Scale Model Photometry Techniques under Simulated Sky Conditions

THIS PAPER WAS PRESENTED AT
THE 1995 IESNA ANNUAL CONFERENCE

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Introduction

The design decision-making process can often be facilitated by using models in order to evaluate different design options. The use of scale model photometry is an established technique that has been used in lighting design practice for many years. The advantage of physical models over the use of computer programs becomes obvious when considering real design situations where especially complex geometry and other calculation methods do not satisfy designers' needs. A scale model provides a simple means of changing one variable at a time; i.e., window geometry, its placement, orientation, skylight shapes, shading system or surface properties of interior spaces. This process provides designers with the selection of optimum conditions in order to integrate the natural and electrical lighting systems.

The use of small scale models during the design process is the oldest method in design.[1] They show the concept more effectively than sketches or perspective drawings. They allow the designer to study problems in all three dimensions. As a communication tool, models are the most understood presentation technique especially when compared to technical drawings and renderings. In some cases, models are needed by the design team to generate forms that are difficult to visualize and analyze. Models are used as an accurate method to evaluate the performance of a design or to find a relationship between the proposed design and its elements under real conditions.

Models are used in many different fields, such as heating, ventilation, acoustical testing, and fire testing. This paper will focus on the application of scale models in predicting daylight illumination in buildings. The scale models used for predetermining daylight distribution are different from interior design models. They are used under real sky or simulated sky conditions in order to measure the light within or to observe and videotape the luminance variation within. The techniques which are used to conduct these experiments have been accepted and, in most cases, validated by lighting engineers and designers.

Theoretical background and methods

The daylight factor concept is a commonly used measure of performance and is defined as: "The ratio of the daylight illumination at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the illumination on a horizontal plane due to an unobstructed hemisphere of this sky. Direct sunlight is excluded for both values of illumination."[2] Computer calculations provide designers with many forms of data and variables that can be analyzed. The scale models using the daylight factor or other ratio concepts[3] combined with photometric instruments bring complete integration of quantitative and qualitative methods in lighting design, if applied accurately. Although calculation methods can give the designers a great deal of data for a given design, early stages of design might not require all that information. Sometimes a look through a model provides enough information to some designers to continue their work. The reasons and advantages for using the daylight factor concept in scale model photometry were given by Hopkinson and other researchers.[2,4] Hopkinson and his colleagues commented:

"The concept of daylight factor has two advantages. First, it is an expression of the efficiency of the room as a lighting installation, i.e., as a means of penetration of available outdoor light into the room. Even though the daylight outdoors may increase or decrease, the daylight factor will remain constant because the interior illumination is also changing with the exterior daylight. Constancy is therefore one of the advantages of the daylight factor. The second advantage is associated with the concept of adaptation. Appreciation of brightness is governed not only by the actual luminance of the area at which we are looking, but also by the brightness of the whole surroundings which govern the level of visual adaptation." Other researchers' efforts have been to change the daylight factor concept to clear skies. As Robbins commented:[5] "The daylight factor method does not apply to the clear sky condition as easily as it does to the overcast sky because interior illuminance under the clear sky depends upon solar location, whereas under the overcast sky it does not."

Some of the above limitations such as sky condition variation or luminance level changes are eliminated when scale models are used under sky simulators. The capabilities and limitations of such facilities are discussed below.

Scale of models

The selection of the scale for models is governed by two opposing limitations. The model should not be too

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small, due to the difficulties in making accurate photometric measurements inside the model using the available size of photometers. The model must not be too large or it will create major errors in photometric studies under simulated sky conditions inside the sky simulator. The horizon scale error or the inter-reflection obstruction in the sky simulator are caused by large-size models. The commonly used scales in scale model photometry techniques have proportions of 1:10 or 1:12 or 1:16. The usual scales encountered in model work are presented in **Table 1**. Using models at these scales means the size of an office space would be approximately 76 cm (30 inches) in length and width and 30 cm (12 inches) in height. This would be a very comfortable size to work with from a model builder's point of view.

Features such as windows, doors, partitions, and room surface properties are easily fabricated. The reflectance of these surfaces can be measured and altered using interchangeable moving parts. The photometer holder and its position with respect to windows and sunlight penetrating the inside of the model can be measured or made adjustable. The photocell holders should be horizontal or vertical with the flexibility of adjusting the angle of view in all directions inside the model.

The shading devices or glazing samples can be mounted or dismounted as daylighting design studies require. The need for sensors to be added or positioned separately within the model can be made possible in models with 1:10 or 1:12 proportions. The scale model for daylighting studies can be made from many different materials. Walls, floors, and ceilings can be constructed out of cardboard, foam board, or wood. The surfaces should be covered or painted with the known reflectance. The models should be light sealed. The glazing can be actual glass or plexiglass with known transmittance factors, which is required for final calculation of illuminance levels inside the model. **Figure 1** shows the options and issues related to scale model photometry under outdoor or simulated conditions.

Simulation facilities for models

Design and research tools vary enormously in their capabilities and applications.[6] No single tool has the capability to solve all lighting design problems. The information and input data required by these tools also varies widely, therefore the design tools should vary during the design process. Some are needed at the preliminary stage of design, and some are needed at later stages as analytical tools that help in the evaluation of the performance of a design solution or to satisfy the building code requirements. Overall, some tools deal solely with lighting and daylighting in such a way as to predict the quantity of the variable in question. They require a great deal of personal as well as monetary investment. The appropriateness of each model for the given design problem varies with the process for each project. The use of these models is essential to the architectural profession and to the lighting designers in the methods of proper application.

Outdoor testing facility

It is obvious that there are significant differences between indoor and outdoor model testing. In general, the sky simulator is an answer to many of the problems of outdoor testing. However, it is possible to record measurements for several models simultaneously to avoid this problem. It may be desirable to test the effects of different sky conditions. The sites of buildings affected by unique environmental factors such as microclimates, landscaping, and possible obstructions, are important in daylighting prediction. Long-term data collection is also helping to determine the effects of seasonal and annual conditions. Outdoor model testing is still the choice of most designers because it is often the only option available. These tests should be conducted properly with a good understanding of the effects of changing sky conditions.[6]

Sky simulator

Since 1914, various types of simulation facilities were designed and built with many different limited capabilities, notably, the sky chamber, mirror sky, and artificial sky.[1,7,8] They were constructed using painted white or mirror boxes, spherical or elliptical structural frames, and opaque or translucent surface materials. They have been used for various applications such as development of some earlier graphic design tools in daylighting.

Since 1978, some old sky simulators were put back into operation, and some new ones have been built in order to educate the new generation of designers in the field of lighting.[8,9] Given the importance of computer applications in architecture and lighting design studies, simulators have had a major impact on computer validation[11] and lighting quality studies. Scale model photometry provides an accurate design and analysis tool for quantitative and qualitative daylighting performance evaluations of buildings.

Light measurements can be made outdoors, but outside conditions are not ideal due to the dynamic changes of sky luminance distribution. Due to the high cost of energy, the contributions of this type of facility have been recognized by researchers, educators, and designers throughout the world.[12,7] The objective was to provide a facility in which various architectural spaces could be modeled and tested, and that would be available to research, teaching, and other professionals in the design community. This new facility is designed in such a way as to be used as a prototype for fabrication by other interested educational and research institutions.

