Daylighting Prediction Software: Comparative Analysis and Application

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ABSTRACT

Daylighting is a beneficial design strategy since it may provide energy savings and contribute to a more sustainable design. In recent studies, daylighting has also been shown to increase staff and student productivity and to decrease absenteeism.

The consulting engineer is often faced with the dilemma of how to design a daylighted building. What tools are available to predict the amount of daylighting? What are the design limitations and parameters? How much time is required? How does the data compare to the "real world"?

The purpose of this paper is to answer these questions and provide useful information for the design of daylighted areas with the assistance of software-based simulation. A survey was made of the available software programs for the calibrated modeling of light scattered in enclosed spaces. These software packages used algorithms based on either total radiosity (flux transfer) computations or physically accurate ray tracing. A summary of this survey along with the selection criteria used in selecting a software program are presented.

"Radiance", a reverse ray tracing method software package, was chosen for use in the simulations. An existing school was modeled with the Radiance software and predictions of daylighting contributions were compared with actual data taken at the site location.

The use of daylighting also requires a highly specialized lighting system. This system incorporates the use of controllable ballasts and lighting sensors to maximize the daylighting contribution to the overall required illumination. Some design criteria for this system is also discussed.

INTRODUCTION

Daylighting is a design strategy to provide better illumination in interior spaces and, if integrated properly with the lighting system, potential energy savings. Published papers and books exist which outline broad design rules for achieving daylighting of a building. For a rule-of-thumb guide with practical implementations covering a broad range of issues associated with daylighting, see the Lawrence Berkeley National Laboratory report, "Tips For Daylighting With Windows, The Integrated Approach" [Connor97]. While these guidelines help maximize the available daylight in the building's spaces, the actual numbers for the computation of the daylighting contribution to the overall lighting required for the building are not provided. This quantitative information is needed for design tradeoff studies, energy estimation and the requisite supplemental lighting system requirements. To provide this capability, computer modeling of the distribution of illuminance inside a building is used.

A survey was made of the available software programs for the calibrated modeling of light scattered in enclosed spaces. Most of the programs (or at least some previous version) were the subject of investigation and comparison with other programs by previous investigators. They reported not only on comparisons of the program features, but created test models from existing buildings and compared the results of the simulations with actual light measurements from the test buildings. These previous investigations were used to guide our selection of a software program. A summary of this survey is presented along with rationale used in selecting a software program.

Some details of the selected software are discussed along with the results of modeling two classrooms from an existing elementary school. Comparisons of actual illuminance measurements made in the classrooms with the modeled results are shown. Finally, some discussion of an overall

lighting system incorporating the daylight contribution is provided.

DAYLIGHTING SOFTWARE REVIEW

A number of computer software programs exist which model the distribution of light from sources including luminaires and sunlight/skylight through windows (daylight) inside a building. A literature search revealed a number of papers comparing various software packages and computation methods. The software packages use algorithms based on either total radiosity (flux transfer) computations, physically accurate ray tracing or a combination of the two.

While the ease of use and interoperability with existing CAD programs was desired, the primary focus was on the accuracy of the predicted illumination. The primary focus would be modeling of school classrooms that are mostly replicated throughout the building and are, in general, simple designs. A primary goal was the accuracy of the predicted illumination levels at desk height throughout the room and vertical illumination levels on wall-hanging marker boards and displays. A future goal is to use this information with lighting fixture designs and control systems to model the overall system required to achieve the mandated illuminance in the classrooms.

"Lighting/Daylighting Analysis: A Comparison" [Bryan] reviews the following four packages suitable for daylighting analysis.

1. Lightscape 3.2
2. Desktop Radiance 1.02
3. Lumen Micro 2000
4. FormZ RadioZity 3.80

The comparison is oriented toward daylighting capability (vs. luminaires). The emphasis was on both the accuracy of the results and the usability for designers and architects. A comparison of the modeling features (e.g. CAD data exchange, layers and solids entry capability), daylight specific setup, surface properties, rendering methods, output capabilities, user interface and help system are given. One of the conclusions was that the Radiance processing was the most accurate, although, no specific comparisons of accuracy are given.

