scripting is required to make use of a very powerful Radiance technique for accommodating massive scene complexity within limited computer memory resources. In this, the octree of a compound object comprised of any number of surfaces can be "instanced" (that is, repeated) almost any number of times. Multiple occurrences of the same octree in a given scene will use only as much memory as that required for a single instance, plus a tiny amount to store the associated transformations for each instance's location. This technique is often used for furniture objects and the like - for example, to generate hundreds of seats for a theatre model. Instancing can also be applied hierarchically, where multiple instances of a single octree are used to create a second, enclosing octree. The enclosing octree can then be instanced further, and so on.

It is possible to model scenes with a virtually unlimited number of surfaces using this method. **Figure 21** shows renderings of a pine-tree forest model at four magnifications. The forest model contains 73 instances of a pine tree and 9 instances of a sapling. Each of the two instances were given a different size and orientation and dotted across the landscape. The image at x1000

shows that we can see detail right down to the individual pine needles, and yet the total data structure for this scene used less than 10 Mbytes of RAM during rendering. Note that whilst near-infinite scene complexity is possible using instancing, near-infinite variety is not. Totally unique objects must have their own description, and with these the scene complexity will grow in proportion to the number of surfaces.

How long does it take to create a Radiance model? This is a question that is often asked, especially by prospective clients. It is however extremely difficult to anticipate modelling timescales without first looking at the drawings/plans. Geometrical information from an existing CAD model can be used. But for this to be effective, the CAD model needs to be layered so that material properties can easily be assigned to the relevant surfaces. For many modern architectural designs, most, if not all, of the model could be created using Radiance scripts.Where visual realism is not intended, the scale of modelling complexity should generally be commensurate with the scale of the effect of the modelled structures on internal light levels. For daylight factor calculations therefore, a simple scene is appropriate. When visualisation is required, the complexity of the finished model will depend on the skill of the user and, of course, the fees associated with the project. Having worked-up the model, renderings for multiple views require little extra user effort.

So, how long does it take to generate an image? Once again, the answer must be:Well, that depends... Computer processing power is of course a key factor, but there is a complex relation between rendering time and the following:

- the number of light sources;
- the number of light reflections;
- the image size; and,
- the "accuracy" of the rendering parameters.

Also, computed inter-reflected light values can be saved to a file and reused for subsequent renderings of the same model for different views, shortening the computational time. Some experience is needed therefore before it is possible to accurately estimate the final outcome of a lighting analysis project.

Radiance can also be used to generate animations. One of the application chapters of the Radiance book describes how to do this, using (if available) multiple (UNIX/ LINUX) workstations connected to a network.

## Will the "real" Radiance please stand up!

A newcomer to Radiance may experience some confusion trying to decide what version to use. In addition to the original UNIX version, there are a few systems that integrate Radiance in CAD or other environments, and usually on the PC platform. It would be fair to say however that all of the current non-UNIX variants restrict, to a greater or lesser degree, the full functionality offered by the original UNIX version. To get the most from Radiance, the UNIX version is preferred; this will run under Linux, on a PC. If you require only a limited sub-set of the available functions, then one of the Windows-based versions may suffice.

One of the many myths about Radiance is that it is difficult to use because it does not have a user-interface. There is a certain amount of confusion here, originating with, I believe, the meaning of the word 'difficult'. The difficulties, and every new user has experienced them, result from the almost limitless possibilities that the system offers. It is important to distinguish between complexity that is associated with positive attributes like flexibility, accuracy and optimization and difficulties that stem from, say, poor system design. It is this author's assessment that Radiance is an extremely well designed system, and that the complexities, about which one must be candid, are part and parcel of its virtues.

The real problem people have when starting out in Radiance is that they are not used to the UNIX toolbox model, that is, having many individual programs that are optimized for specific tasks and meant to run together. Most people are instead used to the monolithic application model promoted by Microsoft and most other software companies, where a single, "seamless" interface is presented to the user, regardless of what goes on underneath. In truth, the toolbox model works very well, and is a very efficient method for building up a powerful and flexible software base. However, it takes more time to learn and is nearly impossible to master because the combinations one can create are so unconstrained compared to a menu-driven system.