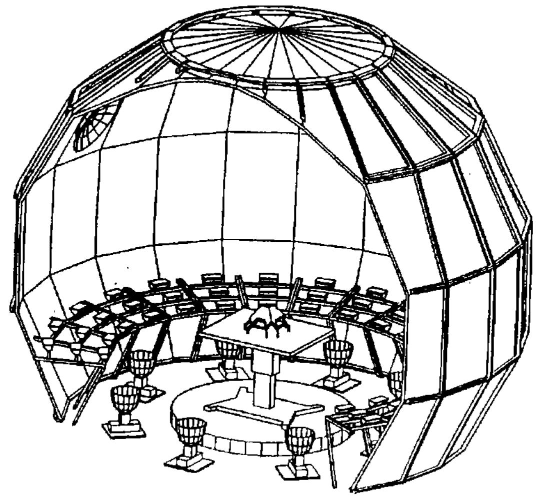

Figure 1—Schematic drawing of the sky simulator section

Design and development—In the following sections performance criteria and some of the capabilities available within some of these sky simulators are summarized.

Lighting system—To provide higher accuracy in producing the various luminance distributions, the curved sphere three-quarters 9.2 m [30 ft] diametersphere structure surface is continued to the ground floor. This feature allows the simulation of horizon luminance to follow more closely the desired luminous distribution by using 72 high-voltage tungsten halogen (500 W) reflector lamps with a computer controlled lighting system located below the horizon line. The simulation of circumsolar luminance was made possible by using 450 W sealed beam lamps positioned inside along the perimeter of the dome platform. The light beam is projected through perforated panels located on top of the fixture. This design prevents the undesirable inter-reflection impact within the sky vault. A variable speed fan will remove the heated air through an opening below the perimeter of the dome.

Lighting control system—The lighting control system consists of a dimming control for the interior lighting system and for the simulation of the circumsolar sky. The interior lighting system using narrow- and wide-angle spotlights provides the azimuthal luminance variation in CIE clear skies or any distribution. The computer controlled dimming system provides rapid fixed or continuous changes of the sky luminance distribution. This also includes rapid feedback on current, voltage, phase status, and photometric output of the total system.

Model platform, sun simulator—A sun simulator is a parabolic dish mounted within a tracking system inside the sky simulator and moves from horizon to zenith using a 1000 W quartz lamp. The sun motion is motorized and its path through the sky vault is matched to the platform rotation in order to simulate the sun's path during the course of a day for a given season. The platform is designed to rotate in order to simulate the time of day while the sun simulator is moving across the sky. The height of the platform is adjustable in order to position the model at the correct horizon level. The simultaneous movements of sun and platform allow examination of the dynamic changes of daylight within scale models. These effects are recorded using a video camera and video scanning system to measure the luminance distribution inside the model or the simulator as part of its calibration.

Instrumentation—A multichannel data acquisition system is used, which can read up to 40 light sensors (silicon photodiodes) in a period of a few seconds. The sensors can be operated under direct sunlight (approximately 100,000 lx) and at relatively low light levels (1 lx) with high accuracy over that range. In a typical test, the data acquisition system will read the output of the cells, convert a voltage signal to illuminance units using stored calibration factors, and display the results on a terminal in illuminance units and daylight factors. Available graphic software is added to aid data interpretation. The entire process of measuring and recording data from a large number of sensors in a model occurs in a matter of seconds, thus one can evaluate a large number of design alternatives and the impact of design changes. The output of each test series can be stored in a permanent file. **Figure 1** shows the schematic design of the sky simulator.

Theory and calibration of sky luminance distribution simulation

The lighting control system is capable of simulating different luminance distributions. It is necessary to calibrate the sky by measuring the various sky luminance distributions and setting the luminance ratios as normalized to zenith luminance according to CIE standards. These luminance patterns normally remain fairly constant.

The simulated sky luminance distribution, including that of the zenith and circumsolar regions, are examined through manual and automatic sky scanning surveys of the sky on simulated clear days. When the sky simulator is set for a particular sky luminance pattern, the luminance of the sky is measured using a fixed sensor all sky scanner. The

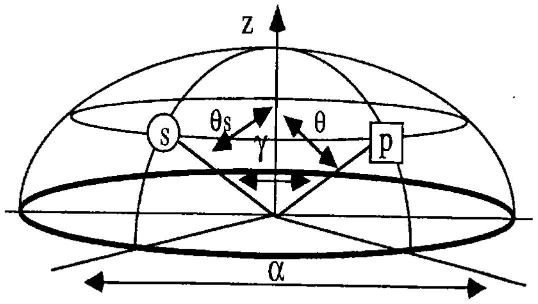

Figure 2—Definition of angles for calculation of the scattering angle γ. The dashed line shows the locus of sky elements having the same γ angle

Table 1—The commonly used scale in scale model photometry

Scale	Proportion	Scale	Proportion
Town Planning Models		Train Station Models (Continued)	
		1" = 10' (TT model-train gauge)	1:120
	1:2000		
1" = 100'	1:1200	Factory and Office Layout Models	
	1:1000		1:100
1" = 60'	1:720	1/8" = 1'	1:96
Architectural Models		HO model-train gauge	1:87
1'= 50'	1:600	OO model-train gauge	1:76
	1:500	3/16" = 1'(S model-train gauge)	1:64
1" = 40'	1 :480	1/4" = 1' (O model-train gauge)	1:48
1/32" = 1'	1:384	Real Estate House Models	
		3/8" = 1'	
Landscape Models		Interior Design Models	1:32
1' = 30'	1:360	1/2" = 1'	
1" = 20'	1:240	Scale Model Photometry Models	1:24
1/16" = 1'	1:192	3/4" = 1'	
Train Station Models		1" = 1'	1:16
000 or N model-train gauge	1:152	Stage-set of Theater Model	1:12
3/32" = 1'	1:128		1:10

manual measurements are taken for every 10 degree azimuth starting at the sun azimuth and for every 10 degrees of altitude using a hand-held luminace meter on a tripod at the center of the sky simulator. The sky was assumed to be symmetric with respect to the sun azimuth; therefore, only half of the sky data was used as an input to fit the sky function. For these measurements, the CIE function and World Meteorological Organization data are used as the criteria for a clear sky. Sky luminance distribution measurements are analyzed and evaluated using a diffusion indicatrix that describes this distribution as a function of the sun-to-sky and the zenith-to-sky element angles. In order to compare the measurements of the simulated sky luminance distribution, the concept of a diffusion indicatrix developed by Kittler was used.[13] The diffusion indicatrix models the dependence of sky luminance distribution on "atmospheric" scattering phenomena.

The computer program applying the concept of the diffusion of indicatrix is used to evaluate the accuracy of a simulated sky luminance distribution.[13] The diffusion indicatrix could be measured along the solar "Almoghandar"; a fictitious horizontal circle for momentary sun position. The diffusion indicatrix models the dependence of sky luminance distribution on atmospheric scattering phenomena.[14] **Equation 1** shows the diffusion indicatrix and it is defined by the following formula:

$$F(\gamma)=[L_\gamma/L_{90^\circ}]=1+N\ (e^{-3\gamma}-0.009)+M\cos^2\gamma \qquad (1)$$

For the CIE standard clear sky N=10 and M=0.45, and γ is in radians. The larger the variables M and N, the more turbid the sky or the larger the circumsolar. In order to test all possibilities of fitting the data to this function, the diffusion indicatrix function with the following form was used:

$$F(\theta,\gamma)=p_1(1-e^{-p_4\sec\theta})*(1+P_2(e^{-3\gamma}-0.009)+P_3\cos^2\gamma \qquad (2)$$

