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A validation of the Radiance three-phase simulation method for modeling annual daylight performance of optically-complex fenestration systems

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2012

To be published in *Journal of Building Performance Simulation*
April 2012

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A validation of the Radiance three-phase simulation method for modeling annual daylight performance of optically-complex fenestration systems

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Abstract

A new capability that enables annual simulation of optically-complex fenestration systems has been added to Radiance. The method relies on bidirectional scattering distribution function (BSDF) input data, which are used in an efficient matrix calculation to compute time-step performance given TMY data. The objective of this study was to explain the value of this capability to designers and developers of innovative daylighting systems and to demonstrate its speed and accuracy via comparisons of simulated to measured illuminance data for a daylight-redirecting optical louver system. The method was shown to provide valid results that accurately replicate real world conditions with an absolute mean bias error below 13% and a root mean square error below 23%. Routine application of this new capability will not be hindered by slow computational speed for illuminance calculations. Instead, the capability will be dependent on the availability of BSDF data for daylighting, shading, and fenestration systems.

Keywords: Daylighting; Bidirectional scattering distribution functions; Radiance; building energy efficiency; validation

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1. Introduction

Energy use from buildings accounts for 41.8 exajoules (EJ) (39.6 Quads) or 39% of total US primary energy consumption in 2005. The three largest uses of energy in buildings, heating, cooling, and lighting, account for 21.6 EJ (20.5 Quads) or 52% of building energy use (US DOE 2005). Optimizing window systems to deliver lighting energy savings could reduce US energy use by 1.1 EJ (1.0 Quads) per year. Optimizing for both daylight and thermal loads could save the US a total of 3.7 EJ (3.5 Quads), or displace the equivalent of 815 200-MW coal-fired power plants per year (Arasteh et al. 2006).

Side lighting provides the best opportunity for daylight harvesting in existing buildings and is likely to be the most common strategy for daylighting in new commercial buildings for the foreseeable future. Use of vertical windows, however, continues to be a challenge because one must mitigate direct sun and glare simultaneous to admitting useful daylight. This is particularly relevant given the architects' and owners' desire to use transparent, large-area windows to increase overall daylighting, improve indoor environmental quality, and potentially, the health of the occupants.

Many daylighting technologies are non-specular in nature and are categorized as optically complex or as complex fenestration systems (CFS). They include systems as banal as woven fabrics for roller shades and conventional Venetian blinds and as exotic as holographic diffractive structures and micro-mirrored nanostructures. Historically, engineers have relied on theoretical models or approximations to characterize the light scattering properties of daylighting systems and have performed limited simulation studies using these models for a few representative days to understand the qualitative and energy-efficiency impacts of these technologies in an interior space.

Lack of accurate and time-efficient tools has not only hindered the adoption of commercially-available daylighting technologies by the architectural-engineering community, it has also slowed the development of new, innovative daylighting technologies by industry. Characterization of daylighting systems required modified laboratory equipment to systematically measure angularly dependent transmittance and reflectance properties and source code modifications or other creative methods to use these data in conventional annual energy simulation tools (e.g., Papamichael et al. 1994, Sullivan et al. 1998). With inefficient assessment methods, developers lacked the feedback needed to iteratively improve prototype systems and the comprehensive data needed to justify the large capital investments needed to scale up manufacturing capabilities.

Federal and state public agencies as well as utilities use impact assessments involving tens of thousands of simulations to estimate US- or state-wide energy impacts in commercial and residential buildings (e.g., Elliott et al. 2004). These studies are used to decide whether to support industry scale up or promotion of new technologies via standards and/or rebates and incentive programs. Again, lack of CFS modeling tools has inhibited informed decision making by these entities.

Simulation tools are advancing to the state where daylighting technologies can be modeled more routinely and accurately on an annual basis. In this study, we discuss a new Radiance CFS annual simulation modeling capability and explain how it differs from existing Radiance capabilities. The CFS modeling capability is shown to be accurate through validation against measured data of a sunlight-redirecting daylighting system. Application of the new tool is discussed in the context of technology R&D and building design to demonstrate how the new solution can be practical for both large-scale parametric analysis and iterative design analyses.

2. Annual daylight simulations of CFS

2.1. Existing annual simulation methods for conventional systems

Radiance is an open source, backwards ray tracing suite of tools developed to model and visualize the luminous effects of daylighting systems (Ward and Shakespeare 1998). Prior to the implementation of the daylight coefficient method in Radiance there were few practical options available that enabled annual daylight simulations.

The DOE-2 building energy simulation program implemented a split flux method for calculating illuminance in 1985 (Winkelmann and Selkowitz 1985). Although the split-flux method is well known to be limited in both accuracy and scope, it continues to play a key role in design decisions because interfaces to DOE-2, like eQuest, are used throughout the building industry for code compliance.

The Sensor Placement and Optimization Tool (SPOT) implemented annual daylighting calculations in order to improve the design, specification, and reliability of photoelectric lighting control systems (AEC 2006). SPOT provides an accessible PC-based user interface to the Radiance tool suite, which is run traditionally through a command line Unix interface. To compute annual performance, it runs Radiance ray tracing simulations for three days and two CIE sky models, then weights the CIE sky models according to direct and diffuse irradiance data from a TMY2 climate data file, essentially interpolating between sky types and dates. While there is no published validation of SPOT, the program's author states that the SPOT method produces useful results for annual work plane illuminance metrics (personal conversation).

One of the first user interfaces to use the Radiance daylight coefficient method to perform annual simulations was the PC-based DAYSIM tool (Reinhart 2010). The daylight coefficient method divides the sky into 145 divisions, then pre-calculates coefficients using backwards ray tracing methods to relate the luminance of each sky division to the illuminance at a point inside the space (Tregenza 1983). For an annual calculation, the illuminance at the point can then be calculated for each time step by multiplying the luminance of each sky divisions by the respective daylight coefficient then summing the 145 resultant values. The daylight coefficient method provides illuminance results that are accurate for individual time steps as well as averaged over the year. DAYSIM uses a modified form of Radiance (*rtrace_dc*) to more efficiently calculate daylight coefficients in the short time frame demanded by the architectural design community. The addition of the *rtcontrib* program to Radiance in 2005 allowed source contributions to be tracked during the simulation, enabling direct and efficient simulation of daylight coefficients in Radiance.

Both SPOT and DAYSIM currently rely on the native Radiance material types to model the generic light scattering technologies used in windows (e.g., plastics, metals, translucent plastics, etc.). Conventional shades and Venetian blinds can be modelled. However, neither tool can reliably simulate specularly reflecting daylighting systems or use bidirectional scattering distribution functions (BSDF) to describe a fenestration system. The ability to use BSDF data in simulations is becoming increasingly important as discussed in the following section because it enables users to simulate the performance of optically-complex technologies that currently cannot be modelled.

