Lightpipe daylight simulation modelling using Radiance backward and forward ray tracing methods: a comparison with monitored data for commercial lightpipes in Ireland

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Abstract

A full-scale vertical light pipe experimental test rig was constructed to investigate the feasibility of light pipes in deep plan buildings. The Test rig allowed for monitoring of the light output from the base of lightpipes through base enclosures. Two light pipes were examined: 1000mm diameter and 530mm diameter, both approximately 6m in length. The light pipes were monitored for one month weeks and the daylight factor at reference points analyzed. The experimental test rig was then modeled in desktop Radiance, the output files of which were simulated using the 'PMAP' edition of Radiance. The results were compared with the monitored data and a comparative analysis presented. The PMAP program predicted luminance levels between 1.79 and 2 times that predicted by Desktop Radiance for the 530 and 1000mm lightpipes respectively. When the luminance ratio is used as an illuminance multiplier for the Desktop Radiance illuminance predictions, values within one per cent of measured illuminance are shown to result for the 530mm lightpipe.

1. Introduction

A light pipe is a 97 per cent specular reflective mirror pipe or duct that is used for the transmission of daylight from outside to a location within a building that would otherwise not experience daylight. Light pipes are commonly found in houses for lighting landing areas and en-suite toilets. Light pipes are also used in daylighting buildings across the industrial, education, and commercial sectors; but only in the capacity of lighting a single level/storey building. A multi-aperture light pipe system, patent pending, that can serve several levels of such buildings is proposed in this paper.

The light levels experienced from light pipes can be derived from experimentation and expressed mathematically which can then be modelled using computational methods. Radiance software was originally developed for prediction of illuminance levels experienced from conventional lighting applications such as windows, luminaries, and sky lights and is based on a backward ray tracing algorithm that derives the illuminance through tracing a ray of light from a point in a room backward reflecting two or three times typically along its path to the source, the sky. A forward ray tracing method has been developed which traces the light rays from the source forward through many reflections to a point in a room. Since light pipes are highly specular and contain many reflections of light, a forward ray tracing method is most suitable. The extent of the suitability of both methods is the subject of this paper which is validated through comparison with monitored data.

Two commercially available, full scale light pipes have undergone experimental analysis for their feasibility in this application. The experimental monitoring began at 17.30hrs on the 22nd July on a cloudy/sunny evening in Dublin, Ireland, and was used as the reference condition for comparison with lighting estimation methods. Forward and backward ray tracing methods using Radiance computer simulation software were then used to derive the expected illuminance contribution from the apertures. The results were compared with the measured values and conclusions drawn relating to the accuracy of Radiance software for predicting illuminance levels from light pipes under clear sky conditions.

3. Outside luminance

The outside luminance level was measured using standard type M light sensors supplied by Megatron. The sensors were calibrated to measure 1000lux per volt through a maximum voltage range of 30v (300,000 lux). The sensors were fitted with human corrective filters to monitor the light level that would normally be experienced by the occupants of a building. The sensors were secured to most central point within each lightpipe dome. The respective luminance levels received at the inlet to the light pipes was thus measured and logged over the month of July. Figure 1. presents the luminance levels available measured for each light pipe for 22nd July 2004 between 5 – 8pm. The smaller inlet dome was more shaded than the larger and so the relative difference between each was interpreted for each inlet about a stable monitoring perid of 40 and 15 klux. These results were later used for the simulation reference input values.