With this concept it is possible to determine the accuracy of simulated luminance distribution compared to CIE standardization; where P_1, P_2, P_3, and P_4 are parameters estimated from measured data, θ=angle between the zenith and the sky element P, and γ=scattering angle between the sky element and the sun. The scattering angle γ can be calculated using the equation

$$\gamma=\cos^{-1}(\sin\theta\sin\theta_s\cos\alpha+\cos\theta\cos\theta_s) \qquad (3)$$

where θ_s=angle between the sun and the zenith, and α=azimuth angle between the sun azimuth and the sky element azimuth (**Figure 2**). Based on **Equation 2**, the parameters P_1–P_4 for 172 data points from simulated clear days with sun positions at 20 degrees, 70 degrees were estimated. The multiple correlation coefficients for these fits were high, indicating good fits to measured data or high accuracy of simulated sky conditions. It was found, however, that the values of the parameters P_1, P_2, P_3, and P_4 derived from analysis of the measured data had considerable scatter around the values given by CIE[14] for simulated sky luminance distribution. **Table 1** compares the average values of the P coefficients suggested by CIE for clear and turbid skies to those derived from the best fits of the simulated sky. All values of the indicatrix derived from the measured simulated data against CIE's equation have been normalized for a scattering angle of γ=90 degrees by dividing each measured and predicted value by the value of the predicted diffusion indicatrix at γ=90 degrees. The agreement is generally good. The fit is unbiased in that the sign of the errors is randomly scattered with respect to scattering angle. This suggests that the exponential form of the equation is suitable for analyzing simulated sky conditions. However, because circumsolar simulation affects the diffusion indicatrix shape in this case, the size of the simulated circumsolar, different parameters (P_1–P_4) may be determined as an index for the accuracy for different simulated sky conditions (**Table 2**).

Table 2—Parameters of diffusion indicatrix equations

	Simulated CIE Clear sky Turbidity			Simulated CIE Sky Circum Solar Size*	
Variable	Low		High	15°	25°
P1	0.5		3	0.69	0.89
P2	2	(5.0, 20.0)**	16	7.0	14.0
P3	0.45	(0.3,0.8)	1.60	0.40	0.86
P4	0.2	(0.2, 0.3)	2.94	0.25	0.63

P1=Lz(fitted) / Lz(simulated), Lz= Zenith Luminance,

*Circum solar size 15° is for simulated sky with low turbidity and Circum solar size 25° is for simulated sky with high turbidity.