2.2. A new method for conducting annual simulations of CFS

The methods described in the previous section do not enable the modeling of CFS. Separately from annual simulation development, Klems proposed a new method to model solar gains through windows with CFS (Klems 1994a, 1994b). Klems' method relies on bidirectional optical measurements of the CFS to determine reflected and transmitted light by direction for all incident directions defined by the hemisphere viewed by the window, termed bidirectional scattering distribution functions (BSDF). Klems also described a means to derive a BSDF for a window system consisting of multiple heterogeneous parallel layers (e.g., exterior metal scrim, insulating glass unit, interior Venetian blind) by matrix multiplying the BSDF for each layer. Klems devised a coordinate system that simplified this matrix multiplication. The coordinate system has 145 input and output directions in nine theta bands. The number of phi divisions in each theta band is modulated so that all divisions have roughly the same cosineweighted solid angle. This BSDF coordinate system is commonly called the Klems full angle basis. With this BSDF, one can derive total window solar gains via a matrix multiplication of the BSDF coefficients with incident flux in each of the 145 window directions, effectively integrating over the hemisphere seen by the window.

A new method has been developed that allows Radiance to use Klems' BSDF data in annual daylight simulations. In 2010, additional tools (*genklemsamp* and *klems_int.cal*) were added to Radiance that enable users to track lighting contributions from a window by exiting direction defined by the Klems basis and a tool to sample the incident Klems directions for a window for daylight contributions. These additional tools provide the ability to model CFS characterized by BTDF data sets (Saxena et al. 2010, Ward et al. 2011). This new Radiance method, called the three-phase method, is based on the daylight coefficient approach, though it separates the light transport between the sky patches and the illuminance sensor points into three phases: exterior transport, fenestration transmission and interior transport.

Each phase of light transport is simulated independently and stored in a matrix form. The resultant illumination is obtained using matrix multiplication:

$$i = V\ T\ D\ s \tag{1}$$

Where, V is a view matrix that relates light from outgoing directions on window to desired results at an interior point, T is a transmission matrix that relates incident window directions to exiting directions (BTDF), and D is a daylight matrix that relates the luminance of sky patches to the incident directions on window. A daylight coefficient matrix can be obtained by multiplying the V, T, and D matrices. The final part of the equation is a vector, s for sky, that contains the average luminance of the sky patches for given time and sky condition. Saxena et al. (2010) provides a more detailed explanation of this method.

This approach has two benefits; first it enables quick computation of many fenestration types, locations and facade orientations. Facades can be changed without simulating the entire light path, simply by substituting a new fenestration transmission matrix. Alternate climates and orientations can be simulated by changing the sky data. The flow chart in Figure 1 illustrates the simulation process for the first simulation of a space and subsequent simulations of the same space for different climates or fenestration systems.

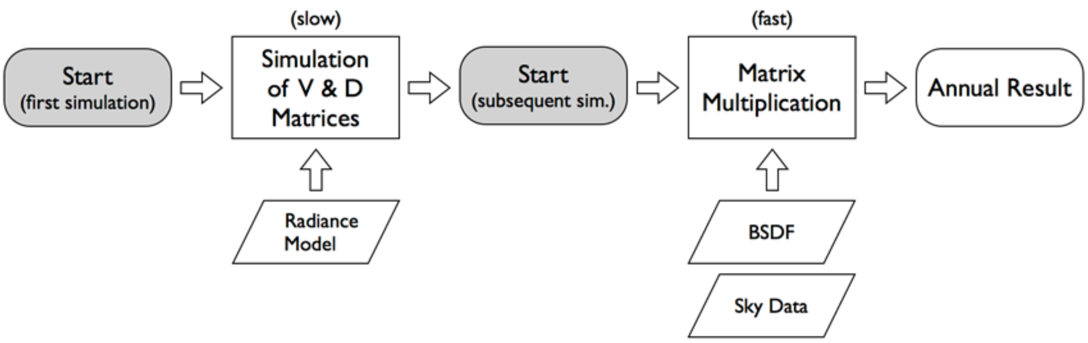

Figure 1. Simulation process flow chart

The second benefit is that the approach can be used to simulate the performance of fenestration systems that can not normally be simulated in Radiance. The transmission matrix or BTDF can come from any number of sources including measurement or forward ray tracing tools.

2.3. Simulation of daylight redirecting systems

This validation uses a daylight redirecting system comprised of specularly reflecting louvers (described in Section 3.1). Modelling daylight redirecting systems has also historically been a challenge. The backwards ray tracing approach used by Radiance (and therefore SPOT and DAYSIM) is not capable of adequately simulating the performance of this type of fenestration system because backwards ray tracing uses probabilistic sampling methods to find specular reflections of the sun. The chance of randomly finding the sun with probabilistic sampling is low due to the small relative size of the sun, requiring a prohibitive large number of samples for an accurate result. Instead, simulation of daylight redirecting systems requires forward ray tracing, starting at the source (sun and sky) and tracing through the daylight redirection system into the room (Ward and Shakespeare 1998).

There have been previous activities to augment Radiance to simulate specular daylight redirecting systems. Schregle (2002) implemented a photon map extension to Radiance enabling a forward ray tracing pre-process to generate a photon map. This photon map was used to augment the ambient calculation. Forward ray tracing for daylighting poses a challenge in that most photons emitted from the sun and sky won't interact with the interior scene. Only the photons that, by chance, hit a window affect the simulation result. Schregle's photon map extension solved this challenge by using photon ports on the windows. Instead of emitting photons from the sun and sky, photons are emitted by photon ports that are mapped with the sky and sun luminance distribution. The photon map approach is well suited for simulating daylight redirecting systems, however it is limited by the inability to account for external inter-reflections due to the photon port optimization. Additionally, the photon map does not support annual simulations. The user is limited to simulating static conditions and extrapolating.

There have also been activities to incorporate data from other forward ray tracing software into Radiance simulations. Guglielmetti et al. (2010) used forward ray tracing to create output distributions of the daylight redirecting system for three days (equinox and solstices) and two sky conditions (cloudy and sunny). These output distributions, in IESNA-LM 63 standard format, were used to simulate daylight in a space. Gugliemetti et al. then used SPOT to provide annual data by interpolating between the static cases based on climate data. While this method provides a reasonable estimate for energy modelling purposes, it does not provide sufficient accuracy to evaluate daylight performance of CFS systems or to develop and optimize new CFS systems.

Another new tool, called *genBSDF*, has been added to Radiance that allows users to generate BSDF data for complex fenestration systems including specular daylight redirecting systems. *genBSDF* gets around the limitations of Radiance in simulating specular redirecting systems by flipping the convention of source and receiver. *genBSDF* essentially operates Radiance as though it were a forward ray tracing program. A user can provide a Radiance model of a system, and *genBSDF* will generate a BSDF in Window 6 XML format for the system. The BSDF file produced by *genBSDF* can be imported into Window 6 as a shading layer (Mitchell et al. 2008). Once imported the shading layer can be combined with any number of glazing layers from the International Glazing Database (IGDB). Window 6 can write a BSDF file for the multi-layer glazing system including glazing and shading layers that can then be read by Radiance for annual simulations.