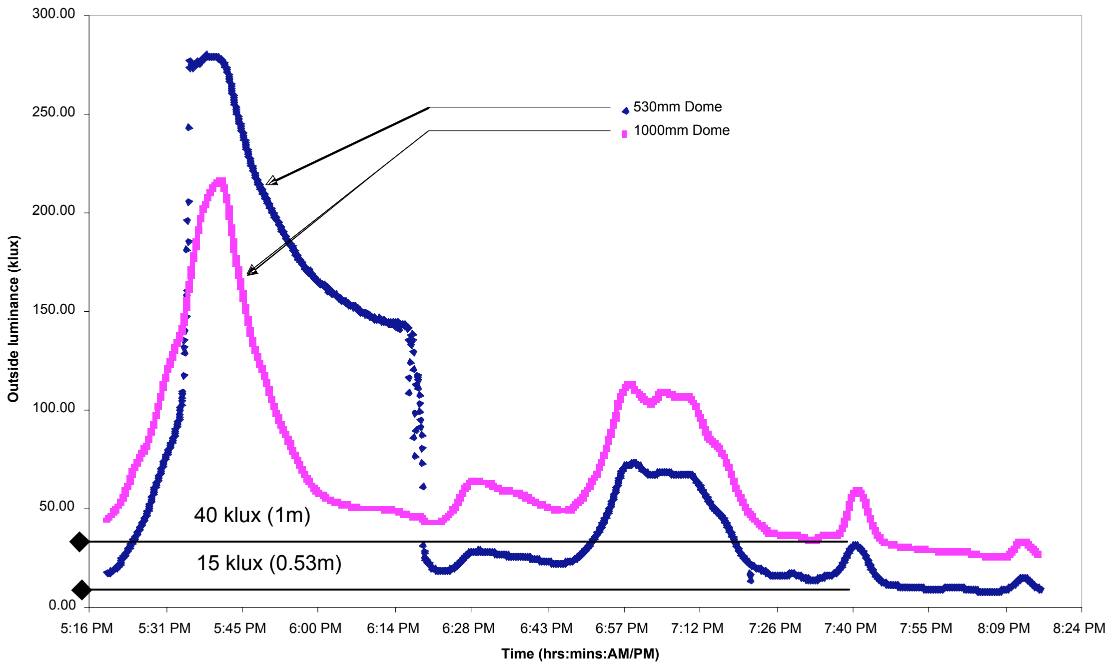

Figure 1. Luminance distribution at inlet to 530mm and 1000mm light pipe domes for 22nd July 2004 showing reference outdoor light levels used in analysis

4. lightpipe base details

Light sensors were placed at central reference beneath each of the light pipe enclosures, a distance of 1.5m from the base of the duct outlet to the working plane surface. The base of the small lightpipe was 600mm clear prismatic square film diffuser which was connected to through a 0.5m circular to square lightpipe transition piece. The large lightpipe base was a parabolic white plastic dome.

5. Desktop illuminance levels

Figure 2. presents the measured illuminance levels for the 530mm and 1000mm lightpipe enclosures respectively, for the same period of the outdoor luminance measurements (Figure 1.).

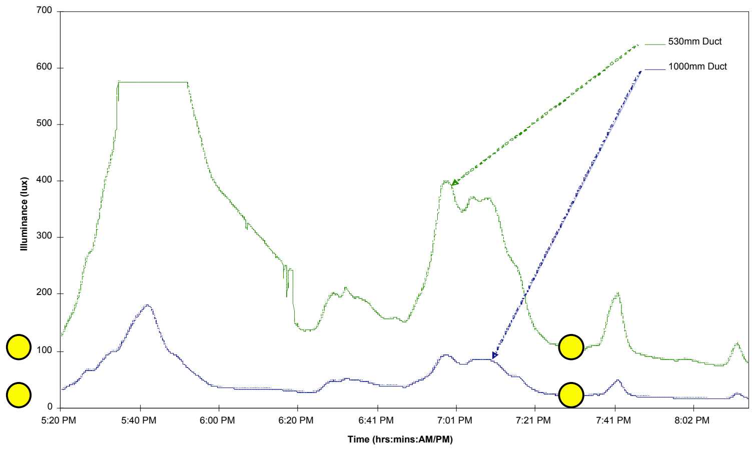

Figure 2. Illuminance measurements from lightpipes for 22nd July 2004

6. Daylight factors

The daylight factor, a common method of representation of light levels in buildings, may be expressed through calculation of the ratio of outdoor luminance to indoor illuminance expressed as a percentage. Figure 3. presents the daylight factors calculated for each enclosure.

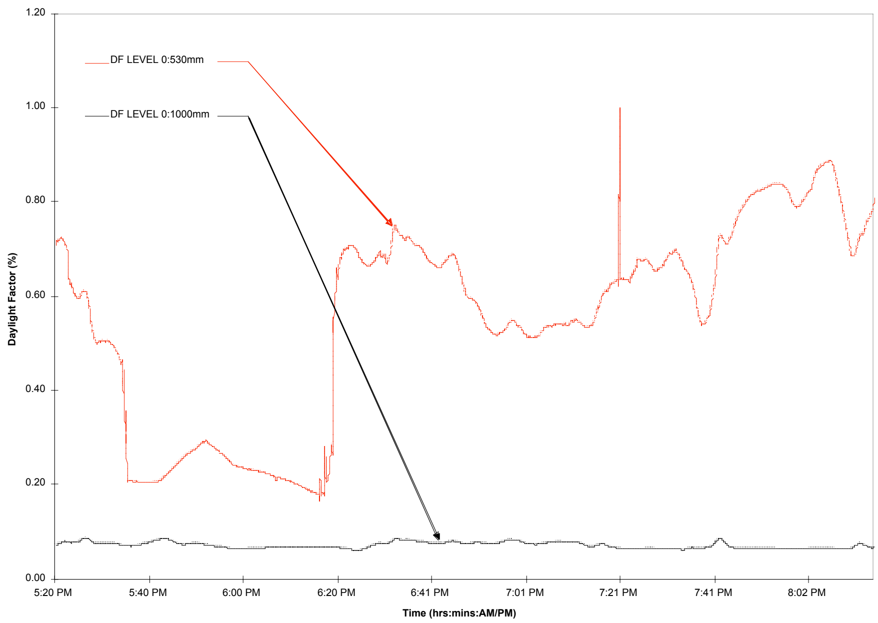

Figure 3. Daylight factors for 530mm and 1000mm light pipe apertures for 22nd July 2004

