Application of Daylighting Computer Modeling in Real Case Studies: Comparison between Measured and Simulated Daylight Availability and Lighting Consumption

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NRCC-42862

A version of this paper is published in / Une version de ce document se trouve dans : IEA (International Energy Agency) Task 21 / Annex 29: Daylight in Buildings, November 1998, 68 pp.

T21/C1-21/CAN/98-11

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INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

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by

Anca D. Galasiu *   Morad R. Atif *

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INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

IEA Solar Heating and Cooling Programme (IEA SHC)

The International Energy Agency (IEA) was established in 1974 as an autonomous agency within the framework of the Economic Cooperation and Development (OECD) to carry out a comprehensive program of energy cooperation among its 24 member countries and the Commission of the European Communities.

An important part of the Agency's program involves collaboration in the research, development and demonstration of new energy technologies to reduce excessive reliance on imported oil, increase long-term energy security and reduce greenhouse gas emissions. The IEA's R&D activities are headed by the Committee on Energy Research and Technology (CERT) and supported by a small Secretariat staff, headquartered in Paris. In addition, three Working Parties are charged with monitoring the various collaborative energy agreements, identifying new areas for cooperation and advising the CERT on policy matters.

Collaborative programs in the various energy technology areas are conducted under Implementing Agreements, which are signed by contracting parties (government agencies or entities designated by them). There are currently 41 Implementing Agreements covering fossil fuel technologies, renewable energy technologies, efficient energy end-use technologies, fusion technology and energy technology information centers.

The Solar Heating and Cooling Programme (SHC) was one of the first IEA Implementing Agreements to be established. Since 1977, its 21 members have been collaborating to advance active solar, passive solar and photovoltaic technologies and their application in buildings.

Australia	Greece	New Zealand
Austria	Finland	Norway
Belgium	France	Spain
Canada	Italy	Sweden
Denmark	Japan	Switzerland
European Commission	Mexico	United Kingdom
Germany	Netherlands	United States

A total of 26 Tasks have been initiated, 19 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition, a number of special ad hoc activities--working groups, conferences and workshops--have been organized.

The Tasks of the IEA Solar Heating and Cooling Programme, both completed and current, are as follows:

Completed Tasks:

Task 1 *Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2 *Coordination of Solar Heating and Cooling R&D*
Task 3 *Performance Testing of Solar Collectors*
Task 4 *Development of an Insolation Handbook and Instrument Package*
Task 5 *Use of Existing Meteorological Information for Solar Energy Application*
Task 6 *Performance of Solar Systems Using Evacuated Collectors*
Task 7 *Central Solar Heating Plants with Seasonal Storage*
Task 8 *Passive and Hybrid Solar Low Energy Buildings*
Task 9 *Solar Radiation and Pyranometry Studies*
Task 10 *Solar Materials R&D*
Task 11 *Passive and Hybrid Solar Commercial Buildings*
Task 12 *Building Energy Analysis and Design Tools for Solar Applications*
Task 13 *Advance Solar Low Energy Buildings*
Task 14 *Advance Active Solar Energy Systems*
Task 16 *Photovoltaics in Buildings*
Task 17 *Measuring and Modeling Spectral Radiation*
Task 18 *Advanced Glazing Materials for Solar Applications*
Task 19 *Solar Air Systems*
Task 20 *Solar Energy in Building Renovation*

Current Tasks and Working Groups:

Task 21 *Daylight in Buildings*
Task 22 *Building Energy Analysis Tools*
Task 23 *Sustainable Solar Buildings: The Optimization of Solar Energy Use in Larger Buildings*
Task 24 *Active Solar Procurement*
Task 25 *Solar Assisted Air Conditioning of Buildings*
Task 26 *Solar Combosystems*

Task reports and ordering information can be found in the IEA Solar Heating and Cooling Programme publications list. For additional information contact the SHC Executive Secretary, Pamela Murphy Kunz, Morse Associates Inc.,1808 Corcoran Street, NW, Washington, DC 20009, USA,Telephone:+1/202/483-2393, Fax:+1/202/265-2248, E-mail:pmurphykunz@compuserve.com
Also, visit our web site at: http://www.iea-shc.org

IEA Energy Conservation in Buildings and Community Systems (IEA ECBCS)

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following have been initiated by the Executive Committee (completed projects are identified by *):

1 Load Energy Determination of Buildings *
2 Ekistics and Advanced Community Energy Systems *
3 Energy Conservation in Residential Buildings *
4 Glasgow Commercial Building Monitoring *
5 Air Infiltration and Ventilation Centre
6 Energy Systems and Design of Communities *
7 Local Government Energy Planning *
8 Inhabitant Behaviour with Regard to Ventilation *
9 Minimum Ventilation Rates *
10 Building HVAC Systems Simulation *
11 Energy Auditing *
12 Windows and Fenestration *
13 Energy Management in Hospitals *
14 Condensation *
15 Energy Efficiency in Schools *
16 BEMS - 1: Energy Management Procedures *
17 BEMS - 2: Evaluation and Emulation Techniques *
18 Demand Controlled Ventilating Systems *
19 Low Slope Roof Systems *
20 Air Flow Patterns within Buildings *
21 Thermal Modelling *
22 Energy Efficient Communities *
23 Multi-zone Air Flow Modelling (COMIS) *
24 Heat Air and Moisture Transfer in Envelopes *
25 Real Time HEVAC Simulation *
26 Energy Efficient Ventilation of Large Enclosures *
27 Evaluation and Demonstration of Domestic Ventilation Systems

28 Low Energy Cooling Systems*
29 Daylight in Buildings
30 Bringing Simulation to Application
31 Energy Related Environmental Impact of Buildings
32 Integral Building Envelope Performance Assessment
33 Advanced Local Energy Planning
34 Computer-aided Evaluation of HVAC System Performance
35 Design of Energy Efficient Hybrid Ventilation (HYBVENT)

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Summary

This official IEA report is a deliverable of the IEA SHC Task 21 / IEA ECBCS Annex 29: Daylight in Buildings. The task focuses on daylighting systems and strategies which can be applied in new and existing buildings with high electricity saving potential such as offices, schools, commercial and institutional buildings. The daylighting performance of these strategies is tested in laboratory facilities, through modeling, and in real case study buildings. This report is a deliverable of the Subtask C research projects. The main objective of Subtask C, as stated in the Implementing Agreement of IEA SHC Task 21 / IEA ECBCS Annex 29 is “to improve the capability, accuracy and ease-of-use of daylighting design and analysis tools for building design practitioners. The practitioners will be able to predict the performance of different daylighting systems and control strategies and to evaluate the impact of the integration of daylighting in the overall building energy concept by using these design tools“. Subtask C work included the development of the Adeline lighting software, along with the assessment of its capabilities and accuracy.

This report investigates the accuracy and limitations of the Adeline 1.0 lighting software in simulating the illuminance distribution from daylighting and the electrical lighting energy savings of an existing atrium building. The purpose of the study was to compare the Superlite, Superlink and Radiance computed outputs against data collected in a real building.

The case study is an enclosed atrium space located in Ottawa, Canada. The atrium is a three-storey octagonal construction roofed by a pyramidal skylight made of several glazing systems. The space is equipped with an automatic on/off lighting control system operated by a daylight photosensor located in another atrium space part of the same facility. Field work was conducted for both summer and winter conditions and included measurements of horizontal indoor and outdoor illuminance, solar radiation and electrical lighting system time-of-use. The computer simulation phase consisted in the creation of two computer models, a Superlite/Superlink simple model and a Radiance model used to simulate the daylighting performance of the atrium space. The accuracy of the Superlite and Radiance programs in simulating interior daylight levels was evaluated based on comparisons between the predicted and the on-site measured illuminance. In addition, the Superlite simulated outdoor illuminance was compared with the measured outdoor illuminance. The amount of electrical lighting displaced by daylighting via the automatic on/off lighting control system was also compared in order to evaluate the prediction of lighting energy savings.

Data shows that the Superlite predicted outdoor illuminance was closer to the measured outdoor illuminance for clear sky conditions than for overcast sky. Despite the fact that the distribution profiles of simulated illuminance followed closely the profiles of measured illuminance under both sky conditions, the instantaneous illuminance was significantly underpredicted especially under overcast sky. Under a summer clear sky, the outdoor illuminance was slightly overpredicted and the discrepancy between the measured and the simulated instantaneous illuminance was between 1 and 16%. Under a winter clear sky, the outdoor illuminance was slightly underpredicted and the difference between the measured and the simulated instantaneous illuminance was between 12 and 29%. The range of measured illuminance differed greatly from the predicted range for overcast sky conditions, the outdoor illuminance being in this case notably underpredicted by up to 60%.

The discrepancy between the outdoor measured and simulated illuminance reflected on the simulated indoor illuminance, which was underpredicted by 50% for both a winter clear sky and an overcast sky. This underprediction was likely to affect the subsequent Superlink long-term energy calculations and suggested that annual savings from daylighting may in reality be higher than predicted. Summer data showed a good agreement in overall range and distribution pattern between the measured and the simulated indoor illuminance under a clear sky. However, despite this good overall agreement, the instantaneous illuminance differed sometimes by 3 to 10 times from the measured value. This high instantaneous discrepancy was attributed to the geometrical differences between the real and the simulated space, and was not likely to alter the long-term energy calculations since both the measured and the simulated illuminance were considerable above the space design illuminance.

The comparison between the measured and the Radiance computed data showed that, for any particular sky condition, the computer model has the potential to accurately model the daylighting performance of a space if relevant input data, such as precise space geometry, construction materials properties and actual sky description are available. For the case study, the range and distribution pattern of the simulated horizontal indoor illuminance were in good agreement with the predicted illuminance under diffuse daylight for both a summer and a winter clear sky. However, the instantaneous simulated illuminance differed at times by as much as 100% from the measured values under direct sun. Indoor illuminance was very well predicted by Radiance for an overcast sky. The instantaneous discrepancy between the measured and the simulated illuminance was in this case below 20%, confirming the fact that diffuse daylight was simulated more accurately than the direct component. The occasional high discrepancy between the measured and the simulated illuminance under direct sun was partly attributed to the overall average transmittance used to account for the three glazing systems of the atrium skylight. It is believed that with more time invested in reproducing the exact configuration of the atrium fenestration, more accurate results could be obtained.

The discrepancy between the measured and the Superlink computed lighting energy savings was 22% for June 1995. On-site lighting control problems caused measured savings to be 3 times lower than predicted for December 1995. The small discrepancy obtained for the summer month was attributed to the overprediction of daylight availability in the weather file. The significant difference between the measured an the simulated data for the winter month was attributed to the snow and frost that covered the skylight during the entire month and the abnormal operation of the lighting control system under these conditions. It is believed that the measured savings would have been much closer to the predicted values, had the control system functioned properly. The poor winter performance of the lighting control system affected greatly the discrepancy between the measured and the simulated annual energy savings. While the predicted annual savings were about 28700 kWh/year, the savings estimated from measurements were only 17830 kWh/year, which is 61% lower than predicted.

Acknowledgements

The authors would like to acknowledge the financial contribution of Natural Resources Canada; Panel for Energy Research & Development Canada (PERD); and the National Research Council Canada. IEA SHC Task 21 Subtask C participants in particular, and IEA SHC Task 21 participants in general, have provided valuable feedback and comments towards this report. Hans Erhorn, Jan de Boer, and Michael Dirksmoller have provided valuable input with respect to the use of the Adeline software. The list of Subtask C participants is provided below.

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Kjeld Johnsen and Marc Fontoynont have also provided feedback that helped improve the content of this document.

APPLICABILITY OF DAYLIGHTING COMPUTER MODELING IN REAL CASE STUDIES: COMPARISON BETWEEN MEASURED AND SIMULATED DAYLIGHT AVAILABILITY AND LIGHTING CONSUMPTION

Anca D. Galasiu **Morad R. Atif**

INTRODUCTION

Problem

Energy savings from daylighting in buildings have always been predicted using computer simulation. Yet, daylight prediction models and computer software have rarely been validated against real case studies with real occupancy. The degree of accuracy and behavior profile of daylighting performance indicators using computer simulation are also not known. Several daylighting and lighting software have been developed and are often used without enough knowledge about their accuracy or limitations. Validation studies are usually limited to test cells that do not include all the operation aspects of normal building activity. For these software to be applied as design tools, it is important to know not only their limitations and applicability, but also their prediction capabilities.

This report presents the validation of the Adeline 1.0 lighting design and analysis software. This work was initiated by the need to use the Adeline software in a future study that has the aim to develop design guidelines for atrium buildings. This report outlines the software accuracy and limitations in predicting specific lighting parameters in a real atrium space. Computed outputs are compared against data collected in a real case study with real occupancy.

Objectives

The objectives of the study are directed towards testing the accuracy of the Adeline 1.0 software in simulating the illumination levels and electric lighting energy consumption of an existing atrium building. These objectives are:

- to verify the accuracy of the Superlite program in calculating indoor horizontal illuminance levels from daylighting;

- to determine the accuracy of the Superlink program in predicting the impact of daylighting on the lighting energy balance of the building;

- to verify the accuracy of the Radiance program in calculating the illuminance from daylighting on several horizontal planes in the atrium building.

These objectives are intended to address the degree of accuracy and the limitations that could realistically be expected when predicting specific lighting parameters in a given space with real occupancy and complex geometry, and when using the Adeline 1.0 software as a design tool for such complex daylighting systems.

Case Study Description

The monitored atrium building is located in the center of a large empty land, in the western suburb of Ottawa, Canada. The site is at a latitude of 45.24°, a longitude of 75.43° and an altitude of 125 m (416 ft). The atrium, which is one of seven atria of a large office\research facility, is a three-storey octagonal construction located at the main entrance of the research complex. Figure 1 shows a plan and a section of the building.

The atrium space is surrounded by walkways leading to adjacent offices and meeting rooms. Main occupancy occurs between 7 AM to 7 PM. Primary activities include standing, walking and occasional reading, or similar work. A linear corridor connects the atrium to the rest of the building. The first floor houses the main building entrance and reception desk and has a floor area of 151 m^2 (1625 ft^2). The second and third floors contain offices and conference rooms adjacent to the atrium and have floor areas of 91 m^2 (980 ft^2) each. The adjacent rooms were not designed to receive light from the atrium and have their own exterior fenestration.

Description of Daylighting Features

Daylight features of the space include a skylight and an automatic on/off daylight-linked lighting control system.

Fenestration

The top-fenestration has an area of 161 m^2 (1732 ft^2). The atrium skylight has a pyramidal shape and was designed to provide abundant daylight in the winter, while minimizing the solar load in the summer. Figure 2 shows a plan and cross-section of the fenestration. As shown, the glazing system along the skylight area is not uniform and consists of three glazing systems. Table 1 summarizes the material on each layer of the three glazing systems. Each system is triple-glazed, consisting of two air spaces and a heat mirror sandwiched between an inner and outer layer of glass. The patterned glass has opaque horizontal lines applied across it (ceramic frit). This pattern reduces the overall glazing area by 20% (80% open, 20% patterned). There are two different types of heat mirrors used in the fenestration glass systems: HM66/clear and HM55/green. Manufacturer's specifications state that HM66/clear has a transmittance of 53% and an exterior reflectance of 24%, while HM55/green has a transmittance of 38% and an exterior reflectance of 28%. No similar information was available about the transmittance of the clear and laminated layers of glass. Consequently, both clear and laminated glass were estimated from the literature to have a transmittance of about 78% and a reflectance of 7%. Similarly, the green-tinted glass was estimated to have a transmission of 46% and a reflectance of 5%.

Electrical Lighting System

Recessed incandescent fixtures, 150PAR38, mounted at a height of 3.8 m from the floor, provide primary artificial illumination in the atrium. There are sixteen of these fixtures identically arranged on each of the three floors. Every second fixture provides emergency lighting and remains always on. A single daylight sensor controls the remaining fixtures. This sensor is located just below the fenestration of another atrium. Upon initial installation, the daylight sensor was adjusted iteratively until occupant complaints in the building were minimized. The sensor also controls eight 500PAR56 recessed incandescent fixtures located on the second floor, that are directed towards the center of the atrium floor at ground level. Figure 3 shows the location of the lighting fixtures for all three floors of the atrium, and Table 2 summarizes the lamps and lighting control system in the atrium. The lighting system also includes eight manually operated MH175 mercury vapor fixtures for floodlighting of the roofline glazing (architectural accent lighting used at twilight and night time), five continually powered recessed incandescent MR75 tasklighting fixtures above each of the two reception counters on the ground floor, and twelve incandescent A19 wallwash lighting in the ground floor reception area.

Internal Reflectances

The reflectance of the walls and ceilings inside the atrium has been estimated to be between 60 and 70% (IESNA Handbook, 1993). The metallic frame of the skylight is light-colored. The walkways surrounding the atrium are covered with a textile carpet, patterned with red and green strips, with an estimated reflectance between 20 and 35%. The atrium floor is partly covered by a central octagonal textile carpet with an average reflectance of 20%, surrounded by a polished marble surface with an estimated reflectance between 30 and 45%.

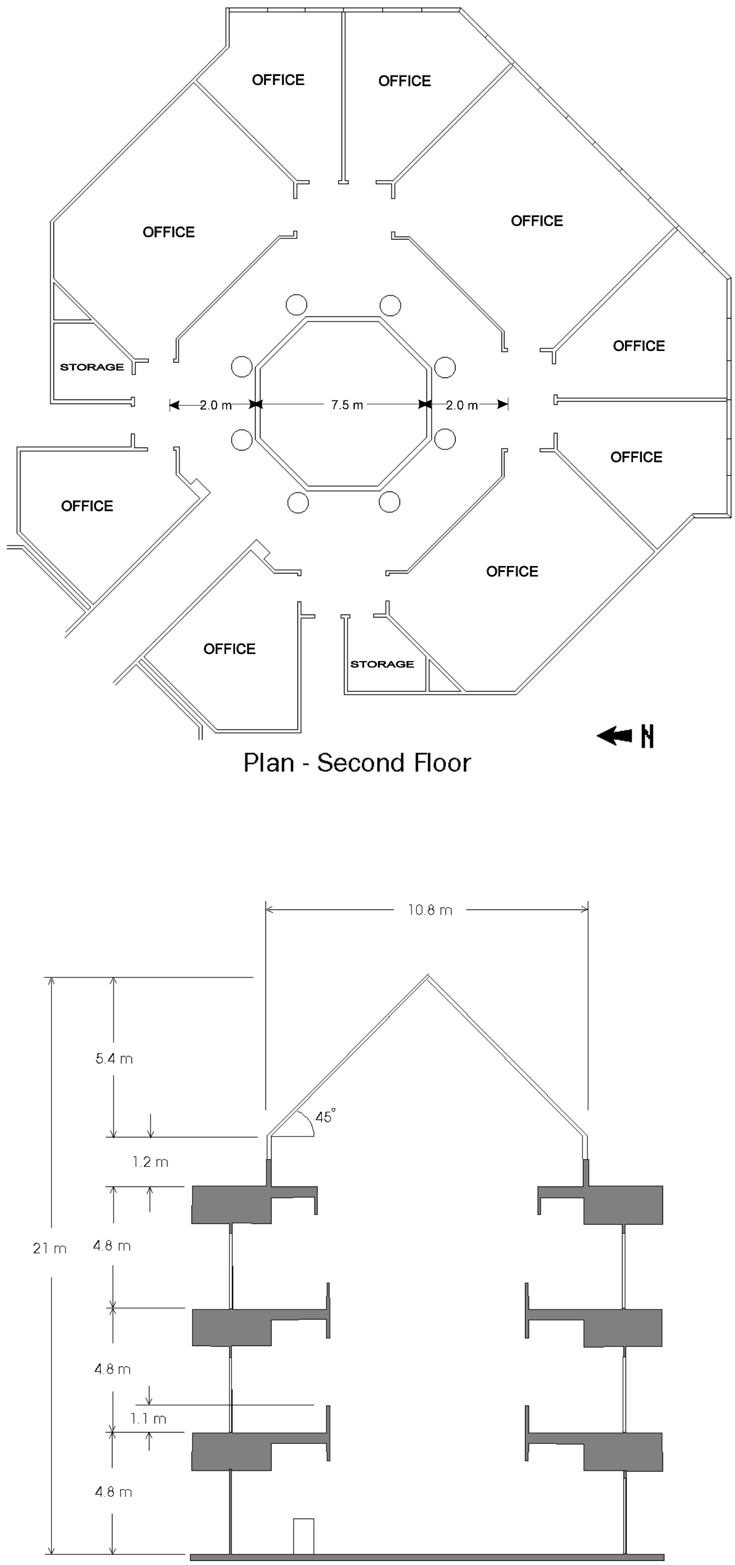


Figure 1 Plan and section of the atrium space

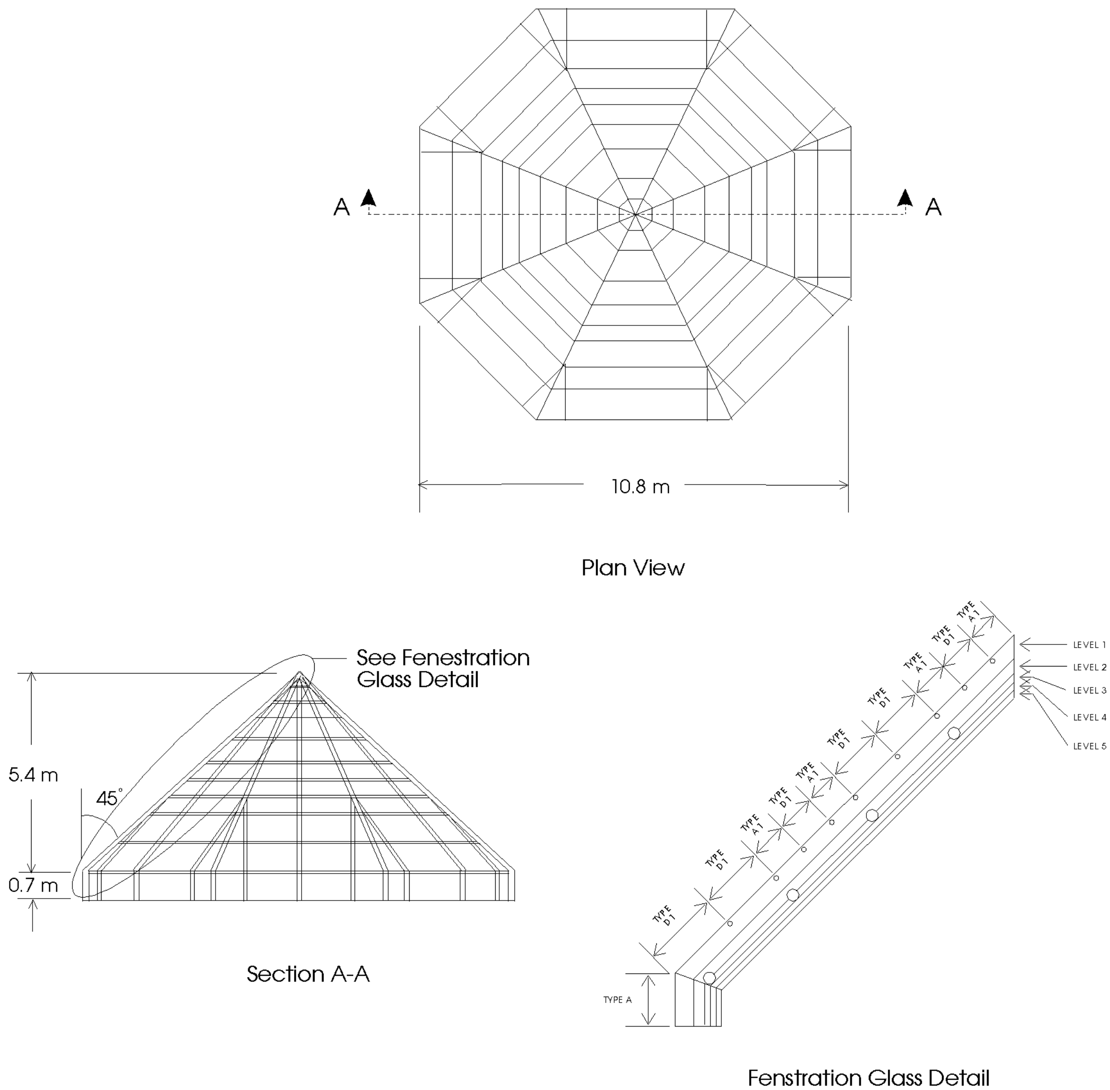


Figure 2 Plan and section of the atrium fenestration

Table 1
Fenestration Glass Systems

Glass Type	Layer 1 (Exterior)	Layer 2	Layer 3	Layer 4	Layer 5 (Interior)
A Low reflectance	6 mm heat strengthened clear glass	13 mm air space	HM66 clear polyester film	13 mm air space	6 mm clear glass
A1 Low reflectance	6 mm heat strengthened clear glass	13 mm air space	HM66 clear polyester film	13 mm air space	6 mm thick clear laminated glass
D1 (Green) Low transmittance	6 mm heat strengthened tinted and patterned glass	13 mm air space	HM55 green polyester film	13 mm air space	6 mm thick clear laminated glass

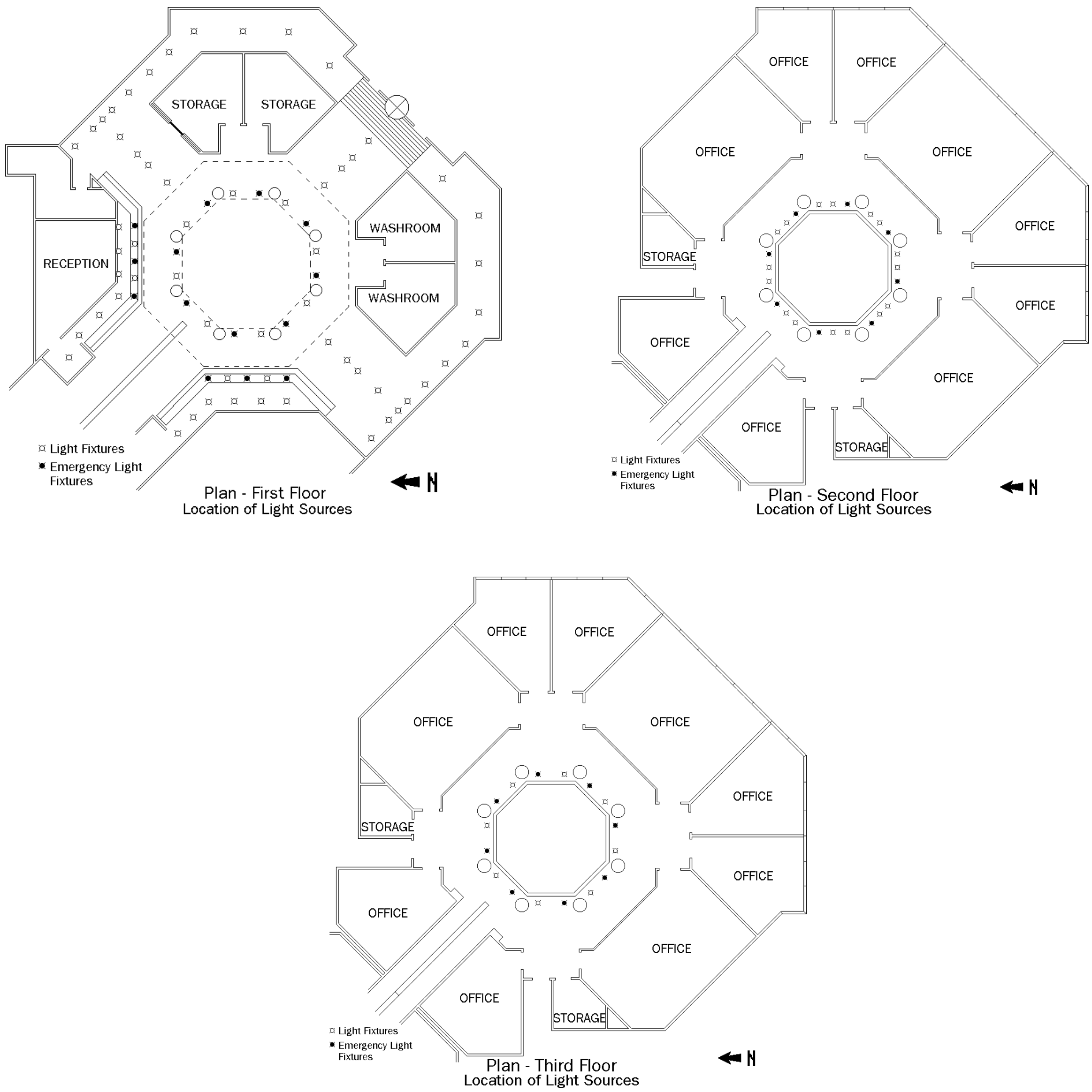


Figure 3 Location of atrium light sources

Table 2
Lamps and Lighting Control System

Lamp Type	Purpose	Location	Number	Control
150PAR38	Corridor Lighting	All Floors	8 per floor	Photo - Auto. On/Off
150PAR38	Emergency Lighting	All Floors	8 per floor	Always On
MR75	Lamps above Reception Desk	1st Floor	10	Always On
500PAR56	Decorative Lighting for 1st Floor	2nd Floor	8	Photo - Auto. On/Off
MH175	Roofline Floodlighting	3rd Floor	8	Manual On/Off

Description of the Adeline Computer Software

Adeline 1.0 includes 5 inter-linked programs (Adeline User's Manual, 1994):

- **Scribe** is a CAD-program used to describe the dimensional characteristics of spaces using 3D-computer modeling. It models the architectural design of the building and generates the skeleton input file for the Superlite and Radiance programs.

