Radiance Workshop, Harvard Graduate School of Design, October 22-23, 2009

Simulating Complex Fenestration Systems: An Overview of R&D Activities

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Greg Ward, Anyhere Software

Dragan Curcija, Carli, Inc.

Charlie Huizenga, UC Berkeley

Rick Mistrick, Pennsylvania State University

Marilyne Andersen, MIT

Maria Konstantoglou, University of Thessaly, Greece

Anne Iversen, Danish Technical University

Motivation

- Net zero energy buildings by 2020, minimize GHG emissions
- Minimize energy use and peak demand impacts of innovative façade technologies for buildings through a proper balance between:
  - Daylight (minimize lighting energy use) and
  - Window solar and thermal heat gains (minimize HVAC energy use)
- While maintaining visual and thermal comfort and occupant satisfaction with resultant environment

- Objective: Simulate annual energy use, peak demand, and comfort impacts of any arbitrary façade system
  - √ Glass (specular) → Optics (glass, laminates), IGDB, Window 5
  - Complex fenestration systems (CFS)

History

Definition of Method

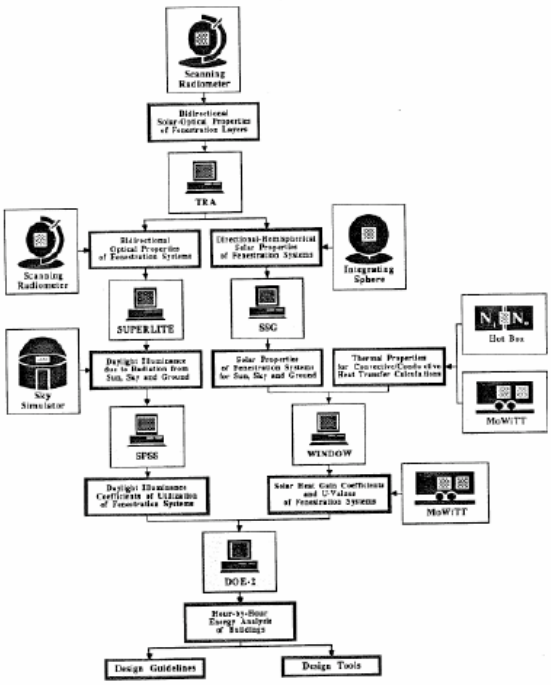
- 1965 Fred E. Nicodemus, "Directional Reflectance and Emissivity of an Opaque Surface," Appl. Opt. **4**, 767-773
- 1977 CIE 38 TC-23 formal definition of BDTF/ BRDF
- 1994 Joseph Klems, LBNL, defines method for use of BSDF in **multi-layer** solar-optical calculation
- 1997 Klems validation against measured solar heat gain values

BSDF Measurement

- 1988 First scanning goniophotometer, LBNL
- 1990s Computer graphics/ Characterization of lighting systems/ CCD capture of BSDFs
- 1990s – present: Development of more accurate scanning and video-based goniometers and virtual goniometers world-wide (Fraunhofer ISE, LESO-PB/ EPFL Switzerland, MIT, Berlin TUB, TNO Delft, Cardiff, DTU Denmark, etc.)

Implementation of Method

- 2005 Incorporation of Klems method in Window 6



BS-251
LBL-23581

Presented at the ASHRAE Annual Meeting, Ottawa, Ontario, Canada, June 26 - 29, 1988, and published in *ASHRAE Transactions*, Vol 94, Part 2.

An Indices Approach for Evaluating the Performance of Fenestration Systems in Nonresidential Buildings

R. Sullivan, D. Arasteh, K. Papamichael, J.J. Kim, R. Johnson, S. Selkowitz, R. McCluney

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Lawrence Berkeley Laboratory
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November 1987

This work was supported by the Electric Power Research Institute and the New York State Energy Research and Development Administration. Project management was provided by the Lighting Research Institute. Additional support was provided by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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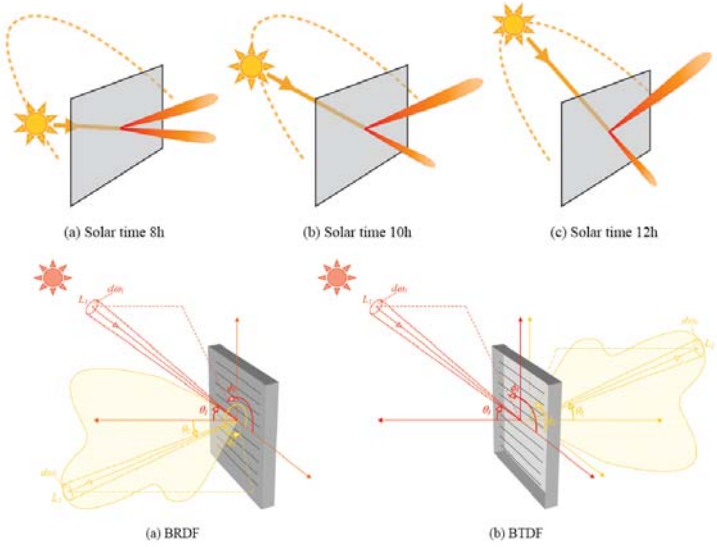
BRDFs and BTDFs



Images from Andersen, 2004

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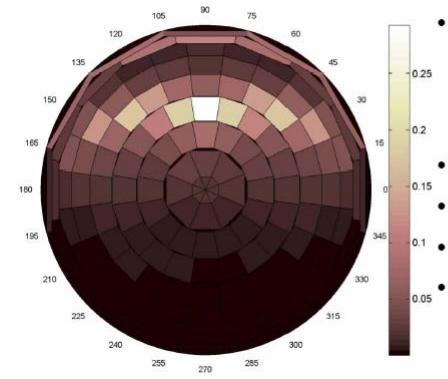
Matrix Calculation

$$\tau(\theta_i, \varphi_i) = \int_0^{2\pi} \int_0^{\pi/2} \mathrm{BTDF}(\theta_i, \varphi_i, \theta_s, \varphi_s) \cos\theta \sin\theta \, \mathrm{d}\theta \mathrm{d}\varphi$$



- Transmittance for normal incidence from the outside of a Venetian blind
- x145 – incident directions
- x2 – BTDF/BRDF
- x2 – Exterior/interior
- On picture is 1/580 of the BSDF