### Radiance and the UNIX toolbox approach

Using the UNIX toolbox model, Radiance programs are linked together in a command pipeline for a combined purpose. An example of a pipeline command tailored for

# a specific task is:

<u>gensky</u> \$skypar \

- | oconv -w -i \$oct \
  | rpict -w -vp \$xp \$yp \$zp -vd \$xd \
   \$yd \$zd -x \$dim -y \$dim \
- | <u>pfilt</u> -1 -e 0.06 -x /2 -y /2 ∖
- | <u>pcompos</u> 0 0 '\!<u>psign</u> -h 20 \
- '"\$month"' '"\$day"' '"\$hrh" 0 0 \ >! tmpl.pic

This command does, of course, look like gobbledegook to most people. What it does illustrate though is the versatility of the UNIX toolbox approach. This one command, spread out over a few lines, results in the execution of no less than six individual Radiance programs (underlined). The pipe (|) command is the link between the programs: reading left to right, the output from one program is 'piped' to the input of another. This example command was taken from a short UNIX shell script that was written by the author to generate a sequence of 280 images for an animation showing the solar penetration into a building throughout the year. Briefly, the example command does the following:

- A sun description is generated (<u>gensky</u>) for a particular time of the year - the parameters are taken from the shellvariable \$skypar.
- 2 The output from <u>gensky</u> is added to an existing octree for the building using the oconv command. The octree data structure is necessary for efficient rendering.
- 3 Using this octree, the <u>rpict</u> program generates a rendering based on the view parameters -vp etc.
- 4 The exposure for the rendering is adjusted and it is filtered down to half the original size using the <u>pfilt</u> program.
- 5 An image created by the <u>psign</u> program is added to the filtered rendering using the <u>pcompos</u> program. The <u>psign</u> command here is executed 'in-line' rather than in the pipeline. Its function is to generate a time-stamp label for each rendering e.g. "March 01 13h15".

A single frame from the sequence is shown in **Figure 22**. The complete script actually generated two views of the building: an external and internal view. The external was from the viewpoint of the changing sun position and shows the sun illuminated external surfaces. The other was from a fixed point above to show the sun penetration into the building. Radiance allows the user to set so called 'clipping planes' that eliminate foreground and/or background objects from the rendering. Using this option, the roof of the building was 'clippedoff', but the predicted transport of light in the model remains unaffected. The entire animation sequence is included on the **Building Performance** CD-ROM.



Figure 22: One of a sequence of renderings generated by a script to show how sun penetration into a building varies through a year

It would be extremely difficult if not impossible to design a 'user-friendly' graphical interface that preserved the flexibility and rich functionality offered by the UNIX toolbox approach, and yet spared the user the task of setting the various program parameters etc. In fact, an entire chapter of the Radiance book is given to an exposition of scripting techniques. To quote from that chapter's conclusion:"Without ever writing a line of C (program) code, one can do almost anything imaginable by combining the various rendering, filtering, and utility programs included in Radiance. Combining this knowledge with the C-shell and other command interpreters, we can create new command scripts that permanently extend the functionality of our system for ourselves and our fellow users".

The newcomer should not feel complete despair however: there is a user-friendly way to get going with Radiance.

#### The graphical interface

The UNIX version of Radiance comes with a simple user interface to help get new users started. Called *trad*, this graphical interface (Figure 23) helps to set up and optimize the rendering process based on a few easy to understand general parameters supplied by the user. For some of these parameters, the options on offer are intuitive — for example, Low, Medium or High. The interface does not access many of the features of Radiance, but it does give a gentle introduction to the system. And for many new users, the first thing they will want to do is to create some renderings — *trad* will help them do this.

The *trad* interface can also fulfil an important teaching role since the user can

view the full set of rendering parameters that were generated from the simplified settings. So, with a little experimentation, he or she can begin to see the relation between the simplified settings, the generated actual parameters and the resulting image quality. Trad is not just for beginners; many people with long experience of Radiance, including the originator of the system, continue to use it to manage routine rendering tasks.