- **Plink** converts models designed in Scribe into a Radiance or Superlite input file. Material properties such as reflectance, chromaticity and visible transmittance are assigned to surfaces and objects.

- **Superlite** calculates hourly values of illuminance and daylight factors on any given planes that describe the space which is being modeled. This program enables the modeling of interior daylight levels for four sky conditions: overcast, clear sky with direct sun, clear sky without sun, and uniform sky. The calculation technique used is based on the radiation flux exchange between surfaces (radiosity method) in which space surfaces are divided into a mesh of small elements and the amount of light distributed from one mesh element to another is calculated. All surfaces are assumed to be perfectly diffuse and the reflectance is assumed to be that of gray surfaces. The program takes into account the variation of the fenestration transmittance with the angle of incidence, the effect of the direct solar radiation and the reflected light component.

- **Superlink** evaluates the energy savings potential of replacing electric lighting by daylighting based on typical weather data and hourly sunshine probability. Using three hourly standard sky conditions, the program calculates the illuminance distribution from daylighting on the workplane (using the Superlite module) and compares the illuminance levels at defined reference points with the workplane target illuminance. Subsequently, based on several electric lighting control schemes such as continuous dimming or on/off systems, the program estimates the energy needed from artificial lighting to maintain the workplane target illuminance. The program also links the Superlite program to energy programs such as DOE or TRNSYS, generating the input (lighting energy that converts in internal heat gains) needed by these programs to calculate the heating and cooling energy.

- **Radiance** creates a three-dimensional photo-realistic representation of a space and allows for glare and visual comfort studies. Illuminance values and daylight factors can be obtained as well, but no energy calculations are possible with Adeline 1.0. The program does not simulate electric lighting control systems. Radiance uses the backward ray-tracing technique (the path of light is traced from its presumed destination to other surfaces and light sources to calculate the luminance values needed for visualization of illuminated spaces).

METHODOLOGY

The methodology included two phases: on-site monitoring and computer simulation. The on-site monitoring phase consisted of measurements of indoor illuminance at 30 locations throughout the building, measurements of outdoor illuminance and solar radiation, and monitoring of the electrical lighting system time-of-use. The computer simulation phase consisted in the creation of two computer models (one for Superlite and Superlink, and the other for Radiance) used to model the lighting performance of the atrium building. Measured data from the building were compared with results from the computer simulation runs in order to determine how close the computer predictions are to the field-monitored values. Description of both phases is provided below.

ON-SITE MONITORING

Measurements of Indoor Illuminance

Horizontal and vertical indoor illuminance measurements were collected manually, at specific locations on each floor, using a hand-held Graseby single-channel photometer model G0352 and a Graseby 286P illuminance sensor. The photometer had an accuracy of ±0.1%. Measurements were collected on each floor, at a height of 1.14 meters (3.8 ft) from the floor, at two selected points in each of the north, south, east and west directions to address the daylighting contribution in the corridor, next and away from the atrium. An additional test-point was located in the center of the atrium floor. A total of 25 test-points were selected for measurements. Figure 4 shows the locations of the test-points on each floor. For accuracy of measurements, a wheeled tripod was used to hold the illuminance sensor.

All manual measurements were collected hourly, during daylight hours, for 10 days in June and 6 days in December, 1995. Two sets of measurements were collected during night-time with all lights on and with emergency lighting only. The night-time measurements were used to calculate the real contribution of daylighting to the space, by subtracting the illuminance provided by the electrical lighting (emergency and on/off lighting) from the daytime measured values of illuminance.

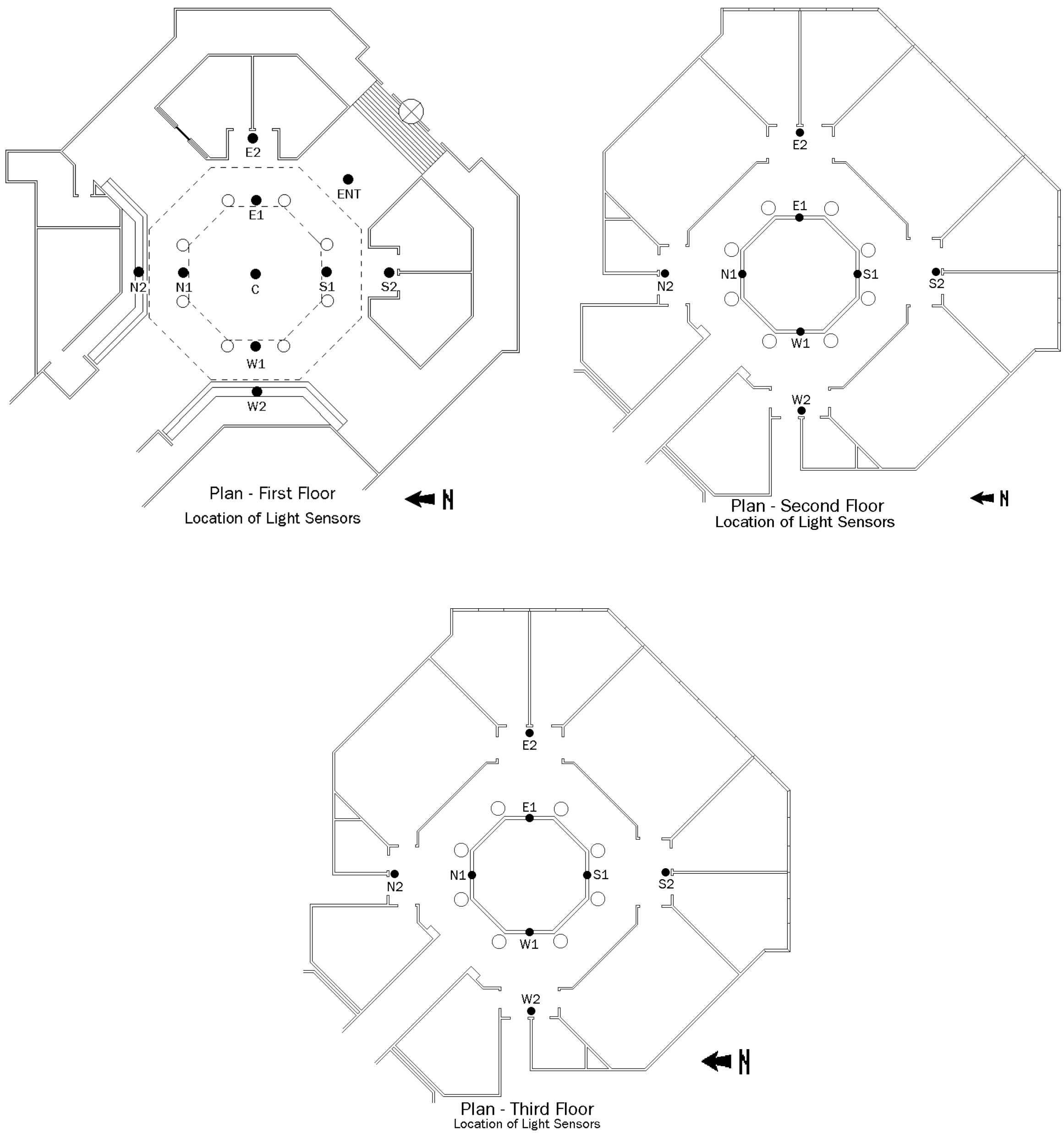


Figure 4   Location of illuminance test-points

Measurements of Indoor Illuminance below the Skylight

Horizontal indoor illuminance measurements were collected at five points just below the atrium skylight using five Graseby 268P illuminance sensors. Figure 5 shows the locations of the illuminance sensors. Three sensors were uniformly distributed in the center, east and west side of an aluminum I-beam positioned at a height of 14.4 meters (48 ft) above the atrium floor. The remaining sensors were secured at the same height to custom mounts located on the northern and the southern side of the skylight. The I-beam apparatus was built for this experiment only and was removed at the end of the monitoring phase. The sensors were connected to an eight-channel Graseby C390 photometer with an accuracy of ± 0.2%, connected to a data acquisition system. Measurements were collected every minute and stored at one-minute and 10-minute averages for the entire month of June, 1995 and for a two-week period in December, 1995.

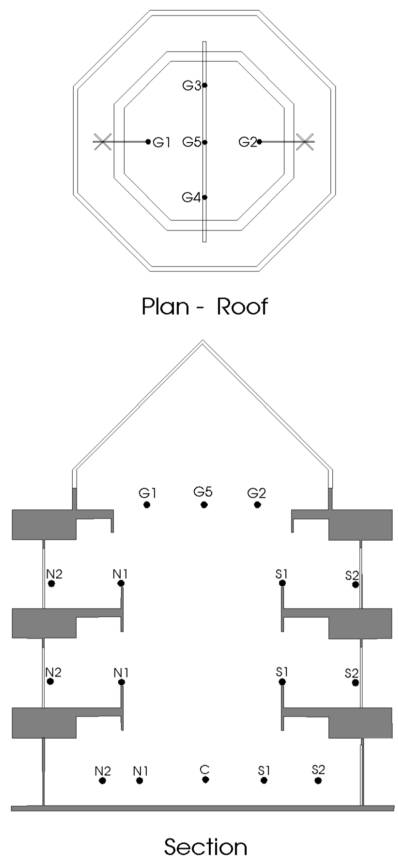


Figure 5 Location of illuminance photosensors below the atrium skylight

Measurements of Outdoor Illuminance

Global and diffuse horizontal outdoor was collected every minute and averaged at 10-minute intervals by a Yankee SDR-1 data acquisition system, connected to three outdoor illuminance sensors (for accuracy purposes), positioned horizontally on the roof, approximately 20 m (66 ft) south of the atrium glazing. From this location, the photosensors were exposed to more than 95% of diffuse sky, and to 100% of direct sunlight. Figures 6 and 7 show a roof plan and a section related to the daylight monitoring station located on the roof. The ideal location for the outdoor monitoring station would have been above the atrium skylight but this was not practical. The station was therefore located so that it could simulate, as close as possible, the outdoor global horizontal illuminance on the top of the skylight.

The following models of photosensors were used:

- one multi-filter rotating shadowband radiometer, model Yankee SDR-1 with an accuracy of ± 3%, to collect global and diffuse horizontal outdoor illuminance;
- one LMT photometric sensor, model BAP with an accuracy of ± 2.2%, to collect global outdoor illuminance (reference);
- one Licor 210SB photometric sensor with an accuracy of ± 5%, to collect global outdoor illuminance (reference).

The sky condition at the time of monitoring was also continuously recorded.

Measurements of Outdoor Solar Radiation

Global and diffuse solar radiation was collected outdoors, at 10-minute intervals, with six pyranometers as follows:

- one multi-filter rotating shadowband pyranometer, model Yankee SDR-1 with an accuracy of ± 3%, positioned on the roof at the same location with the illuminance sensors and connected to the same Yankee SDR-1 system mentioned above, to collect global and diffuse solar radiation;
- one Eppley pyranometer Model PSP, positioned on the roof at the same location with the illuminance sensors and connected to the Yankee SDR-1 system, to collect global solar radiation (reference);
- four pyranometers, Model Licor 200SA with an accuracy of ±5%, secured to the tilted glazing of the atrium skylight in each of the north, south, east and west directions and connected to a PC-data acquisition system, to collect global radiation falling on each sloped orientation.

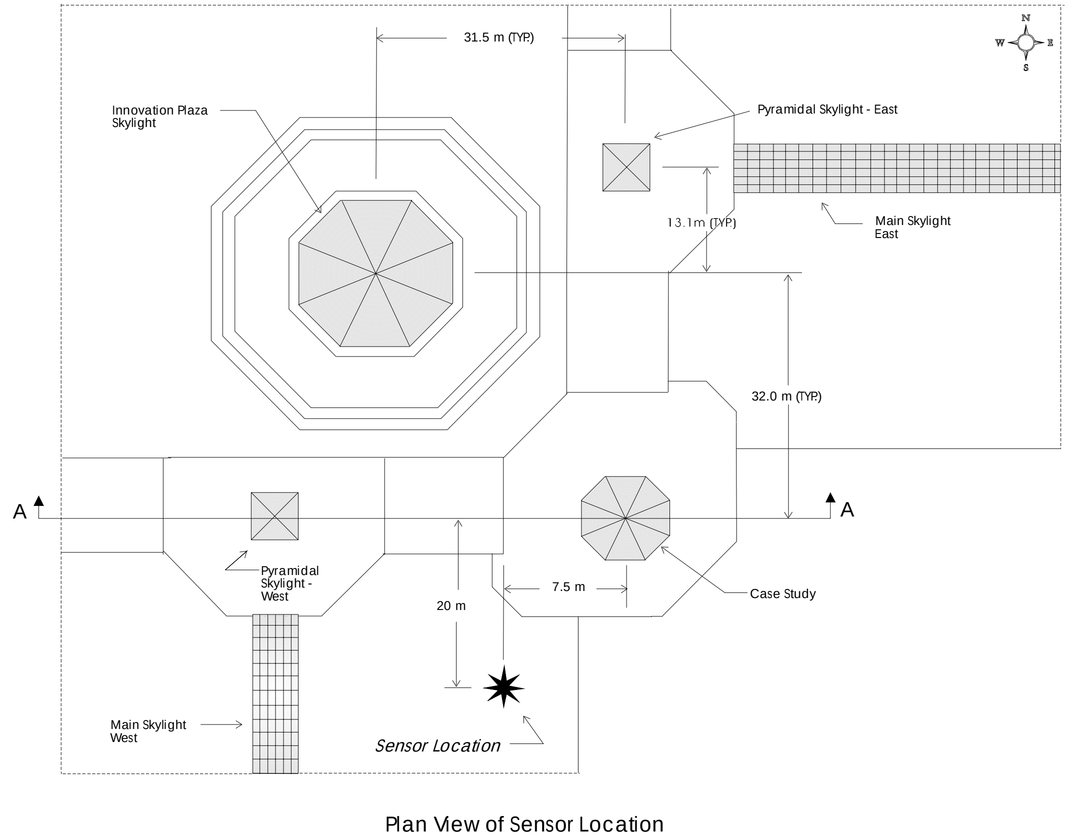


Figure 6 Plan view of the atrium roof and location of the daylighting monitoring station

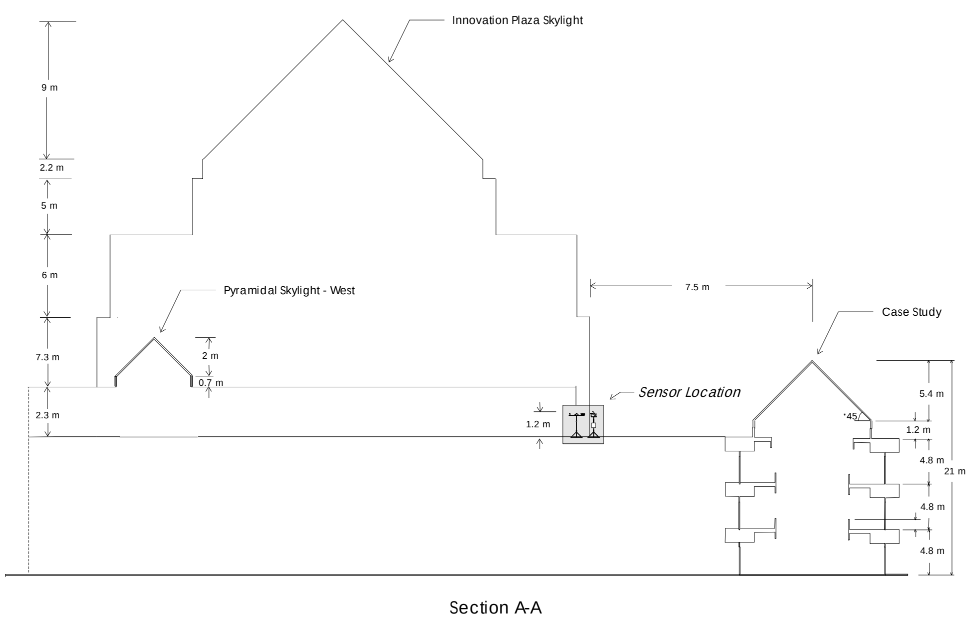


Figure 7 Section view through the atrium building and location of the daylighting monitoring station

Measurements of Electrical Lighting Consumption

The time-of-use of the electric lighting system was continually monitored for the entire months of June and December, 1995 by eight CT (current transformer) loggers installed at the breaker panels serving the lighting circuits. The on/off state of the lighting system was monitored for both, emergency lighting and photosensor controlled circuits. Several lighting circuits were also monitored using a BMI Powerprofiler to record voltage, current and power consumption. The circuits monitored were the photocontrolled 150PAR38 corridor lights, the 500PAR56 tilted accent lighting, the continually powered 150PAR38 emergency lighting, the MR75 lamps above the reception desks and the MH175 roofline floodlighting.

Electrical lighting energy consumption was calculated based on measurements, under the following assumptions:

1. The power rating of the lighting fixtures represented the power consumed (this assumption was verified by comparing the theoretical power consumption with the measured power consumption from the BMI Powerprofiler);
2. The wallwash lighting in the ground floor reception area was not included in the calculations;
3. The tilted lamps on the second floor contribute with a proportion of 2/3 to the lighting of the first floor area, and a proportion of 1/3 to the lighting of the second floor area;
4. The roofline floodlighting was not designed to contribute to the lighting of any floor and was not included in the analysis;

The mean on-time ($M_{on\text{-}time}$) of the photocontrolled lighting for both monitoring periods was used to calculate the daily average electric energy consumption (E_{ave}). The following formula was used:

$$E_{ave} = [(M_{on\text{-}time} \times E_{on/off}) + E_{perm}] \times 24 \text{ hours} \qquad (1)$$

where:
$E_{on/off}$ - represents the total power consumed by the photocontrolled lighting fixtures;
E_{perm} - represents the total power consumed by the emergency lighting and the tasklighting above the reception counters on the ground floor.

COMPUTER SIMULATION

Superlite Simulation Model

Due to the limitations of the Superlite program, this computer model simulates a central pyramidal atrium within a quadrilateral shaped building. However, parameters such as area of fenestration, reflectance and transmittance of construction materials, and orientation of surfaces, were kept similar to the real ones. The model also contains information about the site-measured visible transmittance of the fenestration, calculated by dividing the average horizontal illuminance recorded by the five photosensors installed bellow the atrium skylight to the corresponding outdoor global horizontal illuminance. Table 3 shows the range of measured visible transmittance based on season and sky condition. An average transmittance of 28% was used in the simulation.

Table 3 On-site monitored skylight visible transmittance

Month	Overcast	Clear sky	Partly cloudy
June 1995	26-34%	18-41%	21-37%
December 1995	23-36%	26-48%	25-34%

Limitations of the software did not allow for the model even simplified like that to be studied as a whole and therefore the floors of the atrium building were simulated separately. This obviously eliminated from the calculations the interreflections between floors. Figure 8 shows the three floors as simulated by Superlite.

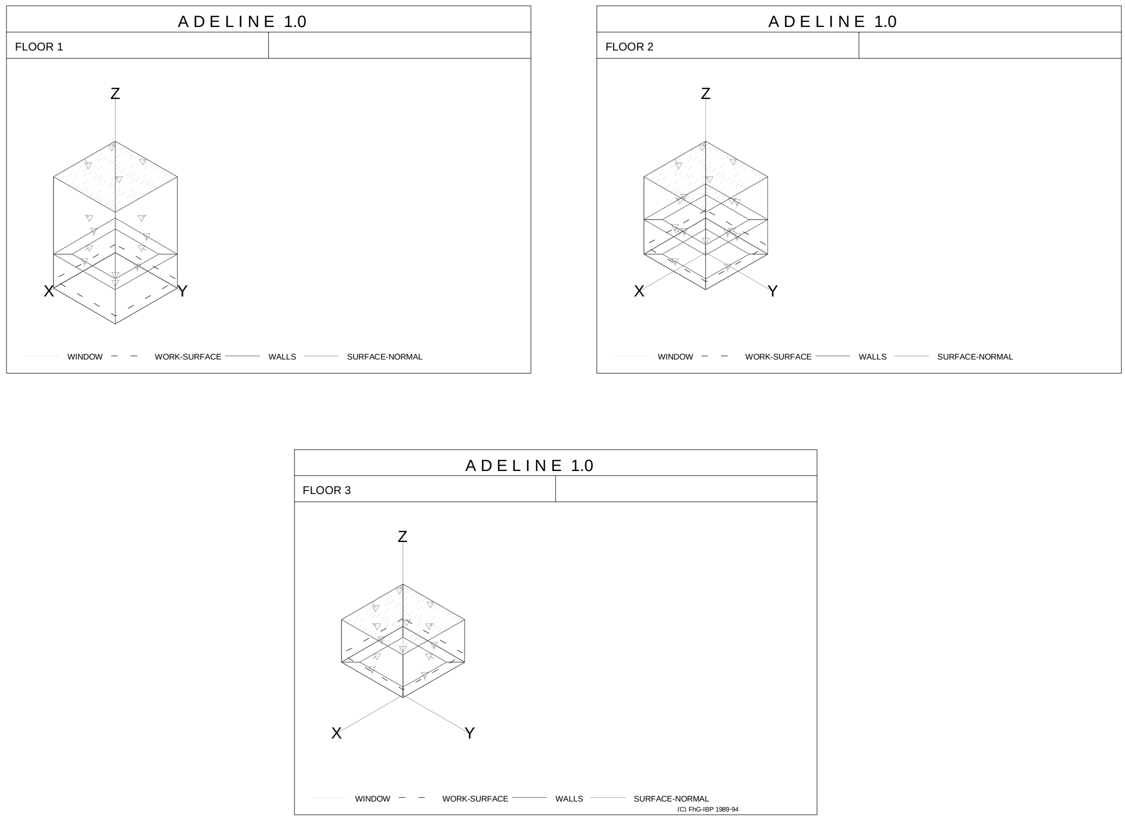


Figure 8 Superlite simulation model - Atrium 1st, 2nd, and 3rd Floors

The on-site measured illuminance was compared with simulation results. The test-points where the field measured horizontal illuminance was recorded were shown previously in Figures 4 and 5. On all three floors comparison was done only for the test-points located at the atrium perimeter (locations N1, E1, S1, W1 and C). Taking into account the changes made in the shape of the simulated building model, these locations were assumed to correspond to the points shown in Figure 9 [North (N) = 47, South (S) = 53, East (E) = 14, West (W) = 86, Center (C) = 50].

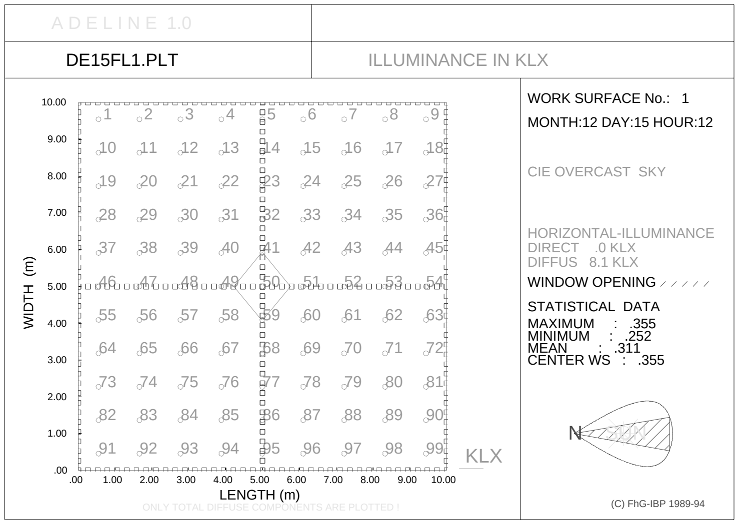


Figure 9 Layout of test-points on the simulated horizontal plane where comparisons between measured and simulated data were performed

Superlink Simulation Model

The Superlite model described above was used to evaluate the energy savings potential of replacing electric lighting with daylighting. Due to computer program limitations, which do not permit the simultaneous simulation of two types of lighting systems (continually powered lighting and daylight-controlled lighting), the following assumptions were made:

- target illuminance was calculated based on field measurements of illuminance collected manually, at night-time, under “full electric lighting” and “emergency lighting only” conditions. The average illuminance measured under “full electric lighting” was about 350 lux. The average illuminance measured under “emergency lighting only” conditions was about 100 lux. The difference between these two illuminance values was assumed to be the design illuminance of the daylight-linked electrical lighting system, in this case 250 lux.

- electric lighting is controlled on each floor by photosensors located at reference points at the workplane level. The photosensors compare the light level at the reference points with the target illuminance level. The available daylight must be equal or greater than the target illuminance for the natural light to replace artificial light.

- all calculations were done based on hourly sunshine probability data for the city of Ottawa, created within Adeline using "typical meteorological year" weather files for energy calculations provided by Environment Canada

The accuracy of the computer program in simulating the energy savings from the use of the existing on/off lighting control system was verified. The measured time-of-use of the photocontrolled lighting system was compared to the simulated time-of-use for the months of June and December 1995. The mean daily off-time of the photocontrolled lighting was used to calculate the average daily savings of electrical lighting energy.

Radiance Simulation Model

This computer model creates a three-dimensional visual representation of the atrium building and generates information about the lighting within the building under a given electric or daylighting illumination system. The input model describes the shape, size, location and composition of each surface and predicts the distribution of visible radiation in the illuminated space. Figures 10 to 12 are typical examples of the Radiance computer model during night-time.

The model's accuracy was verified for daytime only. Measured illuminance was compared with simulated illuminance at the test-points shown in Figures 4 and 5. Data on the actual sky condition, on-site measured direct and diffuse solar radiation, and on-site measured visible transmittance of the skylight were used as simulation input. The atrium skylight was described in the simulation as a compound unit with an average visible transmittance of 28%, rather than a unit composed of three different glazing systems.

Figure 10   Radiance simulation model - Atrium 1st Floor (night time, north-west view)

Figure 11   Radiance simulation model - Atrium 2nd Floor (night time, south-east view)

Figure 12   Radiance simulation model - Atrium 3rd Floor (night time, south-east view)

RESULTS

The results presented below are directed towards the analysis of the degree of accuracy of the Adeline 1.0 software when applied for real buildings with complex geometry. As stated before, they are intended to present the degree of accuracy and the limitations that could be expected when predicting specific light parameters in atria with real occupancy and when using the software as a design tool for such complex daylighting systems. Therefore, instead of comparing measured and simulated instantaneous illuminance levels based on time of day and test-point location, the analysis will be directed more towards investigating the overall pattern distribution and range of predicted illuminance levels in the space and the impact they might have on the long-term lighting energy calculations. The comparison results will be presented individually for Superlite, Superlink and Radiance.

COMPARISON BETWEEN MEASURED AND SIMULATED DATA USING THE SUPERLITE MODEL

This section presents the results of the Superlite computer model analysis.

Comparison between Measured and Simulated Outdoor Illuminance for June 1995

Three summer days were selected for comparison: June 6, June 8, June 14, 1995. The sky was partly cloudy on June 6 and June 14, and clear on June 8. Due to software limitations, the sky was simulated as clear sky for both partly cloudy days. Figure 13 shows a comparison between the computer-predicted outdoor illuminance and the field-measured horizontal outdoor illuminance. Measured illuminance was shifted one hour behind the local time when the measurements were collected to compensate for the daylight-savings time. As shown, for all three days the simulated illuminance followed closely the distribution pattern of the measured illuminance, and this was especially true for June 8, which was a completely clear sunny day. From 9 AM to 6 PM, the instantaneous discrepancy between measured and simulated illuminance at any particular time of the day was between 1 and 25%, and the average deviation was about 10%. For June 8, the discrepancy was even lower, being between 1 and 16% and averaging a very low 4%. It is interesting to notice that for all the three summer days analyzed, the profiles of the computer-predicted outdoor illuminance overlap.

