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A HEMISPHERICAL SKY SIMULATOR FOR DAYLIGHTING MODEL STUDIES

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ABSTRACT

Light measurements in scale models provide a powerful design and analysis tool for quantitative and qualitative daylighting studies. Models can be measured outdoors, but to facilitate measurements under standard sky conditions and for situations where reproducible results are desired without extensive manipulation of measured data, an indoor sky simulator is essential.

This paper describes the design of a 24-foot-diameter hemispherical sky simulator recently completed at LBL. The goal was to produce a facility in which large models could be tested; which was suitable for research, teaching, and design; which could provide a uniform sky, an overcast sky, and several clear-sky luminance distributions, as well as accomodating an artificial sun.

Initial operating experience with the facility is described, the sky simulator capabilities are reviewed, and its strengths and weaknesses relative to outdoor modeling tests are discussed.

1. INTRODUCTION AND BACKGROUND

People have always welcomed daylight in buildings, and much of the history of architecture can be seen as a conflict between the desire to admit daylight, sunlight, and view and the need to control extremes of local weather and other undesired intruders. Because light defines architectural space, the most successful building designers have been those who have successfully manipulated daylight and electric lighting to provide for both function and aesthetics.

A new concern for minimizing energy use in buildings has prompted a re-evaluation of the role that daylight might play. In order to successfully integrate daylighting as an energy-conserving strategy into the design process, the designer must have available an array of appropriate design tools.

Using physical models to analyze and predict daylighting distribution in a space and to assess lighting quality is well established in the literature and in practice.

Model tests conducted out of doors require only the availability of adequate photometric instrumentation and the scale model. The chief drawback to outdoor testing is that the sky is a constantly changing light source--no two clear or cloudy days will ever be quite alike. A solution is to reproduce the sky indoors in a controlled sky simulator. The absolute illuminance in a simulator will be less than the real sky, but if the luminance distribution is properly reproduced, model measurements need be adjusted by only a single scale factor. Depending upon the type of testing to be done and the available resources, a variety of sky simulators can be constructed.

Historically, the first artificial skies were simple light-boxes using a uniform area light source in a white painted box. These were used to study the performance of skylights, lightwells, and vertical windows. A simple light-box, however, does not adequately simulate ground-reflected light or the non-uniform luminance distribution characteristic of most clear and overcast skies.

Various types of three-dimensional skies have been built to simulate ground reflectance and complex sky luminance distributions. In mirror-type skies, the light flux from an overhead luminous source is redistributed by mirrored walls and produces an overcast sky distribution at the model location. Sky simulators have been constructed using spherical or elliptical sky vaults. Both approaches allow for sky distributions other than uniform or overcast and permit the study of ground reflectance and other effects of direct sunlight.

Although sky simulators were used extensively for important studies in the 1940s and 1950s, by the mid-1970s no facilities appeared to be

