# THE APPLICATION, VALIDATION AND FURTHER DEVELOPMENT OF RADIANCE: SOME UK ACTIVITIES

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## ABSTRACT

RADIANCE has emerged as one of the most powerful programs for modelling the luminous environment within and around buildings. It has a large and growing number of users in many countries including the UK. This paper illustrates its use for producing photo-realistic images of proposed building designs and for daylight analysis of a complex atrium building. The results of validation work, using real sky data, are presented and some current UK research involving RADIANCE is described.

## 1. INTRODUCTION

Evaluation of the luminous environment in complex buildings, prior to construction, is only usually undertaken in an approximate way. For example, using scale models or simple computer programs. However, advances in desktop computing power mean that software is now available which is capable of producing realistic images of proposed designs. Some of these are associated with commercial CAD packages (e.g. 3-D Studio[1]) and others are the products of commercial companies (e.g. Visulux from Philips Lighting). These, like most other recently developed imaging systems, are based on the radiosity technique[2]. Many such programs are visually impressive but few have the potential to generate both the visual image and the numerical information which is necessary to quantify an illuminated space.

The program RADIANCE[3] uses a method based on Monte-Carlo backward ray-tracing to calculate diffuse inter-reflection, and is capable of overcoming the problems of conventional ray-tracing and radiosity methods. Its theoretical basis has been described in detail elsewhere (e.g. in reference 4). The operator of RADIANCE has control over the solution strategy used and this influences the results obtained. Two important parameters are: 'ab' the number of light bounces which are tracked and 'ad' the number of rays initially sent out from the eye-point. As the value of these parameters increases the scene is more fully sampled.

The illuminance at specific points can be computed using the 'rtrace' command. Alternatively, the luminance of the whole scene can be computed. The former is useful for lighting analysis, the latter for visualisation. In either case, rays can be traced directly from the outside sky. Alternatively, by tracing firstly to any glazing these can become an 'illum' source for the room.

RADIANCE has the following characteristics: it purports to allow accurate calculation of luminance/illuminance; it produces photo-realistic images; it has the capability to model complex (i.e. realistic) natural and luminous entities (e.g. sky brightness patterns, luminaire output distributions, etc.); it supports a wide variety of reflection and transmission models; and supports complex geometry which can be taken from a CAD system (e.g. AutoCAD[4]). RADIANCE was intended for use in a UNIX environment, but a PC version with associated geometrical modeller and other utilities has recently been released[5]. RADIANCE is still undergoing development and refinement.

RADIANCE is used in a few of the UK's leading building design and consultancy practices when fees allow and lighting issues are crucial. It is also used in numerous Universities, primarily in architectural design departments, for educational purposes and occasional consultancy work. Some consultancy work undertaken within the Environmental Computer Aided Design and Performance (ECADAP) Centre at De Montfort University, will be used here to illustrate the imaging and daylighting design potential of RADIANCE. Work undertaken in the same Centre to validate RADIANCE predictions is also described as are areas of current research involving RADIANCE.

## 2. ATRIUM BUILDING DESIGN

RADIANCE was used to produce images of-, and daylight factors in-, an atrium building designed by Peter Foggo Associates for quasi-clients Stanhope Properties PLC (the design was for the UK Department of Energy's Non-domestic Design Studies Programme). The building was planned for Chiswick Park in London and, in keeping with the style adopted in many UK commercial buildings, it was built on five levels with two main wings which opened on to a central atrium (Fig. 1). The concrete

