To B(SDF) or not to B(SDF)
Peak extraction and other BSDF updates

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Contents

- Peak extraction from BSDF data (aBSDF vs. BSDF)
  - What is it?
  - Why do we need it?
  - How does it work?
  - How do we use it?
  - When should we use it?
  - How does it affect results?
- IEA SHC Task 61 / EBC Annex 77: Integrated Solutions for Daylighting and Electric Lighting
  - White paper: BSDF generation procedures for daylighting systems
  - BSDF round robin test

BSDF Basics

BSDF, BTDF, BRDF, … ?

BSDF bidirectional scattering distribution function

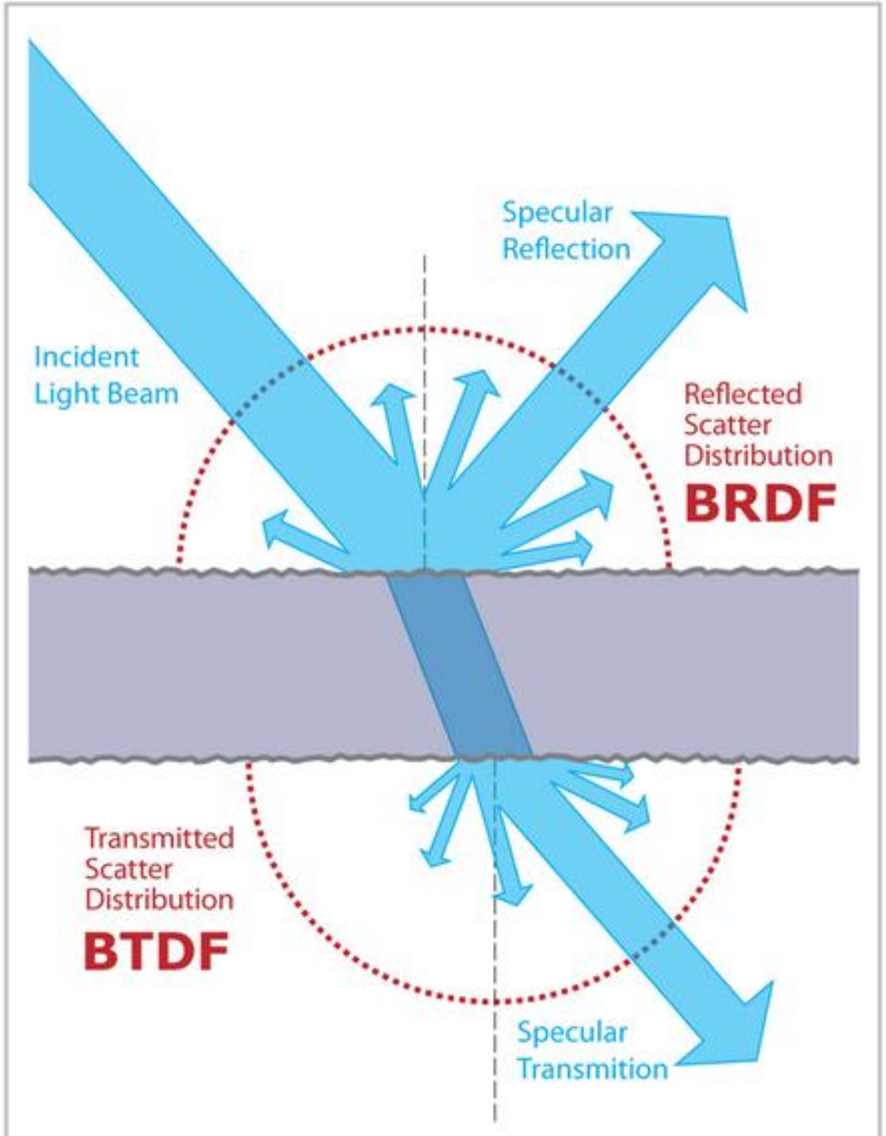
BRDF bidirectional reflection distribution function

BTDF bidirectional transmission distribution function

„BSDF = BRDF + BTDF“

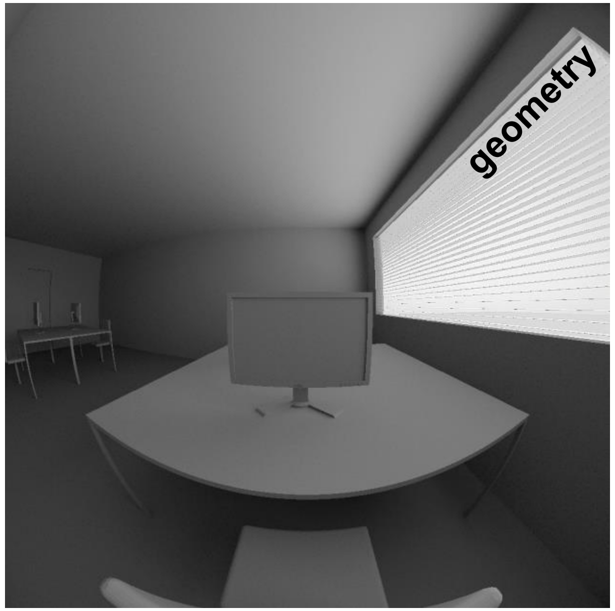
we are talking about

- data-driven BSDFs
- BSDFs representing daylighting systems



source: wikimedia.org

BSDF Basics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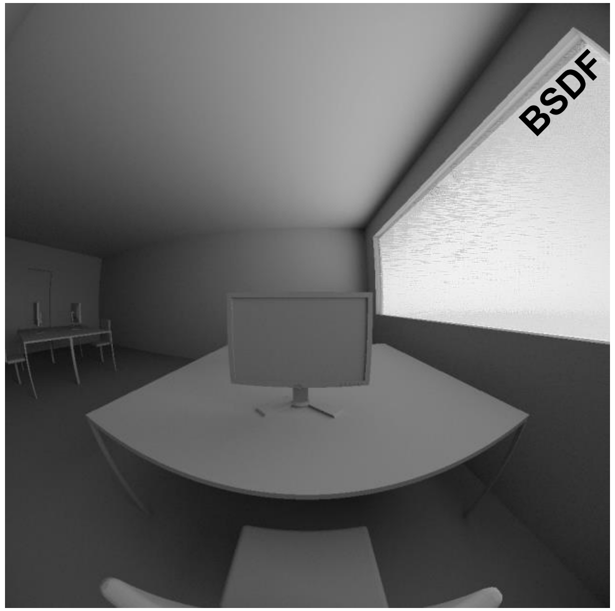
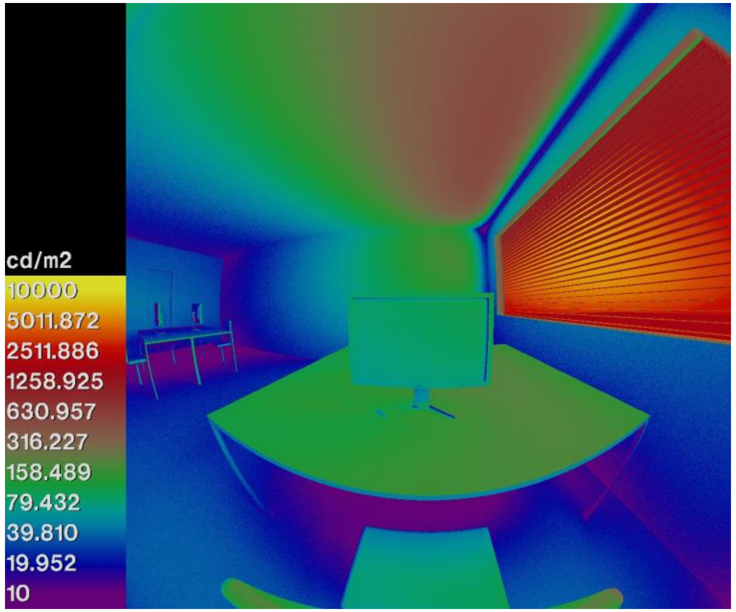

BSDF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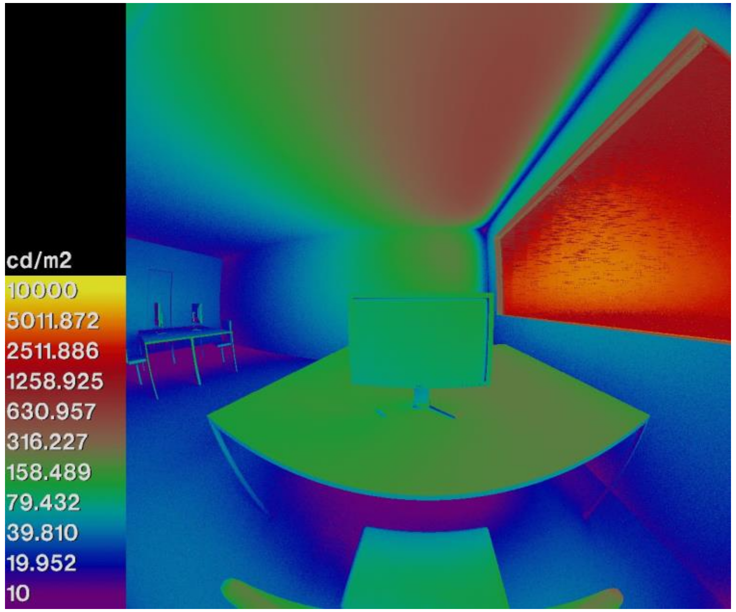
19.952
10


cd/m2
10000
5011.872
2511.886
1258.925
630.957
316.227
158.489
79.432
39.810
19.952
10

Common resolutions of data-driven BSDFs

Table 1.
Resolution of various data-driven BSDF angle bases.

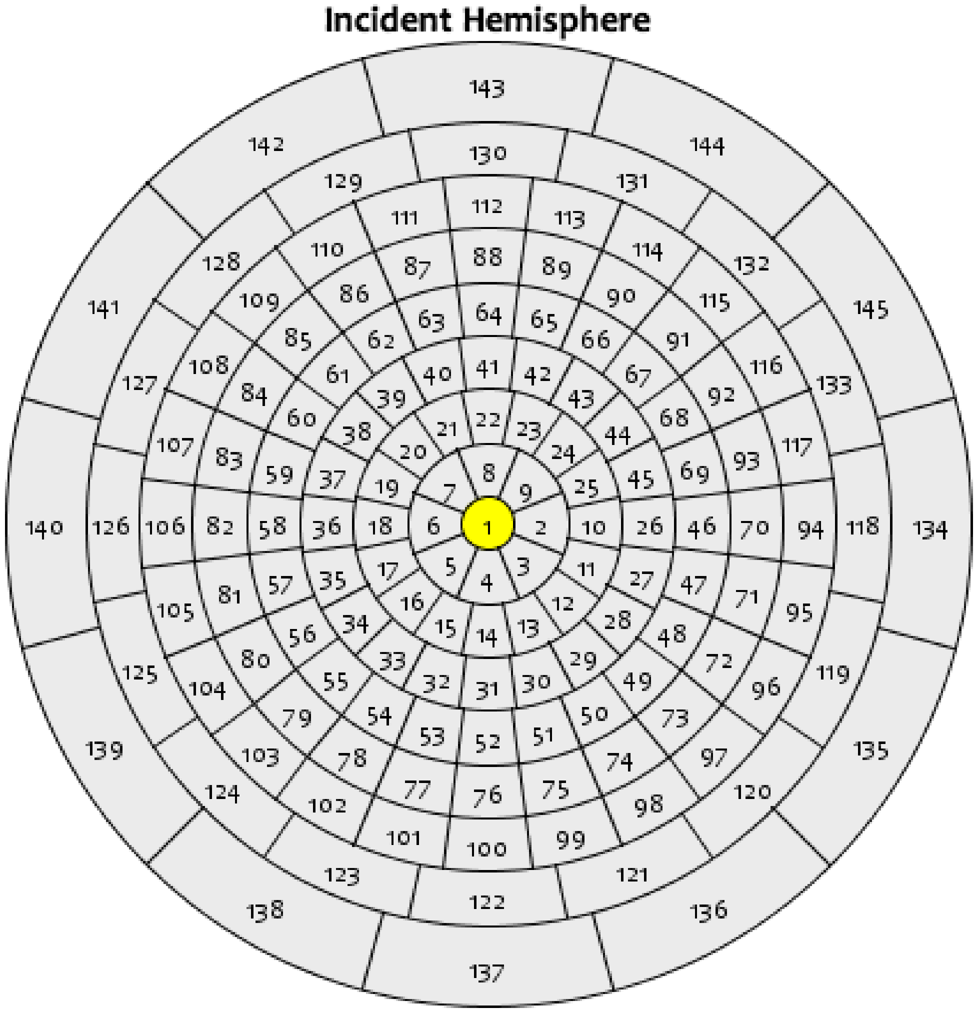
Name	Number of subdivisions per incoming × outgoing hemisphere	Average patch size cone with apex angle (°)	Patch size: average solid angle (st) per subdivision (2π/subdivisions)	N, where sun (0.533° orb) intensity is N times less than reality
Klems [Klems 1994]	145×145	13.5°	0.043000	641**
IEA SHC Task 21 [Aydinli and Kaase, 1999]	145×1297	10-15° incident and 5° exiting	0.0048	253-792
Tensor tree*	$2^{2\cdot k} \times 2^{2\cdot k}$			
	k=5, 1024×1024	5.06°	0.006136	90.3
	k=6, 4096×4096	2.53°	0.001534	22.6
	k=7, 16,384×16,384	1.27°	0.000383	5.6
	k=8, 65,536×65,536	0.63°	0.000096	1.4
	k=9, 262,144×262,144	0.32°	0.000024	0.4
	k=10, 1,048,576×1,048,576	0.16°	0.000006	0.1

Source: Ward, G.J. et al., Modeling specular transmission of complex fenestration systems with data-driven BSDFs, Building and Environment 196 (2021) 107774, https://doi.org/10.1016/j.buildenv.2021.107774

BSDF Basics – Discretizations

Klems‘ discretization

- subdivision of hemisphere into 145 patches
- approx. equal illuminance from each patch if luminance is constant in hemisphere
- 9 θ ranges {0°-5°, 5°-15°, 15°-25°, 25°-35°, 35°-45°, 45°-55°, 55°-65°, 65°-75°, 75°-90°}
- φ subdivisions per θ range {1, 8, 16, 20, 24, 24, 24, 16, 12}
- average solid angle 2π/145 = 0.0433 sr, i.e. cone with 2 x 6.73° apex angle [2π*(1-cos(α/2)) = 2π/145]



further reading:
Klems J.H.: A new method for predicting the solar heat gain of complex fenestration systems; Overview and derivation of the matrix layer calculation. ASHRAE Transactions 100 (1), 1994

BSDF Basics – Discretizations

Variable resolution („tensor tree“)

- idea: high resolution for spikey regions

  low resolution for smooth regions

- based on Shirley-Chiu-mapping

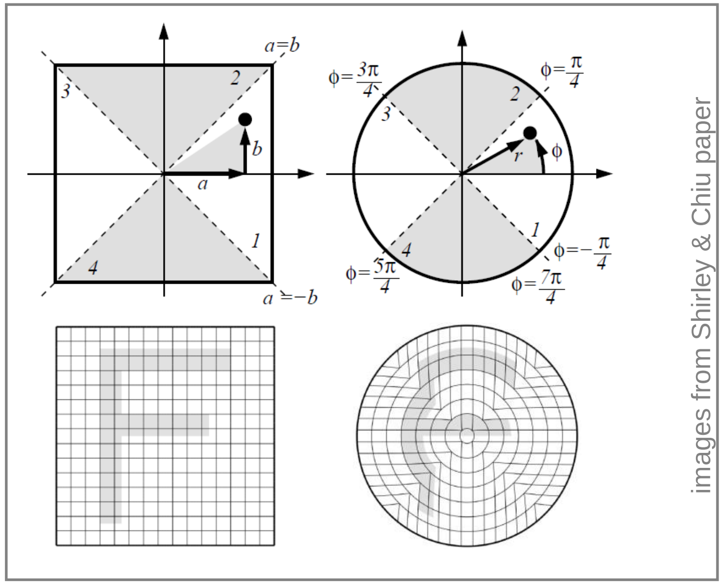
  (preserves fractional area, i.e. projected solid angle)

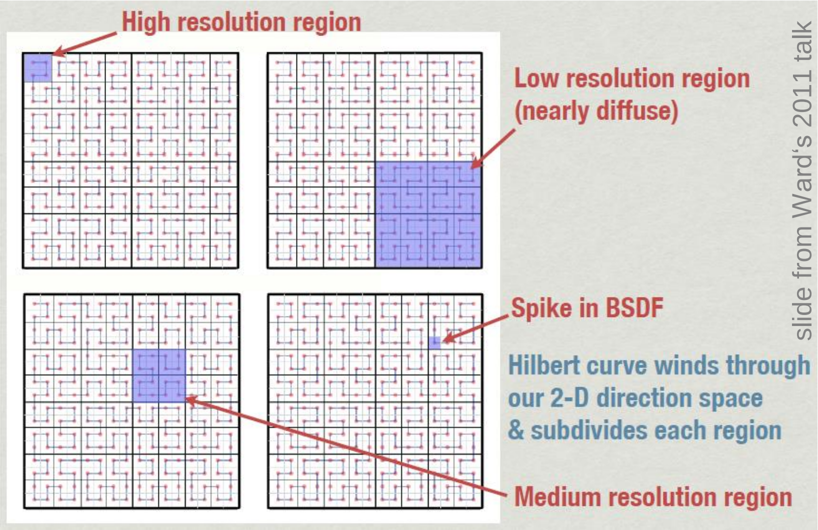
- maximum dimensions in 4D 2^{2n} x 2^{2n}

  (n = 4 / 5 / 6: 256^2 / 1024^2 / 4096^2)

- + efficient data structure (ideal diffuse reflector needs 1 value {1/π})

- – no matrix structure (needed for daylight coefficient approach)





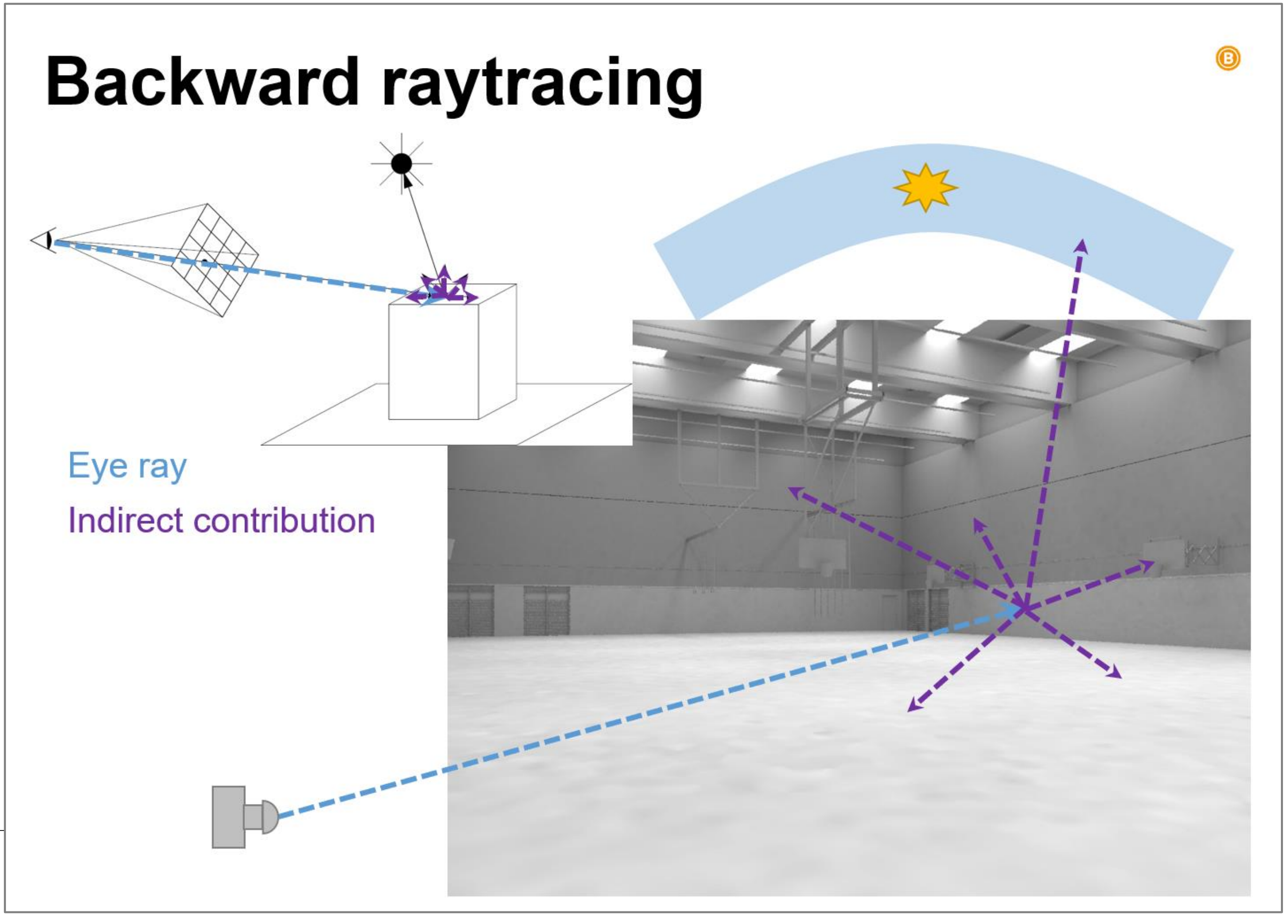
further reading:
Shirley P., Chiu K.: A Low Distortion Map between Map and Square, Journal of Graphics Tools 2(3), 1977
Ward G.: Presentations at the 10th Radiance Workshop, radiance-online.org/community/workshops/2011-berkeley-ca
Ward G. et al.: Reducing Anisotropic BSDF Measurement to Common Practice," Workshop on Material Appearance Modeling, 2014

BSDF peak extraction

Problem

High resolution BSDF vs. backward raytracing

(classical problem e.g. same with sun)



BSDF peak extraction

Problem

High resolution BSDF vs. backward raytracing

(classical problem e.g. same with sun)

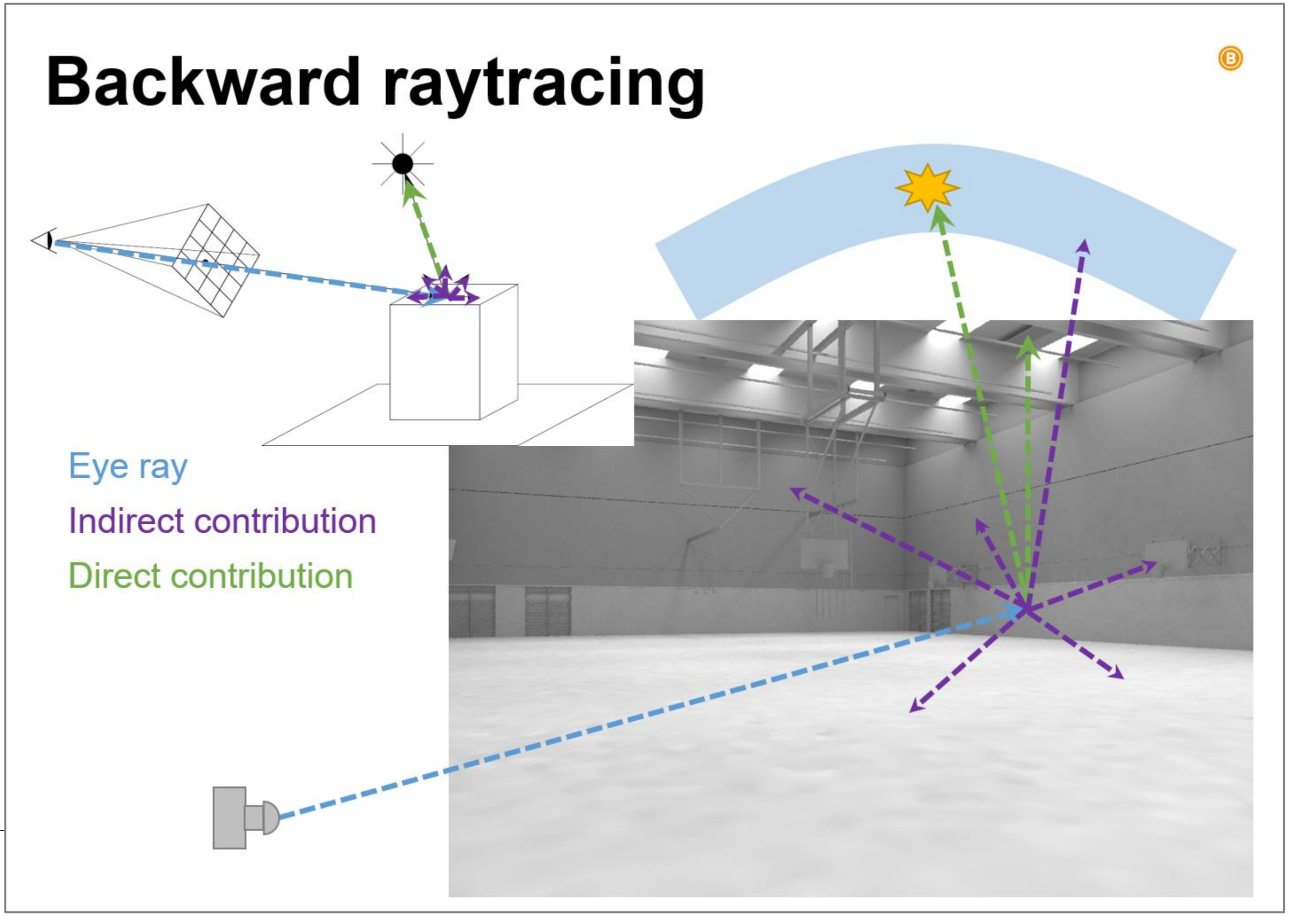
Approach

Treat direct contribution separately:

deterministic sampling (single/multiple samples)

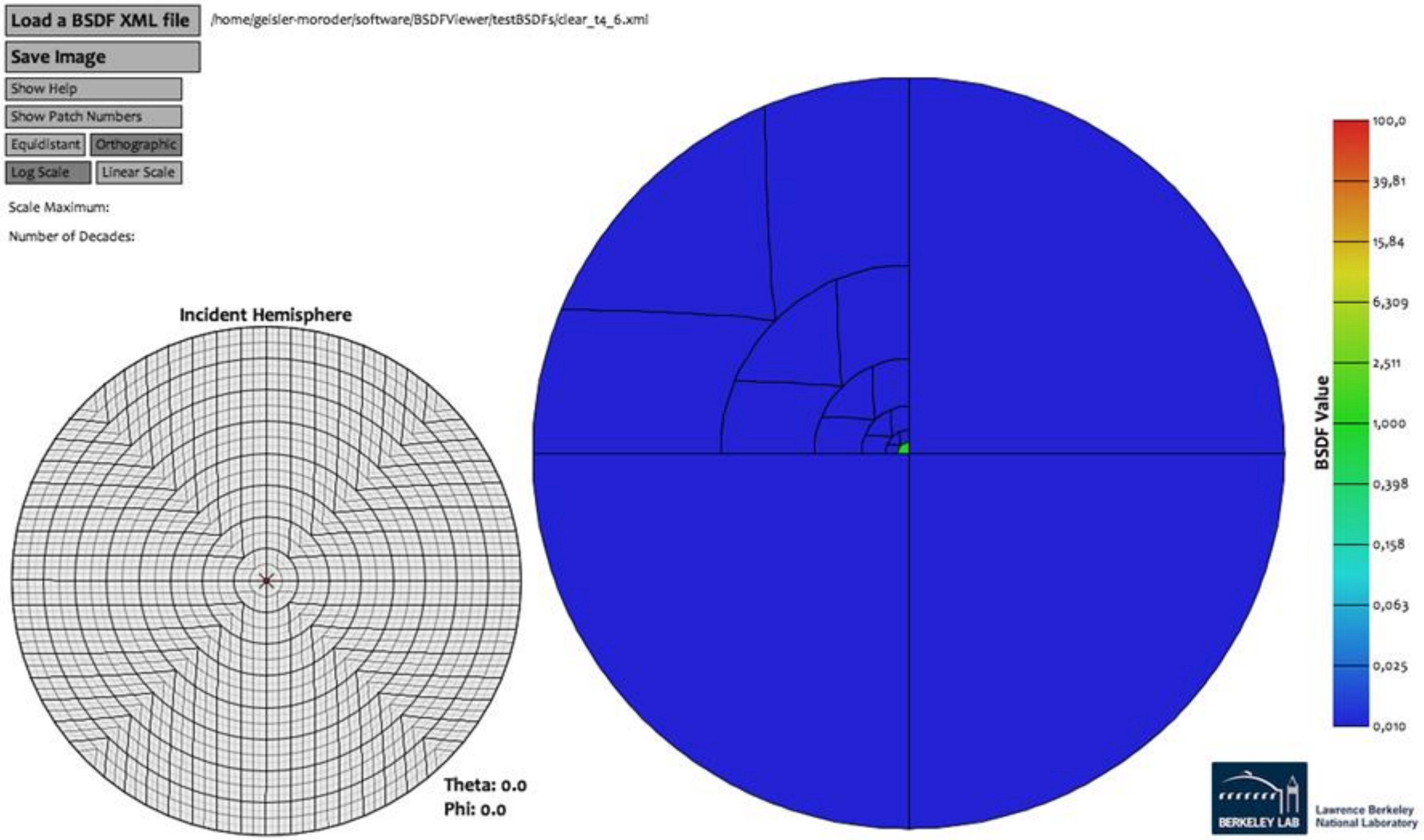
is applied in Radiance for light sources already.

But what if a BSDF is in the way?



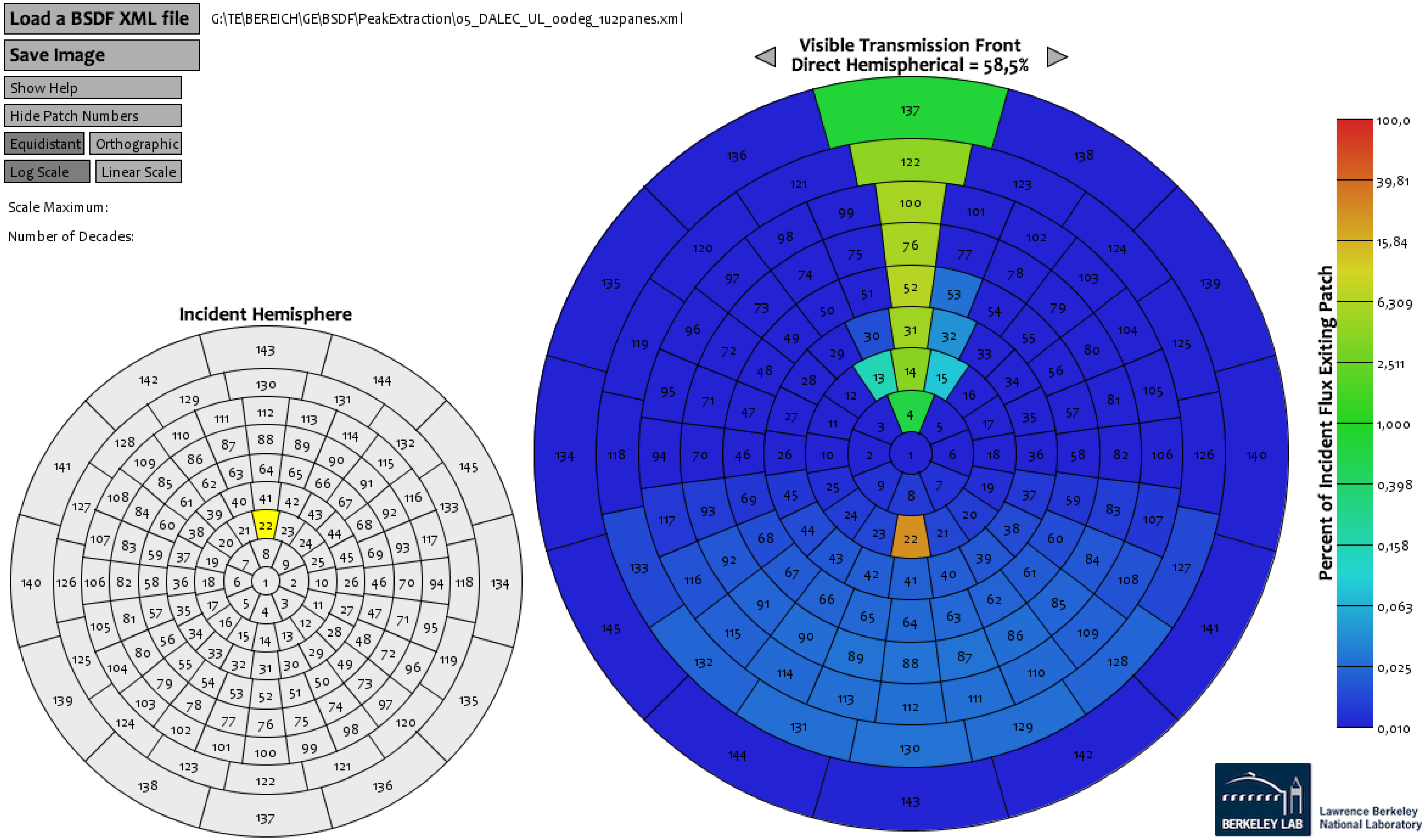
Example BSDFs

Variable Resolution BSDF of clear glazing



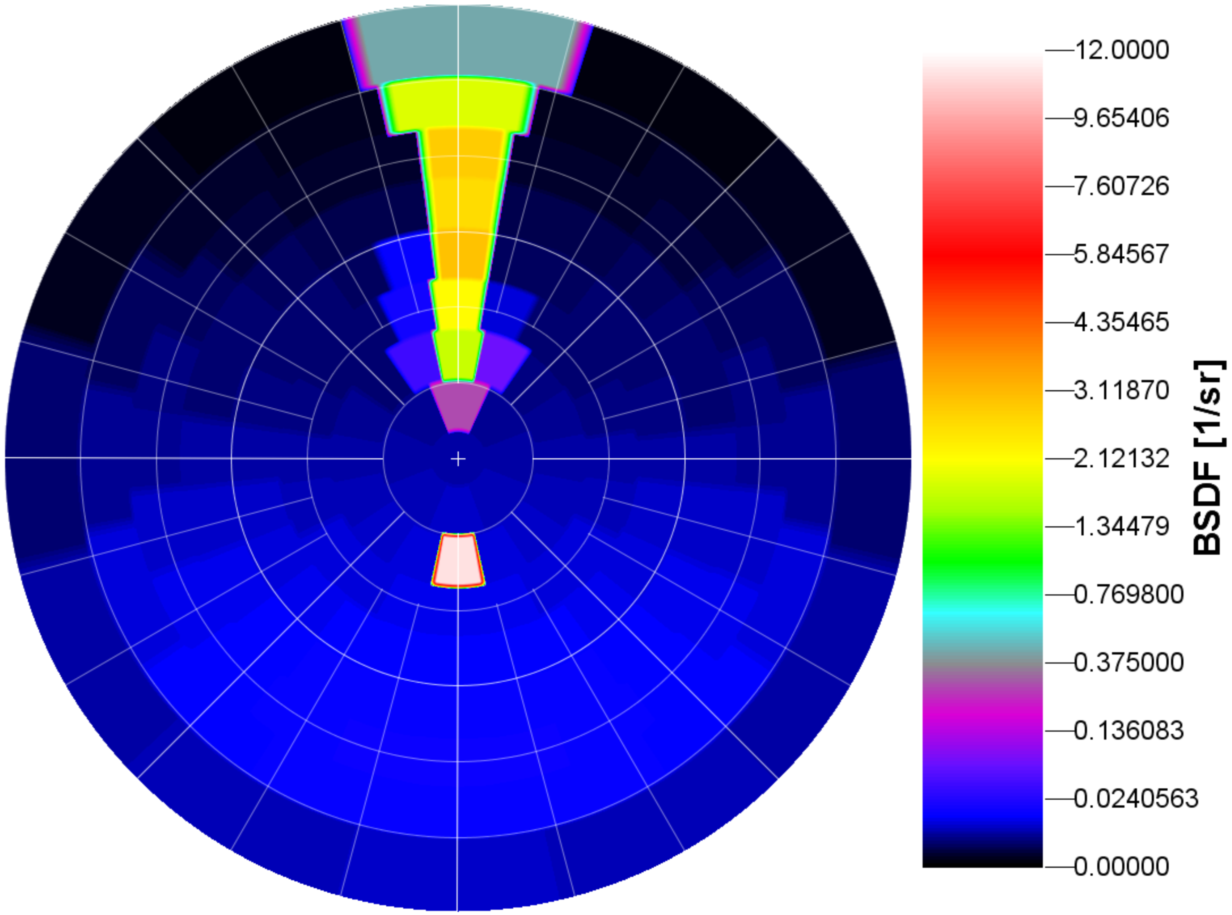
Example BSDFs

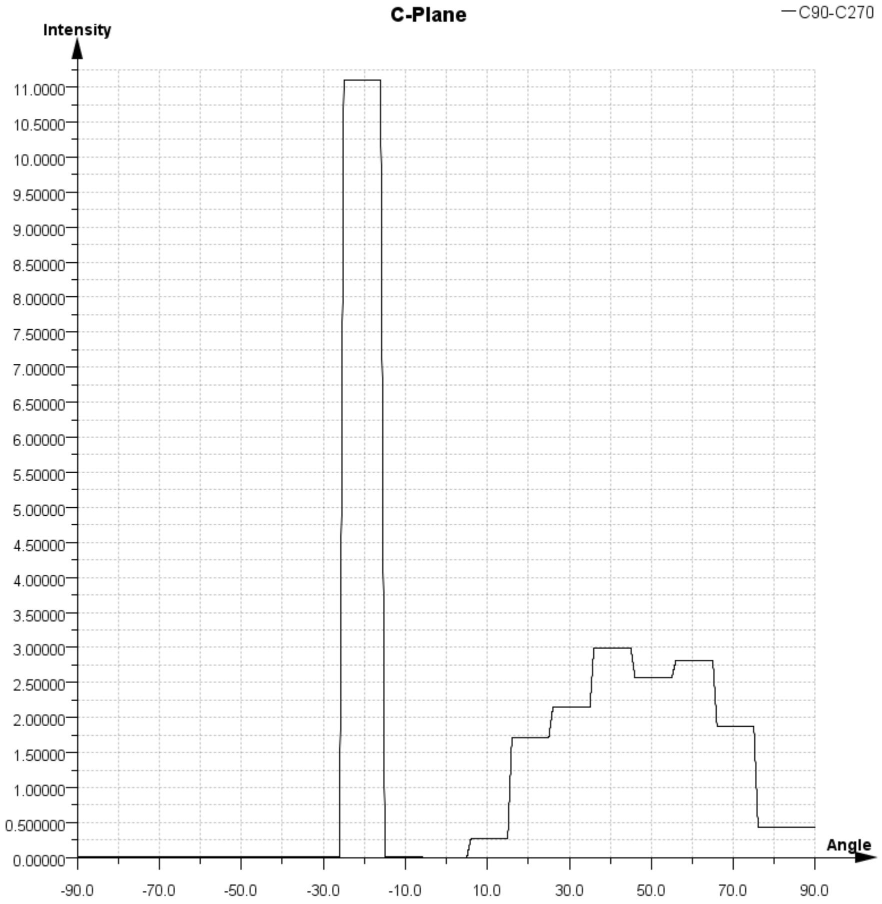
BSDF of redirecting blinds, Klems resolution



