Development of Two Heliodon Systems at MIT and Recommendations for their Use

by

Roselin E. Osser

B. S., Mechanical Engineering (2005)
Tufts University

Submitted to the Department of Architecture in Partial
Fulfillment of the Requirements for the Degree of
Master of Science in Building Technology

at the

Massachusetts Institute of Technology

June 2007

Signature of Author: _____
Department of Architecture
May 11, 2007

Certified by: _____
Marilyne Andersen
Assistant Professor of Building Technology
Thesis Co-Supervisor

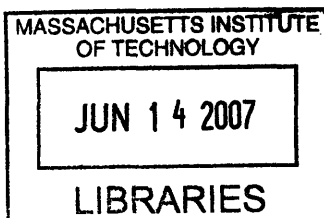Certified by: _____
Leslie Norford
Professor of Building Technology
Thesis Co-Supervisor

Accepted by: _____
Julian Beinart
Chairman, Committee on Graduate Students
Department of Architecture

1

Development of Two Heliodon Systems at MIT and Recommendations for their Use

by

Roselin E. Osser

Submitted to the Department of Architecture
On May 11, 2007 in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Building Technology

ABSTRACT

Heliodons aid the building design process by allowing the simulation of different solar angles with respect to physical scale models. At MIT, two different variations of this kind of setup are being developed. The first one consists of a small, portable heliodon that is manually operated, and meant for use outdoors with the real sun and sky. The second is a larger indoor setup that consists of a computer-controlled moving table exposed to a stationary light source. A computer interface allows the designer to automatically take different sets of model photos from a camera positioned next to or inside a model, and view the images in useful ways. Both approaches are presented in this paper and their limitations, causes of inaccuracy and potentialities are discussed based on experimental verification and through Radiance simulations. The results of a usability study with student volunteers and a case study on an existing research space on the MIT campus are also presented as a means of illustrating the potential value of such devices for building design investigation and development.

Thesis Co-Supervisor: Marilyne Andersen
Title: Assistant Professor of Building Technology

Thesis Co-Supervisor: Leslie Norford
Title: Professor of Building Technology

Acknowledgements

First, the author would like to thank her thesis co-advisors, Marilyne Andersen and Les Norford for their patience and excellent advice. The opportunity to do a project that ended with a working device and exposed her to a wide variety of issues along the way is much appreciated.

The heliodon project is the collaborative effort of many people. The author wishes to thank students Dean Ljubicic, Courtney Browne, Siân Kleindienst, Zachary Clifford and Tim Koch for their contributions to the design and development of the two heliodons, as well as Kess Eburu, Steve Banzaert, Ed Moriarty, and Daniel Cardoso for their technical advice and assistance. Much gratitude is owed to daylighting professionals Stephen Wittkopf, Christoph Reinhart, and Magali Bodart for research advice and to Michael Dutton of MIT I&ST for acting as usability testing advisor.

The author also wishes to thank all of the students who participated in the surveys for their time and interest, as well as for their model donations.

Additionally, the author would like to thank the MIT Gilbert and Sullivan Players, not only for lifting her spirits and for their loyal support but also for providing valuable technical advice and assistance on various aspects of the project, especially Nick Bozard for his extensive help with Flash Actionscript and John Deschene for his outdoor heliodon testing assistance.

Finally, the author would like to thank her family and friends for their unwavering support and encouragement during her time at MIT.

TABLE OF CONTENTS

Chapter 1

Introduction and Motivation

1.1   Daylighting Overview

Proper daylighting design optimizes the use of natural light in order to reduce lighting energy costs and maximize the visual comfort of the indoor environment. Ancient buildings relied strongly on daylight, but after the invention of electric lighting and modern HVAC systems, many modern buildings became sealed boxes with mechanically and electrically regulated indoor environments (Baker and Steemers, 2002). Today, as much as 39% or more of US energy use is due to buildings compared to 33% in industry and 28% in transportation, while lighting comprises18% of total building energy use (US DOE, 2006). It is important to recognize that this load can often be greatly reduced if the building is designed correctly in regards to daylighting and electric lighting design. This is done using both ancient techniques, such as correct building orientation and reflective surfaces interior surfaces to increase room brightness, as well as modern technologies, such as advanced façade systems, or occupant sensors that control electric lighting use.

In addition to the energy saving benefits, many studies have suggested that exposure to properly distributed daylight promotes the satisfaction and productivity of building occupants (Leslie, 2003). Daylight is one way to reconnect with the natural world, sometimes a difficult task for a busy office worker. Studies consistently show office workers' strong preference for daylight over artificial light as well as for views of the outside world through windows (Galasiu and Veitch, 2006). Building occupants have also been observed to tolerate much lower levels of natural daylight than they would of artificial light (Baker, 2000). This implies that buildings making greater use of daylight could allow greater variability in lighting levels, allowing daylight to contribute to even greater energy savings when compared to the higher electric lighting level that would have been required.

Besides the frequently-studied office buildings, schools are another type of building with the potential to greatly benefit from daylighting; however, as with studies of office buildings, it is quite difficult to truly isolate daylight as the direct causes of better performance and mood since there are numerous other factors affecting these parameters. Attempts have been made to prove that children in daylit classrooms not only exhibit better behavior, but perform better on tests (Heschong Mahone Group, 1999) but the statistical accuracy of the methods and observed correlations is considered questionable due to the many influences in such a study (Boyce et al, 2003).

It is important to recognize the direct economic benefit of happier, healthier building occupants. With the case of a company, worker salaries comprise far more of the total budget than the money spent maintaining the building. In retail trade, for example,

payroll and employee benefits comprise about 50% of company expenses, rent and leases make up about 9%, and operation repair and maintenance of the building only account for about 2% (USCB, 2002). If absenteeism, quitting, dissatisfaction, and discomfort can be reduced due to good building design, the increased efficiency could result in large economic benefits for the organization.

Energy savings from reduced building maintenance costs and increased worker satisfaction are not the only economic benefits possible with daylighting; in one case of a retail chain with similar layout for all its stores it was observed that those branches using skylights achieved as much as 40% higher sales than those illuminated with electric light alone (Heschong et al, 2002). Office buildings, schools, and retail centers are considered excellent subjects for daylighting efforts because their occupancy times generally coincide with daylight hours.

The daylight and outdoor view preference reported by building occupants is supported by health studies. Seasonal Affective Disorder is a condition that results in symptoms such as depression, constant tiredness, and weight gain during the less-sunny winter months. Light therapy or serotonin-replacing drugs are prescribed to treat this problem, since it has shown that brain serotonin production is directly related to exposure to bright sunlight (Lambert et al, 2002). This helps to explain the observed preference for daylit spaces by building occupants.

These beneficial health effects can also be observed in more serious medical cases. One early study found that the ability to view a "natural" panorama of trees through a hospital window not only decreased recovery time from surgery but also greatly reduced patient complaints of discomfort (Ulrich, 1984). A variety of other studies have since been performed that validate the positive effects of daylight on patients recovering from surgery and suffering from mental illnesses, among other health problems, as well as on hospital staff working in the often stressful conditions of such facilities (Joseph, 2006).

After understanding the many benefits of daylighting and windows, it may seem like the design solution is a building with as much window area as possible. Indeed, this seems to have been the original thought for many existing buildings that have almost entirely glazed facades. Upon closer examination, however, it becomes evident that this is not the case. The proper placement and sizing of windows and other daylight-aiding devices is in fact a complicated science and art. Besides energy and occupant comfort issues, buildings my have particular daylighting needs that need to be considered. In addition, the affect on and of neighboring structures may be significant.

There are several reasons why unrestricted glazing is not the answer for a high performance building design. The first issue is that of radiative and convective heat transfer. While light pours through a window, it brings with it solar radiation in the form of heat, which varies depending on the window's orientation. This heat gain can be beneficial during cold winter months, but it can necessitate a very heavy cooling load during warmer seasons. Conversely, a window that receives a low amount of solar radiation during colder months will allow heat loss and make the area near the window

cold and uncomfortable. Advanced windows with multiple layers, low-e coatings, and non-conductive frames can greatly reduce the heat transfer that occurs through the glass, but the insulation of a window to the degree possible with the surrounding building structure is not easily achievable.

The problems caused by this thermal leak are dependent on the local climate. In a temperate climate such as that of Boston, windows can cause overheating in the summer and heat loss in the winter, depending on the window's orientation. Correctly designed windows and window systems, however, can minimize winter heat loss and summer heat gain, and even provide helpful winter heating.

Unfortunately, highly insulated windows that remain transparent are not yet on the market. Research into the production of transparent aerogel windows is taking place (Jensen et al, 2004) but it is likely that high expense and the difficulty of casting large continuous pieces will limit their use in the immediate future. Transparent aerogel has an exceptionally low heat transfer coefficient, down to about 0.03 W/m*K, although some radiative heat transfer still occurs through the material. "Smart Windows," such as electrochromic ones which alter their light transmission when voltage is applied, can reduce unwanted heat gains significantly; however, their high cost and the complications of designing an automatic control strategy have so far prohibited their widespread use (Lee and Tavil, 2007).

Besides heat transfer problems, the other main argument against the over-glazing of building facades is glare. Glare is a familiar ocular sensation that ranges from annoyance and discomfort to disability and can even result in eye damage. The different causes of glare sensation can be simplified into two categories. The first scenario that causes discomfort glare is the "saturation effect," when part of or the entire retina is over stimulated by light that is brighter than the neurons can effectively process (Hopkinson, 1972). A commonly used example of this situation is the observation of a snowy landscape on a bright sunny day. The second scenario is an environment of excessive light contrast, meaning that a light source is significantly brighter than its surroundings. In Vos' article summarizing the history of glare categorization and its known biological mechanisms, he suggests that part of our discomfort in the presence of very bright light sources and high contrasts may be due to the fact that we involuntarily draw our eyes towards bright areas just as birds fly into lighthouses and insects are drawn towards light bulbs (Vos, 2002). He states that "stress due to the conflict between phototactic attraction and intentional avoidance may then explain the discomfort." Another common result of glare is when a person is unable to see through a reflective surface, such as a computer screen, because light is bouncing directly off of it.

Glare is a serious problem because not only is it capable of causing extreme discomfort, but it can actually be hazardous. Retinal damage can occur from direct exposure to the sun, and the temporary blindness caused by high glare areas could pose a serious hazard in locations such as stairwells. Glare is sometimes divided into discomfort and disability glare to reflect the distinction between a sensation that is merely annoying or fatiguing and one that is actually disabling a person in some way. Sensitivity to different glare-

8

causing situations varies among different people and is also affected by factors such as age and eye color (Vos, 2002).

Glare problems are usually mitigated through the use of various shading or light-redistributing devices. An extreme case of unpleasant and hazardous brightness contrast is when the sun itself is actually visible through a window. Since static shading devices cannot fully shade east or west facing façades, the blinds or shades on such windows are often closed by occupants and stay that way. It has been observed repeatedly that building occupants have a tendency to shut blinds and leave them that way once the light becomes uncomfortable (Galasiu and Veitch, 2006), completely devaluing the effort to install the windows in the first place.

Besides heat transfer issues and the prevention of visual discomfort, a building may have additional tricky lighting requirements that must be taken into account during design. Museum designers, for example, must be careful to ensure that exposure to sunlight does not damage works of art. Other buildings may require that indoor plants receive sufficient sunlight. Awareness of different building zone functionalities is also quite important, since lighting requirements vary depending on a room's purpose. A room in which tedious manual tasks are performed requires strong lighting of excellent quality, while high lighting quality is probably less important in areas such as hallways.

In addition to considering the indoor effects of daylight and sunlight, a new building's effect on its surroundings should be considered. Many places have "right to light" laws that prevent new buildings from blocking sun to existing buildings without express permission from the existing building's occupant. On the opposite side, one needs to understand the effects of existing surroundings on the new building. Planned outdoor spaces such as parks could be intended as sunspaces but in fact be overshadowed by surroundings for much of the year. Determining the effects of and on surroundings can be a tricky geometric problem but is a very important step in building design for both the design itself as well as for legal reasons.

Today, the traditional approach to designing a building is for architects to decide on a design, engineers to size the equipment necessary to make it viable, and contractors to then perform the work. It is this non-integrated approach and insufficient use of analysis techniques that allows the design of buildings that waste energy unnecessarily. In regards to daylighting, a typical scenario today is for architects to attempt to maximize daylighting by excessive use of windows, forcing engineers to specify very high cooling tonnage. The building occupants will then experience too much glare, leave their shades closed all the time, and use electric lights instead (Kozlowski, 2006). This unfortunate situation illustrates the fact that the proper understanding of daylighting and window systems is key to successful energy saving and comfortable design. Even if ample daylighting is intended, insufficient understanding or planning can in fact make a situation worse. Energy savings, comfort, building use requirements, and consideration of the surrounding environment all require careful investigation of the proposed design.

1.2   Daylight and Sunlight Prediction

Considering all of the benefits of proper daylighting and the variety of design analysis required to achieve this goal, it is unfortunate that most building designers today are not up to date on the best techniques, tools and methods available to plan for daylighting in their designs. This is known both from the observed poor daylighting performance of many current buildings, and also from a number of designer surveys. Common reasons for not using available design and simulation tools include that clients do not demand or pay for this type of analysis. Another barrier is the difficulty in learning to use the more accurate and advanced tools, while simpler or more old-fashioned tools are often less accurate.

A Singapore study showed that not only is building simulation software used minimally, but that daylighting simulation software is even less frequently used than HVAC and energy software. When daylight performance prediction methods are used, designers very often rely on "rules of thumb" and their own experience. These rules are often related to outdated codes of compliance that relate to one aspect of building performance, such as heating and cooling, without considering the overall picture (Lam et al, 1999).

An early Aizlewood and Littlefair survey of building designers found that 11/64 respondents never made any daylighting predictions, and that roughly 1/3 of the architects in the survey never predicted indoor lighting levels. Manual methods were prevalent among the respondents who did make daylighting predictions, while computer programs were primarily used by specialists and scale models by educators (Aizlewood and Littlefair, 1994).

Some of the results of the more recent Reinhart and Fitz (2006) survey on the use of daylighting tools are shown in Figure 1.1. This presents an overview of the types of tools that designers who plan for sun issues are using, though it should be noted that the survey is biased towards computer simulation since participants were recruited through various software user email lists. The motivation for the research was that the team found "a surprising mismatch between an active daylight simulation research community (simulation engines such as Radiance have been available for over 15 years and their output and capabilities are constantly expanded) and the professional building design community which largely ignores these efforts."
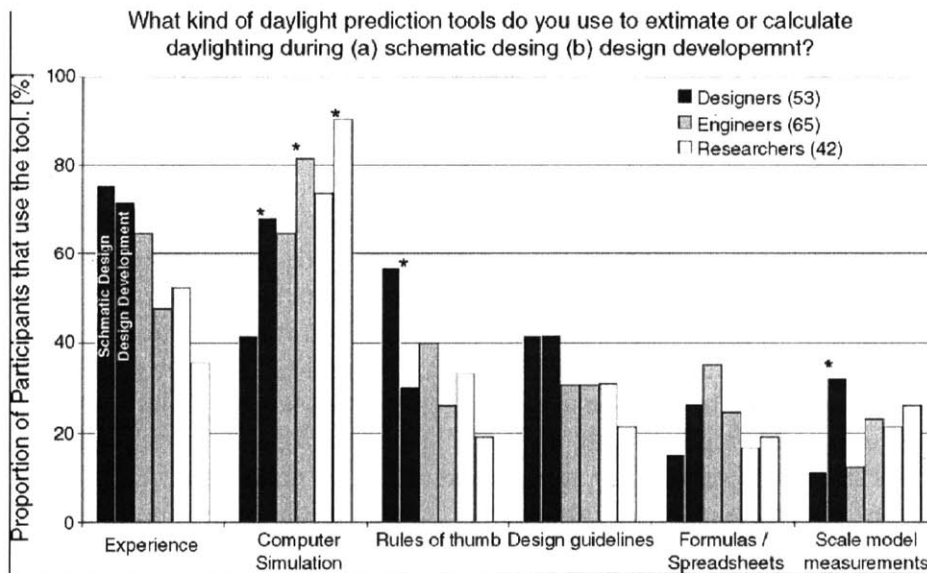
Figure 1.1: Daylight Prediction Tool Survey results (Reinhart and Fitz, 2006)

In terms of architectural education, an educator from Oklahoma State University recently reported his observations of student design habits. Though students were taught about daylighting analysis methods in class, they often failed to actually use the methods in studio. He noticed that daylighting tends to get left out when students are asked to consider the "numerous often-conflicting design factors and objectives," so it is mainly considered for its aesthetic contribution to the overall design (Mansy, 2004). When students do consider daylight they tend to look at successful building examples for inspiration and use basic rules of thumb. Students demonstrate strong interest and attentiveness when studying scale models, but they may not be familiar enough with methods available to test their reaction with sunlight.

1.3   Heliodon Design and Use at MIT

The purpose of this research is to provide user-friendly tools meant to facilitate the in-depth study of daylight and sunlight with scale models. The automated heliodon image acquisition system allows a physical model of any degree of sophistication to be analyzed using imaging capabilities comparable to those available in advanced computer simulation tools for sunlight, including the ability to show representations of passing days. The capabilities of this heliodon are explored and compared to those of the outdoor, manually-operated heliodon. Recommendations for their use to ensure the optimal accuracy for both devices are provided, and an investigation into the potential popularity of such devices is performed.

These two heliodons are both useful learning and design tools that complement each other. Scale models that architecture students have already produced for other assignments can be used with the heliodons, and model photographs used to enhance studio presentations. With the heliodons it is possible to perform experiments with windows and overhangings, shading, urban masking, or colors and materials. The

likelihood of glare and unwanted solar gains can be predicted. Additionally, experiments could be performed with advanced daylighting systems such as anidolics or other reflecting devices. The use of heliodons with scale models should be promoted in order to facilitate the improvement of building designs in relationship to solar issues.

The development of these tools is important in the context of other research projects taking place in the Building Technology Group at MIT. Recognizing that the underutilization of tools for assessing important sustainable building design issues such as HVAC system optimization and daylighting design is partially due to the inaccessibility and complexity of many software programs to architects and building designers, attempts have been made to provide easy to use software that allows quick experimentation with simplified cases. The MIT Design Advisor allows whole-building energy modeling to compare different proposed designs (Glicksman et al, 2007) while CoolVent performs thermal and fluid dynamics computation using simplified modeling parameters (Yuan and Glicksman, 2006).

Similarly, the automated heliodon setup allows quick experimentation with early designs, though more final models could be used as well. It is hoped that the provision of this tool to MIT's School of Architecture will help to make building studies of the technical issues related to sunlight easier and more accessible.

1.4   Organization of Thesis

The chapters of this thesis are organized based on the development and validation of the two heliodon tools at MIT.

Chapter 2 presents an overview of the state of the art of daylight and sunlight performance prediction methods as they relate to the capabilities of the two heliodons being developed. These analysis methods include sunpath visualization, image generation, and numerical analysis. The value of scale model and heliodon use is demonstrated within the context of other daylight and sunlight analysis tools such as advanced computer software. Additionally, existing computer interfaces that allow sunlight analysis are examined.

Chapter 3 presents the portable outdoor heliodon, its setup procedure, and possible uses during sunny or overcast conditions. Additionally, the sources of error involving the heliodon's use outside with surrounding obstructions and for simulating other solar altitudes are discussed and quantified using Radiance simulations. Guidelines are presented in order to help the user minimize illuminance error from these sources. Usability and other issues of heliodon accuracy are also discussed.

Chapter 4 presents the automated indoor heliodon setup and operation. The development of the user's control interface, which includes various image capture and viewing options, is discussed in detail. Additionally, the technical details of the camera are discussed as well as the measured accuracy of the table's movements. Areas for future improvement are also outlined.

12

In Chapter 5, a case study of the use of the automated heliodon as well as some outdoor testing is discussed. This case study investigates the lighting performance of an existing building, part of MIT's Stata Center. Problems with the real building include visual discomfort conditions caused by direct light reflections from neighboring structures as well as inadequate daylight penetration to the back of the room. Automated heliodon and scale model use allowed the causes and occurrence periods of these problems to be explored and solutions suggested.

Chapter 6 presents a user's perspective of the automated heliodon. Seven architecture student volunteers were given usability-related tasks to perform using their own or the author's models on the automated heliodon. Surveys and interviews followed, allowing the acquisition of usability scores and insight into the possible future use of the tool in the context of students' studies in architecture. Suggestions from the students are used to prioritize and plan future improvements to the system.

Chapter 7 is the conclusion of the thesis, which summarizes the major achievements and discoveries of the research project. The possible uses and advantages of the two heliodons are reviewed, as well as accuracy issues and existing areas for improvement.

Appendix A provides sample code and examples of text files used for the Radiance-driven investigation of possible error sources from the use of the portable heliodon outdoors.

Appendix B is a copy of the user's manual for the portable heliodon. The user's manual includes information regarding the setup and use of the advice, including camera and model attachment, as well as detailed instructions for both sunny and overcast operation.

Appendix C contains technical information regarding the recent replacement of the automated heliodon's altitude motor, discussed in Chapter 4, and also describes the remaining electromechanical issues along with potential solutions.

2 State of the Art: Sunlight and Daylight Performance Prediction Methods

Building designers today have a large variety of sunlight and daylight performance prediction tools available to them, regardless of the fact that they are sadly underutilized. Many of them offer capabilities similar or comparable to those offered by heliodons. However, the degree of accuracy, ease of use, and appropriateness to a particular study of all these tools including heliodons varies widely. Such shared capabilities include sunpath visualization, comfort prediction, numerical estimations of building performance, and image generation. Scale models can be used with artificial skies in addition to heliodons, and there are many existing heliodons that are important precedents to this work. Knowledge of the capabilities and limitations of existing daylight and sunlight prediction and assessment tools is required in order to provide an addition to this toolset that is both unique and valuable.

2.1 Sunpath Visualization

One of the first important steps towards the grasp of daylighting science concepts is the understanding of sunpaths. Once yearly sunpaths for a particular building location are understood, this knowledge can be used to plan shading devices, predict the effects of neighboring obstacles, and optimize building façade orientation. Sunpaths vary throughout the year and are different for every place on earth. However, hand calculation of the sun's altitude and azimuth for multiple points is quite tedious and time consuming because of the geometric complexity of the calculations.

Stereographic and cylindrical projections are graphic charts that can demonstrate sunlight information more visually and without mathematical equations. These charts show sunpaths for different times of the year, allowing solar altitude and azimuth of individual hours to be quickly determined estimated. Individual charts are available for different latitudes or longitudes if clock time instead of solar time is used. Additionally, they can be used to help visualize the affects of obstacles adjacent to the building in question, aiding in building orientation and window location decisions. Geometric calculations can be performed that enable the designer to color the areas of the chart that represent hours of the year when a particular façade will experience shading, partial shading, or direct sun. Although these charts may help the user to guess when and where affects such as reflections and shading from obstacles may occur, they cannot actually show these sunlight interactions or what the building itself would look like. However, their frequent reference is quite helpful when performing studies of daylight and sunlight with other tools.

Square One produces two software tools, Ecotect (Ecotect 2006) and Solar Tool (Solar Tool, 2007) that include these sunpath visualizations as part of their interfaces. While stereographic charts are two-dimensional, these programs show three-dimensional visualizations of sunpaths in relation to a computer model. The user can drag the sun to different parts of a solar arc or switch to a path for a different day of the year, aiding in

the three-dimensional understanding of where the sun is in relationship to a building. The inclusion of sunpath visualization is an extremely important and helpful addition to any sunlight or daylight prediction tool because it promotes understanding of the direction and source of solar radiation at a given date and time. The use of these sunpath visualization methods is strongly linked to the use of both heliodons.

2.2   Computer Graphics

2.2.1   Generation of Rendered Images

Image generation is usually one of the main goals of any attempt to predict the outcome of a proposed design with respect to light. While photographs of scale models can be taken such as with a scale model and heliodon, the other option is to create rendered computer images.

There are different algorithms available to solve the complex equations governing the behavior of light in order to provide visual representations of light interactions with geometry, colors, and materials. These methods are attempts to provide approximate solutions to the rendering equation, which uses conservation of energy to predict light's behavior in a particular environment (Kajiya, 1986). Two of the most common rendering algorithms in use today are radiosity and ray-tracing. Radiosity is a light calculation algorithm that solves the equation through the finite element method, dividing surfaces into finite elements or "patches" and then calculating the luminance or illuminance of each element (Goral et al., 1984). One advantage to this method is that calculations are completed for an entire scene which can later be viewed from any angle. The disadvantage of the algorithm is that it considers all surfaces to be perfect diffusers or transparent and therefore cannot account for specular effects. Because of the required individual patches, it also has trouble accounting for bumpiness or texture unless the patches are made very small, drastically increasing rendering time (Dischler et al., 1999).

Raytracing is another rendering algorithm in which paths of light are traced backwards from the viewpoint to scene objects to the source of light. It can account for any light interaction including reflections (IEA, 2000). Renderings are calculated for one viewpoint at a time instead of every possible rendering angle, saving calculation time if few viewpoints are desired but preventing a three dimensional exploration of a scene without generating multiple views.

Visualizations of future buildings are extremely important in the design process for many reasons. Designers can use them themselves to get an aesthetic feel for the building, and experiment with geometries, colors, and materials. Natural and electric light can worked with simultaneously to assess the needs of different areas of the proposed building. Not only are these images used for building designers' own review and analysis but they are also shown to clients. The attractiveness and perceived realism of rendered images is extremely important when they are used to convince clients to hire the designer for a project or to demonstrate the relative differences between various proposed designs.

However, the emphasis on the importance of image attractiveness means that not all rendered images are or are meant to be accurate predictions of how the space will really look. A useful categorization of specific software tools is to classify them either as "accuracy/quantitative-driven" or "effect-driven" (Lawrence, 2005). With some software, such as 3D Studio Max, if the corner of a room appears too dark in an initial rendering, the user may easily add some fictional "ambient light" to the offending area without actually adding an electric light source or altering geometric parameters that would affect daylight penetration to that spot. Even though a user may choose to use only planned electric light sources and the sun, there are so many other parameters to adjust that the accuracy of the resulting image is clearly suspect. In 3D Studio, adjusting the optical properties of a building material is particularly complex because of the vast number of variables relating to parameters such as shadowing and variations of rendering algorithms. Image creation is an iterative process of parameter adjustment and rendering until the scene looks realistic and fits the designer's personal aesthetic goals. Successful image creation is largely dependent on the user's experience with what parameters are critical for image improvement.

Such rendered images are usually then exported to Photoshop for final cropping, brightening, color alteration, or addition of various fictional elements meant to present the images in the best possible way. This practice of doctoring and improving "predictive" images is routine for designers, but considered essential for effective selling of ideas to clients. Software which requires the users themselves to decide when they have achieved "accuracy" after multiple parameter adjustments is clearly not to be relied upon for accurate lighting prediction, though this is not the purpose of this type of software. There should be a clear distinction between this type of image generation and that whose goal is to accurately predict lighting conditions.

In Reinhart and Fitz's recent survey of daylight simulation tool use, they found that over 50% of cited tools used the backwards raytracing package Radiance. Radiance is a software tool with a variety of different capabilities for in-depth and highly accurate study of light (Larson and Shakespeare, 1998). It is capable of producing extremely photorealistic and physically accurate images showing the combined effects of sunlight, daylight, and electric lighting (Larson et al., 1998).

Although the most commonly used program among professionals who use predictive lighting design tools, Radiance is widely considered to be excessively complex when used by itself (Reinhart and Fitz, 2004). The software package itself has no user interface, and requires users to understand Linux programming, entering sky, material, and geometry data through text files. What documentation exists is considered to be confusing, and the software is known to have multiple features that remain undocumented. Appropriate values for rendering parameters such as the number of interreflections are dependent on the particular properties of the space being studied, requiring the users to have a large amount of personal experience with different situations before they can full understand what parameters to enter for different situations. Despite Radiance's advanced capabilities and programmatic flexibility within the small daylight

16

simulation community, the difficulty and time necessary to learn the required skills remain a key deterrent of its frequent use in the wider building design community.

Other software such as Ecotect includes the ability to export models to Radiance for rendering through a user interface. Ecotect, however, is made for simplified building analysis and does not recognize curved surfaces and other complicated geometries. It also has limits in terms of possible materials and other parameters it can use for rendering, even though it does provide a very quick and easy way to use Radiance software for image generation. Another attempt by the IAE (International Energy Agency) to limit Radiance's complexity and also allow integration with electric lighting and overall building energy studies resulted in the invention of ADELINE (Advanced Daylight and Electric Lighting Integrated New Environment). This software uses Radiance to produce images, but offers a much simpler user interface to set up the simulation (IAE, 2000). In addition to the ability to import CAD models, users have the option of choosing from basic building geometries and even filling them with pre-made luminaries and furniture pieces from a library, outputting Radiance-rendered images (ADELINE, 2002). Even with these accessibility benefits, ADELINE's own website notes that only 2% of its users are architects; it is primarily used by lighting design specialists.

Similar to Radiance without a supplementary user interface program, SUPERLITE requires text file inputs and can also create rendered images. Since it uses the radiosity algorithm, however, it models all surfaces as diffuse and also cannot model complex surfaces such as Venetian blinds (SUPERLITE, 2007). Lightscape also uses this algorithm. One experimenter observed that this resulted in surfaces appearing pale and flat compared to equivalent scale model photos she took for a comparison (Sarawgi, 2004). It was also noted that "while the amount of time taken to arrive at a final daylight solution increased, the accuracy of the daylight solution diminished."

While many existing software packages are capable of producing high-quality rendered images that accurate and/or beautiful, they often experience a variety of difficulties related to their use. One of the most common problem causing and time consuming areas with this software is the creation and interpretation of geometry. Complex modeling and rendering is generally quite time consuming unless only simplified initial results are required. In addition to the time spent entering multiple parameters and then waiting for scenes to render or numerical data analyzed, the 3D modeling that must take place beforehand can be an extremely lengthy process. While some software discussed allows simple model creation within the program, others require that a model be imported. The more accurate and attractive the rendered image that is desired, the higher is the complexity requirement of the 3D model that must be made beforehand. If changes need to be made, the model may need to be re-imported.

Additionally, the actual importing may cause problems of its own. Common modeling programs such as AutoCAD model objects as solids, contrasting with the surface-oriented rendering that takes place in the daylighting simulation software. After importing a model into a program such as Ecotect, the user may discover that unusual geometry has

been distorted. Edge artifacts and shadow distortions that need to be altered in Photoshop may appear. A model component that the program had particular trouble interpreting may even disappear completely, leaving the model without a wall or a ceiling, for example. Learning how to handle different file formats and adjustments needed after importing is a lengthy process, and frustration inevitably results when lighting software fails to properly interpret a model that took many hours to build. At the early design stages, these details of geometry and materiality are not yet fixed, making decisions about exploratory computer models quite difficult. Even after these computer models are created and simulations attempted, many parameters must be adjusted while attempting to mimic what real light does naturally.

Despite the impressive capabilities of image software available, the tradeoff between the value of good results and the time and skill required to produce them remains a disincentive for these endeavors. This explains why their use is limited to a relatively small number of lighting simulation specialists and researchers, and rarely used by the majority of building designers (Reinhart and Fitz, 2004 and 2006). Additionally, the dominance of "effect-driven" rendering practices persists as the capability to produce beautiful images is exceptionally important to the business practice of architecture.

2.2.2 Shadow Visualization

Software also exists that can more quickly visualize the behavior of light by simplifying it to direct sunlight and shadows without attempting to show photorealistic effects of diffuse light, a situation quite comparable to that of the automated heliodon being developed at MIT. The observation of direct light and shadows is important for many reasons. It can help a designer select building orientation and observe the possible overshadowing effects of surrounding buildings, aiding in "Right to Light" site analysis. Additionally, shading devices meant to block direct light can be experimented with.

Sketchup and Ecotect are two software options that offer this simplified shadow observation capability. In Ecotect, for example, the available interactive sunpath mentioned earlier can be used to help visualize shadow movement over a passing day. The model can be rotated and viewed from different angles as the sun is dragged to different locations in the sunpath or animated. Right to Light test simulations can be performed if it is suspect that a new building may infringe on the sunlight of neighboring buildings. Algorithms can even be developed that will programmatically determine the tallest allowable heights of different parts of a proposed building within a constrained footprint such that it will never block sunlight from neighboring ones (Ecotect, 2006).

Another interesting new software package that helps study the effects of direct light and shadows is called Solar Tool (Solar Tool, 2007). This software is designed specifically to help plan shading devices, façade elements, and windows themselves. Maps of solar penetration on stereographic charts can be produced automatically to help understand when and to what degree direct light will penetrate a window. While this software seems very specific, it was found that while shading device adjustment is the most likely experimental parameter for designers who use daylight and sunlight prediction software,

18

most programs do not have any automated and helpful way to aid in this process (Reinhart and Fitz, 2006).

2.3   Comfort Prediction

Various methods of assessing and predicting visual comfort or occurrence of glare are available. Several numerical calculation methods exist for the purpose of estimating the likelihood of glare. These glare prediction methods can be useful for helping building designers assess the visual comfort of a proposed design, provided that they are able to obtain the necessary measurements. Since the biological process of experiencing this discomfort is not fully understood, equations have been derived empirically by correlating discomfort reported by test subjects with measured quantities in experimental rooms (Fisekis et al., 2003). The Daylight Glare Index (DGI) is a function dependent on a source's luminance, size, surrounding luminance, and direction of view. However, inaccuracies of prediction are often observed when the glare source comprises a large percentage of the viewing area, as in the case of a large window. The Unified Glare Rating (UGR) is another discomfort indicator that is also restricted in accuracy to certain types of glare sources. A simpler approach by a different study has shown that the Glare Sensation Vote (GSV), a scale of discomfort levels selected by test subjects, can be highly correlated to a simple measure of vertical illuminance measured at the building façade (Velds, 2002).

A very recent study by Wienold and Christoffersen, however, points out that the use of discomfort scales such as the GSV does not take into account the range of human perception and individual interpretation of the GSV levels, which have names such as "just acceptable glare," "just intolerable glare," and "just uncomfortable glare." Instead, they propose the use of a modified indicator called Daylight Glare Probability (DGP). Recognizing the range of human tolerance, the DGP is defined as the probability that a building occupant is disturbed by glare, removing the requirement to define a fictional glare "magnitude," and can be correlated to simple illuminance measurements at eye level (Wienold and Christoffersen, 2006). While these comfort indicators may predict whether or not an occupant will find daylight uncomfortable, they are non-visual estimates and do not help architects to assess whether room and window designs also fulfill their aesthetic objectives. It is also quite difficult to accurately predict glare based on a particular visual environment because the possible geometries, viewing directions, and luminance levels of the surroundings are quite diverse. A visual rather than numerical glare prediction may be more intuitive to a designer, since it is difficult to understand the way a room really looks or feels by looking at a list of numbers.

Radiance-based software can also be used to make glare predictions from renderings of scenes. "Evalglare," a new tool developed by Wienold and Christoffersen, expands upon the existing Radiance "findglare" tool that pinpoints glare source direction and luminances in rendered images. The Evalglare software processes digital photographs taken with a CCD camera in order to pinpoint glare spots. The tool works by locating pixels that exceed a certain luminance threshold set as four times higher than the average

luminance value of the task area (Wienold and Christoffersen, 2006). These pixels are compiled into areas of glare that can be visually highlighted by setting them to a certain bright color while converting the rest of the image to grey scale. This analysis can be performed on photos of real buildings or scale models, or on Radiance-generated computer images to better evaluate glare. However, the examination of one individual scene does not give a good estimation of how the lighting conditions are over the course of a year. In addition, there are many possible viewing directions within a scene even at only one moment of the year. As with most daylighting issues, one of the biggest difficulties is obtaining a general overview of a particular building's performance when there are so many possible viewing environments.

A very simple way to visually predict periods of likely glare in a building can be accomplished using the MIT Design Advisor. After simplified modeling parameters and building window geometry and façade orientation are entered, renderings of the inside of rooms during several times of the day and year can be easily viewed and compared (Glicksman et al., 2007). While shading devices and blinds can be included in the visualization, the allowed geometry is limited to an empty rectangular room. Even though the depth of analysis is limited, the fast calculation time and simple input make it a valuable tool for obtaining a quick overview of lighting conditions and possible periods of glare at a particular building façade.

2.4   Numerical Prediction of Lighting Performance

Besides visual predictions of how a proposed building design will look, it is also quite useful to quantify its predicted lighting performance for easier numerical comparison between proposed designs. It is important to determine if the lighting levels required for a specific space activity have been reached. This can help determine what activities are best suited for each part of the building and also what electric lighting requirements may be to supplement daylight and reach required levels.

2.4.1 Simple Quantitative Methods

One of the most basic ways of predicting daylight performance is to perform calculations to predict light levels by hand or with a spreadsheet. The lumen method, for example, is a set of equations that can calculate illuminance at a certain point in the room by taking into account variables such as the size of the window and other factors that can be looked up in charts (IESNA, 2000). Since the equation assumes a completely empty rectangular room, it has limited use and applicability and can also be quite tedious to use for large areas of a proposed building.

The daylight factor (DF) is a commonly used performance indicator used to estimate the visual comfort level in a room. It is defined as the ratio of the measured illuminance on a work plane to the simultaneous illuminance outside the building. A DF of 2% or above is widely considered sufficient for working. The daylight factor is quite simple to measure and calculate in an existing building or scale model, but harder to predict by hand. Since

20

the daylight factor is the sum of the sky component (SC), the externally reflected component (ERC), and the internally reflecting component (IRC), estimations for these values must be determined individually in a lengthy procedure known as the split flux method. The SC and ERC can be determined using daylight factor protractors, and other values can be looked up in extensive tables. However, the result is only a simplified estimation of whether sufficient lighting conditions will be achieved. Additionally, it is only technically valid for the CIE standard overcast sky which assumes that the sky zenith is three times as bright as at the horizon (CIE, 2003), and does not account for sunny skies, building orientation, or glare (Mardaljevic, 2004).

One advantage of simplified hand calculations is that it is easy to understand that the approximations used for different equation variables make the results only estimations. In contrast, the invisible calculations made by advanced computer programs, for example, make the accuracy level of results less obvious (Aizlewood and Littlefair, 1994). However, any method that manages to reduce the highly complex nature of light into very simple equations and scenarios is clearly limited in accuracy and ability to represent the overall picture. Additionally, these mathematical prediction methods fail to provide the visual information which is so important to designers.

Another traditional method of estimating a design's daylighting performance is to use rules of thumb. The "2.5 rule," for example, states that window sidelighting will sufficiently illuminate the room up to a depth of 2.5 times the height of the window above the work plane (Allen and Iano, 2002). Another is the "15/30 rule," which claims that the region within 15 feet from a daylight source will be sufficiently illuminated from daylighting alone while the region up to 30 feet away will be partially lit but require supplemental electric lights. The "1/10 rule" denotes that the minimum daylight factor in the room is one tenth of the area of the window expressed as a percentage of floor area (Moore, 1993). As would be expected, the accuracy of these rules is highly questionable because they do not account for different sky conditions or building orientation and should not be relied upon when determining the viability of a proposed design. Despite this, they are still used by some designers as quick estimations.

2.4.2 Advanced Numerical Performance Prediction

Software can also be used to predict parameters such as the daylight factor, internal illuminance, or more advanced numerical indicators of lighting performance. False color images are one quite helpful visual representation of numerical results. A computer display cannot match the light contrasts possible in reality; computer monitors have the ability to show a luminance ratio of 100:1 while in reality the contrast may be as much as 10,000:1. False color images overcome this display limitation by using a rainbow of colors to represent different luminance or illuminance values, allowing viewers to detect contrasts they would not have noticed in the original images (Sarawgi, 2004).

Radiance-based software can produce false color maps and graphs of numerical daylight or illuminance indicators in addition to the rendered images. The high accuracy of this software in matching real outdoor illuminance measurements in a wide range of sky

conditions has been thoroughly validated (Mardaljevic, 1995 and 2001). Radiance can use highly accurate sky models such as the Perez model (Perez et al., 1993), which generates sky luminance distributions from diffuse and direct irradiance measurements taken in a particular location, to calculate light values in a scene.

There are other indicators other than specific luminance or illuminance levels that provide insight into the actual value of the light levels within the space. The popularity of different indicators of lighting quality have changed over the years, with daylight autonomy now considered a much more useful parameter than the traditional daylight factor since unlike the daylight factor it uses climate and sky data, façade orientation, and the occupants' lighting needs in order to express the percentage of occupied time that the minimum required light level, generally the CIBSE code office requirement of 500 lux, is maintained using daylight alone. Unlike the daylight factor, which can be calculated by hand for a given point in a room, daylight autonomy must be calculated using software that can analyze sky data from a whole year (Reinhart, 2006). Recently, however, a new indicator called the Useful Daylight Illuminance (UDI) has been proposed by Mardaljevic. He argues that daylight autonomy is limited because it ignores the fact that illuminances less than 500 lux may still be useful for the overall lighting scheme and that excessive illuminances will cause occupant discomfort. Instead of representing the amount of occupied time where the indoor illuminance exceeds a certain level, the UDI instead indicates the percentage of time that illuminances fall within the range 100-2000 lux (Mardaljevic, 2006). This representative indicator may gain popularity in the future because unlike previous methods it takes into account human factors regarding visual comfort while remaining simple to understand.

2.5   Scale Models in Natural Lighting Design

2.5.1 Scale Models

There are many strong advantages to model use for daylighting study (Lechner, 2002, p. 400). Light physics allow a scale model to show light interactions exactly as they would be observed in a full-scale building, assuming the two were actually identical. Any model that a designer may already have created for design planning purposes can be used for a model study, with no interpretative limit on acceptable geometric complexity. Instead, the limit lies with the model builder's skills, availability of resources such as lasercutters, and the physical possibility of modeling detail size and geometry. However, model construction does not require any advanced technology, and has been practiced since ancient times. Models can be transported and displayed anywhere, and viewed from all angles simply by walking around them, making them an excellent tool both for client communication and educational purposes.

Like computer software, models may be used to demonstrate and test both qualitative and quantitative lighting properties. When tested using simulated or real sunlight or daylight, illuminance measurements can be taken at different points within and outside the model, and values such as the daylight factor could be calculated outdoors on overcast days or with sky simulators, to be discussed in the next section. Photos may also be taken to get

an idea of what the space design might look like. To allow quick adjustments during testing, interchangeable parts may be created so that the designer can quickly try out alternative features. There are a wide variety of interesting studies that can be performed with models (Schiler, 1987). These include testing building orientation, window placement and shading, colors and materials, as well as more advanced daylighting systems.

Fragility is an important consideration. Unlike computer models, physical models wear out over time especially if delicate pieces are repeatedly attached and removed. Curved surfaces made of thin cardboard can uncurl, surface treatments wear out, and structural elements can break. The required strength of a model should depend on how long it needs to be used and to what experiments will be subjected. Additionally, a scale model runs the risk of being dropped, stepped on, rained on, or otherwise destroyed by various accidents. Computer model files can be deleted but saved backups are possible. The miraculous saving power of the "undo" command is also sadly unavailable in the physical world.

The physicality of models is both a benefit and a drawback. When it comes to altering and improving designs during model investigation, certain features might be easier to change in a computer model than with a physical one and vice versa. After a computer model is complete, changing the color or reflectance of an internal wall, for example, would probably take very little time while making such a conceptually simple change with a scale model could require entirely new construction. Experimenting with different shading systems, however, might be easier to accomplish with scale models than with computer models, depending on the modeling program being used. Interchangeable parts, such as overhangs of different lengths, can be constructed prior to model experimentation and could be easily swapped if an appropriate attachment mechanism such as the use of magnets is planned (Figure 2.1). However, the ease of this transition depends on the geometry and scale of the model.
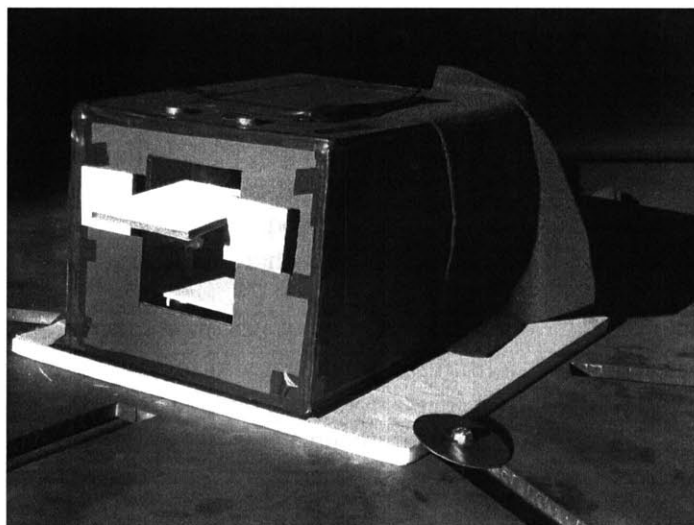

Figure 2.1: Daylighting scale model with magnets for attaching interchangeable parts. A light shelf is currently attached. Two magnets glued above the window allow other shading devices to be added.

Adding correct material properties and natural elements could be easier with a scale model than with a computer model. For example, if it is known that certain paint will be used on interior walls of a future building, that same paint could be used in model construction without needing to know its exact reflective properties and then attempt to represent them correctly in computer software. Creating other elements of varying color or roughness such as partially dirty walls could be much easier to handle physically than through a computer program. Simple found objects that would be difficult to computer model could also provide valuable contributions. If a building courtyard contains decorative boulders, for example, such objects of a reasonable scale could be found and fixed to the model, adding the realism of irregular shapes and materials that would be difficult to model believably in a computer program without considerable skill and time.

Though model building can allow excellent opportunities to make use of available materials, there are important considerations for building models that must be followed as strictly as possible if accurate measurement results are desired from their use (Bodart, 2007). Since model building is quite time consuming, it is important to first consider what building details are necessary for the study. Simple sketch models may be useful for general experiments with orientation and window location, but for more advanced lighting studies the model must be constructed with more care. The designer must understand the questions that need to be answered and build a model that achieves this goal without wasting time and money unnecessarily (Daylighting Lab Seattle, 2004).

Another extremely important aspect of model building is the appropriate choice of building materials if any kind of quantitative analysis is to be performed, such as with a sky simulator or outdoor heliodon. The reflective properties of internal and external surfaces must be as close as possible to those of the real materials, or else measurements could severely over- or underestimate light levels within the building (Lechner, 2002). The model walls must be opaque and the joints light-tight. Incorrect material representation is generally considered the primary cause of the observation that measurements in scale models in fact usually overestimate internal illuminance when compared with measurements in a full size equivalent building (Cannon-Brookes, 1997). The most common causes of this are modeling windows with too much transmittance and overly reflective internal surfaces. Even when a vigorous attempt is made to remove these common discrepancies and also those involving the response behavior of sensors, the overestimation of internal illuminance by scale models can still be observed as at least 30-35% for reasons that are still unknown (Thanachareonkit et al., 2005).

While designers using scale models should make every attempt to model precisely, they should keep in mind that this is a limit to the accuracy of their predictions. Though measurements taken within scale models should not be taken as accurate indicators of a real building's performance, these measurements can still be used for comparison purposes, such as a case where one removes or adds a shading device and observes the results.

There are many different ways to study scale models. If a study of natural daylight effects is desired, one way to test building performance is to bring the model outdoors. Here, the sun conditions it experiences will be almost exactly the same as those on a full-scale building in the same outside conditions, accounting for the effects of disproportionately large shading obstacles such as surrounding buildings, which are discussed in Chapter 3.

