On the sensitivity of daylight simulations to the resolution of the hemispherical basis used to define bidirectional scattering distribution functions

Andrew McNeil

Building Technologies Program, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Mailstop 90-3111, 1 Cyclotron Road, Berkeley, CA 94720 USA

Abstract

The Radiance simulation program includes new tools that enable daylight modeling of complex fenestration systems (CFS) using bi-directional transmission distribution functions (BTDF). The tools use the Klems angle basis to define the number of paired incoming and outgoing data values. However, the Klems angle basis was developed for thermal simulations and may be too low of a resolution for some types of daylight systems, particularly those that exhibit peaky, specular transmission. This study evaluates the sensitivity of the angle basis resolution by comparing simulation results for the Klems angle basis against results using two higher resolution angle bases. The first evaluation compares results for specific points in time. The second evaluation compares simulation results using annual performance metrics. Annual lighting energy data were found to agree to within 1%. Annual assessments of discomfort glare were found to disagree by 7% because high resolution basis resolved glare sources into smaller, more intense sources. We concluded that high resolution bases are appropriate for specific types of CFS and performance metrics.

Keywords: Daylighting; Windows; Shading Systems; Complex Fenestration Systems; Bi-directional Transmittance Distribution Functions.

1. Introduction

Radiance is a free, open-source lighting simulation program [1]. Recent Radiance feature additions enable users to simulate optically complex fenestration systems using bi-directional scattering distribution functions (BSDF). A BSDF is essentially a table of reflectance and transmittance coefficients for incident and outgoing directions. Many of the new Radiance tools support only the full Klems angle basis used by Window 6 [2].

The full Klems basis [3] divides a hemisphere into 145 divisions. Light incident on a window is averaged over a Klems division, and then distributed over 145 outgoing directions according to the BSDF coefficients. In general, both the quantity and spatial distribution of transmitted flux are accurate. However, in specific cases, it is possible that significant errors may occur.

Errors in the quantity of flux transmitted are possible for a CFS with abrupt changes in light transmission for small changes in incident angle. Transmission for some incident angles within the Klems division will vary significantly from the average transmission of the division if there are abrupt changes in transmission over incident angles contained in a the Klems division. For example, flux from a point source that strikes the CFS at an angle that would have theoretically low transmission is transmitted instead at the (higher) average transmission of the Klems division. Errors in spatial distribution of flux can occur for systems with peaky output. The output peak is averaged over the Klems division, spreading what would be a sharp peak of light by many degrees.

Bi-directional transmission distribution functions (BTDF) data are currently used in two types of Radiance analysis: static single condition simulations (renderings or illuminance calculations) and dynamic annual simulations (using the three-phase method):

- The typical goal of a static simulation is to provide an accurate representation of light in the space for the simulated condition. For a rendering, this is typically a photo-realistic rendering. The smeared look of a space rendered using a Klems basis BTDF to characterize a fenestration system is likely to be deemed unacceptable by many users. These types of simulation require a variable resolution BTDF capable of reproducing sharp peaks which is not currently supported by Radiance.
- A dynamic annual simulation, however, is characterized by a smeared look because of how light from the sun is handled. Many argue that averaging is preferred for an annual simulation because an individual time step solution represents conditions over a period of time, commonly one hour. However, averaging introduced by a BTDF may still introduce systematic errors in an annual analysis, particularly for a CFS with peaky output.

This study aims to determine the sensitivity of simulation results to BTDF resolution for various daylight simulations. The study looks at three BTDF resolutions for an example CFS. The full Klems angle basis is used as a reference. Two higher resolution angle bases were created by subdividing the full Klems angle basis creating a 2x Klems angle basis and 4x Klems angle basis (Figure 1). Simulation results for various times of day and year are evaluated in detail. Annual simulations results are also compared.

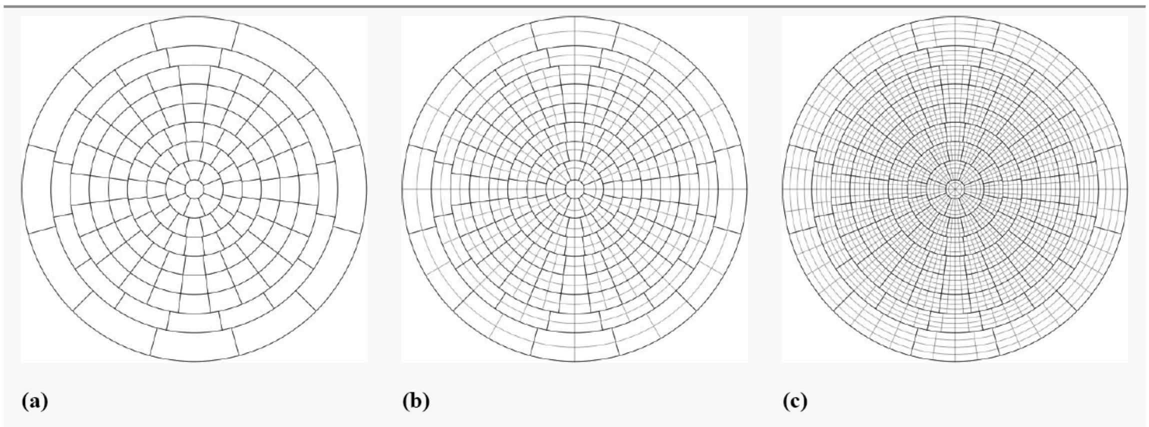

Fig. 1. Three angle bases used for BTDF resolution sensitivity study (a) full Klems:145 divisions, (b) 2x Klems: 580 divisions, (c) 4x Klems: 2320 divisions.

2. Generating the BSDF datasets

The Radiance *rtcontrib* tool was used to produce illuminance and luminance data in an open plan furnished office zone with clerestory daylight windows and view windows. The clerestory window was modeled with an idealized passive optical light shelf known to produce "peaky" specular distributions. The lower windows were modeled with conventional glazing. A detailed description of the 17.1 x 17.1 x 2.9 m office zone is given in the Appendix.

The Radiance *genBSDF* tool was used to generate the BSDF datasets for a passive optical light shelf. Geometry for the device was provided by the manufacturer. A hypothetical highly reflective, highly specular material was used for its surfaces. The material is perhaps unrealistically close to an ideal mirror. However, the intent is to study BTDFs with sharp peaks and a more specular material provides sharper peaks for the study.

For this device, BTDFs were created at the three different levels of basis resolution. The *genklemsamp* tool was modified to generate sample rays for the subdivided Klems angle bases. Additionally, *cal* files were created to allow *rtcontrib* to accumulate contributions for subdivided Klems divisions. Each BTDF was created by tracing 9,280,000 sample rays: a) 64,000 per division for the full Klems BTDF, b) 16,000 per division for 2x Klems subdivided basis, and c) 4,000 per division for the 4x Klems subdivided basis. The following Radiance parameters were used for sampling: -ab 2 -ad 1000 -st 0.005 -lw 1e-8.