Example BSDFs

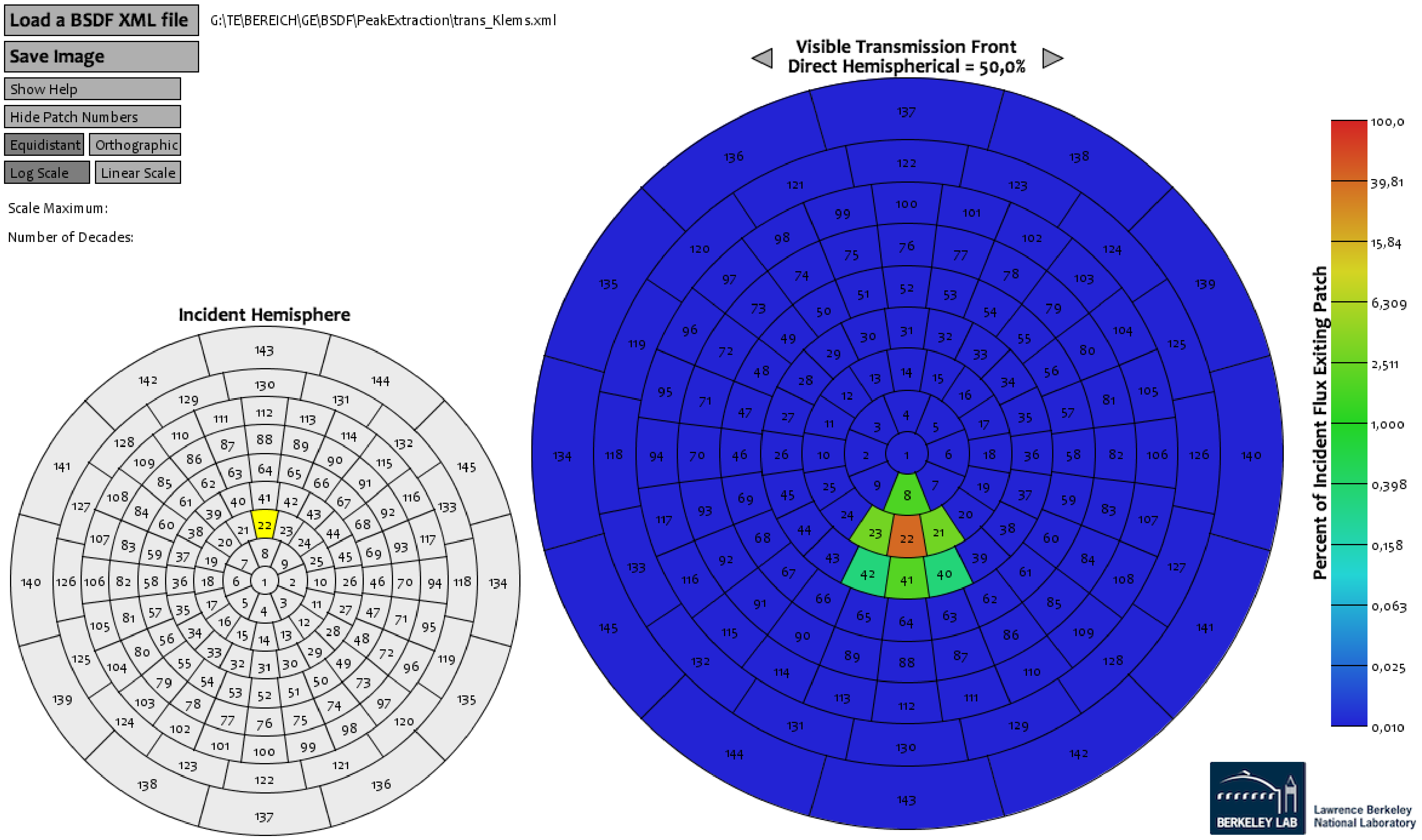
BSDF of redirecting blinds, Klems resolution





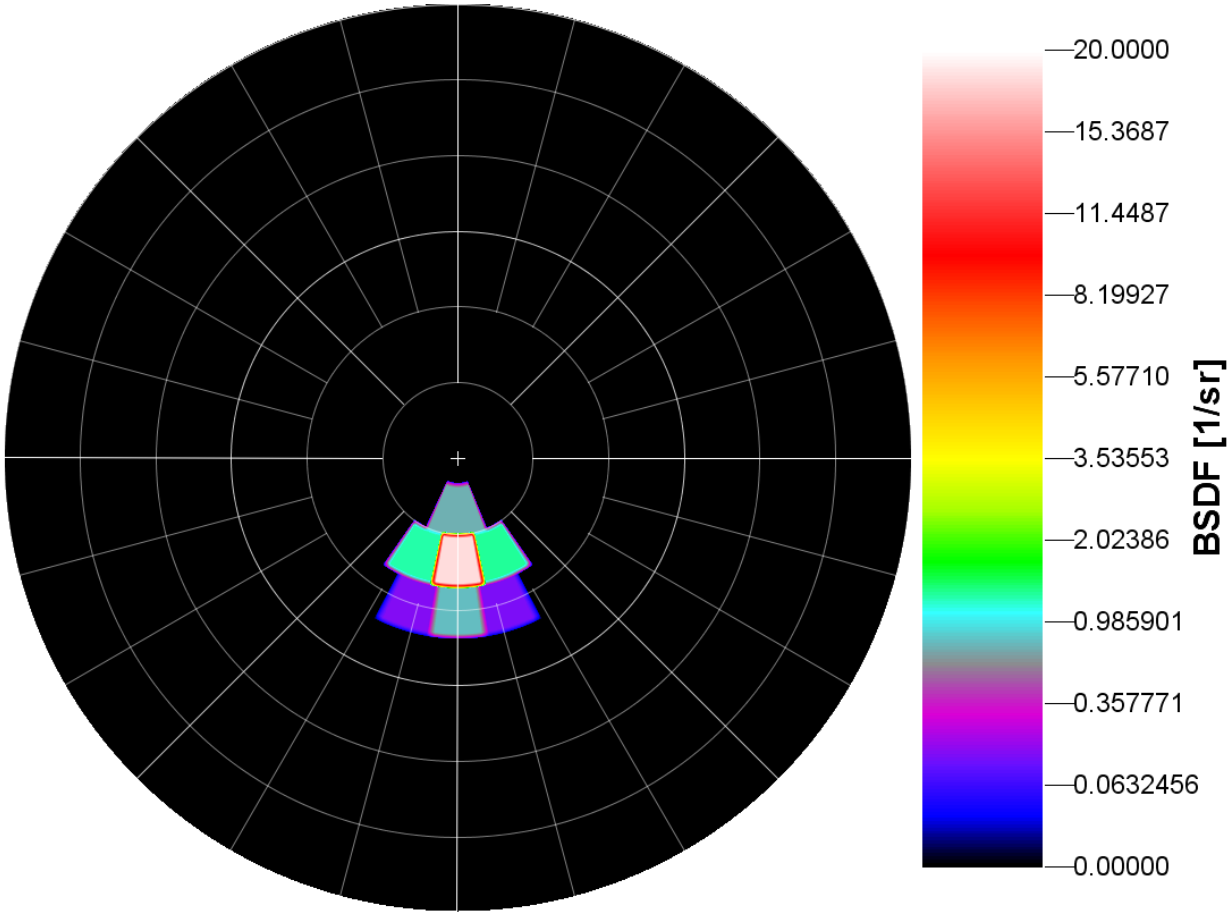
Example BSDFs

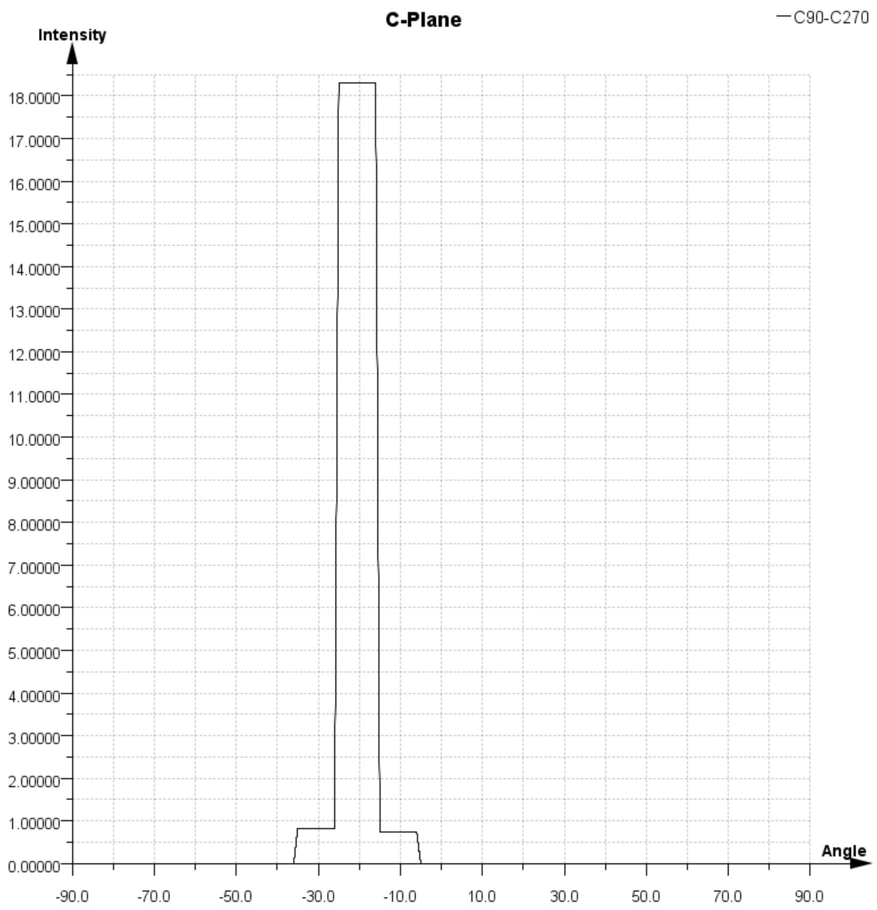
BSDF of translucent material (2x5°), Klems resolution



Example BSDFs

BSDF of translucent material (2x5°), Klems resolution





Peak extraction algorithm

(i) Shadow ray or view ray?

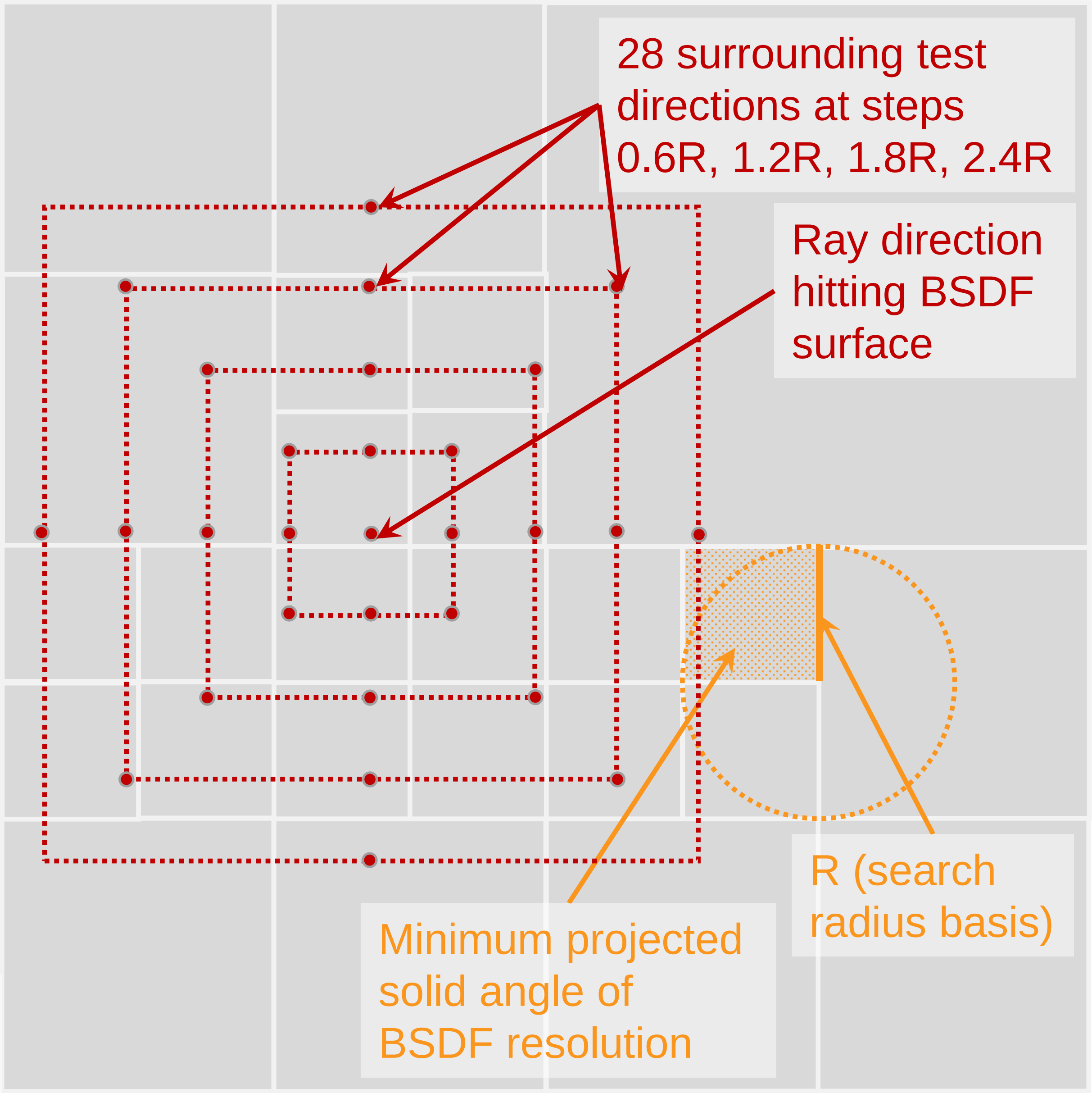
(ii) BSDF minimum projected solid angle?

Evaluate 28 surrounding directions within 2.4 times the search radius

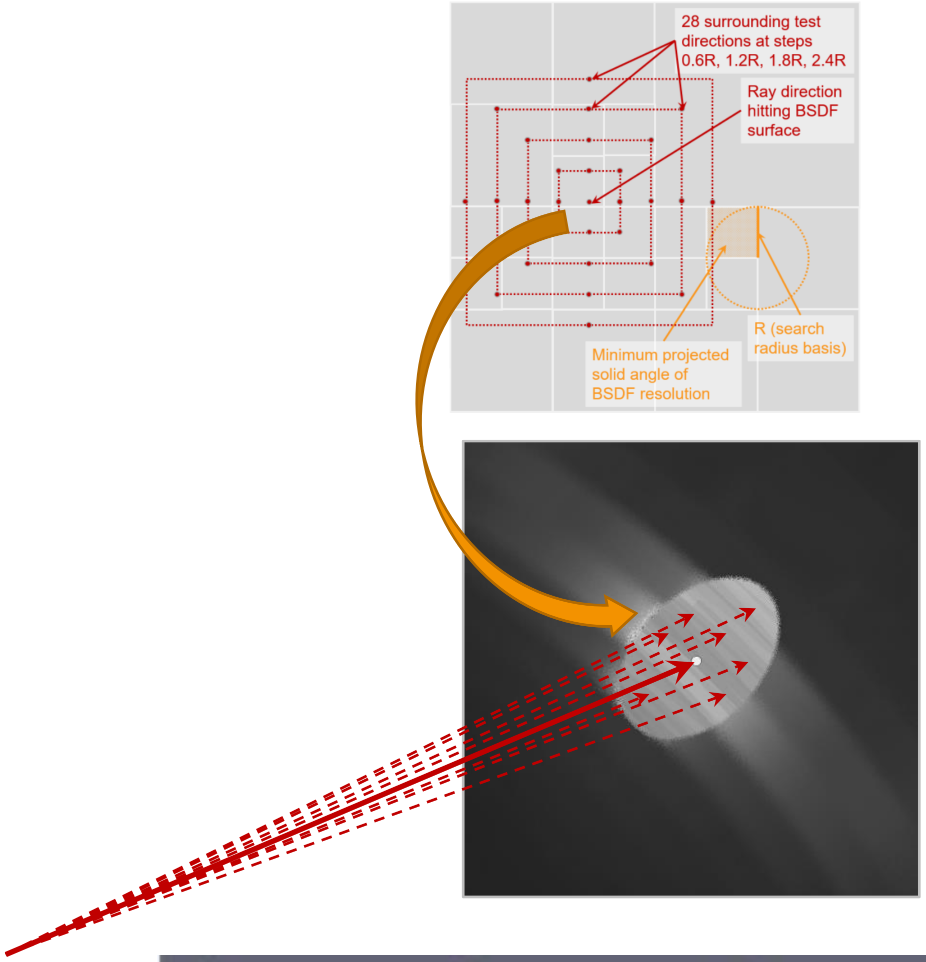
(iii) Brightness of possible peak > 1.5 times surrounding brightness?

➢ If (i), (ii), and (iii) are true: extract peak

Tensor tree BSDF



Peak extraction algorithm

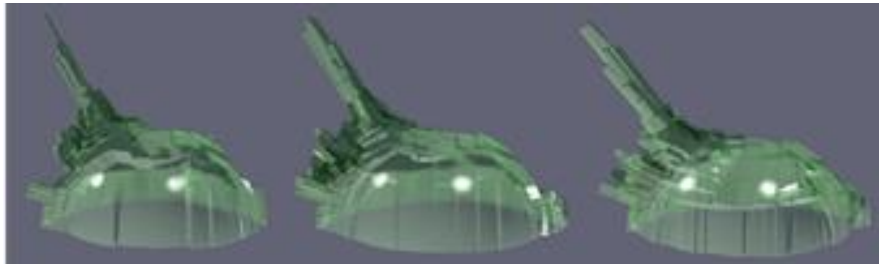


If peak extraction is triggered:

- treat surface for sample ray as purely specular transmitting, i.e., transmit ray unperturbed
- modify by direct-direct transmission value in this direction computed from the BSDF data
- avoid double-counting of near-specular transmission
- substitute these ray contributions in the exclusion zone with an average brightness determined from the 28 surrounding test directions*

➢ Higher accuracy (estimator for flux from surrounding of the peak)

➢ Better appearance



* added July 2020, src/rt/m_bsdf.c version 2.61

Enabling peak extraction: the aBSDF material

- BSDF material (no PE)

```
mod BSDF material
6+ thickness BSDFfile ux uy uz funcfile transform
0
0|3|6|9 rdf gdf bdf
        rdb gdb bdb
        rdt gdt bdt
```

- aBSDF material (with PE)

```
mod aBSDF material
5+ BSDFfile ux uy uz funcfile transform
0
0|3|6|9 rdf gdf bdf
        rdb gdb bdb
        rdt gdt bdt
```

```
/*
 *     Arguments to this material include optional diffuse colors.
 *  String arguments include the BSDF and function files.
 *     For the MAT_BSDF type, a non-zero thickness causes the useful behavior
 *  of translating transmitted rays this distance beneath the surface
 *  (opposite the surface normal) to bypass any intervening geometry.
 *  Translation only affects scattered, non-source-directed samples.
 *  A non-zero thickness has the further side-effect that an unscattered
 *  (view) ray will pass right through our material, making the BSDF
 *  surface invisible and showing the proxied geometry instead. Thickness
 *  has the further effect of turning off reflection on the reverse side so
 *  rays heading in the opposite direction pass unimpeded through the BSDF
 *  surface.  A paired surface may be placed on the opposite side of
 *  the detail geometry, less than this thickness away, if a two-way
 *  proxy is desired.  Note that t
 *  A positive thickness hides geo
 *  front reflectance and transmis
 *  hides geometry in front of the
 *  and applies only the transmiss
 *  Reflection is ignored on the h
 *     For the MAT_ABSDF type, we
 *  Such a component will cause di
 *  A separate test prevents over-
 *  too close to this "through" di
 *  will also have a view componen
 *  A MAT_BSDF type with zero thickness behaves the same as a MAT_ABSDF
 *  type with no strong through component.
 *     The "up" vector for the BSDF is given by three variables, defined
 *  (along with the thickness) by the named function file, or '.' if none.
 *  Together with the surface normal, this defines the local coordinate
 *  system for the BSDF.
 *     We do not reorient the surface, so if the BSDF has no back-side
 *  reflectance and none is given in the real arguments, a BSDF surface
 *  with zero thickness will appear black when viewed from behind
 *  unless backface visibility is on, when it becomes invisible.
 *     The diffuse arguments are added to components in the BSDF file,
 *  not multiplied.  However, patterns affect this material as a multiplier
 *  on everything except non-diffuse reflection.
 *
 *  Arguments for MAT_ABSDF are:
 *     5+      BSDFfile        ux uy uz        funcfile        transform
 *     0
 *     0|3|6|9 rdf     gdf     bdf
 *             rdb     gdb     bdb
 *             rdt     gdt     bdt
 *
 *  Arguments for MAT_BSDF are:
 *     6+      thick   BSDFfile        ux uy uz        funcfile        transform
 *     0
 *     0|3|6|9 rdf     gdf     bdf
 *             rdb     gdb     bdb
 *             rdt     gdt     bdt
```

The best documentation is the code:
see ray/src/rt/m_bsdf.c

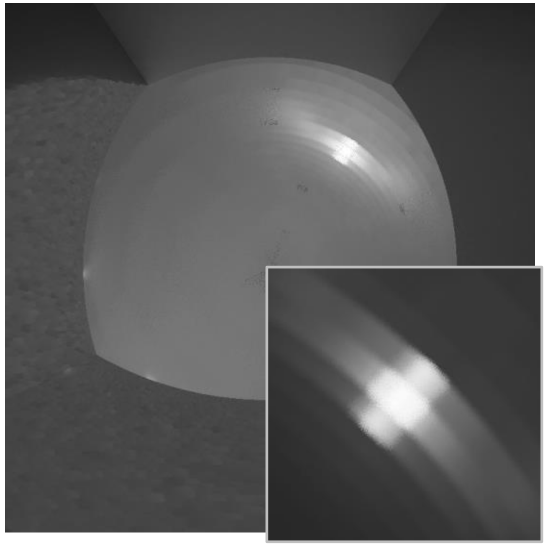
Enabling peak extraction: the aBSDF material

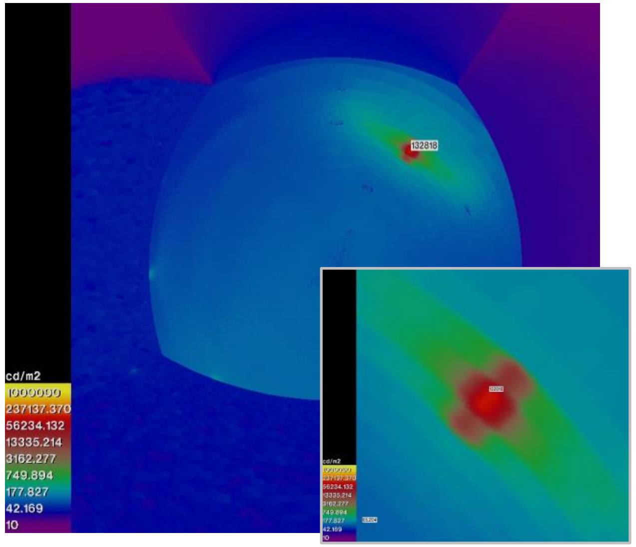
- BSDF material (no PE)

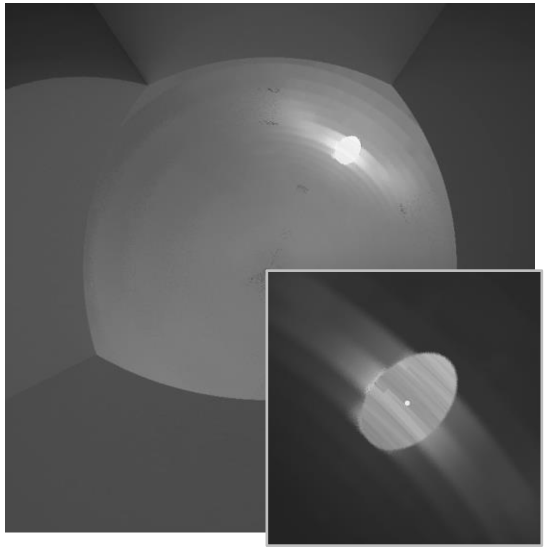
```
void BSDF my_BSDF
6 0 system.xml 0 0 1 .
0
0
```

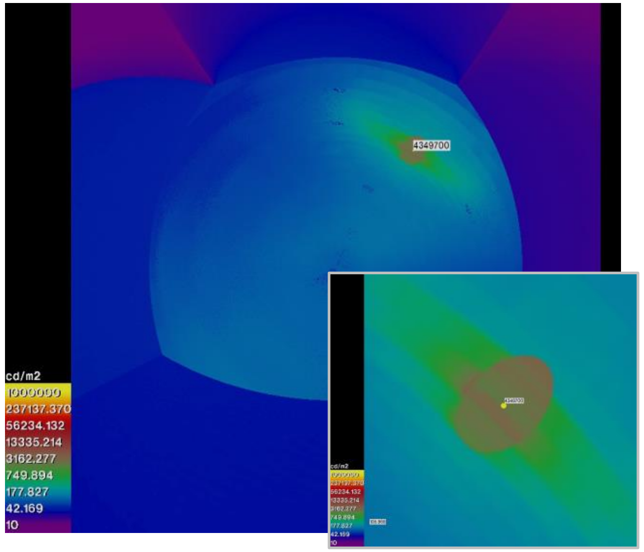
- aBSDF material (with PE)

```
void aBSDF my_aBSDF
5 system.xml 0 0 1 .
0
0
```



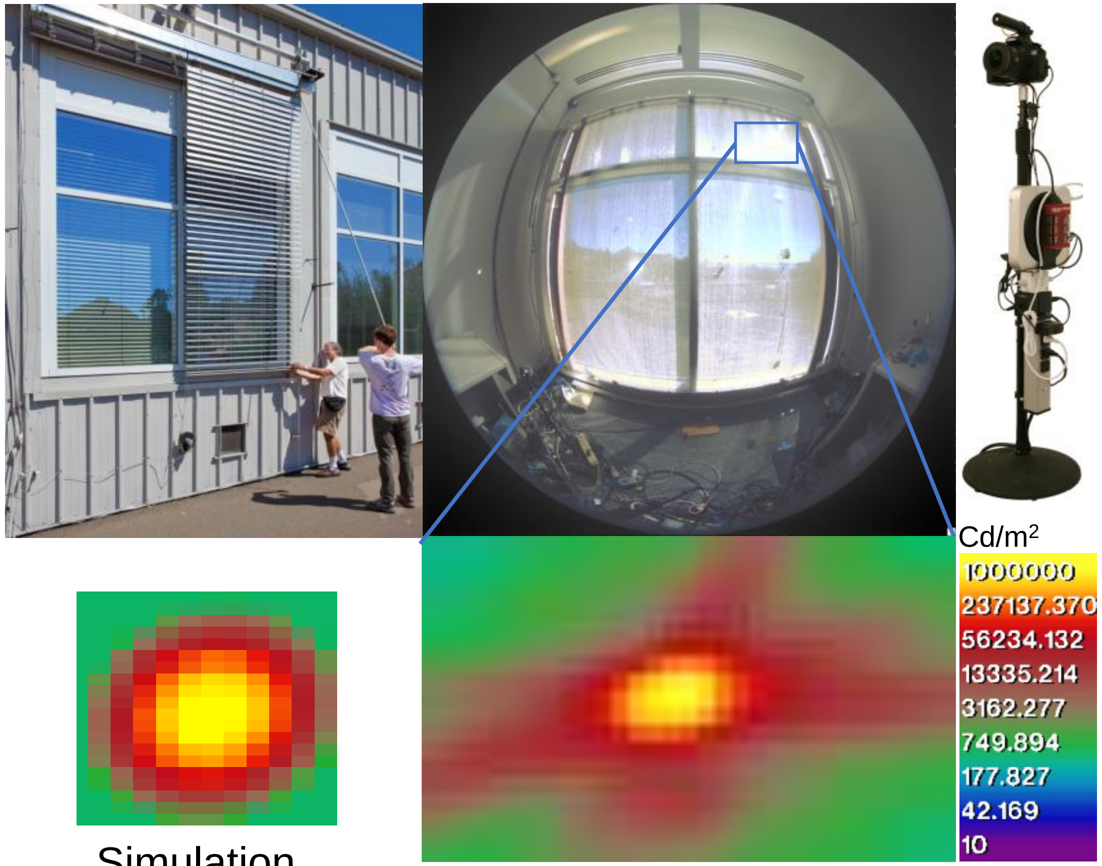






Field validation at LBNL

- Completed initial validation of modeling workflow using field measured data from the Advanced Windows Testbed at LBNL*
- Verified that intensity and distribution of transmitted flux are accurate using point measurements and calibrated high dynamic range (HDR) imaging
- Initiated second phase field validation of a broader range of materials to test robustness of the algorithms



