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A validation of a ray-tracing tool used to generate bi-directional scattering distribution functions for complex fenestration systems

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Abstract

Fenestration attachments are anticipated to produce significant reductions in building energy use because they can be deployed quickly at low-cost. New software tools enable users to assess the building energy impacts of optically complex fenestration systems (CFS) such as shades, Venetian blinds, or daylighting systems. However, such tools require users to provide bi-directional scattering distribution function (BSDF) data that describe the solar-optical performance of the CFS. A free, open-source Radiance tool *genBSDF* enables users to generate BSDF data for arbitrary CFS. Prior to genBSDF, BSDF data for arbitrary fenestration systems could only be produced using either expensive software or with expensive equipment. genBSDF outputs CFS data in the Window 6 XML file format and so can be used with CFS-enabled software tools to model multi-layered window systems composed of glazing and shading layers.

We explain the basis and use of the genBSDF tool and validate the tool by comparing results for four different cases to BSDF data produced via alternate methods. This validation demonstrates that BSDFs created with genBSDF are comparable to BSDFs generated analytically using TracePro and by measurement with a scanning goniophotometer. This tool is expected to support accelerated adoption of fenestration attachments and daylighting technologies.

Keywords: Daylighting; Solar Heat Gain; Complex fenestration systems; Bi-directional scattering distribution function.

1. Introduction

Complex fenestration systems (CFS), have an estimated staged potential to reduce US commercial and residential building source energy use in both new and retrofit applications by about 1 quad/yr (1015 Btu) in 2030 (Farese et. al. 2012). The term CFS covers all non-specularly transmitting fenestration system components including layers that provide shading, such as fabric shades, louvered blinds, and metal mesh systems, and layers that improve interior daylighting, such as prismatic films and mirrored louvered systems. In order to promote and improve upon the performance of these technologies, researchers world-wide have been developing the computational methods, tools, and supporting data to more accurately characterize the solar-optical and daylighting performance of CFS (Papamichael et al., 1988; Klems, 1994a,b; Aydinli and Kaase, 1999; Schregle, 2004; deBoer, 2006; Andersen and deBoer, 2006). Existing tools make simplifying assumptions about the light-scattering properties of CFS and therefore are inherently inaccurate (Apian Bennewitz, 2013). As we progress toward net zero energy-efficient solutions for buildings, it becomes increasingly important to be able to model more precisely not only the quantity but also the directional transfer of solar and daylight flux within the window system and to indoor zones. Such capabilities can also be applied to evaluations of human comfort and indoor environmental quality.

Recently, through the continued support of the US Department of Energy and the California Energy Commission through its Public Interest Energy Research Program, CFS modeling capabilities have been added to building performance simulation programs. These new modeling capabilities use bi-directional scattering distribution functions (BSDF) to characterize the angularly resolved transmission and reflection of light by CFS. Window 6 (Mitchell et al., 2008) now includes the ability to create a BSDF for CFS layers combined with glazing layers, Radiance (version 4.1)(Ward and Shakespeare, 1998) includes a data driven BSDF material type and support for contribution coefficients, and EnergyPlus (version 7.2) includes the ability to use BSDF data in determining solar gains. Nicodemus introduced the bi-directional reflectance function (BRDF) to describe light-scattering of opaque materials (Nicodemus, 1965) and it can be expanded to describe transmitted scattered light (BTDF). In 1994, Klems proposed an efficient calculation method to use BSDF datasets (which is the combination of BRDF and BTDF) to model solar heat gains for multi-layered fenestration systems (Klems, 1994a). This method was implemented in the tool suite listed above.

A CFS manufacturer has two choices to obtain BSDF data for a product: measurement or simulation. Measurements of the physical system can be made with a device such as a scanning goniophotometer (in general (Stover, 1992), example instruments (Klems and Warner, 1995; Germer and Asmail, 1997; Apian-Bennewitz and von der Hardt, 1998) or imaging systems (Ward, 1992; Andersen et al., 2001)). Measurement of the actual physical sample is ideal but time-consuming and therefore expensive to conduct, considering the wide variety of products offered in a multitude of colors, weaves, and finishes. An alternative to measurement is simulation through ray-tracing. Ray-tracing is ideal in the design phase of a product since there is no need to manufacture prototypes, enabling rapid evaluation and comparison between similar designs. However, the result of the simulation is only as good as the models used to describe the materials and geometry. Currently there are few goniophotometers in existence that can fully characterize a CFS and commercially available forward raytracing software are rather expensive.

This paper describes an open-source Radiance software tool, *genBSDF*, that was developed to enable generation of BSDF datasets, given input on the geometry of macroscopic systems and surface properties of the base materials from which the system was constructed. We describe the fundamentals of BSDF conventions and the ray-tracing algorithm. We then compare datasets produced by genBSDF to two hypothetical cases (air and a Lambertian diffuser), a mirrored blind simulated with the commercial ray-tracing package (TracePro), and a micro-perforated shade measured using a scanning photogoniometer. Discrepancies between the datasets are explained. This tool combined with other methods is expected to support accelerated adoption of CFS by the buildings industry.

Currently genBSDF produces an XML file where the BSDF data is given a visible spectrum tag. However in the discussion section we describe a simple method for using genBSDF to produce BSDF data for an arbitrary wavelength band, including the solar spectrum.

2. Background

A BSDF characterizes the way light interacts with a material or system. Outgoing light distributions (transmitted and reflected) are characterized for many incident directions. In his description of methods used to model CFS solar heat gains, Klems described a means to derive a single BSDF for a multi-layer window system (e.g., dual pane window with an interior shade is a three-layer system) by multiplying the BSDF matrix for each layer (Klems, 1994b). The software program Window 6 implemented Klems' matrix multiplication algorithm to generate a single BSDF for a complete multi-layer window system. Window 6 output for the window system is then used in Radiance and EnergyPlus to determine window heat gains and daylighting performance in the modeled zone.