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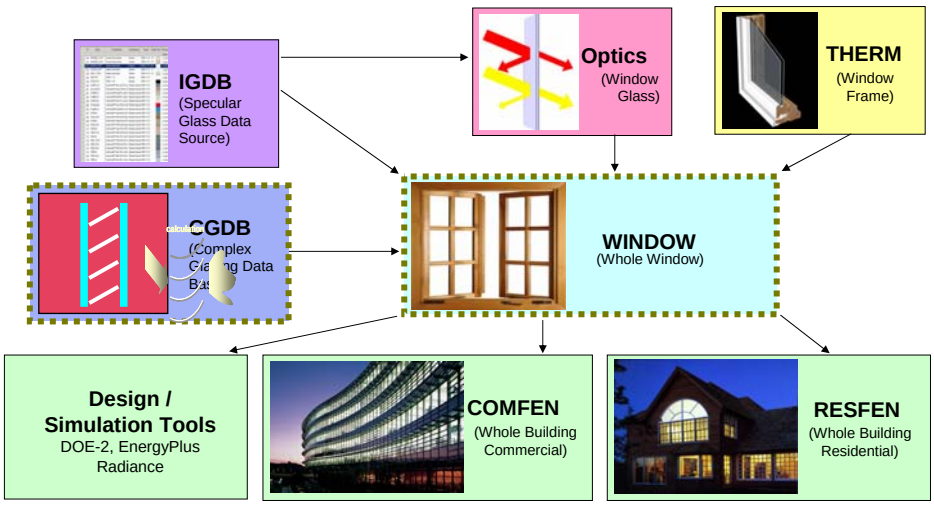
Software Tools Overview



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Window 6

- Availability: http://windows.lbl.gov/software/window/6
- Methods of generating BSDF data for a single layer:
  - 1) Import BSDF-XML file from CGDB database
    - Full BSDF dataset generated using any combination of measured or virtual photogoniometer data and mathematical models
  - 2) Measured material data, + Radiosity or Ray-tracing within Window 6
    - Specify geometry and limited measured solar optical data to tune to specific product)
    - Flat or curved slat Venetian blind (ISO 15099)
    - Woven shade model (square holes)
    - Fritted glass model (specify % coverage of frit)
    - Others under development…
- Use Window 6 tool to define each layer and combine into a single BSDF-XML file for use with simulation programs
- Basis: Klems adaptation of Tregenza 145x145 – solid angles more equally weighted over entire hemisphere
- [Thermal/ calorimetric properties defined separately (i.e., A, Ni, inward flowing fraction)]

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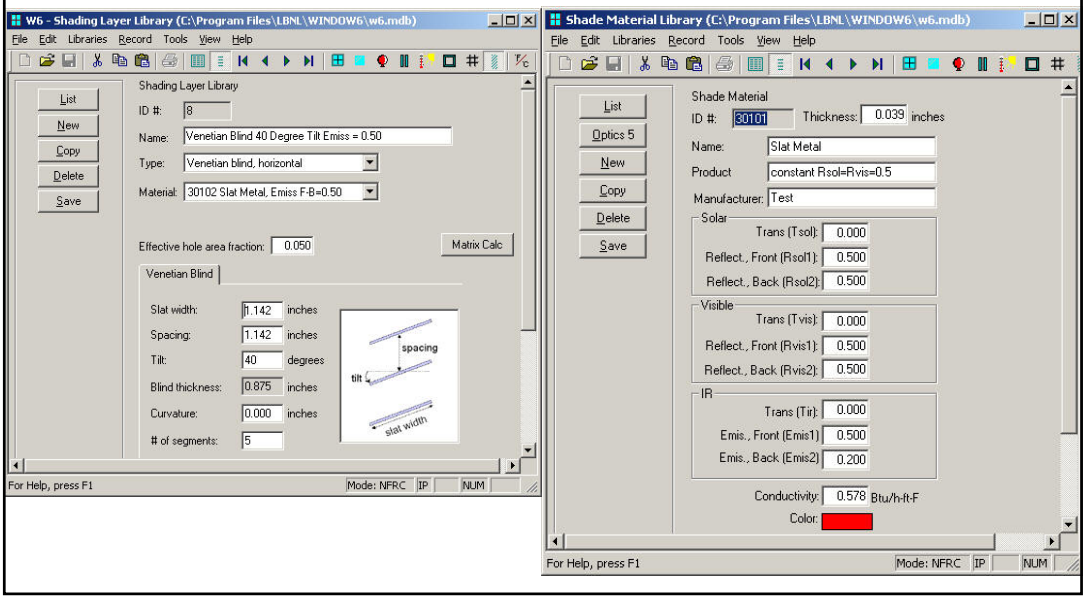
Layer definition: Venetian blind



