Verification of Light-box Devices for Earth Albedo Simulation

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Contents

1 Objective

The objective of this report is to report the two experiments conducted to verify the design and construction of Light Emitting Diode (LED) light-box devices. The purpose of the light-box devices is to create an illumination environment representative of what would be observed by vision-based navigation systems in space. The light-box devices used in the two experiment were prototypes for a set of light-boxes installed at the Space Rendezvous Laboratory. The structure of the report is as follows: experiments description, results of the experiments, experiment conclusion and comments.

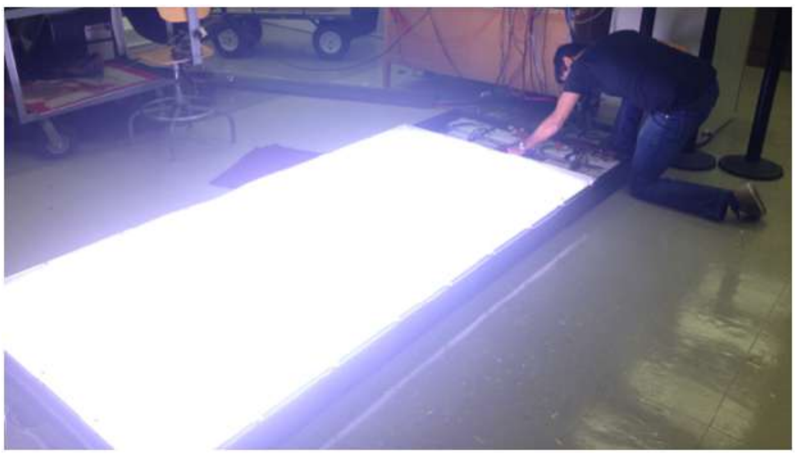

Figure 1: Prototype of the Light-box device.

2 Experiment Description

We conducted two main experiments, which each contained multiple tests. This section details the experiments and the tests conducted therein. The purpose of the first experiment was to compare three candidate diffuser plates on a small scale light-box device and provide a recommendation for the candidate that should be used in the full-scale prototype. The purpose of the second experiment was to measure the radiance of the full-scale prototype and verify that it matched the design prescriptions. Both experiments also verified the construction and general design of the prototypes.

2.1 Diffuser Plate Comparison

This sub-section describes the two tests conducted to compare the candidate diffuser plates, namely, the Plate-LED Separation Test and the Radiance Output Test. Both tests were done for each of the three diffuser plates. The tests conducted as part of this experiment and the associated results concluded in August 2015. The diffuser plates are shown in Figure 2.

Figure 2: Segments of the three diffuser plates used in the experiment; the plate with manufacture marking of (00010, 0.118) is referred to as Plate B, (0M001DC, 0.177) as Plate C, and (W0008, 3.0) as Plate D.

2.1.1 Plate-Frame Separation Test

The objective of the Plate-Frame separation test was to find the separation between the diffuser plate and the light-box frame such that the radiance from the light-box appears to be uniform to the human eye. Specifically, we are interested to find the minimum separation required such that the LED strips inside the light-box, turned to their maximum voltage potential difference, are indiscernible from each other. A lower separation is preferred to minimize construction cost and feasibility. The test was done for each of the three diffuser plates by mounting them on the preliminary light-box prototype frame with spacers.

2.1.2 Radiance Output Test

The objective of the radiance output test was to measure the radiance output of the light-box for each of the diffuser plates as well as to characterize uniformity. The procedure began with each diffuser plate raised on styrofoam columns to a separation distance found from the results of the Plate-Frame Separation Test. The LED strips were switched to their maximum voltage potential difference and the irradiance was measured using the PS-300 Spectroradiometer manufactured by Apogee Instruments. For each of the three diffuser plates, the spectroradiometer probe was

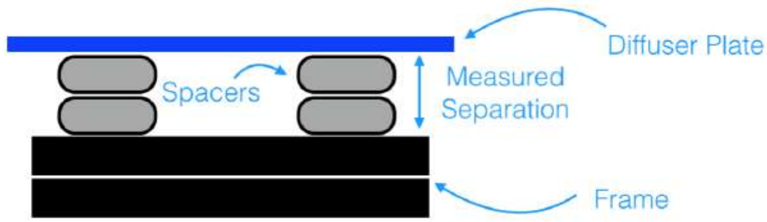

Figure 3: Side view of the light-box during the Plate-Frame Separation.