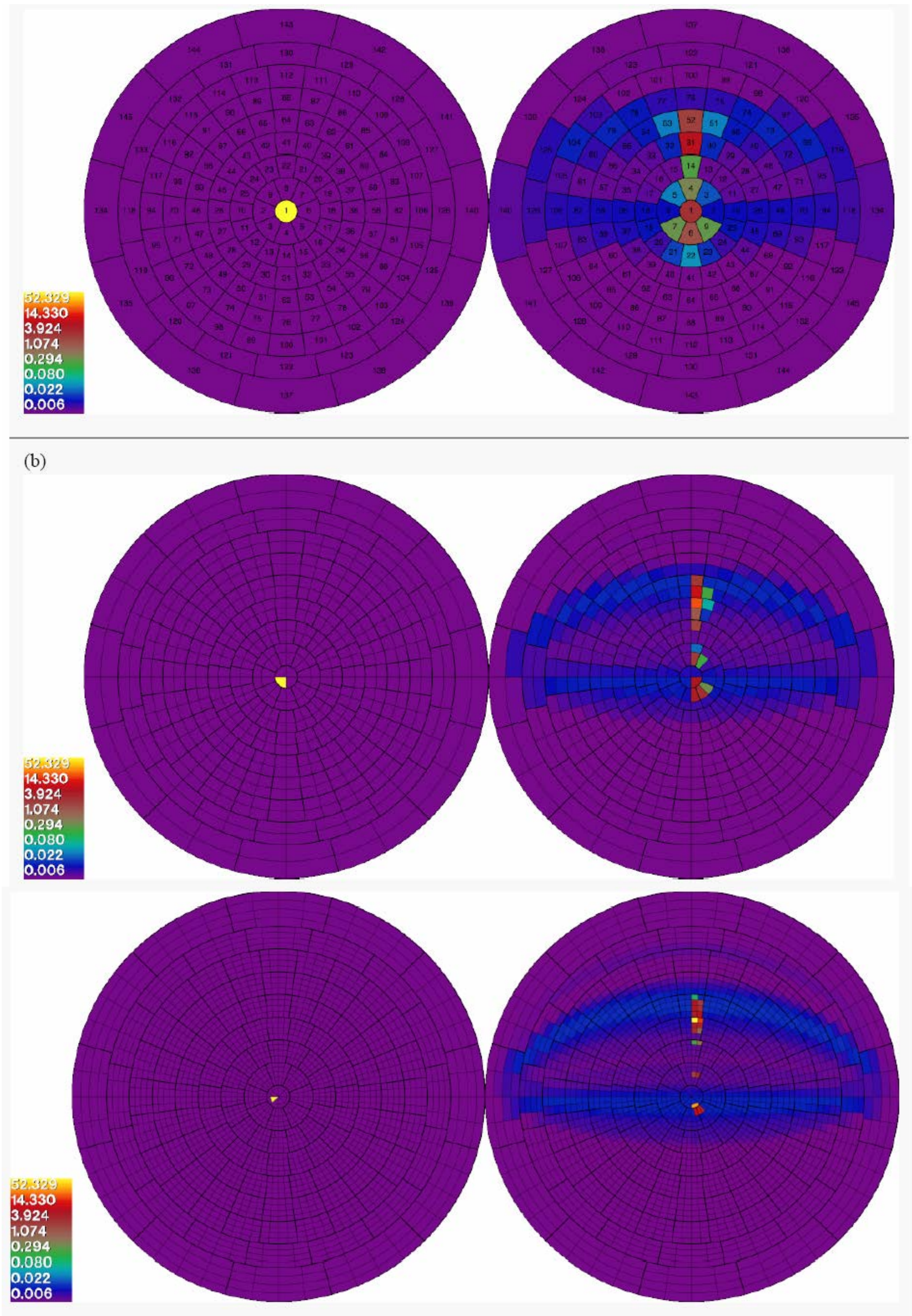

Fig. 2. Visualizations of input and output light distribution for division 1 of (a) full Klems, (b) 2x Klems and (c) 4x Klems angle basis resolution.

Visualizations of the normalized output for one input direction (division 1) for each of the three BTDFs are presented in Figure 2. Remember that size and centroid of incident flux changes for each BTDF which explains some potentially perceived inconsistencies between the BTDFs.

3. Discrepancies between point-in-time simulations

Single, point-in-time simulations were made of the south-facing office zone using the CIE clear sky model for Berkeley, California (latitude 38°N). Nine simulations were run: three times of day (10:00, 12:00, 14:00 ST) for three days of the year (summer solstice, winter solstice and equinox). Of the nine simulations, two are presented here: the one with the most discrepancy between BSDF resolutions (14:00, December 21) and the one with the least discrepancy between BSDF resolutions (10:00, March 21).

3.1. Window output distribution

Figures 3 and 4 depict the luminous output of the south-facing clerestory window with the passive optical light shelf for the two incident angles defined by December 21 at 14:00 and March 21 at 10:00, respectively. For each figure, the top row of images show the luminance output of the window projected on the outgoing Klems basis hemisphere defined by the window looking horizontally into the room. The falsecolor images depict luminance levels with a logarithmic scale. The lower row of images shows the percentage difference in luminance between the 4x Klems and the full Klems basis on the left and then the difference between the 4x Klems and the 2x Klems basis on the right, also with a logarithmic scale.

Note how in Figure 3, sunlight in the afternoon comes from the southwest and is redirected upward to the northeast corner of the zone. In Figure 4, sunlight coming from the southeast is redirected upwards to the southwest corner of the zone. With the 4x Klems basis, the reflected sunlight peak becomes narrower and of greater intensity than the 2x and full Klems basis because the source intensity (the sun) is no longer being averaged between three incoming patches and the reflected sunlight is also being assigned more precisely in its output direction.

The greatest percentage differences (yellow) occurred either at the peak or in the regions where luminance levels were very low. These images serve to illustrate the nature of the problem: high resolution bases produce more accurate intensity and spatial depictions of where luminous flux is distributed within a zone. For peaky systems, like this passive optical light shelf, the output flux intensity could be in error by as much as 200%. Energy is conserved, however; the flux is simply spread out over a larger area with a lower resolution basis.

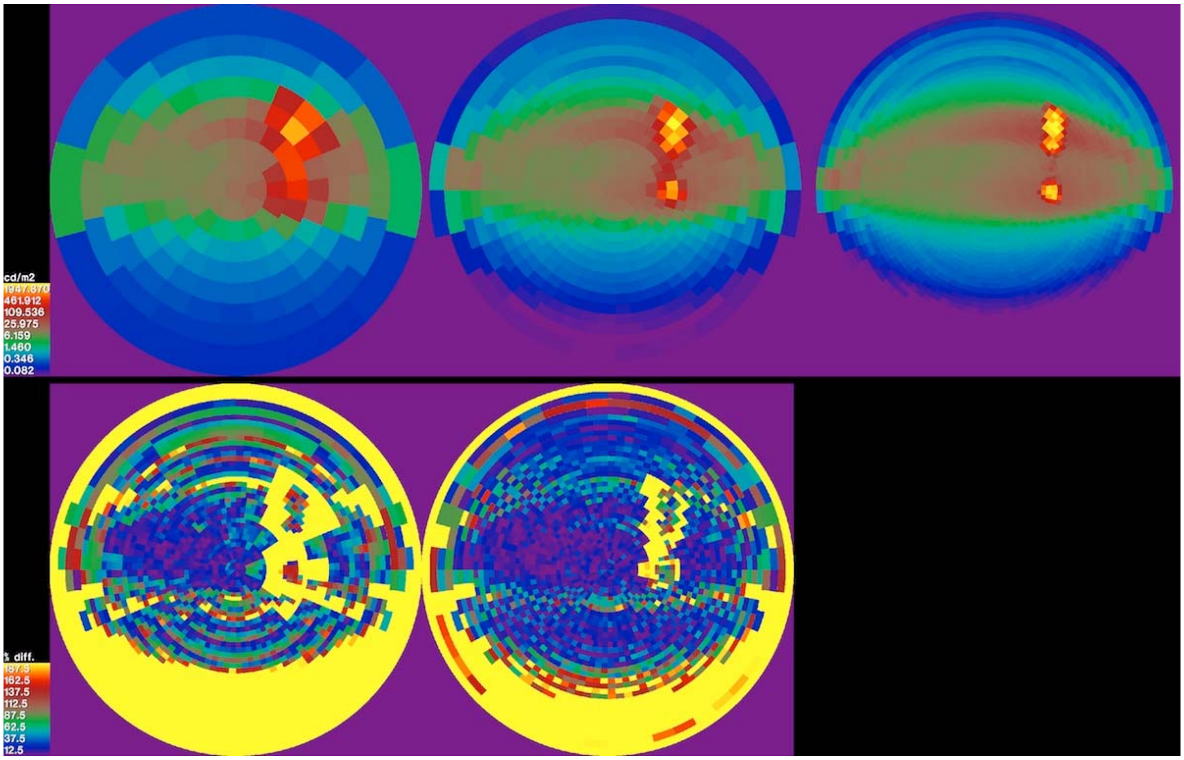

Fig. 3. Window luminance for three BSDF resolutions at 14:00 ST on December 21.

