DEVELOPMENT OF RADIANCE FOR ADVANCED LIGHTING SIMULATION OF NOVEL DAYLIGHTING TECHNOLOGIES

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SUMMARY

Several new algorithms have been developed for the RADIANCE lighting simulation program to better simulate new daylighting devices. Developments include algorithms to accurately simulate two new daylight redirecting devices. Measurement of devices' luminous outputs, sensitivity studies and improved sky models were also developed. Further investigations focussed on more accurate material modelling, and validation assessment techniques.

Each algorithm has been applied to many simulation studies, improving simulation performance when compared with measurements and expectation. Thus, the developments outlined in this paper have improved the capability of RADIANCE to accurately assess the contributions of new daylighting devices to improved building performance. Following descriptions of the developed algorithms, the method of implementation in a typical RADIANCE simulation is discussed.

INTRODUCTION

Daylight in buildings provides many benefits to building occupants and owners. These benefits include the displacement of artificial lighting, with corresponding cuts in energy consumption and greenhouse gas emissions (Littlefair *et al.*, 1994; Nelson, 1997; Steemers, 1994; Zonneveldt & Pernot, 1994). There are also numerous physical benefits for building occupants. Increased daylight levels and views through windows improve occupant satisfaction and comfort, and decrease stress levels, thereby improving worker morale and motivation (Abdou, 1997; Clanton, 1999; Nazzal, 1998).

For daylight to be utilised to its full potential, its effect on building performance must be understood early in the design process. Computer lighting simulation permits the swift evaluation of different lighting design alternatives, and their influences on the luminous environment and energy consumption. RADIANCE is a highly advanced program that is able to model almost any existing material and geometry (Greenup *et al.*, 2001; Greenup *et al.*, 2000; Jarvis & Donn, 1997; Mardaljevic, 1995; Ward, 1994). RADIANCE allows for the modelling of diffuse, specular and semispecular reflection and transmission, refraction in dielectrics, patterns and textures, material mixtures, and general bi-directional reflection/transmission functions. RADIANCE's ability to model such an extensive range of materials makes it ideal to simulate novel daylighting technologies.

It is important that computer simulations of new daylighting devices should agree closely with measurements. However, such devices often make use of materials and geometry that are difficult to simulate (Apian-Bennewitz *et al.*, 1998; Greenup *et al.*, 2000; Mischler, 2001). It is the purpose of this paper to demonstrate the author's approach to this problem. A number of new algorithms are described that have improved RADIANCE's capability to accurately model new daylighting devices.

ALGORITHMS DEVELOPED FOR IMPROVED RADIANCE MODELLING OF DAYLIGHTING DEVICES

Numerous algorithms have been developed to ensure the accuracy of simulations of novel daylighting devices developed by the authors. These devices aim to effectively redirect light from the exterior of a building into its interior. Accurate simulations of the devices required the development of new materials and geometries within the RADIANCE environment. In order to test that these models were working as desired, methods were developed to test their angular luminous throughput. Once it was determined that the model was working as required, sensitivity tests could be performed using the above algorithms. These tests could examine the sensitivity of light throughput distributions to device parameters (eg. geometry, materials, design parameters). New sky luminance models have also been created, based on the Standard Sky Luminance Distributions (SSLD) (Kittler *et al.*, 1997). Further examinations have involved RADIANCE's specular reflection model and a statistical technique by which to compare experimental and simulated results.

Each of these algorithms and investigations is described in the following sections. The discussion that follows shows how all of these results are combined to simulate a new daylighting device.

Models of Novel Light Redirecting Devices

In order to effectively deliver daylight deep into buildings, light must be redirected from outside a building into its interior regions. Light redirection can be achieved using a number of different technologies, including laser cut panels, reflective venetian blinds, prismatic glazing, light shelves and sun-tracking mirrors (Edmonds *et al.*, 1998; Schuman *et al.*, 1992). Such devices necessarily deflect light through large angles by various purposes and in various forms. As such, these devices are difficult for lighting programs to effectively simulate (Apian-Bennewitz *et al.*, 1998; Greenup *et al.*, 2000; Mischler, 2001). RADIANCE is not ideally set up to model such devices, but efforts are being made to facilitate such simulations (Greenup *et al.*, 2000; Mischler, 2001). Models of two powerful light redirection devices - the laser cut panel (LCP) and the micro-light guiding shade (LGS) panel - are described below.