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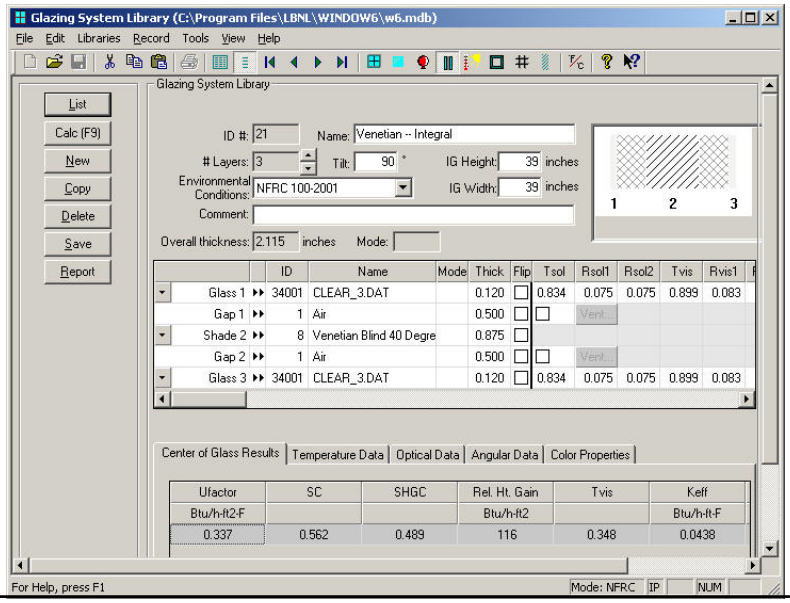
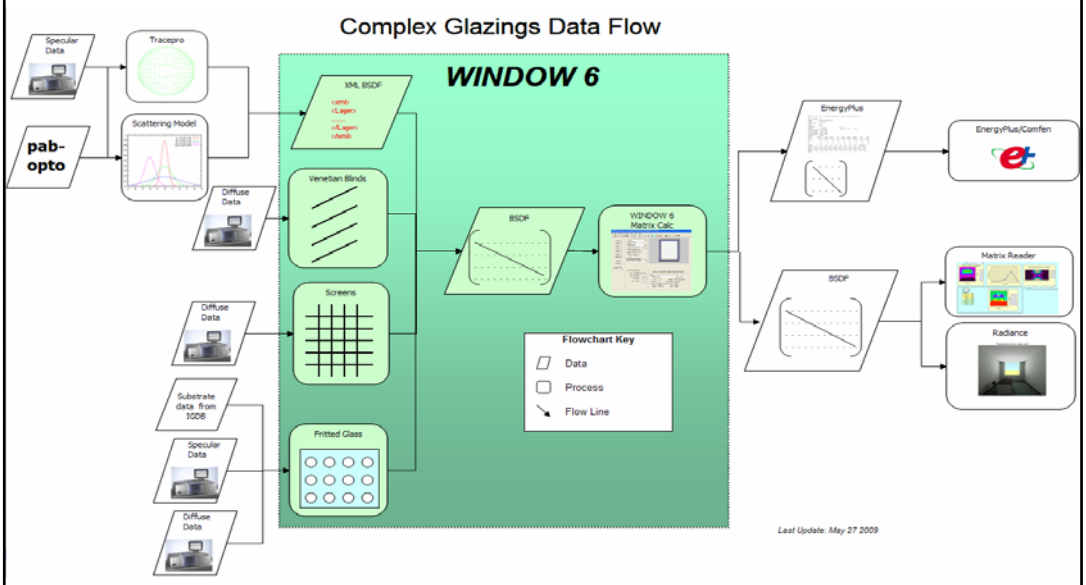
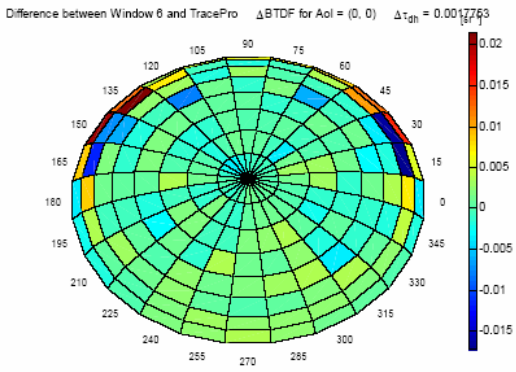
System: Between-pane Venetian blind

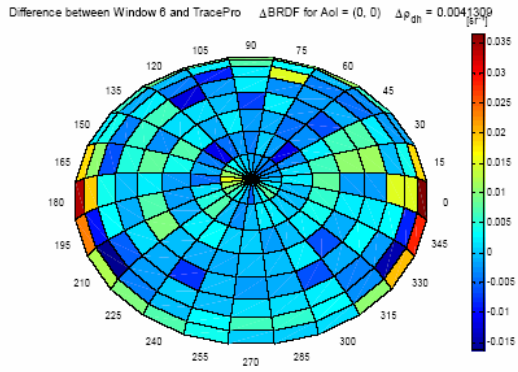




Validation of Window 6 Radiosity model against TracePro Monte Carlo model



Transmission



Reflectance

ISO blind configuration A45, Normal incidence

http://windows.lbl.gov/software/window/6/Bidirectional%20Properties%20of%20Slat%20Shading.pdf

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Klems Multi-layer Calculation Method (1994)

- Method focused on solar heat gains:
  http://gaia.lbl.gov/btech/papers/34715.pdf
- http://gaia.lbl.gov/btech/papers/34716.pdf
- Single layer BSDFs are combined into a single system BSDF (e.g., glass pane 1 + pane 2 + interior shade → 1 system)

- **Assumption: Spatial homogenity**: average taken over suitably-sized area of sample CFS
  - e.g., average over multiple periods of Venetian blind system
- **Implications**:
  - Not applicable to two layers with inhomogenities of comparable size in same dimension (e.g., two venetian blinds with different slat angles, translate vertically → 1,0)
  - Spatial information is lost → for daylighting, must discretize non-uniform layers into separate apertures or portals (e.g., fritted glass that transitions gradually from 50% to 0% coverage)

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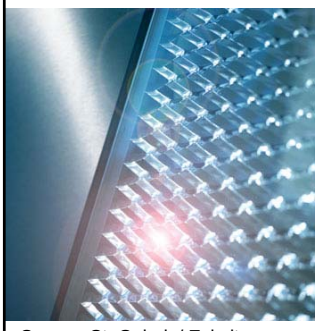
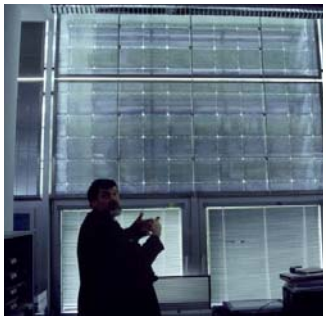
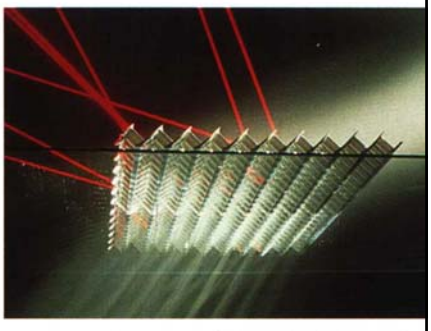
Complex Fenestration Systems (CFS)







Source: St. Gobain/ Eckelt
DLS COOLSHADE HR 32/9

←South North→

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Implications with Daylight Modeling

- System BSDF's with no geometric information:
  - Lose ability to construct an image of the fenestration system (fuzzy, not sharp shadow visualizations)
  - Lose ability to model view out
  - Visual discomfort models due to window (e.g., DGP Wienold & Christopherson): loss of resolution of small solid angle glare sources
- → must use detailed geometric models to obtain sharp shadows

mkillum-BSDF visualization with Venetian blind within Window 6 (rendering time: 180 min)