positioned at eight different positions (see Table 1) to capture the irradiance (or, flux density) at eight different solid angles. The probe was always kept pointed in the negative z direction (see Figure 4). The spectroradiometer outputs raw spectral irradiance, i.e., the irradiance measured for wavelengths ranging from 226nm to 1100nm. Using MATLAB, the spectral irradiance was used to calculate the irradiance for the visible spectrum of light (wavelength of 330nm through 700nm). For each of these eight probe locations, a "zero reading" was recorded to account for radiant flux of sources other than the light-box LED strips. In addition, a dark scan was captured by covering the head of the probe to characterize and subtract spectroradiometer noise.

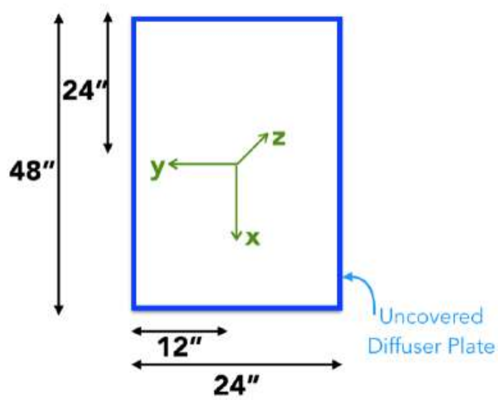

Figure 4: Reference frame for the spectroradiometer probe positions.

The irradiance, $E = \Delta\Phi/\Delta A$, has units of Watts per square meter (W/m^2). It is the radiant flux, $\Delta\Phi$ that is either incident upon or emitted from a surface area ΔA. The radiance, L, has units of Watts per square meter per steradian (W/m^2/sr). It is the radiant flux propagating toward or away from a surface in a specified direction with a solid angle $\Delta\Omega$. The flux is emitted from or incident upon an area, ΔA, inclined at an angle, θ, to the direction of energy propagation. Radiance is then written as $L = \Delta\Phi/(\Delta\Omega\Delta A\cos\theta)$. Since the solid angle $\Delta\Omega$ is defined as

Position	x-position (inches)	y-position (inches)	z-position (inches)
1	0	0	20
2	24	0	20
3	48	0	20
4	48	48	20
5	0	0	44
6	24	0	44
7	48	0	44
8	48	48	44

Table 1: Spectroradiometer probe positions for irradiance measurements

$(\Delta A \cos\theta)/r^2$, radiance can then be simply written as a function of ΔA, θ, r, and E, i.e., $L = (Er^2)/(\Delta A \cos^2\theta)$. Note that r is the Euclidean distance between the emitter and receiver.

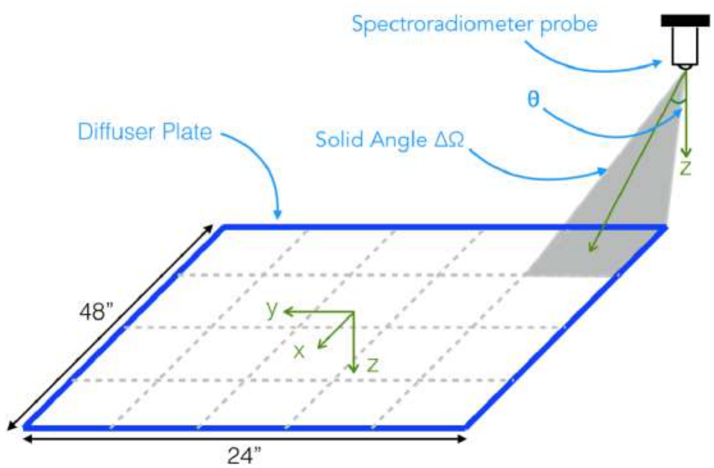

Figure 5: Representation of the virtual discretization of the light-box to calculate projected solid angle, each virtual section had a surface are of 0.01 square inches.

Radiance is essentially the amount of power emitted by a surface that will be received by a sensor looking at the surface from some angle of view (which we have called θ above). We refer to $\Delta\Omega\cos\theta$ as the projected solid angle. We discretize the diffuser plate into small elements each of surface area ΔA (Figure 5) and calculate the projected solid angle for each. These projected solid angles are then summed to report a projected solid angle $(\Omega\cos\theta)$ for the entire light-box as viewed from the spectroradiometer. In our computation, we used 115,200 cells each with surface are of 0.01 sq. in. to discretize the surface of the diffuser plates.