The Laser Cut Panel

The laser cut panel (LCP) is a powerful light redirecting device created by making thin laser cuts in sheets of acrylic plastic (Edmonds, 1993). Each laser cut acts as a tiny mirror, redirecting incident illumination, and converting the panel into a powerful light deflecting system (Figure 1). The LCP can replace conventional windows, or take numerous alternative arrangements in conjunction with conventional windows, skylights and atriums. Installed as a clerestory window, it redirects incident daylight across the ceiling, pushing daylight illumination deep into the room. In another application, LCPs form a square based pyramid skylight (Edmonds *et al.*, 1998; Edmonds *et al.*, 1996). The skylight then rejects sunlight and solar heat gain around midday and in summer, but admits it in the morning and in winter (Figure 2). This angle selective skylight provides a more constant level of illumination across the course of the day and year.

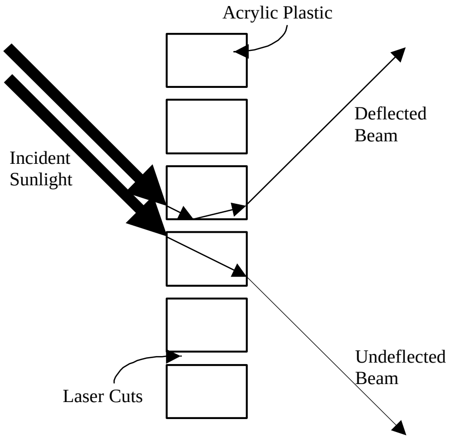

Figure 1 The Laser Cut Panel Deflects Incident Sunlight Using Laser Cuts Acting as Tiny Mirrors

RADIANCE's ‘prism2’ material primitive was used to model the LCP. This primitive is used to describe reflectance or transmittance, and allows for a maximum of two ray redirections. Referring to Figure 1, the LCP transmits incident light rays through the panel, resulting in two emergent rays, the deflected and undeflected beams. A RADIANCE function file performs the calculations required to find the fractions deflected and undeflected, and the directions of the emergent beams. More details regarding the application of the algorithm are described by Greenup *et al.* (2000). The required function file is also appended to this publication, and can be obtained from the author.

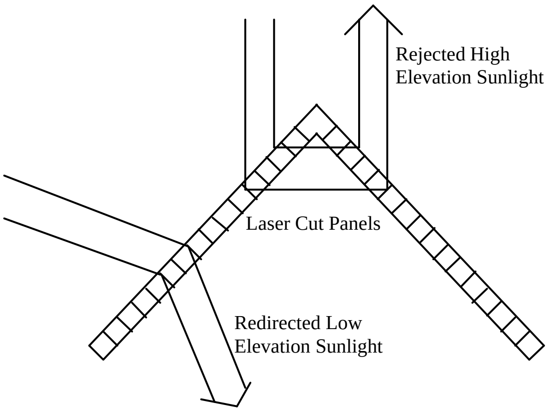

Figure 2 Laser Cut Panels Forming an Angular Selective Skylight. High Elevation Sunlight is Rejected, while Low Elevation Sunlight is Redirected

The application of the LCP material is illustrated in Figure 3. This application involves the simulation of ten angular selective skylights (Figure 2) over a large enclosed volume. Figure 3 displays illuminance profiles on the floor of the enclosure for different external conditions with and without the LCP skylights installed. This analysis has shown that the skylights are working as desired, providing more even illumination between mid-summer and mid-winter, and only small reductions under overcast skies, when compared with plain skylights.