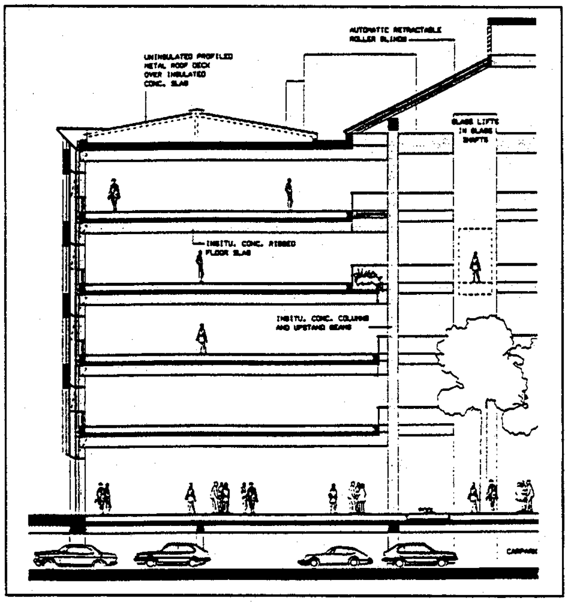

Figure 1: Half section of Foggo atrium building

floor slabs were exposed on the underside, and specially designed light fittings with acoustic baffles nestled between the downstand beams. The offices were daylit through clear double glazing from the atrium roof and outside windows, but external shading devices and light shelves were used to diffuse the light deep into the floor spaces and avoid glare. Such a geometrically complex building is difficult to analyse in a conventional manner so RADIANCE was used.

## 3 VISUALISATION

The geometry was based on architects' drawings and design detail sketches. The architects advised on the colour schemes, surface finishes, and reflectivities of materials. This process would be improved if a palate of materials, colours and textures had been available from which the architect could have indicated his ideas - this would be a useful addition to the RADIANCE package.

In all, the building took around two weeks to model using the standard RADIANCE text interface (a reliable CAD (DXF) file translator would have undoubtedly speeded things up but none were available at the time). The repeating structure allowed the scene to be built from a hierarchical set of octree structures using the detailed office cell description (see below) as the basic octree. A cell was instanced to create a line of offices, an octree made of that, then this was instanced vertically to create one side of the building, and an octree made of that. Then finally, this octree was instanced to make up both long sides of the building. Details such as the lifts, and the lift shafts, were added for realism. This hierarchical-octree data-structure was sufficiently compact to allow rendering of this extremely complex scene on a 32Mb RAM computer - fairly modest by today's standards. For the rendering, two ambient bounces were used - enough to provide sufficient 'visual' realism (see shading on underside of floor between elevators). A higher

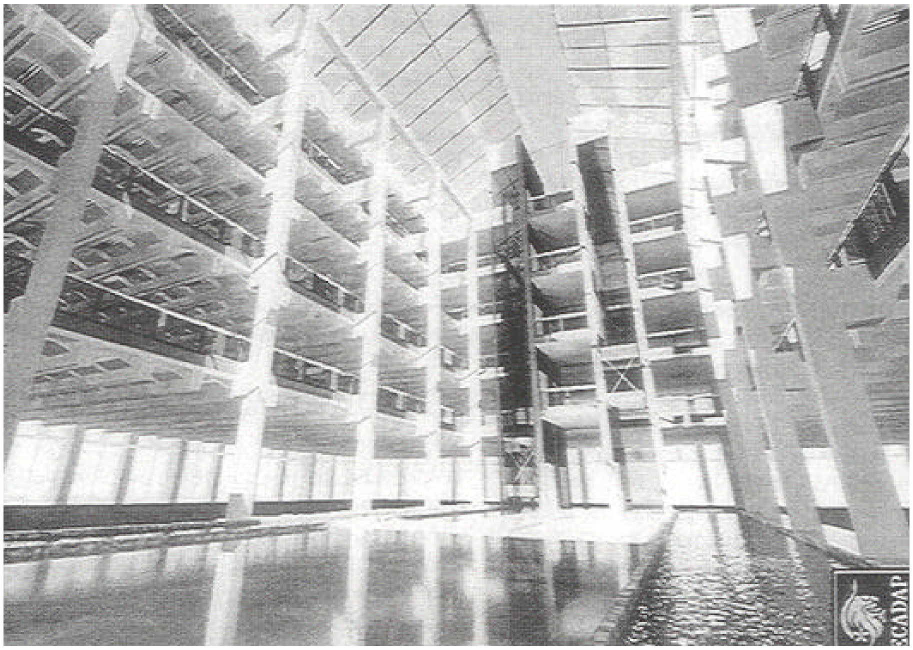

Figure 2: Atrium building illustrating visualization potential of RADIANCE

number of ambient bounces would not have changed the visual impression noticeably, yet the computational cost would have been significant.

The image of the atrium space (Fig. 2) took around two days to compute on a SUN SPARC 2 workstation. It has been found, however, that by partitioning the image and processing it on a number of machines (say 4) the solution time could be reduced (to roughly a quarter in this case). RADIANCE seems particularly well suited to the new shared-memory parallel processing workstations.