2.2 Full-Scale Prototype Verification

This sub-section describes the two tests conducted to verify the illumination properties of the full-scale prototype of the light-box device. Figure 1 shows the full-scale prototype light-box device used in this experiment. The tests conducted as part of this experiment and the associated results concluded in December 2015.

2.2.1 Radiance Output Test

The objective of this test was to measure the irradiance output of the entire light-box (measuring 98.8 inches x 48 inches) when mounted vertically. The prototype was mounted on a wall at the Space Simulator Room in Durand 006, in the same manner in which the production version light-boxes are expected to be mounted (see Figure 6).

Figure 6: Full-scale prototype light-box device mounted vertically to a wall at the Space Rendezvous Laboratory.

The LED strips were switched to their maximum and the irradiance was measured using the PS-200 spectroradiometer (manufactured by Apogee Instruments). The spectroradiometer probe was positioned at eight different positions (see Table 2) to capture the irradiance (or, flux density) at eight different solid angles. The probe was always kept pointed in the negative z direction (see Figure 7). For each of these eight probe locations, irradiance measurements were recorded four times. With the light-box switched off, a single "zero reading" was recorded to account for the for radiant flux of sources other than the light-box LED strips.

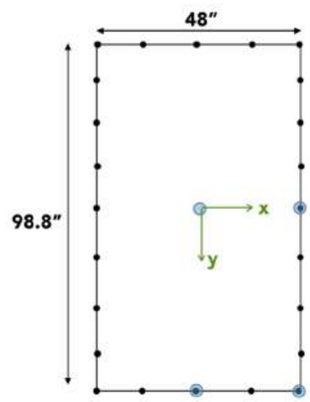

Figure 7: Reference frame for the spectroradiometer probe positions. Black dots represent mounting studs while blue circles represent measurement locations.

Position	x-position (inches)	y-position (inches)	z-position (inches)
1	0	0	-20
2	0	0	-45
3	0	48	-20
4	0	48	-45
5	24	0	-20
6	24	0	-45
7	24	48	-20
8	24	48	-45

Table 2: Spectroradiometer probe positions for irradiance measurements of the complete illumination experiment.

2.2.2 Plate-LED Separation Test

This test was conducted to measure the separation between the LED mounting panel and the front of the diffuser plate. Since this distance directly influences the diffusion of the light, it is necessary to ensure that the diffuser plate does not flex excessively in any region of the light-box device. Figure 8 shows the distance measured in this test. This distance was measured at several locations along the height of the light-box device.

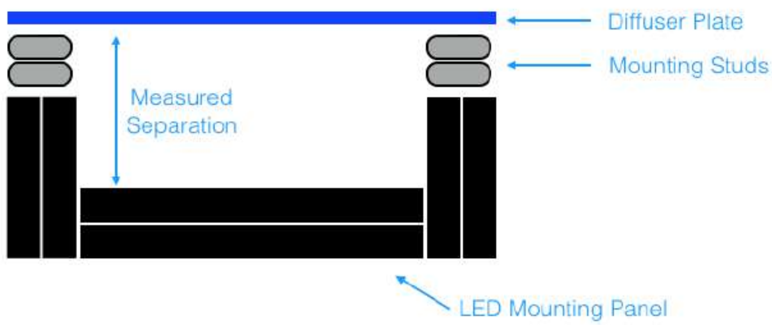

Figure 8: Measurement of the distance between the diffuser plate and the LED's.

3 Results

3.1 Diffuser Plate Comparison

3.1.1 Qualitative Assessment of Construction

The light-box always appeared the brightest as soon as it was turned on, it was operated with all Red, Green, Blue (RGB) and white LED strips turned on to their maximum voltage setting (see Figure 9). We found that this prototype could only be operated for a maximum of 15 minutes at a stretch at this setting before the controller starts switching LED's off due to heat accumulation in the LED dimmer (see Figure 10). Some of the RGB LED's in one of the strips were malfunctioning (see Figure 11). The fans in the HRP 600 power supply (see Figure 12) made loud audible noise during normal operation.

