DAYLIGHTING SYSTEMS FOR THE KUWAIT NATIONAL MUSEUM

A Thesis

by

BYOUNGSOO AHN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Architecture

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Approved as to style and content by:

Liliana O. Beltran (Chair of Committee)	Paul K. Woods (Member)
Rodney C. Hill (Member)	Phillip J. Tabb (Head of Department)

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ABSTRACT

Daylighting Systems for the Kuwait National Museum.

(May 2005)

Byoungsoo Ahn, B.E., Dong-A University

Chair of Advisory Committee: Dr. Liliana O. Beltran

Daylight has a deteriorating effect on the museum objects. For this reason, usually museums totally block the daylight. This research is the part of restoration works of Kuwait National Museum (KNM), which was destroyed during the Gulf War in 1990.

The purpose of this research is to investigate the lighting performance of the top lighting and side shading devices in KNM. This research will cover daylighting systems for Building 3 and 4 of the KNM. Daylighting systems are evaluated by using the scale model and Desktop RADIANCE, a lighting simulation program. This research will present how to make use of daylight in museum buildings while protecting museum objects from the harmful portion of daylight.

ACKNOWLEDGMENTS

I would like to express sincere appreciation to my committee members: Liliana O. Beltran, Paul K. Woods, and Rodney C. Hill, for their valuable advice and encouragement throughout the research. And I would like to give special thank to Judy Lai in Lawrence Berkeley National Laboratory. She helped me whenever I had problems with Desktop RADIANCE.

My family has been a constant source of support. My parents have always believed in me. I would to thank my wife, Mijin Kim. I cannot thank her enough for her patience, helpfulness and encouragement throughout the research.

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INTRODUCTION

Daylight in Museums

In most museum buildings, bioclimatic, environmental-friendly and energy-conscious design have been completely ignored. There are good reasons to support the opinion that museums are lit, heated and ventilated by artificial means. This leads to fully dependable on mechanical equipments. The sensitivity of the objects exhibited is the main argument to justify this position. The exhibits are considered to be better preserved when light, temperature etc. are fully controllable and adjustable according to the special requirements of the exhibits (Tombazis and Preuss, 2001). In terms of the lighting issue, the use of daylight in museums is a somewhat controversial issue for two reasons: the ultraviolet component of natural light has a deteriorating effect on museum objects, and daylight is difficult to control because of variability of sky condition through a day and seasons. These concerns have tended to curtail the use of daylight in museum buildings (ROM, 1976).

Effects of Exposure to Light in Museum Objects

Light is the radiant energy, and exposure to light causes permanent damage to most of museum objects. When radiant energy is incident on the surface of a material, some portion of that energy is absorbed. It can promote two distinctly different processes

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This thesis follows the style and format of *Solar Energy.*

which can cause the degradation of museum objects: radiant heating and photochemical action.

Radiant heating produces the rise of temperature at the surface of the material exposed to the source of energy. The surface expands relative to the body of the object, and moisture is driven from the surface material. The symptoms include surface cracking, lifting of surface layers, and loss of color. The symptoms of photochemical action is similar, however the process is quite different and often more serious. A chemical change occurs when a molecule irreversibly changes its structure. Photochemical action may include fading or darkening of colors, yellowing, brittling, loss of strength, fraying of fabrics, and even dramatic color changes of some pigments (IESNA, 2000).

Spectral Composition of Light

Visible light is the portion of the electromagnetic spectrum with wavelengths between 400 and 700 billionths of a meter (400 to 700 nanometers). Infrared is the region of the electromagnetic spectrum that extends from the visible region to about one millimeter (in wavelength), and Infrared (IR) waves include thermal radiation. Ultraviolet radiation (UV) has a range of wavelengths from 400 billionths of a meter to about 10 billionths of a meter (Figure 1). Visible light contributes to both vision and damage; IR and UV energy, which are not visible, contribute only to damage. Unless all artifacts in a display area are totally insensitive to exposure, UV and IR should be controlled, usually with filters (IESNA, 2000). And it can be noted that the most hazardous radiations are those having spectral distributions which are dominant in the shorter wavelengths. The relative damage factor increases logarithmically in inverse ratio to wavelength. Thus ultraviolet is far more hazardous than visible light (IES, 1972).

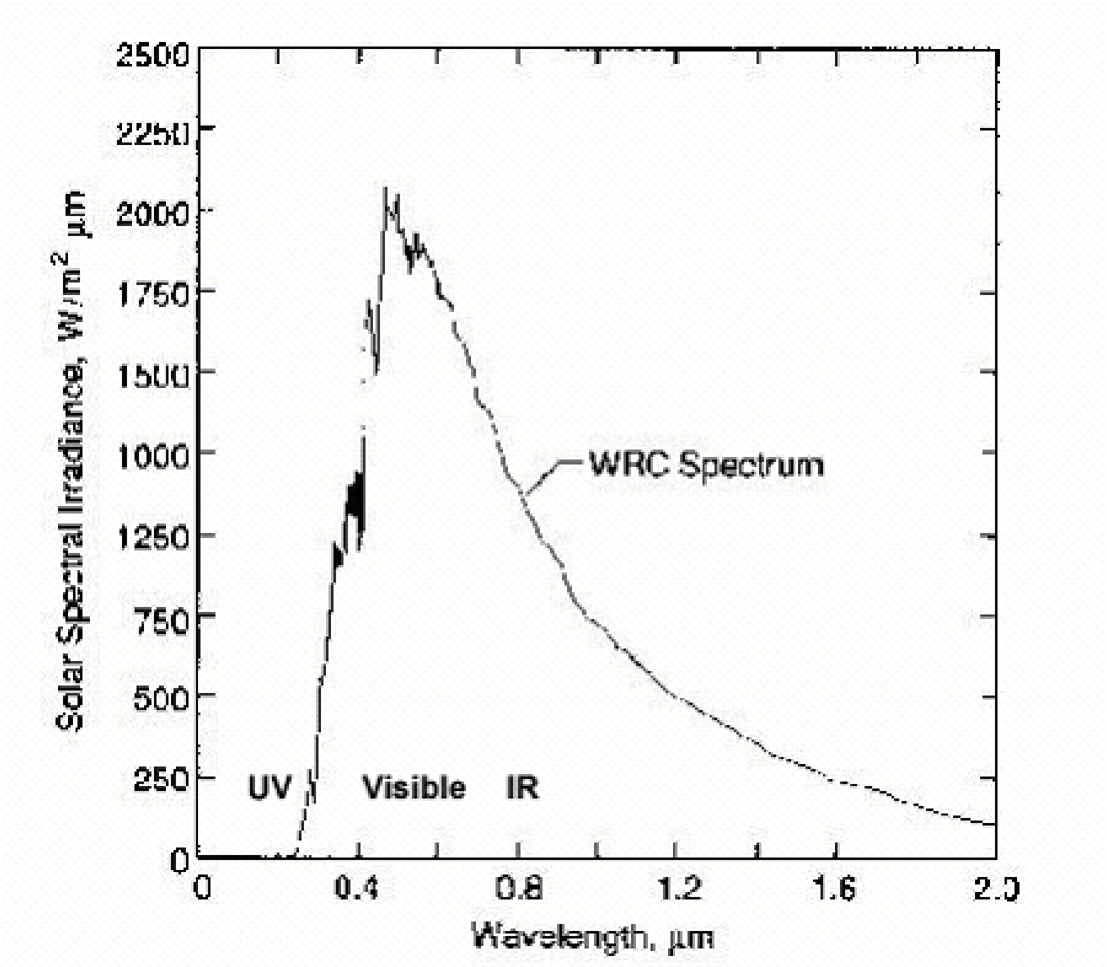


Figure 1 Electromagnetic spectrum and the WRC standard irradiance curve at mean earth-sun distance (Beckman and Duffie, 1991).

Benefits of Daylight in Museums

The most important criterion for museum lighting is spectral distribution. In this respect, daylight is considered as the best choice. Some museum curators even consider that the daylight, because of its superior color properties, has no substitute in art galleries during the daytime. No electric light source can exactly simulate the color composition of daylight (Neeman, n.d.). Daylight, whether bright or dim, always offers a continuous spectral curve, meaning that it can reveal all colors in works of art (Darragh and Snyder, 1993). In addition, daylight also gives natural feeling to the museum visitors. By using daylight in museums, electric lighting loads will be decreased during the daytime.

RESEARCH DESCRIPTIONS

Kuwait National Museum

The Kuwait National Museum (KNM) was opened in 1983. On a square site, the museum comprises four buildings, rectangular in plan and irregular in their massing. They are set around a central garden and linked to each other through bridged galleries. One of the four blocks contains all administrative functions, offices, and an auditorium. The permanent exhibits are displayed in other three blocks on two levels. Access between these levels is via a layout of ramps, a composition of double height space which connects the exhibition floors to create possibilities of extensive and multiple

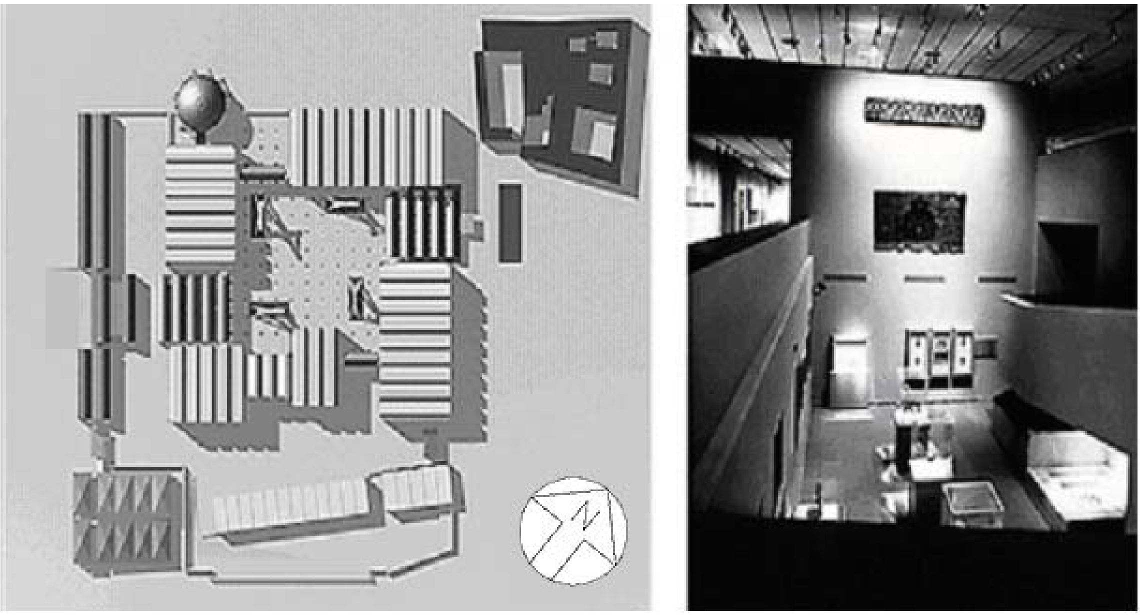


Figure 2 Site plan and interior view of the Kuwait National Museum (Courtesy: UNESCO KNM Advisors, ArchNet, n.d.).

views over the large, exposed objects (Figure 2). The collections of KNM are the finest pieces of Islamic arts, which include manuscripts, textiles, jewelry, and ceramics.

Figure 3 Interior view of southeast gallery in Building 3 after the Gulf War (Gulf Museum Consultancy Company, 2001).

In 1990, the KNM was destroyed by the Iraq during the Gulf War. Galleries, offices, and records of the museum were burned and most collections were stolen. After the Gulf War, the KNM has been closed (Figure 3).

Climatic Conditions in Kuwait City

The KNM is located in Kuwait City (Latitude: 29.13' N, Longitude: 47.59' E), Kuwait. Kuwait is located in the northeastern corner of the Arabian Peninsula. The country is almost entirely flat desert except for the northwest of the country. Kuwait has no mountains and no rivers (Kuwait Information Centre, 2004).

As the Kuwait is in the desert zone of the Sahara geographical region, the summers are long, extremely hot and dry with monthly average highs ranging from 81.5°F to 101.1°F (27.5°F-38.4°C). The highest temperature in summer is 119°F (48.3°C). The summers are long and lasting from late May until early October. July and August are the hottest months. Winters in Kuwait, which generally last from early December until February, are relatively cool and humid. In January, the coldest month, daily average temperatures range from 54.7°F to 58.6°F (12.6°C-14.8°C). The lowest temperature is 34°F (1.1°C) which is just above the freezing point (Figures 4 and 5). Most rain falls between November and March. Average annual precipitation varies from 30 mm (1 inch) to 220 mm (9 inches) with most rainfall occurring between November and April (Latimer Clarke Corp., n.d.).

Solar radiation is highest in June and lowest in December (Figures 4 and 5). And another feature of Kuwait's weather is a sand and dust storm during the summer. And Table 1 shows the turbidity of Kuwait throughout whole year.

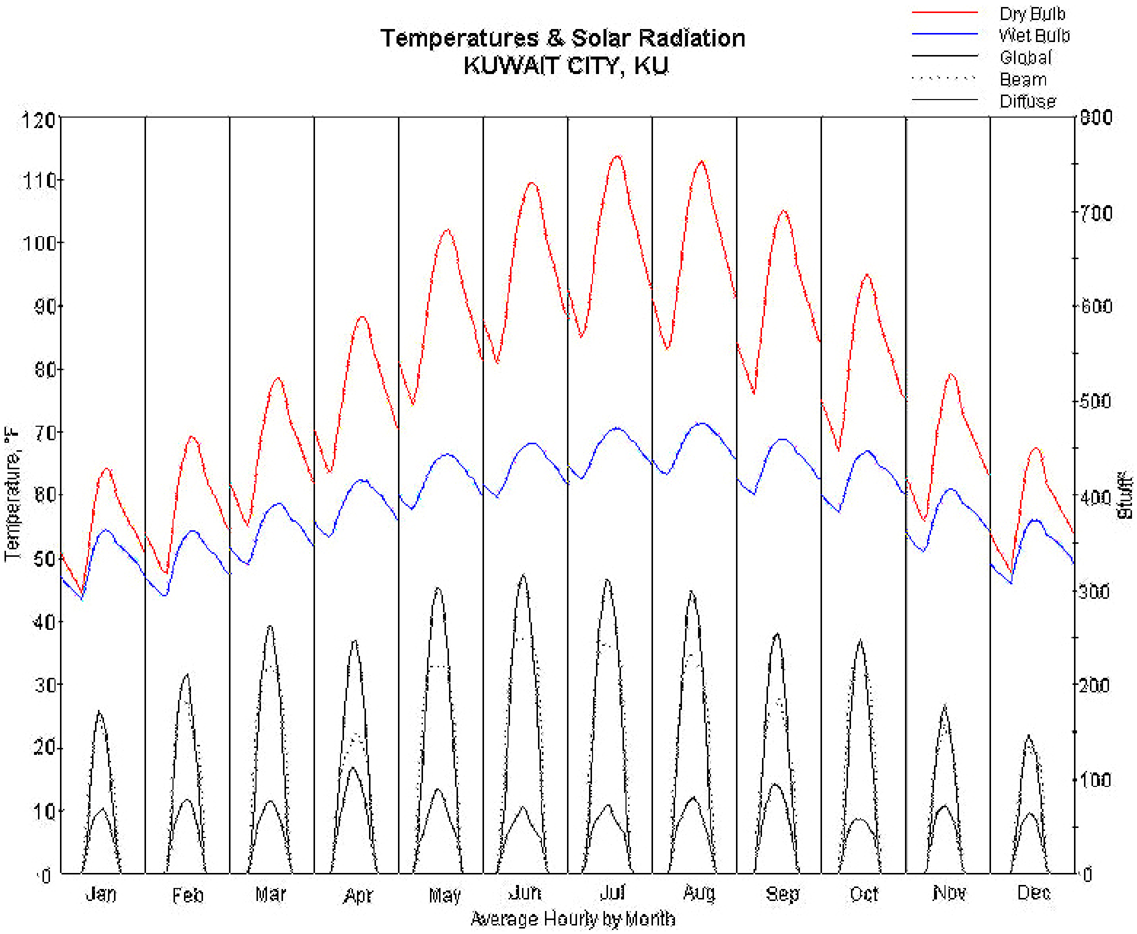
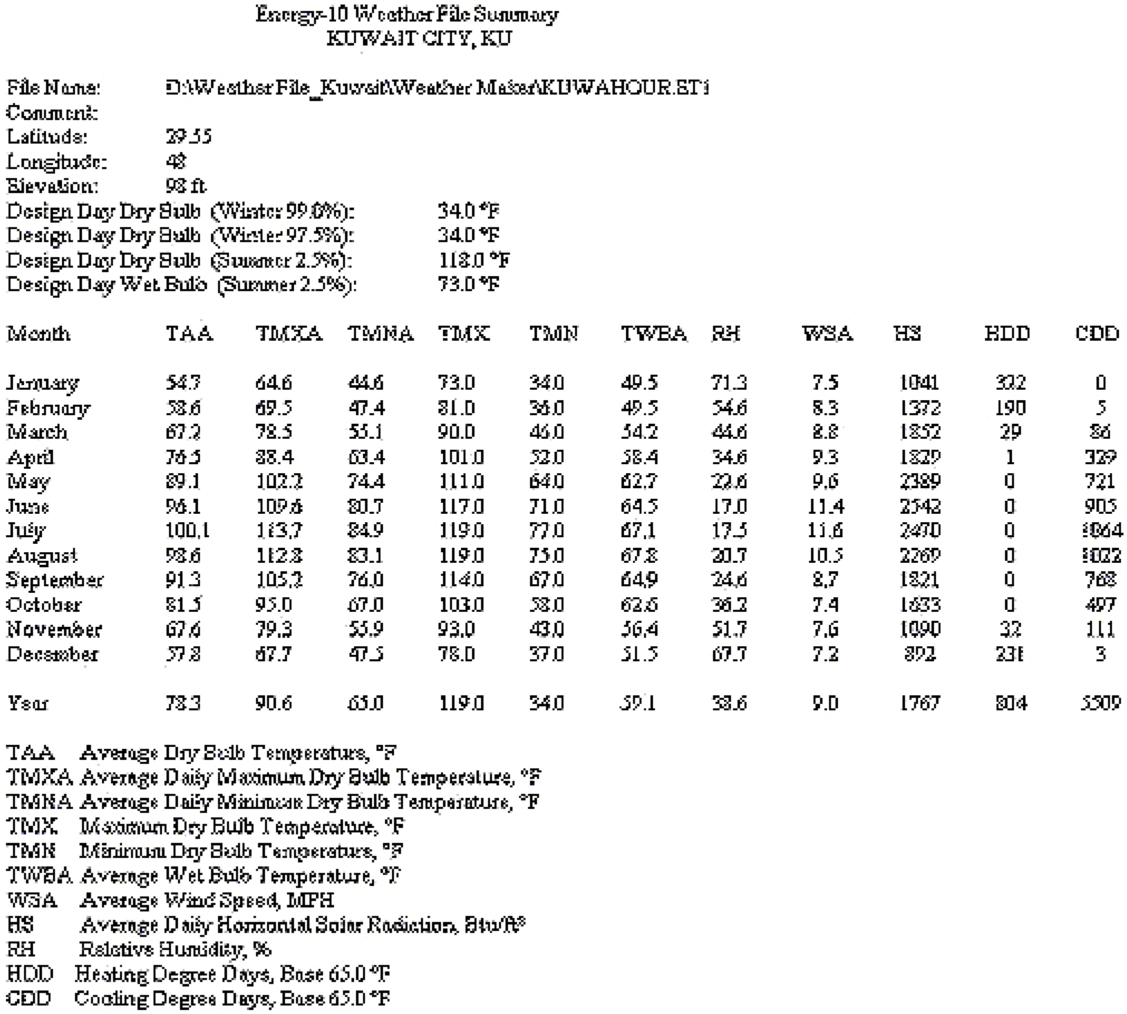


Figure 4 Hourly temperature and solar radiation



Energy-10 Weather File Summary
KUWAIT CITY, KU

File Name: D:\Weather File_Kuwait\Weather Maker\KUWAHOUR.ET1
Comment:
Latitude: 29.55
Longitude: 48
Elevation: 98 ft
Design Day Dry Bulb (Winter 99.0%): 34.0 °F
Design Day Dry Bulb (Winter 97.5%): 34.0 °F
Design Day Dry Bulb (Summer 2.5%): 118.0 °F
Design Day Wet Bulb (Summer 2.5%): 73.0 °F

Month	TAA	TMXA	TMNA	TMX	TMN	TWBA	RH	WSA	HS	HDD	CDD
January	54.7	64.6	44.6	73.0	34.0	49.5	71.3	7.5	1041	332	0
February	58.6	69.5	47.4	81.0	36.0	49.5	54.6	8.3	1372	190	5
March	67.2	78.5	55.1	90.0	46.0	54.2	44.6	8.8	1852	29	86
April	76.5	88.4	63.4	101.0	52.0	58.4	34.6	9.3	1829	1	329
May	89.1	102.2	74.4	111.0	64.0	62.7	22.6	9.6	2389	0	721
June	96.1	109.6	80.7	117.0	71.0	64.5	17.0	11.4	2542	0	905
July	100.1	113.7	84.9	119.0	77.0	67.1	17.5	11.6	2470	0	1064
August	98.6	112.8	83.1	119.0	75.0	67.8	20.7	10.5	2269	0	1022
September	91.3	105.2	76.0	114.0	67.0	64.9	24.6	8.7	1821	0	768
October	81.5	95.0	67.0	103.0	58.0	62.6	36.2	7.4	1633	0	497
November	67.6	79.3	55.9	93.0	43.0	56.4	51.7	7.6	1090	32	111
December	57.8	67.7	47.5	78.0	37.0	51.5	67.7	7.2	892	231	3
Year	78.3	90.6	65.0	119.0	34.0	59.1	38.6	9.0	1767	804	5509

TAA Average Dry Bulb Temperature, °F
TMXA Average Daily Maximum Dry Bulb Temperature, °F
TMNA Average Daily Minimum Dry Bulb Temperature, °F
TMX Maximum Dry Bulb Temperature, °F
TMN Minimum Dry Bulb Temperature, °F
TWBA Average Wet Bulb Temperature, °F
WSA Average Wind Speed, MPH
HS Average Daily Horizontal Solar Radiation, Btu/ft²
RH Relative Humidity, %
HDD Heating Degree Days, Base 65.0 °F
CDD Cooling Degree Days, Base 65.0 °F

Figure 5 Energy-10 weather file summery for Kuwait City.

Table 1 Turbidity data for Kuwait (Linke Turbidity Factor, 2001)

January	**3.5**
February	**4.0**
March	**4.0**
April	**5.0**
May	**5.5**
June	**5.0**
July	**5.5**
August	**5.5**
September	**5.0**
October	**4.5**
November	**4.0**
December	**3.5**

Purpose and Scope of Research

This research is the part of restoration works of the KNM sponsored by the United Nations Educational, Scientific and Cultural Organization (UNESCO). The purpose of this research is to investigate the lighting performance of top lights and side shading devices for the Kuwait National Museum. This research covers the daylighting systems for building 3 and 4. Electric lightings and mechanical devices such as automated louvers will not be considered. This research presents how to make use of daylight in the KNM while protecting museum objects from the harmful portion of sunlight.

METHODOLOGY

Desktop RADIANCE

Desktop RADIANCE was used to test the lighting level in the gallery. Then, to verify the data from Desktop RADIANCE, the data were compared with scale model measurement. Desktop RADIANCE was used for evaluation of designed daylighting system. Desktop RADIANCE is an advanced lighting analysis and visualization tool that can be used to model simple or complex daylight and electric lighting systems. RADIANCE was initially developed as a research tool for a UNIX environment, where it utilized a rather complex text-based input format.

RADIANCE is one of the most powerful daylight and electrical lighting analysis tools available since it can handle virtually any space geometry, as well as non-diffuse reflectances. The Desktop RADIANCE version provides the opportunity for more lighting professionals to easily access this powerful software tool through a graphical user interface (Mistrick, 2000). There are several lighting simulation programs which can predict daylighting performance in buildings. Ubbelohde conducted research of comparative evaluation of four daylighting software programs: Lumen Micro, SuperLite, Lightscape, and RADIANCE. In this research, she found RADIANCE has proven in this study to be much more accurate in predicting illumination levels than other programs and is the program of choice if accuracy is important (Ubbelohde, n.d.).

Scale model

Scale model was used to test the sun penetration through the top light and verify the lighting level of Desktop RADIANCE. To simulate sun path of Kuwait City, sundial was used (Figure 6). Scale model was made with Crescent board (Appendix C) to match the exact reflectance values in the Desktop RADAICE. Reflectance values in Figure C 1 were measured in Lawrence Berkeley National Laboratory (LBNL). Table 2 shows the material used for scale model.

Figure 6 Scale model

Table 2 Scale model materials

PART	COLOR	COLOR #	REFLECTANCE (%)
Wall, ceiling	Pearl	934 A	61.1
Floor	Dark Gray	924 A	14.3
Top Light	Gold	970	83.0

ECOTECT v 5.20

ECOTECT is software package for the conceptual building design. It comprises several unique features such as Shadows and Shading, Solar Analysis, Lighting Design, Thermal performance, Ventilation, and Acoustic Analysis (ECOTECT: Design and Analysis, n.d.) Of these features, Shadows and Shading Analysis were used to test the sun penetration though the side shading devices (Figure 7).

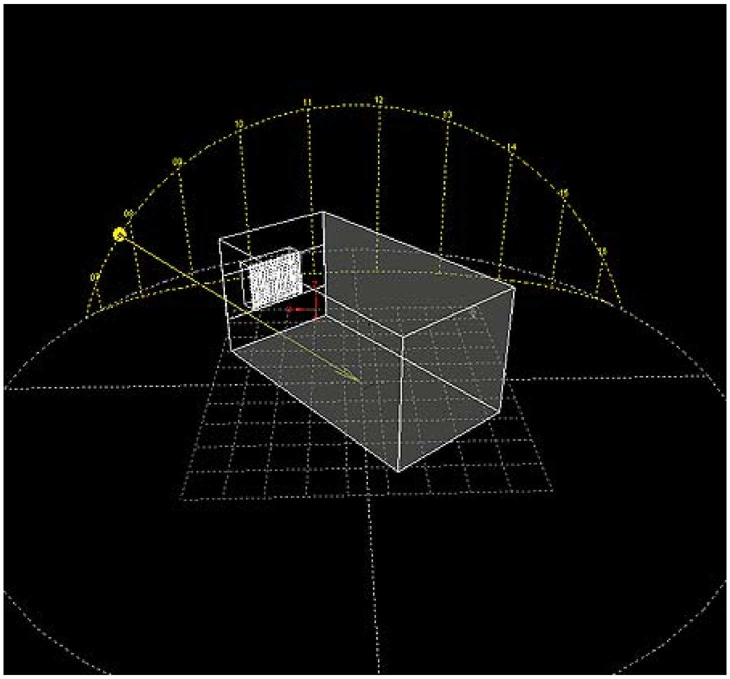


Figure 7 Screenshot of sun penetration test for southeast facing façade in Building 3.

DESIGNING THE DAYLIGHTING SYSTEMS

Design Considerations for Museum

Effective exhibit lighting must balance exhibition and conservation needs and enrich the museum experience (IESNA,1996). To increase the ambient lighting level, top lights will be installed on the roof of the building 3 and building 4 in KNM. Top lights can increase the indoor lighting level without changing the original architectural design context. For the side openings, shading devices will be installed to block the direct sunlight entering through the side opening. In designing daylighting system, followings should be considered to protect material deterioration.

Table 3 Recommended total exposure limits in terms of illuminance hours per year (IESNA, 1996).

Types of Materials	Maximum Illuminance	Lux-Hours Per Year*
Highly susceptible displayed material: textiles, cotton, natural fibers, furs, silk, writing inks, paper documents, lace, fugitive dyes, watercolors, wool, some minerals	50 lux	50,000
Moderately susceptible displayed material: textiles with stable dyes, oil painting, wood finishes, leather, some plastics	200 lux	480,000
Least susceptible displayed material: metal, stone, glass, ceramic, most minerals	Depends on exhibition situation	Depends on exhibition situation

Note: All UV radiation (400 nm and below) should be eliminated. The visible spectrum is defined as extending from 380 nm to 760 nm. Museum conservators treat all wavelengths shorter than 400 nm as UV; the damage potential is high below this wavelength and the visual effect is very small.

* These values follow the reciprocity principle, and therefore the maximum Illuminance values can be altered for different annual exposure times.

- All UV radiation (400 nm and below) should be eliminated (IESNA, 2000).
- Total exposure limits should be considered (Table 3).
- Direct beam radiation should be blocked.

In designing top light and side shading devices, the first consideration was blocking the direct beam radiation. And UV filter will be installed on both top light and side shading devices to block the UV radiation as recommended from IESNA.

Top Light Design

To increase the ambient lighting level in the gallery, seven types of the top lighting devices were designed to be installed on the roof of the building. In order to block the direct beam radiation, every types of top light has T or H shape (Figure 8). However, the illuminance level in Desktop RADIANCE was too low. Thus, scale model measurement was conducted to verify illuminance level of these prototype designs.

From checking of Desktop RADIANCE settings and scale model measurement, low illuminance level may come from the inappropriate design. In previous designs, suggested top lights had low illuminance level because they were over shaded. To get the more lights coming through the opening, reflector was reduced in size and placed in lower position compared to the previous design. From the checking with Desktop RADIANCE, lighting level in the gallery is increased. However, by reducing the reflector size and changing the reflector position, direct sun will come through the opening. To block the direct sun, vertical fins were placed at the top light (Figure 9).