The window coordinate system, called the Klems angle basis, was designed specifically to simplify the required matrix multiplication. The Klems angle basis has 145 input and output directions in

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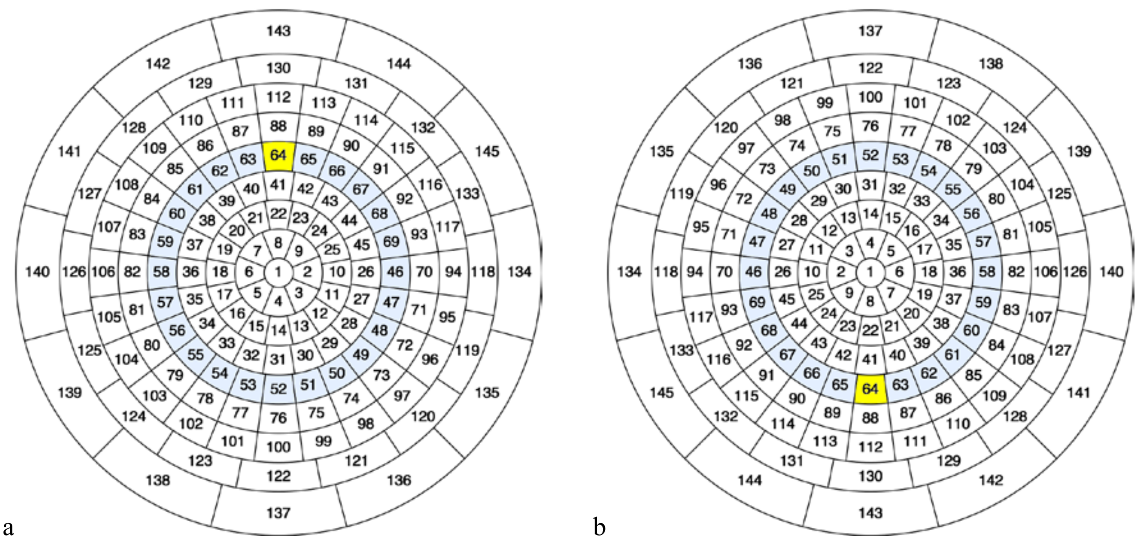
nine concentric theta bands (Fig. 1). The number of phi divisions of each theta band and the width of the theta band are modulated so that all divisions have roughly the same cosine-weighted solid angle. Consistency in cosine-weighted solid angle ensures that the contribution to hemispherical transmittance is roughly the same for all patches.

In the Klems angle basis, angular divisions are indexed starting from the normal patch working outwards. The incident hemisphere uses a right-handed coordinate system and the transmitted hemisphere uses a left-handed coordinate system. These coordinate systems are shown in Fig.1. Light incident at theta 40° and phi 90° are in the Klems incident patch 64. If this light is transmitted specularly, it leaves at a theta angle of 40° but phi angle of 270°; however, it is still in patch 64 on the outgoing Klem's coordinate system. Switching coordinate systems allows the incident and specular transmission patches to have the same index, simplifying BSDF multiplication for layered systems.



a b

Fig. 1. Angular projection of Klems angle basis viewed from the incident side for (a) incident (normal direction out of the page) and (b) transmitted hemispheres (normal direction into the page). The blue shaded regions indicate a Klems "theta band" which is all the patches with the same theta angles. A "phi division" is a single patch in the theta band (eg shaded in yellow). Note that the numbering scheme of the patches is different for the two hemispheres. This numbering is chosen to allow a specular beam to be described by the same patch number for incident, reflected and transmitted directions.

Window 6 uses an XML file specification to organize data in a BSDF file. The XML file contains data blocks describing reflection on front and back surfaces and transmission on front and back surfaces (transmission data for front and back are the same due to reciprocity). Each data block contains 21,025 values made up of 145 outgoing directions for each 145 incoming directions (145 x 145). Radiance and EnergyPlus support BSDFs using the Window 6 XML specification and Klems angle basis.

The method used for creating a BSDF varies based on the CFS to be characterized. Macro-scaled CFS, such as louvers or specular blinds often require ray-tracing simulations to generate a BSDF because the incident light source of most measurement devices cannot cover variations in the CFS adequately. BSDFs for micro-structured or homogeneous systems can be obtained via measurement. Systems whose non-specular transmission can be approximated by a Lambertian transmitter can be measured using an integrating sphere with a port to exclude or include specular transmission. Angled sample holders and calibration procedures are required for off-normal measurements. A goniophotometer provides high-resolution spatial transmission data. For non-isotropic systems, the overhead of adjusting sample orientation limits the number of incident angles measured on a goniophotometer without an automated sample rotator. Ray-tracing has been compared with other methods to produce BSDFs before (Andersen et al., 2005; Andersen et al., 2003) and it is clear that a ray-tracer must be set up to replicate the conditions of the other method as closely as possible to get good agreement. Poor agreement does not necessarily indicate that one method is incorrect. Whenever a BSDF value is measured at an angle where the function has a non-zero derivative, be it with a physical detector or a virtual detector in a ray-tracer, the result can depend on the solid angle of the detector. The measured value is an average over the solid angle of the

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detector, a limitation of trying to measure a per solid angle property using a finite area sensor. This is not only a concern when comparing ray-tracers with goniophotometers, but also when comparing different ray-tracing configurations.

3. Overview of *genBSDF*

3.1. Generating a BSDF

genBSDF uses the Radiance source geometry primitive to create two infinitely distant hemispheres (one for transmission and one for reflection) to receive emitted rays. These receiving hemispheres are combined with CFS geometry in a Radiance model. Imaginary rectangular surfaces on both the outdoor (front) and indoor (back) sides of the CFS model emit rays to optically sample the system. The origins of emitted rays are randomly distributed over the emitting surface and ray directions are randomly distributed within the range of angles defined by the angular boundaries of the Klems patch. Distributing the sample ray directions over the Klems patch, genBSDF is illuminating the model using the full solid angle of each patch (Fig. 2). By using an area source, the outgoing BSDF distribution is integrated over all incident angles within the Klems patch.

Measurement devices use a (nearly) collimated source to illuminate the sample. When a collimated source is used, all light arrives at the sample with the same incident angle (corresponding to the center of the Klems patch). In a simulation, the same output distribution is used for energy arriving at any angle within the patch, regardless of incident direction within the patch. For simulation, BSDFs produced using an area source that characterizes optical properties integrated over the incident patch is preferred. Generating BSDFs using area sources is not difficult via simulation, but producing an area source the size and shape of a Klems division for measurement is a challenge (it is also difficult to generate a purely collimated source, for measurement, but the beam of most measuring devices more closely resembles a collimated source than a Klems patch source).