Subsequent tests revealed that the same scene fully expanded, (i.e. using an explicit description for each material surface rather than using hierarchical-octrees) would have rendered in approximately ~1/5th of the time! A fully expanded scene requires more memory, but even the fully expanded atrium would have used only 40 to 50Mb of RAM. The difference in simulation time arises because the calculation has to 'unfold' an octree each time a ray passes from one octree bounding surface to another. This happens often enough with a direct-only calculation; with ambient bounces as well, rays are constantly being spawned to sample the environment, and in doing so, they cross many octree bounding surfaces. With hindsight, the hierarchical-octree structure used in atrium is not the best when enough RAM is available. The problem is, it is not always obvious what 'enough' is!

## 4. DAYLIGHT ANALYSIS

Output from RADIANCE need not be in the form of an image, and in fact for daylighting design, the most useful information may be in the form of an illuminance (or daylight factor) map at the working plane height. This analysis is much quicker to compute than the visual images: (i) because the building need only be modelled at the same level of detail that would be adopted in a very good physical model; (ii) because, although significant partitions and internal furnishings could also be modelled, the clutter which is typically found in offices (shelves, moveable furniture and chairs) would normally be omitted; and (iii) because ray-tracing need only take place to a grid of a few hundred points, rather than to millions of pixels as in a high resolution visual image.

Because the model is computer based it is very simple to change surface reflectance, adjust the geometry, add features such as light shelves or shiny surfaces, and re-calculate to find the new illuminance distribution. Such an iterative process is not normally possible with physical modelling because of the time involved.

To study daylight levels, the atrium was modelled as a top-lit 'box'. Although its roof was modelled in detail, its internal structure was modelled as alternating bands of high reflectance material for the pale coloured edge beams and low-reflectance material to represent the open floor cavity. These dark bands were overlaid with glass so that the specular reflections from the glass edge-barriers was considered.

Openings were provided to sections of level 2 and level 4 in which the daylight analysis was required. The interior geometry (e.g. downstand beams), surface colours, transparent edge-barriers, internal and external light shelves, and shading devices, were all modelled in detail. The CIE diffuse overcast sky model was used. At each level a grid of points was defined at which the illuminance values and hence the daylight factors were to be calculated.

The windows, glass-railing and void above the railing, were treated as 'illum' sources. Their light output magnitudes and distributions were pre-calculated using the 'mkillum' facility. Three ambient bounces were used to produce illuminance values at the chosen point, using the 'rtrace' program. The values were dumped into a data analysis package, converted to daylight factors, and displayed. They are shown here as interpolated contours of equal daylight factor (Fig. 3).

The contours show that the window detailing succeeded in preventing the daylight levels rising to very high values close to the external windows and thus the daylight uniformity was improved. The daylight factor decreased to around 1.0% towards the centre of the floor. The roughly symmetrical distribution makes it easier to devise an artificial lighting scheme and control system which can optimise the use of daylight.

## 5. VALIDATION MEASUREMENTS AND MODELLING

Most of the RADIANCE research in the ECADAP Centre has focused on empirically validating the accuracy of its numerical predictions. Long-term measurement of sky luminance distribution had been collected by the UK Building Research Establishment (BRE) using a sky scanning device. It made measurements of the sky luminance at 145 positions (evenly distributed over the sky vault) every 15 minutes from 9.00am until dusk.

In conjunction with this sky measurement programme, the BRE measured the illuminance in two full-size mock offices with a range of innovative glazing systems. The offices, with south-facing glazing, were constructed next to each other. The window of one office was adapted so that an innovative daylighting system could be installed and