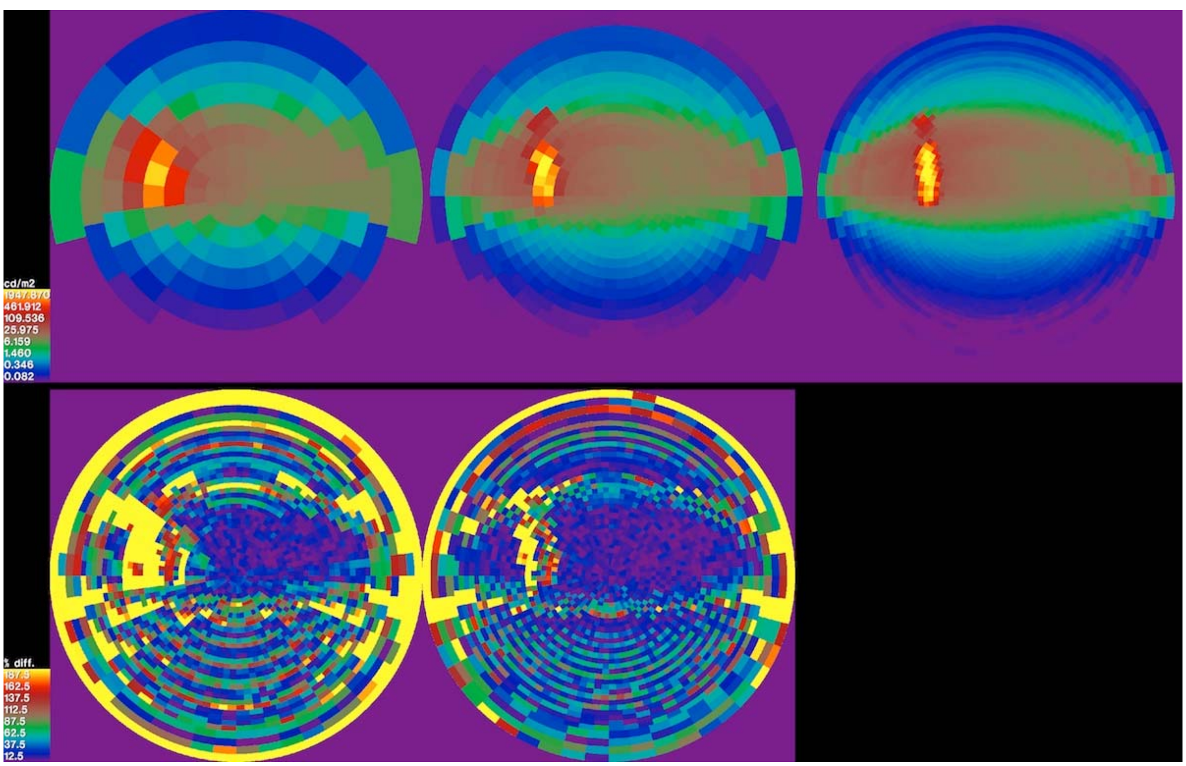

Fig. 4. Window luminance for three BSDF resolutions at 10:00 ST on March 21.

3.2. Illuminance

Similarly, illuminance renderings were produced to illustrate how BSDF resolution can affect the illuminance distribution in a space (Figures 5-6). Note in Figure 5 how the reflected sunlight from the southwest illuminates the corner in the northeast region of the zone (upper right hand corner of the floor plan) producing greater illuminance levels with the 4x Klems rendering (third row of images on the right) compared to that for the full Klems rendering (on the left). The percentage difference in workplane illuminance between the 4x Klems and full Klems basis renderings are shown in the fourth row of images on the left where illuminance levels in the rear zone differed by 80-95% or more. For regions closest to the window, illuminance levels in the second row of workstations were between 22-70 lux and these values differed by 200%.

3.3. Luminance renderings

Luminance renderings are the basis for glare ratings such as the daylight glare index (DGI) and daylight glare probability (DGP) (Figures 7-8). Again in the worst case example with the largest discrepancies, there are significant differences in ceiling luminance level (95% or more) between the full and 4x Klems basis renderings (Figure 7). Note that the upper clerestory window is modeled with the CFS device, not the lower, and one can see luminance of the patches defining the outdoor hemisphere looking out the window. Meaningful glare metrics could not be calculated based on these images: the lack of supplemental electric lighting and daylight from the view windows results in a low adaptation luminance for calculating glare metrics.

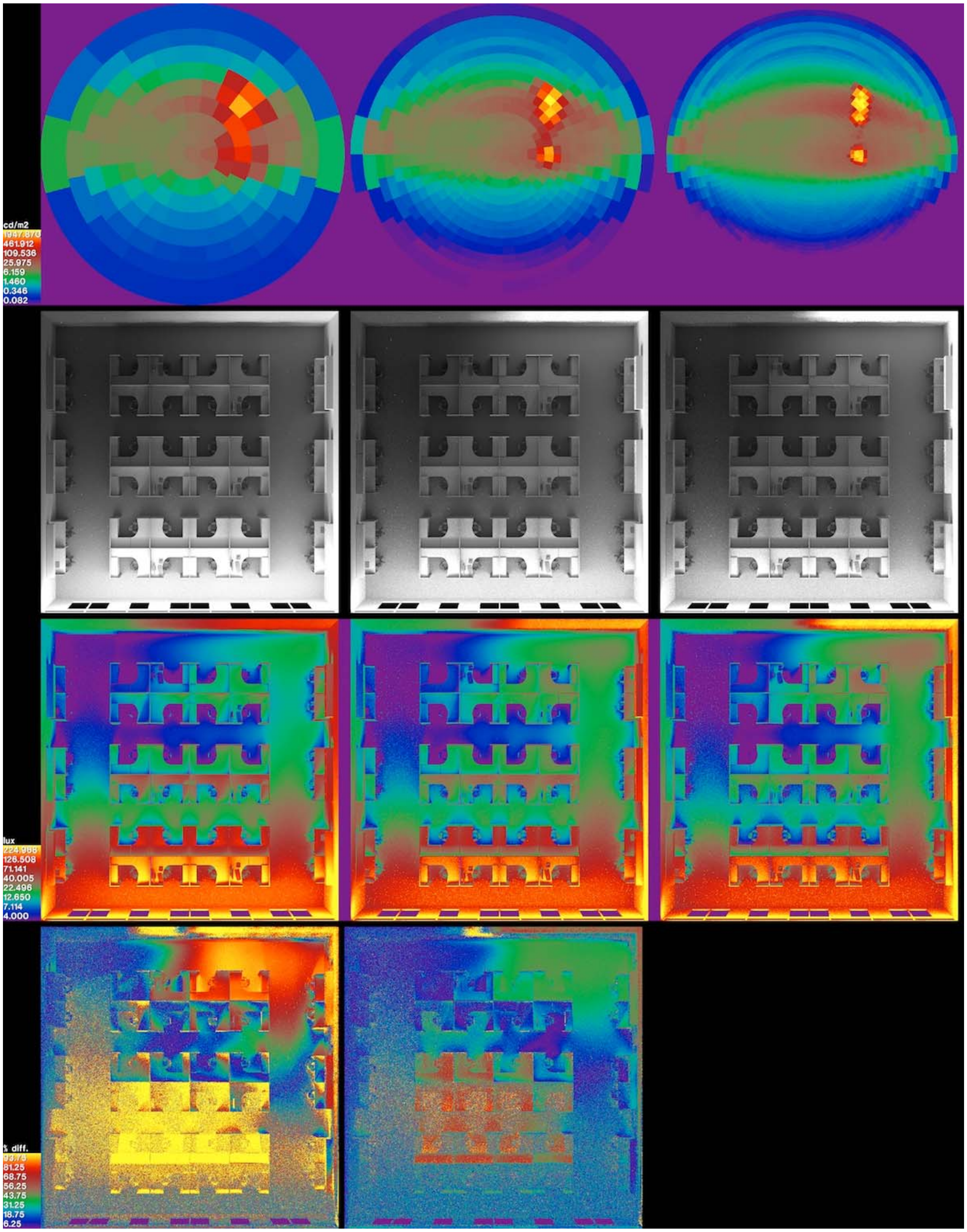

Fig. 5. Floor plan illuminance renderings for three BSDF resolutions at 14:00 ST on December 21. **Top:** window output (for reference). **Middle Top:** Luminance rendering looking down from the ceiling. **Middle Bottom:** Falsecolor rendering of luminance looking down from the ceiling. **Bottom:** Percent difference compared against 4x Klems basis.