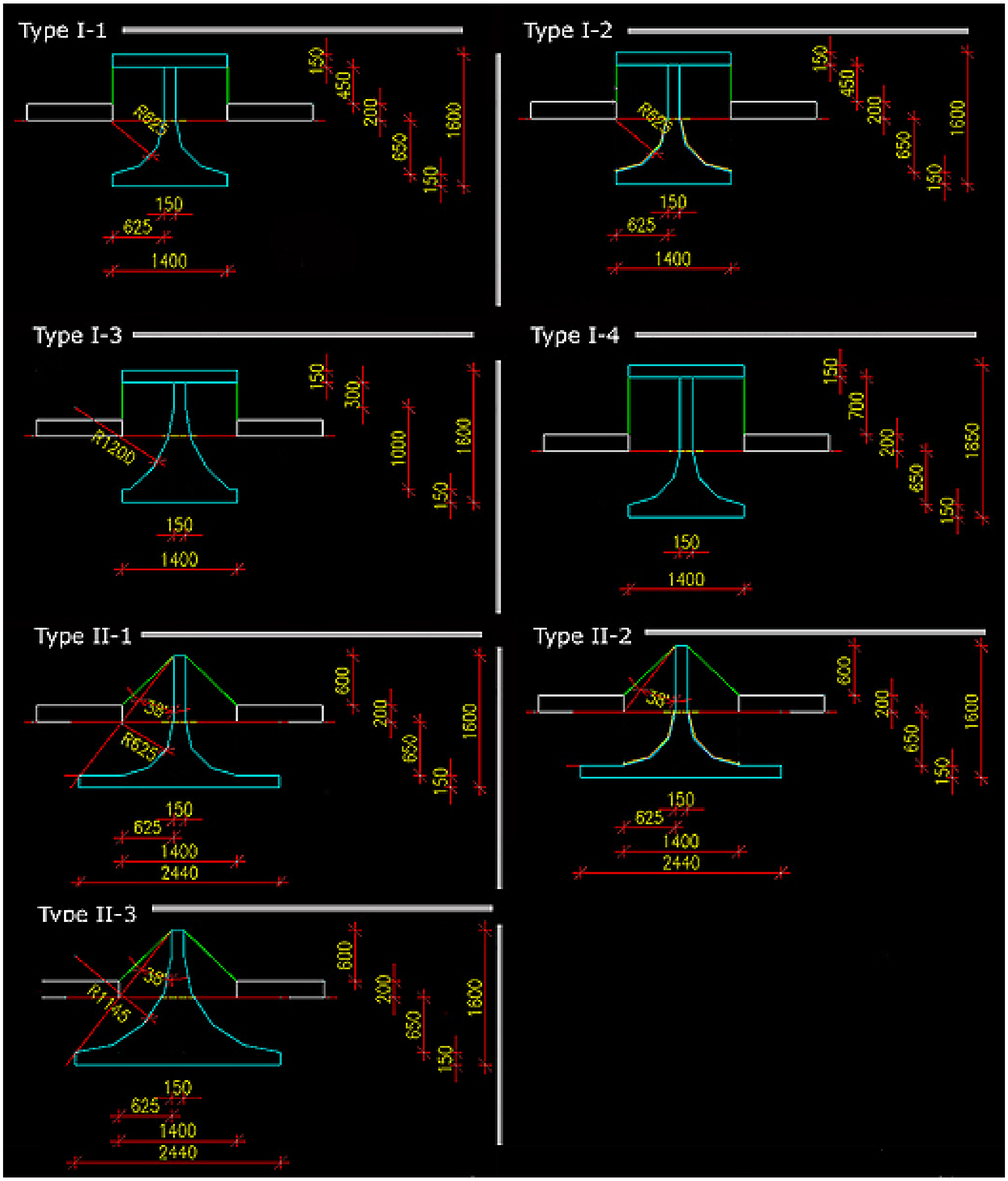


Figure 8 Dimensions of top light designs

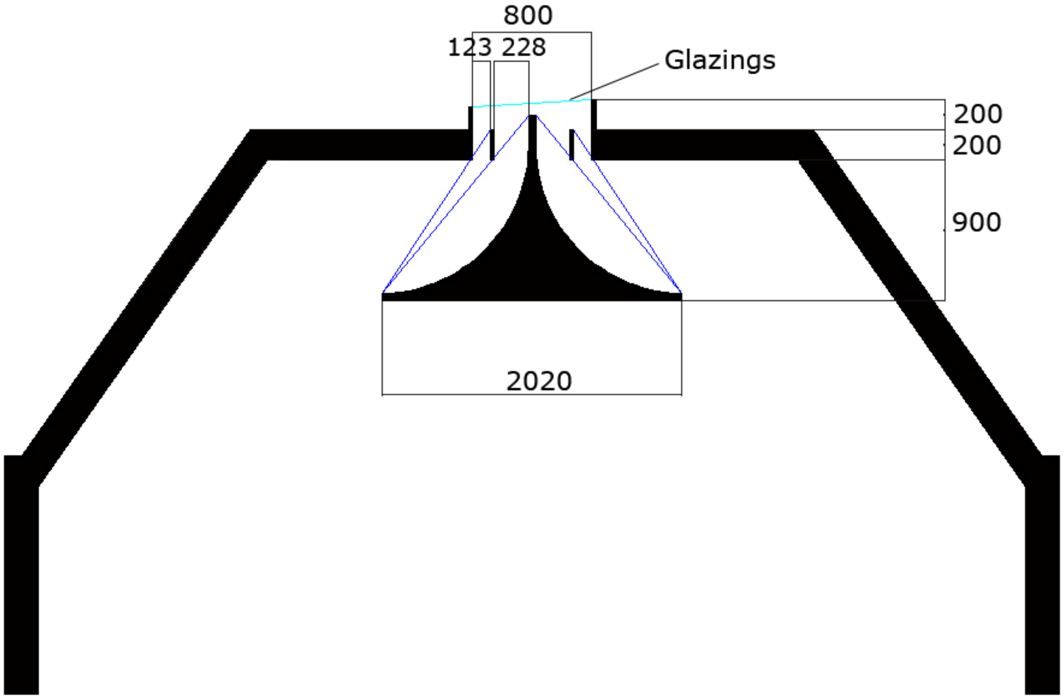


Figure 9 Section of top light

Shading Design for the Existing Openings

Kuwait National Museum has four different side openings; southeast, northwest facing openings in Building 3 and southwest, northeast facing openings in Building 4. In designing side shadings, direct sun light should be blocked throughout the whole year. As the profile angle and cut off angle of each side opening is different, different design of shading would be required for each opening. For the southeast and southwest facing opening, vertical and horizontal louvers would be required. However, for the northeast and northwest openings, vertical louvers could block the sun light without horizontal louvers.

As shown in the Figures 10 and 11, the concrete structure has various sizes of openings, and needed to install shading devices. Of these openings, the shaded part was selected to start shading design (Figures 11 and 12). Figure 13-24 show the dimension of each shading design.

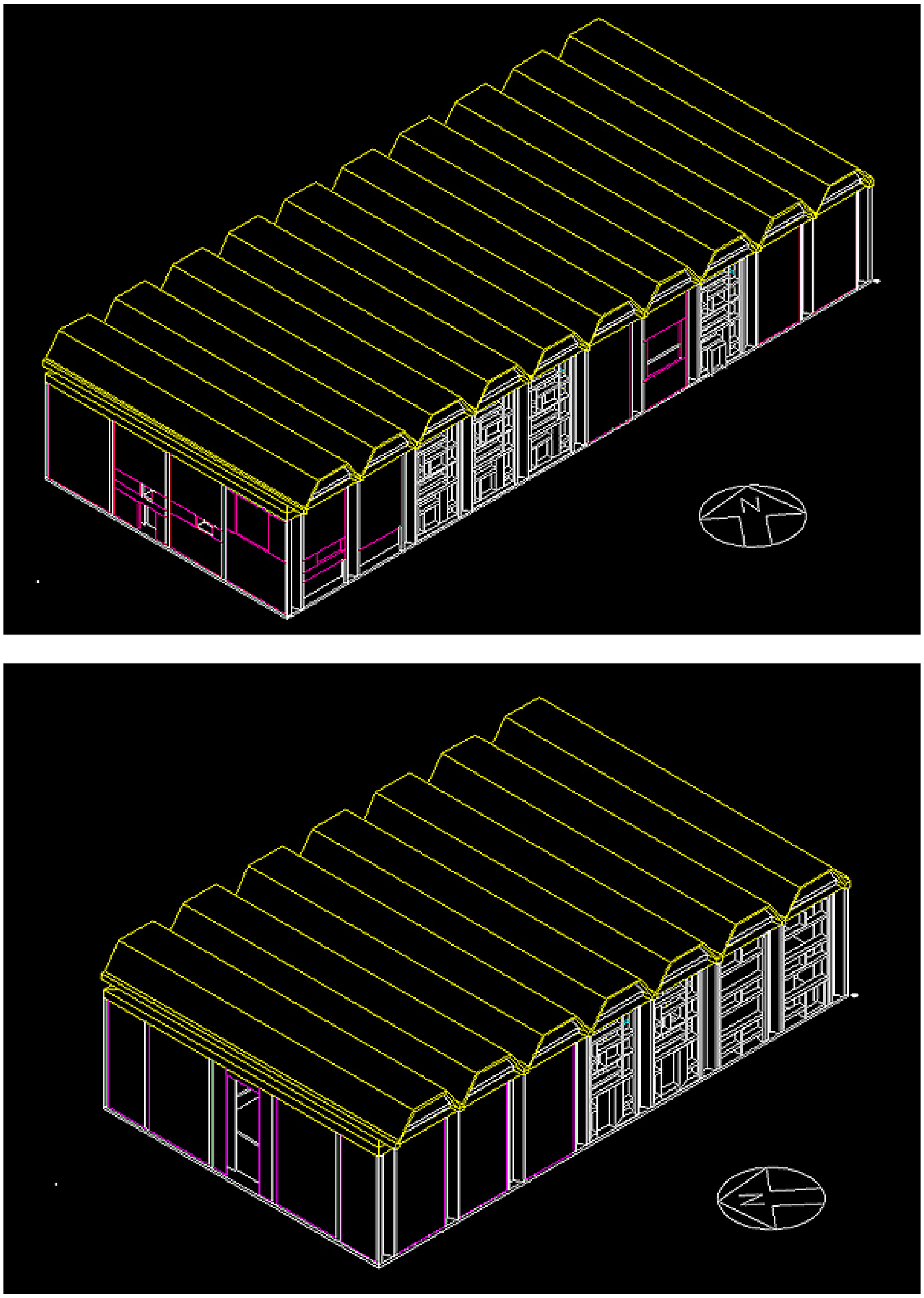


Figure 10 Building 3 (upper) and 4 (lower) of Kuwait National Museum

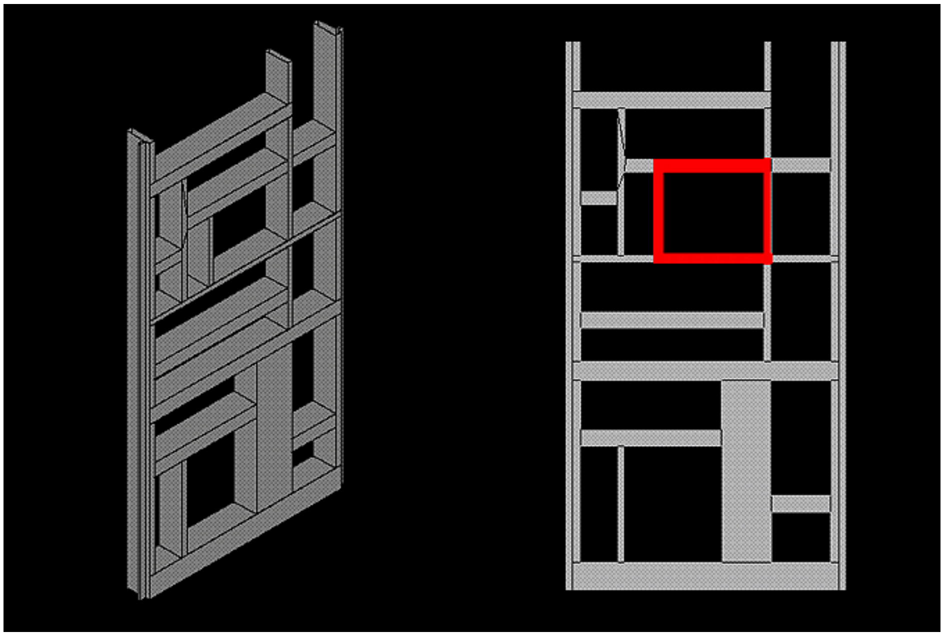


Figure 11 Concrete structure in Kuwait National Museum

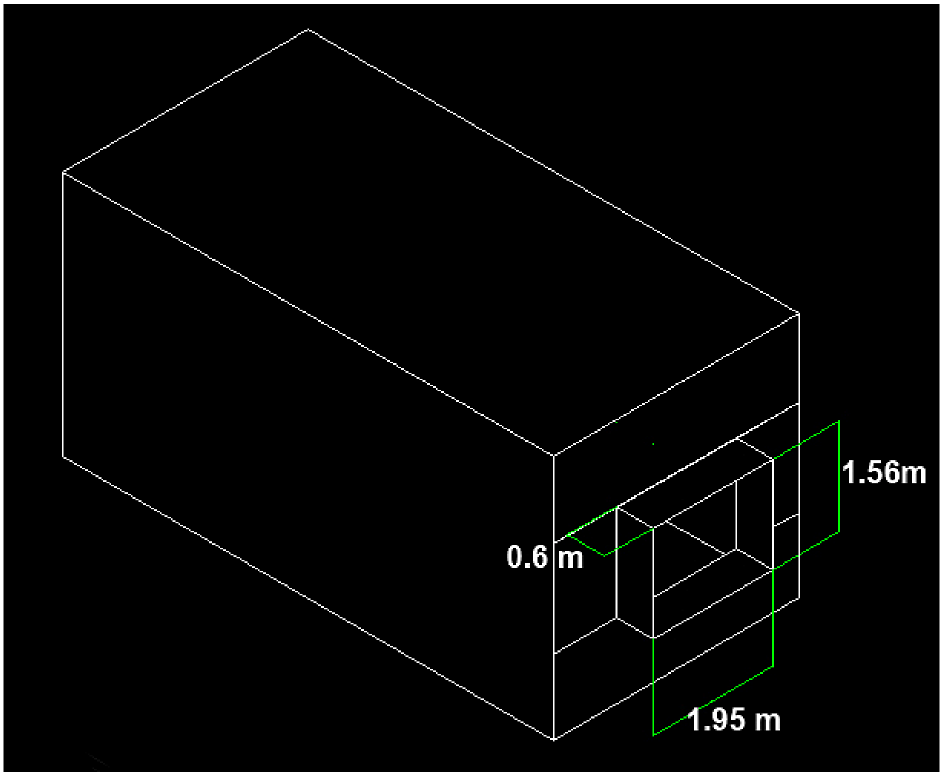


Figure 12 CAD drawing of testing unit for sun penetration.

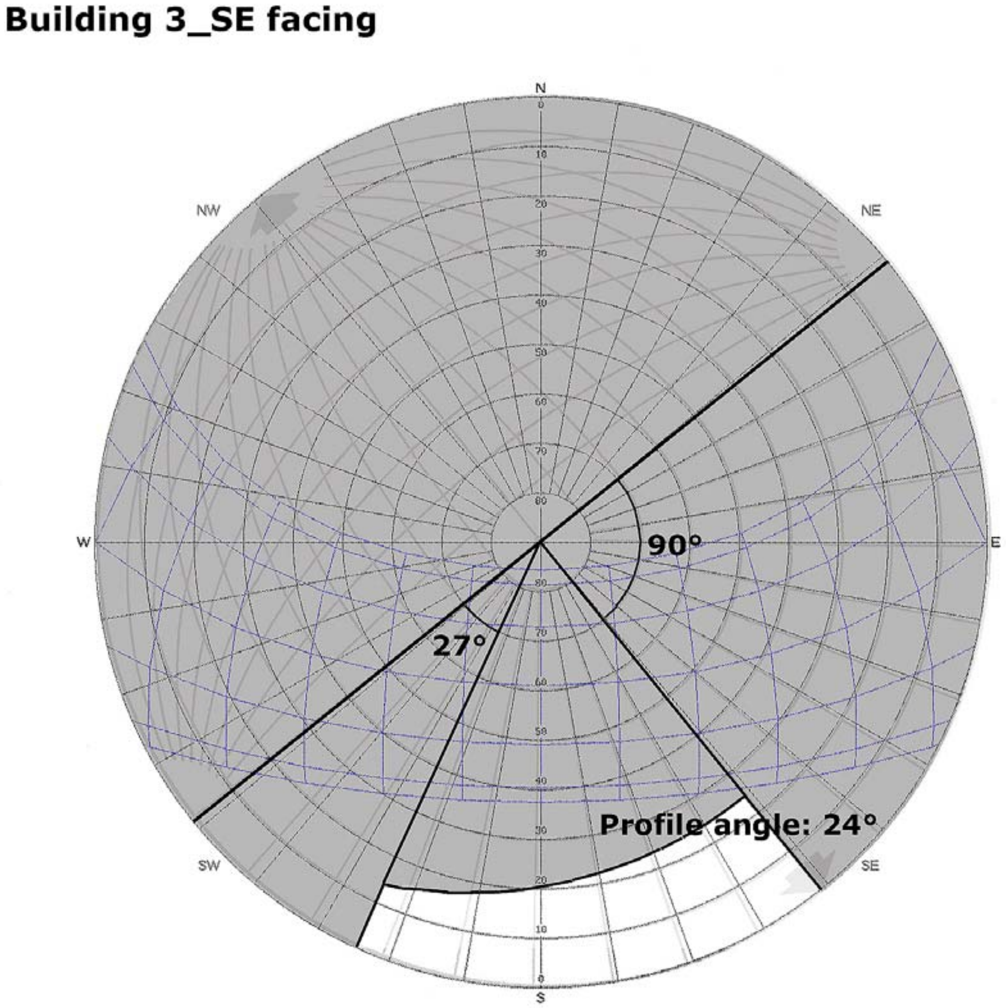


Figure 13 Shading mask for southeast facing openings in Building 3

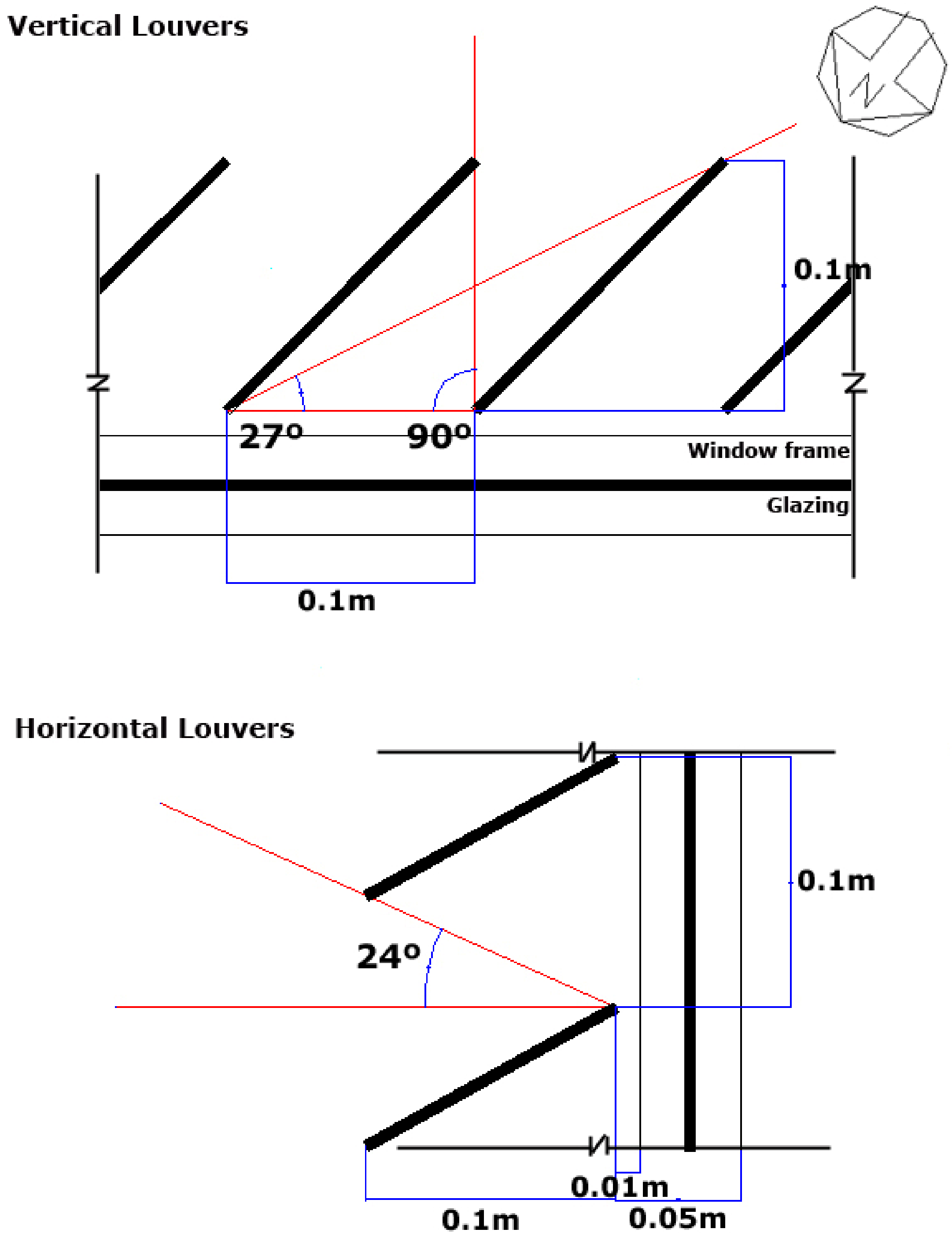


Figure 14 Dimension of shadings for southeast facing opening in Building 3

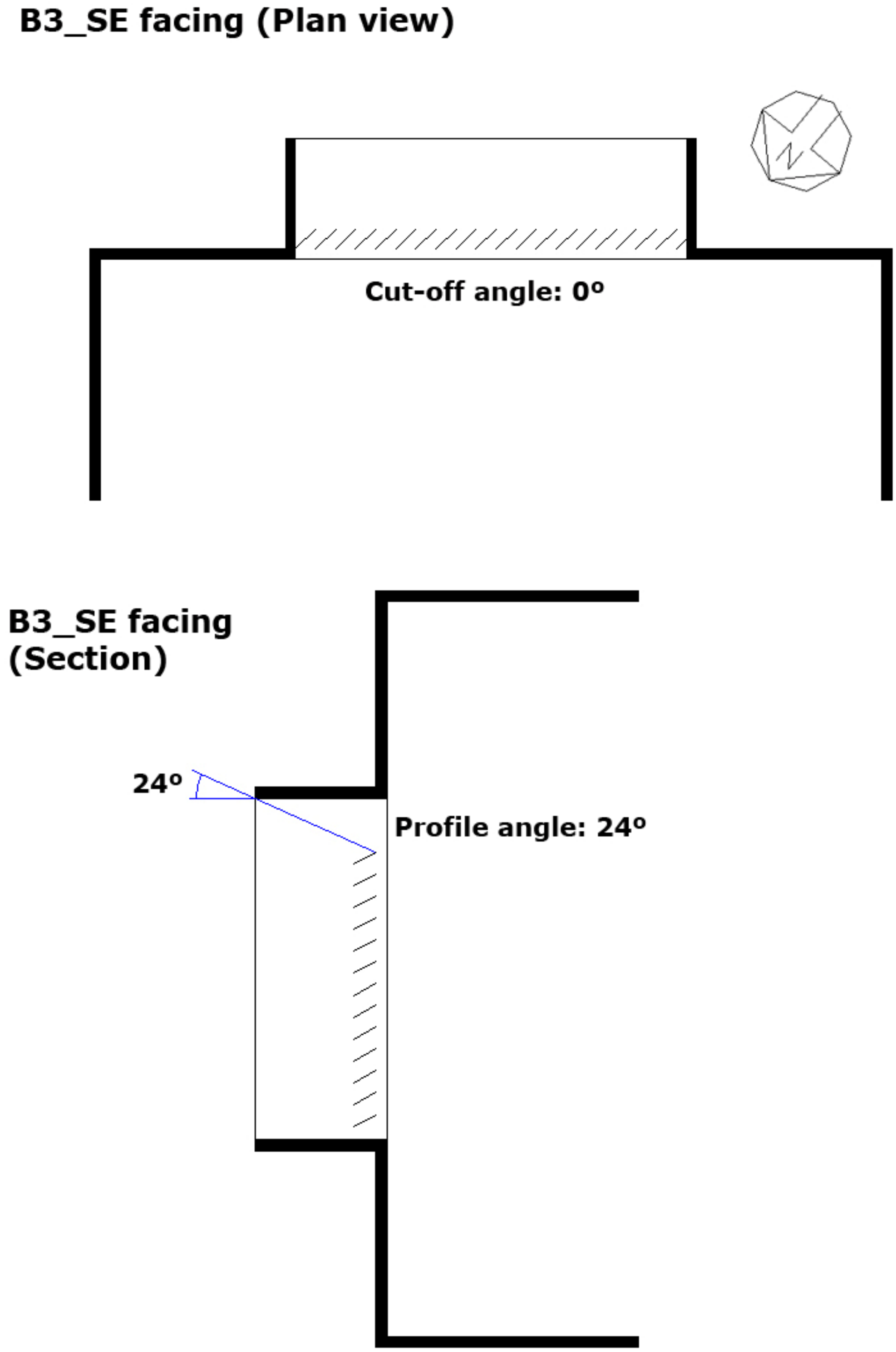
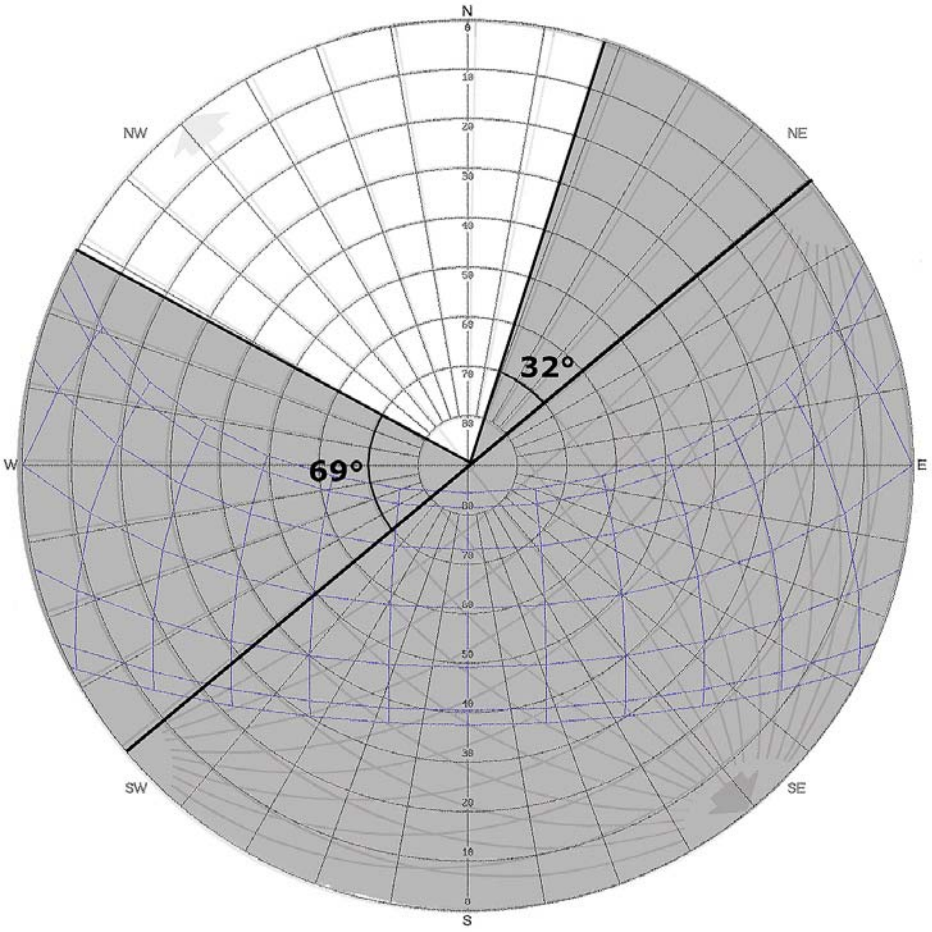


Figure 15 Plan view of vertical louvers (upper) and section of horizontal louvers (lower)



Building 3_NW facing

Figure 16 Shading mask for northwest facing openings in Building 3

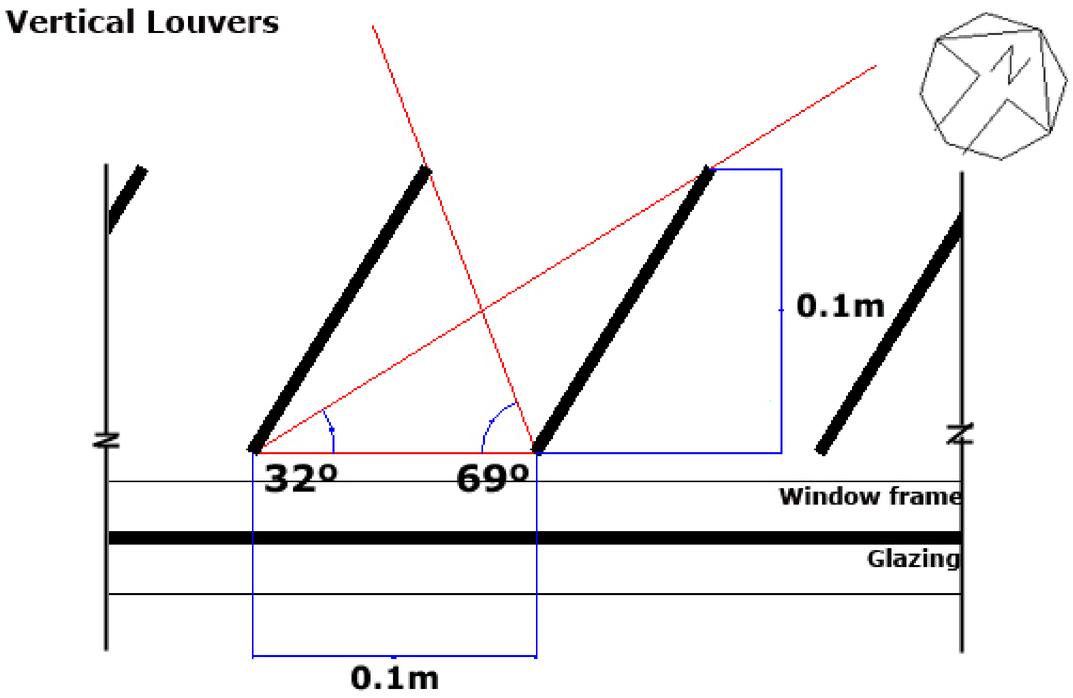


Figure 17 Dimension of shadings for northwest facing opening in Building 3

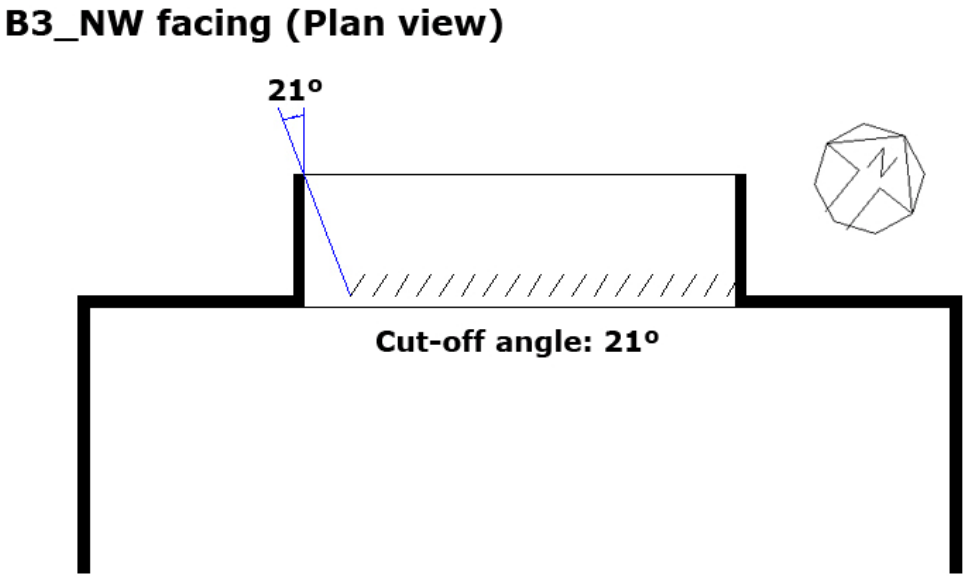


Figure 18 Plan view of vertical louvers for northwest facing opening in Building 3

