# CHAPTER V

# DATA ACQUISITION

## 5.1 DAYLIGHT ILLUMINANCE MEASUREMENT

### 5.1.1 Instrument Setup

Daylight illuminances under simulated clear and overcast sky conditions were measured using the seven photometric sensors of the Illuminance Data Acquisition System (IDAS). The photometric sensors were placed on wooden holders measuring 2.5(*w*) x 2.5(*l*) x 1(*h*) in. with precision-drilled holes to accommodate the sensors. As shown in Figure 5.1, one photometric sensor (No. 2) was located at the center floor position, four other sensors (No. 4, 5, 6 and 7) were located at the quarter floor positions, while the other two sensors (No. 1 and 3) were located at the 1/8th positions on the center axis near the south (No. 1) and north (No. 2) walls. The elevations of the photometric sensors were slightly enhanced by the holders to match an actual work plane 3 ft above the floor. In addition, after leveling the model stand, the level of each photometric sensor was also adjusted so that each sensor would represent a point on the horizontal plane.

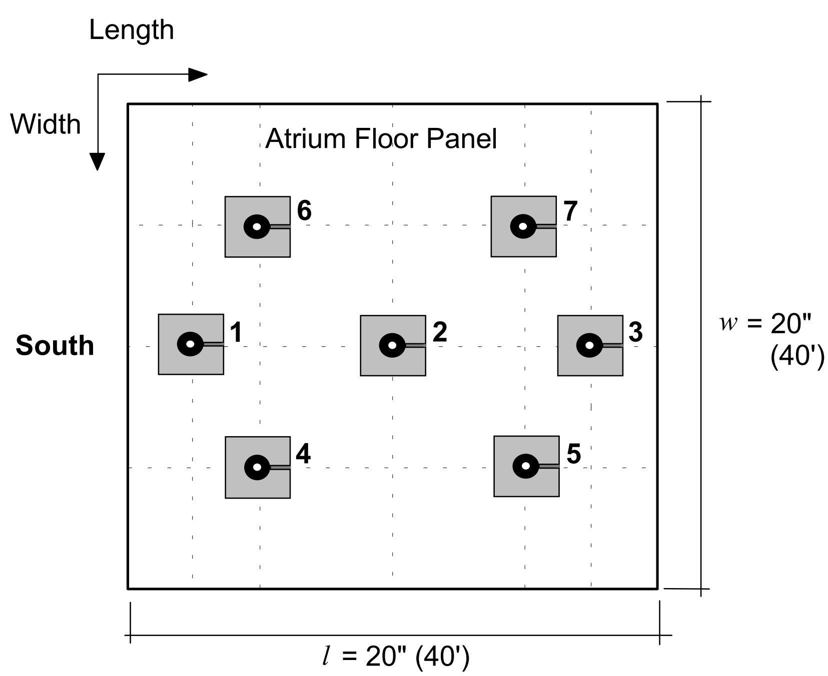



Figure 5.1 Seven Atrium Floor Positions for Illuminance Measurement

### 5.1.2 Exterior Horizontal Daylight Illuminance Levels

The unobstructed horizontal illuminances at the center floor position on the model stand were measured in the absence of atrium models under clear sky and overcast sky conditions. The measured illuminance under the clear sky was 575 lux. Meanwhile, 2530 lux was measured under overcast sky which was created with half of the HID lamps turned on.

It must be noted that measuring exterior illuminances inside a sky simulator must be different from a measurement under a real sky. Under a real sky, as illustrated in Figure 5.2, the exterior horizontal illuminances can be measured on the roof of the subject building, while the other sensors concurrently measure interior illuminances of a real space or a scale model. This is because the real sky vault is the light source with an imaginary surface which provide the same amount of light flux to point locations at different elevations on the earth's surface.

However, when the exterior horizontal illuminances for atrium buildings with different heights are measured inside a sky simulator which has a fixed surface, they must be measured at the same elevations and locations as designed interior locations. If the exterior illuminances are measured on the roof levels of atrium models with different heights, the measured illuminances become different, because the photometric sensors see different portions of the sky simulator surface. Since, the concept of Daylight Factor is the ratio of the interior illuminance to unobstructed exterior illuminance, it must be derived from the interior illuminance reduced by the building structure and the exterior illuminance available from the total surface of the simulated sky vault. Figure 5.3 illustrates the correct and incorrect methods of exterior illuminance measurements.