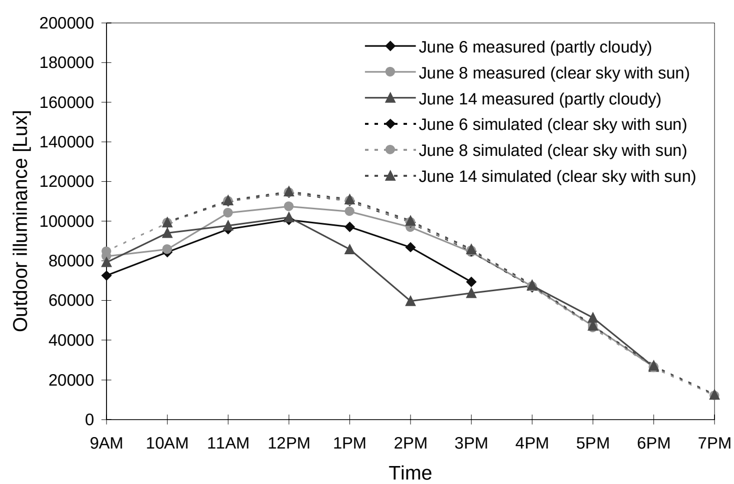


Figure 13 Measured and Superlite simulated horizontal outdoor illuminance for June 6, June 8 and June 14, 1995.

Comparison between Measured and Simulated Indoor Illuminance for June 1995

Figures 14 through 17 show the measured and the computer-predicted indoor horizontal illuminance at the east, west, north and south test-points on each floor and below the skylight. Figure 18 shows the measured and the simulated indoor illuminance in the center of the atrium floor, and the center test-point below the skylight. In all the following Figures, the continuous illuminance profiles represent measured values, and the dotted ones represent simulated values. All plots account for the daylight-savings time.

On the atrium ground floor, at all the five investigated test-points, the simulated illuminance pattern followed closely the distribution pattern of measured illuminance. As shown in Table 4, on all three clear sky summer days, the illuminance measured on this floor from 9 AM to 5 PM varied between 400 lux and 29300 lux and the simulated illuminance ranged from 600 lux to 28700 lux. At the test-point located in the center of the atrium ground floor, during the same period of time, the measured illuminance ranged from 1000 to 3700 lux and the simulated illuminance was between 700 and 2700 lux.

Table 4 Measured versus Superlite simulated indoor horizontal illuminance for June 6, June 8 and June 14, 1995 (Lux)

	Atrium perimeter (clear sky)	
	Measured illuminance	Simulated illuminance
Ground floor	400-29300	600-28700
Second floor	700-48400	1000-29700
Third floor	2700-38700	1700-31200
Base of skylight	6500-54800	3300-32800

On the second and third floors of the atrium space, as well as at the base of the atrium skylight, the simulated illuminance followed also closely the trend of measured illuminance. The only major pattern discrepancy occurred at the eastern test-point of the second floor, simulated to be under direct sun from 12 PM until 3 PM. In reality, on all three days no measurements were taken under direct sun at this location. This is probably due to the deviation of the computer model input from the actual building geometry, allowing the interior space to see more direct sun than in reality. A reasonably low discrepancy between measured and simulated illuminance was found at the center test-point just below the skylight where from 9 AM to 5 PM, the measured illuminance was between 10500 and 36800 lux and the simulated illuminance ranged from 13100 to 32800 lux (Figure 18). The minimum illuminance recorded at this location at 11 AM, as well as the peak recorded at 5 PM, are probably due to the fact that the sun patterns at these test-points under measurement and simulation were not identical.

Despite an overall good agreement between the trends and the ranges between measured and simulated values, there were however situations when, at certain hours and locations, the simulated illuminance was 3 to 10 times lower or higher than the instantaneous measured values. This was expected due to Superlite’s limitations in simulating the geometry of the real space. First, the three glazing systems that form the skylight and which affect greatly the way daylight is admitted into the building, were accounted for as one overall transmittance. The substitution of a pyramidal-shaped skylight to represent the real octagonal-shaped skylight altered also the skylight visible transmittance. Second, the fact that the three floors of the building were treated separately eliminated the interreflections between space surfaces. In addition, on all three floors, the measurements were collected manually due to the impractical installation of a fixed measuring system on each floor and, occasionally, the time of day when they were recorded did not always correspond perfectly with the simulated time. This evidently has also increased the instantaneous discrepancy between measured and simulated values.

It is noteworthy to mention that for all three summer days analyzed the predicted illuminance distributions were very similar from 9 AM to 7 PM. At all test-points, the profiles of simulated illuminance depended only on the test-point location and did not vary significantly from one day to another. At each test-point, the only difference between the illuminance predicted for these three days consisted in a 2 to 15% variation of absolute illuminance values. However, considering the difficulty of simulating the daylight availability in buildings with real occupancy and complex geometry, summer data shows a fairly good overall agreement between measured and simulated illuminance, in both range and distribution pattern. The occasional high discrepancy between measured and simulated instantaneous illuminance does not appear to impact significantly on the long-term energy calculations subsequently done by Superlink, since at all test-points, from 9 AM to 5 PM, both the measured and the simulated illuminance were much above any reasonable target illuminance that might be considered for the analyzed space.

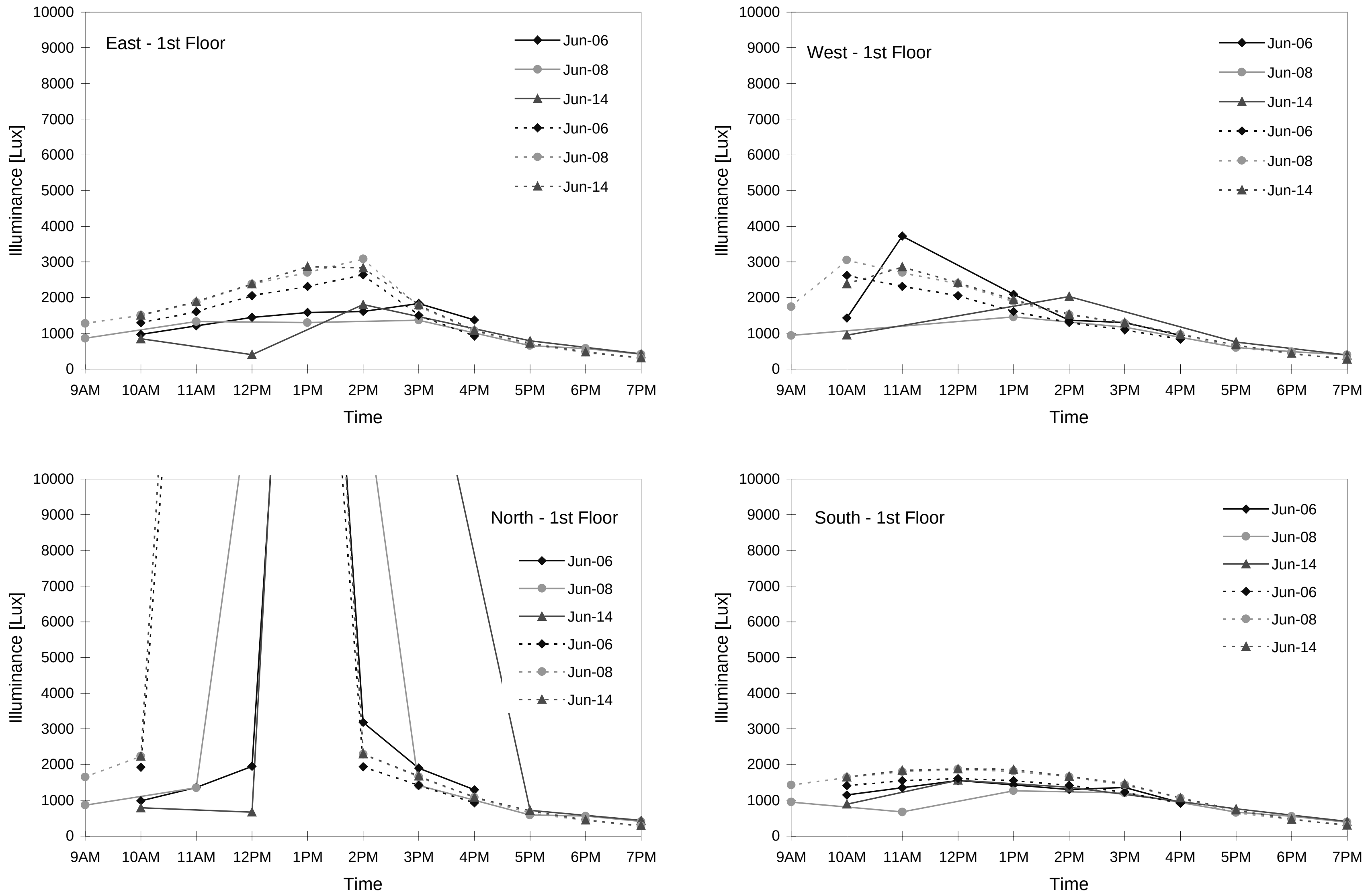


Figure 14 **Measured and Superlite simulated indoor horizontal illuminance for June 6, June 8 and June 14, 1995 - 1st Floor - east, west, north and south test-points.**

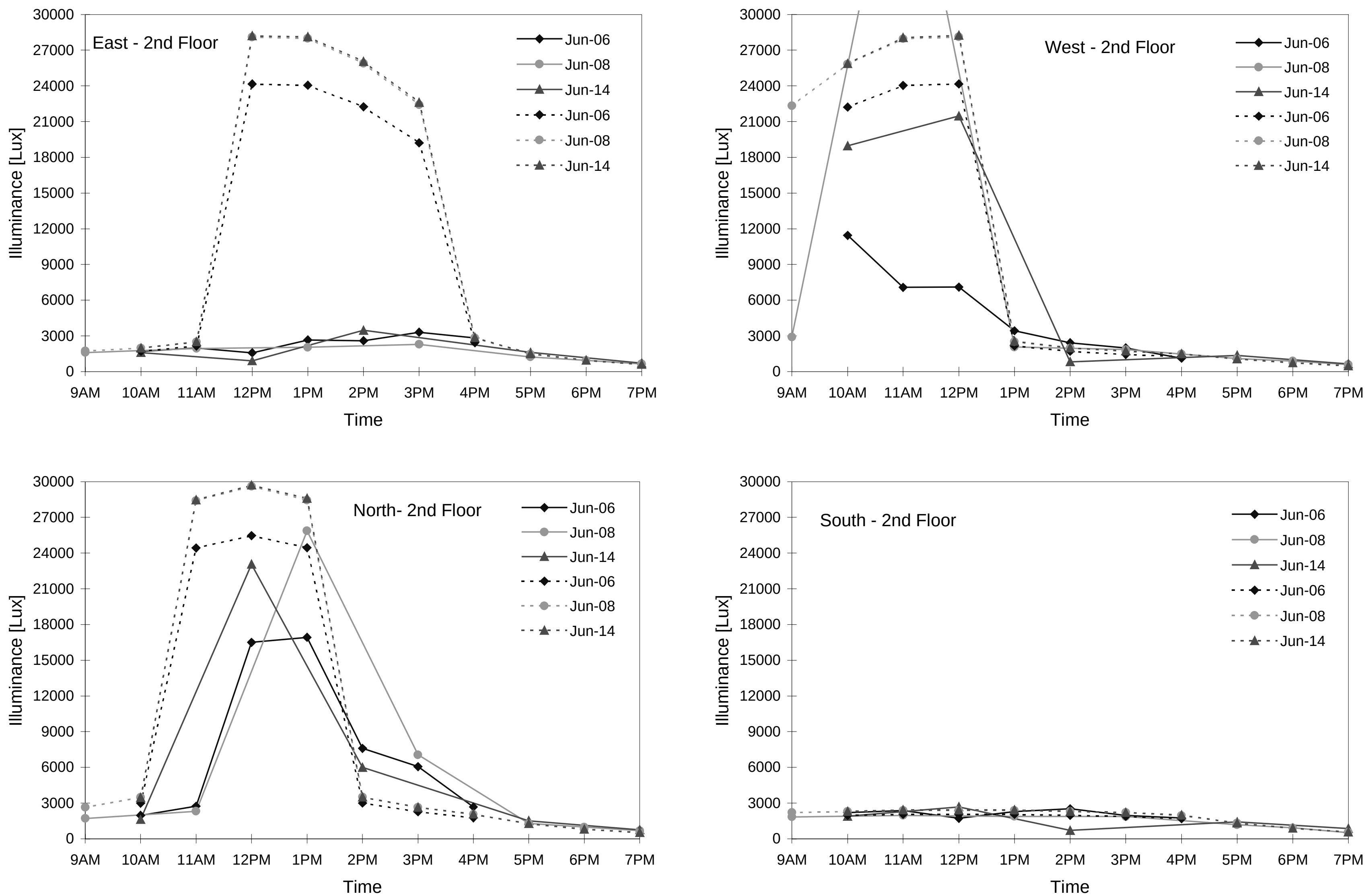


Figure 15 **Measured and Superlite simulated indoor horizontal illuminance for June 6, June 8 and June 14, 1995 - 2nd Floor - east, west, north and south test-points.**

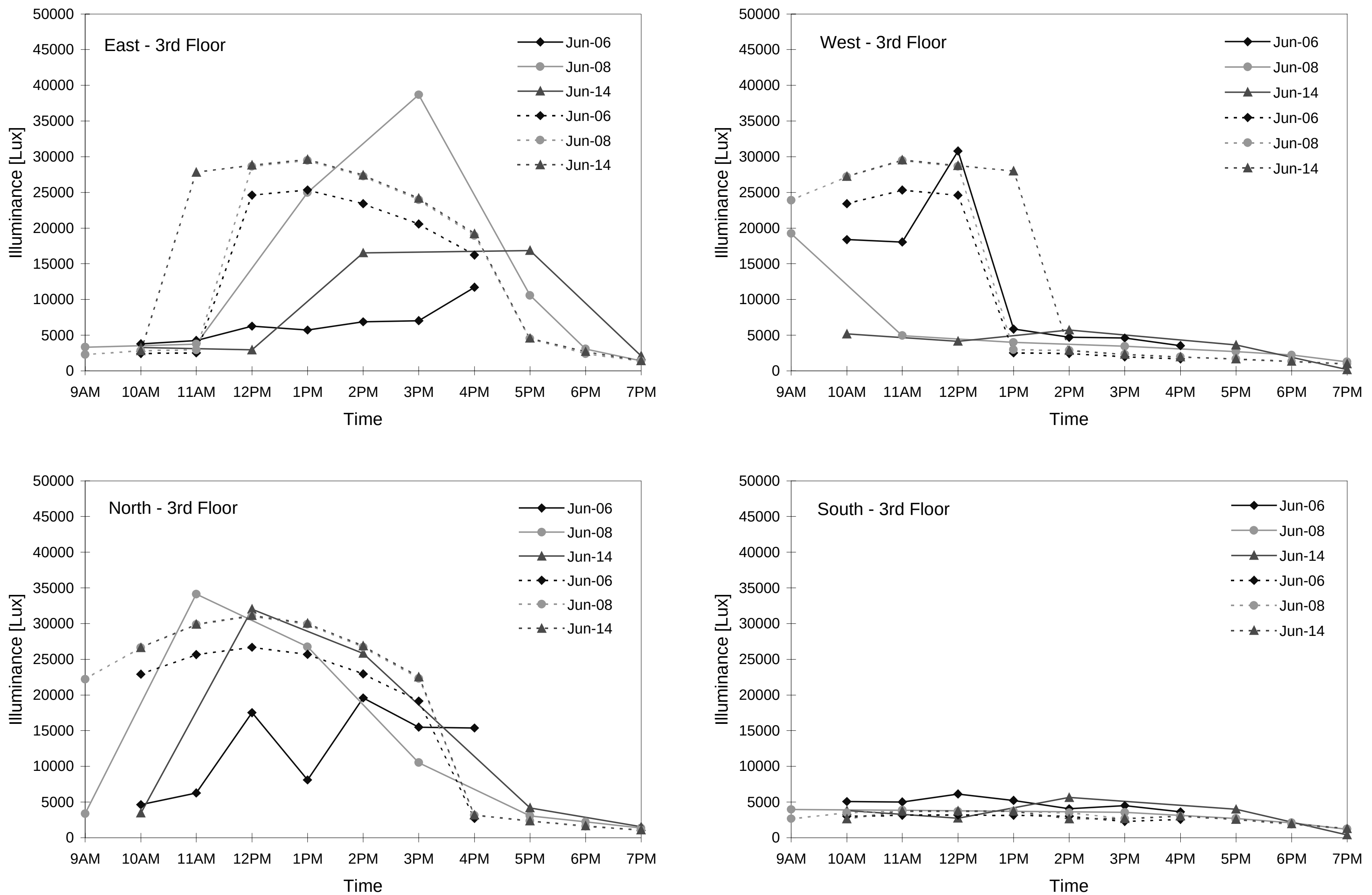


Figure 16 **Measured and Superlite simulated indoor horizontal illuminance for June 6, June 8 and June 14, 1995 - 3rd Floor - east, west, north and south test-points.**

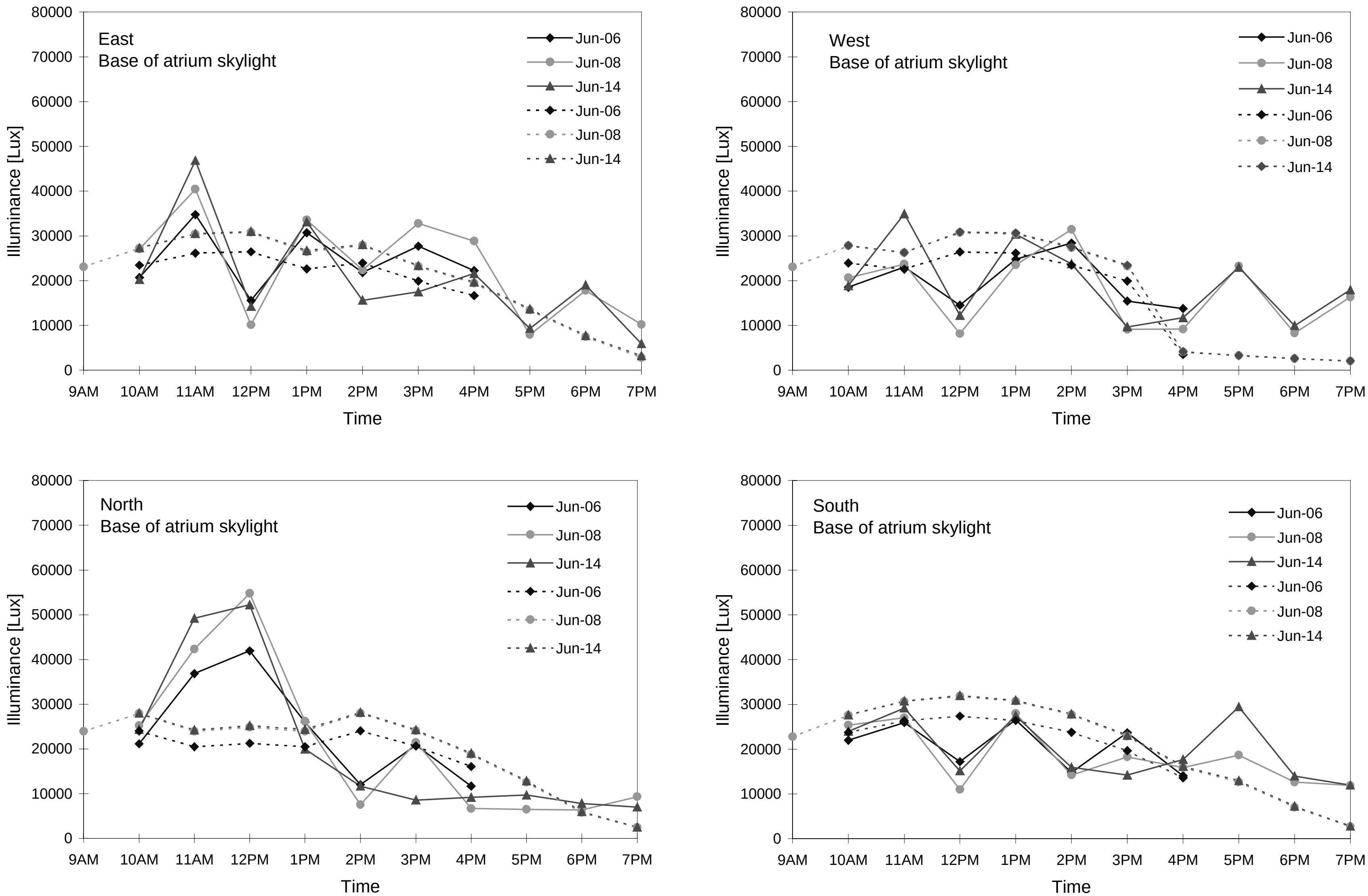
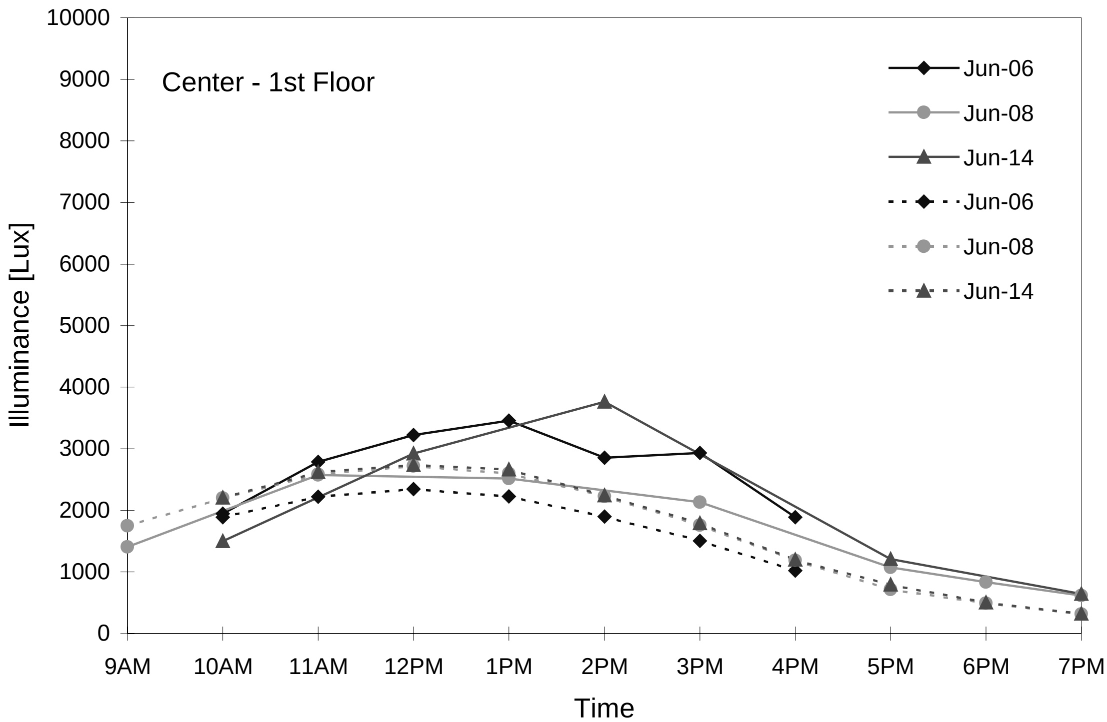


Figure 17 Measured and Superlite simulated indoor horizontal illuminance for June 6, June 8 and June 14, 1995 - east, west, north and south test-points at base of skylight.



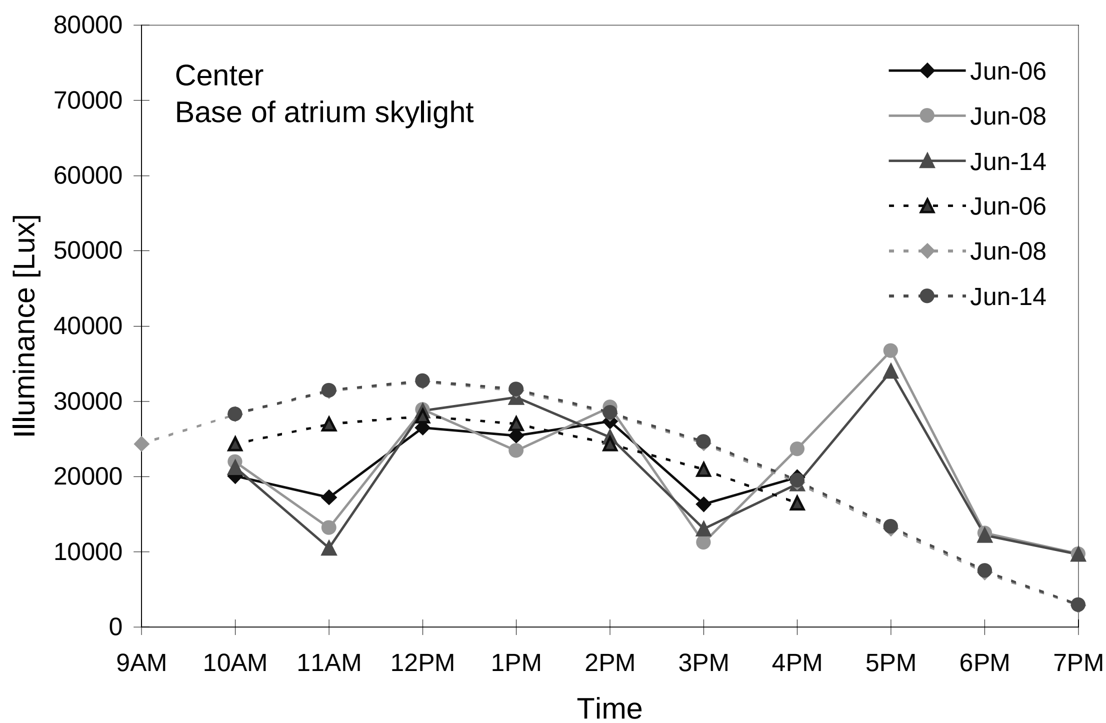


Figure 18 Measured and Superlite simulated indoor horizontal illuminance for June 6, June 8 and June 14, 1995 - Center of atrium ground floor and base of skylight

Comparison between Measured and Simulated Outdoor Illuminance for December 1995

Three days in December 1995 were selected for the analysis. Comparisons were done on an hourly-basis for December 4, December 8 and December 15, 1995. The sky was overcast on December 4 and December 15, and clear with sun on December 8.

Figure 19 shows with dotted lines the computer-predicted, and with continuous lines the field measured outdoor horizontal illuminance. Under clear sky, the absolute discrepancy between measured and simulated values was between 12 and 29%. From 9 AM to 3 PM, the outdoor illuminance under clear sky ranged from 18000 to 41000 lux and the simulated illuminance was between 14000 to 34000 lux. A greater difference occurred in the simulation of overcast sky, for which the difference ranged from 47 to 76%. In this case from 9 AM to 3 PM, the measured outdoor illuminance varied between 7000 and 26000 lux and the simulated illuminance was between 4000 and 8500 lux. Under both sky conditions, the measured and the simulated illuminance followed similar distribution patterns, but the outdoor illuminance was mostly underpredicted, especially under overcast sky. The peak shown at 2 PM on December 4 was due to frequent changes in sky condition recorded on this particular day. This will also reflect in the indoor illuminance profiles presented further in the report.

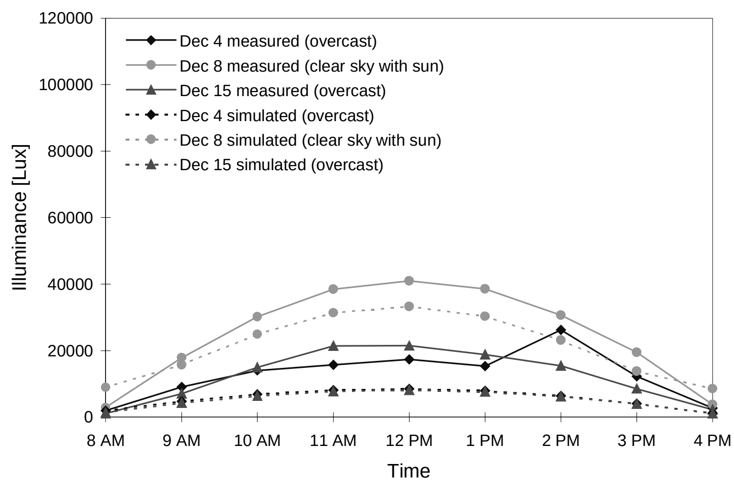


Figure 19 Measured and Superlite simulated outdoor horizontal illuminance for December 4, December 8 and December 15, 1995.

