

Changing mindsets: A passive-first artificial sky

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ABSTRACT: Architectural design that meets the goals of Architecture 2030 or results in zero net-energy performance is most elegantly achieved when employing effective passive strategies before adding high-technology components. With this ideal in mind, I posed a research question to a graduate seminar in natural lighting, “Can an artificial sky for testing daylighting models be designed that uses only daylight, rather than electric lamps, as its light source?” My threefold motivation for the question was: (1) matching—use a passive device to test a passive system (daylighting), (2) quality—use high-quality daylight to test daylighting systems, and (3) energy—use a low-energy system for testing models of low-energy designs. Currently, all artificial skies use an array of fluorescent lamps to simulate sky conditions. These skies are solely mechanical systems, have color rendering capabilities far inferior to daylight, and consume thousands of kilowatt-hours of electricity. The seminar students were up to the task and developed and tested successful scale models of two basic types—mirror-box and conical. We chose to build the conical prototype because its geometry is unlike that of any existing skies. To further encourage a sustainability-sensitive mindset, we designed the sky to be made of modular, bolted segments for non-destructive deconstruction and easy reconstruction. The building phase of the project was completed by the end of Spring 2013, and testing commenced in Fall 2013. This paper reports on the actions necessary to make the prototype a viable tool for learning about daylighting from prototype construction, calibration, and adjustment to test equipment set-up; to a users’ manual describing how to employ useful test methods.

In summary, the project not only focused on the design, fabrication, and testing of the sky, but is also about the change in mindset—valuing the efficient and elegant use of resources—required for a sustainable future stressing: (1) employing appropriate technologies for the task at hand (passive systems), (2) using high-quality resources (daylight), and (3) saving energy (100% lighting energy savings). The daylighted artificial sky serves as a hands-on exemplar, which has involved the collaboration of teams of students over a four-year span to design, develop, and test the artificial sky. To date about 30 students have participated in the project by answering the design question, writing and presenting research papers, designing and building the full-scale prototype, testing its performance, and, finally, testing their daylighting design proposals in the sky. Aspirationally, this shift in mindset will translate into the students’ future work in the design professions.

KEYWORDS: Daylighting, Artificial Sky, HDR Photography, Daylight Models

INTRODUCTION

One of the most viable strategies for reducing energy use in buildings is to use natural daylight to replace electric lighting during daytime hours. Successful daylighting reduces both electrical and cooling loads. To achieve satisfactory results, daylighting schemes must be tested for light levels, light distribution, sunlight penetration, glare, and overall spatial quality before the actual building is built. Physical scale models of daylighted spaces offer a reliable means of testing daylighting options. This type of testing is also valuable in architectural education where students propose designs of buildings that most likely won’t be built; yet require verification of the fitness of their designs. The design and testing also builds practical skills for their professional careers.

When testing physical scale models of architectural spaces, useful parametric comparisons of design options can be achieved only under reliably consistent sky conditions. The natural sky poses a problem: natural skies are dynamically variable in brightness and distribution of light,

not only from day-to-day, but from minute-to-minute, defeating the principle of consistency required for accurate comparisons. This problem has led lighting designers to create electrically lighted artificial skies for testing daylighting models. These artificial skies must be able to simulate a standard uniform overcast sky condition where the zenith is about three times brighter than the horizon with gradual darkening from zenith to horizon. It is not necessary that the artificial sky match the luminance (brightness) of a real overcast sky: it's only necessary that the distribution of light in the sky meets the criteria for a CIE standard uniform overcast sky—a 3:1 brightness ratio from zenith to horizon. In theory, it's most critical that the artificial sky provide the proper and consistent distribution of light rather than the proper intensity of light (Haglund, 2011).

While electrically-lighted artificial skies are adequate for model testing, there are three reasons why they are not optimal: philosophical, qualitative, and environmental.

Philosophical: Daylighting, like all passive design strategies, requires sensitivity to context, yet today's artificial skies are machines for testing daylighting models independent of natural sky conditions. They offer the convenience of being able to conduct model testing at any time, including nighttime, no matter what outdoor sky conditions occur. Passive design requires a mindset that places natural processes in the forefront, relegating mechanical devices to backup status. Is there a passive tool that could encourage this mindset while accurately testing daylighting models?

Qualitative: The spectral distribution of daylight is dissimilar to that of any electrical lighting source, though many aspire to replicate daylight. Therefore, viewing daylight models under electrically lighted artificial skies that provide accurate distribution of light does not capture the aesthetic essence of light. Could natural light be used for model testing?

Environmental: From an energy-conservation standpoint, the irony of using high-energy artificial skies for designing low-energy buildings is palpable. Currently, a mirror-box artificial sky uses twenty-two 59-watt fluorescent lamps (1.3 kw total), while an 8-meter diameter sky consists of 640 CFL luminaires (12.8 kw total)¹ and a smaller sky (5.2-meter diameter) has 270 CFLs (5.4 kw total).² Is there a zero-energy alternative?