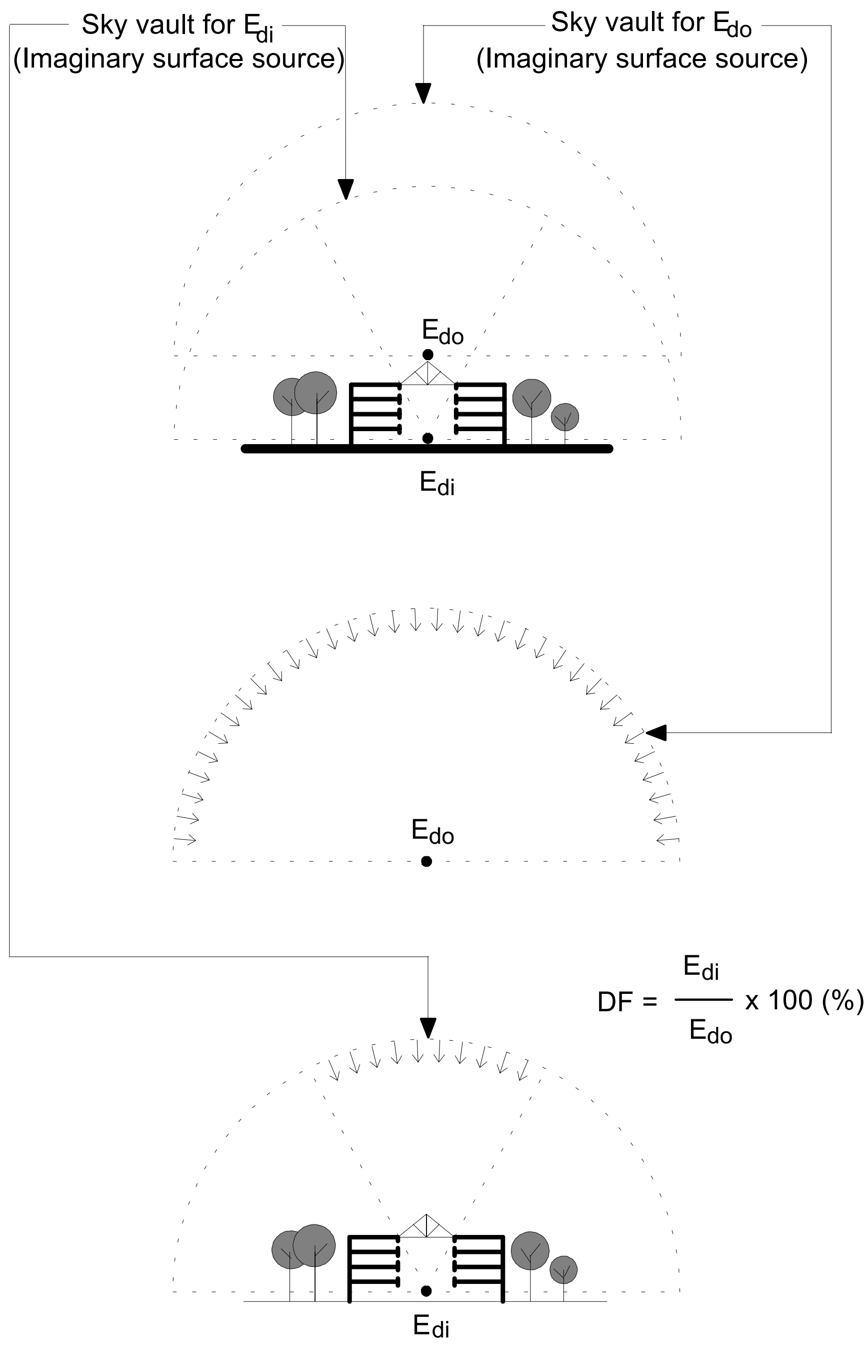



Figure 5.2 Illuminance Measurement under Real Sky

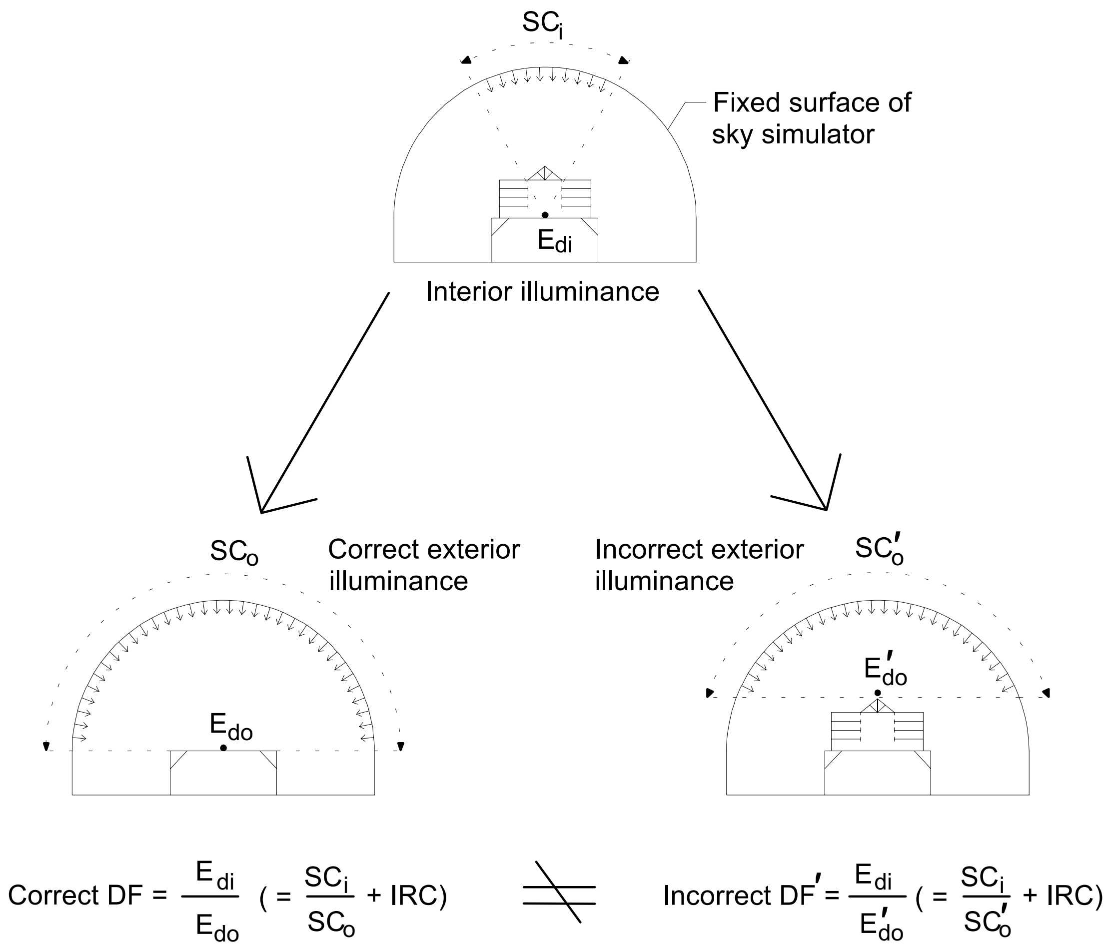



Figure 5.3 Illuminance Measurement inside Sky Simulator

### 5.1.3 Interior Horizontal Daylight Illuminance Levels

After stacking the atrium side modules around the floor panel to generate a four-sided square atrium with a designed Well Index value, in such a way that the window walls with white surfaces face inward, the illuminances on the seven floor positions were measured in the absence of canopy systems as shown in Figure 5.4. The results were recorded as the base cases.

Subsequent measurements were conducted with the 36 canopy systems for each of the seven different atrium spaces under the clear and overcast sky conditions. Figure 5.5 shows an example with the tinted pyramid canopy installed on the atrium with a Well Index value of 1.2 (four stacks, atrium A4). The results were then recorded as actual daylight illuminances at the seven floor positions. Since the atrium wall had the white surfaces, the measured illuminances consisted of Sky Components (SC) and Internally Reflected Components (IRC) as discussed in Chapter 2. After completing these measurements, the same procedures were repeated with the atrium models with flat black walls. The results of these measurements were then recorded as net sky illuminances.

### 5.1.4 Daylight Factor (DF) Calculation

After completing the measurements under the two diffuse sky conditions, the measured illuminance data were converted into Daylight Factors (DF) using the simple relationship given in Equation 4.1. In addition, the Internally Reflected Components (IRC) were also calculated by subtracting the Sky Components (SC) measured with black-interior atrium spaces. Then, tables and graphs were generated for the analyses which will be discussed in the next chapter. Several examples are presented in Figures 5.6 through 5.9.

Figure 5.6 shows clear sky DF values at WI = 0.6 (atrium A2). Figure 5.7 shows clear sky DF values at WI = 1.2 (atrium A4). Figures 5.8 shows overcast sky DF values at WI = 1.2 (atrium A4). Finally, Figure 5.9 shows overcast sky DF values at WI = 2.4 (atrium A8).

South

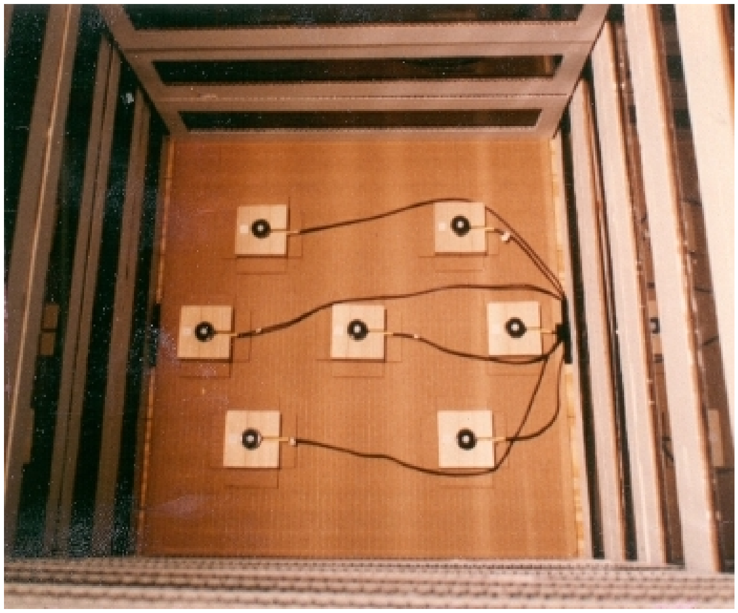


Figure 5.4 Photometric Sensors Located on Floor of Atrium Scale Model

Figure 5.5 Tinted Pyramid Skylight Installed on Atrium Scale Model

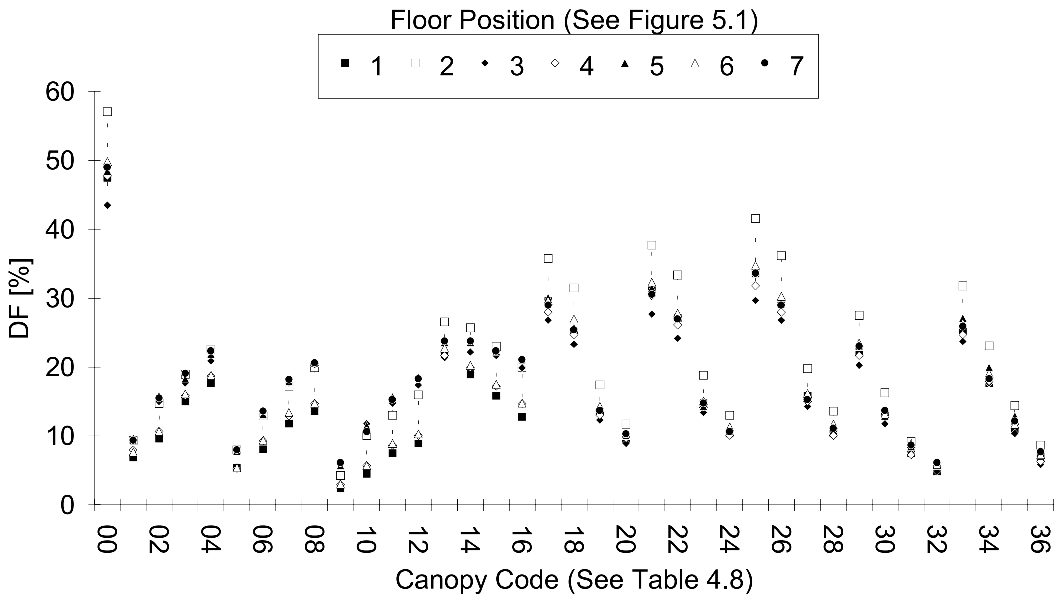



Figure 5.6 Example of Clear Sky Daylight Factors at WI = 0.6 (Atrium A2)

