Generating high-resolution BSDFs for the direct beam component

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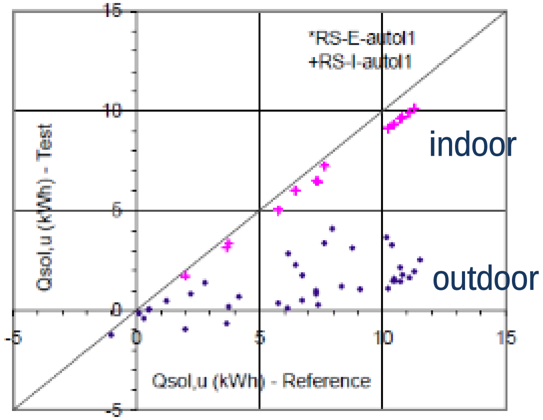
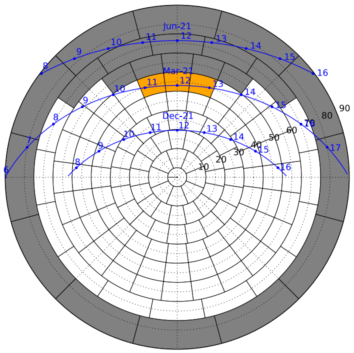
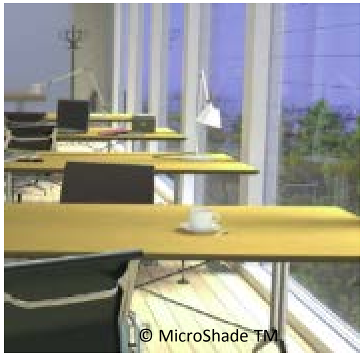
Reduce building energy use by 30% by 2030 compared to 2010 levels

→ optically-complex shading and daylighting "attachments"

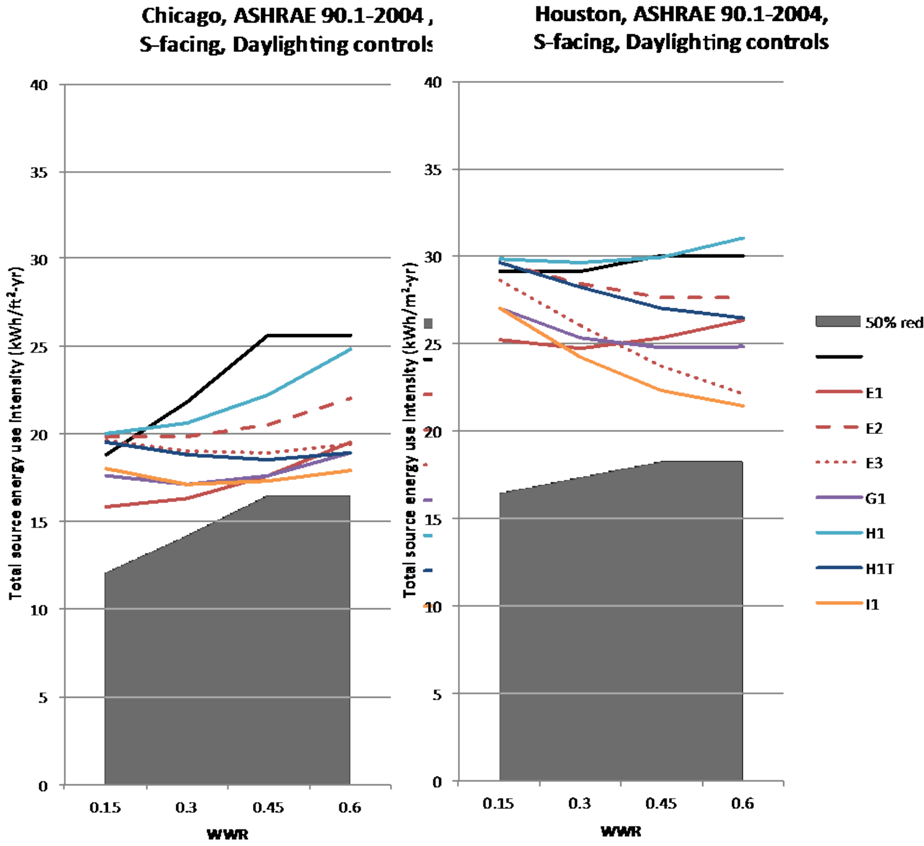






2 angular selective shading system with outdoor view (solar cut-off angles in image above)