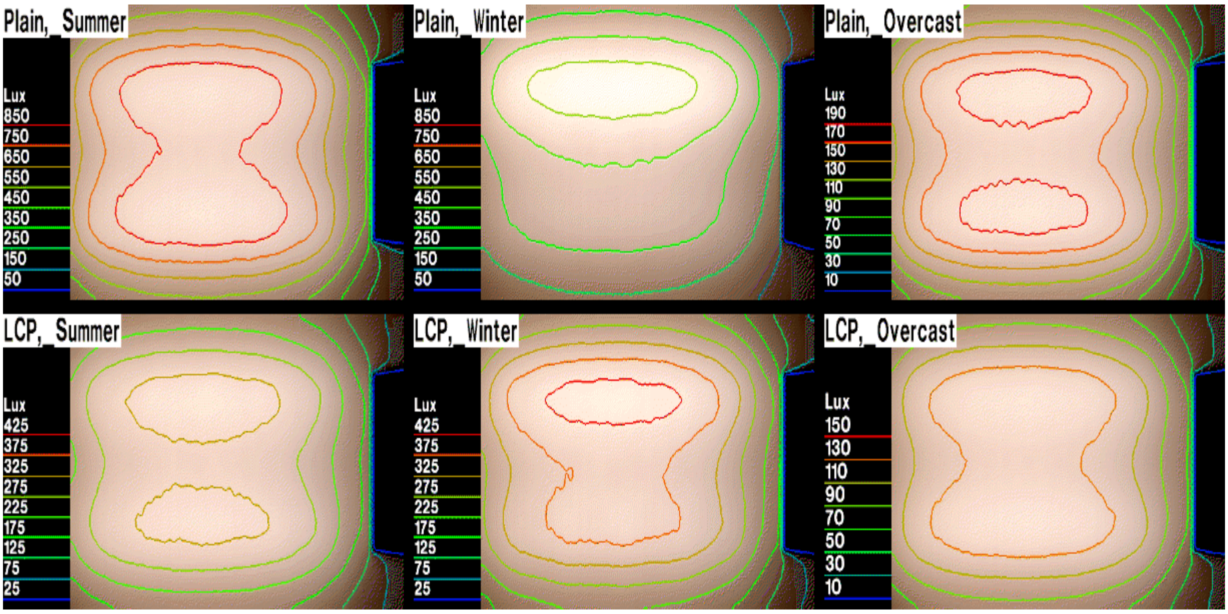

Figure 3 Simulation of Ten Angular Selective Skylights Over an Indoor Sports Enclosure. 60% of the Incident Sunlight is Rejected in Summer, 20% is Rejected in Winter, and 25% is Rejected Under Overcast Sky, Providing More Constant Illumination Throughout the Year

Micro-Light Guiding Shade Panels

The micro-LGS panel acts to both shade the façade from direct sunlight and distribute daylight deep into a building. The device has the form of a shade panel consisting of numerous 'micro-reflecting elements' (Figure 4). Each element consists of a diffusing input aperture and two specially shaped reflectors designed to direct light into the room within a specified angular range (Edmonds, 1992). Many such elements combined together form a shading panel, which resembles more conventional shading panels, yet performs the dual purposes of shading and light redirection (Greenup & Edmonds, 2000a; Greenup & Edmonds, 2000b).