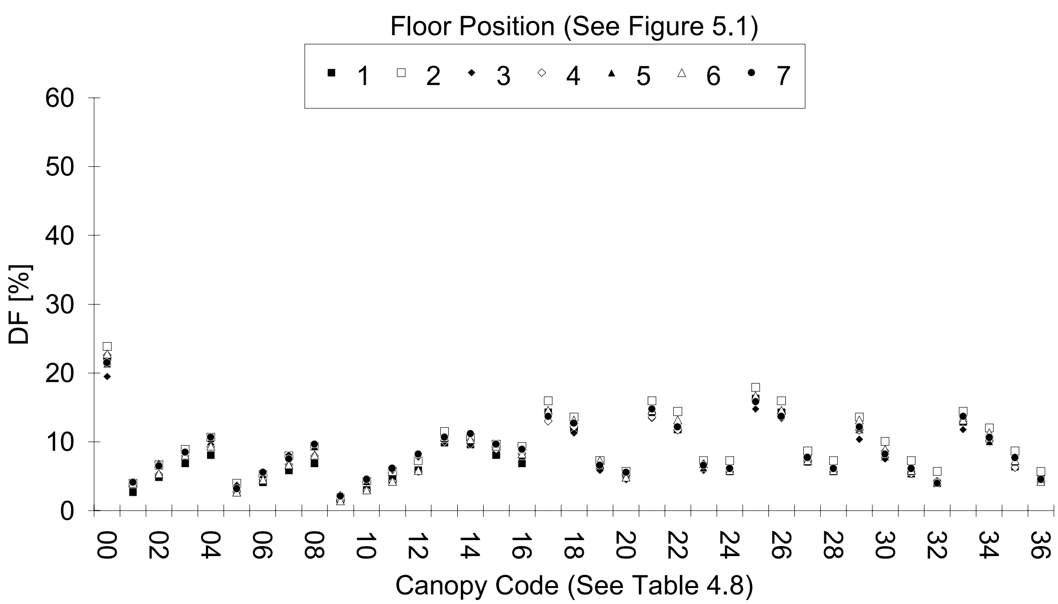



Figure 5.7 Example of Clear Sky Daylight Factors at WI = 1.2 (Atrium A4)

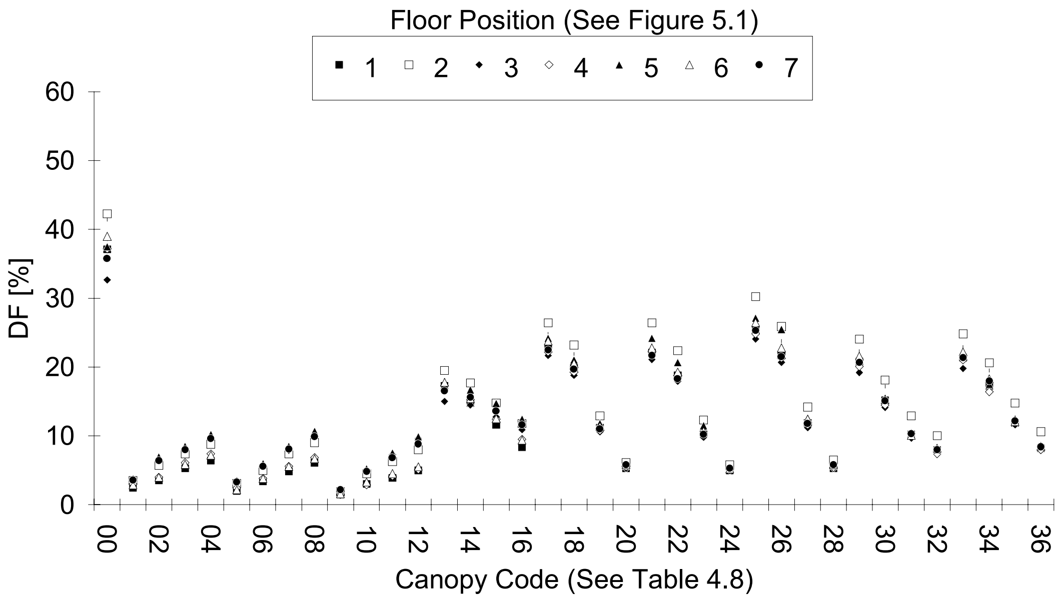



Figure 5.8 Example of Overcast Sky Daylight Factors at WI = 1.2 (Atrium A4)

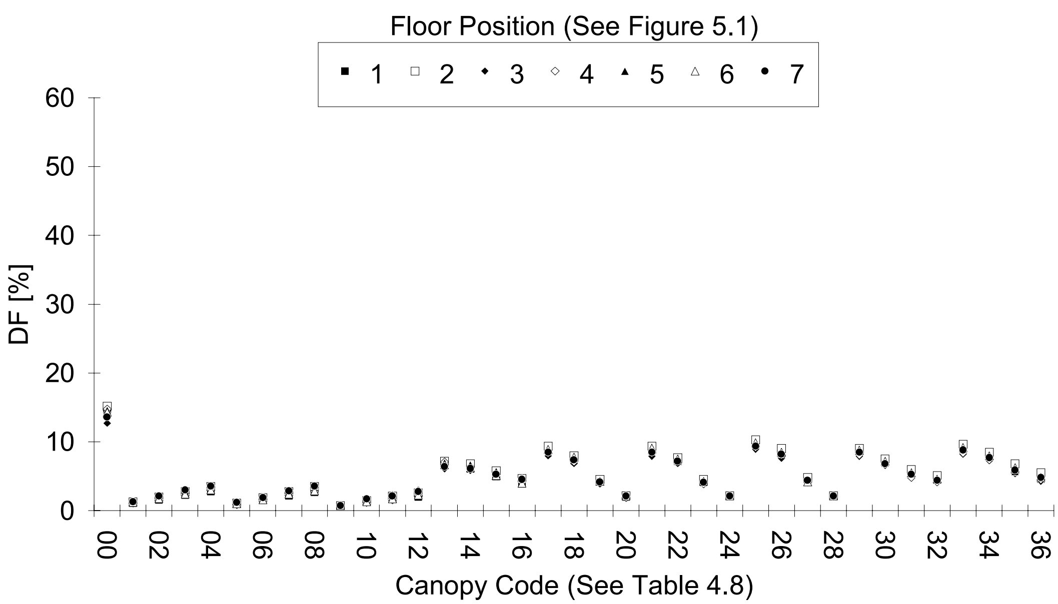



Figure 5.9 Example of Overcast Sky Daylight Factors for WI = 2.4 (Atrium A8)

## 5.2 SUNLIGHT ILLUMINANCE MEASUREMENT

### 5.2.1 Instrument Setup

Initially, several pilot measurements of sunlight illuminances were conducted with the artificial sun inside the sky simulator. However, two serious problems were observed. First, the surface of the simulated sky dome was illuminated by straying light and then reflected a considerable quantity of diffuse light toward the atrium models. Second, enough distance to produce near parallel light rays could not be obtained especially at high altitude angles due to the limited height of the sky simulator. This serious error was observed when the waffle skylights were tested at high altitude sun angles. Some skylight wells showed different shadow angles from others.