Simulation

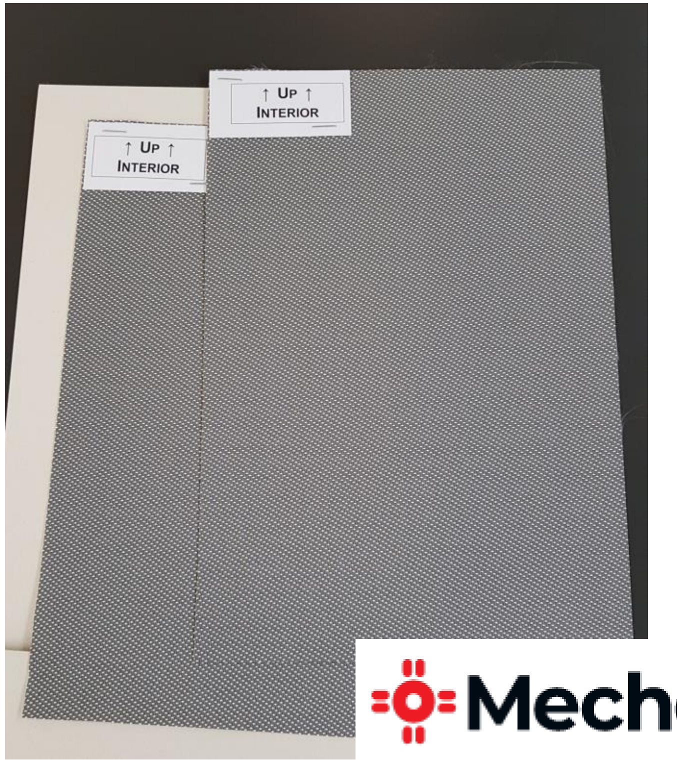
Measurement

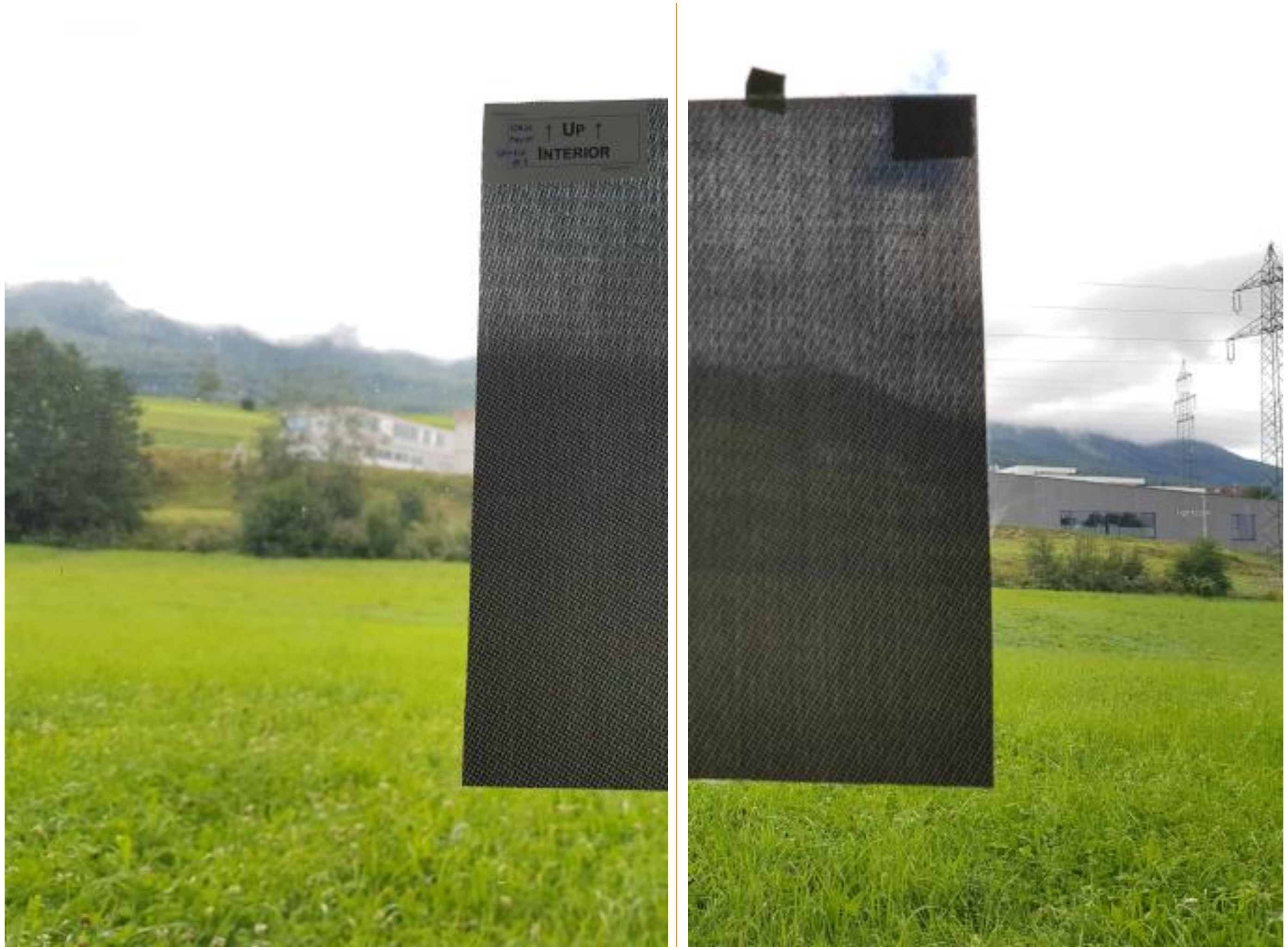
Example: Check for energy conservation at various solid angles

* Ward, G.J. et al., Modeling specular transmission of complex fenestration systems with data-driven BSDFs, Building and Environment 196 (2021) 107774 (open access), https://doi.org/10.1016/j.buildenv.2021.107774

Examples: (i) MechoShade fabric

- Textile roller blind (MechoShade)
  - Fabric sample

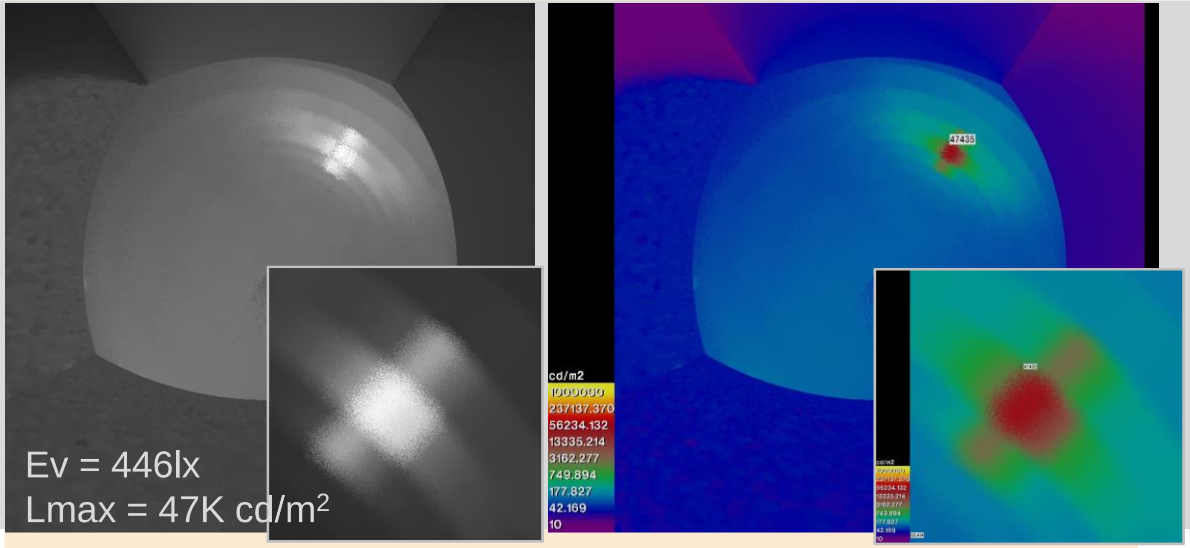


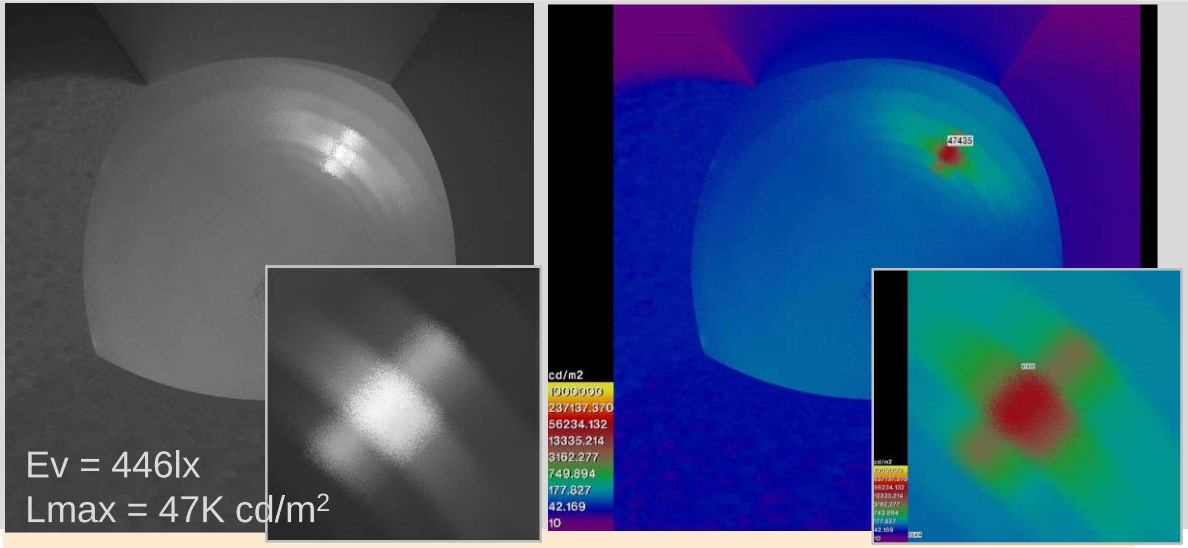


Examples: (i) MechoShade fabric: BSDF t35

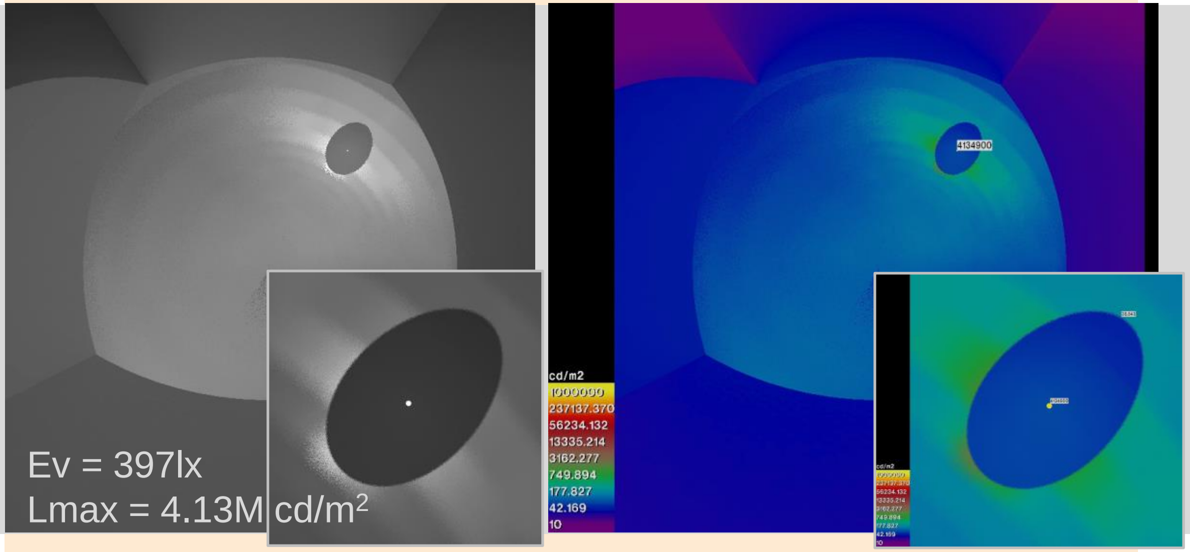
src/rt/m_bsdf.c: v 2.60 | src/rt/m_bsdf.c: v 2.61

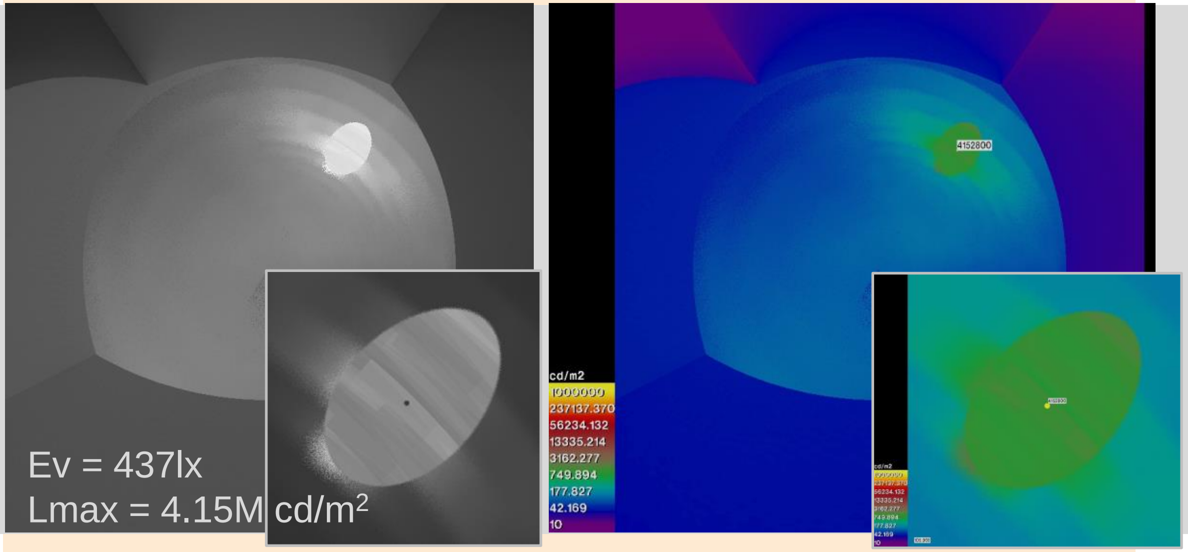
„BSDF“: without PE





„aBSDF“: with PE





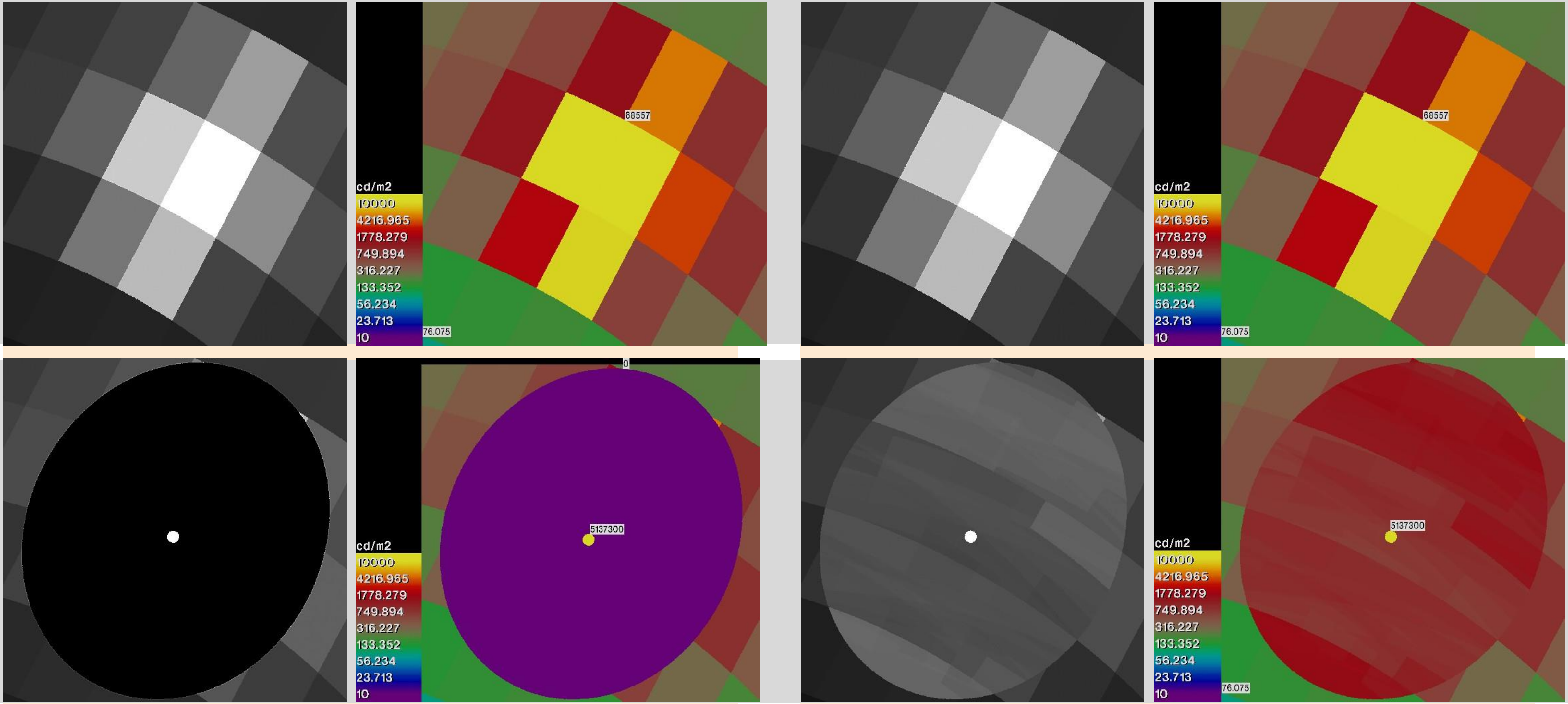
rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

Examples: (i) MechoShade fabric: BSDF t35

src/rt/m_bsdf.c: v 2.60 | src/rt/m_bsdf.c: v 2.61

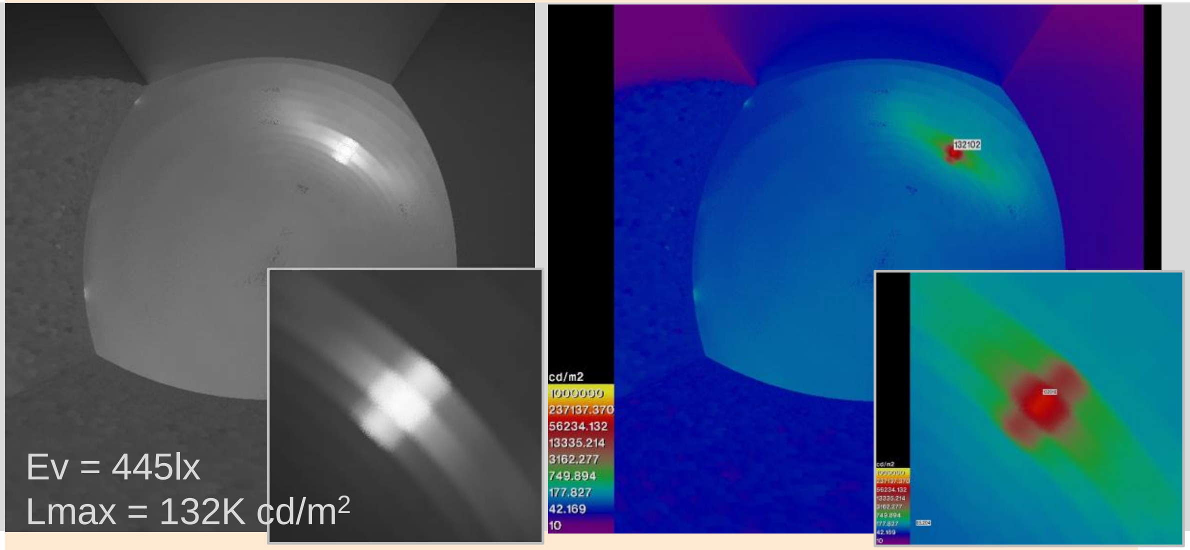
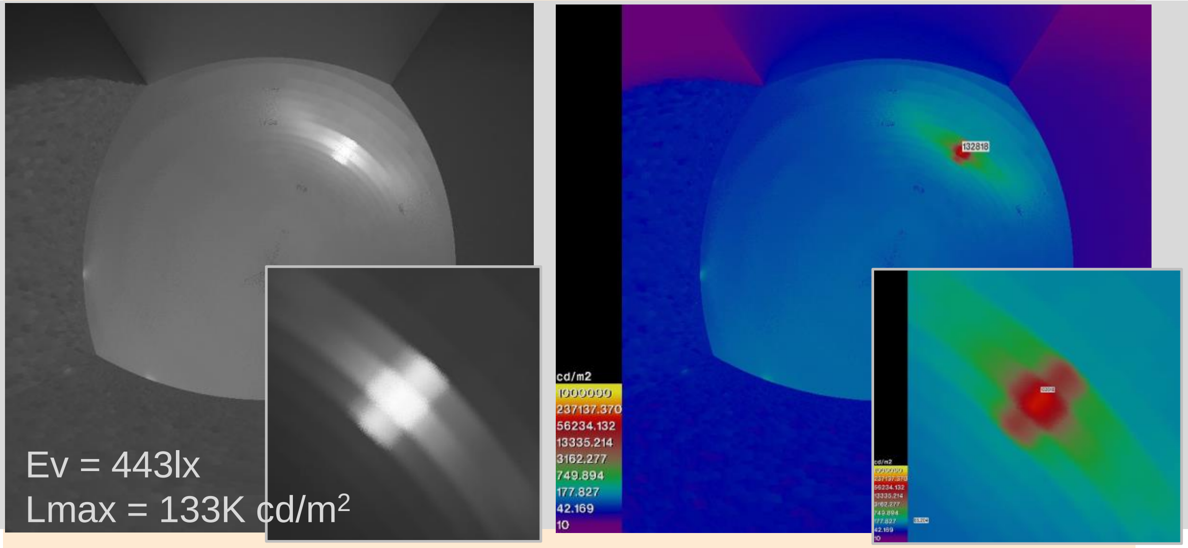
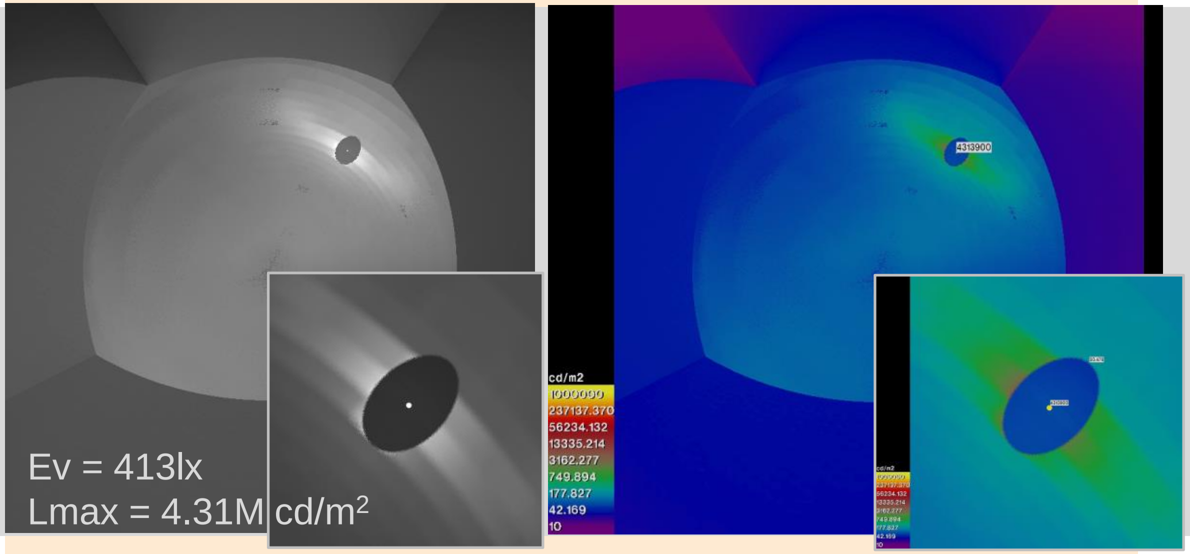
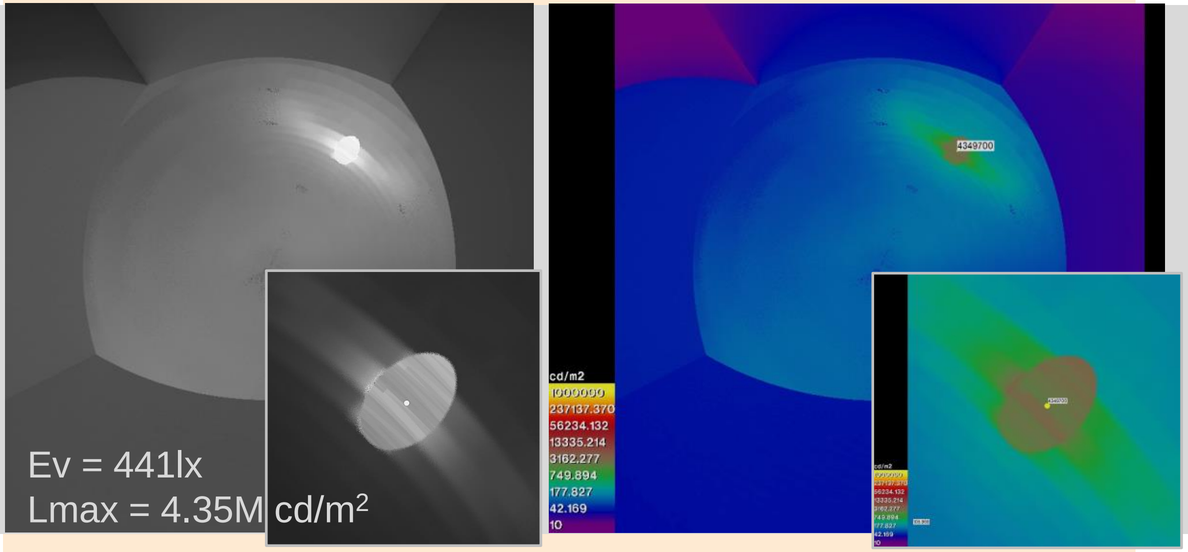
„BSDF“: without PE

„aBSDF“: with PE



rpict parameters: -ps 1 -ab 1 -ss 0 -dj 0

Examples: (i) MechoShade fabric: BSDF t36

	src/rt/m_bsdf.c: v 2.60	src/rt/m_bsdf.c: v 2.61
„BSDF": without PE		
„aBSDF": with PE		

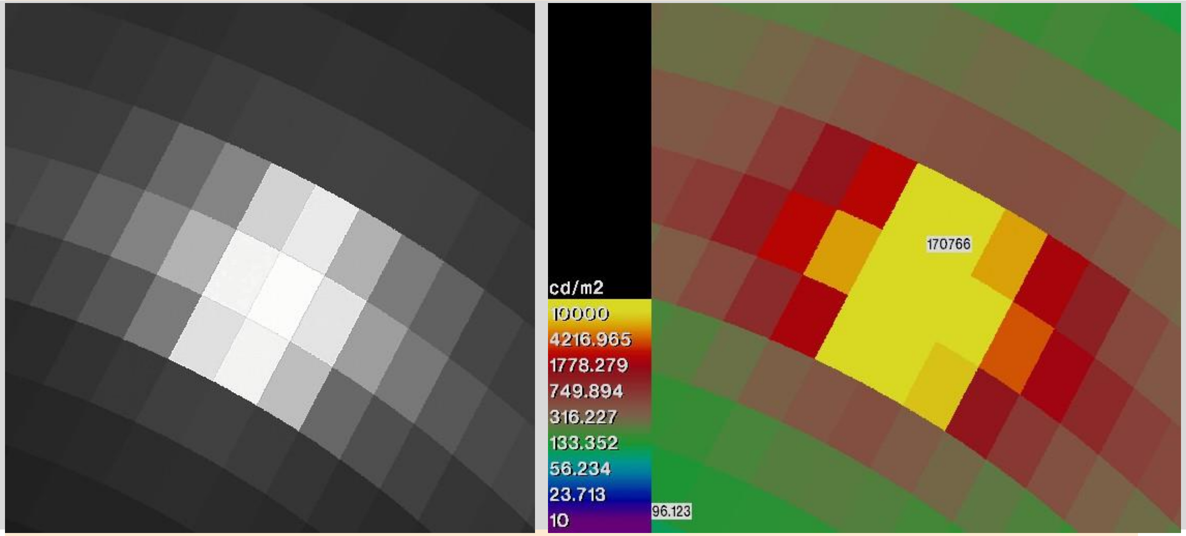
rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

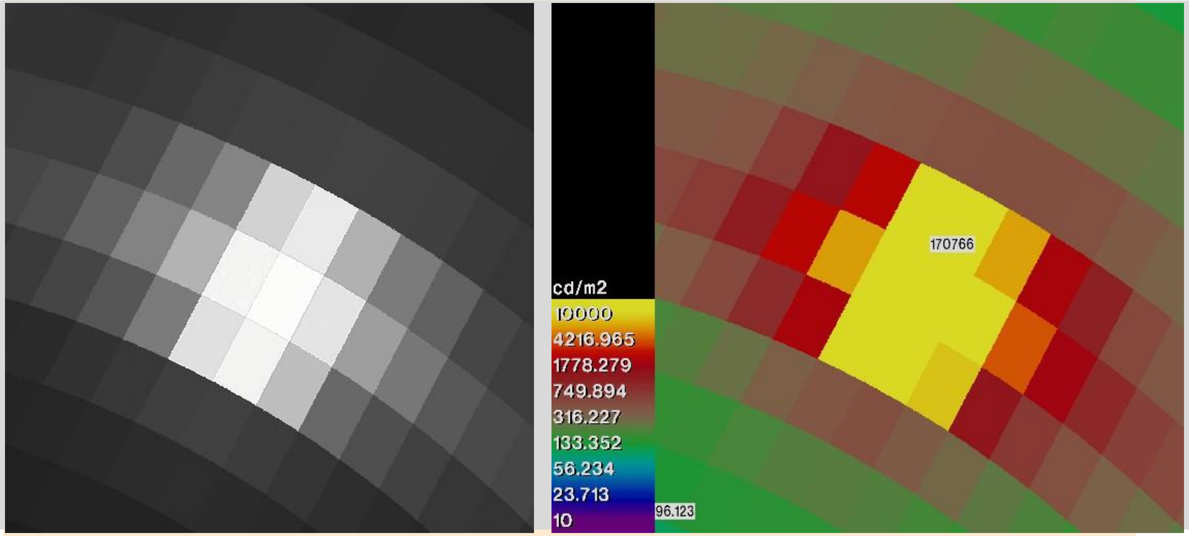
Examples: (i) MechoShade fabric: BSDF t36