**The values inside the parenthesis show range of the CIE parameters.

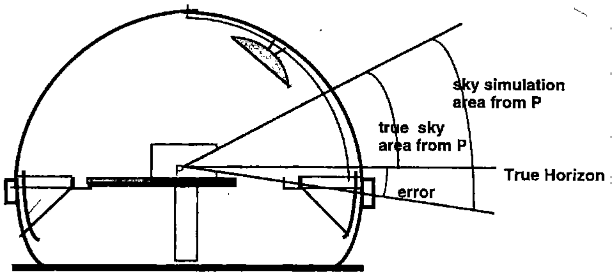

Figure 3—Horizon scale error

Sources of error

A common source of error called horizon scale error exists in the hemispherical sky simulators. The horizon position and the sky surface distances in relation to the openings of scale models (windows) create this source of error. This means that the ceiling of the scale model and a portion of the back side wall receive light directly from the sky. These errors differ for different model scales and different sky luminance distributions. For example, if a 1 inch scale model is placed at the center of the sky simulator and a photocell is positioned at point P, the model location shows that a portion of the light is visible at the ceiling surface. It should be mentioned that the horizon scale error exists only for clear openings without obstructions. There is also a fictitious volume at the center of the sky simulator that governs the size of models. It is called

```
MULTIPLE CORRELATION COEFF. SQ.= 0.954334
PARAMETER #   VALUE        STD. DEVIATION
 1           0.924994     0.208971
 2          12.0088       4.71072
 3           0.569923     1.41926
 4           0.300056     0.162891
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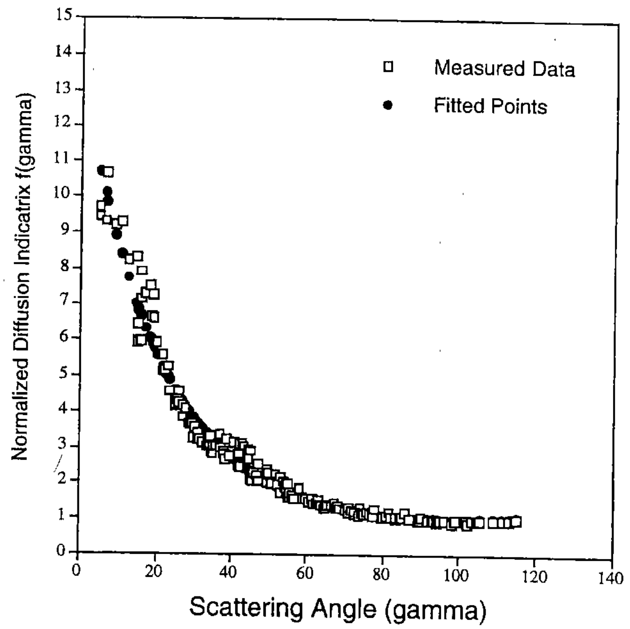

Figure 4—Normalized diffusion indicatrix vs scattering angle γ of simulated sky luminance distribution for 70 degree sun altitude. Parameters for this equation: P_1=0.93, P_2=12.01, P_3=0.57, P_4=0.30

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MULTIPLE CORRELATION COEFF. SQ.= 0.895943
PARAMETER #   VALUE        STD. DEVIATION
 1           2.42359      0.530833
 2          10.2689       2.77750
 3           0.863799     0.878131
 4           0.199346     0.583968E-01
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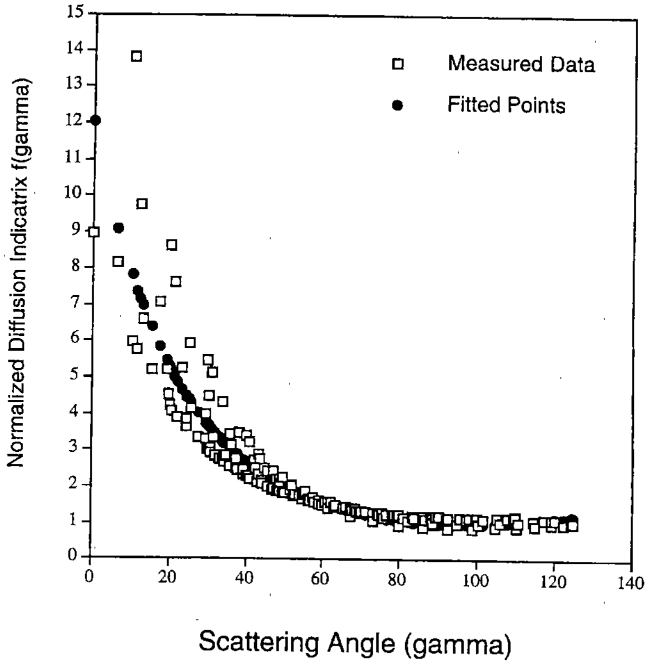

Figure 5—Normalized diffusion indicatrix vs scattering angle γ of simulated sky luminance distribution for a 50 degree sun altitude. Parameters for this equation: P_1=2.42, P_2=10.27, P_3=0.86, P_4=0.20

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MULTIPLE CORRELATION COEFF. SQ. 0.687459
PARAMETER #   VALUE        STD. DEVIATION
 1           0.533130     0.141348
 2           2.08849      1.71682
 3           1.53537      1.26354
 4           2.93559      1.42426
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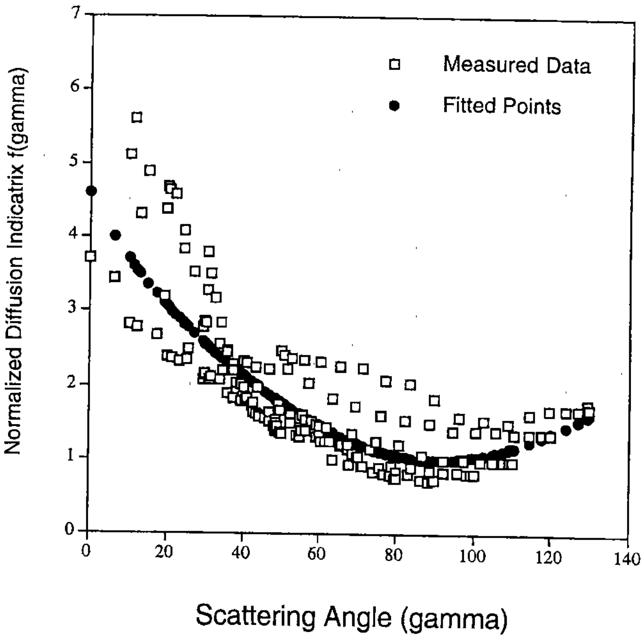

Figure 6—Normalized diffusion indicatrix vs scattering angle γ of simulated sky luminance distribution for 30 degree sun altitude. Parameters for this equation: P_1=0.53, P_2=2.09, P_3=1.54, P_4=2.94

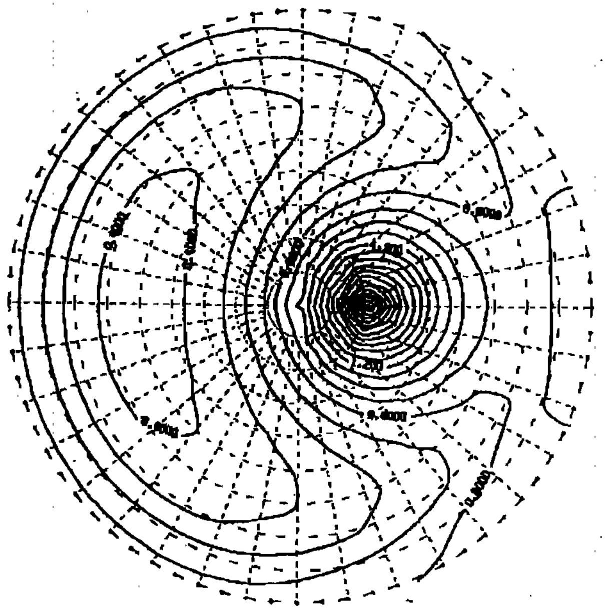

Figure 7—The sky luminance distribution simulated for sun at a 70 degree altitude; P_1=0.80, P_2=9.0, P_3=0.73, P_4=0.435

"correct volume." This volume is created by the interception of the angle of the reflectors, and lamps positioned around the perimeter of the sky simulator with respect to the horizon line. Any model positioned outside this volume causes interruption in the interreflection of the lights inside the sky simulator. This reduces or increases the light levels, which results in measurement errors. (**Figure** 3).

System accuracy

The following is the recommended procedure for determining the accuracy of a system.

1. Check the horizontal and vertical illuminance measurements inside the simulators and their ratios as compared to CIE ratios for the same simulated sky luminance distribution given a sun position.

2. Position the model within the correct volume and place it level with the horizon line in such a way that the top of the meter is on the same plane as the horizon.

3. Measure the luminance of the zenith and the first circum solar and diffusion indicatrix for that circum solar.

4. Check results against reference data. **Figures 4–6** show the typical set of measured data compared to the fitted function for sun at 70, 50, and 30 degrees of altitude, respectively. The multiple correcation coefficient for each function is indicated. The low correlation for simulated sky luminance distribution at 30 degree sun altitudes is due to the difficulty in eliminating inter-reflection produced by the circumsolar lighting system. **Figure** 7 shows the measured data for sky luminance distribution simulated for sun at 70 degrees of altitude.

Video simulation, photography, and computer image processing

Combining different simulation techniques and using a new medium for communication (video) can remarkably accelerate decision making. A study of these new design tools will help in understanding fundamental principles involved in assessing the visual environment with respect to specific design issues. The existing methods for daylighting performance analyses of buildings are based on the CIE standards for overcast and clear sky conditions. The use of computer programs, nomograms, and various diagrams only allow designers to examine or evaluate the daylight distribution for a fixed period of time or sun position within the space. The daylight factor-based analysis provides information on the availability of daylight while the dynamic changes of daylight are unexamined.

New techniques have been developed that reproduce the architectural space in a three-dimensional rendering using a video system that records the effects of lighting simulations on scale models while simultaneously registering photometric measurements for an accurate and realistic prediction of lighting conditions in the space.[12,19,20,21] The combined use of these techniques will

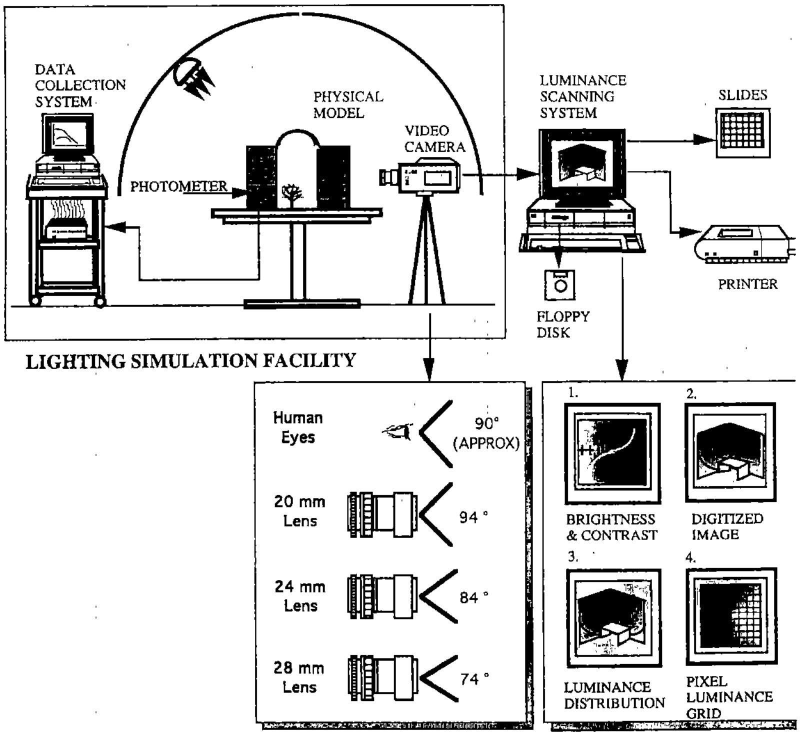

Figure 8—Lighting simulation lab

Figure 9—The sky simulator provides for scale modeling of the Rock and Roll Hall of Fame general sale area