"Comparative Evaluation of Four Daylighting Software Programs" [Ubbelohde98] reviews the following daylighting capable software packages.

1. Lumen Micro
2. SuperLite
3. Radiance
4. Lightscape

The study was oriented toward the designer, who is interested to what extent the software could predict the quantity and distribution of daylight in a building not yet constructed. The study examined the time and difficulty of learning the software, integration with existing CAD packages and documents, the ability to use complex geometries and model execution time along with the accuracy of predicted illumination levels and the rendered visualization. An example building was used and modeled with each of the four programs. The results of this modeling were analyzed and compared with actual illumination measurements compiled in the building. One of the conclusions is again that Radiance was the most accurate for prediction of illumination levels but lacks a "reasonable" user interface and the complexity of this program requires a lot of time and training to master. Lightscape had many advantages for architects and lighting designers such as ease of use and model input along with relatively high speed rendering.

The current status of these software packages has changed over the last few years since the studies were completed and is as follows.

1. Lightscape was acquired by Autodesk (makers of AutoCAD) and has recently been discontinued in favor of Autodesk® VIZ 4 which contains the functionality of Lightscape but is more tightly integrated with other AutoCAD products. The stated reason for discontinuing the standalone Lightscape release was low sales volume.

2. Desktop Radiance has languished in recent years although the computational back-end, the "Radiance" suite of programs, has continued to advance.

3. Lumen Micro is now Lumen Designer, a full featured CAD system with the lighting computation and rendering capability from Lumen Micro.

4. FormZ RadioZity is a version of the FormZ solid modeling software that includes radiosity based rendering using the LightWorks engine. This product is still being actively developed.

5. SuperLite2.0 was last released by Lawrence Berkeley National Laboratory. It is a radiosity based program written for DOS/Windows which is no longer under active development.

The Radiance[1] [Ward98] system is a suite of command line oriented programs (UNIX based) which provide the basis for lighting analysis: file format conversions, ray tracing, rendering, sky models, output images, etc. The Radiance source code is available and now licensed under an open

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[1] Home page: http://radsite.lbl.gov/radiance/

source license[2] which allows for commercial use, modification and even distribution. Radiance is the back-end processing suite for the programs: Desktop Radiance, Adeline, Rayfront and others.

SOFTWARE SELECTION

Based on our requirements and the information presented in the previous section, the Radiance software package was chosen. The previous studies showed it to be among (if not) the most accurate and flexible. Although this flexibility comes with a cost of complexity for use of the model and a steeper learning curve, a couple of front-ends to Radiance are available and a few others are under development. The front-ends are under investigation for future use to ease the process of inputting models into Radiance, providing an easier-to-use interface for the designer and delivering some extra analysis capabilities to the base Radiance package.

The Radiance source code suite was downloaded and compiled on an AMD Athalon based Linux (Red Hat 9) workstation. Utilities are included to generate primitive shapes for the input geometry model along with utilities to convert some CAD file formats to the Radiance input model format. Since we primarily use AutoCAD for building drawings, we chose to edit a desired existing model and then convert it to DXF format. A DXF-to-Radiance converter was used to input the information into Radiance. Once converted, the file was hand edited to add object properties (e.g. surface reflectance, color, window characteristics) and surface normal definitions.

Radiance includes utilities to generate sky lighting distributions, window properties and luminaires. It contains individual processing capabilities to compute entire renderings, contours of illumination on some plane (normally a work surface) and illuminance levels at individual points in the space. This latter capability allows computation comparisons with illuminance meter measurements taken in the space. The process speed is also increased since only the desired points are computed and many iterations and parameters (i.e. different sun positions, time-of-day, ray tracing parameters, etc.) are quickly computed.