On sunny days, simulations of daylight on the model at different times and in different locations can be performed using sun-peg experiments. These consist of manually tilting and rotating a model while watching the shadow of a peg placed in the middle of a stereographic chart attached to the model. If the model is rotated skillfully, a passing day simulation could be attempted. However, coordinating this model tilting for a simulation of this complexity requires a group effort, and results may be confusing to observe and document.

Even though outdoor sun and daylight testing offers the most realistic possible scale model observations, difficulties caused by a moving sun, changing weather, and obstacles cannot be avoided. If more controlled conditions for measurements or photographs are desired, indoor simulations of various types may be performed.

2.5.2 Artificial Skies

Artificial skies allow the simulation of different sky conditions with scale models. Sky simulators generally model the effects of the sky without the sun and are therefore used to simulate overcast days as well as clear days without the sun itself. The problem with including the sun in these setups is that it is impossible to create an artificial sun and sky that have a brightness contrast as high as in reality. However, the study of overcast days is quite important in some climates where these darker skies predominate but the use of daylight in building designs is still desired. Several setups exist than can be useful for scale model measurements, but offer some problems when realistic model images are desired, especially when the effects of both sky and sun are desired.

The simplest type of sky simulator is the mirror box. It consists of a box with mirror walls and a luminous ceiling that can be placed over the target. The mirror box only models the CIE standard overcast sky, which represents a sky as equally luminous everywhere except the ceiling, where it is three times as great. Characteristic inaccuracies are caused by uneven luminance distribution in the ceiling and walls (Arnesen and Matusiak, 2005). Though this sky simulator has the smallest space requirements, the large size of the model compared to the box size means that the model may interfere significantly with internal reflections between the mirrors. Photography is another challenge with the mirror box. Photos taken with the setup are confusing images because the camera holder is reflected repeatedly by the mirrors (Lechner, 2001).

Diffusing domes are another type of sky simulator, where a model is placed under a large dome to simulate the sky. However, problems of parallax error arise when non-uniform skies are modeled. This means that the illuminance at a particular point in the model is

dependent on its position under the dome, due to the necessarily small size of the dome compared to the real sky (Mardaljevic, 2002). Those parts of the model farther away from the middle of the dome will receive different amounts of illumination than those in the center region. In the study, it was found that even by severely limiting the size of the model compared to the size of the sky dome, it was nearly impossible to reduce error from parallax alone below 25%.

Scanning sky simulators, another type of artificial sky, work by representing only a portion or "patch" of sky with an array of lamps, avoiding the undesired interreflections caused by modeling the whole sky at once. Examples of this type of setup exist in Belgium (Bodart et al., 2005), Switzerland (Michel et al., 1995), and the latter's close replica in Italy (Aghemo et al., 2007). With this setup, the model must be rotated to separately expose different portions to the sky patch. Measurements taken at each step are then combined and mapped to assess the overall illuminance of the subject. To combine sun and sky effects, separate measurements taken with a sun simulator alone are scaled appropriately and then combined with the results from the sky simulator. These simulators are primarily used for measurement purposes, rather than imaging. When images from a scanning sky simulator are desired, separate photos from each scan have to be taken and then digitally combined to show the daylight over a whole room. However, combining this with sun effects for images would be nearly impossible because of the brightness contrast problem already mentioned.

2.5.3 Heliodons

In contrast to sky simulators, which are used to study diffuse light in scale models, heliodons can be used to study direct light and are often used to take images rather than measurements. These devices require movement of a platform that supports a model in relationship to a light source in order to simulate different solar angles of other times, dates, and places on earth. Either the light source or the platform can move since it is the relative angle between them that is important. Sunlight penetration, building façade orientation, and window configurations on a scale model are key parameters that can be analyzed quite effectively with such a device though the observation of shadow and sun patch movement. Heliodons could also be used to help plan the placement of solar panels to optimize their exposure to direct light throughout the year. The devices being developed at MIT are an indoor, automated heliodon that simulates only the sun as well as a portable heliodon for use outdoors.

The direct light and shadow analysis possible with an automated heliodon is most easily comparable to shadow visualization options in software such as Ecotect and Sketchup, which can show shadows over the course of a day on a computer model. Ecotect can also show a visualization of the sunpath arcs, allowing the user to manually drag the sun around on a given day and observe the effects. However, these simple modeling programs have limits in the complexity of models that are allowed; for example, Ecotect cannot recognize curved surfaces, and breaks up curves from imported models into visible facets. In addition, these programs will not show the specular effects of direct light on complex shiny surfaces. The automated heliodon can also show effects of direct

26

light other than shadows, such as reflections, helping highlight areas of possible glare, such as in the case study of Chapter 5, which deals with reflections, including those from complex curved surfaces.

While scale model tests with an automated heliodon and sun simulator can help designers make predictions about glare likelihood by allowing observation of patches of direct light, it would be meaningless to try to calculate numerical glare ratings such as the Daylight Glare Probability or Unified Glare Rating from this setup. If only direct light is simulated, the contrast between areas of direct light and those also illuminated by diffuse light or perhaps electric light is much higher than it would be in the real building. If automated heliodon photos were to be analyzed for glare sources, software such as the Evalglare tool mentioned earlier would pinpoint every patch of direct light as a glare source when in reality they might not be due to ambient light levels from other sources, lessening the contrast. However, photos of a model interior taken on an outdoor heliodon using the real sky and sun could be effectively analyzed in this way. Additionally, illuminance measurements taken an occupant's eye level inside the model could be correlated to the Daylight Glare Probability (Wienold and Christoffersen, 2006).

While measurements can be taken inside a model interior using an outdoor heliodon, there are many limitations. Besides of the known inaccuracies of scale model measurements mentioned earlier, it is best to use measurements only comparatively such as when comparing different options. When using heliodons to simulate other times and places, it is important to consider the consequences of using one solar altitude to simulate another, as well as surrounding obstructions, as discussed in detail in Chapter 3. Additionally, the ability to get very thorough coverage of a model interior is limited, requiring individual sensors at each point of interest. The sensors might happen to be placed in unusually dark or bright areas, giving misleading information about the model's daylight penetration. This situation is in contrast to computer model programs that allow illuminance or luminance maps to be generated, showing the light levels of a whole scene. Additionally, outdoor heliodon tests with the sky are limited to the types of skies available in the testing location. With computer software, accurate sky data from any location can be used to generate images or measurement maps.

Another interesting comparison of physical and computer model studies found that physical models caused difficulties when studies at many scales were required. The experiment involved evaluating the daylight penetration of individual apartments in an enormous collection of high rise buildings using both a heliodon with a sun simulator as well as Ecotect with Radiance (Jones et al., 2004). A large collection of buildings needed to be modeled in order to accurately portray the shading effects they had on one another. Even with a final physical model of two meters in diameter, the individual apartments inside the buildings were still too small to fully investigate. Photographs of shadows on the outsides of the buildings had to be used to guess the likelihood of illumination inside apartments, but no numerical quantification was possible. In contrast, the use of Ecotect and Radiance allowed both apartment interiors and larger exterior site illuminances to be studied and quantified with maps of parameters such as daylight factor.

However, the study also noted that heliodon and sun simulator tests have the benefit of quickly showing the presence of important shadows. Any major mistakes in the test are probably quite obvious even to non-experts. This is in contrast to computer software where a less experienced user could easily provide incorrect input that would seriously alter the results. Though physical model testing is in many ways not as versatile as computer simulation, its conceptual simplicity is certainly a strong point.

Heliodons are generally considered excellent teaching tools for use with architecture and design students because they are so visual and do not require the extensive skill often needed to operate computer simulation software. When experimenting with the outdoor heliodon, the author noticed that the experiments attracted considerable interest from passers-by, who asked various questions about the setup and meaning of the studies. One passing architectural educator commented that his students always showed particular enthusiasm when he demonstrated the principles of natural light using scale models and a heliodon. This was also observed by Mansy (2004) who observed that his architecture students showed by far the most attention and interest when learning with scale models. He considers computer programs unsuitable learning tools for beginners because of the strong background required to use them. In contrast, the construction of basic physical models does not necessitate a large amount of learning time, even though it can be quite time-consuming if complicated features are desired.

A heliodon setup can include a sky simulator, though this poses relative brightness problems as mentioned earlier, or a sun simulator by itself. There are a variety of possible setups and existing examples of heliodons. Heliodons for use outdoors can use the sun as the light source, having a surface that is tilted in relationship to the sun at the moment of testing. Indoor heliodons can have either a moving sun or moving platform setup, and be either manually operated or automated.

2.5.4 Existing Heliodon Setups

One of the most intuitive heliodon setups is the ring heliodon. This setup consists of a stationary table with a series of light sources suspended above it on rings representing the arcs of sunpaths. Each ring has multiple small electric lights attached, representing possible sun positions at different times of the day and year. Since the support table remains stationary, the model does not need to be clamped down or design to withstand sharp tilts as would be on a moving platform heliodon. This also makes it quite intuitive as a learning tool since the earth remains stationary relative to the sun, mimicking the human experience on earth. The visibility of light sources for different times of the day and year helps to understand the 3D geometry of sunpaths, similar to the tool available in Ecotect's interface. The setup is also relatively compact. Examples of this setup exist at Ball State University's Lighting Laboratory (CERES, 2005), Hong Kong University (Cheung et al., 2000), which uses different colors of lamps to represent different seasons.

However, there are some disadvantages to the ring heliodon setup. The light sources are positioned relatively close to the table, meaning that there is a large different in

illuminance between the center of the table and the edges. This means that shadows caused by the lights are most accurate in the direct path of the light beam but become distorted near the edges, limiting the accuracy of the device. Additionally, the fixed positions of the lights on the rings make it difficult for a single ring heliodon setup to show every possible sun angle on earth. The Hong Kong University heliodon, for example, is designed only to show sun angles possible in Hong Kong. Photography with these setups is limited to the use of handheld cameras and is not automated; additionally, a smooth representation of a day passing is difficult as days are divided into discrete representative solar angles.

At the Welsh school of Architecture, a heliodon setup with a moving sun that includes the sky is available (WSA 2007). Instead of individual suns such as in the ring heliodon setup, the light source is a large, heavy theater spotlight that moves across a skydome to change altitude while a model support platform beneath is rotated to change azimuth. A solar position accuracy within less than half a degree is claimed, and the passing of a day can be simulated in under three minutes. Movements are controlled through a Visual Basic interface. This setup that includes both the sky and sun is unlikely to be accurate for illuminance measurements because of the problems of combination sky and sun simulators discussed earlier. No camera control interface is included, however, so photographs must be taken manually.

Fixed sun, moving earth configurations of various types also exist. The automated heliodon at EPFL is another important precedent to this work. It consists of a fixed sun simulator and a moving table (Rhyner et al., 1991). The control interface for the table is meant to be user-friendly to architects, and so is simple and graphic. Video cameras, endoscopes, and photometers are available for use, but the computer interface does not allow for their manipulation.

Another fixed-sun, moving earth platform heliodon exists at the Belgium Building Research Institute (CSTC, 2007), mentioned earlier. This heliodon is used primarily to perform simulations using both sun and sky with a scanning sky simulator. Measurements are taken separately from the sun and sky components, and then scaled appropriately to find the overall light levels at different points in a building model. However, as mentioned earlier, image capture is not the primary use of the device as with the patch setup multiple images would have to be combined to get photographs representing the lighting throughout a scene.

A simple and compact version of the fixed sun, moving earth configuration is currently being marketed. Consisting of a computer-driven moving table, it can be used under an artificial sun. Equipped with a camera, image acquisition is in fact part of the user interface, allowing automatic photo and video capture complete with descriptive annotations. The table movement is smooth and accurate; accuracy in representing time differences as small as 3-4 seconds is claimed (Boosinger, 2006). This device and software package intended for mass market is an interesting alternative to the university and other research heliodons that have been developed over time for specific needs and might not be easily reproducible for other labs. A quite similar and compact setup exists

at the Rensselaer Polytechnic Institute, consisting of an automated moving table positioned under a stationary light source, whose control interface includes image capture capabilities (Van Den Wymelenberg et al., 2005). In this setup, a spotlight across the room reflects on a mirror which then directs light towards the heliodon. Though their compactness is an advantage, these are small setups that cannot accommodate models larger than about two feet wide.

2.5   Interfaces for Sunlight Analysis

One of the most important capabilities of the automated heliodon being developed at MIT is its image acquisition and viewing options. Image acquisition during studies with scale models is important for documentation and comparison of different options and strategies during experimentation with scale models. These images are important not just for the researcher's own analysis but also as presentation material when one wishes to demonstrate the advantages or key issues of a particular design. In addition to having this capability, users should be aided in their choices of images to acquire by being provided with options to capture and view large groups of images useful for observing effects over time instead of just at individual moments.

Other existing automated heliodons are controlled by computer interfaces, but not all of them include image capture capability, requiring the user to take images by hand or with a different photo capturing setup. To the author's best knowledge, those that do include integrated image capture only allow the capturing of videos on specific days or individual moments during chosen days, without providing a way to automatically take large sets of images at once.   One example of such an interface, shown in Figure 2.2, is used with the automated heliodon at RPI, mentioned earlier (Van Den Wymelenberg et al., 2005). The control interface for Boosinger's heliodon (Figure 2.1) is similar (Boosinger, 2006).
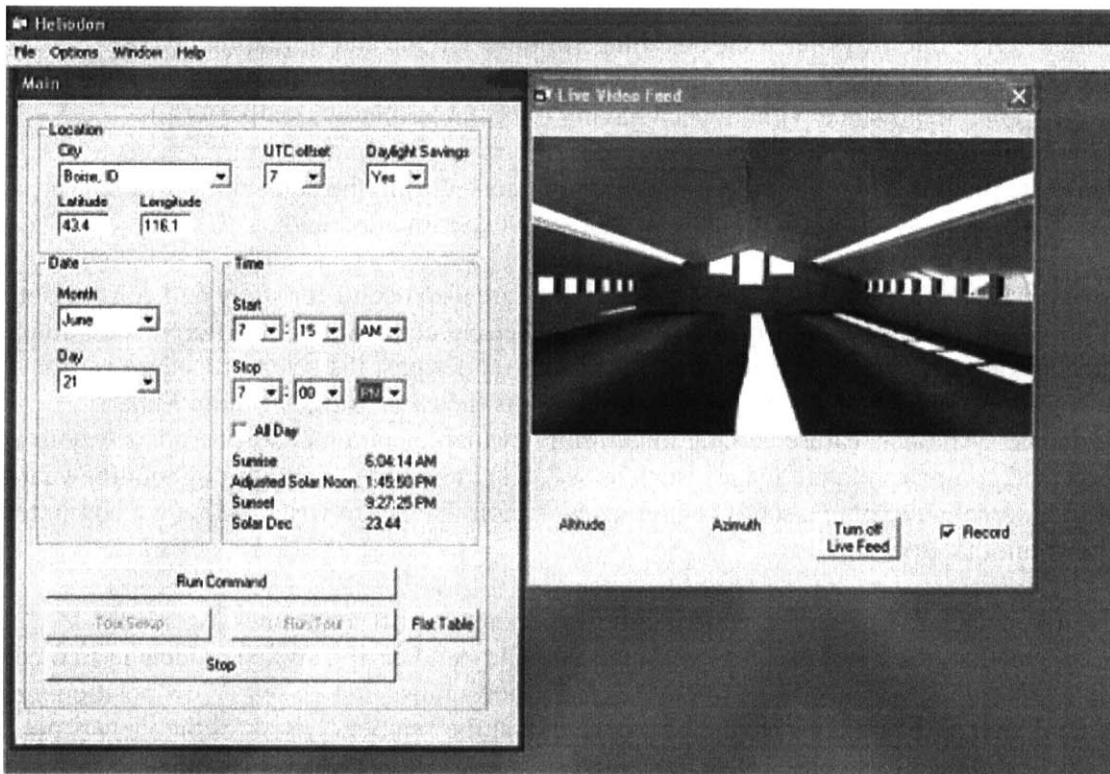
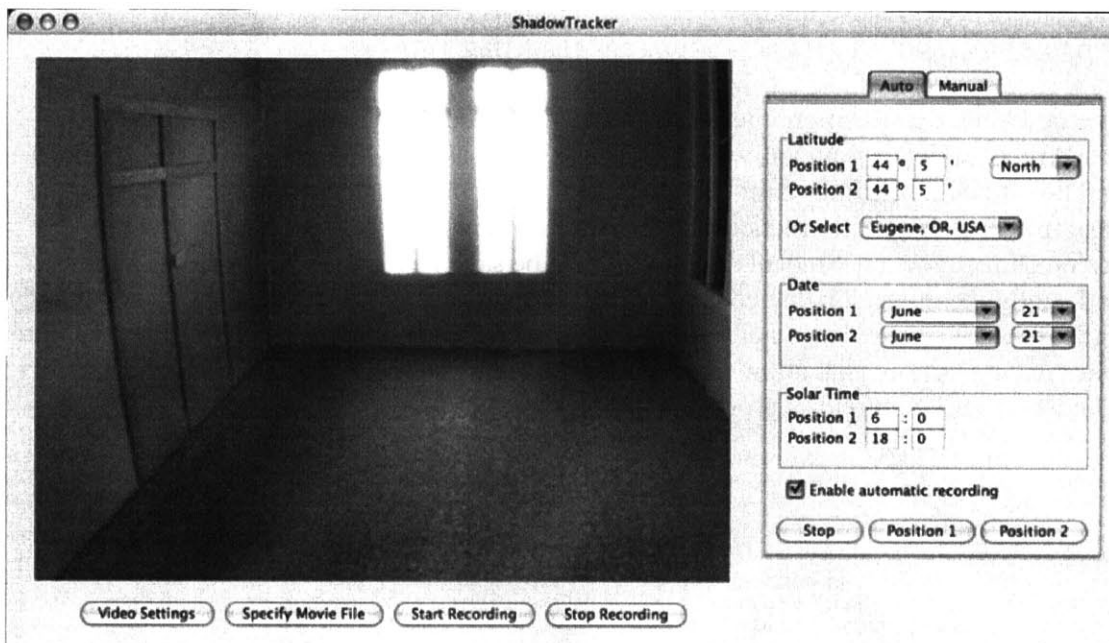Figure 2.2: The automated heliodon control interface at RPI (Van Den Wymelenberg et al., 2005).

Figure 2.1: The "JD Shadow Tracker" heliodon image acquisition interface (Boosinger, 2006).

31

Both of these interfaces have the advantage of quite simple and utilitarian layout. However, they do not provide options for the capture of multiple images that can be pre-programmed in advance without each having to be entered individually. While individual images can be interesting, large numbers of images are required to get a complete picture of a building's sunlight interactions during the course of a whole year, especially if many different model variations are experimented with.

Image acquisition systems of software packages are also useful for study and comparison. While many rendering tools offer the option of setting up a variety of different situations such as views or different times of day for batch renderings, the setup procedure is often difficult or requires programming skills, such as is the case with 3D Studio Max or Radiance. Another feature lacking in currently available computer software is a way to view and compare related images, such as several at one time of day throughout the year, or to automatically plan a set of such images without having to write one's own computer algorithm that does this.

Even in packages known for user-friendliness, there are still sometimes logistical problems that make it difficult to get images quickly and easily. When models in Ecotect are exported to Radiance, for example, camera views must first be set. View positioning in computer software does have the advantage that the "camera" used for the view is not a physical object that could cause unwanted shadows. Camera views can also be positioned in places that might be extremely difficult to reach with a camera in a scale model. However, getting the desired camera view in software can actually be quite difficult since the position and the angle must be manipulated in 3D. The results of what the camera sees are also unknown until rendering is complete. This necessitates an iterative process of camera positioning and rendering.

The new image acquisition interface for the automated heliodon at MIT is developed based on experience with software packages as well as knowledge of existing heliodons and how their capabilities could be expanded. The control interface is meant to be quite easy to use to drastically reduce learning time and encourage frequent operation by architecture students. Students' time will also be saved by providing an image capture and sunlight exploration device that can be used with scale models they may have already built for studio classes or other projects. In addition, the interface includes image capture and viewing options that allow examination of useful sets of images, helping the user get a better overall picture of a proposed building's interactions with sunlight.

3 Portable Heliodon Setup

3.1 General Description

The manually operated heliodon is a portable device meant for outdoor experiments utilizing the real sky and sun. Designed to fit inside a rolling suitcase, its wooden components are assembled once the study location is reached. The suitcase includes a manual with detailed instructions for assembly and use; the entire manual can be found in Appendix B (Koch, 2006). Once assembled, the heliodon table surface has the ability to tilt and rotate to any angle and orientation. There are three degrees of freedom for the device: rotation of the base, rotation of the tabletop, and tilting of the tabletop. C-clamps are used to fix a scale model to the table. The entire table setup takes under 10 minutes for a first time user.

The operation procedure of this heliodon is dependent on the sky condition at the time of the experiment. It can be used in either sunny or overcast conditions. Under sunny conditions, a sun-peg diagram is used to find the desired simulation time. After securing the model on the heliodon, the user first selects the diagram with the appropriate latitude for study. The diagram is placed over the small platform designed for this purpose, so that the peg fits through the small hole in the diagram. While watching the peg's shadow on the diagram, the user rotates and tilts the heliodon until the shadow's tip touches the marking of the date and time to be simulated. At this point the user can then take illuminance measurements or photos as desired.
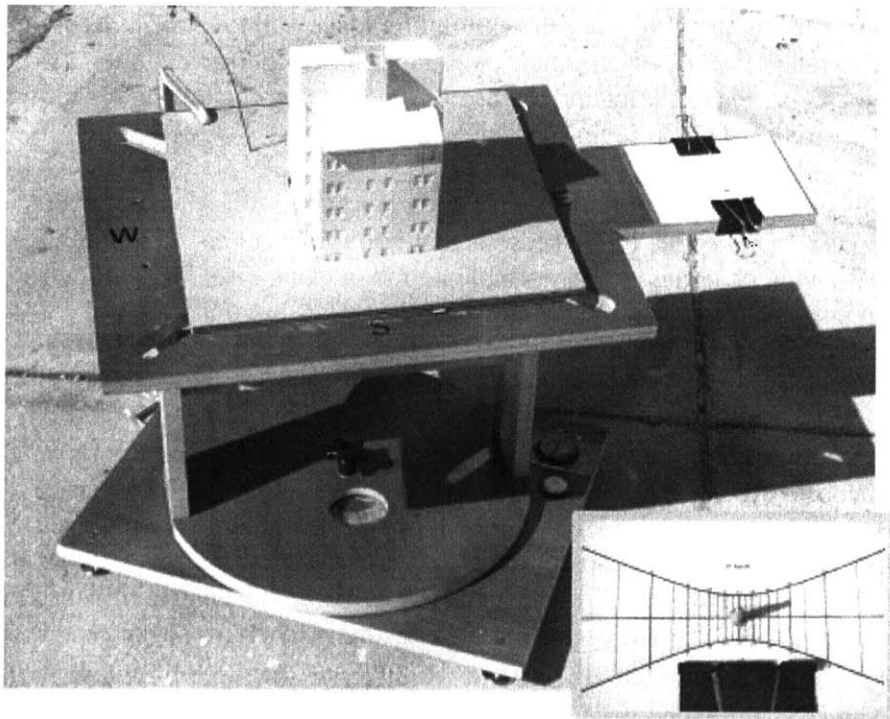

Figure 3.1: The portable heliodon in sunny operation, showing the use of the sun peg to achieve a desired simulation date and time. Photo courtesy of Marilyne Andersen.

On overcast days without shadows, a set of stereographic charts for different latitudes can be used to look up the altitude and azimuth of both the "current" testing conditions and the desired conditions. These four angles are then used to calculate how much the table should be moved by following angle markings on the axes of rotation without the aid of shadows (Koch, 2006). After positioning the heliodon so that the compass attached to the base points north, the base of the table is rotated to the "current" azimuth. The top of the table is then rotated to the "desired" azimuth. Next, the "current" altitude is subtracted from 90 and added to the "desired" altitude. This angle is used to tilt the top of the table. Exact instructions for this calculation with diagrams and example calculations are found in the manual in Appendix B.

After the table has been moved to the desired location, it can be secured in place using the knobs that tighten to reduce each degree of freedom. If photographs are desired, a camera may be held in place with a tripod or the articulated arm also described in the manual. The process of moving the heliodon to various configurations, tightening it in place, and taking photographs may require an assistant.

3.2   Radiance Validation of Outdoor Heliodon Testing Method

Though the manual heliodon can theoretically simulate the sky conditions of any other place and time from any daylight hour at the testing site (Figure 3.2), there are some combinations of testing and theoretical times and locations that clearly give more accurate results than others. Ideally, the simulation place and time, or at least the corresponding solar altitude, should be close to that of the theoretical one. Additionally, the relative percentages of direct and diffuse illuminance on the testing location should also be similar to those possible in the desired location.

Sky conditions vary considerably throughout the world and of course at different times of the day and year. This is one of the reasons that both physical and computer sky simulation is such a challenge. The portable heliodon can be used to simulate solar angles of other places on earth and times of day and year, but this does not account for the fact that the difference in sky conditions between the desired and actual testing locations may be quite drastic. Many factors cause differences between skies. The color of the sky affects the quality of light at a particular time and place. The amount of low-wavelength light scattered by the earth's atmosphere increases as the light's path through the atmosphere lengthens, which is known as Rayleigh scattering. This causes the sky to appear blue while the sun is directly overhead, but in the evening and morning when the light's path lengthens due to its position tangential to the observer, even more wavelengths are scattered leaving only the characteristic reddish hues of sunrise and sunset. Pollution gases present in the air cause the atmosphere to absorb and radiate light in different ways. In addition, particles of water and dust due to pollution or even volcano emissions can strongly affect the way light is scattered.

34

Though an outdoor heliodon user has the option of testing the heliodon at different times of day, the fact that outdoor heliodon testing requires use of the available sky in the testing location is a limitation of the practice. If the sky conditions in the desired location are extremely different from those available in the testing location, such as always overcast and polluted versus always sunny and clear, high inaccuracies from this factor will result.

Another cause of inaccuracy in these outdoor simulations is the sky vault visibility. If the heliodon needs to be tilted at a very steep angle, only a portion of the model's theoretical sky dome is comprised of real sky vault. At a 90 degree tilt the rest of the view will consist of the ground or neighboring obstacles such as buildings as shown below in Figure 3.2. The obstacles present in the simulated sky vault, such as buildings, concrete, or grass, also have their own optical properties which are unlikely to be similar to that of sky. The sky from the horizon will also have different brightness and color than sky that would really be overhead. Of course, the most ideal outdoor scale model testing location is the one in which the proposed building would be constructed. The model could be tested at varying times of the day and in different weather conditions, without worrying about inaccuracies from tilting or from extremely different atmospheric conditions.

In order to quantitatively determine the resulting error from these tilted simulations of other solar conditions, replications of these outdoor experiments were run using Radiance software, as explained in the following sections.
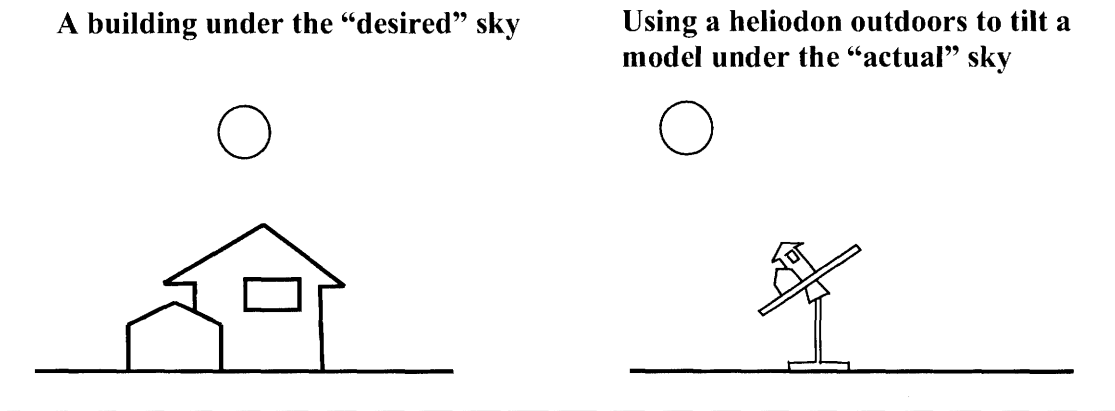
A building under the "desired" sky   **Using a heliodon outdoors to tilt a model under the "actual" sky**

Figure 3.2: Two-dimensional simplification of outdoor heliodon operation. A lower-altitude sun is used to mimic the sun at noon.

3.2.1 Methodology

In these tests, illuminance measurements were taken with illuminance sensors pointing straight up under a simulated sky of a desired time and location, and then compared to the measurements taken with sensors appropriately oriented to mimic this same desired time and location under the sky conditions of the testing location.

Three variations of the simulation were conducted. The first and simplest case compares the illuminance measured by a single sensor pointing straight up under a "desired" sky, and that of a sensor appropriately tilted under an "actual" sky, calculating the error in illuminance for a variety of different cases. Next, similar tests were run inside a model of Killian Court, attempting to match the conditions that MIT students using the heliodon could experience, and other cases of surrounding obstructions were explored. Finally, AutoCAD, Ecotect, and Radiance were used jointly to build and tilt a whole building model on a platform. Generated false-color images show the difference between an upright model under a "desired" sky, and a tilted model under an "actual" sky.

The CIE standard sunny sky model was used in most of these tests, in addition to some experiments with the CIE intermediate and overcast skies. Figure 3.3 shows a sample luminance distribution for each of these skies. This model was selected for its simplicity and the relative ease with which a sky can be defined. In the CIE model, the luminance of a particular point in the sky is determined by its relative distance from the sun and its altitude (CIE, 2003). Creation of a CIE sky for use with Radiance only requires knowledge of the desired solar time, date, and latitude. Additionally, this is the sky model used by Ecotect, which was used for the more complex full-model simulations.
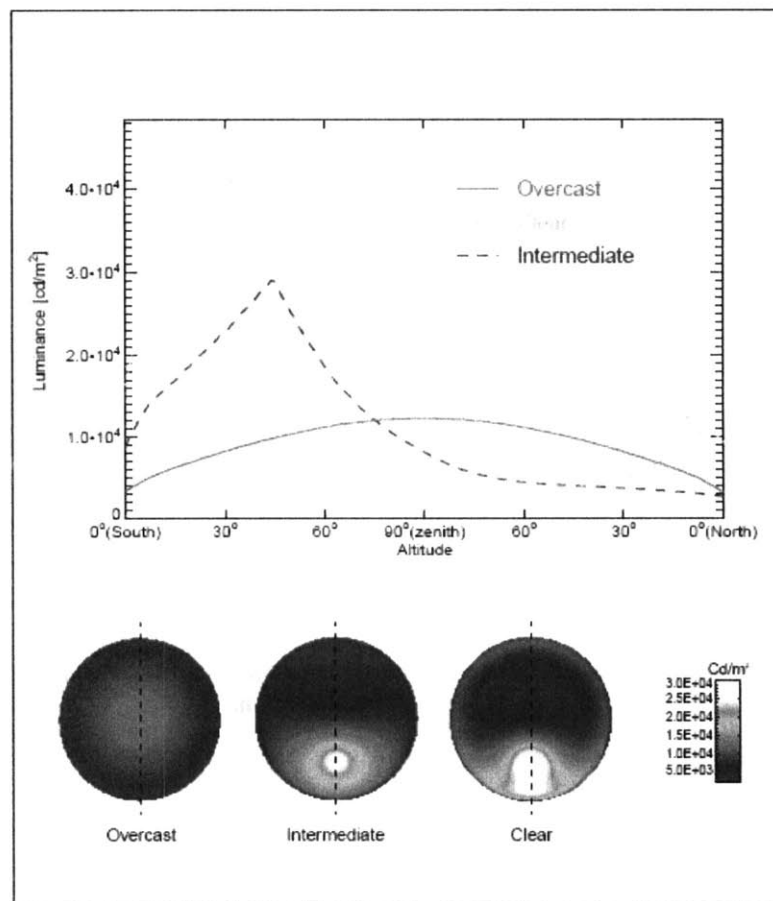

Figure 3.3: Luminance profile and maps for the CIE overcast, intermediate, and clear skies; the sun is not included in the models (Mardaljevic, 1999).

36

While the Perez model (Perez, 1993) is known to be of higher accuracy than the CIE for modeling specific and variable real skies (Vartiainen, 2001) the CIE models are still appropriate for this study as their purpose is to represent simple idealized cases. The Perez clear sky model can in fact reduce to the CIE model for the simple case of a very bright, clear sunny sky (Reinhart, 2006). When realistic hourly sky conditions are required for modeling calculations of parameters such as daylight autonomy, however, the Perez model is needed for simulations.

Radiance was the software of choice for doing these simulations, due to its high accuracy and adaptability to a variety of simulation types.

In this section, the term "desired" is used to refer to the conditions one wishes to simulate; for example, a time and place on earth different from the site of the experiment. "Actual" is used to refer to the conditions where the heliodon experiment is being performed.

Although the first method of using a single sensor lacks the complications of creating a computer model of a whole building with sensors inside, the required positioning differs from that of a whole model. A building model, unless perfectly radially symmetric, has an orientation with respect to cardinal directions, which is quite important in regards to the positions of windows and other features. A point sensor, however, has no orientation. A bare sensor pointing straight up will receive the same illuminance whether the sun is at 45 degrees altitude in the east or 45 degrees altitude in the west, though these conditions would produce quite different results for a sensor inside a scale model with an east-facing window, for example. This difference is illustrated in Figure 3.4. This lack of sensor orientation means that there are in fact infinitely many ways to expose a bare sensor to a certain solar altitude which would all result in the same measurement and helped determine the necessary procedure for analysis to take this into account.
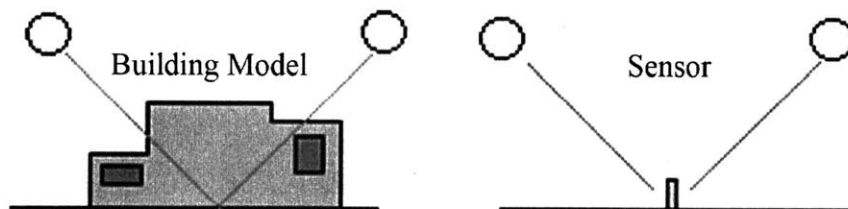

Figure 3.4: The sun azimuth can affect a real building significantly, while a bare luxmeter will read the same illuminance for any azimuth as long as the altitude remains the same.

In order to represent these conditions simply, the azimuth of the "desired" conditions is disregarded. The calculation of these coordinates is instead dependent on the position of the "actual" solar azimuth and altitude, and the difference between this altitude and the "desired" one.

The position of the sun or the particular facing direction of a sensor can be described using spherical coordinates. By subtracting a solar altitude (β) from 90 degrees, the altitude is translated into phi (ϕ), the angle from vertical. Theta (Θ), the angle about the z axis, is equivalent to azimuth as long as azimuth values are adjusted appropriately so that $\Theta = 0$ is in the east to comply with Radiance convention.

The sensor facing direction was calculated using two different methods. This is because a solar angle in relationship to an object can be achieved in two different ways in relationship to the ground. For example, if the "desired" sun altitude is lower than the "actual" one (Figure 3.5), the model can be tilted away from the model towards the rest of the sky to increase the angle between the sensor facing direction and the sun. This same angle can also be achieved by flipping the model around 180 azimuthal degrees tilting the model further towards the ground. Students who perform outdoor tilting simulations have been observed to achieve the correct solar angle by tilting a model further towards the ground than the sky, sometimes to the point of tilting a model upside down, as illustrated in the example in Figure 3.6.

Equations 3.1 and 3.2 below show these two different methods derived for calculating phi (ϕ) for the sensor facing direction. Method 1 is the choice to point the model further towards the ground than the sky, while method 2 points the model towards the larger area of the sky vault.

$$\phi_{sensor} = (90 - \beta_{desired}) + (90 - \beta_{actual}) \quad\quad\quad\quad\text{(Equation 3.1)}$$

$$\phi_{sensor} = |(90 - \beta_{desired}) - (90 - \beta_{actual})| \quad\quad \beta_{desired} > \beta_{actual} \quad\quad \text{(Equation 3.2)}$$
$$\phi_{sensor} = |(90 - \beta_{desired}) - (90 - \beta_{actual})| + 180 \quad\quad \beta_{desired} < \beta_{actual}$$
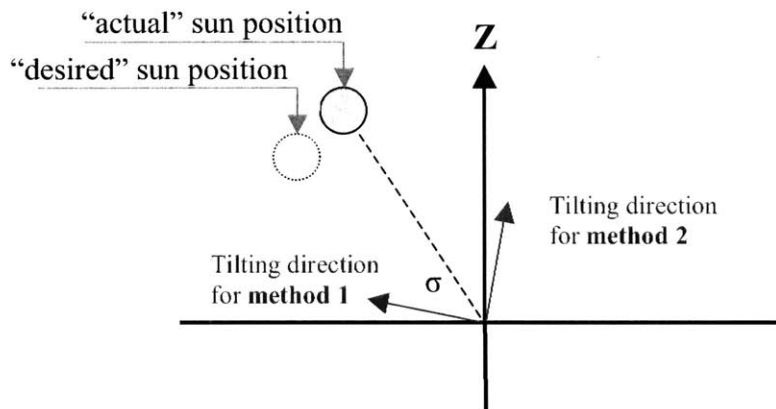

Figure 3.5: Diagram showing methods 1 and 2 for a sample simulation with a bare sensor
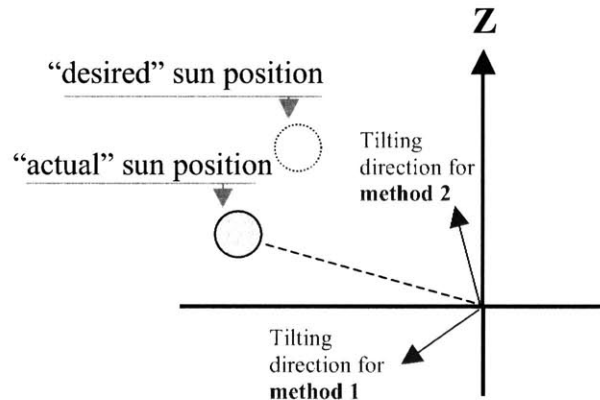
Figure 3.6: Diagram showing methods 1 and 2 for a case in which method 1 requires tilting upside-down
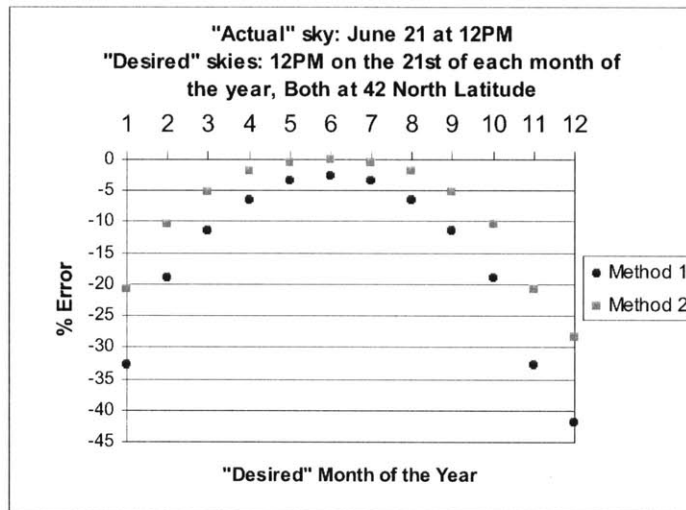
In these methods, the theta (Θ) used is the azimuth of the "actual" sun position. After obtaining the appropriate values of ϕ and Θ, these are translated into Cartesian coordinates as required for sensor file input. The basic method of running the tests was to set up files of the sky and the ground, and compile them in such a way that a sensor placed at a specified location is used to output an illuminance measurement at that point. The error in illuminance, calculated by subtracting the "actual" illuminance from the "desired" illuminance and dividing the result by the "desired" illuminance, is used to determine how closely the tilted simulation matched the conditions of the "desired" time and place. The Radiance commands required to run these tests as well as sample sky and sensor files can be found in Appendix A.

% error = [("desired" illum – "actual" illum)/ ("desired" illum)]* 100   (Equation 3.3)
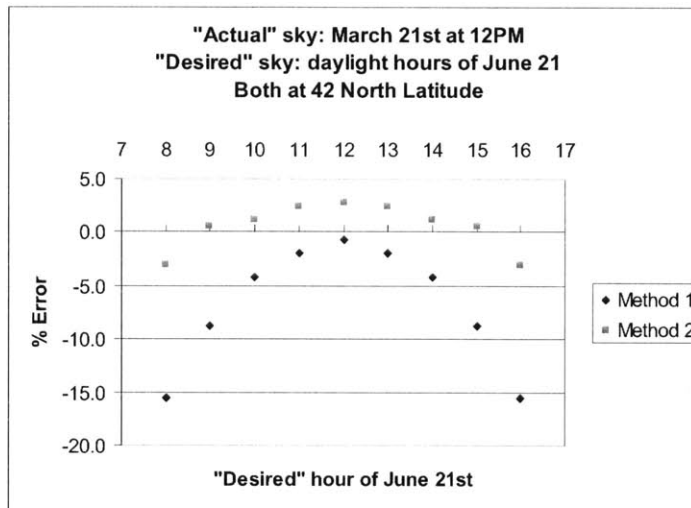
According to this method, a positive error means that the heliodon simulation of a foreign date and time would underestimate illuminance, where a negative error means that it would overestimate illuminance.
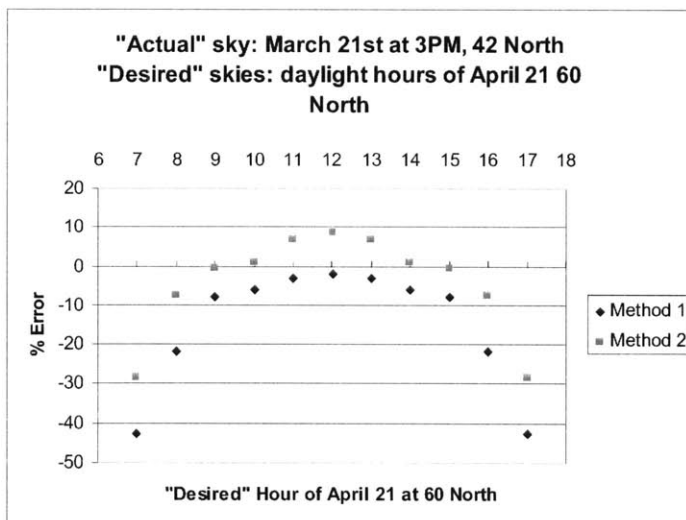
3.2.2   Tilting Error Results

Below are graphic results of these tests for several different scenarios (Figure 3.7 a-c). Their assessment leads to conclusions about when these tests are appropriate, and when they will result in an error that is too high.

"Actual" sky: June 21 at 12PM
"Desired" skies: 12PM on the 21st of each month of the year, Both at 42 North Latitude

3.7a

"Actual" sky: March 21st at 12PM
"Desired" sky: daylight hours of June 21
Both at 42 North Latitude

3.7b

"Actual" sky: March 21st at 3PM, 42 North
"Desired" skies: daylight hours of April 21 60 North

3.7c

Figure 3.7 a-c: Illuminance error graphs from methods 1 and 2 for several scenarios

The three graphs above represent sample scenarios that a heliodon user might experience. Most likely the user will go outside at a given time of day, and be interested in daylight conditions in one particular location, perhaps at different times of the year, or perhaps at different hours of one particular day. The ground reflectance is 0.2, which was considered an approximation for an average dark ground from the graph in Figure 3.8.
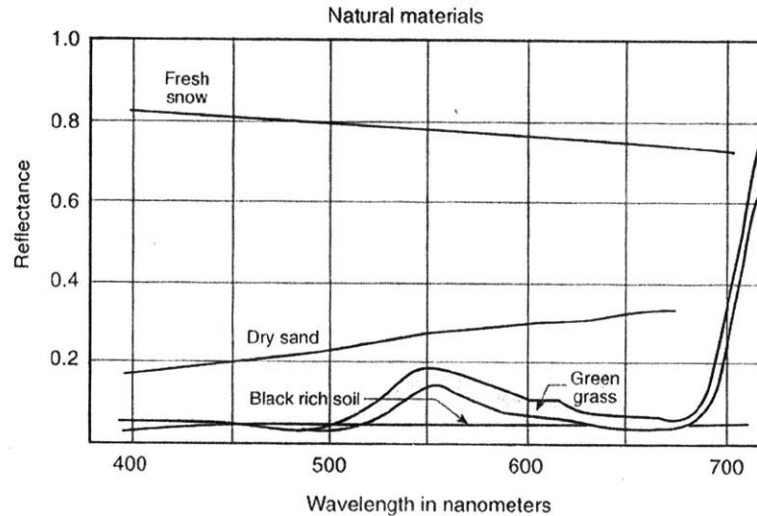

Figure 3.8: Material reflectances for natural ground substances (IESNA, 2000).

One interesting observation is that method 1, which involves pointing the sensor further towards the ground, gave consistently higher illuminance than method 2, even though it might be expected that a sensor which is exposed to more sky will always read a higher illuminance than one which is exposed to more ground. However, an explanation for this is evident when one examines graphic representations of the CIE sunny sky luminance distribution (Figure 3.3).

As shown, the half of the sky hemisphere that contains the sun in the clear model is nearly an order of magnitude brighter than the opposite side. Even the horizon on the same side of the sky hemisphere as the sun, around 1.5×10^4 Cd/m^2, is much brighter than the 3.0×10^3 Cd/m^2 in the middle of the opposite hemisphere. This explains why tilting the sensor into the opposite half of the sky gives a lower illuminance than pointing it further down on the same side that the sun is on when using this sky model. The overall error is lower for method 2, even though method 1 gives lower error in some cases. From a practical standpoint, method 2 can mean less model tilting, while method 1 would require a model to be actually upside down in some cases. Method 2 is also preferable from the point of view that a model will be illuminated bye more sky instead of ground reflections, giving more accurate colors and illuminance distribution for photos within the model.

As expected, examples involving testing locations other than Boston work similarly. Below is a graph showing the results one might obtain from simulating a day in Japan

from Singapore (Figure 3.9). The error results due to differences in altitude are consistent with previous tests.