Since the purpose of this measurement was to obtain illuminances only from the sun, the initial instrument setup could not be used. Instead, all measurements of sunlight illuminances were conducted at an outdoor location at night with the artificial sun. In this way, the problems due to the extra light reflected from the sky dome surface and the non-parallel incoming light flux could be solved. Figure 5.10 shows the instrument setup at an outdoor location at night.

### 5.2.2 Exterior Horizontal Sunlight Illuminance Levels

Exterior horizontal sunlight illuminances at the seven floor positions were measured at the sun angles which were previously shown in Table 4.1. The positions of the artificial sun for the designed sun angles were determined by two sun angle charts with shadow pegs. One of them has a 30 mm peg to cast shadows at low sun angles (15° through 45°). The other one has a 100 mm peg to cast shadows at high sun angles (45° through 90°). Figure 5.11 shows the 30 mm sun angle shadow peg measuring sun altitude angle. As the sun angles at solar noon hours were tested in the study, the symmetries between illuminances measured at positions 4 and 6 and those at positions 5 and 7 were examined for further small adjustments on the azimuthal location of the artificial sun.

Differently from the previously discussed daylight illuminance measurements in which only one exterior illuminance was recorded as the reference value for each sky condition, the exterior horizontal sunlight illuminances were recorded for the seven floor positions. This was necessary because the sun simulator did not provide perfectly uniform illuminances at the different floor positions.

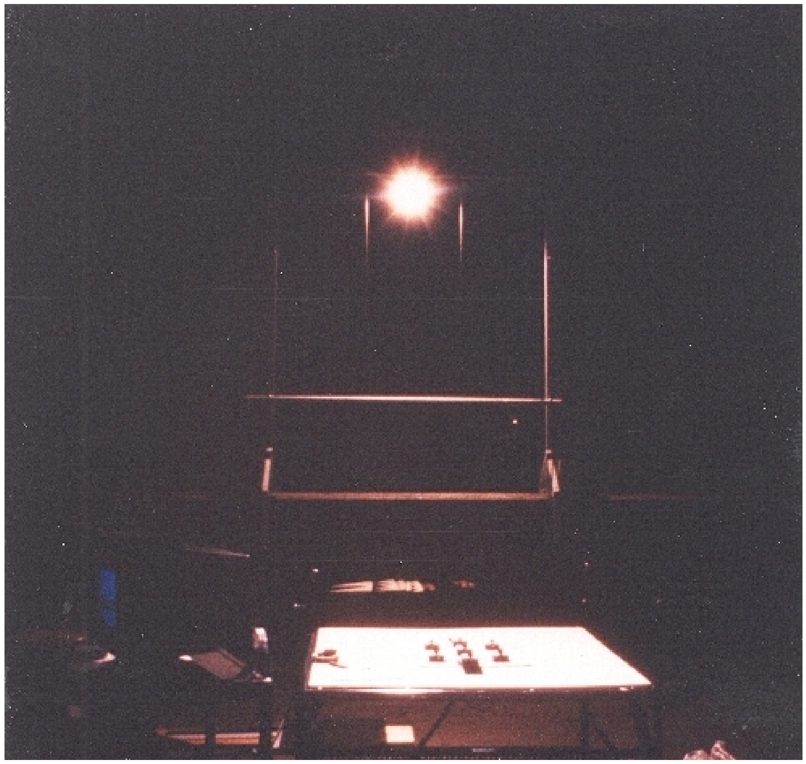


Figure 5.10 Outdoor Instrument Setup for Sunlight Illuminance Measurements at Night

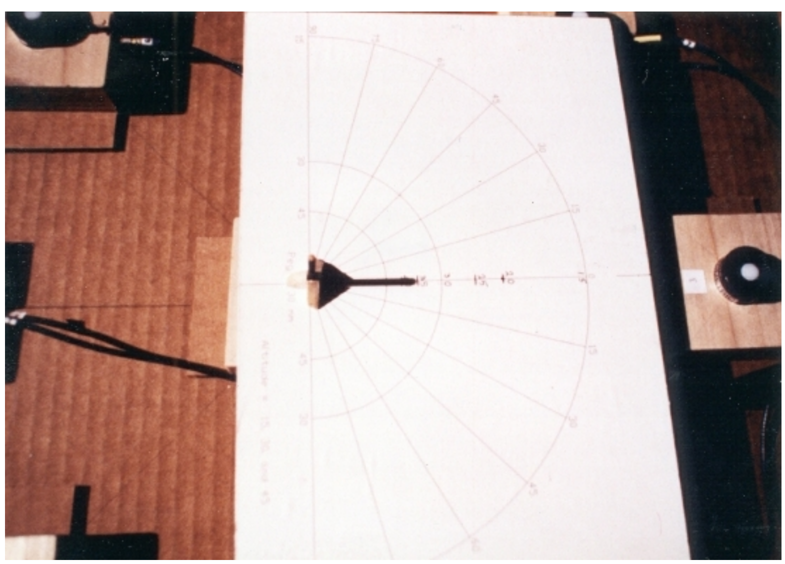


Figure 5.11 Sun Angle Shadow Peg Measuring Sun Altitude Angle

### 5.2.3 Interior Horizontal Sunlight Illuminance Levels

The measurements of interior direct sunlight illuminances were conducted with the reduced number of canopy systems and atrium Well Index values as shown in the matrix diagram of Figure 4.12. However, as will be discussed in the next chapter, the reduced number of measurements produced sufficient data to explain the characteristics of the different form types and glazing materials.

The procedures were mostly identical to those of daylight measurements except for several methodological differences. The measurements with black interiors to separate Direct Sun Component (DSC) and Internally Reflected Component (IRC) were not conducted. Actually it was not necessary, because the behavior of direct sunlight is totally different from that of diffuse light in terms of its directional property. Even a small patch of shadow on a photometric sensor drastically reduces the illuminance. As a matter of fact, a measured value at a floor position in shadow represented the IRC at that position.

Because of this reason, before conducting actual measurements, the shadow lengths cast by the front wall structure at given sun altitude angles and atrium heights were calculated and lists of floor positions which should be exposed to the sun were tabulated. During the measurements the tables were checked to precisely adjust the geometric relationship between the atrium structure and the incident light. Tables 5.1 through 5.3 show exposed floor positions at given sun angles and atrium models with different heights.

TABLE 5.1
Atrium Floor Positions Exposed to the Noon Sun (Houston, TX)

| Day | Sun Alt. | Atrium | Positions Exposed to the Sun | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6/21 | 84.0° | A2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | A4 | | 2 | 3 | 4 | 5 | 6 | 7 |
| | | A6 | | 2 | 3 | 4 | 5 | 6 | 7 |
| | | A8 | | 2 | 3 | | 5 | | 7 |
| 9/21 | 60.3° | A2 | | 2 | 3 | | 5 | | 7 |
| | | A4 | | | 3 | | 5 | | 7 |
| | | A6 | | | | | | | |
| | | A8 | | | | | | | |
| 12/21 | 37.1° | A2 | | | 3 | | | | |
| | | A4 | | | | | | | |
| | | A6 | | | | | | | |
| | | A8 | | | | | | | |

TABLE 5.2
Atrium Floor Positions Exposed to the Noon Sun (Oklahoma City, OK)

| Day | Sun Alt. | Atrium | Positions Exposed to the Sun | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6/21 | 78.2° | A2 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | A4 | 2 | 3 | | 5 | | 7 |
| | | A6 | 2 | 3 | | 5 | | 7 |
| | | A8 | | 3 | | 5 | | 7 |
| 9/21 | 54.5° | A2 | 2 | 3 | | 5 | | 7 |
| | | A4 | | 3 | | | | |
| | | A6 | | | | | | |
| | | A8 | | | | | | |
| 12/21 | 31.3° | A2 | | | | | | |
| | | A4 | | | | | | |
| | | A6 | | | | | | |
| | | A8 | | | | | | |

TABLE 5.3
Atrium Floor Positions Exposed to the Noon Sun (Minneapolis, MN)

| Day | Sun Alt. | Atrium | Positions Exposed to the Sun | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6/21 | 68.9° | A2 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | A4 | 2 | 3 | | 5 | | 7 |
| | | A6 | | 3 | | 5 | | 7 |
| | | A8 | | | | | | |
| 9/21 | 45.2° | A2 | | 3 | | 5 | | 7 |
| | | A4 | | | | | | |
| | | A6 | | | | | | |
| | | A8 | | | | | | |
| 12/21 | 22.0° | A2 | | | | | | |
| | | A4 | | | | | | |
| | | A6 | | | | | | |
| | | A8 | | | | | | |

Another important difference in instrument setups between the sunlight illuminance measurements with the artificial sun and the daylight illuminance measurements inside the sky simulator was the elevation of the atrium floor panel. The daylight illuminances were measured at a fixed elevation of the atrium floor panel. On the other hand, two different methods were used in measuring interior sunlight illuminances with the consideration of the sun altitude angles.