SIMULATION VALIDATION

In order to verify the accuracy of the simulated results, two existing classrooms from different schools were modeled and illuminance measurements taken for comparison with the predicted values. The first classroom chosen was in Rockbrook Elementary School, Lewisville ISD in Lewisville, Texas. The classroom is typical of elementary school designs in Texas with one-story construction and the grade levels separated by "wings". The school was recently opened and afforded access for making illuminance measurements. The school's classrooms were designed with limited window area that did not run the length of the outside walls. The small window area would not provide significant daylighting. However, the rooms could still be modeled to confirm the capability of the software to accurately predict the levels and distribution of the illuminance.

The second classroom modeled was in Walker Elementary School in McKinney ISD, McKinney, Texas. It was one of several schools designed to be "sustainable" incorporating many elements of energy and resource management including a design for using daylighting as the primary source of classroom illumination [McClure2000]. The primary daylighting design feature is a "light monitor" built above the ceiling of each classroom with a south facing window. Some more description and views of the model are included later.

As discussed in the previous sections, existing research had shown that accurate simulation was possible. Depending on the application and under some circumstances, the resulting accuracy may not be adequate. The eventual application is to model the rooms (including auditoriums, band halls, teaching rooms, halls, etc.) and predict the illumination for various design tradeoffs. The target illuminance for desk height level in the teaching areas is usually 50 footcandles (fc). To be of maximum utility in the overall design process, the simulation accuracy needs to be 20% or better. The Radiance model is very complex due to the number of required parameters needed to supply the computation routines along with an accurate model of the room geometry and material properties. In addition, options are required for the modeled sun/sky intensity and irradiance distribution generated from the input sky conditions. A significant motivation for this validation was to gain confidence in our ability to correctly understand and run the simulation, and gain insight into the effect of the models' inputs on absolute accuracy.

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[2] http://radsite.lbl.gov/radiance/misc/license.txt

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Rockbrook Elementary Classroom Modeling

A 3-d wireframe drawing for the first classroom (number 319) that was modeled and corresponding illuminance measurements obtained is shown in Figure 1. The orientation of the school is such that the window is facing north and, except for a small tree, has an unobstructed view of the sky. The north facing window guaranteed that there would be no direct sun into the window, just "sky" illumination from the light scattered in the atmosphere.
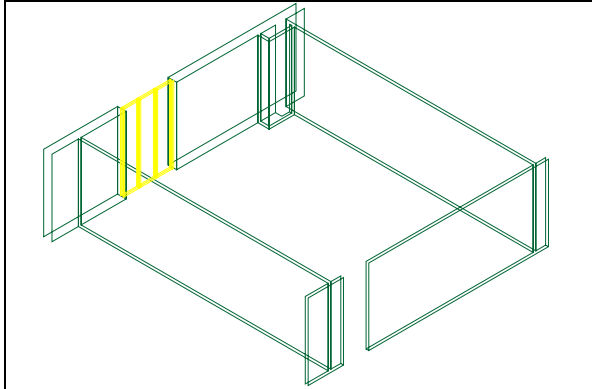

Figure 1.   Wireframe drawing view of the classroom without ceiling, door or window detail

The Radiance geometry was created by "cutting" the classroom out of the complete school's AutoCAD drawing, removing all extraneous objects and then saving it as a DXF format file. A file format conversion utility converted the file to a RAD format file which is the Radiance scene description input format. The file was then hand edited (with a text editor) to add a floor, ceiling and the detailed window geometry not available in the original drawings. Only the basic elements were included in the model such as the interior walls, a simple door and exterior wall containing the window needed for modeling. The window was modeled as glass and metal with no thickness, but set properly inside the window box. The lockers at the back of the room, cabinets and furniture were not included. A photo of the window in the actual room is shown in Figure 2. Color and reflectivity values for the painted walls, acoustical ceiling and dark blue carpet in the room were estimated by using a range of values from reflectivity measurement tables of similar materials. The reflectivity and color components for the actual materials in the room were not measured. A number of illuminance readings were taken inside and outside the window glass to estimate the transmittance. An average value of 0.43 was obtained which falls into the range of values published for other lightly tinted, tempered, double-pane glass.