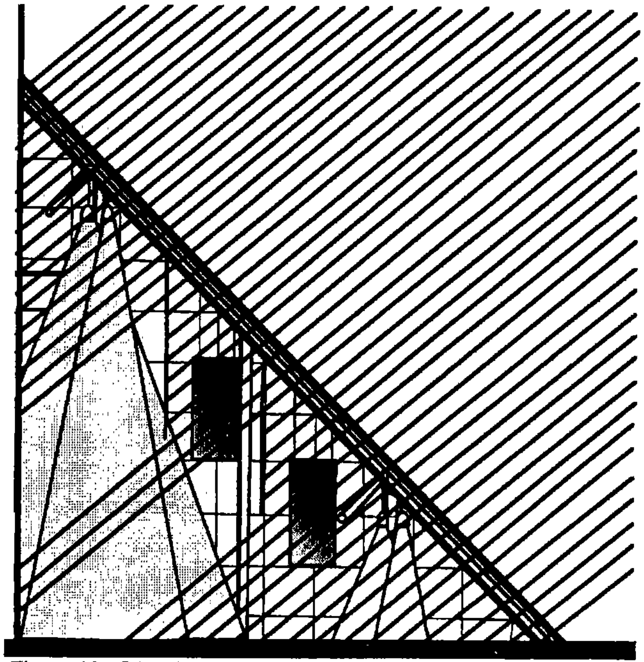

Figure 10—The sky simulator provides for sun angle studies for the Rock and Roll Hall of Fame June 21, 10:00 am

reduce the risk of misinterpreting lighting quantities, as well as the overall quality of architectural spaces. The use of scale models and the heliodon, sky simulator, or outdoors, in conjunction with a video recording system allows observation of the dynamic play of light within the space. If done properly, this technique provides a unique and accurate representation of daylighting distribution changes in a scale model of the space. This method brings designers and engineers together and can be used as a means to communicate various ideas regarding design problems and their solutions to the client. It is also very cost effective in comparison to full-scale modeling.

Methodology

Once the model is completed at no less than 1:48 or 1/4-inch scale, calculate the sun altitude and azimuth of the location and position the scale model at the desired orientation for the specific day of the study. Determine the speed of the model platform and sun simulator or heliodon. Calculate the total time in seconds for east orientation of the platform (sunrise) to reach the south at azimuth zero. Calculate the time in seconds for the sunrise of zero altitude to the noontime altitude. These time intervals divided by the total azimuth degrees of rotation for different seasons provide the speed of the model platform. The sun simulator or heliodon should have simultaneous movements. Video cameras provide a permanent record of the simulation of daylight and sunlight within the space. The same technique could be applied under outdoor conditions if the third angle movement of the platform could be calibrated against sun position in the sky. Also, one should be careful of the light intensity for protection of the video camera. **Figure** 8 shows the schematic of a possible model and lighting simulation facility set-up.

Photography

Photography provides a permanent record of daylighting conditions inside the space (real or scale model). This technique provides an evaluation method for observation of the quality of light and comparison to other design options. The limitations of this method are based on the sensitivity of the equipment. The human eye is more capable and has a much wider range of sensitivity than any film or camera, yet there are instances when design evaluation observation through the scale model is not possible or adequate. There are obvious problems such as determining the correct film or proper exposure.

The best approach has been to take many different exposures and select the frame that most accurately represents the lighting qualities of the space. A 35 mm camera is recommended for this application. Wide angle lenses are recommended for model photography as well as image processing using computer software or video scanning. The 20 mm (94 degrees), 24 mm (84 degrees), and 28 mm (74 degrees) lenses are best because their viewing angles approximate that of the human eye (90 degrees). The camera aperture should be at f22 for the greatest depth of field. The use of a tripod is always recommended. High-speed films are useful if the camera is used in handheld positions. ASA 200 daylight film should be used if different types of light sources (color temperatures) are present.

Computer image processing and luminance scanning in models

The above limitations for photography are eliminated if computer image processing is used. The latest software allows the designer to scan the space with the desired space layout and produce an instant image in black and white or color. This system provides unique capabilities that allow the designer to observe the lighting conditions of the space from various viewing angles and instantly produce an image of each condition with various brightness and contrast levels printed on the image. These images are put on library disk and then reproduced on the laser printer. They can be enlarged and rendered as traditional drawings of lighting schemes. The images are also good tools for the documentation of the design process. Any wall, window, shading system, or space layout can be changed and evaluated under the same lighting conditions. The software is capable of recording many images and storing them on a disk. A camera acts as a human eye and can be positioned at many viewing angles.

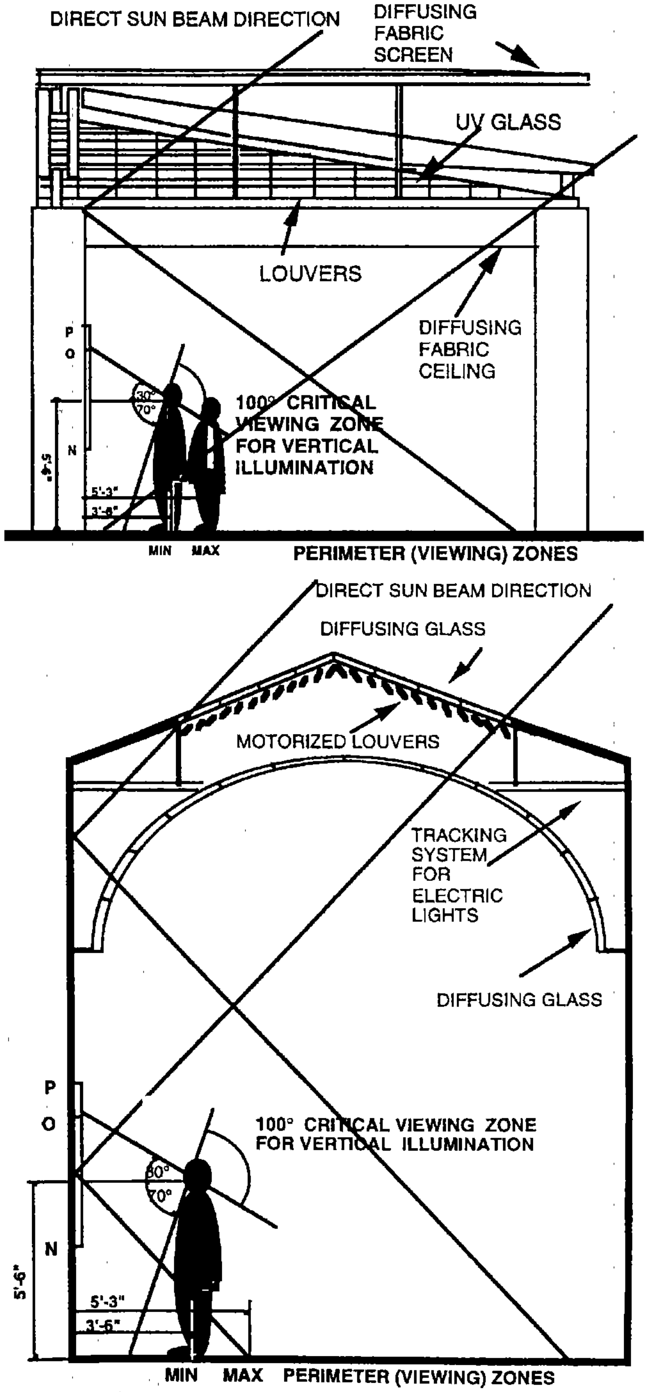

Figure 11—(A) The views of the Cy Tombly gallery with the fabric and (B) MCA with the diffuse glass, which show the geometruic relationship of artwork to the daylight admitting systems as a function of viewing angles. The effect of daylight penetration by the sunbeam intensity into the space and the possible glare problems from a given viewing angle

A video system controlled by computer software has been developed in order to provide a rapid on-the-spot scanning system that records the scene and processes it in the form of photometric quantities.[15–19] The video camera signal is digitized, calibrated by functions, and then converted to engineering units. It may be plotted as luminance distribution or other photometric quantities for that portion of the field of view as small as a single printed letter. The system has great potential for use in determining the availability, distribution, and evaluation of luminance in interior as well as exterior spaces, such as office buildings and task stations, for industrial lighting, daylight availability measurements, and roadway lighting studies. The computer software records the lighting distribution for research or educational applications in two- or three-dimensional graphic form to facilitate communication among architects, lighting designers, educators, and other professionals in related fields. The software is compatible with the current microcomputer software for image storing or data manipulation. The photos, schematic drawings, and the scanned results in **Figures 9–13** show the computer screen images of various stages of the scanning process for three different lighting case studies conducted under simulated sky conditions.