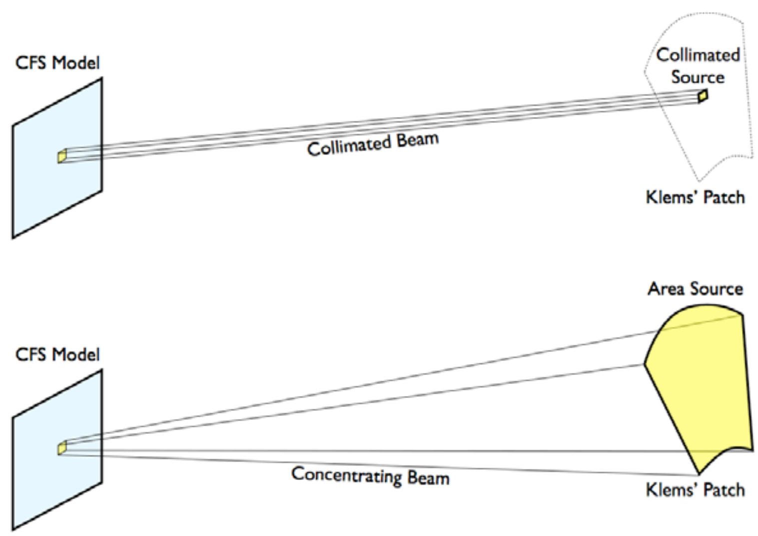

Fig. 2. Diagrams depicting a collimated source (top) and patch area source (below).

The rays emitted navigate through the CFS model until they hit the receiving surface. When a ray strikes a surface of the CFS model, additional rays are spawned to simulate both diffuse and specular reflection. As multiple inter-reflections occur, an ever-expanding ray tree is produced. When rays finally hit the infinitely distant receiving sphere, they are binned into Klems patches according to the final ray's direction vector. The weights of child rays accumulated in a Klems patch are summed to generate the contribution coefficients for each emitted ray. Once all the rays are traced, contribution coefficients for all the emitted rays for an incident Klems patch are averaged. To calculate the BSDF values, the averaged coefficients are divided by the solid angle and average cosine theta of the emitting patch. A full BSDF will contain this data for front and back transmission and front and back reflection.

The genBSDF tool uses the ray tracking capabilities of *rtcontrib* to record exiting ray directions. The core Radiance programs evaluate a ray tree recursively and discard potentially useful information about the origin of light in the process. The recent addition of rtcontrib allows the origin of light to be tracked through the ray tree, providing contribution coefficients for sources based on scene geometry or binning based on ray direction. For example, in an electric lighting simulation with two light fixtures, rtcontrib can report the illuminance contribution from each of the light fixtures individually. In a daylight simulation, the illuminance contributions can be reported for angularly divided sky regions by tracking the directions of the rays that reach the sky.

Similar to other tools in Radiance, the rtcontrib program traces rays backward from the point of measurement to the light source. Because the physics of light transport is reversible, the choice between backward and forward simulation is based on which is most efficient for a particular application. When rays are focused at a measurement position such as a camera, backward ray-tracing is usually the most efficacious. When there is a single source and one is trying to determine the entire output distribution such as for a luminaire, forward ray-tracing may be preferred. In the case of BSDF computation, there is no advantage to one direction over the other, so there is there is no handicap using a backward computation.

3.2. Using genBSDF

Since genBSDF is written in Perl, it can be run on any operating system capable of running Perl (including MS Windows, Mac and Linux). Running genBSDF requires a working installation of Radiance since genBSDF uses system commands to run the Radiance programs rtcontrib, rtrace, cnt, rcalc, oconv, rad2mgf, and mgf2rad. Radiance installers for Windows, Mac and Linux are available from NREL's openstudio website.

The first step for using genBSDF is to create a geometric model of the system to be characterized. The model can be in either the *Material and Geometry Format* (Ward, 1996) or Radiance scene format. There are various converters available to convert geometry from other formats to Radiance format, however Radiance material descriptions must be added by hand. If geometry output is desired, genBSDF will include an XML tag with the system description in MGF. MGF is a description language for three-dimensional environments expressly suited to visible light simulation and rendering, but can be adapted to represent full spectrum simulations. The materials are physically based and rely on standard and well-accepted definitions of color, reflectance and transmittance for good accuracy and reproducibility. The geometry is based on boundary representation using simple geometric primitives such as polygons, spheres and cones. The original purpose of the format was to describe light fixtures as part of the IESNA standard, but it is equally applicable to fenestration systems and other detailed fixtures. Using a Radiance or MGF input model permits measured BSDF materials to be incorporated via the new BSDF primitive.

The genBSDF tool uses the Klems coordinate system, so the model must be oriented accordingly. The +Z direction points inside and +Y is up for the fenestration. The model should be entirely in the -Z half-space. Geometry that protrudes into the +Z half-space may cause unexpected errors in subsequent simulations using the BSDF. Since Radiance defines the emitting planes (plane just above and below the CFS, where the two planes define the "bounding box" in Table 1 below) as rectangular, genBSDF expects that the CFS is contained within a rectangular profile. For CFS not contained within the profile, output will be produced but some sample rays will be generated outside of the system model and taint the resulting BSDF. We can override this behavior using the –dim option to specify a subregion for sampling.

The genBSDF program is run from a command prompt. Table 1 contains the command-line options recognized by genBSDF. The default operation for genBSDF only generates data for back (indoor) reflection and transmission and emits 2000 samples per Klems patch, 290,000 sample rays in total. The sampling direction (forward, backward or both) and number of ray samples can be specified by the user.

Table 1. Command line options for generating Klems basis BSDFs with genBSDF.

Command Line Option	**Description**
-c Nsamp	Sets the number of sample rays per Klems division. The default is 2000 samples per Klems division.
-n Nproc	Sets the number rtrace processes to run. This option allows users to make use of multiple processors to reduce computation time. The default is 1.
-r '*rtcontrib* opts...'	Set simulation options passed to rtcontrib (-ab, -ad, -ss, -lw etc.)
+b (-b)	Create a BTDF and BRDF for back (indoor) surface of CFS.
+f (-f)	Create a BTDF and BRDF for front (outdoor) surface of CFS.
{+|-}mgf	Specifies the input model format. The default for input model format is Radiance (-mgf). MGF can be used with +mgf.
{+|-}geom unit	Geometry will be included in the resulting XML file if +geom is set (this is the default). Geometry is excluded with -geom. The length unit must be given in either case, and must be one of meter, foot, inch, centimeter, or millimeter. Output geometry is MGF regardless of input format.
-dim Xmin Xmax Ymin Ymax Zmin Zmax	Normally, "emitting" rectangles are positioned according to the bounding box of the model. This option allows the user to specify a different bounding box.

4. Validation

Four test cases were used to validate genBSDF (Table 2). A BSDF was created using genBSDF for all four cases. The resulting front transmission data from genBSDF was compared against analytically derived values, TracePro simulation data, or goniophotometer measurements.