3. Validation of the new method against measured data

Ward et al. (2011) provided a theoretical validation of the three-phase method by comparing renderings produced by classic Radiance ray tracing methods against renderings produced by the three-phase method. This work, based on clear glazing, established that there were no bugs in the fundamental algorithms and illustrated how the two methods agreed to within about 10% on average over the rendered scene. The study did not, however, compare simulated results to measured data, which can instil greater confidence in those who will rely on the results of the simulations to make critical decisions.

There are two potential sources of error in the input that could cause the method to produce less accurate results: a) the BSDF inadequately or incorrectly characterizes the scattering distribution of the system, and b) inadequate resolution of the BSDF data results in incorrect spatial distributions of flux within the interior space. The latter is particularly true for peaky, sunlight-redirecting systems where peak intensities can be averaged over a single or multiple patches. For the standard Klems 145x145 basis, a single patch equates to an average solid angle of 0.0433 (cone with a 13.5° apex angle). Other sources of error could result from the underlying algorithms, although the first theoretical validation provides some confidence that gross potential errors were addressed.

To validate the new simulation capability, the three-phase method was used to model a peaky, sunlight-redirecting system and the same system was tested in a full-scale outdoor test facility over a one-year period in Berkeley, California. Illuminance data were compared to establish the level of accuracy that can be expected from the simulation tool.

3.1. Description of the test setup

An optical light shelf (OLS) was selected for testing. The OLS is a commercially available, specular louver system (LightLouver LLC) designed to redirect sunlight to the ceiling of a space (Figure 2). The system consists of multiple 0.062 m (2.4 in.) deep, vertically stacked, concave-up, reflective louvers that span the width of the window opening. A reflective film is applied to the concave-up louver surface and the sloping surface facing the space. A matte gray plastic was used for the remainder of the exposed surfaces. The patented reflective louver geometry was designed to redirect incident sunlight uniformly onto the ceiling and to block sunlight below a 5° solar altitude angle to prevent glare. The optical daylighting system is static (passive), requiring no adjustment over the year, and is typically installed in the upper portion of a window, at a minimum of 2.13 m (7 ft) above the finished floor.

Figure 2. (left): Side view of the OLS on the inward face of the clerestory glazing. (middle): Oblique view of the OLS. (right): Photo of the test space with OLS installed (looking from the back of the space towards the window)

The OLS was installed in one of the chambers of a full-scale instrumented testbed facility. The chamber was designed to emulate a typical private office and had a large south-facing window. The office was 3.0 m (10 ft) wide by 4.6 m (15 ft) deep and 3.35 m (11 ft) tall (to facilitate thermal measurements). The window was 2.5 m (8.3 ft) tall by 2.7 m (8.9 ft) wide. Figure 3 provides a plan drawing of the test space and Table 1 gives the center of glazing performance for the windows in the test space. A horizontal mullion divided the window into a 0.76 m (2.5 ft) high upper portion and a 1.7 m (5.6 ft) high lower portion. The lower edge of the upper windows was 2.0 m (6.5 ft) above the floor. A vertical mullion divided the horizontal width equally. During the test, the lower windows were blacked out with an opaque fabric while the OLS was installed in the upper windows.

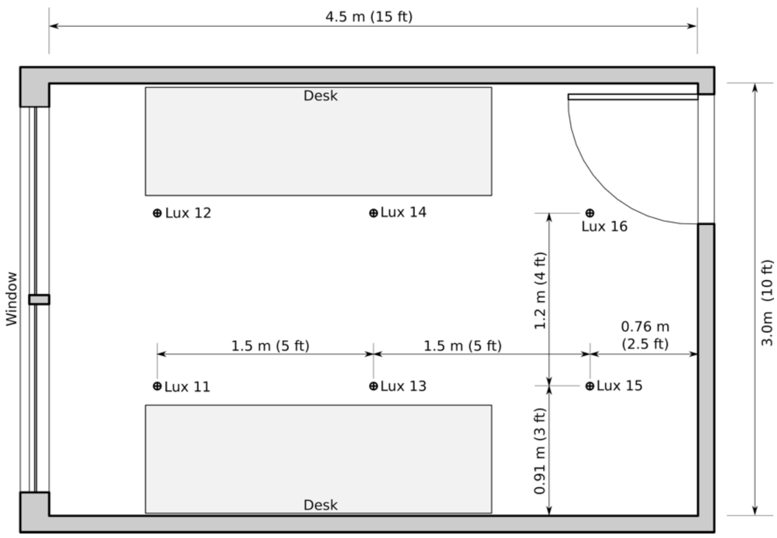

Figure 3. A plan drawing of the test space showing the locations of work plane illuminance sensors

Table 1. Centre-of-glass window glazing properties

Description	T_{vis}	SHGC	U-value (W/m^2K)	U-value (Btu/h $ft^{2\circ}F$)
Double glazed insulated units with clear low-iron glass and Viracon VRE67 low-e coating on surface #3	0.641	0.456	1.850	0.33

Sensor data were sampled and recorded at a 1-min interval, including global horizontal irradiance, direct normal beam irradiance, vertical illuminance, and work plane illuminance at six points within the room. The locations of the internal illuminance sensors are shown in Figure 3 (labelled lux 11 – 16). The work plane illuminance sensors are 0.76 m (2.5 ft) above the floor.

The test was conducted in Berkeley, California. Berkeley summer and autumn periods are typically dry and sunny with frequent morning fog persisting until 10:00 - 12:00 AM. Winter and spring are characterized by a mix of overcast and sunny conditions. Additionally there is a hill to the east of the site that blocks morning sunlight until 6:45 – 8:15 AM varying by season. Data were collected on 58 days intermittently spaced throughout a year (January 2010 to January 2011). Test days were divided into three categories based on sky condition: overcast (6), dynamic (29), and sunny (23).

3.2. Description of the Radiance simulations

A calibrated Radiance model of the test space was used for the simulation. For the three-phase method, the 'D' daylight matrix was generated using the Radiance *rtcontrib* program for the upper portion of the window. The exterior model included a local ground plane and a minor obstruction above the window. The exterior ground was uniformly diffusing with a reflectance of 0.12. An illuminance 'V' matrix containing the six work plane illuminance sensors was generated for the test space. Table 2 contains the Radiance parameters used for the matrix simulations.