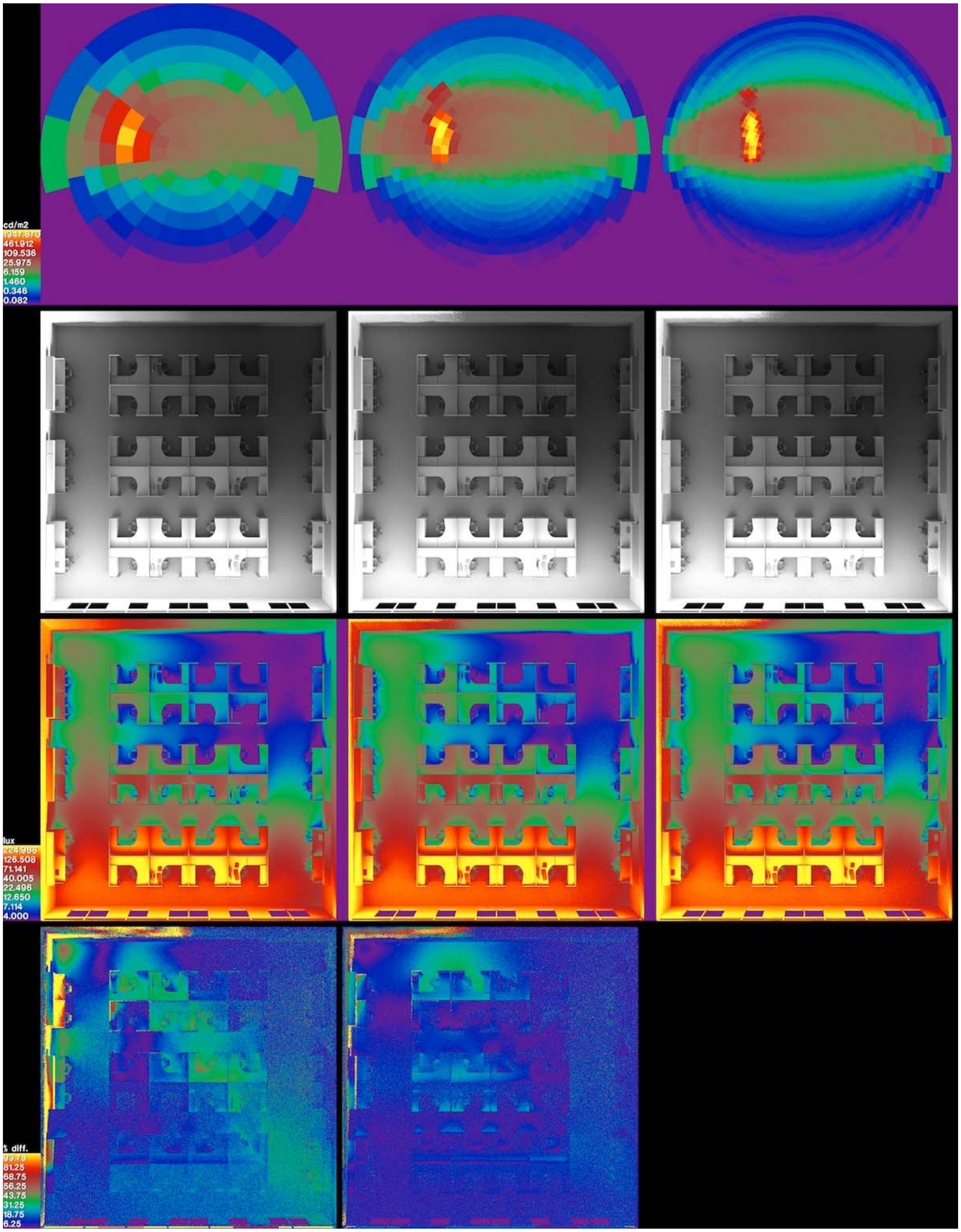

Fig. 6. Floor plan illuminance renderings for three BSDF resolutions at 10:00 ST on March 21**.** **Top:** window output (for reference). **Middle Top:** Luminance rendering looking down from the ceiling. **Middle Bottom:** Falsecolor rendering of luminance looking down from the ceiling. **Bottom:** Percent difference compared against 4x Klems basis.

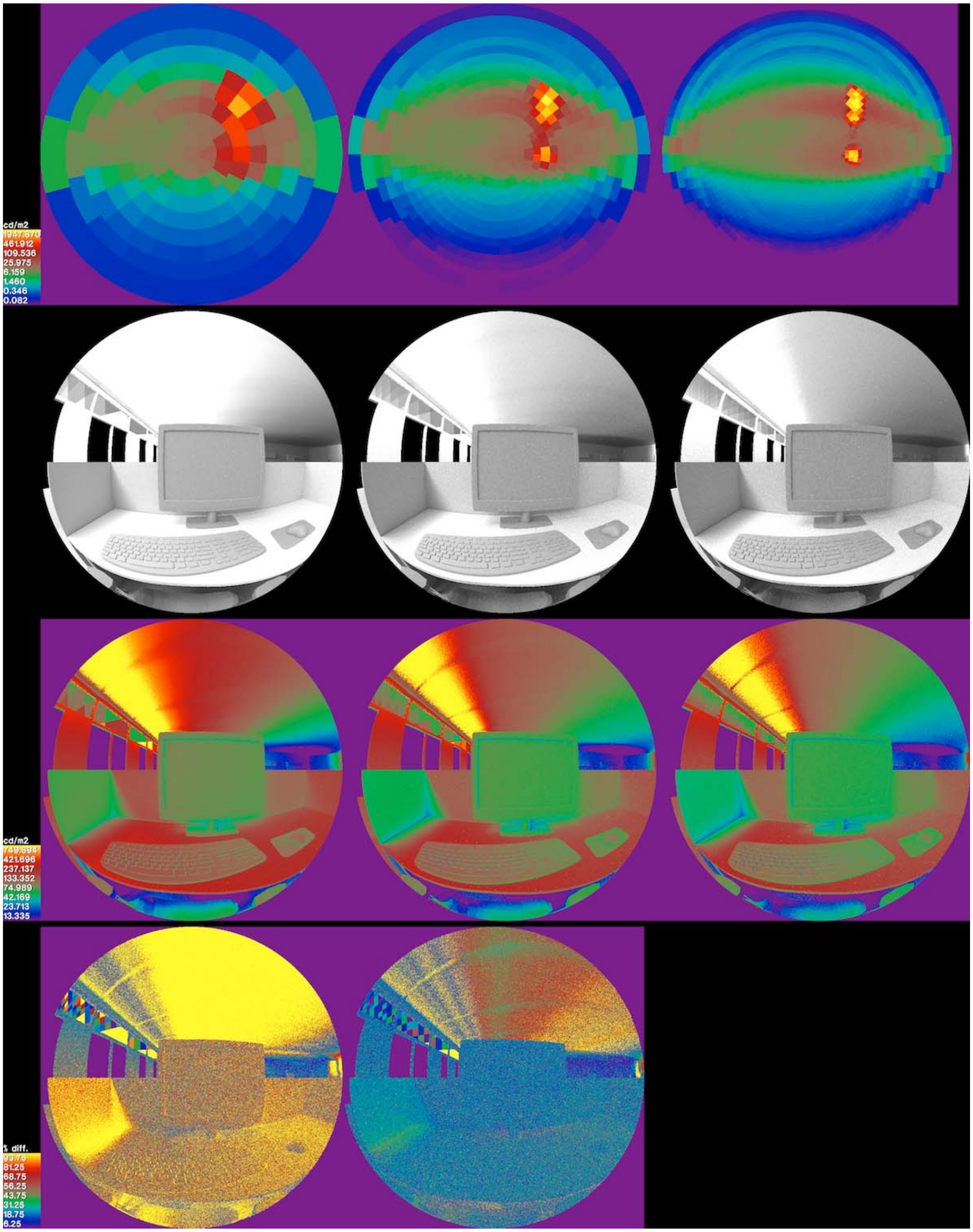

Fig. 7. Hemispherical view renderings for three BSDF resolutions at 14:00 ST on December 21**. Top:** window output (for reference). **Middle Top:** Luminance rendering looking up at ceiling. **Middle Bottom:** Falsecolor rendering of ceiling luminance. **Bottom:** Percent difference compared against 4x Klems angle basis.