When a sun altitude was high and most of the photometric sensors were exposed to the artificial sun, the same methods as in daylight illuminance measurements were used. In this case, it is important to comply with the inverse square law and the cosine law of incident light from the point source to obtain consistent data from different well configurations. In this regard, the exterior illuminances were measured on the model stand level. Then, subsequent measurements of interior sunlight illuminances were conducted by stacking atrium side modules around the atrium floor. Figure 5.12 illustrates the sequence of measurements at a high sun altitude angle.

However, at a low sun altitude angle when most of the photometric sensors were shaded by the front wall structure, a reverse method was used. In such a case, the two laws for a point light source are no longer in effect.

Since, only the diffuse reflected light rays from the interior surfaces affect the illuminances on the floor positions, two other factors to be considered are the luminance distributions on the interior surfaces and the geometric relationships between those surfaces and the floor positions which were discussed in Chapter 3. In this context, it is necessary to maintain constant light flux through the atrium opening and luminance distributions on the interior surfaces at a given sun altitude angle which will be the case in real situations. This can be achieved by maintaining a constant distance from the atrium opening to the artificial sun and a constant incident angle at the atrium opening.

In this regard, the exterior illuminances were measured by placing the atrium floor panel on the top of the highest stacked atrium scale model (WI = 2.4, atrium A8). Then, subsequent measurements were conducted by lowering the floor panel inside the atrium. The measurement scheme is illustrated in Figure 5.13.

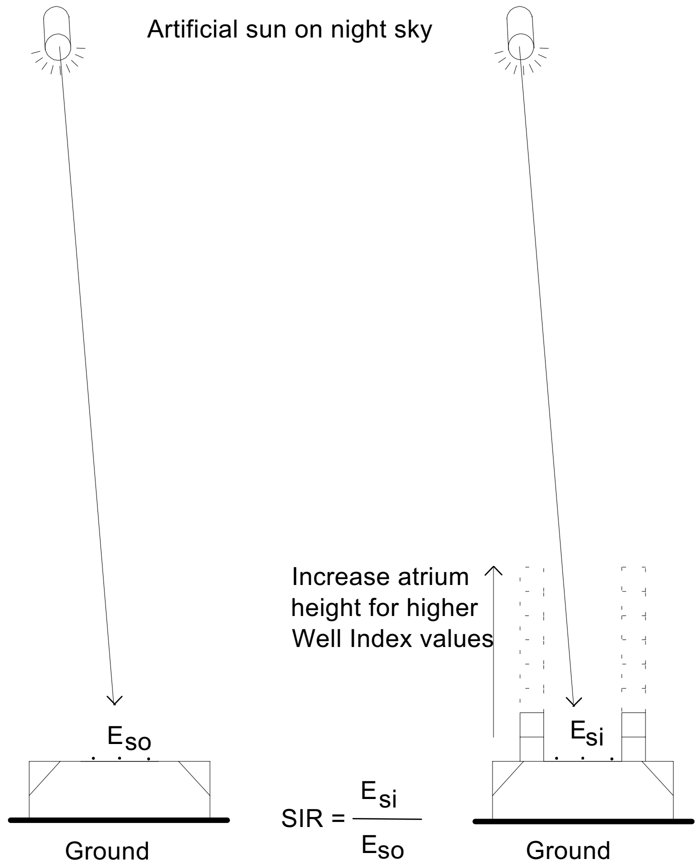



Figure 5.12 Sunlight Illuminance Measurement at High Sun Altitude Angles

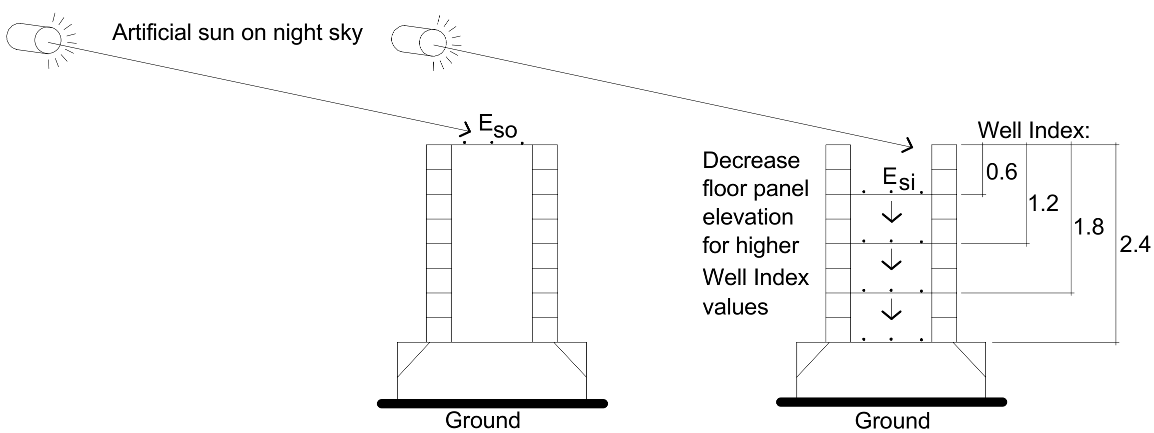



Figure 5.13 Sunlight Illuminance Measurement at Low Sun Altitude Angles

### 5.2.4 Sunlight Illuminance Ratio (SIR) Calculation

After completing the measurements, the measured sunlight illuminance data were converted into Sunlight Illuminance Ratio (SIR) using the relationship given in Equation 4.2. It must be noted that there is a difference between the concept of Daylight Factor (DF) and SIR. DF values calculated from measured interior illuminances become always smaller than 100 % because the building structure blocks certain portion of the sky hemisphere. However, SIR values can be greater than 100 % when the illuminances are measured inside a building structure with no glazing materials for the openings. This is because the measured illuminances comprise both the direct illuminance from the sun and the diffuse reflected light from the interior surfaces.

Several examples are presented here. Figure 5.14 shows SIR values at WI = 1.2 (atrium A4) at solar noon hour on June 21 (sun alt. = 84.0°) in Houston, TX. Figure 5.15 shows SIR values at the same WI value on September 21 (sun alt. = 54.5°) in Oklahoma City, OK. Finally, Figures 5.16 shows SIR values at the same WI value on December 21 (sun alt. = 22.0°) in Minneapolis, MN. As shown in Figures 5.14 and 5.15, the SIR values at several floor positions exposed to the artificial sun was greater than 100 %..