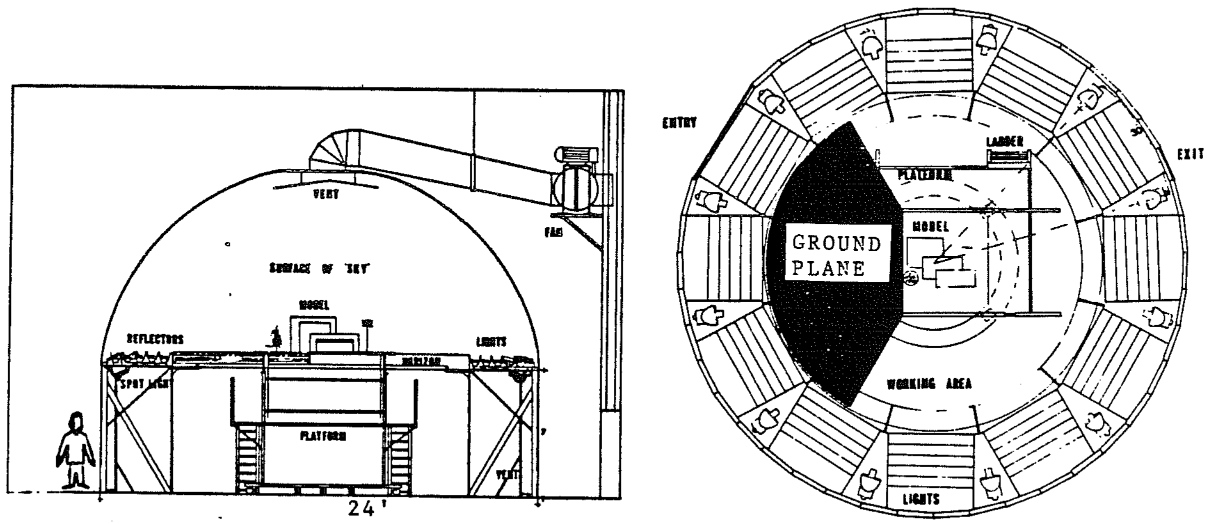


Fig. 1. Plan and Section of LBL sky simulator.

in routine use in the United States. Given the value of these facilities for design studies, computer model validation, and lighting quality studies, in 1978 we decided to explore the possibility of building such a facility as part of a DOE-supported program to advance the use of daylighting techniques in energy-conserving buildings. We anticipated a joint-use facility having three primary purposes: 1) research, 2) architectural design, and 3) teaching. Specific performance capabilities envisioned for the sky included: 1) uniform, CIE overcast, and CIE clear-sky luminance distributions; 2) variable ground reflectance; 3) a sun simulator; 4) a lighting control system that allowed easy conversion from one type of sky to another; and 5) photometric instrumentation and data recording capabilities. In addition, an important goal was to develop a facility that could be reproduced elsewhere at low to moderate cost. These requirements have been largely met.

2. DESIGN AND CONSTRUCTION

A variety of design approaches and numerous specific construction details were developed and reviewed in the course of this project. A large, dome-type sky was selected as providing the greatest possible flexibility for future model measurements (Fig. 1).

2.1 Dome Concept and Structure

Two basic options were considered for the dome structure: an opaque shell illuminated from the inside or a translucent shell illuminated from behind. A review of the advantages and disadvantages of each led us to select the opaque reflecting shell (2,4,5,6,7). After investigating a variety of sources for ready-made domes, we selected a pre-manufactured 24-foot-diameter metal dome used as the top of a silo. These are cheap, provide a rigid fireproof structure, are easily assembled with unskilled labor, and with minor modifications provide an adequate interior reflecting surface.

To provide better working conditions within the simulator, the metal dome was placed atop a seven-foot high cylindrical plywood wall having double doors to allow large scale models to be moved in and out (Fig. 1). Two coats of high-reflectance white paint were sprayed on the interior surface to provide a reflectivity of approximately 80% and a good diffusely reflecting matte finish.

2.2 Lighting System Concept

Developing an interior lighting system to provide the desired luminance distribution on the underside of the dome is generally a long and tedious trial-and-error process. We developed a procedure that worked well to speed this process. Any single light source and/or fixture will provide a unique luminance distribution over the inner surface of the dome. The net luminance distribution over the entire surface from all light sources can be found by superimposing the contributions from each source. A computer program was developed that stores a library of luminance distributions and adds the contributions from any selection of sources to produce the net total distribution. Using a limited set of luminance measurements and this computer program we were able, through an enlightened trial and error process, to arrive at desired luminance distributions with a minimum of hardware investment and time.

2.3 Ventilation

Due to the large heat load generated by the lighting system inside the dome, it was important to limit the heat buildup in the structure. A 2-speed, 2600 cfm fan was installed to remove air through a circular duct attached to the top of the dome (Fig. 1). With a full lighting load of 15-20 kW, the fan limits the temperature increase to less than 5°F.