src/rt/m_bsdf.c: v 2.60

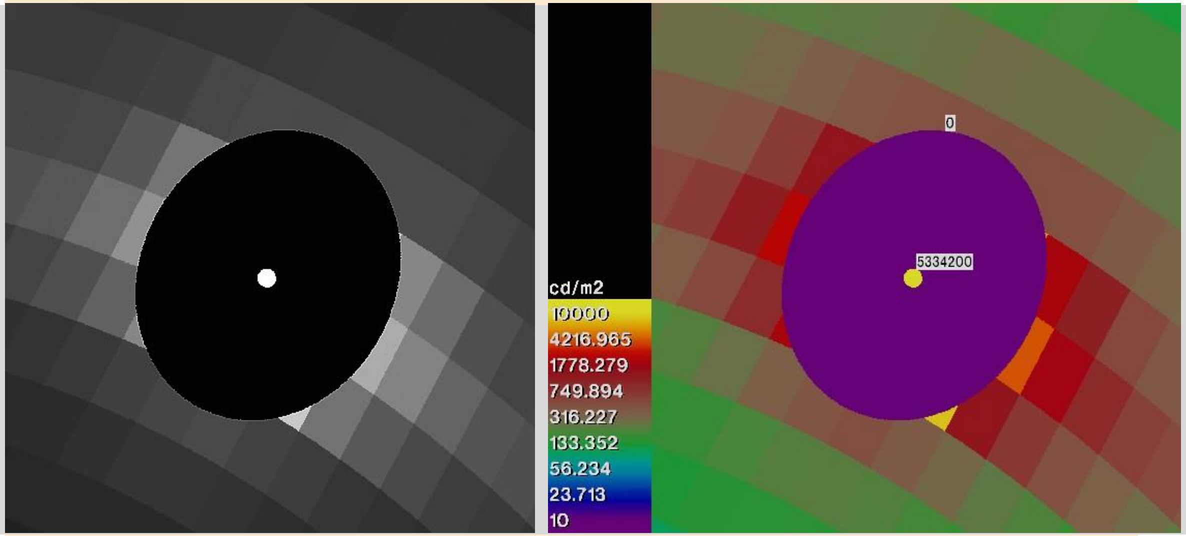
src/rt/m_bsdf.c: v 2.61

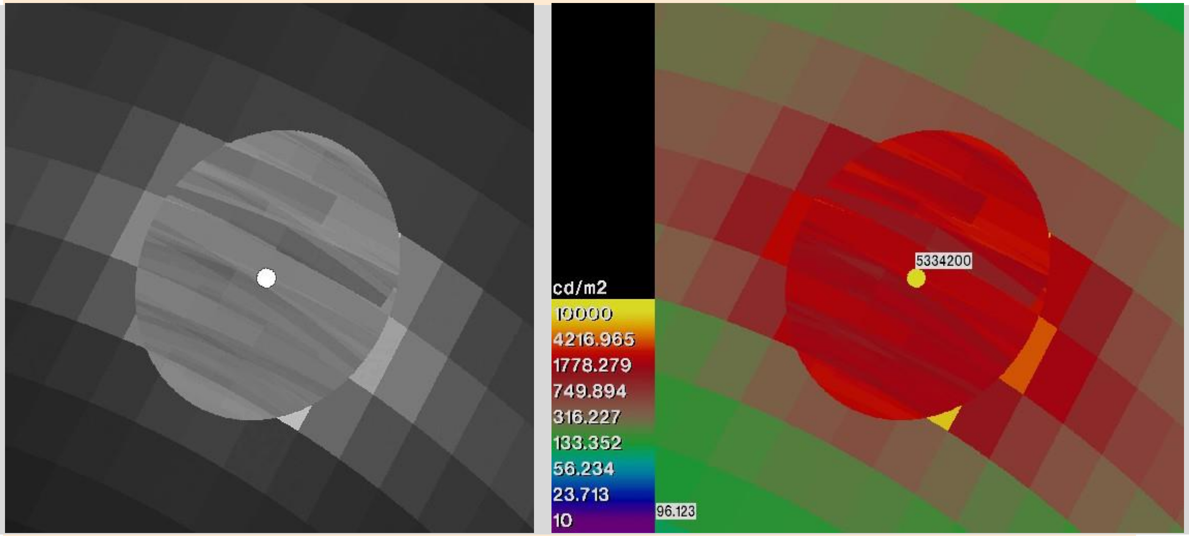
„BSDF“: without PE





„aBSDF“: with PE





rpict parameters: -ps 1 -ab 1 -ss 0 -dj 0

Examples: (i) MechoShade fabric: BSDF t37

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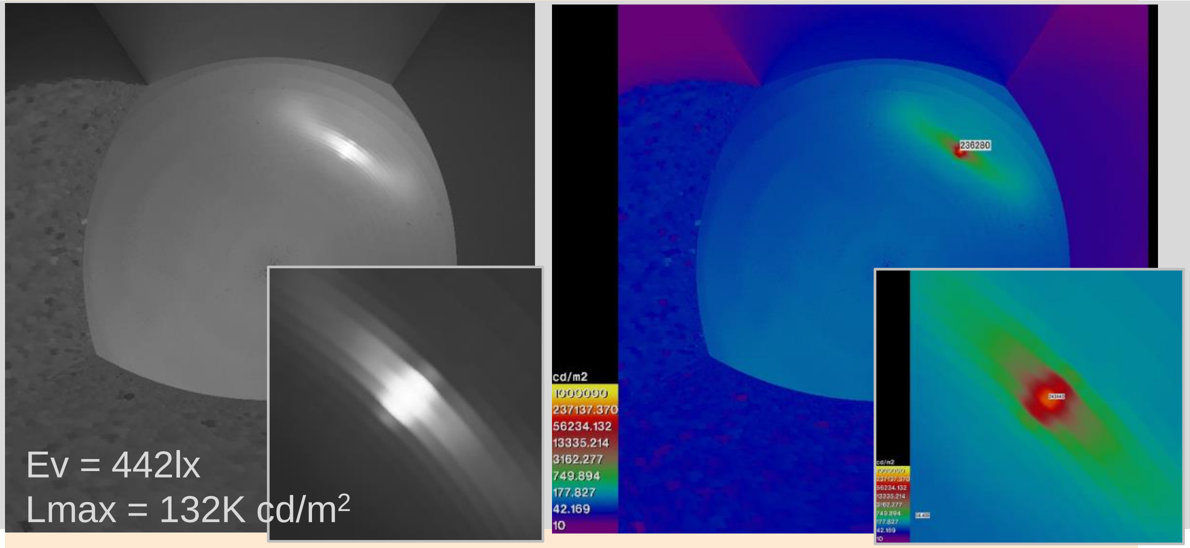
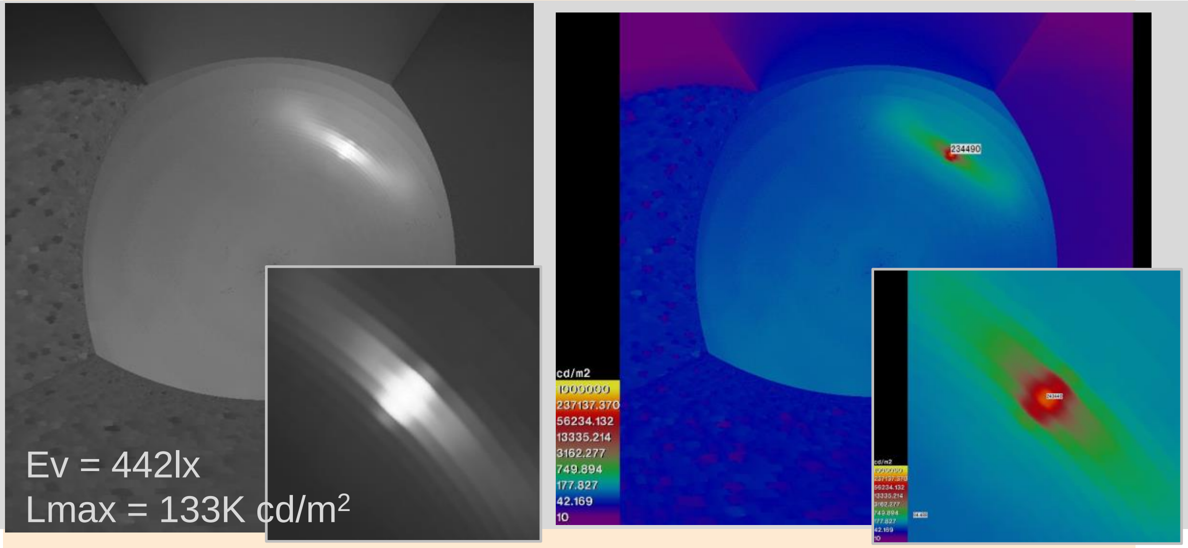
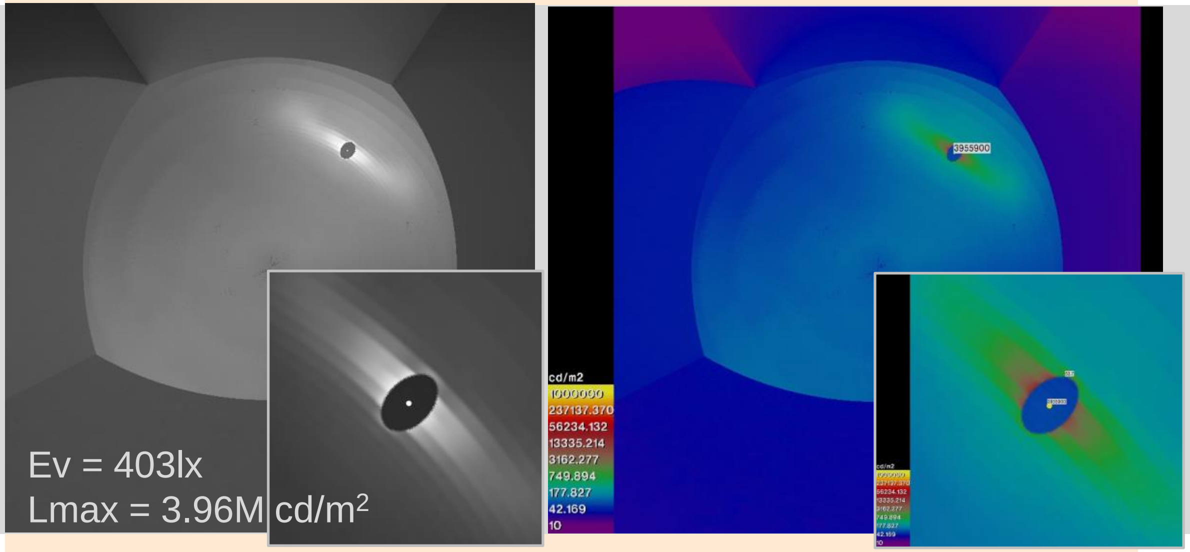
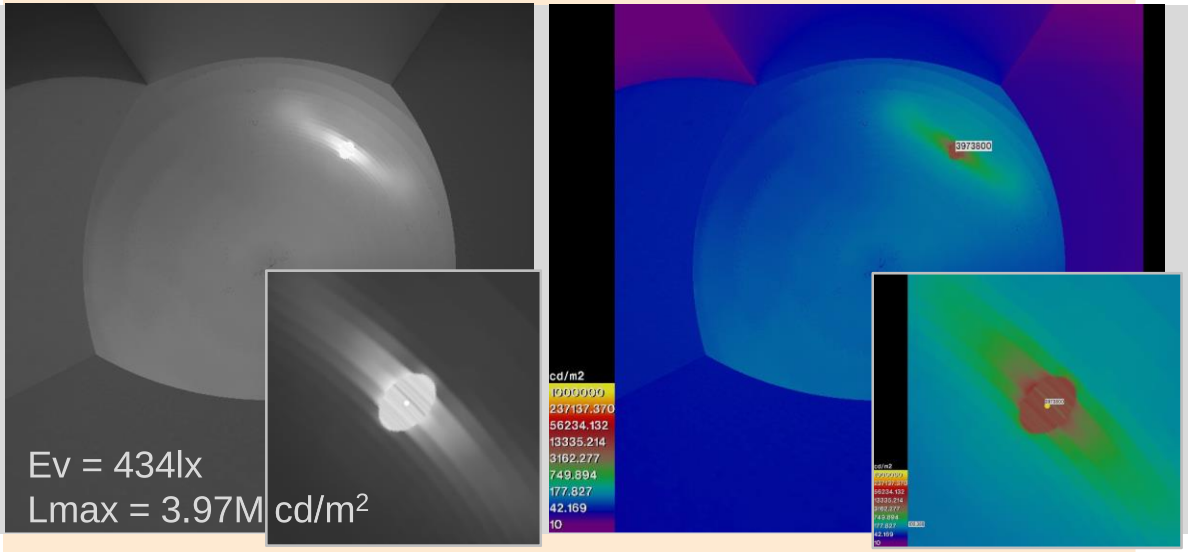
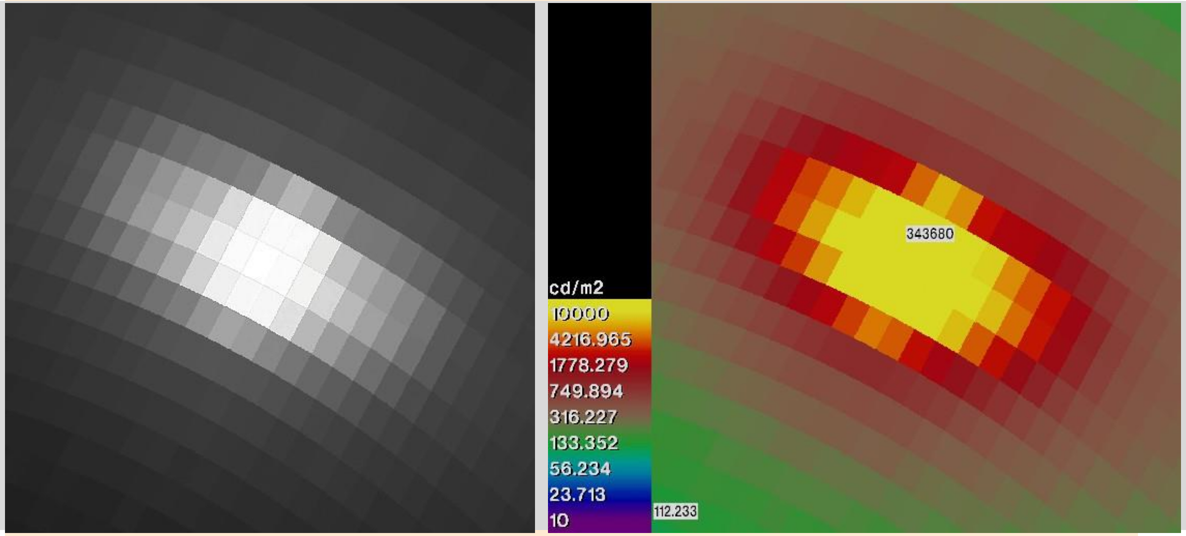
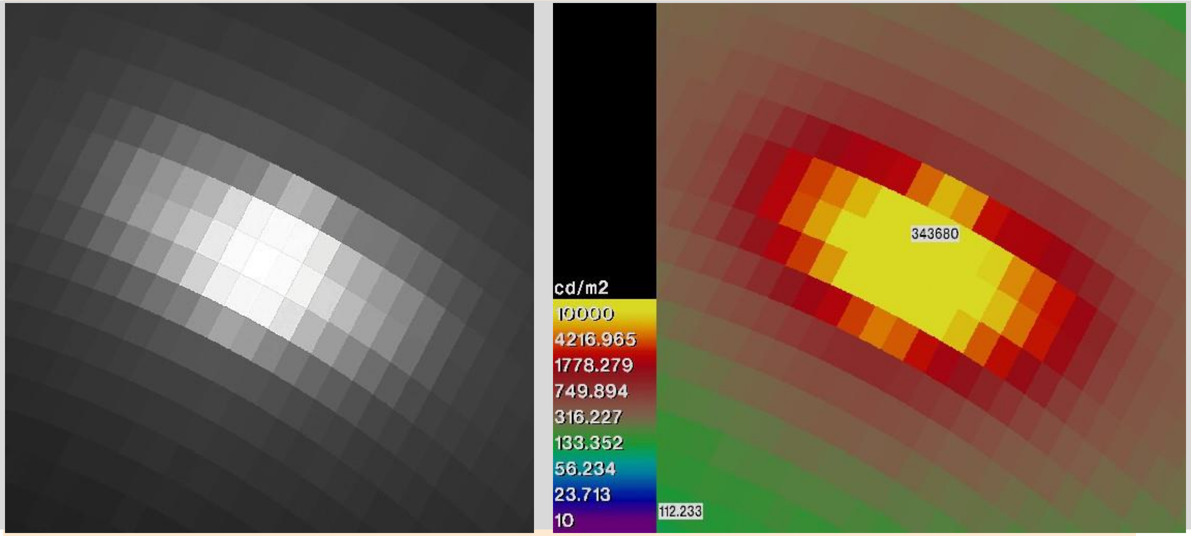
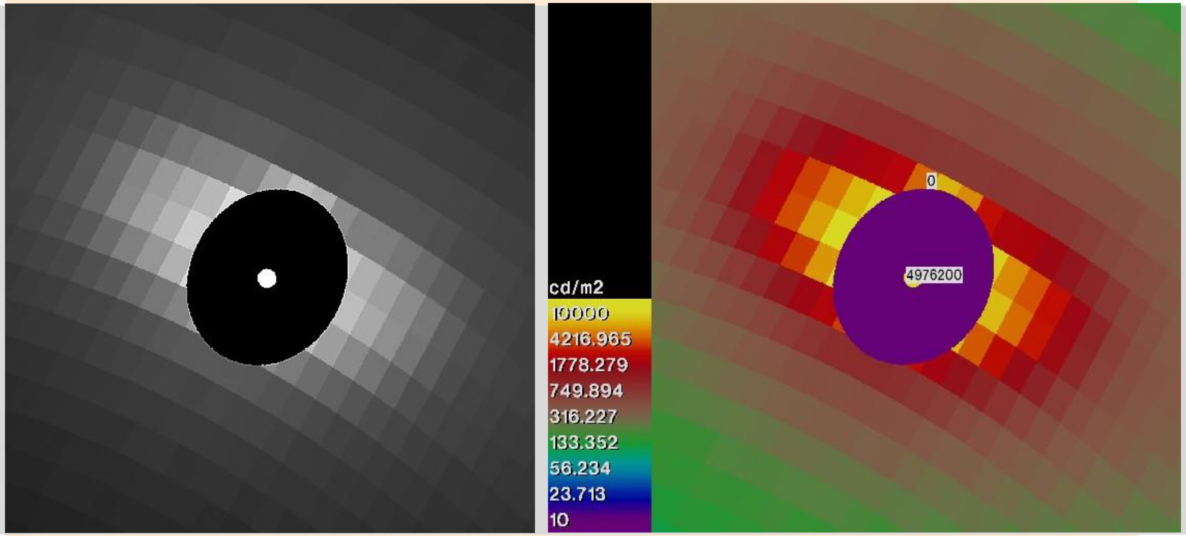
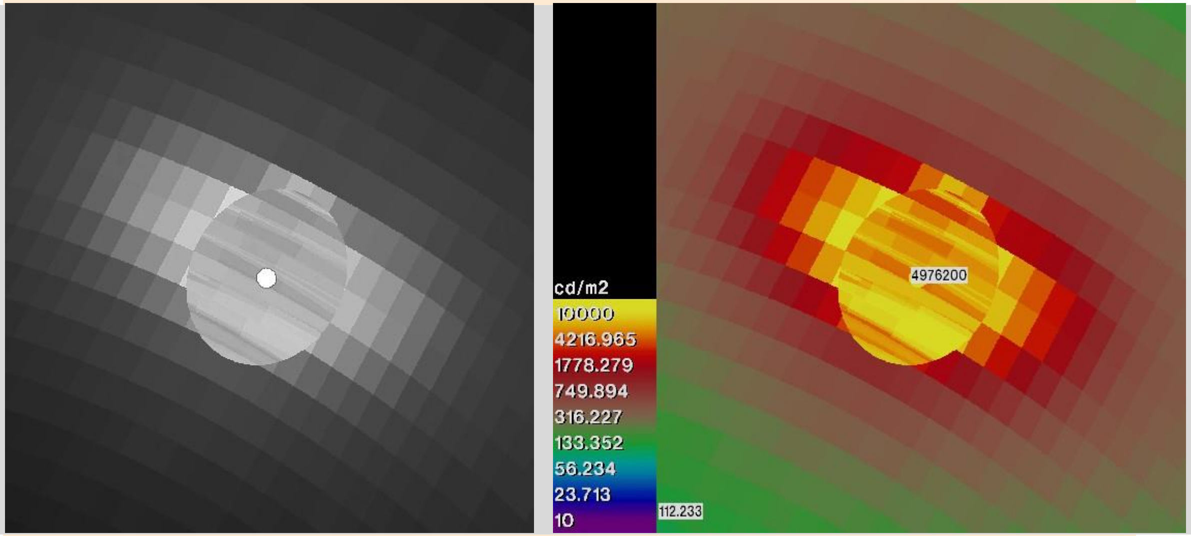
„BSDF“: without PE		
„aBSDF“: with PE		

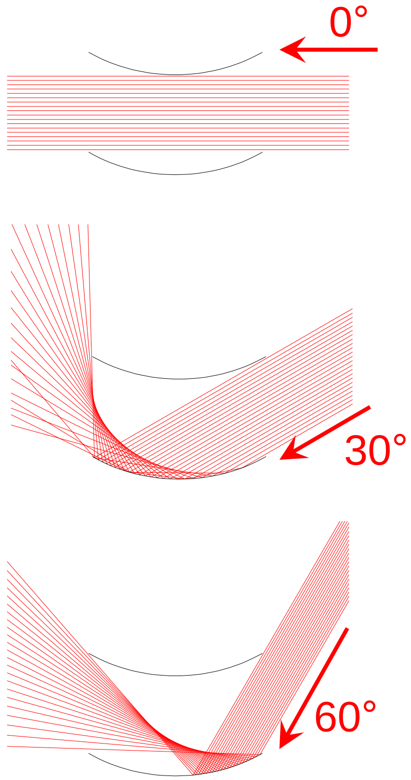
rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

Examples: (i) MechoShade fabric: BSDF t37

	src/rt/m_bsdf.c: v 2.60	src/rt/m_bsdf.c: v 2.61
„BSDF“: without PE		
„aBSDF“: with PE		

rpict parameters: -ps 1 -ab 1 -ss 0 -dj 0

Examples: (ii) Redirecting blinds

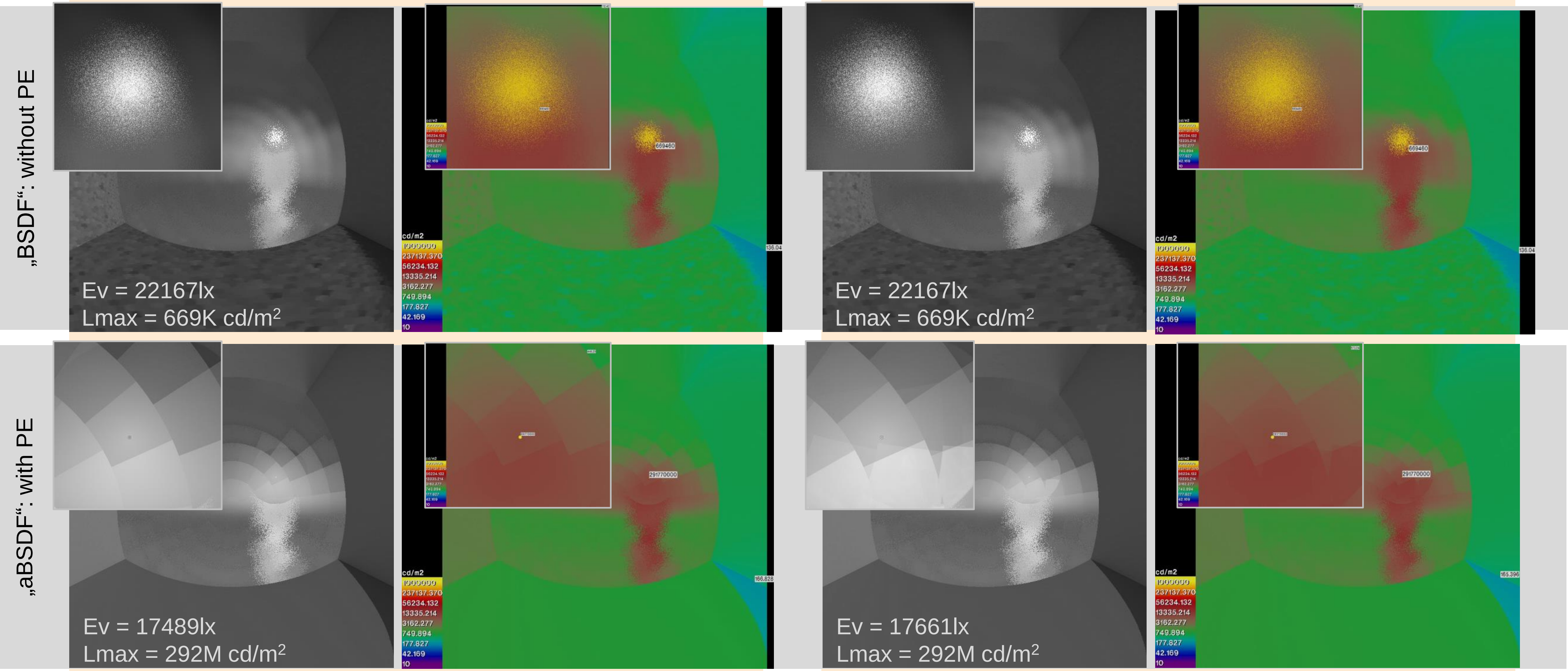


rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

Examples: (ii) Redirecting blinds: BSDF Klems

src/rt/m_bsdf.c: v 2.60

src/rt/m_bsdf.c: v 2.61



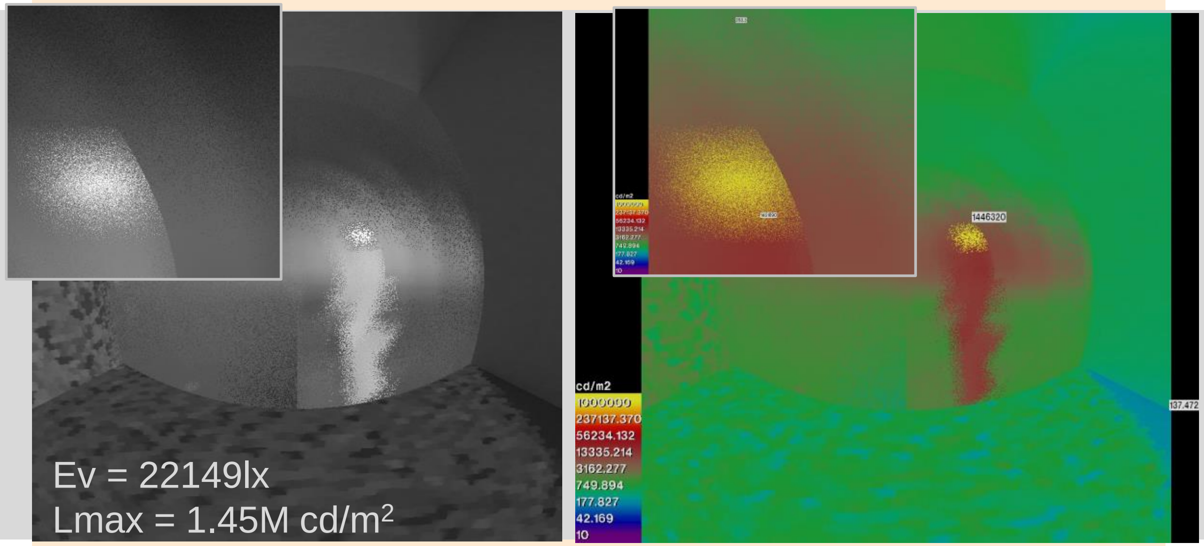
rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

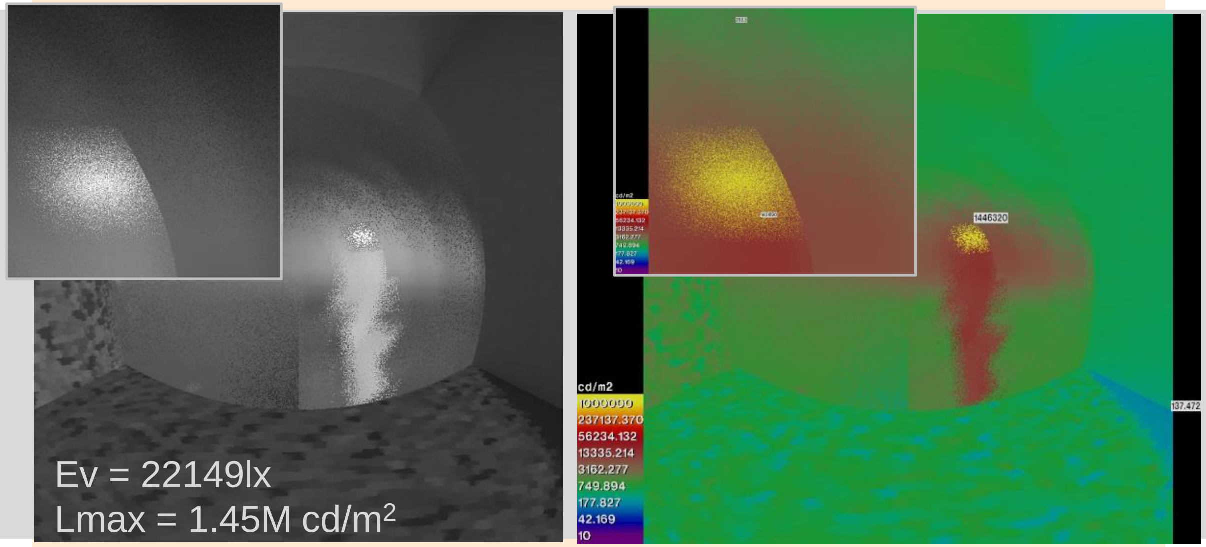
Examples: (ii) Redirecting blinds: BSDF t44

src/rt/m_bsdf.c: v 2.60

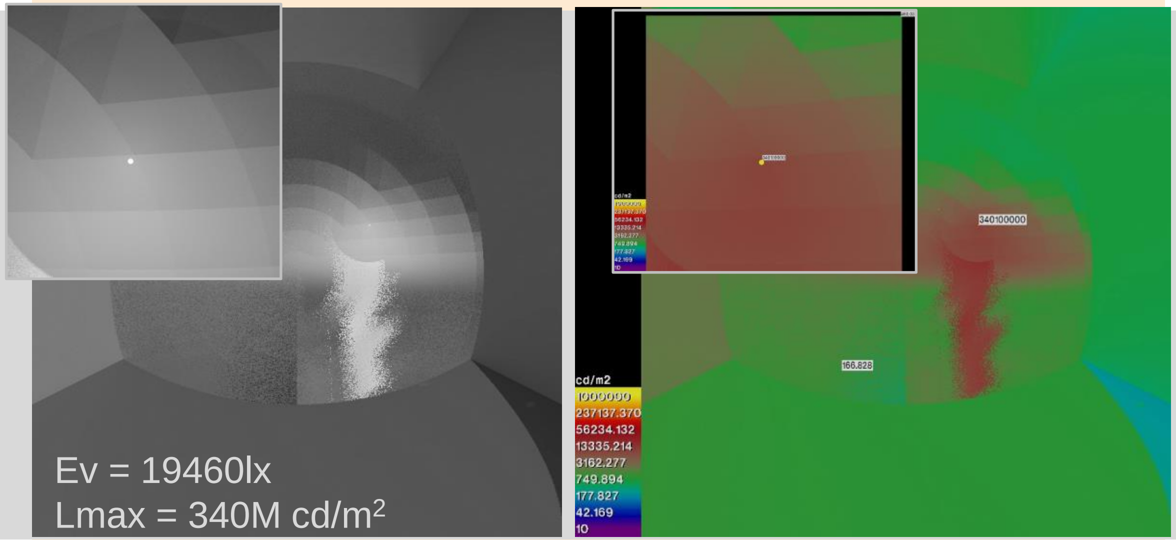
src/rt/m_bsdf.c: v 2.61

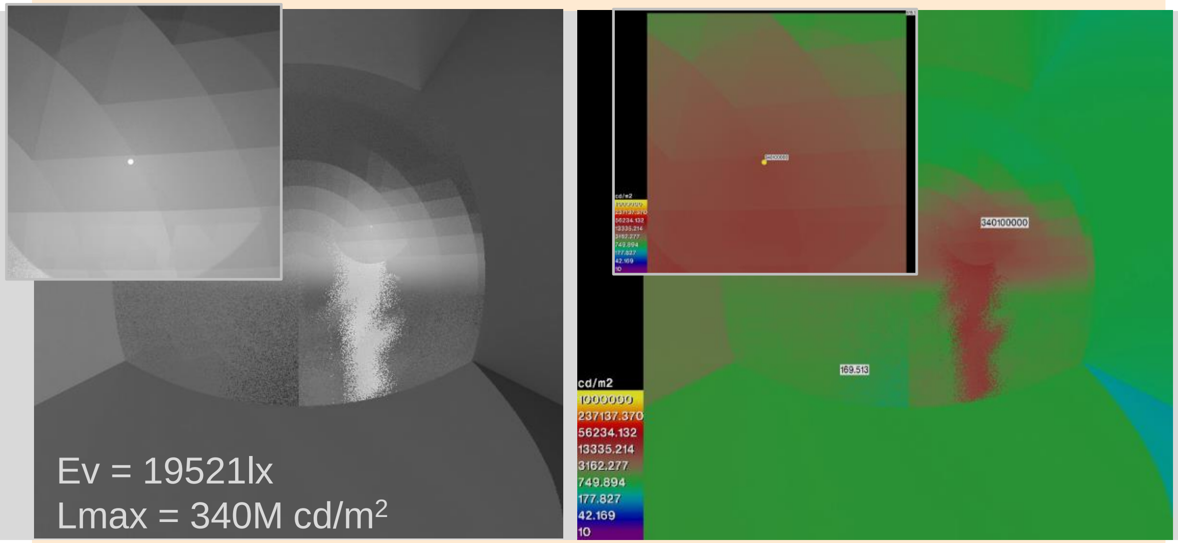
„BSDF": without PE





„aBSDF": with PE



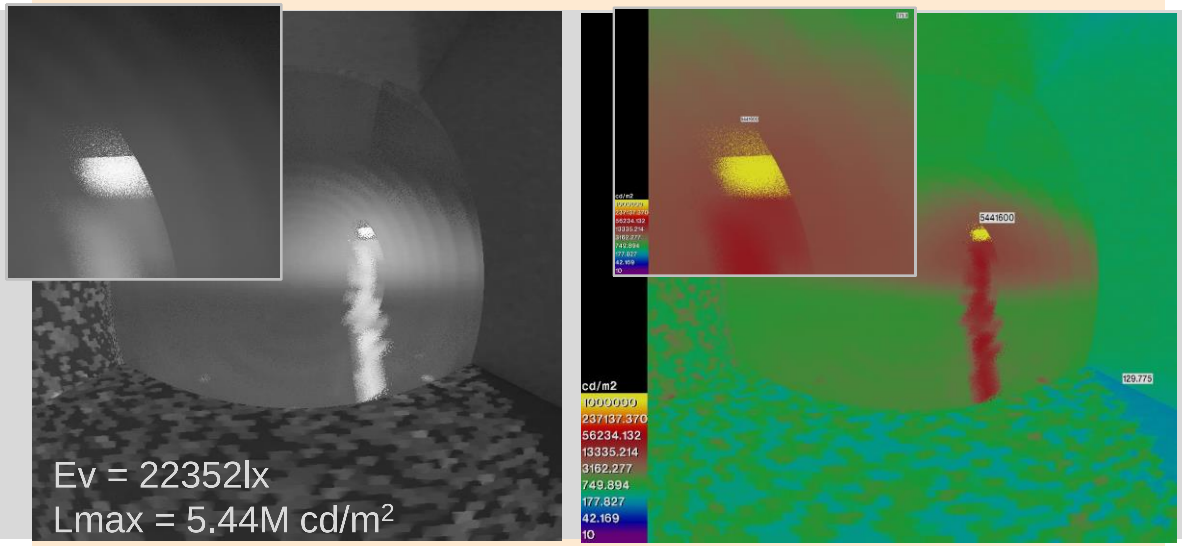


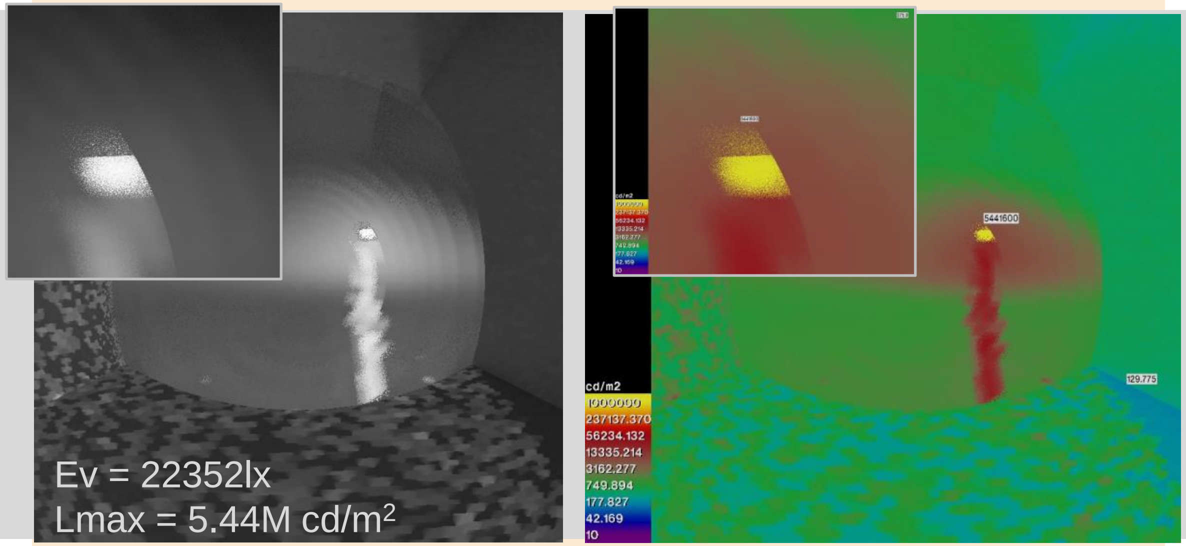
rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

Examples: (ii) Redirecting blinds: BSDF t45

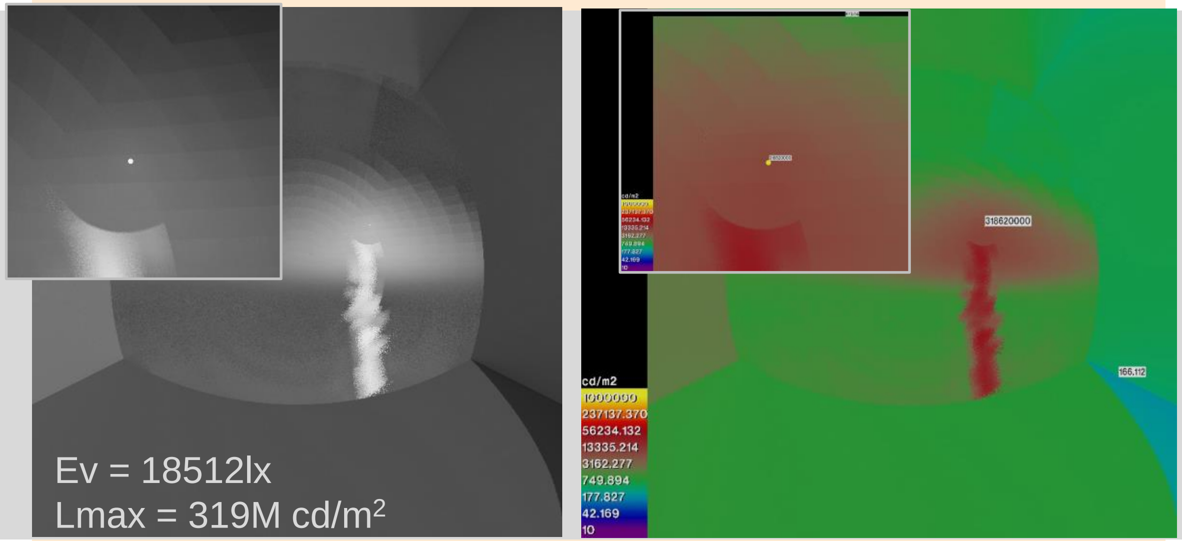
src/rt/m_bsdf.c: v 2.60	src/rt/m_bsdf.c: v 2.61