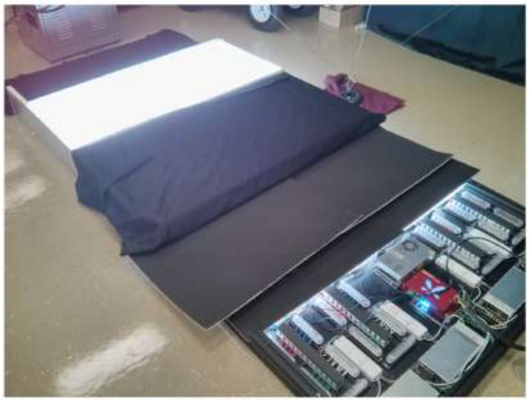

Figure 9: Light-box with all RGB and white LED strips at maximum voltage setting. Sections of light-box not being tested were covered with black cloth.

3.1.2 Plate-LED Separation Test

Table 3 summarizes the minimum separation required between the light-box frame and the diffuser plate to obtain uniform illumination.

Diffuser Plate	Plate-Frame Separation Test (inches)
B	4
C	5.5
D	2.25

Table 3: Minimum Plate-Frame Separation required for each diffuser plate.

Figure 10: Light-box after a 15 minute operation. The two band of LED strips on the peripheries were automatically switched off by the LED controller.

Figure 11: Malfunctioning RGB LED strips in the light-box, this particular section was not used in the Radiance Output Test.

3.1.3 Radiance Output Test

For each of the eight spectroradiometer probe locations, respective ”zero readings” were subtracted from the respective measurements to remove the effect of stray radiant flux from the radiant flux of the light-box. Spectral irradiance for the visible spectrum was then integrated to report the irradiance (see Figure 13) as a function of spectroradiometer probe position (expressed in projected solid angle, $\Omega \cos\theta$). We see that diffuser plate B has the highest irradiance for all probe positions, followed closely by diffuser plate C. Next, in Figure xx, we report radiance as a function of spectroradiometer probe position (expressed in projected solid angle, $\Omega \cos\theta$). We see that for all diffuser plates radiance is relatively uniform for projected solid angles greater than 0.3 steradian. As expected from the irradiance plot, the diffuser plate B has the greatest radiance while plate D has the least radiance. Relatively non-uniform radiance for small values of projected solid angle is expected as the spectroradiometer sees the light-box illumination in the fringes of its field of view, i.e., at high zenith angles. Apogee Instrument reports that the Cosine response of the

Figure 12: Light-box electronic housing. The components marked with red are the LED dimmers while the components marked in green are the HRP 600 power supply units.

PS-300 is expected to deteriorate at high zenith angles (±4% at 80°). Diffuser plate D has the most uniform radiance, followed by diffuser plates B and C, respectively.

3.2 Full-Scale Prototype Verification

3.2.1 Qualitative Assessment of Verification

The full-scale light-box prototype was turned on with all RGB and white LED's at max power. It was in this configuration for a minimum of one hour. There were very faint lines between LED strips (see Figure 15). Unlike the previous prototypes there was no audible noise from the fans in the power supply. The back-panel was warm to touch. The illumination from the edges of the light-box were visibly not uniform (see Figure 16). There were no apparent issues from vertically mounting the prototype.

3.2.2 Plate-LED Separation Test

The measurement of the separation between the LED's and the front of the diffuser plate (see Figure 8) was taken in the following two step procedure:

- Measurements from the LED mounting panel to front of diffuser plate at the bottom center edge subtracted from measurement from back of light-box to front of diffuser plate. Assumed as a constant baseline separation of LED from back panel: 0.55 cm.
- Measured distance from back panel to front of the diffuser plate at multiple locations along the height of the light-box prototype and subtracted constant baseline for distance between LED and front of the diffuser plate:
  - Minimum plate-LED separation distance: 13.95cm 5.5 in.