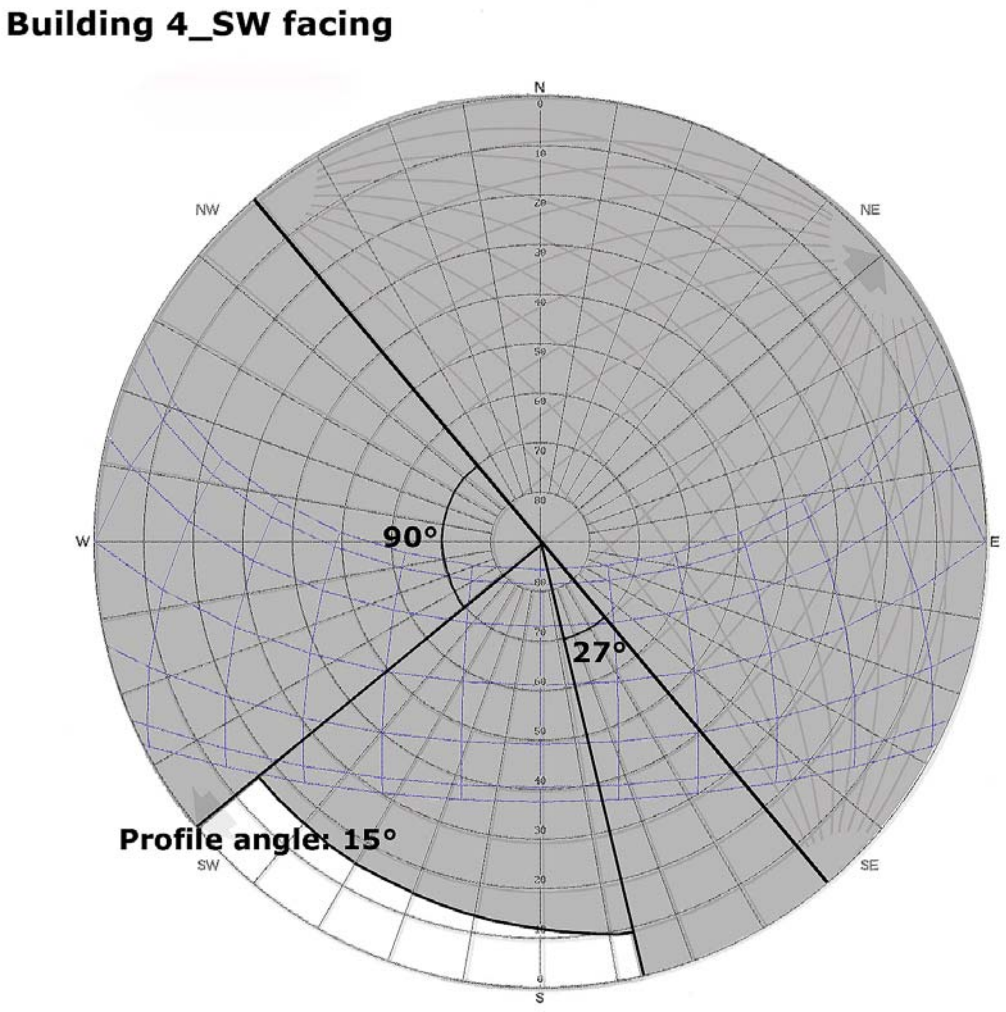


Figure 19 Shading mask for southwest facing openings in Building 4

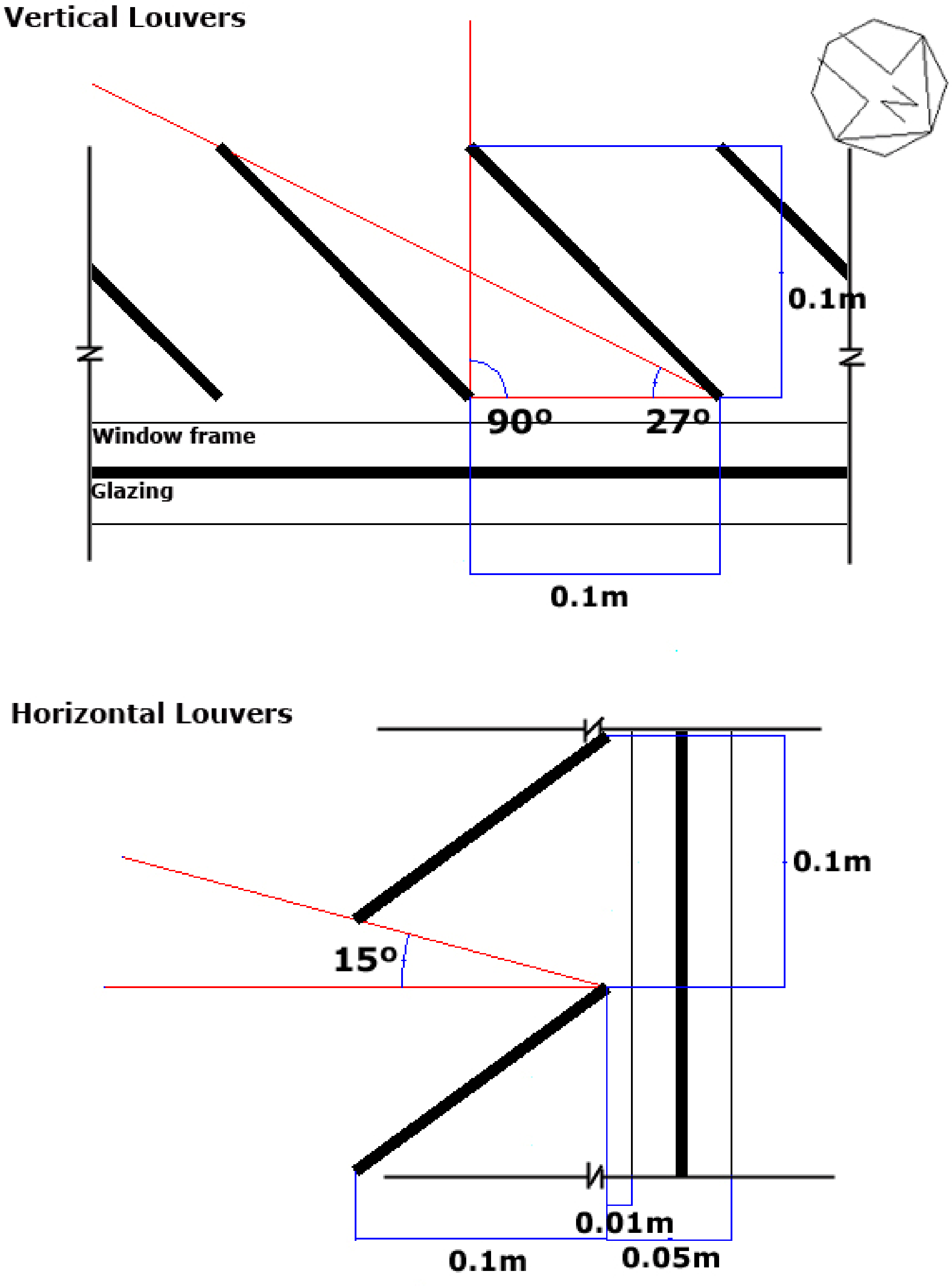


Figure 20 Dimension of shadings for southwest facing opening in Building 4

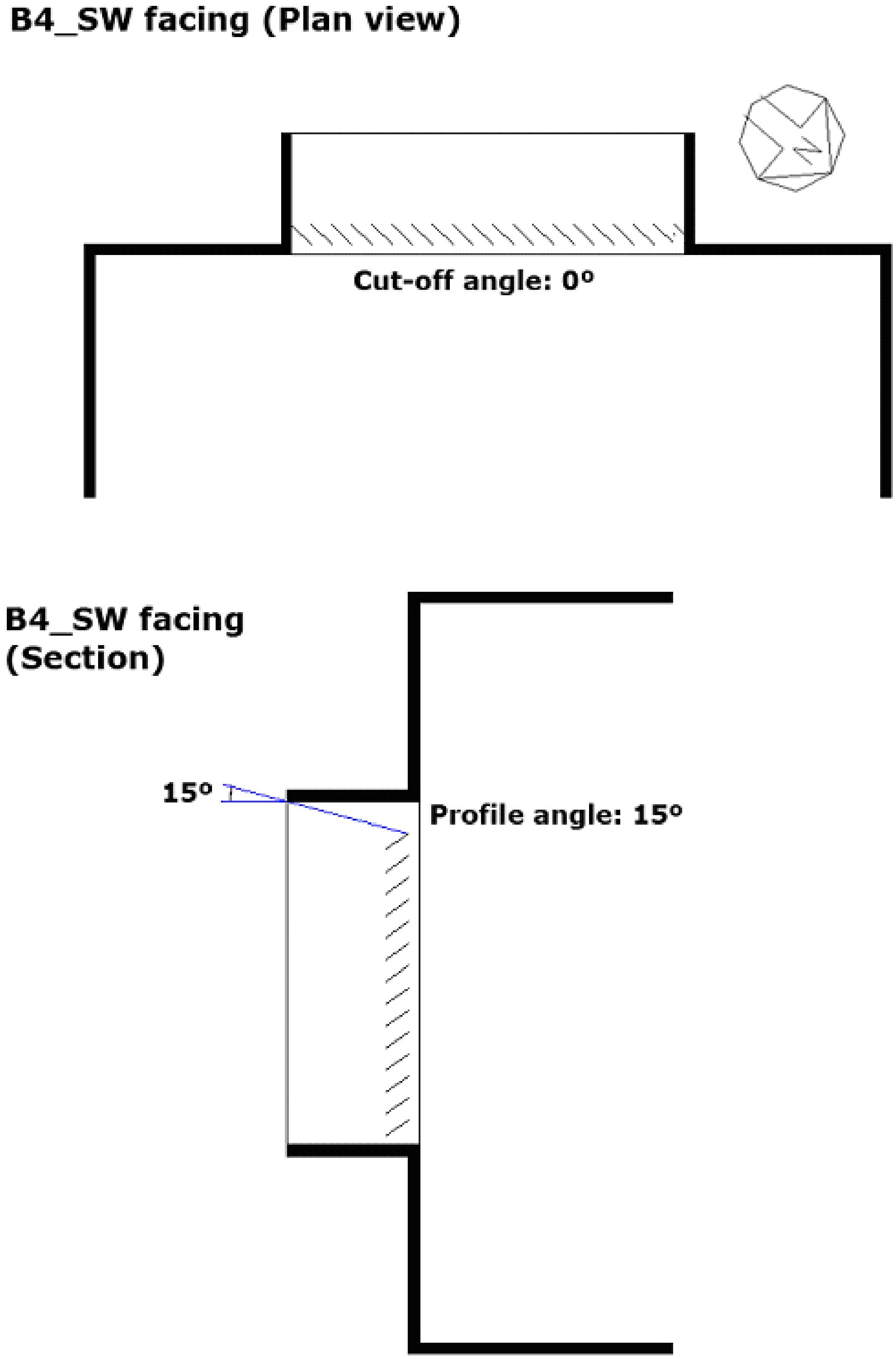


Figure 21 Plan view of vertical louvers (upper) and section of horizontal louvers (lower)

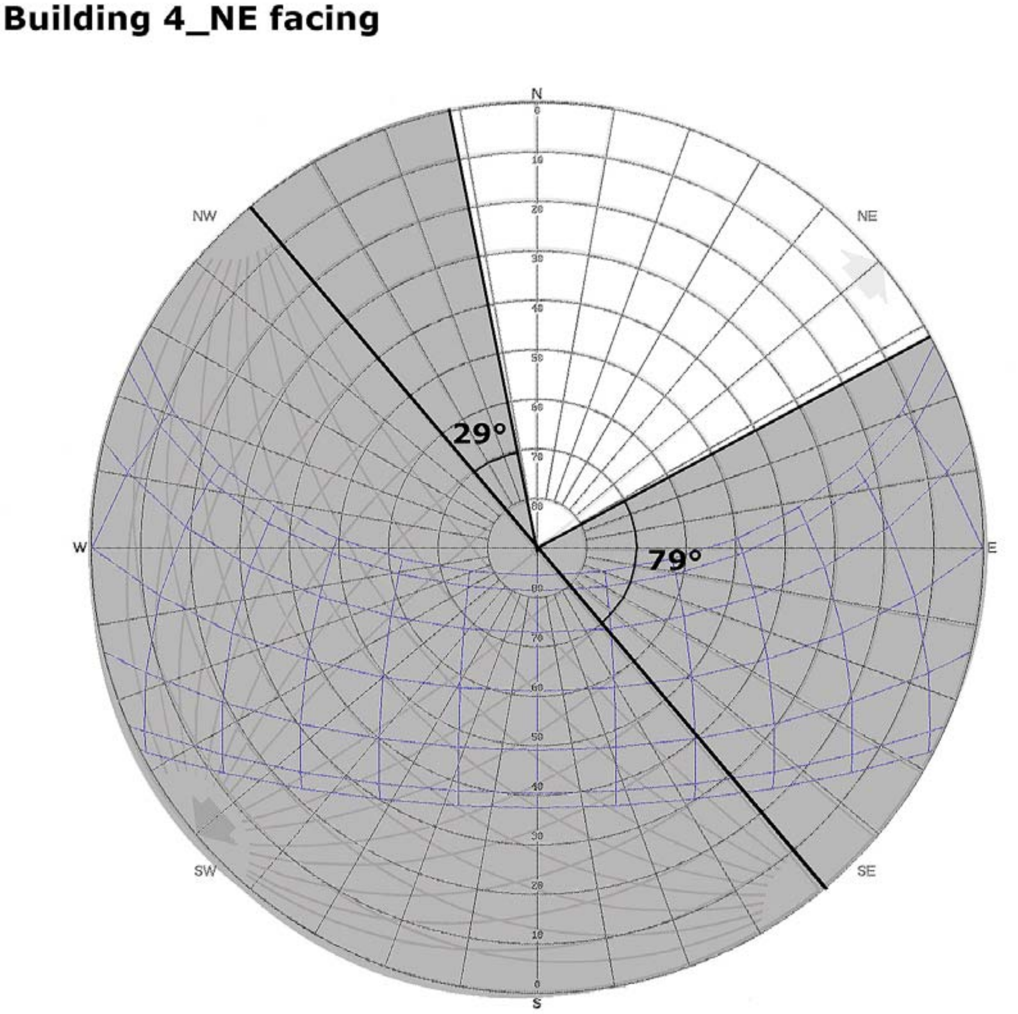


Figure 22 Shading mask for northeast facing openings in Building 4

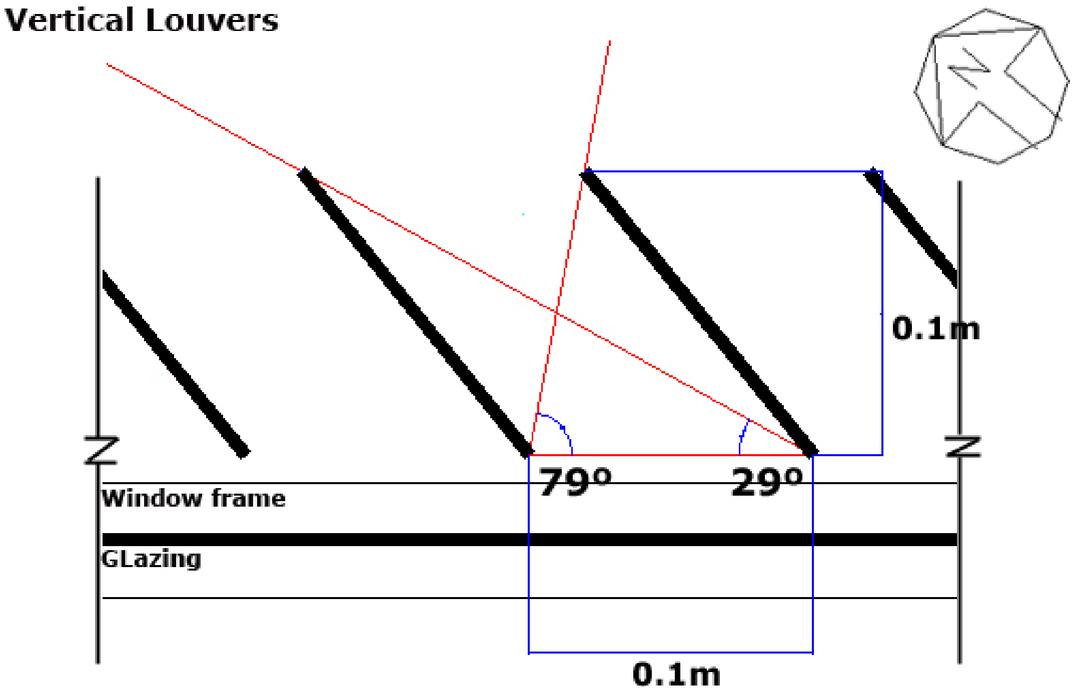


Figure 23 Dimension of shadings for northeast facing opening in Building 4

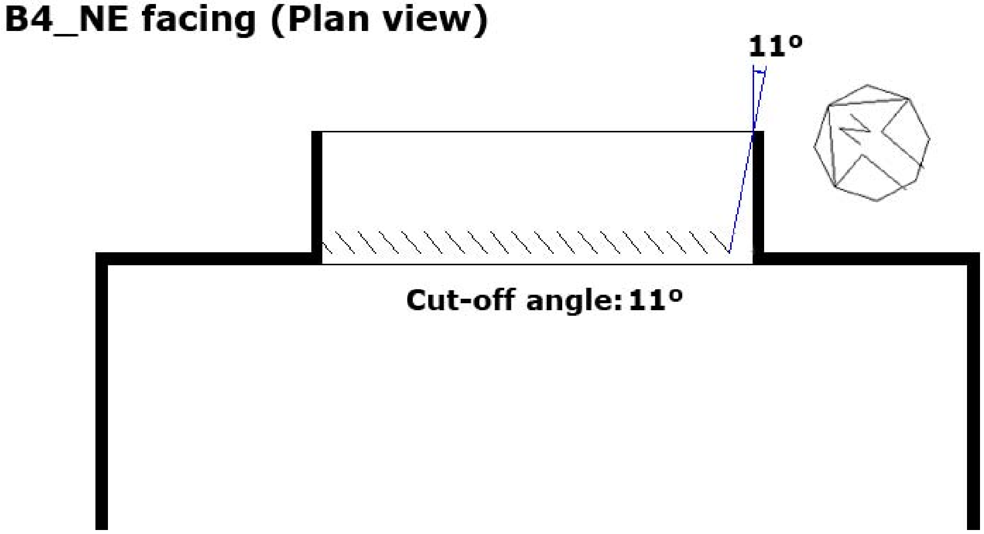


Figure 24 Plan view of vertical louvers for northeast facing opening in Building 4

ANALYSIS OF DAYLIGHTING SYSTEMS

Test for Solar Penetration

To test the solar beam penetration, scale model and ECOTECT were used. Scale model was used for the top light design. To simulate the sun path in Kuwait City, horizontal sun-dial was used. By the check scale model with sun-dial, no beam penetration occurred through the top light throughout all days of year (Figure 25). For the sun penetration through the side shading devices, ECOTECT was used. From the computer model testing in ECOTECT, no direct sun was hit the inside of the room all year round (Figure 7).

Test for Lighting Level

To verify the lighting level from the Desktop RADIANCE, testing unit was setting as shown in Figure 25. In this test, effect of the side opening is not considered. In Desktop RADIANCE, sensors were put on the wall and floor. The sensor height is 5 foot (1.5m) from the floor (Figures 26 and 27). Then, to verified output from the RADIANCE, scale model measurement was conducted at the same spots to compare the data between Desktop RADAINCE and scale model. For the scale model measurement, two illuminance meters were used to get the correct daylight factor (Figure 25). Scale model measured under the clear and overcast sky conditions. Materials with same reflectance were assigned in Desktop RADAINCE model to match the scale model material.

Figure 25 Interior view of scale model (left)
and illuminance meters (Konica Minolta, T-10, right)

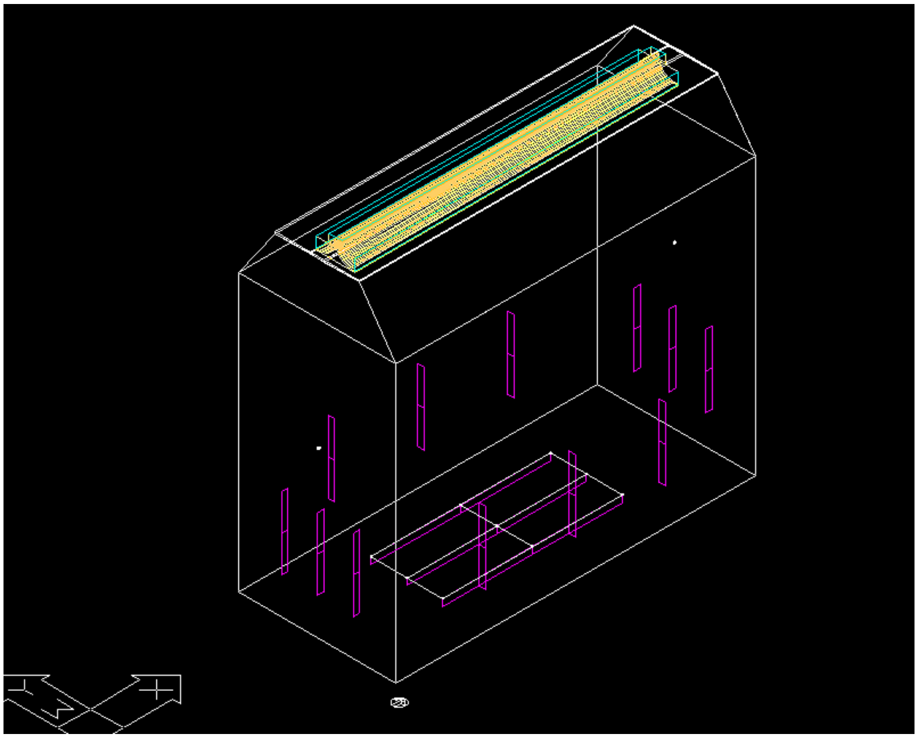


Figure 26 Desktop RADIANCE model for illuminance test.

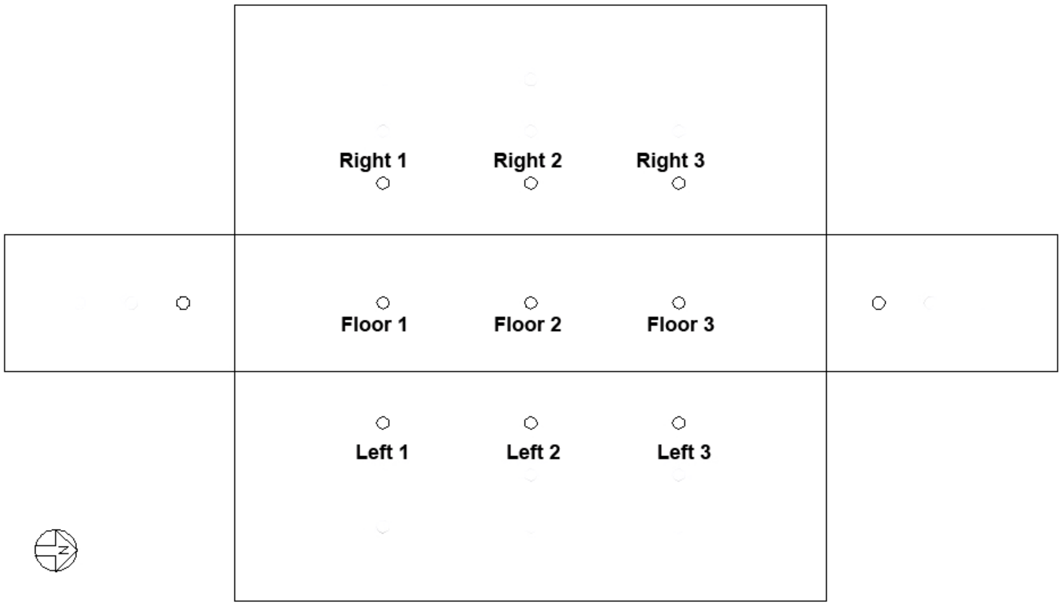


Figure 27 Reference points in scale model and RADIANCE model

Table 4 Simulation settings of Desktop RADIANCE for data comparison

Time and Date	**12:00 pm, 1:00 pm, 1:15 pm (CDT) @ Oct 4th** **1:10 pm, 1:30 pm (CDT) @ Oct 7th**
Location	**College Station, TX**
Sky and Weather	**Clear/ Overcast**
Orientation	**Front façade of the building facing south**
Simulation Quantity	**Daylight Factor**
Simulation Mode	**Batch to ACSII**
Ambient bounces	**4**
Mkillum	**1**

For the illuminance comparison, scale model was measured under the clear sky (Table 4). By the comparison of illuminance level between the Desktop RADIANCE and scale model (Figures 28-31), simulated illuminance level on the wall is pretty close to the measured data. However, simulated data is higher on the floor. And the lighting distribution pattern has pretty close match each other.

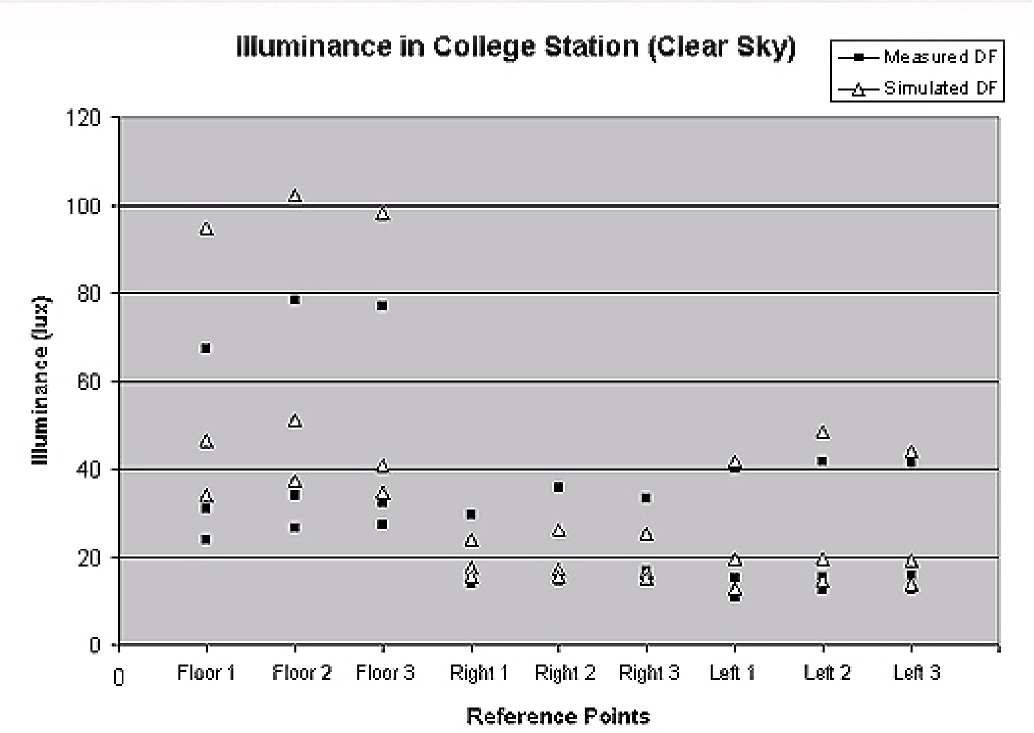


Figure 28. Illuminance comparison between scale model and RADIANCE model. (College Station, Clear sky)

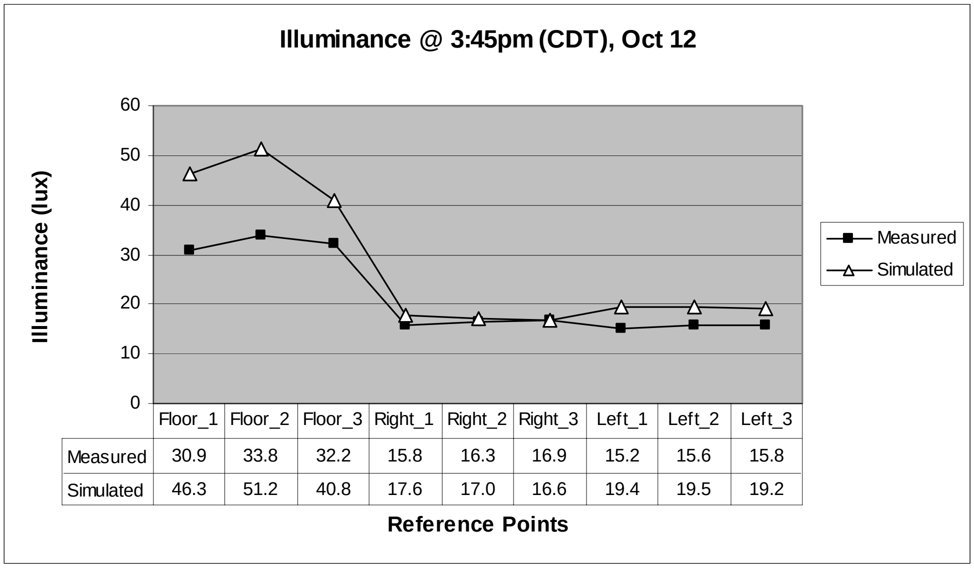


Figure 29 Illuminance comparison between scale model and RADIANCE model (3:45 pm (CDT), Oct 12th, College Station, Clear sky)

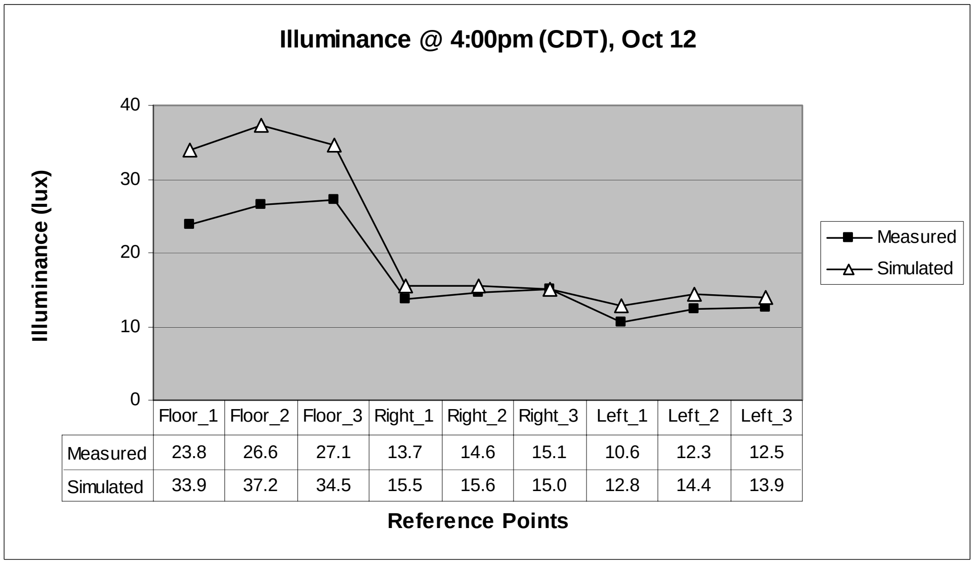


Figure 30 Illuminance comparison between scale model and RADIANCE model (4:00 pm (CDT), Oct 12th, College Station, Clear sky)

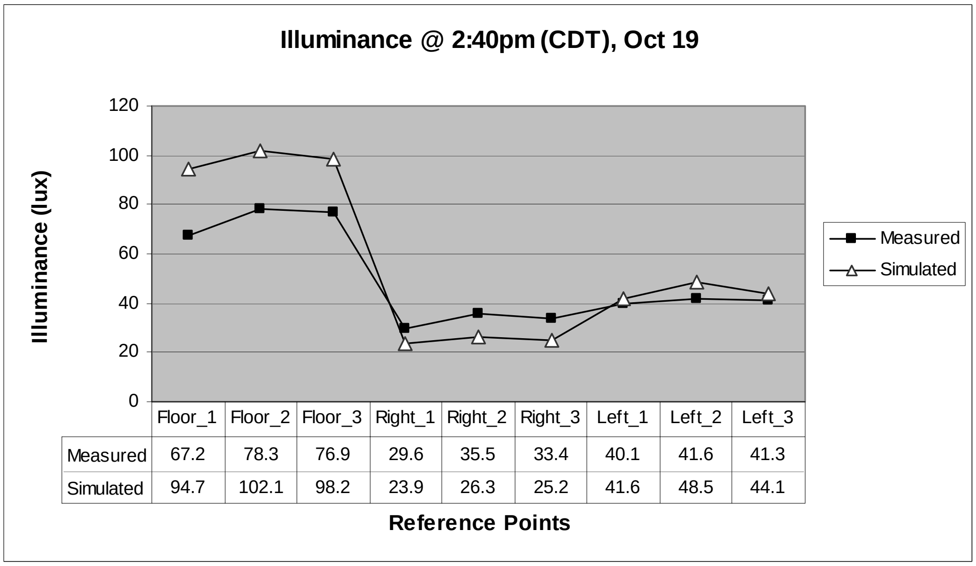


Figure 31 Illuminance comparison between scale model and RADIANCE model (2:40 pm (CDT), Oct 19th, College Station, Clear sky)

Like result from illuminance comparison, Daylight Factors (DF) between from the Desktop RADIANCE and scale model measurement have pretty close match especially on the wall (Figures 32-37). However, for the horizontal sensors, DF factors from the RADIANCE are slightly higher than measured value. One possible reason of this difference may come from the site condition. The site of scale model measurement has adjacent buildings and trees as shown in the Figure 38. As buildings and trees block some portion of the sky, the lighting level in scale model can be lower than RADIANCE. However, the difference is within the margin of errors.