"Actual" sky: February 21st at 11 AM, at 0 North
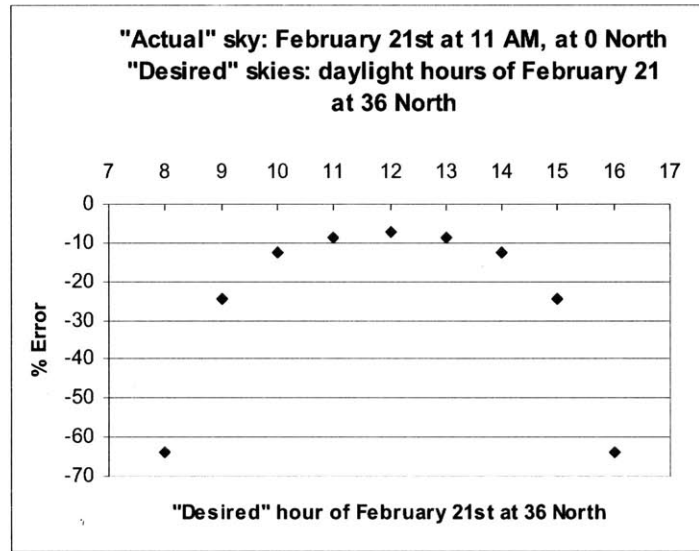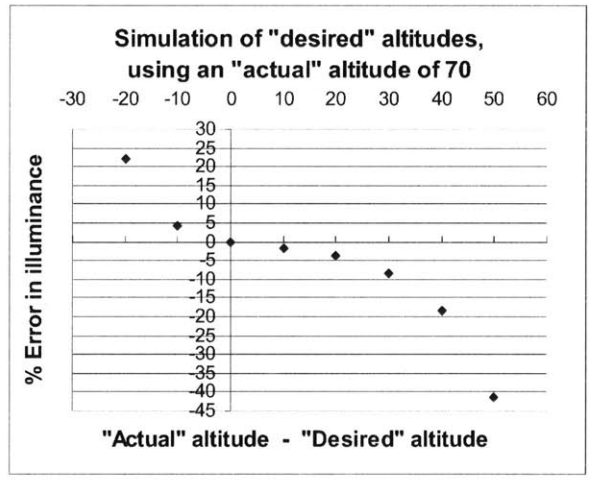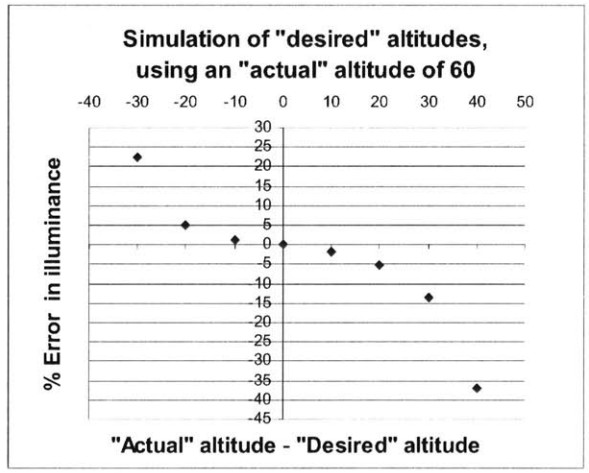**"Desired" skies: daylight hours of February 21 at 36 North**

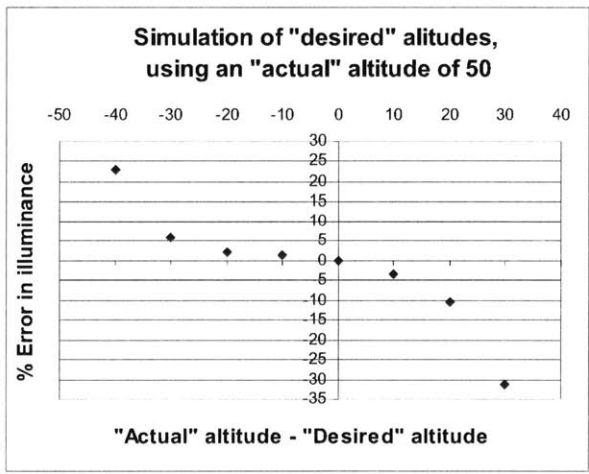**Figure 3.9: Method 2 Illuminance error graph for a foreign location.**

Since there are infinitely many combinations of testing location and desired conditions that one might have, the scenarios were next simplified to altitude differences between "desired" and "actual" locations for error analysis. Assuming the point of view of a heliodon user at MIT, Boston solar altitudes between 30 and 70 were examined as conditions for simulating other altitudes. In increments of 10, each Boston solar altitude between 30 and 70 was used to simulate altitudes between 10 and 90. Error is calculated as above, with the independent variable as the difference between the "actual" testing altitude and the "desired" altitude. A positive difference means than the "actual" testing altitude in Boston is higher than the "desired." In all of the experiments below (Figures 3.10 a-e), "method 2" was used to calculate the tilting direction. Of course, any of these graphs can be taken from the point of view of a heliodon user at any time and place where the solar altitude lies between 30 and 70.
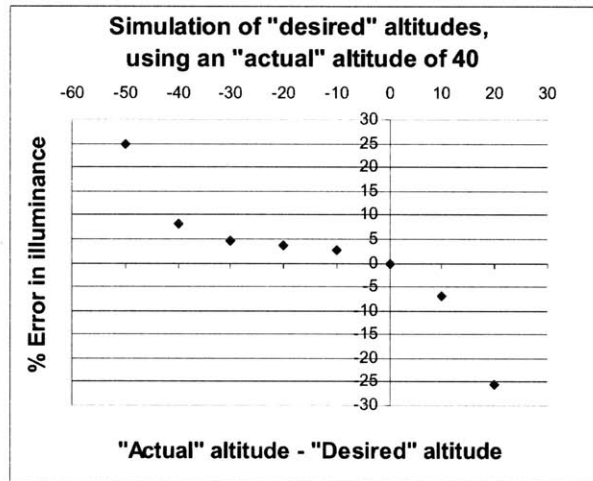
42

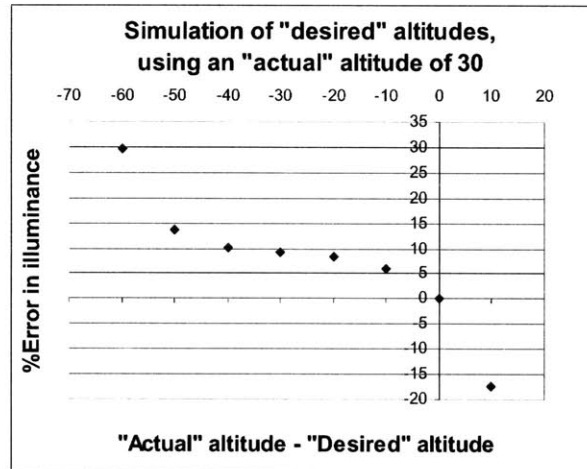**3.10a**

3.10b

3.10c

43

Simulation of "desired" altitudes, using an "actual" altitude of 40

"Actual" altitude - "Desired" altitude

3.10d

Simulation of "desired" altitudes, using an "actual" altitude of 30

**"Actual" altitude - "Desired" altitude**

3.10e

**Figure 3.10 a-e: Altitude-based categorization of errors for outdoor heliodon simulations.**

The figures above allow outdoor heliodon users to assess whether particular simulations they have in mind are likely to yield unreasonable amounts of error in illuminance measurements due to differences in altitude and tilting. As seen in the graphs above, there are many potential simulations that will yield tilting errors below 5 to 10 percent. The graphs suggest that using the more extreme testing altitudes (30 and 70) allows less altitude difference for the same amount of error. With some forethought and luck with weather, a heliodon user can look up these altitudes before testing in order to get an altitude match that minimizes error from tilting on a sunny day.

As a point of comparison, similar test sets were performed outdoors on a sunny, cloudless day, making use of the different altitudes available throughout the day. The procedure for the tests was to take vertical illuminance measurements outdoor from solar altitudes 10 to 50 throughout the day, in increments of 5. This data was used as the "actual" illuminance measurements for comparison as in the methods described above. Next, simulations of these different altitudes were performed by placing a luxmeter on the heliodon and tilting to simulate as many "desired" solar angles as possible. The resulting error graphs showed the same general pattern as the Radiance results (Figure

3.11a-b). Deviations may be due to surrounding obstructions (described in 3.2.3), the difference between the real sky and the simplified CIE clear sky model, and the fact that the procedure for getting outdoor measurements did not allow all measurements to be taken simultaneously as was required to get the measurements simulating other times of day during solar altitudes 30 and 50. During the course of the testing, illuminance on a vertical sensor was observed to change by up to 3-5% over the course of only 5 minutes, even though the sky remained completely clear.
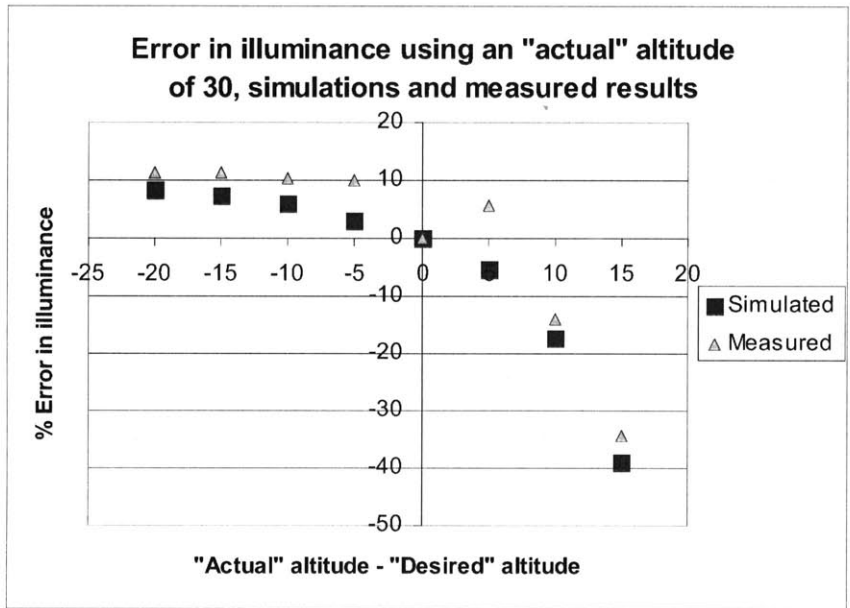
3.11a
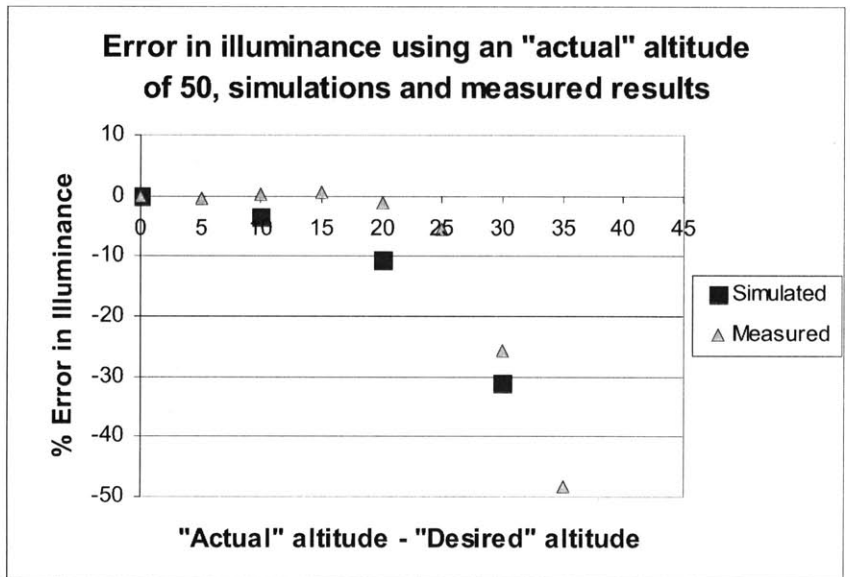
3.11b

Figure 3.11a-b: Comparison of errors from outdoor tilting (real outdoor measurements) to the Radiance simulations of the same procedure.

3.2.3 Surrounding obstructions

Another important issue to explore is the effect of surrounding obstructions on the illuminance of a sensor. While a model builder should be sure to include important shadow-causing contextual elements in the model, outdoor heliodon tests may subject the model to the life-size obstructions of the testing location. It is important to understand when these surroundings significantly affect the model's measured illuminance and when their effects are minimal. Radiance simulations similar to the ones described in previous sections were used to assess these effects.

Experiments were first performed in the context of a modeled Killian Court, a convenient location on the MIT campus which is in fact used by a class at MIT for this purpose, in order to determine whether being surrounded by buildings had a significant effect on illuminance received by the sensor. Figure 3.12 shows a Radiance rendering of the modeled court, with a small cube in the middle to represent the sensor location. The cube, whose left vertical surface faces due south, is used to show that the court itself faces 24.5 degrees east of south, according to MIT Facilities. The court is approximated by a 22 meter-high set of three buildings. In this model, the rear building, known as Building 10 on the MIT campus, is 110 meters wide on the inside of the court, while the adjacent buildings are each 150 meters long.
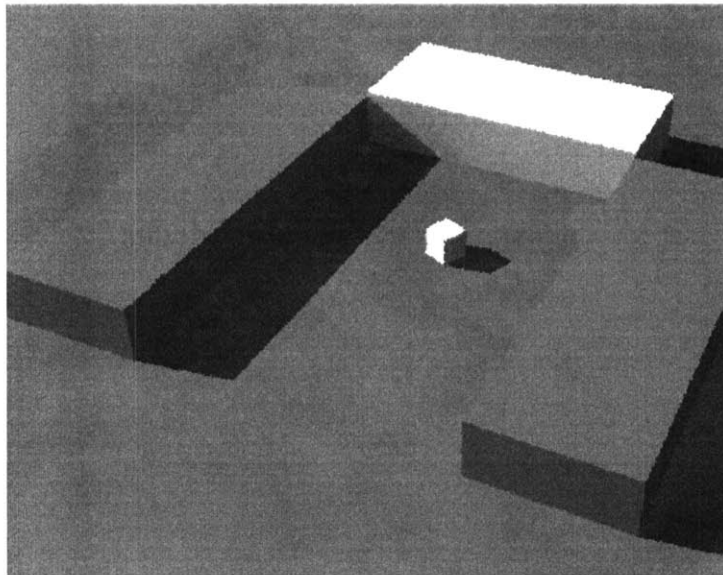

Figure 3.12: A simple Radiance-modeled rendering of Killian Court.

The results from the Killian Court simulations were interesting. In general, the presence of the Court did not alter illuminance error by more than one or two percent. However, whether the illuminance error was higher or lower than that of an unobstructed sensor depended on the reflectance of the buildings. A higher reflectance such as 0.5 for the walls of surrounding buildings caused the court to act as sort of a light box, increasing illuminance on the sensor. A lower reflectance such as 0.2 reduced this number.

46

However, these examples were for cases when the sun was still actually visible from the court and not completely blocked by one of the buildings.
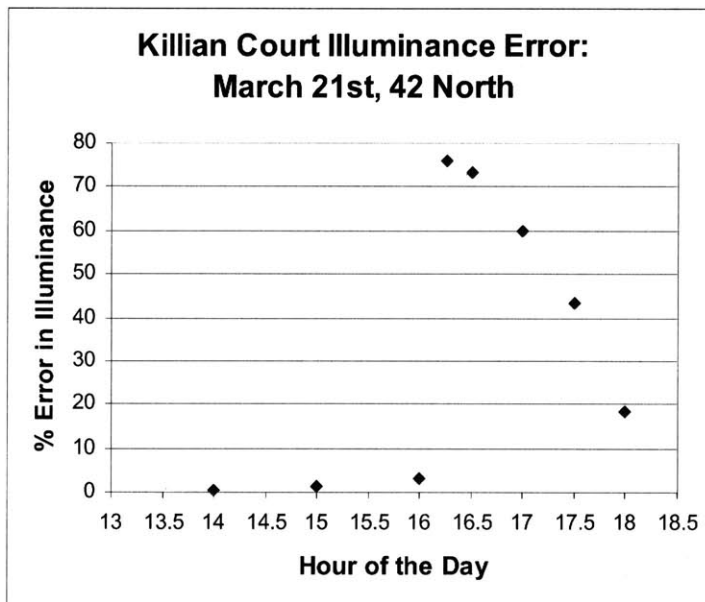

Figure 3.13: Killian Court illuminance error graph. When the sun drops behind the building at around 4:15, the blockage of direct light severely reduces sensor illuminance.

For a test case in which an unobstructed, vertically oriented sensor at 42 North on March 21 at various times was compared to a sensor under identical conditions plus the addition of Killian court, the illuminance on the sensor in the second case was reduced up to nearly 80% once the sun went behind the building. As solar altitude decreased, however, the error lessened. The illuminance error due to the presence of Killian court on this day is displayed in Figure 3.13 above. It was calculated using the following method (Equation 3.4):

$$\% \text{ error} = [(\text{illum}_{NoObstructions} - \text{illum}_{WithObstructions}) / (\text{illum}_{NoObstructions})] * 100$$

(Equation 3.4)

As can be seen from the graph, the sun drops behind the west building at around 4:15 PM, severely decreasing interior court illuminance and bringing error up to nearly 80%. However, during the time when direct sun is visible from the court, the error caused by the effect of the court remains quite low, under 5% as shown in Figure 3.13.

After this initial experiment with Killian Court, errors from surrounding obstructions were investigated and categorized in greater detail. Even though the Killian Court example did not reduce sensor illuminance significantly, it remained to be seen at what point taller surroundings or different arrangements of surroundings would make a difference.

To investigate the effects of surrounding walls that blocked the sky but not the sun, the court was reoriented pointing directly south (instead of 24.5 degrees east of south). Using a CIE clear sunny sky of March 21st at 12PM at 42 North, which corresponds to an altitude of 47.6, the heights of the three walls were gradually increased from 22 meters to 188 meters, calculating illuminance error as in Equation 3.4. The experiment was repeated for different values of wall reflectance for the buildings. In addition, the same tests were performed using the CIE intermediate sky and a CIE overcast sky on the same date and time. The reflectance values for surrounding buildings were varied between 0.2 and 0.5, which were estimated as reasonable values from the graph in Figure 3.14 (IESNA, 2000).
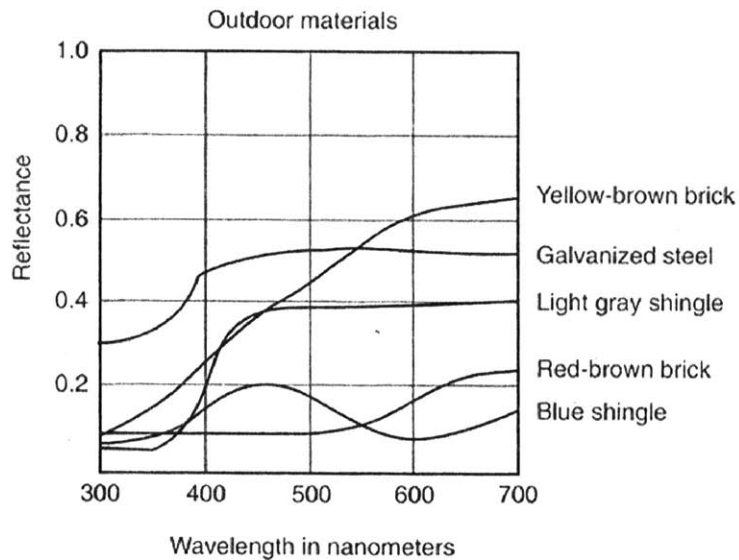
Figure 3.14: Reflectance values of some outdoor building materials (IESNA, 2000).

This height change from 22 meters to 188 meters means that the angle between the top of the wall and the sensor ranged from 19.3 to 72.2 degrees for the back wall and 20.9 to 73.6 degrees for the side walls, taking into account the distance from the sensor to the walls and the fact that the sensor is placed one meter above the ground in the simulations. The results are graphed in Figures 3.15, 3.16, and 3.17.

48

Figure 3.15: Illuminance error due to three surrounding walls of increasing height, clear sky; Lower reflectance values decrease illuminance within the walls while higher ones increase it.

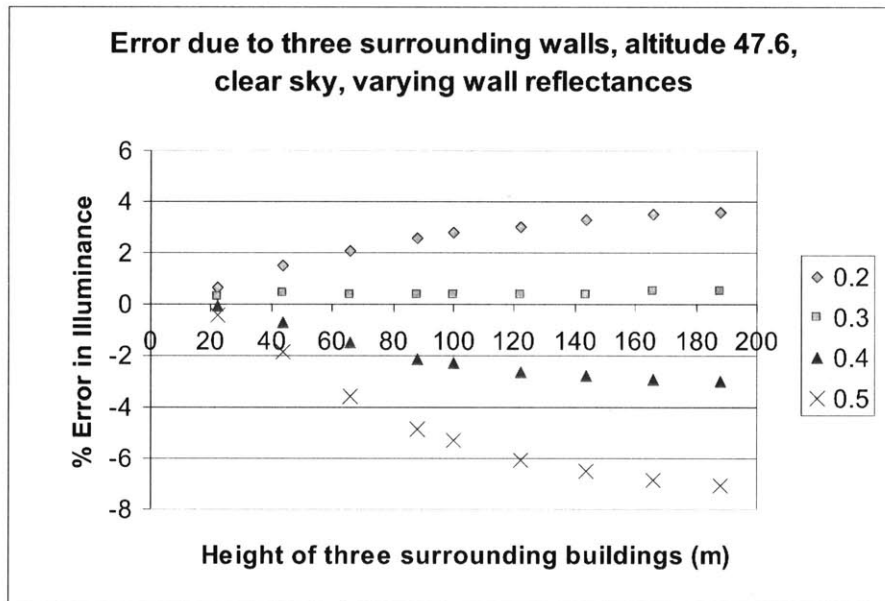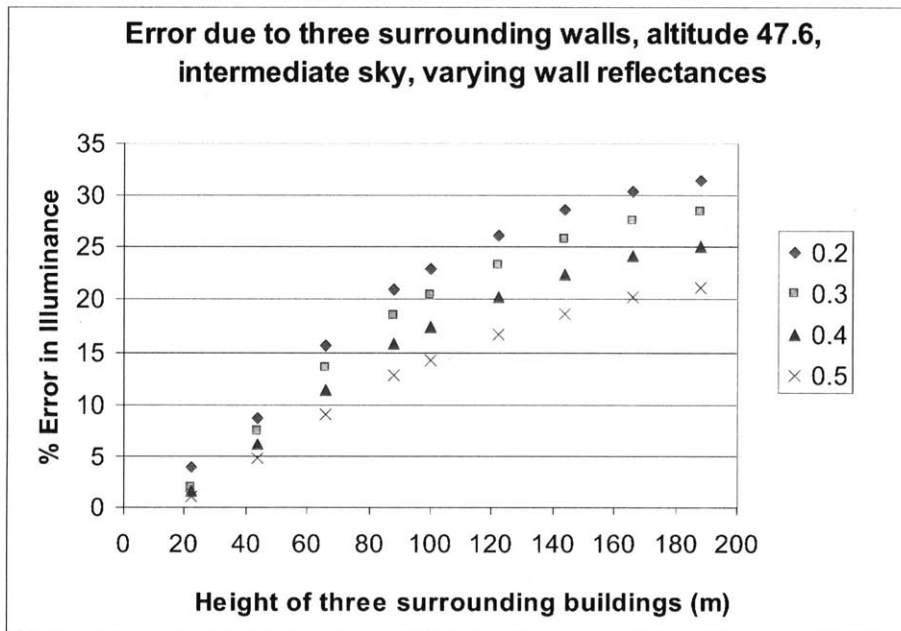**Figure 3.16:** Illuminance error due to three surrounding walls with increasing height, intermediate sky; all four reflectance values cause a decrease in illuminance.
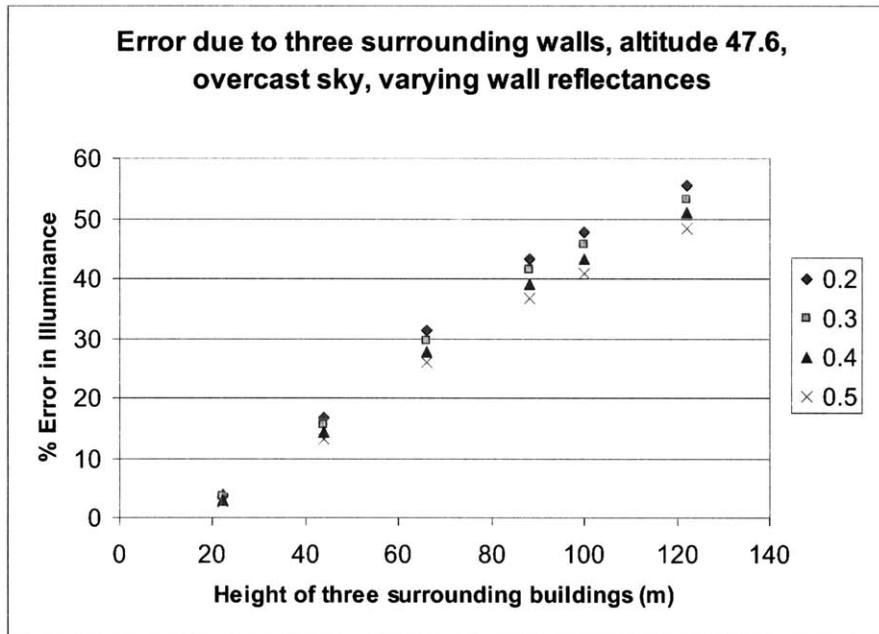
Figure 3.17: Illuminance error due to three surrounding walls with increasing height, CIE overcast sky; changing the reflectance makes less of a difference but the overall error is greater for the same height than for intermediate or sunny.

These graphs allow a comparison between the effects of the sky versus the sun on sunny, intermediate, and overcast days. For the intermediate day, the illuminance error reached over 30% for a wall height of 188 meters and a reflectance of 0.2, while this same scenario caused less than 4% error on the clear day. For the overcast sky, 30% error was reached with a building height of only 66 meters. Another interesting point of comparison is that with the intermediate and overcast skies, every wall reflectance tried caused the illuminance within the court to decrease (Figure 3.16, 3.17), while for the case of the clear sky, reflectances of 0.4 and 0.5 actually caused an increase (Figure 3.15). Interestingly, a building reflectance of 0.3 with the clear sky caused the illuminance error to remain relatively constant, between 0.3 and 0.5%, as the heights of the buildings were increased.

In addition, experiments were performed by placing a single wall between the sensor and the sun, blocking the brighter part of the sky for the CIE clear sky case. The single wall used was 110 meters wide and placed at a distance of 60 meters from the sensor location. The height of this wall was gradually increased while illuminance error due to the wall was recorded. Solar altitude angles of 30, 50 and 70 were tried. The wall reflectance was also varied between 0.2 and 0.6 for each of these solar altitudes while increasing the height of the wall. It was found that the reflectance of this wall placed between the sun and sensor made almost no difference for any wall height, changing the percent error by 1% at most as higher wall reflectances slightly increased sensor illuminance, with the effects highest for the highest wall.

As expected in the cases studied, the error increased greatly at the moment that the angle of the sensor in relationship to the wall increased above the solar altitude at the simulation time, as previously observed in Figure 3.13. Prior to this error jump caused by cutting off of the sensor from direct sunlight, the error increased to a maximum of about 3.5 % when the angle of the obstruction to the sensor is just under the solar altitude angle. Results are graphed in Figure 3.18. For each solar altitude a few data points are kept above the wall angle which is equal to that solar altitude, showing the error jump. It is observed that the jump is slightly higher for the higher altitude, reaching 89% for the solar altitude of 70 degrees.
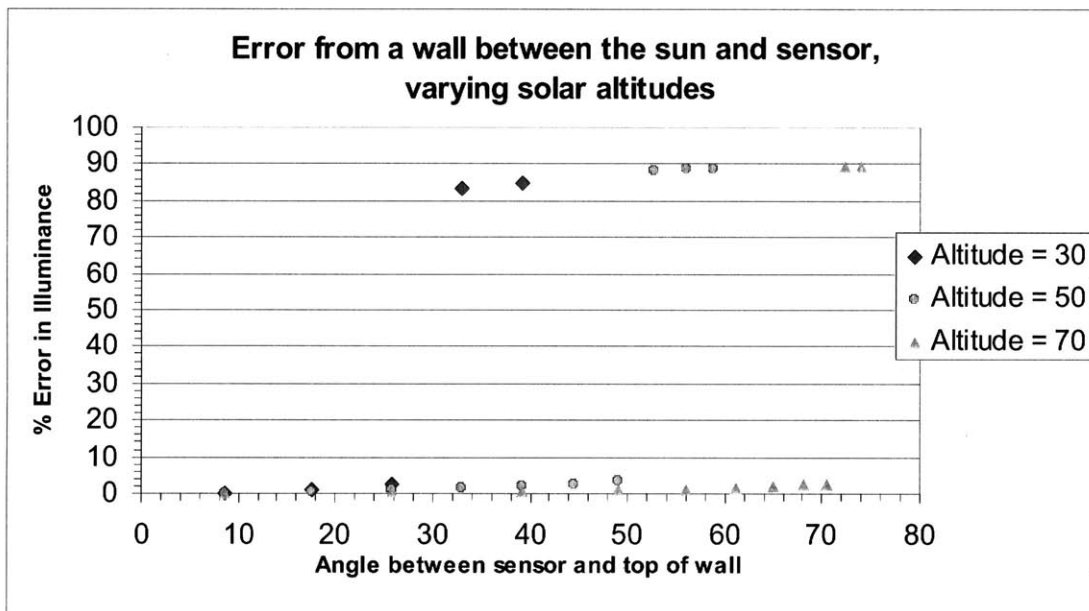
Figure 3.18: Illuminance error due to one wall between the sun and sensor for several different altitudes. The jump in each case occurs when the angle between the sensor and the top of the wall is equal to the solar altitude.

Another single wall experiment was performed in order to determine the effects of a wall on the other side of the sensor, opposite from the sun. This was equivalent to removing the two side walls from the experiments of Figure 3.15. In these cases, where direct sun hits the surface of the wall before bouncing off and hitting the sensor, the wall reflectance matters much more than it does with the case of the wall between the sun and sensor.

Error from one wall on the opposite side of the sensor as the sun, altitude 30

3.19a

Error from one wall on the opposite side of the sensor as the sun, altitude 50

3.19b

Error from one wall on the opposite side of the sensor as the sun, altitude 70
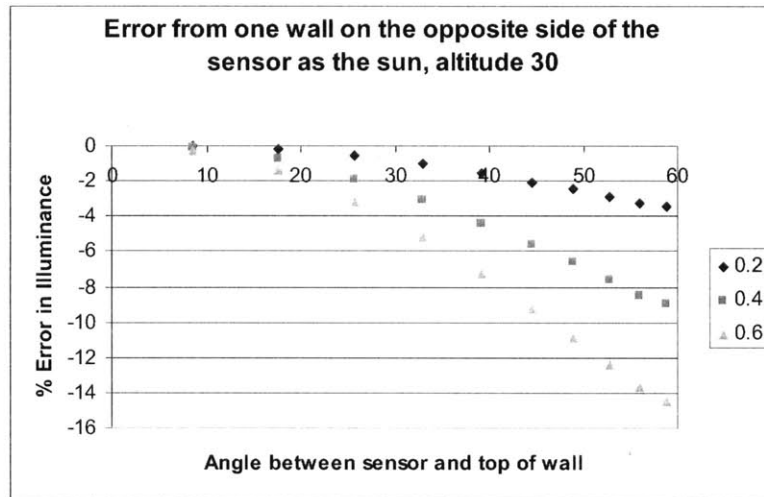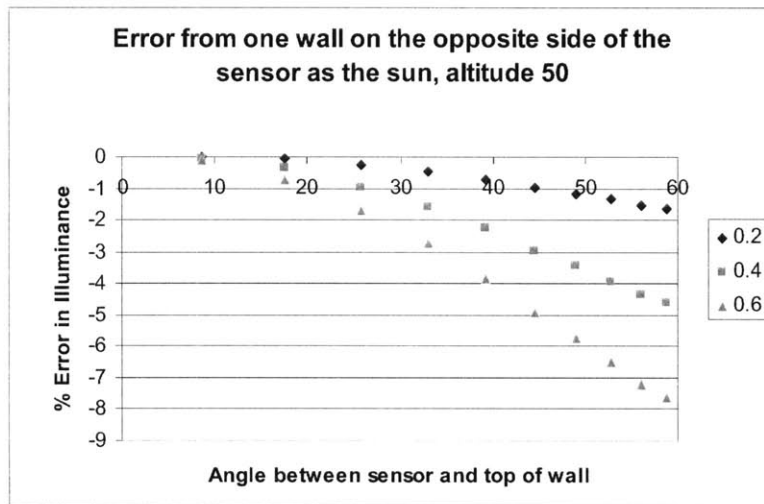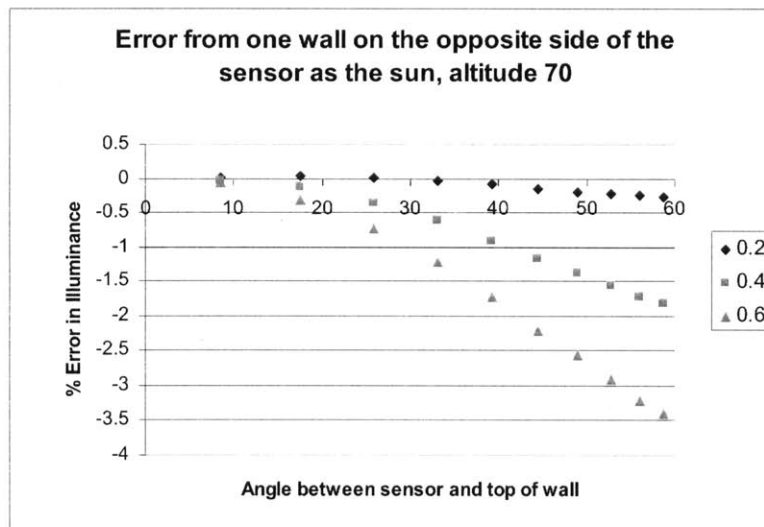
3.19c

Figures 3.19 a-c: Error caused by one wall on the opposite side of the sensor as the sun, arranged by testing altitude, for different wall reflectances, with the CIE clear sky.

In Figures 3.19 a-c that show the effects at each solar altitude, one observes that the presence of the wall behind the sensor always causes an overestimation of illuminance except for the lower angle cases with an altitude of 70 and a wall reflectance of 0.2 (Figure 3.19c). The overestimation of illuminance is greatest for the lowest solar altitude, with a maximum of about -15% for the wall of 0.6 reflectance at an angle of 60 degrees (Figure 3.19a). The same data can be compared by altitude for constant wall reflectances in Figures 3.20 a-c below.

3.20a

3.20b

Error from one wall on the opposite side of the sensor as the sun, wall reflectance 0.6
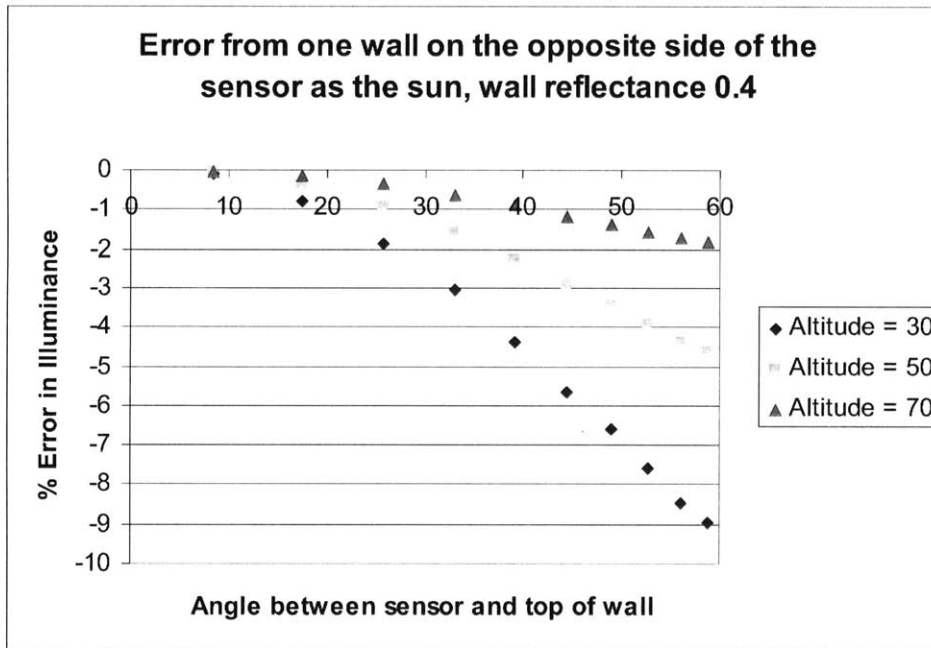
3.20c

Figures 3.20 a-c: Error caused by one wall on the opposite side of the sensor as the sun, arranged by wall reflectance, for different solar altitudes, with the CIE clear sky.
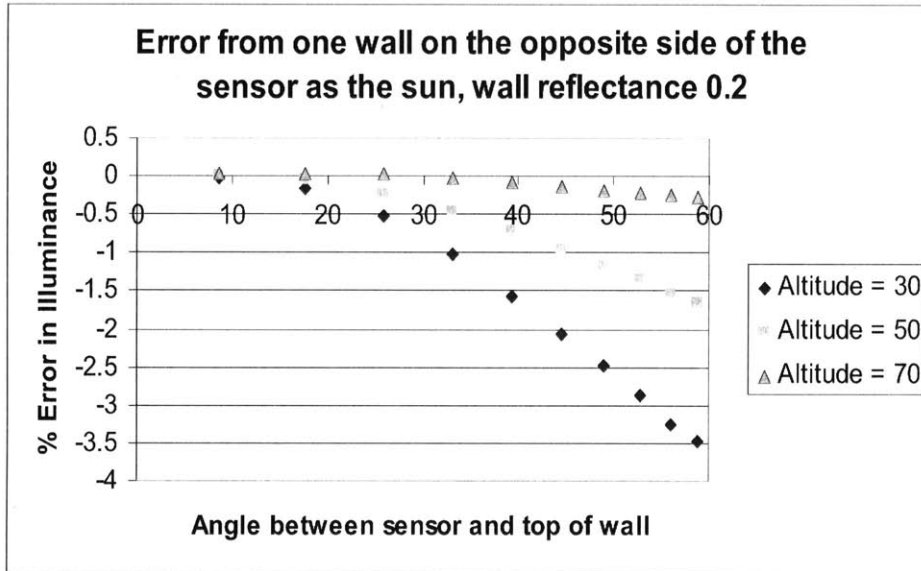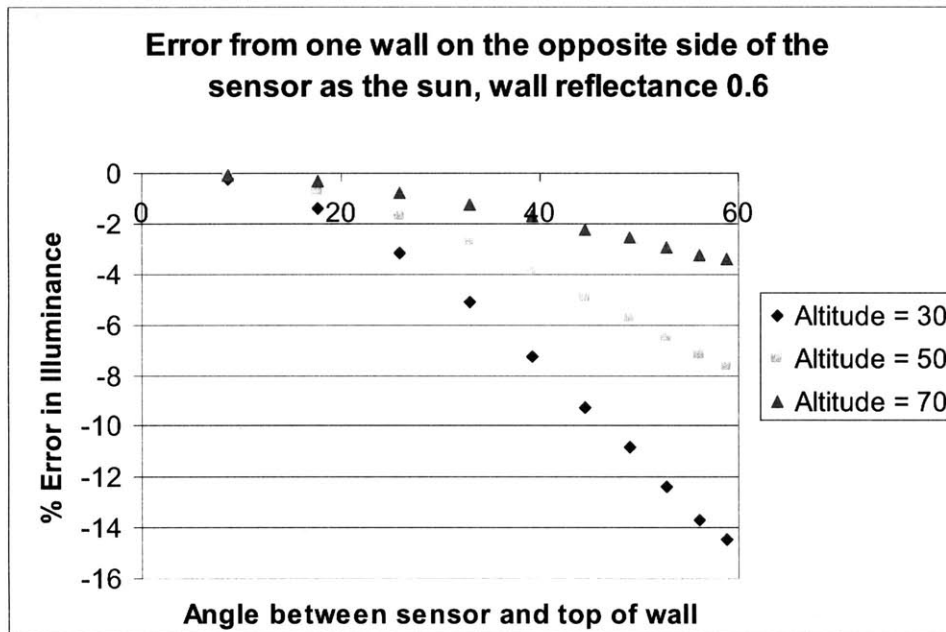
3.2.4 Tilting of Whole Models

The next logical stage of this study of tilting errors was to extend the simulation to whole building models. This was accomplished by tilting an AutoCAD model, importing it into Ecotect, and then exporting it to Radiance for renderings. The model used for the studies is very simple, consisting of one room with four windows in it so that direct light penetration from these windows could be observed easily. A table and chair also exist for minimal scene interest. In AutoCAD, a base resembling that of the outdoor heliodon, was added to the model, and placed on a stalk above the ground. Next, the model and base were tilted as if performing an outdoor heliodon simulation, using the altitude and azimuth of sample "actual" and "desired" conditions.

The first step of AutoCAD tilting was to rotate the model counterclockwise about the x axis. Next, using the azimuth convention of zero as north, the model is rotated counterclockwise about the z axis. When using the 'rotate3d' command in AutoCAD, counterclockwise is positive. The angles required for these rotations are calculated from the derived equations 3.4 and 3.5 below.

Rotation angle about x axis =

$$| \beta_{desired} - \beta_{actual} | \qquad \beta_{desired} > \beta_{actual} \qquad \text{(Equation 3.4)}$$
$$- | \beta_{desired} - \beta_{actual} | \qquad \beta_{desired} < \beta_{actual}$$

Rotation angle about z axis = $azimuth_{desired} - azimuth_{actual}$ (Equation 3.5)

54
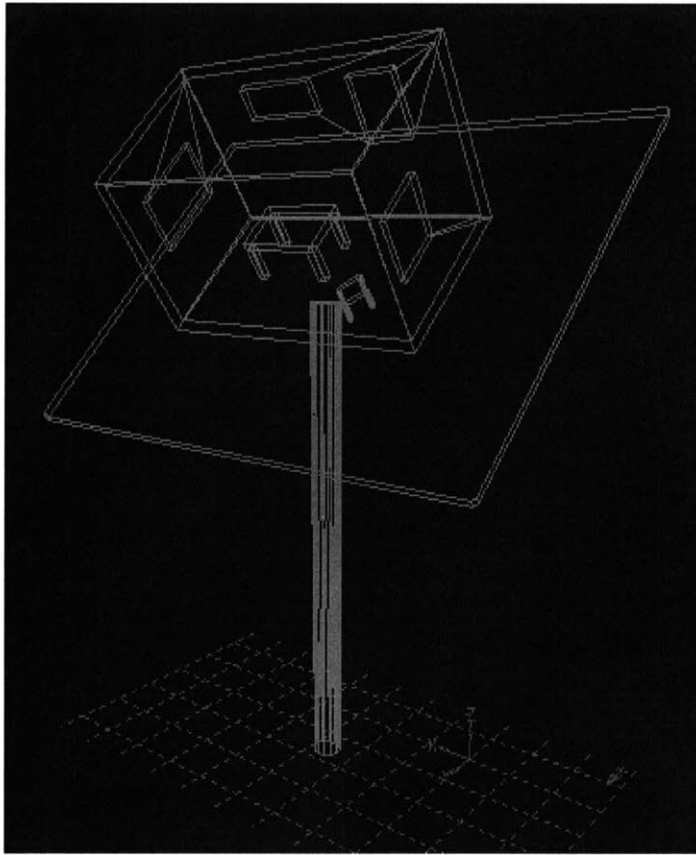
Figure 3.21: A tilted model imported into Ecotect from AutoCAD

After importing into Ecotect, images were generated for several cases of desired and actual testing conditions. In the resulting set, the images on the left represent untilted models under desired skies, while the right hand images are rendered using the actual sky with a model on a platform tilted according to the equations 3.4 and 3.5, as in Figure 3.21. Surface material values were kept constant for all simulations and surfaces to simplify the tests.

The derived tilting method described above is easily validated by observation of the direct sun patches in the resulting images. When these sun patches appear in the same place inside the room for both images, this means that the sun angles are the same relative to the building and therefore the tilting method is accurate. Discrepancies between sun patch locations would indicate mistakes in the angle calculation or AutoCAD tilting. Below are sample results, as renderings and false-color images (Figures 3.22 to 3.24). It should be noted that in the simple model used for the renderings, the windows on the left are oriented towards the south. Care was taken to use the same exposure for the two renderings in comparison, and the same illuminance scale for comparative false-color images. The room views in comparison for each case are slightly different because of the difficulty of positioning the camera precisely in Ecotect.

10 AM on December 21st at 42 North, no tilting

Tilted simulation of 10 AM on December 21st at 42 North, using a sky at 3PM on April 21st at zero North

Lux
9500
8500
7500
6500
5500
4500
3500
2500
1500
500
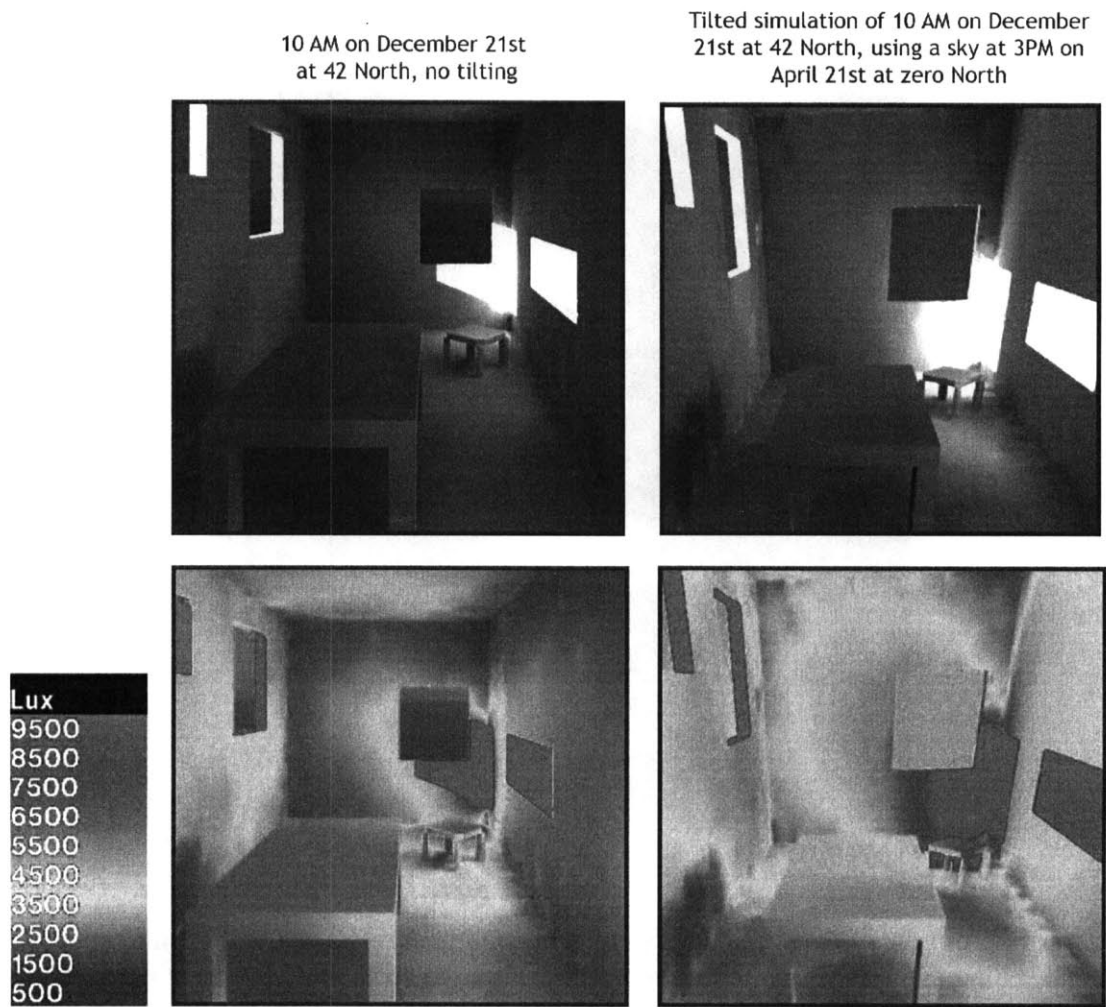
Figure 3.22: A comparison in which the actual altitude is 25 degrees higher than the desired altitude. The overestimation of illuminance for the tilted simulation is clear.