7. Radiance simulated results

The latest version of desktop radiance, v 2.0 Beta, was originally used for estimating the luminance and illuminance distribution throughout the lightpipes but following several simulation runs errors occurred that inhibited further simulation exercises. The errors included failure to simulate the base of the light pipe properly, showing a semi disc shape rather than a full disk that forms the base of the lightpipe; program 'crashing' during simulation runs following minor changes to geometry; failure of program to re-open after several simulation runs; and failure for program to model a dome inlet to the lightpipe. Version 1.02 was then used to simulate the same scenarios. The program was more stable, produced a full disc shape for the base of lightpipes and continued to run without problems following minor changes to the geometry; but could not model a glass dome inlet. A glass disc inlet was therefore adopted as a compromise. Initially the outside of the test rig was simulated and modified through an iterative process to achieve approximate reference light levels at the reference points within each dome. The actual simulated results for the reference illuminance levels at 18:00hrs was approximately half the actual values. The time of simulation was therefore brought forward until similar values were reached. The illuminance level within the small lightpipe dome was difficult to attain because the exact shading configuration resulting from the site geometery did not now exist owing to the new higher sun position. The glazing was therefore modified from clear (clear3.rad) to one with approximately half its transmission (afg-Es140.rad). Reference discs of similar 'specular reflective' material (galvanized.rad modified to 97% specular reflection) were placed as reference markers 200mm beneath each dome which defined the plane of the illuminance plot. The simulation yielded an illuminance level within the small dome of approximately 15.625 klux and in the large dome of some 40.25 klux, approximating the reference values of 15 and 40klux respectively. Figure 4. presents the results from the final simulation of outside the test rig and illustrates the arrangement of the ducts about the enclosure scaffold fixture.

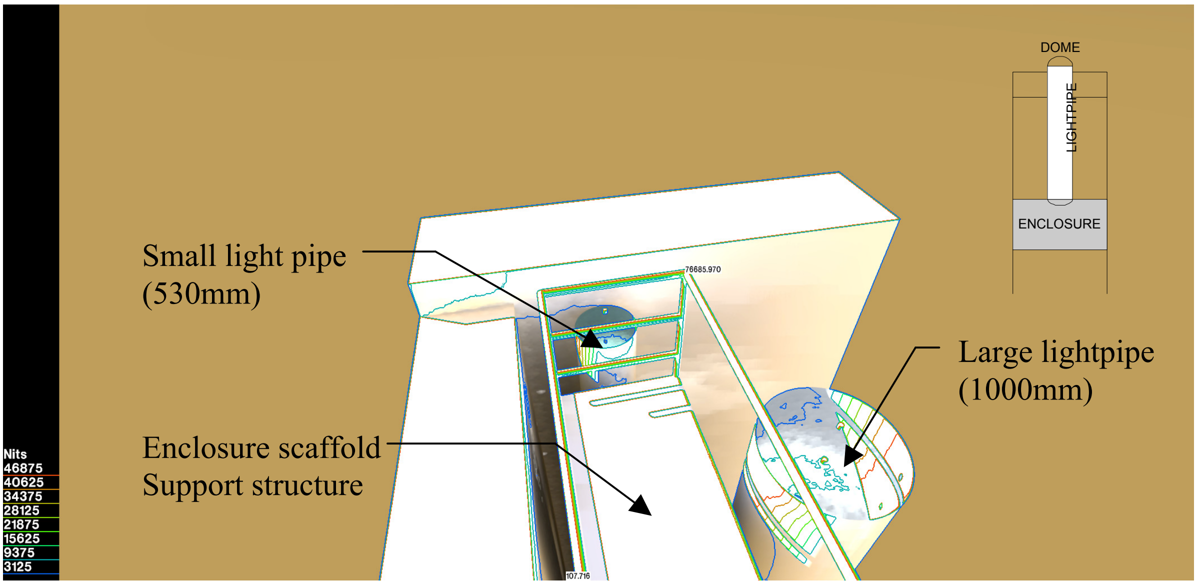

Figure 4. Outdoor illuminance plot at 15.00hrs (22/07) using reference aluminium discs within each light pipe

Data: 530mm duct = **15,625 lux** at reference marker; 1000mm duct = **40,625 lux** at reference marker

7.1 Enclosure light levels

The following range of figures present the simulated illuminance and luminance levels for both enclosures taken at the reference date and time, i.e. as per Figure 4. light levels.