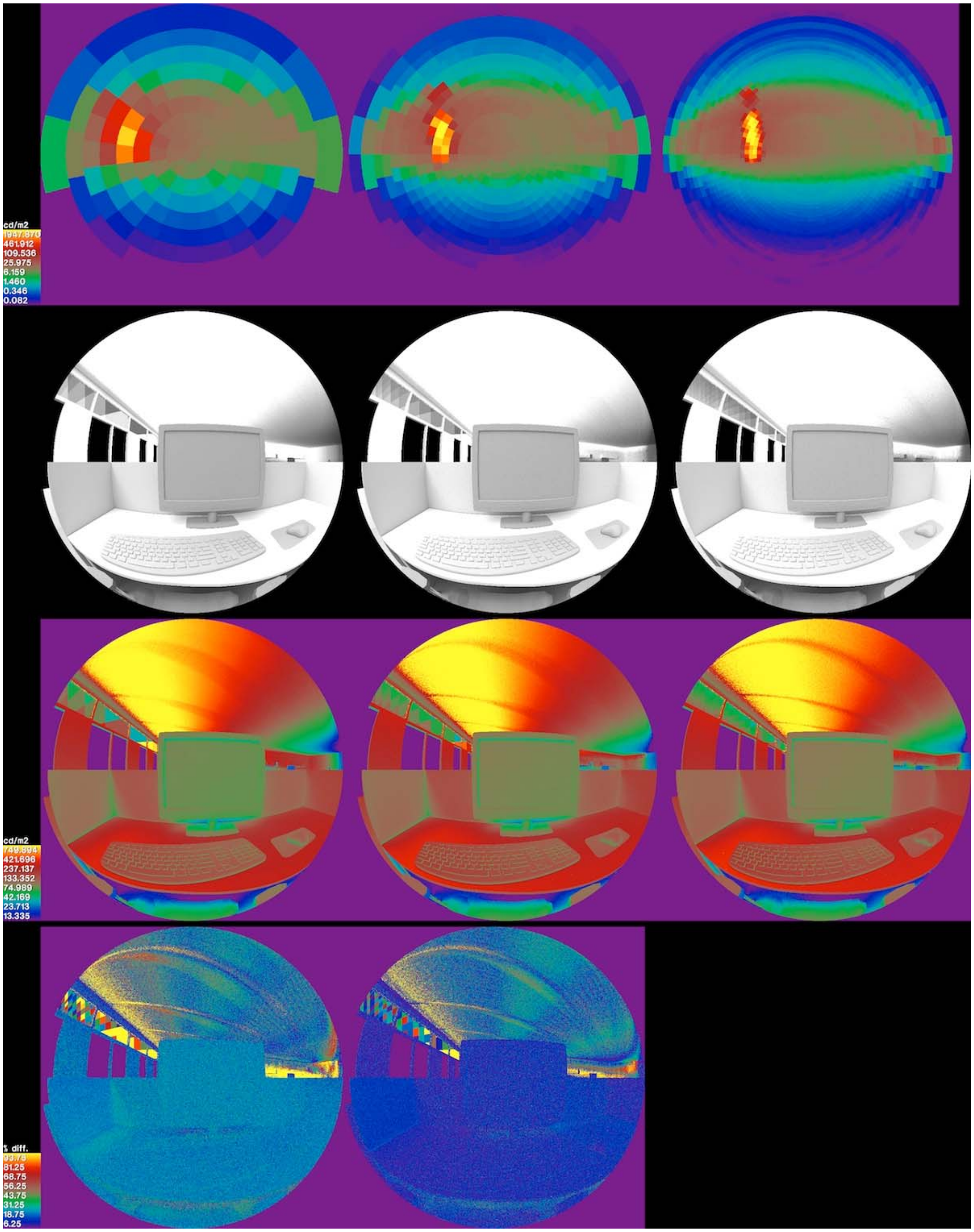

Fig. 8. Hemispherical view renderings for three BSDF resolutions at 10:00 ST on March 21. **Top:** window output (for reference). **Middle Top:** Luminance rendering looking up at ceiling. **Middle Bottom:** Falsecolor rendering of ceiling luminance. **Bottom:** Percent difference compared against 4x Klems angle basis.

4. Annual Simulation

While point-in-time *rtcontrib* calculations have shown that there can be significant differences between simulated values computed with a high versus low resolution basis, one could argue that the flux and spatial distribution is largely correct and further precision is not necessary to evaluate the overall performance of a system. The three phase method of analysis was designed to facilitate annual simulation. Do point in time discrepancies affect accumulated results for annual simulations? To address this question, annual simulations were run using the three BSDF resolutions. The annual simulations used weather data for Phoenix, Arizona and the simulations were run with the passive optical light shelf in the upper window and a venetian blind with a 45° blocking slat angle in the lower window.

Point in time discrepancies are evident in the annual temporal plots for lighting power (Figure 9) and DGI (Figure 10). Lighting energy savings were calculated by subtracting daylight illuminance for each zone from the design illuminance (300 lux). The power used for supplemental lighting was taken from the dimming ballast output versus input power curve assuming that 100% power provides 300 lux.

The DGI was calculated for each hour for three rendered viewpoints. Recessed fluorescent lighting on dimming control supplemented daylight when daylight provided less than 300 lux at the work plane. Including the electric lighting provides a more accurate adaptation luminance when computing the glare metric.
Tables 1 and 2 contain annual summary data for illuminance and glare. The difference in simulated lighting energy savings between BSDF resolutions is minor (within a few of percent). However, the summary glare data is significantly different with a 450% increase in glare occurrence between 4x Klems and full Klems resolutions for View 3.

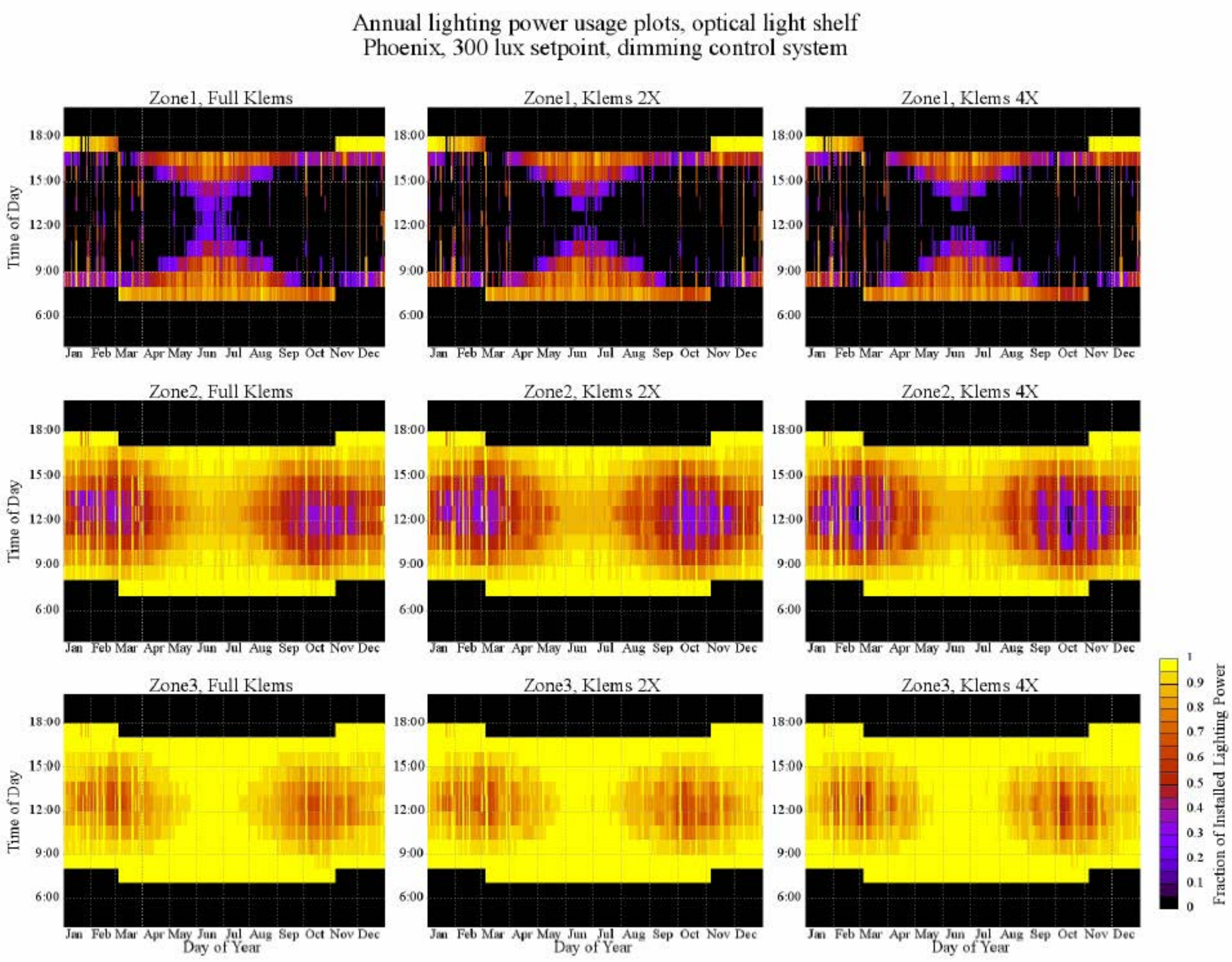

Fig. 9. Annual lighting energy use plots for lighting zones 1-3 (rows) for the three BSDF resolutions (columns).