12PM on March 21 at 60 North, no tilting

Tilted simulation of 12PM on March 21 at 60N, using a sky at 12PM May 21 at 42 North

Lux
9500
8500
7500
6500
5500
4500
3500
2500
1500
500

Figure 3.23: A comparison in which the actual altitude is about 40 degrees higher than the desired one, greatly overestimating interior illuminance.

56

12 PM on December 21st at zero north, no tilting

Tilted simulation of 12 PM on December 21st at zero north, using a sky at 3 PM on March 21st at 42 North
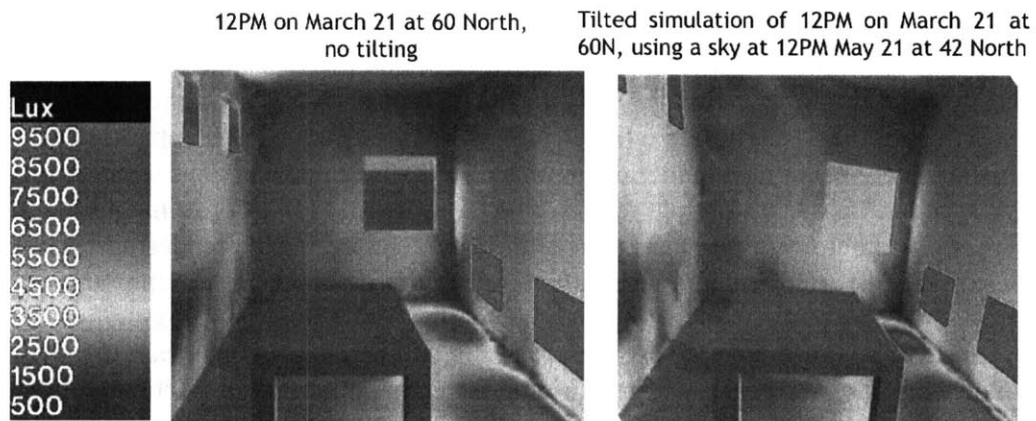
Lux
9500
8500
7500
6500
5500
4500
3500
2500
1500
500
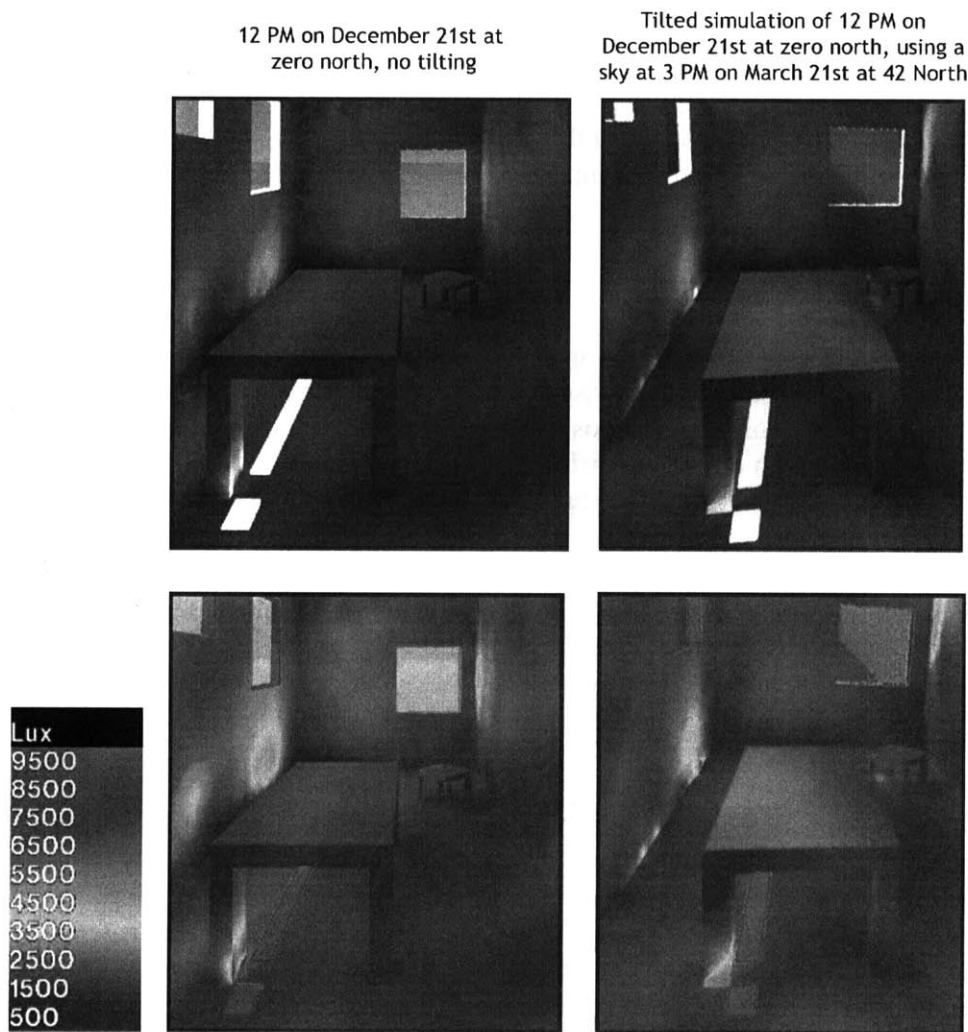
Figure 3.24: A comparison in which the actual altitude is 25 degrees lower than the desired altitude. Surprisingly, the table gets less illumination in the "actual" location on the left, despite the higher altitude; however, other surfaces in the room are brighter in this image.

These image results are generally in agreement with the predictions made using bare sensors. High altitude differences between desired and actual conditions generally result in large illuminance errors. However, the presence of materials and surrounding obstacles do complicate the situation. In Figures 3.23 and 3.24, the lower desired altitude results in clear overestimation of illuminance. However, in figure 3.24, in which the desired altitude is higher than the actual one, the difference is not as clear. The table receives less illuminance in the actual location than in the desired one, which is unexpected. However, close observation reveals that though the table is brighter in the second image, the walls are brighter in the first one. This is also a case in which very little direct light enters the room, as demonstrated by the very small, thin sun patches; this means that diffuse light has a higher relative component. This is a good example of a case in which despite a large difference in solar altitude, the presence of the room and the playoff between direct and diffuse light produces results that are somewhat more unpredictable.

One drawback of these false color images is that unfortunately the illuminance scale has very similar regions of green at 2500 and 5500 lux. This is confusing for a rendering which predicts large areas that lie between these two values. For this reason, renderings are included with some of the false color images in order to add an additional visual perspective.

3.2.5 Discussion

The results of this study differ from those originally expected. It was originally assumed that all situations involving steep tilting or surrounding obstacles would produce high errors because of the reduction of sky exposure. However, this underestimates the effect that solar altitude has on both direct and diffuse solar radiation. The sun and surrounding sky at midday are much brighter than they are near sunrise or sunset. This difference generally outweighs any loss of illuminance caused by cutting off portions of the sky. As observed in the experiments, tilting can decrease illuminance but it can also increase it, depending on which tilting method is used. Surface reflectances of surroundings have an impact but this is dependent on where they are in relation to the sun. However, if the sun used for testing is actually behind a nearby building that wouldn't exist in the desired scenario, this causes a massive loss of illuminance, as demonstrated by the Killian Court example.

This research can be considered a supplement to studies such as Cannon-Brookes (1997) and Thanachareonkit et al (2005), which investigated the sources of model overestimation when comparisons between illuminance measured inside real buildings and corresponding outdoor scale models are made. These studies investigated cases where measurements are taken inside a building while the same measurements are taken in a corresponding model sitting next to it outdoors. When manual heliodons are used for outdoor tilted simulations of other altitudes, there are sources of error additional to those observed in previous studies where tilting was not considered. Model overestimation without tilting appears to be consistent over various sky conditions (Thanachareonkit et al, 2005) while in the case of heliodon use illuminance errors can vary greatly due to the difference in "desired" and "actual" solar altitudes as demonstrated, as well as to very high surrounding obstructions.

As described in the background chapter about heliodons, scale model measurements very often overestimate internal illuminance for various reasons, and this should also be kept in mind when performing these experiments. Knowing that overestimation is expected, erring on the side of underestimating illuminance due to altitude differences is preferred. When one considers the effects of surroundings and tilting and makes appropriate judgments about when and where the tests should be performed, these sources of error can be minimized relatively easily.

The graphs and examples contained in this section can be summarized as specific advice for someone who wishes to test models outside. These are the steps that should be taken to ensure that error from these sources remains low.

1. *Try to match the testing and the desired altitudes as closely as possible.* Since exact matching may not be possible, Figures 3.10 a-e show how much of a difference in altitude is permissible for each testing altitude while keeping errors low. From the graphs, a testing altitude of 60 allows the greatest range of difference between actual and desired altitudes, up to plus or minus 20 in order to keep errors under 5%. The lowest testing altitude tried, 30 degrees, has the least flexibility; both plus and minus 10 for altitude difference give errors greater than 5%. An altitude of 70, the highest altitude used, is flexible in allowing testing of an altitude up to about 20 degrees less than the testing altitude while keeping errors below 5%, but desired altitudes more than 10 degrees above 70 will result in error higher than 5%.

2. *Try to find a testing location where surrounding obstructions are minimized.*
However, there are many situations of surrounding obstructions where their effect will be minimal.

If testing in Killian court on the MIT campus, the relatively low surroundings make less than 5% of difference for clear, intermediate, and overcast skies when various possible building reflectances are considered, since their exact average reflectance value with trees and many other details is not known (Figures 3.15, 3.16, 3.17). Intermediate or overcast days in a similar situation but with higher buildings cause errors over 5% if the height of the building is doubled. However, for clear days their effect could remain under 5% for all tested reflectances if the building heights are less than 100 meters, which corresponds to an angle between the sensor and the top of the walls of about 60 degrees.

If a wall exists between the sun and the sensor, the error remains under 5% for various testing altitudes, wall angles, and the wall reflectances, as long as the angle between the sun and sensor does not exceed the solar altitude, causing the wall to block direct light (Figure 3.13). If an obstruction is present on the opposite side of the testing spot as the sun, its presence tends to increase illuminance on the testing spot (Figures 3.20 a-c). If the average wall reflectance is 0.2, the error stays below 5% for the range of altitudes tried. If it is 0.4, the angle between the testing location and the top of the obstruction must stay under 40 degrees for the various altitudes, while for a reflectance of 0.6 it must stay below 35 degrees to keep error below 5%.

3.3   Operation and Usability

3.3.1   Movement accuracy

In contrast to the automated heliodon, the accuracy of the portable heliodon's position is dependent on the user. On sunny days, the user must make sure that the sun peg's shadow is in the correct position. Overcast day accuracy, however, is dependent on altitude and azimuth estimates from stereographic charts, correctly adjusting three degrees of freedom individually, and constantly adjusting the table as the sun moves overheard.   In both these cases, there is the possibility that the user will read charts or make angle

adjustments incorrectly, yielding a simulation which is different from the one that the user thinks it is.

Even if the user of the manual heliodon makes no mistakes in angle determination or adjustment, all of the calculations are approximations. The stereographic charts used to determine the altitude and azimuth of the "current" and "desired" coordinates only have markings at the 21st of every month, the times are hourly, the altitude values are only marked every five degrees, and the azimuth angles every 10 degrees. The charts are in solar time though clock time charts are obtainable. The user must make an approximation of what altitude and azimuth angles to use when values are between the marked ones. A straight edge may be helpful for connecting points but this is impossible with curved lines such as the days of the year. One factor that probably contributes to operator error is that these calculations are likely to be performed outside in the testing conditions and cannot be worked out beforehand unless the user knows exactly what time he or she will perform the experiments. Also, by the time these calculations and table movements are completed, the original "current" time used for the calculations is no longer correct. If high accuracy is desired, this planning before going outside should take place. This would also allow angles to be calculated from more precise methods than looking at the graphs, such as through the use of various websites that calculate altitude and azimuth for any time and place.

These errors may cause shadows to appear in slightly different locations than they would really be at a given moment; the significance of sun patch location errors is dependent on the scale of the model. However, the exact sun position at an individual moment is less important than understanding of the general trends through longer periods of time. Slight inaccuracies in shadow positions would only be significant in rare cases such as with a design that called for a tiny patch of sunlight to hit a certain point in a room at a precise moment of the year.

3.3.2 Image Capture Capability

While photos may be taken by hand while using the manual heliodon, videos such as those of passing days would be difficult or impossible without very coordinated movements and a better method of securing a camera. However, luminance measurements may be taken and daylight factor calculated with the manual heliodon on cloudy days, procedures that would have little meaning with the sky-less indoor setup.

When using a regular camera with the manual heliodon, images descriptions must be written down in the order they were taken and this list consulted later when photos are downloaded. If images are not correctly documented in this way, it is impossible to tell what simulations the pictures represent from examination later on.

As shown in Figure 3.25, photo capture on the heliodon in Killian Court, for example, can create backgrounds that are quite distracting and thus unacceptable for presentation purpose without a lot of time-consuming work with Photoshop. This problem is usually more significant for exterior shots of models than for interior ones, as the outside world

visible through a model window can contribute favorably to realism and the composition of a photo (Figure 3.26).

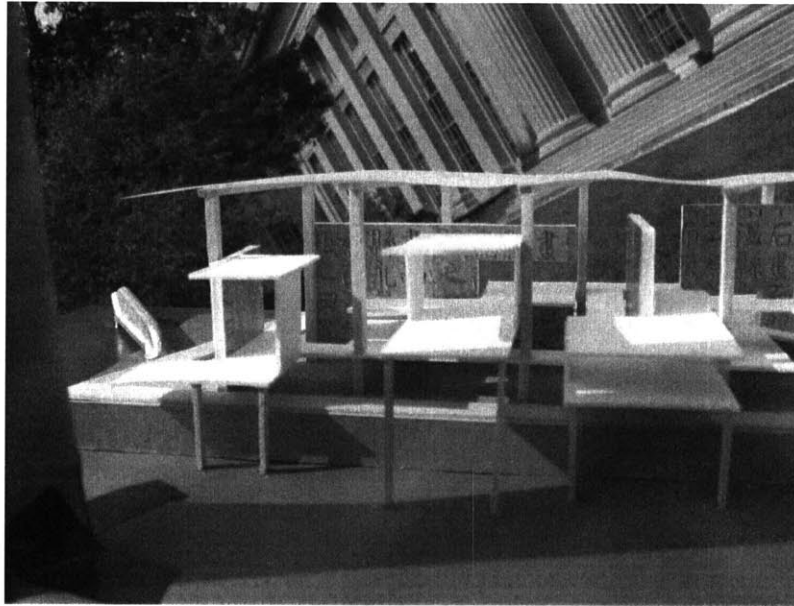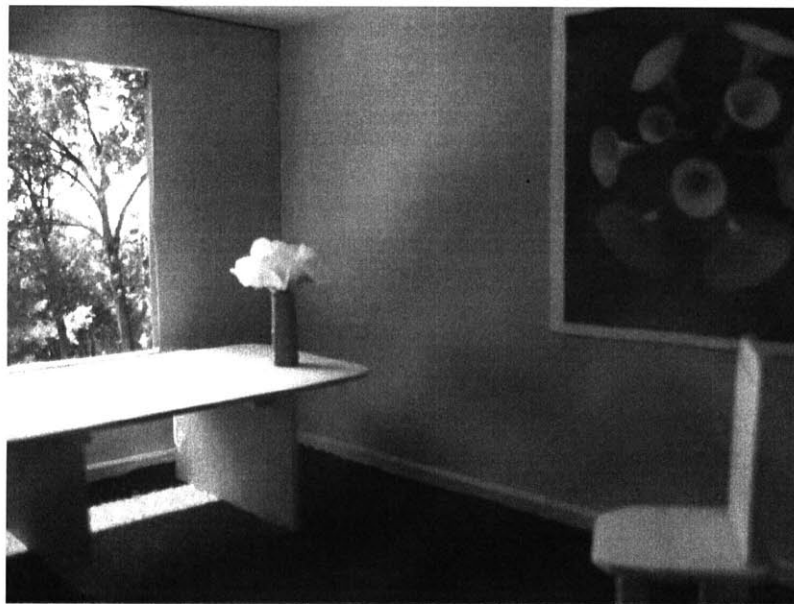**Figure 3.25: Photo of a scale model on heliodon, with distracting background (Killian Court)**

Figure 3.26: Interior photograph of a model using the outdoor heliodon, with a pleasant view of trees from the window.

3.3.3 Ease of Use

Simulating a sunny day with the sun peg is considerably easier than the cloudy day operation because it does not require angular calculations. The cloudy day operative

method involves reading altitude and azimuth from two separate stereographic charts, performing one angle calculation, and then adjusting three separate angles on the table. The entire procedure must be repeated in order to move to a different time of day. However, both methods require significant agility. The art of loosening the appropriate joints in order to move the table to a new location while keeping the table from tipping over may require some learning time, and an assistant can be helpful. Fortunately, the use of a positionable camera arm that can attach to the table makes it easier to hold the camera stationary, but this arm does add weight to the table and makes moving it slightly more problematic. Nevertheless, the work of the experimenters can become a delicate ballet, and is not to be attempted with an incompatible team.

Obviously, another very important factor to consider when using the manual heliodon is the weather. Variability of weather prediction makes it difficult to effectively plan testing times. This makes it hard to depend on this method of testing for project deadlines, because there could easily be non-sunny or non-overcast conditions for several weeks. Unacceptable testing conditions include variably cloudy weather, where the sky luminance distribution changes too fast to effectively compare images, and of course days when it is raining or snowing. This last possibility gives the use of the outdoor heliodon an element of risk. An experimenter and an assistant may have achieved the perfect model setup and have completed half of an image series only to have the sky suddenly change dramatically. Of course, the worst case of this is an overcast sky that starts raining and then ruins a delicately constructed model. A comparable experience is that of the unanticipated operation of a sprinkler system, experienced personally by this hapless experimenter.

In addition to the changing weather and sky conditions, the position of the sun also changes constantly during experiments with the outdoor heliodon. If a sun peg is used, care must be taken to readjust the table if the table is left stationary for a period of time. This is much more difficult and time consuming during overcast operation, where the correct angles need to be calculated individually and adjusted as the sun moves overhead.

3.3.4 Limitations on Types of Models

Though many scale models could be used on either the portable or automated heliodon, there are some limitations. In terms of size, only models whose bases are smaller than about 22 inches in one direction can still be clamped to the surface of the portable heliodon. Of course, models must be robust enough to withstand tilting without falling apart.

Building models for daylighting studies requires special procedures if one wishes to create a model that is closely representative of the proposed building in terms of photographs or interior illuminance measurements. Colors, materials, and geometry must be as close to those of the real building as possible, and care must be taken that as little light as possible enters the building through cracks in the model, translucent building materials, or the hole used for a camera lens. Proper procedures and suggestions for

daylighting model building to minimize error have been described in detail by Bodart (2007).

There are some building features that are appropriate for sun-only testing and others such as anidolic systems whose main advantage is performance under overcast skies. However, reflective elements such as anidolics can be used on the automated heliodon to investigate glare issues associated with their presence during sunny conditions (see Chapter 5).

Mirrors, which are sometimes used to double the apparent size of a symmetric room, are another model feature that should not be included for sun-only testing, because the sun will reflect directly off the mirror causing inappropriate visualization of the interior. These mirrors are more appropriate for overcast outdoor or sky simulator testing but may contribute to inaccurately high interior illuminance by causing too many internal reflections (Sarawgi et al., 2004).

If simple shadow observation is desired, the materials used in the model are not as important. For these tests with either the portable or automated heliodon, any model of the type normally produced in a design studio is fine for use, including early sketch models.

4   Automated Heliodon Setup

4.1   General Description

4.1.1   Lab Setup and Light Source

Developed by students under the direction of Professor Marilyne Andersen, the indoor automated heliodon is used both for goniophotometric measurements and scale model investigations (Andersen et al 2005). This setup consists of a computer-controlled moving table and a fixed light source. A smaller, separate light source is used for the goniophotometer. The setup does not include an artificial sky, and is thus useful for observation of the effects of direct sunlight only. Equipment is contained with in the daylighting lab, a 12' by 14' room in which everything has been painted black or covered in black fabric to minimize error caused by external surface reflectance during operation (Figure 4.1).
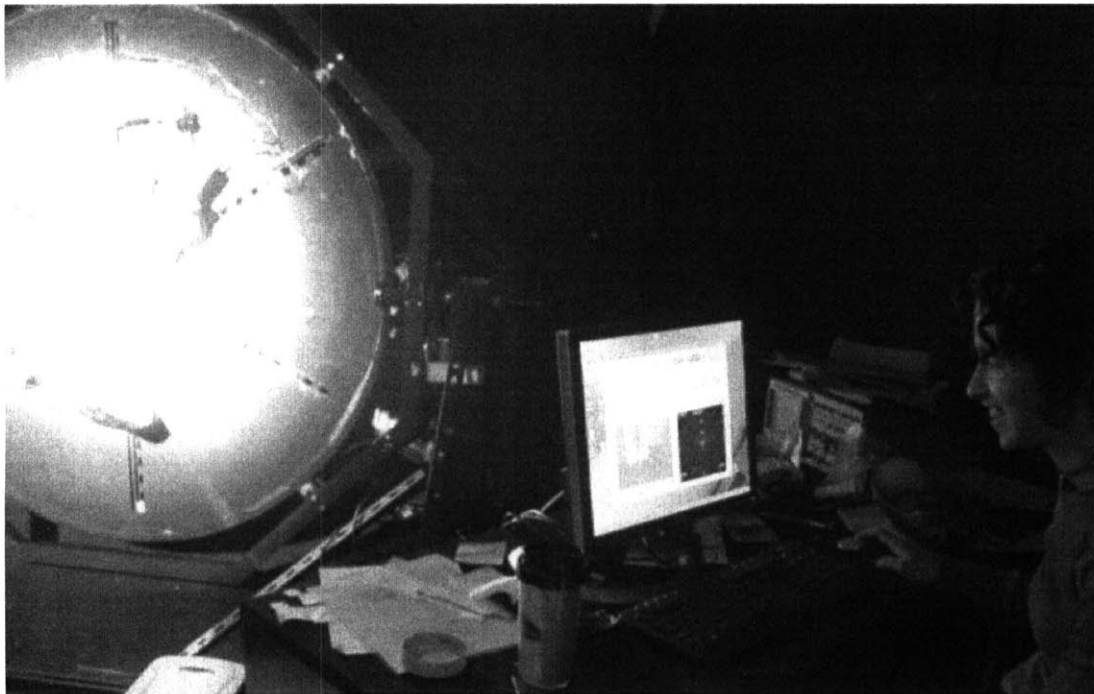
Figure 4.1 The lab setup, showing an illuminated scale model on the heliodon and the control computer.

The heliodon itself consists of a table of 1.5 meters (about 5 ft) in diameter mounted inside a frame. A building scale model to be studied is mounted on the center of the table using clamps. The perimeter of the inner platform is covered with spur gear teeth, allowing it to be rotated and held in place by bearings and gears placed around the outside. It is controlled by two motors, which handle the azimuth and horizontal axes of rotation (Ljubicic, 2005). Table movements are controlled remotely by the user from a computer interface written using Visual Basic in Visual Studio 2003. This interface

communicates with Microchip microcontrollers which control the actual heliodon motors (Clifford, 2006). When the table has reached the target location simulating a particular place, date, and time, digitals photos of the model are taken automatically for analysis. Details of the computer interface are discussed in Section 4.2, while details of the mechanical setup and recent improvements can be found in Section 4.4.

For sun simulation with scale models, a spotlight is reflected off a mirror before hitting the surface of the heliodon; the geometric configuration can be observed in Figure 4.2. Positions of the spotlight, mirror, and heliodon were optimized to maximize the "virtual beam distance" while ensuring that no possible angle of the heliodon itself could block the light source (Browne, 2006). The light source for scale model testing is a Mole Richardson "Molebeam" HMI (Hydrargyrum medium-arc iodide) spotlight of 18 inches in diameter.

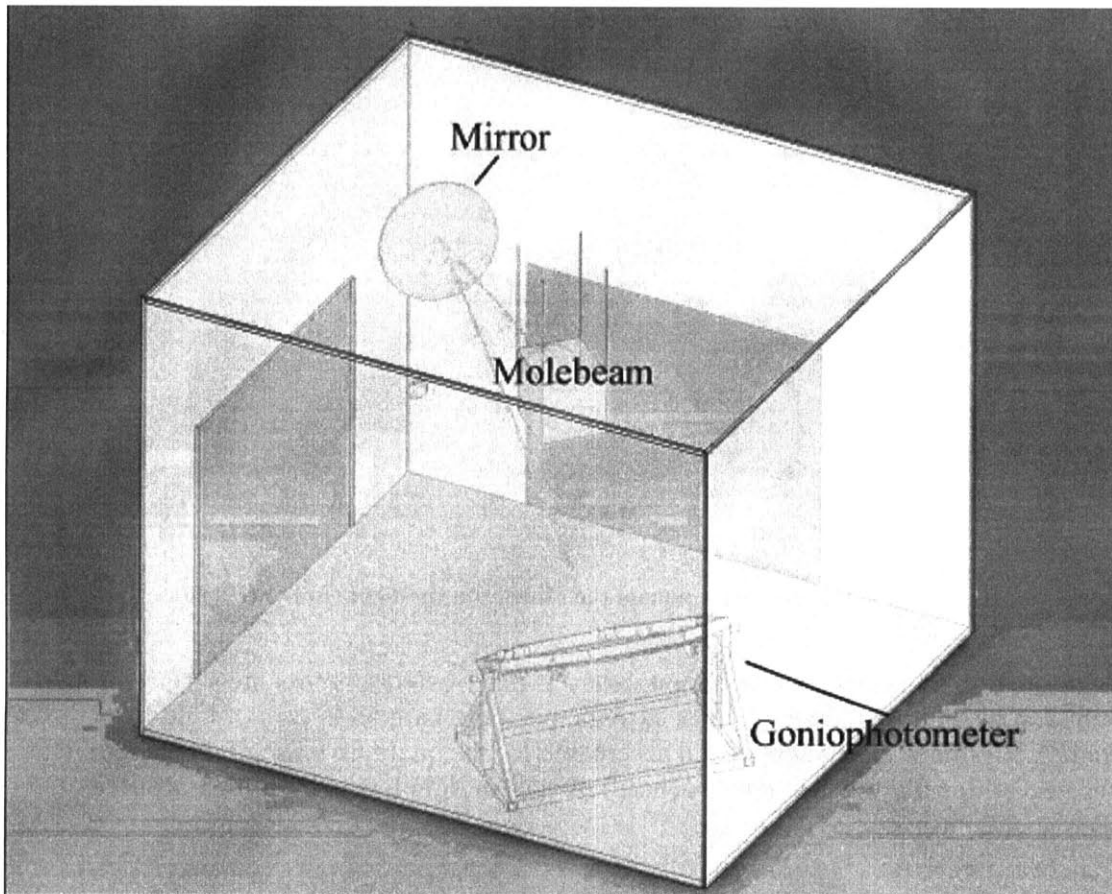Figure 4.2: Heliodon testing room setup (Browne, 2006).

While it was desired that light from the chosen source be reasonably collimated to mimic that of the sun, this meant that the light needed to travel as far as possible in order to get enough spread to illuminate a large area on the surface of the table. The sun's own light is considered to be approximately but not perfectly collimated, with about half of a degree

of deviation. The selected Molebeam spotlight has a spread of about 5 degrees, which was considered sufficiently collimated for the purpose.

In addition to generating appropriately parallel beams, the Molebeam has a color temperature of 5600 Kelvin, which is quite close to that of sunlight, 6000K, and also has a similar spectrum. The illumination from the spotlight ranges from 17,000 to 22,800 lux, with the exception for a very small central area of 10,000 lux caused by slight blocking of the beam by the bulb itself inside the spotlight. Outside of that small area, the uniformity of the light varies by 7.4% (Browne, 2006). This illuminance map can be observed in Figure 4.3. The illuminated area on the heliodon surface is about 3 feet 6 inches in diameter.
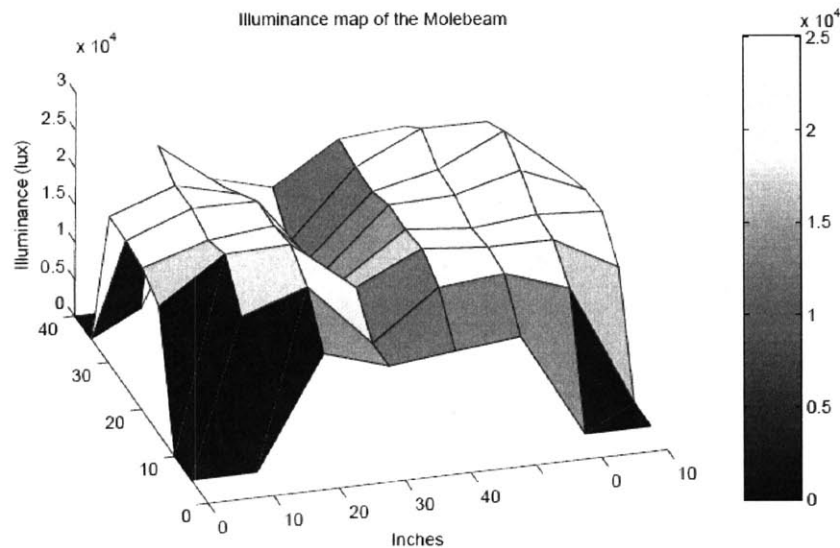
Figure 4.3: Illuminance map of the Molebeam spotlight (Browne, 2006).

Additionally, illuminance distribution varies as much as 30% across the surface of the heliodon when it is tilted in its most extreme position, parallel to rays of light from the source, but this was still considered acceptable for the qualitative use of the heliodon because at this illuminance level such differences in light levels are not perceptible (Browne, 2006).

4.1.2 Shadow Comparison

As described earlier, the sun-simulating spotlight has a spread of about five degrees. Since the spotlight is less collimated than the real sun, the penumbra, or partially blocked area of a cast shadow, is thicker than in outdoor shadows, meaning the shadows appear less sharp. The light source is not far enough away to appear as a single point so it is therefore possible for part of a shaded object to receive illumination from part of the light source but not the whole thing. The thickness of this transition region from unshaded to

the umbra or darkest part of the shadow, where complete shading occurs, varies based on how far away the shadow casting object is from the surface.

A qualitative shadow test was previously carried out in order to observe the difference between the Molebeam and the real sun (Browne, 2006). This test consisted of photographing the shadow of a semi-transparent ruler held at one foot and 3 inches away from a white piece of paper outside on a sunny day as well as on the heliodon surface under the spotlight. As predicted, the shadows produced by the Molebeam were slightly less sharp than those produced by real sunlight.

An additional experiment was performed to see if the difference in these shadows could be quantified. First, photographs of a shadow caused by an object held at 34 cm and 12 cm from a white piece of paper were taken outside on a sunny day as well as indoors with the heliodon and spotlight. For all four tests, the camera was held the same distance away from the target shadow by using a positionable camera holder attached to a rigid stand. A Canon PowerShot S30 camera was used, without a flash. Black foam core, used to cast the shadows, was also attached to the stand in such a way that it was held parallel to the ground and could be repositioned for the 12 and 34 cm photos. The outdoor photos were taken on a clear, sunny day at 1:00 PM, and the indoor heliodon photos were taken at the same simulated time and date. The testing setup can be observed in Figure 4.4.

Matlab was used to assess the sharpness of the shadow by graphing the transition of the pixels from white to the darkest gray of the shadow as illustrated in Figure 4.5. A steep slope implied a very sharp shadow, while a gradual one represented considerable color gradation between the light and dark areas, meaning the edge of the shadow was fuzzier. Graphs of the results of the four different cases are shown in Figure 4.6.
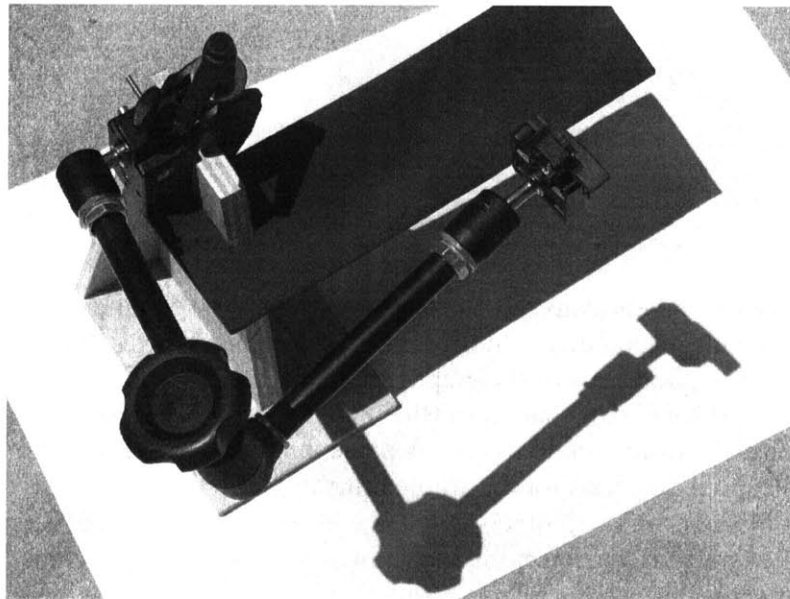
Figure 4.4: Testing setup for shadow comparison test.
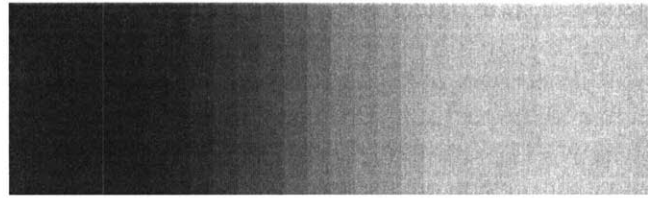
Figure 4.5: Close up of pixelated shadow transition from the outdoor 34cm test.
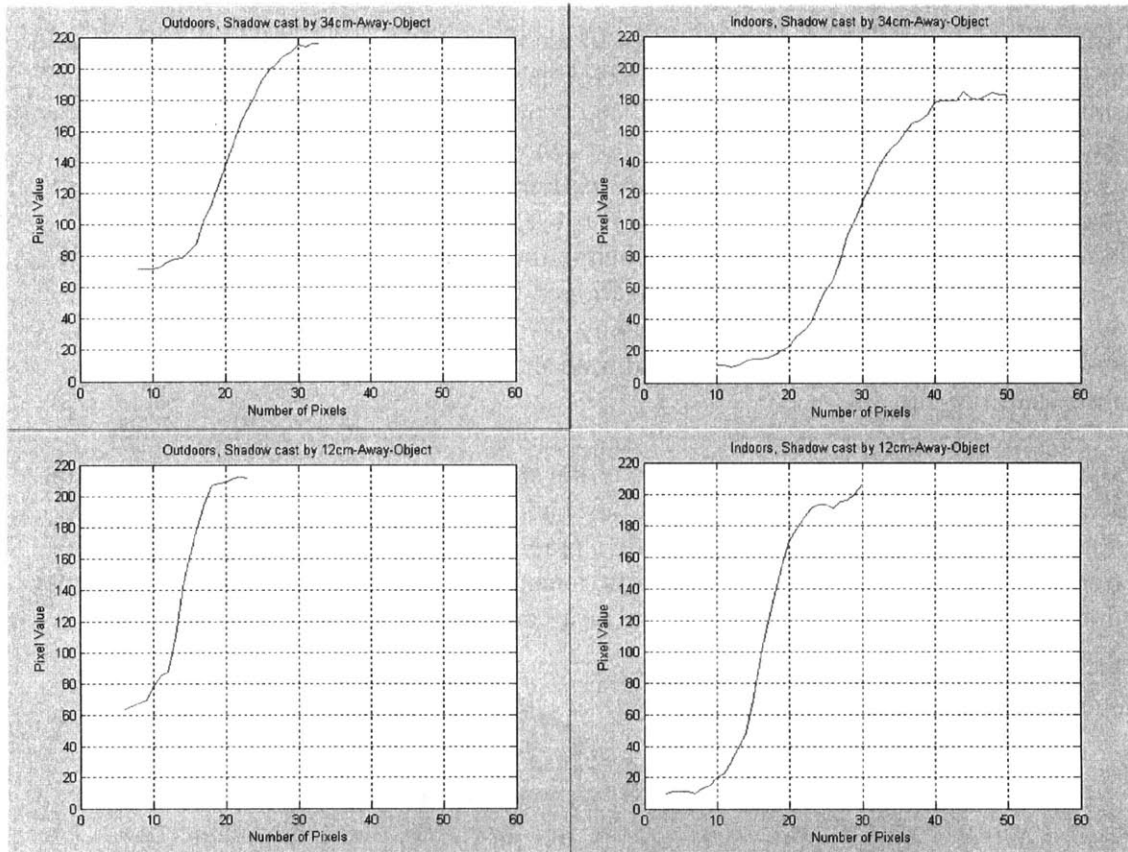
Figure 4.6: Matlab shadow test results.

The particular row of pixels analyzed in each sample was chosen randomly, but experimentation with several different rows yielded quite similar results. As expected, the pixel numbers on the x axes of the graphs show that the transition from the darkest shadow to the white paper was sharper outside than inside. In the case of the 34cm test, the outdoor transition from dark to light took place in about 20 pixels, while that of the indoor test took about 50 pixels for the whole transition. In the 12 cm test, the outdoor transition took place in about 15 pixels, while the indoor one took about 25 pixels. This means that at 34 cm from the object the transition region is 2.5 times as thick as outdoors, while at 12 cm away this is reduced to 1.6 times. The average squared error of deviation from a perfect step function was also computed for each case. For the outdoor 34 cm test

this error was 57.8 compared to the 148 of the indoor test. For the outdoor 12 cm test the error was 28.7 compared to 67 for the outdoor test.

These tests show that real sunlight makes shadows significantly sharper than does the spotlight, as expected due to the sun being much closer to perfectly collimated as described previously. The shadow fuzziness is more significant in close-up photos and small models than in shots of larger models taken farther away because of the width of this smear region in comparison to the scale of objects in the photo. However, despite the fact that the shadows are roughly twice as fuzzy with the sun simulator as with the real sun, this was only demonstrable by evaluating individual pixels, and is nearly undetectable under simple observation. Even though the edges are fuzzier, the shadows themselves are still quite easy to see and thus sufficient for the qualitative shadow observation the setup is used for.

4.1.3 Operation

The operation of the automated heliodon is relatively simple, since by definition the table's angular movements are controlled automatically. The automated heliodon can accommodate models of up to about three feet wide to ensure good lighting coverage. Small models can also be accommodated as long as they are equipped with bases at least 26 inches wide in once direction to be able to reach across the hole in the middle of the table to the channels and be clamped down. Models are attached to the table using clamps that fit in the Unistrut channels of the table. At the time of this writing, models are attached using a system of disks and bolts that is difficult to use (Figure 4.7), but plans for much more ergonomic clamps have been made for the future (Figure 4.8).
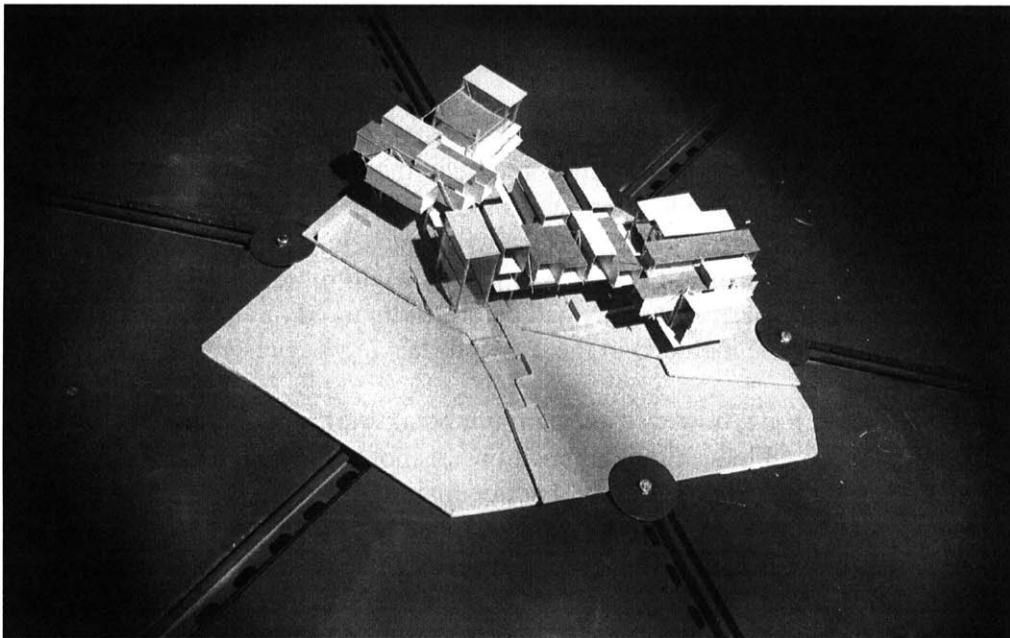
Figure 4.7: A model attached to the heliodon showing the current disk clamping system that will be replaced by more ergonomic sliding toggle clamps (Figure 4.8). Model created by Emily Lammert.
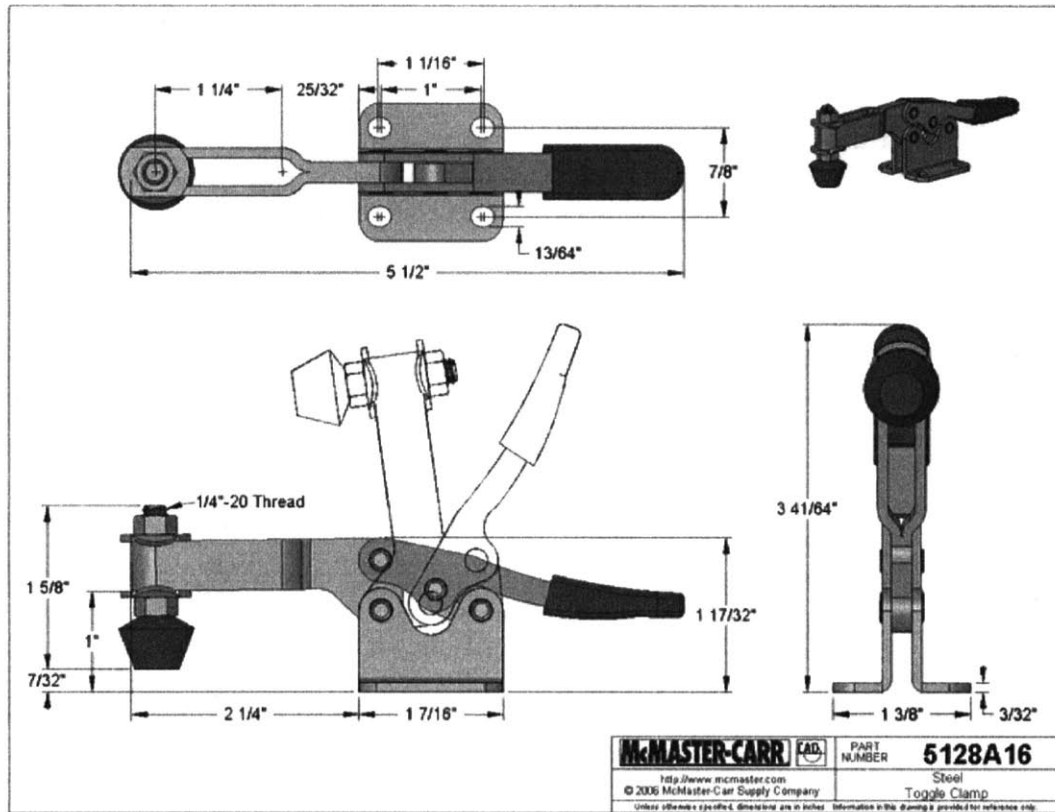
Figure 4.8: McMaster-Carr specifications for the new clamps that will be set up to attach models to the surface of the heliodon.

Current operation of the heliodon requires models to be positioned on the table differently based on whether they are meant to be in the northern or southern hemisphere in order to restrict movement and allow wires to remain plugged in, as discussed in Section 4.4. One side of the heliodon surface will represent south for the northern hemisphere, while the direction 180 degrees from this will represent south for the southern hemisphere. These directions will be clearly marked on the table in the future to aid in installation, and are included in the user interface, to be presented in Section 4.2.

At the time of this writing, however, the azimuth breakbeam sensor to create a fixed value of home for the table's azimuthal position was not yet installed. Because of that, fixed directions for south and north could not be marked on the table. Instead, the software recognizes south for the northern hemisphere as whichever side of the table is pointing directly towards the mirror when power is switched on. For the southern hemisphere, south points in the opposite direction, and the model should be installed appropriately.

After positioning the scale model as well as the digital camera, discussed in further detail in Section 4.3.1, the Visual Basic control interface is used to tell the table what dates,

times, and locations should be simulated. The interface allows the simulation of any date and time during daylight hours, at any location on earth, as well as automatic photo capture. These photos can be taken individually or in planned series and sets. Video capture is also possible. After the images are taken they can be examined and compared in various ways using linked Flash interfaces. The development and implementation of these control and analysis interfaces are discussed in detail in Section 4.2.

4.2 Interface Development and Integration

4.2.1 Interface Planning

The automated heliodon setup is for use by architecture students in various stages of design work, aiding their ability to make good decisions in regards to lighting issues. For this reason, it was important to design an interface that is very easy to use even for beginners, and does not require extensive training or expertise; this is a major drawback in many lighting software packages.

The new interface design and setup expands the options offered by an earlier interface originally developed by project predecessors Siân Kleindienst and Zachary Clifford, who had designed and implemented the main elements of the heliodon control setup along with a simple interface. The original interface consists of a single screen equipped with input boxes for desired latitude, longitude, time and date, as well as time zone (Figure 4.9). Additionally, there is an interactive map allowing a user to select the desired location by clicking on it. An equidistant graph, revealed by clicking the "Hide Map" button, shows the sun position relative to the table for each simulation. Once the user has selected the desired parameters, the "Start Motors" button is clicked to cause the table to move to the appropriate position for the simulation.
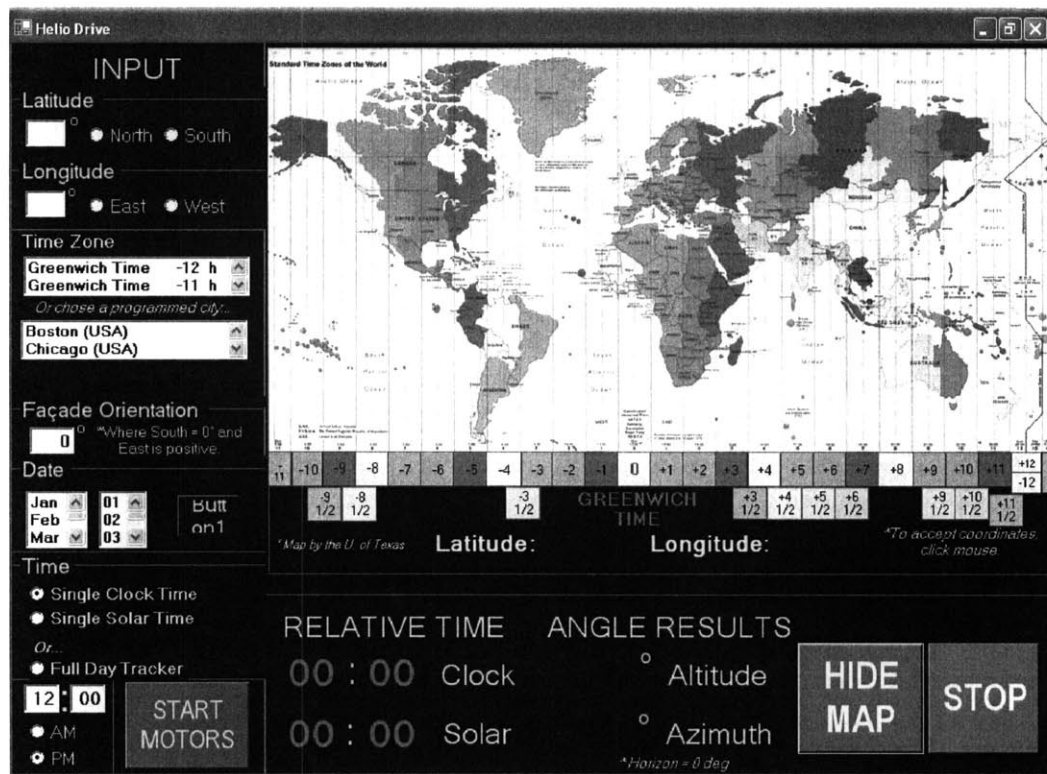
Figure 4.9: Original heliodon control interface design.