Table 2. Test cases for validation.

Test Case	**Validated Against**
Air (100% specular transmission)	Analytically derived values
50% Lambertian transmission	Analytically derived values
Mirrored blinds with flat slats	TracePro simulation
Micro-perforated shading film	Goniophotometer measurements

4.1. Validation Case 1: air (100% specular transmission)

The BSDF matrix for air (and other specularly transmitting materials) is a diagonal matrix. The diagonal values of the matrix are specular transmission times cosine theta integrated over the discrete patch divided by the solid angle of the patch. To test this case, we used a polygon with no material specified (void):

```
### void.rad ########
void polygon plane
0
0
12    0     0     0
      0     10    0
      10    10    0
      10    0     0
```

genBSDF void.rad > void.xml

We ran genBSDF using this polygon description and set the number of sample rays per Klems patch to 10,000. The result is a diagonal matrix as expected. The results for theta bands 1-9 were all identical to the expected value to six significant digits. Table 3 contains the expected BSDF value and the mean of genBSDF results for each theta band. Fig. 3 shows a scatter plot of the results with a linear regression.

Table 3. Expected BSDF value and mean *genBSDF* results.

Theta band	Patch numbers	Theta range	Solid angle	Average cosine theta	Analytically derived BSDF value for specular patch	*genBSDF* result (mean for theta band)	Percent difference
1	1	0-5°	0.0239	0.9981	41.9043	41.9043	0.00%
2	2-9	5-15°	0.0238	0.9811	42.8864	42.8764	0.02%
3	10-25	15-25°	0.0234	0.9361	45.6281	45.6281	0.00%
4	26-45	25-35°	0.0274	0.8627	42.3330	42.3330	0.00%
5	46-69	35-45°	0.0293	0.7631	44.6724	44.6724	0.00%
6	70-93	45-55°	0.0350	0.6403	44.6724	44.6724	0.00%
7	94-117	55-65°	0.0395	0.4981	50.7996	50.7996	0.00%
8	118-133	65-75°	0.0643	0.3407	45.6281	45.6281	0.00%
9	134-145	75-90°	0.1355	0.1294	57.0215	57.0215	0.00%

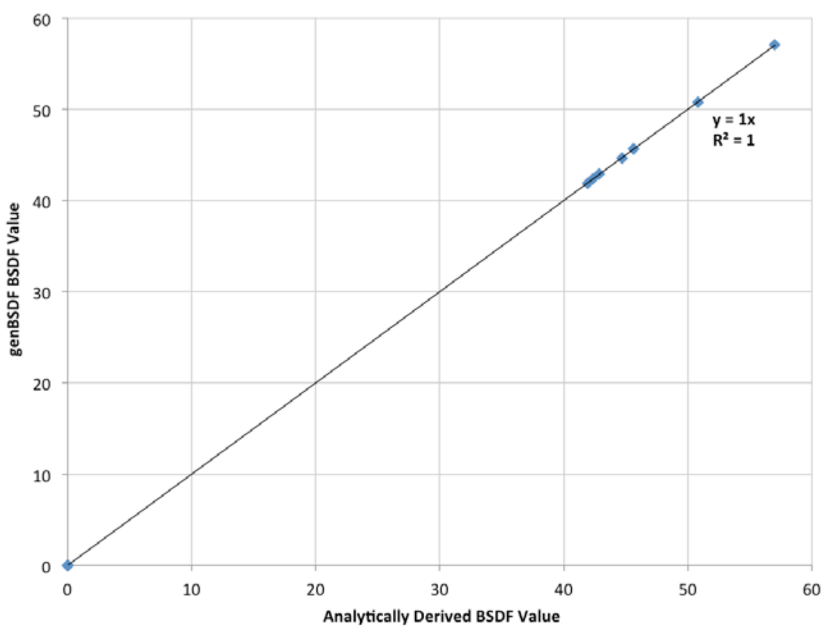

Fig. 3. Scatter plot of the genBSDF results versus the analytically derived BSDF values for air. The 21,250 transmission values are correlated with a linear regression fit (r^2=1.0).

4.2. Validation Case 2: lambertian diffuser with 50% transmission

The BSDF for a Lambertian transmitter equals the total transmission divided by π. For a 50% Lambertian transmission the BSDF value is 0.1592 for all patches. The Radiance *trans* material provides the ability to model diffuse transmission. The input model for genBSDF was as follows:

```
### diffuse50.rad ########
void trans diffuse50
0
0
7    0.5    0.5    0.5    0    0    1    0
```

The BSDF for this model was generated using genBSDF with 1000 sample rays per Klems division. The resulting BSDF was comprised of values ranging between 96 and 104% of the anticipated

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result. For most simulations, this is likely within acceptable limits. To satisfy our curiosity, we also generated a BSDF using 10,000 samples per Klems division and generated a BSDF by changing the default -ad parameter from 700 to 7000. The –ad parameter sends out more ambient samples, which reduces noise in the inter-reflected component. Table 4 contains statistical analysis of the BSDF values from the 1000 and 10,000 sample genBSDF runs. As the number of samples is increased, the mean bias error and RMS error decrease, demonstrating that the noise in the results is reduced with more samples. Increasing the –ad parameter has a similar effect for this case.

Table 4. Distribution of values in generated BSDF for the Lambertian diffuser.

***genBSDF* settings**	**-c 1,000 -r '-ad 700'**	**-c 10,000 -r '-ad 700'**	**-c 1000 -r '-ad 7000'**
Mean	0.15916	0.15915	0.15915
maximum BSDF value	0.16507	0.16265	0.16231
maximum relative error	3.7%	2.2%	2.0%
minimum BSDF value	0.1525	0.15660	0.15915
minimum relative error	-4.2%	-1.6%	-1.0%
mean bias error	0.00058%	-0.000071%	0.000034%
RMS Error	0.89%	0.56%	0.53%

4.3. Validation Case 3: mirrored blinds

A flat slat blind system with specular upper and matte lower finishes was modeled in Radiance and TracePro to compare BSDF output. The blind slats are 80 mm deep, 0.4 mm thick and spaced 72 mm apart. The width of the blinds was 2 m. The top side of the blind slats had a purely specular reflectance of 91.7%. The underside of the slats had a Lambertian reflectance of 29%. The slats were horizontal (0 degree tilt angle).