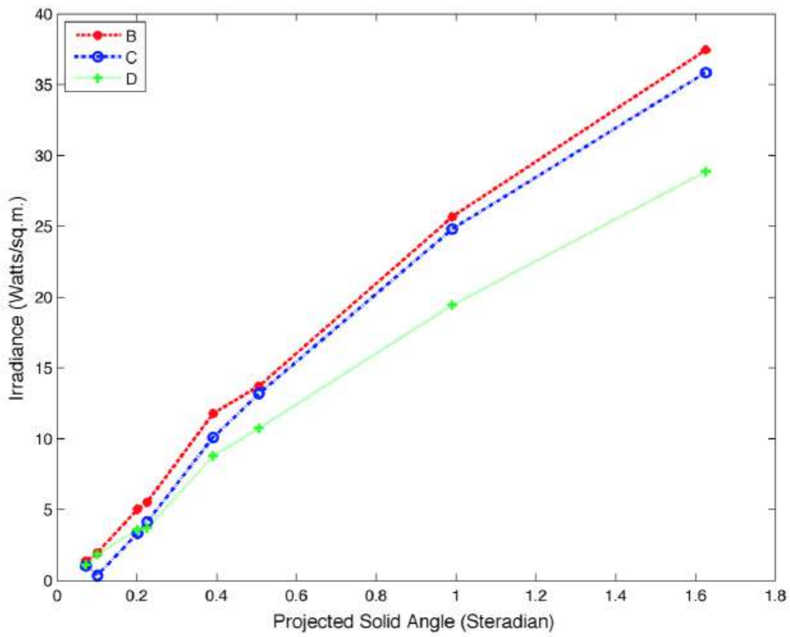

Figure 13: Irradiance for each of the three diffuser plates for varying spectroradiometer probe position, expressed as projected solid angles, i.e., $\Omega \cos \theta$.

– Maximum plate-LED separation distance: 14.35cm 5.65 in.

3.2.3 Radiance Output Test

Figure 17 and 18 show the plots for irradiance and radiance as a function of solid angle. The irradiance plot shows reasonable trend from expectation, with slight deviations due to measurement technique and edge uniformity issues. Note that the spectroradiometer probe was hand-held during this test. The radiance data shows spikes from the expected flat line due to the measurement technique and edge uniformity issues. In particular, there is a gradual drop off in the irradiance output near the edges of the light-box.

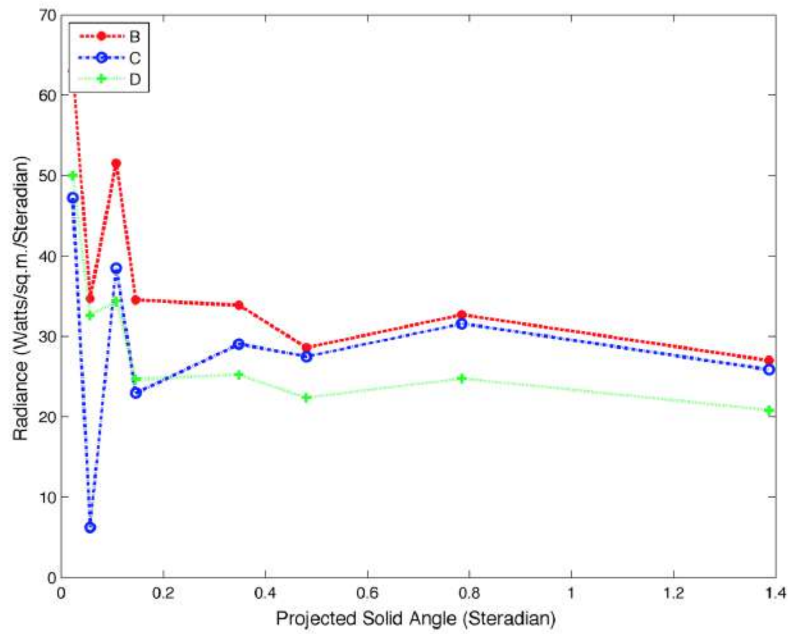

Figure 14: Radiance for each of the three diffuser plates for varying spectroradiometer probe position, expressed as projected solid angles, $\Omega \cos\theta$.