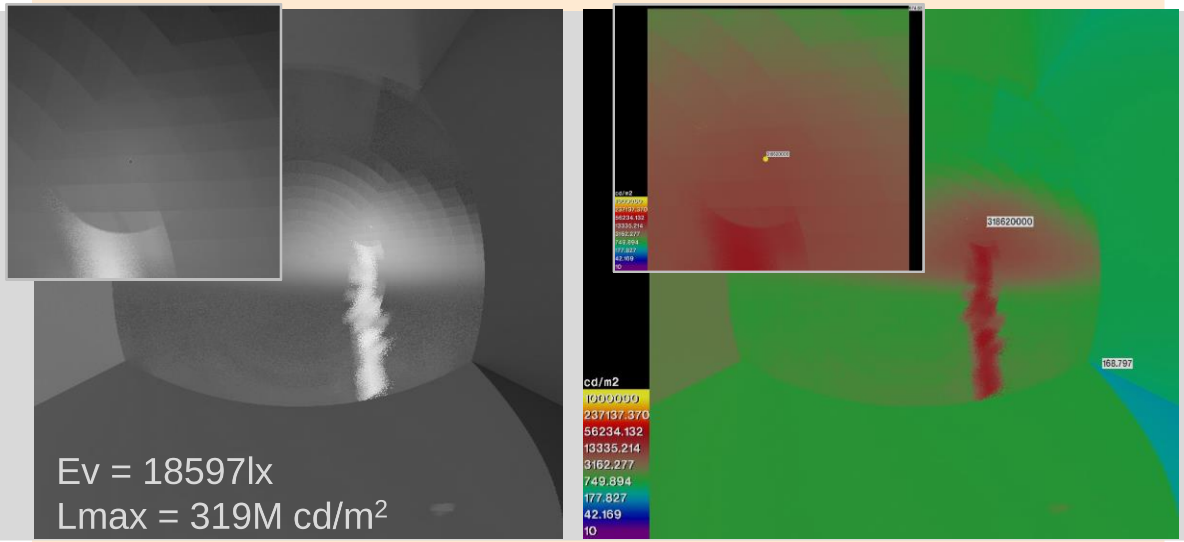
„BSDF“: without PE





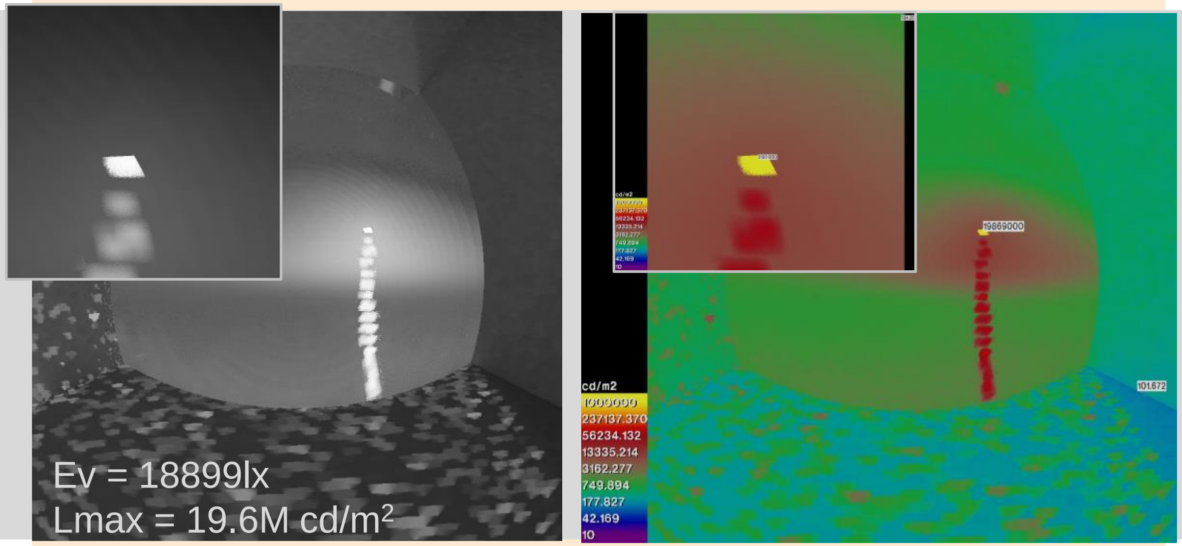
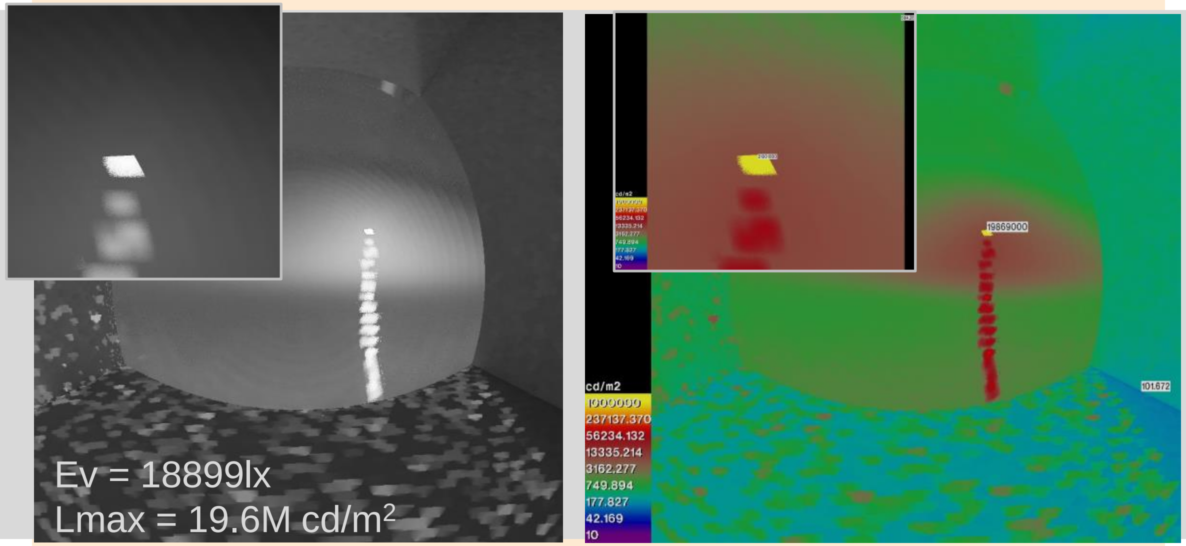
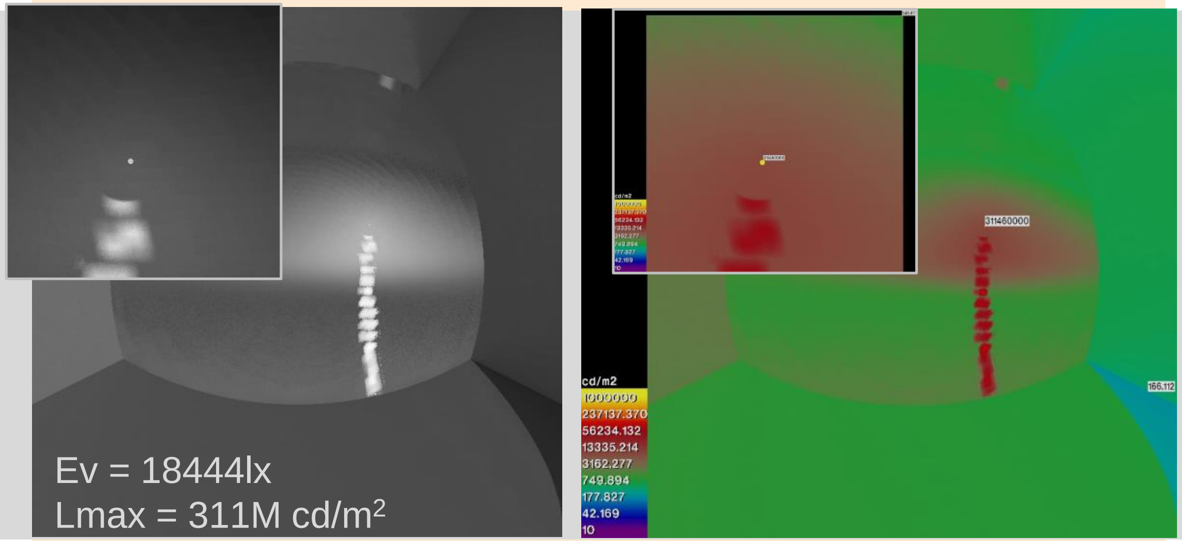
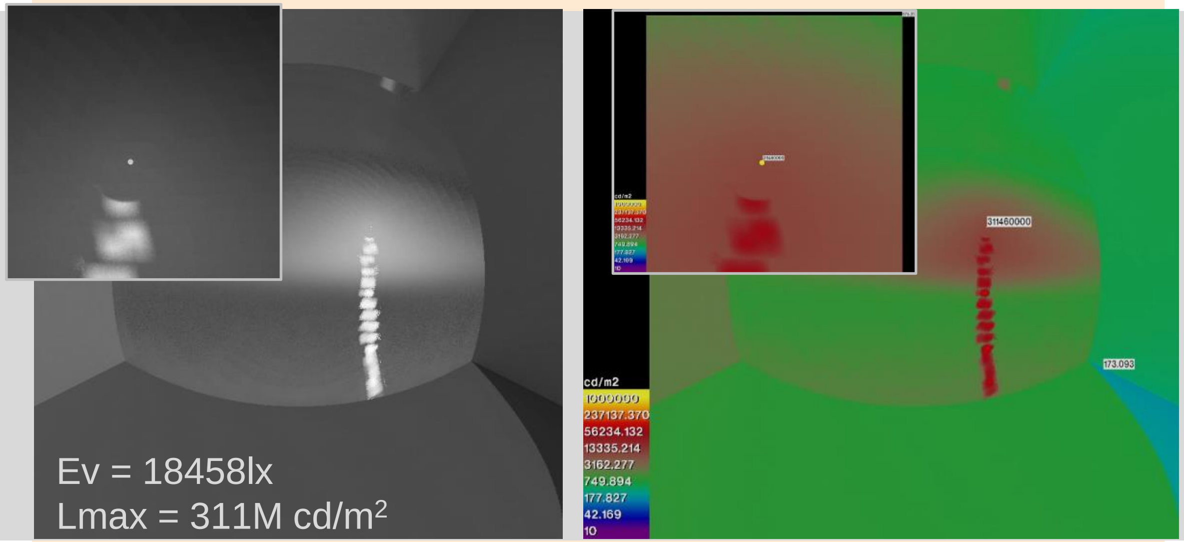
„aBSDF“: with PE





rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

Examples: (ii) Redirecting blinds: BSDF t46

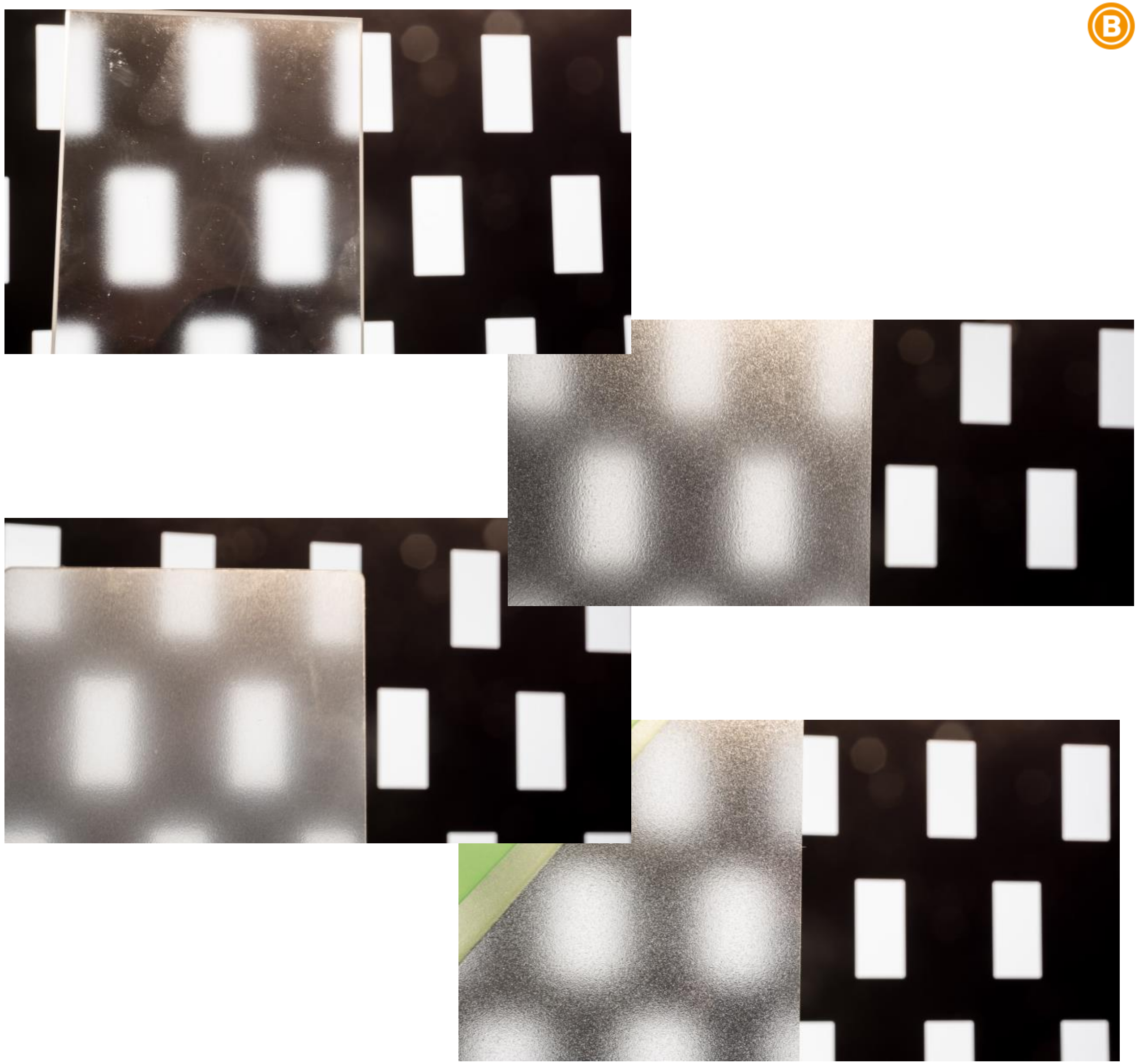
	src/rt/m_bsdf.c: v 2.60	src/rt/m_bsdf.c: v 2.61
„BSDF“: without PE		
„aBSDF“: with PE		

rpict parameters: -ps 1 -pj 0 -ab 2 -aa 0.1 -ad 1024 -ss 64 -dj 0.6

Examples: (iii) Translucent material

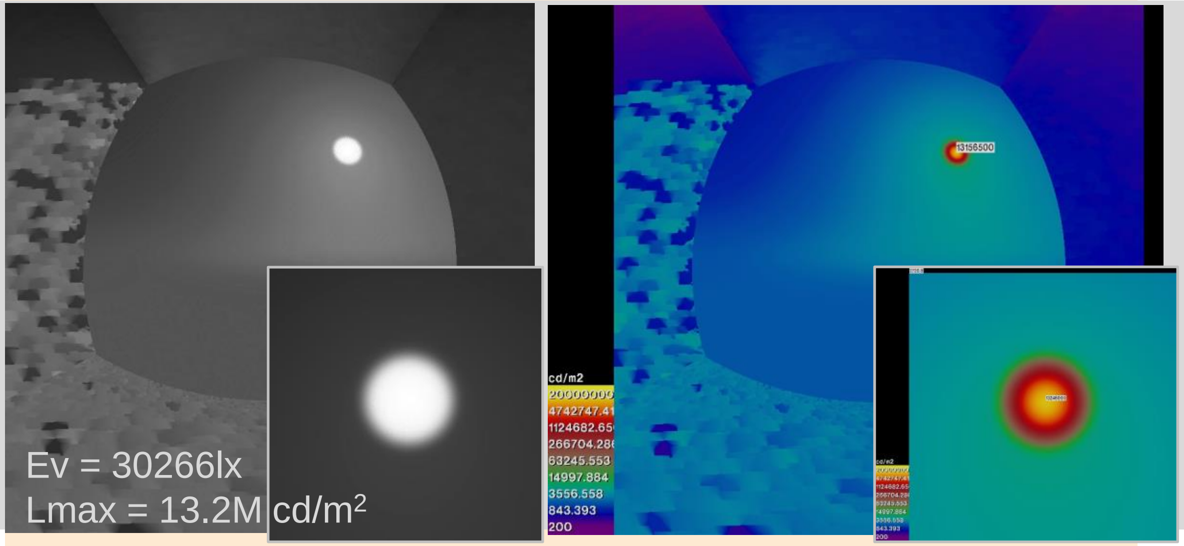
- BSDF generated from Radiance trans material (10° full width tenth max):

```
void trans 2x5deg_tenth
0
0
7 0.5 0.5 0.5 0.0 0.02874 1.0 1.0
```

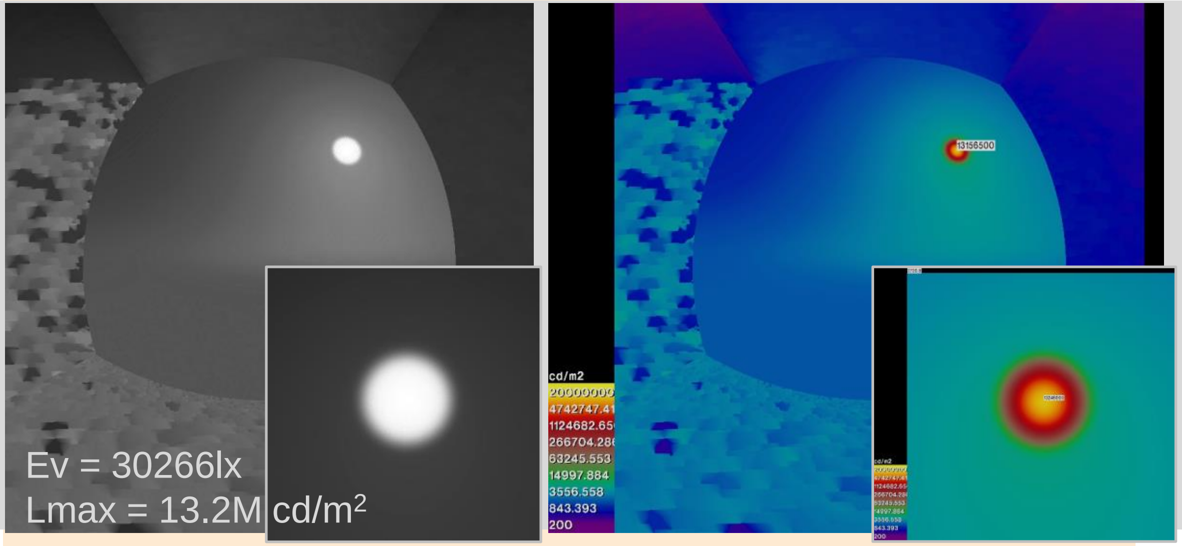


Examples: (iii) Translucent material: ground truth

src/rt/m_bsdf.c: v 2.60



src/rt/m_bsdf.c: v 2.61

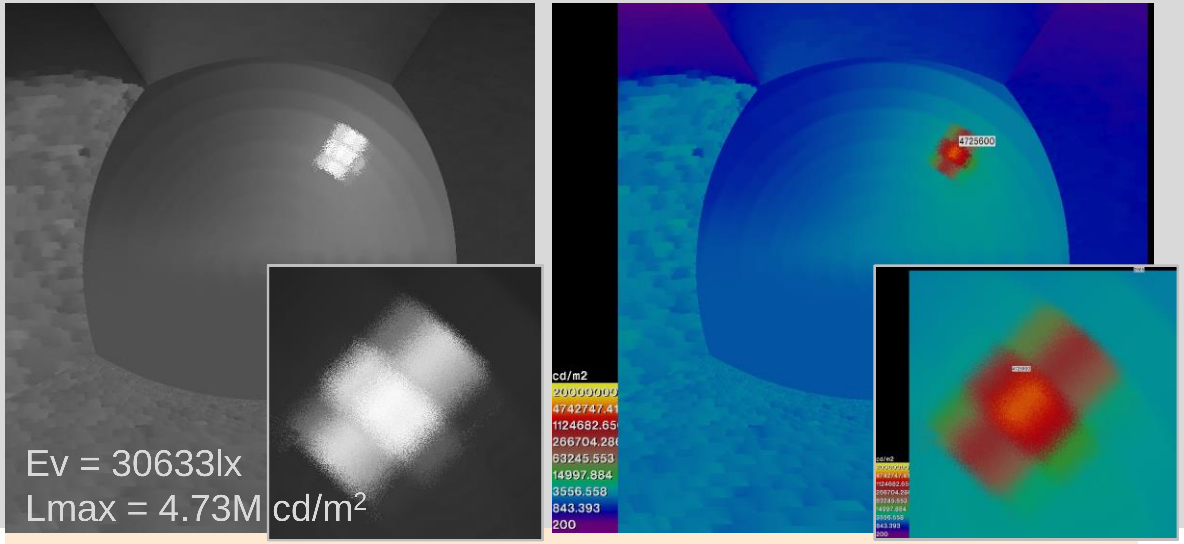


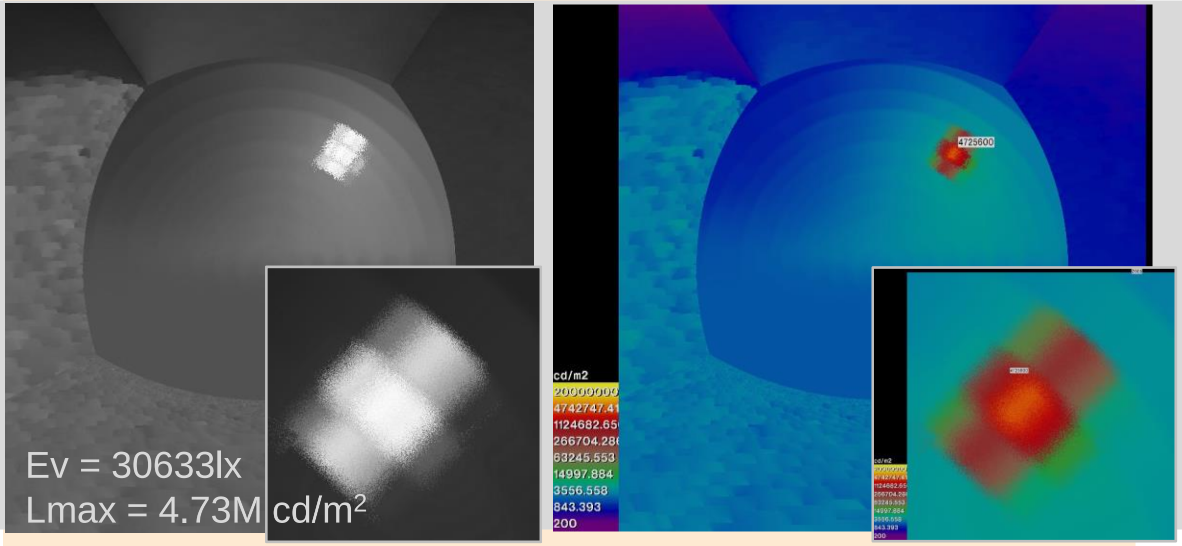
rpict parameters: -ps 1 -pj 0 -ab 2 -ss 64 -dj 0.6

Examples: (iii) Translucent material: BSDF t35

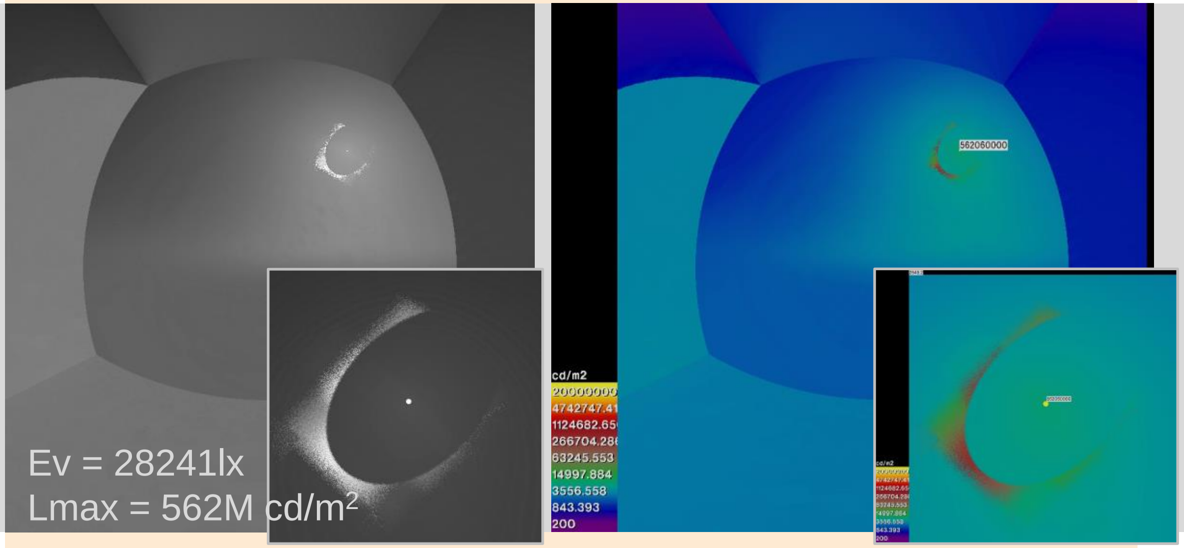
src/rt/m_bsdf.c: v 2.60	src/rt/m_bsdf.c: v 2.61

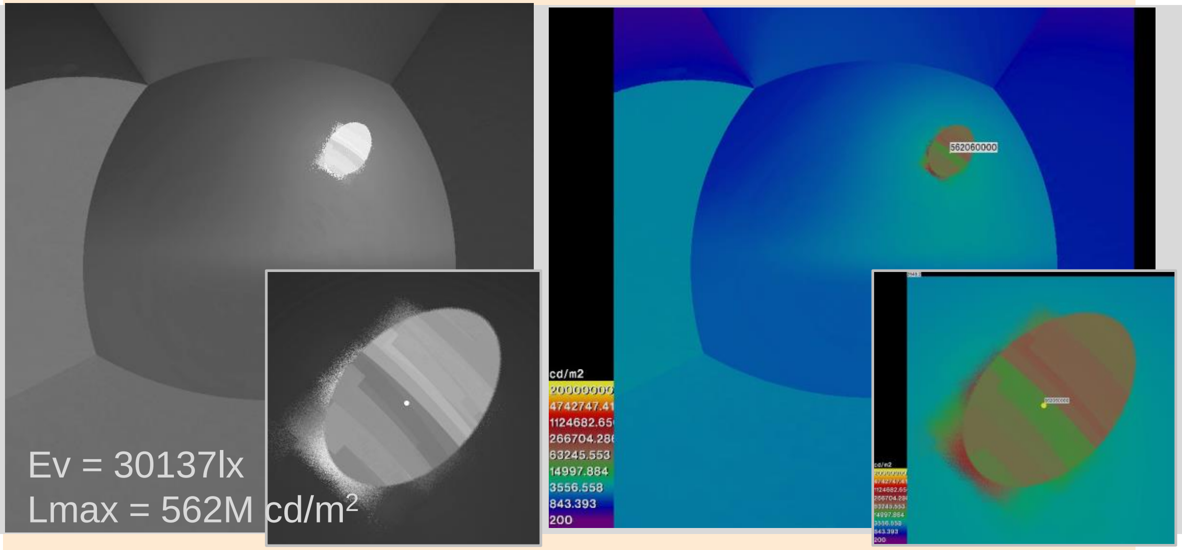
„BSDF“: without PE





„aBSDF“: with PE





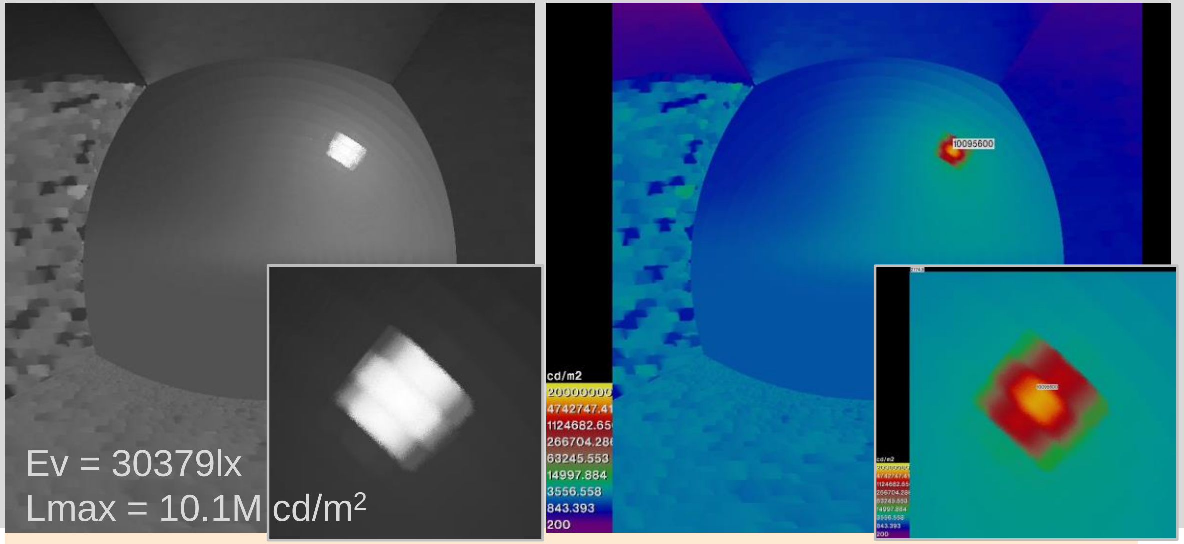
rpict parameters: -ps 1 -pj 0 -ab 2 -ss 64 -dj 0.6