Comparison between Measured and Simulated Indoor Illuminance for December 1995

Figures 20 through 23 show the measured and the computer-predicted indoor horizontal illuminance for the east, west, north and south test-points, on each floor of the building and below the skylight. Figure 24 shows the measured and the simulated indoor illuminance in the center of the atrium floor, and the center test-point below the skylight. For all three winter days, from 9 AM to 3 PM, the measured indoor illuminance mostly exceeded the predicted illuminance with sometimes up to twice or three times the simulated values, regardless of the sky condition.

Under clear sky, from 9 AM to 3 PM , the illuminance in the center of the atrium ground floor varied between 400 and 1000 lux, while the predicted illuminance was between 300 and 500 lux, resulting in an underpredicted maximum space illuminance of 50% the measured value. Under overcast sky in the center of the atrium ground floor, the measured illuminance was between 150 and 1000 lux, and the predicted illuminance was between 170 and 400 lux. The maximum illuminance in the space was again underpredicted by 50%. At the center test-point located at the base of the atrium skylight, the maximum illuminance was more than twice the predicted values, especially under overcast sky. Under clear sky, the measured illuminance ranged from 5000 to 14000 lux and the simulated illuminance was between 4000 and 10000 lux. Under overcast sky, measured illuminance ranged from 2000 to 8000 lux, while the predicted illuminance was between 1000 to 2000 lux.

Table 5 Measured versus Superlite simulated indoor horizontal illuminance for December 4, December 8 and December 15, 1995 (Lux)

	Atrium perimeter (clear sky)		Atrium perimeter (overcast sky)	
	Measured illuminance	Simulated illuminance	Measured illuminance	Simulated illuminance
Ground floor	300-1000	300-500	100-1000	150-400
Second floor	400-1200	450-1000	100-1300	250-600
Third floor	1100-3600	900-3100	300-3300	400-1000
Base of skylight	4100-25200	2000-10000	1300-7900	750-1800

Indoor illuminance levels in the space were mostly underpredicted under both sky conditions during all three winter days analyzed, and this was most probably due to the significantly underpredicted outdoor illuminance levels. This aspect is likely to have a direct impact on the long-term energy calculations and suggests that the actual savings from daylighting could be significantly higher than those predicted by the computer simulation. The fact that during the winter monitoring the skylight was covered by snow and that daylight availability in the space could have been even higher than measured if the snow had been removed, suggests that the subsequent energy savings computed by Superlink are likely to be significantly underpredicted for the winter season. However, this would only happen if the simulated illuminance were lower than the space target illuminance, which for the case study appears to be critical on the ground floor only.

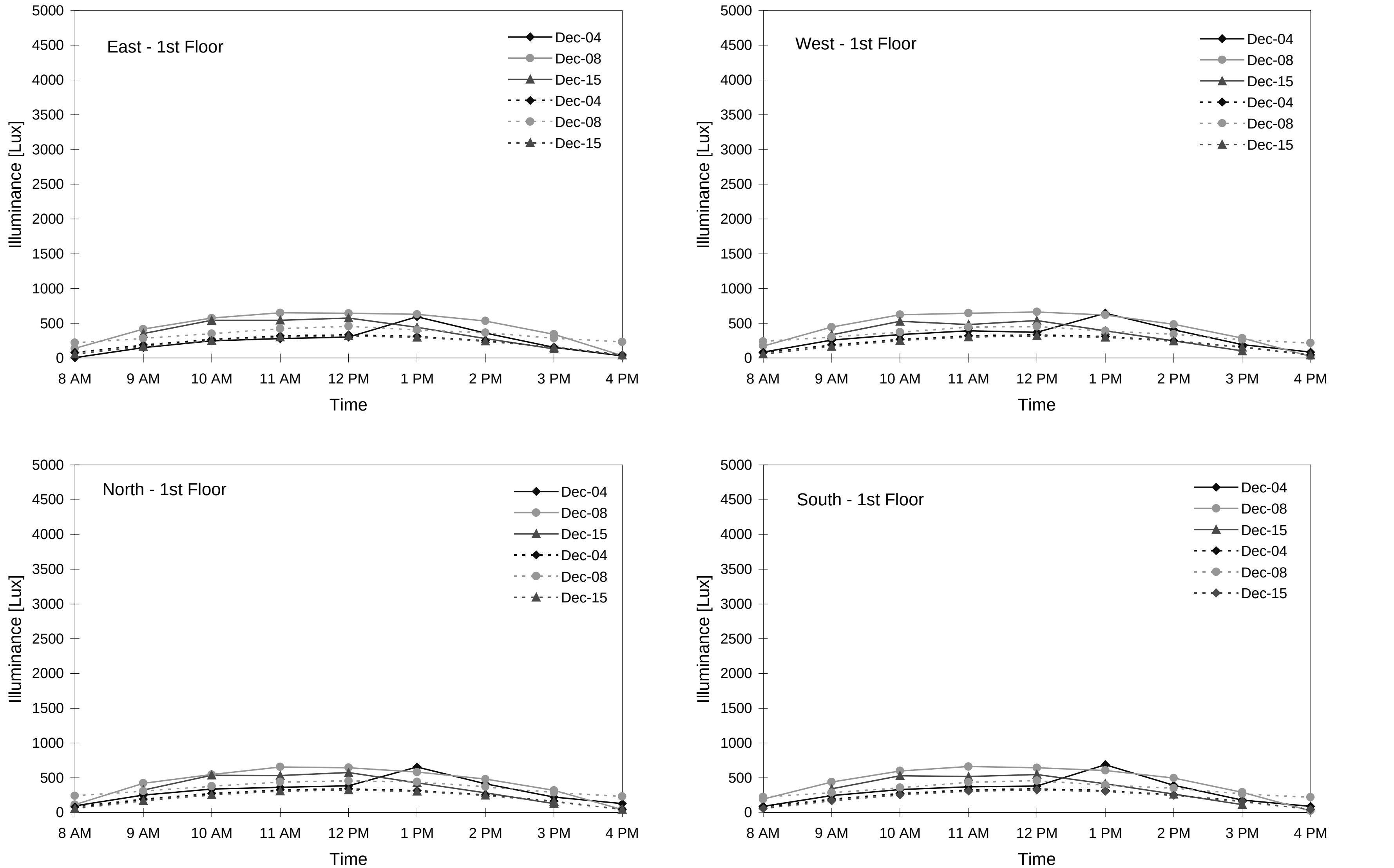


Figure 20 Measured and Superlite simulated indoor horizontal illuminance for December 4, December 8 and December 15, 1995 - 1st Floor - east, west, north and south test-points.

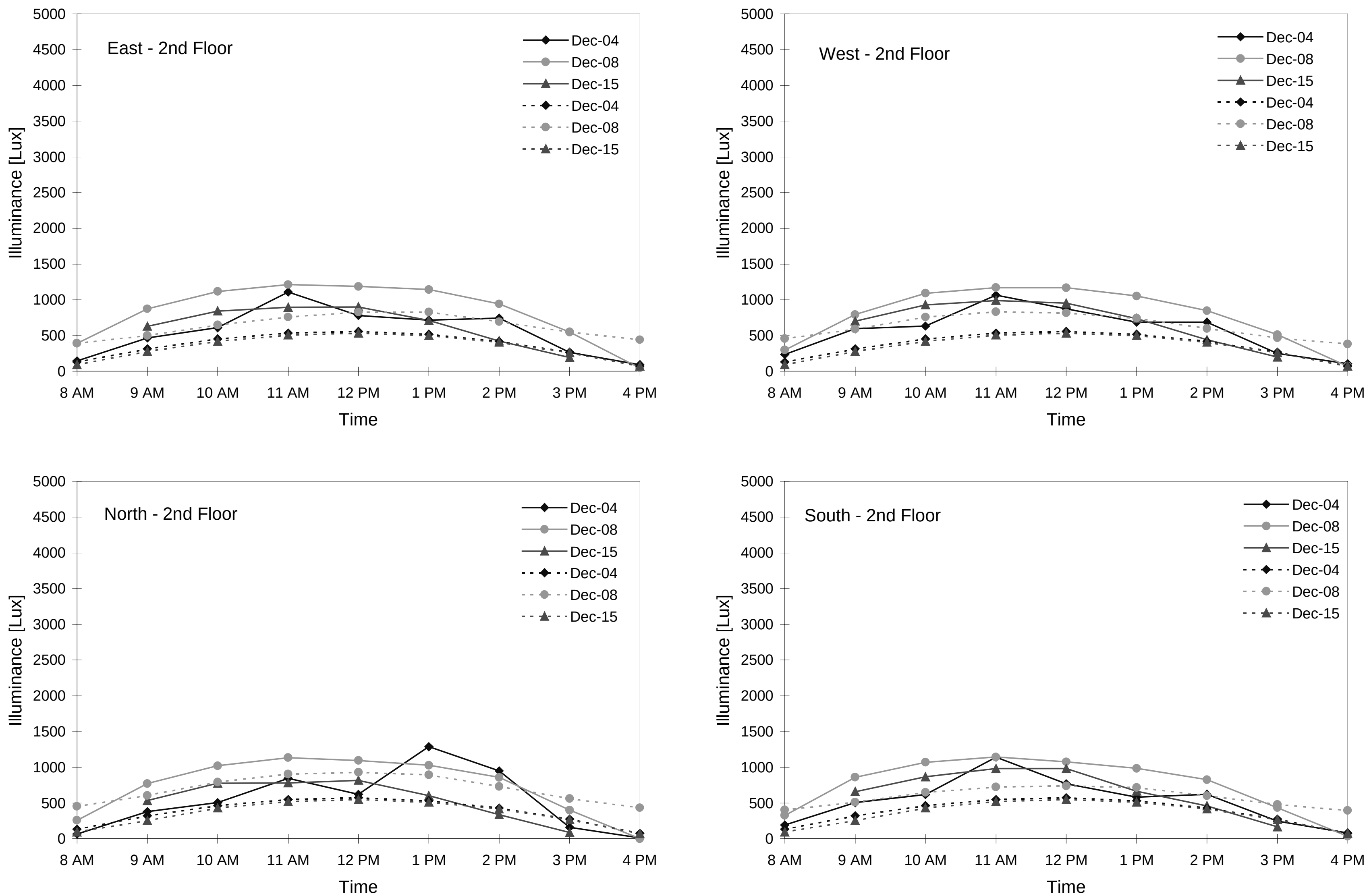


Figure 21 Measured and Superlite simulated indoor horizontal illuminance for December 4, December 8 and December 15, 1995 - 2nd Floor - east, west, north and south test-points.

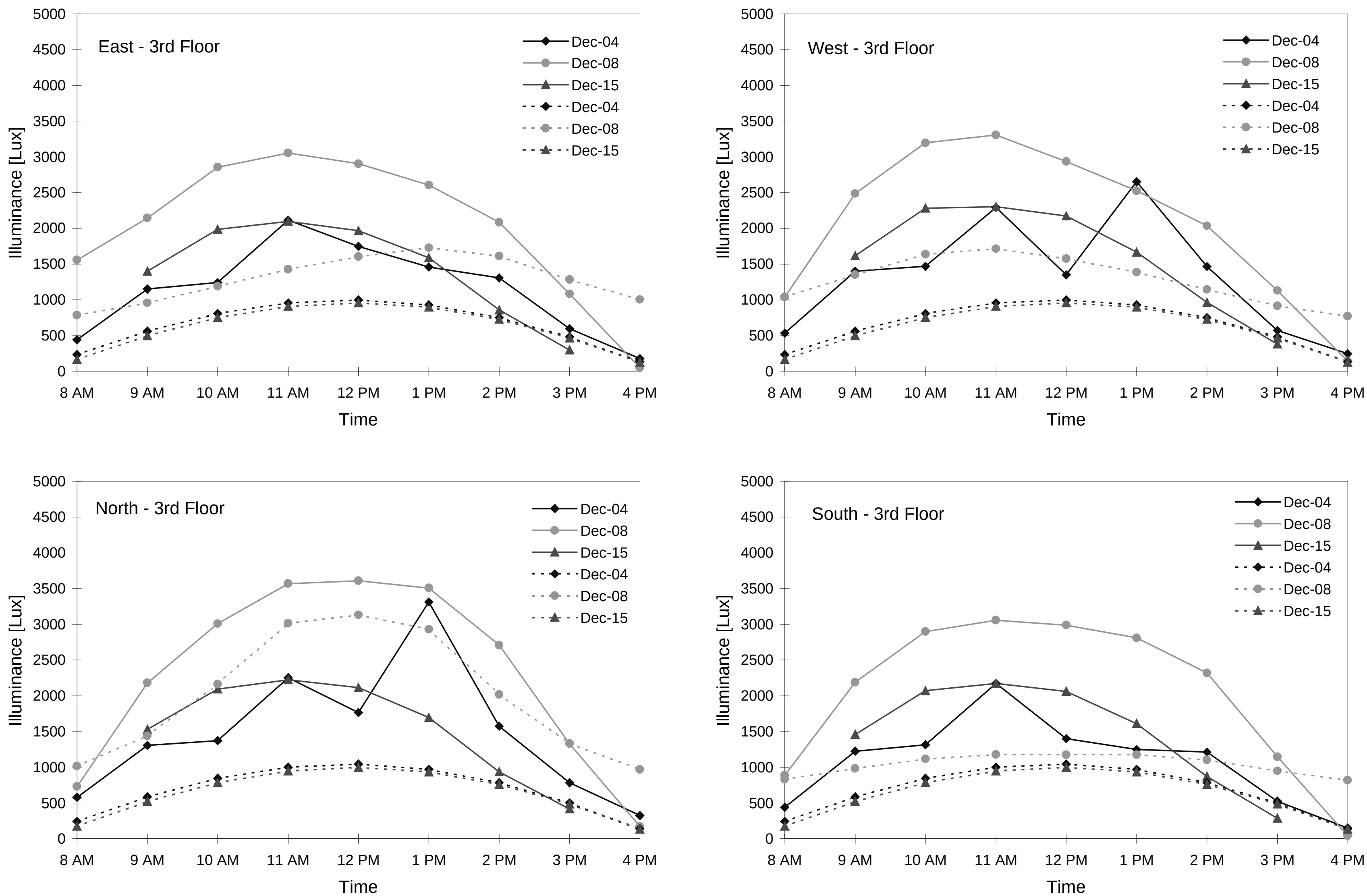


Figure 22 Measured and Superlite simulated indoor horizontal illuminance for December 4, December 8 and December 15, 1995 - 3rd Floor - east, west, north and south test-points.

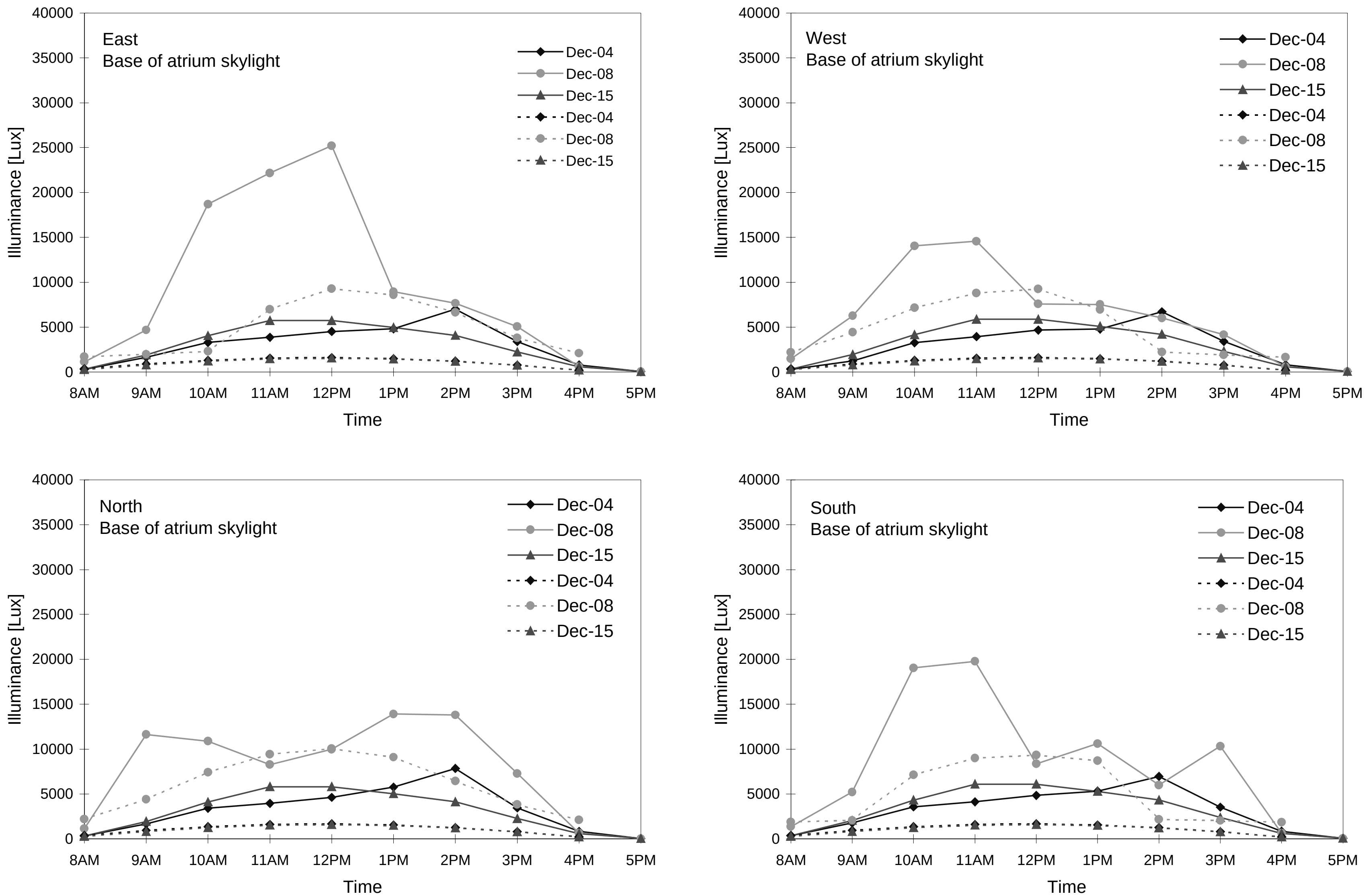
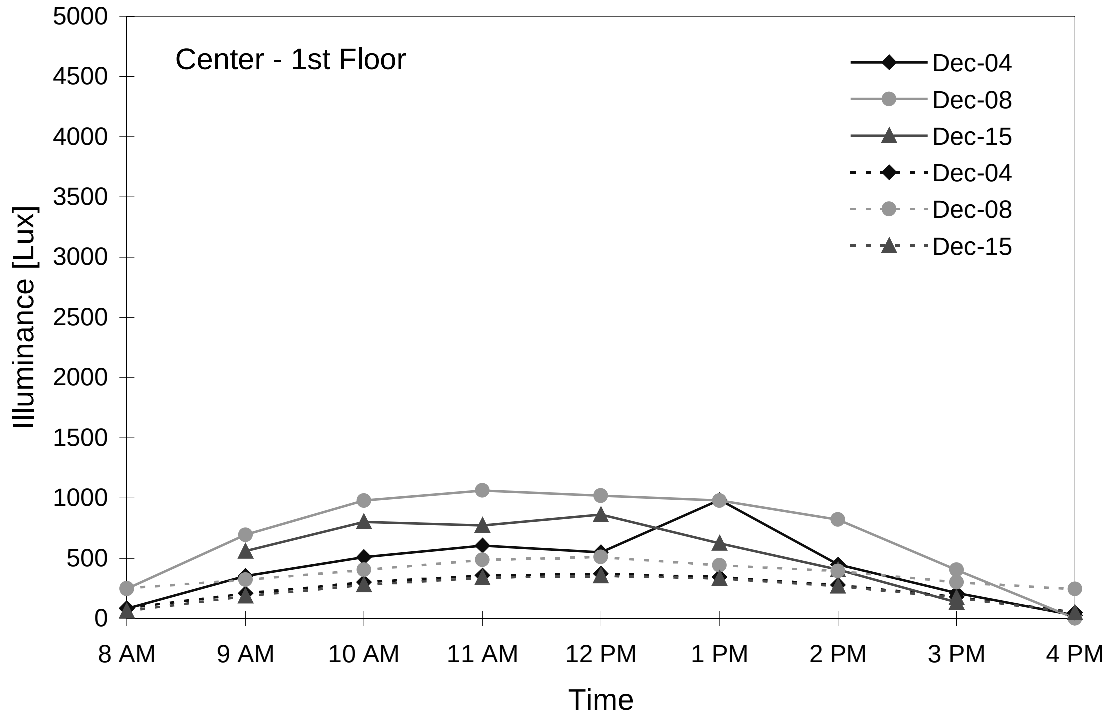


Figure 23 Measured and Superlite simulated horizontal indoor illuminance for December 4, December 8 and December 15, 1995 - east, west, north and south test-points at base of skylight



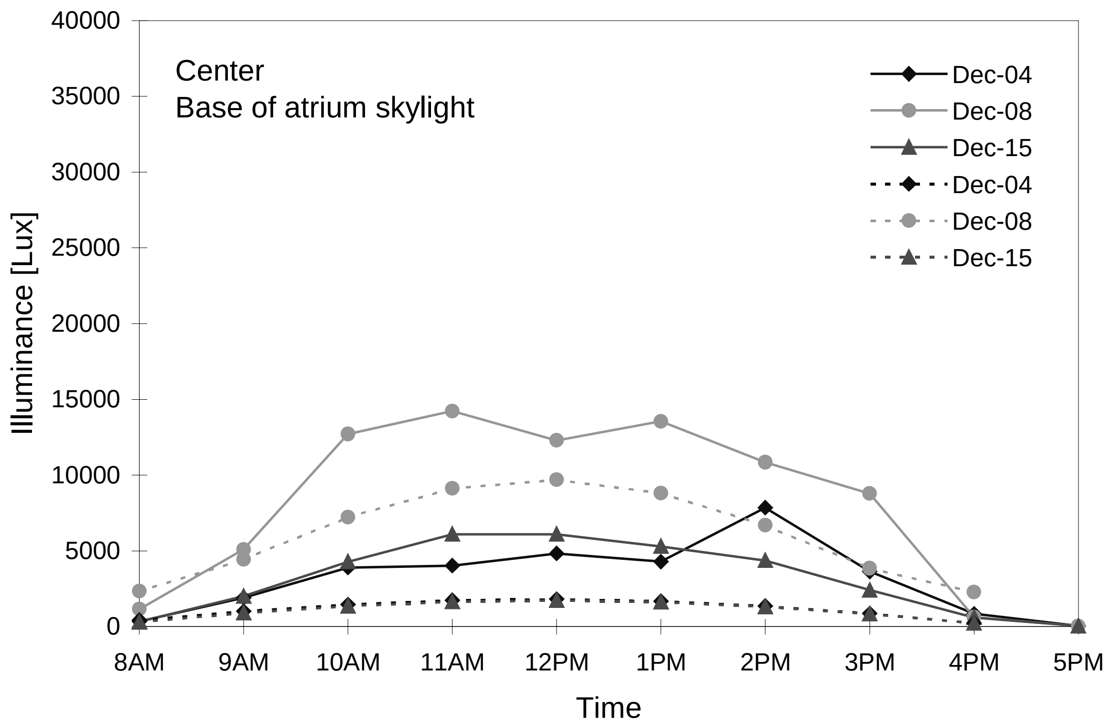


Figure 24 Measured and Superlite simulated indoor horizontal illuminance for December 4, December 8 and December 15, 1995 - Center of atrium floor and base of skylight

COMPARISON BETWEEN MEASURED AND SIMULATED DATA USING SUPERLINK

The Superlite model was used to evaluate the energy saving potential of replacing electric lighting with daylighting. Table 6 shows the measured and the simulated monthly and annual lighting energy savings resulted from the use of the installed automatic on/off lighting control system.

Table 6 Lighting energy savings resulted from the use of daylighting in combination with an on/off lighting control system (based on 24 hours/day time-on for photocontrolled lighting)

	Predicted lighting energy savings (kWh/month)	Measured lighting energy savings (kWh/month)
Jan	1570.0	
Feb	1800.8	
Mar	2354.9	
Apr	2665.5	
May	3158.5	
Jun	3095.9	2526
Jul	3201.6	
Aug	2972.5	
Sep	2608.6	
Oct	2203.9	
Nov	1676.1	
Dec	1368.8	418.5
Annual (kWh/year)	28677.1	17830*

(* estimation based on the average daily energy savings recorded for June and December 1995)

As shown in Table 6, the simulated lighting energy saving potential was 3095.9 kWh/month for June, which would translate into average lighting energy savings of 103.2 kWh/day. Measured data for June 1995 shows that the mean daily off-time (over 24 hours) for the photocontrolled lighting was 46.15% [Atif and Galasiu 1997]. This translates into average lighting energy savings of 84.2 kWh/day for June, or 2526 kWh/month, which is 22% lower than the simulated value. One main reason for this difference is the overprediction of daylight availability from the "typical meteorological year" weather file used by the computer simulation program instead of measured outdoor parameters.

The difference between measured and simulated energy savings was even more accentuated for the winter month due to malfunctions of the electrical lighting control system. As shown in Table 6, the simulated energy saving potential for the month of December was 1368.8 kWh/month, which translates into average lighting energy savings of 44.1 kWh/day. Measured data shows that the mean daily off-time (over 24 hours) for the photocontrolled lighting was 7.4%, which translates into average lighting energy savings of only 13.5 kWh/day, or 418.5 kWh/month [Atif and Galasiu 1997]. The measured lighting energy savings were about 3 times lower than the computer predicted savings. On-site observations indicated that this was greatly due to the heavy snowfall which occurred during the month of December 1995 and the accumulation of snow on the atrium fenestration which diminished greatly the daylight penetration. The daylight sensor that controls the on/off operation of the lighting fixtures is located below the skylight of another atrium than the case study, which was also covered by snow and frost during the entire monitoring season (aspect not taken into account by the simulation). Measured data of daylight contribution to the atrium space suggest that the existing on/off lighting control system can provide greater savings in the winter. It is obvious that the simulation cannot account for the malfunctioning of the lighting control system.

The simulation suggests that annual savings of about 28700 kWh in electric energy could be expected for the case study if the existing on/off system would be adequately enhanced (e.g. one daylight sensor per floor, removal of snow during winter months, scheduled fenestration cleaning, etc.). As currently installed, the automatic on-off system saves an estimated 17830 kWh/year, which is 61% lower that the predicted annual energy savings. This estimation was based on the average daily energy savings recorded for June 1995 (84.2 kWh/day) and December 1995 (13.5 kWh/day) and therefore included the poor performance of the automatic lighting control system during the winter season.

COMPARISON BETWEEN MEASURED AND SIMULATED DATA USING THE RADIANCE MODEL

This section presents the results of the Radiance model analysis. The model was investigated for daytime conditions only in order to verify its accuracy in predicting illuminance levels from daylight alone. Field-measured horizontal illuminance was compared with hourly computer-predicted illuminance for each floor of the atrium space, for two clear sky days, June 8 and December 8, 1995 and one completely overcast day December 15, 1995. Illuminance measured at the atrium perimeter, as well as 3.5 meters away from the perimeter toward the adjacent spaces was analyzed.

Comparison between Measured and Simulated Illuminance for a Clear Sky in the Summer

Figure 25 shows the distribution of measured and simulated illuminance for June 8, 1995 at the test-point located in the center of the atrium ground floor. Figure 27 shows the hourly horizontal illuminance measured at the atrium perimeter on each floor at the east, west, north and south test-points, along with the computer-predicted illuminance at the same locations. Figure 28 shows for each floor the distribution of measured and simulated horizontal illuminance at 3.5 m from the atrium perimeter toward the adjacent spaces. Corresponding hourly Radiance rendered pictures and falsecolor representations of all three floors are presented in Figures 29 throughout 34.

Table 7 summarizes for each level of the building the ranges of simulated and measured illuminance, from 9 AM to 5 PM for June 8, 1995. On the atrium ground floor, the distribution pattern of simulated illuminance followed closely the pattern of measured illuminance. The horizontal illuminance measured at the atrium perimeter ranged from 600 to 24000 lux, and the simulated illuminance ranged from 500 to 42000 lux. On the ground floor, at 3.5 meters from the atrium perimeter towards the adjacent spaces, the measured illuminance was between 18 and 350 lux and the simulated illuminance was between 25 and 600 lux. In the center of the atrium ground floor, the measured illuminance ranged from 1000 to 2600 lux and the simulated illuminance varied from 800 to 2400 lux. Overall, on the atrium ground floor the illuminance levels in the space were fairly well simulated, especially under diffuse daylight at the atrium perimeter and in the center of the atrium floor. However, the illuminance was sometimes overestimated next to the adjacent spaces and under direct sun at the atrium perimeter. In this cases, instantaneous predicted illuminance varied sometimes significantly from the measured values, being sometimes twice (or half) the measured values.