The first goal of the new interface was to incorporate the use of a digital camera that could be fixed near or inside a model in order to automatically take photographs during heliodon use. Automatic photo capture is quite important not only to allow documentation and later comparison but to ensure that the viewpoint of the camera can remain constant to more easily show the different between two subsequent images. Though photos could be taken manually with a portable camera fixed to the table, automatic photo capture allows quicker groups of simulations to be performed without having to wait for a person to manually take each photo. Also, a fixed camera may become difficult to reach in some positions. Having a person following it around during a group of simulations just to click the button would be quite awkward, and could create unwanted shadowing if the person needed to stand in front of the light source.

In addition to the new camera setup, it was desired that there be several options of pre-programmed groups of simulations that would generate associated photographs. A single simulated date and time gives little information about the general trends of sunlight interactions with a proposed building since sun angles vary so much over the course of a single day, not to mention throughout the year. Solar altitude can vary between 0 and 90, and azimuth through a full 360 degrees, though the range of possible values is dependent on the latitude of a given location. Presenting the user with different options for quickly capturing multiple images at once was meant to facilitate this broad experimentation.

It was decided that while capture of single images should still be possible, there should be a way to take videos of single days, series of mathematically related images, and a simple button for a fixed default set. Additionally, the images captured were to be automatically sorted and displayed in different ways. The final developed interface meant to achieve all of these goals is described in the next section.

4.2.2 Interface Design

The main embellishments to the previously existing system were the addition of various options allowing different combinations of pre-planned dates of times to be simulated all at once as well as the inclusion of a digital camera to automatically take photos once each simulated date and time was reached. This camera, equipped with an articulated arm for precise positioning, is fixed to the table itself allowing the view to remain stationary relative to the building geometry during simulations. The camera has to be wired to a power outlet and the computer; a temporary system of supports ensures that cables connecting it to the computer are not tangled or endangered during use. Details of the camera setup are described in Section 4.3; a new system involving wireless communication is to be developed for the future.

Most of the original features of the interface were left intact, while a new image capture interface was added, and some features were moved. On the opening screen, titled "Location Selector" (Figure 4.10), the user first selects the desired location. There are three possible ways to do this: manually entering the latitude, longitude, and time zone, selecting a pre-programmed city, or selecting a location from the interactive world map. The user can then enter a façade orientation if different from the way the model was originally fixed to the table (see Section 4.1.3). Solar time is applied to the entire interface.

As part of the currently adopted solution to allow wires to remain attached to the camera, the azimuth motor movement was restricted to 360 degrees of allowed rotation. In order to make this possible, the model needs to be fixed to the table differently depending on whether the building is located in the northern or the southern hemisphere as mentioned earlier. These instructions are mentioned on the opening screen of the interface (Figure 4.9) though they will eventually become clearer once the new sensor is installed and different cardinal directions for northern and southern hemisphere can be permanently marked on the table.
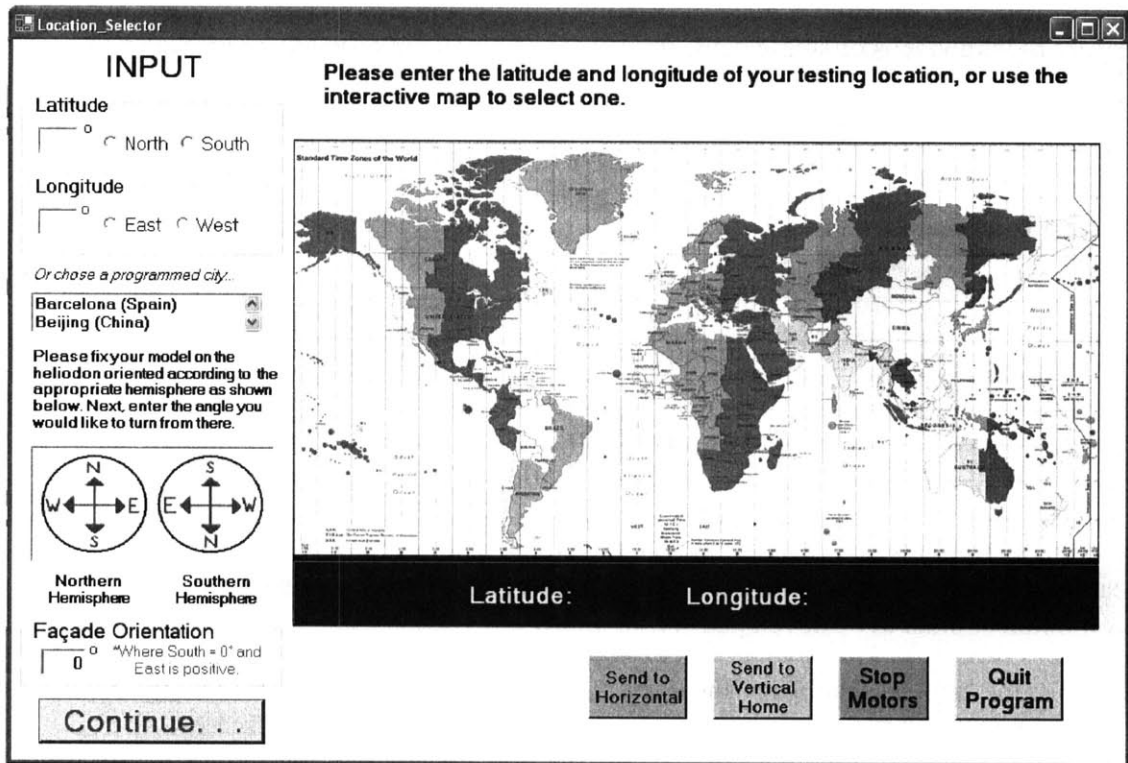
Figure 4.10: The opening screen of the interface where location and façade orientation are selected.

After parameters from the LocationSelector interface are entered, the user continues to the Image Interface (Figure 4.10) which allows different combinations of dates and times to be selected for simulation. This new screen for image capture includes a camera viewport as well as an equidistant graph showing the altitude and azimuth of the sun position being simulated. These two features remain visible while the upper half of the interface changes based on which radio button of image capture option is selected.

The camera viewport shows the view through the camera at all times. This is helpful to ensure that the images being taken are reasonably well adjusted. Camera properties can be adjusted using the camera properties button. The feature labeled "Equidistant Graph" shows the position of the "sun" relative to the table in terms of altitude and azimuth. While the table is moving to a new location, the yellow point shows this movement towards a target while the blue point shows the target itself.

The several control buttons at the top of the interface provide basic capabilities that need to be available at all times. One button stops the motors, one sends it to home, and one sends it to a horizontal position that is useful for the adjustment a model or the camera. The "Change Location or Orientation" button returns the user to the original LocationSelector interface in order to change the location or façade orientation value. The "View Image Folder Contents" button opens up image viewing software called XnView that shows the folders of images. Images can also be viewed by finding the "Your Photos" folder that appears automatically on the desktop.

74

From the Image Interface, four image capture options are available. These options are "Planned image Sets," "Default Design Day Set," "Image Series" and "Videos;" however, both "Planned Image Sets" and "Default Design Day Set" are available by clicking the "Image Sets" radio button. Having these two options under one radio button instead of as two separate options caused confusion as described in Chapter 6, since users did not see the "Default Design Day Set" option on the right (Figure 4.11). The "Planned Image Sets" option allows the user to enter several different mathematically unrelated dates and times, and then use a "Capture Set" button to command the heliodon to move to those positions in succession, taking a photo after each move. The "Default Design Day Set" option allows a user to take a set of 20 images at 4 times of day on the two solstices and equinoxes.
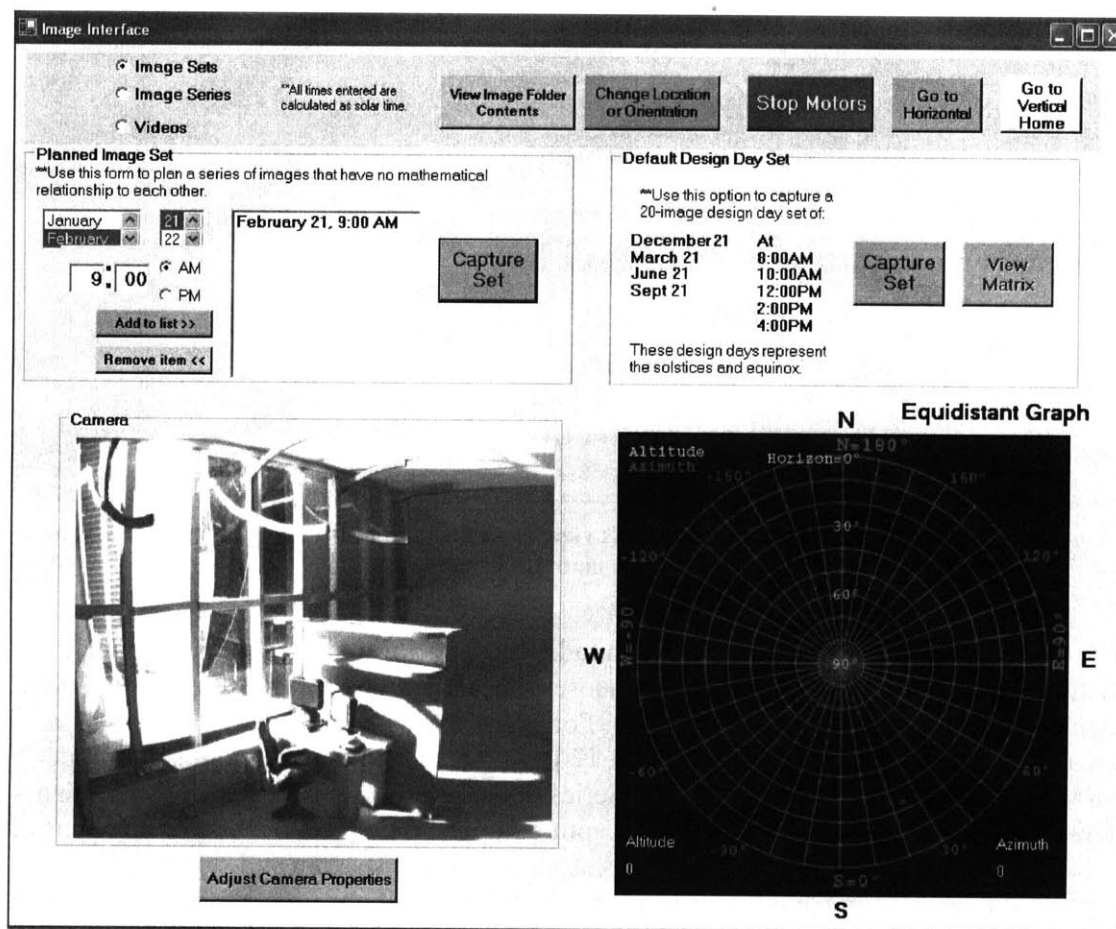
Figure 4.11: The Image Interface, showing the two options available by selecting the "Image Sets" radio button in the upper left.

The photos captured by using the "Default Design Day Set" option can be viewed as a matrix so that the rows show images at different times on the same day and columns show the same time at different months of the year (Figure 4.12). This matrix viewing option is one of the two Flash applications designed for this interface, described in

Section 4.2.4. Rolling the mouse over an image activates a tooltip feature showing the date and time of that image, and clicking on an image brings up its full sized version on the right. If the sun is not up at one of the default times, such as the December at 4:00 PM point at a high northern latitude, its spot will appear blank as a useful placeholder. The camera properties remain the same for the whole set of images to allow comparison, as can be observed in the example in Figure 4.12. In the case of this particular model, which is the one used in the case study of Chapter 5, direct light does not enter the space as much in the afternoon, making the later images appear quite dark.
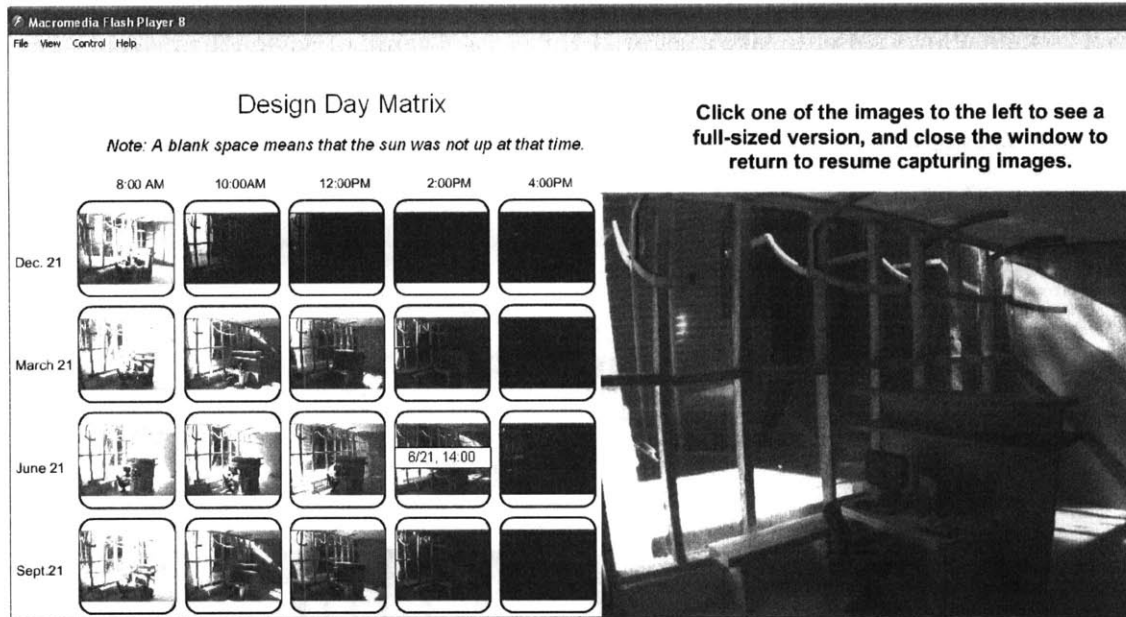
Figure 4.12: The Flash application that allows viewing of the "Default Design Day Set" photos as a matrix.

The "Image Series" option under the next radio button allows images to be taken in a mathematically related series; the user chooses the starting and ending date and time and then selects a time interval between them. For example, this would be a good option to use if someone wanted to see an image at 12 PM on the first of every month. The upper part of the Image Interface showing the Series option is shown in Figure 4.13. When a desired series to be taken is set up and "Capture Series" is clicked, a message box appears with the number of images that will be taken as well as the starting and stopping times appears. In order to prevent a user from accidentally taking one image for every hour of the year or another extremely large number of images, the simulation is prevented from taking a series of more than 12 images. This was considered a reasonable number for such a series option, allowing the user to take one image per month, for example. However, the allowed number could easily be changed if this is found to be too much of a restriction.

76
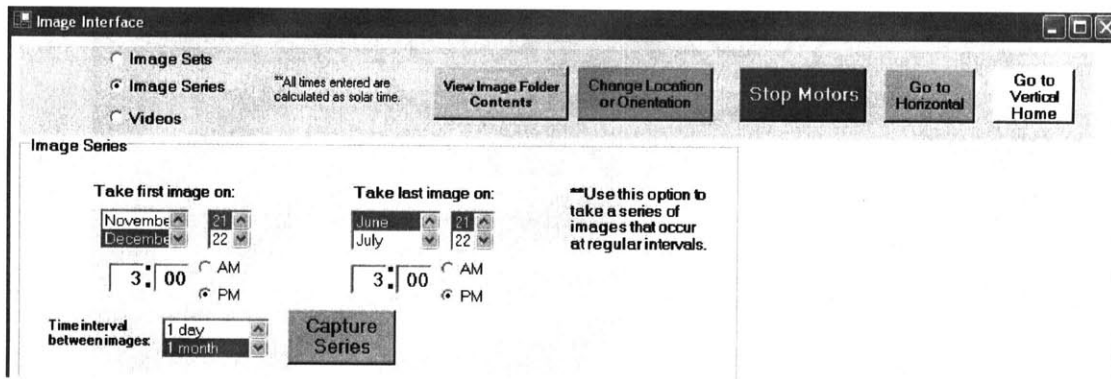
Figure 4.13: The upper half of the Image Interface showing the "Image Series" option.

The video option, which will eventually allow the user to take a smooth video of any desired day, now works by taking one image every hour while the sun is up on that day. The video capture portion of the interface is shown in Figure 4.14. The series of images on that day can then be viewed as a simulated video through a Flash interface that fades one picture out as the next fades in while the user clicks through the passing day. A screenshot of this Flash application is shown in Figure 4.15. In addition, these images are automatically saved in a .wmv file.
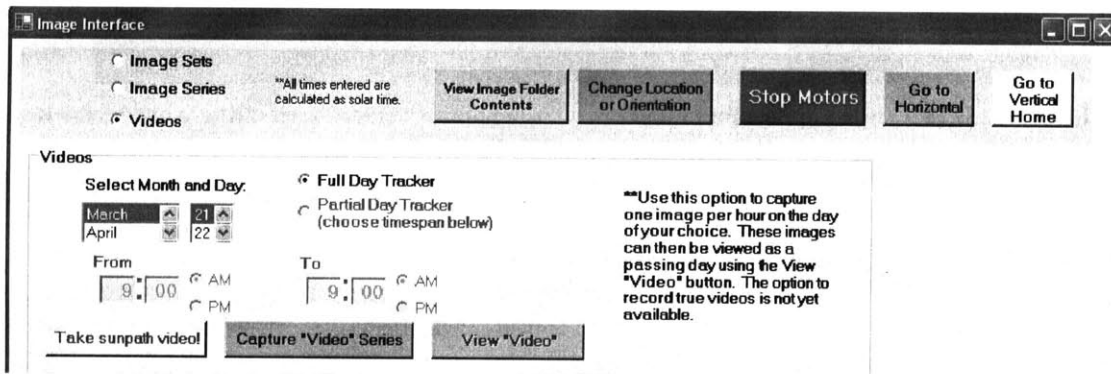
Figure 4.14: The upper half of the Image Interface showing the "Videos" option.

Figure 4.15: The Flash application that allows viewing of the "Video" series, where one image is taken every hour while the sun is up.

Various features were added to prevent errors and make it easier to navigate the system. After the image capturing button is clicked for each of the four options, a message box appears describing where the images can be found. Additionally, error checking for all of the entries in both the Location Selector and the Image Interface occurs to prevent invalid values from causing calculation errors. If an invalid value is entered for anything, a message box stating the problem appears and the image capture routine is prevented from proceeding until the issue is corrected.

A simple flowchart summarizing the capabilities and structure of the completed interface is shown in Figure 4.16.
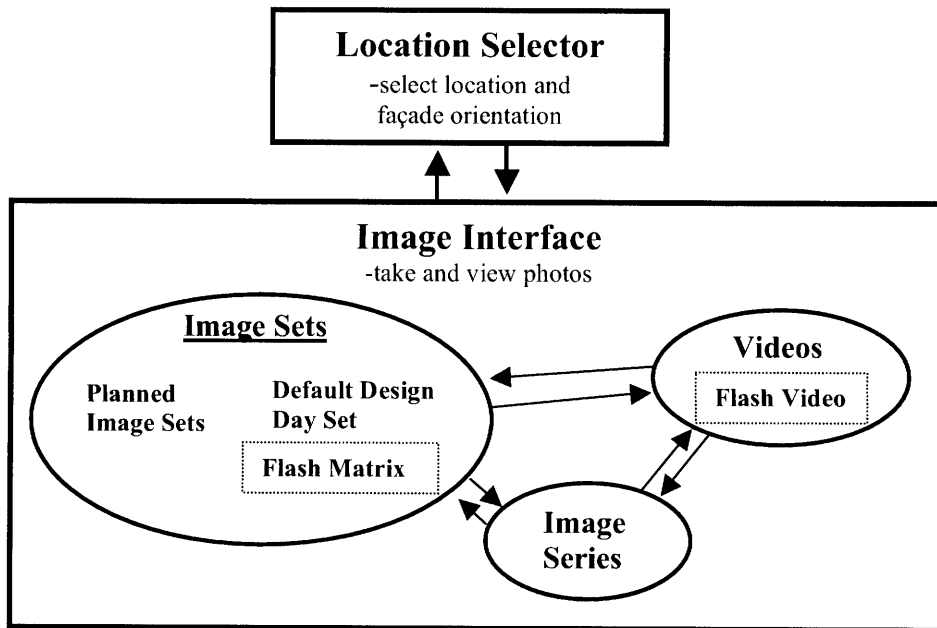
Figure 4.16: A simple flowchart of interface structure and capabilities.

4.2.3 File Storage and Sorting

In order to facilitate retrieval and examination of the captured images, each captured image is named automatically according to the date and time of the simulation. This is done using the numeric format of month-day-time; for example, an image taken on March 21st at 4:30 PM would be called "03-21 16.30.jpg."

The images are stored in a folder called "Your Photos" which appears on the desktop, with subfolders containing images from each of the four image capture options and named accordingly. At any time, the user can look in this image folder and rename or move around images as desired. After each session, this folder should be renamed, saved to a USB memory stick, or dragged to the trash. If this is not done, new images from the next session will also be stored in this folder, causing confusion if the user ends up with someone else's old images.

An important aspect of the image naming and storing system is that if more than one image is taken of the same name and in the same image capture option, the first image will be rewritten. For example, if the user takes a December 2nd at 3 PM image, changes the façade orientation, and then takes it again, the first option will be written over. This means that the user should change the name of the image file if he or she plans to take another image at the same simulated date and time. This may be inconvenient in some cases but could also be convenient in the case where the camera properties are wrong or some other mistake was made for the initial photo or photos.

4.2.4 Flash Application Development

The "Video" and "View Matrix" options described above were created using Macromedia Flash 8. This software, which is often used to make graphic interactive websites, can also be used to make standalone applications. It is much better suited for interactive image viewing than Visual Basic; it is in fact widely known as "the de facto standard for rich user interfaces (Bedoe and Shapiro, 2006)."

The goal in creating these Flash applications is to have them show the sets of images currently being taken by the user while he or she is using the software. Therefore, they needed to be able to incorporate recently captured images without requiring the program to be recompiled. This problem is solved through the use of XML files.

When a group of images is taken, the module ImageFileMaker.vb in the Visual Basic code (described in the next section) creates an XML file that contains the path to each one of the images saved in the particular folder assigned to that image capture option. The Flash application contains a path to the XML file in that folder. The XML file is then read by the application which allows it to "collect" the images for display. If a new set of images of the same type is collected, the XML file gets rewritten with the new video series photos or matrix photos, even though the images themselves will not be deleted unless they have the same file names as the new ones as is always the case with the matrix photos. This means that these new images will appear the next time the Flash video application is run. If a person takes several different video series, for example, only the most recent one can be viewed through the Flash video application.

A disadvantage to this system is that users cannot easily take the video or matrix-viewing Flash applications with them to use on their own computers. This is because the applications read XML files located at paths that are specific to the particular computer being used for all of the software. However, this problem could be remedied by adding a file path entry to the Flash application.

4.2.5 Control System

The Visual Basic software is divided into several modules which handle different parts of the program. The major routines, inputs, and outputs of these sections are outlined below. The various public properties that can be called during different routines as well as additional information about the software can be found in Zachary Clifford's report (Clifford, 2006).

LocationSelector.vb
This module deals with the initial processing of input parameters from the Location Selector, the interface in which the user selects the testing location and façade orientation. The inputs are the value of the latitude, which can be entered in several different ways, as well as the façade orientation value. An important Boolean value, SouthFlag, is set based on whether the user has selected the a northern or southern

latitude. This determines whether the table moves as if situated in the northern or southern hemisphere. These input parameters, along with those obtained from Form1, are passed to TableConnection.vb to be translated into properties such as altitude and azimuth.

Form1.vb
Similar to LocationSelector, this module deals with the input from the user form titled "Image Interface" that is used to enter in dates and times for each of the image capturing options available. Depending on which image capturing option is selected, it deals with determining the number of images and the order in which they are taken. The various groups of desired simulations are sent to TableConnection.vb as lists of dates and times to be simulated in the correct order as well as to ImageFileMaker.vb so they can be appropriately named and stored in files. This module also opens up data communication to and from the camera so that a preview image of what the camera sees is available in the interface. Additionally, after the images are taken, this module opens up the two Flash applications in the Default Day and Video options that allow interactive image viewing. It calls these applications by referring to their specific file path; this path should be checked and altered if the Flash applications need to be stored somewhere new.

ImageFileMaker.vb
This module, developed by Kess Eburu during the camera integration, is the control center for everything related to storing the images captured during one of the image capturing events. It creates the "Your Photos" folder that appears on the desktop along with its four subfolders. After each image is taken, it is named according to the simulation date and time. Additionally, it creates an XML file for each subfolder which refers to each image in that folder. These XML files are referred to by the two Flash applications used for the "Default Day" and "Videos" options. This reference in the Flash Actionscript code allows the images in the folder to be used in the application for display. These XML files are rewritten when new sets of images are taken, even though the old images will be retained in the folder providing they have names that are distinct from the new group. XML files are also created for the other two image capturing options, though they are not currently used for anything. See section 4.2.2 for more about the Flash applications. Additionally, the automatic compiling of the "Video" Series photos into a .wmv file is performed.

TableConnection.vb
This module performs most of the calculations in regards to the relevant solar positions. Variables and properties such as altitude and azimuth are defined formally, and calculated in the "Math Functions" section using the input from LocationSelector.vb and Form1.vb described above. In particular, the StartSequenceTracker public property, which parses the sequences of table movements requested from Form1, is defined. This module also defines the correct ports for communication with the two motors as well as the commands that send the table to home and stop the motors.

Additionally, it contains the code for the "Daytracker" option which is meant to allow smooth, coordinated motor movement to simulate a passing day, but is now disabled

because sufficient coordination allowing this smooth motion had not yet been achieved. This unsolved problem was the reason for creating the "Video" Series option which takes discrete images every hour for assembly into video-like form by way of the .wmv creation or the Flash video application.

ManualTableConnection.vb

This module defines more properties and variables related to the table position and the state of table movement. The individual parts of the homing procedure are defined so they can be used together in the TableConnection.vb property GoHome, which is used for the homing buttons on the LocationSelector and Form1 forms as well as the automatic homing that occurs when Form1 is initially opened. The two parts of the homing procedure for the altitude motor are defining zero as being the position at which the mirror is on the "horizon" relative to the table, followed by the command that tells the table to rotate until it hits the breakbeam sensor, with a slight offset. The public function MoveCoordinated is defined, which converts angular values calculated by the TableConnection.vb into degrees of motor rotation and motor encoder counts. The serial ports that communicate with the motor are opened so that the chips can receive the movement commands.

CRS232.vb

This module helps control the direct communication between the serial port and the motors.

Chip code: altitudecalibrate.c and rotationcalibrate .c

This code is not contained within the Visual Studio project; rather, it is the code that was used to compile the chips that control the two motors using the encoders. One of the main functions of this code is to manage a variable called "dest." One step in the dest variable is equal to one encoder count. The goal of this variable is to get to zero, meaning it has reached the location it has been commanded to go. When the chip receives the number of encoder counts from ManualTableConnection.vb, it sets the "dest" variable to this number and tells the motor to move. The "dest" variable also changes if the table is forcibly pushed in one direction by a person or by inertia from the table load. The motor then starts moving, while counting down encoder counts towards zero. However, it does not necessarily reach zero; a window of plus or minus 15 encoder counts is allowed for the altitude motor, while the azimuth motor is allowed plus or minus 20. These numbers were chosen as the minimum window that would prevent perpetual oscillation due to all the motor couplings being too imprecise to hit a particular point exactly. The plus or minus 15 counts was optimized for the altitude motor before the recent replacement described in section 4.4.

After the motor moves within the required window, it stops, but the chip remembers what non-zero value of dest it is at. It then keeps this value to add or subtract it from the next command. For example, if it were told to move 60 counts, it would count down from 60 until it reached zero, where the motor would be shut off. However, it might then drift to dest = -8 due to inertia. This value is within the allowed window of error. If it were next given a command to move 30, it would set dest = 30+8. This would in theory prevent

error accumulation even though each move has a margin of error. Unfortunately, error accumulation has been observed for the azimuth motor as well as the altitude motor in the case of eccentric loading on the near side of the table for reasons that are not yet known. These cases as well as the measured accuracy of movements are discussed in section 4.4.

4.3 Camera Setup and Control

4.3.1 Camera Positioning and Viewing Options

Before starting simulations with the automated heliodon, the camera, a Kappa DX20N-1394 CCD device, should be secured, positioned, and plugged in, though the exact position can easily be adjusted later. The camera itself is attached to the end of an articulated arm and mounted to the table with a specially created attachment that allows the base of the arm to be positioned anywhere in the Unistrut channels that extend radially out from the center of the table (Figure 4.17). Once the articulated arm is secured to the table, the exact position of the camera at the end of it is adjusted by turning the knob that loosens all three degrees of freedom at once. Because of this unusual design, the user should be careful to hold the camera itself when the knob is loosened to prevent it from dropping. Details and pictures regarding the articulated arm and its use can be found in Appendix B. The power and firewire cords to the camera should be plugged in and cords taped to the table to prevent them from getting caught in the bearings on the edges of the table during azimuthal rotation.
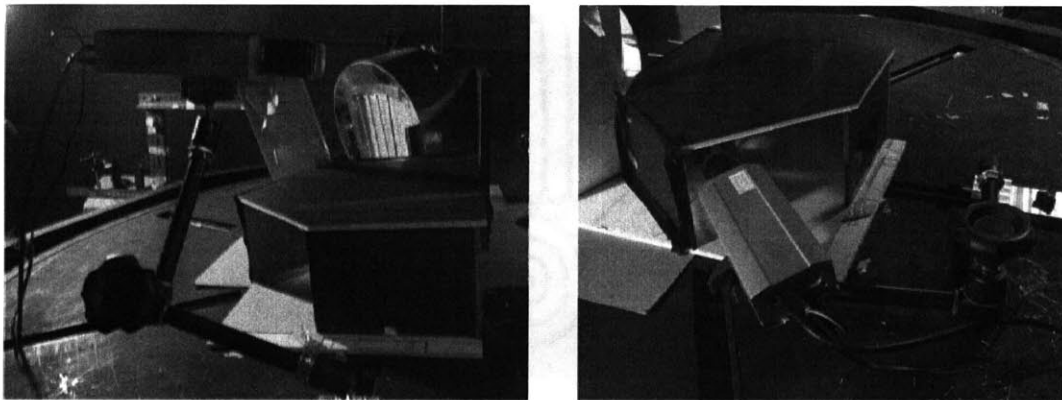
Figure 4.17: The camera attached to the extended articulated arm, left, and the camera positioned for an inside view of a model, right.

Both a wide angle lens and an endoscope are available. The wide angle lens is a Tamron CCTV lens that has a ½" angle of view and manual adjustment of the focus, iris (exposure) adjustment, and zooming (Figure 4.18). The FRS-Omega endoscope attachment, which has an outer diameter of one centimeter and length of 45 cm, is useful for obtaining interior views of models with small openings (Figure 4.19). It also has the option of using an attachment allowing viewing at a 90 degree angle. The fixed,

relatively long length of the rigid endoscope causes some positioning problems and also makes the end of it more likely to wobble during use. A shorter endoscope may be preferable for the future.
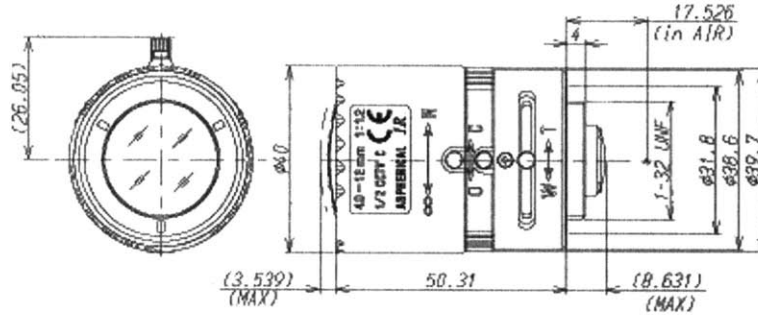
Figure 4.18: Diagram of the wide-angle lens. Source: Tamron website.
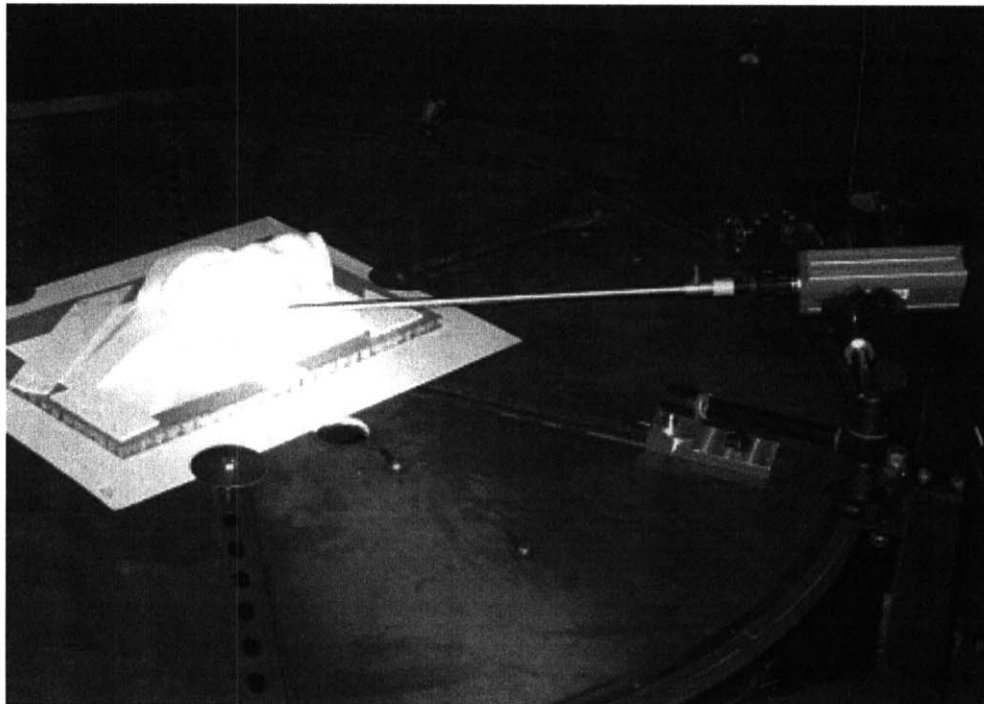
Figure 4.19: The endoscope attachment being used to view the inside of a model.
Photo courtesy of Marilyne Andersen.

The position of the camera is quite important, not only for model photos but also because of cast shadows. Generally the camera is placed on the North side of the model so that the stand does not cast shadows on the model. However, this is unfortunate because camera views that show the south side of the model may be interesting. The experimenter may be able to take some photographs from the south side; depending on the hour of the day shadows may or may not be a problem.

4.3.2 Wiring System

The automated heliodon is currently equipped with a wiring system that allows the power and firewire cords to remain plugged in during use. To accommodate this, the table movements are restricted to prevent cording tangling and models are fixed to the table differently depending on whether the proposed building is located in the Northern or Southern hemisphere, as described in Section 4.3 about interface use. Developing a wireless system is planned for the future even though the current wired setup does not pose any problems for the use of the table for scale model studies; however, the restricted movement makes it impossible to use the table for the goniophotometer application.

While table movement is restricted programmatically to prevent excessive twisting or overextension, the wires also had to be protected from strain or tangling. This was accomplished using a support system that only allows the wires to rotate in a predictable way without putting direct stress on wire connections to the camera. The camera's power cord has a transformer on one end and a cord that is not long enough to reach to a power outlet. An extension cord was purchased, but the heavy transformer had to be well supported to reduce strain on the wires or wire connections. The firewire cord, which transmits information to the computer, was found to be sufficiently long.

A cradle to support the transformer and the connection between the transformer and the extension cord was designed to hang from the middle of the table using three screw holes that already existed on the sides of the central opening used for the goniophotometer setup (Figure 4.18). The cradle was sewn out of nylon webbing, pieces of ribbon, and Velcro. The Velcro straps are sized to fit and support the transformer while it is plugged into the end of the extension cord. Ribbon loops on the outside of the cradle are used to attach the cradle to holes on the edges of the opening using string. The firewire cord is also drawn through the cradle for support. The support of the cradle means that the amount of cord available to be threaded through the underside of the Unistrut channels to be plugged into the camera is kept at a fixed length and that no strain is put on the connection of the power cord to the transformer.
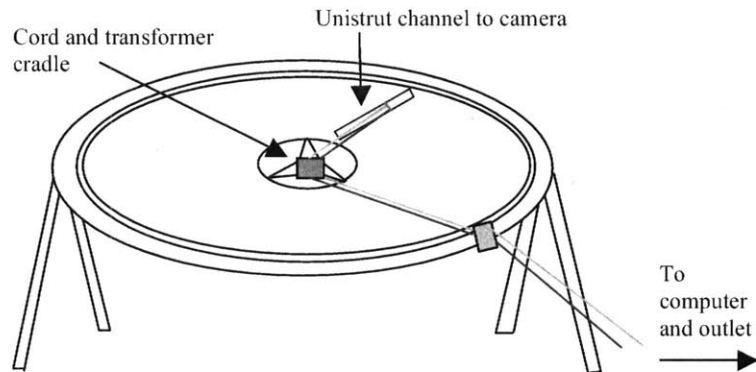
Figure 4.18: Wiring diagram showing the underside of the table. The red and blue (dark and light) wires represent the power cable and the firewire, which lead to a power outlet and the computer, respectively.

Before reaching the cradle, the rest of the cord is supported by an additional nylon strap on the right side of the heliodon that prevents it from disturbing the gears or altitude motor breakbeam sensor when the table is in the vertical position. In all sections of the wire support system, extra looseness is added to ensure that cords never get stretched. The camera cable support system was found to work quite successfully and has not posed any problems. It can easily be removed by untying or cutting the string that attaches the cradle to the center of the table and unthreading the cables from the extra support on the right and from the Unistrut channel. The wire system must be dismantled during goniophotometer use but takes only about five or ten minutes to restring.

4.3.3   Camera Communication and Image Property Adjustment

The Kappa DX20N-1394 CCD camera used for heliodon image acquisition is a scientific camera that is also used for the goniophotometer application. It was necessary that it could be programmed and controlled directly from the Visual Basic interface. However, the SDK (software development kit) for the camera only allows programming in C, C++, or Delphi. A VB.NET "wrapper" was created by programmer Kess Eburu to allow camera programming and control from the VB interface without requiring additional programming in other languages.

The camera has many adjustable properties which were set up to be controlled from the heliodon control interface. These control such parameters as the gain, sharpness, high and low values, and other factors. However, as mentioned earlier, the wide angle camera lens used in the setup has adjustable knobs to manually control three camera parameters: the focus, the iris (exposure), and a zooming capability. Unfortunately, the focus parameter cannot be adjusted from the computer and must be turned manually to optimize the image quality. This is quite inconvenient as this requires the user to look at the image on the monitor while manually turning the lens, a procedure which must be repeated if different camera views are used during the course of the experiments. During experimentation, it was found that the other camera parameter that is most important to image quality is the gain, equivalent to the exposure, which can also be adjusted by

86

turning another part of the lens. Adjusting other camera parameters made little perceivable difference, resulting in the camera property adjustment control feature being underused at this point.

Camera exposure or gain and focus should be adjusted with the spotlight turned on in a table position representative of the simulations before they begin. In the case of an interior camera view, there may be some experimental solar angles for which no direct light enters the windows or openings in the model, such as in the model of the case study of Chapter 5. If videos are taken, for example, the room will suddenly become completely dark when direct light no longer penetrates since the automated heliodon setup does not include diffuse skylight. This may be confusing and imply the real space would be completely dark at this hour; however, during daylight hours diffuse light from the sky would still enter the building. While it is somewhat bothersome that some pictures will show up completely black unless they are individually readjusted, these photos without direct light penetration do not show anything important except that no direct light enters at that moment in time. Therefore, they should not be used as images representing lighting conditions in the space.

4.3.4 Areas for Improvement

There are several areas for potential improvement of the camera setup; during student tests of the device camera-related issues were the number one complaint, which was readily admitted by the author to participants during the student evaluations of Chapter 6. The first and biggest problem is the image resolution available. The camera has two image resolutions options, HiRes RGB32 and LoRes RGB24. The LoRes option yields images of only about 700 by 500 pixels. The HiRes option yields images of about 1400 by 1000 pixels. The architects surveyed find the LoRes option far too low in quality to use for image presentation, one of the main reasons they are interested in obtaining images. The HiRes option is still a lower resolution than that of the digital cameras they usually use, which might be about 2000 by 1500 pixels, for example, or higher, but it is obviously preferred over the LoRes option.

Unfortunately, there are problems with using the HiRes option in the current setup. While the LoRes option uses about 30% of computer CPU, switching to HiRes moves this up to 99%, slows the software down to almost unusable, and causes various program malfunctions and crashes, though it is usually possible to take a few single images before this happens. The processor speed of the computer in the current setup is 2.79 GHz, a relatively fast computer. When the camera is run by itself in a Kappa-developed interface with none of the motors or control interface aspects running simultaneously, the CPU usage remains at 99% for the HiRes option, suggesting that it is the camera which is taking up the CPU and not the rest of the program or some inefficiency in the VB.NET wrapper code. RGB24 or RGB32, options which control the number of colors being collected, can also be used with either LoRes or HiRes, but changing these does not make a noticeable difference in CPU usage.

The HiRes option also takes only about one image per second. When used with the motor control, this lag time in image acquisition causes errors because the camera may not yet have updated its image at the moment the heliodon reaches the correct position for a photo. The photo it captures could instead be the image from the heliodon's position one second before the motor-coordinated image capture event, as was observed several times during HiRes experiments.

These findings were confirmed by Kappa customer service as being the correct behavior of the device. A scientific camera, the DX20N-1394 is not optimized for speed like commercial models but rather to obtain precise pixel values from the CCD without the interpolation that may occur in commercial cameras. They suggested that if faster image acquisition was needed with low CPU usage on the HiRes setting, the DX40 series and DXc100 get between 10 and 15 HiRes images per second. The Kappa engineers also suggested that the LoRes option be used most of the time while running the software and getting preview images, and that the HiRes option be turned on only at the moment of photo capture. This was tried but resulted in seemingly random crashes and general malfunction.

The next step in resolving this issue is to try replacing the computer used to control the heliodon with one with a faster processor. The other computer in the lab, for example, has a processor speed of 3.50 GHz. When the camera is run in HiRes on this machine, only about 40 or 50% of CPU is used. Getting a faster computer could be a much easier and cheaper solution to the problem than programming an entirely new camera, though due to the slow image acquisition of the HiRes option, about one image per second, some kind of delay would have to be added to the code at the point of photo capture to ensure that the camera had updated itself before an image was taken.

It is very important that the effect on CPU usage of a new wireless image acquisition system or any other major programmatic additions be carefully monitored and a control computer selected accordingly to avoid extreme slowness and crashes, accounting for the fact that the HiRes camera option will always use a very large amount of CPU.

Besides the major problem of image resolution, the other problem is the inconvenience of having to adjust the camera focus manually. A lens that could be adjusted from the computer along with other camera properties would make the system much easier. If this is not immediately possible, a simpler solution would be to open an existing Kappa camera control interface that shows a much larger photo preview than the small one included in the heliodon control interface. It would be easier to see this image from the location of the camera while adjusting it. The option to see a much larger image from the heliodon control interface itself could also be added.

4.4 Mechanical Operation and Recent Improvements

At the time of this writing, the azimuth breakbeam sensor was not installed. This means that the azimuth motor could not be homed as the altitude motor could be. However, this did not prevent operation of the system. Instead of having each side of the table represent

a specific direction, the system considers south for the northern hemisphere to be the side of the table closest to the mirror when the software is started. The only inconvenience to this system is if a model is left on the table after experiments and then used another day or the program restarted, power to the motors must be shut off and the table manually rotated until the correct façade faces south. Rotating and reattaching the model itself is also an option.

Various mechanical improvements to the system were recently made in order to fix several problems. The main problem was that though the table seemed to operate relatively well with nothing on it, as soon as a model and camera stand were attached, oscillations were induced in the altitude motor. The table seemed unable to take any uneven or mildly heavy loading of any kind. Even when an effort was made to counterbalance weight on the table with weight on the opposite side, oscillations still occurred as the altitude motor was unable to react fast enough and with enough power to resist applied torque. These oscillations were extremely severe, up to 45 degrees, when the extra weight was positioned on the side of the table closest to the computers, but they still sometimes occurred when weight was placed on the opposite side.

It was decided that a great improvement could be made to the setup with a replacement of the altitude motor with one of higher torque. The new motor, though it moves at only a third of the speed of the original one, has three times the torque, 300 in-lbs. In addition to replacing the motor, various wire connections were improved and a box constructed to house the chips and other electrical elements. Details of the new motor and also the wiring and control system can be found in Appendix C.

Both the altitude and azimuthal motors of the automated heliodon were tested for accuracy after the new altitude motor installation. These tests were performed by commanding the table to move to various angular positions and then measuring how close it came to reaching the correct positions. The altitude and azimuth motors were tested separately since their movements are independent. For the case of the altitude motor, the tests were carried out using a bubble level that allows rotation for measurements of surfaces tilted at angles. The accuracy of the azimuthal motor was investigated using a thin brass rod filed to a point positioned in the middle of a polar graph and attached to the table. With the spotlight switched on, the rod made a shadow whose position could be measured relative to the polar graph while the table was commanded to rotate.

The altitudinal movements of the table appear accurate to within 0.5 degrees with a relatively light model and appropriate use of the table's counterweight, though this error margin can increase to three degrees with very eccentric loading. This is a reasonable amount of error to observe because of the gear ratio from the drive gear to the table and the plus or minus 15 encoder counts mentioned earlier as the allowed position error for any move. The encoder is attached to the driving gear. There are 1024 encoder counts in one revolution of 360 degrees. This means that every encoder count is about 0.35 degrees. If this is multiplied by the gear ratio from the gear driven by the motor to the gear that moves that directly moves the table, 60/112, this gives 0.19 degrees of motion

of the table for every encoder count. If this is multiplied by the 15-count allowed margin of error, this means that the margin is equivalent to plus or minus about 2.8 degrees of altitudinal table movement. The 0.5 degrees of accuracy for a minimally loaded table must indicate that the table is well balanced and that inertia causes the table to drift to the correct spot but stop before overshooting too much, even though the position can be off by up to about three degrees with eccentric loading.