Case study 1

The lighting and daylighting performance with respect to glare was evaluated at the Rock and Roll Hall of Fame and Museum designed by Pei Cobb Freed & Partners, New York City. The contribution of natural light to any environment can be a valuable asset, however it can be a detriment if it is not controlled properly. A daylight analysis of the Rock and Roll Hall of Fame and Museum was conducted under simulated sky conditions. The study examined the following: 1. The shading coefficient of the existing glazing system, solar and visible transmission, and lighting impact on the space at various times of day, during the four seasons were evaluated. 2. Sun angles that could cause direct or reflected glare and brightness (luminance) that could create glare conditions between the atrium and interior retail spaces were determined. 3. The impact of sunlight on the video screens was examined. From this information, it was possible to assess shading systems, filters (e.g., for lighting

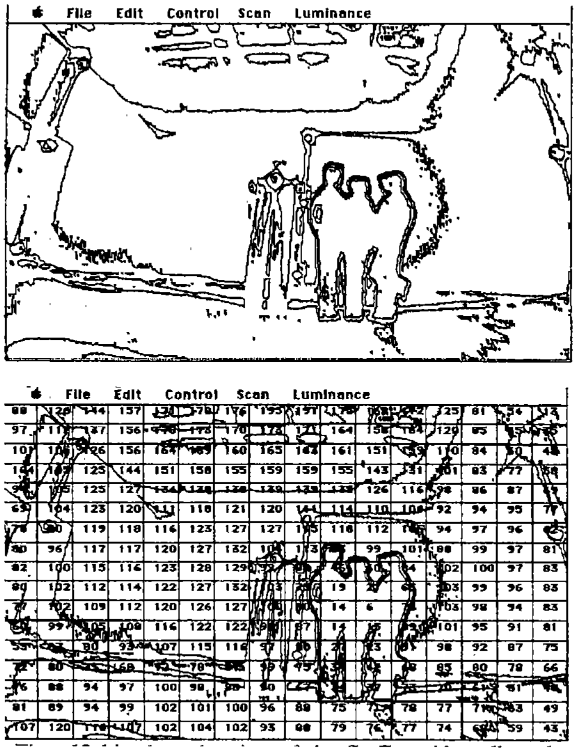

Figure 13–The view of the Cy Twombly gallery showing the fabric ceiling and the artwork on the wall. The digitized and luminance distribution patterns show daylight penetration through the fabric ceiling

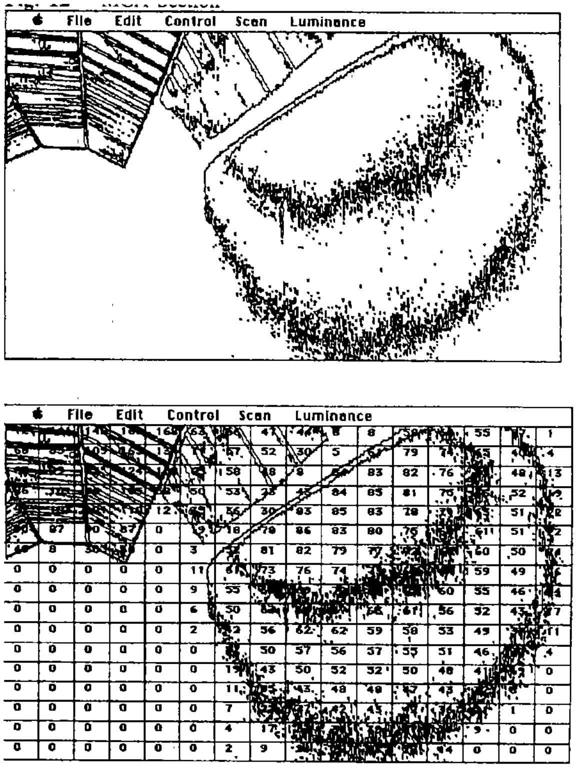

Figure 14—The north wall of Museum of Contemporry Art (MCA). The digitized and luminance distribution patterns show daylight penetration through the glass ceiling.

systems, reflectance values of surfaces, the brightness level needed inside the low-ceiling area, and controls needed to balance the electric lighting with the daylight. Several control strategies were recommended.

Case study 2

The Menil Collection is constructing a new annex to house a permanent exhibition of the works of Cy Twombly. The building was designed by Renzo Piano and engineered by Ove ARUP & Partners. The new building will contain eight exhibition rooms arranged within a square plan at ground level. Seven of these rooms will be top-lit through a glazed roof system; the eighth, central room has an opaque ceiling and is not naturally lit. A model of a corner gallery was constructed at a scale of 1-1/2 inch to 1 ft (1:8 scale). Each element of the roof light system has been constructed to scale, including the system of moveable louvers beneath the glazing system. Mirrors were placed on the internal walls above fabric level to simulate adjacent rooms.

Three fabrics were available as alternates for the external fabric shading system with high, mid, and low light transmittance. Five alternative fabrics were available for the interior gallery ceiling fabric with light transmittance ranges from 24 to 72 percent. Three alternative panel types were available for insertion in the glazing layer: clear glass, fritted glass, and opaque panels.

Alternative fabrics and glazing elements were examined during a series of tests within the sky simulator. The model was positioned within the sky simulator so that it represented the gallery in the southwest corner of the building. This is probably the gallery where patterns of direct sun and shadow will be most discernible. In general the test results provided the knowledge that in reality some of these possible options were applicable to control the excessive light levels in each gallery.[15]

Case study 3

The scale model photometry studies using the sky simulator, real sky conditions, and computer simulation provided the photometric database in order to evaluate the performance of the gallery spaces within the new Museum of Contemporary Art in Chicago, designed by Joseph Paul Kleihues and engineered by Ove ARUP & Partners. The simulation results are based on the information provided by the architect's office, architectural drawings and scale model (1 inch=1 ft), and surface reflectances which were white lambertian. The gallery space daylight-admitting system using tilted glazing at the ceiling shows an overall efficient daylighting system at work. The daylight being admitted through the gallery space provides enough ambient light for circulation and exhibit wall surface area within each gallery at all viewing angles and levels.

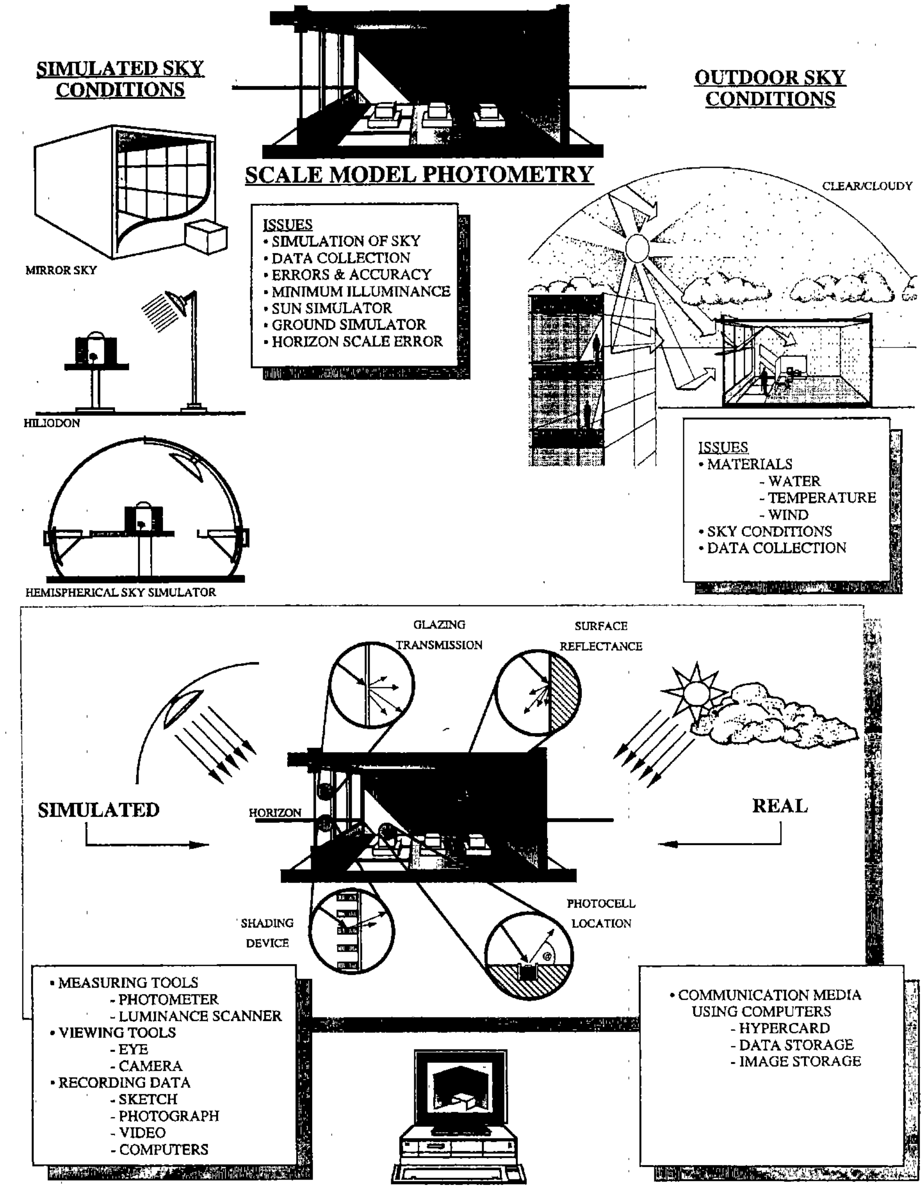

Figure 17

Research utilization

The CIE Technical Committee 3.19 task work is conducting studies on the application and use of scale model photometry techniques and will provide a performance database and design guidelines to aid in the design of energy-efficient buildings. Given the access to either an indoor or outdoor testing facility the best selection will depend on the objective of the research or specific study. In either case, gathering accurate information and a detailed evaluation of the performance criteria for these tools in this field is essential. Systematic information on the daylighting performance of buildings is being collected and modeled with various tools. These data will be most useful to architects and designers as a validation source in design application. Use of these tools by practicing architects and others in the design and academic community will no doubt generate further extensions and improvements in the design for better luminous environments (**Figure 17**). The ongoing research will further enhance the simulation models that are now available. The application of scale model photometry under simulated sky condition's is presented including selected case studies. The design, development and calibration of a daylight simulator is presented. Simulated sky luminance distribution measurements are evaluated using the diffusion indicatrix concept. The parameters of this equation, as given by the CIE,[13] are strongly dependent on simulated circumsolar. These parameters may vary over a wide range. However, the estimated average value of each parameter (P) is a good index of accuracy with the corresponding values proposed by CIE.[13,14]