Table 2. Radiance parameters used in simulations

Radiance Simulation Parameters	V Matrix (Sensor Points)	T Matrix (BSDF)	D Matrix
ambient bounces (-ab)	12	5	4
ambient divisions (-ad)	60,000	700	2,000
ambient subdivisions (-as)	0	0	0
ambient accuracy (-aa)	0	0	0
limit weight (-lw)	1e-42	3e-6	1e-8
direct source subdivision (-ds)	0.05	-	-
direct jitter (-dj)	1	-	-
direct threshold (-dt)	0	-	-
direct certainty (-dc)	1	-	-

To create the 'T' transmission matrix, the Radiance *genBSDF* tool was used. The manufacturer provided detailed information on the geometry of the product. Surface properties of the manufactured system were measured using a handheld spectrophotometer (Minolta CM-202). The specular surface had a 85% reflectance and 96% specularity. The matte surface had a 54% reflectance and 1% specularity. The *genBSDF* tool calculated the transmission matrix using the full 145x145 Klems basis and output the data in an XML format that could be read by Window 6. Window 6 was then used to generate a single BSDF file characterizing the optical properties of the combined insulating glass unit (IGU) and the OLS. The IGU was defined by a clear inboard and spectrally-selective, low-e outboard glazing layer from the International Glazing Database (IGDB), matching conditions in the testbed facility. The OLS BSDF file was imported into Window 6 and combined with the IGU to create a system BSDF. These data were output by Window 6 and used for the Radiance simulations.

The measured weather data, vector “s”, were prepared for use by the Radiance software. For each 1-minute time step, a Perez sky was generated by *gendaylit* using the measured global horizontal and direct normal irradiance. The vertical façade illuminance was simulated using the Perez sky model and compared to the measured vertical illuminance. A large discrepancy between simulated and measured vertical façade illuminance indicated that the sky luminance distribution was inaccurate. Some of the discrepancy between measured and simulated work plane illuminance was attributed to this inaccuracy in the sky model. To separate the sky model error from the simulation error we generated a calibration factor by dividing the measured vertical façade irradiance by the simulated vertical façade irradiance (Reinhart and Walkenhorst 2001). To apply the calibration factor, the sky vector, created using the original Perez sky model, was multiplied by the calibration factor for each time step. Since the vertical illuminance is directly proportional to the amount of light transmitted into the space, calibration using the vertical illuminance ensured that the overall luminous input into the system was correct. Simulation data with and without the calibration factor are reported, the later being the error to be expected for conventional simulation.

The three-phase method was used to produce illuminance data at the six interior work plane sensor locations. The illuminance data was then processed using a low-pass filter to reduce the error caused by non-synchronous sensor polling. The sensors at the test facility were not polled simultaneously at each time step. Under dynamic, partly cloudy sky conditions, the typical polling difference of 5-15 s in sampling indoor and exterior sensors could result in significant differences between measured illuminance and simulated illuminance (which are based on external measurements). For this reason, a low-pass filter was applied to both the simulated and measured data to smooth dynamic spikes casued by rapid changes in sky condition. The low-pass filter consisted of a weighted average of the current time step with the two time steps before and two time steps after. In chronological order, the weighting for each time step was 1 – 2 – 3 – 2 – 1, where the current time step in the middle received the greatest weighting.

3.3. Comparison of results

A plot of measured and simulated illuminance versus time shows that for an overcast day, the simulated illuminance tracked the measured illuminance very closely (Figure 4). A similar plot for a sunny day shows that the simulated illuminance curve was not as smooth as the measured illuminance curve, but that the simulation is close to the measurement throughout the day (Figure 5). The variation in the sunny day simulation can be attributed to the relatively low resolution of the BSDF combined with the presence of the sun. The resolution of the BSDF had less effect under diffuse lighting conditions.

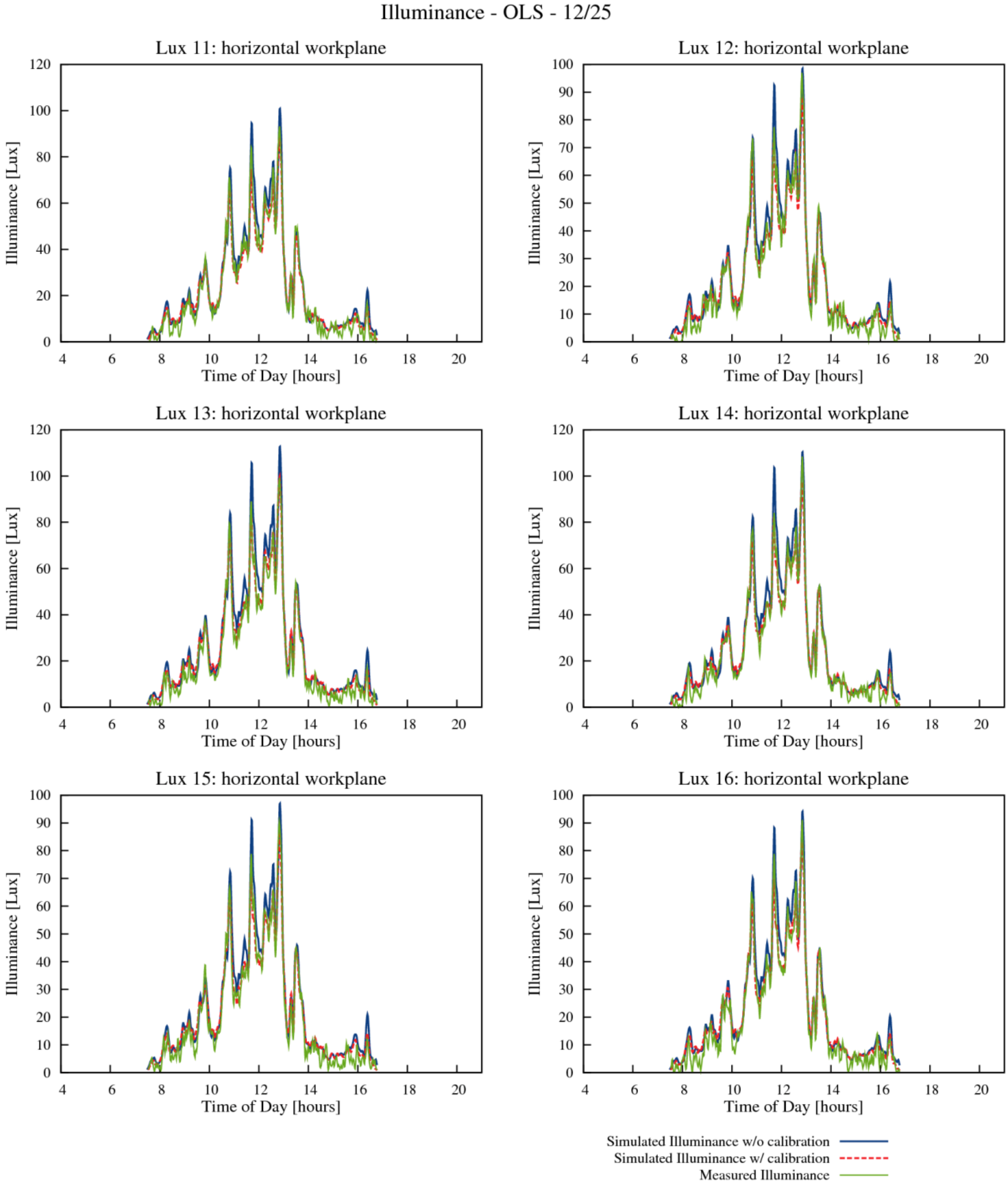

Figure 4. Measured and simulated work plane illuminance on an overcast day (December 25, 2010). Sensors Lux 11 and 12 are closest to the window. Sensors 15 and 16 are furthest from the window.