Altitude motor related problems arose when the table was loaded heavily on the side of the room facing the computer, which still induces oscillation in the system for a reason that is not yet known, as mentioned above. When allowed to oscillate in this way for a period of time, the oscillations were observed to increase in amplitude while the table gradually rotated upward. If left to oscillate for a period of time and then told to move to another position, the next position may be off by 20 degrees or more; this may be because the system is missing encoder counts when the table moves too rapidly. This oscillation should be avoided at all costs, and tables should be weighted slightly more heavily on the opposite side when possible. Fortunately, this is the usual setup because the camera needs to be on the side of the table farthest from the mirror to prevent shadows from the camera stand.

For the azimuthal table movements, movements under a degree were possible, but drift was observed. For example, when the table surface was rotated one degree at a time in one direction, in 28 of the one-degree movements the table was behind by half of a degree. When it was rotated back and forth between 0 and 30 degrees, the angle it was covering began to drift steadily in one direction. After about five such cycles the table was off by over 10 degrees. This is quite problematic since it clearly demonstrates significant error accumulation over time. Homing the azimuth motor frequently may be required until this problem is fixed.

As explained in Section 4.2.5, according to the code, error should not accumulate in this way because the chip "remembers" where the motor is even when it over or undershoots within its allowed margin of error. In the case of the azimuth movements, this margin of error should actually be much less because of the gear ratio. In this case, while there are still 1024 encoder counts per revolution of the driving gear, the gear ratio is 1.5/59.25, meaning that there are 0.009 degrees of azimuthal table movement for each encoder count. If this is multiplied by the allowed plus or minus 20 encoder counts, this is plus or minus 0.12 degrees of expected accuracy. The problem may be due to imperfect calibration between the number of counts the computer sends to the chip and what angular movement this translates to for the table, or possibly because of other electrical issues (see Appendix C).

The new, stronger motor is a definite improvement over the previous one. Though the table moves more slowly, most models can be attached to the table with no problem. The oscillation problem when the table is unevenly loaded on the side closest to the computers still exists, though this is much less of a problem than before since the previous setup was totally unusable with any loading at all. Careful adjustment of the counterweight should occur for heavier models to reduce the likelihood of these oscillations that cause drastic accumulation of error if allowed to occur. If they are

observed to occur when the table is left unused for a period of time during a session the table should be homed before continuing. Appendix C describes the existing problems in more detail and offers possible explanations and solutions.

5 Case study: Combined Automated Heliodon and Outdoor Testing[1]

5.1 Space Investigation

This section presents a case study in which both the indoor automated heliodon and outdoor testing was used to perform an investigation of part of an existing building. The work performed was the result of an assigned class project to investigate Frank Gehry's Stata Center on the MIT campus in order to suggest methods of improving the space. After some exploring, the robotics laboratory in room 32-376 was selected based on its unique and unfortunate lighting conditions. During a review and discussion of the lab with occupants, it was discovered that the cubicles immediately adjacent to the large window, particularly that of one robotics graduate student, were subjected to extremely uncomfortable glare conditions.

Figures 5.1 and 5.2 show a plan view of the building and a cross sectional diagram of the space. Photographs of the outside and inside of the space are shown in figure 5.3 and 5.4. The window in question faces 23.5 degrees east of south, and is situated nearly directly opposite from a large titanium and glass structure which blocks most of the view from the window. This structure houses another office, whose window contributes to the reflection problem. The blinds of this office are closed at all times. The exterior horizontal surface is also glass and is in fact a skylight for the floor below.

Details of the situation were revealed in a recorded interview. The occupant's current desk arrangement is such that the shimmering brightness of the opposing titanium structure as well as the exterior horizontal surface lie within his peripheral vision while working at his desk (Figure 5.4). He finds this to be uncomfortable and distracting although he said that direct light never actually hits his two main computer monitors in their current positions. It does, however, hit the small worktable opposite the window, which is equipped with an additional laptop computer (Figure 5.5). Inspired by these conditions, the student had in fact designed a window-climbing robot, capable of opening a large fan on command, in an attempt to block a source of glare. Unfortunately, the large scintillating surfaces visible from the window have many simultaneous areas of high brightness, making it impossible for the robot to make a big difference, especially as the bright patches slowly migrate with each passing minute. Morning hours seemed to be the most uncomfortable; other occupants confirmed that they occasionally wear sunglasses during these hours. However, the most uncomfortable conditions occur during partially-cloudy weather. As the sun disappears and reappears from behind clouds, the large variation of outdoor surface luminance forces the eyes to readjust constantly. Luminous patches measured from the titanium structure at one sample time ranged

---

[1] This section is derived from work completed for the Fall 2006 course 4.430, "Daylighting," taught by Marilyne Andersen. Fellow project participants were architecture masters students Lucille Ynosencio and Phillips Park.

between 84 cd/m^2 and 37,000 cd/m^2 for the dark and bright patches, respectively, with multiple contrasting patches visible on the surface of both the opposite reflective structure and the horizontal exterior reflective surface.

At the same time that the occupant experiences glare discomfort from the overly bright outdoor conditions, he finds that he lacks sufficient light for precision tasks. For small part assembly, he relocates to a halogen-lamp-lit workstation deeper in the room, even during the brightest hours of the day, remaining in his cubicle only for computer work. The illuminance under this halogen lamp was measured to be 2450 lux at 11:30 AM, which included the contribution of daylight and other overhead fixtures in the room, and 1600 lux at night without the contribution of daylight.

The occupant also commented about the electric lighting and HVAC systems. He explained that the overhead electric lights are on at all times, with no individual control for the overhead lamps in the large room. Since most occupants do not find the fixtures bright enough, workstations are supplemented with small halogen task lamps. The HVAC system is also said to function poorly. When asked if solar gains made the area next to the window uncomfortably hot during warmer months, the occupant replied that the air conditioning is usually on so high that any extra heat is welcome, though he admitted that winter months are rather chilly. However, the occupant described himself as a person who is not overly sensitive to temperature. This supported the decision to make the lighting problems the top priority for investigation.

Robotics Lab

BUILDING 32 - 3RD FLOOR
RAY AND MARIA STATA CENTER
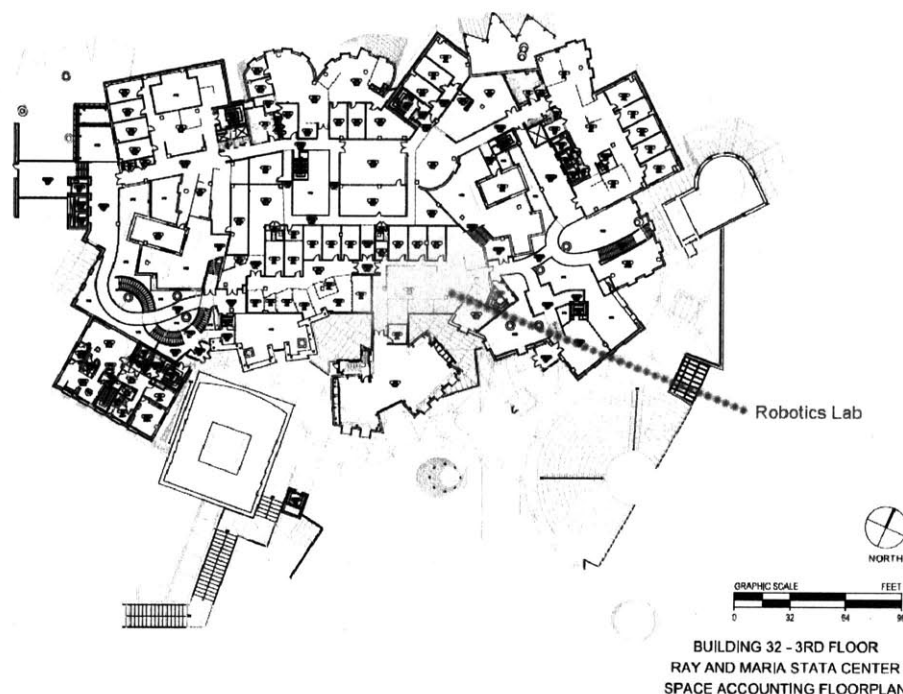SPACE ACCOUNTING FLOORPLAN

Figure 5.1: Floor plan of the 3rd floor of the Stata Center showing the lab in question.
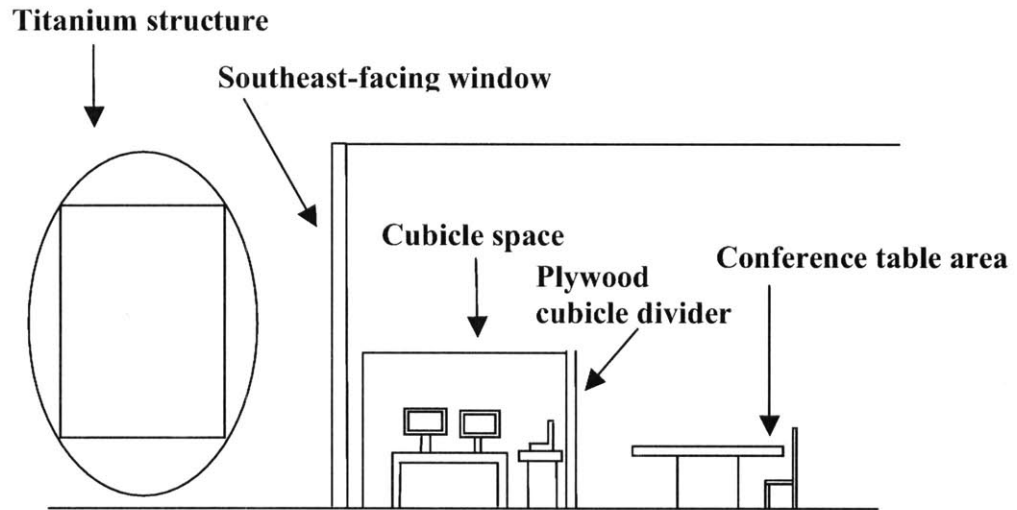
Figure 5.2: Simple cross section of the space with key elements labeled.

Figure 5.3: A photograph of the space from the outside. The space in question is inside the window beneath the yellow structure, circled in red. Source: Joanne Shapiro, City of Cambridge website
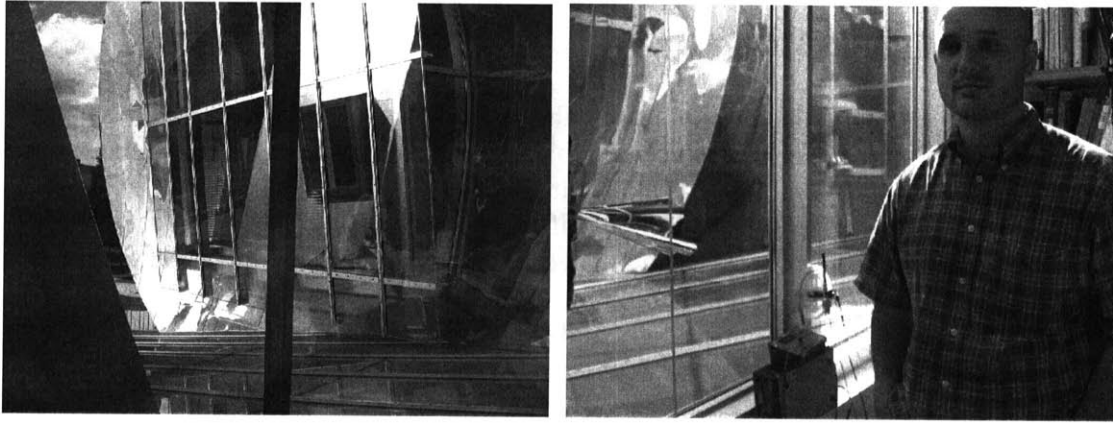
Figure 5.4: View from the window in partially cloudy conditions.

Figure 5.5: Desk directly opposite from the window with high contrast glare.

The interview with the occupant and investigation of the space showed that the space had quite interesting problems to be explored. Because of poor planning, a space with a large window area suffered from both glare problems and unnecessarily high electricity use from the overhead electric lights which could not be turned off and had to be supplemented with additional task lights to provide sufficient illumination for delicate robotics tasks. The strange geometry of the titanium-clad forms visible from the window suggested that the reflections causing the offending glare were likely to be quite complicated. In addition to investigating the causes of the glare, an inquiry into the possibility of making better use of daylight for tasks was needed in the theoretical situation that individual control for electric lamps could be implemented.

5.2 Investigation Methodology

After considering the project group's strengths, resources, and the available time frame, as well as the project goals, it was decided to use a physical scale model and heliodon to investigate the problem and test potential solutions. By using the automated heliodon as well as outdoor model testing, a variety of different studies covering different areas of investigation were performed. The automated heliodon was used for investigating the effects of direct light, a major motivation for the study, while the outdoor tests was used for investigations involving diffuse light and measurements.

5.2.1 Model Construction

When planning the model, the goal was to create something that could be used to study the effects of the enormous titanium exterior forms on the graduate student's small cubicle space, as well as to investigate possibilities for getting more light to the conference space behind the cubicle walls. Another design constraint for the model was the need for one person to be capable of carrying it. It was also designed to be small enough to fit on the portable heliodon, even though tests from this heliodon did not end up being used in the results of the study. Due to all of these restrictions as well as time constraints it was not possible to construct the full Robotics Lab and all connecting rooms and surfaces affecting daylight in the space. The abbreviated version cuts off the office spaces behind the conference table as well as other rooms connecting at the east and west ends of the lab. The final scale of the model is 1 foot equal to ¼ inch. The completed model has a footprint of about 22 inches by 27 inches, with a height of 15 inches in the tallest place. A plan of the space indicating the interior area that was modeled is shown in Figure 5.6.

During the model building, the known guidelines for daylighting model studies (Bodart, 2007) were followed as closely as possible. In addition, the model was designed to be versatile and modifiable in order to accommodate different types of studies. First, an attempt was made to select model construction materials whose reflective properties most closely match those of the real building in order to best simulate indoor lighting conditions, but many approximations had to be made. The shiny titanium exterior is modeled with reflective, flexible, mirror-like material of about 75% reflectance, while the slightly less reflective brushed metal surface beside the window is modeled with the less-shiny side of aluminum foil. The floor of the interior is modeled with cardboard that resembles concrete with a reflectance estimated to be close to concrete's 30%. The walls of the interior are covered with a speckled wallpaper material with an estimated reflectance of 50%. This was considered a crude compromise between the bright white walls of an estimated 85% reflectance that actually exist and the fact that all of the walls and interior of the room are literally covered with shelves filled with all kinds of objects and materials, which would have been impossible to fully model. All of these very rough approximations would have had a devastating effect on a study meant to predict actual illuminance measurements inside a real building. However, this study was intended mainly to investigate the times and effects of direct light, whose presence and location

would not be greatly affected by material properties. Measurements taken outdoors were used only comparatively and were not expected to predict real values.

Care was taken to ensure that as little light as possible entered the room through any opening other than the window. Black foam core was used as a principal structural material to ensure that walls were not translucent. The side walls and ceiling were glued and then sealed with black electrical tape to ensure that light did not enter through the joints, a common problem for daylighting models. The back of the room is removable in order to have the ability to insert cameras and luxmeters. While taking measurements and images, attempts were made to completely cover the open space with extra pieces of thick fabric. When luxmeters were used for outdoor measurements, the cords were led out of a very small hole in the bottom of the back wall and also covered with fabric.
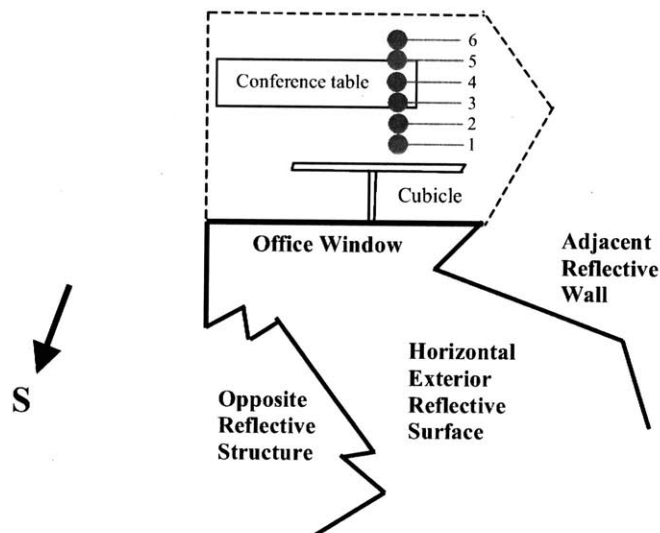
Figure 5.6: A plan view of the space useful for understanding the geometry and modifications that took place during testing. The dotted line encloses the interior modeled area, while the other elements are exterior. The numbered spots behind the cubicle wall refer to the illuminance measurement locations during the testing of the anidolic system.

One cubicle next to the window was also modeled, complete with the two computer monitors, desks, and chair of the occupant in order to see when direct light hit his work area as well as to add realism to the photos. A removable conference table was also added to the space (Figure 5.6) so that experiments aiming to increase daylight penetration to the back of the room could investigate this area. The model construction also included the creation of various interchangeable parts to be used during the course of the investigations. Since experiments to increase daylight penetration into the space were intended, two elements were created that could be used for improvement of this aspect.

One of these removable model components was an anidolic system. This advanced fenestration technology consists of a set of parabolic mirrors which collect and focus

light in order to increase daylight penetration depth (Figure 5.7). The equations governing the parabolic shapes and sizes required to attain the desired light collection and redistribution inside the space were originally developed by Welford and Winston (Welford and Winston, 1989). Development and study of these systems on real buildings has largely taken place at EPFL in Switzerland (Scartezzini and Courret, 2002) and has yet to be implemented on a wide scale.
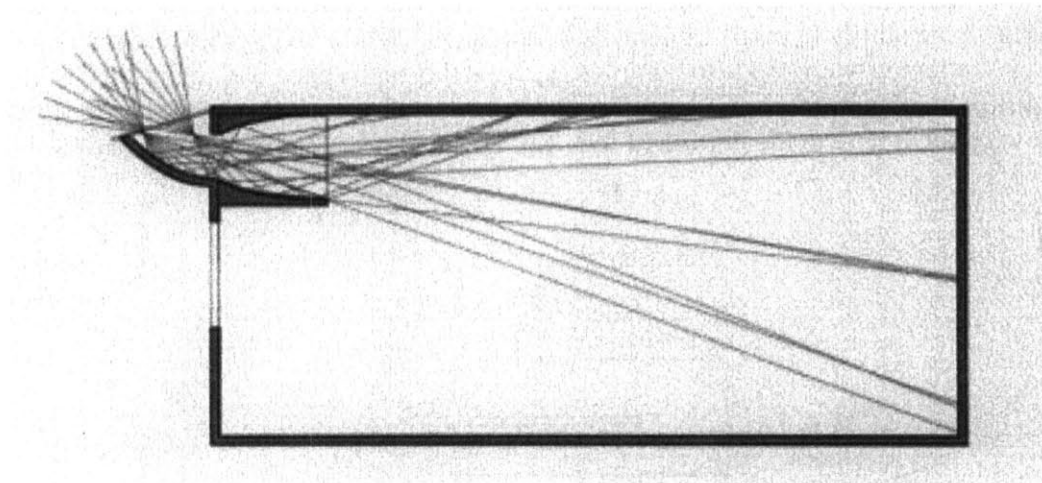
Figure 5.7: Diagram showing how diffuse light from a large portion of the sky is collected and redistributed inside the room by the anidolic system (Scartezzini and Courret, 2002)

The miniaturized model system was constructed by assembling laser cut pieces of cardboard (Figure 5.8) into a frame with the correct parabolic shape and then attaching curved pieces of reflective material using a system of loops, allowing the curved pieces to be easily added or removed from the model. In addition to the three parabolas, an additional horizontal part was added to the frame (being held in Figure 5.8), enabling the addition of an extended overhang during experiments.
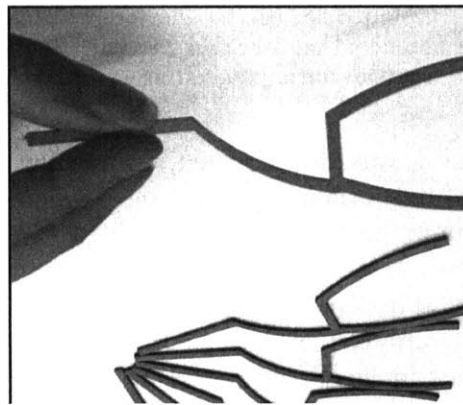
Figure 5.8: Laser cut anidolic frame pieces, with an extended support for a detachable horizontal overhang.

In addition to the anidolic system, a translucent cubicle divider was constructed in order to be able to later compared illuminance measurements in the conference table area (Figure 5.6) with this new divider compared to the older opaque one.

5.2.2 Automated Heliodon Use

MIT's automated heliodon was used to investigate the causes and potential solutions to the glare problem. While the automated heliodon can be used as a tool for glare analysis, there are some limitations. Since the automated heliodon only simulates direct light without the diffuse light of the sky, any luminance or illuminance measurements would not be representative of those in the real space. Contrasts between those areas that are hit by direct light are much higher than without the effects of other light sources which in this case are both skylight and electric lights within the room. Therefore, by looking at photos from the automated heliodon, one can guess about times and locations of glare likelihood but cannot measure any actual glare metrics.

One advantage to this is that patches of direct light are very easy to see, while in a sun-and-sky situation on a very bright day it might be hard to see exactly where direct light penetrates a room. It is useful to know where the patches of direct light are because they are those that can be most damaging to the eyes and also indicate areas of most likely solar heat gain. However, such a high contrast environment makes it difficult to get the correct photographic parameters adjusted to show both the dark and bright areas simultaneously.

For these experiments, several trial runs were done with different camera settings before deciding on the one to use for the tests. This is because settings that were optimized for periods of massive direct light penetration were too bright for periods of little light penetration. The contrast between bright and dark images with the same camera setting was especially pronounced with an interior model which during morning hours of the day receives a great deal of light while in the afternoon the sun is completely blocked. Additionally, certain photos tended to be extremely bright in some areas while quite dark in others, requiring a compromise of the various camera properties to strike a balance between them. This problem can be observed while examining several consecutive images of the space taken during this camera brightness adjustment process (Figure 5.7).

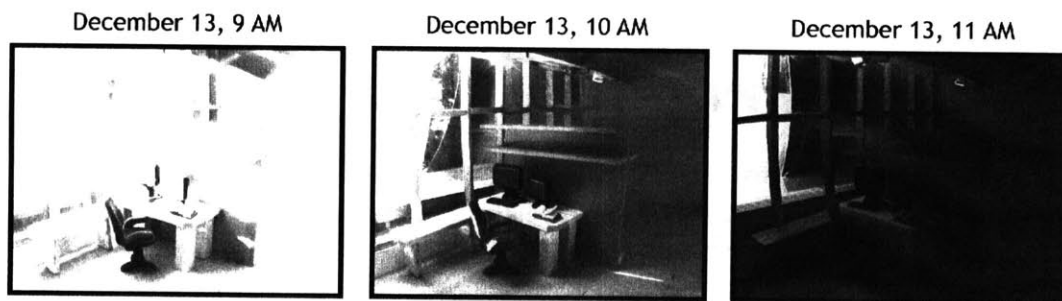December 13, 9 AM   December 13, 10 AM   December 13, 11 AM

Figure 5.7: Several consecutive images of the same exposure showing the control problem; it is difficult to optimize camera properties for a large range of brightness.

However, it was desired that the same camera settings be used for all of the photos in order to show contrast. The issue was resolved in this case by the decision to optimize camera gain for the brightest pictures with the most direct light penetration. Not only was this the main focus of the study, but brightening pictures without direct light penetration would have had little true meaning with the sky-less indoor heliodon setup.

To investigate glare, the various reflective surfaces outside of the window were to be systematically darkened in order to determine which ones were causing glare and when. At first, it was assumed that the visible opposing titanium structure and its contained window were the principle cause of the problem. Upon further consideration, however, it was noted that since this surface faces mostly north it is more likely to be a secondary reflective surface. It is in fact the south-facing reflective surface adjacent to the window that gets the most sunlight. The reflections off this surface cause the brightness of the titanium structure visible from the occupant's window. Experiments with potential glare caused by installation of an anidolic system were also performed with the automated heliodon.

At the time of the experiments, the new altitude motor (discussed in Section 4.4) had not yet been installed. The obvious mechanical problem at this time was the observed altitudinal oscillation of the table during eccentric table loading, which was later observed to cause severe error accumulation. An effort was made to weight the table more heavily on the side closest to the back wall to minimize this, but some oscillation still occurred. However, results were consistent when the same simulations were performed repeatedly and seemed generally reasonable from observation of the model and knowledge of what the correct sun angles were. The azimuth movements were also later found to be accumulating error, which may have accumulated to a high degree when many sets of images were run repeatedly without resetting the table.

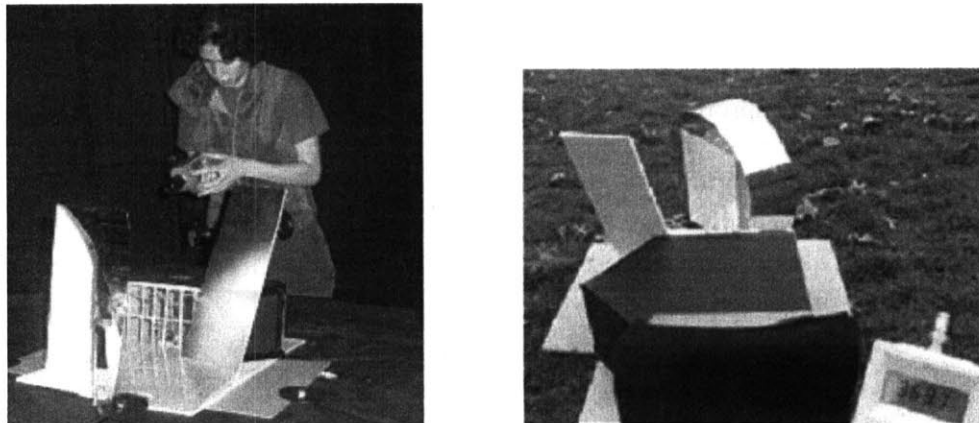**Figure 5.8: Left: setting up the camera on the automated heliodon; Right: taking an interior illuminance measurement outside with a luxmeter.**

Simulations may have been off by a several degrees in many cases. The exact positions of observed shadows and bright patches should not be considered to be perfect due to these mechanical problems as well as possible model imperfections. However, the

general patterns and times of direct light and shadows could still be observed in order to gain a better understanding of their causes and to gain further insight into the use of the device. The left side of Figure 5.7 shows the model and camera being prepared for use on the heliodon.

5.2.3 Outdoor Testing

Outdoor model tests with luxmeters were performed in order to test modifications meant to increase the light penetration to the back of the room (Figure 5.8). These features were the addition of the anidolic system as well as the translucent cubicle divider. Quantitative results from these tests were meant to show potential positive effects of the changes in the form of increased daylight factors or illuminance values, but, as mentioned earlier, were not meant to represent the actual values of these parameters within the real building.

With the anidolic system, several measurements were taken outdoors on an overcast day both with and without the system. Measurements were taken in the cubicle next to the window as well as at several points on the other side of the cubicle wall, indicated in Figure 5.6. These points were marked one inch apart in the model, which means they are about four feet apart in the real building. The measurements were taken on an overcast day, November 30 at 4 PM, and daylight factor was calculated using the ratio of indoor illuminance on the workplane to measured horizontal external illuminance. The translucent cubicle divider was tested on a sunny day, December first at 3:30 PM. Within the time constraints for the project, these were the only fully sunny and fully overcast days available.

The outdoor model tests were performed in Killian Court on the MIT campus. As investigated in Chapter 3, the presence of surrounding obstacles can cause errors in illuminance measurements. However, the buildings of Killian Court, at an average of about 22 meters high, are not tall enough to cause severe error. From Figure 3.15, it is likely that measurement errors from this source during sunny days were less than 1%, although for an overcast day these errors could have been as much as 5% (Figure 3.17).

5.2.4 Design Objectives and Constraints

The goal of this project was to investigate the possible sources of glare in order to determine possible mitigation strategies and also to explore possibilities to increase the use of daylight in the space including beyond the window cubicles, even though the current situation requires electric lights to remain on at all times. Even right next to the window, the interviewed occupant never used daylight to perform his precision tasks and instead retreated to a halogen-lamp-lit workspace deeper in the room. If increased daylight penetration was shown to be possible, this could in theory lead to a redesign of the space to take advantage of natural light and save electricity.

During the course of the investigation there were several important factors to keep in mind. First, view, though largely blocked by the opposing titanium structure, is appreciated by the occupants and should be preserved. Also, the lab is a space that

changes over time due to the preference of different occupants. The cubicle dividers and furniture are moveable and contribute to the space's versatility. Also, since the room is a PhD student work area, it is important that lighting effects are not distracting.

5.3   Experimental Results

The automated heliodon was used to perform glare source analysis of the existing situation. Advantage was taken of the computer interface features that allow many images to be taken in sets, especially the "Default Design Day Set" option. A screenshot of the matrix showing one of these sets is found in Figure 4.12. From this it can be seen that the camera exposure was optimized to show the bright images, and the dark ones represent times when little direct light enters the space. Of course, this should not be interpreted to mean that the real room is completely dark at these moments, but rather that little direct light enters, while diffuse light and electric light are still present.

Experiments were first performed to determine exactly when direct light was likely to be a problem throughout the year. Initial experiments suggested that there were three possible glare situations: when direct light actually entered the room itself, when it was visible on the opposite structure, and when it was visible on the horizontal exterior (Figure 5.9). As mentioned earlier, the condition of no direct light for these camera settings gives an almost entirely dark image. Even when no direct light enters the space itself, visibly bright exteriors can still cause discomfort.

| Direct light inside | Bright opposite structure | Bright horizontal exterior |
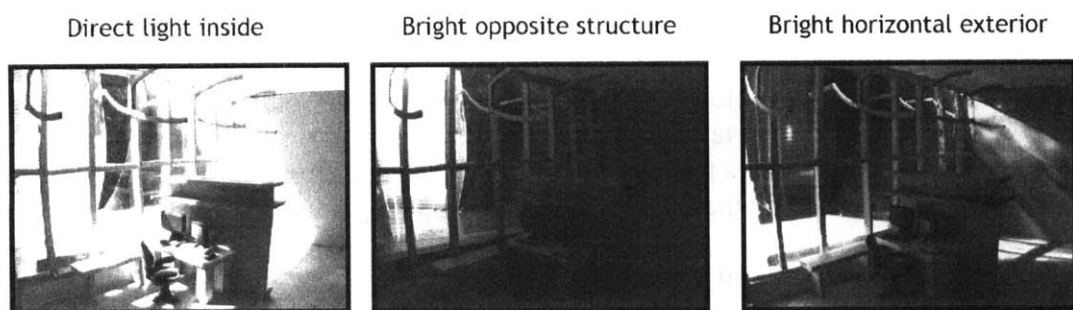
Figure 5.9: Examples of the types of lighting conditions that could cause discomfort glare.

Knowledge of these divisions could in theory affect what types of shading devices would be needed at what times if a future control system was ever designed. By taking many images using both the "Default Design Day Set" and the "Planned Image Sets" options to hone in on specific hourly transitions, the following table of glare problem likelihood was produced (Table 5.1).

In addition to this table that divides the potential glare problem into different surface occurrences, another attempt to summarize the times and causes of possible glare was made using a stereographic chart, considering the different angles present and estimating their effects on the interior (Figure 5.10).

direct light inside
bright opposite structure
bright horizontal exterior
no direct light

Hour	Dec	Jan/Nov	Feb/Oct	Mar/Sept	Apr/Aug	May/July	Jun
8:00 AM							
9:00 AM							
10:00 AM							
11:00 AM							
12:00 PM							
1:00 PM							
2:00 PM							
3:00 PM							
4:00 PM							

Table 5.1: Table of glare problem likelihood from different surfaces, obtained by automated heliodon experimentation.

Figure 5.10: Stereographic diagram showing the hours of the year when glare is likely to be a problem

5.4 Improvement Proposals and Validation

5.4.1 Proposals

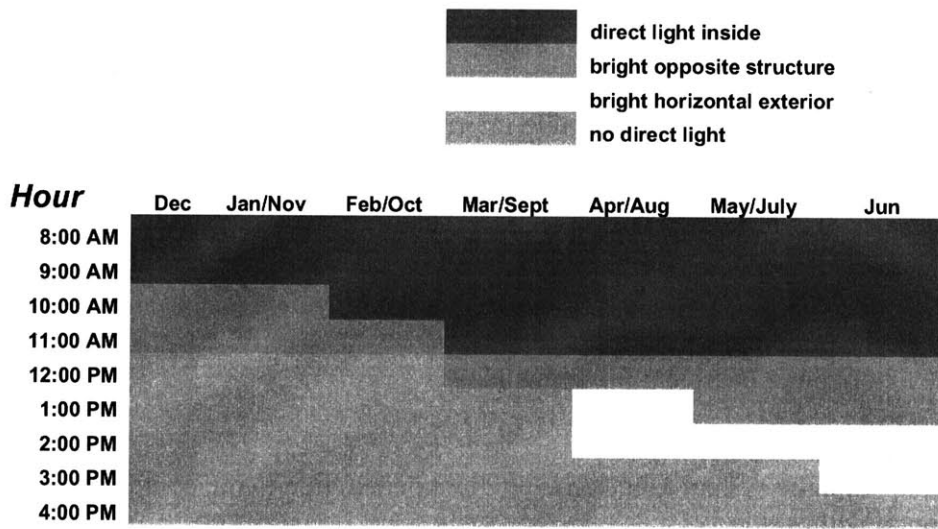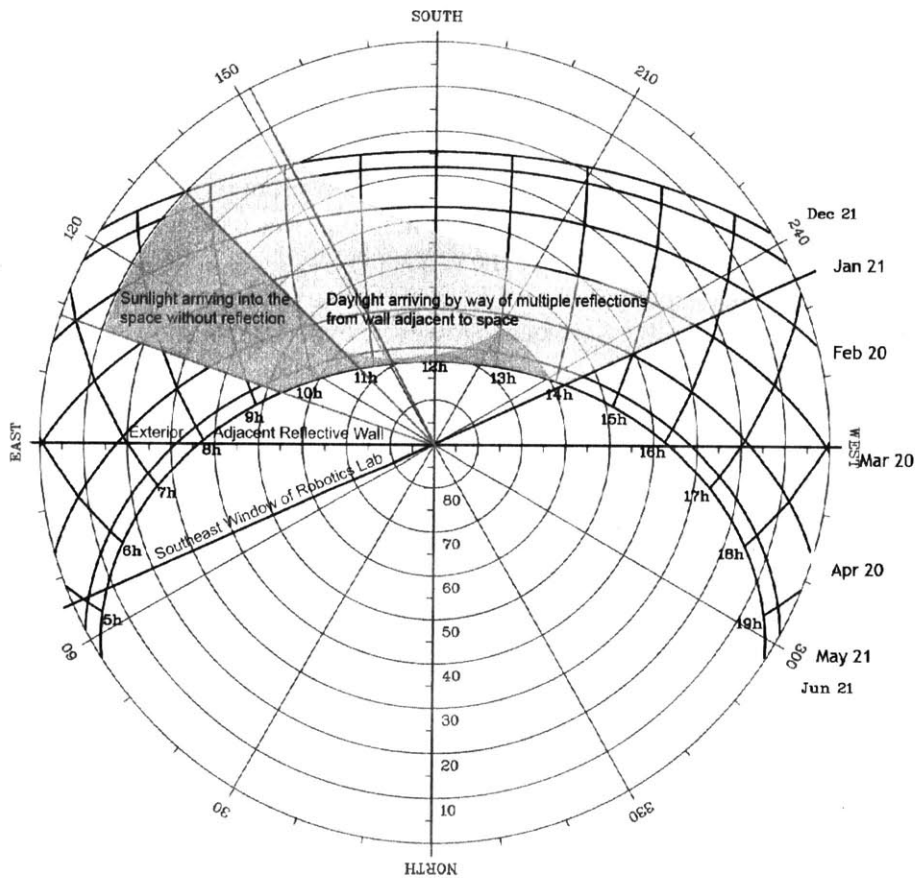The following proposals were made as possible improvements to the space. Estimates about their effectiveness in the real building were then made through experiments both on the automated heliodon and outdoors.

To decrease glare:
1) Substitute dark and diffuse materials in place of the reflective metals and glass located on the building exterior.
2) Provide a horizontal overhang for the window.

To increase the use of daylight:
1) Provide an anidolic system to increase daylight penetration to the conference tables on the other side
2) Substitute the opaque cubicle dividers with translucent particians to allow more light to penetrate to this area.
3) Move the occupant's extra table across from the window directly adjacent to the window to use as a robotics worktable during the day instead of the halogen-lit area.

5.4.2 Validation

Following the procedure of systematically darkening different reflective surfaces in an attempt to fix the glare problem, the automated heliodon was used to take multiple images of each configuration to observe the effects. Since the adjacent vertical surface faces south, it was expected that darkening this surface would remove the glare problem without needing to darken other surfaces. However, experiments showed that this did not mitigate the periods where direct light hit the exterior horizontal surface. An overhang was tested as well in hopes that this simple structural element would make a difference.

The image that follows shows an example of the effects of darkening the adjacent vertical reflective surface. Since during much of the day sunlight from the south reflects off this surface and then hits the opposing, visible structure, darkening it managed to cut out this source of glare without needing to alter the visible structure itself, which faces north (Figure 7.9). However, this measure did not prohibit direct light from entering the room itself or from hitting the visible exterior horizontal surface.
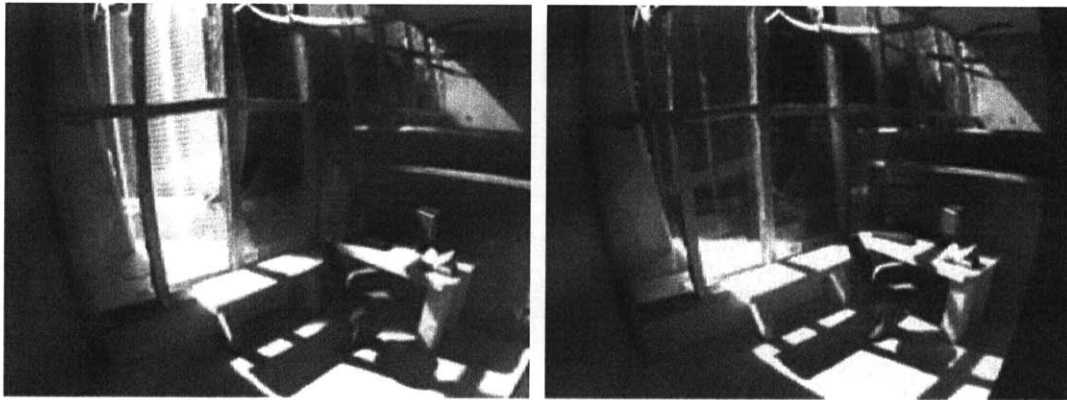
Figure 5.11: Sample results of darkening the adjacent, south-facing wall. The image on the left shows the model without modifications and the brightness visible on the opposing structure. On the right, the adjacent vertical surface has been covered with black fabric to keep it from reflecting light onto the opposite structure. Both images are simulations of March 21 at 10 AM.

Since glare remains at some hours from the exterior horizontal surface, it was shown that this surface also needed to be darkened (Figure 5.12). However, some direct light still entered the space.
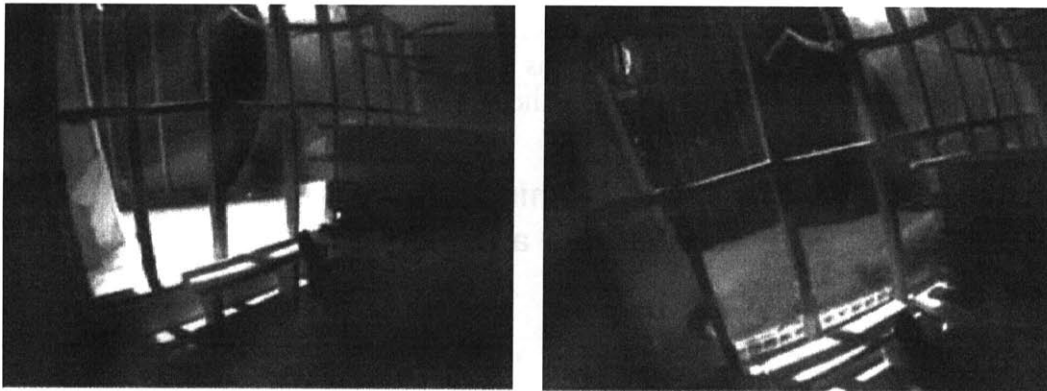
Figure 5.12: Results of darkening both the horizontal exterior surface and the adjacent wall. Both images are simulations of June 21 at 10 AM.

A horizontal overhang was then added to determine if it cut down direct light in any significant way. However, it was shown that this did little to help, when added to a scenario where the adjacent vertical and horizontal surfaces were both already darkened (Figure 5.13). In the example shown, it removed some direct light from the computer desk workplane but not the desk placed next to the window; this was also the photograph that showed the most difference between the two options; most photos taken showed no difference at all.
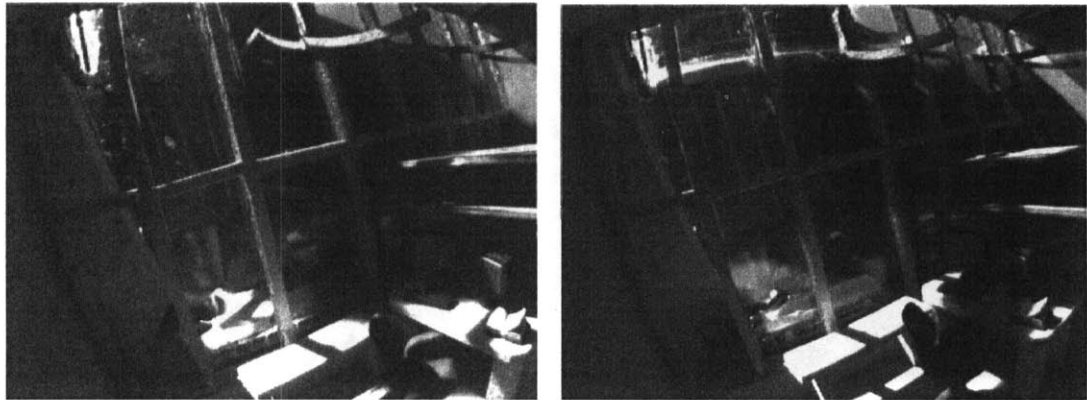
Figure 5.13: Results of adding a horizontal overhang while also covering adjacent surfaces with diffuse fabric; the shading device did little to mitigate the problem. The left image has no horizontal overhang while the right image has one. Both images show simulations at June 21st at 10 AM.

After the automated heliodon investigation of direct light, outdoor testing was used to assess the potential performance of the anidolic system and the translucent cubicle divider. Figure 5.14 shows the daylight factor at the six points in the room indicated in Figure 5.6, both with and without the anidolic system. The opaque cubicle divider was left in place for these experiments. Since point 1 is directly behind the cubicle wall, measurements taken here were lower than further into the room. Point six with the anidolic system was removed as an outlier as it was later realized that its very low value was most likely due to accidental tilting of the sensor during measurement.
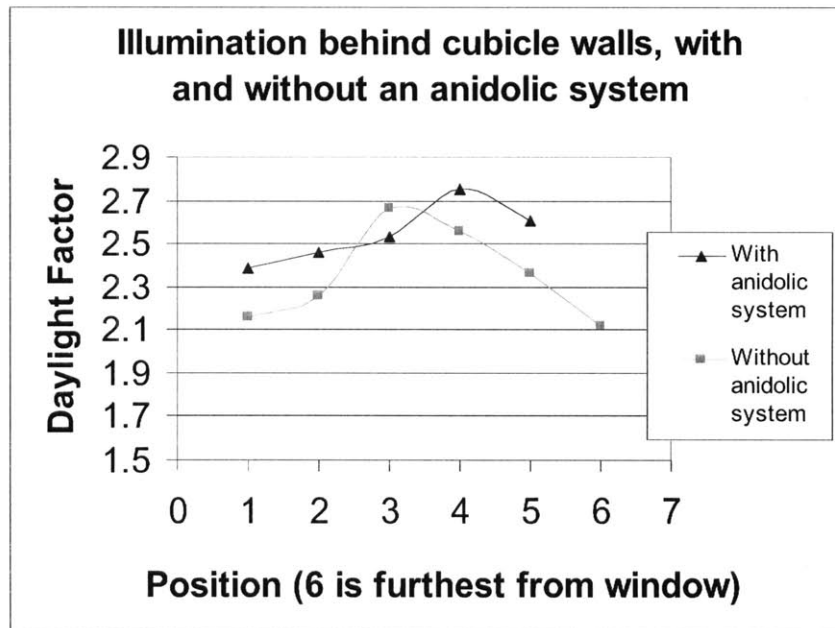
Figure 5.14: Table of daylight factor (%) with and without the anidolic system, taken outside on November 30 at 4 PM, an overcast day. These positions behind the cubicle wall are indicated in Figure 5.6.

Figure 5.14 shows only a very small increase in daylight factor with the addition of the anidolic system, only about 0.2%. However, the daylight factor peak did occur in the most desired location, around point 4 in the graph, which is the center of the conference table. Additional measurements were taken within the cubicle space, next to the window. Installtion of the anidolic system was found to decrease the daylight factor there from 15.3% to 12.2%. This reduction in daylight factor next to the window is expected since the part of the system outside of the window acts as a horizontal overhang.

Even though the improvement with the model's anidolic system was small, the improvement resulting from installation of a real anidolic system in the building would likely be greater, primarily due to model imperfections. Even though the cardboard parabolic reflectors rest on a frame of the correct shape, the cardboard itself is not perfectly curved; it tended to flatten out between frame supports, as similarly observed by Siân Kleindienst, who also built a miniature anidolic system for scale model testing (Kleindienst, 2006). Additionally, there are imperfections in the material itself, such as smudges and wrinkles. Also, the inside of the anidolic system is not entirely flush with the window surface; there is a gap through which some light could escape. Lastly, a crude test with a laser pointer and luxmeter revealed that the reflectance of this material is only about 75%, while that of a real anidolic system should be over 90% (Scartezzini and Courret, 2002). Correction of all of these factors would surely increase the positive difference observed with the model system.