TracePro and genBSDF have different methods for sampling a model. In TracePro, the sample rays were generated along a line between two blind slats, and are collimated – all rays have the same direction. In genBSDF, sample origins are emitted randomly over the exterior plane of the blinds and sample ray directions are not collimated, but are distributed randomly over the Klems patch.

The scatterplot in Fig. 4 compares the BSDF values from genBSDF against those of TracePro. The 0.88 slope of the linear fit indicates that the two simulated BSDFs are not consistent with each other. The matrix plot in Fig. 5 illustrates the percent difference between the two results with the incident patch number on the x-axis and outgoing patch number on the y-axis. Agreement between genBSDF and TracePro results vary and depend mostly on incident patch (shown as columns in Fig. 5). Results for most incident patches are consistent between programs. In the case of Klems patch 76 where percent differences are less than 10%, the incident flux strikes the matte surface (underside) of the slat. The diffuse reflection is evident in results from both TracePro and genBSDF simulations.

Results for some incident patches are not consistent between programs: for example, the Klems patch 1 (normal incidence) shows 100% disagreement for all outgoing angles (the leftmost column in Fig. 5). Since the incident light in TracePro is collimated and Klems patch 1 is perpendicular to the blind, most of the flux is transmitted directly – the 0.4 mm thin edge of the slat blocks only a small fraction of incident light. In Radiance, the incident light is distributed over the patch, so some light reflects off the matte and specular surfaces. The flux reflecting off the matte surface exits in many patches, registering a larger percent error. None of the flux in TracePro strikes the matte or specular surfaces of the slat, therefore the percentage difference is large – up to 100%.

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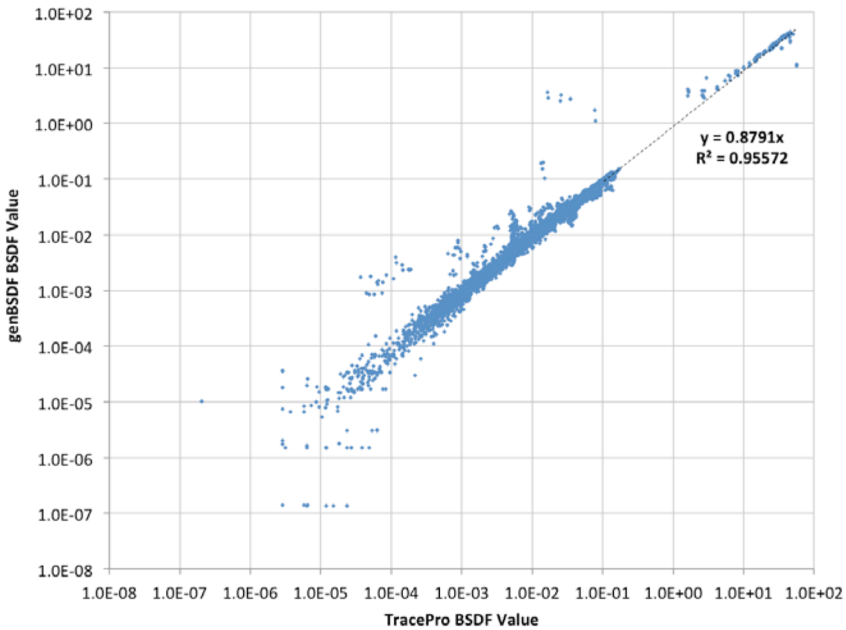

Fig. 4. Scatter plot of the genBSDF results versus the analytically derived, TracePro BSDF values for the specular Venetian blind. The 21,250 transmission values are correlated with a linear regression fit (r^2=0.95572).

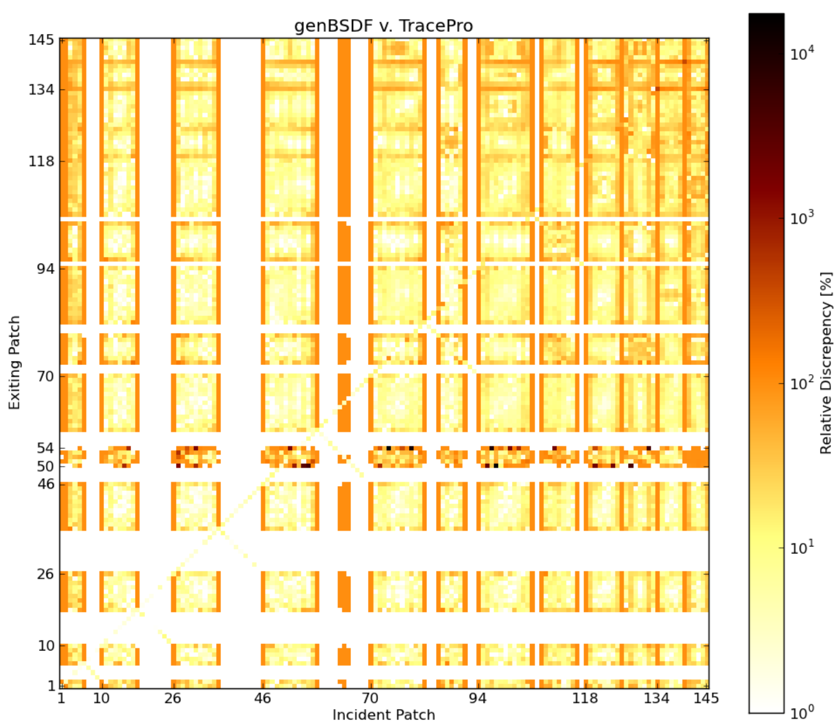

Fig. 5. Percent difference between genBSDF- and TracePro-generated BSDFs (transmission) for flat specular blinds positioned at a horizontal angle.

To verify that the difference between results from genBSDF and TracePro is attributable to the difference in simulation procedure, we created a modified version of genBSDF that mimics the simulation procedure of TracePro. First, the illuminating source was changed from an area source to a collimated

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source originating from the center of each patch (Fig. 2) by removing the random variables in ray direction. Second, since the TracePro model emits rays from a thin strip, the genBSDF "emitting" surface was reduced from the 2 m square covering the entire system to the section of the CFS modeled in TracePro: a 2 mm wide and 72 mm tall strip aligned with one period of the blind system (the TracePro model was sufficient to characterize the system and kept the calculation time to a minimum). Finally, since TracePro cannot model infinitely distant receivers, the genBSDF infinitely distant "receiving" hemisphere was changed to a 20 m disk, which is the size of the hemisphere used in TracePro. This final change mimics the hemisphere used in TracePro to collect and bin outgoing flux.