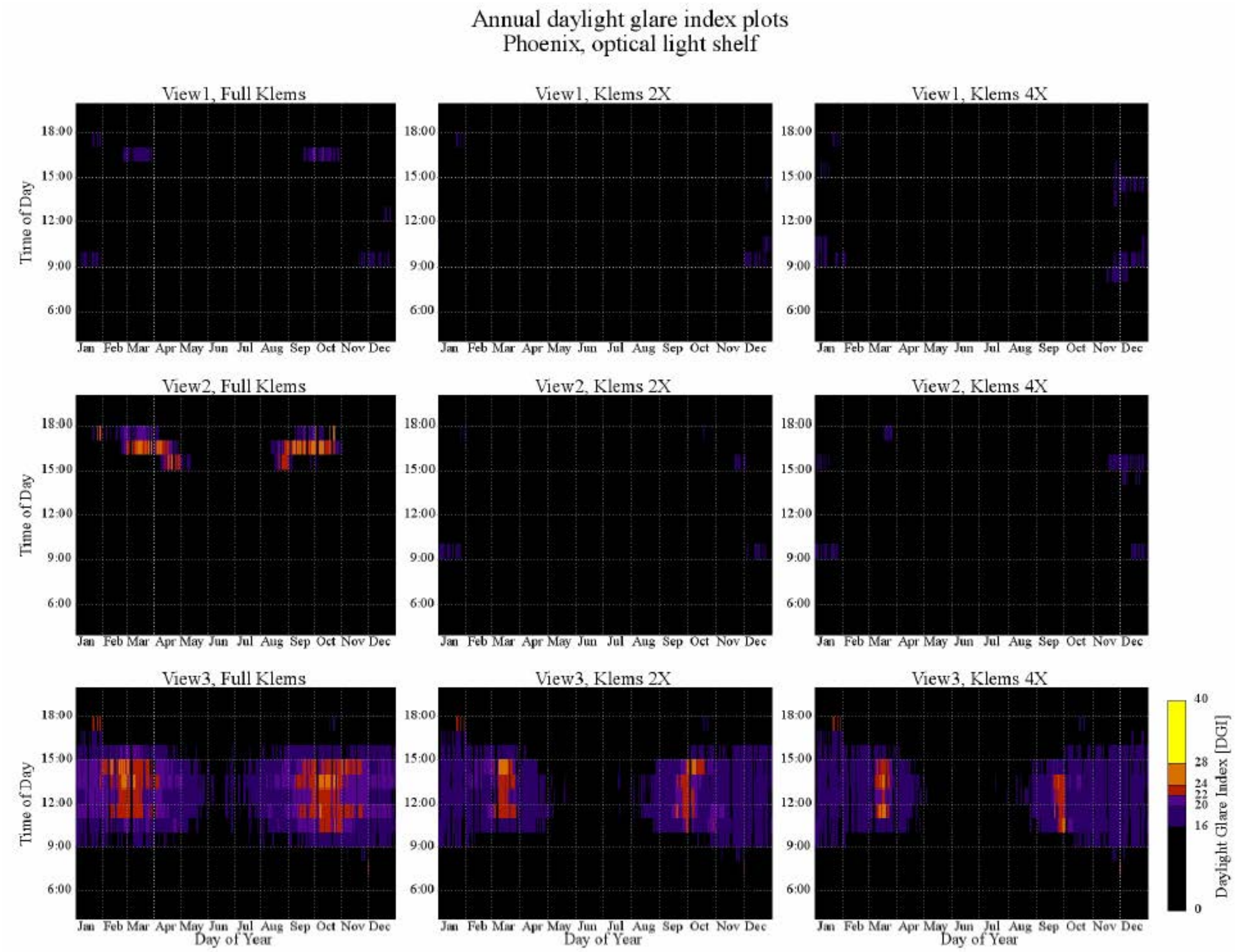

__Fig. 10.__ Daylight glare index for views 1-3 (rows) for the three BSDF resolutions (columns).

Table 1
Lighting energy savings simulated per zone using three BSDF resolutions for an optical light shelf

	Distance to center of zone (m)	Full Klems	Klems 2x	Klems 4x
Zone 1	3.7	72%	73%	74%
Zone 2	8.5	20%	21%	23%
Zone 3	13.4	8%	7%	7%

Table 2
Percent of hours where simulated DGI is greater than 22 using three BSDF resolutions for an optical light shelf

		Full Klems	Klems 2x	Klems 4x
View 1	Looking at window, zone 1	0%	0%	0%
View 2	Looking west at VDT	3%	0%	0%
View 3	Looking at window, zone 3	9%	3%	2%

5. Discussion

For this assessment, we assume that the 4x Klems basis provides the most accurate result of the three resolutions tested. This may not be true for all time steps. Between sky divisions, Klems divisions, and interior obstructions, alignment effects may cause the higher resolution case to exhibit more error for isolated cases. On average, though, it is believed that the higher resolution provides the more accurate result.

Using high resolution BSDF datasets increases the computation time on two fronts. The Radiance simulation parameters need to be increased to ensure that the window is sampled at a resolution matching the BSDF. If the window is sampled at a lower resolution, then the BSDF angles of peak intensity might be missed or weighted too heavily causing noisy and inconsistent results. Effectively sampling also requires changing MAXSPART, a hard coded variable in Radiance. MAXSPART limits the number of subdivisions for direct sampling of a source to 64. For this study MAXSPART was increased to 1024. For changes to MAXSPART to take effect, it is necessary to recompile Radiance.

In addition, increasing the BSDF resolution increases the dimensions of all the matrices for the multiplication step. Larger matrices increase the duration of the matrix multiplication step. The typically fast multiplication step takes longer to perform for higher resolution BSDFs, although this hurdle has been addressed by enabling the matrix calculation to be handled by GPUs [4].

6. Conclusion

Accuracy gains resulting from increasing the BSDF resolution are compelling for point-in-time calculations. However, for annual simulations, the result for illuminance-based daylight metrics and for accumulated energy savings show little difference between BSDF resolutions, as demonstrated by a limited example. Glare calculations do appear to benefit from increased BSDF resolution. It still may be possible to use lower resolution BSDF to compare two systems (i.e., which causes more glare).

Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and by the California Energy Commission through its Public Interest Energy Research (PIER) Program on behalf of the citizens of California.

This research used the Lawrencium computational cluster resource provided by the IT Division at the Lawrence Berkeley National Laboratory (Supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231).

References

[1] Larson, Ward G, Shakespeare R. 1998. Rendering with Radiance: The Art and Science of Lighting Visualization. San Francisco. Morgan Kaufmann.

[2] Mitchell, R., Kohler C, Klems J, Rubin M, Arasteh D, Huizenga C, Yu T, Curcija, D, editors. 2008. Window 6.2/ Therm 6.2 Research Version User Manual. Lawrence Berkeley National Laboratory. LBNL-941. Berkeley, CA 94720.
[3] Klems, JH. 1994. A new method for predicting the solar heat gain of complex fenestration systems: I. Overview and derivation of the matrix layer calculation. ASHRAE Transactions 100 (1): 1065-1072.
[4] Zuo, W., A. McNeil, M. Wetter, E.S. Lee. 2011. Acceleration of Radiance for lighting simulation by using parallel computing with OpenCL. Proceedings of the 12th International Conference of the International Building Performance Simulation Association (Building Simulation 2011), Sydney, Australia, November 14-16, 2011.

Appendix

Description of the open plan office space

The open plan office space measures 17.1 m wide by 17.4 m deep by 2.9 m high (56 x 57 x 9.5 ft). The model is purposely deep to asses the ability of fenestration systems to deliver daylight beyond the typical perimeter daylight zone. The model contains basic furnishings including (24) 1.8 x 2.4 x 1.1 m (6 x 8 x 3.7 ft) cubicles with desk chairs and cabinets and (12) smaller 1.7 x 0.8 x1.1 m (5.5 x 2.5 x 3.7 ft) desks with chairs and overhead cabinets along the side walls. Figure X depicts the layout of the space. Table X contains surface reflectances used in the model.

The model contains punched windows along one wall. There are two window types in the model daylight and view. Daylight optimized windows are 2.3 m wide (7.58 ft) and 0.55 m tall (1.75 ft). The bottom of the daylight window is 2.2 m above the floor (7.25 ft). View optimized windows are 1.14 m (3.75 ft) wide and 1.4 m (4.75 ft) tall. The bottom of the view windows is 0.69 m (2.25 ft) above the floor. There are seven daylight windows and eight view windows. The window to wall ratio is 35% assuming 3.66 m (12 ft) floor to floor height.

The space was divided into three lighting control zones. Zone 1 contains the two rows of desks closest to the window (3.7 m, 12 ft to the centerline between workstations), zone two contains the middle two rows of desks (8.5 m, 28 ft) and zone three contains the two rows of desks furthest from the window (13.4 m, 44 ft). Sensor points are spaced 0.6 m (2 ft) apart on the desk (Fig. 5).

Table A1
Model surface reflectance values

Surface	Visible Light Reflectance [Rvis]
Floor	30%
Wall	60%
Ceiling	80%
Cubical Partitions	50%
Desks	65%
Chairs	20%