Between-pane shading systems with daylighting: 45% savings compared to ASHRAE 90.1 2004

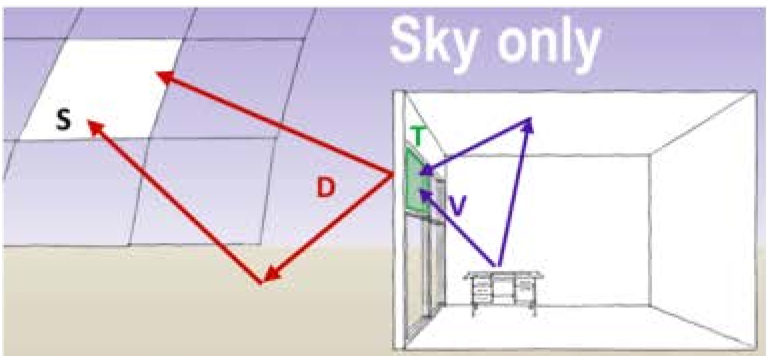


3 annual source energy use for angle-selective shade (G1, G1R) compared to code, unshaded low-e (E1), E1+indoor shade (E2), and E1+outdoor shade (E3)

Evaluation

Five-phase method for annual simulations:

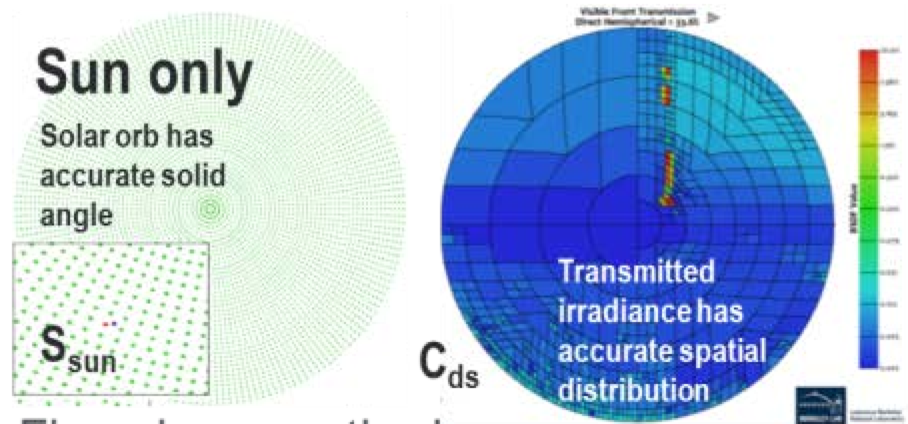
Separate sun and sky contributions



Three-phase method

$$I_{3ph} = VTDS$$

+



Five-phase method

$$I_{5ph} = VTDS - V_d T D_d S_{ds} + C_{ds} S_{sun}$$

145xN resolution

BSDF

(bidirectional scattering distribution function)

↓

gigo

(garbage in, garbage out)

Objective

Define **standard methods for generating BSDF data** in support of modeling daylight and solar radiation impacts in buildings such that **simulated values agree with measured data to within an RMSE<5-10%**.

Focus: accurate representation of the specular and forward scattering aspect of the BSDF

3% openness factor, pearl white roller shade fabric

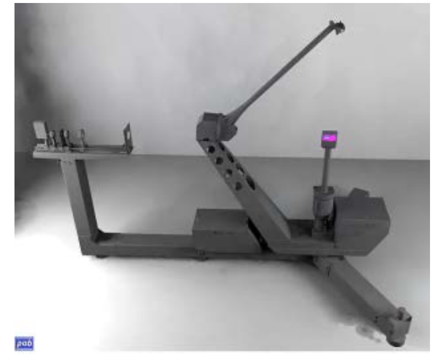
Method

a) Develop a "gold standard" BSDF dataset based on goniophotometric data

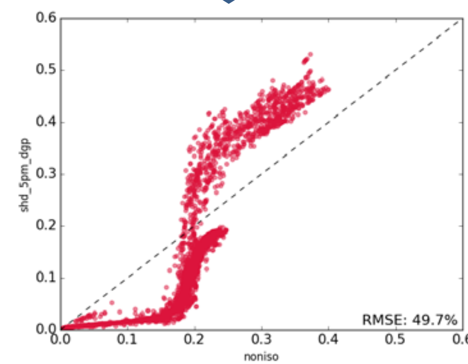
b) Evaluate BSDF dataset by comparing simulated data to measured data (e.g., WPI, DGP)