The comparison of the other levels of the building (2nd and 3rd floors and base of skylight) produced similar results. As shown in Table 7 and Figure 27, at the atrium perimeter on both the second and third floors, there was a good agreement between the range and the distribution pattern of measured and simulated illuminance. Similarly to the first floor, whenever a test-point was under direct sun, the simulated illuminance at that test-point was either twice or half the measured illuminance. This tendency was also noticed at the test-points located at the base of the skylight, which shows a sensitivity of the simulations towards direct sun as it reaches the space. Figure 26 shows the distribution of measured and simulated illuminance at the five test-points located just below the atrium skylight. Despite a good agreement between the overall range of measured and simulated illuminance, instantaneous illuminance was mostly higher than the measured illuminance, especially during afternoon from 12 PM to 4 PM. Next to the adjacent space (Figure 28), the illuminance was occasionally overpredicted on the second floor and underpredicted on the third floor. On the second floor at 3.5 meters from the atrium perimeter, the maximum measured illuminance was about 500 lux and the maximum simulated illuminance was 1050 lux. At these latter test-points on the third floor, the minimum measured illuminance was 700 lux and the minimum simulated illuminance was about 450 lux.

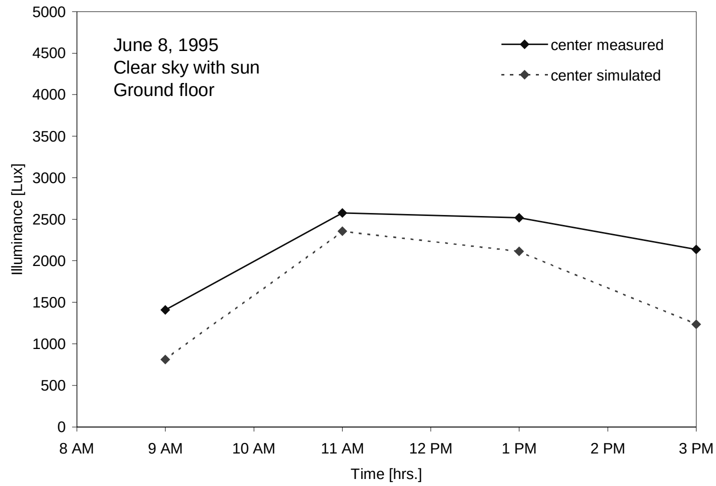


Figure 25 Measured and Radiance simulated indoor horizontal illuminance in the center of the atrium ground floor for June 8, 1995

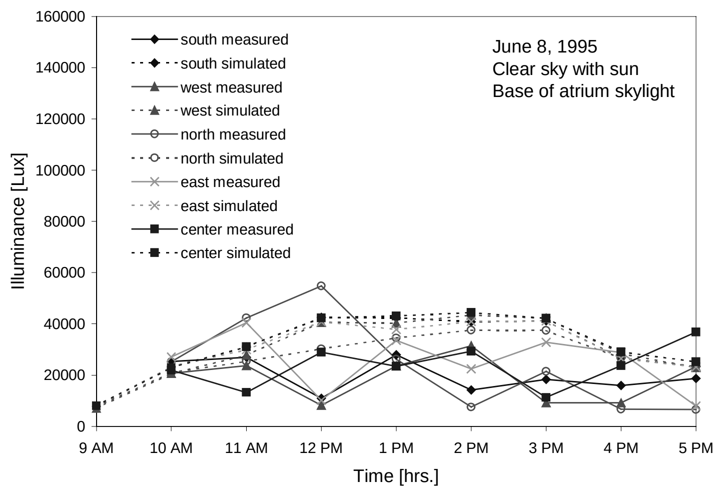
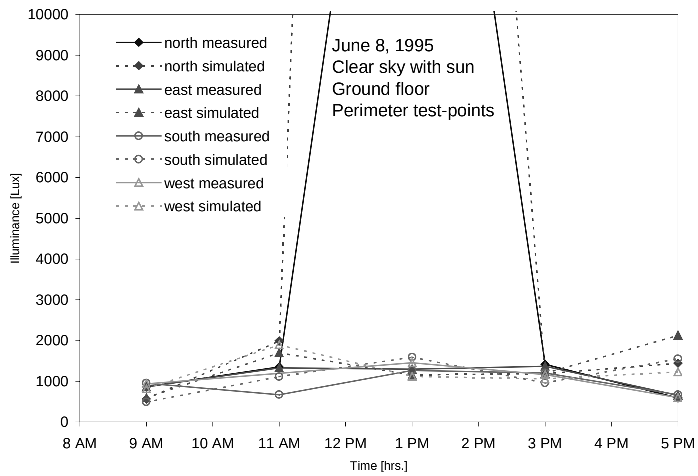
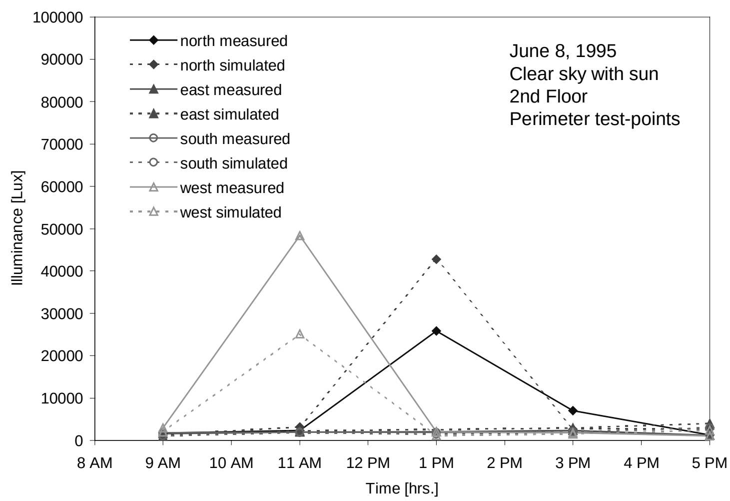


Figure 26 Measured and Radiance simulated indoor horizontal illuminance for June 8, 1995 at various test-points located at the base of the atrium skylight

Table 7 Measured versus Radiance simulated indoor horizontal illuminance for a clear sky on June 8, 1995 (Lux)

	Atrium perimeter		3.5 m from atrium perimeter	
	Measured illuminance	Simulated illuminance	Measured illuminance	Simulated illuminance
Ground floor	600-24000	500-42000	18-350	20-600
Second floor	1100-48400	980-42800	140-500	60-1050
Third floor	2700-38700	1350-42500	700-13300	450-8100
Base of skylight	6500-54800	7000-44400	N/A	N/A





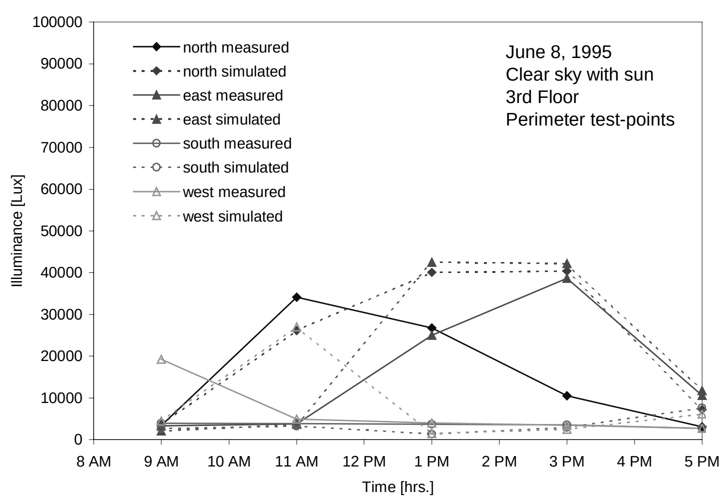


Figure 27 Measured and Radiance simulated indoor horizontal illuminance for a clear sky in the summer at various test-points located at the atrium perimeter

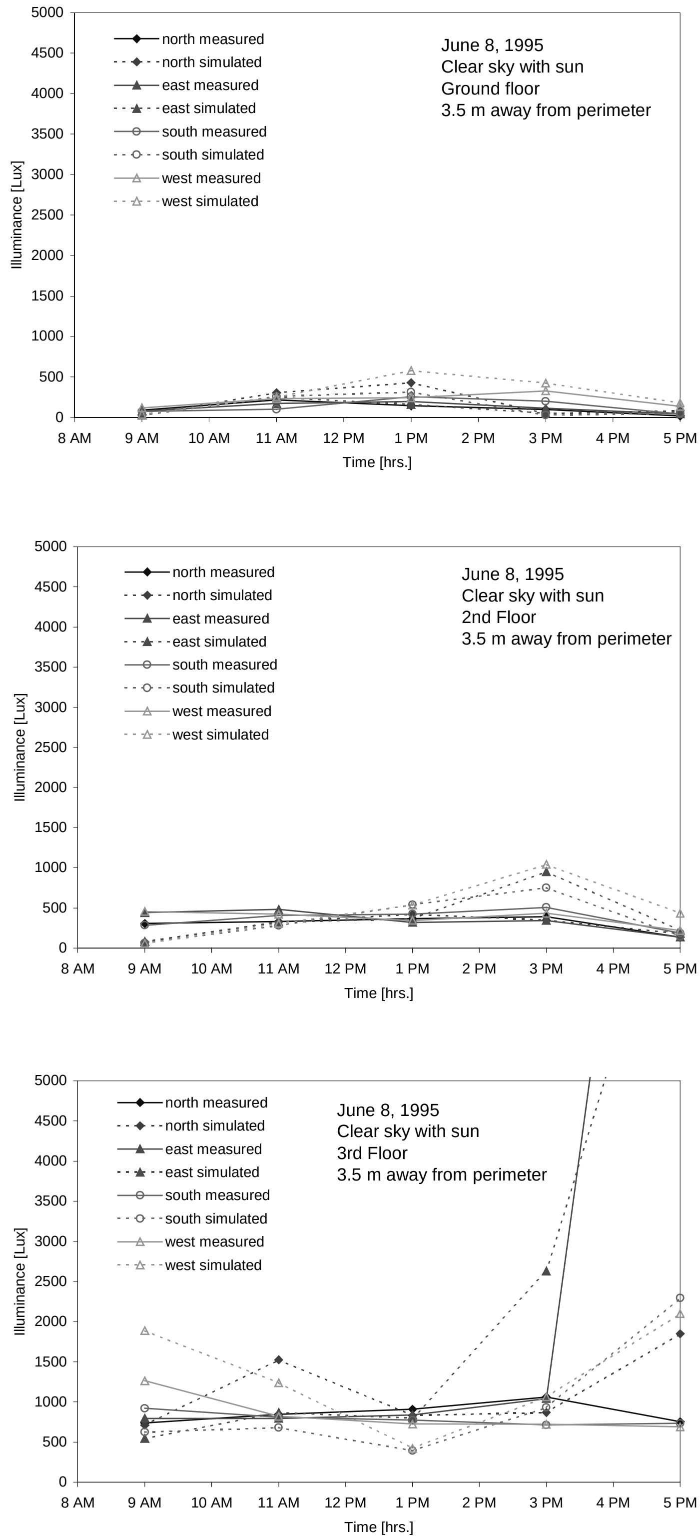


Figure 28 Measured and Radiance simulated indoor horizontal illuminance for a clear sky in the summer at various test-points located 3.5 meters away from the atrium perimeter

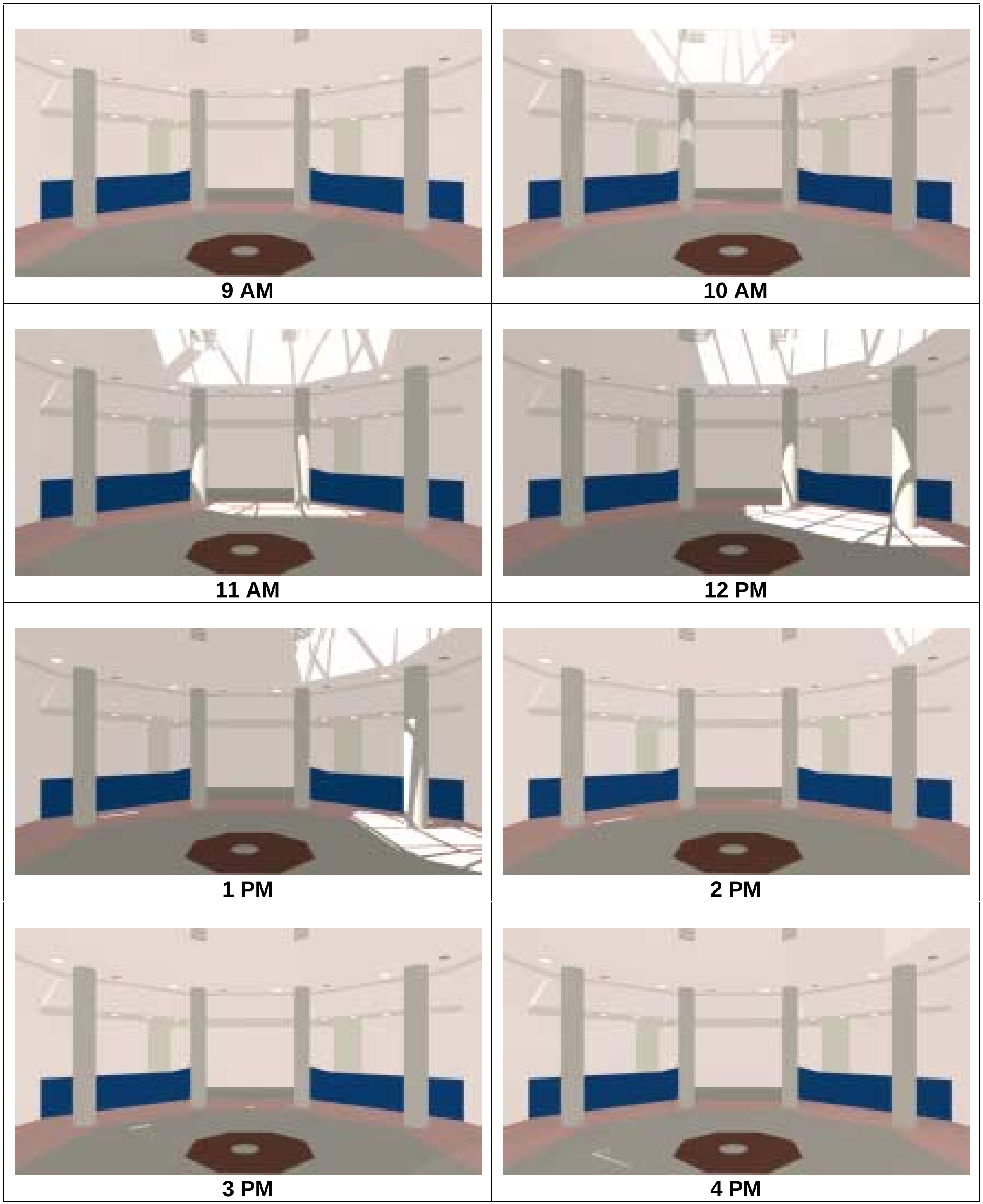


Figure 29 Radiance representation of the atrium ground floor under a clear sky in the summer (simulated day: June 8, 1995; north-west view)

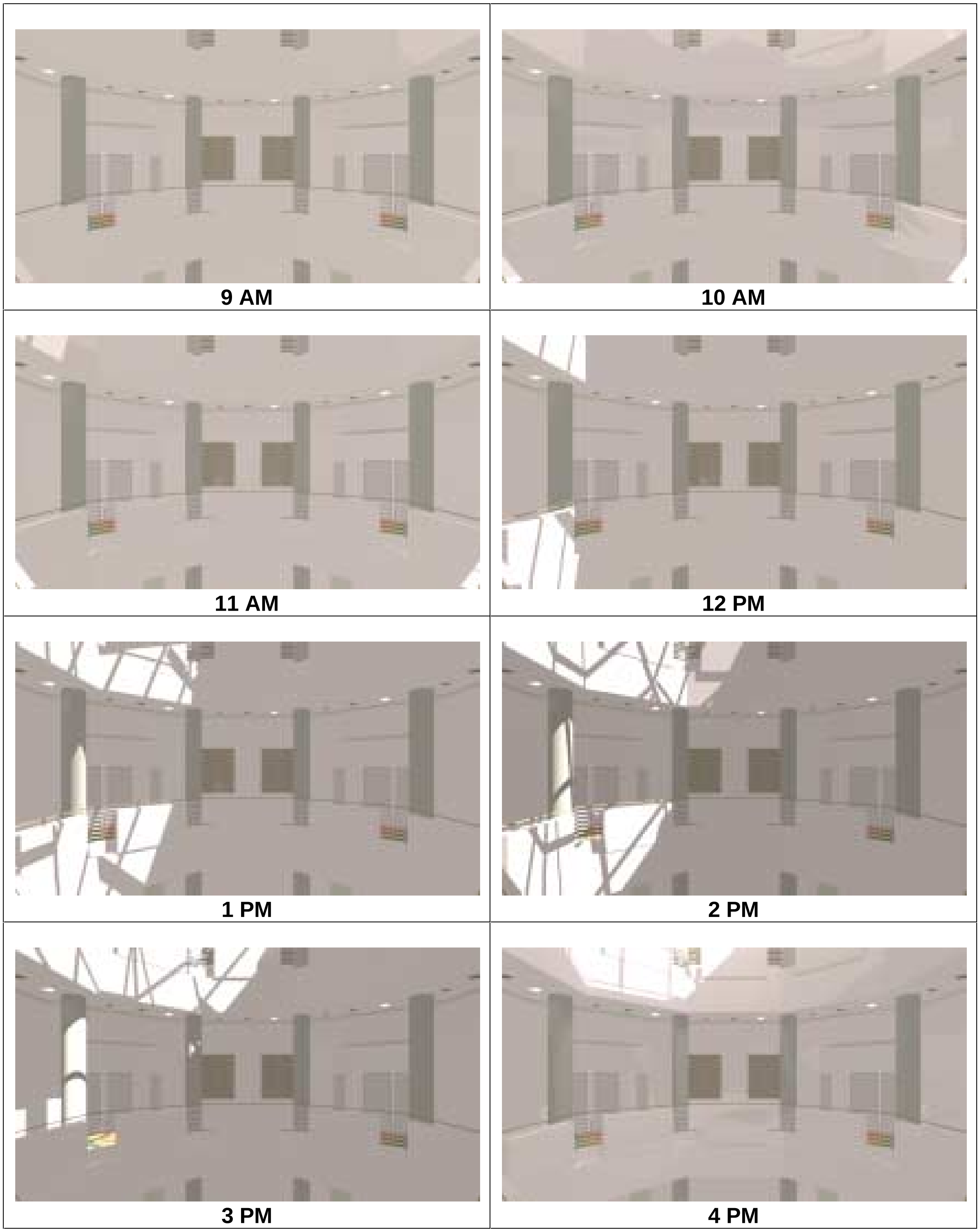


Figure 30 Radiance representation of the atrium 2nd floor under a clear sky in the summer (simulated day: June 8, 1995; south-east view)

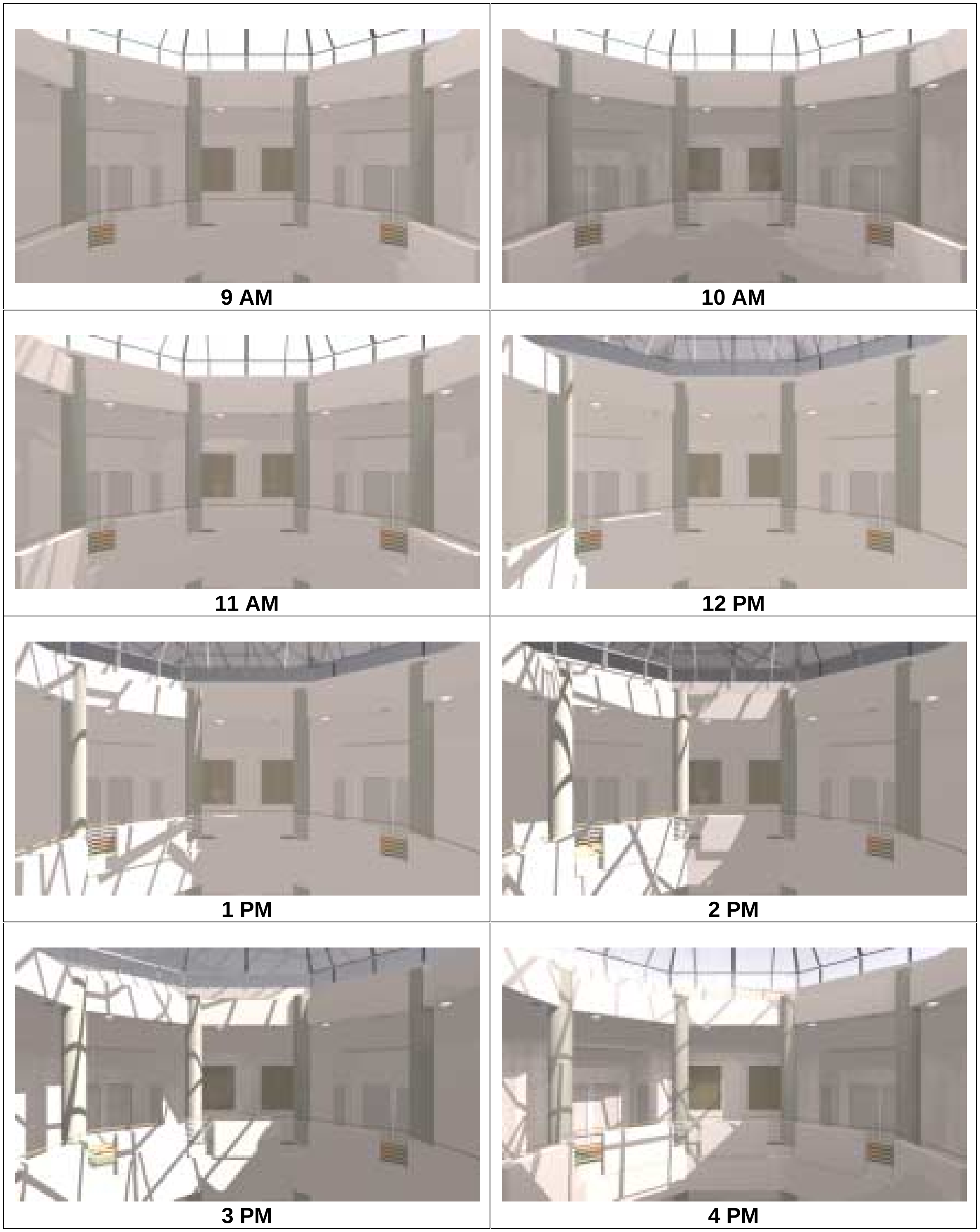


Figure 31 Radiance representation of the atrium 3rd floor under a clear sky in the summer (simulated day: June 8, 1995; south-east view)

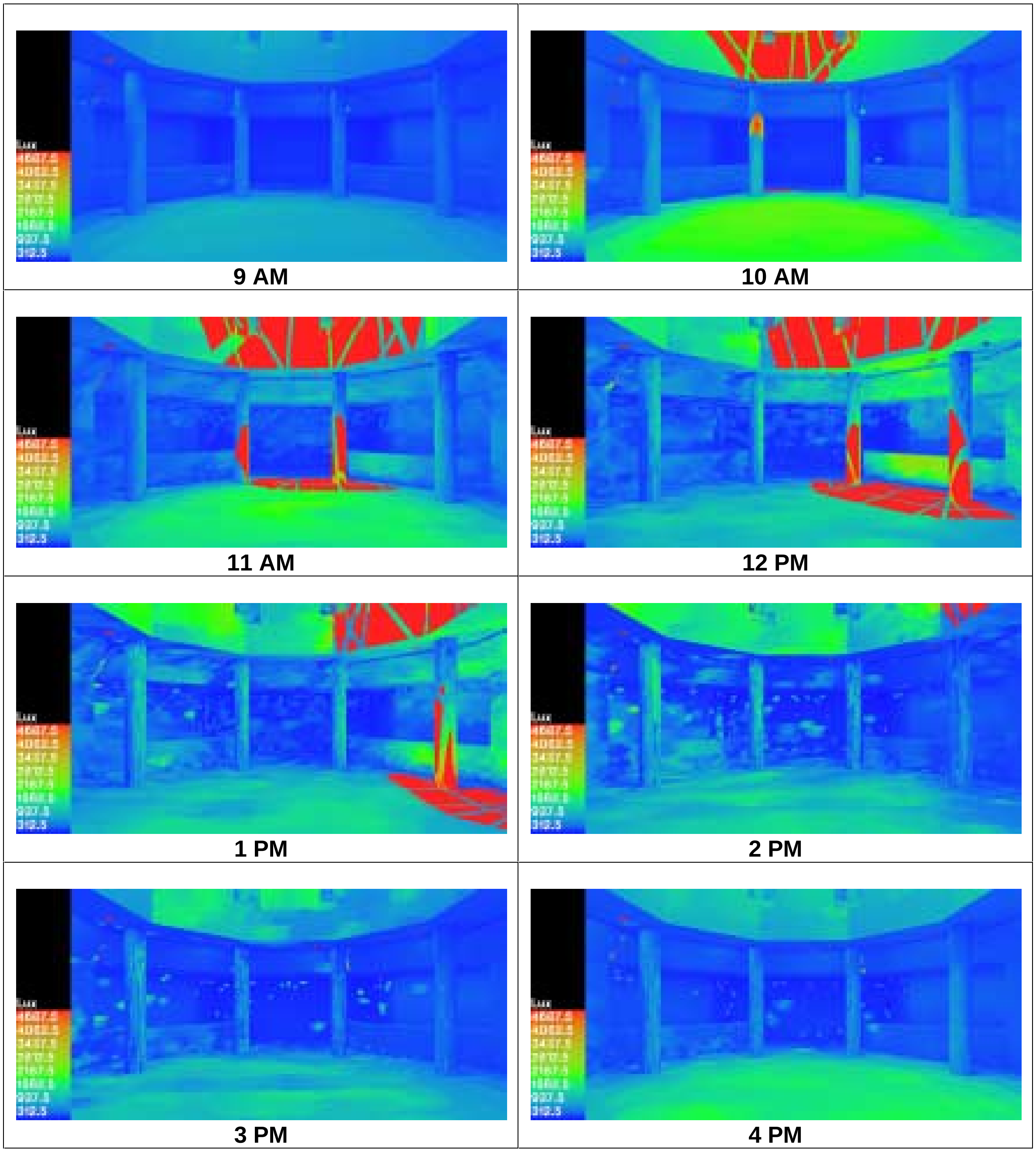


Figure 32 Falsecolor Radiance representations of the atrium ground floor under a clear sky in the summer (simulated day: June 8, 1995; north-west view)