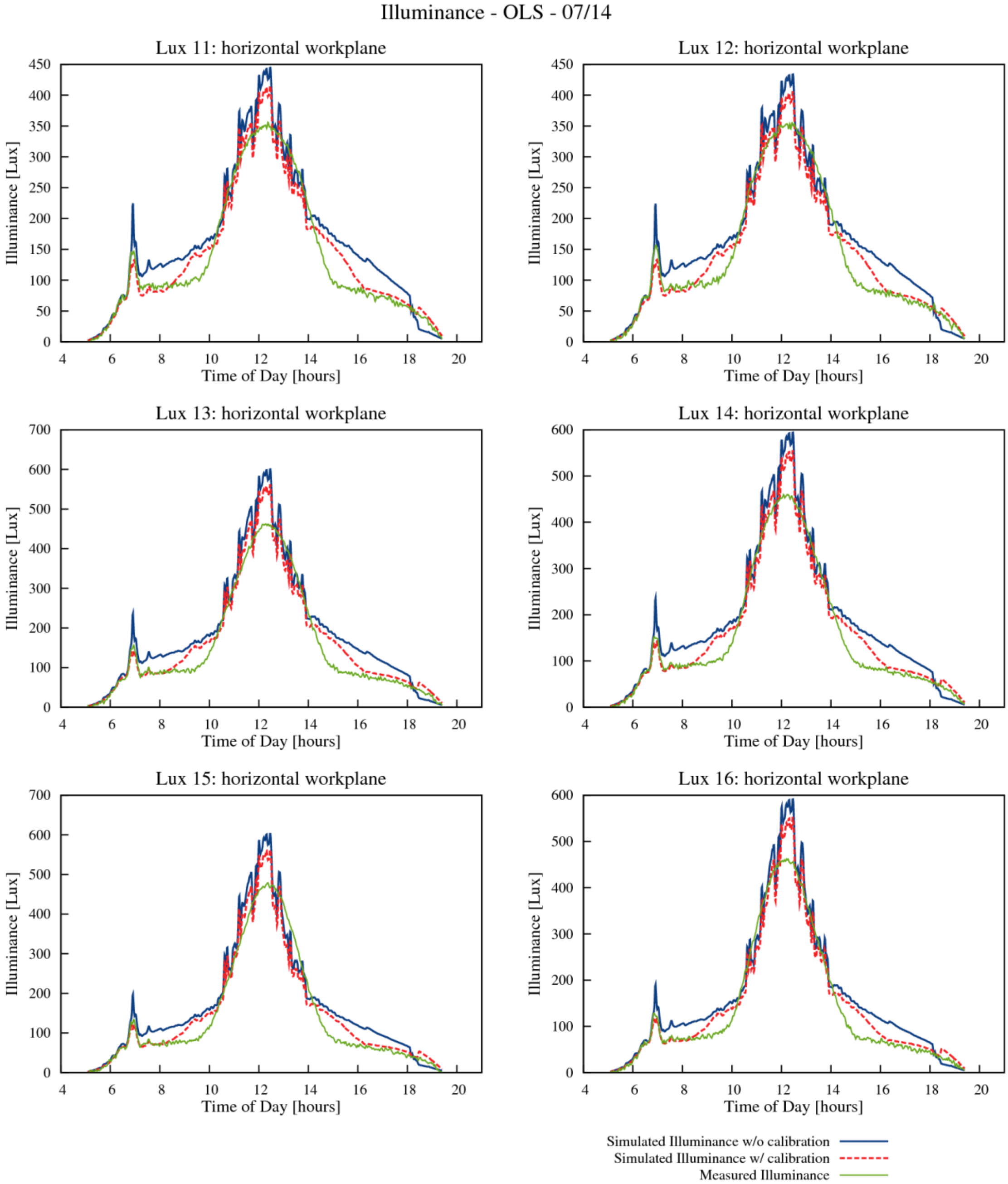

Figure 5. Measured and simulated work plane illuminance on a sunny day (July 14, 2010)

Plots of the 1-minute simulated illuminance versus measured illuminance for all measured days show that the simulated values correlate well to measured values (Figure 6). The percentage error increases for lower values – below 30 lux – but the absolute error at these low illuminance levels were determined to have minimal influence on annual simulation results (Reinhart and Breton 2009).