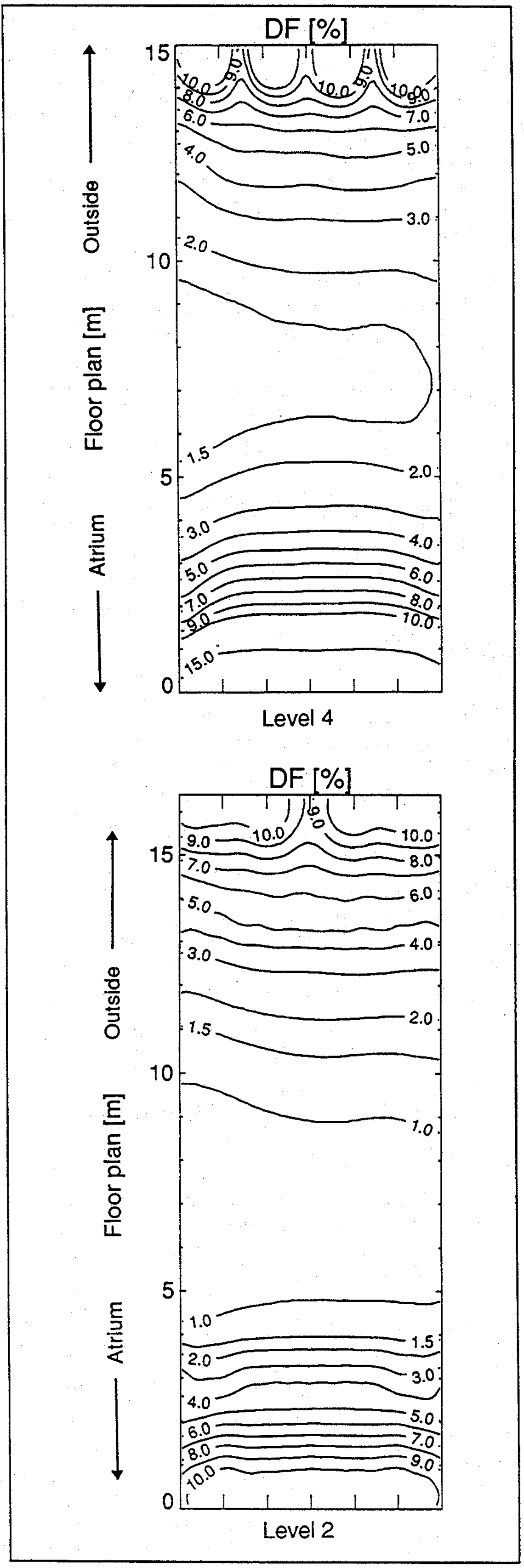

Figure 3: Predicted daylight factor contours at level 4 (top) and level 2 (bottom)

the other had conventional single glazing. Six illuminance cells regularly spaced along the centre-line of each room were used to measure the illuminance distribution (Fig. 4).

The sky monitoring apparatus was positioned on the roof directly above the experimental rooms and the room illuminance and sky luminance measurements were recorded within seconds of each other[6]. Together, the two monitoring programmes provide, for what is believed to be the first time, real data with which the predictions of lighting simulation programs such as RADIANCE can be tested.

The rooms were modelled in RADIANCE as accurately as possible and rays were traced to the sky vault (i.e. 'illum' sources were not used). Particular attention was paid to window bars and glazing elements. The opaque surfaces were modelled as diffuse reflections and assigned an average measured reflectance. A window transmittance appropriate to single glazing was used with a maintenance factor as recommended by the experimenters, applied.

A sky luminance distribution was re-constructed from the 145 measured values with estimates being made for sky vault brightness close to the sun. The measured direct normal illuminance enabled the solar disc brightness to be ascertained. Using the data from the sky-scanner and other fixed instruments, it was possible to identify times when the sky condition remained stable for the 25 seconds which each scan took. Validation of RADIANCE was possible for such times.

## 6. VALIDATION RESULTS

The reconstructed sky luminances and the predictions of RADIANCE, when operating at a high resolution (ab = 7 and ad = 4096) are shown here for two different rooms and two different sky conditions (Fig.5).

(i) A room with clear glazing under a dull overcast day (day 121 in 1992 at 14:15). It is under such conditions that the daylighting designs of UK buildings are assessed (i.e. CIE overcast).