Figure 2. Photo looking out classroom 319 window

A shaded 3-d perspective image of the model as viewed from the outside is shown in Figure 3. Notice that there is only a thickness associated with the "window" wall so that the window position in the window box can modeled. In general, the run times for the computations would be increased with additional complexity in the geometry and total objects in the space. Consequently, only the necessary objects were chosen for the model. Also note that the classroom sits on a disk (ground plane) of radius 20 m which is assigned an overall reflectance and color like the other materials in the model. This allows for the modeling of sun and sky reflections into the window (and generally, off the ceiling). Figure 3 was generated with a program called rshow[3] which provides for visualization of the Radiance generated "scene" files containing all the geometry, materials and light sources for a complete model.
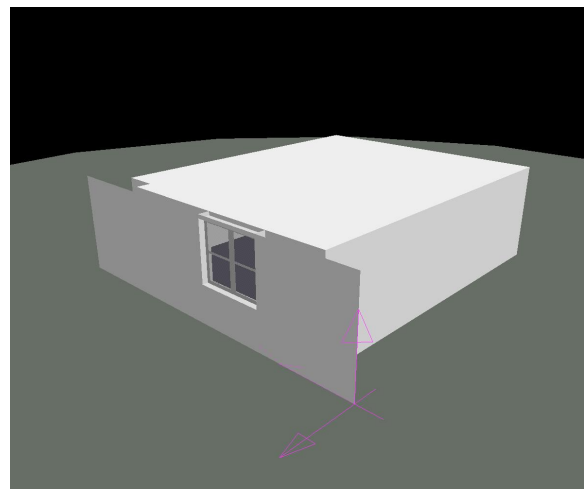

Figure 3.   Shaded view of the outside of the modeled classroom

Sets of light measurements were taken on

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[3] http:/pab-opto.de/progs/

November 24, 2003, which was a cloudless, clear sunny day. A grid of points was chosen for the horizontal illuminance measurements. The grid consisted of three columns, each going away from the window. The first column is 1 m from the near wall with 2 m separation between the columns. The layout and numbering of the measurement positions are shown in Figure 4. An illuminance meter was placed at a reference point, 2m from the near wall and 2 m from the window. Its value was recorded while the other points on the grid were sampled so as to monitor for overall variations in the input sky light. The day was so clear that less than a 5% variation was recorded over the approximately 10 minutes taken to sequentially sample the 12 grid points with another illuminance meter. All points were sampled at a height of 0.75 m.
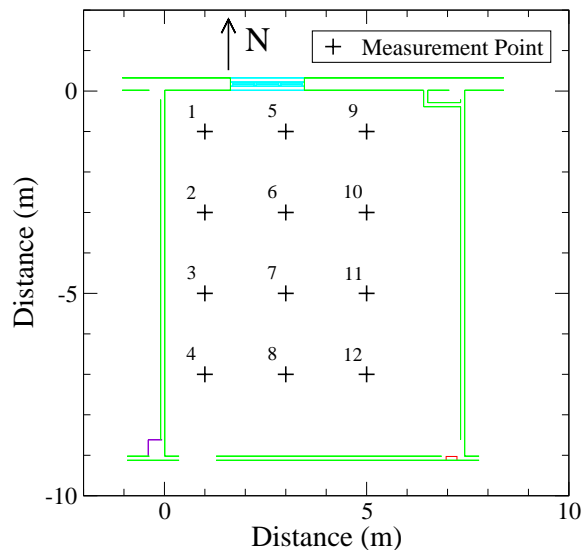
Figure 4. Position of measurement locations in the classroom