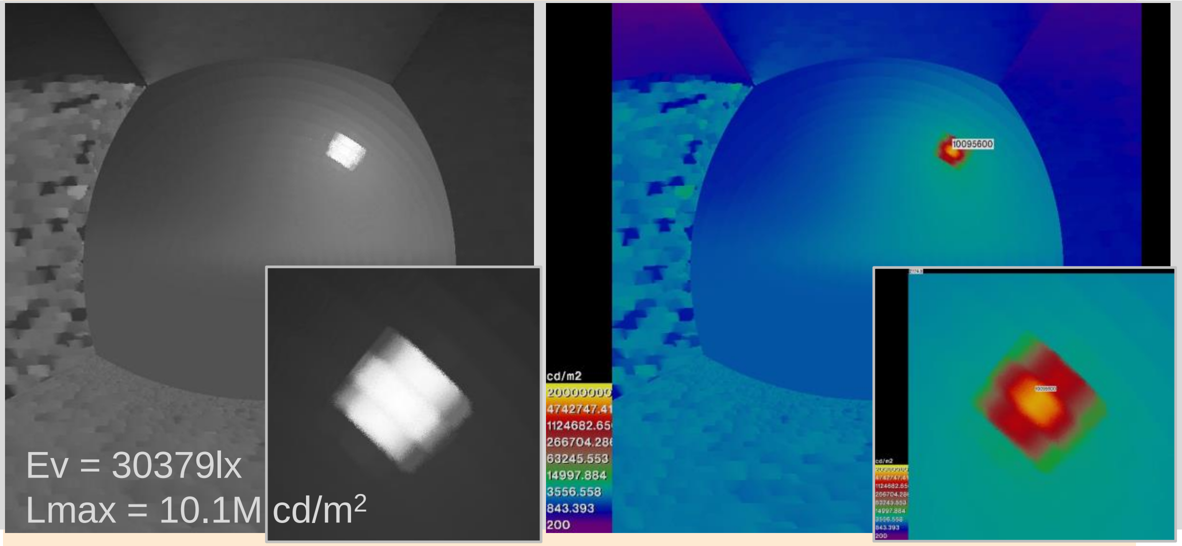
Examples: (iii) Translucent material: BSDF t36

src/rt/m_bsdf.c: v 2.60

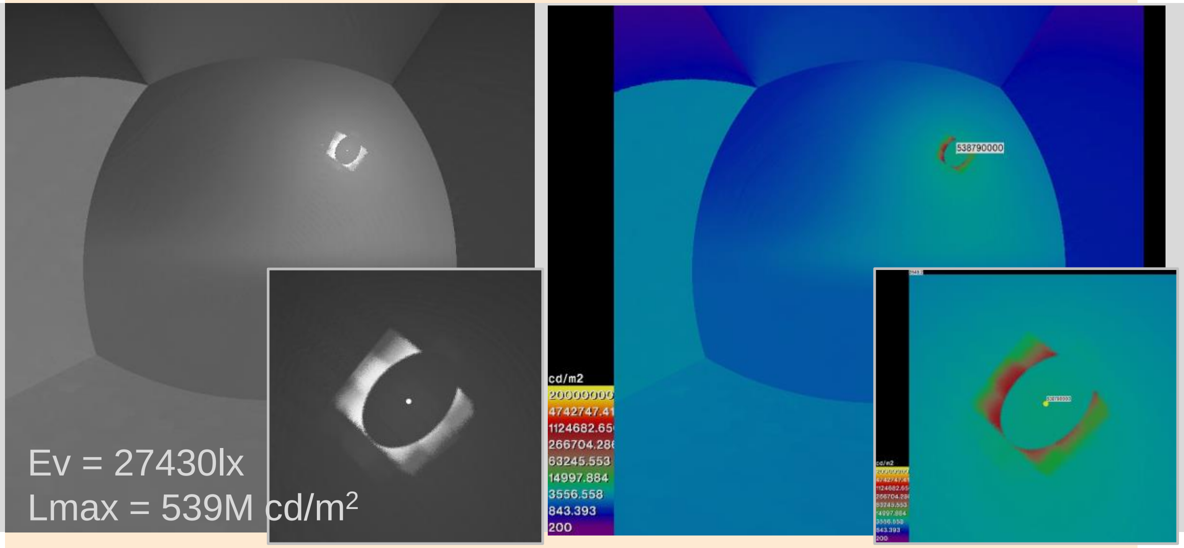
src/rt/m_bsdf.c: v 2.61

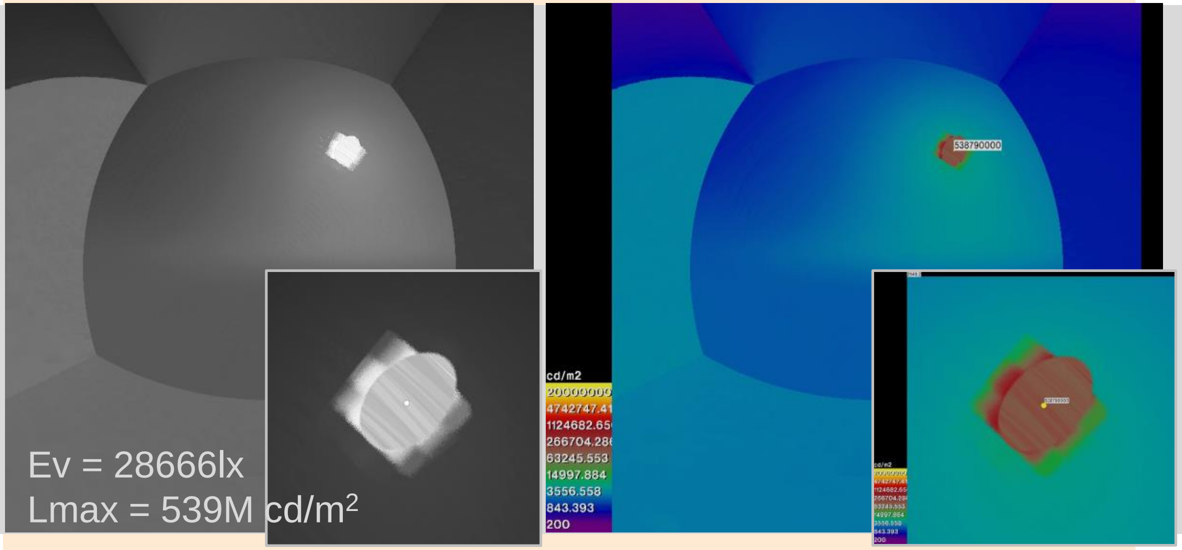
„BSDF“: without PE





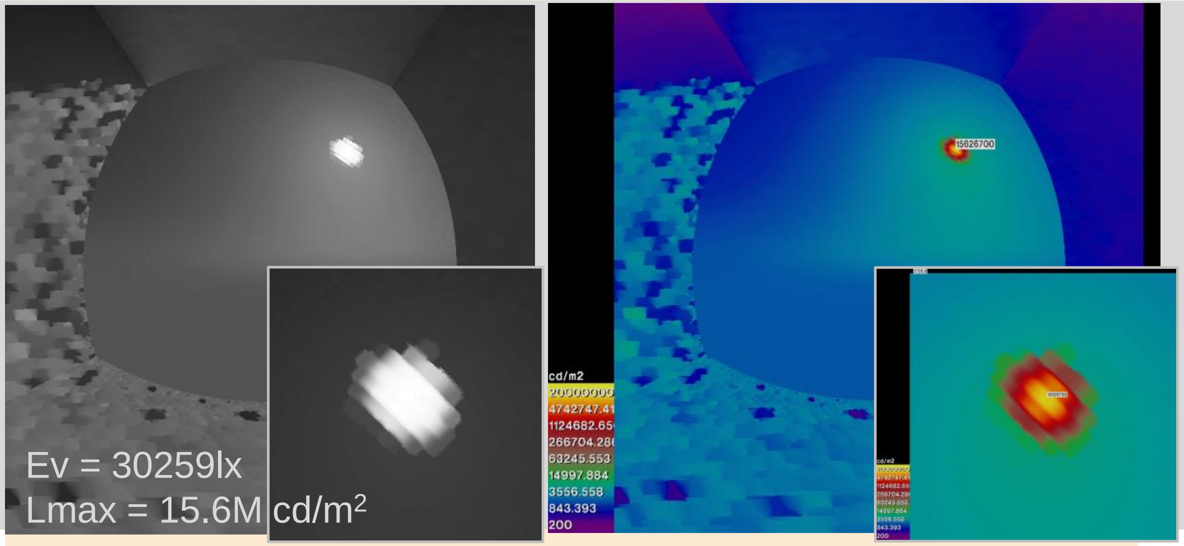
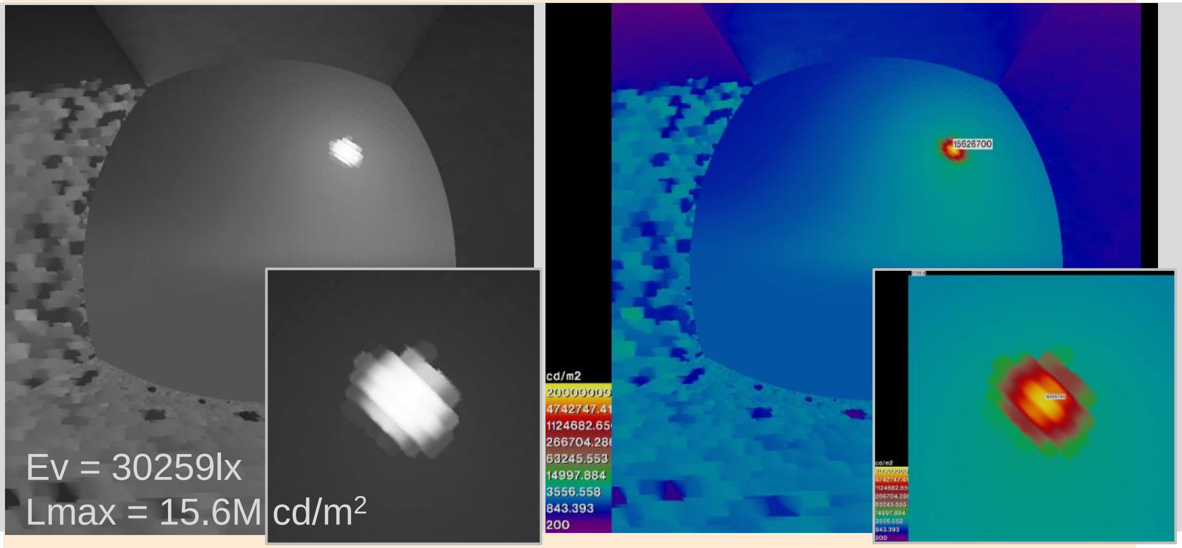
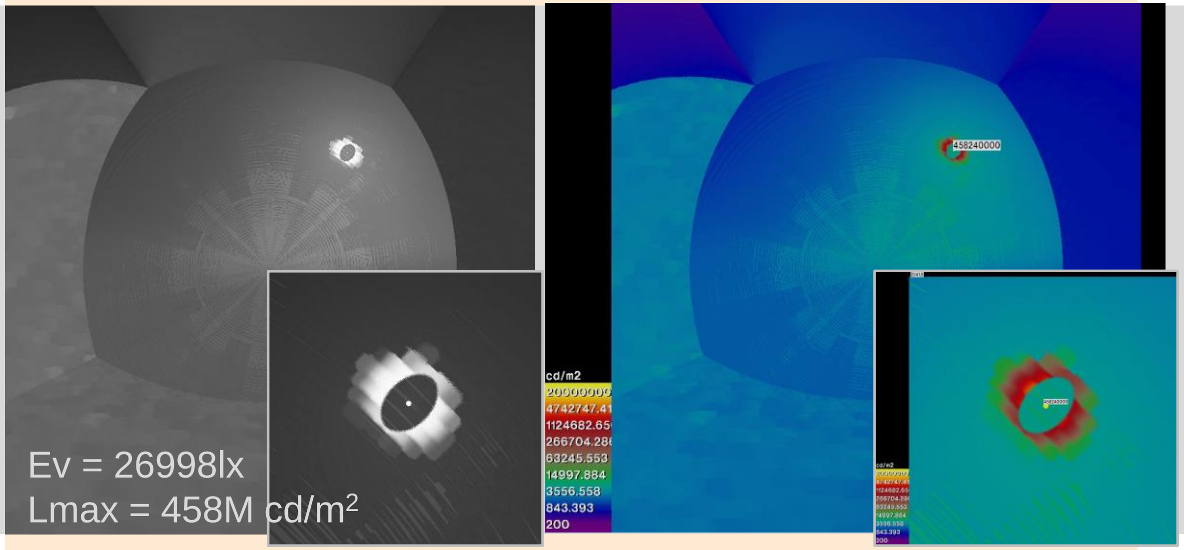
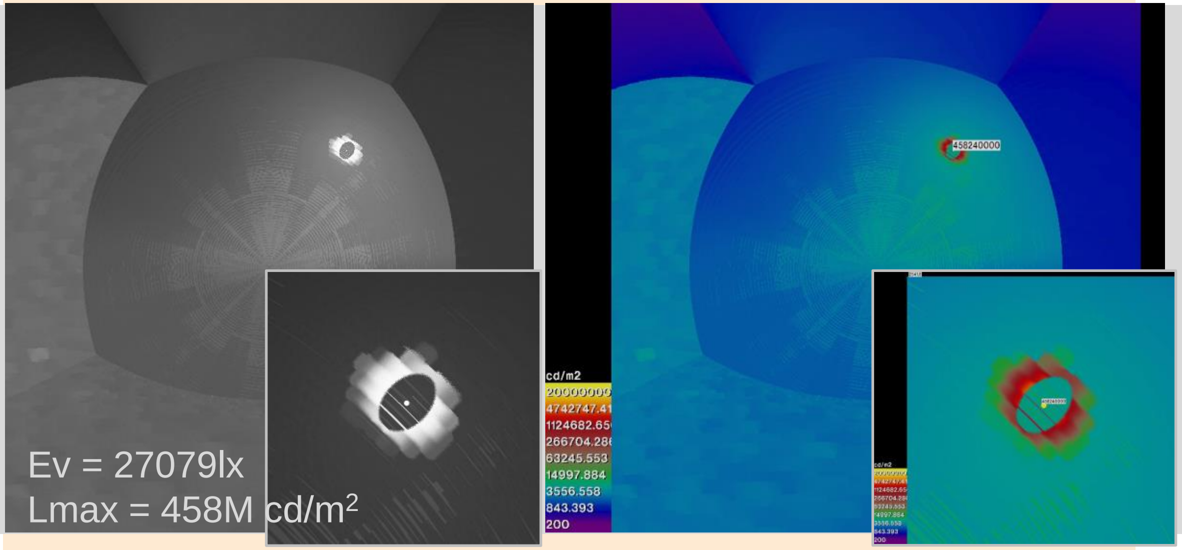
„aBSDF“: with PE



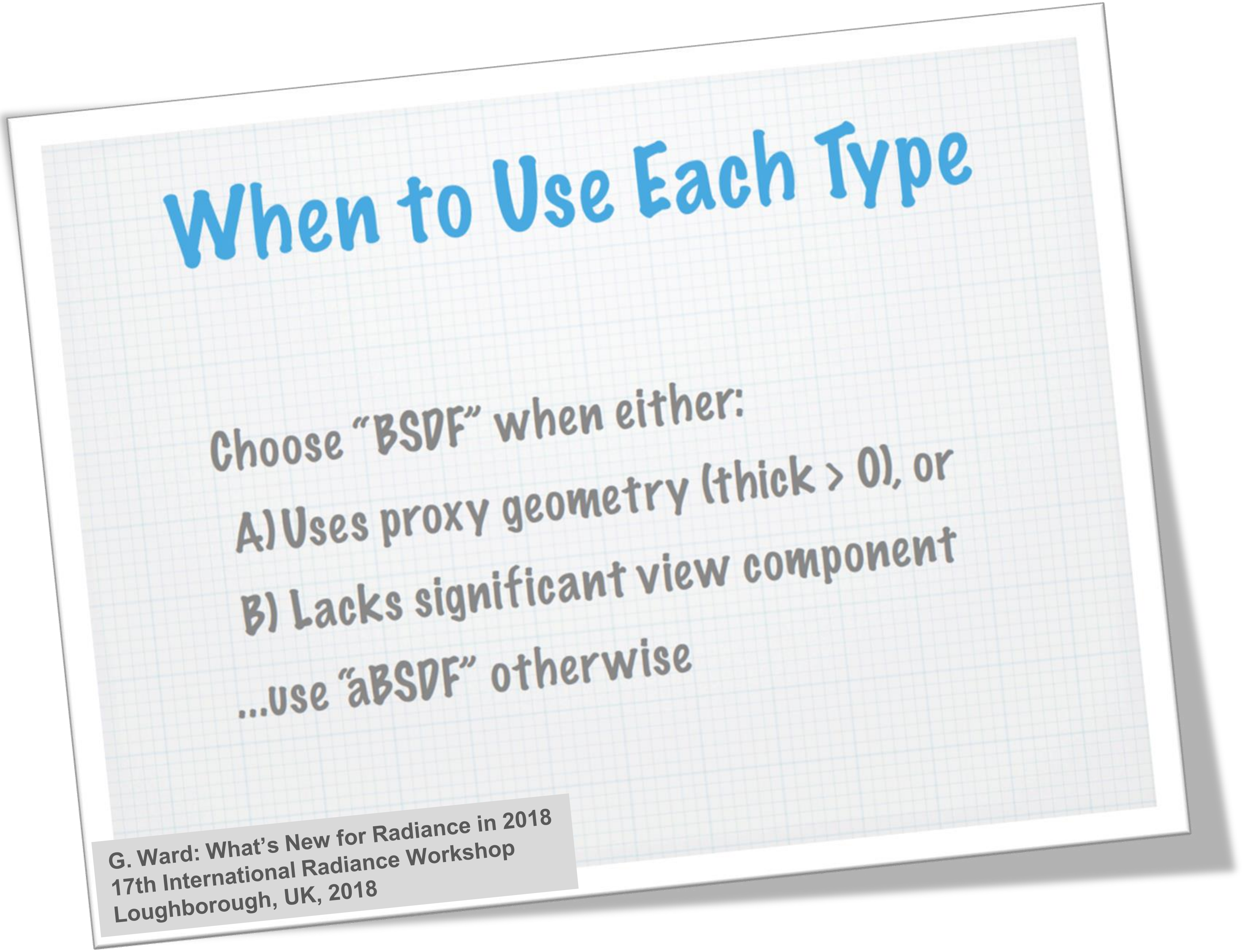


rpict parameters: -ps 1 -pj 0 -ab 2 -ss 64 -dj 0.6

Examples: (iii) Translucent material: BSDF t37

	src/rt/m_bsdf.c: v 2.60	src/rt/m_bsdf.c: v 2.61
„BSDF“: without PE		
„aBSDF“: with PE		

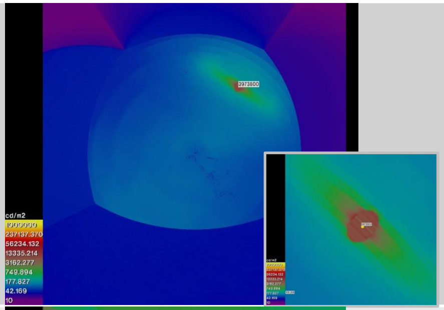
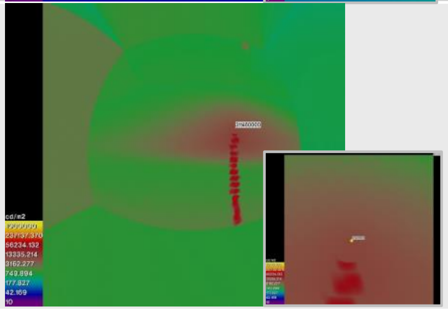
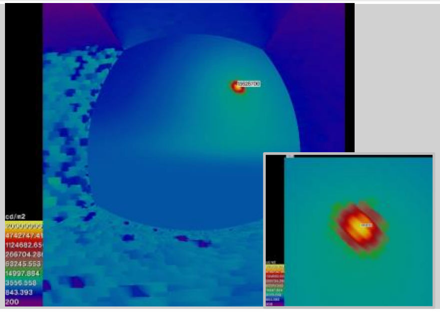
rpict parameters: -ps 1 -pj 0 -ab 2 -ss 64 -dj 0.6



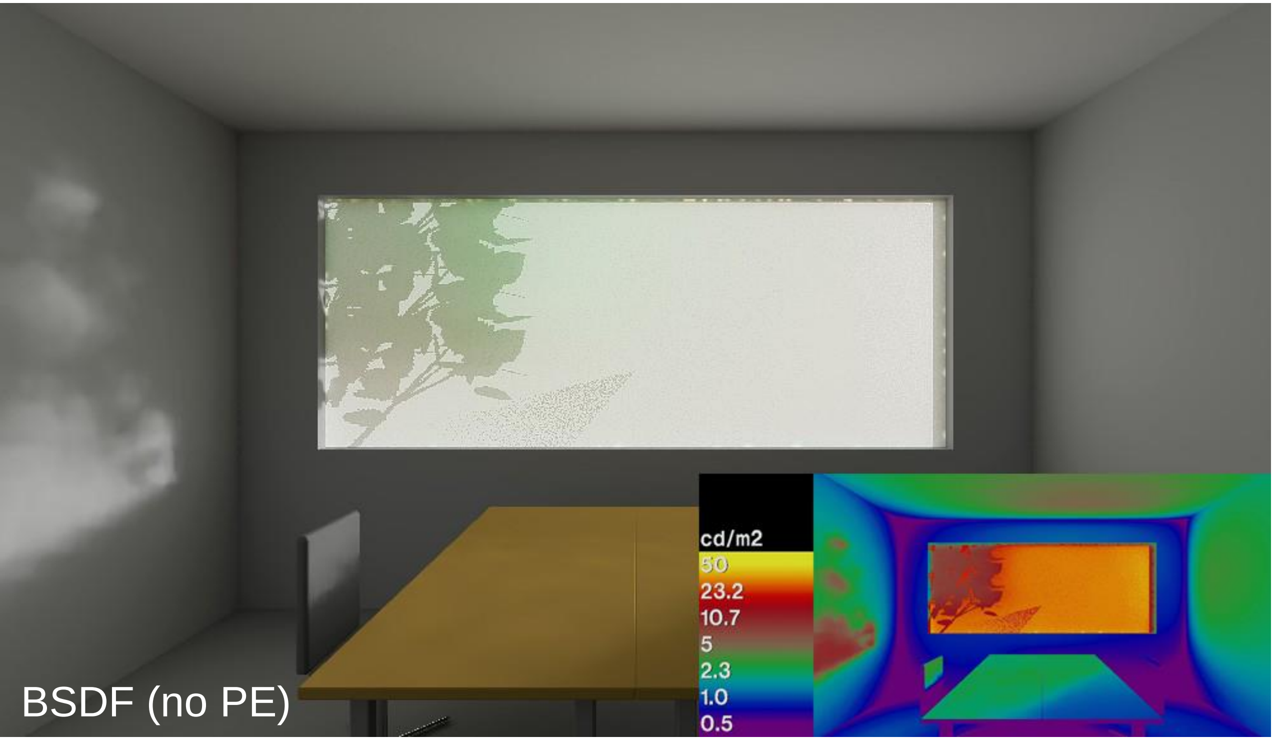
G. Ward: What's New for Radiance in 2018
17th International Radiance Workshop
Loughborough, UK, 2018

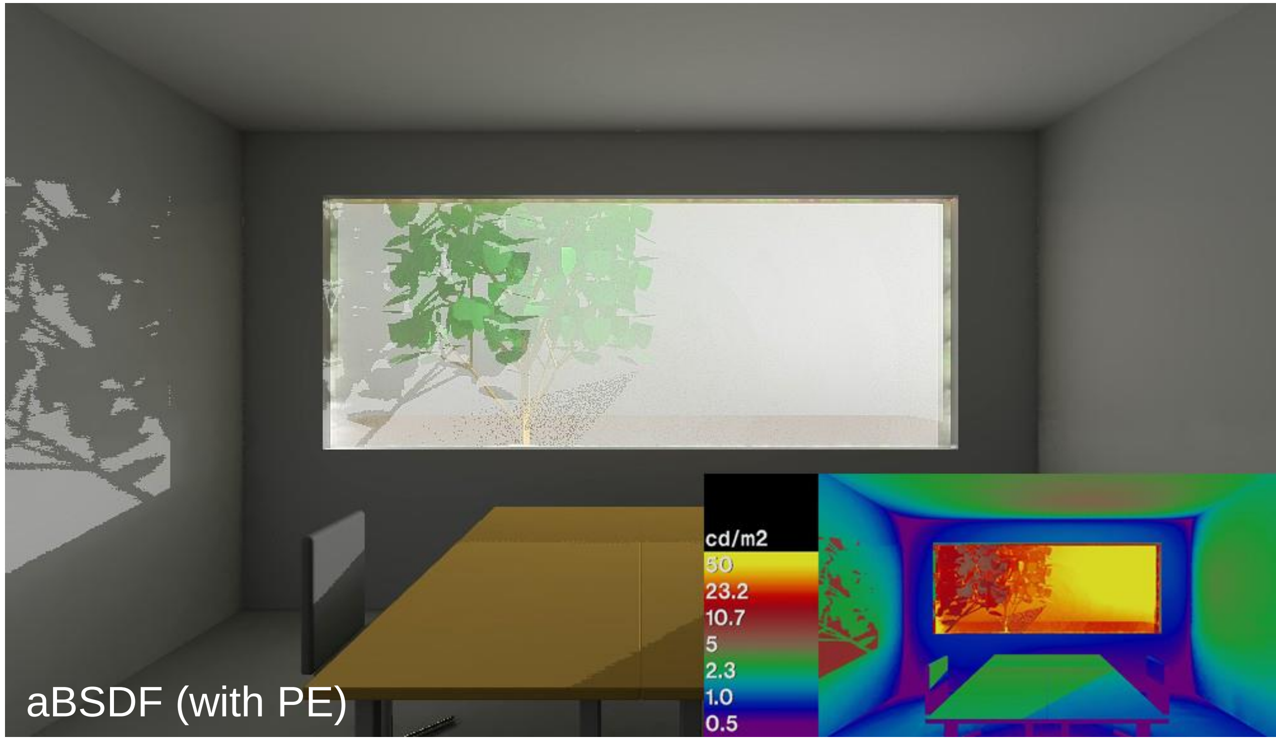
and take care about near-specular scattering (BSDF resolution)!

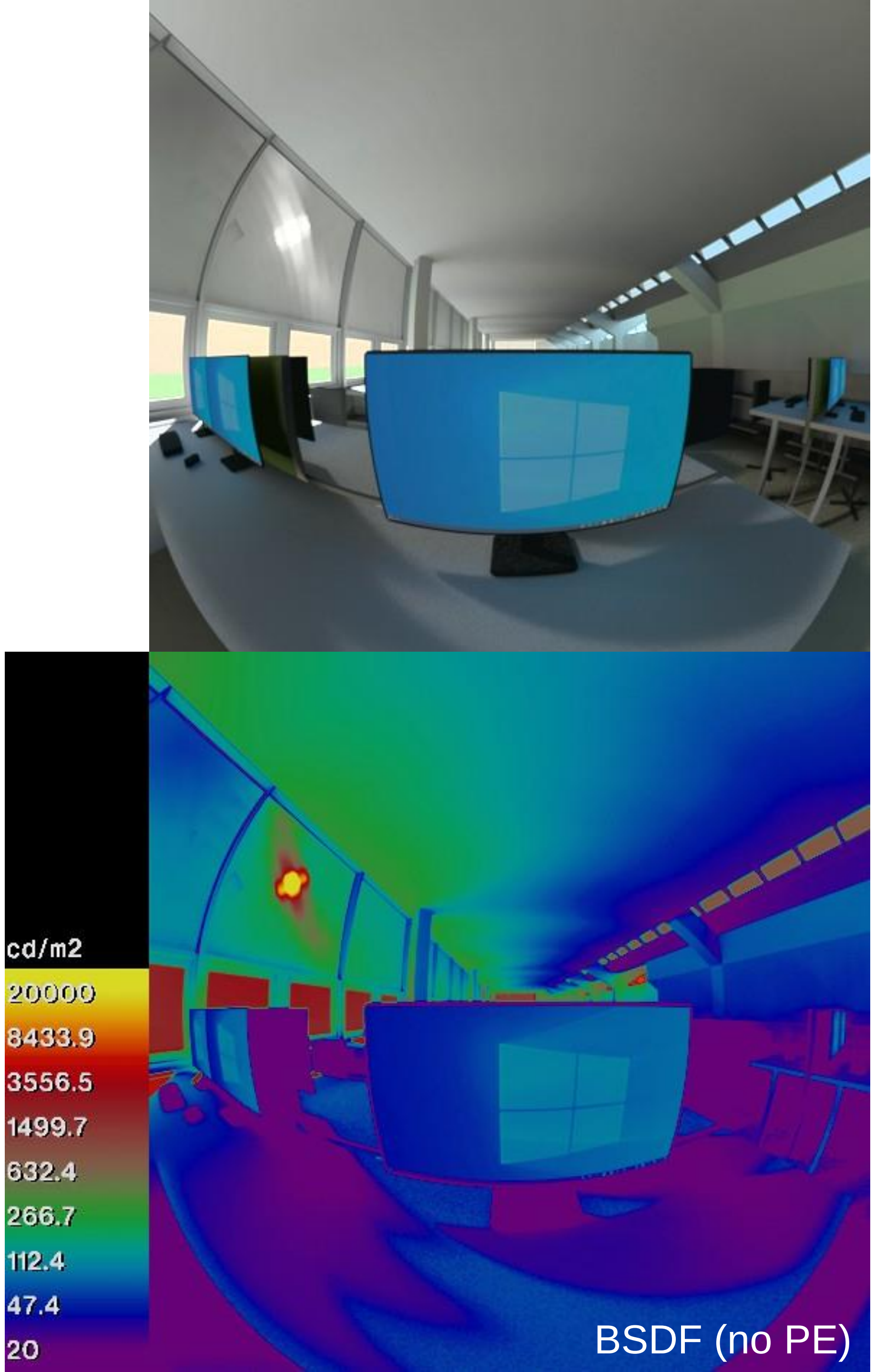
When to use aBSDF or BSDF?

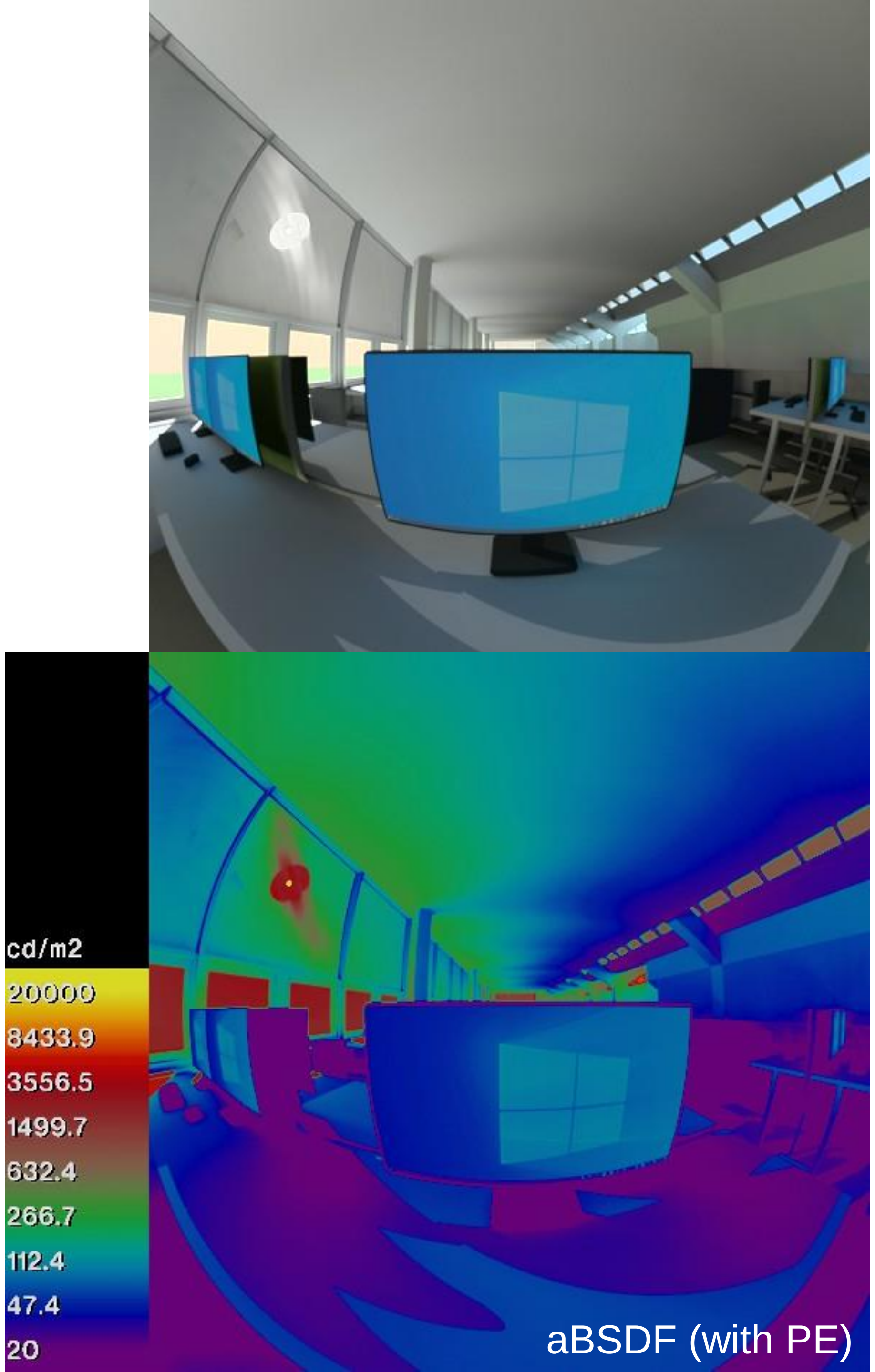
Example		Proposed type	Comments
(i) MechoShade fabric		aBSDF	Choose BSDF resolution adequate for forward scattering portion
(ii) Redirecting blinds		BSDF with proxy geometry	aBSDF does not represent geometric patterns, i.e. averages over area – can be ok for small geometry
(iii) Translucent material		BSDF	Choose BSDF resolution to resolve scattering distribution

Rendering examples






cd/m2
20000
8433.9
3556.5
1499.7
632.4
266.7
112.4
47.4
20
BSDF (no PE)


cd/m2
20000
8433.9
3556.5
1499.7
632.4
266.7
112.4
47.4
20
aBSDF (with PE)

BS2021 paper

- https://bs2021.org/

Peak extraction in daylight simulations using BSDF data

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[2]Anyhere Software, Berkeley, California, USA
[3]Lawrence Berkeley National Laboratory, Berkeley, California, USA

Abstract

Bidirectional scattering distribution function (BSDF) data are used in design practice to represent optically complex daylighting and solar control systems in lighting and energy simulation software. Visual comfort assessments (e.g., daylight glare) require accurate determination of luminance and corresponding solid angle of glare sources. For the sun, the necessary resolution of the BSDF causes problems both in terms of data volume and computational effort. With "peak extraction" (PE), we present a new method that simulates the direct solar contribution at its real size and spread, while efficiently using the underlying BSDF data set for the scattered light. PE enables practitioners to evaluate daylight performance metrics for their designs at improved accuracy.

Key Innovations

- Novel peak extraction method to extract direct transmission from daylighting and solar control system BSDF data
- Improved accuracy of glare calculations (e.g., DGP) and daylight renderings (shadow patterns)

Practical Implications

The PE algorithm presented in this study provides practitioners with a method of simulating daylighting systems at higher accuracy and efficiency. It is suited for systems with a view component such as typical fabrics with some openness which are widely used as glare protection devices. It can also be applied for Venetian blinds, but the use of proxy geometry is preferred here to allow also the characteristic striped shadow pattern. The method should not be applied to systems that do not have a direct, "see-through" component.

Introduction

Over the past years, tools and processes have been developed to accurately characterize and simulate the performance of optically complex daylighting and solar control systems in buildings using BSDF data (Nicodemus et al., 1977; IEA, 1999; Ward et al., 2011). BSDFs describe how light from each incident direction is scattered (reflected and transmitted) by a simple or composite surface, such as a window shade. BRDFs (R for reflectance) describe surface properties of opaque materials (that e.g. can make up a shading system such as slats of a Venetian blind). BTDFs (T for transmittance) describe properties of transmissive materials and systems (e.g., translucent panels or acid etched lamellas). Both reflectance and transmittance scattering properties are included in BSDFs.

BSDF data can be generated using parametric or data-driven models. Parametric or analytical BSDF models are widely used in computer graphics. As examples, a clear glazing or an ideal mirror are described by Dirac delta functions defining the transmittance or reflectance for the direct transmitted or mirrored direction, respectively, and zero elsewhere. Examples for scattering models include the Phong model (Phong, 1975), Cook-Torrance model (Cook and Torrance, 1981), and Ward-Geisler-Moroder-Dür model (Geisler-Moroder and Dür, 2010). These analytical models are widely used for generic material descriptions in simulations, but their assumptions must be reviewed if applied to façade systems that differ from those initially considered. Data-driven models are based on measured angularly-resolved data of real-world materials and systems. A detailed description on how to generate BSDFs from these measurement data is given by Ward et al. (2014), Lee et al. (2018), and Geisler-Moroder and Lee (2021).

Tabulated BSDFs are derived from BSDF models, i.e., BSDF data described by a discrete set of values for a defined number and set of directions (Ward et al., 2021). Various angular basis representations for tabulated BSDFs have been defined for different simulation purposes (Geisler-Moroder and Lee, 2021). The resolution of tabulated BSDF data needs to match the optical properties of the represented system and the respective application.

While low resolution BSDF data is likely sufficient for calculations of daylight autonomy based on hourly illuminance, high resolution BSDF data are needed to represent the direct solar component for calculations of discomfort glare and other metrics requiring granular spatial modeling of sunlight, especially for systems that allow specular transmission or reflection, e.g., for fabrics with openness, blinds, or (mirror) louvers (Ward and McNeil, 2011; McNeil, 2011; Ward et al., 2012; Geisler-Moroder et al., 2017; Lee et al., 2018; Grobe, 2019). Sunlight, whether transmitted, scattered, or reflected, needs to be predicted at highest accuracy due to its high

1

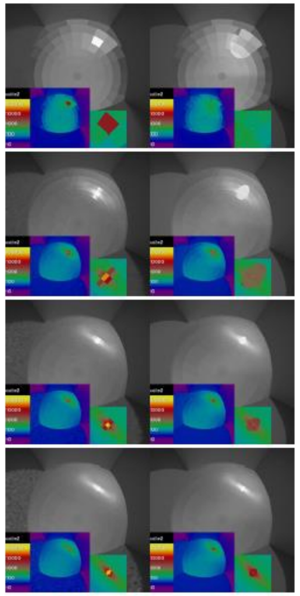


Figure 7: Test room renderings for Klems 145x145 (upper row) and tensor tree bases with resolution: 1024x1024 (second row), 4096x4096 (third row), and 16384x16384 (lower row) for a fabric shade at the façade with PE (right column) and without PE (left column).

...nce and DGP values ...lerings in Figure 7 using different BSDF resolutions with and without PE.