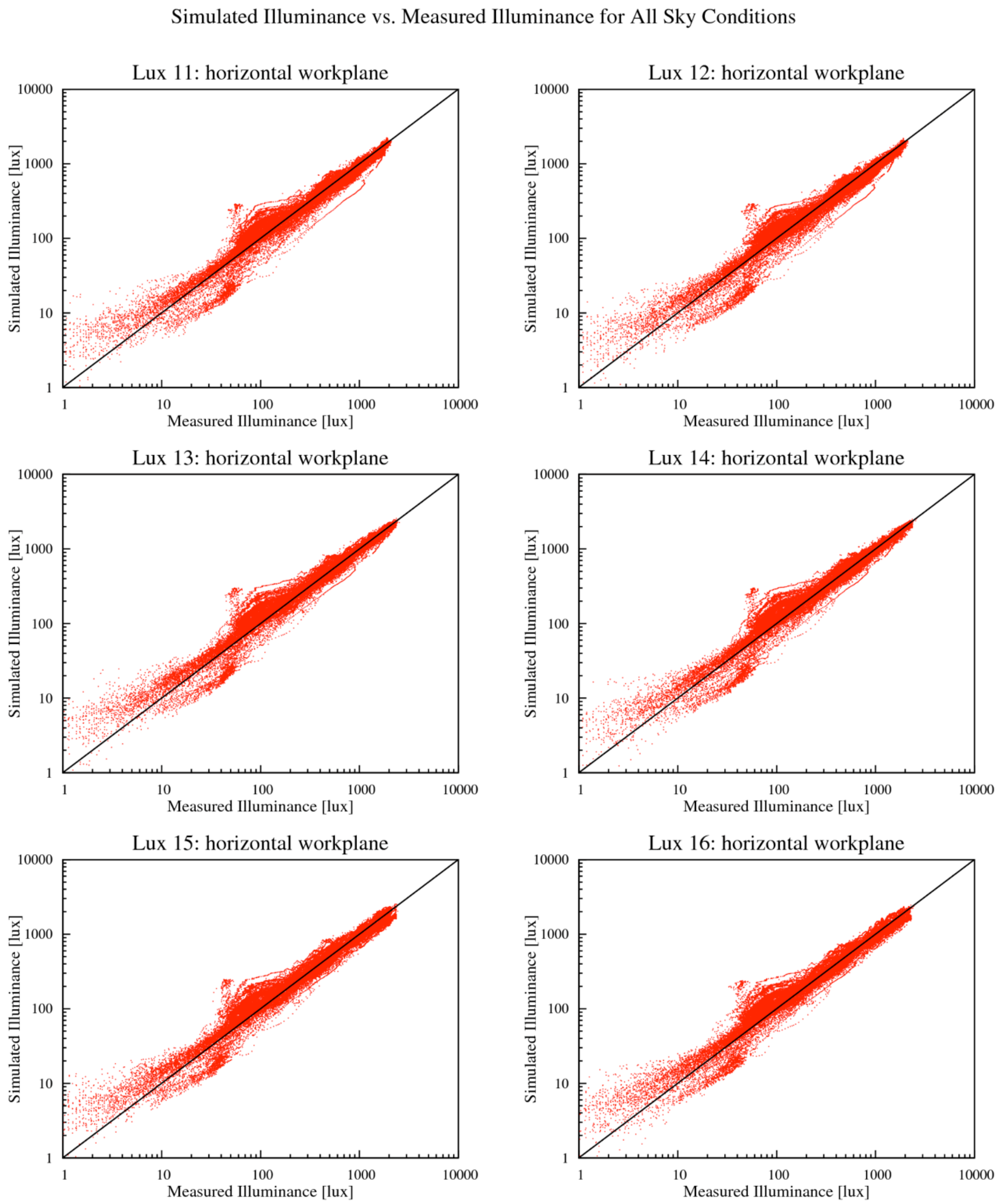

Figure 6. Simulated illuminance vs. measured illuminance for each work plane illuminance sensor, plotted on a log scale

Simulation results are considered reliable if the mean bias error (MBE) is less than 15% and the root mean squared error (RMSE) is less than 35% (Reinhart and Breton 2009). To calculate percentage error, we computed the difference between the measured and simulated illuminance then divided the result by measured illuminance, excluding data when the measured illuminance was below 30 lux. Interior illuminance of 30 lux correlated to an exterior horizontal illuminance of 5000 lux which was the threshold used by Reinhart and Breton to exclude times of low brightness (2009). Table 3a contains the simulation error without calibration factor for the six work plane illuminance sensors by sky category and Table 3b shows the same with calibration factor. Table 4 contains the relative simulation error for the average work plane illuminance (average of six sensors). The difference in error between with and without calibration factor is a result of the inability of the Perez sky model to accurately reproduce the luminance distribution of the sky. The Perez sky isn't able to reproduce luminance distribution resulting from non-uniform cloud patterns of overcast and dynamic sky types. This is demonstrated by the larger discrepancy in errors between calibrated and un-calibrated results for overcast and dynamic sky types. Error distributions are shown in for each sky type in Figure 7. In all cases, absolute MBE is below 13% and RMSE is below 23%. These results indicate that the simulation method reliably reproduced real-world conditions and is therefore valid.

Table 3a. Relative percent simulation error for work plane illuminance sensors

Sky type	Lux 11		Lux 12		Lux 13		Lux 14		Lux 15		Lux 16	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Overcast	5.3	14.7	4.3	14.7	12.2	18.6	10.1	17.4	10.0	16.7	9.3	16.3
Dynamic	-3.8	17.1	-5.3	17.4	1.8	18.0	-0.1	17.4	-2.2	19.7	-2.5	19.1
Sunny	-0.6	17.5	-2.5	17.3	5.8	19.6	4.1	18.2	6.3	22.9	5.0	21.3
All	-2.1	17.2	-3.7	17.3	4.0	18.7	2.2	17.8	2.0	21.1	1.3	20.0

Table 3b. Relative percent simulation error for work plane illuminance sensors with calibration factor

Sky type	Lux 11		Lux 12		Lux 13		Lux 14		Lux 15		Lux 16	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Overcast	-2.6	6.8	-3.5	7.3	4.0	7.9	2.0	7.1	1.9	7.0	1.1	6.8
Dynamic	-1.4	10.0	-2.9	10.3	4.5	12.6	2.6	11.7	0.4	14.3	0.1	11.0
Sunny	-0.6	12.8	-2.5	12.5	6.0	15.8	4.3	14.4	6.4	19.7	5.2	18.1
All	-1.1	11.2	-2.8	11.2	5.2	14.0	3.3	12.8	3.2	16.7	2.4	15.7

Table 4. Relative simulation error for average work plane illuminance

	MBE		RSME	
Sky type	With Calibration Factor	Without Calibration Factor	With Calibration Factor	Without Calibration Factor
Overcast	0.4	8.5	6.3	16.1
Dynamic	0.4	-2.2	11.0	17.5
Sunny	2.8	2.7	13.7	18.1
All	1.4	0.4	12.1	17.7

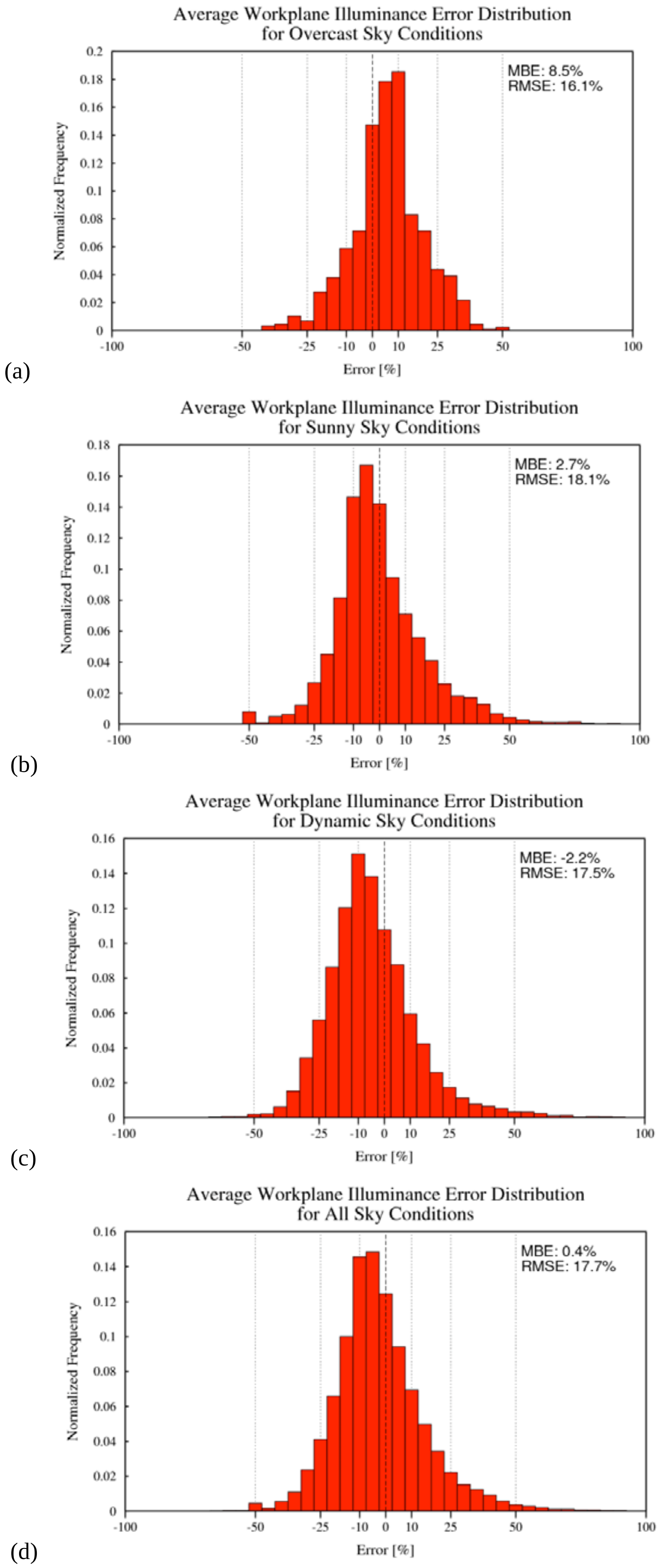

Figure 7. Error distributions for average work plane illuminance under (a) overcast, (b) sunny, (c) dynamic, and (d) all sky conditions