7.1.1 530mm Duct base enclosure

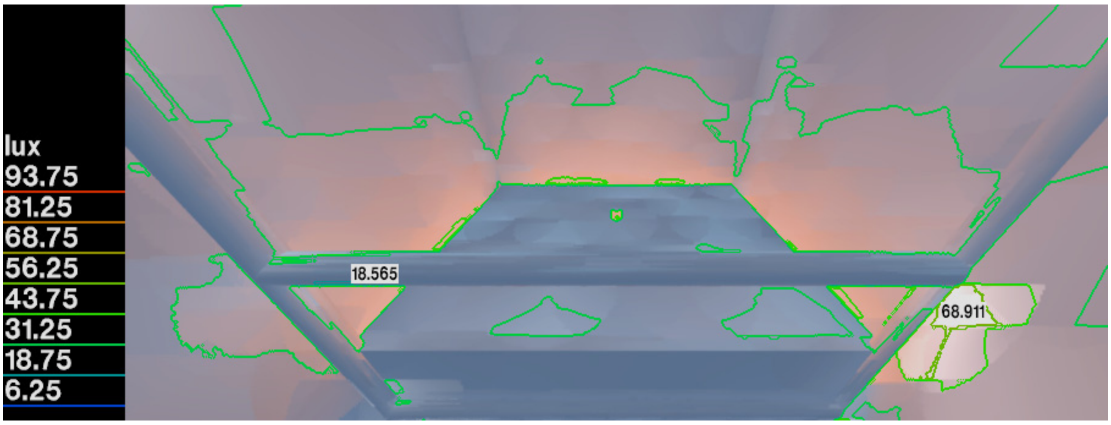

Figure 5. Illuminance plot (DR V 1.02)

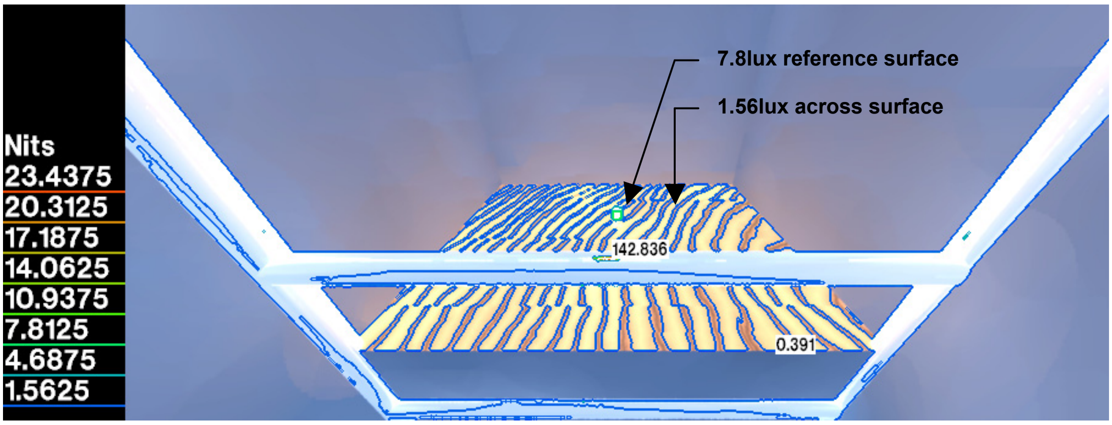

Figure 6. Luminance plot (DR V 1.02)

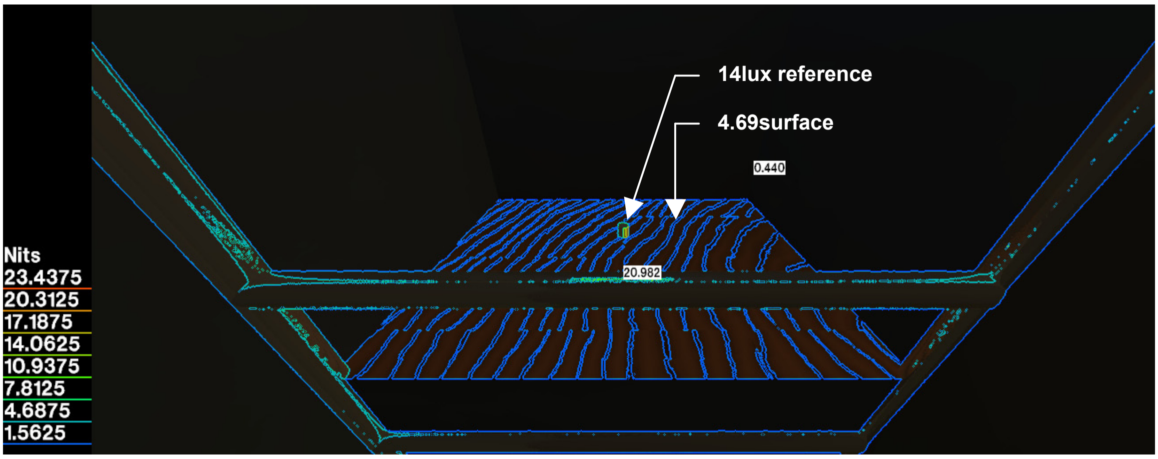

Figure 7. Luminance plot (PMAP)