The scatter plot in Fig. 6, comparing modified genBSDF result against TracePro result shows better agreement compared to the scatterplot in Fig. 4. The 1.00 slope of the linear fit indicates agreement between the two simulation programs. Fig. 7 shows the percent difference of BSDF values between the modified version of genBSDF and TracePro. Overall, the percent error is low. However, exiting patches 50-54 exhibit high percent error over many incident patches. These errors are not alarming because the magnitude of error is small. To arrive at patches 50-54, light first illuminates the underside (matte side) of a slat. A small fraction of the diffuse light leaving the back 8mm of the underside of the slat will go towards the front 8mm of the specular surface of the slat below and this light is specularly reflected to patches 50-54. The probability of an ambient sample ray from the sliver of matte surface going to an equally small sliver of the specular surface to reflect in the direction of patches 50-54 is low and thus the Monte-Carlo simulation results are noisy. These patches appear in the tail of the scatter plot in Fig. 6.

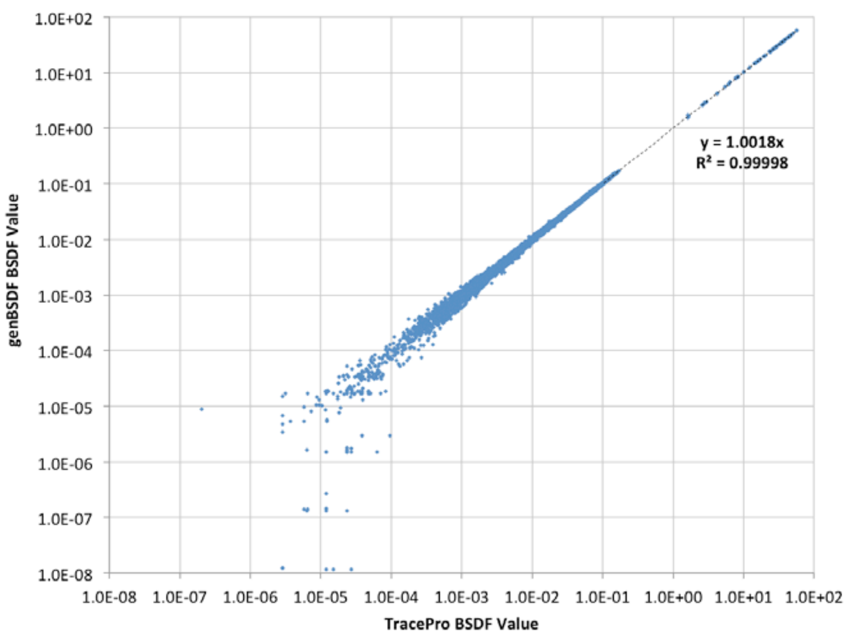

Fig. 6. Scatter plot of modified genBSDF (with a collimated source) versus TracePro BSDF values for flat specular blinds. The 21,250 transmission values are correlated with a linear regression fit (r^2=0.99998).

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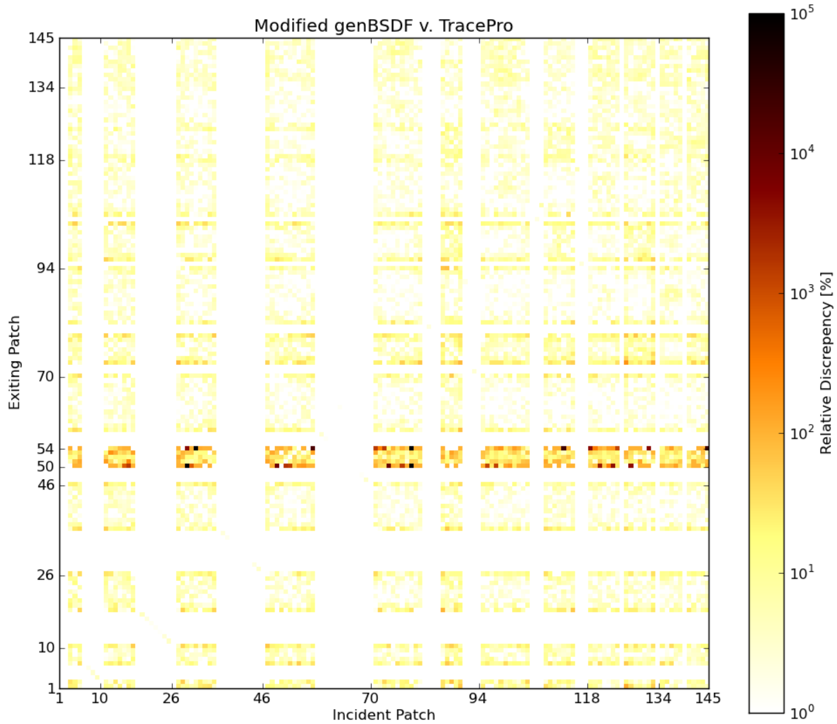
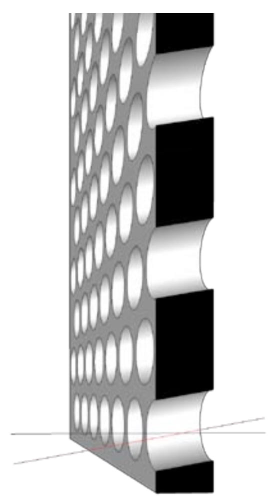


Fig. 7. Percent difference between modified genBSDF- and TracePro-generated BSDFs (transmission) for flat specular blinds positioned at a horizontal angle.

4.4. Validation Case 4: micro-perforated shade

The final validation case involves a micro-perforated shading system measured with a goniophotometer and modeled in Radiance with genBSDF. The micro-perforated metal screen is a thin sheet of metal with elliptical holes less than 1 mm in width and less than 0.5 mm in height (Fig. 8). The holes are cut in a downward direction (when viewed from the indoors). Maximum transmission of the perforated shade occurs when looking from indoors to outdoors in a downward direction about 10° below horizontal.

a



b

Fig. 8. (a)View through the micro-perforated shade held at arm's length and (b) a section view of the micro-perforated shade - not to scale.

A CAD model of the micro-perforated shade was created using a dimensioned drawing provided by the manufacturer. An un-cut sample of metal provided by the manufacturer was measured in a spectrophotometer to obtain the reflectance properties of the material. The BSDF for the shading system was then determined using the geometry and measured reflectance in the modified version of genBSDF (with the collimated source). The modified genBSDF with collimated source was used because it more closely resembles the source used by the goniophotometer.