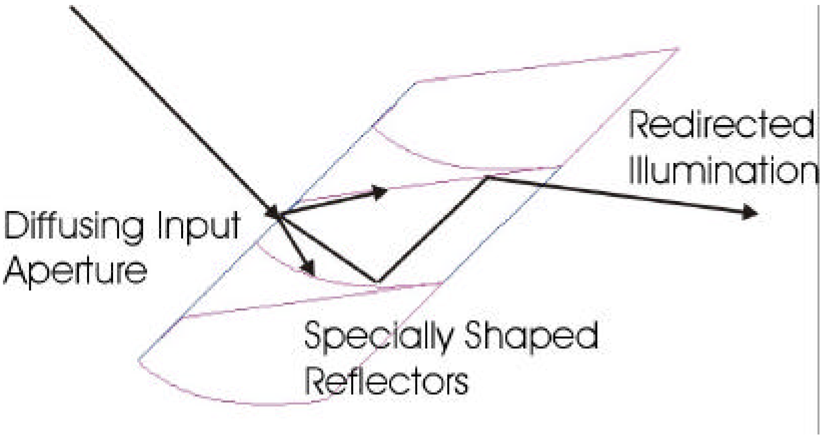

Figure 4 Micro-Reflecting Elements of the Micro-Light Guiding Shade Panel. Numerous Elements Combine to Form a Panel

The specially shaped reflecting surfaces are created in RADIANCE using 'gensurf', with a large number of intermediate surfaces, and smoothing applied. As mentioned above, RADIANCE is not ideally suited to the simulation of light undergoing strong light deflection. In order to overcome this problem, 'void' surfaces are created to cover the output apertures of the micro-reflecting elements. 'Mkillum' is then run to pre-calculate the device's luminous output, taking the void surfaces as input. This program directs a large number of rays at the output of each void surface and pre-calculates the resulting luminous output distribution. The resulting distribution is then added to the RADIANCE octree, and the final simulation may then be initiated.

Figure 5 displays visualisations of the panels in the window of a test room. These images show the room with and without the micro-LGS panels and exterior shading. Iso-luminance contours are overlaid on each of the images, revealing the distribution of illumination within the room. The lower images show the distributions of room illumination due to the shaded lower window and the micro-LGS panels respectively. The influence of the micro-LGS panels on room illumination is clear in the lower right image, where light is clearly thrown across the upper wall and ceiling. These visualisations have thus shown that the model of the micro-LGS panel system is working as desired.

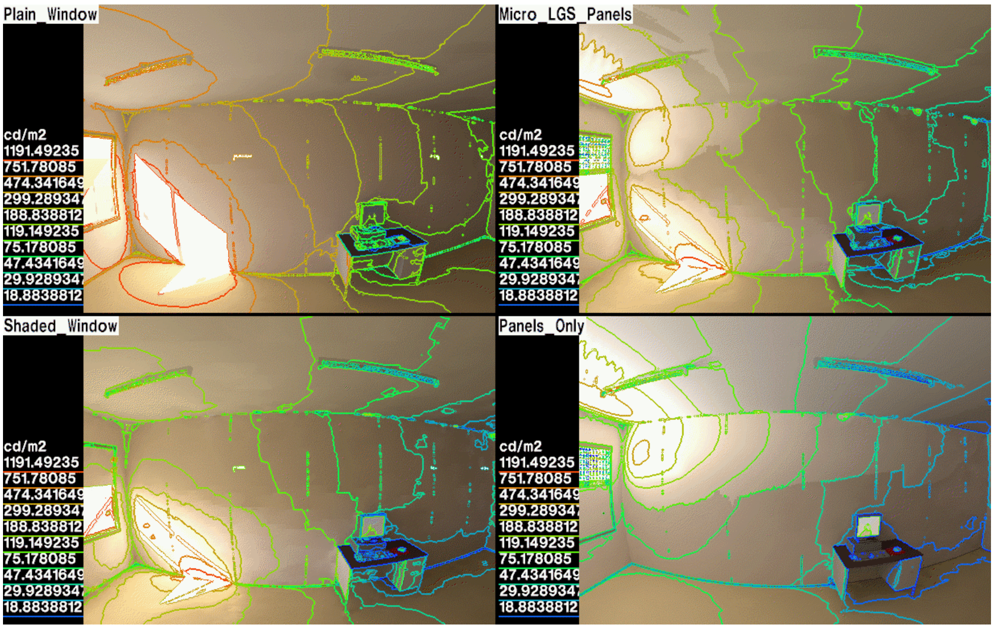

Figure 5 Micro-LGS Panels on Test Room - Light Redirection by the Panels is Clear in the Lower Right Image

Angular Throughput of Modelled Devices

Following the development of light redirecting devices such as those described above, it is helpful to examine the light throughput distribution of the modelled device. The distributions thus obtained can then be compared with measurable quantities for validation purposes.