7.1.2 1000mm Duct base enclosure

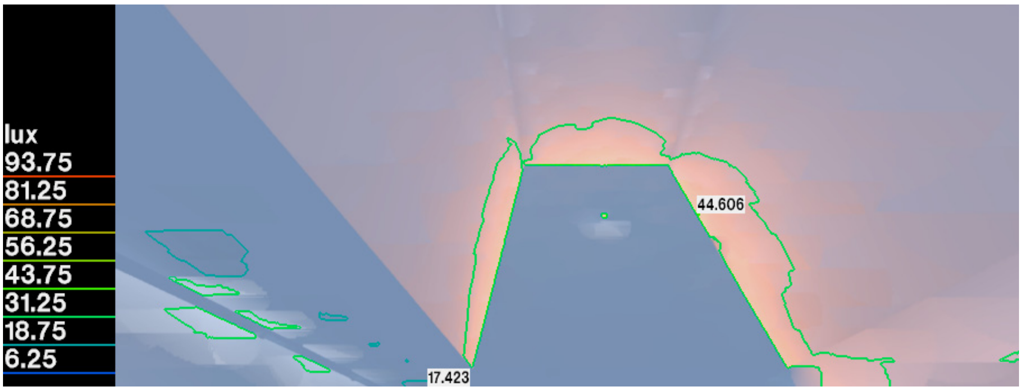

Figure 8. Illuminance plot (DR V 1.02)

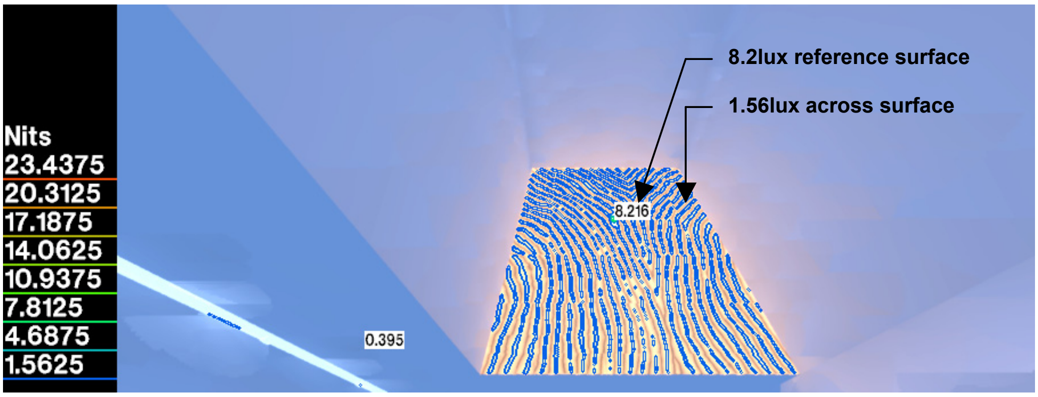

Figure 9. Luminance plot (DR V 1.02)

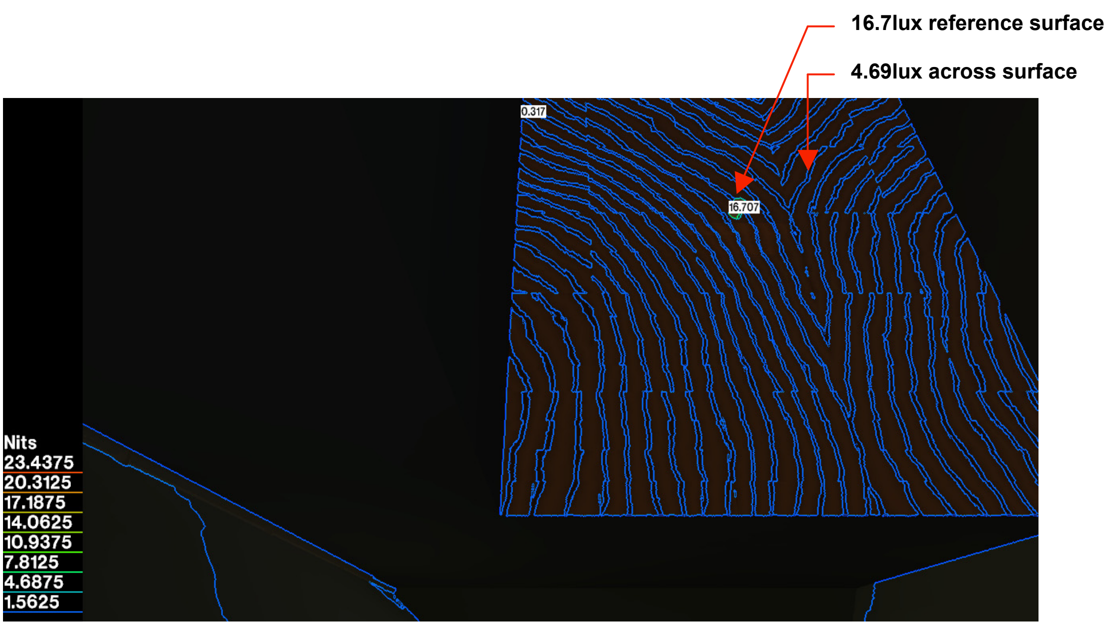

Figure 10. Luminance plot (PMAP)