20ME	+ Interior		- Extension			- 1940 -
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Auto	х;	Y2		Z;		- 206
#Lrown	-0.25	F F	1.5		0	V1545
Notati:	⇔ High		o Nedism		⇔ Lov	U OPTION
						U ACTION
Indirects		1				U RESULT
						HELP
Variability:	$\sim$ High		r Nedium		$\sim$ Low	quar
Exposure:	-3				Cop	21
					Reve	et

Figure 23: trad, a more user-friendly interface for the simpler features of Radiance

# **Non-UNIX versions of Radiance**

There are several PC versions of Radiance available, some newer than others. A comparative evaluation is difficult to make because there are very few people, if any, that have used all the currently existing versions. The best known include:

- ADELINE: A collection of CAD, simulation, and visualization tools for MS-DOS systems, which includes a DOS version of Radiance. This package is perhaps the best known PC version of Radiance. It was within the framework of the International Energy Agency (IEA) Solar Heating and Cooling Programme Task 12. Integration between components is of variable quality, but it does include a good translator from DXF format CAD files, and it includes I BNI 's SUPERI ITE program in addition to Radiance. This package is available from LBNL and other contributors. Visit LBL's Adeline pages at http://radsite.lbl.gov/adeline/index.html.
- GENESYS: A lighting design package from the GENLYTE Group. It runs on MS-DOS computers. It includes an earlier DOS version of Radiance and has a nice user interface for designing simple layouts with a large catalogue of luminaires. There are contact details on http://turboguide.com/cdprod1/swhrec/007/ 762.shtml.
- SiView: An advanced, integrated system featuring Radiance for MS-DOS and Windows platforms. It is available from Siemens Lighting in Traunreut, Germany.

It requires the separate purchase of both AutoCAD and ADELINE. There is more information (in German) on Siemens Website http://w2.siemens.de/newsline.d/ pressfor/nd96493.htm.

- CANDLE: A simple to use package that integrates a WINDOWS 95 version of Radiance with an object manipulating tool (PANGEA). The package includes a luminaire database and a materials editor. It was developed at the Bartlett, University College London and is currently undergoing testing. Contact Peter Raynham for further details at p.raynham@ud.ac.uk.
- DESKTOP RADIANCE: Currently under development, this package aims to include many of the quantitative and qualitative capabilities of UNIX Radiance in a WINDOWS NT/95 version. DESKTOP RADIANCE includes an AutoCAD-based graphic editor that allows the user to select from libraries for materials, electric lighting fixtures, glazing systems and furniture. It is being jointly developed by Lawrence Berkeley National Laboratory and the Pacific Gas and Electric Co. First release is planned for spring 1999. Visit LBL's Website for the latest information on http://radsite.lbl.gov/radiance/desktop.html.

None of these versions are free, and none of them are directly supported by the originator of the original UNIX version. *DESKTOP* is being developed at LBNL who maintain the UNIX release. It may be therefore that this PC version will have the greatest correspondence to the original UNIX Radiance. At present however, *ADELINE* is probably the most used of the PC versions, and the best one to try first.

#### Learning how to use Radiance

For some time now, both newcomers and experienced users have voiced the need for a definitive guide to the Radiance system.

The documentation with the UNIX release includes manual pages for all the programs, a brief tutorial, a guide to material behaviour and some technical notes. Useful though these are, they only give a glimpse of what is possible. What was needed was a thorough exposition of the basic functionality in the form of graded tutorials, material on specialist applications and a description of the calculation methods.

This eventually appeared in *Rendering* with *Radiance:The Art and Science of Lighting Visualization*, published by Morgan-Kaufmann in March 1998.This excellent book is accompanied by a CD-ROM containing the complete UNIX software (release 3.1), tutorial scene files, image gallery and much additional material. It is aimed primarily at users of the UNIX version of Radiance. The book contains a great deal that is not available elsewhere and it is strongly recommended to beginners and experienced users alike. The author must disclose at this point that he wrote one of the specialist application chapters, 'Daylight Simulation', for the book. *Rendering with Radiance* is reviewed by Milan Janak on page 17 of this issue of **Building Performance**, and there is a detailed contents list on the Radiance Web site http://radsite.lbl.gov/radiance/.

The response from readers has, so far, been very favourable. The majority were experienced Radiance users who had placed advance orders; the release of the book had long been anticipated. For this group, the book fulfilled several functions. First and foremost, it became the standard reference, containing the answers to a great many questions. Secondly, it served as a guide to "good practice". The tutorial and application sections contain plentiful examples from which even the most experienced user can learn. Lastly, the chapters on calculation methods, intended principally for researchers, provide a deeper understanding of the system and describe the key algorithms and their relation to rendering parameters.