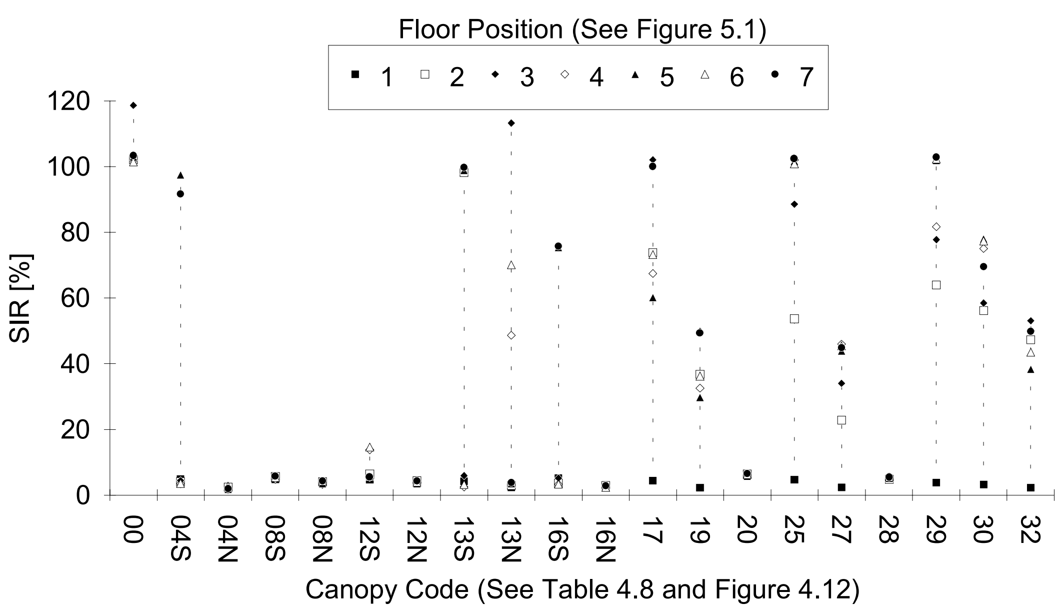



Figure 5.14 Example of Sunlight Illuminance Ratios at WI = 1.2 (Atrium A4) at Solar Noon Hour on June 21 in Houston, TX

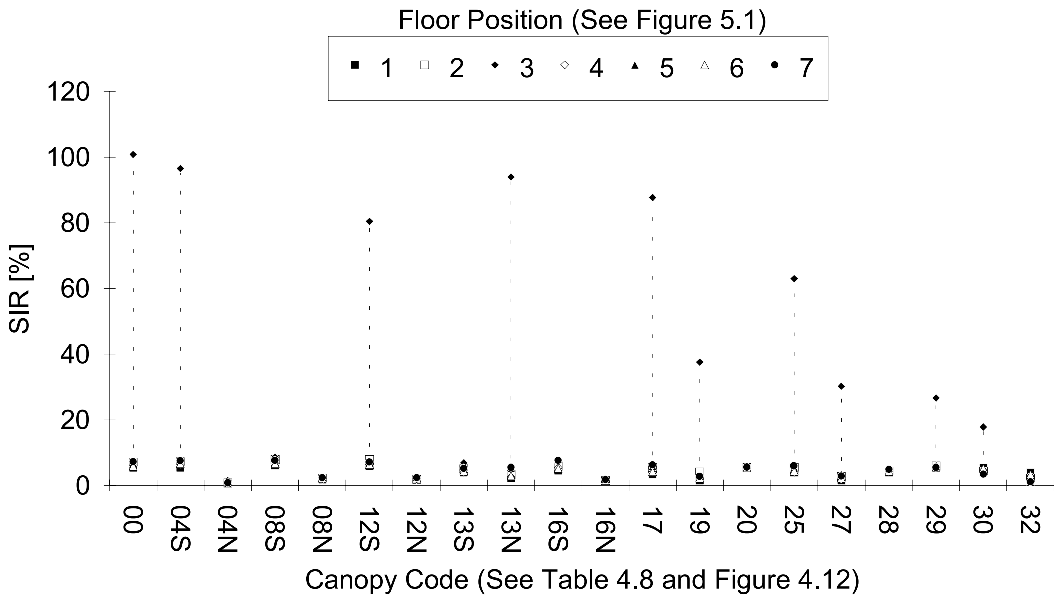



Figure 5.15 Example of Sunlight Illuminance Ratios at WI = 1.2 (Atrium A4) at Solar Noon Hour on September 21 in Oklahoma City, OK

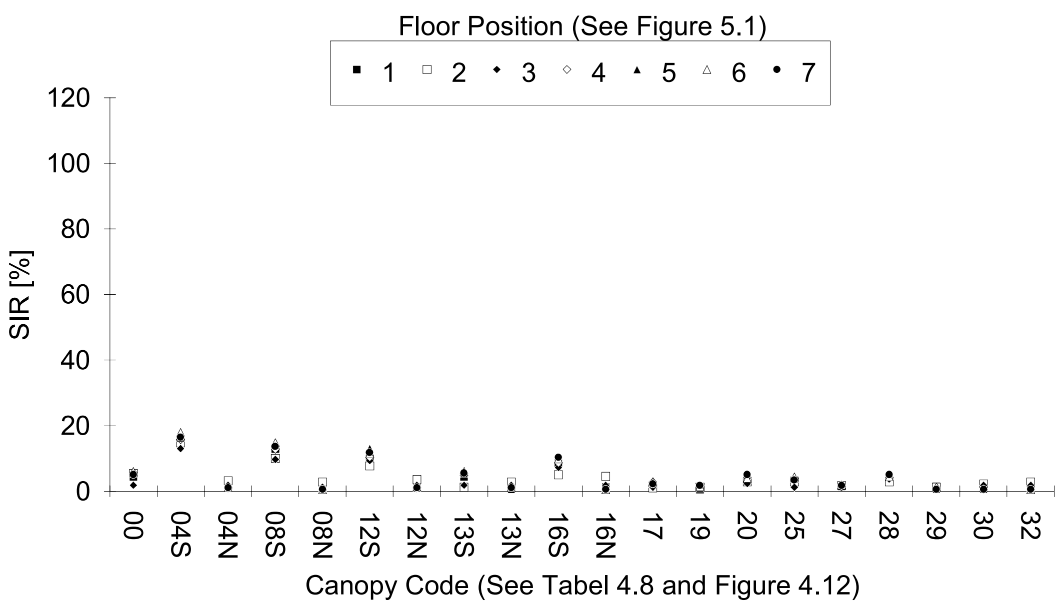



Figure 5.16 Example of Sunlight Illuminance Ratios at WI = 1.2 (Atrium A4) at Solar Noon Hour on December 21 in Minneapolis, MN

## 5.3 LUMINANCE DISTRIBUTION MAPPING

The luminance distributions on interior surfaces were mapped by the video-based luminance mapping system discussed in Chapter 3. The instrument setups were identical to those of diffuse daylight measurements and direct sunlight measurement procedures. Instead of using photometric sensors, The fisheye lens of the luminance mapping system was placed at the center floor position under overcast sky condition and direct sunlight conditions. The atrium scale models used for luminance mapping included A2 (WI = 0.6), A4 (WI = 1.2), A6 (WI = 1.8), and A8 (WI = 2.4) for both overcast sky and direct sunlight conditions. Figure 5.17 shows the fisheye lens intruded from the bottom of the model stand. Since the image capture method and image processing procedures are discussed in Appendix B, several examples are presented here.

Figures 5.18 and 5.19 show examples of the mapped luminance distributions under overcast sky at WI = 0.6 with pyramid skylights with tinted glazing (No. 27) and white translucent glazing (No. 28), respectively. Figures 5.20 and 5.21 show the mapped luminance distributions at WI = 1.8 with the same canopy systems under overcast sky. Finally, Figures 5.22 and 5.23 show the mapped luminance distributions of direct sunlight at WI = 1.2 with tinted and translucent glazing, respectively, at solar noon hour on December 21 in Oklahoma City.