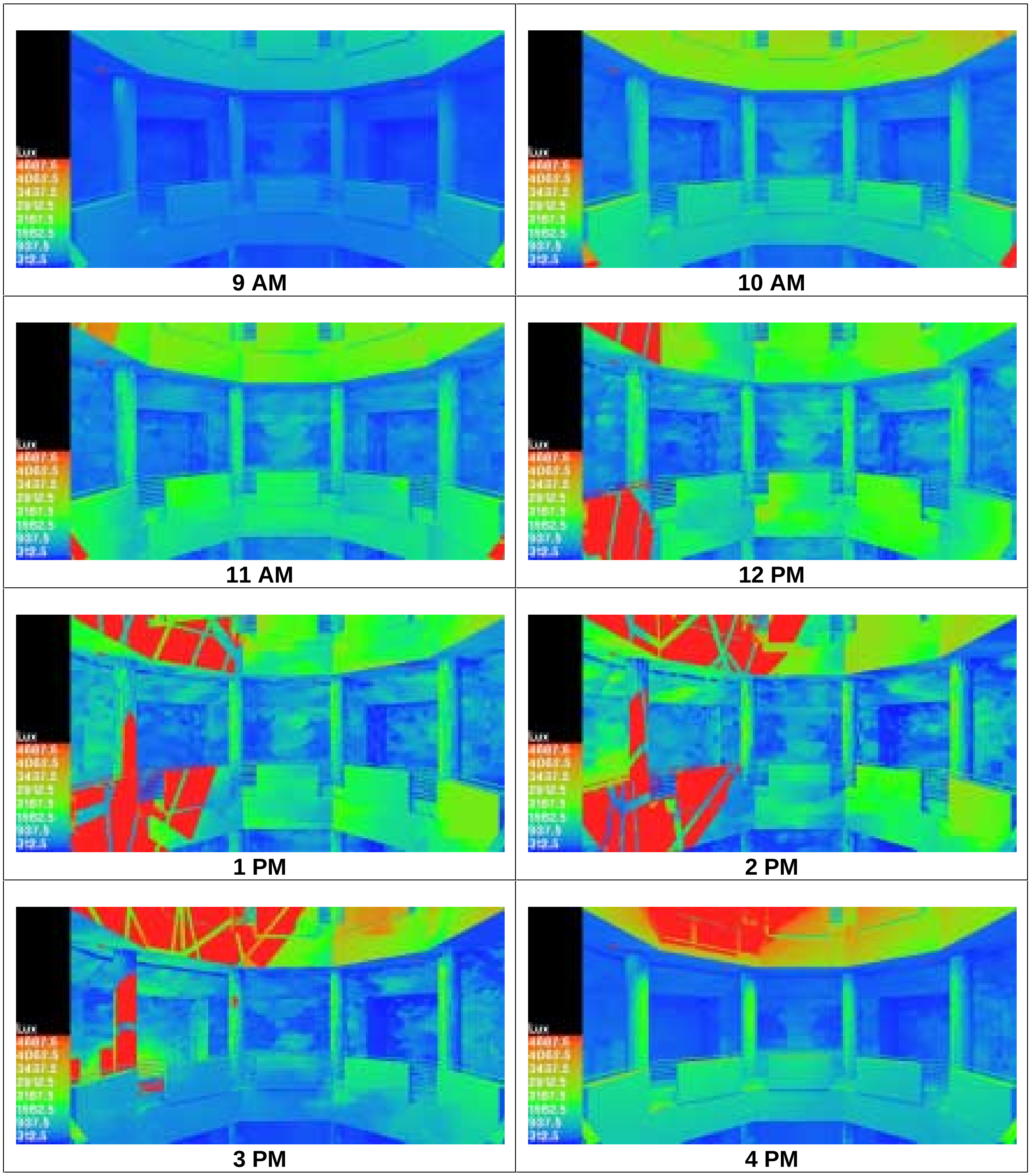


Figure 33 Falsecolor Radiance representation of the atrium 2nd floor under a clear sky in the summer (simulated day: June 8, 1995; south-east view)

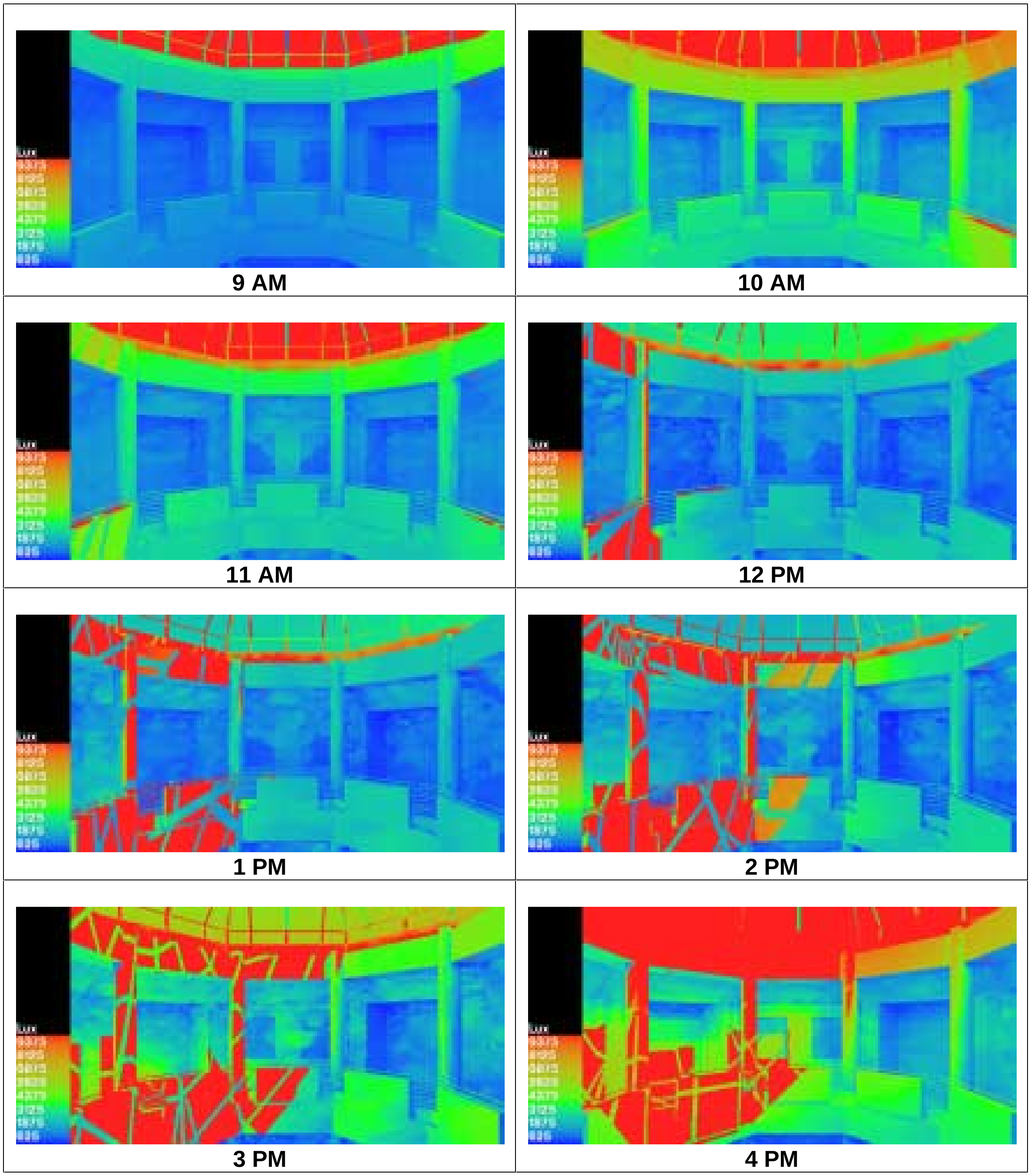


Figure 34 Falsecolor Radiance representation of the atrium 3rd floor under a clear sky in the summer (simulated day: June 8, 1995; south-east view)

Comparison between Measured and Simulated Illuminance for a Clear Sky in the Winter

Figure 35 shows the distribution of measured and simulated for December 8, 1995 at the test-point located in the center of the atrium ground floor. Figure 37 shows the hourly measured horizontal illuminance at the atrium perimeter on each floor at the east, west, north and south test-points, along with the computer-predicted illuminance at the same locations. The illuminance measured and simulated at 3.5 m from the atrium perimeter is presented in Figure 38. Figures 39 throughout 44 show corresponding hourly Radiance rendered pictures and falsecolor representations of the atrium floors.

Table 8 summarizes for each level of the building the ranges of simulated and measured illuminance from 9 AM to 3 PM for December 8, 1995. On the atrium ground floor, the simulated illuminance followed closely the trend of measured illuminance and, especially at the atrium perimeter and in the center of the space, there was a very good agreement between the measured and the simulated values. The illuminance measured at the perimeter ranged from 300 to 1000 lux, while the simulated illuminance was between 200 and 1500 lux. In the center of the atrium floor, the measured illuminance ranged from 250 to 1050 lux and the simulated illuminance was between 270 to 1000 lux. On the same floor, at 3.5 meters from the atrium perimeter towards the adjacent spaces, measured illuminance was between 10 and 130 lux and simulated illuminance was between 5 and 130 lux.

Overall, data shows a very good agreement in range and pattern between measured and simulated illuminance for the atrium ground floor. This was attributed to the fact that, due to the sun's low position in the sky during the winter season, no direct sun reached the ground floor during daylight hours and, therefore, the sensitivity of the simulations towards direct sun as observed for the investigated summer day did not affect the winter data. This is also confirmed by the data obtained for the second floor where direct sun did not reach either, and where the illuminance from diffuse daylight was also well predicted at both the atrium perimeter and 3.5 m away from the perimeter.

On the third floor, however, there were cases where the illuminance was overpredicted at the atrium perimeter, and this happened mostly during afternoon hours, at test-points simulated as being under direct sun, whereas in reality direct sun was present only at the eastern and northern test-points located further away from the perimeter, as shown in Figure 38. In these situations, the maximum illuminance measured at the atrium perimeter was about 3600 lux, and the simulated illuminance was about 9100 lux. Similarly to the summer data, when a test-point located at 3.5 m from the perimeter was under direct sun, the simulated illuminance was twice the measured value. This tendency was also shown by the data collected at the test-points located at the base of the skylight (Figure 36), which once again indicates a sensitivity of the simulations towards direct sun. The instantaneous illuminance simulated at this level was mostly twice the measured illuminance, especially during afternoon from 12 PM to 3 PM. As mentioned before, this sensitivity might partly be attributed to the skylight design and the average visible transmittance used in the simulations instead of instantaneous measured values. However, this does not exclude software justifications for the overpredicted illuminance values.

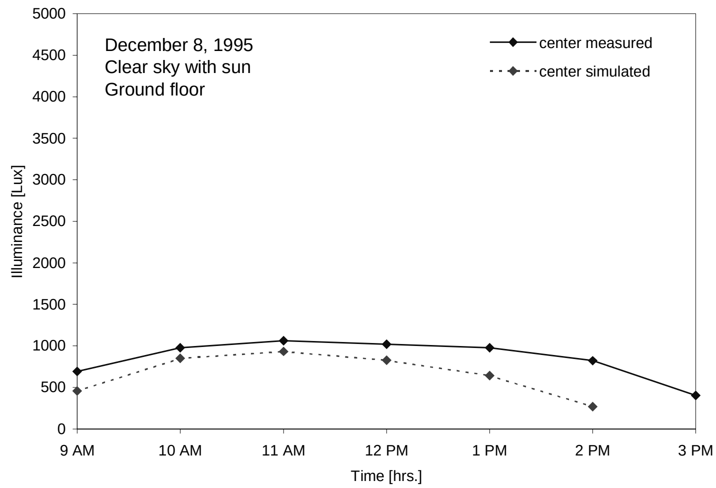


Figure 35 Measured and Radiance simulated indoor horizontal illuminance in the center of the atrium ground floor for December 8, 1995

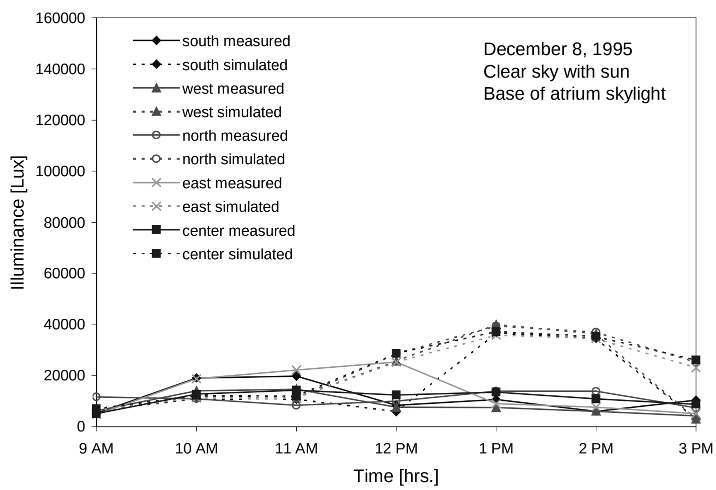


Figure 36 Measured and Radiance simulated indoor horizontal illuminance for December 8, 1995 at various test-points located at the base of the atrium skylight

Table 8 Measured versus Radiance simulated indoor horizontal illuminance for a clear sky on December 8, 1995 (Lux)

	Atrium perimeter		3.5 m from atrium perimeter	
	Measured illuminance	Simulated illuminance	Measured illuminance	Simulated illuminance
Ground floor	300-1000	200-1500	10-130	5-130
Second floor	400-1200	500-2500	30-170	20-200
Third floor	1100-3600	1800-9100	200-23000	300-46000
Base of skylight	4100-25200	3000-40000	N/A	N/A

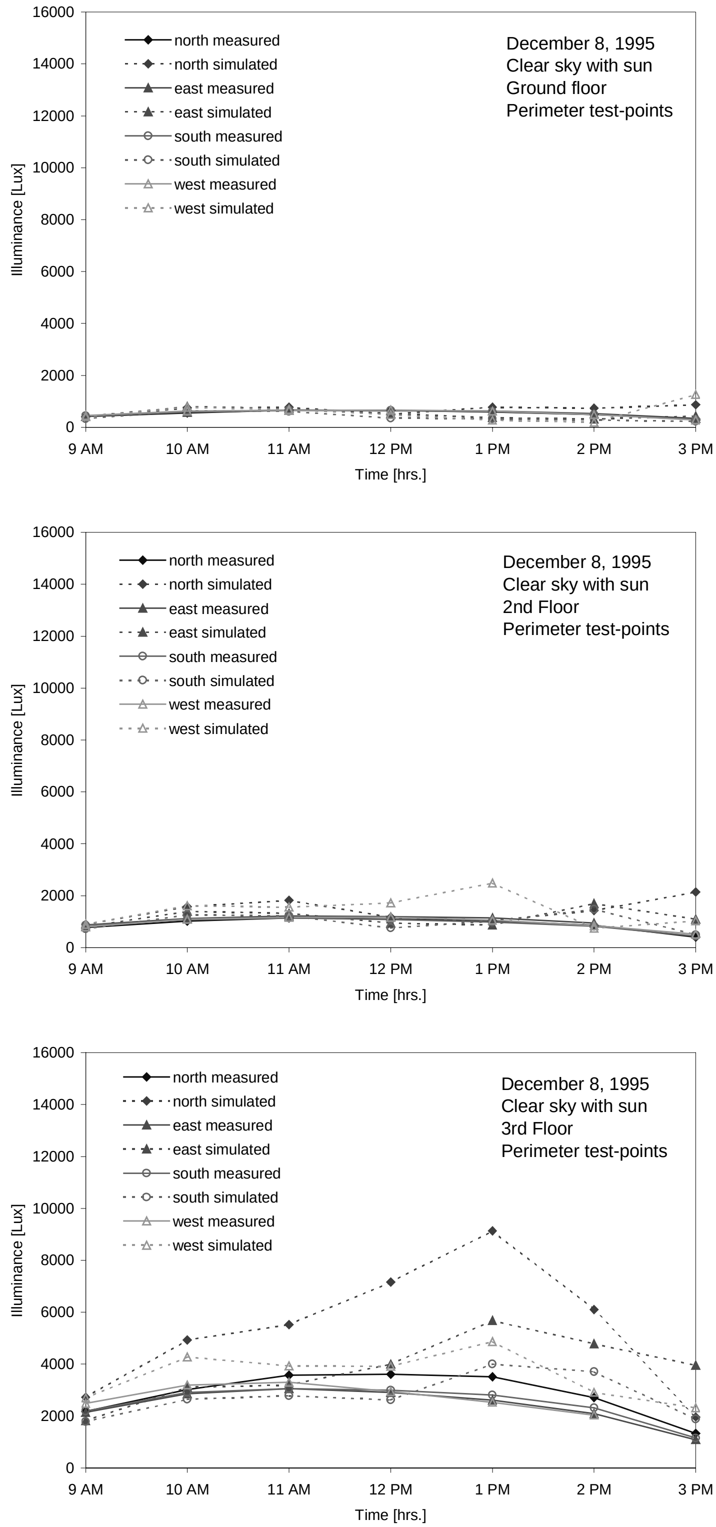
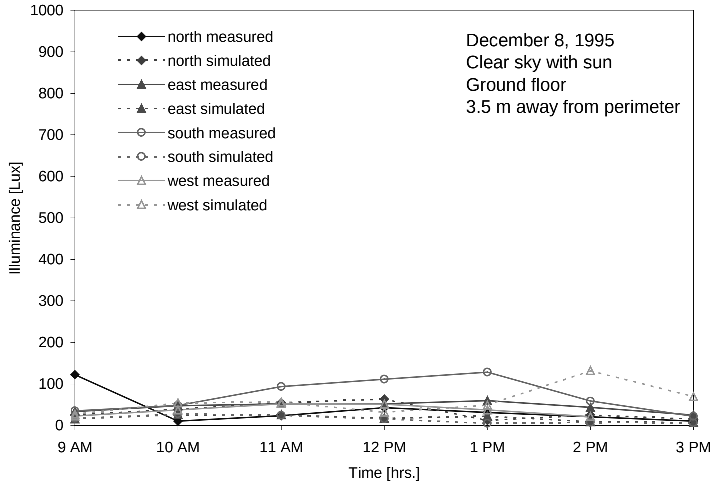
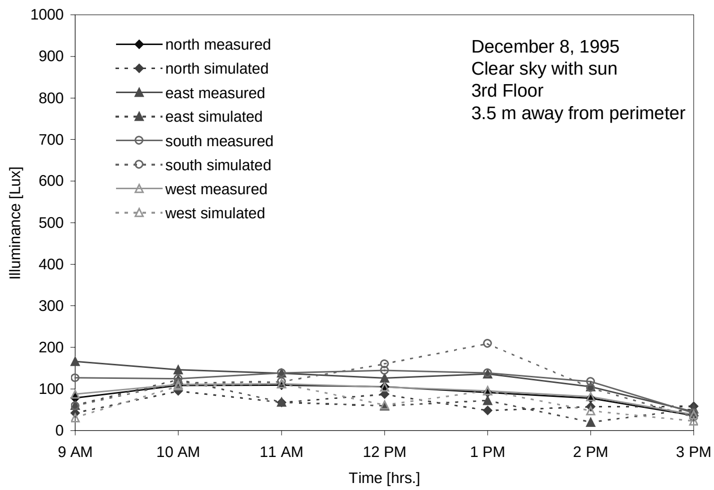


Figure 37 Measured and Radiance simulated indoor horizontal illuminance for a clear sky in the winter at various test-points located at the atrium perimeter





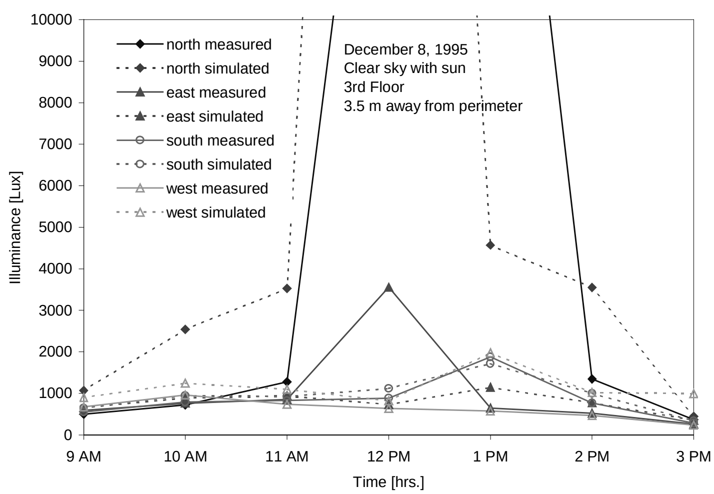


Figure 38 Measured and Radiance simulated indoor horizontal illuminance for a clear sky in the winter at various test-points located 3.5 meters away from the atrium perimeter

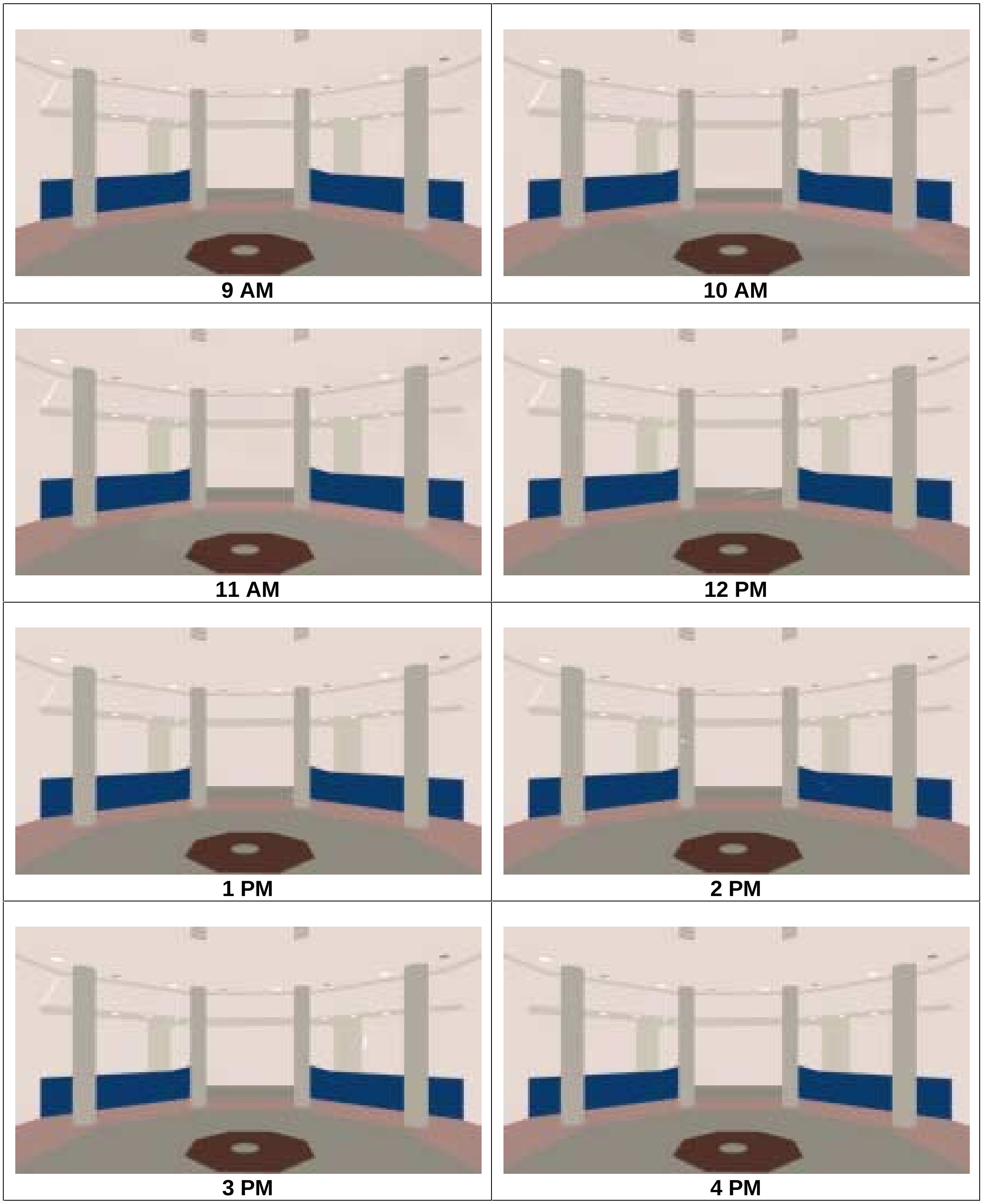


Figure 39 Radiance representation of the atrium 1st floor for a clear sky in the winter (simulated day: December 8, 1995; south-east view)

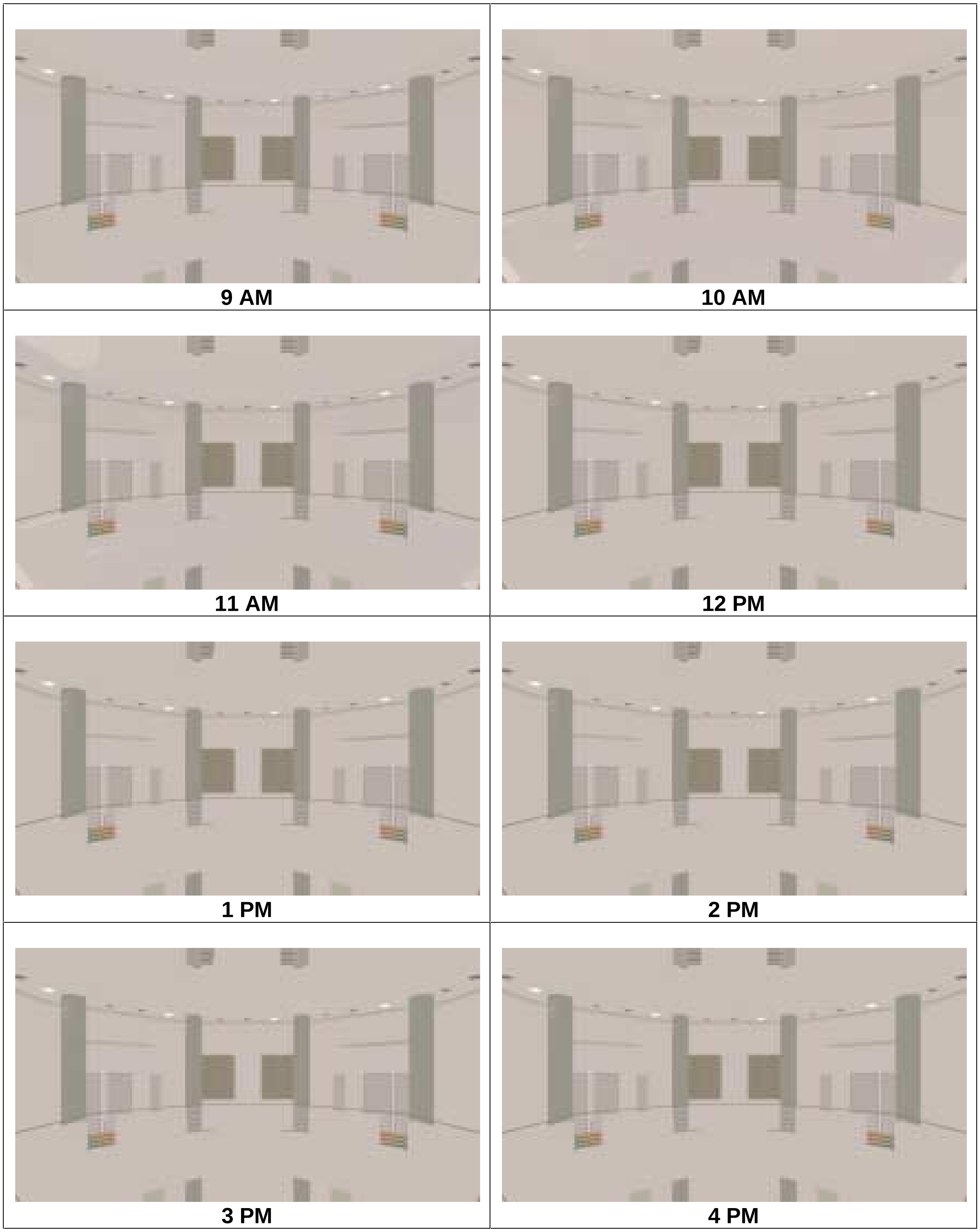


Figure 40 Radiance representation of the atrium 2nd floor for a clear sky in the winter (simulated day: December 8, 1995; south-east view)

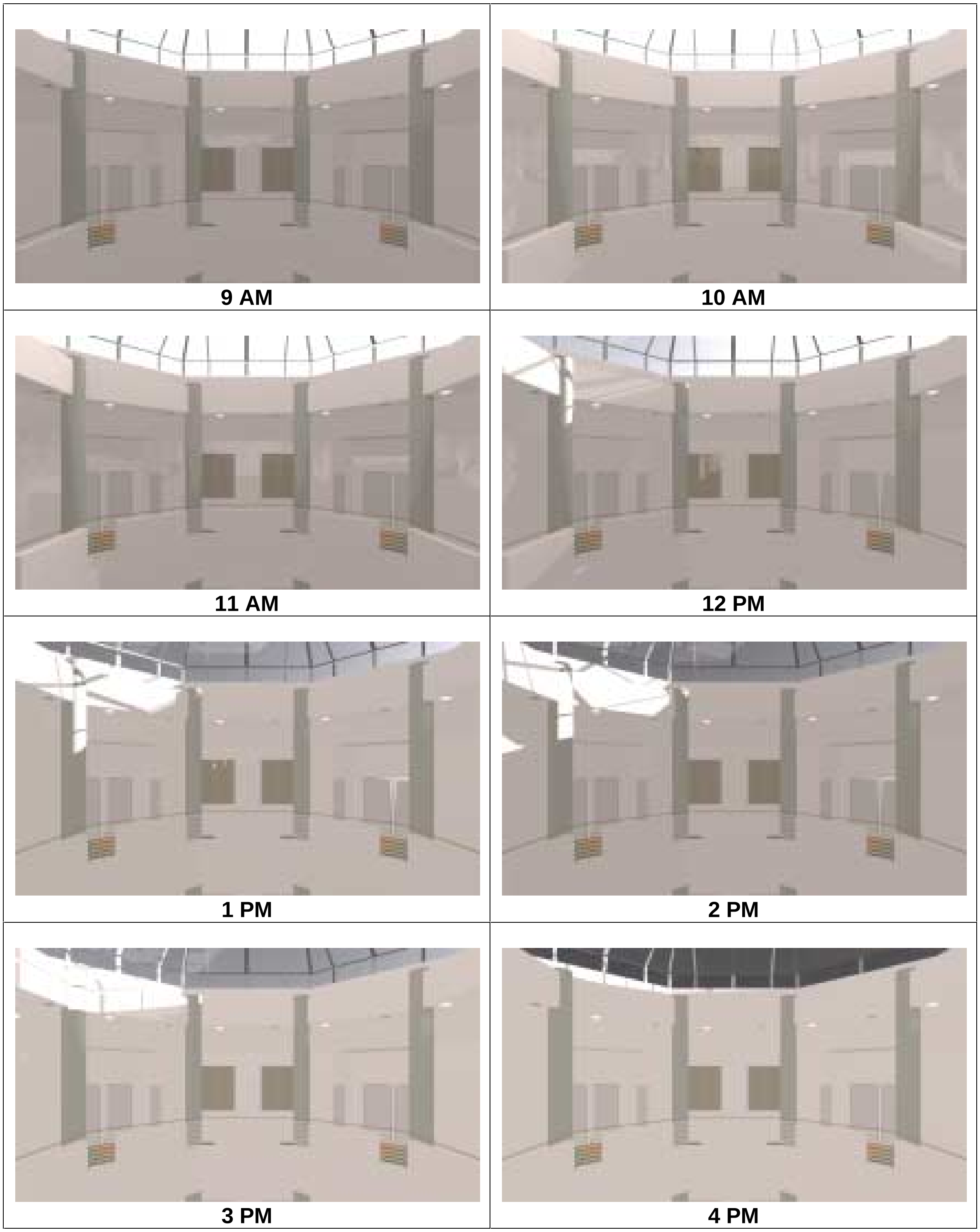


Figure 41 Radiance representation of the atrium 3rd floor for a clear sky in the winter (simulated day: December 8, 1995; south-east view)