c) If RMSE limit is met, then use the gold standard as a benchmark to develop more time-efficient methods of generating BSDF datasets

(a)

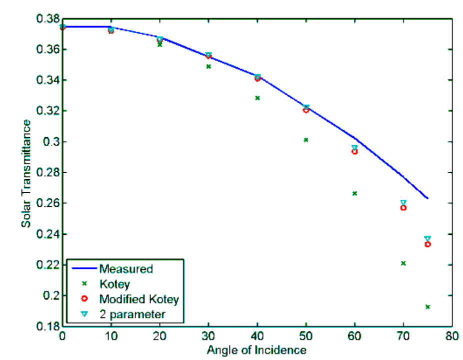


(b)



shade6220

(c)



Workflow

1. Measure sample material with scanning goniophotometer
2. Generate interpolant based on measured data
3. Use interpolant to generate BSDF XML file
4. Generate point-in-time data and scene image using the five-phase method with peak extraction

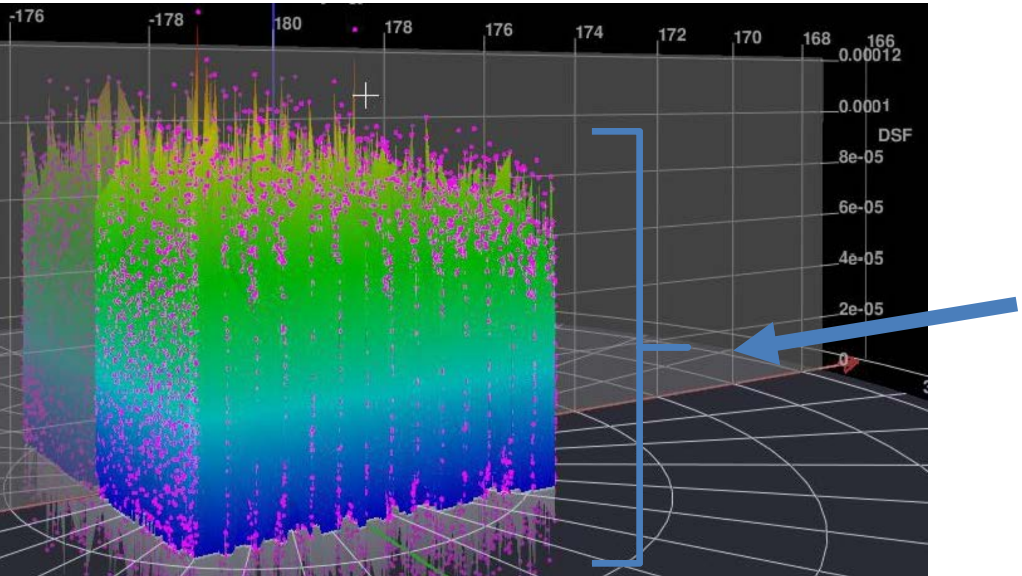
then calculate DGP:

5. Post-process image using peak scalar to simulate optics of a camera lens
6. Use *evalglare* to determine DGP
7. Compare simulated DGP to field measured DGP and assess error
8. Determine sources of error, modify, then re-do calculations until within acceptable error

Step 1. Measure sample material with scanning goniophotometer

Factors affecting accuracy (configurable) of PGII (PAB Adv. Techn.)