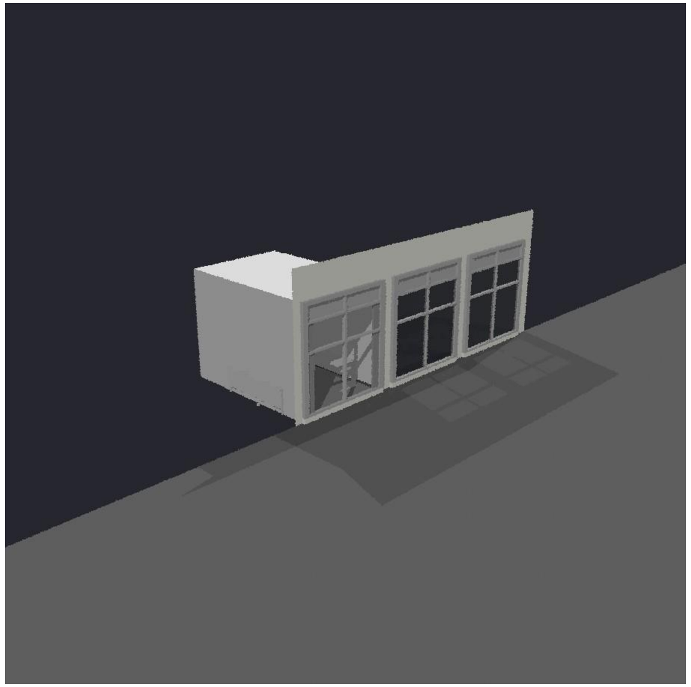
BSDF resolution	Without PE Ev	Without PE DGP	With PE Ev	With PE DGP
Klems:				
145x145	388lx	0.191	389lx	0.389
Tensor tree:				
max. 1024x1024	444lx	0.222	433lx	0.415
max. 4096x4096	440lx	0.267	439lx	0.418
max. 16384x16384	441lx	0.276	430lx	0.409

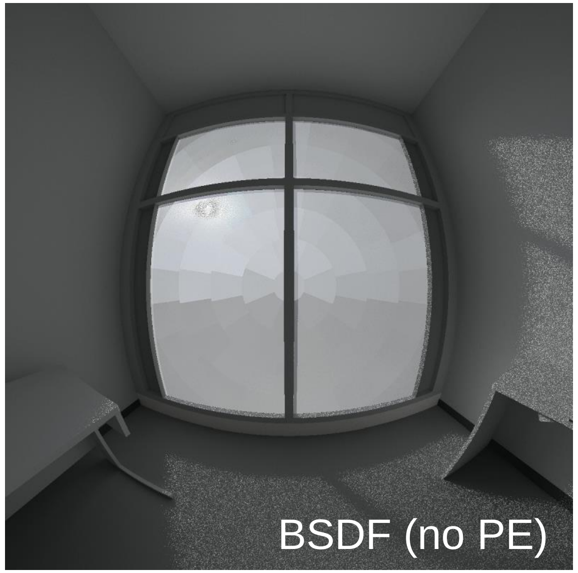
Discussion

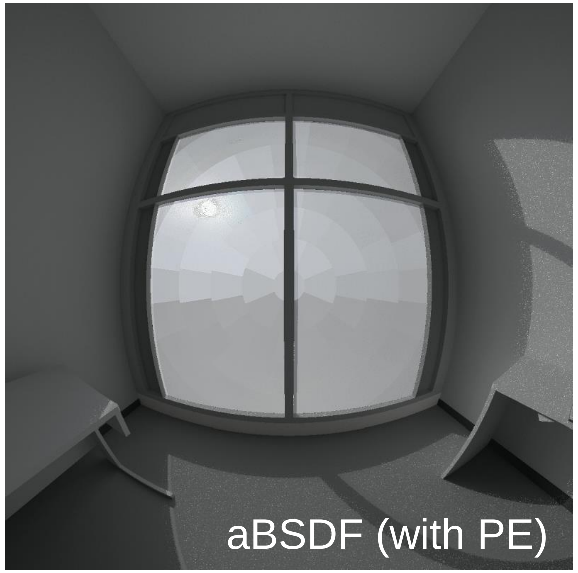
The current implementation of the PE algorithm is limited to direct-through contributions, which is often the most critical peak contribution for luminance-based daylight performance metrics, especially for glare evaluations. However, if off-specular and upward-reflected peaks are expected, the method of photon mapping with high-resolution BSDFs (Grobe, 2019a) is recommended. Photon mapping adds the benefits of forward raytracing for small and high intensity light sources (e.g., the sun) to the general backward raytracing functionality and thus allows one to simulate reflected

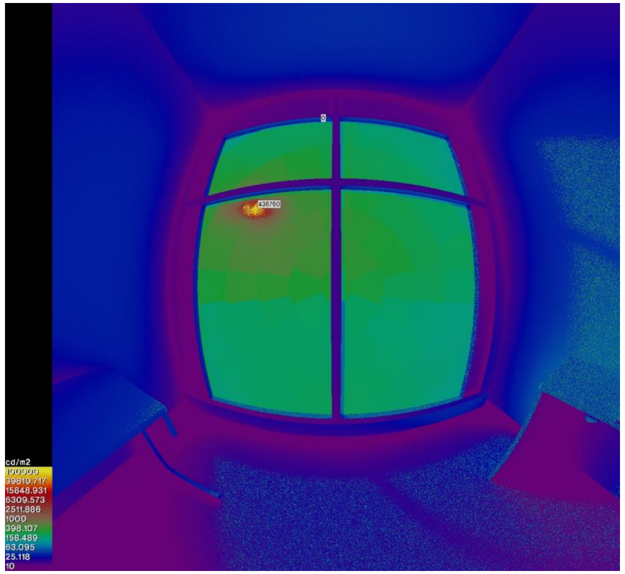
5

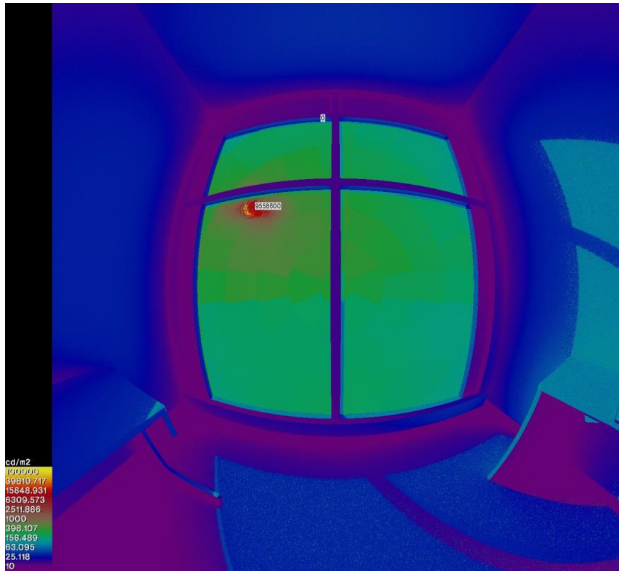
Effect of peak extraction on results (work in progress)







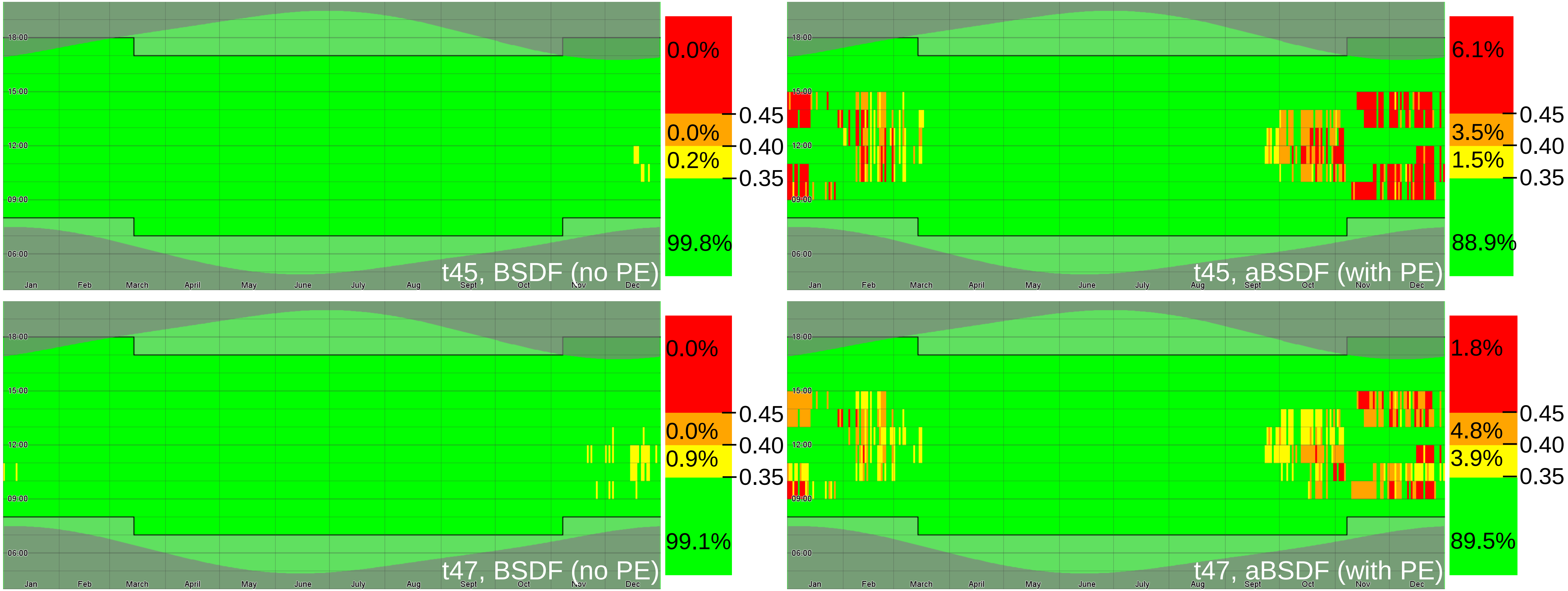


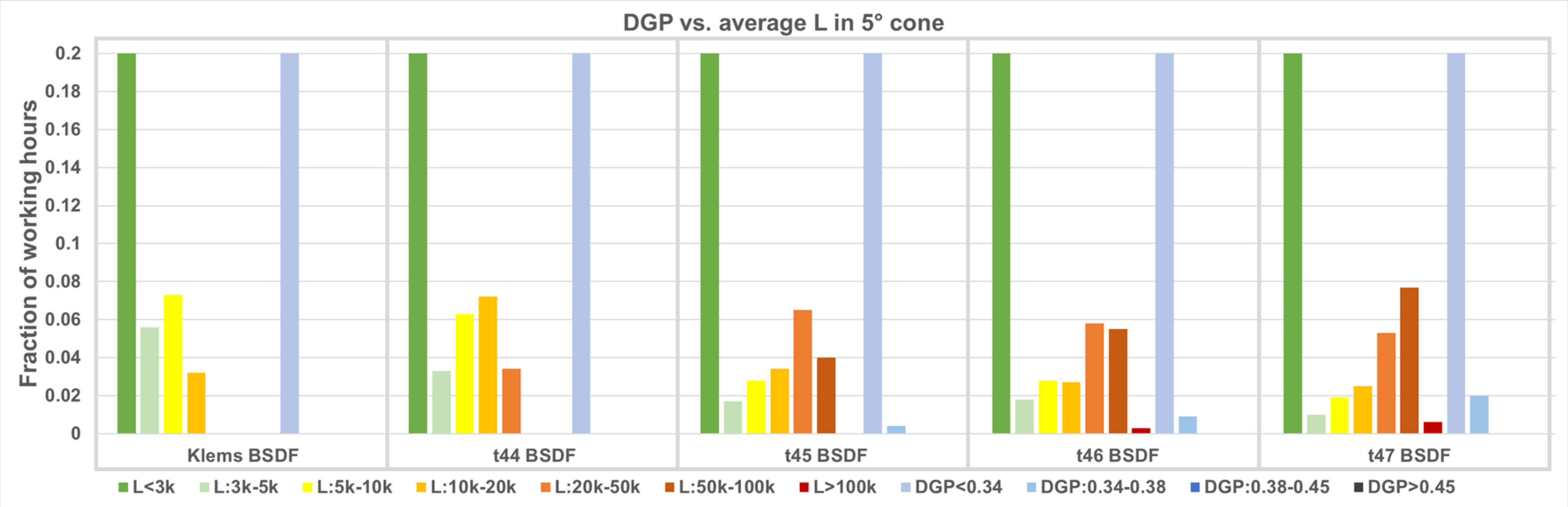


Effect of peak extraction on results (work in progress)

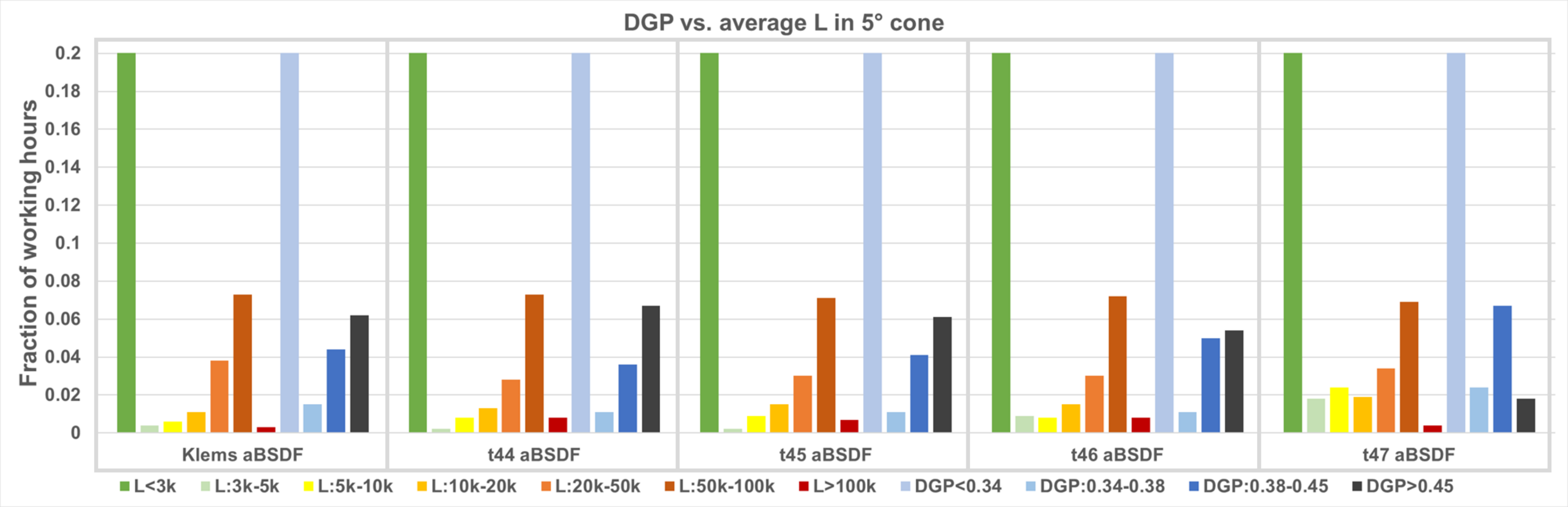
Daylight Glare Probability (DGP)

EN17037 limit: DGP above 0.45
for max. 5% of working hours





DGP vs. average L in 5° cone
Fraction of working hours
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Klems BSDF
t44 BSDF
t45 BSDF
t46 BSDF
t47 BSDF
L<3k
L:3k-5k
L:5k-10k
L:10k-20k
L:20k-50k
L:50k-100k
L>100k
DGP<0.34
DGP:0.34-0.38
DGP:0.38-0.45
DGP>0.45



DGP vs. average L in 5° cone
Fraction of working hours
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Klems aBSDF
t44 aBSDF
t45 aBSDF
t46 aBSDF
t47 aBSDF
L<3k
L:3k-5k
L:5k-10k
L:10k-20k
L:20k-50k
L:50k-100k
L>100k
DGP<0.34
DGP:0.34-0.38
DGP:0.38-0.45
DGP>0.45

IEA SHC Task 61 / EBC Annex 77

Integrated solutions for daylight and electric lighting

From component to user centered system efficiency

Operating Agent: J. de Boer, Germany

Subtask A

B. Matusiak, Norway

User Perspective, Requirements

Subtask B

M. Fontoynont, Denmark

Integration and optimization of daylight and electric lighting

Subtask C

D. Geisler-Moroder, Austria

Design support for practioners

(Tools, Standards, Guidelines)

Subtask D

N. Gentile, Sweden

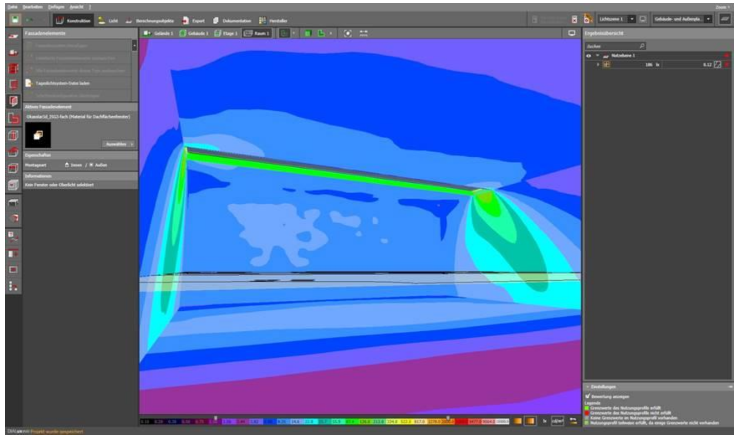
W. Osterhaus, Denmark

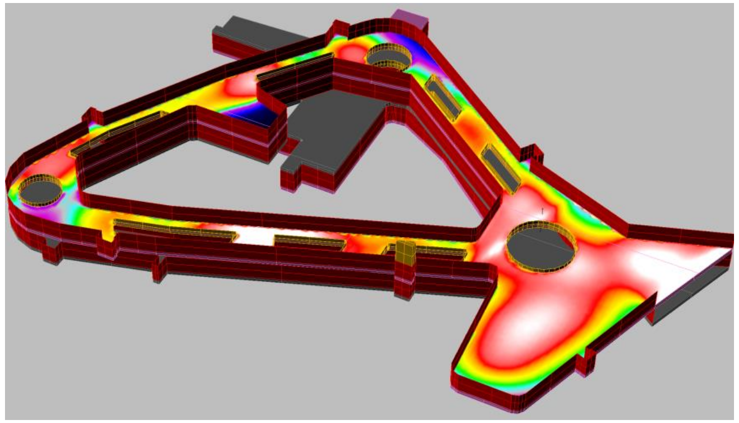
Lab and field study performance tracking

Joint Working Group

- Evaluation method for integrated lighting solutions
- Virtual reality (VR) based Decision Guide

Subtask C: Design Support for Practitioners





Objective

Focus on the application of technical innovations in the field of integrated lighting solutions in practitioners’ workflows. Bring findings onto the desktops of designers by integration into widely used software tools, standards and codes, and design guidelines.

C.1 Review of state of the art design workflows

C.2 Standardization of BSDF daylight system characterization

C.3 Spectral sky models for advanced daylight simulations

C.4 Hourly rating method for integrated solutions

BSDF generation procedures: white paper

White paper available at

https://task61.iea-shc.org/publications

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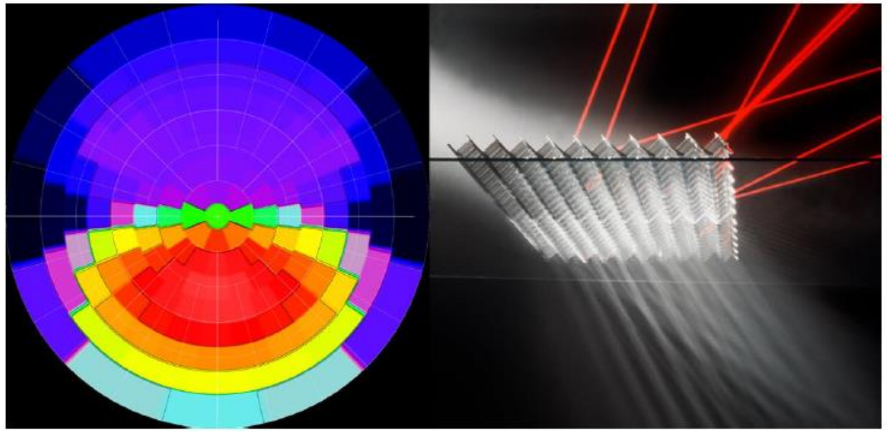
SHC
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

BSDF generation procedures for daylighting systems

White paper



IEA SHC Task 61 / EBC Annex 77: Integrated Solutions for Daylighting and Electric Lighting

BSDF generation procedures: white paper

2 BSDF definitions

This section provides a summary of fundamental concepts and term definitions related to BSDFs. For more detailed background information, see [Nicodemus 1977, Lewis 1994].

A bidirectional scattering distribution function (BSDF) $f(\theta_1, \phi_1; \theta_2, \phi_2)$ describes the scattering properties of a material by specifying the amount of radiance incident from direction (θ_1, ϕ_1) that is reflected and/or transmitted in the exiting direction (θ_2, ϕ_2) (see Figure 1), i.e., the overall radiance exiting in direction (θ_2, ϕ_2) is given as:

$$L_2(\theta_2, \phi_2) = \int_0^{2\pi}\int_0^{\pi} L_1(\theta_1, \phi_1)\, f(\theta_1, \phi_1; \theta_2, \phi_2)\, |cos\theta_1| sin\theta_1 d\theta_1 d\phi_1 \quad (1)$$

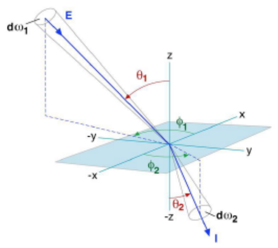


Figure 1. Polar and azimuthal angles of incident and exiting directions. Source: LBNL.

A physically plausible BSDF exhibits three properties:

1. Positivity:
   $f(\theta_1, \phi_1; \theta_2, \phi_2) \geq 0$ (2)
2. Helmholtz reciprocity:
   $f(\theta_1, \phi_1; \theta_2, \phi_2) = f(\theta_2, \phi_2; \theta_1, \phi_1)$ (3)
3. Energy conservation:
   $a(\theta_1, \phi_1) = \int_0^{2\pi}\int_0^{\pi} f(\theta_1, \phi_1; \theta_2, \phi_2)\, |cos\theta_2| sin\theta_2 d\theta_2 d\phi_2 \leq 1\ for\ all\ (\theta_1, \phi_1)$ (4)

   i.e., the overall reflected and transmitted energy is bounded by 1.

This BSDF definition in four dimensions (two for the incident direction and two for the exiting direction) implicitly assumes spectral uniformity and insensitivity to polarization at least for two broadband spectral ranges (visible with wavelengths from about 380 nm to 780 nm and solar from 280 nm to 4000 nm). For typical window attachments in combination with uncoated glazing units, the angular differences in spectral reflection or transmission behavior for finer spectral ranges is negligible, thus this assumption is legitimate in this context. The assumptions need to be re-examined for the combination with coated glazing units. Spectral characterization for analysis of the non-visual effects of lighting and daylighting for atypical materials may be addressed in future work.

3 Scope

The proposed procedures are intended to be used to characterize the light-scattering properties of a single layer, planar window attachment, i.e., an attachment that can be represented as a thin flat surface with analogous light-scattering properties (layer model). This includes systems like clear or translucent glazing, fabrics, films, or blinds. The resulting BSDF is independent of the intended

4 BSDF resolution

Tabulated BSDFs are specified via a discrete set of values for a defined number and set of directions $(\theta_1, \phi_1; \theta_2, \phi_2)$. As an example, they can be generated from discrete measured BSDF data and using an interpolation model [Ward et al. 2014]. The resolution of measured- and tabulated BSDF data needs to match the optical properties of the represented system and the respective application. For example, a prismatic, daylight-redirecting film with pronounced peaks in the scattering distribution requires significantly higher resolution BSDF data than a nearly-Lambertian, translucent panel. Likewise, the calculation of daylight autonomy, which is based on hourly illuminance readings over the year, is less critically dependent on high-resolution BSDF based metrics, such as discomfort glare.

For the remainder of this document, we use the nomencla resolution BSDF to refer to *tabulated* BSDFs as follows:

- BSDF resolutions based on hemisphere subdivisi angles corresponding approximately to cones wit referred to as low-resolution BSDFs.
  Examples: Klems, Tregenza, McNeil, Tensor tree
- BSDF resolutions with average patch sizes coveri to cones with full opening angles of smaller than 1
  Examples: Tensor tree with basis resolution 1024

4.1 BSDF angular bases

Various angular bases for tabulated BSDFs have been de purposes.

4.1.1 Klems basis

The Klems 145x145 subdivision of the incident and exiting solar heat gain calculations [Klems 1994]. See Figure 2.

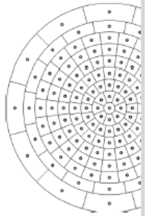


Figure 2. Klems BSDF angular basis [Klems 1994]

5 Proposed BSDF generation procedures

We describe empirically-based procedures for generating BSDF data sets for façade systems subsequent use in lighting simulation software. The overall procedure differs for microscopic macroscopic systems. A simplified procedure for generating BSDFs for microscopic systems rotational symmetry is also given.

For **macroscopic systems**, the procedure consists of four main steps and one optional step including system geometry:

1. Characterize the base material using fundamental data (e.g., index of refraction, diffu reflectance) or BSDF data generated for microscopic systems using the procedure ab
2. Set-up a three-dimensional geometric model of the window attachment; then,
3. Use simulations to produce a tabulated BSDF in the desired resolution using a virtual goniophotometer (optical ray-tracing software).
4. Validate the direct-hemispherical transmission values.
1. (optional): Prepare proxy geometry for inclusion in the BSDF XML file.

For **microscopic systems**, the procedure consists of four steps:

2. Take goniophotometer measurements of exiting transmittance and reflectance for sel incident directions.
3. Compute a four-dimensional interpolant from the measured data.
4. Sample the interpolant to derive a tabulated BSDF in the desired resolution.
5. Validate the direct-hemispherical transmission values.

For **microscopic systems with rotational symmetry without highlights** (e.g., isotropic fab or without a direct, through component (openness), but without light redirection) and for which optical transmittance can be approximated by a specular/diffuse split, an alternate procedure follows:

1. Take integrating sphere measurements of normal-hemispherical and normal-diffuse transmittance and reflectance, and cut-off angle. Ensure that the angular range exclu "normal-diffuse" is well-defined (see e.g., NFRC 300 or EN 14500:2020 [CEN 2020]).
2. Calculate normal-normal transmittance by subtracting the normal-diffuse transmittanc the normal-hemispherical transmittance.
3. Forge a Radiance BRTDfunc model as described in [Wienold et al. 2017]. This model input parameters the normal-normal and normal-diffuse transmittance, the normal-hemispherical reflectance, and the cut-off angle of the fabric.
4. Use simulations to produce a tabulated BSDF in the desired resolution using a virtual goniophotometer (optical ray-tracing software).
5. Validate the direct-hemispherical transmission values.
6. (optional): Use the BRTDfunc model as proxy geometry in the simulations.

5.3.6 Step 6 (optional): Use the BRTDfunc model as proxy geometry in the simulations

The BRTDfunc model developed in Step 2 can directly be used, e.g. to calculate simplified images for the Enhanced Simplified DGP method in annual glare risk assessments. This ensures that the direct-direct transmittance is treated purely specular in the simulations. More details are given in the Discussion Section 7.8. As described in Section 4.2, the proxy model of the daylight system can be included in the BSDF XML file.

6 Proposed characterization types for various kinds of daylight systems

As stated in Section 0, different systems require different BSDF data resolutions for different applications. Based on several studies [McNeil 2011, Geisler-Moroder et al. 2017, Kurt 2018, Geisler-Moroder 2019, Pedersen and Rasmussen 2019], the following tables recommend characterization methods and BSDF resolutions for different classes of systems. The classes of systems are clustered according to their optical properties and the resulting requirements for data resolutions.

For selected metrics, some system types are best modelled using an analytical or material model (e.g., clear glazing via a single transmittance value without any scattering) or even using a geometric model of the system with an appropriate base material (e.g., diffuse venetian blinds), as described in Section 5.1. This however presumes that either an adequate analytical model or the system geometry is available.

The "peak extraction" algorithm, which is for example implemented in Radiance, enables modelling of peaks in the unscattered direct-through direction of a tabulated BSDF. For systems with a strong specular transmission component such as clear windows, venetian blinds (direct transmission between slats) or perforated fabrics (with a relevant openness factor), this algorithm enables calculation of the direct solar contribution to the interior light levels based on a transmission value estimated from the directional BSDF value. This is also assumed to be the most critical peak appearance for the investigated performance metrics, especially for glare evaluations. However, if off-specular and upward-reflected peaks are expected, the method of photon mapping with high-resolution BSDFs [Grobe 2019] is recommended.

As another option for detailed calculations of the direct solar component, proxy geometry can be useful in various simulation methods. The pros and cons of having proxy geometry available are given in Step 5 in Section 5.1.

In the tables, the "example simulation methods" (middle column of the tables) provide working examples but makes no claim to be complete. The "proposed system characterization" (right column) or BSDF resolution applies to the overall system, not to the base material.

7 Discussion

There are several open issues for discussion when it comes to the BSDF characterization of daylight systems and their application in lighting simulation tools. A few of these discussion points are mentioned here, knowing that this list is not exhaustive.

7.1 Intended uses of BSDF data

The procedures proposed in this document support the evaluation of energy efficiency and visual discomfort. Further work is needed to determine whether these procedures are sufficient for modelling view, privacy, black out capabilities, or other qualities desired by the consumer. Additional work is needed to determine if spectrally resolved BSDFs are needed to evaluate the non-visual, health-related performance of daylighting products.

7.2 Analytical models

As mentioned in the introduction, this white paper does not discuss methods for deriving analytical BSDF models from measured goniophotometer data such as e.g. the model developed in [Kotey 2009] from spectrophotometer data for solar heat gain simulations of fabrics. However, there is considerable importance and urgency for further research to develop adequate methods to derive such analytical models. This issue is particularly relevant for products that are available in hundreds or thousands of permutations of design, shape, and color (e.g., fabrics). Analytical models will enable generation of extensive databases that include the most relevant shading and daylight systems. There is an open question as to who should be responsible for creating such parametric models and how they can be verified sufficiently against measurements.