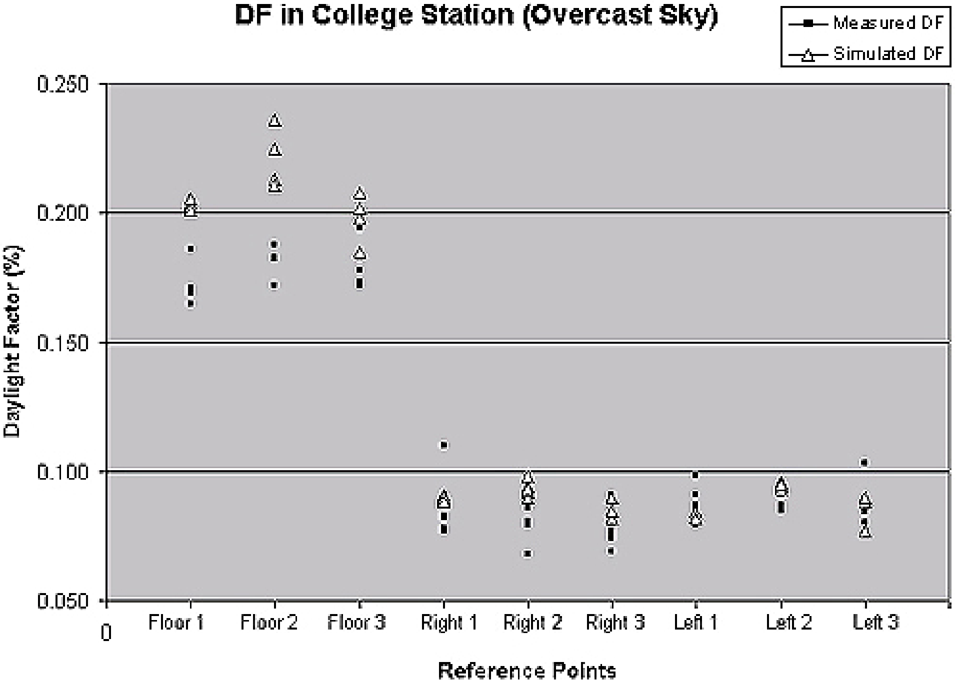
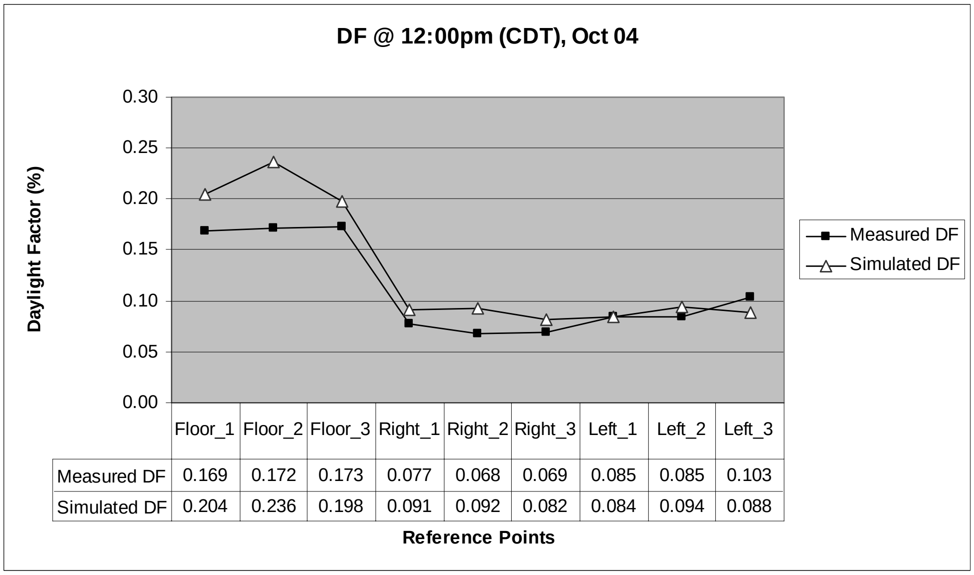
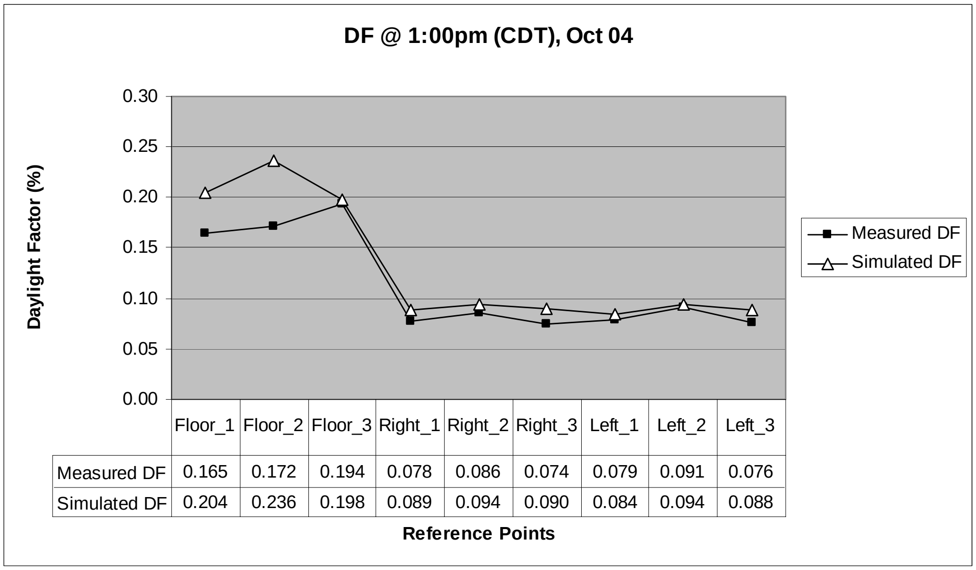


Figure 32. DF comparison between scale model and RADIANCE model. (College Station, Overcast sky)



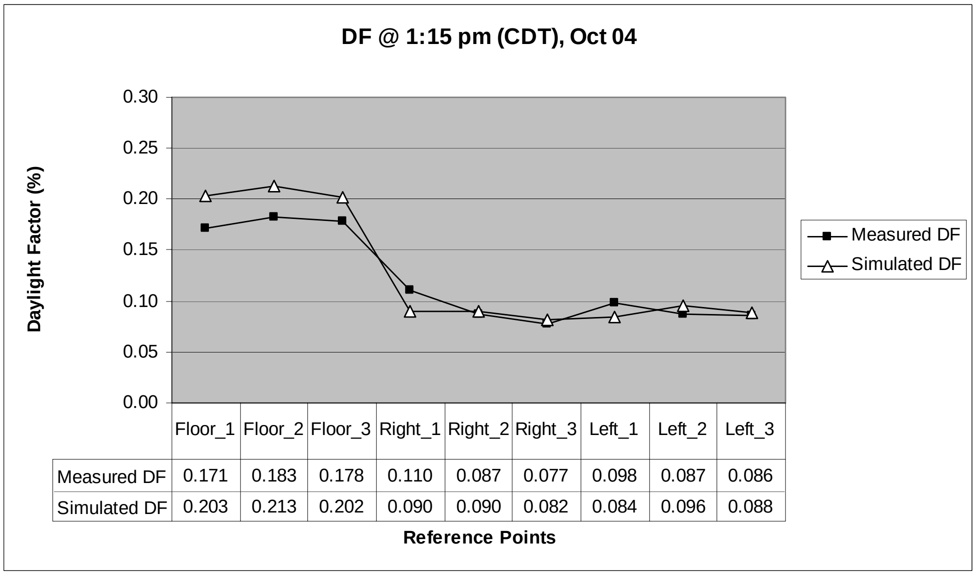
	Floor_1	Floor_2	Floor_3	Right_1	Right_2	Right_3	Left_1	Left_2	Left_3
Measured DF	0.169	0.172	0.173	0.077	0.068	0.069	0.085	0.085	0.103
Simulated DF	0.204	0.236	0.198	0.091	0.092	0.082	0.084	0.094	0.088

Figure 33 DF comparison between scale model and RADIANCE model (12:00 pm (CDT), Oct 4th, College Station, Overcast sky)



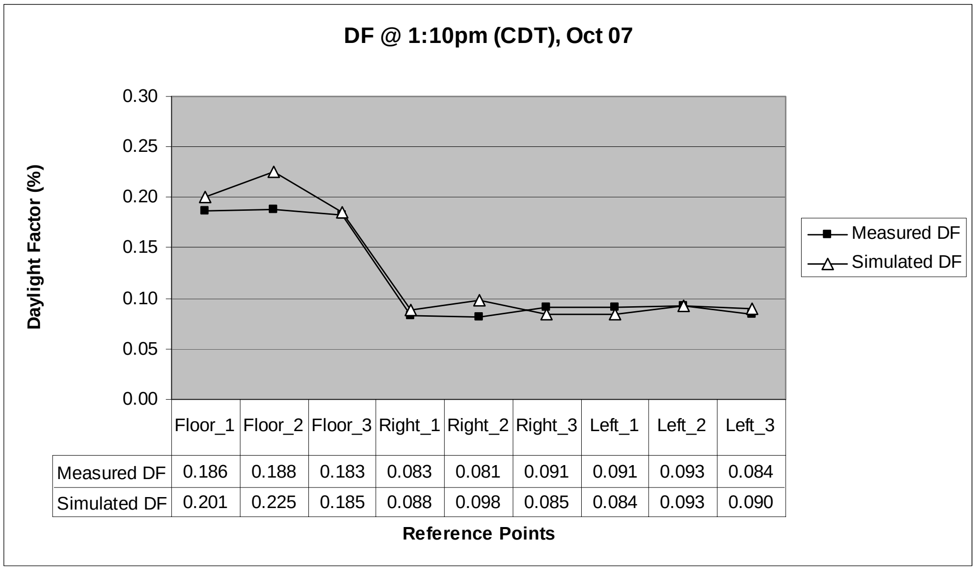
	Floor_1	Floor_2	Floor_3	Right_1	Right_2	Right_3	Left_1	Left_2	Left_3
Measured DF	0.165	0.172	0.194	0.078	0.086	0.074	0.079	0.091	0.076
Simulated DF	0.204	0.236	0.198	0.089	0.094	0.090	0.084	0.094	0.088

Figure 34 DF comparison between scale model and RADIANCE model (1:00 pm (CDT), Oct 4th, College Station, Overcast sky)



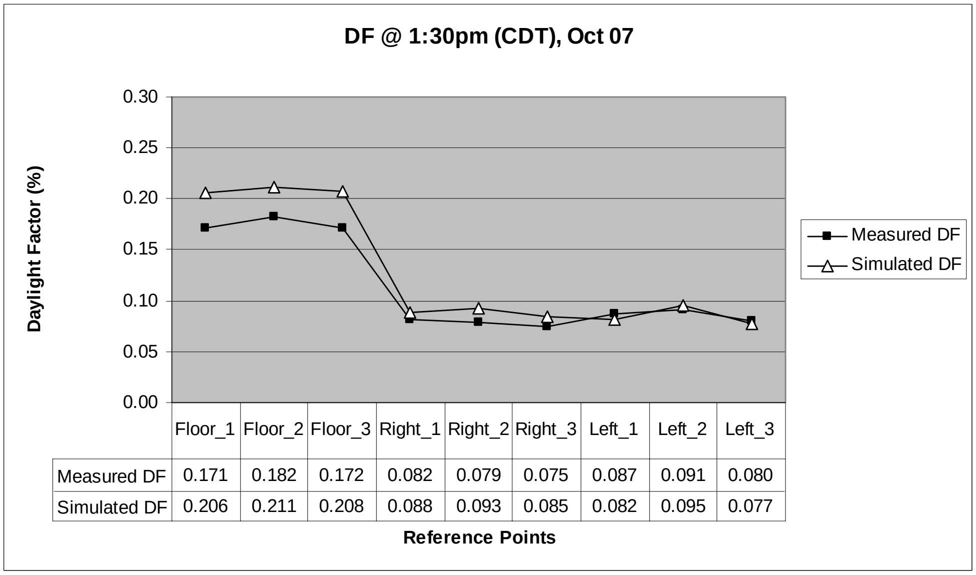
	Floor_1	Floor_2	Floor_3	Right_1	Right_2	Right_3	Left_1	Left_2	Left_3
Measured DF	0.171	0.183	0.178	0.110	0.087	0.077	0.098	0.087	0.086
Simulated DF	0.203	0.213	0.202	0.090	0.090	0.082	0.084	0.096	0.088

Figure 35 DF comparison between scale model and RADIANCE model (1:15 pm (CDT), Oct 4th, College Station, Overcast sky)



	Floor_1	Floor_2	Floor_3	Right_1	Right_2	Right_3	Left_1	Left_2	Left_3
Measured DF	0.186	0.188	0.183	0.083	0.081	0.091	0.091	0.093	0.084
Simulated DF	0.201	0.225	0.185	0.088	0.098	0.085	0.084	0.093	0.090

Figure 36 DF comparison between scale model and RADIANCE model (1:10 pm (CDT), Oct 7th, College Station, Overcast sky)



	Floor_1	Floor_2	Floor_3	Right_1	Right_2	Right_3	Left_1	Left_2	Left_3
Measured DF	0.171	0.182	0.172	0.082	0.079	0.075	0.087	0.091	0.080
Simulated DF	0.206	0.211	0.208	0.088	0.093	0.085	0.082	0.095	0.077

Figure 37 DF comparison between scale model and RADIANCE model (1:30 pm (CDT), Oct 7th, College Station, Overcast sky)

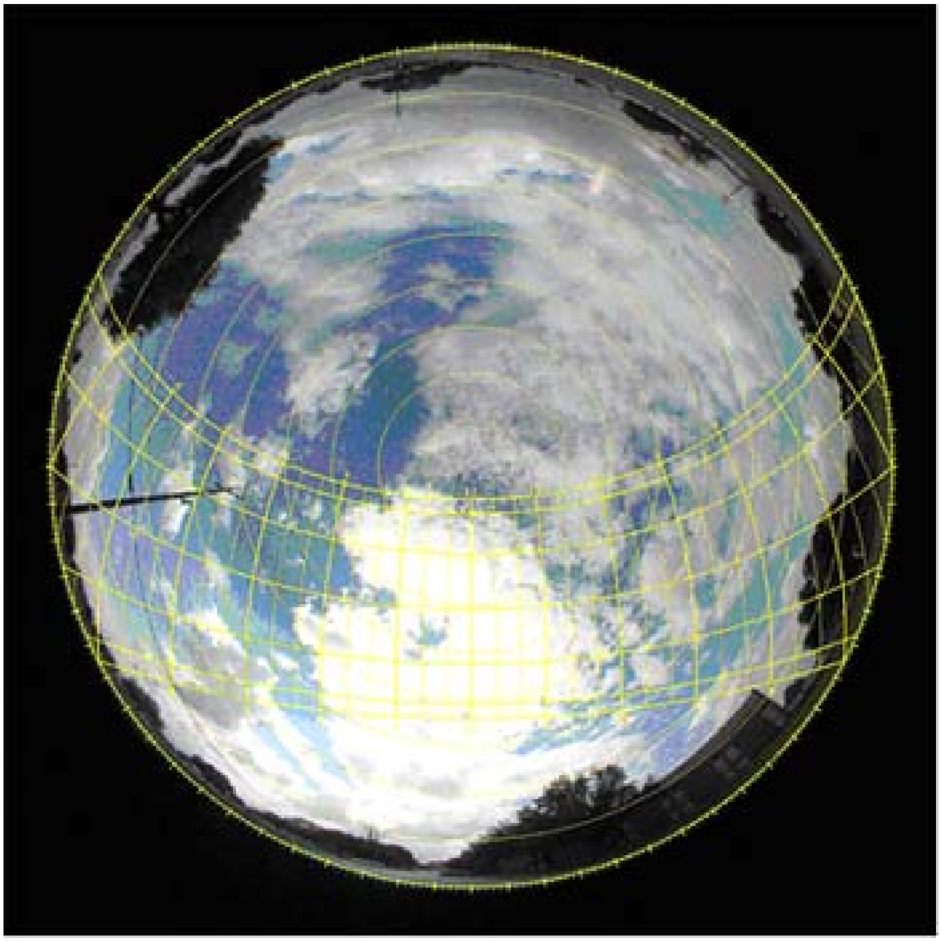


Figure 38 Sky view from the site of measurement
(Generated by SunPath, Pacific Gas and Electric Company).

To verify the scale model measurements, two set of measurements were conducted under the clear sky and overcast sky conditions. Ten measurements were conducted at each reference point and these were compared to the simulated data. Although there were some variations of the scale model measurement, the distribution patterns have pretty close match (Tables 5-6, Figures 39-40).

Table 5 Scale model measurements and simulated illuminance (lux)
(3:15 pm- 3:40 pm, Dec 13th, College Station, Clear sky)

	Measured											Simulated
	1	2	3	4	5	6	7	8	9	10	Ave.	
Floor_1	23.27	23.04	24.92	23.04	22.81	24.17	23.90	23.91	23.46	23.25	23.58	34.30
Floor_2	24.15	24.19	24.03	23.97	23.97	23.94	23.96	23.87	23.78	23.87	23.97	34.93
Floor_3	23.28	23.37	23.35	23.36	23.60	23.26	23.21	23.35	23.23	23.19	23.32	33.84
Right_1	11.30	11.30	10.10	10.03	9.91	9.89	9.96	9.94	9.91	9.90	10.22	12.45
Right_2	11.35	10.75	11.12	11.21	11.48	11.76	11.70	11.73	11.70	11.58	11.44	12.68
Right_3	10.75	10.97	10.72	10.85	10.92	10.85	10.76	10.84	10.74	10.77	10.82	12.35
Left_1	10.13	10.18	10.10	10.08	10.04	9.96	9.95	9.94	9.95	9.92	10.03	13.45
Left_2	11.55	11.35	11.24	11.47	11.54	11.49	11.37	11.63	11.57	11.42	11.46	15.02
Left_3	11.26	11.39	11.36	11.43	11.23	11.37	11.12	11.40	11.40	11.40	11.34	13.76

Table 6 Scale model measurements and simulated DF (%)
(12:35 pm- 1:00 pm, Dec 16th, College Station, Overcast sky)

	Measured											Simulated
	1	2	3	4	5	6	7	8	9	10	Ave.	
Floor_1	0.180	0.180	0.180	0.180	0.181	0.181	0.181	0.182	0.182	0.183	0.181	0.201
Floor_2	0.196	0.197	0.197	0.197	0.197	0.196	0.198	0.197	0.198	0.198	0.197	0.230
Floor_3	0.184	0.186	0.185	0.185	0.185	0.185	0.185	0.185	0.185	0.184	0.185	0.193
Right_1	0.073	0.073	0.073	0.073	0.072	0.072	0.072	0.071	0.071	0.070	0.072	0.086
Right_2	0.085	0.084	0.084	0.084	0.084	0.084	0.084	0.083	0.083	0.083	0.084	0.089
Right_3	0.077	0.076	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.075	0.077
Left_1	0.096	0.098	0.098	0.100	0.101	0.102	0.102	0.106	0.105	0.105	0.101	0.082
Left_2	0.099	0.100	0.100	0.100	0.101	0.101	0.101	0.102	0.102	0.102	0.101	0.095
Left_3	0.096	0.095	0.108	0.094	0.094	0.094	0.094	0.092	0.091	0.090	0.095	0.088

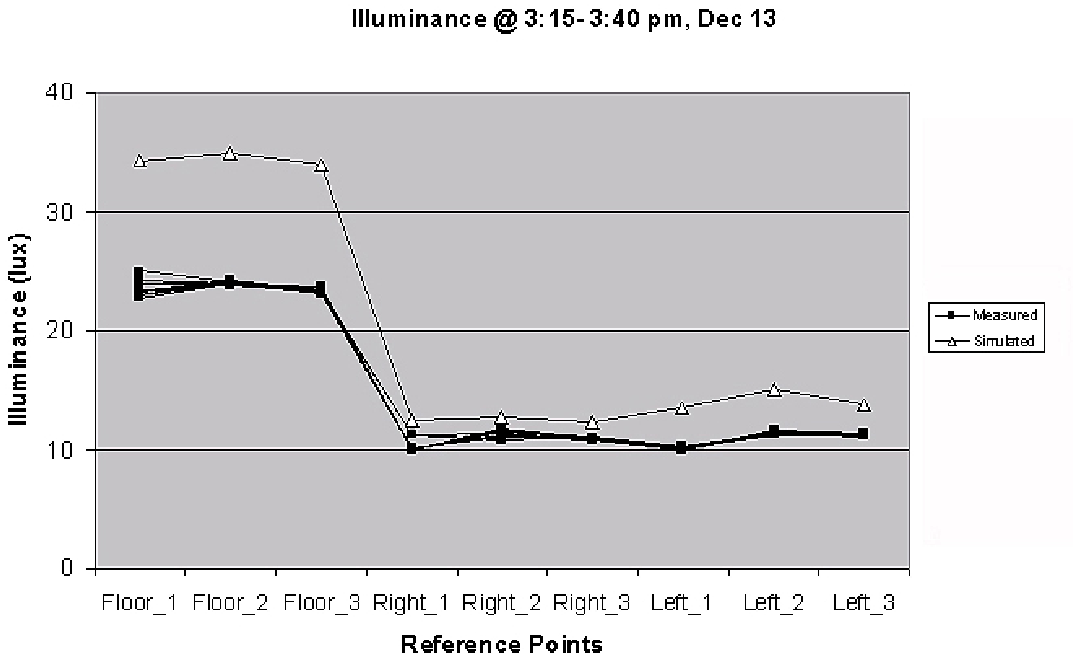


Figure 39 Illuminance comparison between scale model and RADIANCE model (3:15 pm- 3:40 pm, Dec 13th, College Station, Clear sky)

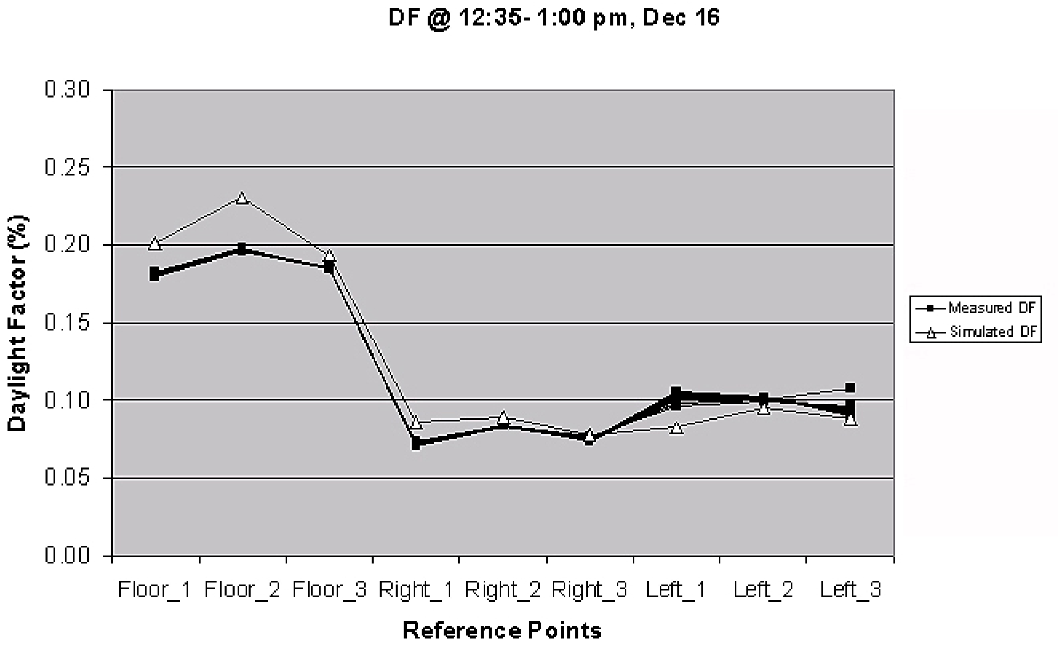


Figure 40 DF comparison between scale model and RADIANCE model (12:35 pm- 1:00 pm, Dec 16th, College Station, Overcast sky)

Analysis with Desktop RADIANCE

The focus of Desktop RADIANCE analysis was on the southeast facing gallery in Building 3 and Northeast facing gallery in Building 4. As these two galleries have three story heights, the diffuse light will reach from the top light design. And these two also have side openings which could affect the lighting levels inside of the galleries (shaded area in Figure 41). To get the lighting levels in side of the galleries, reference grids were set as shown in Figure 42. For the reference points, 77 points (11 by 7) on southeast facing gallery in Building 3 and 35 (7 by 5) points on northeast facing gallery in Building 4 were measured. The sensor height is 4 foot (1.2m) from the floor.

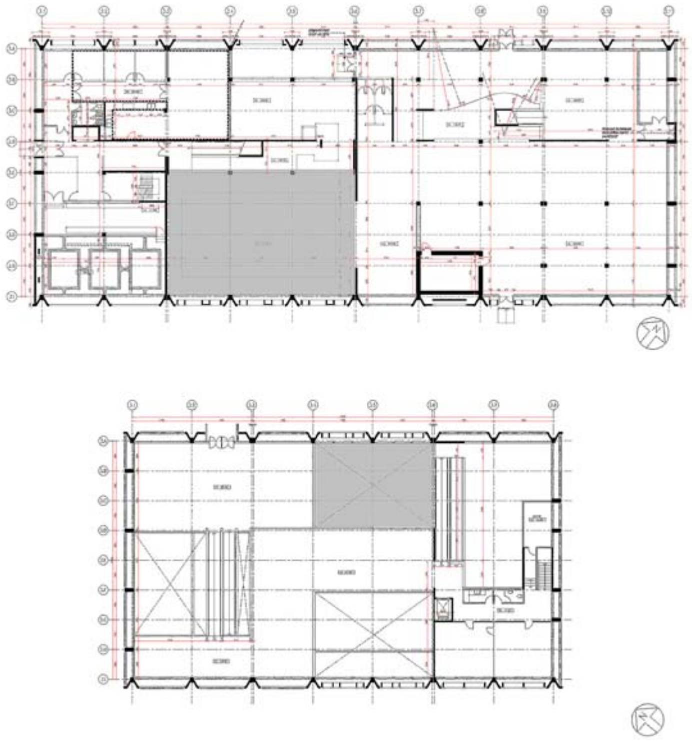


Figure 41 Floor plan of Building 3 (upper) and Building 4 (lower)
(Gulf Museum Consultancy Company, 2001)

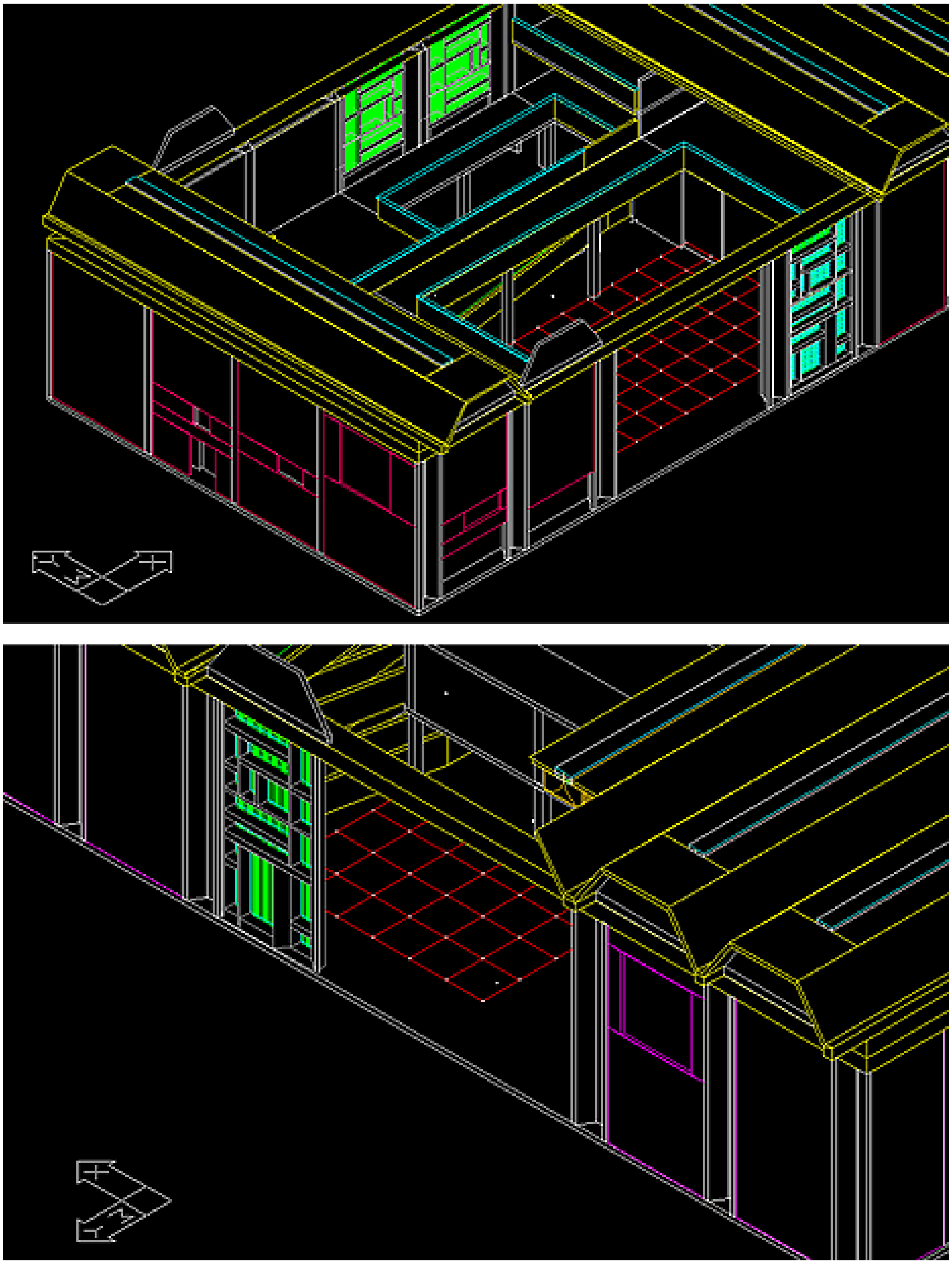


Figure 42 Reference grid on Building 3 (upper) and Building 4 (lower).

From the output of the Desktop RADIANCE, Daylight Factor on Building 3 ranges from 0.037% to 0.151% at 12:00 pm, on Jun 21st (summer solstice) and from 0.034% to 0.148% at 12:00 pm, on Dec 21st (winter solstice). For the Building 4, DF ranges from 0.062% to 0.284% at 12:00 pm, Jun 21st and from 0.055% to 0.283% at 12:00 pm, Dec 21st. The difference of DF of these two galleries may mainly come from the difference of side shading devices. For the southeast facing gallery, it has both vertical and horizontal louvers to block the direct sun light from through the side opening. However, the northeast gallery only has vertical louvers. It means that northeast gallery has more chance to see the sky. Of course, the orientation of the top light and building may cause the difference. For the illuminance levels in southeast gallery ranges 10.7-53.0 lux under the overcast sky and 484.3-994.52 lux under the clear sky at 12:00 pm, Jun 21st. During the wintertime, illuminance levels range 7.9-31.0 lux under the overcast sky and 80.5-207.9 lux under clear sky condition at 12:00 pm during the summer. For the northeast gallery, illuminance level varies 19.8-93.1 lux under the overcast sky and 359.0-663.0 lux under the clear sky at 12:00 pm during the summer and 11.3-58.0 lux under the overcast sky and 47.6-113.1 lux under the clear sky in winter solstice. Lighting distribution looks uniform at the specific time of the day except at the center of northeast gallery (Figures 41-44). However the lighting level is keep changing by the time and sky condition in these two galleries. By comparing the images of before and after installing top light and side shading devices, the lighting level after installing the daylighting systems is more uniform compared to before installing (Figures 47-54). By installing the top light and side shadings, the ambient lighting level will be increased while blocking the direct sun entering the galleries. Table 7 shows the simulation settings.