However, the group that have most to gain from the book are newcomers to Radiance, for whom it is a definitive learning resource. With this book as a guide, newcomers will be spared much of the frustration that past users have experienced on the way up the Radiance learning curve. In fact, because both Radiance and Linux are freely available, learning how to use Radiance at home is a practical option: the only cost investment (beyond a PC) is the price of the book. This makes Radiance one of the few professional simulation toolkits that can be learnt, and used, at home without licensing costs.

#### **Future developments**

It is more than likely that the Radiance userbase will continue to expand, both in research and in practice. There are Radiancebased packages and systems that link with Radiance currently under development, and more can be expected in the not-too-distant future. Now that the dynamic calculation of daylight has been demonstrated, the linking of Radiance to dynamic thermal simulation models is an area that needs to be developed. (This was discussed in an article by Joe Clarke and Milan Janak on pp21-3 of **Building Performance** issue 1).

Work on Radiance is also being continued by the originator, Greg Ward Larson, who now works for Silicon Graphics. In addition to minor bug fixes and enhancements, Greg has developed some new visualization tools. One is a previewer that uses OpenGL (SGI's 3D graphics toolkit) to enable interactive walk-throughs of Radiance scenes with local lighting for checking geometry. A more advanced visualization tool employs a "holodeck ray cache" to enable interactive walk-throughs of complete lighting simulations, which can be computed in real time on one or more processors or precomputed in batch mode beforehand. This is like a "super-rview" program, called "rholo," which permits one to move about freely in the simulation, never losing any of the ray samples that have been computed. The calculation process may also be replaced, so that the ray computation could take place on a massively parallel computer or other specialized hardware. Greg hopes to release this as freeware later this year.

The modelling of complex materials, such as prismatic films, with Radiance is an important area of research. The system has the capability to model materials based on empirical bi-directional reflection transmission distribution properties. However, these quantities are only just being measured, and their use in Radiance is not straightforward.

#### **Radiance in practice**

Views from David Baker of **CBS Simulations** and Jeff Shaw, Darren Woolf and Anne Selby-Smith of **Ove Arup & Partners** 

#### **CBS Simulations**

CBS Simulations Limited is an independent consultancy which provides specialist simulation services to the building industry. We aim to provide creative building solutions by use of engineering judgement, supported by a wealth of information to be acquired through computational simulation. Radiance is just one of a range of tools we use for building environmental analysis.

Historically, CBS Simulations has used Radiance primarily for daylight factor analysis, solar shading refinement, solar penetration tracking and artificial lighting simulation, running on PCs under Redhat Linux 5.1. Very little use has been made of the photo-realistic visualisation, with the exception of a fly through video. The few perspective images generated have mainly been a by-product of other models, created by making minor modifications to surface finishes and view points. Generally there is very little or no funding available within tight project budgets for high quality perspective graphics, the emphasis being on the production of engineering and technical information in a timely manner. The provision of engineering information is one of the main reasons we use Radiance.

To the beginner, Radiance can be very daunting to use. The problem is not particularly the complexity of the software, but knowing where to start. There is minimal pre-defined structure or methodology imposed on the user and the resulting flexibility can be a hindrance at first. As experience with the software grows this is a bonus, but for a novice it can detract from project objectives. This means that to make Radiance commercially viable you have to be fluent in its use and application.

Until the advent of the Web site, and more recently the book, finding concise information on Radiance was piecemeal at best. Tutorials and demonstrations of functions in action are probably the most useful sets of information published. The online manual, as with all Unix packages, are only helpful once the subject is familiar.

Once mastered, the strengths of Radiance by far outweigh the initial difficulties. One of the most important issues to CBS's clients is that the software is validated. Also taking on a varied range of projects the geometrical flexibility provided by Radiance is vital. Simulations incorporating both daylight and artificial lighting schemes are a common requirement and this is simply undertaken providing a realistic interpretation of the real building environment.

Future improvements to Radiance could include an interface (though the *trad* interface is very useful). However userfriendliness can be a double-edged sword if it limits the inherent flexibility of the software by masking some of the features/ technical issues from the user.

#### Ove Arup

Building Engineering Group 4 is a mediumsized division of Ove Arup & Partners staffed by around 50 electrical, mechanical, structural and public health engineers. A large variety of projects are undertaken including office and retail developments, art galleries and museums.