Acknowledgment

This project was supported by the National Science Foundation.

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Discussion

This paper describes scale model photometry techniques and a particular daylight simulation facility that has been built at University of Michigan. I have some questions regarding the facility:

1. Since the interior of the sky dome is white, light on any point is interreflected. Would the author explain what he means when he states that the design of the circumsolar simulator prevents unwanted inter-reflection?

2. Are some of the values in **Table 1** supposed to represent values typical of real skies?

3. How does the size of the error shown in the figures compare with other simulators?

4. How much error do they introduce inside the scale models?

5. Is the simulator capable of skies other than Kittler's luminance distributions?

6. Would the author explain how a particular sky condition is set up? Is there a known pattern of lights that can be called up from the console or are lights manually switched?

7. Is there an explicit procedure to produce a given Kittler (or other) sky luminance distribution or is it by trial and error?

R. Clear
Lawrence Berkeley National Laboratory

Would the author explain the recommended procedure for the validation of the simulated sky luminance distribution for a measured real sky luminance pattern?

R. Mistrick
Pennsylvania State University

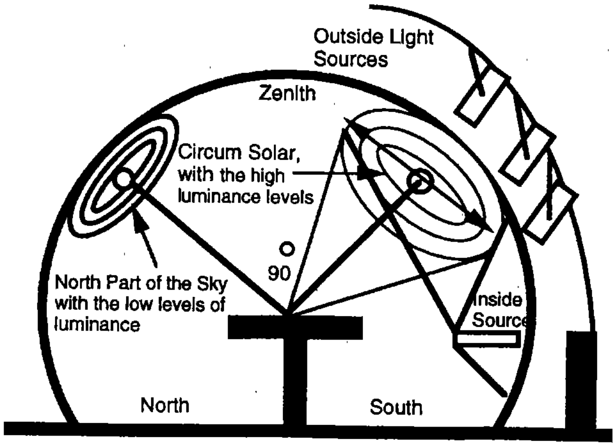

Figure a—The lighting system set-up for the simulation of the circumsolar

Author's response

To R. Clear

1. Due to a characteristic of the lighting system design for the opaque sky simulators, the luminance on the surface of the hemisphere is produced using light sources below the horizon line within the simulator. The sky luminance distribution (SLD) varies as a function of sun position. Changing the intensity of this lighting system produced such variations. The variation of the SLD is based on the azimuthal variation of the light distribution on the sky vault and is achieved using the lighting system controls. Some of the required ratios within the SLD are simple and easy to obtain given the capability of the lighting system. For example, the SLD for the sun at 70 degrees of altitude has the circum solar variation ratio of 3:1 with respect to zenith luminance. However, for lower sun positions these ratios are higher and harder to achieve given the total available light intensity within the sky simulator.[a] The differences between the circumsolar luminance ratios with respect to zenith for various sun positions creates a large amount of interreflection at the south hemisphere. If the luminance in the hemisphere increases, the amount of interreflection and the horizontal or vertical illuminance levels also increase, therefore some SLD-required V/H ratios are not achievable due to this effect. The use of outside light sources through the perforated dome surface and the narrow-spot beamspread light source within the simulator for a given solid angle projected or transmitted through the circumsolar area have minimized or prevented this effect (**Figure a**).

2. The high and low values of P_1, P_2, P_3, and P_4 are the maximum and minimum values of the fitted functions based on what was achieved for all sky conditions simulated within the sky simulator. The values in parentheses show the high and low values obtained using the CIE clear sky function. The CIE SLD was used as a frame of reference for all calibration.

Due to the flexibility of the lighting system and the limits of measuring the SLD using the fixed sky scanner or the video luminance scanning system, the SLD was simulated with two different circumsolar sizes. The ranges for the values of P_1, P_2, P_3, and P_4 are shown in **Table 1** within the paper. The overall goodness of fit with respect to the CIE sky luminance distribution, for high sun positions with small circumsolar size (15 degrees) was about 0.85. The simulated SLD with low sun positions with large circumsolar size had the multiple correlation (goodness of the fit) of above 0.75.[b]

3. Other sky simulator facilities have not reported such calibration data. It is possible to examine the accuracy of any simulated SLD if one knows the horizontal and vertical illuminance achieved at the horizon line within the simulator. The author would welcome any future exchange or collaboration with other research organizations or facilities to extend the use and application of this new procedure.

4. Scale model photometry is the technique to check the accuracy of the sky luminance distribution and determine the degree of errors (See the response to R. Mistrick below). **Table a** shows the calculated results based on a program that computes the normalization for horizontal and vertical illumination from Kittler's clear sky formula using the double Simpson's rule integration routine. The V/H illuminance ratios are for sun altitudesof 0–90 degrees at 5 degree steps and for azimuth variation at 10 degree steps. The limits or the intervals for the integration were set at (0,90,–90,90). The –10 indicates the horizontal plane, the 0 and above give the solar azimuth for the vertical plane. This table is used to check against the V/H ratios obtained in the simulator.