1.0 PROTOTYPE DESIGN AND CONSTRUCTION

1.1. Design Phase

Four teams of five students in the Fall 2011 Natural Lighting seminar were given four flawed prototype scale models of the proposed first-ever daylighted artificial sky. They were tasked with testing and modifying these models to the point that they could simulate a standard overcast sky under any exterior daylight condition. The students tested their model iterations under the natural sky using a circular fisheye lens pointed upward through the model base to record the lighting conditions and *Culplite*³ to analyze their results. The resultant successful models were of two basic types—mirror-box and matte white conical (Haglund et al, 2012). We used these research results to successfully apply for a modest university seed grant of \$12,000 to fund the design, building, and instrumentation of a full-scale prototype. We chose to build the conical prototype because its geometry is unlike that of any existing skies (our mirror-box prototypes mimic electrically lighted mirror-boxes) and showed greater potential to meet the performance goals elegantly.

1.2. Lost in Translation?

Going from the successful scale model skies to the full-sized prototype was not without challenges. Upon obtaining the seed grant we proposed two options for the full-size prototype—an outbuilding that could be built near the architecture building or a device that could be built inside the architecture building. We favored the indoor version because the outbuilding posed several problems—the need for a weather-resistant envelope (expensive), for wintertime heating (problematic), for electrical service (expensive), and for easy access for students and their models (not easy). Thankfully, the architecture faculty supported our indoor option for the project by designating a space for the sky proximate to the fourth-year and

graduate studios so it could be easily accessed by students for testing their design studio projects' daylighting schemes. We also had to obtain university approval to install a skylight for the sky in the roof of our historic building. Amazingly, permission was granted. Once all these hurdles were cleared we were able to convince a manufacturer⁴ to donate a high-efficiency skylight to the project.

The ideal form for the sky is a perfect cone. However, we chose to approximate the cone with a ten-sided form constructed of lumber and plywood segments bolted together for non-destructive deconstruction and easy reconstruction, which is also in accord with a sustainability-sensitive mindset.

1.3. Construction Phase

The construction phase of the project began during Fall 2012, after the award of the internal seed grant and approval by the faculty and the university. The first item to be dealt with was installation of the high-performance, commercial skylight in the pitched roof of the historic Art and Architecture building. We strategically chose an installation site near the top of a north-facing hip—receiving full access to the sky dome while being sheltered from prevailing SW winds and high enough to avoid snow loads. Getting the project approved and bringing the sub-contractors to the site to install the skylight consumed the entire semester. Meanwhile, we were generating construction drawings in *Sketch-Up*, which allowed us to accurately cut the compound angles in the plywood and lumber that the ten-sided form required. The exact configuration of the skylight installation geometry became an emerging issue, we weren't sure of the exact location of the skylight on the roof or of the depth of penetration of the extension tube and diffuser into the space below. This uncertainty stalled finalizing the construction drawings and initializing actual construction of the prototype sky structure until after skylight installation was complete (Fig. 1)—Spring semester 2013. We wanted to leave a gap between the top of the prototype and the bottom of the skylight to allow stack ventilation of solar and internal gains in the sky. Once we determined the floor-to-diffuser height, we were able to finalize the construction drawings for the prototype and begin actual construction. The brunt of the work was completed by the end of Spring 2013, and finish work and testing commenced Fall 2013. The donated skylight allowed the project to come in about \$2,000 under budget, so the seed grant funding was extended to May 2014 to cover new materials, equipment, and travel expenses. Hopefully, we will be able to report on both design and performance testing phases in February 2014.



Figure 1: Skylight mounting details, interior and exterior.

2.0. HDR PHOTOGRAPHY FOR CALIBRATION

In order to ascertain that the artificial sky is performing as expected, we need to be able to accurately evaluate the luminance of the surfaces of the cone. To do this, photographs are taken using a camera with a 180 degree, circular fisheye lens placed in the center of the artificial sky at the height of its horizon and pointed toward its zenith.

Because the characteristics of daylight are constantly changing, it is important that data collection within the artificial sky be done instantaneously. A digital camera with a fisheye lens

fulfills this requirement by collecting data from all points within the space at high resolution, which can be evaluated with per-pixel accuracy if desired (Inanici and Jim, 2004).

2.1. Camera Calibration

All photos exhibit a phenomenon known as light fall-off, or vignetting, where the amount of light entering a lens is diminished at the edge, causing reduced brightness at the periphery of the image compared to the center. When evaluating the performance of the artificial sky or architectural models this light reduction must be corrected before analysis can take place.