Recent Radiance projects include the Rothko Chapel (Houston), Musee D'Art Moderne (Luxembourg), Walsall Art Gallery and some large office developments in London including Tower Place, 40 Grosvenor Place and London Bridge City. Visualization and quantitative design studies are undertaken on projects using a Silicon Graphics Indigo 2 workstation running Irix 6.2. The model building is done using a combination of up to three methods: a simple 3-D'nodes & connectivity' generator called 'mpalm'; directly from Radiance; and importing through AutoCad.

Radiance has a wide variety of applications in Arup. These include visualisation and quantitative studies of electric and natural lighting schemes. One advantage Radiance has is its ability to accurately analyse the behaviour of light in models far more complex and irregular than any other computer design tool can cope with.

One application we have been using Radiance for recently is shadow (movement of shadow over a site) and sunview (view of the site from the sun's viewpoint) studies over typical chosen days (e.g. the equinoxes and solstices). Although this can be completed using a number of alternative programs, the ability to 'user program' enables job specific development on the quantitative design side using Radiance. The visualization is also much more realistic.

A number of skills need to be learnt to derive the maximum benefit from Radiance. These include model building, scripting (which can be complex at times) to the postprocessing 'animated sequences' side. The tutorials are quite useful but it takes quite a bit of time to understand where everything is coming from and perhaps the alternatives available. Quite often a sensitivity study of the effect of a particular parameter is useful in indicating its role in the whole scene.

The new tutorials in the book give more in depth training, and allow for a slightly simpler leaning process. Furthermore, with its comprehensive index, the book is very useful as a tool (that did not exist before) for looking up advice on specific aspects of Radiance when a puzzle or problem is encountered. The book is also written in a language that is easier to understand by the inexperienced user than the original manual pages. That said, Radiance still has a steep learning curve.

Newcomers to Radiance would be well advised to go through the tutorials in the book in some depth, as they do demonstrate the use of the programs well. An understanding of the properties and behaviour of light and daylight is essential also, to allow meaningful studies to be carried out. The most is gained, however, in the long run, by applying this knowledge to real studies. As such one encounters real questions that need answering and difficulties that need solving. Even a very experienced user can learn new techniques of saving time and improving the quality of his or her output.

As for the wish list — there's not much I can think of right now. Radiance as it is is very sound. Most things we require can be achieved with time and patience. The only thing I am often searching for is better modelling techniques — AutoCAD isn't a great 3D modeller, but it is currently still the easiest program to transfer to Radiance models from. There are a few things that are missed out or difficult to find in the book also. One thing that would be nice would be an update of the manual (or a companion to it), making it more comprehensive, easier to read and giving better explanations of some of the more obscure arguments, and an explanation of the likely errors encountered.

A newcomer's view is interesting. Anne Selby-Smith, a new member of our office, has been doing some simple Radiance visualisations after having learnt from scratch using the book. She seems to have picked it all up pretty well so far. Anne says:

"I found the tutorials a good introduction - demonstrating the potential of Radiance but still understandable to a raw beginner. The modularity of the program was obvious and when I began to build my own simple models I was easily able to apply and adapt elements used in the tutorial examples.

The thing I would have liked most in addition to the information provided in the book was a brief explanation of the error and warning messages which Radiance uses. A short summarising/reference table of TYPEs and the parameters required to define each one would also be useful as an appendix to the book."

## Glossary

# UNIX scripts

A UNIX shell is a command interpreter. There are several available and they are largely interchangeable. Most UNIX scripts are written for the C-shell.

#### Octree

An octree is a compiled form of the scene files. The octree data structure is necessary for efficient rendering, and for including geometry with the instance primitive.

## Linux

Linux is an operating system based on UNIX. It supports both 32 and 64 bit hardware and provides a stable multi-user operating system. Linux effectively offers a UNIX environment for a range of platforms including Intel PCs. Freeware versions are available.

# OpenGL

OpenGL is a software interface for graphics hardware that allows graphics programmers to produce high-quality colour images of 3D objects. The rendering is fast but not physically-based. The (Radiance) program glrad uses OpenGL to permit interactive movement through a Radiance scene.

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All uncredited images/models were created by the author.

The first section of this article, *What is Radiance?*, is quoted by permission from the Preface to *Rendering with Radiance* by Ward Larson and Shakespeare.

Note: The printing process used for **Building Performance** cannot do full justice to the quality of this images in this article. To see them in higher quality, look at the PDF version of the journal on the CD.

The Radiance rendering is the image on the right.