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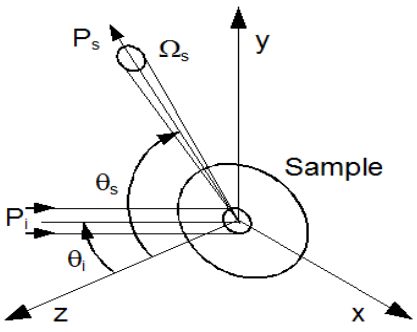
Klems method (cont.): Resolution of basis

- **Assumption: 145x145 Klems basis**
  - Adequate for solar heat gain calculations → less demanding than daylighting simulations because spatial distribution of outgoing flux is typically not as critical
  - Is 145x145 resolution sufficient for most daylighting applications? 2320x145? 2320x2320?
  - Accuracy dependent on methods used to created BSDF: Measurement sampling resolution, interpolation methods between sampled data, measurement + ray-tracing, mathematical model assumptions, capturing peaks, averaging methods across patch (solid angle)….
  - Practical constraints: data management and storage (145x145 =21,025 values)

Windows Testbed Facility, LBNL

Goniophotometer measurements

- Sample can rotate relative light source
- Detector on movable arm



LBNL scanning goniometer (pab-opto)

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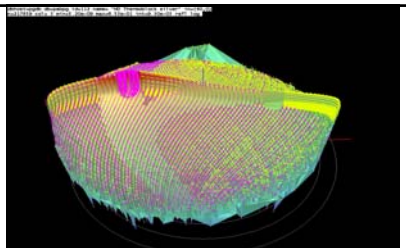
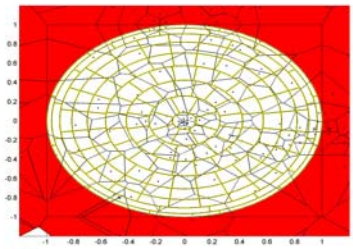
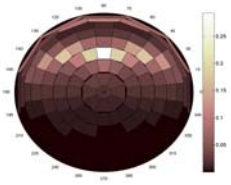
Example: re-sampling 217,000 data down to 145 patches

- Oversampling to resolve specular features
- BSDF was unit [sr^{-1}]
- Associate measured *point* with an area
- Voronoi diagram is a fancy name creating polygons around measurement points so that each polygon only contain one point AND all parts of the polygon are closer to that point than to any other measured point
- Nearest neighbor interpolation at the same time as moving from single point to area







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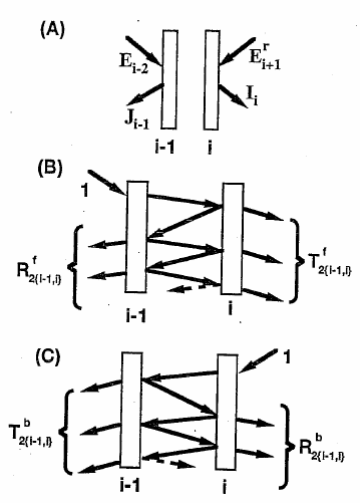
Klems method (cont.): Resolution of basis

- Higher resolution BSDF = greater spatial resolution for both input flux and output flux distributions = greater accuracy
  - Input flux: complex obstructions (urban environment), HDR input of sky luminance distribution (e.g., Mehlika Inanici)
  - Output flux: in cases where distribution is critical (daylight-redirecting systems
  - CCD goniospectrometric characterization enables measurement over continuous hemispherical surface in timely cost-effective manner (EPFL/ MIT Andersen, Solar Energy 2009 in press)
  - Flexibility in definition of resolution of basis: Radiance – yes; Window 6 not yet

Klems Method (cont.)

- **Assumption: Interreflections between layers** computed assuming two infinitely large facing planes)
- Implications:
  - Less accuracy at edges of system (e.g., losses or absorption of energy into window frame)
  - Limits applicability – e.g., 3'-6" deep skylight system with 5'-0" on center structural beams cannot be modeled accurately
  - Impact on error should be investigated
- **Other Assumptions:**
  - Spectral wavelength averaged; if selective layers have peak transmission in very different spectral regions, then spectral characterization is necessary
  - Polarization not (yet) taken into account



Klems: http://gaia.lbl.gov/btech/papers/34716.pdf

Curtainwall mockup

Corner condition, tower, The New York Times Headquarters

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Daylighting simulation tools

- CTI Project 4881.1, BTDF2PRISM2 (Kaempf, Scartezzini EPFL) 2004
- Adeline, daylight simulation tool + CFS database + dynamic façade modeling tools + validation: Jan de Boer, Fraunhofer ISE, ENB 38 (2006): 849-868, www.talisys.de
- Radiance, Greg Ward, Anyhere Software
  - mkillum' (2007, **http://www.radiance-online.org/radiance-workshop6/**)
  - rtcontrib' (2009)
- Others….?

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mkillum-BSDF

- Advantages over mkillum (ray-tracing):
  - Computation time
  - Greater accuracy with some systems: e.g., mirrored curved blinds
- Consult Greg if you really want to know what mkillum-BSDF does…. (or consult documentation)
- Options:
  - L minus: if BSDF has a direct beam component, then use this option with geometry to generate an *illum*
  - L plus: if no beam components or if redirection, then use this option without geometry to generate a *light*

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Validation: mkillum-BSDF

- Validation: Rick Mistrick, Greg Ward, & LBNL
- Tasks:
  - Confirm proper use of BSDF-XML file within Radiance (theta, phi, z+, etc. interpreted correctly)
  - Check conservation of total directional-hemispherical flux
  - Check predicted mkillum-bsdf output values against input BSDF values for various systems and incident angles
    - Translucent fabric shade
    - 45deg Venetian blind
  - Compare room cavity luminance distribution against ray-traced values

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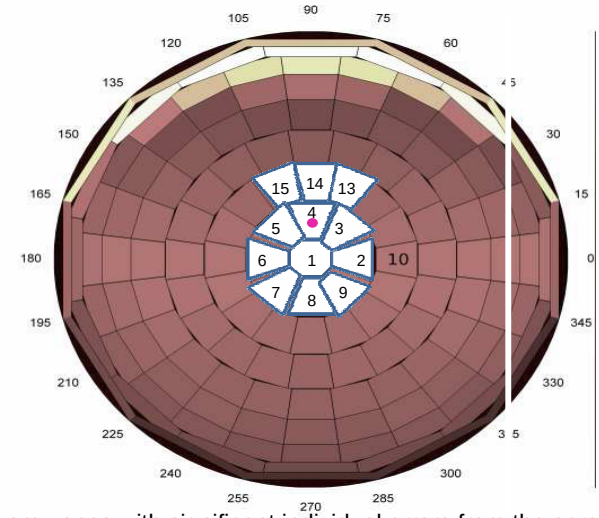
Findings