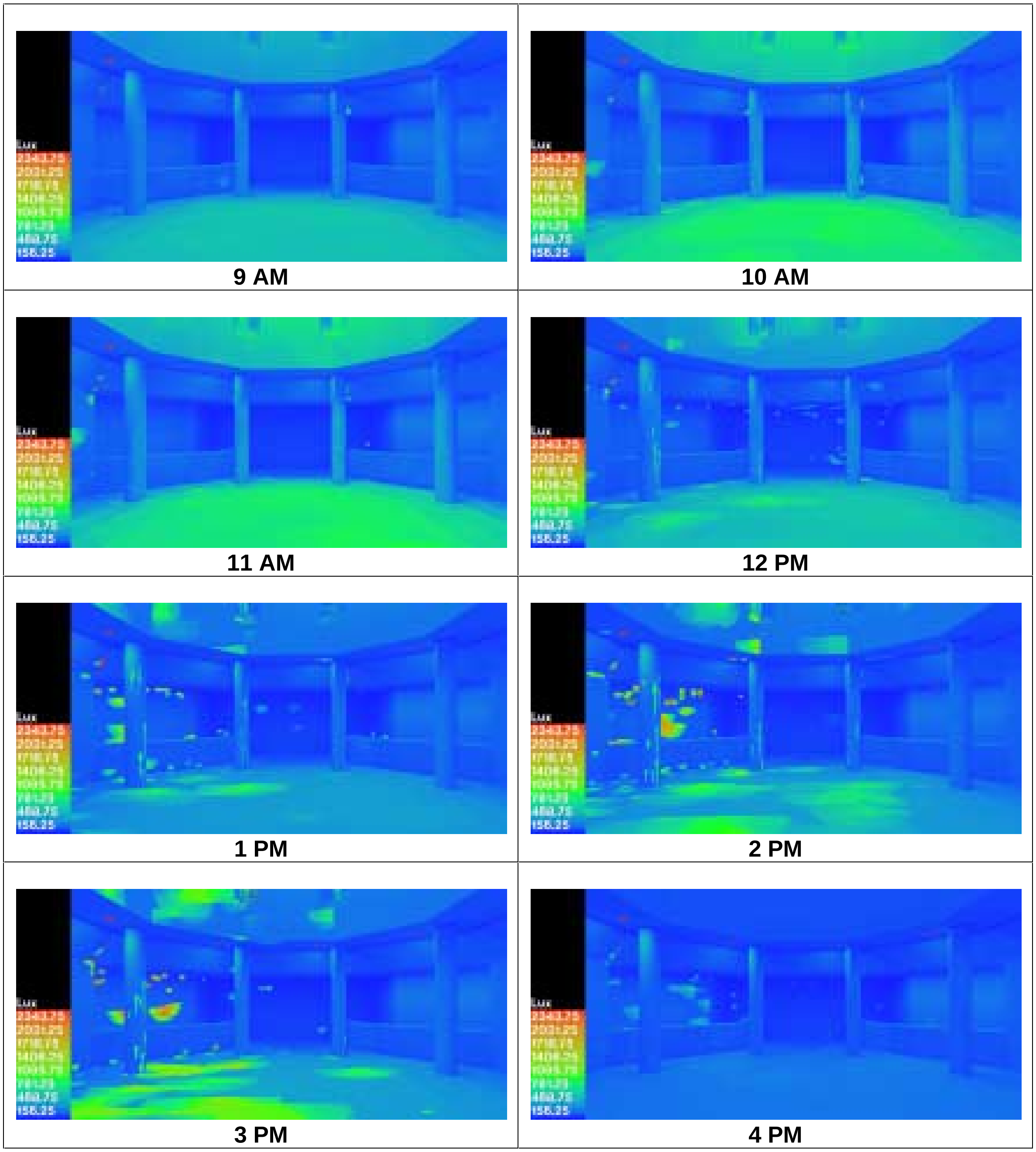


Figure 42 Falsecolor Radiance representations of the atrium ground floor under a clear sky in the winter (simulated day: December 8, 1995; north-west view)

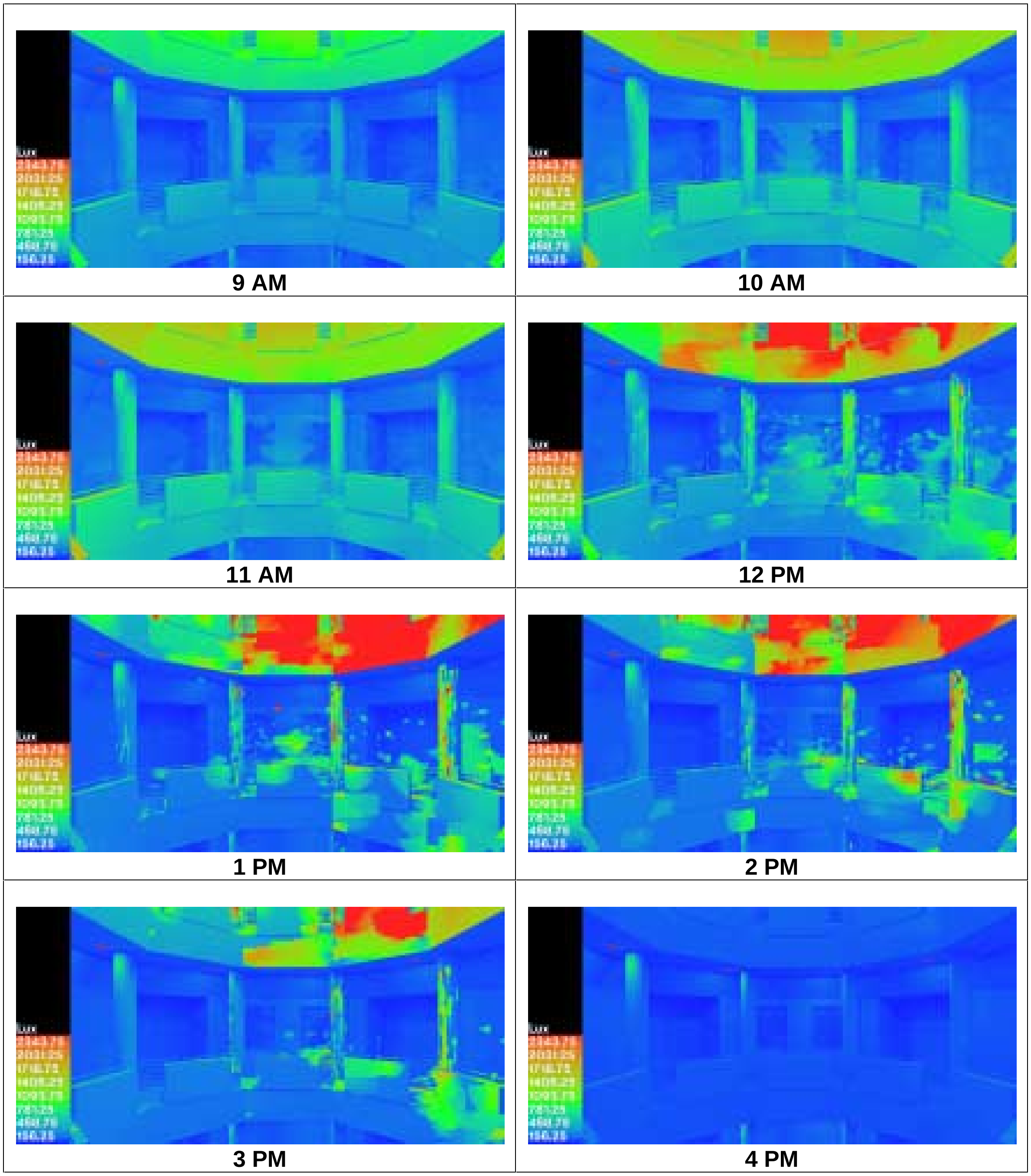


Figure 43 Falsecolor Radiance representation of the atrium 2nd floor under a clear sky in the winter (simulated day: December 8, 1995; south-east view)

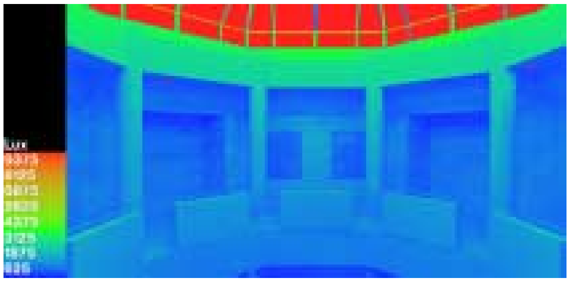
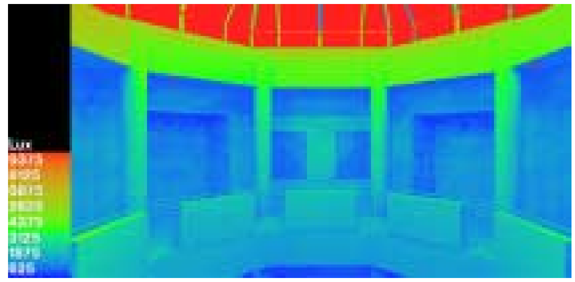
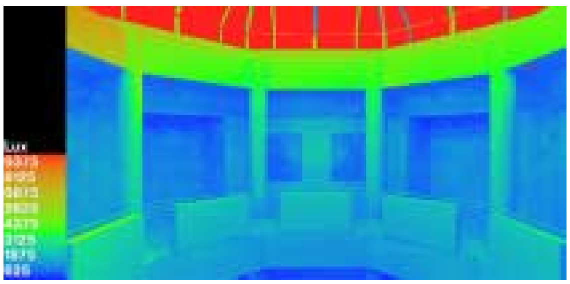
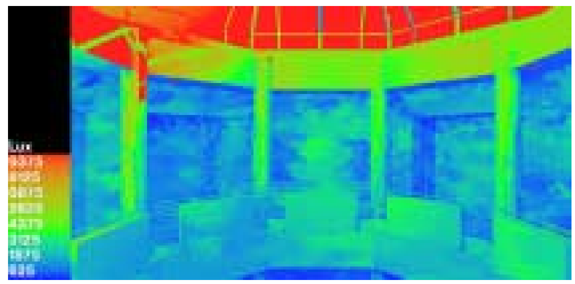
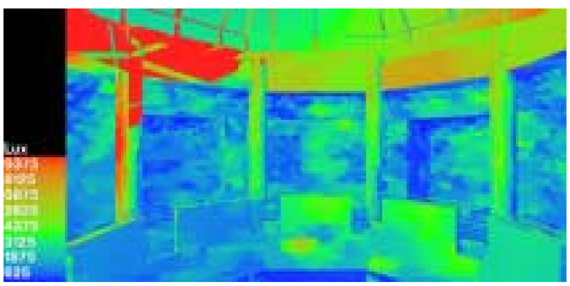
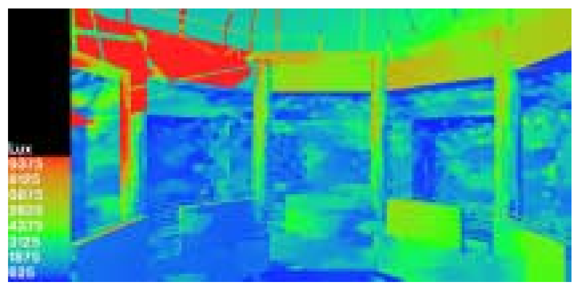
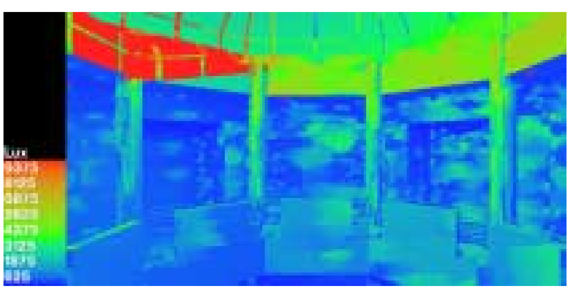
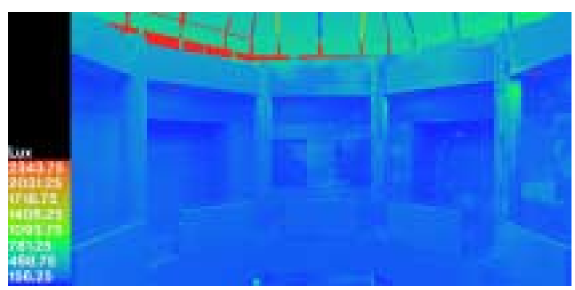
	
9 AM	**10 AM**
	
11 AM	**12 PM**
	
1 PM	**2 PM**
	
3 PM	**4 PM**

Figure 44 Falsecolor Radiance representation of the atrium 3rd floor under a clear sky in the winter (simulated day: December 8, 1995; south-east view)

Comparison between Measured and Simulated Illuminance for an Overcast Sky

Figure 45 shows the distribution of measured and simulated illuminance for December 15, 1995 in the center of the atrium ground floor. Figure 47 shows the measured hourly horizontal illuminance at the atrium perimeter on each floor at the east, west, north and south test-points and the computer-predicted illuminance at the same locations. Figure 48 shows the illuminance measured and simulated at 3.5 m from the atrium perimeter. Figures 49 throughout 54 show the corresponding hourly Radiance rendered pictures and falsecolor representations of the atrium floors.

Table 9 summarizes for each level of the building the ranges of measured and simulated illuminance from 9 AM to 3 PM for December 15, 1995. Under overcast sky data showed a very good agreement in both range and pattern between measured an simulated illuminance at all the test-points located on the atrium ground floor. Data also showed a very good agreement between instantaneous measured and simulated illuminance, especially in the center of the ground floor where throughout the day the instantaneous discrepancy was lower than 20%. On this day, both the measured and the simulated illuminance ranged between 200 and 900 lux.

On the second and the third floors, the simulated illuminance was also very well predicted at all test-points. At the atrium perimeter, measured illuminance ranged from 200 to 1000 lux on the second floor, and from 850 to 2300 lux on the third floor. At the analogous test-points, the simulated illuminance was between 350 and 1200 lux on the second floor, and between 800 and 2500 lux on the third floor. Finally, as shown in Figure 46, there was a very good agreement between measured and simulated values at the test-points located at the base of the skylight, where the instantaneous discrepancy at any time of day and location was between 9 to 19% from 9 AM to 3 PM.

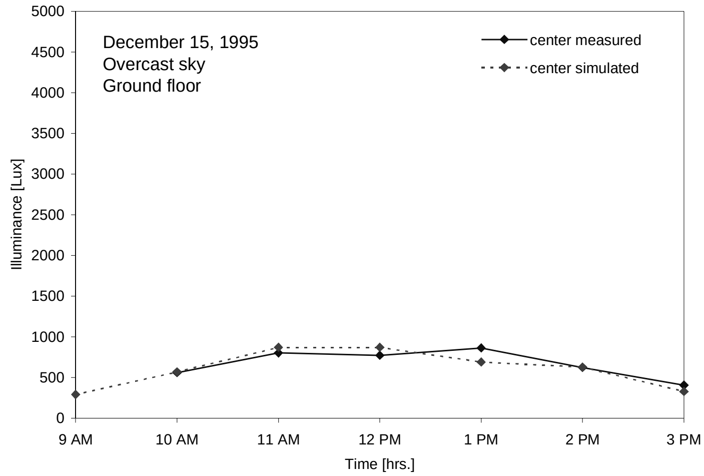


Figure 45 Measured and Radiance simulated indoor horizontal illuminance in the center of the atrium ground floor for December 15, 1995

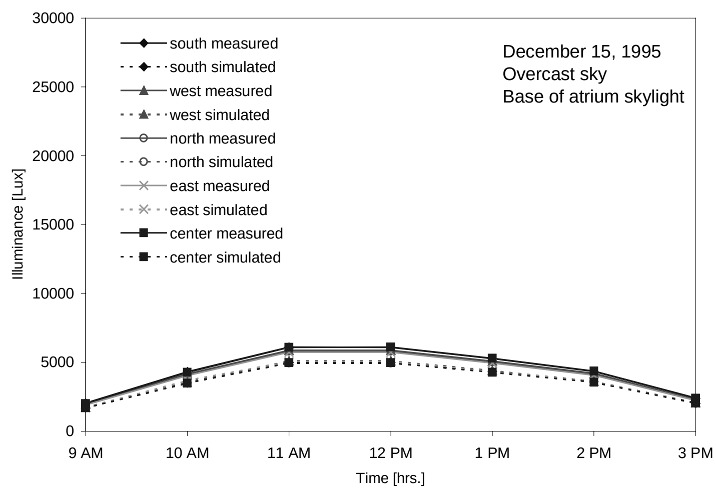
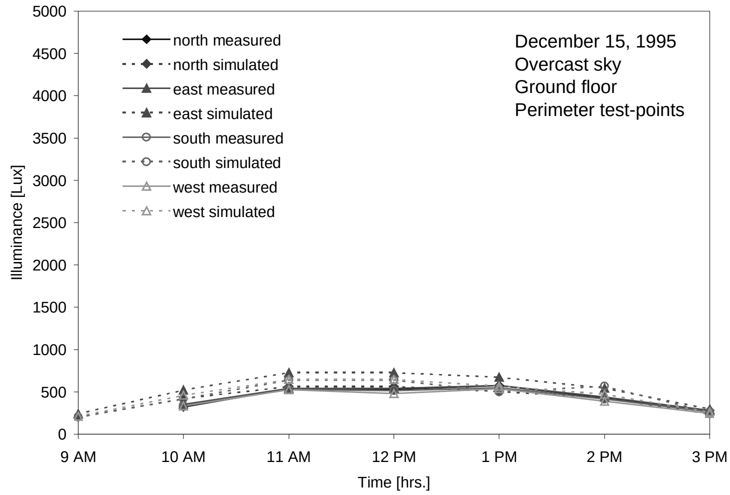
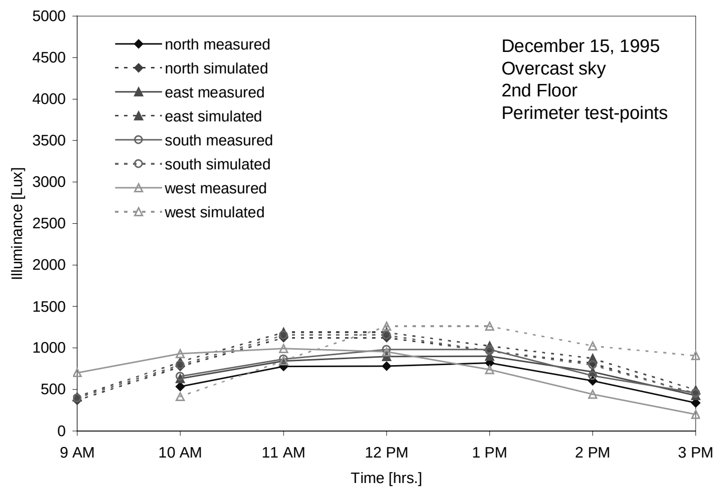


Figure 46 Measured and Radiance simulated indoor horizontal illuminance for December 15, 1995 at various test-points located at the base of the atrium skylight

Table 9 Measured versus Radiance simulated indoor horizontal illuminance for an overcast sky on December 15, 1995 (Lux)

	Atrium perimeter		3.5 m from atrium perimeter	
	Measured illuminance	Simulated illuminance	Measured illuminance	Simulated illuminance
Ground floor	200-900	200-900	7-80	12-50
Second floor	200-1000	350-1200	10-100	20-60
Third floor	850-2300	800-2500	170-450	170-550
Base of skylight	1900-6100	1700-5100	N/A	N/A





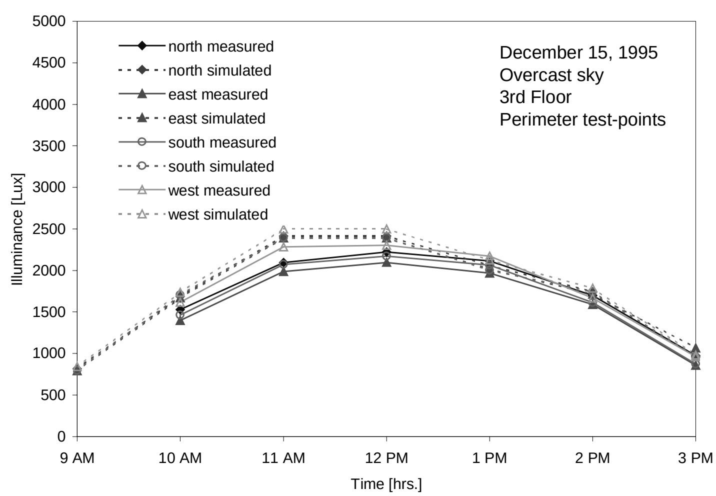
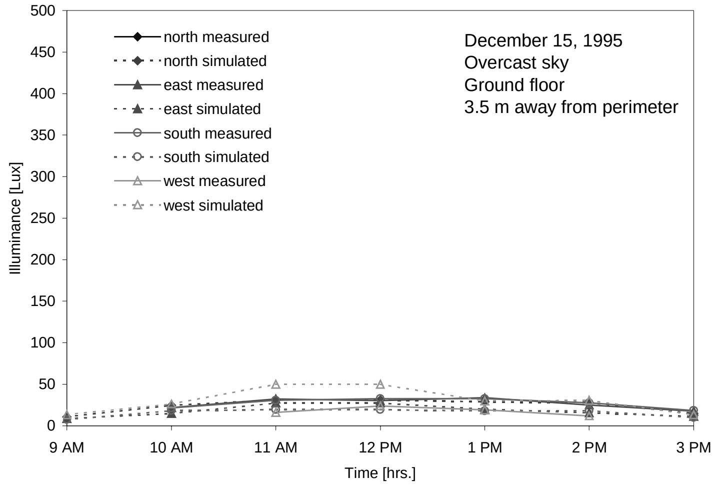
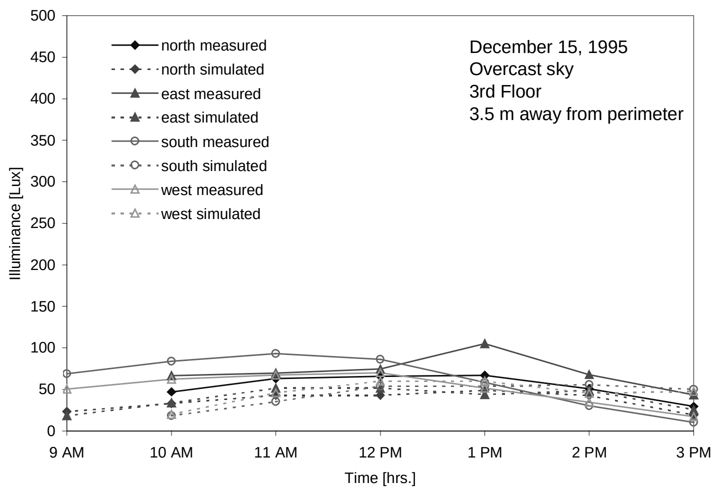


Figure 47 Measured and Radiance simulated indoor horizontal illuminance for an overcast sky at various test-points located at the atrium perimeter





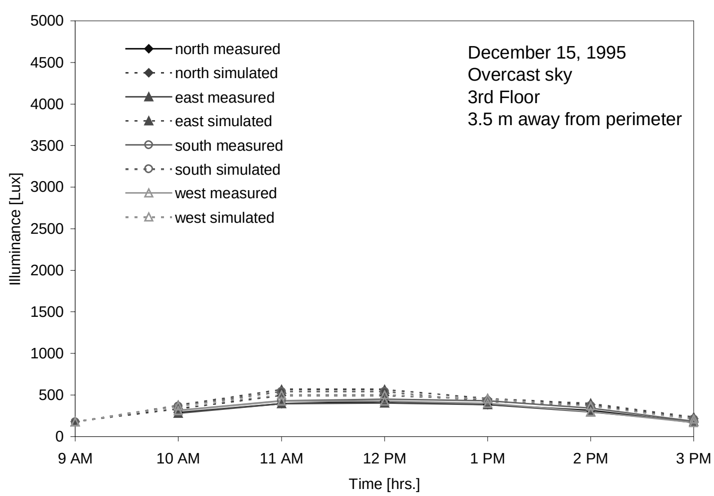


Figure 48 Measured and Radiance simulated indoor horizontal illuminance for an overcast sky at various test-points located 3.5 meters away from the atrium perimeter

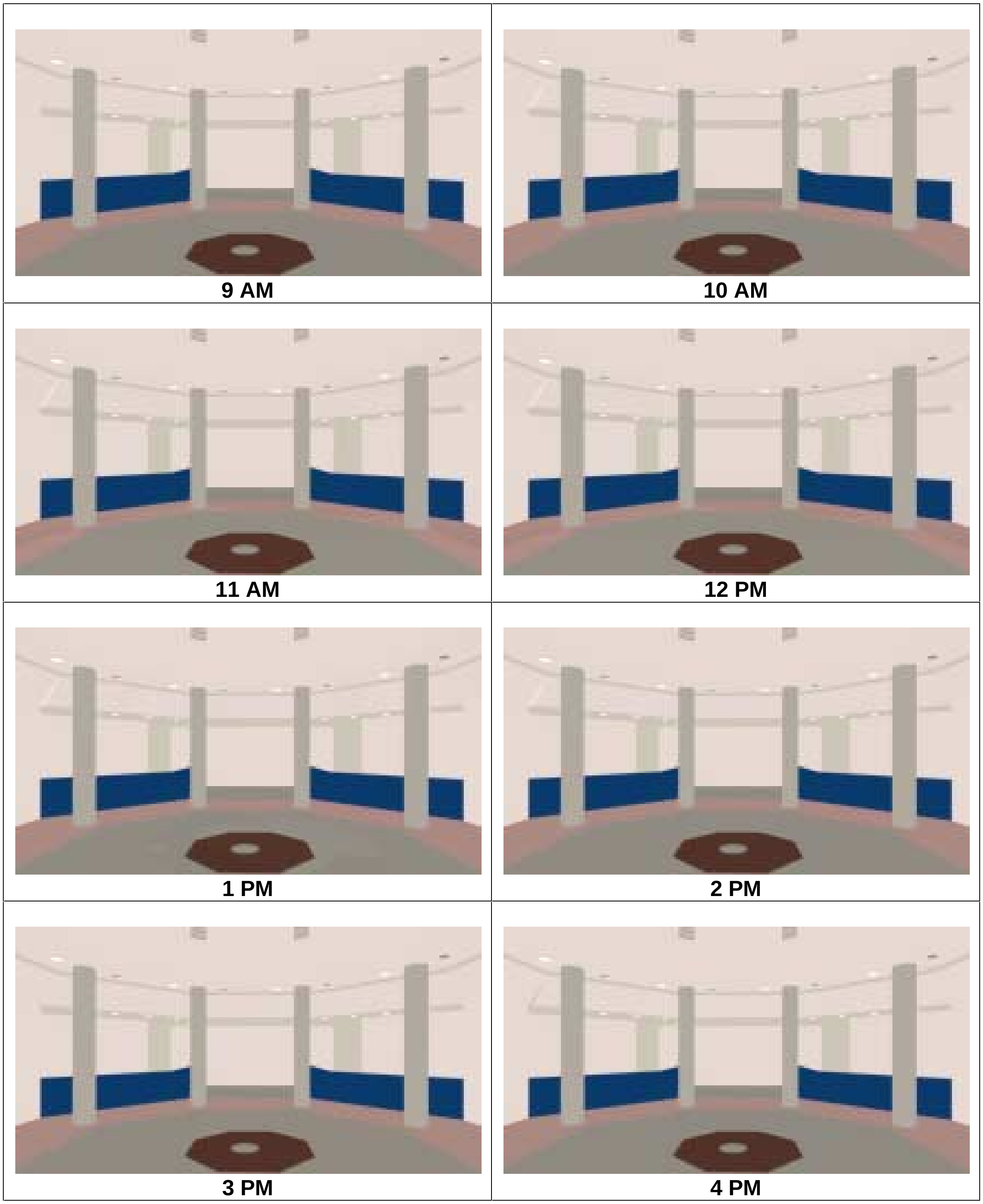


Figure 49 Radiance representation of the atrium ground floor under an overcast sky (simulated day: December 15, 1995; south-east view)