Table 7 Simulation settings

For Image Rendering in Simulation Manager

Sky and Weather	CIE Clear/ CIE Overcast
Location	Kuwait City, Kuwait
Time and Date	12:00 PM @ JUN 21/ DEC 21
Simulation Quantity	Luminance
Simulation Mode	Batch
Ambient Bounces	4
Mkillum Option	1
Turbidity	5.0 (JUN)/ 3.5 (DEC)

For Illuminance, Daylight Factor, Luminance Calculation in Simulation Manager

Sky and Weather	CIE Clear/ CIE Overcast
Location	Kuwait City, Kuwait
Time and Date	12:00 PM @ JUN 21/ DEC 21
Simulation Quantity	Illuminance/ Luminance
Simulation Mode	Batch to ASCII
Ambient Bounces	4
Mkillum Option	1
Turbidity	5.0 (JUN)/ 3.5 (DEC)

For Hourly Illuminance Calculation in Simulation Manager

Sky and Weather	CIE Clear
Location	Kuwait City, Kuwait
Time and Date	Daylight time at 21st of each month
Simulation Quantity	Illuminance
Simulation Mode	Batch to ASCII
Ambient Bounces	4
Mkillum Option	1
Turbidity	2.0

For Iso-contour, False Color Image Rendering in Image Analyzer

Units	Metric (Lux/ Candela per Square Meter)
Quantity	Illuminance/ Daylight Factor/Luminance
Scale	Linear

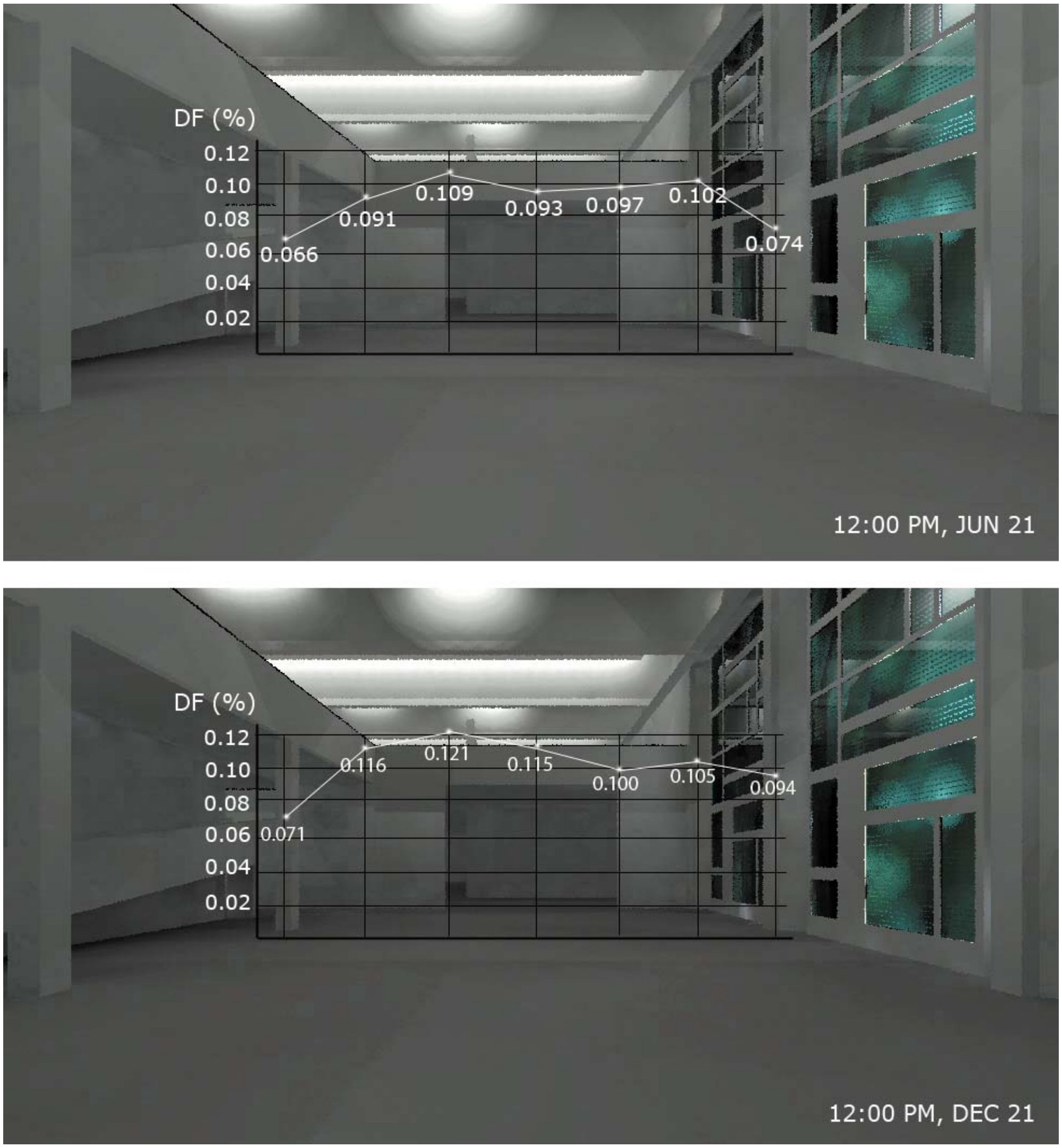


Figure 43 Daylight factor at the center of the southeast facing gallery (overcast sky)

From the Figures 43 and 44, DF in southeast gallery has pretty uniform distribution except left part of the Figure 44. There is no big difference in DF between summer and winter because no direct sun entering the gallery.

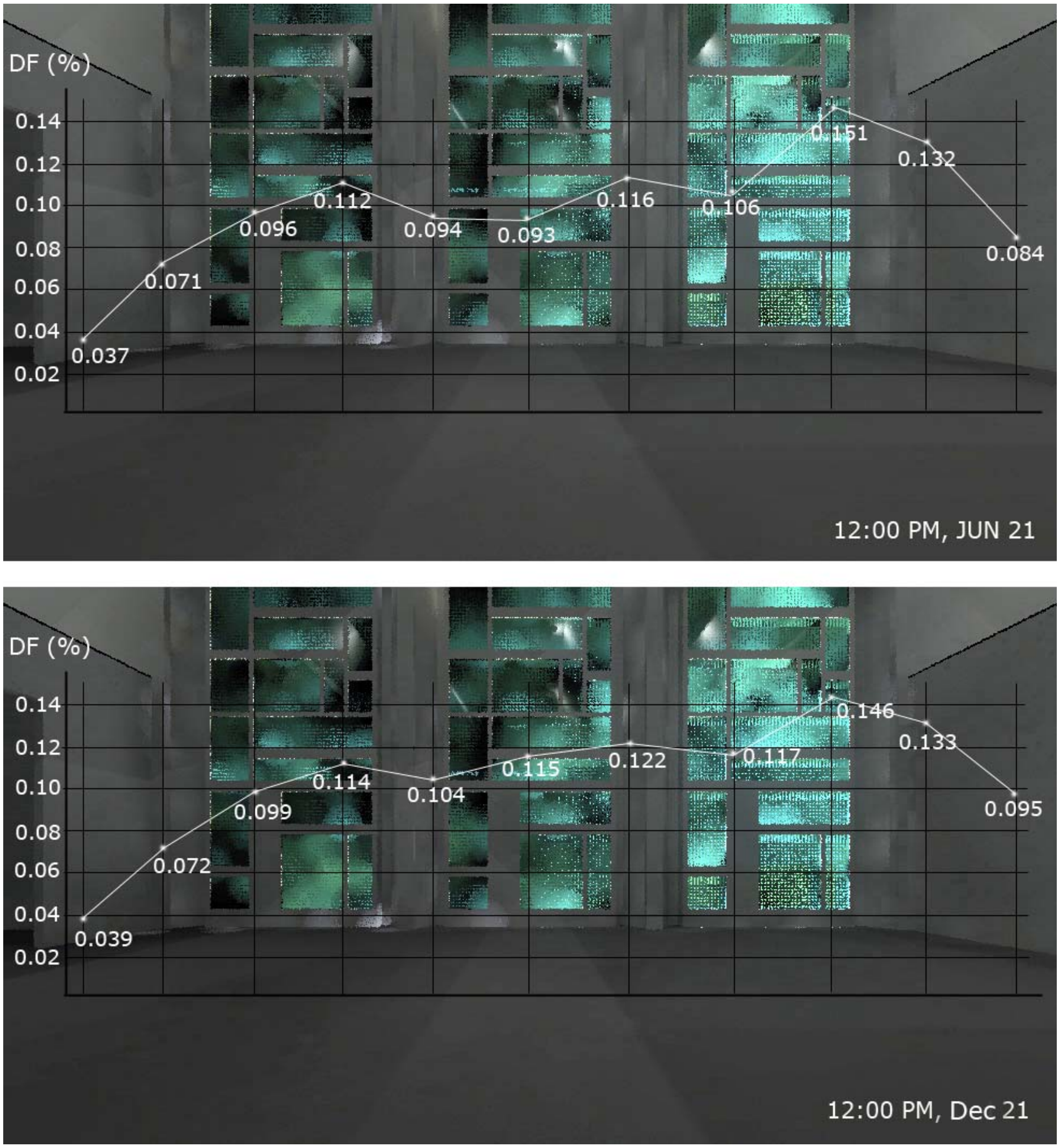


Figure 44 Daylight factor at the center of the southeast facing gallery (overcast sky)

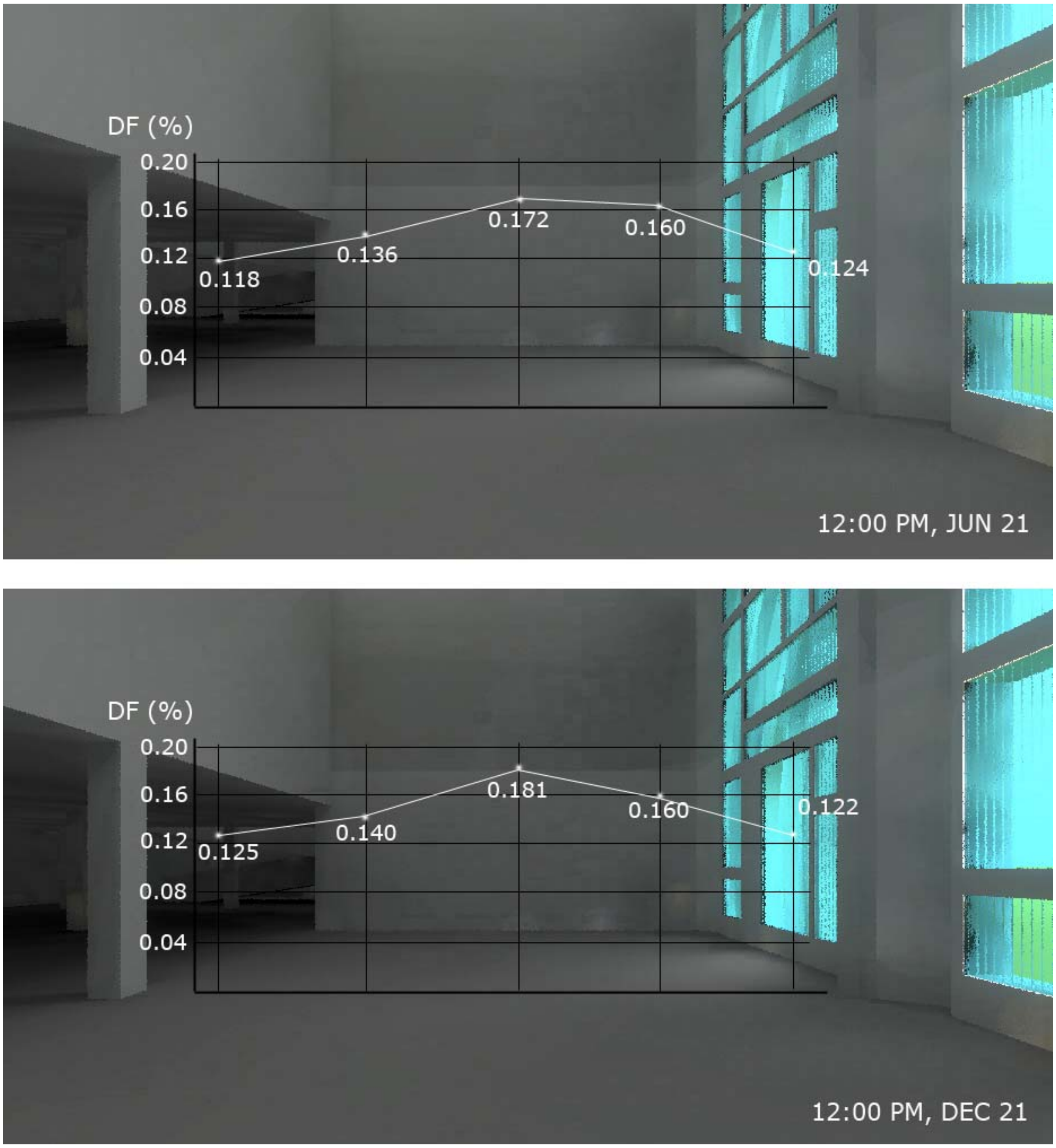


Figure 45 Daylight factor at the center of the northeast facing gallery (overcast sky)

For the northeast gallery, DF looks uniform in Figure 45. However, the distribution is uneven in Figure 46. There is no big difference in DF by seasons.

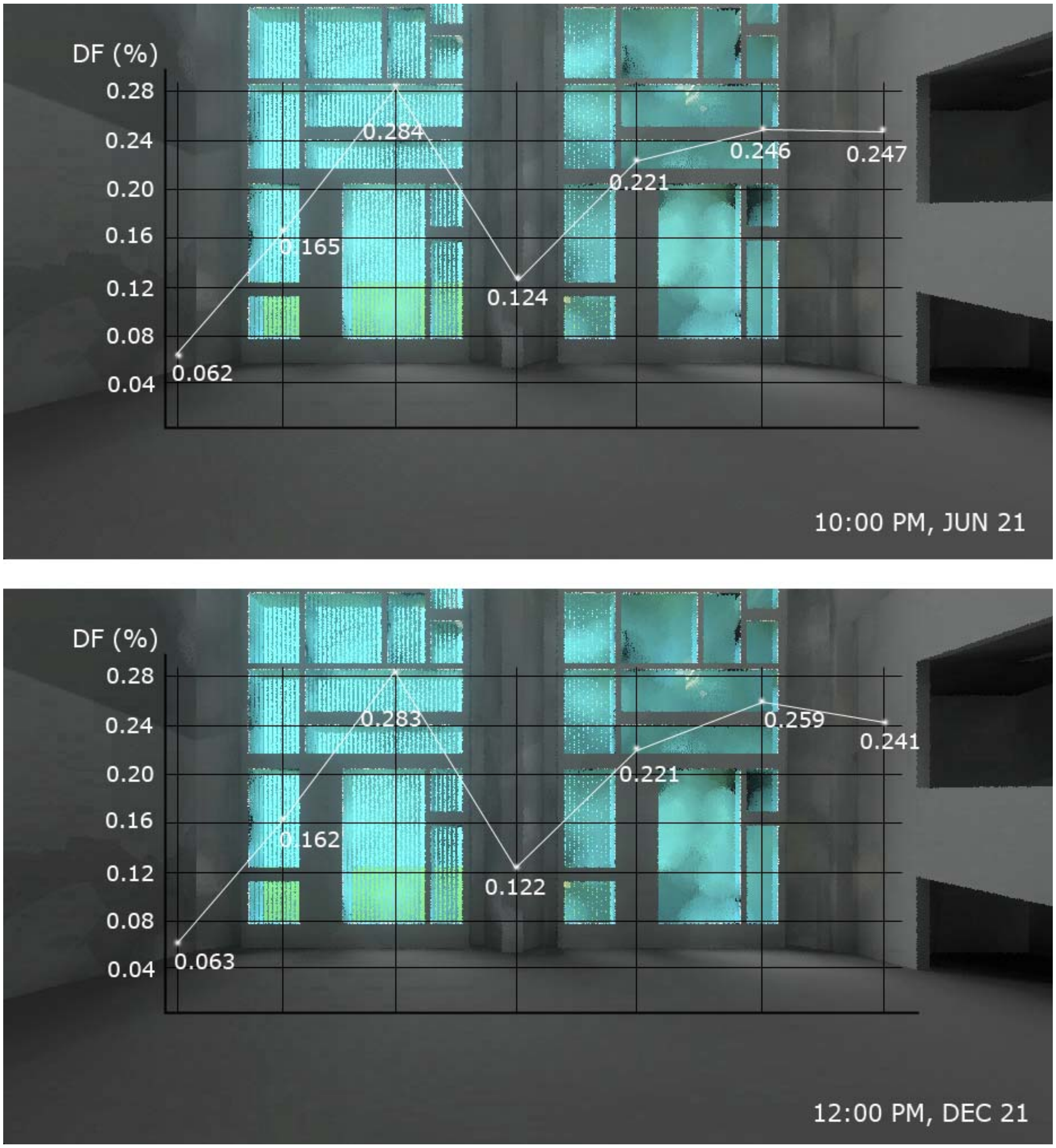


Figure 46 Daylight factor at the center of the northeast facing gallery (overcast sky)

Figure 47 Comparison between before (upper) and after (lower) installing top light side shading (Southeast gallery, 12:00 PM, Jun 21, Clear Sky)

By installing the top light and side shading devices, the lighting distribution is more uniform compared to original condition (Figures 47 and 48). The ceilings of galleries were removed for top lights.

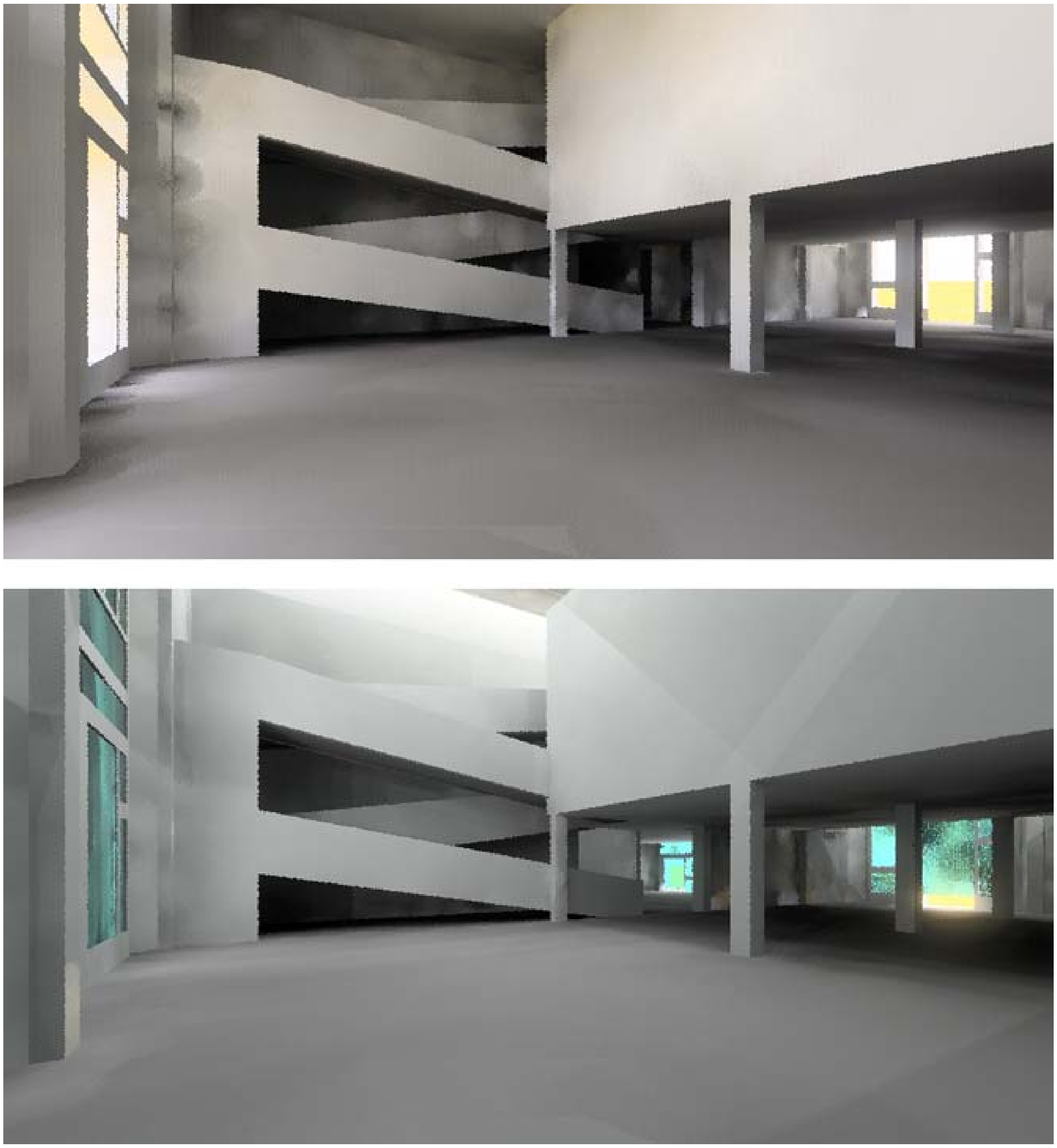


Figure 48 Comparison between before (upper) and after (lower) installing top light side shading (Northeast gallery, 12:00 PM, Jun 21, Clear Sky)

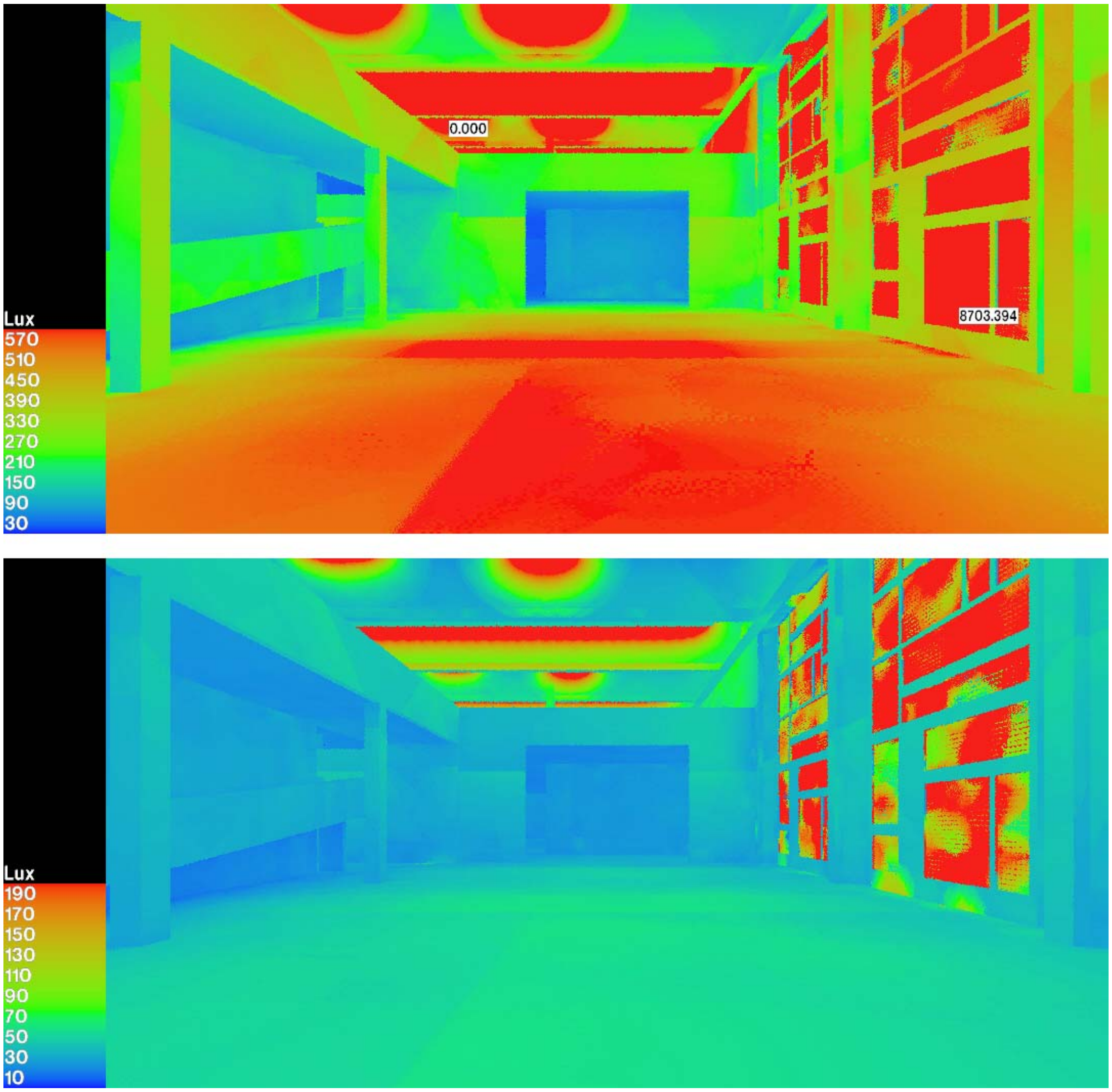


Figure 49 False color image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Jun 21)

From the Figures Iso-contour and False color images (Figures 49-52), illuminance level in the southeast galley looks pretty uniform at the specific time. However, the lighting level will vary with the sky condition, the time and date of the year.

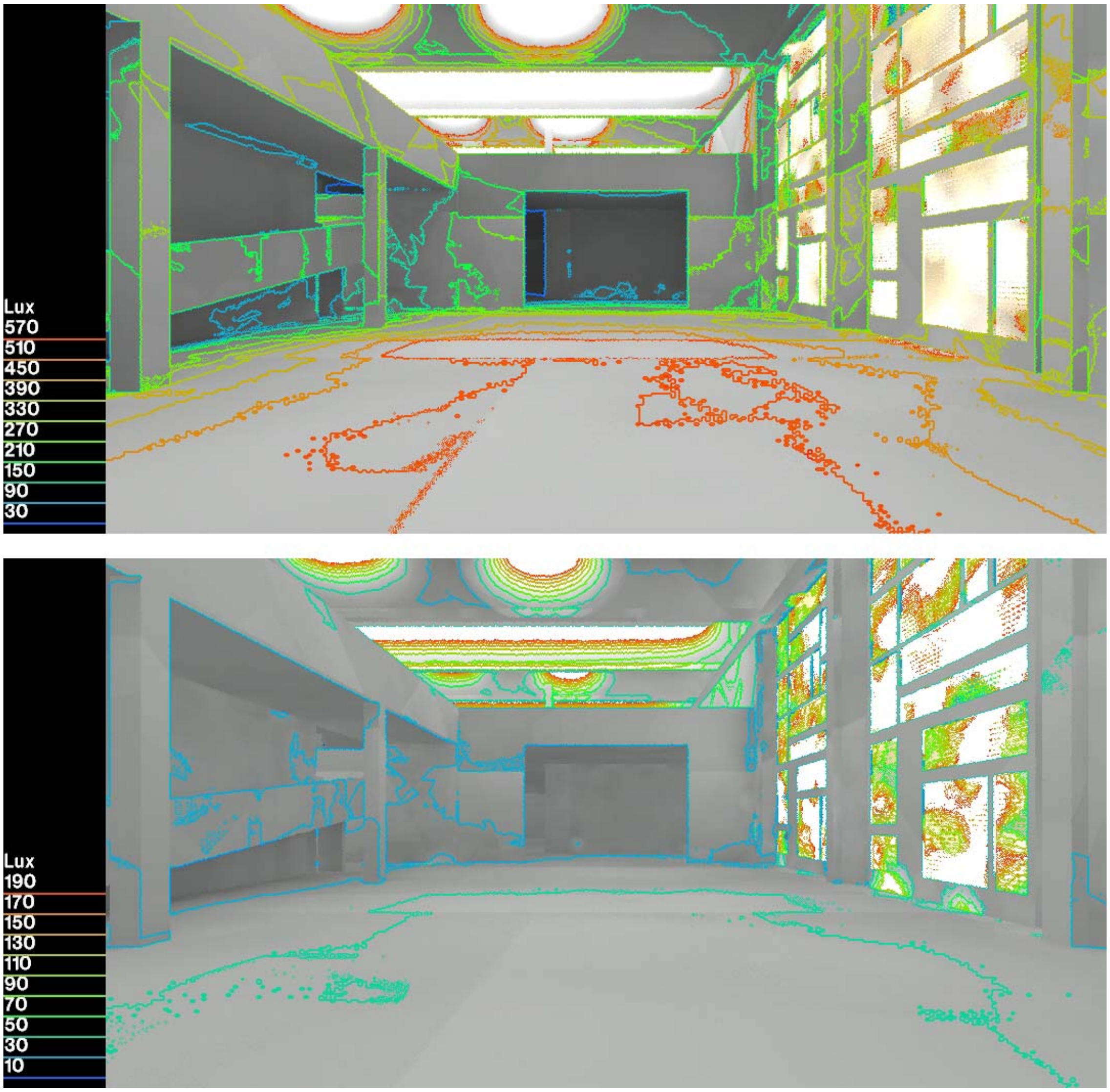


Figure 50 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Jun 21)

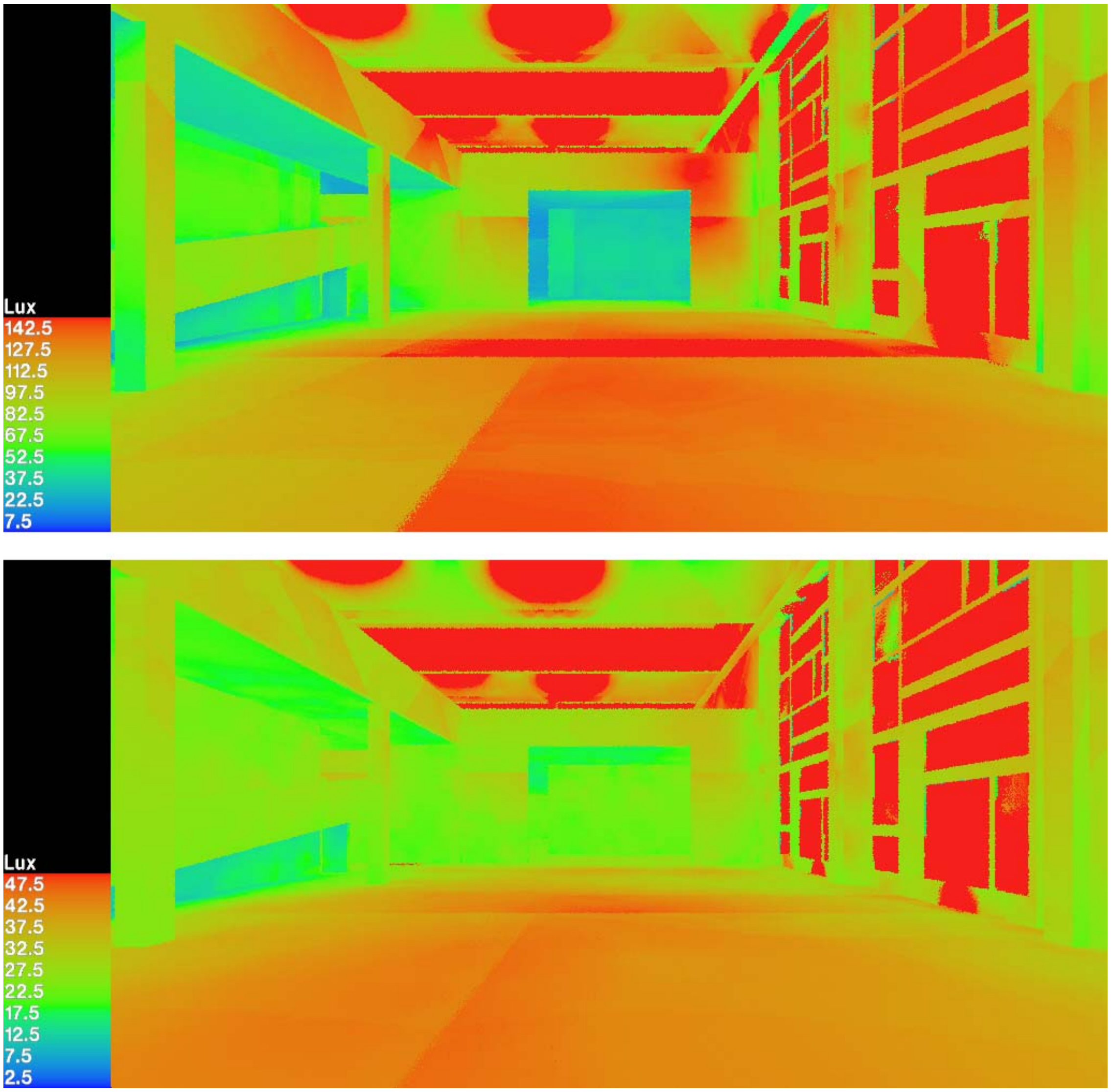


Figure 51 False color image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Dec 21)