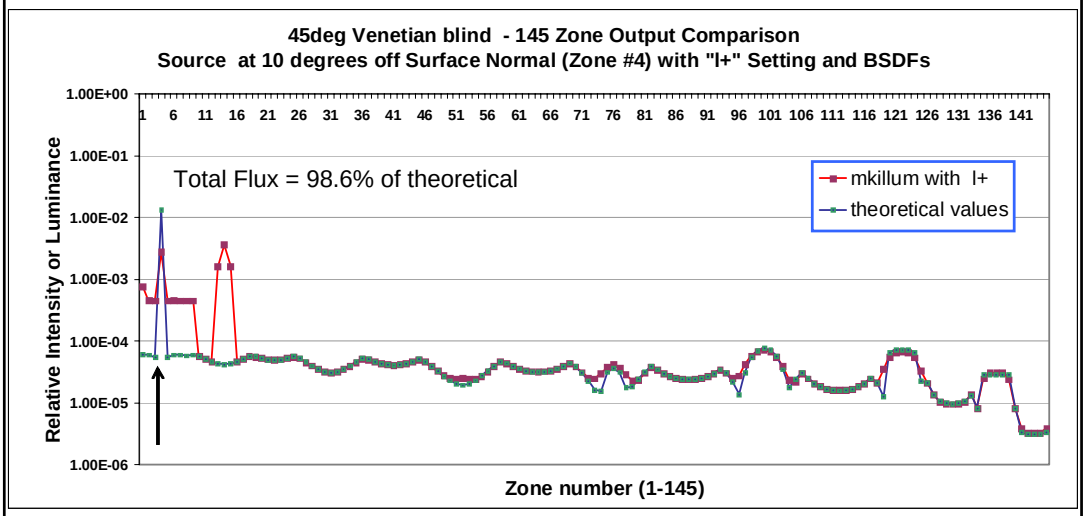
- Some little bugs. These were fixed.
  - Coordinate system of Window 6 BSDF-XML correctly interpreted
  - Energy is conserved
- Proper use of L+ and L- explored.
- Coordinate transformation method used to map Klems basis to mkillum's polar coordinate system resulted in diffusing of flux to adjacent patches, particularly at normal incidence angles (±15°) – could alter mkillum coordinate system but…
- rtcontrib will not be subject to same coordinate transformation problem – uses same Klems basis for both in/outgoing flux

45° blind, (-10°,0°) incident angle



Zones in white are zones with significant individual errors from the spreading of the direct flux that occurs due to the large zone sizes considered by mkillum-bsdf
10-degree off-axis incident light (red dot).

45° Venetian blind, (-10°,0°) incident angle, I+ (no geometry, *light*)



Theoretical values = weighted Window 6 BSDF values

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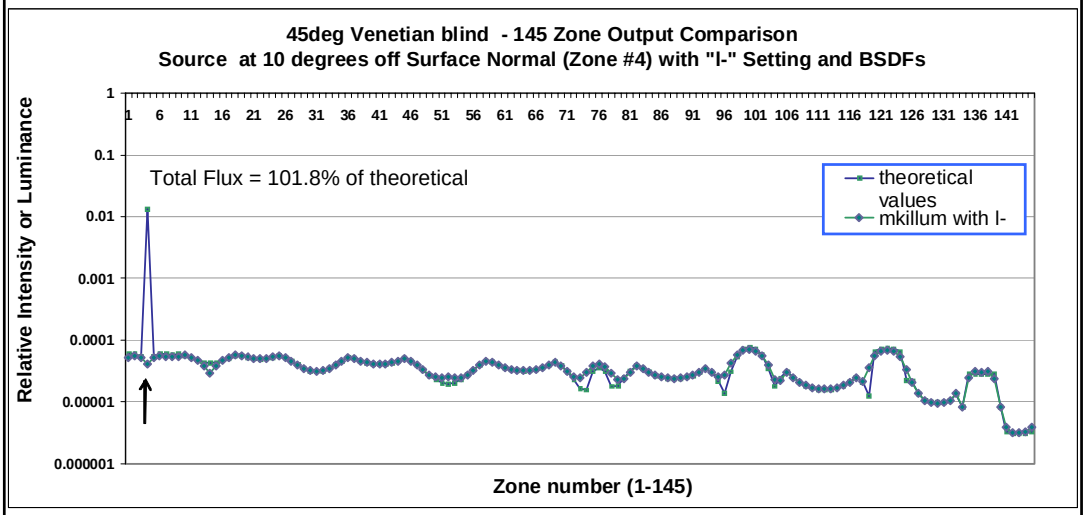
45° Venetian blind, (-10°,0°) incident angle, l- (with geometry, *illum*)



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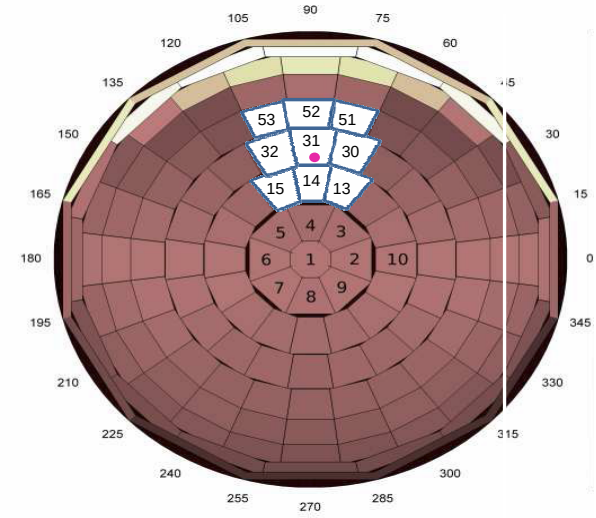
45° blind, (-27.5°,0°) incident angle



Zones in white are zones with significant individual errors from the spreading of the direct flux that occurs due to the large zone sizes considered by mkillum
27.5-degree off-axis incident light (red dot).