2.4 Lighting System and Controls

The lighting system has been designed to provide uniform, CIE overcast, and several CIE clear skies and consists of two major elements. A fluorescent lamp system arranged in 12 banks of fixtures provides the basic background luminance of the sky, which does not vary with azimuth angle. Each sector consists of five fixtures holding two 4-foot fluorescent lamps mounted perpendicular to the dome radius (Fig. 1). By using specially fabricated reflectors positioned at different angles behind the lamps, uniform and CIE overcast skies have been duplicated and the horizon-to-zenith variation of clear skies can be achieved. An array of narrow and wide-angle spotlights has been installed to provide the azimuthal variation in clear skies for several sun altitudes. Agreement between the CIE sky distributions and those achieved in the sky simulator are excellent. Figure 2 compares an overcast and a clear-sky distribution as measured in the dome with standard CIE distributions.

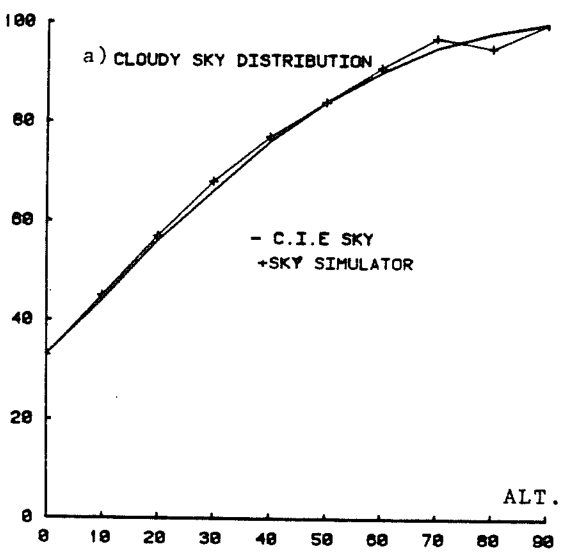
The illumination system in the dome utilizes high-output fluorescent lamps and ballasts. These provide illumination levels on a horizontal surface of about 500 footcandles for a uniform sky, 350 footcandles for the overcast sky, and above 600 footcandles for a typical clear sky. An additional benefit of these high levels is that the facility may become more useful for window glare experiments. Control of the light output is achieved with on-off switching, group dimming hardware, and voltage control techniques.

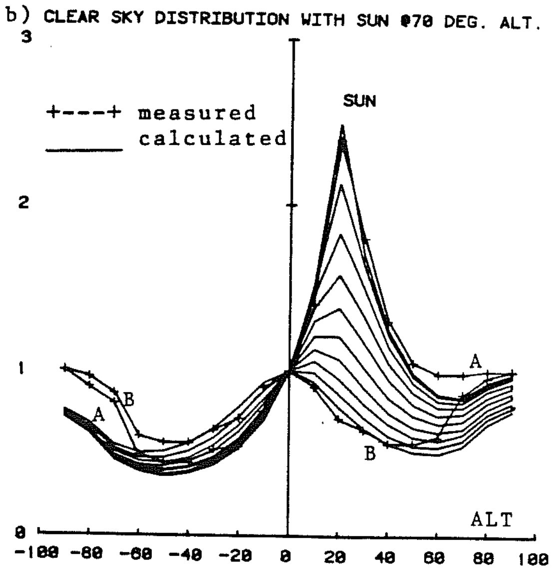
2.5 Model Platform

A platform was constructed to hold large architectural models (up to 6 feet across), to provide the required adjustments of model height relative to sky horizon, and to allow safe access to the elevated model (Fig.1). The height of this platform can be adjusted to position fenestration in multistory buildings at horizon level. The entire platform rotates, allowing the model to be positioned relative to a clear-sky distribution.