To obtain such distributions, it is first necessary to create the appropriate model, including geometry, materials and light sources. Light sources used can be known sky luminance distributions, or defined angular sources such as the sun. An 'rtrace' input file is then created containing rays from a range of directions aimed at a representative position on the device being examined (for more information on the creation of input files, refer to the RADIANCE web-site (Erhlich, 2001)). For instance, to obtain the vertical luminous output distribution of an LCP, a set of rays are created such that the centre of the panel is the focus of rays located in the vertical plane evenly spaced between 90 degrees below and 90 degrees above the horizontal (Figure 6). Rtrace then determines the radiance associated with each of these rays. In the case of devices similar to the micro-LGS panel, it may be helpful to first run mkillum to pre-calculate the device's throughput distribution. Finally, the resulting distribution can be compared with experimental measurements of similar quantities.

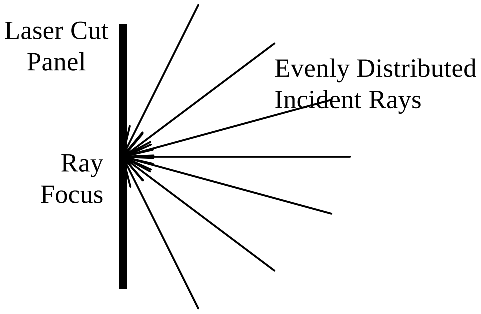

Figure 6 Incident Rays Defined to Measure the Vertical Luminous Output of an LCP

Figure 7 shows luminous output distributions obtained using the above method. This shows the luminance obtained by rtrace through a LCP and a clear glass window exposed to a CIE standard overcast sky. The distribution shown below horizontal displays light passing through the window from above the horizontal. The LCP redirects a large fraction of light incident from around 45 degrees elevation to a direction 45 degrees above horizontal into the room. The dotted bulge above horizontal is the ground reflection seen through the clear window, as modified by the angular transmittance of the window glass.

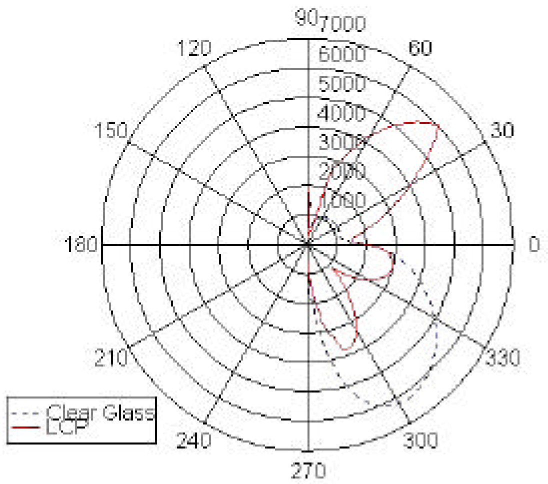

Figure 7 Luminous Throughput of LCP and Clear Glass Exposed to Overcast Sky. The Angular Selectivity of the LCP is Shown by the Peak at 45 Degrees Above Horizontal and Corresponding Dip Below Horizontal

Sensitivity Studies

Sensitivity studies of the modelled devices can use the above test for angular throughput. Such studies can assist in choosing appropriate materials and manufacturing techniques. They can also help with designing the correct device for each particular application, by altering the devices' design parameters.

Once an appropriate model has been created and validated, it is possible to change such factors as surface reflectivity, surface roughness, degree of smoothing of geometrical elements, and other design parameters. For each change made, a new light throughput distribution can be obtained and examined for the effect of the alteration.

Such studies have been performed on the micro-LGS panels, to determine a tolerance in manufacture of the specially shaped surfaces. It was found that panels with greater tilt from vertical are more sensitive to errors in manufacture.