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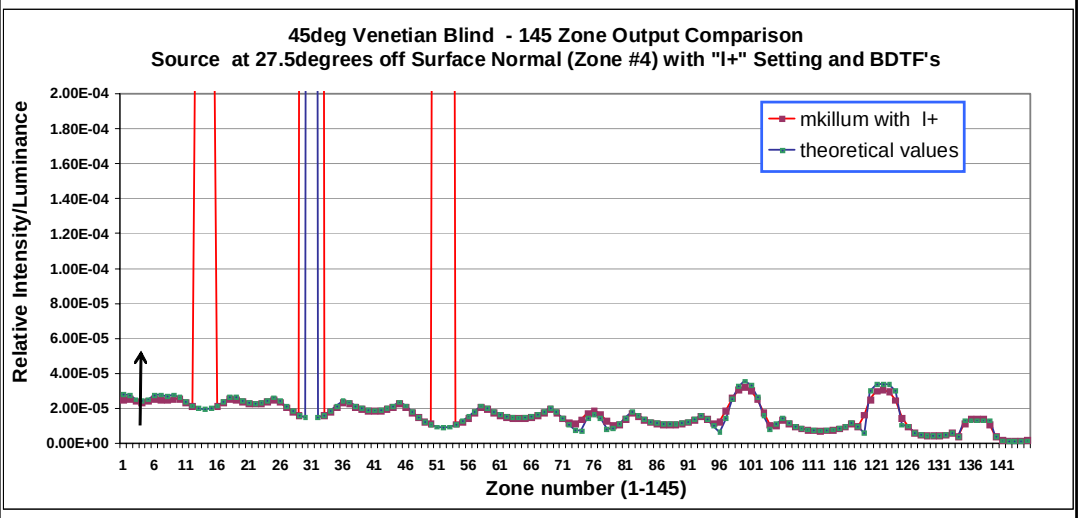
45° Venetian Blind, (-27.5°,0°) source, l+



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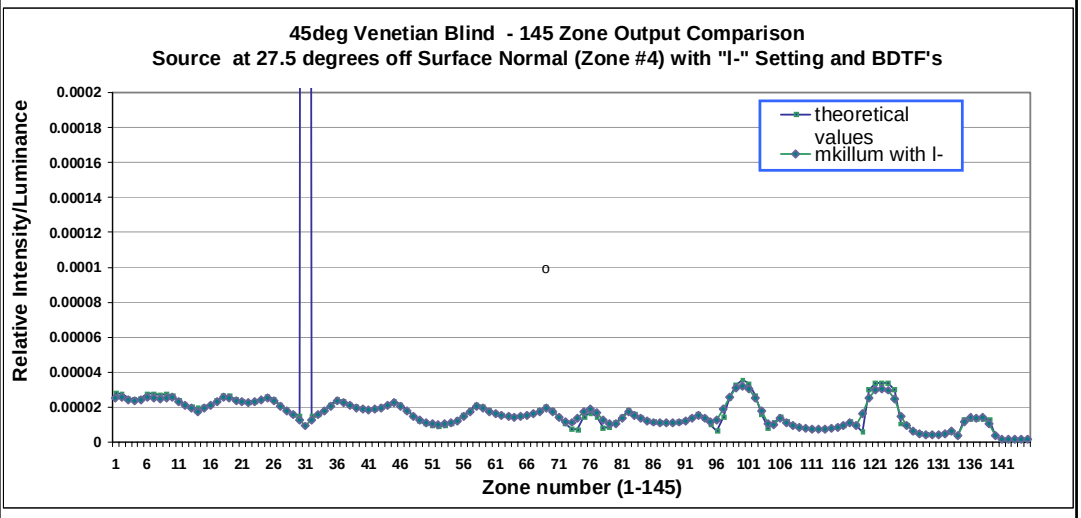
45° Venetian Blind, (-27.5°,0°) source, l-



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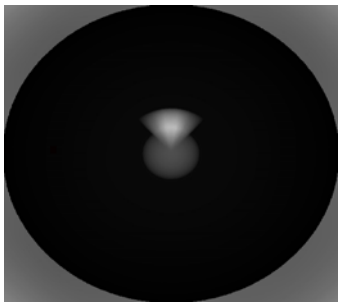
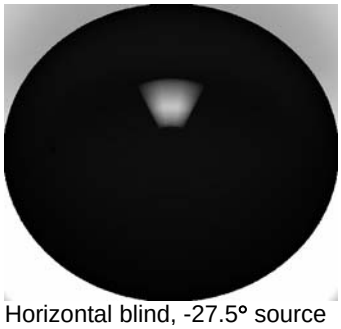
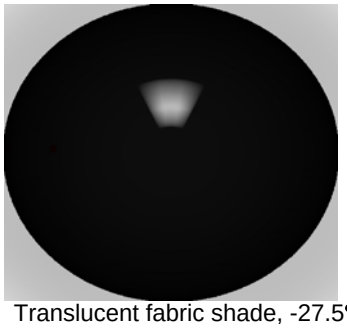
Horizontal blind, -10° source



Translucent fabric shade, -10° source



Horizontal blind, -27.5° source



Translucent fabric shade, -27.5° source

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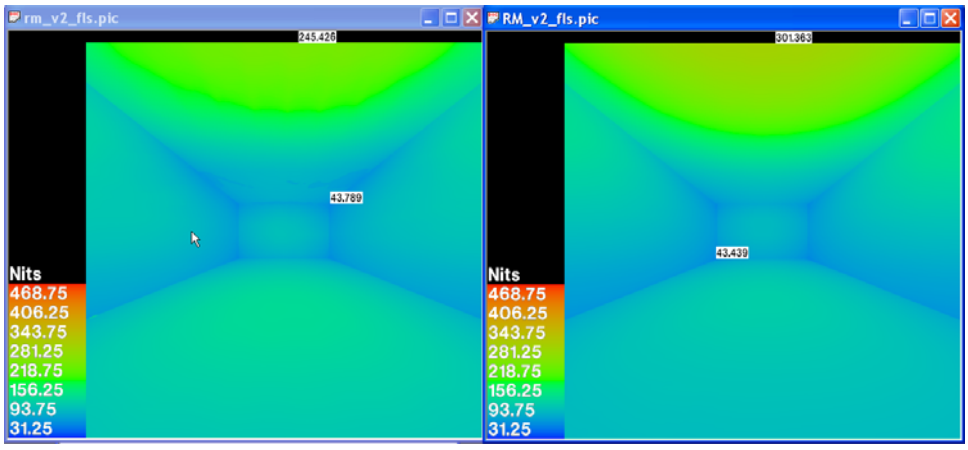
Comparison of BTDF to standard mkillum



False color image of a room with a window. Blinds are considered using their geometry with standard mkillum applied.