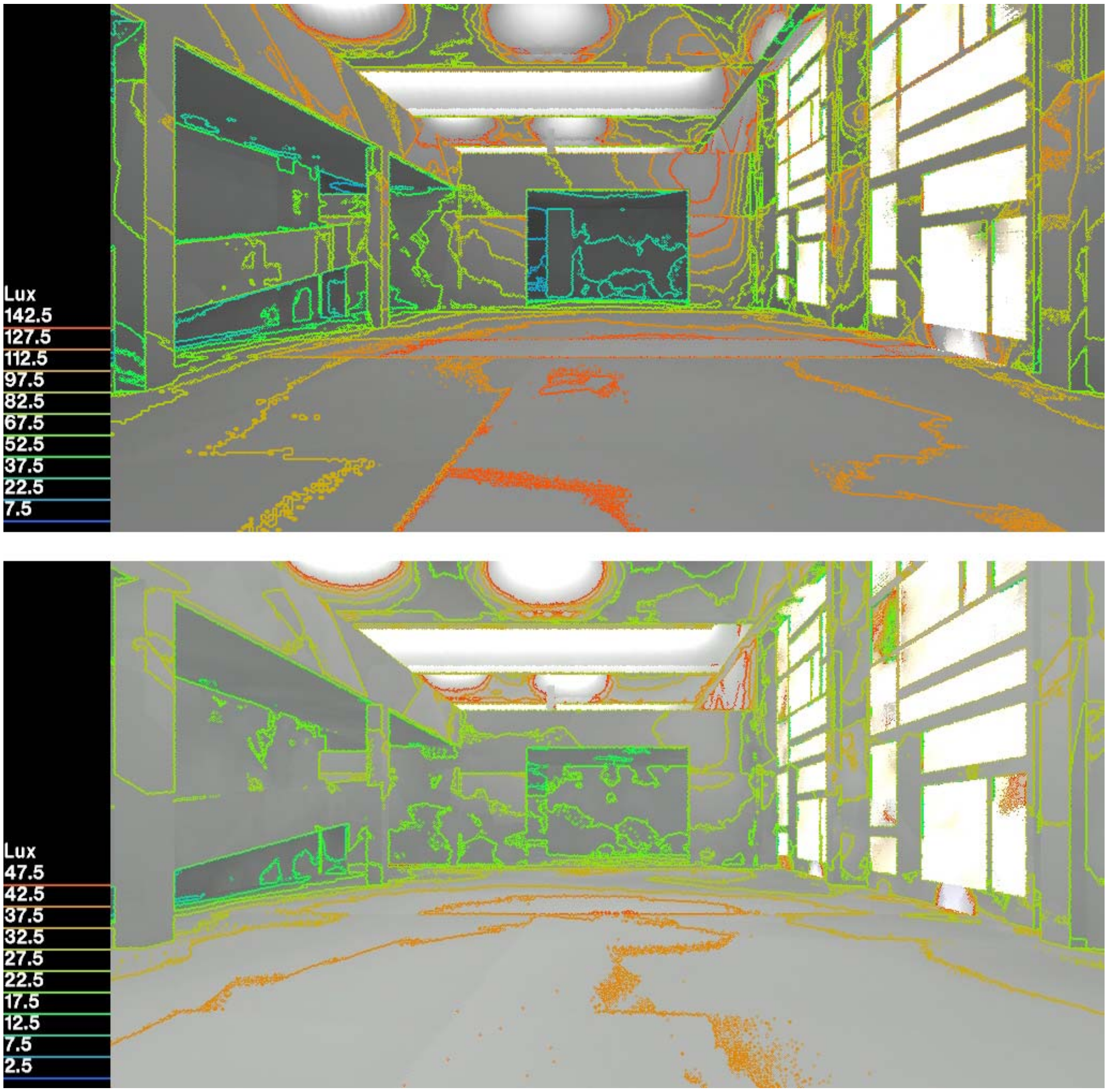


Figure 52 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Dec 21)

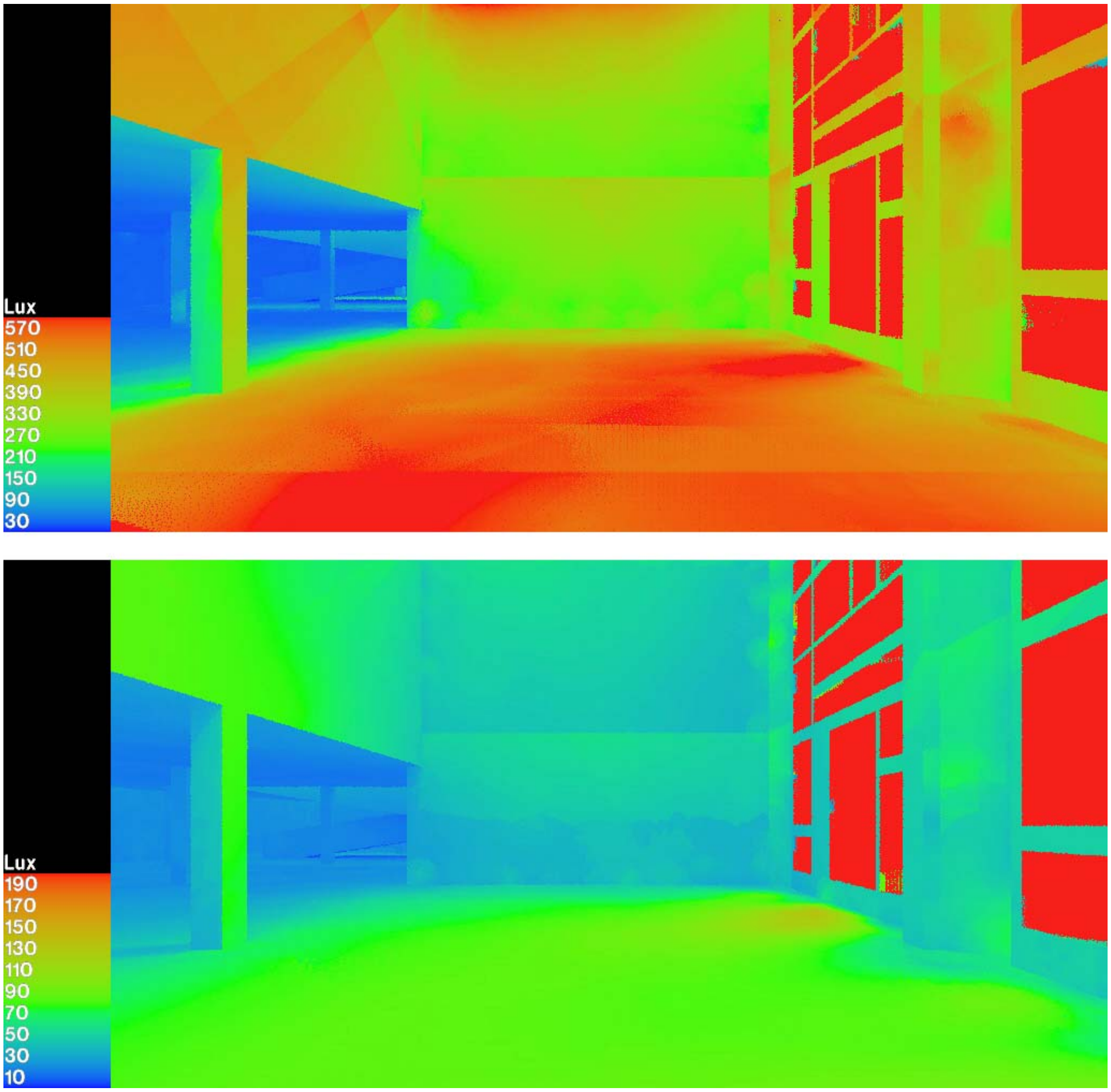


Figure 53 False color image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Jun 21)

Lighting distribution level in the northeast galley looks pretty uniform at the specific time. However, the lighting level will vary with the sky condition, the time and date of the year like southeast gallery (Figures 53-56).

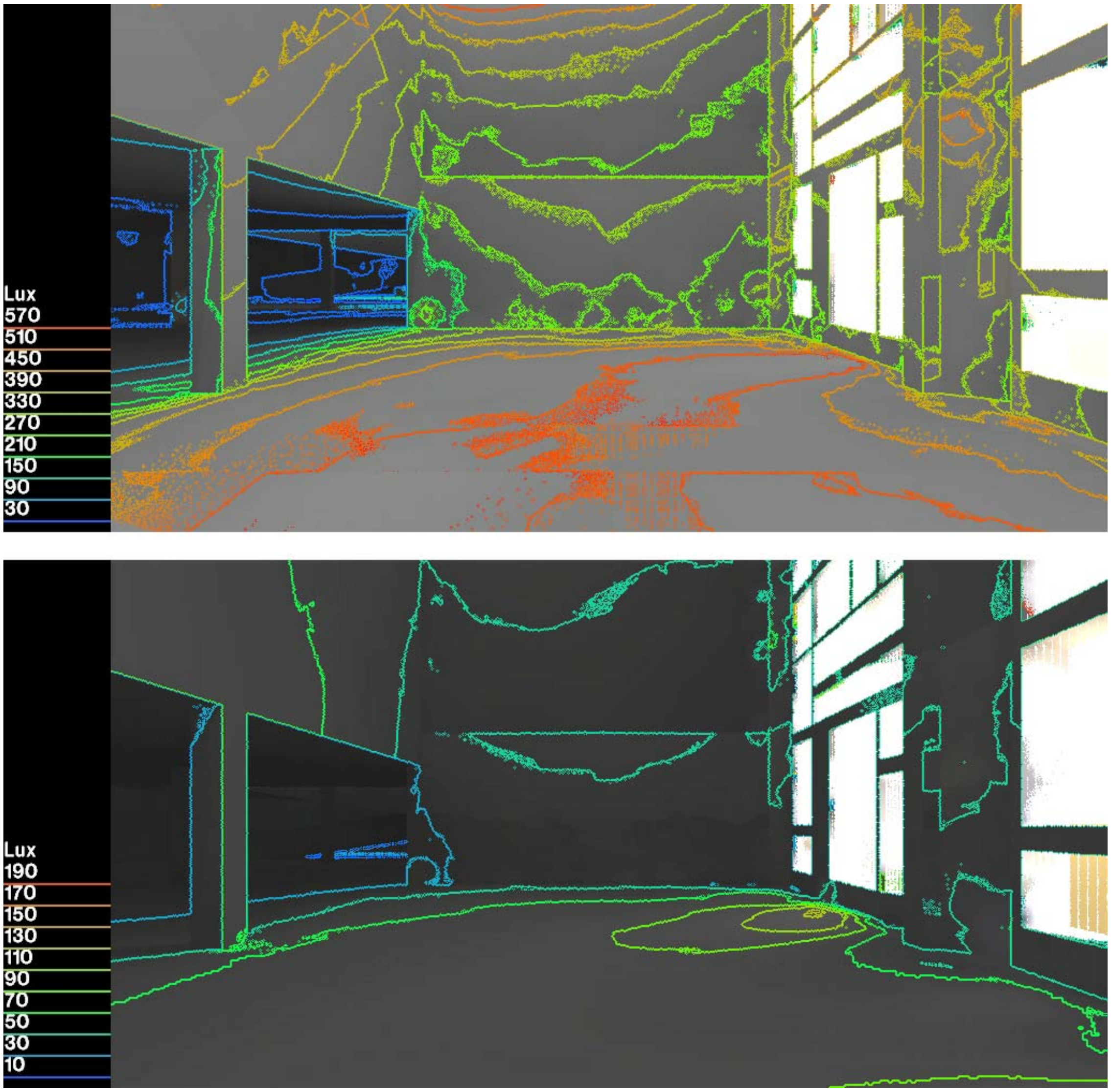


Figure 54 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Jun 21)

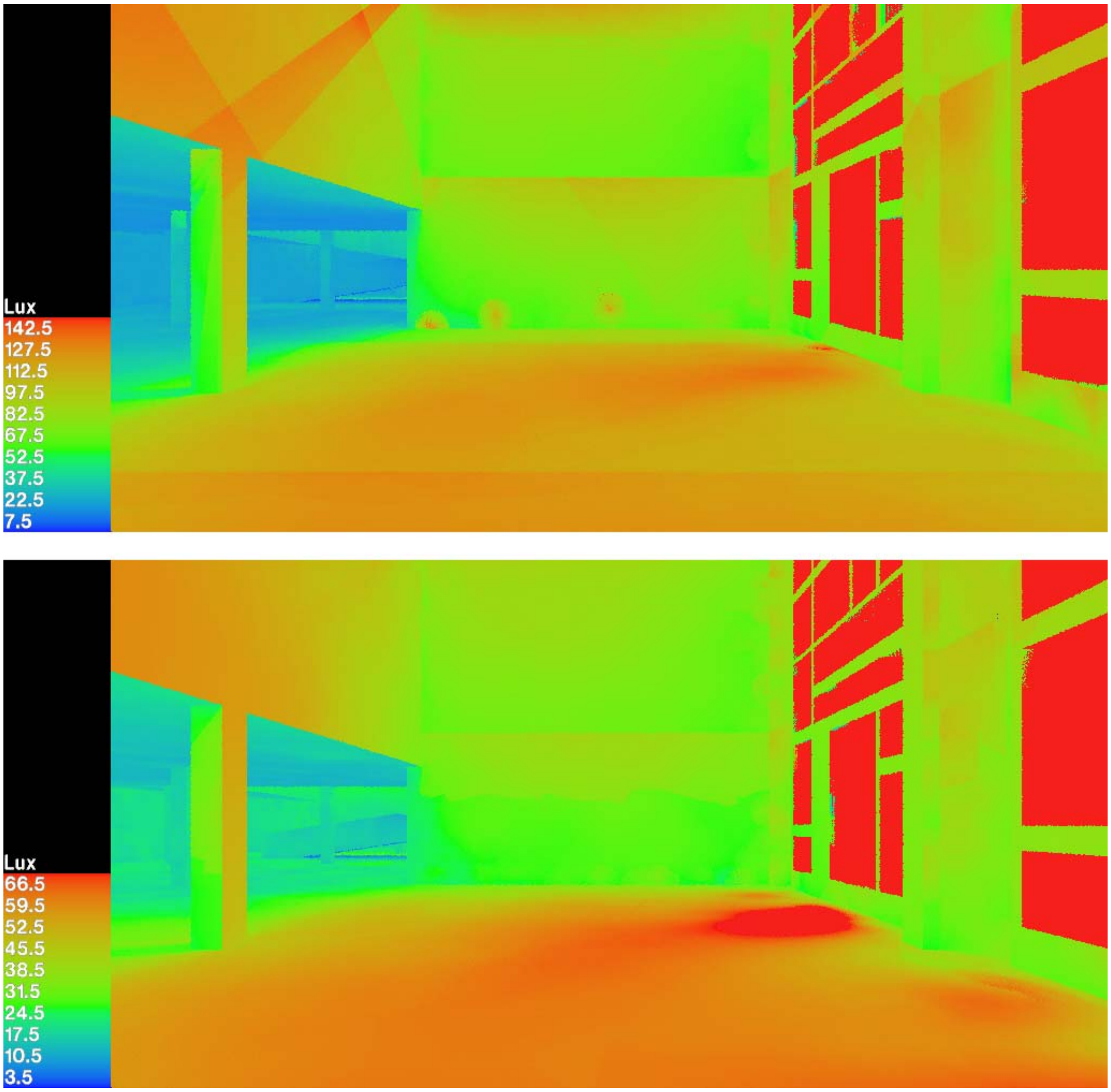


Figure 55 False color image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Dec 21)

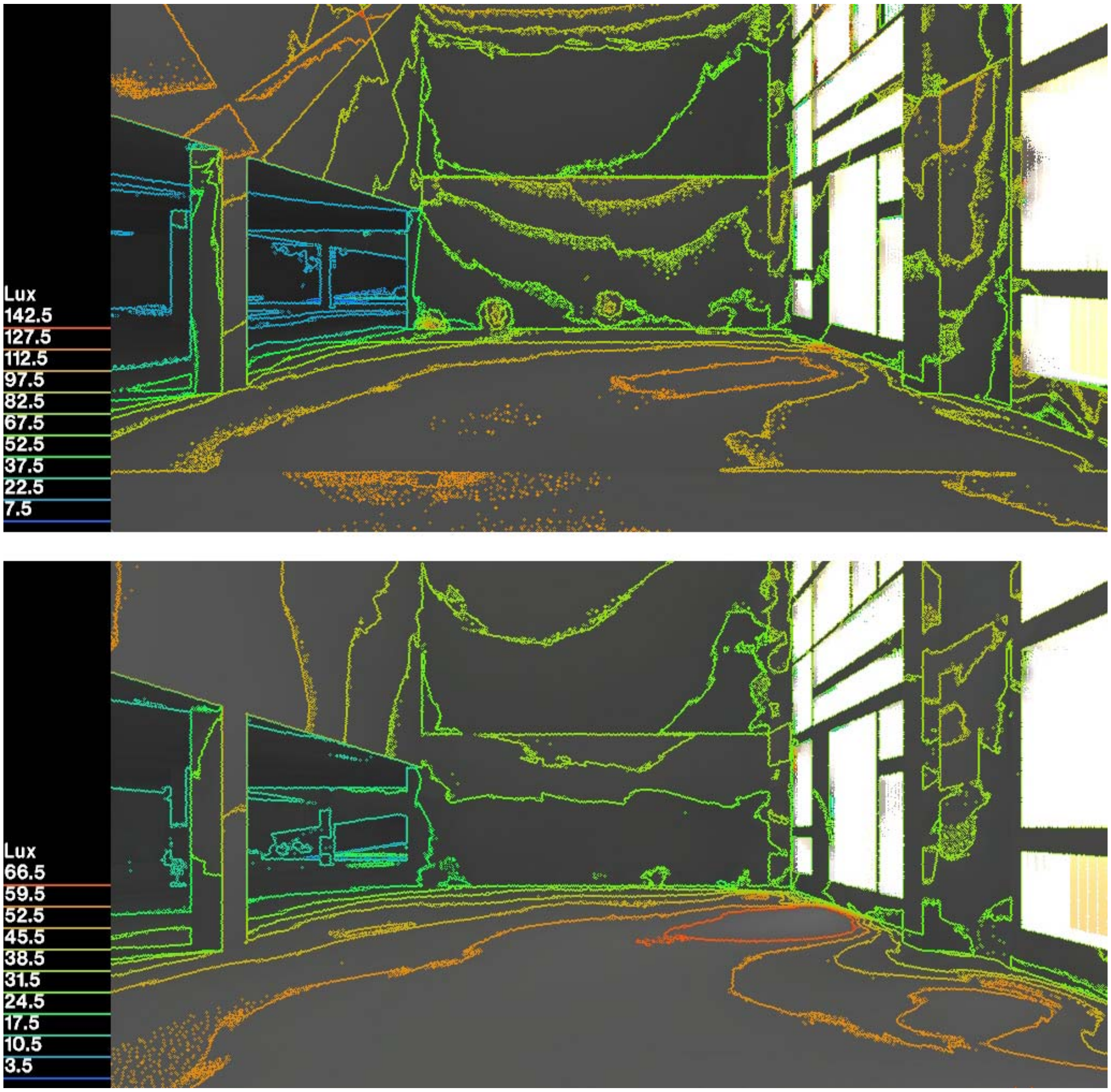
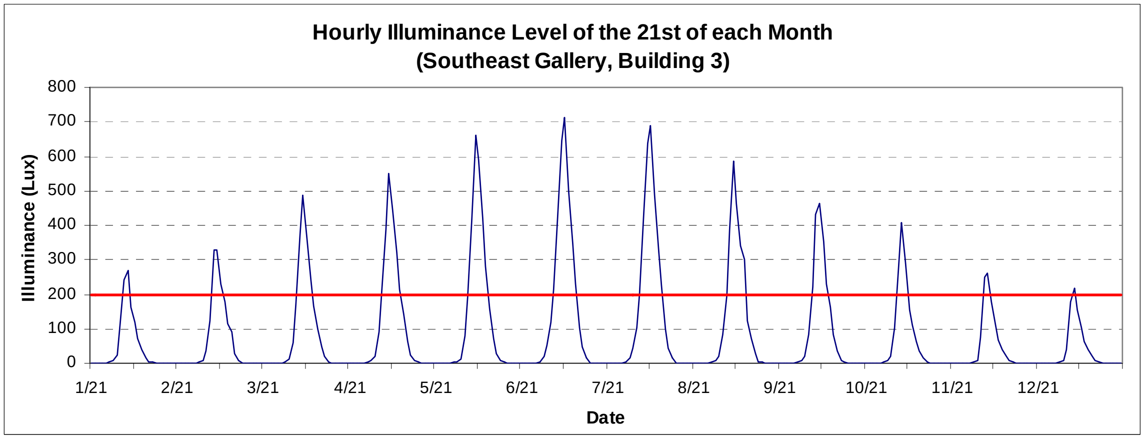


Figure 56 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Dec 21)



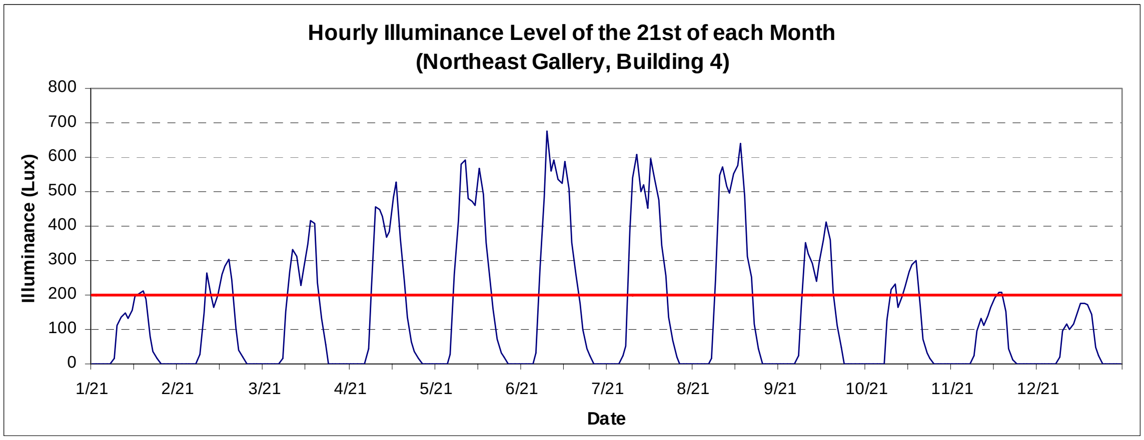


Figure 57 Hourly illuminance level of the 21st of each month for southeast (upper) and northeast gallery (lower)

From the hourly illuminance level simulations, the illuminance levels in southeast and northeast galleries are much higher than 200 lux (Figure 57). The maximum illuminance on southeast gallery reaches 711 lux which occurred 12:00 pm, June 21st. For the northeast gallery, maximum illuminance is 675 lux at 7:00 am, Jun 21st. Total exposure hours for southeast gallery is 758,210 lux-hour/year which exceed 58% higher than exposure limits for moderately susceptible material as shown in Table 3**.** For the northeast gallery, total exposure hours are 1,263,820 lux-hour/year which is 163.3 % higher than that of moderately susceptible material.

The reference point of each gallery was placed at the center of the gallery with 4 foot (1.2m) height of from the floor. Sky condition for the simulation is assumed as clear sky throughout the year. From the result of simulations, highly susceptible and moderately susceptible material such as textiles, paper documents, oil paintings, and leather cannot be displayed in these galleries.

To check the glare inside of the galleries, luminance simulations were conducted. As both galleries have big side openings, glare inside of the galleries should be checked. As these two galleries are facing east, luminance levels in the morning were checked. Luminance ratio ranges from 1:5.3 to 1:28.5 (Figures 58 and 60) in the southeast gallery, and from 1:10.2 to 1:29.7 in the northeast gallery during the morning. These ranges exceed IES recommendations for museums. IES recommends that luminance ratio should not exceed 1:10 and preferably not exceed 1:5 to avoid glare in the galleries (IESNA, 1996). To reduce the luminance ratio, fabric blinds with 10% transmittance were installed on the side openings. After installing blinds, the luminance ratio ranges from 1:2.1 to 1:2.6 in the southeast gallery and from 1:3 to 1:4.6 in the northeast gallery (Figures 59 and 61). These ranges are within the IES recommendations. To avoid glare through the side openings, blinds should be considered especially during the morning time.

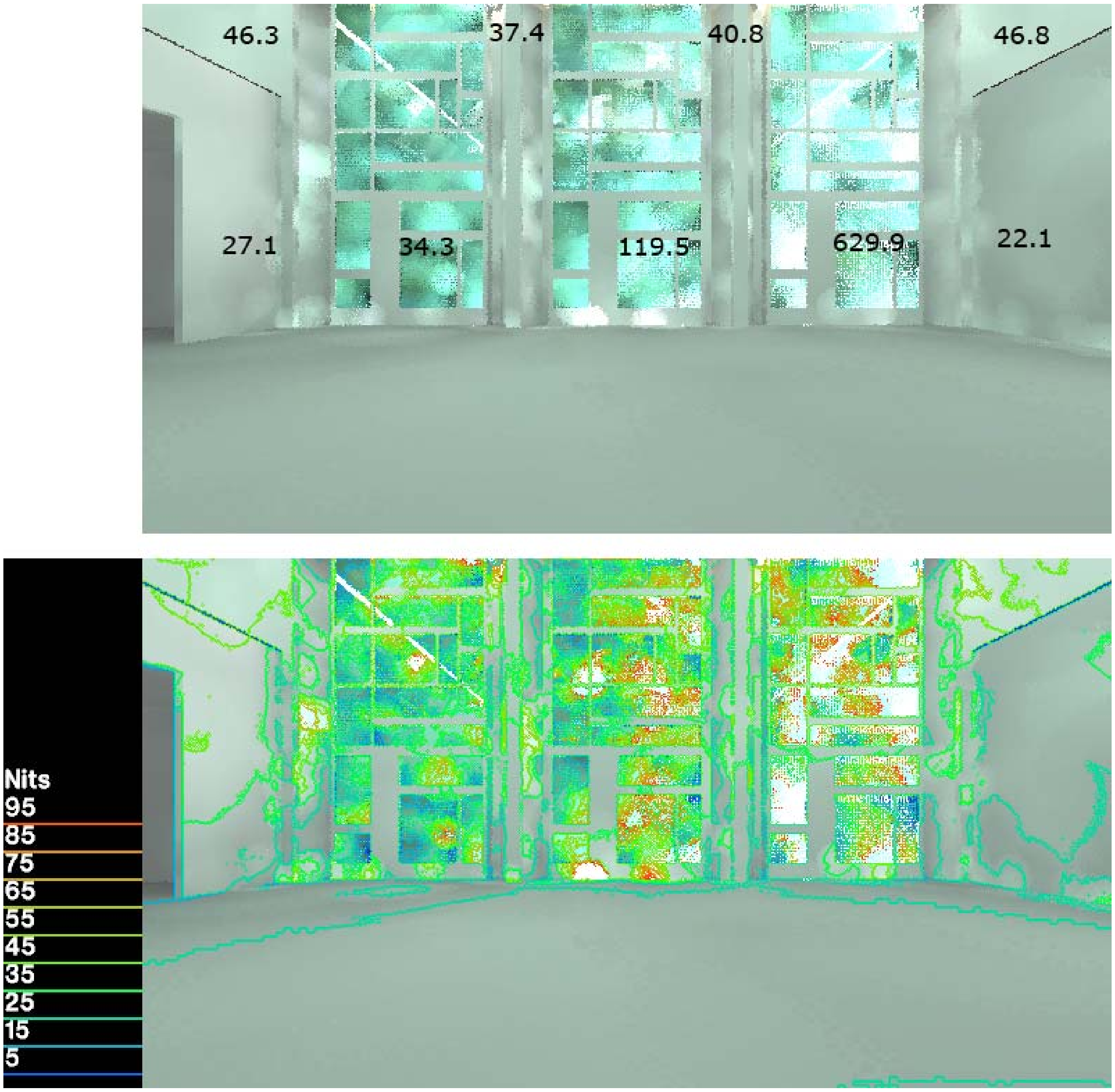


Figure 58 Luminance level (Nits or cd/m^2) in southeast gallery
(9:00 AM, Jun 21, Clear Sky)

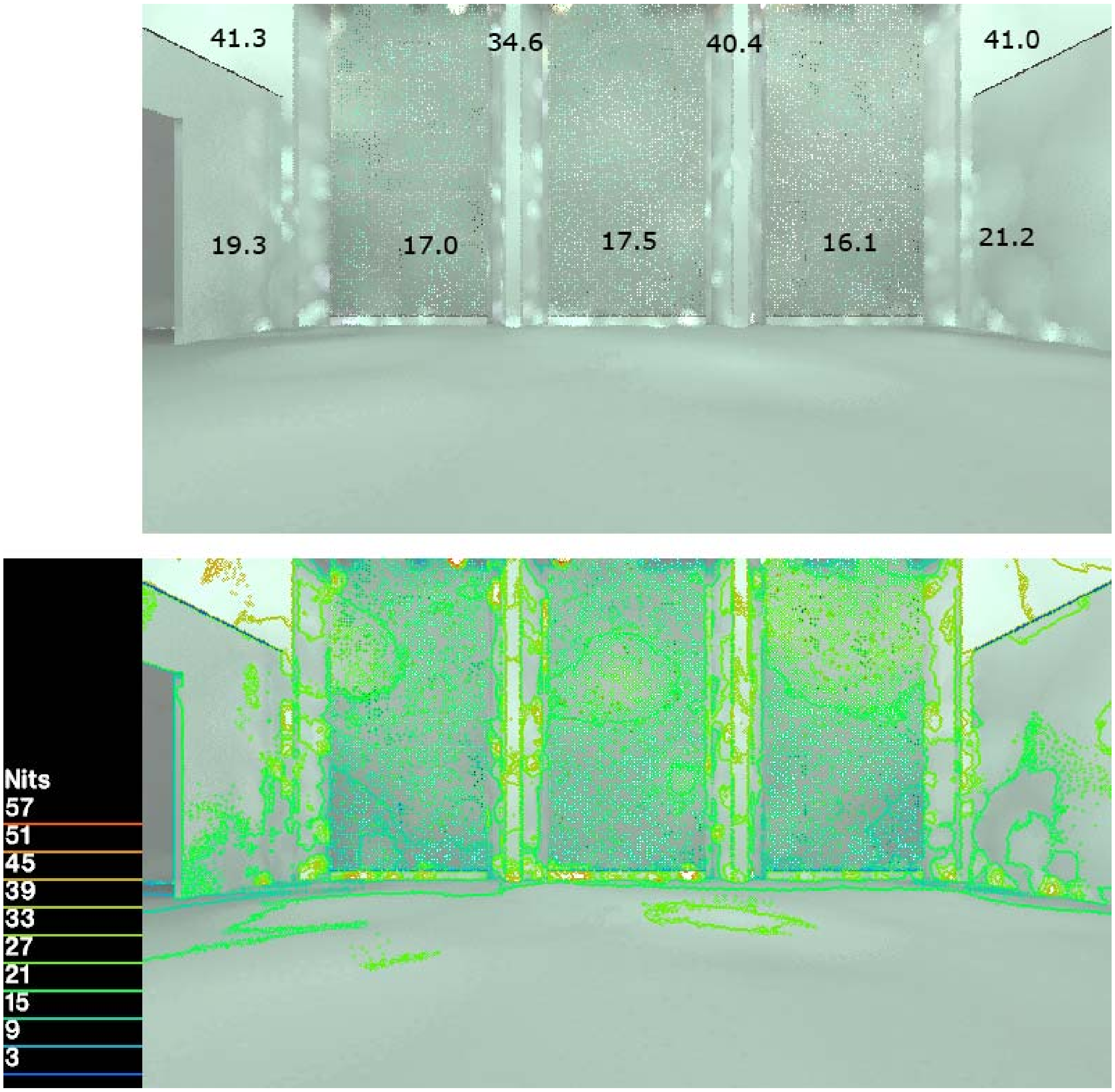


Figure 59 Luminance level (Nits or cd/m^2) in southeast gallery with Blinds
(9:00 AM, Jun 21, Clear Sky)

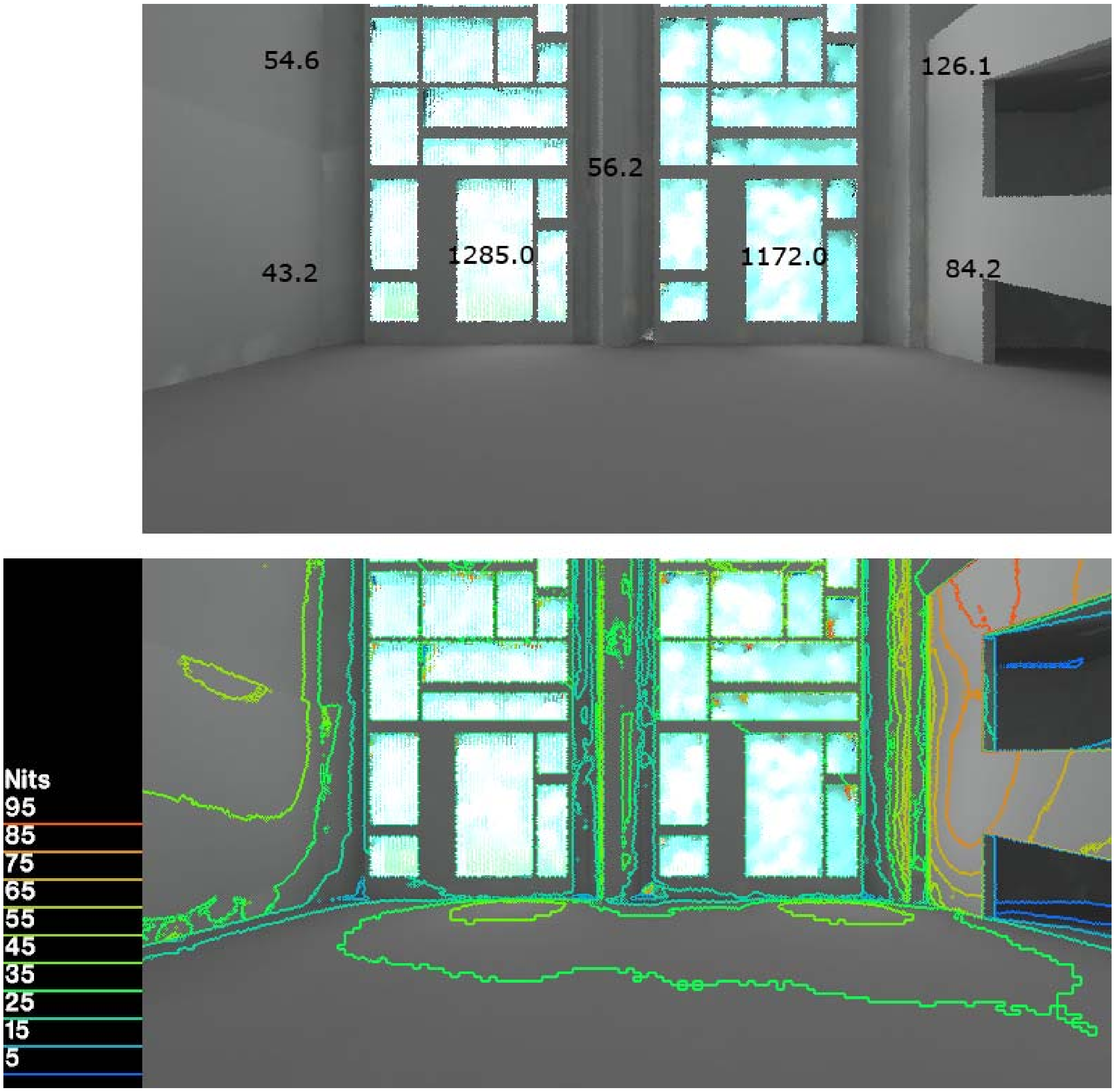


Figure 60 Luminance level (Nits or cd/m^2) in northeast gallery
(7:00 AM, Jun 21, Clear Sky)