5. Yes, it is possible to simulate SLD other than CIE's sky luminance distribution. The accuracy and the degree of errors would depend on the SLD resolution and availability of other independent variables such as horizontal, vertical and direct normal illuminance, atmospheric turbidity, and water content of the atmosphere during the time that SLD was measured. These variables are converted to different indicators such as V/H ratios for various orientations, zenith luminance and horizontal illuminance ratio, circumsolar and zenith luminance ratio, the luminance of the diffusion indicatrix for a given sun position.[c–g]

6. A particular SLD is produced based on the variables mentioned above. These variables are used as an input to a program to create a series of indicators for a given sun position and its SLD. These indicators are used to achieve an SLD using the lighting control system and prerecorded lamp settings for sky and projected patterns of circumsolar areas at various intensity levels. These settings are called up from a computer. After a lighting system achieves its peak outputs, various checkpoint measurements are made against these indicators for final tunings.

7. The procedure for simulating an SLD other than using the CIE guidelines is the same as above. However, the calibration and the sky luminance function has to be fitted to CIE function to obtain the proper indicators with respect to the setting of the lighting system. Other indicators could be used but it would be a time-consuming process and would require more detailed checking.

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To R. Mistrick

A recommended procedure for validation of a simulated SLD and real sky luminance pattern is summarized in the following steps.

1. Measure the SLD of a real sky and all related daylight availability data.
2. Create the indicators required to simulate the real SLD pattern (e.g., P_1, P_2, P_3, and P_4 variables in the sky function).
3. Simulate the SLD with the hemispherical sky simulator for a given set of validated SLD using the sky luminance function.
4. Compute the daylight factor and the V/H ratios from the scale model photometry data gathered in the simulator.
5. Compute the daylight factor and the V/H ratios from the computer model data using a daylight computer program using the same SLD.
6. Compare the results with respect to a given SLD pattern and a sun position. The detailed explanation for each step would be beyond the scope of this paper.[h,i]

In summary, if one claims that they have simulated a SLD of a real sky pattern, it is possible to measure the horizontal and vertical illuminance inside and outside a scale model within the simulator and compute the daylight factors and the V/H ratios. These ratios should be calculated for the same SLD used as an input to a daylighting program. The geometry and the surface reflectance properties of the scale model should be modeled with the same proportions and characteristics.[j] The final comparison would indicate how close the SLD of a real sky is to a simulated sky condition.

Table a—The calculated V/H illuminance ratios based on the CIE's clear sky luminance distribution

ALT./AZ.	-10	0	10	20	30	40	50	60	70	80
0.00	1.91	1.50	1.49	1.44	1.37	1.27	1.16	1.03	0.91	0.79
5.00	2.02	1.54	1.53	1.47	1.40	1.30	1.18	1.04	0.91	0.78
10.00	2.14	1.54	1.54	1.47	1.40	1.29	1.17	1.03	0.89	0.76
15.00	2.24	1.48	1.47	1.42	1.35	1.25	1.13	0.99	0.86	0.73
20.00	2.35	1.41	1.40	1.35	1.28	1.18	1.07	0.95	0.82	0.70
25.00	2.46	1.32	1.31	1.27	1.20	1.12	1.01	0.90	0.78	0.67
30.00	2.55	1.23	1.22	1.18	1.13	1.04	0.95	0.85	0.74	0.64
35.00	2.63	1.14	1.13	1.10	1.04	0.97	0.89	0.80	0.70	0.61
40.00	2.70	1.05	1.04	1.01	0.97	0.90	0.83	0.75	0.67	0.59
45.00	2.77	0.97	0.96	0.93	0.89	0.84	0.77	0.70	0.63	0.56
50.00	2.82	0.89	0.88	0.86	0.82	0.78	0.72	0.66	0.60	0.54
55.00	2.87	0.81	0.80	0.79	0.76	0.72	0.67	0.62	0.57	0.52
60.00	2.91	0.74	0.74	0.72	0.70	0.67	0.63	0.59	0.55	0.50
65.00	2.94	0.68	0.67	0.66	0.64	0.62	0.59	0.56	0.52	0.49
70.00	2.96	0.62	0.62	0.61	0.59	0.57	0.55	0.53	0.50	0.48
75.00	2.98	0.56	0.56	0.56	0.55	0.53	0.52	0.50	0.48	0.46
80.00	3.01	0.52	0.51	0.51	0.51	0.50	0.49	0.48	0.47	0.45
85.00	3.01	0.47	0.47	0.47	0.47	0.47	0.46	0.46	0.45	0.45
90.00	3.01	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
ALT./AZ.	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**
0.00	0.70	0.63	0.59	0.57	0.57	0.57	0.57	0.57	0.58	0.58
5.00	0.68	0.60	0.56	0.54	0.53	0.53	0.53	0.54	0.54	0.54
10.00	0.65	0.58	0.54	0.51	0.50	0.50	0.50	0.50	0.50	0.50
15.00	0.63	0.56	0.51	0.49	0.47	0.47	0.47	0.47	0.47	0.47
20.00	0.60	0.53	0.49	0.46	0.45	0.44	0.44	0.44	0.44	0.44
25.00	0.58	0.51	0.47	0.44	0.43	0.42	0.42	0.42	0.42	0.42
30.00	0.56	0.50	0.45	0.43	0.41	0.40	0.40	0.40	0.40	0.40
35.00	0.54	0.48	0.44	0.41	0.40	0.39	0.38	0.38	0.38	0.38
40.00	0.52	0.47	0.43	0.40	0.39	0.38	0.37	0.37	0.37	0.37
45.00	0.50	0.46	0.42	0.40	0.38	0.37	0.36	0.36	0.35	0.35
50.00	0.49	0.45	0.42	0.39	0.38	0.36	0.36	0.35	0.35	0.35
55.00	0.48	0.44	0.41	0.39	0.37	0.36	0.35	0.35	0.35	0.35
60.00	0.47	0.44	0.41	0.39	0.37	0.36	0.35	0.35	0.35	0.35
65.00	0.46	0.43	0.41	0.39	0.38	0.37	0.36	0.35	0.35	0.35
70.00	0.45	0.43	0.41	0.40	0.38	0.37	0.37	0.36	0.36	0.36
75.00	0.45	0.43	0.42	0.40	0.39	0.39	0.38	0.37	0.37	0.37
80.00	0.44	0.43	0.42	0.41	0.40	0.40	0.39	0.39	0.39	0.39
85.00	0.44	0.43	0.43	0.42	0.42	0.42	0.41	0.41	0.41	0.41
90.00	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44

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h. Yoshiaki, U. and Navvab, M. 1992. Validation of daylight calculation for nonisotropic diffuse reflecting interior or arbitrary geometry under any sky conditions. Presented at the Industry Applications Society of the IEEE, 26th Annual Conference, Houston, TX.

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