The goniophotometer used was a Pab Advanced Technologies Ltd pgII scanning goniophotometer (Grobe et al., 2010). It uses a collimated halogen light source to produce a beam of parallel light with a beam diameter of approximately one inch. The sample is mounted so that it can be rotated to modify the angle of incidence. The detector moves continuously around the sample using two moving arms covering the full sphere except the base of the sample holder (which represents an approximately 5 degree obstruction straight down – patch 143). The detector position and detected radiance is recorded at a high frequency, as the detector is moving. The detector is a silicon detector combined with a v. Lambda filter to measure visible light for use in daylight simulation. The data set is converted from discrete points to the patches of the Klems coordinate system.

Fig. 9 compares the genBSDF results to the goniophotometer measurements for one incident angle (Klems incident patch #88). The most striking difference between the measured and simulated BSDFs occurs at outgoing directions corresponding to patches #64 and #112. There are peaks measured in these directions that are not replicated in the simulations. Patches #64 and #112 are adjacent to the specular patch (#88) and are in the scattering plane defined by the surface normal and the incident ray. The pattern continues out to patch 41 and patch 130 as well, though these peaks are much lower. The Y-axis in Fig. 9 uses logarithmic scale to show those differences, otherwise the direct – direct transmittance through patch #88 would dominate and the chart would not illustrate the energy transmitted to the other directions. The non-specular patches contain 2-5 orders of magnitude less energy than the direct transmission in the specular patch (patch #88).

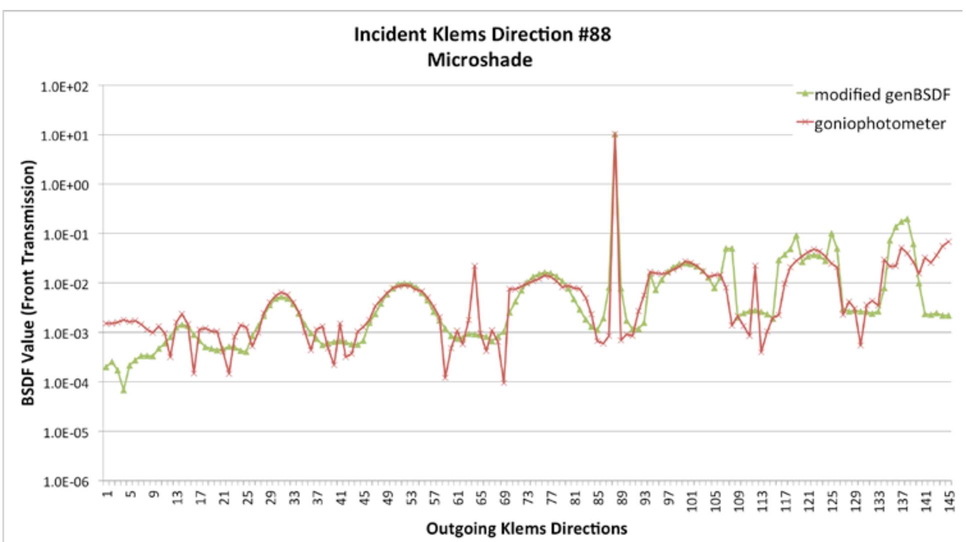


Fig. 9. Chart of measured and simulated BSDF values of micro-perforated shade for Klems incident patch number 88.

In the case of patches #64 and #112, the difference between the measured and simulated values is caused by diffraction. Radiance only simulates ray optics and does not reproduce wave optic phenomenon including diffraction. The ellipse diameter is larger than would commonly be considered to cause substantial diffraction, but diffraction occurs for all apertures of any size, and the magnitude of the effect (1000x smaller than the peak) is consistent with diffraction for an aperture the size of the ellipse.

Fig. 10 contains charts of transmission for incident theta angles ranging from 0° to 82.5°. The phi angle is 90° (azimuthal angle 0°) and above the horizon. Simulation tracks the goniophotometer measurements for both direct-hemispherical and direct-direct with perturbations occurring at some theta angles. These charts illustrate that BSDFs generated via simulation are reasonably accurate.

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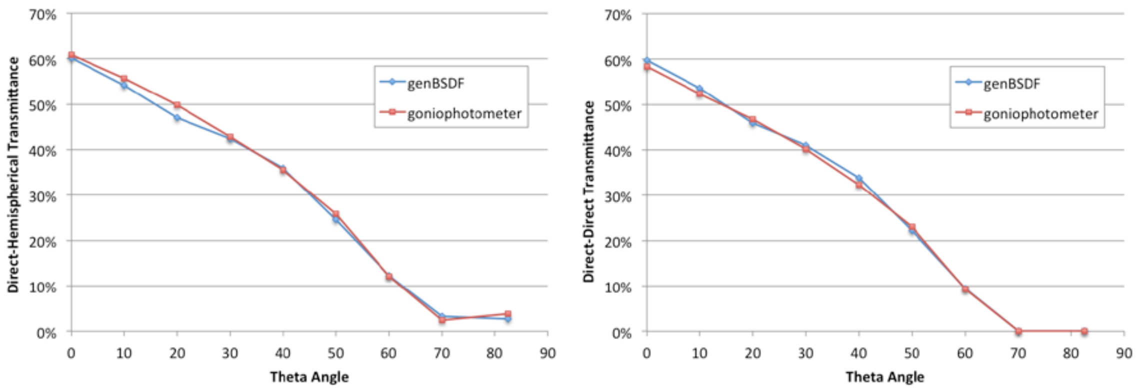

Fig. 10. Charts of (a) direct-hemispherical transmittance (top), and (b) direct-direct transmittance (bottom) for measured and simulated BSDFs for the micro-perforated shade. Simulated BSDFs used the modified version of genBSDF with a collimated source.

The scatter plot (Fig. 11) shows a linear fit with 1.01 slope, which demonstrates agreement between the two methods, however there is quite a bit of scatter in the low intensity patches. This could be the result of noise in either the goniophotometer measurements or the Radiance Monte Carlo simulation (or both). The absolute difference in values is very small and therefore can be ignored.