Improved Sky Model

To accurately simulate novel daylighting devices on buildings, it is necessary to have an appropriate range of accurate representative sky models. The standard distribution of RADIANCE provides a uniform sky, and CIE standard clear, intermediate and overcast skies, with and without sun as appropriate. This range of skies is not broad enough to make an accurate representation of all available sky conditions. It is also difficult to validate experimental data with this selection of sky models.

Following commencement of the International Daylight Measurement Programme in 1991, more than a hundred sky luminance distributions from Berkeley, Tokyo and Sydney were collated (Kittler *et al.*, 1997). These distributions were analysed and 15 new sky types determined. These are known as the Standard Sky Luminance Distributions (SSLD), which are shortly to be implemented as the new CIE standard general sky. This range of skies can be examined using the SDF Sky Modelling web-site (Roy, 2001). A RADIANCE calculation file was written which generates each of these skies, based on the five model coefficients. This calculation file and instructions for its use are available from the author on request. The created algorithm is applied using the 'brightfunc' pattern modifier, making a call to the new calculation file. Hemispherical fish-eye views of the sky overlaid with iso-luminance contours reveals that the created skies are working as expected.

Further Investigations - Specular Reflection and Validation Techniques

Some discrepancies between experiment and simulation have been revealed to be caused by RADIANCE's model of specular reflectivity. Close inspection uncovered that specular reflectivity does not vary with angle of incidence. In most cases, this will not cause serious errors in results. However, errors may appear in simulations involving materials with large specular components, such as large shiny metal surfaces. A comprehensive solution to this problem has not yet been found, and work is still continuing.

Further investigations have been performed in order to find the best way by which to compare experimental results with simulated measurements. The authors have applied the test of Bland & Altman (1986) to comparisons between measurement and simulation. This test plots the difference between measured and simulated results against the mean of the two results. Overlaid on the same plots are 95 percent confidence intervals for the bias and for the difference between results. Thus, the plot becomes a graphical representation of the bias between experiment and simulation, and clearly demonstrates locations at which the simulations do not agree with experimental measurements. This test can be applied to either absolute or percentage differences between results.

DISCUSSION - PULLING IT ALL TOGETHER

The above algorithms have improved RADIANCE's capability for accurate simulations of novel daylighting devices. This section describes how all of the algorithms combine for a complete simulation of a new device.

The first step is to define your model in terms of the objects, geometries and materials involved. The new device should be modelled in a manner similar to the above light redirecting devices. This may require the creation of new calculation files or new geometries. Care should also be taken when defining materials with large specular components.

The next step is to define an appropriate sky model. A set of representative skies should be considered to examine the device's performance under varying external conditions. The SDF Sky Modelling web-site (Roy, 2001) may be consulted at this stage. For each selected sky, the model coefficients are found and entered into the above SSLD sky model.

The angular throughput of the device can be found using rtrace, as described above. If it appears that the device is not correctly modelled, the device's definition must be altered accordingly. Sensitivity analysis can then be performed in order to optimise the design.

Full simulations of the new device can then proceed. It may be appropriate to pre-calculate the device's luminous output using mkillum, depending on the form of the modelled device. Visualisations, luminance contour maps, false-colour images and illuminance maps may be created. If practical, the results of these simulations should be compared against experimental measurements for validation. The test of Bland & Altman (1986) may be applied to aid comparisons.

CONCLUSIONS

Daylight in buildings offers substantial benefits to building occupants and owners. Accurate computer lighting simulations may be used to swiftly assess the effect of proposed new daylighting devices. RADIANCE is the most advanced program available for such modelling, due to its ability to model an extensive range of geometries and materials. Several new algorithms have been developed which have extended RADIANCE's ability to model novel daylighting devices. These algorithms include models of the laser cut panel and micro-light guiding shade panel, calculation of light throughput distributions, sensitivity studies and improved sky models. RADIANCE's specular reflection model has also been investigated, and a method with which to assist validation studies has been proposed. All of these new algorithms have been applied to many simulations and were found to assist greatly in the accurate modelling of novel daylighting devices.

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