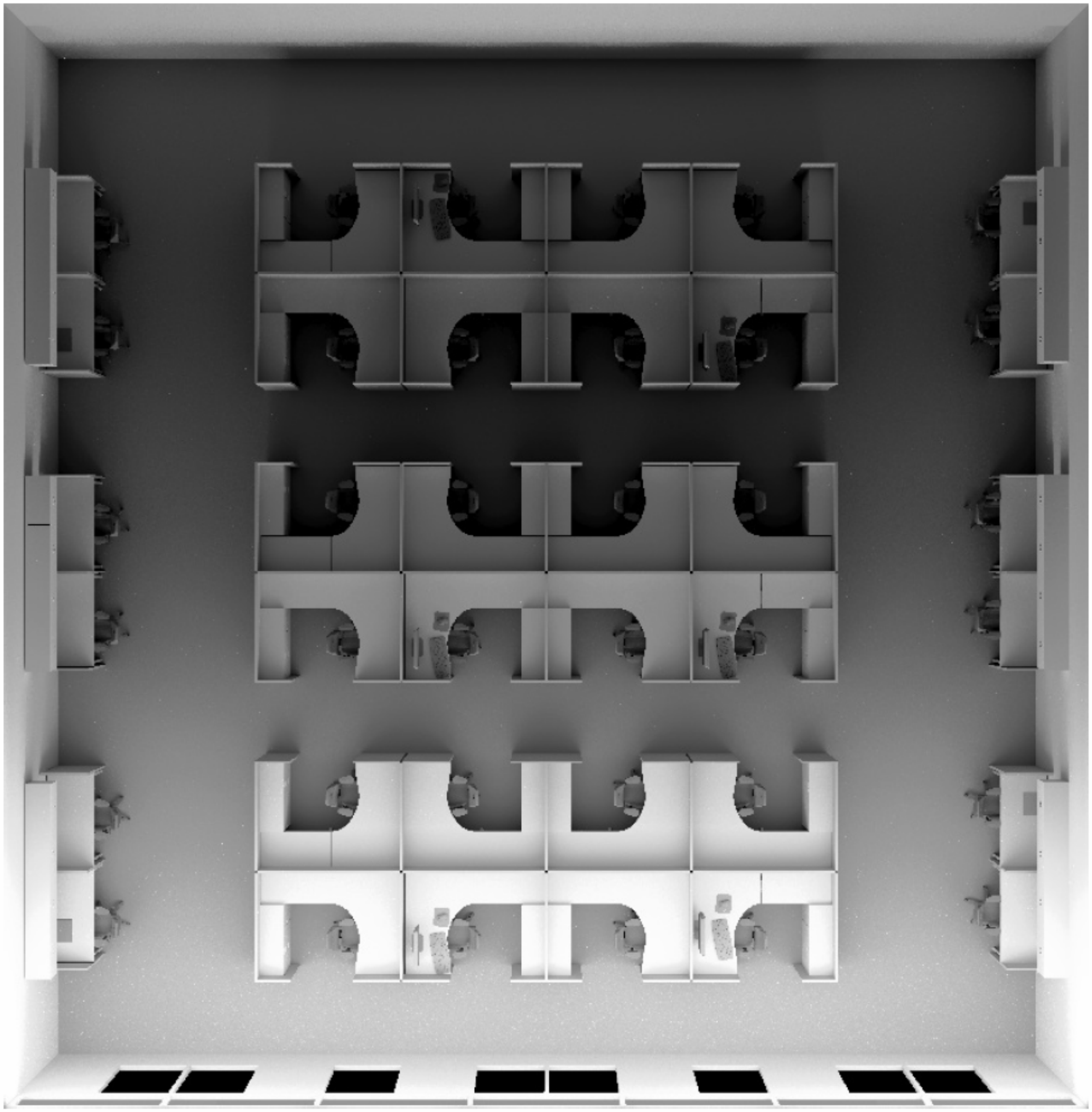

Fig. A1. A rendered floor plan view of the open plan office zone.

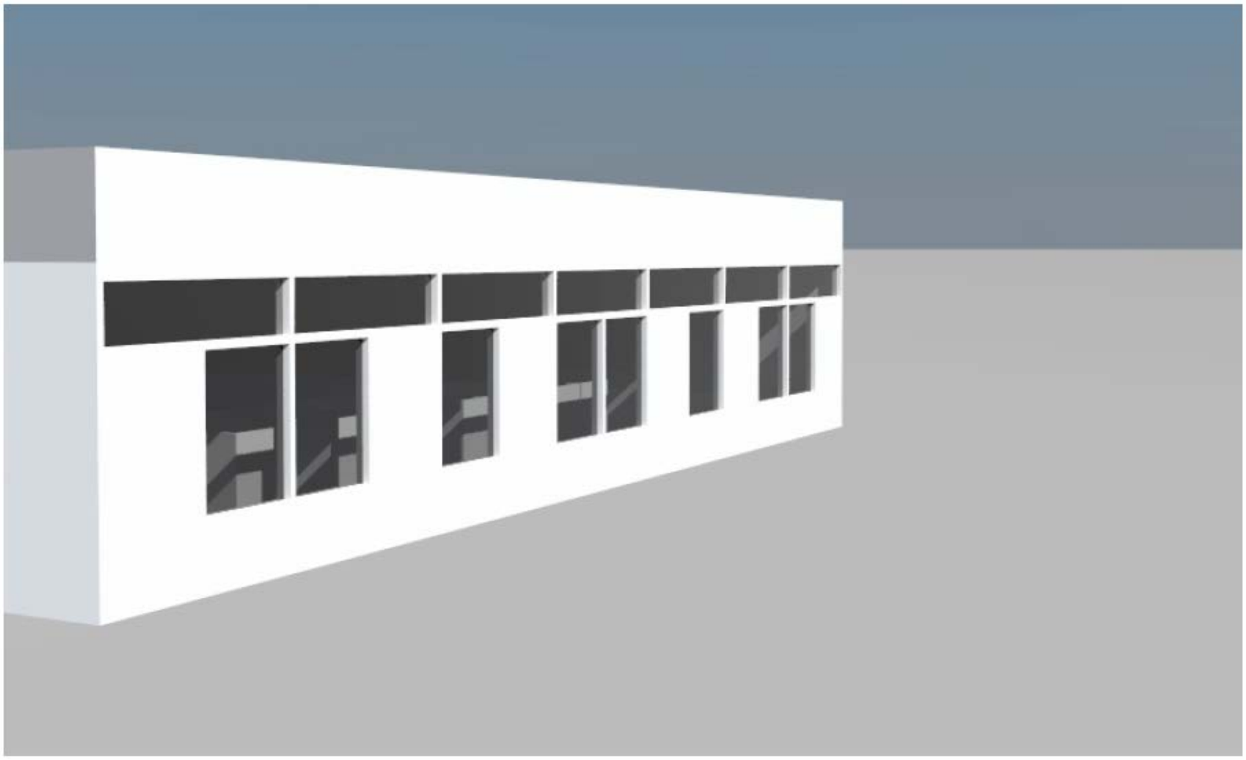

Fig. A2. Exterior view of model with upper daylight windows and lower view windows

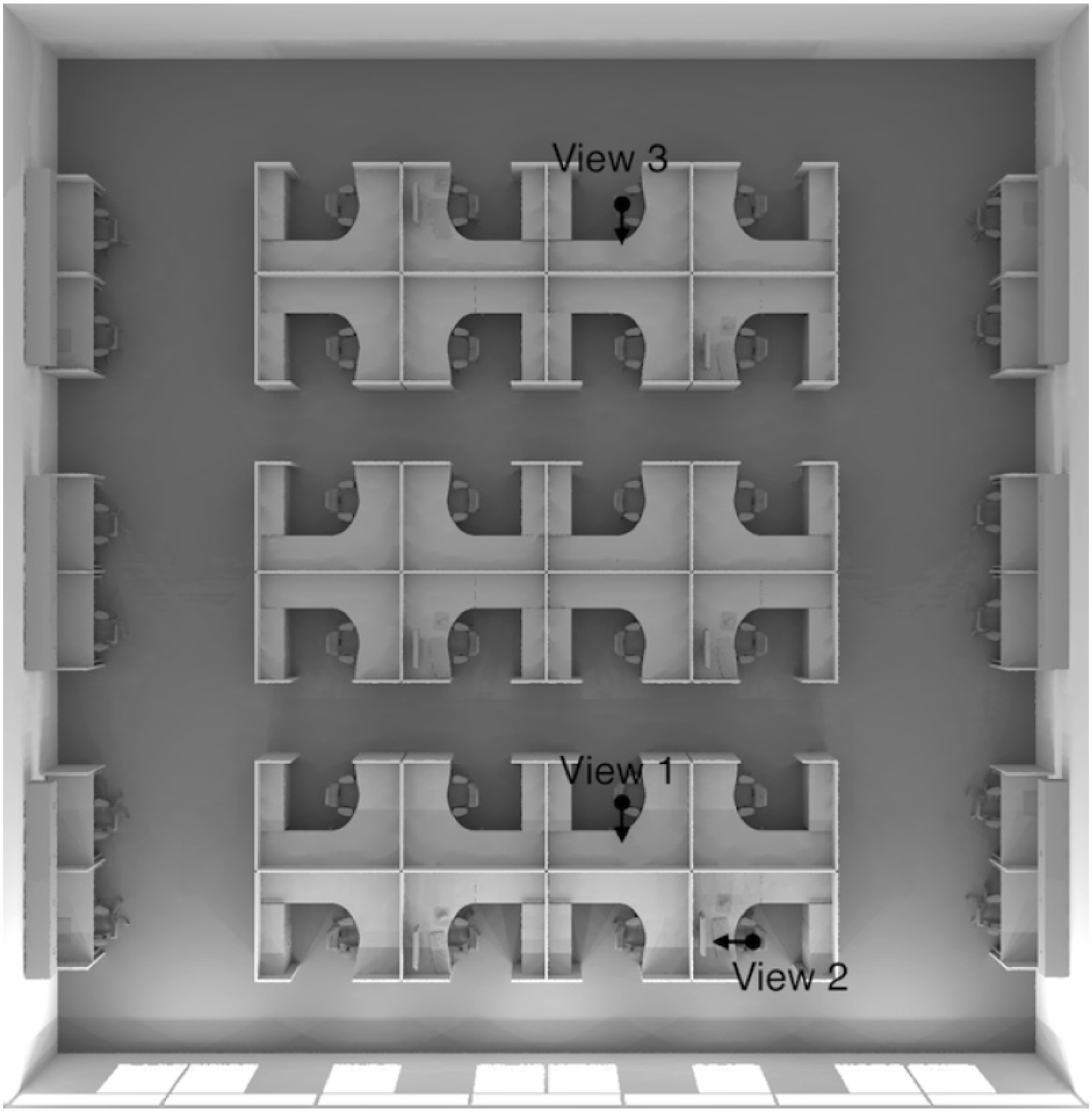

Fig. A3. Rendering viewpoints for glare assessment, red is View 1, green is View 2, blue is View 3.