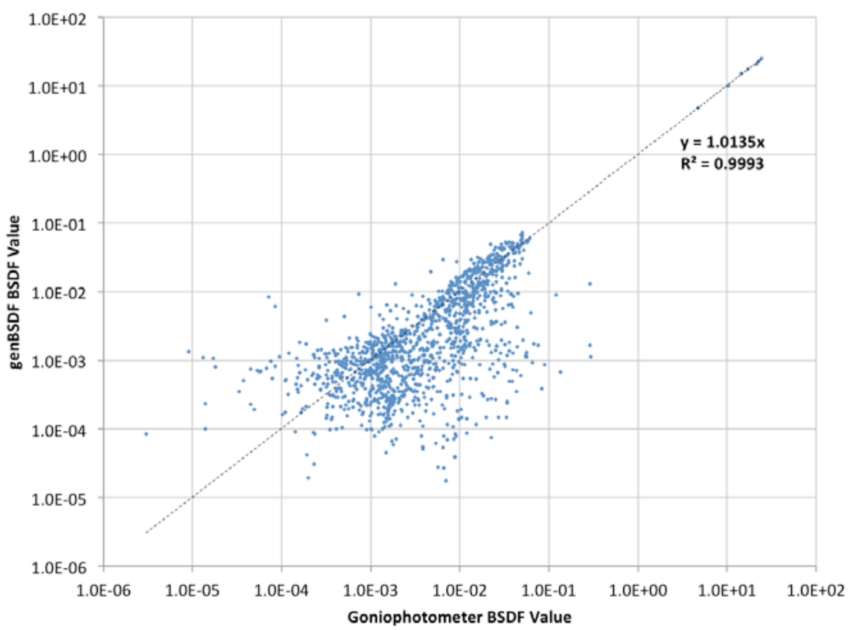

Fig. 11. Scatter plot of BSDF values from modified *genBSDF* (with collimated source) versus goniophotometer measurements for the micro-perforated shade. The 21,250 transmission values are correlated with a linear regression fit (r^2=0.9993).

5. Discussion

Over the course of validating *genBSDF*, critical differences in assumptions were identified that resulted in differences in BSDF values generated by genBSDF and other simulation or measurement methods. Ensuring that the sampled area of the CFS system is representative of the system as a whole is relatively easy to remedy. To characterize optical properties using the Klems angle basis, it is more appropriate to use a solid-angle source matching the Klems patch rather than a collimated source. The genBSDF tool uses a solid angle source, and this can be done in TracePro with some effort. It is unlikely, however, that an area source could be used with the goniophotometer since the source would need to be both large and focused and is further complicated by the fact that area source size and shape is different for each theta ring in the Klems basis.

By modifying *genBSDF* to match the assumptions used to model the system in TracePro software, we were able to demonstrate that *genBSDF* produces the same BSDF data as TracePro for nearly all input and output angles, with the exception of a few exiting patches that could be explained by inadequate Monte-Carlo sampling (Case 3). Comparisons against measured data showed more variation in Case 4 some of which can be explained by diffraction. However, the overall transmission in Case 4 was determined to be reasonably accurate.

Generating comprehensive BSDF datasets to support daylight and energy simulation will be challenging but necessary. Direct measurement of bidirectional scattering properties with a goniophotometer is only possible for systems with small scale, homogeneous structures. These measurements are also time consuming, for non-symmetric systems with anisotropic transmission, obtaining measured data for 145 incident angles can currently take up to a month for a single sample. For macro-geometric systems, like specular blinds, the systems are too large to be practically measured in a scanning goniophotometer. Generating BSDFs by simulation presents a plausible solution. In some cases it will be necessary to measure reflectance and transmittance properties of non-standard materials, which can then be assigned to surfaces of macro, scaled systems in a ray-tracing simulation.

The Window 6 BSDF XML schema is currently the only standardized format that is supported by a suite of simulation tools for describing directionally dependent window optical properties. Users of simulation programs will use BSDF data into improve the accuracy of solar optical modeling in their simulations. Now that BSDF capabilities of Radiance and EnergyPlus are fully functional, users will need a convenient and trusted means to obtain BSDF data for commercially available fenestration systems. To address this need the NFRC and LBNL are in the process of developing a complex glazing database (CGDB) that will contain BSDFs for optically complex fenestration systems. The CGDB submittal process may be similar to the international glazing database (IGDB) where products are tested by independent labs and submitted for review and inclusion in the database.

The genBSDF tool offers a pathway for product data to be included in the CGDB. Currently, genBSDF by default generates data for the visible spectrum. However if genBSDF is given a model with material reflectance and transmittance values for the solar spectrum, then the resulting BSDF will be for the solar spectrum. Using similar methods genBSDF will produce a BSDF for arbitrary wavelength bands. For example, a BSDF containing 10mm wavelength bands could be created by running genBSDF on many models of the system, each with material reflectance and transmittance properties adjusted to suit specific wavelength band. A single BSDF file containing all wavelength bands would then be assembled using the output files from the many *genBSDF* runs. This would be cumbersome for many wavelength bands, but could be automated.

The Klems angle basis is not well suited for resolving sharp peaks in a BSDF, and may not be suitable for simulations of peaky CFS where resolving peaks is necessary for accuracy, such as in the case of glare assessment. However, the Window 6 BSDF XML schema supports arbitrary angle basis definitions, including a variable resolution basis called a tensor tree. The tensor tree BSDF offers higher resolution data where needed (at sharp peaks) and lower resolution data where the BSDF is relatively constant. Tensor tree BSDF data can be generated by genBSDF and is supported by Radiance, but WINDOW and EnergyPlus do not support tensor tree BSDFs. This validation focused solely on the Klems angle basis because characterization of systems using the tensor tree format is still under development. Further, validating the accuracy of genBSDF produced Klems BSDFs is an important step in ensuring reliable data is available for simulating whole building energy with CFS and calculating annual daylight metrics for CFS with using the Radiance three-phase method (Ward et al., 2011).

6. Conclusion

As part of the Radiance simulation suite of tools, a new ray-tracing tool was developed to generate bidirectional scattering distribution function datasets for shading and daylighting systems. The genBSDF tool is free, open source, and has been validated against TracePro and measured data. The output BSDF data produced by this tool follows the BSDF file format defined by the Window 6 program, by the daylighting simulation tools in Radiance (mkillum, rtcontrib), and by EnergyPlus. The tool provides end users with the ability to create BSDF data for macroscopic scale complex fenestration systems (CFS) of any arbitrary geometry and then evaluate the performance of these systems using building simulation tools. System geometry and material bidirectional reflectance properties are needed to model CFS accurately.

The ability to model the performance of CFS using BSDF data is a relatively new capability. There is still significant work to be done to build and validate tools that address the broad range of available optically complex fenestration systems. Measurement systems need significant improvements to enable more routine data collection. Quality control is needed to ensure that the methods used to create BSDF data by different parties are generated using consistent protocols.

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