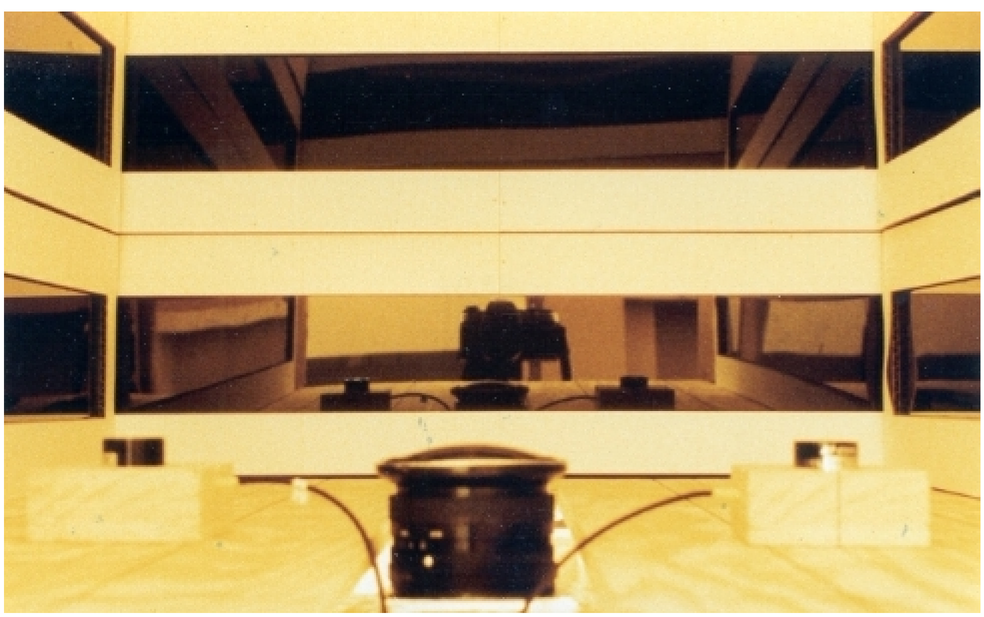
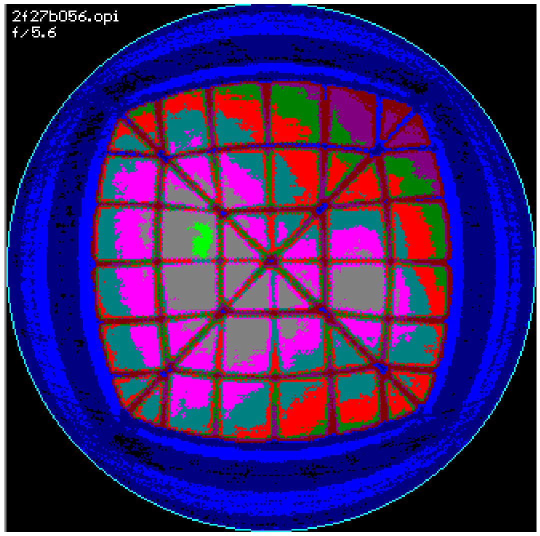
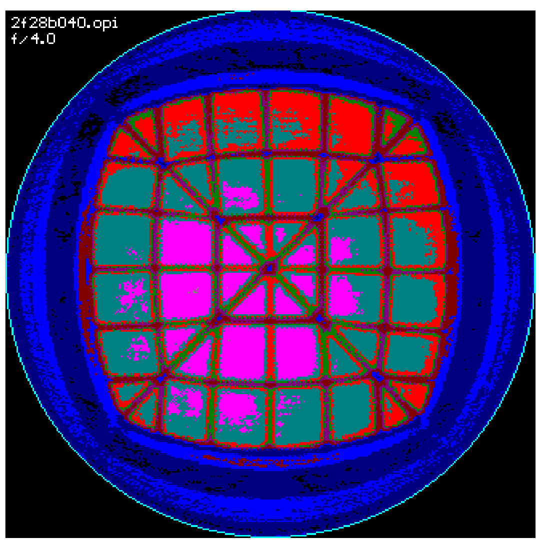


Figure 5.17 Fisheye Lens in Atrium Scale Model



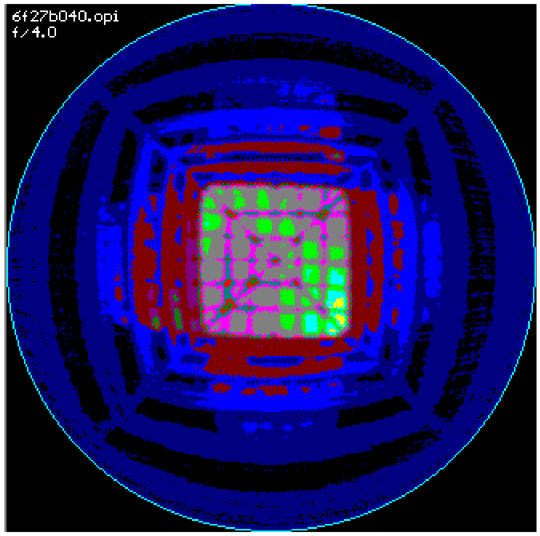

South

Figure 5.18 Luminance Distribution Map for Atrium A2 with Pyramid Skylight (No. 27) of Tinted Glazing (Overcast Sky, f/5.6)



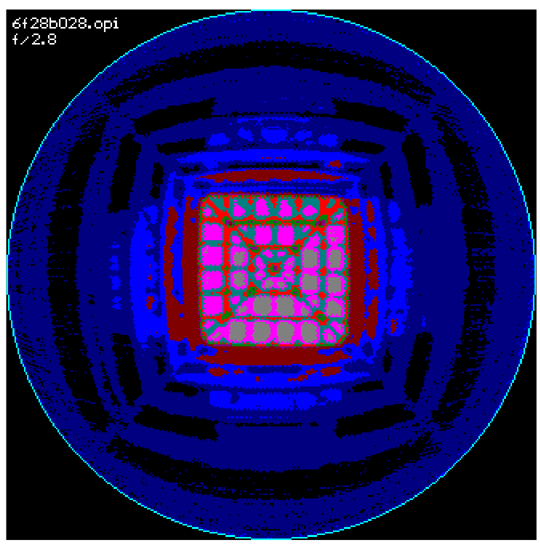

South

Figure 5.19 Luminance Distribution Map for Atrium A2 with Pyramid Skylight (No. 28) of White Translucent Glazing (Overcast Sky, f/4)



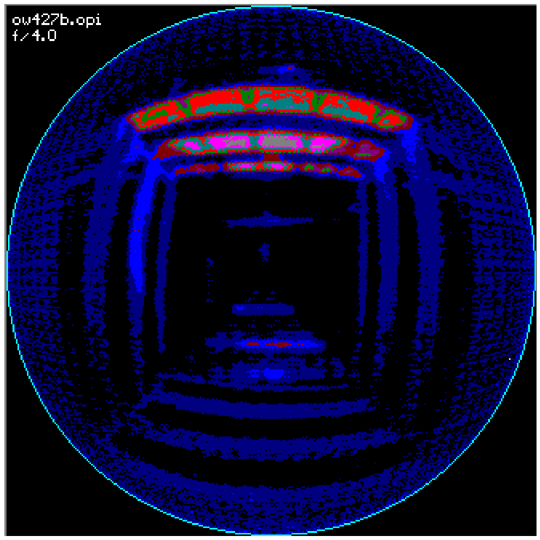

South

Figure 5.20 Luminance Distribution Map for Atrium A6 with Pyramid Skylight (No. 27) of Tinted Glazing (Overcast Sky, f/4)



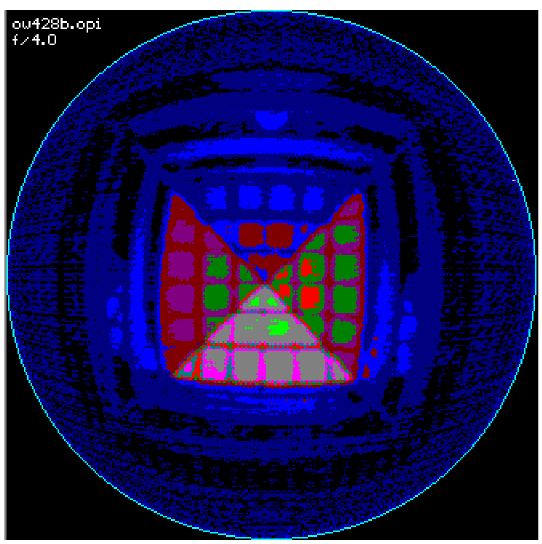

South

Figure 5.21 Luminance Distribution Map for Atrium A6 with Pyramid Skylight (No. 28) of White Translucent Glazing (Overcast Sky, f/2.8)




South

Figure 5.22 Luminance Distribution Map for Atrium A4 with Pyramid Skylight (No. 27) of Tinted Glazing on December 21 in Oklahoma City (Direct Sun, f/4)




South

Figure 5.23 Luminance Distribution Map for Atrium A4 with Pyramid Skylight (No. 28) of White Translucent Glazing on December 21 of Oklahoma City (Direct Sun, f/4)

## 5.4 HEMISPHERICAL TRANSMITTANCE (HT) MEASUREMENT

The Hemispherical Transmittances (HT) of the flat glazing materials and the canopy systems were measured with the integrating box under the simulated clear and overcast sky conditions. As discussed in Chapter 3, the light flux passing through the opening of the integrating box was integrated by the interreflections among the interior surfaces and measured with the five photocells and averaged.