8. High quality luminance renderings of view upward to luminance source to each enclosure

The following figures illustrate a view upward from the working plane edge nearest the scaffold structure toward the light outlet to each enclosure. The simulation runs were performed at maximum accuracy using Desktop Radiance V 1.02. Luminance plots were then performed to indicate the overall luminance from the enclosure surfaces and to illustrate the ability of the program to generate a realistic image of the base of the lightpipe. The small lightpipe was fitted with a square outlet and the large lightpipe with a dome outlet. Owing to restrictions in the Desktop V 1.02 it was not feasible to introduce a dome geometry and so a flat disc shape instead was used.

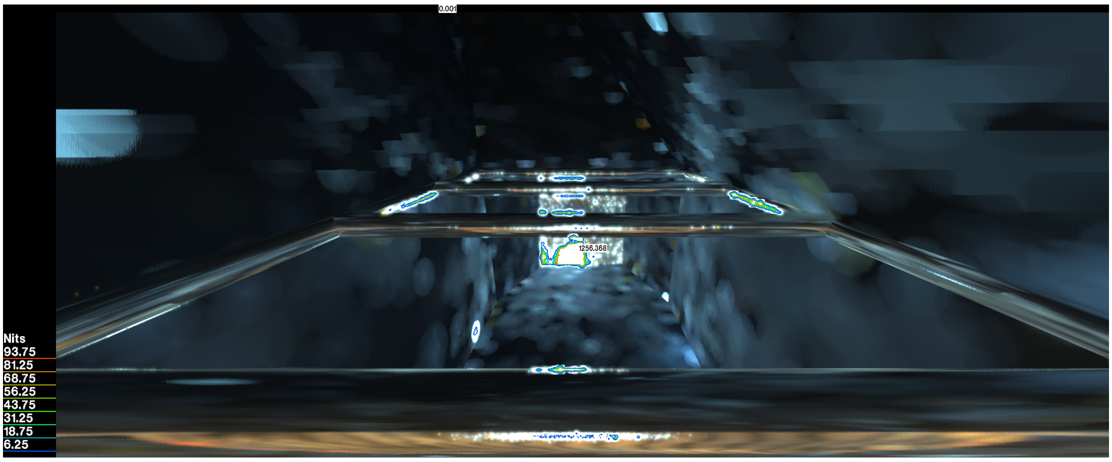

Figure 11. Luminance about the 530mm lightpipe base

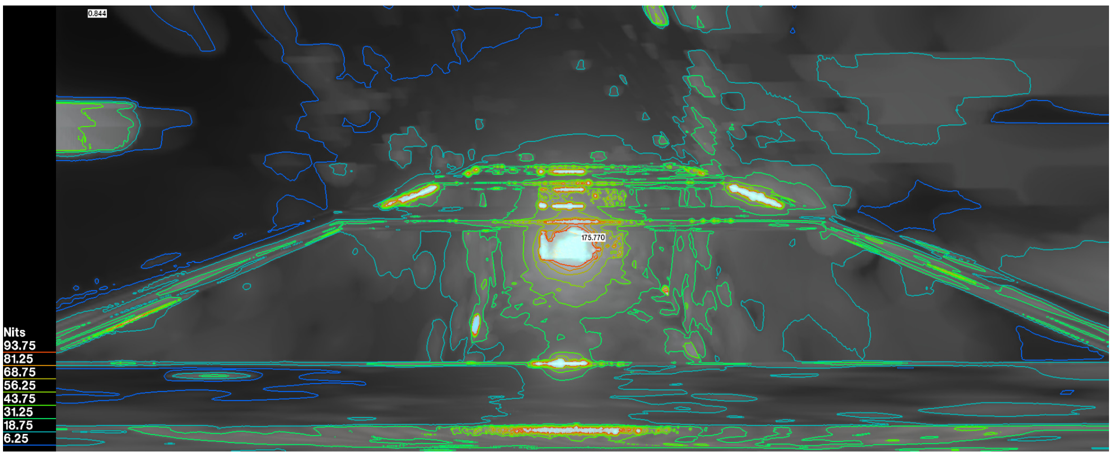

Figure 12. Luminance of 530mm lightpipe base with human correction

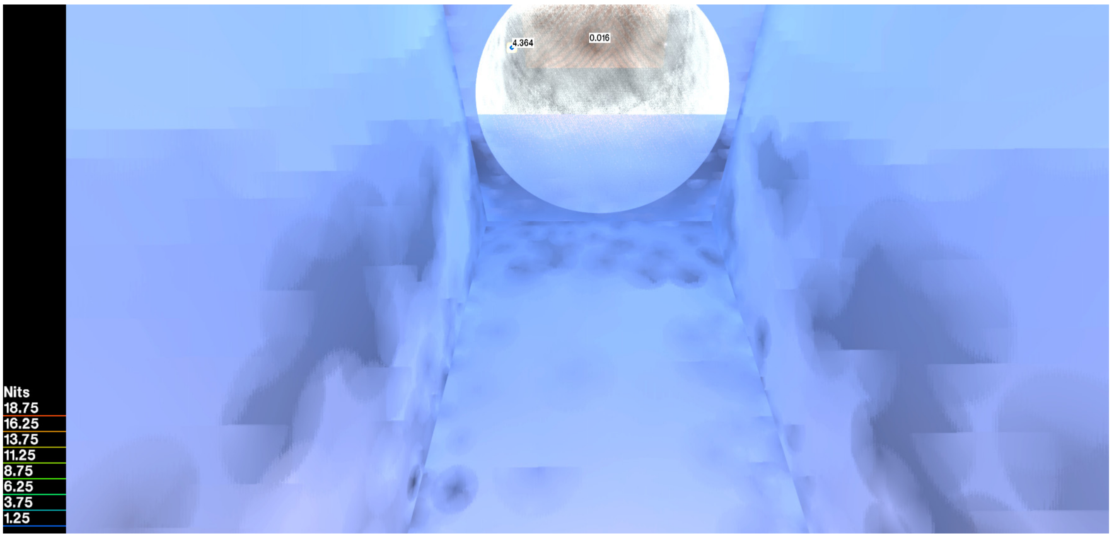

Figure 13. Luminance about the 1000mm lightpipe base

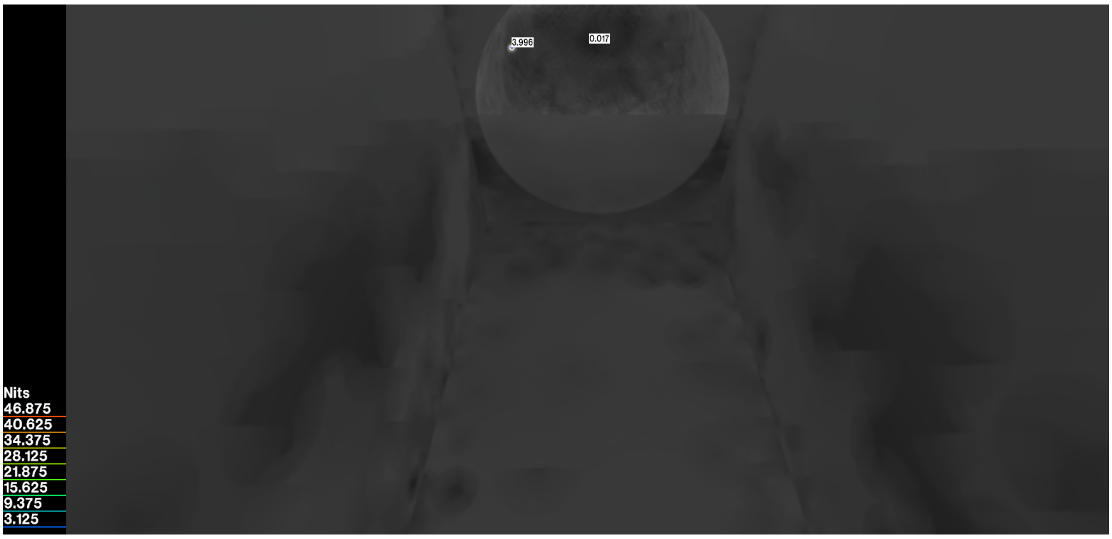

Figure 14. Luminance of 1000mm lightpipe base with human correction

9. Monitoring and Simulation Results

Table 1. presents in summary the results from the measured and simulated light levels for the light pipe test rig. The location refers to the area of the test rig under examination whereas the reference point illuminance is the illuminance measured or simulated at the reference point set out in section 4. The luminance level could not be measured directly and so is simulated for both enclosures thereby acting as one indicator of simulation performance.

9.1 Comments on monitoring of test rig

Shortly after completion of the test rig the large lightpipe allowed ingress of some water during heavy rain storms. The water accumulated on the surface of the outlet dome and when drained prior to the monitoring, a green mould surface remained. This surface covered approximately 50 per cent of the dome base and was practically opaque to light transmission from the lightpipe to the enclosure. Furthermore, dust and dirt may have entered during the period which would reduce surface specular reflectivity to below the manufacturers 97 per cent rating.