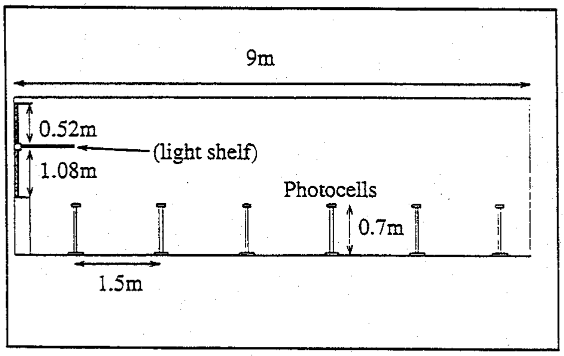

Figure 4: Long section of experimental rooms

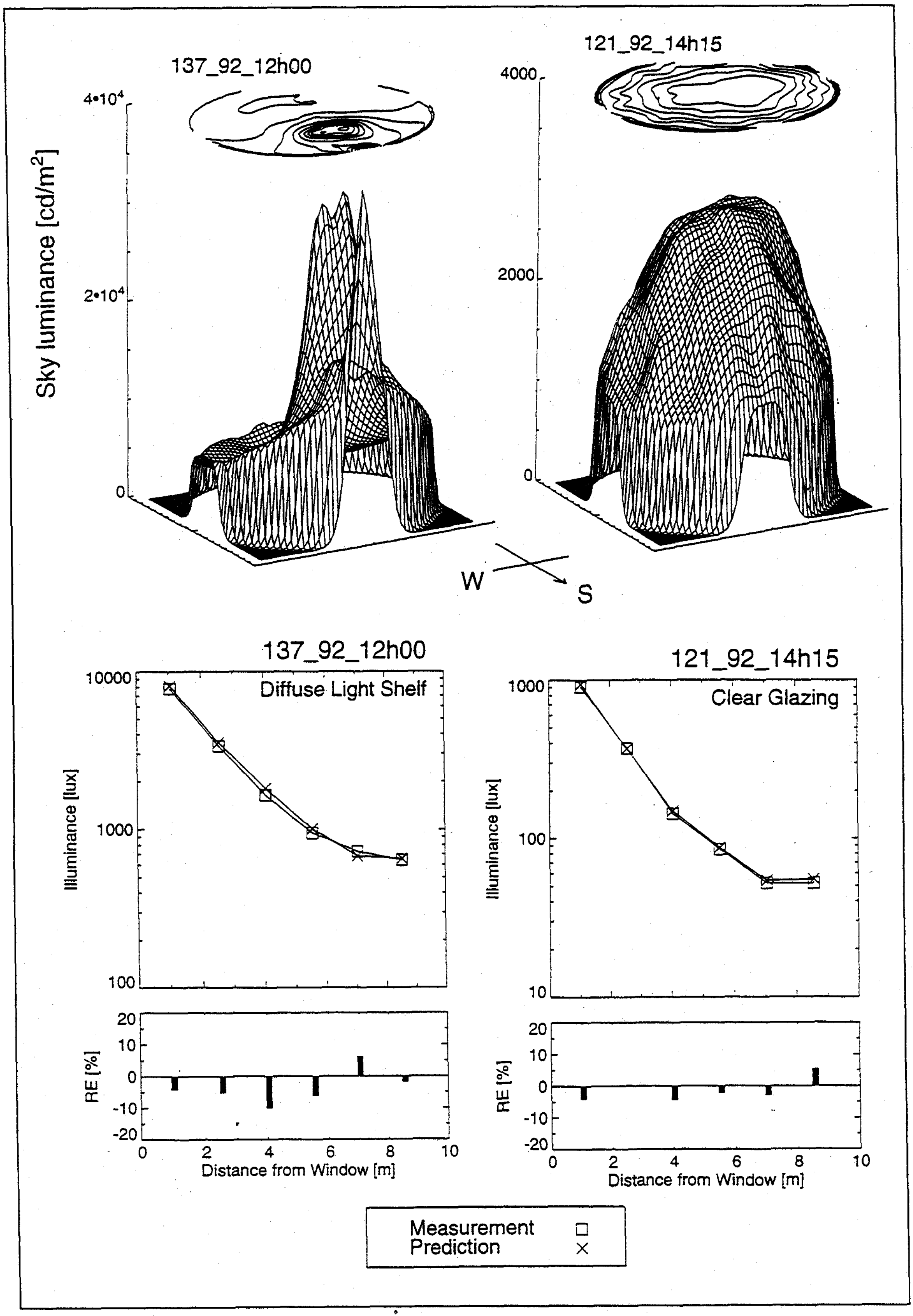

Figure 5: Measured sky illuminance distributions and predicted measured illuminances in the offices

(ii) A room with an internal 1m deep diffusing light shelf on a sunny intermediate day (day 137, 1992 at 12:00). It is under such conditions that the light re-distribution effects of light shelves are most beneficial.