- Dynamic range 10^7 to measure peaks & diffuse background
- Asymmetric resolution of incident, outgoing directions
- Spectral resolution (here only NIR, VIS) vs SNR, speed
- Representative sample area to account for non-uniformity
- Scatter in the optical system (e.g. by lenses)

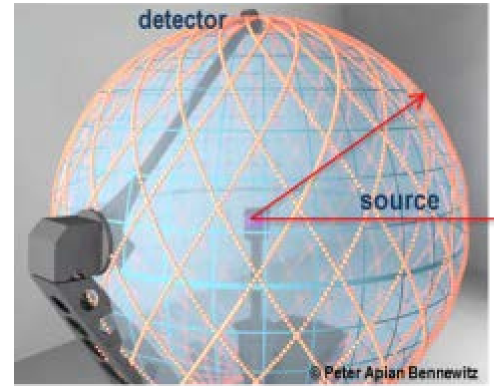


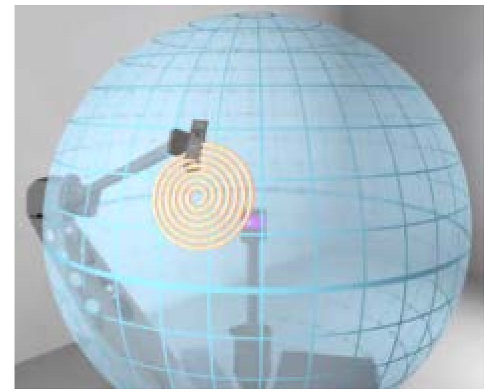
Noise (here: DSF measured in the dark)

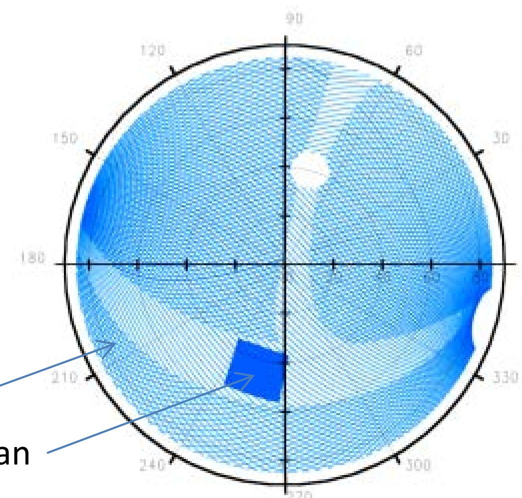
- Sets the lower limit of measurable BSDF
- Should fluctuate around zero (not the case here...)
- Maximum here approx. 0.0001
- Compare: Maximum measured peak DSF of our fabric is about 65.2

Resolution, representivity, and speed (i.e., cost)

- Conflicting targets, you never get it all
- Next magic term: “instrument signature”
- Depends on size of detector, source (fixed) and configuration of illumination and scan
- Focusing the beam (illumination)
  - Collimated “parallel light”, focus at infinity
  - Focus on sample
  - Focus on detector
- Scan path:
  - Full scan: capture “background”, locate peaks
  - Peak scan(s): Refine peak resolution