The Radiance program, gensky, computed the radiance distribution used for the simulation. Required input was the time of day, timezone and latitude and longitude for the location. Gensky also has a turbidity factor that relates to the amount of scattering in the atmosphere. Since no measurement was available for this value, we started with the default of 2.7. Increases in this value correspond to greater scattering in the atmosphere and a higher horizontal diffuse irradiance while smaller values correspond to less scattering with a value of 1 for an ideal clear atmosphere (dark sky). A value, 3.2, was chosen such that the computed horizontal illuminance for a point just outside the window matched the value we measured with a meter located 1 foot outside the window (340 fc). We also obtained accurate agreement with a measurement made 1 inch inside the window which gave us confidence in the values used for the window glass transmittance and sun intensity. The sky model also allows input of

measured solar radiance and horizontal diffuse irradiance. Many validation studies measure the sky values directly and use them as input, however, this requires special sensors which we did not have available so we relied directly on the model and a check of the measured outside illuminance. Since the measurement point was just outside the window it was shaded from the sun and therefore was only a measurement of the scattered "sky" illuminance. Figure 5 is a plot of the Radiance modeled illumination levels along with the actual measurements.
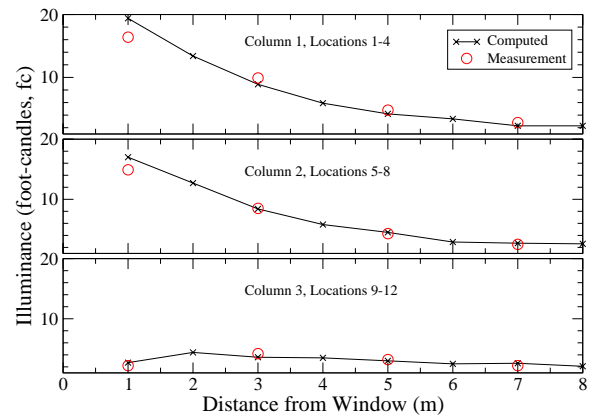

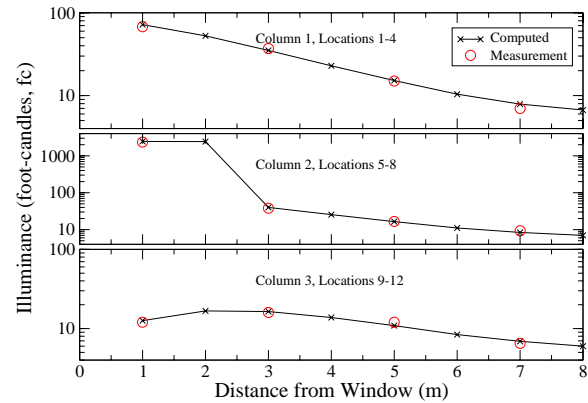**Figure 5. Plot of Radiance predicted illuminance levels and measured values vs distance from the window wall for the 3 columns**

The next classroom modeled was room 318 which is directly across the hall from room 319 and has a south facing window. The window is located on the south wall just 1 m from the west wall. The input model classroom is identical to the room 319 model with the exception of location of the window and the orientation. A photo of the window from inside the classroom is shown in Figure 6. The photo was taken a little after 1 pm which was around the time of the first set of measurements. The data was taken 1 to 3 hours later on the same day as the room 319 data. The measurements were again taken on a grid of 3 columns of points, each one going away from the window. The first column is 1 m from the west wall near the window. The next two columns are spaced 2 m apart. All measurements were made at a height of 0.75 m from the floor. The first measurement point of the 2nd column was in the direct sun, along with a reference point located 2 m from the side wall and 2 m from the window.

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Figure 6. Photo from classroom 318 taken at 1 pm

Using the same sky model as before a computed value was obtained for the horizontal illuminance of 4800 fc just outside the window and 1720 fc just inside the window (at a height of 1.2m). Actual measured values were 7500 fc and 2650 fc, respectively. Recall that the only free parameter to the gensky program used earlier was the turbidity factor which when properly chosen gave us a modeled value which matched the measured value for the sky. The values for the north facing room (room 319) were, however, only for the diffuse "sky" component since the direct sun was shielded by the building. The horizontal illuminance value for room 318 just outside the window is a combination of both the diffuse sky component and the direct solar component. For this simulation we gave the gensky program a value for direct solar irradiance of 360 watts/m^2. The sky component was the same as was previously used. Simulated values for illuminance just outside and inside the window were now 7420 fc and 2630 fc. In addition the computed value for the 2 m from the window reference point was 2440 fc versus a measurement of approximately 2400 fc.