Illuminances ranging from 50 lux to 10,000 lux are accurately predicted under very different sky conditions. The relative error is always 11% or less and on most occasions less than 5% (Fig. 5). Given that the sky luminance/illuminance data is accurate to within 10% and the room illuminance to within 5%[8] further discussion of these errors is unwarranted.

The sensitivity of the results to the number of ambient bounces 'ab' and ambient divisions 'ad' was investigated. As the values of either parameter increased the simulation progressively converged onto a final set of predictions (Fig. 6). However, for this room, convergence was obtained much more quickly when ad was increased rather than ab. This is illustrated for the room with clear glazing at 12.00 noon on a sunny day. Here ad varied in the sequence 16, 32, 64 ... 4096 (with ab = 7) and ab varied from 1 to 7 (ad = 1024).

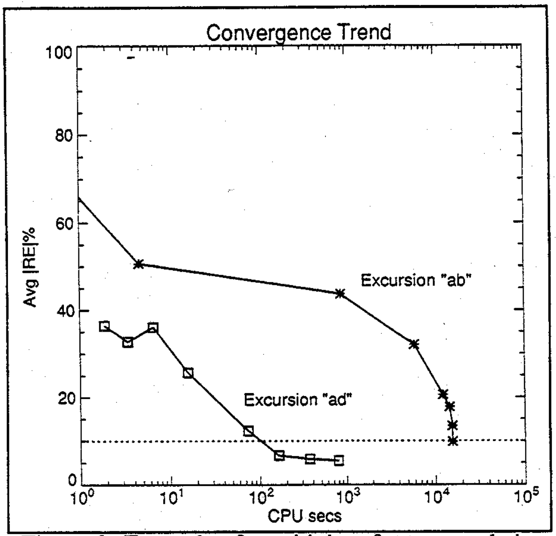

Figure 6: Example of sensitivity of average relative error and simulation (CPU) time to changes in ambient bounces and ambient resolution

The optimal values may vary with the room geometry (in this case ab = 7 and ad = 1048 were chosen) but, for any chosen geometry, they were found to work well for all sky conditions.

Using the optimal parameters, simulations are being undertaken for all 800 15-minutely sky-data sets. Illustrative results, again for the clear glazed room, on a sunny day, are given in Fig. 7. At virtually all times, and at all sensors, the predictions lie inside the estimated measurement error of 10% - with obvious exceptions. These exceptions, for the photo-cell closest to the window (P-cell 1), seem to occur when the sun is in line with the glazing bars. They are therefore likely to be due to geometrical errors in measuring up the room and positioning the photo-cell - investigations continue. Further validation results will be published elsewhere[7].

## 7. FURTHER RESEARCH AND DEVELOPMENT

The use of RADIANCE is likely to demand a highly skilled operator for some time to come, however, the provision of domain-specific interfaces could make the system more widely usable. Interfaces to standard CAD systems could be improved and enhancements to the libraries of internal furnishings and fittings, databases of luminaire characteristics, and the reflections and transmission properties of materials would also widen the user-base of the software.

The release of ADELINE[5] with its PC implementation of RADIANCE, linked to a simple CAD system, and other building analysis software, opens up opportunities for PC based design teams.

In other work in the ECADAP Centre, RADIANCE is being used to produce the lighting coefficients[8] which can be the basis for rapidly predicting the time-varying illuminance in complex spaces[9]. This will enable the interaction of natural and artificial lighting under real sky conditions to be evaluated accurately. Preliminary work has shown that this approach is feasible.

The authors of ESP[10] (a detailed thermal simulation program) have also begun to explore the use of RADIANCE to predict illuminance levels and thus, based on chosen artificial lighting control strategies, the internal heat gains and energy demands of electric lights.

RADIANCE is also being used at the BRE and in the ECADAP Centre to examine, in a generic way, daylight levels in and around atria.

## 8. CONCLUSIONS

The RADIANCE lighting simulation system offers unique capabilities for predicting illuminances, luminances and daylight factors in highly complex daylit spaces and for producing photo-realistic images.

Its application for daylight analysis and the visualisation of a low-energy commercial building incorporating an atrium has been discussed. At present however, such consultancy work requires operator skills beyond those which reside in a typical architect's office.