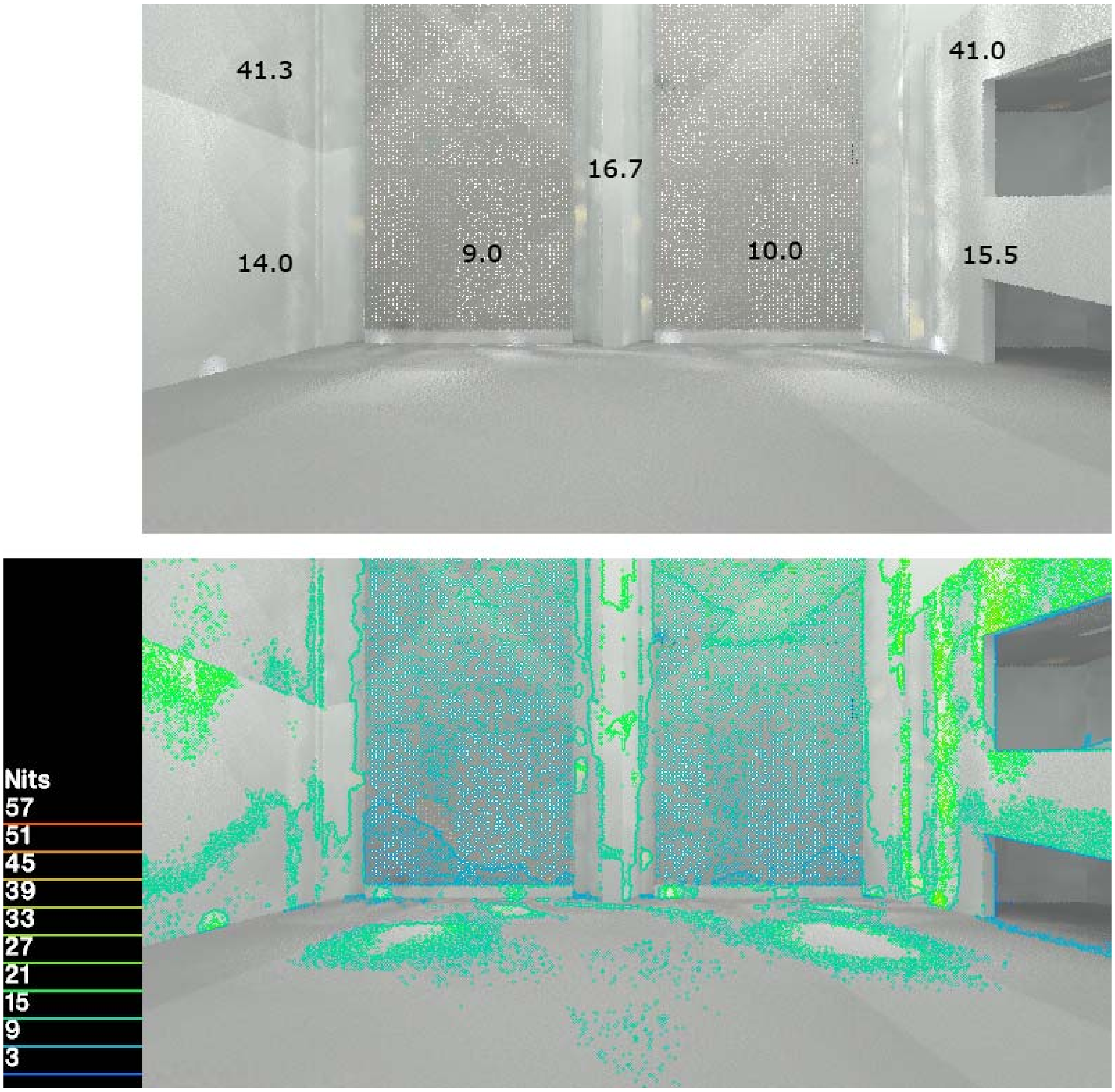


Figure 61 Luminance level (Nits or cd/m^2) in northeast gallery with blinds
(7:00 AM, Jun 21, Clear Sky)

CONCLUSIONS AND FUTURE STUDIES

The focus of this research is to increase the ambient lighting level while preserving museum objects in KNM by using top lights, and installing side shading device to block the direct sun entering through the side openings. To verify the output from the simulation, scale model measurement conducted and the illuminance and DF from Desktop RADIANCE simulation and scale model measurement have close match while the values from the scale model measurement were slightly higher than that of simulation. By installing the top light, ambient lighting level in the gallery was increased and no sun beam will heat the galleries throughout the year. This will reduce the artificial lighting loads during the daytime. And lighting level in the gallery is fairly uniform at the specific time. However, lighting level varies with the sky condition, and time and date of the year. From the annual illuminance analysis, illuminance levels in these two galleries exceed 200 lux during the daylight hours. And total exposure times also go over the limits for moderately susceptible material. So, highly susceptible and moderately susceptible material can not be displayed in these two galleries. Among the collections of KNM, jewelry and ceramics objects can be displayed in these areas. In addition, blinds should be considered to avoid glare in these two galleries.

In designing the top light and side shading devices, mechanical devices was not considered. To reduce the variation of lighting level, mechanical devices such as automated louvers can be considered. Another consideration would be the motorized shutter or curtain which can block the daylight coming through the opening. As the museum objects start deteriorating when it is exposed to light, it could reduce exposed time of museum objects. In addition, daylight cannot totally replace the artificial light because the museum objects, such as jewels, still required the artificial light to show their features clearly.

This research only covers the evaluation of daylighting performance by using the Desktop RADIANCE and scale model. As the site of KNM, Kuwait City is located in cooling dominant climate, installing the top lights and will change the pattern of cooling loads. Thus, energy performance after installing the top lights should be considered.

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APPENDIX A

Amon Carter Museum

The Amon Carter Museum was designed by Philip Johnson and originally opened in March 1961 (Figure A 1). Phillip Johnson redesigned the major renovation which was completed in 2002. The East gallery on the first floor has serious lighting problems because of its orientation and large windows early in the morning. (Figure A2). The northeastern part of the wall received direct sunlight as shown in Figure A3. Three paintings are displayed in this wall and the sunlight will deteriorate the paintings. And sunlight will reach the opposite side wall during the early morning year-round (Figure A4). The illuminance level in reference point, upper left corner of the painting which is on the closet window side, is over 2000 lux during the morning on March 6th. Even though, the illuminance is higher than that of recommendation from IESNA (Table 3).

Figure A 1 Façade of east gallery (left) and floor plan of Amon Carter Museum (right)

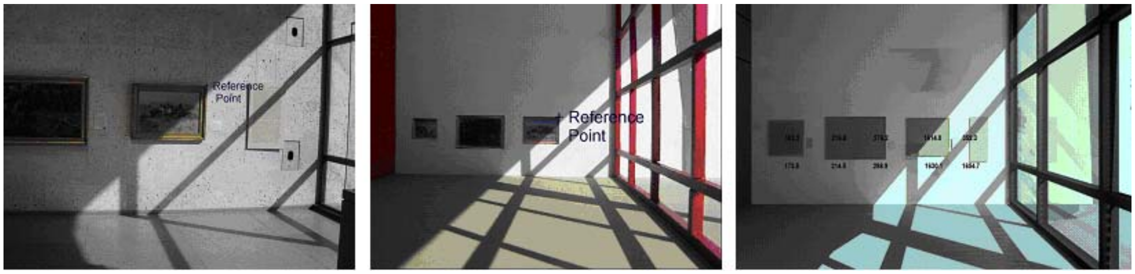


Figure A 2 Pictures of northeastern wall: the museum site (left), scale model (center), and Desktop RADIANCE model (right).

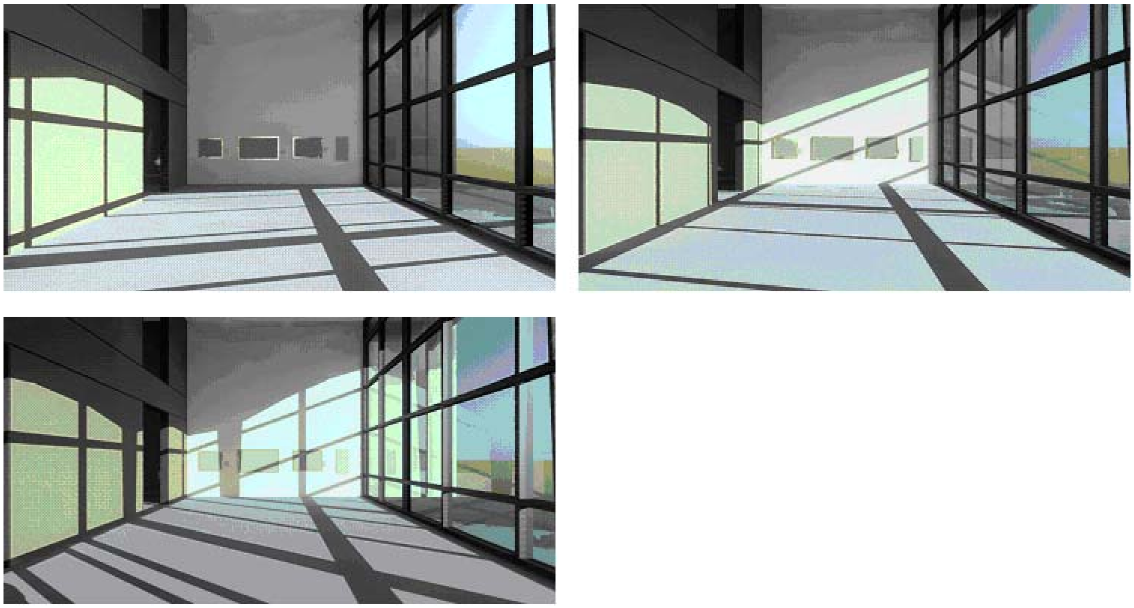


Figure A 3 Scenes of Desktop RADIANCE at extreme angles; Jun 21st 7:00 am (upper left), Sep 21st 8:00 am (upper right), Dec 21st 9:0 am (bottom left)

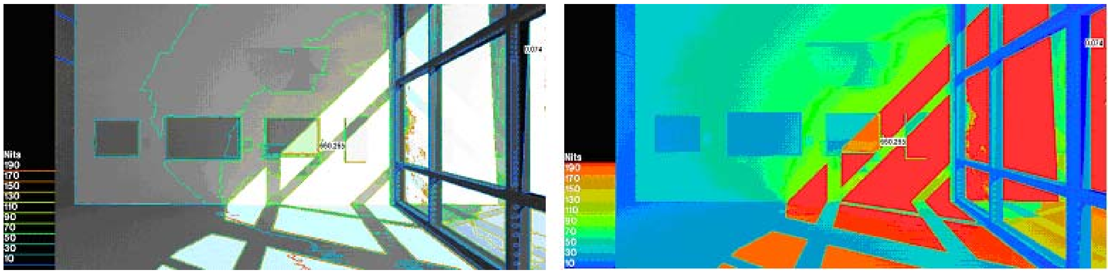


Figure A 4 Iso-contour plot (left) and false color plot (right) at 10:00 am, Mar 06.

Kimbell Art Museum

The Kimbell Art Museum was built in 1972. One of unique features of this building is top light which is installed in the vaults of the gallery. Through the reflector in the top light, the diffuse light is provided in the gallery while blocking direct sunlight (Figure A5). Illuminance level of daylight contribution is around 50 lx. This is good example in designing the top light in museum buildings.

Figure A 5 Interior view of Kimbell (left) and top light (right)

Nasher Sculpture Center

Nasher Sculpture Center designed by Renzo Piano (Figure A 6). The gallery spaces are covered with glass roof with an egg-crate shading system to block the direct sunlight while taking diffuse skylight (Figure A 7). The opening of shading device is toward to north, and the shape of opening is decided by the sun path of Dallas. The natural lighting performance of the roof shade has been tested under a Lighting Simulator at the Bartlett School of Architecture, University College London, UK (Ove Arup & Partners

International Ltd, 2001). Lighting levels inside the galley was tested by the software package RADIANCE. Illuminance level in the gallery ranges around 340 -1550 lux during the summer, and 150 – 870 lux during the winter. The lighting level of Nasher is much higher than that of Kimbell because most of the museum objects are sculpture which is insensitive to light. Thus, if a more sensitive material is on display, it will be required temporary protection on the roof.

Figure A 6 Exterior view (left) and interior view (right)

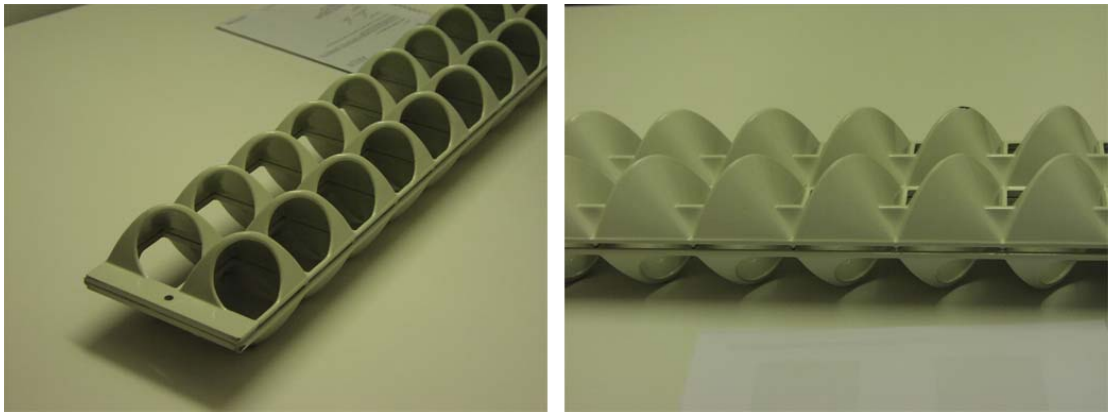


Figure A 7 Egg-crate shading system

APPENDIX B

Figure B 1 Comparison between before (upper) and after (lower) installing top light side shading (Southeast gallery, 12:00 PM, Jun 21, Overcast Sky)

Figure B 2 Comparison between before (upper) and after (lower) installing top light side shading (Southeast gallery, 12:00 PM, Jun 21, Clear Sky)

Figure B 3 Comparison between before (upper) and after (lower) installing top light side shading (Southeast gallery, 12:00 PM, Jun 21, Overcast Sky)

Figure B 4 Comparison between before (upper) and after (lower) installing top light side shading (Southeast gallery, 12:00 PM, Jun 21, Clear Sky)

Figure B 5 Comparison between before (upper) and after (lower) installing top light side shading (Southeast gallery, 12:00 PM, Jun 21, Overcast Sky)

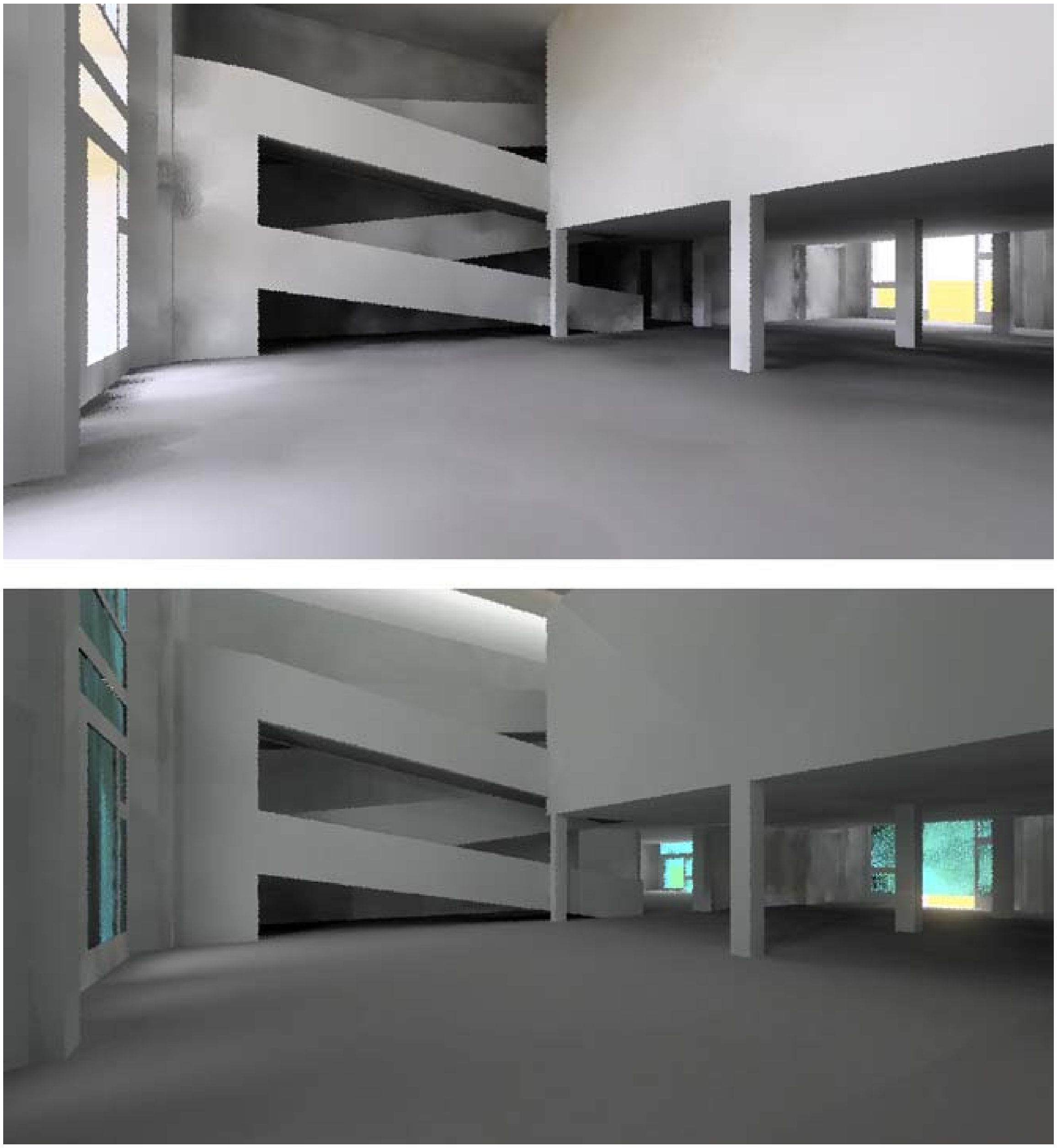


Figure B 6 Comparison between before (upper) and after (lower) installing top light side shading (Southeast gallery, 12:00 PM, Jun 21, Overcast Sky)

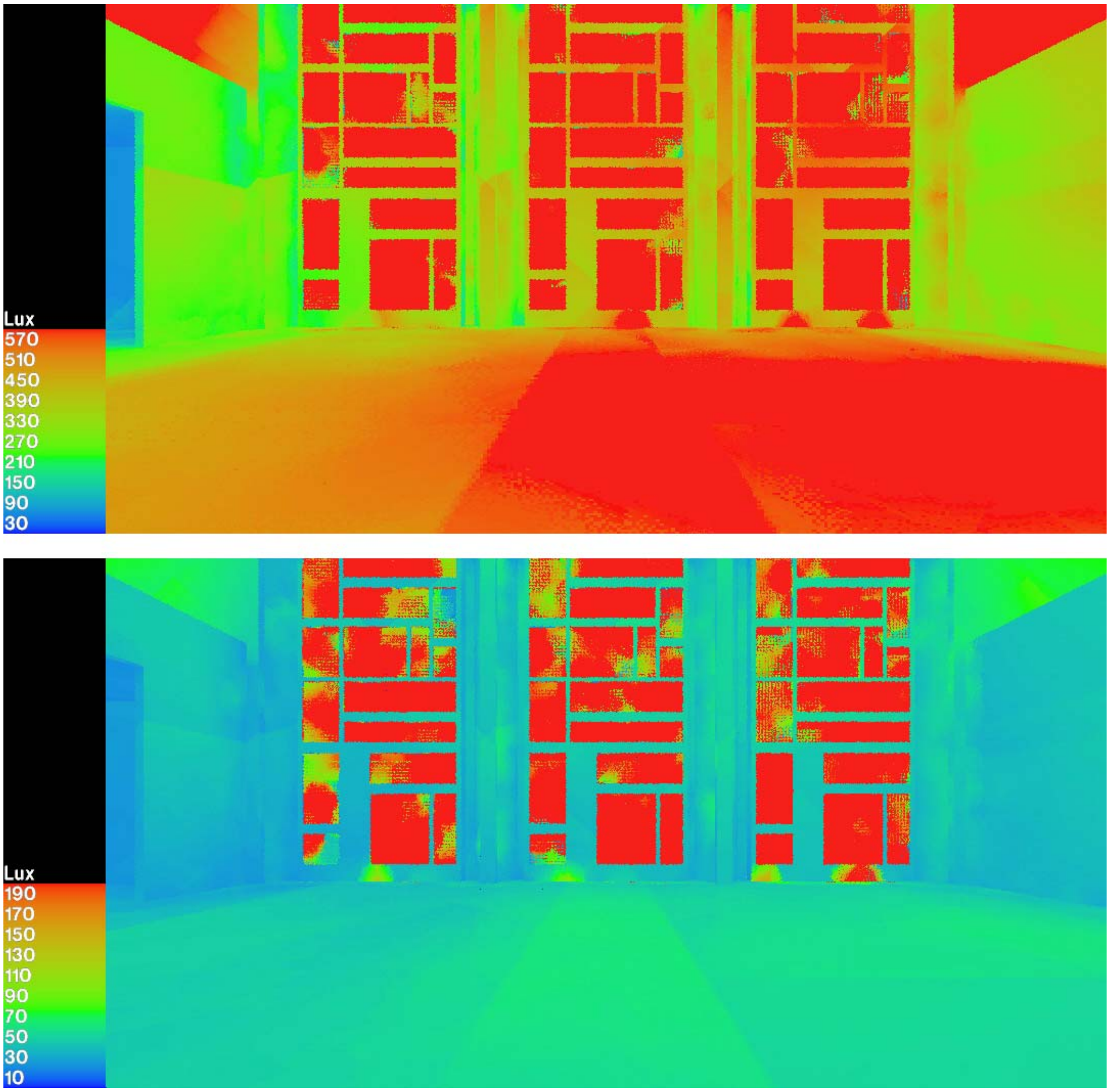


Figure B 7 False color image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Jun 21)

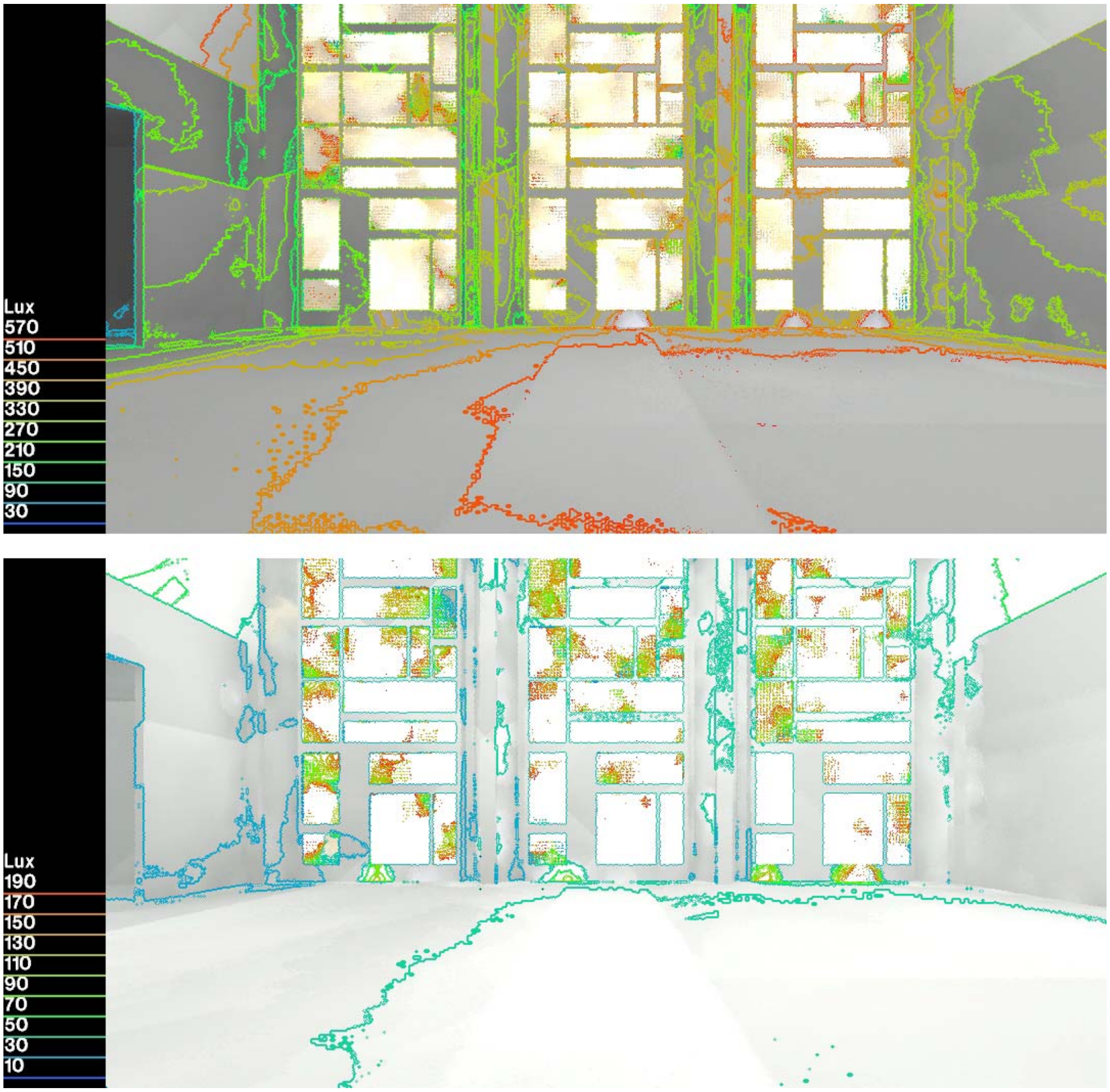


Figure B 8 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Jun 21)

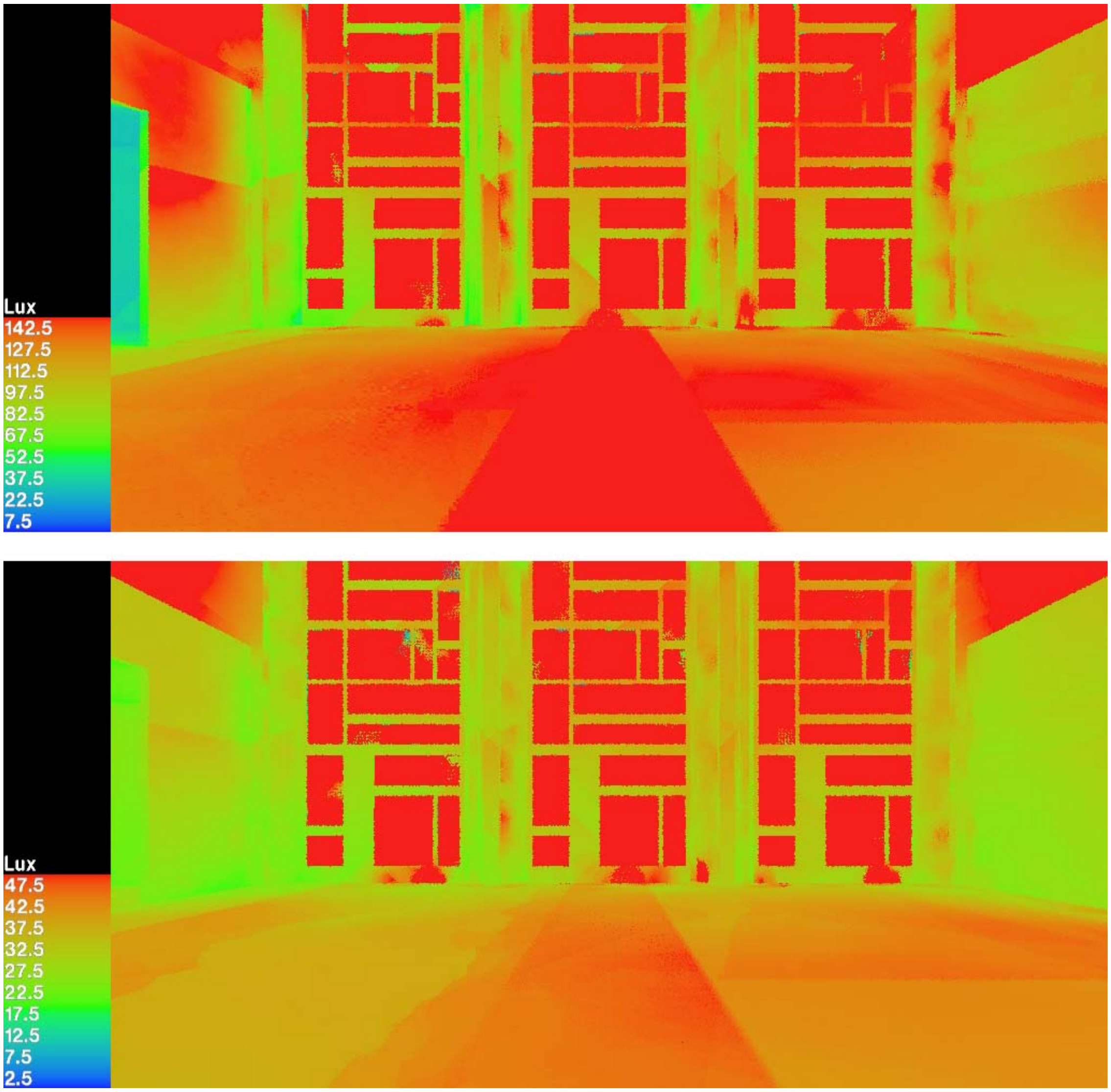


Figure B 9 False color image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Dec 21)