To evaluate the color response of the camera sensor a color response curve was generated by taking a series of photos with a fixed aperture size of f/4.0 and varying the shutter speed from 1/4000s to 2s at one stop intervals. These photos were processed in a program called *Photosphere* to get an accurate color response for the camera's sensor.

The amount of light fall-off caused by a lens is determined by the geometry of the lens and the aperture size of the lens (Inanici, 2006). This light fall-off can be expressed as a quartic expression, and will change as aperture size is increased or decreased. A fixed aperture size of f/4.0 was chosen for the calibration and testing because of its appropriateness for balanced exposure with a shorter exposure time in indoor light levels.

To determine the light fall-off of the lens a series of photos were taken in a room with controlled, constant light levels. An area of focus, with even lighting, was chosen and measured to be five degrees of the lens' view. A photo was taken from a tri-pod mounted camera, and then the camera was rotated five degrees before taking the next photo. This procedure was continued from zero to ninety degrees to move the area of focus from the center of the lens to the edge. The area of focus of each image was then analyzed for its brightness using *Grasshopper* for *Rhino* and the relative brightness was used to create a quartic expression representing the light fall-off caused by the lens.

A filter was created from this quartic expression which was combined with calibration photos to increase the brightness of the individual pixels at the correct rate from the center of the image to the edge, giving a fully corrected photo that can be used for the analysis of the artificial sky or for architectural models.

2.2. Sky Calibration

Using the procedure listed above, calibrated photos represent an accurate data set for relative luminosity within the artificial sky. The photos can be analyzed using a *Grasshopper* script in *Rhino*. Using this method, the artificial sky will be tested to see if it achieves a 3:1 brightness ratio from the zenith to the horizon with a linear reduction in brightness.

After initial tests are completed, modifications will be made to the sky to get as close as possible to the 3:1 CIE standard brightness ratio. These modifications may include adding a shroud to the top of the cone, to capture some light that is escaping through the gap between the diffuser and the top of the cone, or adding materials between the skylight and the cone to modify the distribution of light.

3.0. DATA ACQUISITION SCHEMES

Physical architectural scale models can be tested for satisfactory daylighted schemes within the artificial sky prototype in two different ways: Data Acquisition System (DAQ) and Fisheye Lens.

Data Acquisition Systems allow for a sampling of signals that measure real world physical conditions (such as daylighting) and converting the resulting samples (taken using photometric sensors) into digital numeric values that can be manipulated by a computer. There are three main components of a DAQ setup: Sensors, Hardware, and Software. The sensors measure the daylight illuminance, and are connected to the hardware⁶: an analog-digital converter. The hardware is also connected to the computer via a USB port and its data stream is analyzed using specific software⁶ (usually paired with the hardware when purchased).

3.1. Data Acquisition System

Because our sky uses the constantly changing natural sky as its light source, it is important to collect the data from the five probes simultaneously. While the brightness of the sky constantly changes, the design of the prototype ensures that the lighting distribution- under all outdoor sky conditions remains constant.

We will use five photometric sensors⁵, specifically located within the prototype and connected to a DAQ system⁶, to gather the most accurate results. One photometric sensor will be placed externally, outside the scale model with full exposure to the “sky” and without blocking any of the model’s apertures to test outdoor sky conditions funneled in through the skylight. The other four sensors will be placed internally at different points within the model to test for interior light distribution, which will then be used to calculate the daylight factor at each of the interior points. In order to properly connect the photometric sensors to the DAQ system, millivolt adapters⁷ are required.

3.2. Fisheye Lens

This is another successful method for testing the effectiveness of student’s designs for daylighting schemes. Scale models made with a 76.2 mm (3 in) diameter hole at the base allow enough space for our circular fisheye lens (of that size) to be placed and pointed upward through the model. In conjunction, the model will be placed on a testing table, whose surface is level with the artificial sky’s horizon, which also has a same size hole to allow the student to photograph from underneath the table and capture an image of all surfaces in the scale model. (Fig. 2)