False color image of a room with a window. Blinds are considered using BTDF's.

The daylight condition is a clear sky with solar altitude of 65° at solar noon with a South-facing window that has horizontal blinds at 45 degrees (view of ground from inside).

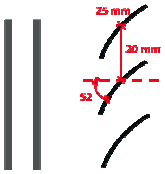
mkillum Validation: Matte Venetian Blinds (Maria Konstantoglou, Ward, LBNL)

LBNL Integrating Sphere Spectrophotometer

Window 6

Window 6

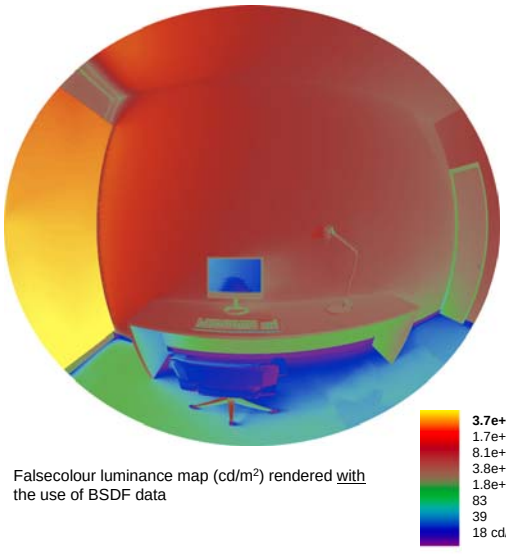
Radiance



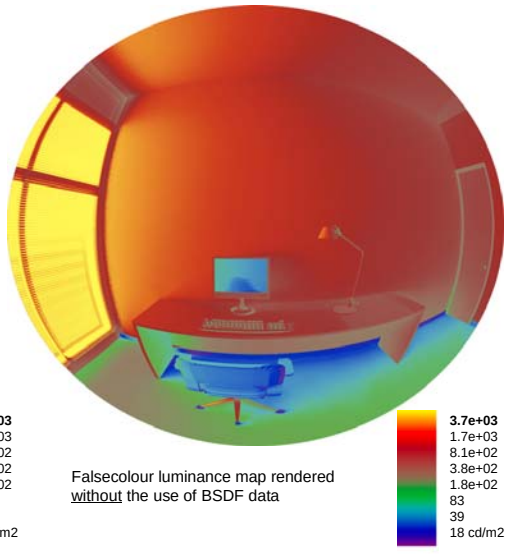
52 blind tilt

date: 01/15
time: 10:00 am
model: 71T room

Matte Venetian Blinds



Falsecolour luminance map (cd/m^2) rendered with the use of BSDF data



Falsecolour luminance map rendered without the use of BSDF data

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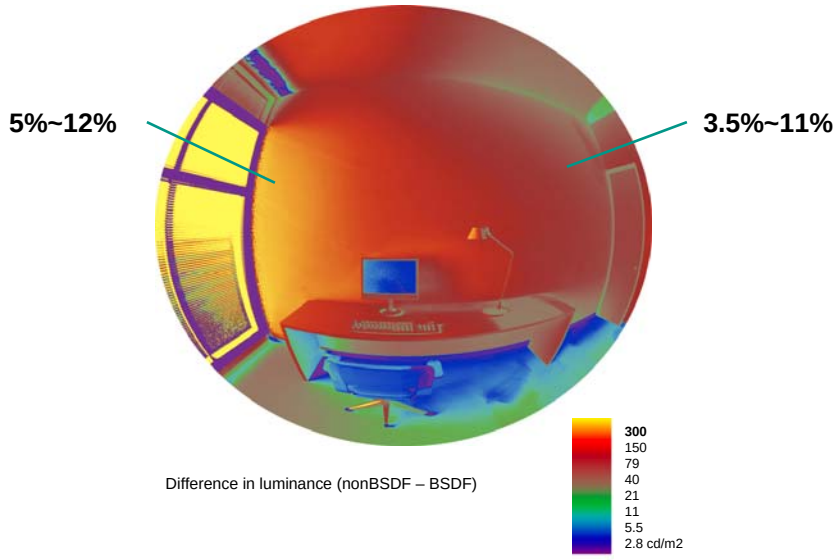
1st Case study: Matte Venetian Blinds



Difference in luminance (nonBSDF – BSDF)

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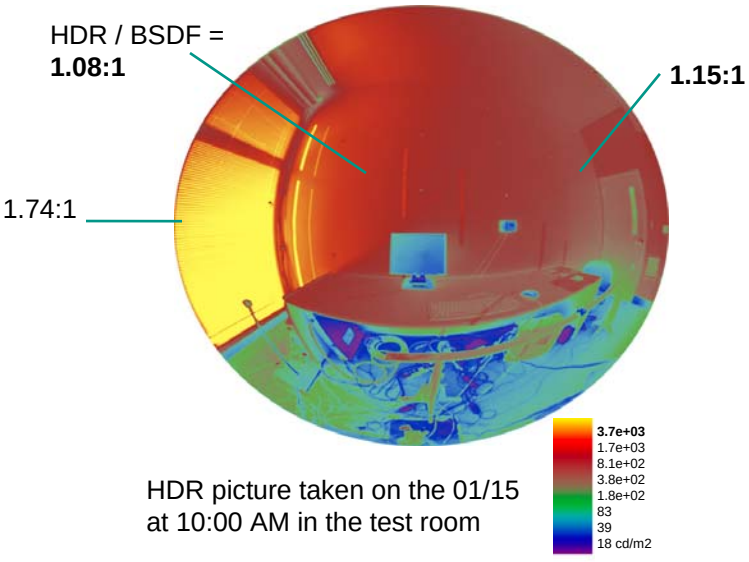
Field Measured Data: Matte Venetian Blinds