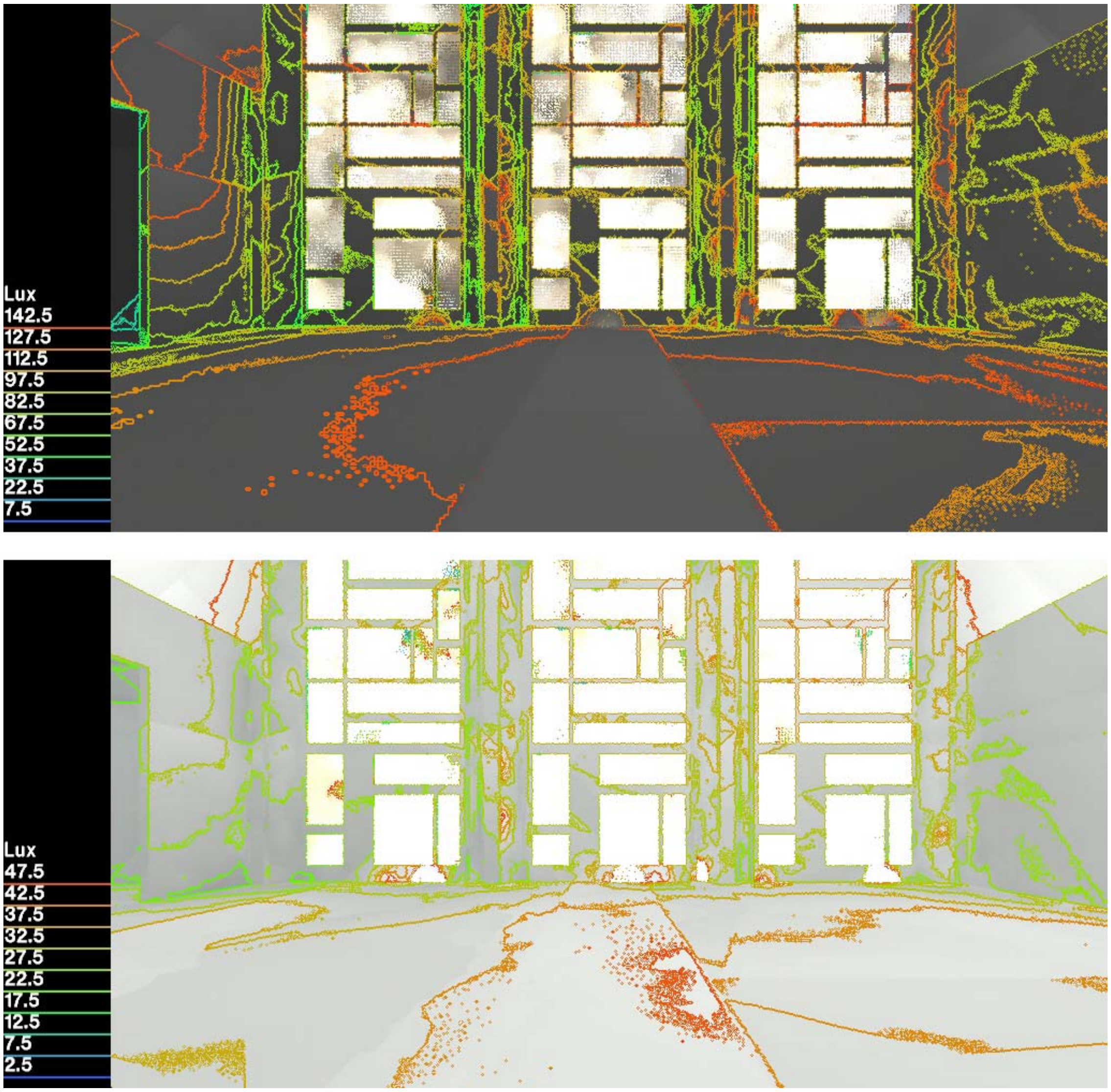


Figure B 10 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Dec 21)

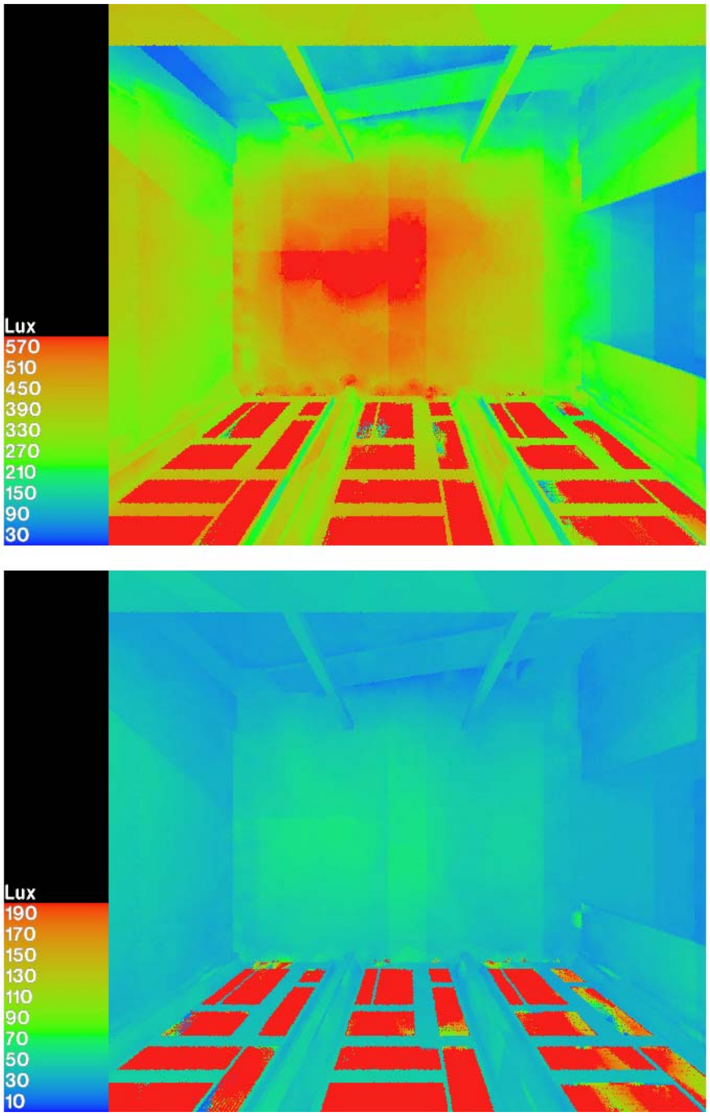


Figure B 11 False color image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Jun 21)

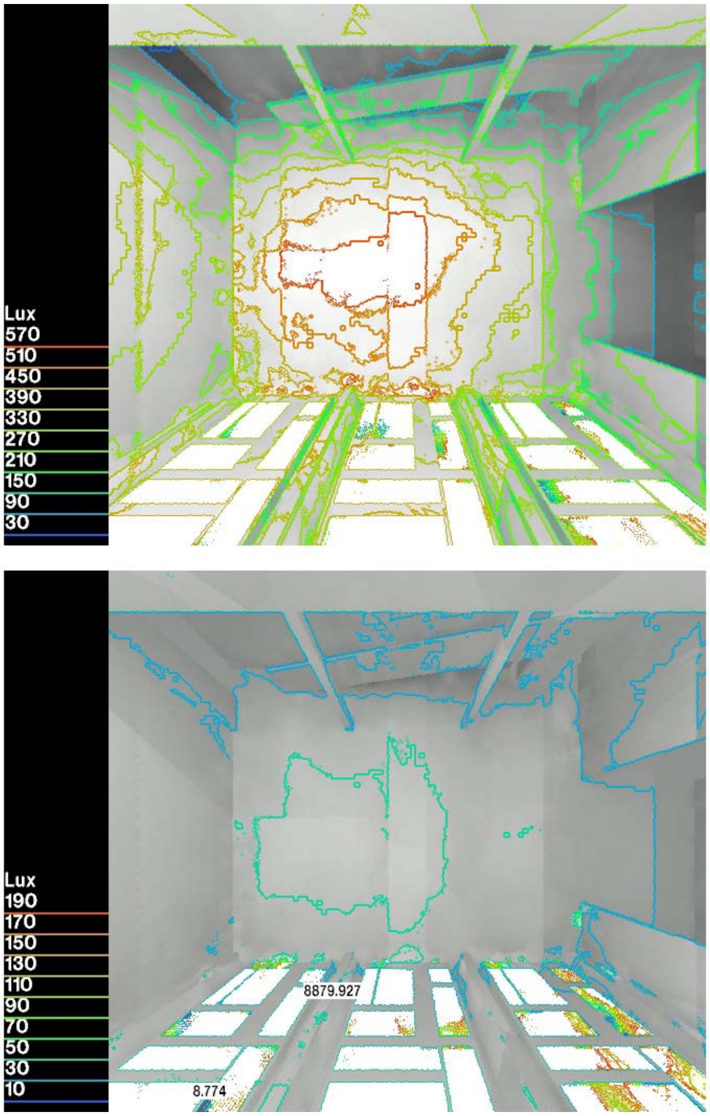


Figure B 12 False color image under the clear sky (upper) and overcast sky condition (lower) (Southeast gallery, 12:00 PM, Jun 21)

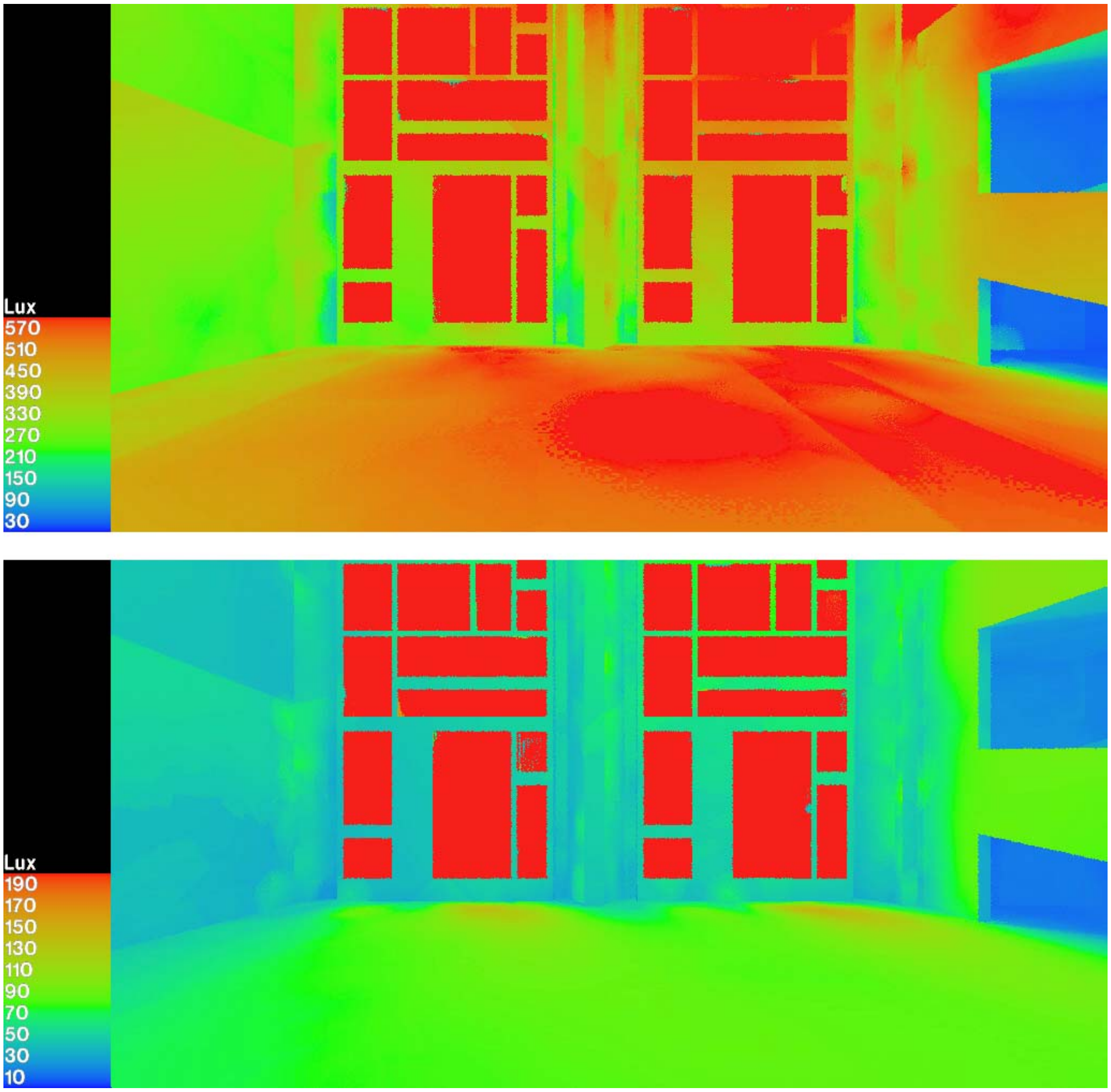


Figure B 13 False color image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Jun 21)

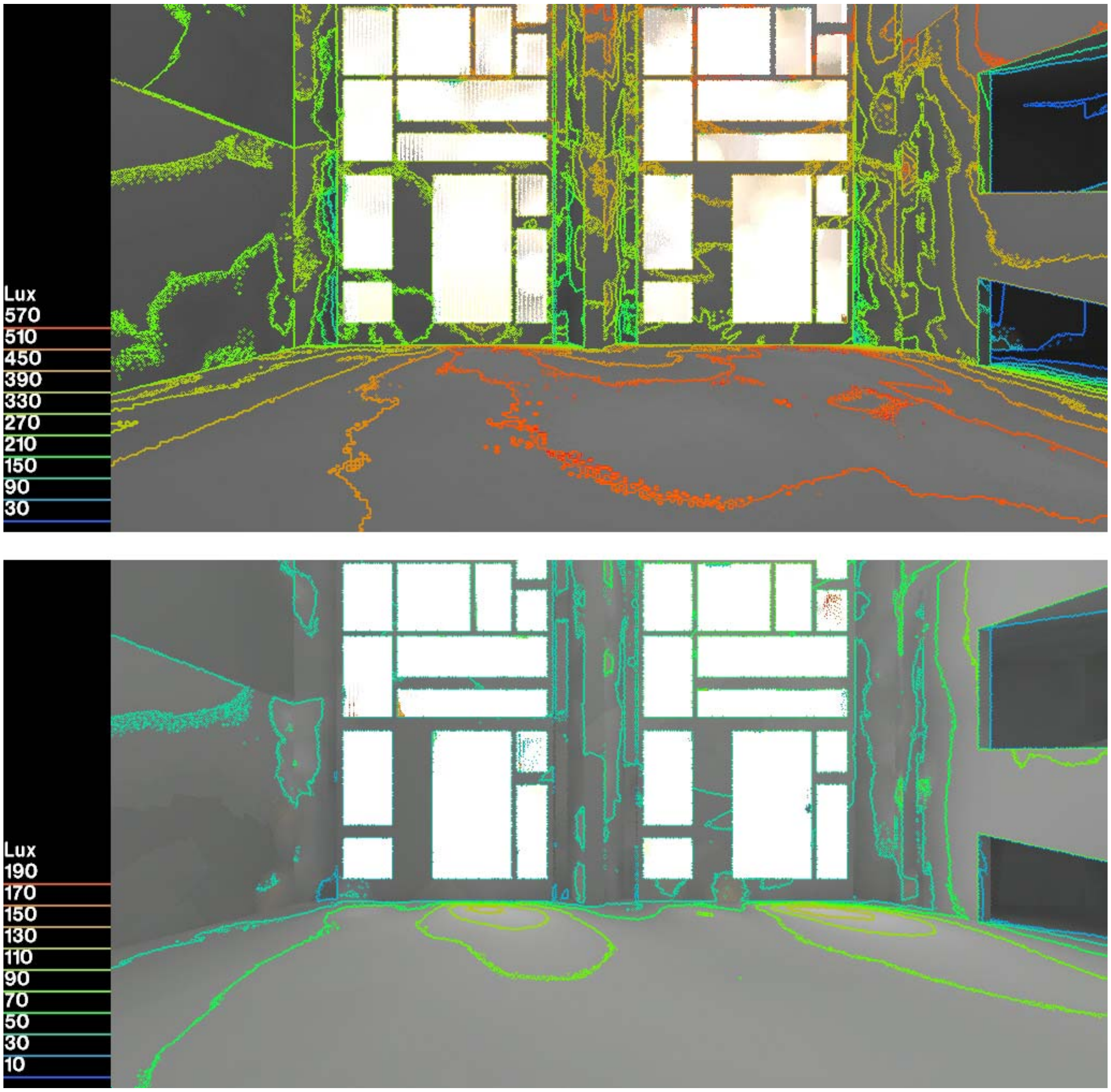


Figure B 14 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Jun 21)

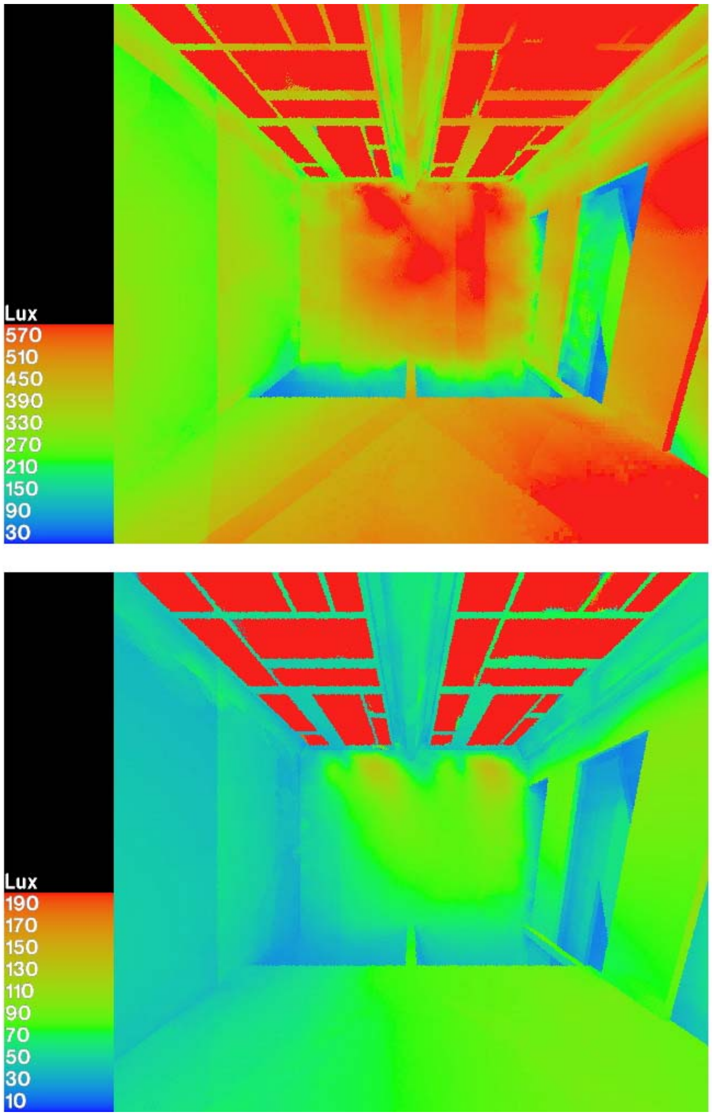
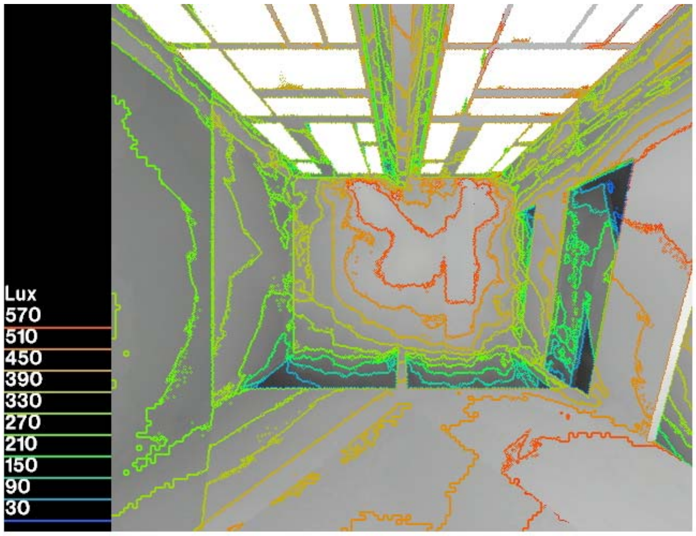


Figure B 15 False color image under the clear sky (upper) and overcast sky condition (lower)
(Northeast gallery, 12:00 PM, Jun 21)



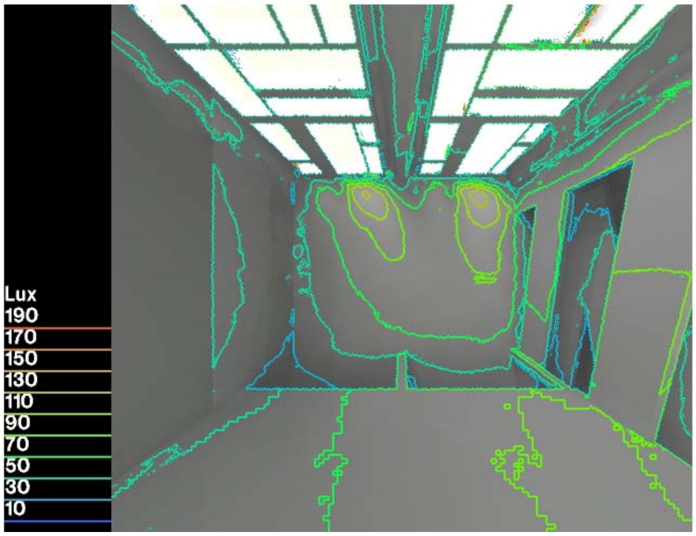


Figure B 16 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Jun 21)

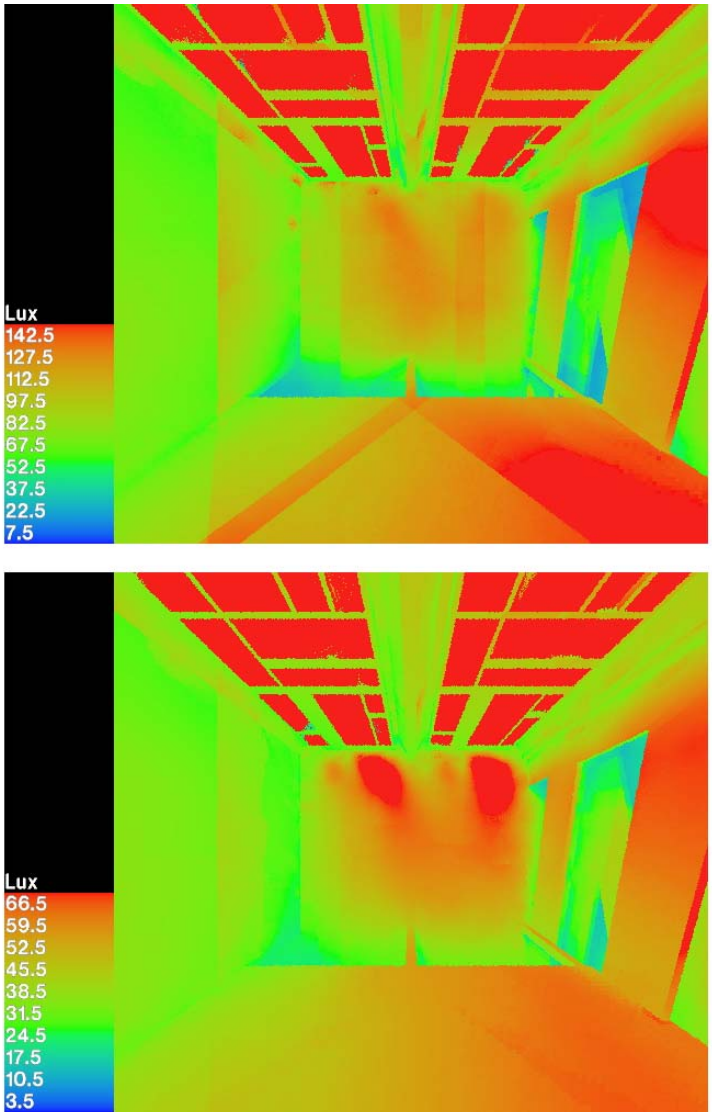


Figure B 17 False color image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Dec 21)

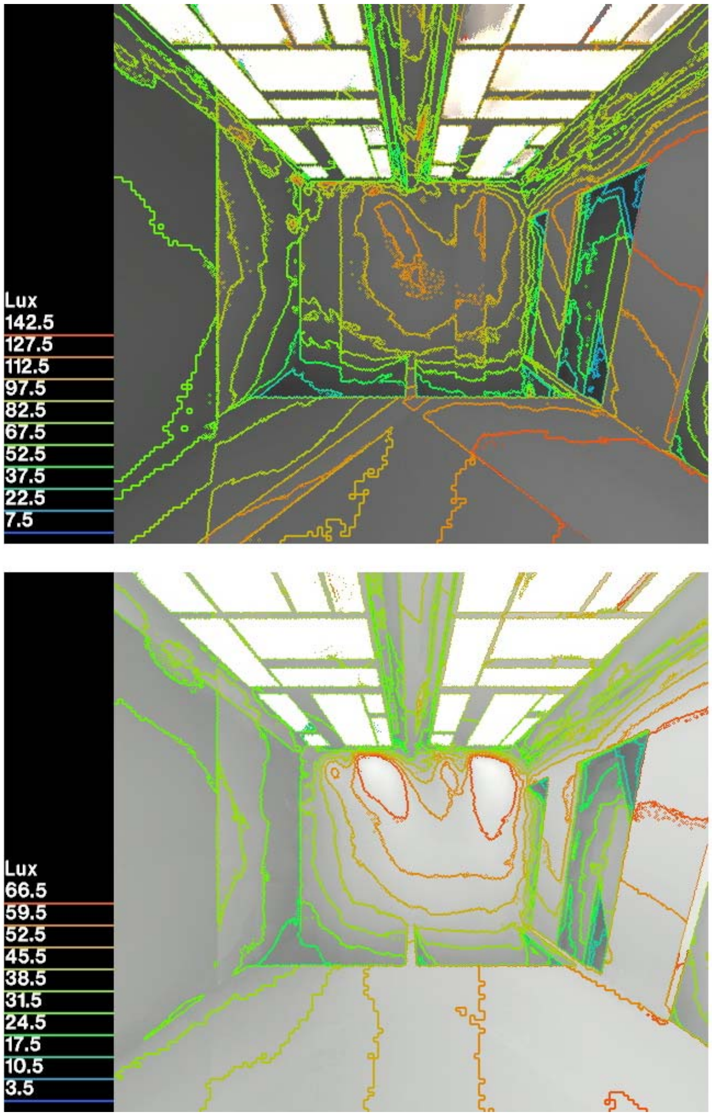
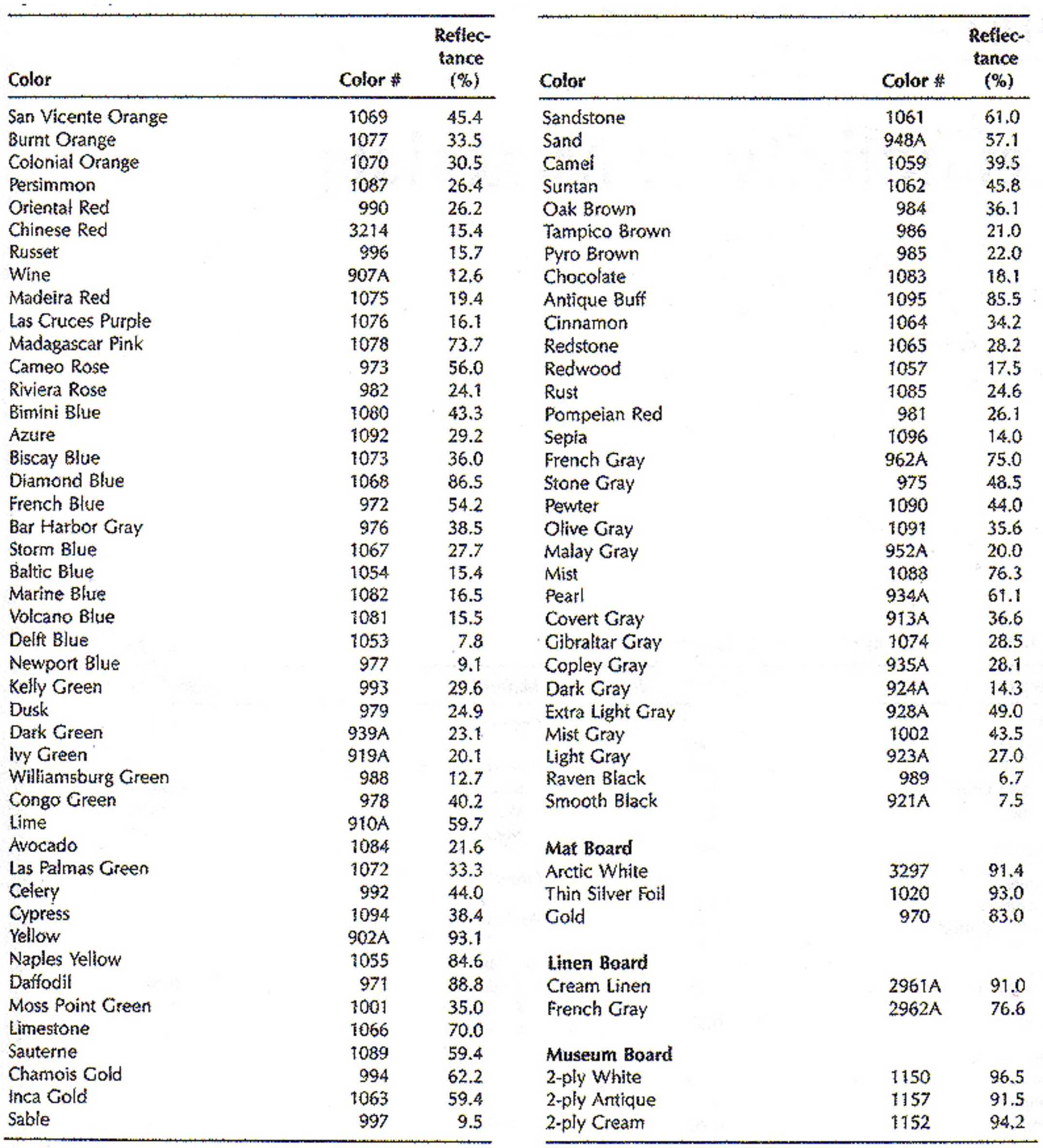


Figure B 18 Iso-contour image under the clear sky (upper) and overcast sky condition (lower) (Northeast gallery, 12:00 PM, Dec 21)

APPENDIX C



Color	Color #	Reflectance (%)
San Vicente Orange	1069	45.4
Burnt Orange	1077	33.5
Colonial Orange	1070	30.5
Persimmon	1087	26.4
Oriental Red	990	26.2
Chinese Red	3214	15.4
Russet	996	15.7
Wine	907A	12.6
Madeira Red	1075	19.4
Las Cruces Purple	1076	16.1
Madagascar Pink	1078	73.7
Cameo Rose	973	56.0
Riviera Rose	982	24.1
Bimini Blue	1080	43.3
Azure	1092	29.2
Biscay Blue	1073	36.0
Diamond Blue	1068	86.5
French Blue	972	54.2
Bar Harbor Gray	976	38.5
Storm Blue	1067	27.7
Baltic Blue	1054	15.4
Marine Blue	1082	16.5
Volcano Blue	1081	15.5
Delft Blue	1053	7.8
Newport Blue	977	9.1
Kelly Green	993	29.6
Dusk	979	24.9
Dark Green	939A	23.1
Ivy Green	919A	20.1
Williamsburg Green	988	12.7
Congo Green	978	40.2
Lime	910A	59.7
Avocado	1084	21.6
Las Palmas Green	1072	33.3
Celery	992	44.0
Cypress	1094	38.4
Yellow	902A	93.1
Naples Yellow	1055	84.6
Daffodil	971	88.8
Moss Point Green	1001	35.0
Limestone	1066	70.0
Sauterne	1089	59.4
Chamois Gold	994	62.2
Inca Gold	1063	59.4
Sable	997	9.5
Sandstone	1061	61.0
Sand	948A	57.1
Camel	1059	39.5
Suntan	1062	45.8
Oak Brown	984	36.1
Tampico Brown	986	21.0
Pyro Brown	985	22.0
Chocolate	1083	18.1
Antique Buff	1095	85.5
Cinnamon	1064	34.2
Redstone	1065	28.2
Redwood	1057	17.5
Rust	1085	24.6
Pompeian Red	981	26.1
Sepia	1096	14.0
French Gray	962A	75.0
Stone Gray	975	48.5
Pewter	1090	44.0
Olive Gray	1091	35.6
Malay Gray	952A	20.0
Mist	1088	76.3
Pearl	934A	61.1
Covert Gray	913A	36.6
Gibraltar Gray	1074	28.5
Copley Gray	935A	28.1
Dark Gray	924A	14.3
Extra Light Gray	928A	49.0
Mist Gray	1002	43.5
Light Gray	923A	27.0
Raven Black	989	6.7
Smooth Black	921A	7.5
Mat Board		
Arctic White	3297	91.4
Thin Silver Foil	1020	93.0
Gold	970	83.0
Linen Board		
Cream Linen	2961A	91.0
French Gray	2962A	76.6
Museum Board		
2-ply White	1150	96.5
2-ply Antique	1157	91.5
2-ply Cream	1152	94.2

Figure C 1 Crescent board material reflectivity for model making (Robbins, 1986)

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