Anidolic systems work most effectively under overcast conditions, and glare problems can result during sunny days when direct light hits the parabolic mirrors. To visualize these possible effects, the system was tested on the automated heliodon (Figure 5.15).
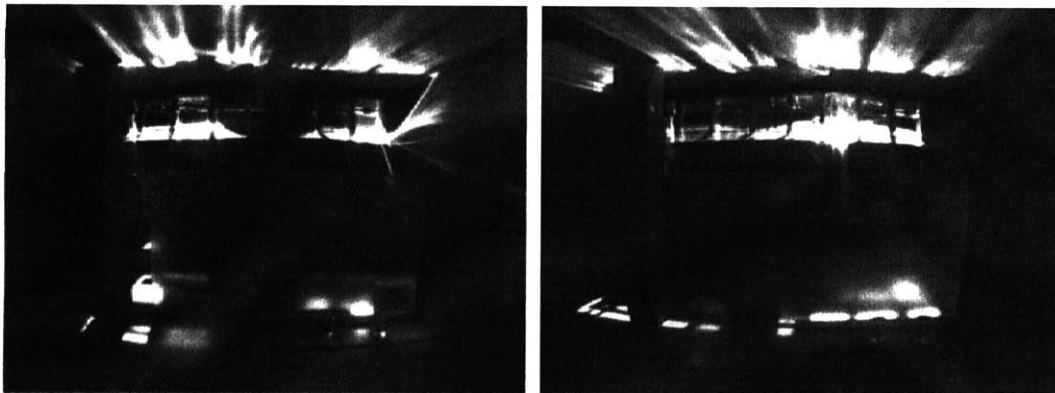
Figure 5.15: Images from the automated heliodon on March 21, 10 AM (left) and 11 AM (right), showing that direct light on anidolic systems can be a source of glare.

The images above show typical morning conditions of direct light, viewed from the conference table area. Just like the other glare problems at the window, these effects essentially follow the schedule shown in Table 5.1, with some variation. An automated diffusing shade would probably be necessary during morning hours to prevent discomfort and distraction for those using the conference table on sunny mornings, even though these effects can appear quite interesting. The light patches caused by direct light on the

model's anidolic system are similar to the effects observed in a real building with such a system, as shown in the comparison below (Figure 5.16). Figure 5.17 shows another model image with the anidolic system where the light reflections look quite similar to the ray-tracing diagram of light interacting with an anidolic system in Figure 5.7.
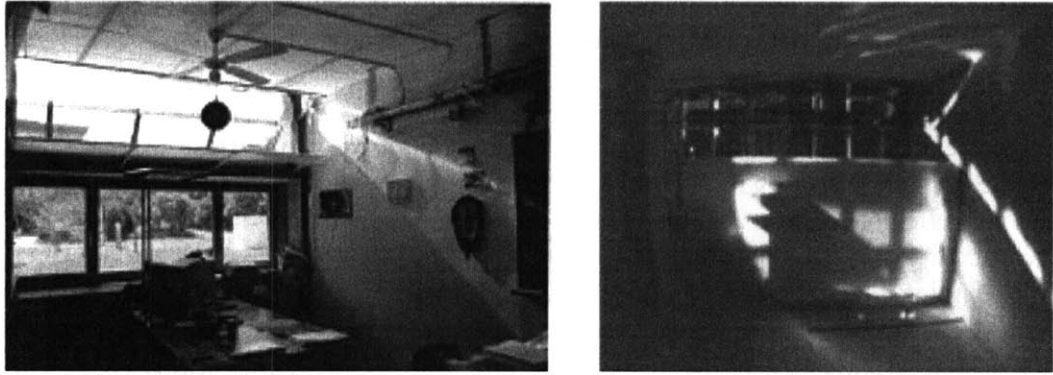
Figure 5.16: Left: Interior of a room with an anidolic system exposed to direct light (Photo courtesy of Siân Kleindienst); Right: A model photo from the automated heliodon showing a similar light pattern caused by the anidolic system. In this image, the cubicle shelf behind the divider makes a shadow that happens to resemble a grand piano.

Figure 5.17: Another view of the model with the anidolic system, showing that it creates lighting effects that look very similar to the ray-tracing diagram in Figure 5.7.

The translucent cubicle divider was also tested outdoors on a sunny day, December 1 at 3PM. From this experiment, it was shown that replacing the opaque cubicle divider with a translucent on did increase the illuminance on the conference table area, from 110 lux

to 162 lux. Even though this difference is small, this experiment was only performed at once time on one day, and a larger variety of measurements could show different results. However it is likely that the translucent divider would increase illuminance in all cases since it allows light from the window to more easily reach the back of the room. Though the divider could be removed altogether, the translucent option retains the privacy of the occupant.

The last and most simple experiment meant to investigate potential ways to increase the use of daylight involved a comparison between potential work areas near the window and the halogen-lamp-lit area the interviewed student uses for his more detailed robotics work. Though the occupant claimed that the desk immediately across from his window (Figure 5.2) did not get enough light to perform precision tasks, it was discovered that this is partially because his own body blocks light from the window when he sits in front of the desk. While the halogen lamp area measured 2450 lux on the workplane during an October morning at 11:45 and 1600 lux at night without the contribution of daylight, the desk across from the window measured 1388 lux at the same time provided that no one was sitting in front of the desk and blocking the light.

5.5   Conclusions

5.5.1   Recommendations

From these experiments, it is highly recommended that the reflectivity of the adjacent vertical surface be reduced by changing the material to something such as the more diffuse brick that is used in other parts of the building, though this is probably infeasible. The surface could also be sandblasted or covered with another diffusing material. Since the exterior horizontal surface is a skylight, an attempt to reduce its reflectivity would result in less illumination of the room below. Unfortunately, the horizontal overhang did little to mitigate any of the problems, as the addition of this simple structural element would probably have been relatively easy and inexpensive to implement. The complete removal of the visible titanium structure could also fix some of the problems, even though experiments in this configuration were not performed. Some kind of blinds or shading system is likely to be necessary, though if automated it could be removed during the correct hours of the afternoon when direct light no longer enters the inside or visible outside of the space, or on overcast days.

While the addition of both the anidolic system and the translucent cubicle divider showed some improvement in illuminance behind the cubicle walls, the effect was small and further experimentation would be needed to be able to recommend confidently that they would significantly improve the space. Perhaps with a more sophisticated physical or computer model, an anidolic system with a higher surface reflectance with fewer imperfections could be created for experimentation. However, with the anidolic system, a system of blinds for morning hours should be installed to prevent distracting glare.

In the case of the desk across from the window, it is suggested that the table be moved directly in front of the window; the table was in fact placed in this position in the

constructed model. Unfortunately, this does not account for the fact that there is likely to be visual discomfort in this location with the current setup as direct light would often hit the table itself or be visible on the exterior horizontal surface and opposite structure during the morning. However, overcast days or afternoons may be quite feasible times for using this workspace.

5.5.2 Discussion

The Stata Center robotics lab in question is unique. The various reflective surfaces around the window interact to create a space that is far more problematic than any ordinary façade. Effective shading of the window requires consideration of the orientation of the façade and also the other reflective surfaces, as well as their tilt angles.

This is not the only example of Gehry's signature reflective forms causing this type of problem. The Walt Disney Concert Hall, for example, is famous for having caused extreme glare problems and unwanted heat gains to surroundings due to the geometry and orientation of some of its polished stainless steel surfaces (Archiseek, 2007). Massive sandblasting of the offending surfaces took place in 2005 to mitigate the problem, and could be helpful in this case as well.

Besides the glare problem, the other drawback to the space is that it does not make very good use of daylight for tasks. For additional energy savings, better control is needed over the electric lights if ways to increase daylight penetration are implemented.

Despite the approximations that needed to be made during construction and testing, the methods used seemed quite appropriate for the study at hand. The automated heliodon, which only shows the effects of direct light, was appropriate for diagnosing the causes and occurrence times of glare likelihood from direct sun. However, the method of systematically darkening different surfaces could be seen as counterintuitive, since in the case of this building a "good" image is one that is almost completely dark, meaning that little direct light enters at that moment.

While outdoor testing was used comparatively for measurements, more measurements at different times or simulated times with the outdoor heliodon would have been useful. With more time, it would have been possible to use large grids of luxmeters inside the model under different conditions in order to determine if specific workplane illuminance goals were met. However, the "before and after" measurements that were taken clearly showed improvements resulting from the modifications, even if they did not predict the exact values that would occur within the real building.

As an alternative to the automated heliodon glare analysis, glare data could have been obtained using outdoor photos analyzed with Evalglare pixel analysis software, which highlights areas of a photo whose pixel luminance is four times brighter than the average value (Wienold and Christoffersen, 2006). This would have allowed a more concrete

110

assessment of whether glare actually occurred as it would take into account the effects of both direct and diffuse light.

There were of course some drawbacks to scale model testing methods observed during this experience. It was often hard to schedule outdoor testing based on weather and time of day, when project team members were not available to meet during many overlapping times. It was also difficult to get a great deal of quantitative measurements reflecting the performance of the space before and after modifications. However, the method did allow a great deal of qualitative information to be gathered at once, which helped to quickly reach conclusions about which improvement methods worked best. With one versatile scale model, many different parameters were tested in a very short amount of time. The amount of visual information obtained far exceeded that which would have been possible with software and limited experience in the same time period allowed for the project.

6   User's Perspective

6.1 Student Survey

In order to evaluate the usability of the automated heliodon as well as to generate and assess interest in the setup, student volunteers were recruited to try out the system and take a survey.   Participants were given several tasks to perform with the automated heliodon while their ability to figure out how to perform them was observed. These tasks simply measured the participants' ability to find options on the interface and did not test their knowledge of sun issues or their particular model designs. Results are used to plan improvements to the software interface. In addition, survey and interview questions were given to help assess if, when, and how the students would like to use the setup for future projects.

6.1.1 Procedure

The procedures and tests used for this study were based on consultation with Michael Dutton of the MIT Information Services and Technology Usability Group. Students were recruited from both the undergraduate and graduate architecture programs at MIT. Among the sampling of students, there is a bias towards students actually interested in sun issues and those who are personal acquaintances of the author. Participants were asked to bring their own models that they were interested in investigating with regards to sunlight. Two of the students who did not have models ready used the author's interior model, represented in the investigation of Chapter 7. The first step in the procedure was to explain the working principles of the setup to the student when he or she entered the lab: the light source, mechanical table, and computer interface. The student was then assisted in attaching the model to the table, positioning the camera, and securing the wires. A permission slip was signed to begin audio recording, so that the experience with the interface and following interview could be more easily documented. The participant was then told to open the program and perform a series of tasks.

The tasks were divided into four sets, given to students on slips of paper. These four sets of instructions were meant to test the use of each of the four image capture options, integrated with viewing and managing the acquired photos. Tasks were assigned in random order for each student. Additionally, the participant was asked to "think aloud" while performing the tasks, as this is considered a valuable way to obtain usability information by revealing the user's thought process if correct technique is used (Boren and Ramey, 2000). The student was first asked to select Boston, MA as the testing location and then follow the tasks below:

1. **Testing the use of the Default Design Day Set**
    -Take a set of images that represents four typical design days at different times throughout the day.
    -After the set is taken, view this set as a matrix.

-Look in your folder of images and find the image which represents December 21 at 4PM from the set you just took.
-Change the name of this image to "Interesting.jpeg"
- Return to the interface.

2. Testing the use of the Planned Image Set
- Take a single image on March 8 at 3PM and another single image on May 1 at 9AM.
-Find these 2 images in the folder. Change their names to "Image1.jpg" and "Image2.jpg" respectively.
-Return to the interface and change the building orientation value to 15 degrees west of south.
-Take the same photos that you took before. Find these in the folder and change their names to "Image1a.jpeg" and "Image2a.jpeg"
-Return to the interface.

3. Testing the use of the Image Series
-Find a way to take an image at 12PM on the first of each month, starting on January 1 and ending on December 1.
-Locate these images in the correct folder, find the image for April 1, and delete it.
-Reposition the camera for a different point of view of the model.
-Take a single April 1 at 12PM image with the camera at this new location.

4. Testing the use of the Video option
 -Find the video simulation tool and run it for December 21.
-Watch the video simulation.
-Close the video simulation window and return to the location selector. Change the location to Tokyo, Japan.
-Repeat the video simulation and viewing, but this time for September 2.

After the tasks were completed the students were asked to fill out a survey, which consisted of some questions specific to the heliodon mixed together with the ten standard questions of the widely used System Usability Scale, or SUS (Brooke, 1996). An SUS score from 0-100 is meant to be a true numerical indicator of the user's attitude towards a system. The SUS is categorized as a Likert scale, meaning that respondents indicate their level of agreement with a statement (Likert, 1932); the SUS uses a five point scale from "strongly agree" to "strongly disagree." On the SUS questionnaire, the user chooses a number between one and five, with one meaning "strongly disagree" and five meaning "strongly agree;" selecting the number three means that the participant neither agrees nor disagrees with the statement. The SUS was originally constructed by selecting statements that were likely to provoke strong negative or positive responses. The statements themselves alternate between negative and positive with which the participant may agree or disagree, requiring the person to more carefully consider each statement. This means that choosing "1" for a negative statement indicates a positive attitude, while selecting

"1" for a positive question indicates a negative attitude. This is meant to prevent response bias caused by a questionnaire where all of the statements to respond to are positive or all are negative. It is quite possible that in this situation a person could initially choose several "1" responses in a row, for example, and then continue to do so for the rest of the survey without fully considering each new question (Brooke, 1996).

The ten standard SUS questions were mixed with ten other questions of special interest to the author. While some of these were meant to provoke positive or negative responses to certain specific features, others regarded if, when, and how the participants might use the heliodon setup for their work. An attempt was made to switch between negative and positive with these questions as well.

However, this switching between negative and positive did cause confusion for one participant who seemed to initially expect all "strongly agree" responses to indicate a positive attitude about the system. The person was later contacted in order to double check her intended responses when several of them indicated a strongly negative attitude that conflicted with the very positive attitude she expressed in the interview following the survey. It is also considered likely that this source of error could have occurred in the case of others' responses where a difference between opinions indicated in the survey and those expressed in the interview were more subtle and therefore inappropriate to question. This possible source of error caused by an unfamiliar survey format should be considered when administering this type of test. It may be worthwhile to precaution participants about the style of the questionnaire in advance so as to prevent the awkwardness of later needing to question participants' individual responses without seeming like one is attempting to influence their honest opinions of the system.

The ten SUS statements followed by the author's own statements are given below and their numbers referred to in the results.

SUS Statements
1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in the system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

Additional Questions
11. It is easy to find, view, and compare the photos from each set after they are taken.
12. I find the mechanical setup (Camera placement, model attachment, etc.) quite difficult.

114

13. My studio reviewers or clients would be interested in seeing these photos.
14. I would only use the photos taken with this software for my own use, and not show them to clients or studio reviewers.
15. This software is appealing/fun to use.
16. I would most likely use this program to look at large site models.
17. I would most likely use this program for detailed interior studies.
18. I would use this device in the very early design stages
19. I would use this device in the later or intermediate design stages
20. I would prefer to use computer modeling methods instead of physical model testing.

The first two of the author's questions were meant to elicit negative or positive responses towards specific features of the setup, while the others were an attempt to find out if and how the system might be used.

After filling out the survey questions, the users were asked to comment about how and when the system would be useful for their work, and invited to make any other suggestions they might have about the interface design or the setup itself.

6.1.2   Number of Participants

Seven students performed the usability tests, which is within the 5-8 range generally preferred by usability professionals. A good deal of research has taken place regarding the number of participants necessary for conduction of usability studies. Since this testing is often quite time consuming, researchers have had ample motivation to discover what number of participants will yield the information they need. Unlike other statistical endeavors involving many users, it has been shown that a small number of participants can uncover most of the important problems in a system. Virzi (1990 and 1992) found that five participants uncover 80% of these problems, while increasing the number to ten could find 90%.

One usability researcher states that these studies led him to a successful practice of running 5-8 participants and stopping when he ceased to encounter additional problems (Dumas, 1997). Continuing to uncover new problems after 5-8 people suggested that more participants were needed, though this rarely occurred except in instances of extremely high user variability.

The author's experience during the heliodon usability testing reflected the findings of these studies. While seven official tests were carried out in total, three early unofficial testers of the setup who did not perform identical interface tasks also uncovered similar flaws in the system. After about the second official tester, the author did not find any new and surprising information related to "major" system problems. Complaints of cosmetic problems varied according to individual users' particular tastes.

While a large body of research exists supporting both the use of only 5-8 subjects for usability tests as well as the value of the SUS as a true usability indicator, an apparent paradox exists because such a small number of participants cannot be considered a

statistically significant sample size in regards to responses to individual SUS or other questions taken during the testing procedure. Generally, a sample size of 30 or above is recommended in order to make inferences about a larger population. While this issue has not yet been thoroughly resolved, one study of 123 participants which compared the usability of two websites using the SUS and other scales additionally experimented with what results would have been obtained with a smaller number of participants. Randomly selected groups of 6,8,10, 12, and 14 were analyzed to determine the likelihood of a statistically significant preference for the "correct" website, that is, the preferred website discovered by the testing of 123 participants. The SUS performed better than the other scales in this test, reaching a 75% accuracy with a sample size of only 8, although 6 testers yielded only 40% accuracy (Tullis, 2004). If one of the early unofficial tester's SUS scores is added to the seven official testers, the eight participants' scores are suggested by this study to be representative of a much larger population.

6.1.3   Results

The total SUS score is obtained by summing the score contribution from each item. For the positive questions 1,3,5,7 and 9, the contribution is the scale position minus one. For the negative questions 2,4,6,8 and 10 the score contribution is five minus the scale position. The sum of the score contributions is then multiplied by 2.5 to get the SUS score.

The usability scores from the SUS questions ranged between 75 and 98 out of 100, with an average of 84.6 and standard deviation of 8.6, indicating a quite favorable response from the small sample size surveyed (Figure 6.1). If the early unofficial tester's score of 85 is added, this average becomes 84.7. There is still some debate as to what SUS score is considered good or bad; usability consultant Michael Dutton stated that there is current research taking place which seems to suggest a correlation between extremely negative interview comments and an SUS score of 65 and below.
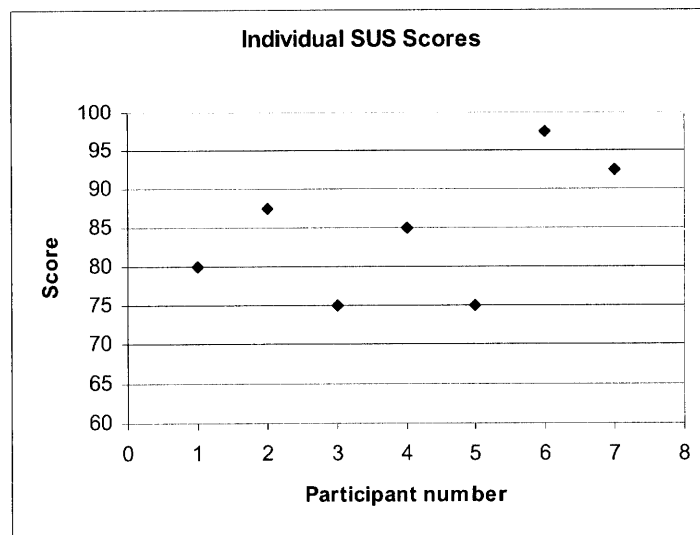
Figure 6.1: SUS score distribution from the seven participants.

116

Responses to the individual components of the SUS questionnaire are displayed in the graphs below (Figures 6.2 a and b). Since selection of high scale positions for the positive statements and low scale positions for the negative statements contributed to a higher overall SUS score, these graphs show why a high average overall SUS score was obtained. Even if the actual meaning of specific SUS scores is still debatable, examination of the responses to individual questions clearly indicates a very positive response overall to usability of the heliodon setup.
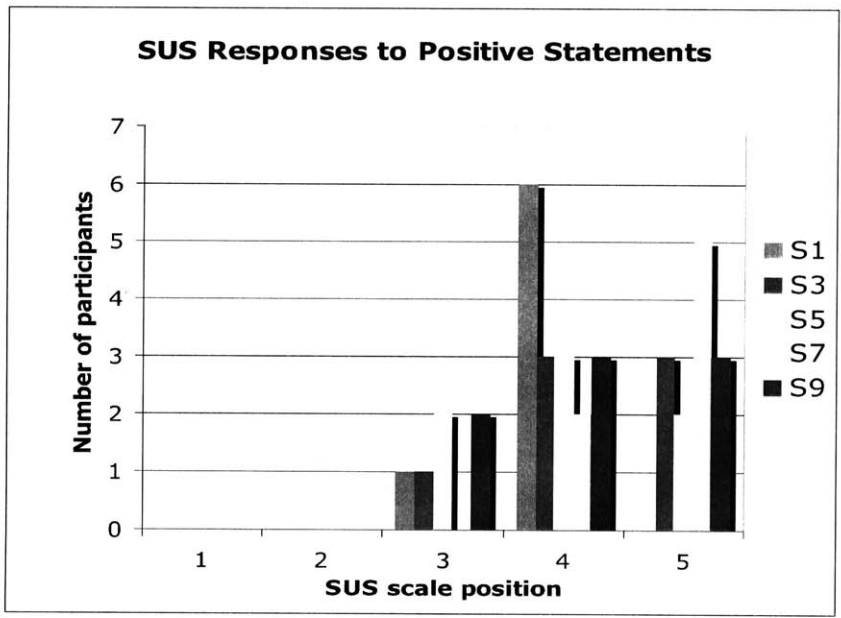
6.2a
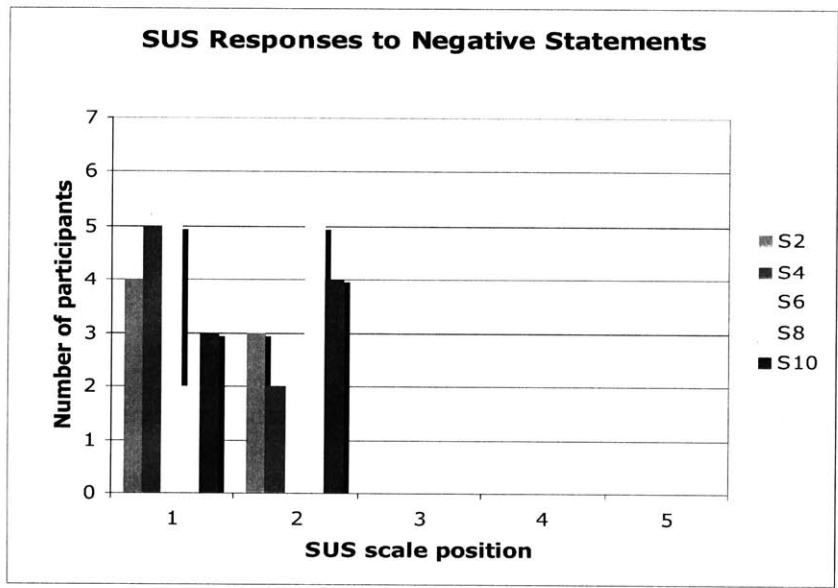
6.2b

Figure 6.2 a-b: Responses to individual SUS statements S1-S10, grouped by positive and negative statements.

The additional questions that were mixed with the SUS had more varied responses, making it difficult to generalize the results. A large number of responses for these questions were also threes, meaning that the participants neither agreed nor disagreed with the statement. This indicates a lot of variability among the sample size tested but in retrospect may have been the fault of the wording of the questions. For example, statements 16 through 19 about how and when the student might use the heliodon could be interpreted to imply that the student would only use the heliodon at those times when in fact a student might use it in many different situations and would therefore disagree with all of the statements. A summary of the results is given below. As mentioned above, though some of them regarded specific features of the setup, others were meant to investigate how the participant might like to use the system. Responses to statements 11 and 12 (Figure 6.3) suggested that the image file viewing capability was adequate but that the mechanical setup was somewhat difficult for some people. This is probably mainly due to the camera focusing problem and the use of the current clamping system which will be replaced with a more ergonomic one.
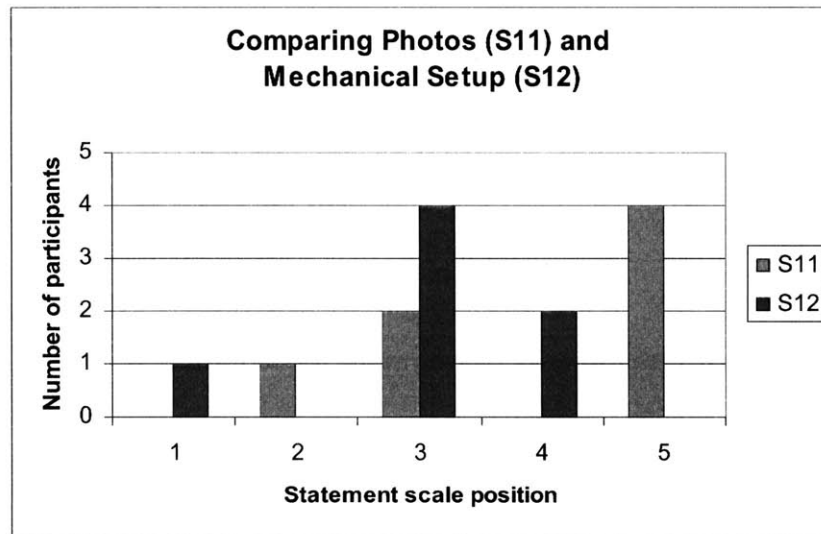
Figure 6.3: Responses to statements 11 and 12.

Responses to statements 13 and 14 suggested that the photo analysis capability would be useful in the process of studio or client reviews for the students surveyed; six out of seven participants agreed or strongly agreed that their studio reviewers or clients would be interested in seeing the photos, and four out of six students disagreed or strongly disagreed that they would use the photos for their own use and not show them to reviewers. Six out of seven students agreed or strongly agreed that the software was appealing/fun to use.

Statements 16-19 regarded how and when the students might use the device with what types of models (Figure 6.4). The wide spread of the results suggests that the students foresaw themselves using the device in many different possible ways. However, this question might have been inappropriate for students who had just tried the device once

and had not had the opportunity to consider how it might be useful during the course of various projects.
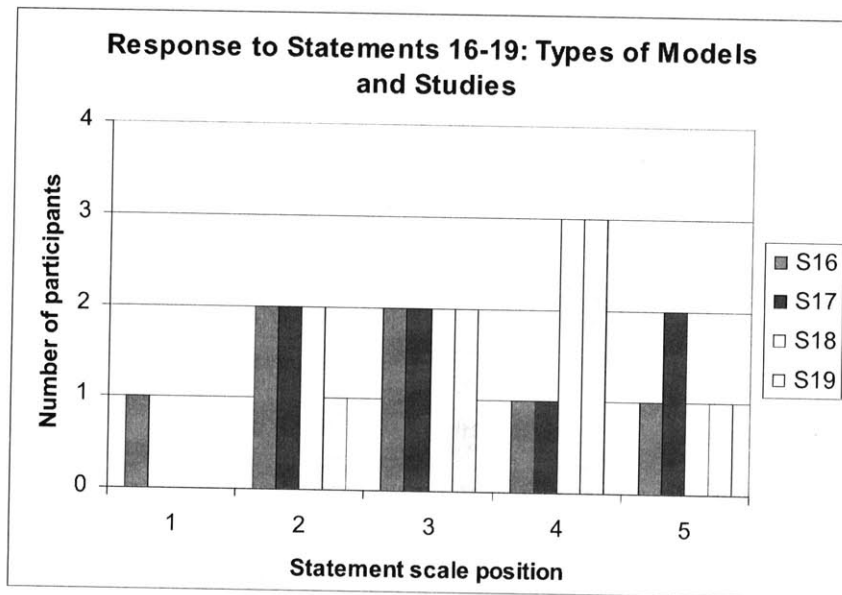
Figure 6.4: Responses to statements 16-19.

Statement 20 regarding the use of the heliodon versus computer programs also elicited a varied response that leaned towards preference for heliodon use. One student declined to answer, writing in "depends on how easy you have access to a system like this," though he did express enthusiasm for using the device in his subsequent interview. This also may have been an "unfair" question since the student had just experienced using the heliodon without being given a chance to perform tasks using Ecotect, for example, right after. Not all of the students involved had necessarily used software to perform any type of analysis other than to create renderings.
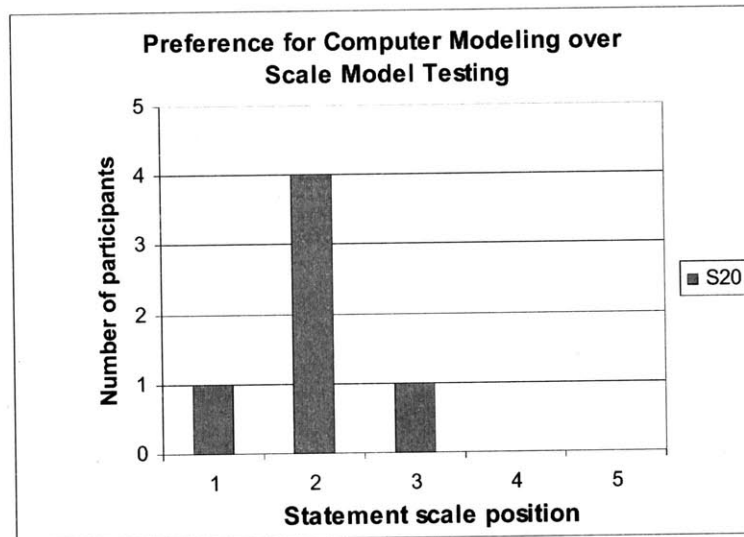
Figure 6.5 Response to statement 20 regarding the use of computer modeling.

A better understanding of the reasons for these responses can be made from summaries of the participants' attempts to carry out each set of tasks as well as from the comments they each made in their interviews. Participants are referred to by P1 through P7 for privacy reasons. It should be remembered that the tasks 1-4 were given in random order, which affected the participants' ability to find features that they had already used in another task. The tasks are titled by the primary image capture option featured in the description.

Opening screen/starting the program

In the opening screen where the user selects the location, the participants generally did not have trouble finding the list of pre-programmed cities when they were told to select Boston. However, some of them were somewhat unsure of when and why they were expected to click the continue button to continue to the interface that actually controls image capture. P1 later commented that since one is required to go back and forth between the two interfaces to change façade orientations or location, this switching "is not compatible with the linearity implied by the word 'continue.'"

1. Default Design Day Set

This option caused confusion for all of the participants except for P2, who found all of the required features and completed all of the tasks with absolutely no problems or confusion at all on any of them. The default set option caused problems in two ways. First, the participants (except for P2) seemed not to notice the feature. It was positioned on the same screen as the "Planned Image Sets" option, on the right side of the screen. This was probably confusing since the other options, Image Series and Videos, had their own radio buttons with only one feature per screen, while the "Image Sets" radio button showed a screen with both the "Planned Image Set" and the "Default Design Day Set" options. Since they did not see the option, three of the participants initially tried to enter what they thought were good design days using the "Planned Image Set" option until they were asked if they could find an easier way to automatically get the large set of images.

120

There also seemed to be confusion with the term "design day," meant to refer to an extreme or average condition such as the solstices or equinox. This is likely to be more of an engineering term that is not used as frequently in architectural education.

2. Planned Image Sets

This option, which allows a set of mathematically unrelated images to be taken by choosing dates and times to add to the list, posed almost no difficulty for any of the participants. No participants had any trouble adding or removing dates from the list. P1 initially thought that he should use Image Series instead, but quickly realized that the Sets option was more appropriate. However, three people had trouble figuring out how to change the façade orientation, another part of this task, and two people had trouble finding the correct folder that would store the images.

3. Image Series

This option did not pose a huge problem for most people, though three people initially tried to enter the 12 required images using the "Planned Image Sets" option instead. Some people had initial confusion about what exactly 'series' meant but understood it after they read the input screen and considered it for a few moments.

4. Videos

Participants were generally clear about how to use this, though the fact that the images taken were not really a video but rather a set of one image per hour while the sun was up on the chosen day caused some confusion. P1 was initially confused by the request that he take a video because he thought that what the camera viewport showed while the table was homing was the video. In general, however, participants liked the video option.

Other Issues

There were a few software features common to the whole interface with which there were issues. Several participants seemed annoyed with having to scroll down to the month or number they wanted when they entered dates and times, though it was discovered that typing the first letter or number could help immediately jump to the desired spot. The message boxes that popped up after different image capture buttons were clicked, which provided information about where the photos were being stored, were often ignored as error messages and clicked through without being read. The person might later have trouble finding the images even though the unread message box had said exactly where they were being stored. One person complained that when the box popped up it blocked other features on the interface, even though it would have been fine to click Ok and close the box at any time.

The biggest usability issue, however, was the camera property adjustment. The camera needs to be focused manually while looking at the computer monitor, which is difficult to see if the camera is relatively far away. Other properties can be adjusted from the interface but it is usually easiest to adjust the exposure manually after focusing. This exposure might also be correct for certain camera positions and solar angles but too bright or too dark for others. Also, because of remaining issues regarding the use of the high resolution option with the camera (See Section 4.3), the setup had to remain in low

resolution for the surveys. Several students were quite unhappy with this and essentially denounced the usefulness of the device until the issue is resolved.

While it is valuable to see what interface features were clear from simple examination and which need improvement, it should be remembered that participants were given no initial "tour" of the interface or advice about its functions. All of the participants stated that although they might have had some trouble finding certain options, in a future session with the device they would easily be able to use any of the features. P6 in fact strongly objected to the idea of being made to figure everything out without any initial advice. A mere five minute explanation of the interface would probably clear up the majority of questions a new user might have. SUS scores may have been different if participants were familiarized with everything beforehand, removing a sizable percentage of any frustration they might have had.

Interview Summary
The interviews uncovered interesting perspectives about how and when the students might use the setup with their work, contrasting with how they usually planned for sun issues. Three of the participants stated that it would be most useful for dense-packed urban settings so you could see how the building affects or is affected by the context, especially if you are planning an outdoor space. P3 emphasized that clients would be particularly interested in this as opposed to other aesthetic or energy concerns since information about urban masking for a proposed building could prevent lawsuits.

After obtaining this basic information, participants believed experiments could then be performed with basic building geometries and volumes and how they affect each other. P7, who had taken the Daylighting class at MIT, was the only student who said he would use it to experiment with façade shading elements, though P6, who only began studying architecture this year, joined him in saying that it could be used to guess about periods of likely solar gain and try different orientations.

While P1, P6, and P7 stated that they would like to use the device for interior studies, the other participants brought up the fact that interior models are hardly ever made in their studios or required at the companies they have worked at because of lack of time and money.

P4, who heavily emphasized the importance of getting extremely high image quality as well as the needed improvements in the aesthetic design of the interface, felt that she and many others would be most likely to use the setup to get attractive photos and videos to help sell a project at the very end of the design. However, she said she might use it as a tool during the design process by repeatedly taking design day sets of different options for examination.

The students surveyed were currently using techniques of various degrees of sophistication to plan for lighting issues. P5 stated that she sometimes used the Sketchup

option of showing shadows at different times of day. Other participants such as P1 said that he usually used basic rules of thumb such as "Light from the north is good for office spaces on the equator" and "Daylight is good six meters from a window." P5 normally "just kind of eyeballs the situation" or looks at a chart while choosing a façade orientation. None of the participants mentioned ever taking measurements or trying to calculate actual light levels within a proposed design.

The students also had interesting comments about the context of the device in the MIT program, prompted by the question about whether or not their studio reviewers or clients would be interested in the device. P3 implied that while those instructors interested in the "technical and experiential" aspects of architecture would be quite interested in this type of study, those focused in the theoretical aspects would not be interested at all. He explained that "sustainability is a really negative term in design culture" because it is considered by some to be a box that restrains creative expression. P4 also described experiences in her studio where fellow students would joke during a design project "I don't even know where South is, I don't know where North is, I just don't design like that." She wondered how the device would be valuable to those types of people. While emphasizing that the interface should be made much more attractive, she acknowledged that if it were improved in this way it might just encourage people to use it to easily get presentation images with a black background, without actually caring about any sun issues.

P6, a beginning architecture student, expressed concern about the lack of continuity in her program between sustainability issues, which do interest her, and what takes place in her foundation studios. She stated that many of her classmates are quite dedicated to and interested in their Building Technology classes, but that the only continuity she sees between these classes and studios are the students themselves. Attempts to apply knowledge regarding sustainability aspects such as daylighting and solar gains into her studio projects have been largely ignored by her instructors, who prioritize the fostering of new aesthetic design sensibilities for the beginning students. Additionally, she expressed disappointment that Building Technology instructors do not come to her Level One studios.

Some students also discussed their experience with various rendering software packages that could be used as an alternative to scale model studies. As previously mentioned, P5 stated that she did use the time of day feature of Sketchup. P3, who currently works at a professional firm while finishing his degree, described the heavy use of rendering software in his firm. However, he emphasized that the software was used solely to get attractive presentation images that he felt were totally artificial in terms of accuracy. He described a case where he once tried to use 3d Studio to simulate what he thought were real lighting conditions for a museum project. Others in his company informally corroborated his work, saying the renderings looked like they were accurate representations, but no one actually knew or cared whether they really were.

The students had a variety of suggestions about how the setup could be improved. All participants clearly desired an easier way to focus and adjust the camera as well as higher

resolution. They were also universally dissatisfied with the graphic look of the interface, though most agreed that it had good functionality. Their negative comments about various aesthetic features may have been overemphasized by excessive prompting of the interviewer for additional criticism. The overall layout of the interface was generally considered satisfactory; P3 mentioned that he thought it was quite clear that the top area of the image capture interface is for the overall structure (choosing different image capture options, general control buttons), the middle area is for the specific task being performed (the selected image capture option), and the bottom for the results (the image viewport and equidistant graph of relative sun position). However, most participants suggested major renovation of the fonts, colors, and button shapes and sizes. A reduction in extra information was also requested, referring to the extra notes written next to each feature as well as the message boxes that appear. P1 had very good specific suggestions for using icons to reduce confusion, using families of colors, and developing a "continuity of style."

6.2   Improvement Plans

From the results of the surveys described in the previous sections, several improvement requirements are clear. Overall, students seemed quite satisfied with the capabilities of the interface in terms of image capture versatility. Their first priority is to be able to get good high quality images and be able to adjust and focus the camera more easily. After that, they expressed a strong desire to have cosmetic changes made to the interface that would make users feel more like they were using an advanced design tool that is a pleasure to use.

As suggested by P6, various fonts will be experimented with for readability and aesthetic effect. A coherent color palate will be developed to distinguish different types of buttons. The interface will be simplified by removing extra information. This information could instead be contained in tooltips, hidden information boxes, or contained in additionally supplementary materials describing interface use. Word choice will be reevaluated and words reduced through the addition of graphic icons, as suggested by P1.

Though this emphasis on aesthetic issues may seem superficial, it is understandable when the target users are architecture students who are often very accomplished graphic artists themselves. Additionally, it has been shown that attractive interfaces are actually perceived to work better than less attractive ones with identical functionality (Kurosu and Kashimura, 1995). As P6 put it, "MIT is like the perfect place for having really souped-up technology but having it look kind of outdated." It is hoped that a future interface design revision can help to challenge this stereotype.

124

6.3   Survey Case Studies

This section describes some of the projects of specific students used in the usability testing procedures. It was originally intended that after the planned tasks and survey were over, students would be allowed to do their own experiments on their models. Unfortunately, none of the students had the time or interest to do this, except in one case where unfortunately one of the motors became decoupled right as the student was trying her first experiment (the problem was later repaired). Glaser's earlier study, which included videotaping and analysis of students using a heliodon after an instructional session, describes interesting cases of student interpretation of their own projects using the device as well as the influence of instructors (Glaser et al., 2006). A future study of this kind at MIT could reveal interesting findings.

P2 brought a model she had built that was to be situated by the Charles River in Boston. She was interested in seeing what times of day direct light was hitting the façade. While looking at her photos, she was intrigued that an "inferno" seemed to appear in her building when the "sun" was directly visible from the camera (Figure 6.6). This could help her indicate a period of extreme glare problems since this means the sun itself would actually be visible from the window. Unfortunately, the overexposure the camera gets when the mirror reflection is actually visible is difficult to deal with if the camera brightness has already been optimized for much less exposure. Even though these pictures look interesting a client might not particularly appreciate the illusion of the proposed building catching fire and going up in smoke. However, the student was quite pleased with her results and was glad that she had added the Plexiglas in the windows to create these effects.
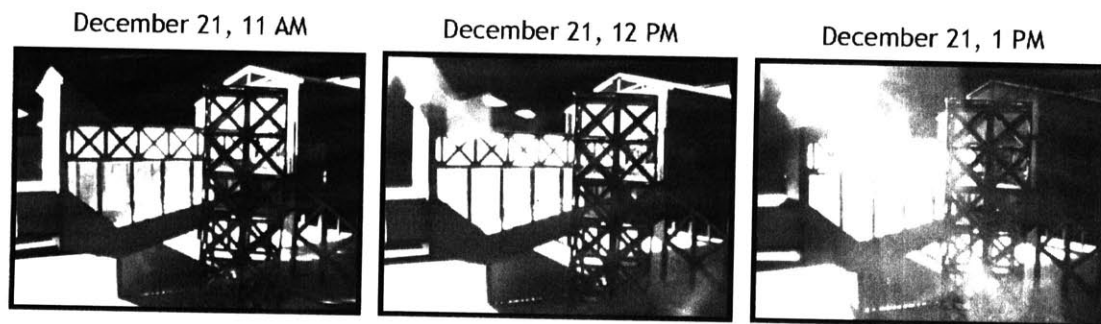
Figure 6.6: P2's model during part of the video simulation, as the "inferno" appeared at 1 PM when the mirror reflection moved into the camera's field of view.

P3's experience is useful as an example of a particularly unsuccessful use of the heliodon. He brought a particularly large and tall model which was difficult to balance with the counterweight and caused errors with the machine when it started oscillating. Most of the model consisted of the detailed topology of the mountainside on which the building was situation. The entire model, which included both the mountain and the building, were made of white foam core, which appeared very shiny and contrasted too sharply with the dark surroundings even when a serious effort was made to adjust camera

properties to optimize the image. It was also difficult to distinguish between the mountain and the building itself because of the color and reflectivity, and shadows did not seem to show any obvious information. These problems are unfortunate because of the potentially interesting impact of the building context. Despite these troubles, P3 was particularly enthusiastic about the concept of the heliodon and remained a very good sport throughout the testing, though he very justifiably gave it one of the lowest SUS ratings of the group, 75.

P5's testing experience was an interesting contrast to that of P3. Out of all the models students brought, hers, an interesting courtyard surrounded by three walls, seemed like the most obvious candidate for heliodon testing that would yield useful and concrete information. Within the courtyard, one could easily see which parts of the courtyard would be shaded at different times of day, and observe the effects of the interesting façade elements (Figure 6.7). However, in contrast to P3, she seemed rather uninterested in the results, did not keep her photos, and gave the device the other lowest SUS rating of 75, though this was probably related to her expressed dissatisfaction with the low image resolution available at the time.

September 2, 9 AM   September 2, 12 PM   September 2, 3 PM
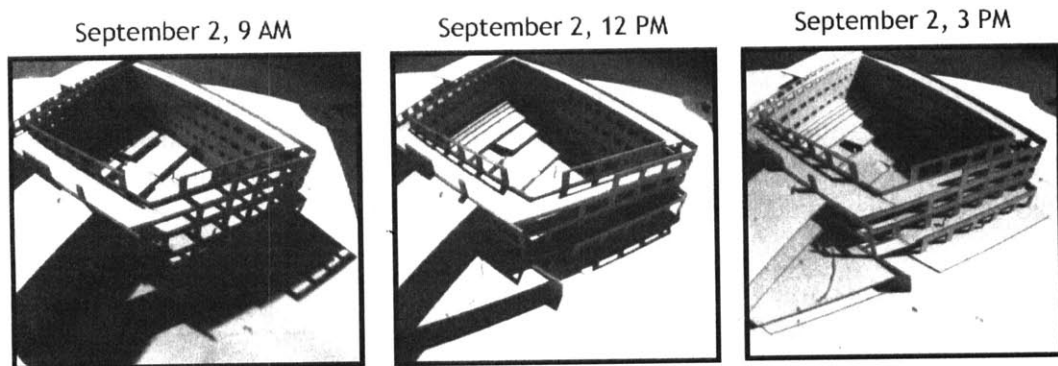
Figure 6.7: P5's model of a structure with an interior courtyard could be used to examine exactly when and where the courtyard is shaded through the use of the heliodon.

P6 was another enthusiastic participant who was quite excited about the results of her study and the potential of the device. The model she brought was a very preliminary mock up of a larger project designed in a novel and interesting way (Figure 6.8). The building was apparently designed by placing an initial model in direct sunlight coming through a studio window and tracing the shadows of the forms as they moved across a piece of paper. The shadows were then cut out and used to design the final building's structure. P6 expressed enthusiasm for the possible future use of the tool in such atypical artistic ways as well as technical ones.

126

June 1, 12 PM   September 1, 12 PM   December 1, 12 PM

Figure 6.8: P6's model structure is based on tracings of shadows in direct sunlight.
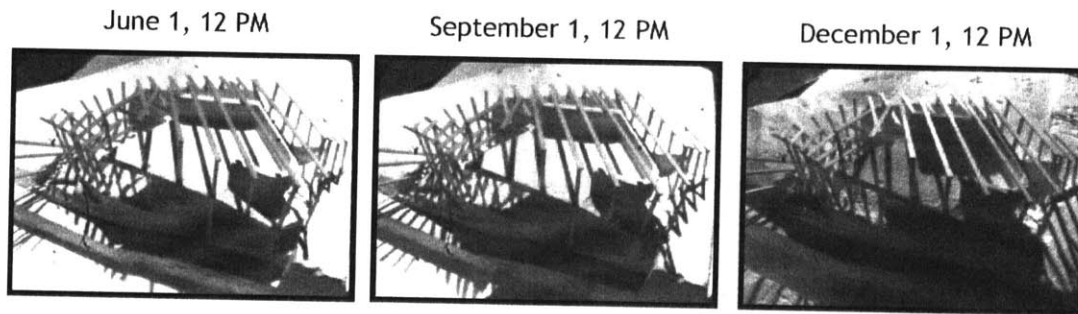
A former art student, P6 also had extensive photography and cinematography experience. This helped her to understand issues with camera positioning that may not be obvious to someone less experienced. For example, she quickly realized that the amount of foreground and background that should be included in the camera view is dependent on which way the shadows are being cast in a particular situation so as not to miss important shadow information. She spent a lot of time positioning the camera in various ways to try out different views.

P6 also expressed a desire to obtain all of the sunpath information that the computer was calculating. When told that this information was contained in stereographic charts available for any location, she eagerly asked for an explanation of how they worked and where she could get them. As a beginning architecture student she had very little understanding of sun angles but was extremely interested in learning more about them.

6.4   Discussion

This investigation of usability and student use is extremely important as an evaluation of the existing device as well as for predictions about what role the automated heliodon could eventually play in the design process at MIT. The sample size of seven was sufficient to discover the main previously unknown problems of interface layout, as revealed by various studies. For the small sample size tested, the average SUS rating of 85 suggests that the current interface posed no major problems for the students. However, improvements will be made to both the camera setup and the graphics of the interface as suggested by the volunteers.

Participants envisioned themselves using the automated heliodon in a variety of different ways. They cited urban contextual studies, building shapes and volumes, and shadows as likely areas of evaluation. While some expressed interest in interior studies, others regarded this as overly detailed work which they did not usually include in their design process. Solar gain and façade design was also mentioned. Students emphasized the importance of getting attractive images as a priority, and admitted that the setup might very well be used by those interested in capturing these presentation images without actually studying the effects of sunlight on their models.

The interviews revealed a general interest in using the device by the participants themselves, but left some doubt as to how widespread its use as a building design tool would become. The interviews suggest that sustainable design issues such as optimal use and management of sunlight are not a priority for all architecture students and instructors. However, the enthusiasm observed in some of the students makes it clear that there are those who would greatly value the setup as a design tool.