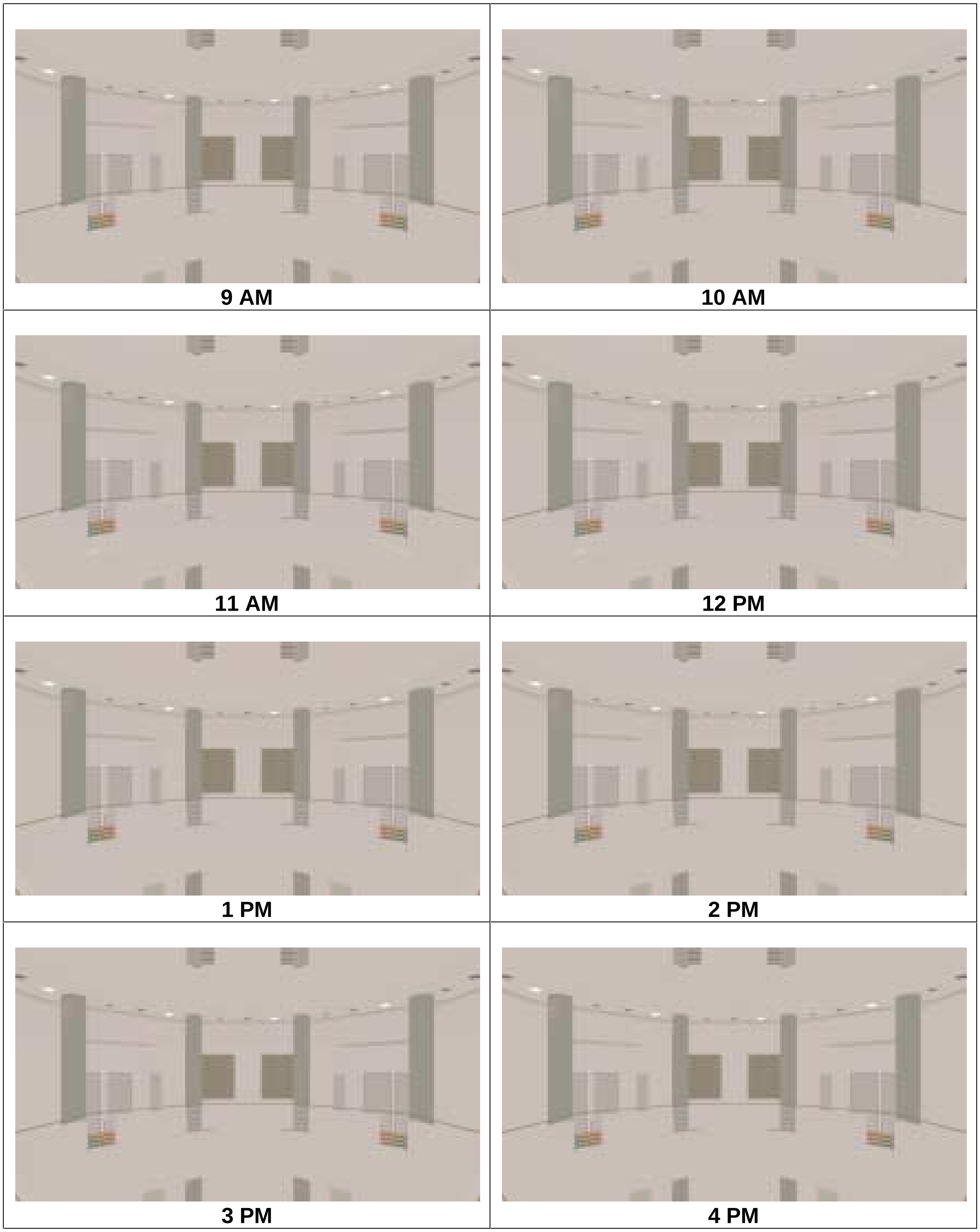


Figure 50 Radiance representation of the atrium 2nd floor under an overcast sky (simulated day: December 15, 1995; south-east view)

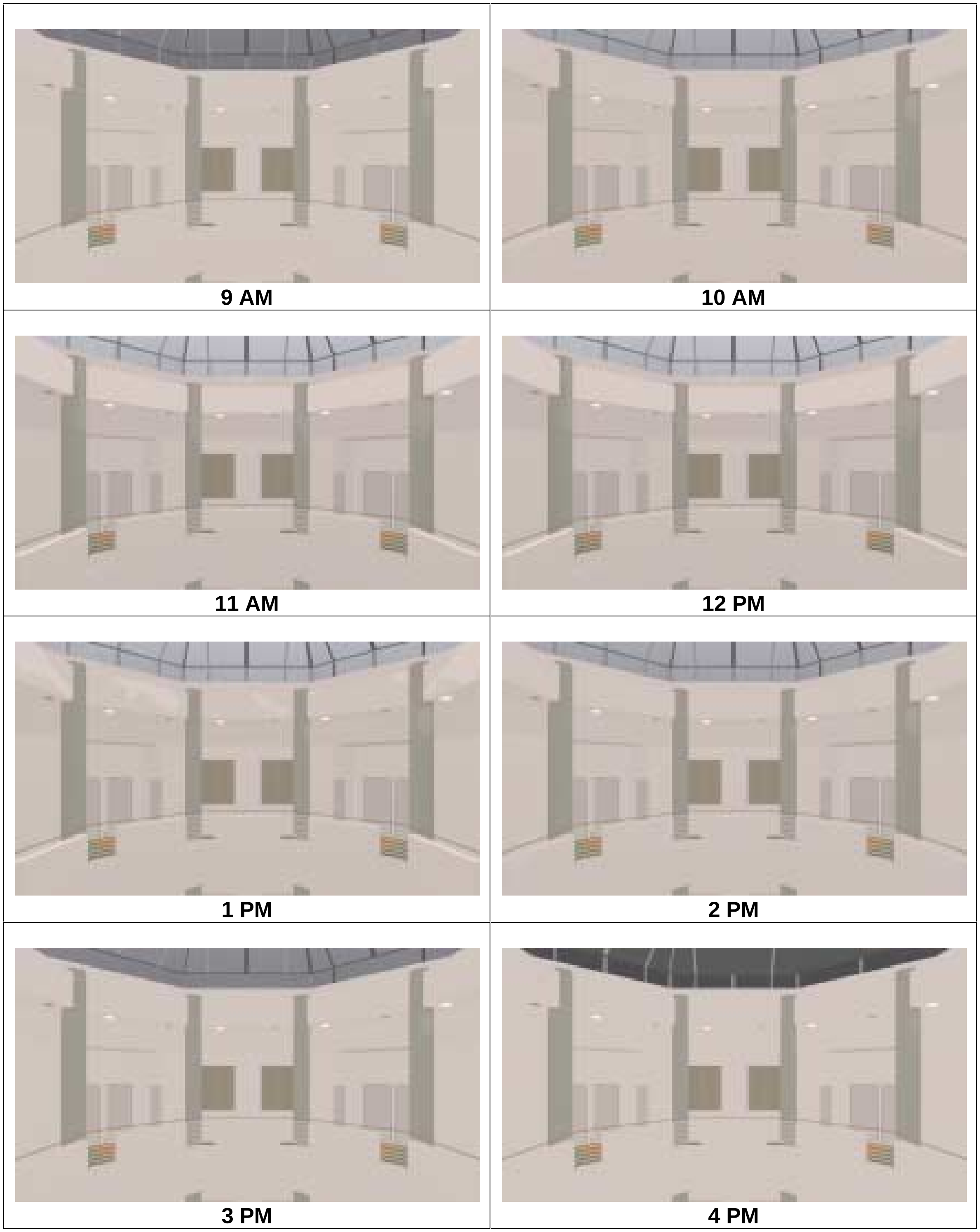


Figure 51 Radiance representation of the atrium 3rd floor under an overcast sky (simulated day: December 15, 1995; south-east view)

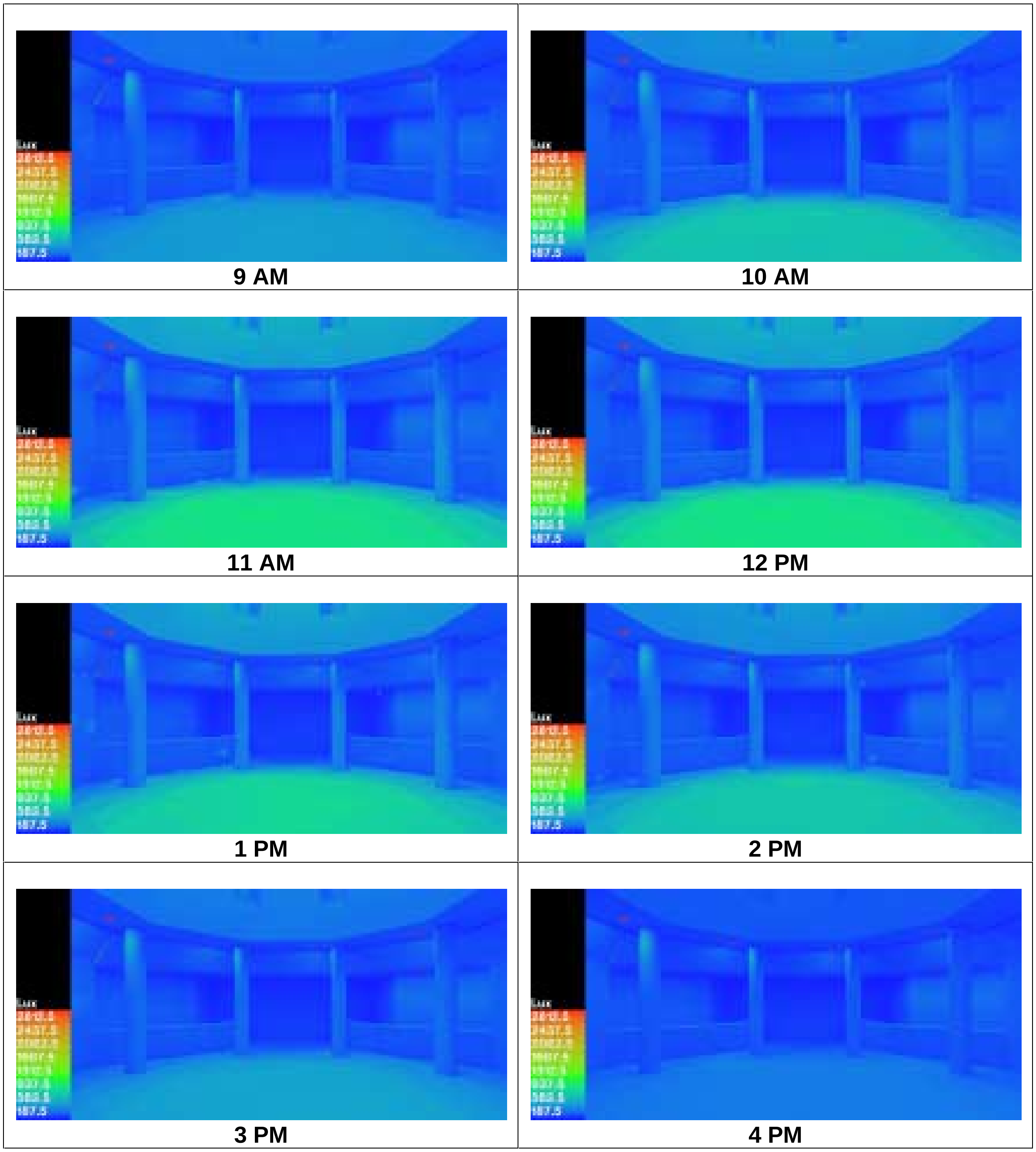


Figure 52 Falsecolor Radiance representations of the atrium ground floor under an overcast sky (simulated day: December 15, 1995; north-west view)

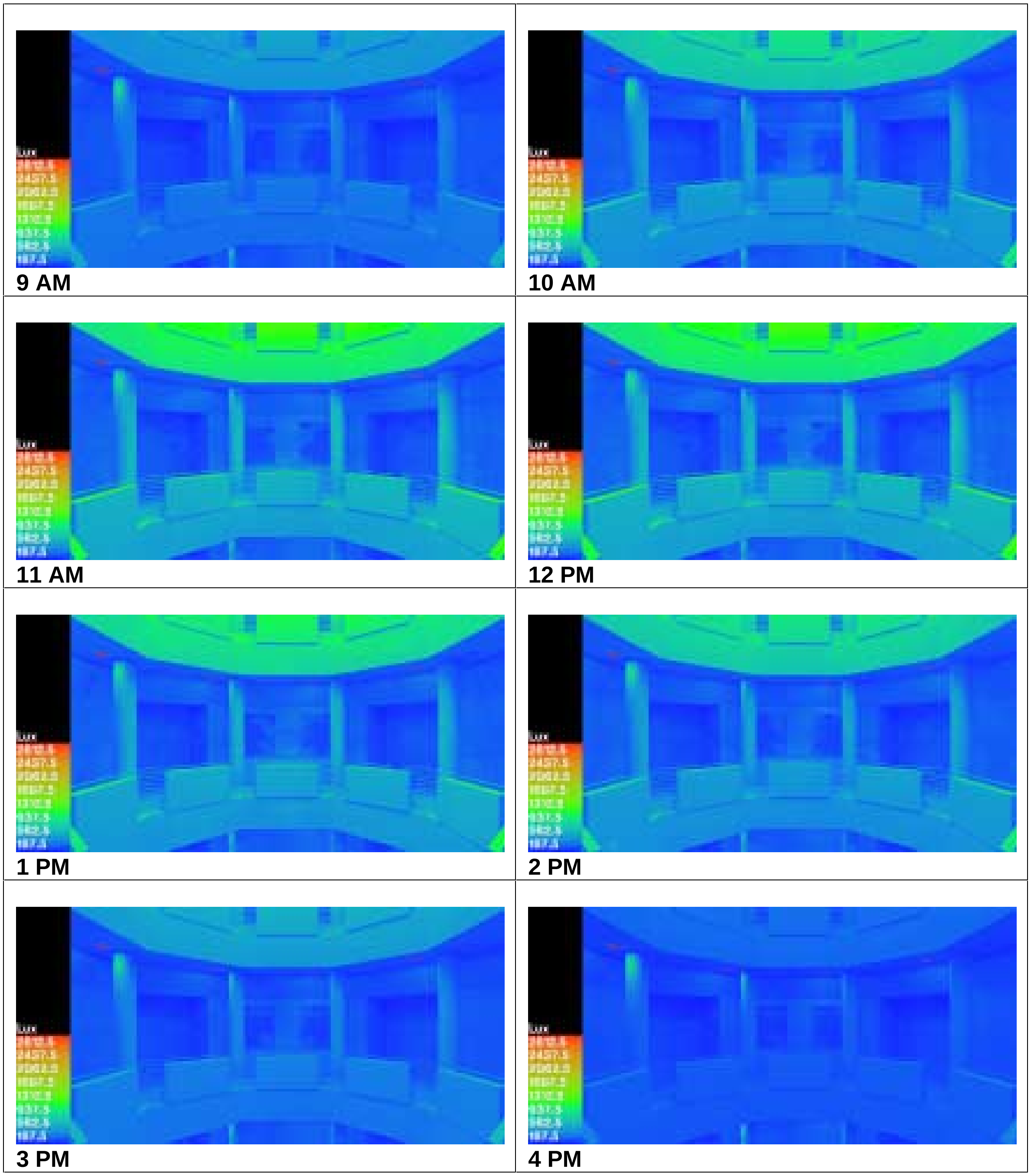


Figure 53 Falsecolor Radiance representation of the atrium 2nd floor under an overcast sky (simulated day: December 15, 1995; south-east view)

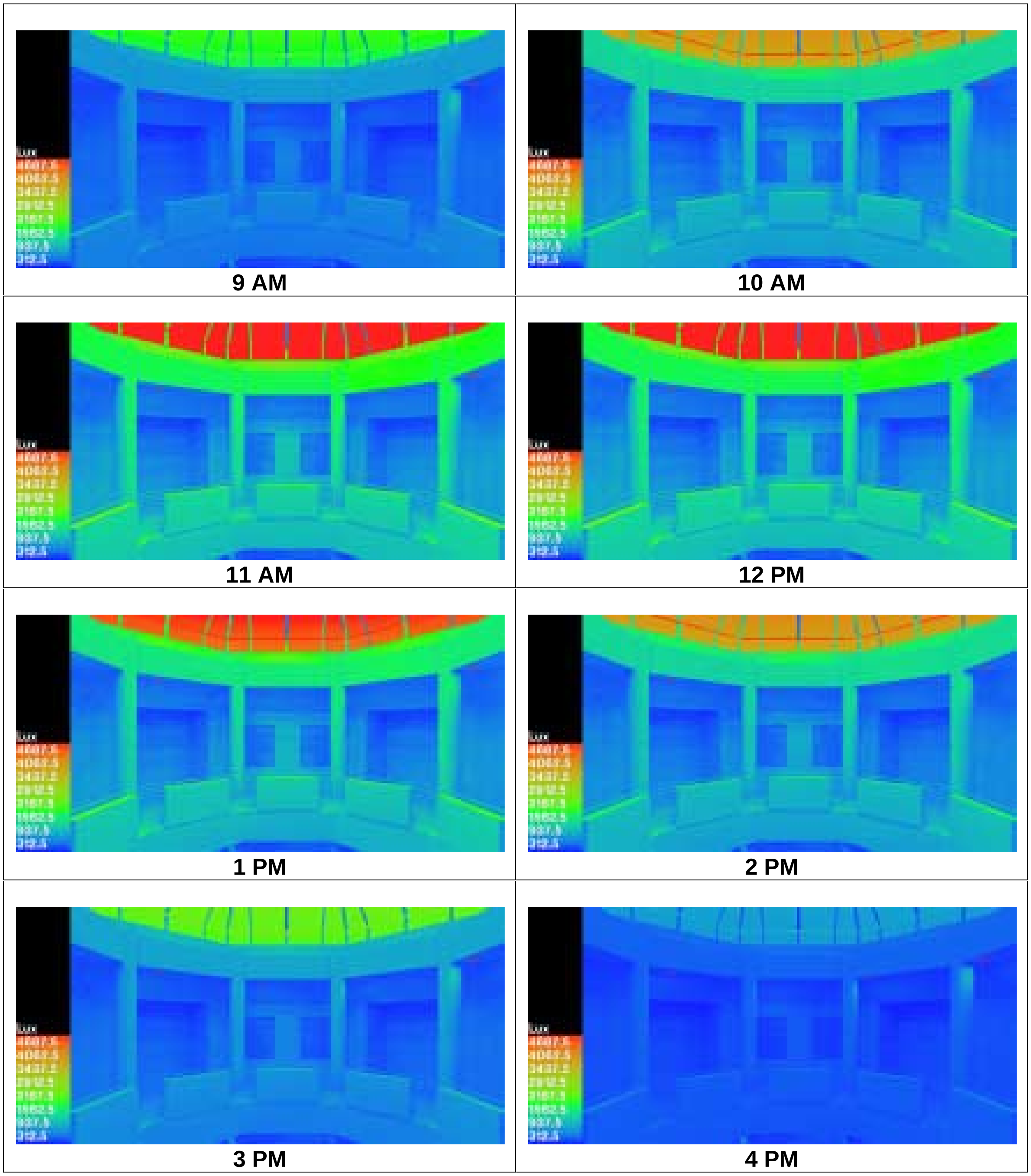


Figure 54 Falsecolor Radiance representation of the atrium 3rd floor under an overcast sky (simulated day: December 15, 1995; south-east view)

CONCLUSIONS

Two computer models of an existing atrium building created with the Adeline 1.0 software were validated against on-site measured data. Performance indicators included the degree of accuracy and limitations of the program to predict the outdoor and indoor illuminance on several horizontal planes in the building, and the electrical lighting energy savings from the use of daylighting.

SUPERLITE MODEL

Outdoor Horizontal Illuminance

- The distribution pattern of the simulated outdoor illuminance followed closely the pattern of the site-measured illuminance for all summer and winter days analyzed. The agreement between instantaneous measured and simulated illuminance was extremely good for a clear sky in the summer, for which the discrepancy ranged from 1 to 16%. Overall, from 9 AM to 5 PM, the measured illuminance ranged from 47000 to 107000 lux, while the simulated illuminance was between 47000 and 115000 lux. The discrepancy was slightly higher for a clear sky in the winter, for which the difference between measured and predicted outdoor illuminance varied between 12 and 29%. In this case, from 9 AM to 3 PM, the measured illuminance ranged from 18000 to 41000 lux and the predicted illuminance was between 14000 and 34000 lux. In general, clear sky was fairly well simulated for both summer and winter days analyzed and the outdoor illuminance was just slightly overpredicted in the summer and underpredicted in the winter.

- The overcast sky distribution, however, was not that accurately predicted. In this case, despite of similar distribution patterns, the range of measured illuminance differed greatly from the predicted range. From 9 AM to 3 PM, while the measured illuminance was between 7000 and 26000 lux, the simulated illuminance was between 4000 and 8500 lux, being notably underpredicted throughout most of the day. This obviously would affect significantly the indoor illuminance profiles under an overcast sky.

Indoor Horizontal Illuminance

- Considering the limitations of Superlite in simulating complex building geometry, the summer data showed a fairly good overall agreement in range and distribution pattern between measured and simulated indoor illuminance. On the atrium ground floor, from 9 AM to 5 PM, the measured illuminance varied between 400 and 29300 lux and the simulated illuminance was between 600 and 28700 lux. In the center of this floor, during the same time frame, the measured illuminance ranged from 1000 to 3700 lux, while the simulated illuminance was between 700 and 2700 lux. Similar agreements in range and distribution pattern between measured and simulated illuminance were found for most test-points located on the remaining two floors of the building and at the base of the skylight.

- Summer data for a clear sky revealed a few of uncertainties that may occur when a simple design tool such as Superlite is used to predict the illuminance distribution in a complex building. First, due to the geometrical differences between the real and the simulated space, some test-points that in reality were not under direct sun were sometimes simulated as being under direct sun. Second, despite the fairly good agreement in overall range of measured and simulated illuminance, the instantaneous simulated illuminance was sometimes between 3 to 10 times lower or higher than the measured value. Nonetheless, since the profiles of illuminance distribution are used subsequently by Superlink to predict the need for artificial lighting in the space based on daylight availability, this occasional high discrepancy between measured and simulated instantaneous illuminance under a summer clear sky would not affect significantly the long-term energy calculations. This is because on all floors of the atrium space both the measured and simulated illuminance were considerably above the space design illuminance. However, special attention has to be paid to the correct selection of the points where the illuminance levels from natural and artificial light will be compared by Superlink, since an incorrect selection of these locations may lead to inaccurate results.

- Winter data shows that for both clear and overcast sky, the illuminance simulated at all test-points was mostly underpredicted, usually by 50% the measured value. This is likely to be due to the significantly underpredicted outdoor illuminance and might have a direct impact on the long-term energy calculations. The fact that the measured illuminance was collected under a skylight fully covered by snow, suggests that illuminance from daylighting may be even higher in the actual space. This obviously increases even more the discrepancy between the measured and the simulated illuminance and suggests that in reality the savings from daylighting may be higher than predicted. However, this high discrepancy will impact significantly on the long-term energy calculations only if the simulated illuminance is lower than the space design illuminance, which for the case study appears to be critical on the ground floor only.

SUPERLINK MODEL

- The simulated lighting energy savings were 3095.9 kWh/month for June 1995, and 1368.8 kWh/month for December 1995. The measured lighting energy savings were 2536 kWh/month for June 1995, and 418.5 kWh/month for December 1995. This translates into a 22% difference between the measured and the simulated lighting energy savings for June 1995, and measured savings 3 times lower than predicted savings for December 1995.

- The relatively small discrepancy obtained for the summer month was most likely due to the overprediction of daylight availability from the “typical meteorological year” weather files used by the simulation program, instead of measured outdoor parameters. The substantial discrepancy obtained for the winter period was due to the heavy snowfall which occurred in December 1995. The accumulation of snow on the atrium fenestration diminished greatly the daylight penetration and the photosensor of the automatic lighting control system was located below another atrium skylight than the case study which was also covered by snow and frost. These conditions affected negatively the measurements and it is understandable that the simulation could not account for the incorrect operation of the lighting control system.

- The poor performance of the lighting control system also affected the discrepancy between measured an simulated annual energy savings. The simulation suggests that 28700 kWh/year could be saved through the utilization of an on/off lighting control system. As installed at the time of measurements, the on/off lighting control system was saving an estimated 17830 kWh/year, which is 61% lower than the predicted annual savings.

RADIANCE MODEL

Summer Clear Sky

- Under a clear sky, from 9 AM to 5 PM, at all test-points on the atrium ground floor, the simulated illuminance followed closely the distribution pattern of measured illuminance. Overall, the measured and the simulated illuminance levels in the space were in good agreement, especially under diffuse daylight at the atrium perimeter and in the center of the ground floor, where the measured illuminance ranged from 100 to 2600 lux and the simulated illuminance varied between 800 and 2400 lux. Under direct sun, however, at the atrium perimeter as well as at 3.5 m towards the adjacent spaces, there was a tendency to overestimate the instantaneous illuminance by sometimes 100%.

- The distribution pattern of measured illuminance was well reproduced on the second and third floors with some exceptions. Whenever a test-point was under direct sun, the simulated instantaneous illuminance was either 100% higher or lower than the measured illuminance. This tendency was also present at the test-points located at the base of the skylight, where, despite an overall good agreement in range and pattern between measured and simulated illuminance, the instantaneous simulated illuminance was mostly higher than the measured illuminance, especially during afternoon from 12 PM to 4 PM.

- The falsecolor images of the space showed a fairly accurate overall representation of the illuminance levels on all floors of the building and the occasional high discrepancy between the instantaneous measured and simulated illuminance at some test-points was attributed to the overall transmittance used as simulation input to account for the three glazing systems of the skylight. It is believed that with more time invested in reproducing the exact configuration of the atrium skylight more accurate results could be obtained.

Winter Clear Sky

- Under a clear sky, from 9 AM to 3 PM, there was a good agreement in range, distribution pattern and instantaneous measured and simulated illuminance on the atrium ground floor. At the atrium perimeter, the measured illuminance varied between 300 and 1000 lux, while the simulated illuminance was between 200 and 1500 lux. At 3.5 m from the perimeter, both the measured and the simulated illuminance were below 130 lux. Direct sun did not reach this floor during daylight hours due to the low position of the sun in the sky during the winter season, and the sensitivity of the simulations towards direct sun observed for the summer season did not affect the winter results. This aspect was also confirmed by the low discrepancy obtained between the measured and the simulated illuminance on the second floor, where direct sun was not present either.

- On the third floor, however, as well as at the base of the skylight the discrepancy between measured and simulated illuminance was higher, especially in the direct sun patches where once again the instantaneous illuminance was as high as twice the measured illuminance.

- Similarly to the summer conditions, the falsecolor images of the space under a clear sky in the winter showed a fairly accurate overall representation of the illuminance levels throughout the space.

Overcast Sky

- The simulation of a completely overcast sky provided the best agreement between measured and predicted values, confirming once more the fact that diffuse daylight was more accurately simulated than the direct component. From 9 AM to 3 PM, the illuminance was very well simulated on all floors, as well as at the base of the skylight, and the instantaneous discrepancy was mostly below 20% at all test-points.

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