First, the intensity of light passing through the opening was measured in the absence of the canopy systems. Then, as shown in Figure 5.24, after placing each canopy system on the integrating box, the intensities of transmitted light under the two different sky conditions were measured. Finally, the Hemispherical Transmittances (HT) were determined by Equation 5.1.

$$HT = \frac{E_c}{E_o} \times 100\,[\%] \tag{5.1}$$

where HT = Hemispherical Transmittance
$E_o$ = average of light intensities measured without canopy
$E_c$ = average of light intensities measured with canopy.

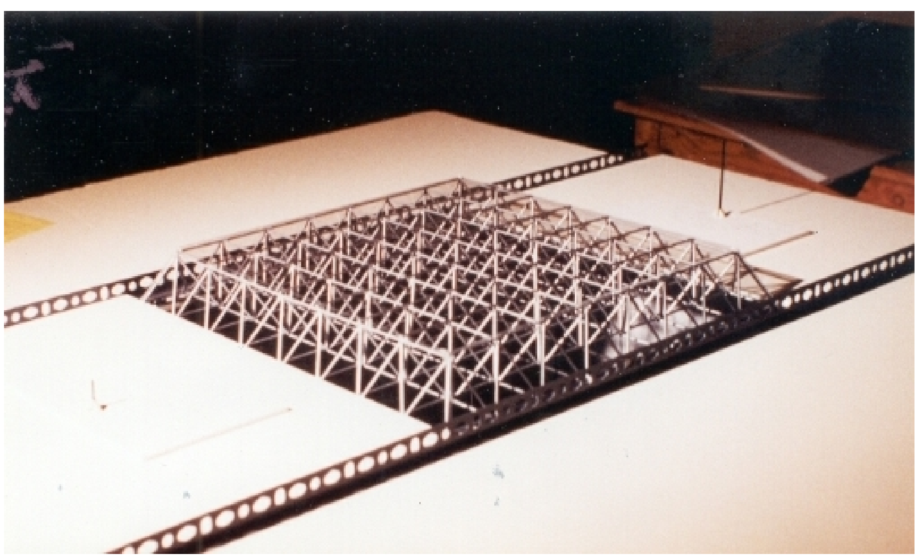


Figure 5.24 Photo of Flat Horizontal Skylight (No. 25) Setup for Hemispherical Transmittance Measurement

The measured HT values are presented in the following figures. Figure 5.25 shows the HT values of the three glazing materials with different transmittance and translucency under the simulated clear and overcast sky conditions. As indicated in the figure, the HT values of transparent glazing materials (clear and tinted) were about 2 % greater under overcast sky condition than they were in clear sky conditions. However, the transmittance of the white translucent material was about 7.4 % higher under clear sky than it was under overcast sky.

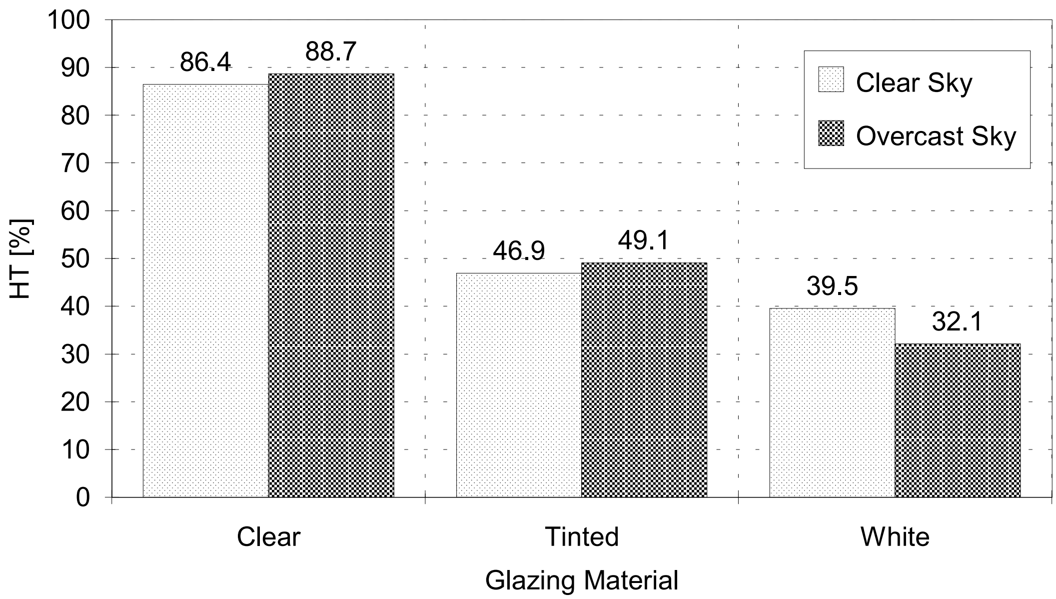



Figure 5.25 Measured Hemispherical Transmittances of Flat Glazing Materials under Clear and Overcast Skies

Figure 5.26 shows the HT values of 36 different canopy systems under the two different sky conditions. As revealed in the figure, the HT values of sawtooth type canopy systems (No. 1 through 16) were greater under clear sky condition than they were under overcast sky condition. In reverse, the HT values of the skylight types (No. 17 through 36) were greater under overcast sky than they were under clear sky, except for the skylights with white translucent glazing material (No. 20, 24, and 28).

The differences in HT values between different canopy systems and between the different sky conditions will be referred to during the analysis procedure which will be discussed in the next chapter.

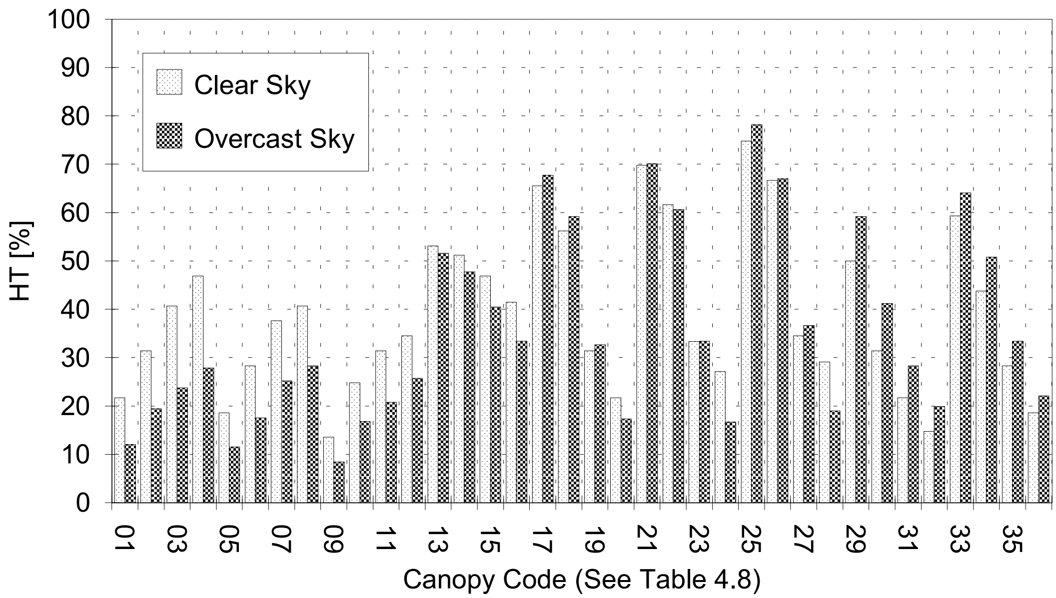



Figure 5.26 Measured Hemispherical Transmittances of 36 Canopy Systems under Clear and Overcast Skies