7   Conclusion

The provision of tools that simplify and encourage the process of predicting sunlight and daylight performance of proposed buildings is extremely important. These sun-related factors are strongly linked to building energy performance, occupant comfort, and the fulfillment of aesthetic design goals.

The motivation for this project is to facilitate natural lighting design consideration for architects, especially at the very early stages of the design process. Though the computer modeling programs available today offer many capabilities useful to designers, physical modeling remains an important means of expressing design ideas. If a building is to make optimal use of natural light, this goal must be incorporated into early brainstorming and experimentation. Within the variety of methods for sunlight and daylight performance prediction that exist, the portable outdoor heliodon and indoor automated heliodon setups described in this thesis provide a combination of features that complement and expand the choices architects have today when designing for lighting performance, and are in fact particularly suitable for use at an educational institution.

During the course of this thesis work, the existing automated heliodon setup was equipped with an image acquisition system that allows automatic capture and viewing of useful sets of images. Measures to investigate and improve the mechanical accuracy and usability of the device were taken, and students were used in an exploratory study of its future use. A case study further demonstrated potential investigation methods possible with the device. In addition to the further development of the automated heliodon, the capabilities and accuracy of the portable heliodon were explored, and methods derived to reduce measurement errors from tilting and surroundings.

While the heliodon setups now available at MIT have high potential for a variety of uses, there are stipulations regarding accuracy that are important to consider when using these tools. Because of the known unreliability of physical model interior illuminance studies that could be performed with the outdoor heliodon, any measurements taken should be used comparatively rather than as sure predictions of the proposed building's performance, though it is important to model a building as accurately as possible.

Outdoor measurement error from surrounding obstructions as well as from the use of drastically different solar altitudes can be minimized if careful planning occurs before outdoor model testing. Keeping the difference between the solar altitude of the actual testing conditions and that of the desired conditions less than 10 degrees will keep error from this source under 5% for testing altitudes of above 40 degrees. In terms of surrounding obstructions, the buildings of Killian Court, a likely location for model testing at MIT, are not tall enough to significantly affect measured illuminance by blocking part of the sky; however, taller surrounding obstacles can have more of an effect, depending on the position of the sun in relation to the obstacle as well as on the obstacle reflectivity. These guidelines meant to minimize error from these sources should be considered for all outdoor model testing endeavors.

The main accuracy issues associated with the automated heliodon involve the motor movements. Though the altitude motor replacement drastically improved the setup, relatively careful balance of the table is important when using larger and heavier models. Eccentric loading on the wrong side of the table can induce oscillations in the altitude motor that cause error accumulation. In addition, error accumulates for azimuth motor movements to a degree that could add up significantly during the course of many simulations. Electromechanical improvements to the system are necessary in order for the MIT heliodon's movement accuracy and reliability to compete with other heliodons that exist.

Another aspect of the automated heliodon setup to be improved is the image acquisition. The ability to obtain high resolution images is essential for architecture students desiring excellent quality images to show at presentations. Additionally, an easier way to adjust camera image properties such as focusing is important to make the system less cumbersome.

The interviews and usability assessment with students provided key insights into the likely future use of the heliodon as a regularly-used design tool. The seven students interviewed generally liked the capabilities of the device and found it relatively simple to use, giving it an average System Usability Scale (SUS) score of 84.6, while making helpful suggestions about how it could be improved. The importance of having an extremely attractive user interface was emphasized as being nearly equal in importance to actual capability.

While some students seemed eager to make use of the device and understood its capabilities for design modification and experimentation, it was also made clear that sunlight performance prediction is not a top priority or even a low priority for some people. When the device is made generally available for use, it is quite likely that at least some students will want to use it simply as a convenient photo capture device without any actual interest in sunlight analysis. However, the students surveyed who were interested in the heliodon stated that they would like to use it for a broad variety of studies including glare issues, façade design, urban masking, and aesthetic experimentation. The device could also be opened to the broader architecture community, allowing local practitioners to bring models to MIT for experiments.

Different image capture options available for the automated heliodon make it easy to capture and view large numbers of useful images in sets that can act as performance indicators of the building over the whole year. During experimentation, building features, façade orientation, or camera angle can be altered in order to compare different results. Images taken during the project can be used both for review by the designer during the design process as well as for design presentation, an extremely important aspect of both architectural education and practice.

The image acquisition system for the MIT automated heliodon should provide a useful tool for architecture and design students, as well as provide a precedent for heliodon

imaging capabilities, an area of the field that has yet to be fully developed. Though heliodons for scale model testing are by no means the only method of predicting daylight performance, they are a useful tool that could be more fully exploited if there were a more efficient method available of capturing and studying image data. It is hoped that the development of these heliodon tools will simplify and facilitate the building design process in regards to sun issues by providing additional methods that will fit in with the continuing use of scale models by architects. Experiments with heliodons allow exploration of diverse and interconnected design concerns that are integral to building performance optimization during the design process.

8 Appendices

Appendix A: Radiance Code and Files

The simulations performed in Chapter 3 to investigate error in outdoor heliodon illuminance measurements when simulating different altitudes and with surrounding obstructions were performed using the Linux simulator Cygwin. Illuminance measurements were obtained in the following way. Further explanation for this code and that in the text files can be found in Larson and Shakespeare (1998). Gratitude is owed to Siân Kleindienst for her help with sample code.

First, the scene is compiled into an octree using the command below. Mat.rad is the file that describes materials, sky.rad the sky, and scene.rad the geometry of the scene, such as buildings. These are all simple text files written with Notepad.

```
oconv mat.rad sky.rad scene.rad > scene.oct
```

Illuminance is obtained using a sensor file which describes the sensor's coordinates. The following command compiles the scene.oct above with the sensor to get an illuminance value in the illum.out file.

```
cat sensorfile.xyz | rtrace –w –h –It –ab 3 –aa .1 –as 64 –ar 128 –ad 1024 scene.oct | rcalc
–e '$1=(.265*$1 + .67*$2 + .065*$3)*179' > illum.out
```

Below are some examples of the text files compiled in the code above.

MAT.RAD
```
#
# materials file
#

#PAINTS

#white paint for adjustable
void plastic whitepaint
0
0
5 .83 .83 .83 0 0

#medium paint for adjustable
void plastic midpaint
0
0
5 .55 .55 .55 0 0
```

SKY.RAD

Sky definition.

different types of skies
#!gensky 3 21 +12:00 +s -a 42 -o 0 -m 0

gendaylit's clear sky
#!gendaylit -ang 60 0 -W 840 135

!gensky -ang 70 0 +s

skyfunc glow sky_mat
0
0
4
    1 1 1 0

sky_mat source sky
0
0
4
    0 0 1 180

#skyfunc glow ground_glow
#0
#0
#4
1 .8 .5 0

#ground_glow source ground
#0
#0
#4
0 0 -1 180

SCENE.RAD

```
# 0.01 = 1 meter

#ground
#!genbox groundmat ground 10 10 .01 | xform -t -5 -5 -.01


#constructing Killian Court from three boxes
#this construction faces it south; it will be reoriented in the KIllianscene file


!genbox darkpaint building10 1.1 .1 1 | xform -t -.55 .60 0


#!genbox darkpaint building10 1.1 .5 .22 | xform -t -.55 .60 0


#!genbox darkpaint building4 .5 1.5 .22 | xform -t .55 -.90 0


#!genbox darkpaint building3 .5 1.5 .22 | xform -t -1.05 -.9 0
```

SENSORFILE.XYZ

```
0      0      .01    .1    .6    1

# in this file, the first three numbers represent the x, y, and z
coordinates of the position of the sensor and the last three represent
the x, y, and z components of the facing direction.  In Chapter 3,
spherical coordinates of the facing direction for each experiment are
converted to Cartesian coordinates in order that they can be used as
the last three numbers in this file.
```
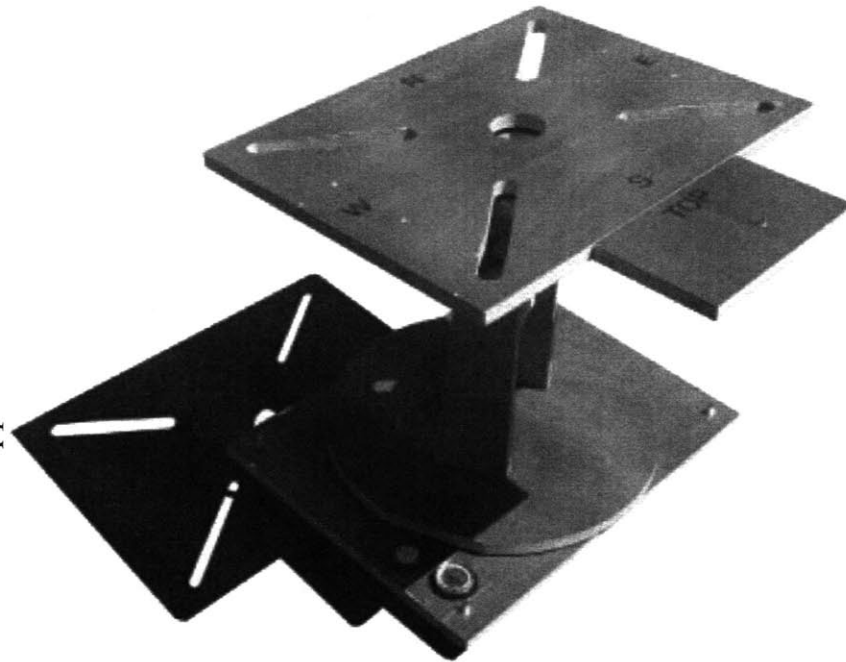
Portable Heliodon Instruction Manual

Table of Contents

Kit Parts

The heliodon includes:

Square base   Round base   Legs

Rotating top   Sun path diagram holder   Laminated sundials and stereographic diagrams

Assembly hardware   Carrying Case

Basic Setup

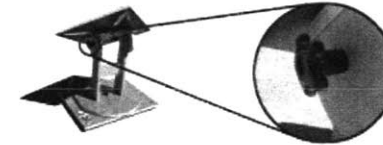1.   Attach the legs to the circular base using the four machine screws. Align the red dots when assembling.

x 4

Attach the circular base to the rectangular base by placing a bolt through both center holes. Tighten the black knob onto bolt.
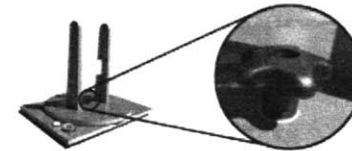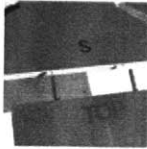
Mount the rotating table top to the legs by inserting a carriage bolt through each hole. Tighten a black knob onto the bolt.

Use the c-clamps to mount model onto the table.

Sunny Operation

1. Insert the platform to hold the sun path diagram into the "south" side of the table.

2. Place the appropriate sun path diagram for the desired latitude onto the platform. Make sure the peg goes through the hole in the sundial. Align the edge of the diagram with the edge of the platform.

3. Clip it in place.

4. Rotate and tilt table until the peg's shadow tip is at the desired time/day intersection on the diagram. Tighten the knobs to hold the position. *Note: A knob under the table prevents top rotation.*

Example:

The user wants to study the sun in Tokyo, Japan (35° 40' N, 139° 45' E). The desired time is 8 am solar time on March 18.

Method:

Set up table as described on the left.

Select the 36° N sun path diagram and clip it to the platform.

Tilt and rotate the table until the tip of the peg's shadow is at the intersection of the 8 am and March/September 21 lines. (To be more precise have it ever so slightly -- 1/10 of the distance -- to the February 21 line.)

Note: Remember to re-adjust the table as the sun moves overhead so that the shadow tip remains at the desired day and time intersection.

4

5
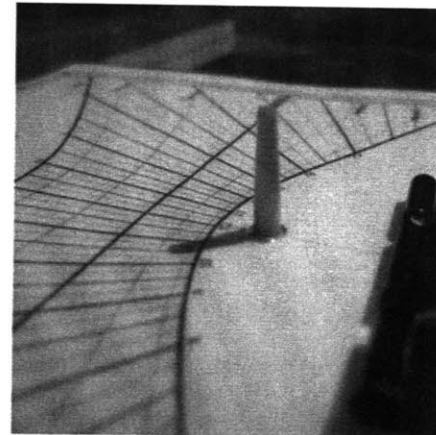
Cloudy Operation

1. Level the base by centering the bubble in the level. The flat-head screwdriver can be used to raise or lower the feet from above.

2. Orient the table with north by aligning the red needle with the magnetic north line. Near Boston, MA, USA, true north is 15.5° west of magnetic north. The compass is glued to take this into account.

3. Determine the "current" altitude and azimuth angles of the current sun conditions by using the MIT stereographic chart in "real clock time." Go to the intersection of the current date and time lines. The chart is in polar coordinates so the altitude is the distance from the center of the chart and the azimuth is the angle from north. (See an example chart below.)

4. Determine the "desired" altitude and azimuth angles for the desired location and time in the same way as above using the sun path diagram for the desired latitude.

5. Rotate the round base to the "current" azimuth value found in Step 3.

6. Rotate the table top to the "desired" azimuth angle found in Step 4 using the dial in the center hole.

7. Subtract the "current" altitude angle found in Step 3 from 90° then add the "desired" altitude angle found in Step 4. Tilt the table to this angle using the protractor on the side.

6   *Stereographic Chart for 36°N*

Example:

The user, in Cambridge, MA, on January 21, at 2 pm, wants to study the sun in Tokyo, Japan (35° 40' N, 139° 45' E). The desired time is 3 pm solar time on March 18. Cloud cover makes the shadow method impossible.
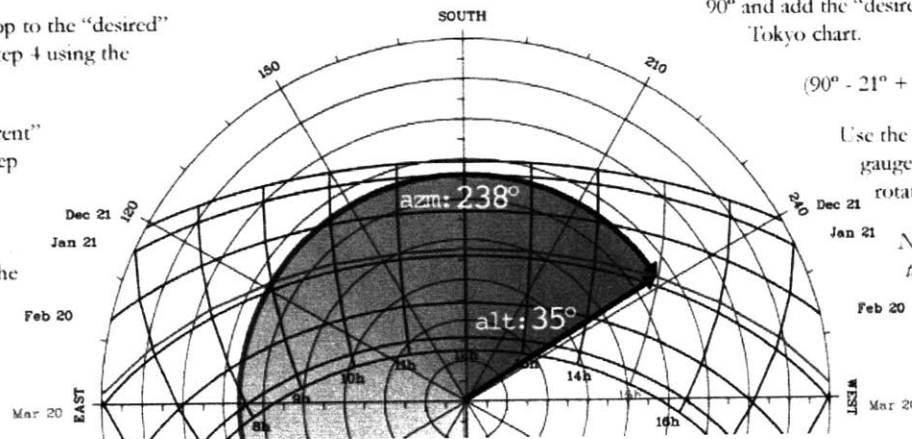
Method:

Set up table as described on the left. Make sure the table is truly leveled and pointed toward true north.

Select the chart in "real clock time" for Cambridge's latitude (42.36°N). Find the "current" azimuth and altitude angles for January 21 at 2 pm. The azimuth is 212° so turn the round base so it points to the 212°. Note: 0° is north. The altitude is 21°.

Select the chart for 36° N, the latitude closest to Tokyo, Japan. Find the point that intersects the lines for 3 pm and March 18. The "desired" azimuth is 238° and the altitude is 35°. Take the "desired" azimuth angle, 238°, and use the pointer in the center hole to rotate the model to this angle.
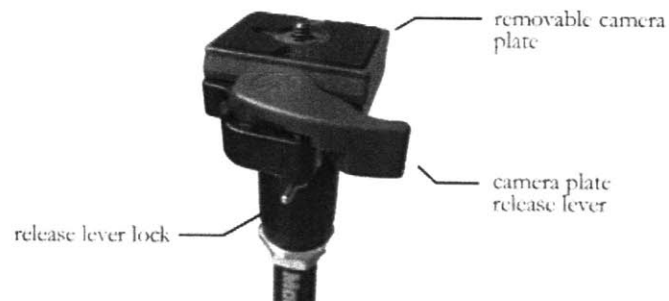
Subtract the "current" altitude angle in the Cambridge chart from 90° and add the "desired" altitude angle in the Tokyo chart.

$$(90° - 21° + 35°) = 104°$$

Use the outer numbers on the gauge on the side of the table to rotate the table to 104°.

Note: Remember to re-adjust the table as the sun moves overhead.

7

alt:35°   azm: 238°

THE CAMERA PLATE

removable camera plate

camera plate release lever

release lever lock

To attach camera:

1. Move the release lever lock to the left, unlocked position.

2. Pull the camera plate release lever.

3. Remove the camera plate and attach it to the bottom of your camera.

4. Snap the camera plate back into the holder.

5. Move the lever lock to the right, locked position.

8

FAQs

Are there any special considerations when mounting models?
Yes, you should try to balance the table top's total weight over the hole in the center to prevent unwanted rotation.

How do I measure the rotation of the table top?
If you look under the table you will see a needle in the center hole. The markings around the hole will tell you how much you have rotated.

The top keeps rotating unexpectedly. What do I do?
If you look under the center of the table there is a black knob that will prevent table rotation.

How do I adjust the height of the feet to level the table?
Use the flat-head screwdriver to turn the leg from the top.

The kit doesn't include a sun dial diagram for my desired latitude. What should I do?
Estimate. Pick the diagram that is closest to your desired latitude. The diagrams come in 6° increments, so a suitable approximate diagrams should be available. The sun diagrams were produced in Shadows 2.2.0, available at www.shadowspro.com. The stereographic charts are from http://solardat.uoregon.edu/PolarSunChart-Program.html.

The sun keeps moving. Does this matter?
Yes, periodically adjust the table to account for the sun's movements.

There is no sun. What do I do?
Follow the instructions for cloudy operation on pages 6-7.

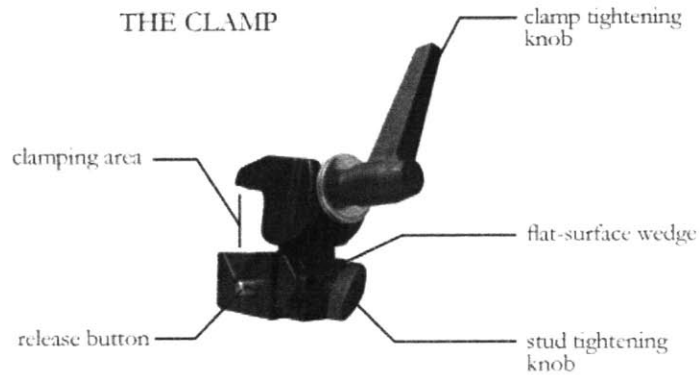**What do I do when I'm finished?**
Pack the equipment neatly back in its case. Everything fits so don't force it. Put the sun path diagrams back in their correct order.

What if I still have questions?
Email the student designers, mahalia@mit.edu and timknoch@mit.edu, or their faculty advisor, mand@mit.edu.

Camera Arm

To assist in taking pictures, a camera arm and clamp is included in the kit. This section of the manual describes how to set up and use the clamp and adjustable arm.

THE CLAMP

- clamp tightening knob
- clamping area
- flat-surface wedge
- release button
- stud tightening knob

How to use:

Turn the clamp tightening knob to secure the clamp onto a pole or shelf-like surface. The clamp can attache to poles between .5" and 2.1" in diameter.

For attaching to flat surfaces, loosen the stud tightening knob and remove the wedge. Press the wedge into the V-shaped notch on the clamp.

Note: Leave the wedge secured onto stud tightening knob when not in use.

THE ARM

- removable camera plate
- ball joints
- adjusting knob
- elbow joint
- 5/8" stud
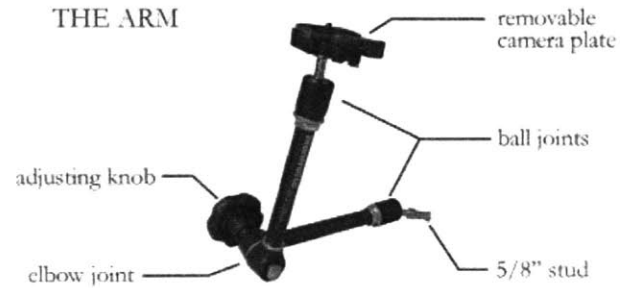
To attach arm to clamp:

Loosen the stud tightening knob (1) and depress the release button (2). Insert the arm stud (3) into the clamp hole (4). Re-tighten the stud tightening knob (1) to secure the connection.

To adjust arm position:

Loosen the adjusting knob to release all joints. Adjust the arm to the desired position. Tighten the adjusting knob to secure arm position.

Note: The arm is designed to reach every position. If it's not reaching, try rotating the ends of the arm.

Appendix C: Electromechanical Issues and Updates
Heliodon wiring and hardware
as of 3/07

The two table motors are controlled by two independent 40-pin PIC 16F877 microcontrollers with identical programming. The altitude (tilt) motor is driven directly by its microcontroller; the azimuth motor is driven through a homemade H-bridge motor driver.

Both microcontrollers have the same interface:

Inputs	Outputs
Serial in (instructions from PC software)	Serial out (to PC software)
Encoder A/B	Motor direction
Breakbeam	Motor speed

Additionally, there are a number of power connections – each encoder and breakbeam sensor has power and ground connections, as does the altitude motor. For both motors, motor speed is encoded in a PWM output; direction is the TTL output of a microcontroller pin. In the case of the altitude motor this is contrary to the interface specifications, which require a connection of either GND or NC (open circuit) to specify the direction. This may be the cause of the asymmetric motor braking, but more testing is needed to verify.

Each controller is designed to drive its position error to zero (strictly speaking, to zero plus or minus a small errorbar). When started, position error is set to zero. Signals from the encoder increment or decrement the position error. The controller responds to error != 0 by driving the table in the direction opposite the error; the resulting encoder signal then increments or decrements the error back to zero. The rotary encoders are connected directly to the drive gears and are therefore somewhat isolated from backlash in the motor coupling.

A typical PC command consists of a numeric "move" order. The number transmitted to the controller is added to the error counter; the control routine responds by sending the table in whatever direction drives the error back to zero. Note that the microcontroller therefore has no information about the absolute position of the table; it only "knows" that it is either at the position it's been ordered to, or that there is some error (and therefore it's on its way to the ordered position). The PC software must keep track of table position if sequential moves are to be made. The microcontrollers have no mechanism for correcting error in sequential moves or any other form of accumulated error. There is no error-checking or any method for determining if encoder signals are missed.

Altitude motor hardware:

Encoder	US Digital E6MS-1024-1000 (metallic housing, single-ended differential output, 1024 counts per revolution, 1" shaft mounting)
Motor	Merkle-Korff 8001 Brushless DC gearmotor, 300 in-lb stall torque / 7.2 no-load rpm

1. CAMERA ISSUES

Problem: Software runs very slowly, especially when high resolution image option is used; in this case it slows down to being almost unusable. This is due to the software/motor/camera using up all the CPU (there *is* enough RAM according to CRO). Current computer is 2.70 GHz processor speed, 512 MB RAM. Also, the HiRes option only takes 1 image per second.
Possible solution: Switch to a computer with a faster processor, add code that delays photo capture to makes sure the camera has updated itself at the moment of photo capture, or get a new camera that takes information faster, though this would require reprogramming.

2. ALTITUDE MOTOR ISSUES

Problem: There is a lot of backlash (>10 degrees of altitude rotation) in the system from the motor shaft to the small gear (with the encoder on it). Backlash refers to being able to move the table without the motor engaging at all. This is also an issue when the table is turning one way and needs to start turning the other way; the motor can run with no resistance until there is any actual contact that causes movement.

Possible solution: To decrease this backlash a new motor and small gear could be "tuned" in a machine shop to get a very good connection; once it was complete it could be installed as a unit (this would avoid leaving the table unusable for long periods of time.) There was originally a slot milled in the old motor shaft to improve this connection, but when we got a new motor the new shaft was installed without this slot. This connection also needs to be occasionally tightened. The way to do this is to remove the encoder and wiggle the table until you find the place it "wants" to be and then tighten the set screw while keeping it at that location. Steve Banzaert suggests another connection between the shaft and the first gear that could be machined and then inserted without too much difficulty.

Problem: The margin of error for the altitude movements is about plus or minus three degrees with eccentric loading (separate from the altitude motor oscillation problem, discussed later), as is expected due to the gear ratio and allowed +-15 encoder counts. This three degrees of possible error is higher than desired.

Possible solution: The chips could be reprogrammed since the new stronger motor means that this window could probably be smaller without eternal oscillation when it tries to reach a certain point. However, this would require undoing a lot of the circuits inside the box to get to the chips, which would probably be quite difficult to get back the way they

142

were. However, it is estimated that if a high level of accuracy is required (movement error smaller than 0.5 degrees) even with eccentric loading, much stronger and faster motors are needed, along with a much tighter coupling to prevent backlash as described previously. This would mean that the instant the table starts to overshoot the position the motor can quickly reengage in the opposite direction to prevent the overshooting. With a stronger, faster, and tighter setup like this, the +-15 encoder count allowed margin of error could be reduced further.

Problem: The altitude motor has an asymmetric braking problem. This means that the motor resists being forced in this direction much less than when it is forced in the other direction. When the table is more heavily loaded on this side than the other side, oscillation occurs as the table starts to drift downward, catches it self to go back up, and then drifts downward again. If left to oscillate this way for a while, this side of the table drifts steadily upwards. If then commanded to move to a different location, it may be off by 20 degrees or more.

Possible Solutions: The direction pin for the motor may be wired differently than dictated in the specifications. From Steve Banzaert: "The spec sheet for the altitude motors says the direction is set by connecting this pin to ground or not connecting it to anything. Right now the direction is set by connecting it to ground and to +5 volts, which may be close enough under most circumstances but may look a lot like ground when the motor is forced. There's no quick fix for this but if can be most easily remedied with a relay which would give you a hard connection to either GRD or nothing. It may also be possible to find an interface chip with high impedence output mode (these are called tri-state interfaces) but I don't know how high is high enough to be a good approximation of infinity, which is what the specs call for."

The observation that the table is off by 20 degrees after being allowed to oscillate could be the result of missing encoder counts during fast table movement, and these errors would add up over time.

3. AZIMUTH MOTOR ISSUES

Problem: Drift has been observed with the azimuth movements even though according to the chip code, which accounts for where within the allowed +-20 encoder count window the table ends up in order to add or subtract this amount from the next move, error should not accumulate over time. The margin of error from the +-20 encoder counts also translates to plus or minus 0.12 degrees of table azimuthal rotation. After being commanded to move 12 individual degree steps, the position was behind by 0.5 degrees. After 28 steps, it was behind by a whole degree. This is a larger error than should be allowed by the +-20 count window allowed in the chip code. There is a bigger problem when the motor needs to switch directions. When the motor is told to rotate back and forth between 0 and 30 degrees, for example, the 30 degree area it is covering starts to

143

drift in one direction, overshooting the 30 degree point and undershooting the 0 degree point by about 2 degrees for each cycle.

Possible Solutions: The correlation between the number of encoder counts being given to the chip from the computer and what this translates to as actual azimuthal table rotation (through the gear ratio of 1.5/59.25) may be imperfect and could be part of the cause of the problem.

The azimuth motor encoder itself could also be missing counts, or have other electrical issues. From Steve Banzaert: There are a few things that influence encoder accuracy. The microcontroller is triggered by a falling edge on the encoder A line; this triggers an interrupt routine. You'd need to know how many instructions it takes to trigger this interrupt, save context, run the interrupt code, restore context, and page back to the code you were running before you got interrupted; then you could take the (known) instruction time of the microcontroller and figure out the minimum interrupt period; if pulses come while you're in that period the pulses come within that period you'd miss them. There are also electrical issues that could mask the encoder signal if the pulses get too close together; basically if the cabling is too long/resistive and the match to the impedance of the microcontroller isn't good, it can take too long for the encoder to raise the voltage from 0 to 5—so it'll be partway to the top of the square wave, but now it's time to drop to 0, so you get a stunted triangle wave. The only way to accurately diagnose this would be to buy a real encoder-reader and compare its output to the position the microcontroller thinks it's at. You could also program some code into the microcontrollers for testing purposes. At a minimum you could look at the assembly listing for the controller code (most compilers will output this intermediate step with annotations so it's marginally human-readable) and see how many instructions are called in order to enter, run, and exist the interrupt routines."

General Notes about Software/Hardware Error Prevention:

- Make sure that "Buffer Overflow Protection" is in the VirusScan Console is disabled; this causes problems when programming (and running?) VB code.
- Be careful when running more than one program that communicates with the motor chips (heliodon/photo software, manual control, gonio-control). Do not try to run two at the same time or it will not work at all (COM2 errors). Also, switching from one to the other often causes errors because one program may send some last piece of garbage information to the com port when shutting down, which the chips will try to interpret when starting to run the other one. This results in errors such as angles being off by random amounts. Resetting the computer, or shutting off the motors, may be necessary between usages of two programs that communicate with the motor chips.
- If one of the motors stops turning the table when commanded but still makes a noise as if it is trying to, redo the set screw connections from the motor shaft to the drive gear.

144

9 Bibliography

(Aghemo et al., 2007) Aghemo, C., Pellegrino, A., and LoVerso, V.R.M. "The approach to daylighting by scale models and sun and sky simulators: A case study for different shading systems." *Building and Environment*, In Press, 2007.

(Allen and Iano, 2002) Allen, Edward and Iano, Joseph. The Architect's Studio Companion: Rules of Thumb for Preliminary Design. John Wiley & Sons, Inc., New York, 2002

(Andersen et al., 2005) Andersen, M., Ljubicic, D., Browne, C., Kleindienst, S., Culpepper, M. *Automated Assessment of Light Redirecting Properties of Materials and Sunlight Penetration within Scale Models: The Heliodome Project.* Proceedings of the ISES 2005 Solar World Congress, August 8-12, 2005.

(Archiseek, 2007) Archiseek Online Architecture Resource. Available at http://usa.archiseek.com/california/losangeles/disney_concerthall.html. Accessed May 23, 2007.

(Arnese and Matusiak, 2005) Arnese, H. and Matusiak, B. "The limits of the mirror box concept as an overcast sky simulator." *Lighting Research and Technology,* Vol 37 (4), pp. 313-328, 2005).

(Aizelwood and Littlefair, 1994) Aizlewood, M.E., and Littlefair, P.J. *Daylight Prediction Methods: A survey of their use.* Proceedings of the CISBE National Lighting Conference, Bath, UK, pp. 126-140, 1994.

(Baker, 2000) Baker, N. *We are all outdoor animals.* Proceedings of PLEA 2000, Cambridge, 2000.

(Baker and Steemers, 2002) Baker, N. and Steemers, K. Daylighting Design of Buildings. James & James Ltd., London, 2002.

(Bedoe and Shapiro, 2006) Bedoe, Charles and Shapiro, Ray. "Using Macromedia Flash as an embedded device UI." Vibren Technologies, 2005. Available at http://linuxdevices.com/articles/AT4241834585. Accessed July 10, 2006.

(Bodart et al., 2005) Bodart, M., Deneyer, A., De Herde, A., and Wouters, Peter. *The New Belgian single-patch sky and sun simulator and its validation.* Procedings of the Lux Europa Conference, Berlin, p. 214-217, 2005.

(Boosinger, 2006) Boosinger, John. "JD Shadowtracker." Available at http://www.jekob.com. Accessed July 2006.

(Boren and Ramey, 2000) Boren, M., & Ramey, J., Thinking aloud: Reconciling theory and practice." *IEEE Transactions on Professional Communication*, Vol 43(3), pp. 261-278, 2000.

(Boyce et al., 2003) Boyce, P., Hunter, C., and Howlett, O. "The Benefits of Daylight through Windows." Capturing the Daylighting Dividend Program, U.S. Department of Energy, 2003.

(Brooke, 1996) Brooke, J. "SUS: A quick and dirty usability scale." *Usability evaluation in industry*, P. Jordan, B. Thomas, and B. Weerdmeester, Editors. Taylor and Francis: London, 1996.

(Browne, 2006) Browne, Courtney. *Development of a light detection system for bidirectional measurements over the solar spectrum and sun course simulations with scale models,* Master's Thesis in Mechanical Engineering, Department of Mechanical Engineering, Massachusetts Institute of Technology, 2006.

(Cannon-Brookes, 1997) Cannon-Brookes, S.W.A. "Simple scale models for daylighting design: Analysis of sources of error in illuminance prediction." *Lighting Research and Technology*, Vol 29 (3), pp. 135-142, 1997.

(CERES, 2005) CERES Heliodon Facility. Ceres Lighting Laboratory, Ball State University. Available at http://www.bsu.edu/ceres/heliodon. Accessed November 3, 2005.

(Cheung, 1998) Cheung, K. P. "A heliodon with dichromatic lamps for horizontally placed building models." *Hong Kong Papers in Design and Development.* Department of Architecture, University of Hong Kong. December 1998.

(Cheung et al., 2000) Cheung, K . P. Kam, H.M., Lam, C.F. "A multi-lamp Heliodon for architectural schools." *International Journal on Architectural Science*, 1(1): pp. 46-58, January 2000.

(CIE, 2003) CIE, S 011/E. Spatial distribution of daylight—CIE standard general sky. Standard, CIE Central Bureau, Vienna, 2003.

(Clifford, 2006) Clifford, Zachary. "Heliodon Application Hardware and Software Control." UROP technical report, Massachusetts Institute of Technology, Cambridge, 2006.

(CSTC, 2007) CSTC, Centre Scientifique et Technique, Belgian Building Research Institute. "Le soleil artificiel à une lampe." Available at http://www.cstc-lumiere.be/files/frameset_fr.html, accessed May 11, 2007.

(Daylighting Lab Seattle, 2004) Daylighting Lab Seattle: "Building Daylighting Models." University of Washington, 2004. Available at http://www.daylightinglab.com/daylighting/Building_Daylighting_Models_Tips.pdf. Accessed May 23, 2007.

(IEA, 2000) Daylight in Buildings: A Source Book on Daylight Systems and Components. Report of IEA SHC Task 21 / ECBCS Annex 29, July 2000.

(Dischler et al., 1999) Dischler, L., Mostefaoui, D., and Ghazanfarpour, D. "Radiosity including complex surfaces and virtual surfaces." *Computers and Graphics*, Vol 23 (4), 1999.

(Dumas, 1997) Dumas, Joseph. "How many participants in a usability test is enough?" *Common Ground, Usability Professionals Organization,* 7 (October), 2-6, 1997.

(Ecotect, 2007) Ecotect program website. Square One Research, Cardiff University, 2006. Available at http://www.ecotect.com. Accessed April 3, 2007.

(Fisekis et al., 2003) Fisekis, K., Davies, M., Kolokotroni, M., and Langford, P. "Prediction of discomfort glare from windows." *Lighting Research and Technology,* Vol 35 (4), pp. 360-371, 2003.

(Galasiu and Veitch, 2006) Galasiu, Anca and Veitch, Jennifer. "Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review." *Energy and Buildings,* Vol 38 (7) pp. 728-742, 2006.

(Glaser et al., 2006) Glaser, Daniel, Smith, Whitney, and Cutler, Bob. "Using video for analyzing daylight simulation tools." Computer Science Department, Rensselaer Polytechnic Institute, 2006.

(Glicksman et al., 2007) Glicksman, L.R., et al. MIT Design Advisor. Available at http://designadvisor.mit.edu/. Massachusetts Institute of Technology, 2007.

(Goral et al., 1984) Goral, C. M., Torrance, K. E., Greenberg, D. P. and Battaile, B., "Modeling the Interaction of Light Between Diffuse Surfaces", *Computer Graphics,* Vol 18(3), pp 213-222, 1984.

(Heschong et al., 2002) Heschong, L., Wright, R., and Okura, S. "Daylighting impact on retail sales performance." *Journal of the Illuminating Engineering Society,* Vol 21, pp. 21-25, 2002.

(Heschong Mahone Group, 1999) Heschong Mahone Group. *Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance.* Study submitted to The Pacific Gas and Electric Company on behalf of the California Board for Energy Efficiency Third Party Program. Fair Oaks, CA, 1999.

(Hopkinson, 1972) Hopkinson, R.G. "Glare from daylighting in buildings." *Applied Ergonomics*, Vol 3 (4) pp. 206-215, 1972.

(IESNA, 2000) Illuminating Engineering Society of North America. *The IESNA Lighting Handbook: reference and application.* 9th edition. Edited Mark S. Rea. Pub: IESNA, New York, 2000.

(Jensen et al., 2004) Jensen, K., Schultz, J., and Kristiansen, F. "Development of windows based on highly insulating aerogel glazings." *Journal of Non-Crystalline Solids*, Vol 350, pp. 351-357, 2004.

(Jones et al., 2004) Jones, P.J., Alexander, D., Marsh, A., and Burnett, J. "Evaluation of methods for modeling daylight and sunlight in high rise Hong Kong residential buildings." *Indoor and Built Environment*, Vol 13, pp. 249-258, 2004.

(Joseph, 2006) Joseph, Anjali. "The Impact of Light on Outcomes in Healthcare Settings." The Center for Health Design, Concord, CA, Issue Paper #2, August 2006.

(Kajiya, 1986) Kajiya, J. "The Rendering Equation." *Computer Graphics*, Vol 20(4), pp. 143-150, 1986.

(Kleindienst, 2006) Kleindienst, Siân. *Improving the Daylighting Conditions of Existing Buildings: the benefits and limitations of integrating anidolic daylighting systems using the American classroom as a model*, Master's Thesis in Building Technology, Department of Architecture, Massachusetts Institute of Technology, 2006.

(Koch, 2006) Koch, Tim. "Portable Heliodon Instruction Manual." Massachusetts Institute of Technology, 2006.

(Kozlowski, 2006) Kozlowski, David. "Harnessing Daylight for Energy Savings." *Building Operating Management*, Vol 53 (4), 2006.

(Kurosu and Kashimura, 1995) Kurosu, M., and Kashimura, K. Apparent Usability vs. Inherent Usability. Experimental Analysis of the Determinants of the Apparent Usability. In *Proceedings of CHI'95*. ACM Press, pp. 292-293, 1995.

(Larson and Shakespeare, 1998) Larson, Greg and Shakespeare, Rob. Rendering with Radiance. Morgan Kaufmann Publishers, Inc., 1998.

(Lawrence, 2005) Lawrence, Mark. "Integration of Lighting Early in the Design Process: Evaluations of tools and methodologies." Technical Paper for 4.481, Building Technology Seminar, Massachusetts Institute of Technology, 2005.

(Lam et al., 1999) Lam, K.P., Wong, N.H., and Henry, F., in: Proceedings of the Building Simulation '99 Conference on A Study on the Use of Performance-Based Simulation

Tools for Building Design and Evaluation in Singapore, vol 2, Kyoto, Japan, pp. 675-682, 1999.

(Lambert, 2002) Lambert, G. W., C. Reid, D. M. Kaye, G. L. Jennings, M. D. Esler. "Effect of sunlight and season on serotonin turnover in the brain." *The Lancet*, Vol 360, pp.1840-1842, December 7th, 2002

(Lechner, 2001) Lechner, Norbert. Heating, Cooling, Lighting. John Wiley & Sons, 2001.

(Lee and Tavil, 2007) Lee, A.S., and Tavil, A. "Energy and visual comfort performance of electrochromic windows and overhangs."*Building and Environment*, Vol 42 (6), 2007.

(Leslie, 2005) Leslie, R. P. "Capturing the daylight dividend in buildings: Why and How?" *Building and Environment*, Vol 38, pp.381-385, 2003.

(Leung et al., 2005) Leung, T., Chau, C., Lee, W., and Yik, F. "Willingness to Pay for Improved Environmental Performance of the Building Envelope of Office Buildings in Hong Kong." *Indoor and Built Environment*, Vol 14 (2) pp.147-156, 2005.

(Li et al., 2006) Li, D.H.W., Cheung, G.H.W., and Cheung, K.L. "Evaluation of simplified procedure for *indoor daylight illuminance determination against data in scale model measurements.* " *Indoor and Built Environment*, Vol 3(15), pp.213-223, 2006.

(Likert, 1932) Likert, R. "A Technique for the Measurement of Attitudes," *Archives of Psychology* Vol 140 (55), 1932.

(Ljubicic, 2005) Ljubicic, D. *Automated Support for Experimental Approaches in Daylighting Performances Assessment*. Undergraduate thesis, Massachusetts Institute of Technology, Cambridge, 2005.

(Mansy, 2004) Mansy, Khaled. A user-friendly procedure to visualize the hourly quantitative performance of daylighting systems. *Solar Energy*, Vol 77 (4) pp. 373-380, 2004.

(Mardaljevic, 1999) Mardaljevic, J. "Daylight Simulation: Validation, Sky Models, and Daylight Coefficients," PhD thesis. Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK, December 1999.

(Mardaljevic, 2002) Mardaljevic, J. "Quantification of parallax errors in sky simulator domes for clear sky conditions." *Lighting Research and Technology*, Vol 34 (3), pp. 313-332, 2002.

(Mardaljevic, 2001) Mardaljevic, J. "The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques." *Lighting Research and Technology,* Vol 33 (2), pp.117-136, 2001.

(Mardaljevic, 1995) Mardaljevic, J. "Validation of a lighting simulation program under real sky conditions." *Lighting Research and Technology,* Vol 27 (4) pp.181-188, 1995.

(Mardaljevic and Nabil, 2005) Mardaljevic, J. and Nabil, A. "Useful Daylight Illuminace: A new paradigm for assessing daylight in buildings." *Lighting Research and Technology,* Vol 37(1), 2005.

(Michel et al., 1995) Michel, L., Roecker, C., and Scartezzini, J. "Performance of a new sky scanning simulator." *Lighting Research and Technology,* Vol 27(4), 1995.

(Moore, 1993) Moore, Fuller. Environmental Control Systems. McGraw Hill Inc., USA, 1993.

(Nabil and Mardaljevic, 2006) Nabil, Azza and Mardaljevic, John. "Useful daylight illuminances: A replacement for daylight factors." *Energy and buildings,* Vol 38(7) pp. 905-913, 2006.

(Osterhaus and Bailey, 1992) Osterhaus, W.K.E.and Bailey, I.L. "Large area glare sources and their effect on visual discomfort and visual performance at computer workstations." Industry Applications Society Annual Meeting, 1992.

(Perez et al., 1990) Perez, Richard, Ineichen, Pierre, Seals, Robert, Michalsky, Joseph, and Stewart, Ronald. "Modeling Daylight availability and irradiance components from direct and global irradiance." *Solar Energy,* Vol 44 (5), pp. 271-289, 1990.

(Perez et al., 1992) Perez R., Michalsky J., Seals R., Modelling Sky Luminance Angular distribution for Real sky conditions: experimental evaluation of existing algorithms, Journal of the IES, pp. 84-92,1992.

(Perez et al., 1993) Perez, R., Seals, R., Michalsky, J. "All-weather model for sky luminance distribution—Preliminary configuration and validation." *Solar Energy,* Vol 50 (3), pp. 235-245, 1993.

(Phillips, 2004) Phillips, Derek. Daylighting: Natural Light in Architecture. Architectural Press, Oxford, 2004.

(Reinhart and Fitz, 2004) Reinhart, Christoph and Fitz, Annegret. *Key findings from an online survey on the use of daylight simulation programs.* Proceedings of the ESIM 2004 Conference, Vancouver, pp. 1-8, 2004.

(Reinhart and Fitz, 2006) Reinhart, Christoph, and Fitz, Annegret. "Findings from a survey on the current use of daylight simulations in building design." *Energy in Buildings*, Vol 38 (7), pp.824-835, 2006.

(Reinhart, 2006) Reinhart, Christoph. "Tutorial on the Use of Daysim Simulations for Sustainable Design." Institute for Research in Construction, National Research Council Canada, 2006.

(Rhyner et al., 1991) Rhyner, Roeker, and Scartezzini. An Automated Heliodon for Daylighting Building Design. Proceedings CISBAT'91, Ecole Polytechnique Fédérale de Lausanne, 1991.

(Sarawgi, 2004) Sarawgi, Tina. "Determining the suitability of computer-aided simulation method in the design process." *International Journal of Architectural Computing*, Vol 2(2) pp. 155-175, 2004.

(Scartezzini and Courret, 2002) Scartezzini, Jean-Louis, and Courret, Gilles. "Anidolic daylighting systems." *Solar Energy*, Vol 73 (2), 2002.

(Schiler, 1987) Schiler, Marc. <u>Simulating Daylight with Architectural Models.</u> Daylighting Network of North America, Los Angeles, 1987.

(Solar Tool, 2007) Solar Tool program website. Square One Research, Cardiff University, 2006. Available at http://squ1.com/solartool. Accessed May 11, 2007.

(SUPERLITE, 2007) SUPERLITE 2.0 program website. Lawrence Berkely National Laboratory. Available at http://btech.lbl.gov/tools/superlite/about_sl.html. Accessed May 11, 2007.

(Thanachareonkit et al., 2005) Thanachareonkit, Scartezzi, and Andersen. "Comparing daylighting performance in scale models and test modules." *Solar Energy*, Vol 79 (2), pp. 168-182, 2005.

(Tullis and Stetson, 2004) Tullis, T.S., and Stetson, J.N. *A comparison of Questionnaires for Assessing Website Usability*. Proceedings of Usability Professional Association Conference, 2004.

(USCB, 2002) US Census Bureau. Business Expenses Survey, 2002. Available at http://www.census.gov/prod/ec02/be0200i1.pdf. Accessed May 22, 2007.

(US DOE, 2005) US Department of Energy. Energy efficiency and renewable energy, 2004. Available at http://www.eere.energy.gov/buildings/info.html. Accessed November 3, 2005.

(Ulrich, 1984) Ulrich, R.S. "View through a Window may influence Recovery from Surgery". *Science* 224, 1984.

(Van Den Wymelenberg et al., 2005) Van Den Wymelenberg, Kevin, Loveland, Joel, and Meek, Christopher. "Daylighting Lab Operation and Management Plan completed for Rensselaer Polytechnic Institute / Lighting Research Center." Integrated Design Lab, 2005.

(Vartianinen, 2001) Vartiainen, Eero. *Daylight Modeling and Optimization of Solar Facades*. Doctoral dissertation, Helsinki University of Technology, January, 2001

(Velds, 2002) Velds, Martine. "User acceptance studies to evaluate discomfort glare in daylit rooms." *Solar Energy*, Vol 73 (2) pp. 95-103, 2002.

(Virzi, 1992) Virzi, Robert A. "Refining the test phase of usability evaluation: how many subjects is enough?" *Human Factors*, Vol 34 (4), pp.457-468, 1992.

(Virzi, 1990) Virzi, Robert A. *Streamlining the design process: Running fewer subjects*. Proceedings of the Human Factors Society, 34th Annual Meeting. Santa Monica, CA: Human Factors and Ergonomics Society, pp. 291-294, 1990.

(Welford and Winston, 1989) Welford, W. T. and R. Winston. *High Collection Nonimaging Optics*. Academic Press, San Diego: 1989.

(Wienold and Christoffersen, 2006) Wienold, Jan and Christoffersen, Jens. "Evaluation methods & development of a new glare prediction model for daylight environments with the use of CCD cameras." *Energy and Buildings*, Vol 38 (7) pp. 743-757, 2006.

(WSA, 2007) WSA Environmental Laboratory. "The Skydome: technical details." Available at http://www.cardiff.ac.uk/archi/school/resources/envlab/sky2.html/. Accessed May 11, 2007.

(Yuan and Glicksman, 2006) Yuan, J. and Glicksman, L. R. "Validation of a multi-zone model with integrated energy equation and impact of thermal mass modeling methodology," Procedings of *Simbuild*, 2006.