3.4. Computation Time

Two computer systems were used: an eight-core Mac OSX desktop computer and a two-core Mac OSX notebook computer. Table 5 shows computation times for the matrix steps and annual parametric runs. Computation time is the number of CPUs used multiplied by the duration of CPU use to complete the simulations.

Table 5. Computation times

Process	Computation Time (CPU hours)	Elapsed Time (hours)	Number of CPUs Used
V Matrix	10.67	2.67	4
T Matrix	8.52	2.13	4
D Matrix	1.32	0.33	4
Minutely Sky Vectors (for all 58 days - 39,515 time steps)	6.54	6.54	1
Matrix multiplication (for all 58 days, 39,515 time steps)	0.10	0.10	1

The view and daylight matrix simulations were run on the desktop computer using only four of the eight available CPUs.

To reduce repetition in sky vector generation, a year's worth of hourly sky vectors was pre-computed and compressed. Sky vectors were generated on the notebook computer.

The time step calculations were run on the notebook computer. Running a single time step (with pre-computed sky vector) took approximately 0.2 s using the standard version of *dctimestep*. For a typical day with approximately 720 1-minute time steps, computation time is approximately 144 s (2.4 min). To accelerate the run for all 58 days, we used an optimized version of *dctimestep* that reduces computation time by, among other things, storing the result of the VTD multiplication (that remains the same for all time steps) and parallelizing the multiplication of RGB channels (Zuo et. al. 2010). The optimized version of *dctimestep* reduced the matrix calculation for a single day with 720 1-minute time steps from 144 s down to 6.5 s. The speed of this calculation method puts parametric analysis into the practical realm of possibility.

4. Discussion

As with any simulation tool, the end user must assess whether the tool is both sufficiently accurate and fast enough to address the scope of work. Earlier, we described two possible uses of the new three-phase modeling capability in Section 1: technology R&D and evaluation of designs for actual building applications. With informed use, the new tool is able to accomplish objectives of both speed and accuracy to the degree that is practical for both uses.

4.1. Technology R&D

There are two critical path items that need to be addressed in order to enable performance-based development of innovative daylighting technologies to be performed routinely by industry: a) the ability to independently generate BSDF data for prototype designs, and b) the ability to conduct parametric analysis within a timely manner in order to quantify benefits across the expected range of conditions (e.g., climate, window orientation, window area, interactions with exterior and interior attachments such as overhangs, interior shades, etc.).

For the first item, it should be noted that characterization of the technology is probably the most challenging aspect of the problem. The difficulty of solar-optical characterization depends on a number of factors such as the scale of the device, whether flat samples of the base materials are available for measurement using a goniophotometer, etc. Macroscopic systems are generally easier to characterize (e.g., louvered systems). Micro- and nano-scale materials pose unique challenges, depending on the degree of diffraction caused by the technology. If diffraction is significant, then its best to characterize the system using measurements rather than using packaged ray tracing tools that inadequately model diffraction. There are various paths to obtaining full BSDF datasets, most combining detailed measurements with simulations and/or mathematical models. Andersen et al. (2009) provides a detailed overview of the various methods used to create BSDF datasets. Further developments of the Radiance tool are underway that will enable more accurate depiction of the scattering patterns produced by specular systems, particularly those with peaky distributions.

For the second item, speed of multiple calculations is of greatest interest. The three-phase method, as mentioned earlier, enables the T matrix to be substituted with a new matrix without the need to recompute the V and D matrices. The annual simulation calculation time is initially dependent on how quickly the computer can conduct the initial ray tracing calculations for the V and D matrices. For subsequent annual simulations the computation time is dependant on how quickly the computer can conduct the matrix calculation. Using the single private office case modelled in Section 4 as an example, we present, in Table 6, estimates of the time required to run an annual CFS simulation to produce illuminance data. Admittedly the simulation parameters used for generating the view matrix in this validation may be a bit excessive and can be relaxed without sacrificing too much accuracy. It is estimated that valid results could be achieved with 30 minutes computation time for the view matrix. Generating the BSDF is likely to be the most computationally intensive part of the simulation. A comprehensive BSDF database will replace the need to generate a BSDF, reducing simulation time significantly.

Table 6. Approximate computation time for an annual simulation on a 4 core desktop computer

Process	Initial simulation including BSDF generation (hours)	Subsequent simulation including BSDF generation (hours)	Initial simulation using a BSDF database (hours)	Subsequent simulation using a BSDF database (hours)
V Matrix	2.67	0	2.67	0
T Matrix	2.13	2.13	0	0
D Matrix	0.33	0	0.33	0
Generating Hourly Sky Vectors	1.45	0	1.45	0
Matrix multiplication using accelerated dctimestep	0.10	0.10	0.10	0.10
Total Simulation time	6.68	2.23	4.55	0.10

The CFS modelling tool is of course able to produce a rich dataset encompassing luminance within a scene for daylight quality and visual comfort assessments, but this analysis has focused on illuminance as a means of determining lighting energy use savings for cost-benefit analyses.

4.2. Daylighting design

Practical use by the architectural and engineering (A/E) community is dictated by ease of use, ready access to BSDF data for commercially available products from a trusted source, and integration of the tool with other simulation software in order to determine overall impacts on building energy use (e.g., window and lighting heat gains, lighting energy use, etc.).

At present, Window 6 accesses a complex fenestration database, similar to its IGDB database for specular glazings, and has built-in models based on measured angular data for roller shades, flat and curved slat Venetian blind systems, honeycomb shades, and other common interior, between-pane, and exterior shading systems. Development of models for other systems continues to be a task that the Window team will address. Other research organizations are developing BSDF libraries in parallel (Andersen and de Boer, 2006). There are also international efforts currently underway to standardize methods of characterizing systems and the format used to store the data.