2.6 Ground Reflectance

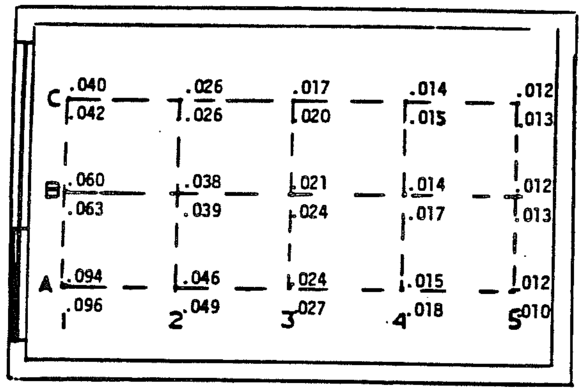
Early daylighting studies showed that ground-reflected light must be considered in both indoor and outdoor model studies. We have developed a unique ground reflectance capability without the limitations found in previous skies. The model foreground is constructed as a translucent surface, lit from below by a dimmable light source. For any given sun position, sun intensity, and ground reflectance being simulated, the ground luminance is easily determined. Dimmers are used to adjust the light output of the sources below the translucent foreground to provide the proper luminance relative to the sky luminance.



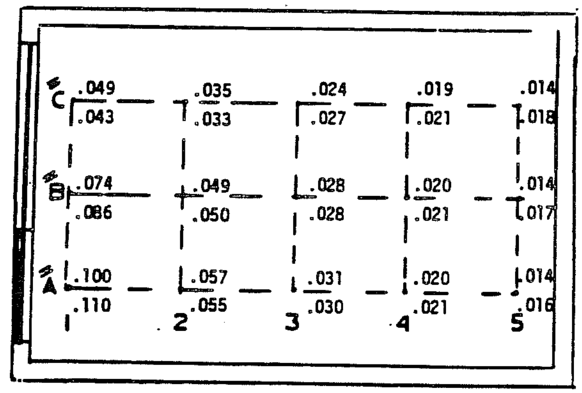


A: Cross-section of (0,180) azimuth.
B: Cross-section of (90,90) azimuth.

Fig. 2 a) and b). Measured luminance vs. altitude for a) CIE Overcast Sky and b) CIE Clear Sky.



a) **Ground Reflectance = 0.01 Indoors**
= 0.06 Outdoors



b) **Ground Reflectance = 0.86 Indoors**
= 0.89 Outdoors

Fig. 3 a) and b). Values shown are dimensionless: measured interior illumination divided by vertical surface illumination at the window. At each point, upper value is measured in the sky simulator; lower value is measured outdoors.

This method provides the proper ground brightness for the model, but would add an unacceptably large luminous flux to the sky vault, altering the sky luminance distribution. This problem is solved by placing a louvered screen over the translucent ground plane so that the emitted light flux is selectively directed toward the model aperture. This permits a high apparent ground luminance for the model with a minimal disturbance of the sky luminance distribution.

2.7 Sun Simulator

The implications of direct sun penetration for fenestration design are of critical importance to both daylight quality and quantity within a space and to the net energy balance. Shading devices frequently add geometrical complexity to a design, which makes the use of scale models mandatory. It is thus necessary to test these designs under sky conditions which include direct sun.

We considered three approaches to adding a direct sun simulation capability. These are: 1) a separate stand-alone sun simulator, 2) an artificial sun mounted on a track inside the dome that traverses from near the horizon to the zenith, and 3) a sun source mounted remotely from the dome structure, with a moving planar mirror used to introduce a collimated beam through a hole in the dome to the model position.

In the short term, a separate sun simulator will be constructed. After some experience is gained we will make a decision about adding an artificial sun inside the sky dome itself.

3. PRELIMINARY RESULTS

Comparative measurements were made for a small office model both in the sky simulator and out-of-doors. Results of indoor tests with variable foreground reflectance were compared to those of outdoor tests made on a day having a dense overcast sky with a luminance distribution that compared well to the CIE standard. Agreement was excellent, as shown in Fig. 3a,b. Studies are in progress comparing the output of several computer programs with results from the sky simulator.