4 Conclusions

We conclude that the diffuser plate D requires the minimum separation from the frame of the light-box, followed by plates B and C. Plate D also has most uniform radiance, followed closely by plate B. However, plate D has a much lower irradiance (and radiance) output. Since plate B has the highest radiance output and is a close second in radiance uniformity, we recommend using the diffuser plate B (manufacture marking 00010, 0.118) for the construction of the light-box. We can also conclude that the uncertainty in determining radiance increases with higher zenith angles as the spectroradiometer response deviates from the cosine response. More experiments are needed to characterize the radiance uniformity at such high zenith angles. In context of the hardware used in the construction of the preliminary light-box prototype, 15 minutes of operation is unacceptable for our application. However, in the next iteration of the hardware, this limitation was alleviated and the full-scale light-box prototype could be used continuously for one hour at maximum voltage. The audible noise from the power supplies and malfunctioning LED's were also notable absent from the full-scale prototype. In context to the full-scale prototype radiance output testing, the light-box meets the requirement of outputting 14 Watts/m^2/sr at all tested solid angles. However, it should be noted that since LED's do not span all the way to the edges of the light-box there is a

Figure 15: LED visibility.

Figure 16: Edge gradient.

gradual drop-off in uniformity near the edges. Further rigorous experiments need to be carried out to characterize the drop in uniformity.

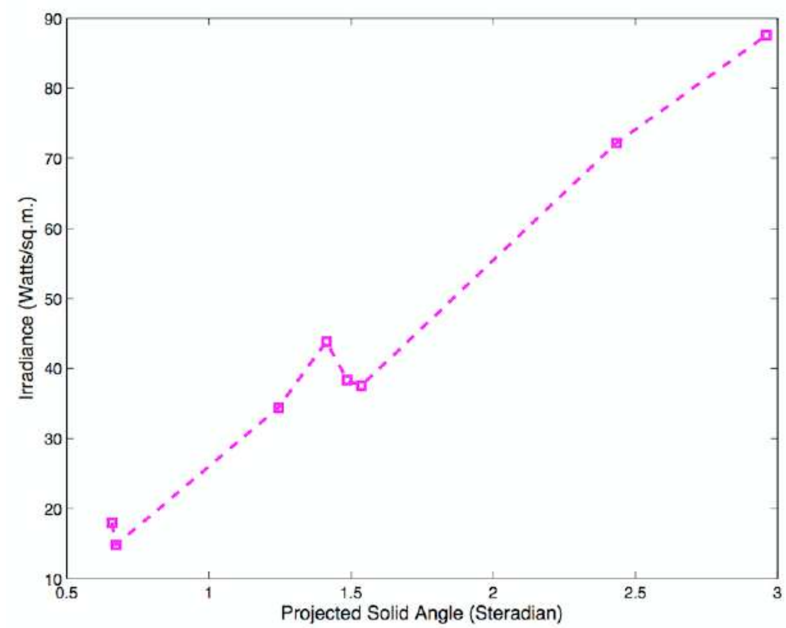

Figure 17: Irradiance data plotted for the eight projected solid angles used in the Radiance Output Test.

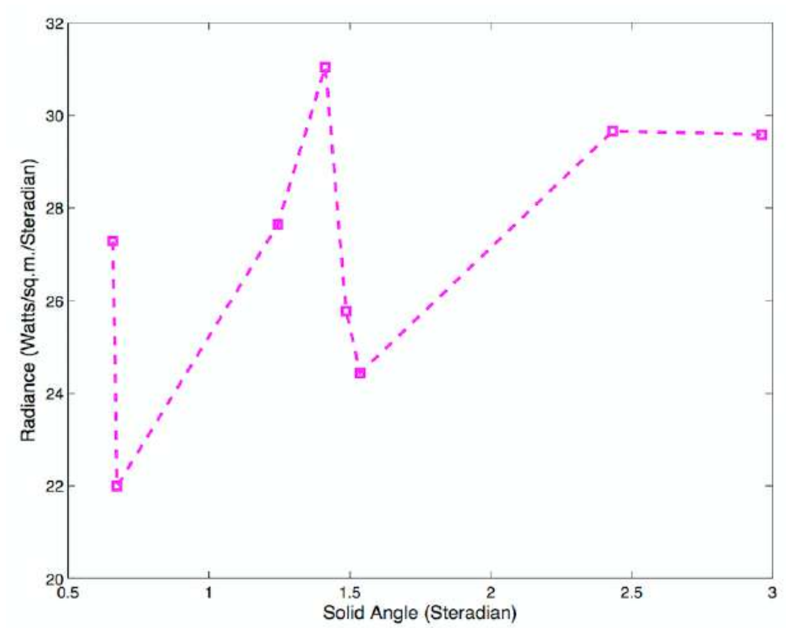

Figure 18: Radiance data plotted for the eight projected solid angles used in the Radiance Output Test.