7.3 Measurement quality

BSDF round robin test

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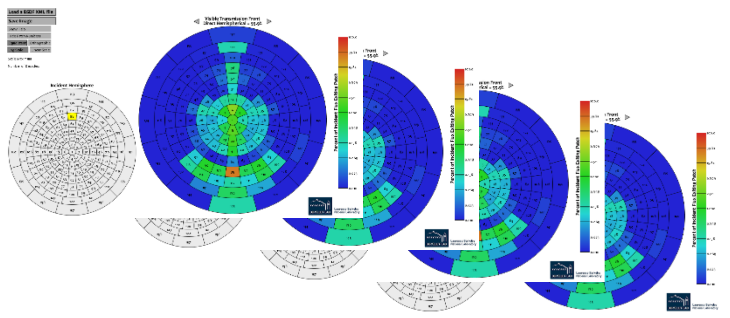
BERKELEY LAB

Bartenbach
research & development

Lucerne University of Applied Sciences and Arts
HOCHSCHULE LUZERN

pab

SOOCHOW UNIVERSITY

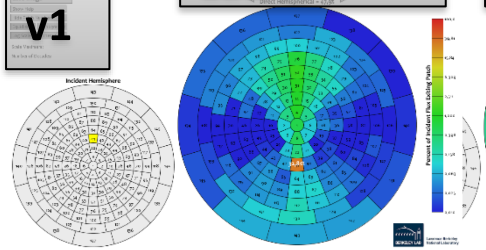


BSDF round robin test

HELLA venetian blinds – Klems: AOI = 30°

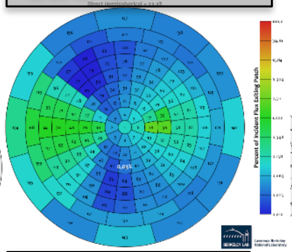
v1

Lab A



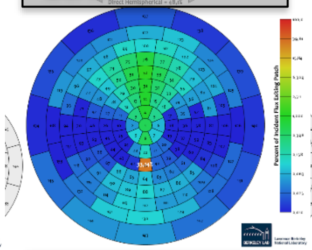
τ_{d-h} = 47.9%
τ_{d-d} = 32.8%

Lab B



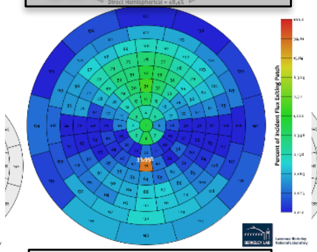
τ_{d-h} = 23.9%
τ_{d-d} = 0.03%

Lab C



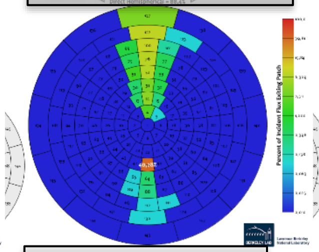
τ_{d-h} = 48.1%
τ_{d-d} = 33.1%

Lab D



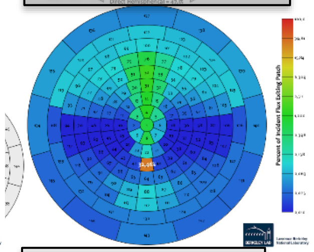
τ_{d-h} = 48.4%
τ_{d-d} = 34.0%

Lab E



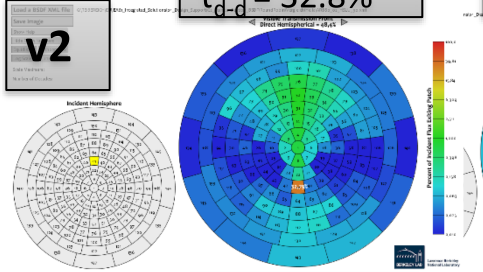
τ_{d-h} = 88.4%
τ_{d-d} = 40.3%

Lab F

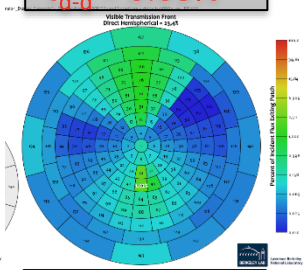


τ_{d-h} = 47.1%
τ_{d-d} = 32.5%

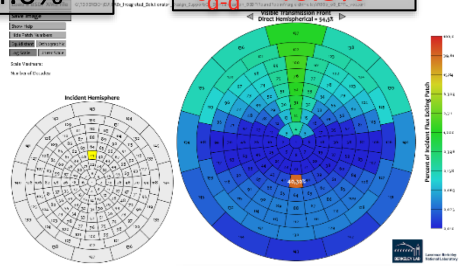
v2



τ_{d-h} = 48.4%
τ_{d-d} = 32.8%

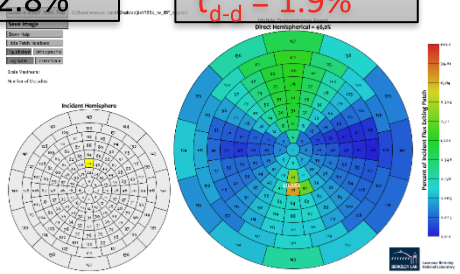


τ_{d-h} = 23.4%
τ_{d-d} = 1.9%

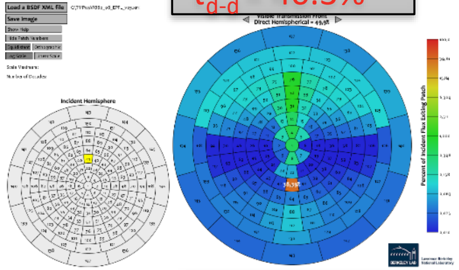


τ_{d-h} = 54.5%
τ_{d-d} = 40.3%

v3



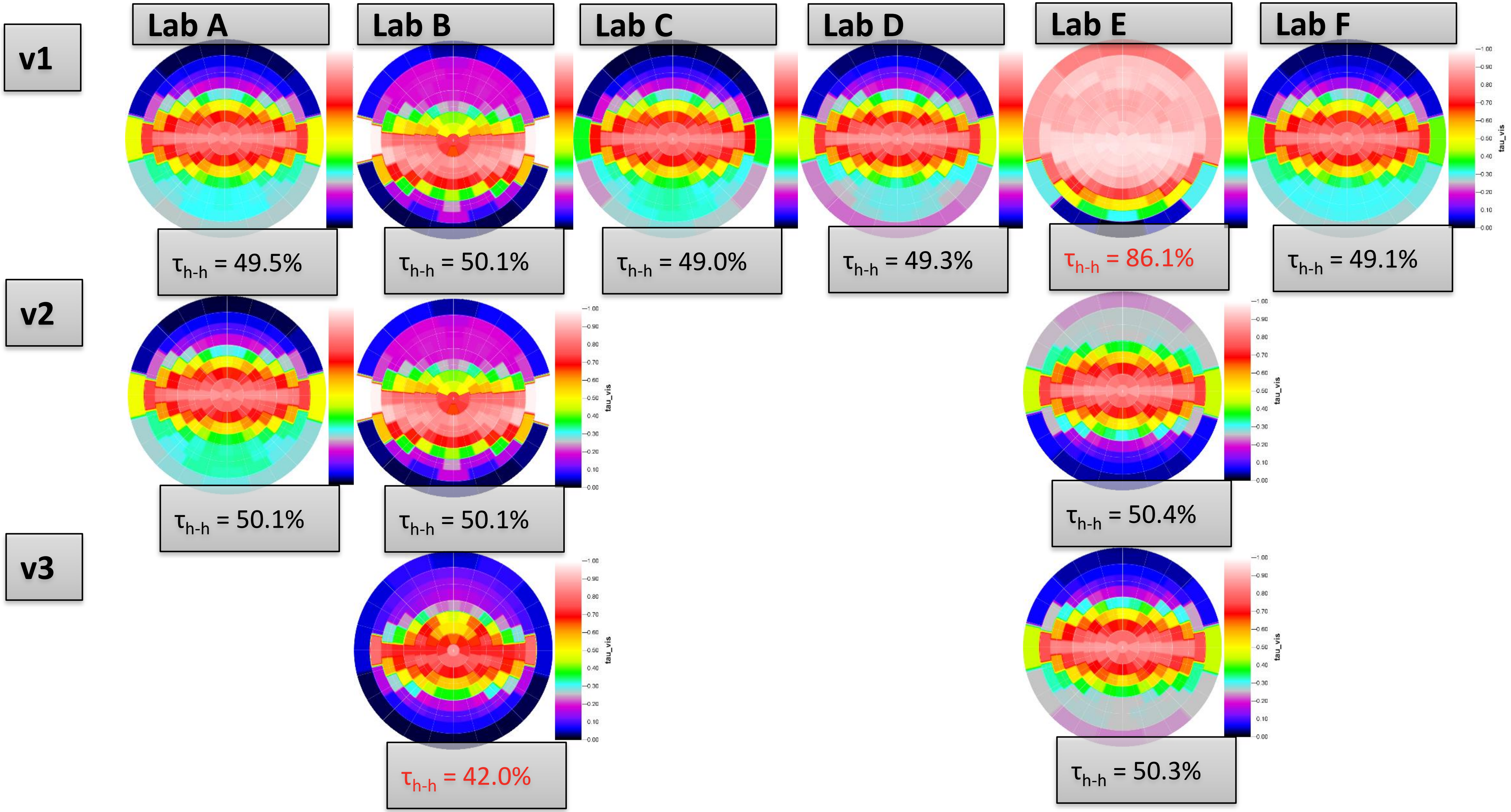
τ_{d-h} = 46.0%
τ_{d-d} = 20.1%



τ_{d-h} = 49.9%
τ_{d-d} = 38.4%

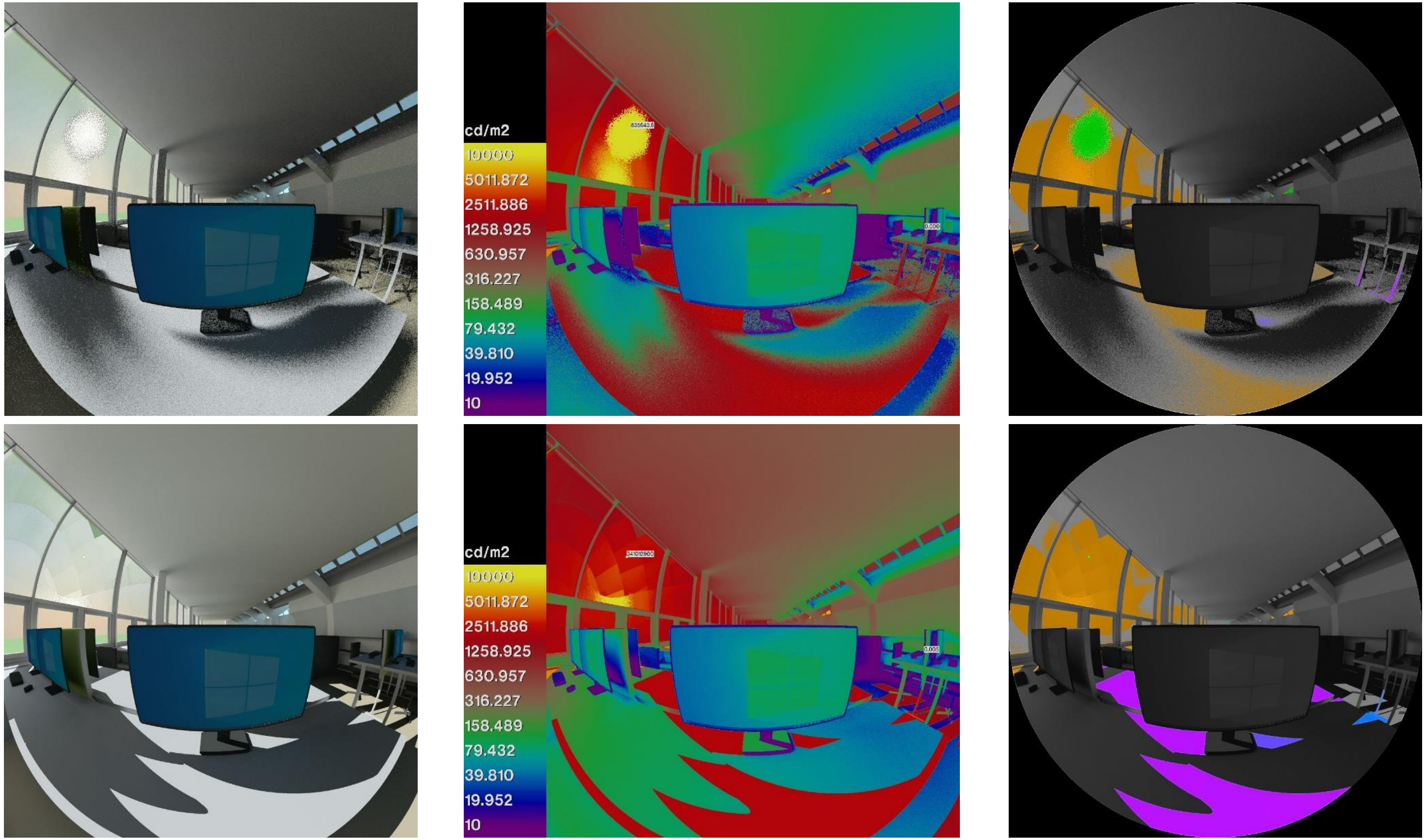
BSDF round robin test

HELLA venetian blinds – Klems: $\tau_{d\text{-}h}$



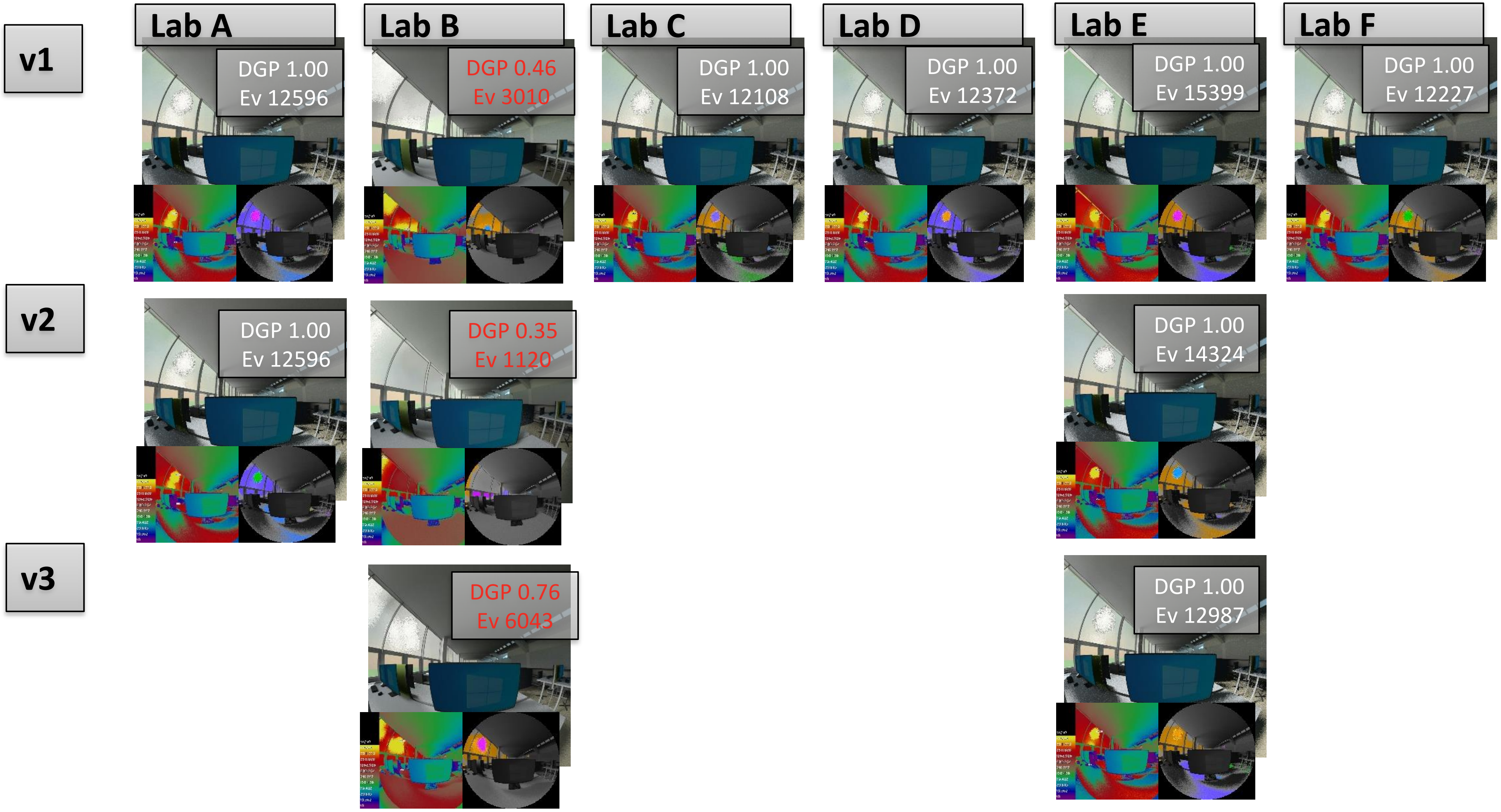
BSDF round robin test

HELLA venetian blinds – Klems, BSDF (no PE; top) / aBSDF (with PE; bottom)



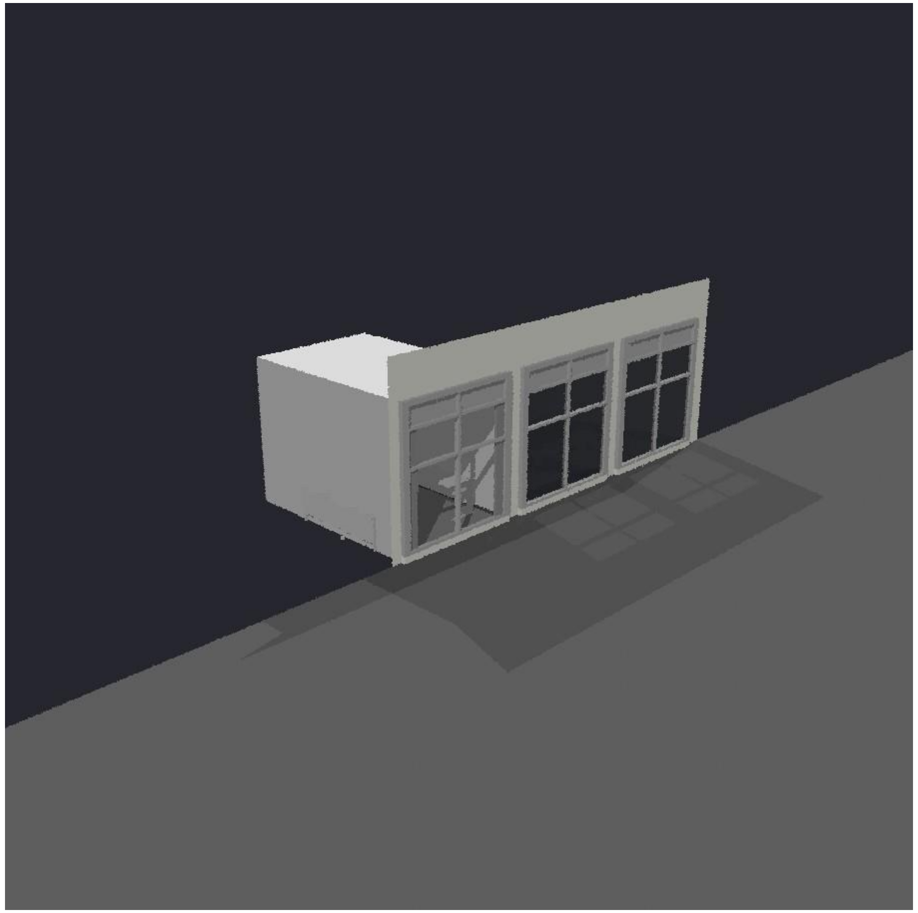
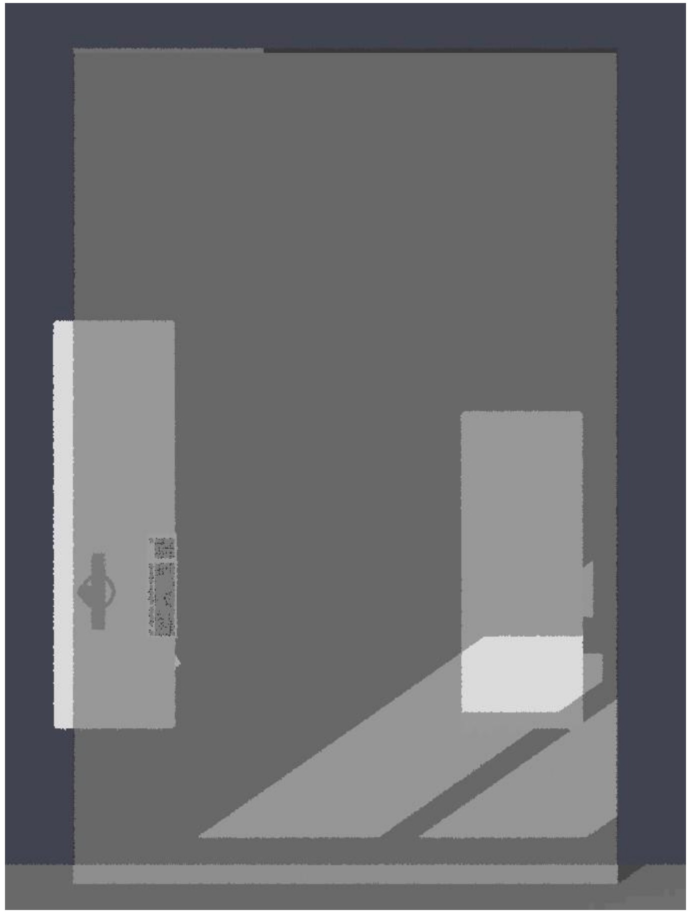
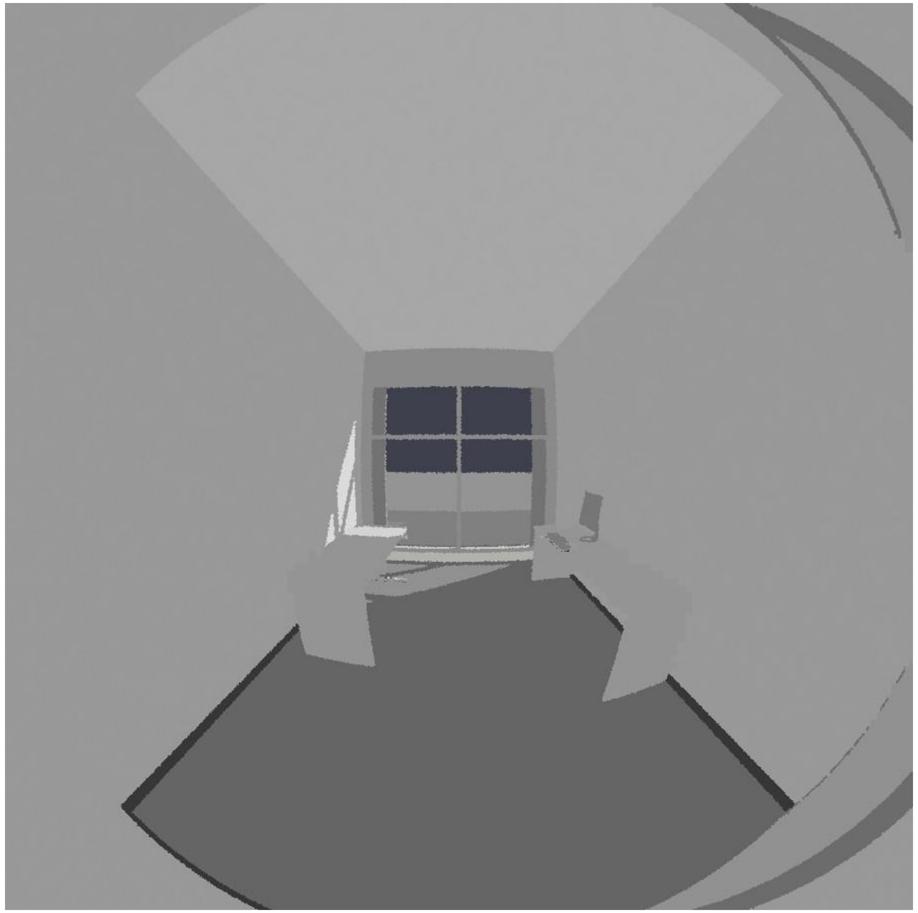
BSDF round robin test

HELLA venetian blinds – Klems, BSDF (no PE)



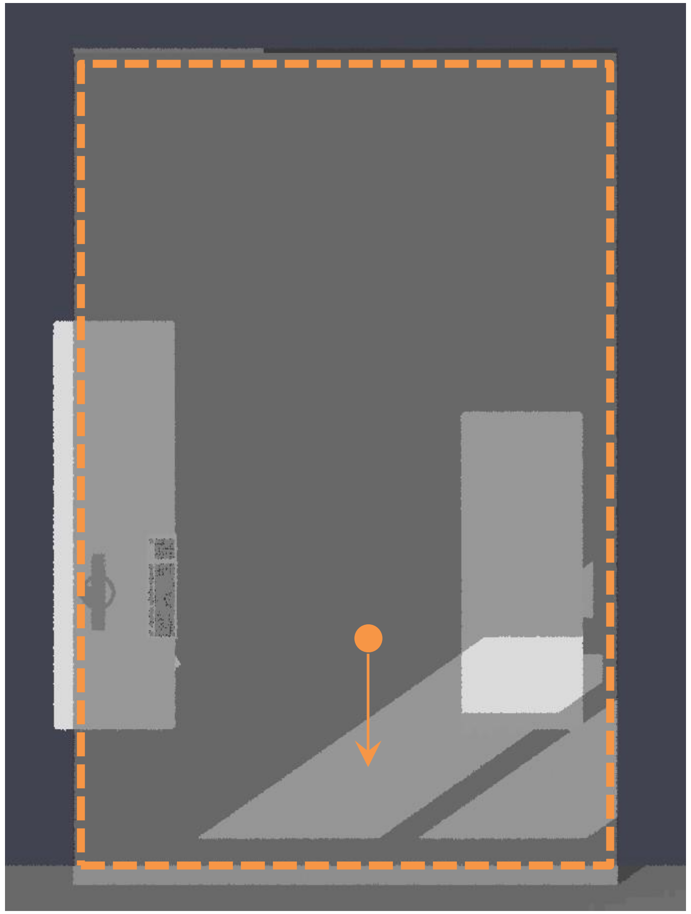
BSDF round robin test

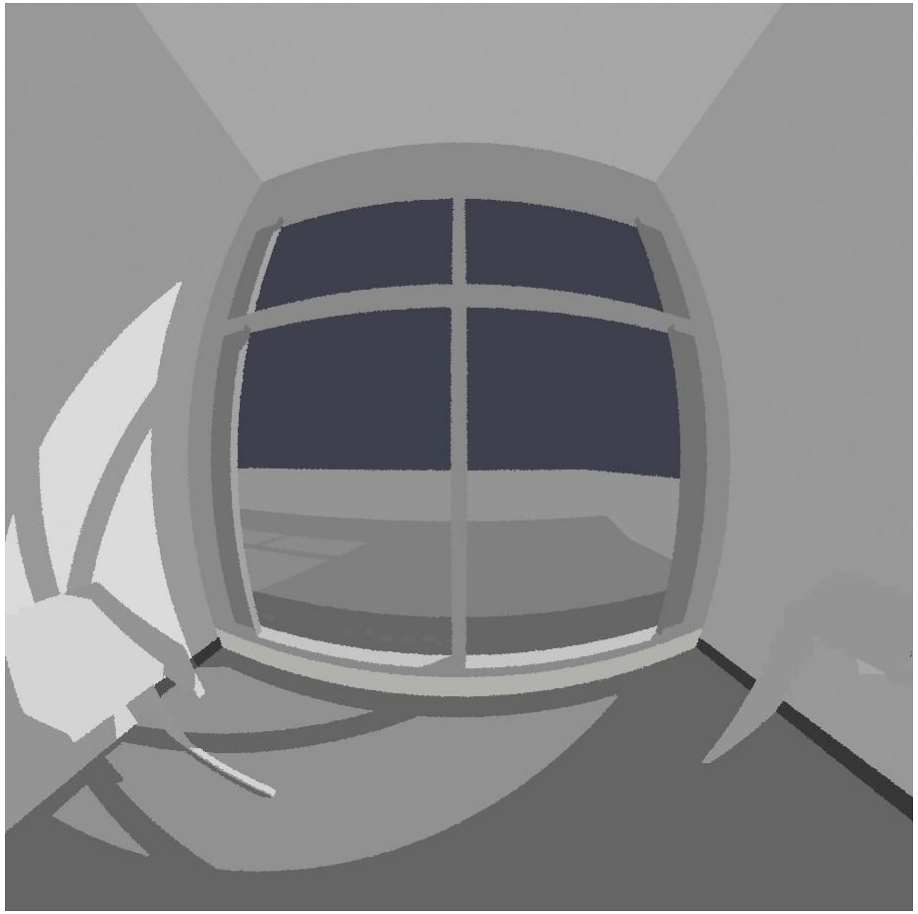
Simulation Setup: 71T testbed @ LBNL

BSDF round robin test

Simulation Setup: 71T testbed @ LBNL



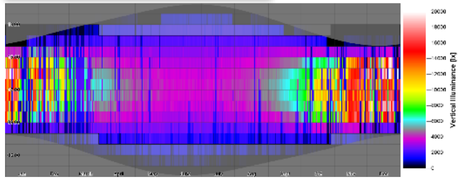


BSDF round robin test

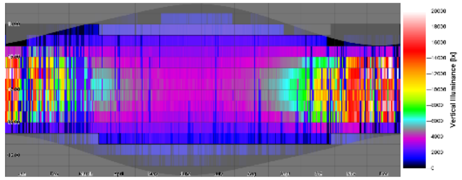
HELLA blinds – Klems Simulation Ev

Lab A

v1

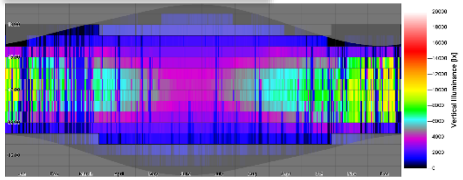


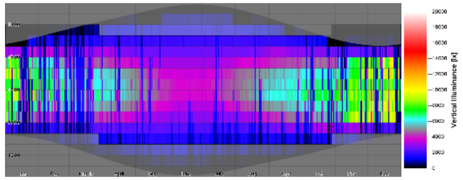
v2

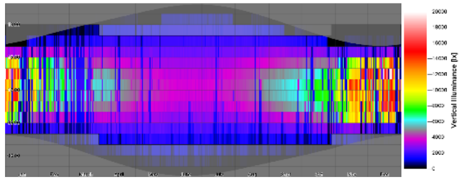


v3

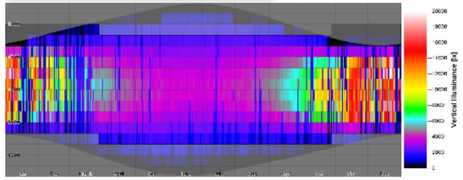
Lab B





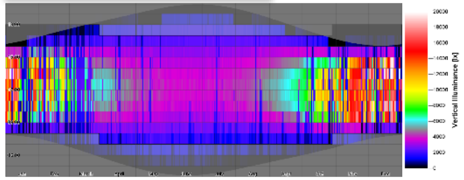


Lab C



Lab D

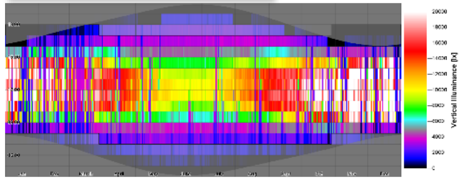
v1

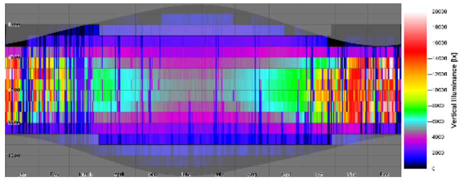


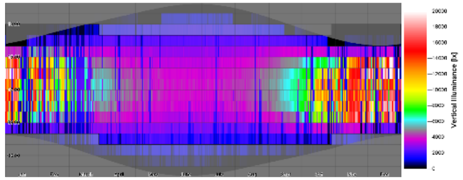
v2

v3

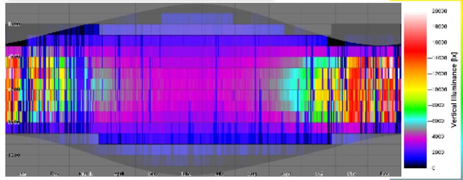
Lab E

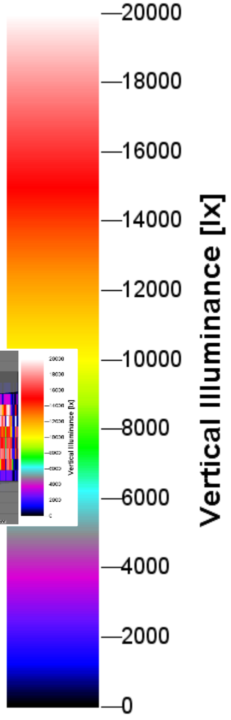






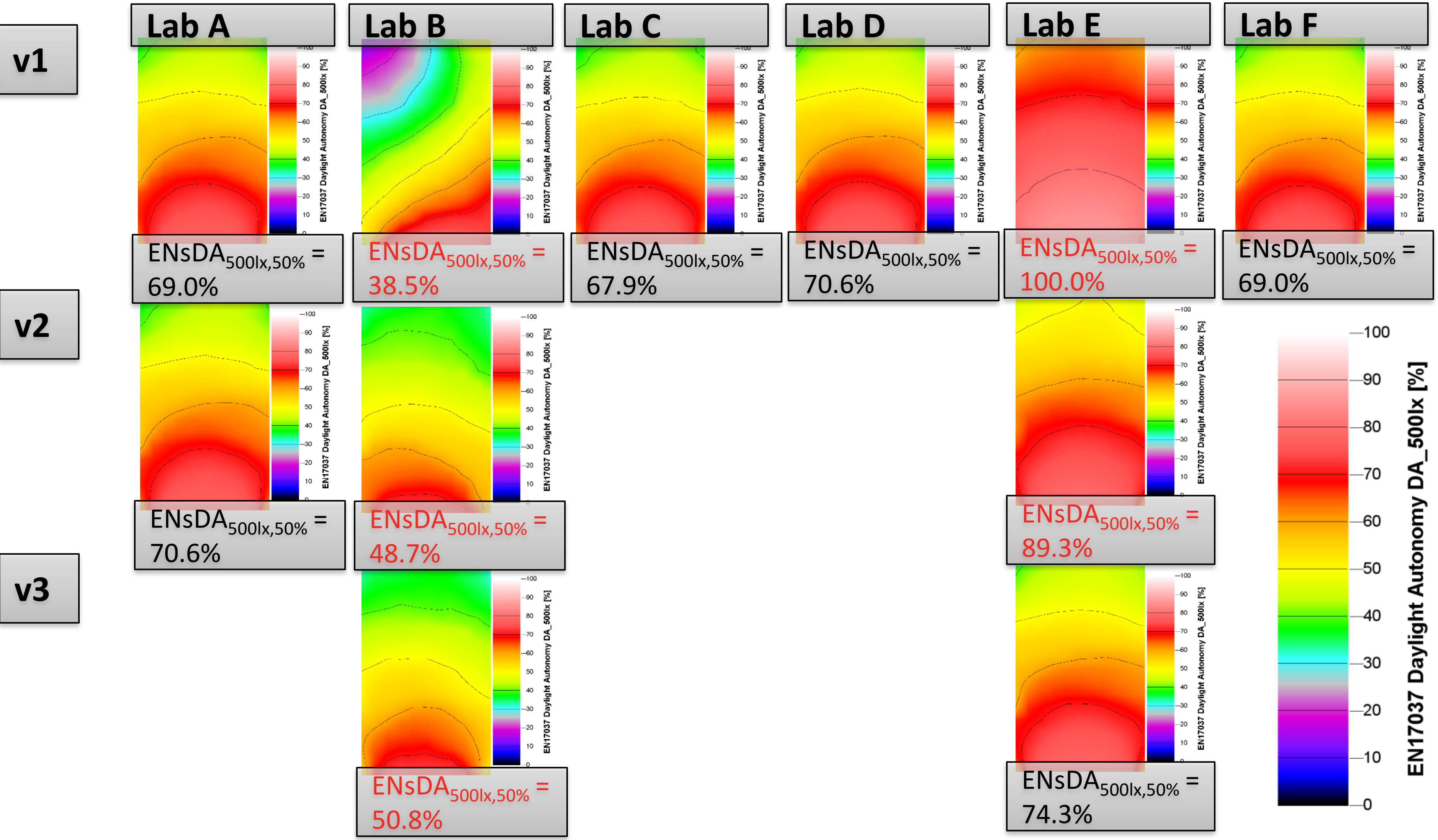
Lab F





BSDF round robin test

HELLA blinds – Klems Simulation EN17037 DA500lx on workplane

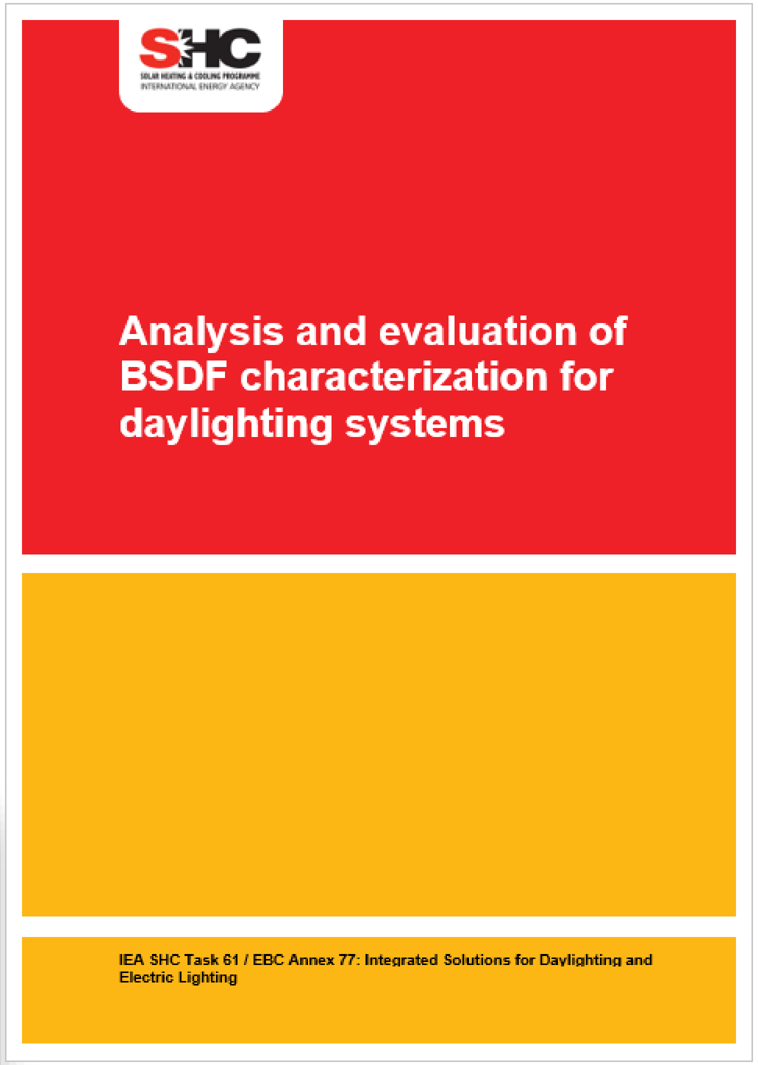


IEA SHC Task 61 / Annex 77

Report C.2 to be finished soon and published on

https://task61.iea-shc.org/publications

Stay tuned!



A Technical Report of
IEA SHC Task 61 / EBC Annex 77
Subtask C2

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