Figure 7 is a plot of the Radiance modeled illumination levels along with the actual measurements. The axes were changed to log scales to accommodate the larger range of values generated due to the direct sun component. In particular, note the values for positions in column 2 which are in the direct sun. Once again we get excellent agreement between the measured values and the Radiance simulation.

Figure 7. Plot of Radiance predicted illuminance levels along with measured values vs distance from the window wall

The Radiance system also contains a program, rpict, to produce a rendering of a model. This program was used to produce a perspective view rendering from inside of classroom 318 at a position near where the photograph in Figure 7 was taken. That rendering is shown in Figure 8. The sky simulation for the model was the same as used to generate the illluminance values except that the time of day was set to be 13:00. This corresponded to the time at which measurements from the walls of the shadow cast by the window were taken. The right corner of the shadow was measured to be 320 cm from the window wall and 197 cm from the side wall. From another rendering similar to the one shown in Figure 8 except that the projection is a plan view, we determined the modeled shadow to be 333 cm from the window wall and 190 cm from the side wall. These measurements from the model are in good agreement with the actual classroom measured values and gave us further confidence in the overall model (and in our ability to use it correctly).
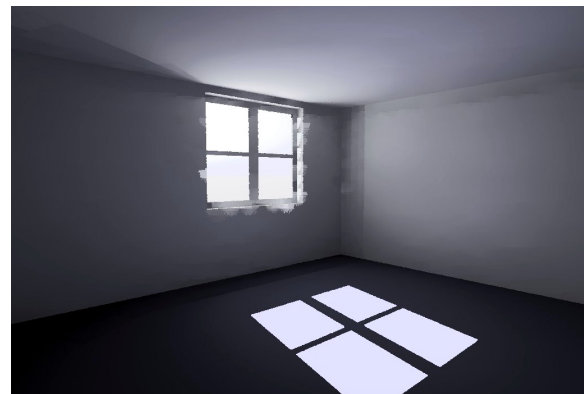

Figure 8. Rendering of the classroom 318 model

Walker Elementary Classroom Modeling

A photo of Walker Elementary School is shown in Figure 9. The classroom modeled was room E114, a classroom in the southern most wing near the west
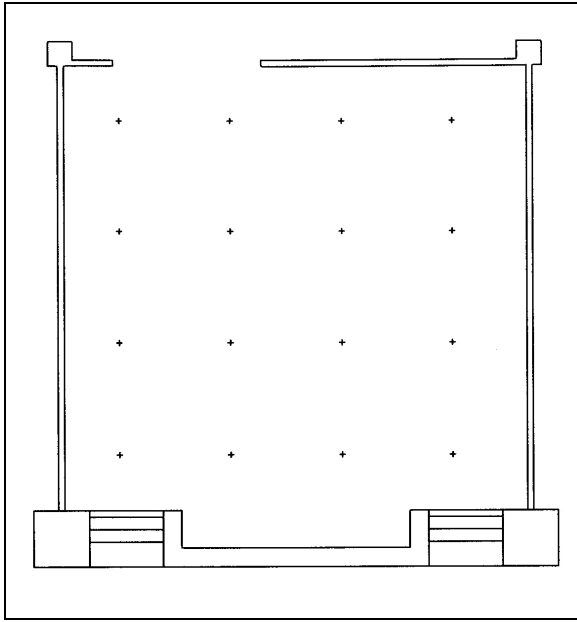
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Figure 12. Walker classroom floorplan with the illuminance measurment locations