The results of validation using real sky conditions and an office with clear glazing and a diffuse light shelf have been presented. This shows that

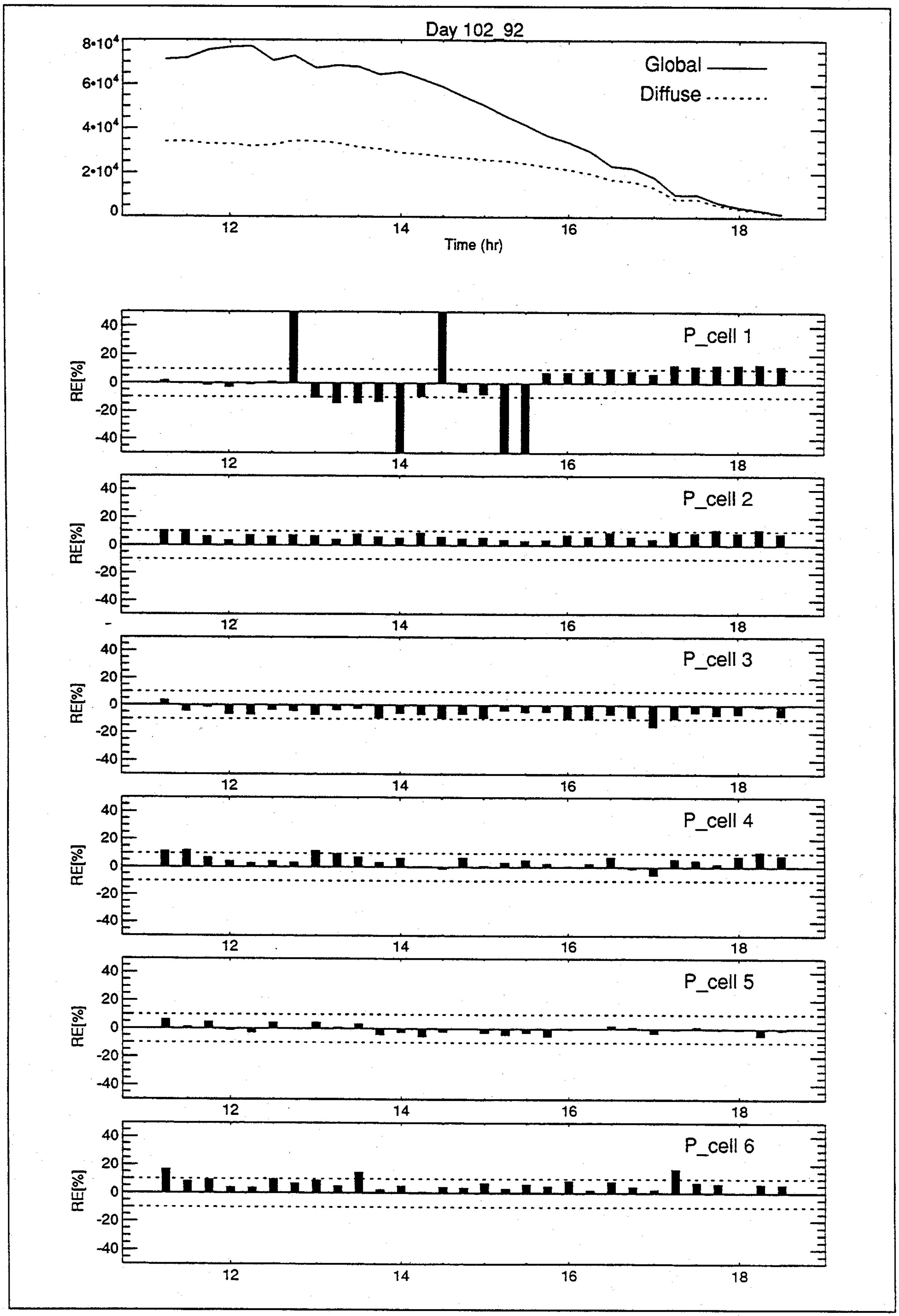

Figure 7: Relative error in 15-minutely predictions of illuminance at each photocell on a clear sunny day in the clear-glazed room

RADIANCE can predict internal illuminances to a high degree of accuracy.

The results and more particularly the simulation times are highly influenced by the program user. Advice on optional parameter settings will be produced.

The development of improved user interfaces, and integration with other building design systems, would enable RADIANCE to play a greater role in the building design process.

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