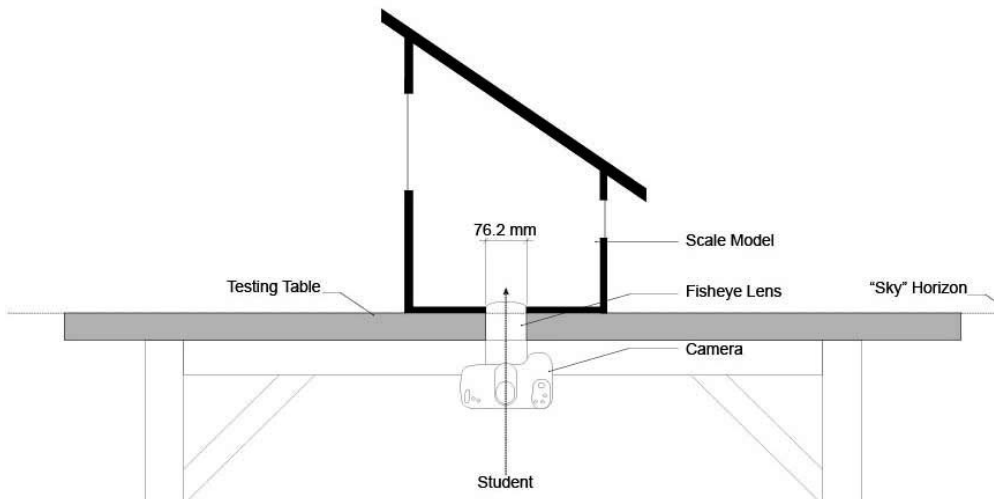


Figure 2: Fisheye lens set-up for model photography.

Using a fisheye lens is beneficial for evaluating daylight distribution because it allows the student to physically examine interior conditions and see how much light gets through the apertures to the point where the camera is located. Through HDR photography captured through the lens, the brightness of the room’s surfaces can be measured and the contrast in the space can be visually inspected. Other possibilities for analyzing the data through the use of a fisheye lens include using outside software such as *Culplite*³ to evaluate glare or using the Fisheye Projections and Dot Diagrams method and superimposing it on an image to calculate the daylight factor (Tergenzer and Wilson, 2011).

The prototype is meant to be used throughout the design process as a resource to influence architectural designs through passive daylight strategies. Both methods for testing daylighting schemes: Data Acquisition System and Fisheye Lens will provide student’s a means for

parametric testing, where the acquired results can be used to alter student's designs and re-test as needed.

4.0. USERS' MANUAL

It is often the case something that is more obvious to the developer is less obvious to the user. Concepts that are second nature to an experienced user may be totally foreign for a novice user. When students need to employ an unfamiliar product, the user's manual can provide a gentle and efficient way to bring them up to speed. Due to the uniqueness and complexity of our prototype and physical daylight modeling in general, it is essential to provide coherent step-by-step guidance through the procedures of placing the sensors, using the fisheye lens, and operating the DAQ's *Omega*⁶ software. We will write a users' manual that will be a valuable resource for future students and designers.

Users will refer to the manual for comprehensive detailed explanations of menu use, settings, preparations, and general information about the prototype and daylight modeling. The user's manual will categorize in detail the two different testing methods—data acquisition system and fisheye lens.

The Users' Manual will consist of:

Introduction

Preparations

- Getting Started
- Testing
- Daylight Model Basics
- Basic Operation of the Camera
- Computer Programs and Sensors

Photography

- Taking HDR Photos
- Diagrams

Data Acquisition

- Terminals on the Devices
- Saving your Information
- Sensor Placement

General Information

- Accessories
- Product Codes
- Specifications, Index

With extensive instructions and illustrations, we will provide a positive experience for students to learn and discover the effects of daylighting in their architectural designs.

CONCLUSION

An overarching goal of this project has been to involve graduate students in on-going research. This paper's co-authors are only three of the thirty-odd students who have taken the project from an odd-ball idea to a practical reality. The student researchers have performed hands-on research tasks from design inquiry to fabrication, to contributing to writing and presenting four conference papers. They have acted as agents of change, instilling their understanding and enthusiasm for the project in their classmates and visiting prospective students and their parents. Having the artificial sky proximate to the upper level design studios will help extend its success in setting a passive-first mindset in future architectural design classes.

We have also aimed to make all of our research freely available to architecture schools and others worldwide. Our plans and findings can help others construct, test, and instrument similar low-cost daylighted artificial skies in their schools and offices. We've also discovered that even electrically lighted mirror-box skies can be converted (easily) to passive, daylighted skies (Haglund et al, 2012).

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ENDNOTES

- 1 The University of Cardiff School of Architecture Skydome is described at: <http://www.cardiff.ac.uk/archi/skydome.php> [7 April 2012].
- 2 The Bartlett School of Architecture artificial sky, is described at <http://www.bartlett.ucl.ac.uk/research/consult/sky/sim01.htm> [7 April 2012].
- 3 *Culplite* is available from Jeff Culp, Center for Energy Research/Education/Service, Ball State University.
4. Solatube donated a Solatube 750 DS-O 530 mm (21 in.) skylight.
5. The Photometric Sensors (LI-210SA) are available through Li-Core and is described at: <http://www.fondriest.com/li-cor-li-210-photometric-sensor.htm> [10 October 2013].
6. The Data Acquisition software and hardware (OMB-DAQ-55) is available through Omega and is described at: <http://www.omega.com/pptst/omb-daq55.html> [10 October 2013].
7. The Millivolt Adapters (2290) are available through Li-Cor and is described at: <http://www.licor.com/env/newsline/2007/07/interfacing-li-cor-radiation-sensors-with-campbell-scientific-dataloggers/>.