One set of illuminance measurements was taken in the classroom at 12:52. Immediately after the measurements were taken the two meters were taken outside where horizontal illuminance and peak sun angled illuminance measurements were acquired at 13:10. Using the same process as previously described with the program gensky, we obtained a characterization for the sky. Both direct sun and diffuse horizontal parameters were estimated. As previously noted, this process is not unique and a range of diffuse horizontal combined with sun direct normal values can produce the same outside illuminance readings. To help reduce the error in this process we took outside readings a few hours earlier and later and used all the values to help constrain the turbidity factor, ground reflectance and sun direct normal component. Measurement of the diffuse horizontal irradiance without sun and direct normal solar irradiance and illuminance components is the preferred method, but we did not have the appropriate instrumentation.

A plot of the Radiance modeled illumination levels along with the actual measurements from the two light meters is shown in Figure 13. The simulation was run with the sky model corresponding to a time of 13:00. All of the measurements and simulations from the first 3 rows of points agree within 10%. The particular classroom chosen for the validation is set up such that the teacher's desk, cabinets, tables and some other items are along the southern wall. The light measurement locations for the bottom row of points had to be moved up about 50 cm from the desired location. Consequently, there is on the order of 20 cm uncertainty in the location. Unfortunately, these locations are in the transition

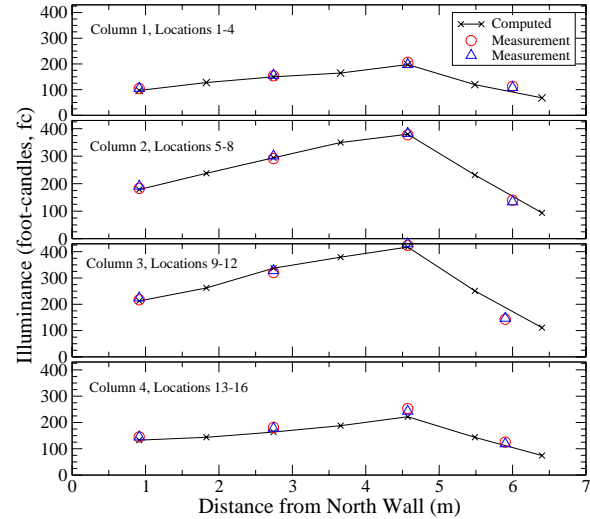just beyond the light well where 30 cm change can yield up to a 25% change in illuminance.

Figure 13. Plot of Radiance predicted illuminance levels and measured values vs distance for each of the 4 columns of measurement locations

LIGHTING SYSTEMS

Light fixtures incorporated in classroom design should include some type of control such as light sensors. The fixtures may be equipped with electronic dimmable ballasts that control the lumen rating of the lamps between 5% to 100%. The fixtures in a classroom with windows on one side might be zoned with each row of fixtures parallel to the windows and controlled by a separate sensor that gradually raises and lowers light levels based on the amount of ambient light in that area. The fixtures bordering the windows may dim to 5% or turn off during the day, in the middle of the classroom the fixtures may dim from 40% to 60%, and the fixtures farthest from the windows may be at 100%. Multiple zones allow for the maximum use of day lighting while simultaneously allowing for greater uniformity in overall room lighting. Classrooms with light wells in the center of the room would implement the same principle of using sensors to maintain a specific light level while adjusting gradually to increasing or decreasing lighting levels. Multiple zones might control fixtures immediately around the light well while a second or third zone might be used for the remaining fixtures in the room. The goal is to utilize daylighting while maintaining light levels throughout the room and preventing sudden light level adjustments to compensate for cloudy skies.

CONCLUSIONS

We have shown that it is possible to achieve accurate modeling of the daylight distribution inside

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an unbuilt classroom for representative sky conditions. The accuracy of the simulation is sufficient to allow for the design of the accompanying luminaire-based controllable lighting system and estimate the energy usage. During the design stage the simulation could have been used to "try out" various window designs, materials and room orientations to accurately assess the level of daylighting achievable. Future goals include incorporating this capability with average sky conditions and adaptive lighting control systems for overall lighting and energy analysis.

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