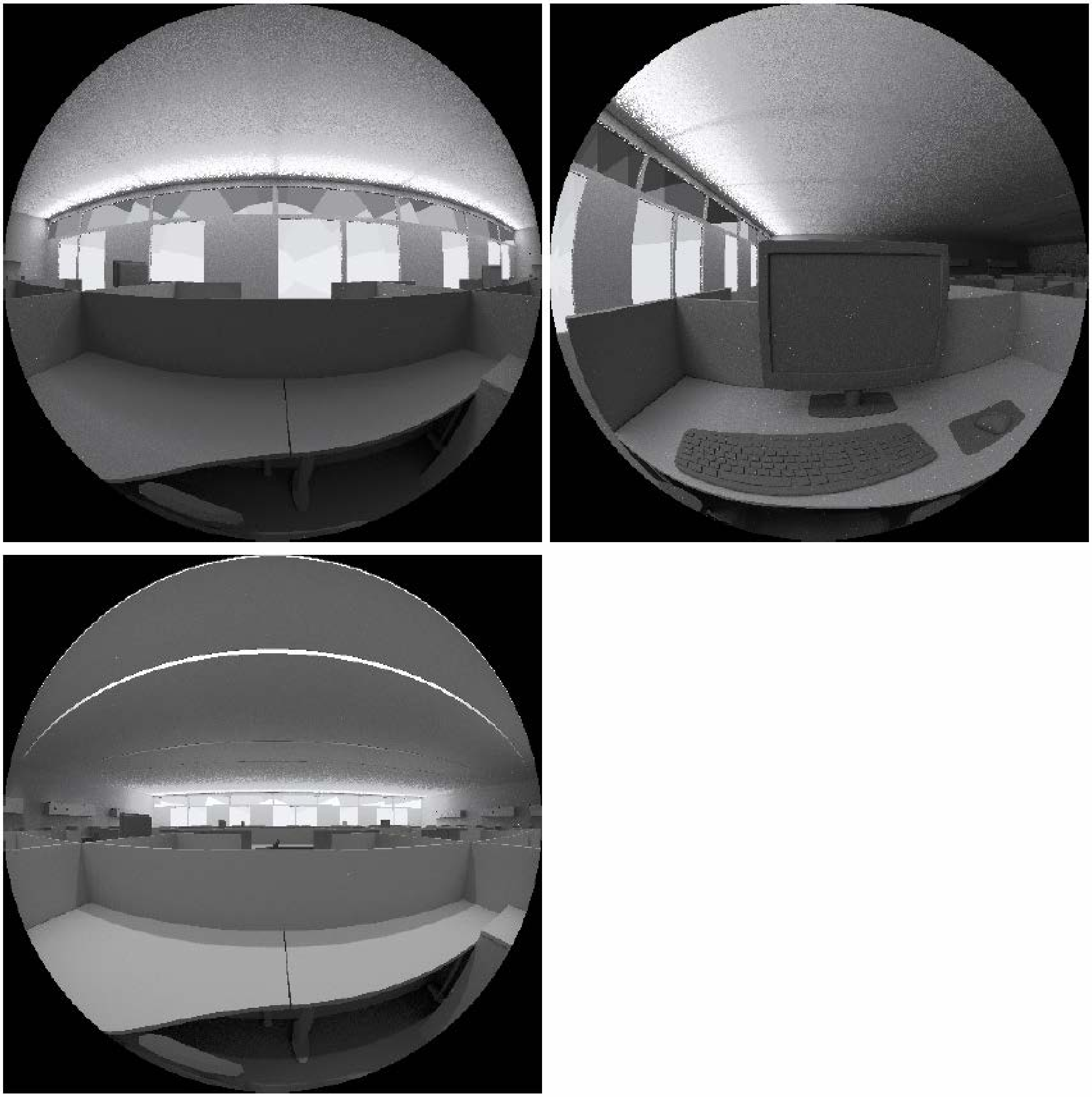

Fig. A4. Rendered views. Top left: View 1, top right: View 2, and bottom left: View 3.

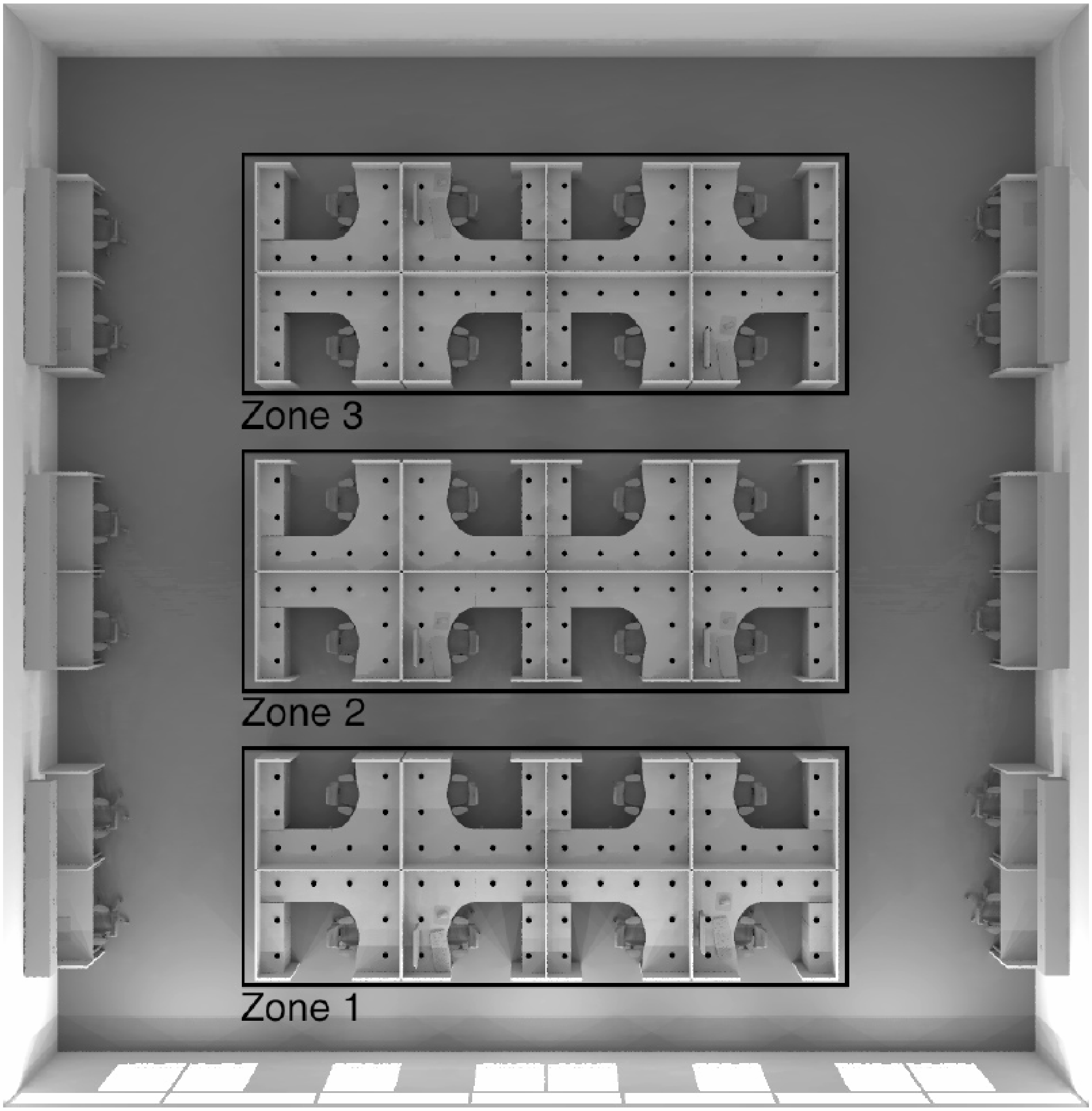

Fig. A5. Workplane illuminance sensor grids.