There are many existing user interfaces to the Radiance core engine: SPOT, DAYSIM, Adeline, Ecotect, Relux. Incorporation of the three-phase method is currently underway by the developer of DAYSIM. Plans are underway to implement the capability in the COMFEN tool (Selkowitz et. al. 2011), which is currently a front-end interface to EnergyPlus and provides limited Radiance visualizations for a single commercial perimeter zone. EnergyPlus has been updated to incorporate the CFS method defined by Klems for solar heat gain calculations. Combined with the Radiance CFS modelling capabilities, the COMFEN tool could provide a consistent approach between both daylighting and window heat gain modelling in a single accessible software package.

5. Conclusions

Radiance's new tools provide a means for simulating CFS on an annual basis with reliable results. Many emerging daylighting products are difficult or impossible to simulate using standard simulation techniques. These latest developments will enable researchers to assess performance during early stages of product development and assess the technical impact of such technologies for a variety of potential markets. In addition, the method provides a base for developing software that allows building owners, architects and engineers to evaluate and compare technological options more critically before making purchasing decisions. Wide spread use of the new three-phase method is dependent on implementation into existing Radiance based GUI tools and improved availability of BSDF data.

This study demonstrates that the new three-phase simulation method provides valid results that accurately replicate real world conditions on a time step basis (1-minute intervals). Work plane illuminance data for a daylight-redirecting optical light shelf were measured in a full-scale, unoccupied private office over the course of a year. These data were compared to simulated data generated by the new Radiance three-phase modeling tool and found to have an absolute mean bias error below 13% and a root mean square error below 23% for all three sky types (overcast, dynamic, and sunny). Prior validation of the DAYSIM tool indicated that a MBE of less that 15% and a RMSE of less than 35% was sufficient to consider simulation results to be reliable. Routine application of this new capability will not be hindered by slow computational speed. Instead, the capability will be dependent on the availability of a comprehensive standard database that includes the many available daylighting, shading, and fenestration systems.

Acknowledgments

We gratefully acknowledge the contributions of Greg Ward, Anyhere Software, and our LBNL colleagues for their support on this project: Robert Clear, Dennis Dibartolomeo, Kyle Konis, Christian Kohler and Ling Zhu.

We thank the LightLouver LLC team – Michael Holtz, Zack Rogers and Mike Plann for providing the LightLouver reflective slat model and LightLouver units for review and for providing comments on this paper.

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards 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.

References

Andersen, M., de Boer, J., 2006. Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems, *Energy and Buildings* 38: 836–848.

Andersen, M., Stokes, E., Gayeski, N., Browne, C. 2009. Using digital imaging to assess spectral solar-optical properties of complex fenestration materials: A new approach in video-goniophotometry. Solar Energy, vol 84 (4), pp. 549-562, 2010.

Arasteh, D., Selkowitz, S., Apte, J., and LaFrance, M., 2006. Zero Energy Windows, Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA.

Architectural Energy Corporation, 2006, SPOT v3.1 User Manual [online]. Available from: http://www.archenergy.com/SPOT/SPOT_UsersManual_3.1.pdf [Accessed 31 March 2011].

Elliott, D.B., Cort, K.A., Anderson, D.M., Dirks, J.A., Belzer, D.B. and Hostick, D.J., 2004. Methodological Framework for Analysis of Buildings-Related Programs: The GPRA Metrics Effort [online]. Available from: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-14697.pdf [Accessed 31 March 2011].

Guglielmetti, R., Pless, S., and Torcellini, P., 2010, On the Use of Integrated Daylighting and Energy Simulations To Drive the Design of a Large Net-Zero Energy Office Building. Fourth National Conference of IBPSA-USA, New York City, New York, August 11 – 13, 2010.

Klems, J.H., 1994a. 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.

Klems, J.H., 1994b. A new method for predicting the solar heat gain of complex fenestration systems: II. Detailed description of the matrix layer calculation, *ASHRAE Transactions* 100 (1): 1073-1086.

Mitchell, R. Kohler, C., Klems, J., Rubin, M., Arasteh, D., Huizenga, C., Yu, T. and Curcija, D., 2008. Window 6.2/ Therm 6.2 Research Version User Manual, Lawrence Berkeley National Laboratory, LBNL-941 [online]. Available from: http://windows.lbl.gov/software/window/6/index.html [Accessed 31 March 2011].

Papamichael, K., Beltrán, L., Furler, R., Lee, E.S., Selkowitz, S. and Rubin, M., 1994. The energy performance of prototype holographic glazings. Proceedings of the SPIE International Symposium on Optical Materials Technology for Energy Efficiency and Solar Energy Conversion XIII, Freiburg, Germany. LBNL-34367.

Reinhart, C. F., Breton, P. F., 2009, Experimental Validation of ‘Autodesk 3ds Max Design 2009 and Daysim 3.0. Leukos 6(1), 7-35.

Reinhart, C. F., 2010, Tutorial on the Use of Daysim Simulations for Sustainable Design [online]. Available from: http://www.daysim.com/pub/Daysim3.0.Tutorial.pdf [Accessed 31 March 2011].

Reinhart, C.F. and Walkenhorst, O., 2001. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings, 33(7), p.683-697.

Saxena M., Ward, G., Perry, T., Heschong, L., Higa, R., 2010. Dynamic Radiance – Predicting annual daylighting with variable fenestration optics using BSDFS, Fourth National Conference of IBPSA-USA, New York City, New York, August 11 – 13, 2010.

Schregle, R. 2002. The RADIANCE Photon Map Manual Version 3.6 [online]. Available from: http://www.radiance-online.org/radiance-workshop1/cd/Schregle/patch/pmap.pdf [Accessed 14 March 2012].

Selkowitz,S., Mitchell, R., McClintock, M., McQuillen, D., McNeil, A., Yazdanian, M., 2011. COMFEN 3.0 – Evolution of an Early Design Tool for Commercial Facades and Fenestration Systems [online]. Available from: http://gaia.lbl.gov/btech/papers/5179.pdf [Accessed 28 October 2011].

Sullivan R., Beltran, L., Lee, E.S., Rubin, M., and Selkowitz, S.E., 1998. Energy and Daylight Performance of Angular Selective Glazings. Proceedings of the ASHRAE/DOE/BTECC Conference, Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater Beach, Florida, December 7-11, 1998.

Tregenza, P.R., 1983. Daylight coefficients. *Lighting Research and Technology*, 15(2), 65-71.

US DOE Office of Energy Efficiency and Renewable Energy (2005). 2005. Buildings Energy Databook, US Department of Energy, Office of Energy Efficiency and Renewable Energy [online]. Available from: http://btscoredatabook.eren.doe.gov/ [Accessed 31 March 2011].

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

Ward, G., Mistrick, R., Lee, E.S., McNeil, A. and Jonsson, J., 2011. Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance. Leukos 7(4), 241-261.

Winkelmann, F.C. and Selkowitz, S., 1985. Daylighting Simulation in the DOE-2 Building Energy Analysis Program. Energy and Buildings 8: 271-286.

Zuo, W., McNeil, A., Wetter, M., Lee, E.S., 2011. Acceleration of Radiance for Low Energy Building Design., Building Simulation 2011, Sydney, Australia, November 14 – 17, 2011.