4. SKY SIMULATOR VS. OUTDOOR MODEL TESTS

Indoor and outdoor model tests share many of the attributes and drawbacks of mathematical or graphical daylighting design procedures. There are significant differences, however, between indoor and outdoor model testing. Outdoor testing allows designs to be evaluated under a wide range of sky conditions, including direct sun. It also permits evaluation of the effects of unique environmental factors at the building site - landscaping, obstructions, and microclimatic effects such as varying air quality. The chief drawback to outdoor testing is that the sky is a constantly changing light source. Two clear or overcast days will never be quite alike. There will also be differences in luminance distributions as well as in illuminance at the window surface. Measurements may be made in several models simultaneously to avoid the problem. However, if comparisons need to be made between measurements made on different days the problem reappears. The significance of these problems depends upon the intentions behind the modeling work. If one desires to compare subtle design differences the uncertainty introduced by the "non-reproducible" sky may exceed the expected performance differences. It seems unlikely that one could get absolute, reproducible agreement better than 10-15% between "identical" models measured on two apparently "identical" days.

It may be desirable to test a model under clear skies with varying solar altitude and it may not be convenient to wait six months until those sun and sky conditions occur. To approximate those conditions the model may be tilted, but that introduces additional error and uncertainty. It may also be frustating to wait for a dense overcast day in a sunny climate and vice versa. Long-term data-collection to assess average performance under seasonal or annual climate conditions can be effectively accomplished in outdoor models.

Outdoor model studies will continue to be the choice of most designers, because that is frequently the only available option. If properly conducted, outdoor model tests will provide the practical data for most design decisions. However, an inadequate understanding of the effects of changing sky conditions on model results can mislead a designer.

Sky simulators solve many of these problems but create new problems of their own. In theory, the sky simulator provides the constancy and reproducibility that the real sky lacks. In practice, lamp output in the simulator will change with age, temperature, dirt accumulation, and applied voltage. Fortunately, these changes generally occur for all lamps so that the distribution will not change although the illuminance may. Care in monitoring illuminance and luminance in the dome should alleviate this problem. The constancy of luminance distribution in a sky simulator is critical for most comparative studies. The coefficients for the IES Recommended Practice of Daylighting were all derived from model studies conducted in a sky simulator.

Since the sky simulator has finite dimensions, horizon errors may be caused by the size of the model relative to the size of the dome. The model must be level and properly positioned in the dome. We are now calculating adjustment factors to correct for these effects.

In summary, given access to either indoor or outdoor model tests, the best choice will depend upon the specific objectives of the testing. In either, a thorough understanding of the critical performance issues involved is essential to the collection of meaningful daylighting data from scale models.

For the appropriate design problems, we believe the facility will be of tremendous value for a wide variety of daylighting studies and should assist us in completing an extensive series of comparative performance tests which will be of value to those interested in using daylight effectively in buildings.

5. ACKNOWLEDGEMENTS

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A lengthier version of this paper is available as LBL Report No. 12286

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6. REFERENCES

1. Christensen, E., 1976, "Sun Simulator at Copenhagen School of Architecture," Lighting Research and Technology, 8 (4): 219-223.

2. Croghan, D., 1964, "The Transilluminated Domical Artificial Sky," Light and Lighting 57:290.

3. Harkness, E.L., 1970, "The Design of a Mirror Chamber Artificial Sky," Models Laboratory Report MR1, Department of Architecture, University of Newcastle, NSW, Australia.

4. Kittler, R., 1959, "An Historical Review of Methods and Instrumentation for Experimental Daylight Research by Means of Models and Artificial Skies," Proceedings 14th CIE Session, Paper P.-59.8: 319-334.

5. Kittler, R., 1974, "New Artificial 'Overcast and Clear' Sky with an Artificial Sun for Daylight Research," Lighting Research and Technology 6 (4): 227-229.

6. Leifeste, A.A., 1966, "Predicting Daylighting with Models," Architecture at Rice Report No. 19, Rice University, Houston, Texas.

7. Reed, B.H. and Nowak, M.A., "Accuracy of Daylight Predictions by Means of Models Under a Artificial Sky," Journal of the Illuminating Engineering Society, July: 336-346.