HDR picture taken on the 01/15
at 10:00 AM in the test room

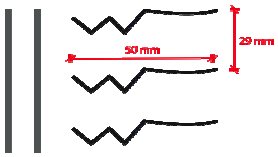
Mirrored Venetian Blinds

LBNL Integrating Sphere Spectrophotometer

TracePro

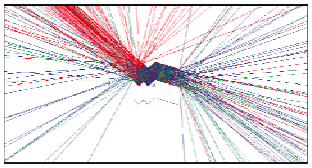
Window 6

Radiance

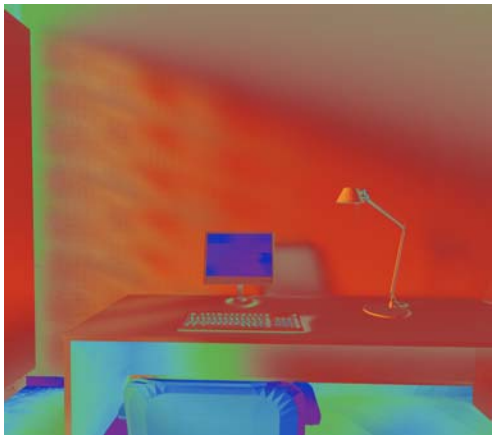


0 blind tilt

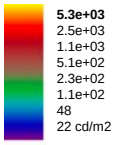
date: 12/21
time: 09:00 am
Model: 71T room

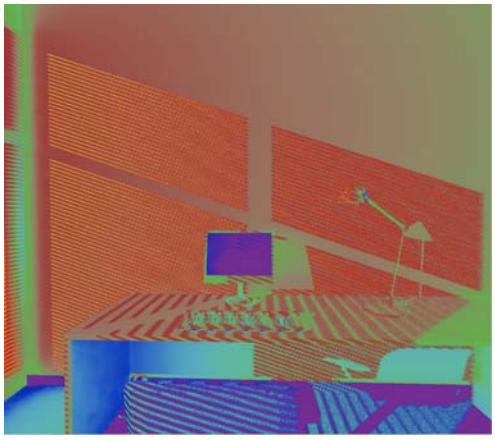


2nd Case study: Mirrored Venetian Blinds



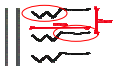
Falsecolour luminance map rendered with the use of BSDF data



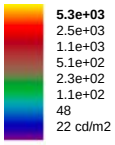


Falsecolour luminance map rendered without the use of BSDF data

"metal" material



"mirror" material



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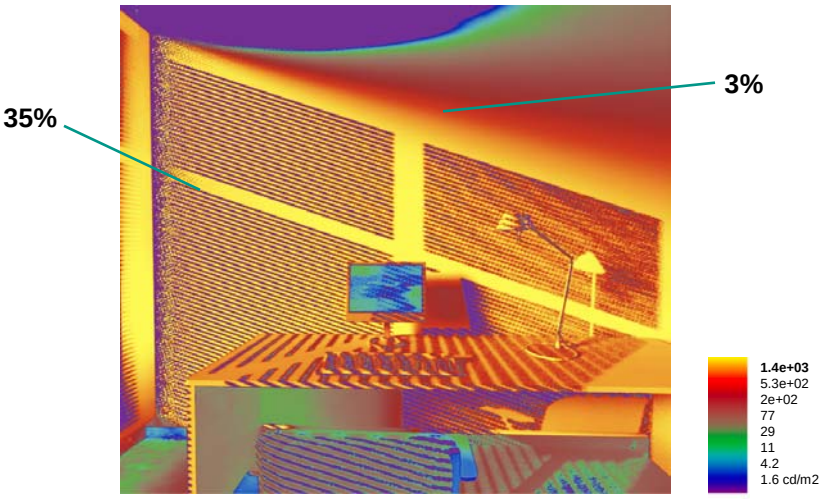
2nd Case study: Mirrored Venetian Blinds



Difference in luminance (BSDF – non BSDF)

Visual discomfort models due to window: loss of resolution of small solid angle glare sources

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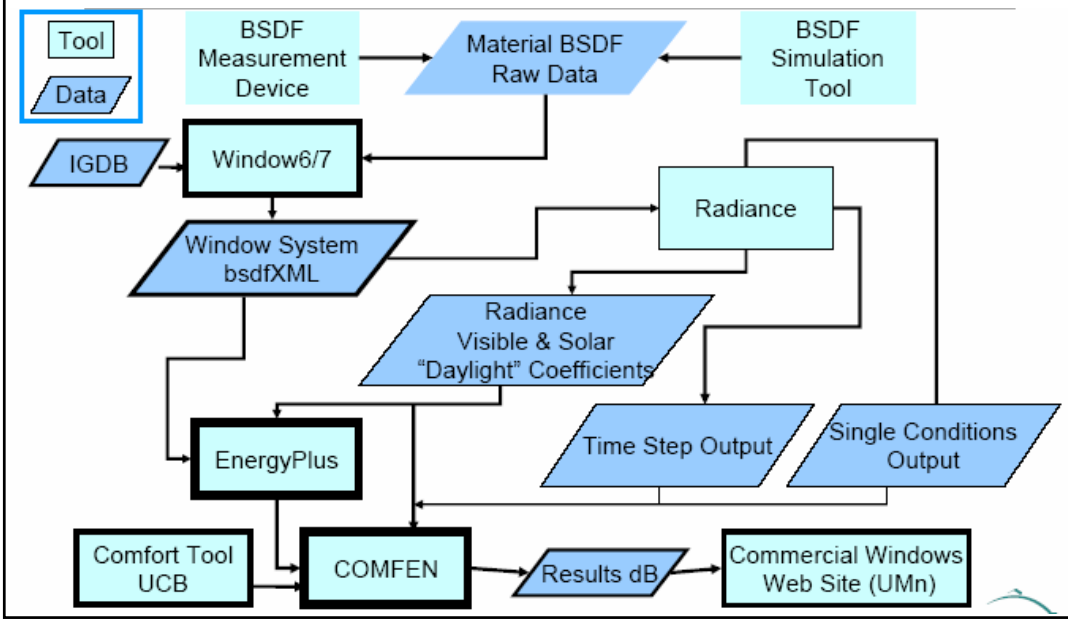
Future Work



Information Resources

Windows and Daylighting Group
Building Technologies Department
Lawrence Berkeley National Laboratory
Building 90-3111
Berkeley, CA 94720
Email: eslee@lbl.gov

More Info:

Window 6
http://windows.lbl.gov/software/window/6

High performance commercial building facades
http://lowenergyfacades.lbl.gov

Acknowledgments

US Department of Energy

California Energy Commission Public Interest Energy Research (PIER)