Location	Reference Point Illuminance (lux)		Luminance (lux)	
	Measured	Radiance (V 1.02)	Radiance (V 1.02)	Radiance (PMAP)
530mm Dome inlet	15,000	15,625	N/A	N/A
100mm Dome inlet	40,000	40,625	N/A	N/A
530mm Enclosure	100	56.25	7.8 (1.56 Ave)	14 (4.69 Ave)
1000mm Enclosure	25	44.6	8.2 (1.56 Ave)	16.7 (4.69 Ave)

Table 1. Summary of measured and simulated data

10. Discussion and conclusions

The simulation exercise demonstrated that the desktop version 1.02 of Radiance can predict illuminance levels generated from the base of a lightpipe to within some + 100 per cent for the large lightpipe or – 50 pre cent for the small lightpipe. The measured daylight factors about the reference outdoor luminance levels varied between 0.0625 and 0.66 per cent for the large and small lightpipes respectively; the simulated results were 0.11 and 0.375 thereby over/under predicting by + 75 and – 43 per cent for the large and small lightpipes respectively.

10.1 The large lightpipe

Considering comments relating to the large lightpipe made in section 8, it is clear that green mould is blocking 50 per cent of the light transmission to enclosure. Furthermore considering the inlet/outlet details outlined in section 4, the white acrylic dome outlet would have a much reduced light transmission than the clear prismatic diffuser. These factors considered the measured light level in the large enclosure will rise to some 100 lux or more with replacement of the base dome to an identical prismatic fitting as used with the 530mm lightpipe. The simulated illuminance level for the large light pipe is slightly lower than the small lightpipe and is related to slight changes in the outlet configuration as discussed; but was attributable to the dome shape or transmittance values as a flat disc shape of equal transmittance (clear3.rad material) was used in all large lightpipe simulation runs.

10.2 The small lightpipe

The 530mm lightpipe modelled had the least discrepancies with the full scale test rig and therefore yielded the least deviation between measured and simulated illuminance level (50 per cent *c.f.* 100 per cent). Furthermore, the PMAP reference point luminance analysis highlighted that the Desktop Radiance (V 1.02) produced values consistently 50 per cent below its predicted levels. Considering luminance level predicted by a simulation program to be an indicator of the illuminance level predicted by that same program then it is possible to derive an illuminance factor or multiplier with reference to the most accurate program. Taking the ratio of the PMAP to Radiance V 1.02 luminance values as a multiplier for the respective point illuminance values then a simulated value within one percent of the measured value results.

10.3 Conclusion

A full scale test rig was constructed to demonstrate the feasibility of lightpipes as a means of providing sufficient illuminance for lighting buildings and to serve as a reference for demonstration of simulation program ability to predict such illuminance levels. Two lightpipes, 530mm and 1000mm diameter, were monitored for a period of one month from which a reference working plane illuminance and daylight factor were derived. The daylight factors varied greatly from 0.66 per cent for the 530mm lightpipe and 0.0625 per cent for the 1000mm lightpipe. It was shown that the large light pipe was inefficient in light transmission due to initial leaking of water to the lightpipe from outside which led to build up of dirt, dust, and mould on the wall surfaces and on the aperture outlet. Furthermore the aperture was white acrylic which had inferior transmittance to the prismatic diffuser used for the 530mm lightpipe.

The Radiance simulation software program was used to estimate the illuminance and luminance from the light pipes. The test rig was drawn into ACAD R14 and both versions of Desktop Radiance (V 1.02 and V 2.0 Beta) were run Windows 2000 Professional. The latter proved unstable and unable to visually represent the basic cylindrical lightpipe outlet shape. Neither program could simulate using 3D surface domes for the inlet or outlet of the system. The original V 1.02 of Desktop Radiance was however stable, and succeeded to generate illuminance and luminance distribution analysis for the test rig. The simulated illuminance level for the 530mm lightpipe best represented the monitored value, owing to physical testing reasons as discussed, but still predicted illuminance levels some 50 per cent below the actual condition.

The photon mapping (PMAP) edition of Radiance was run on Linux (Redhat) and successfully generated luminance distribution analysis for the test rig. The input data (Octree, View, Material, Glazing data) was taken from the initial Desktop Radiance (V 1.02) analysis and the glazing file(s) was/were used as the photon port modifier(s) in the luminance simulation runs. The PMAP program predicted luminance levels twice that predicted using the Desktop Radiance (V 1.02) program and produced more clear and realistic images. Considering the forward ray tracer (PMAP) to produce more indicative results than the backward ray tracer (Desktop Radiance) the luminance from the PMAP edition was taken as most representative of the real value. The difference in prediction methods was established through the ratio of the PMAP/DR luminance reference point values which was in turn used as an illuminance multiplier. When the multiplier was applied to the 530mm lightpipe a simulated value of within 1 per cent of the measured value resulted. The PMAP version of Radiance simulation software suite has been demonstrated to be more accurate than Desktop Radiance V 1.02 and can accurately predict illumination levels of spaces lit by lightpipes through application of a luminance ratio multiplier. In this paper, the multiplier was found to range between 1.79 and 2 for the 530mm and 1000mm lightpipes respectively.