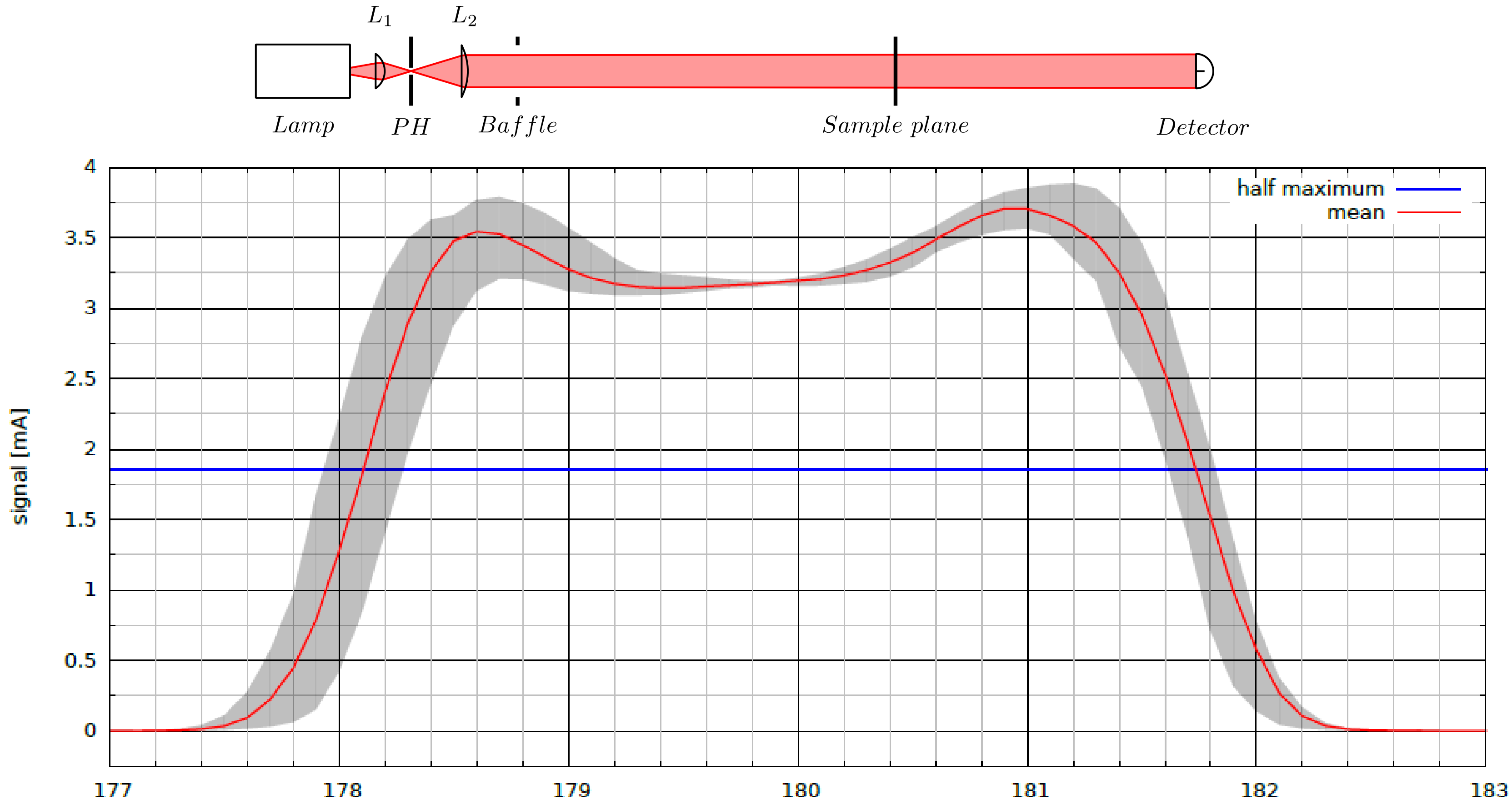






Overall scan
Detailed peak scan

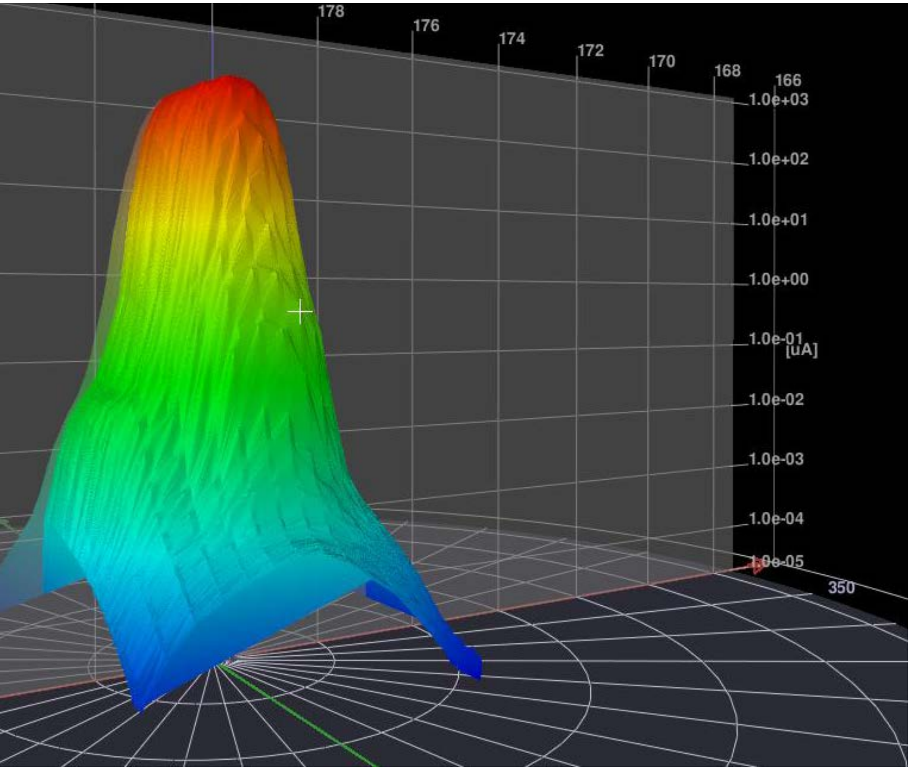
Focus at infinity: Illumination profile

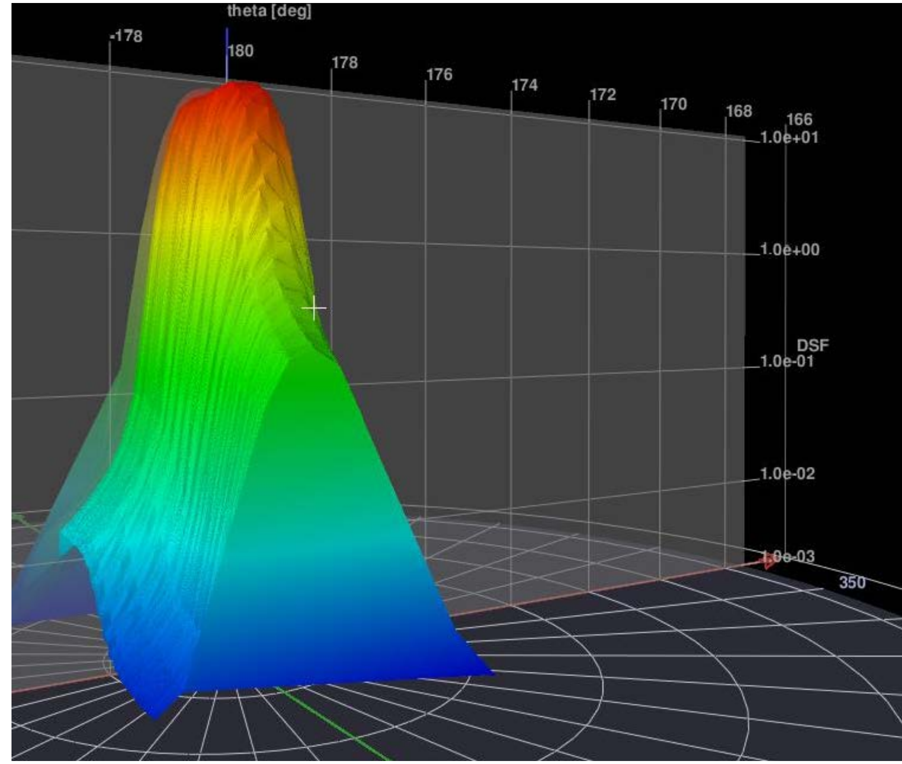


Close to collimated beam which averages out inhomogeneities but projects large-scale structures; 65 mm diameter lens, FWHM=3.5-4.0° angular resolution

Image: HSLU

Focus at infinity: Illumination & sample peaks



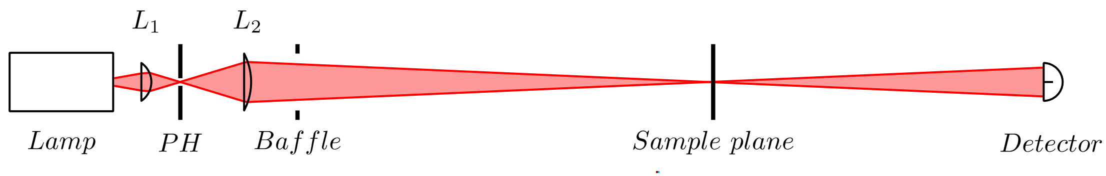


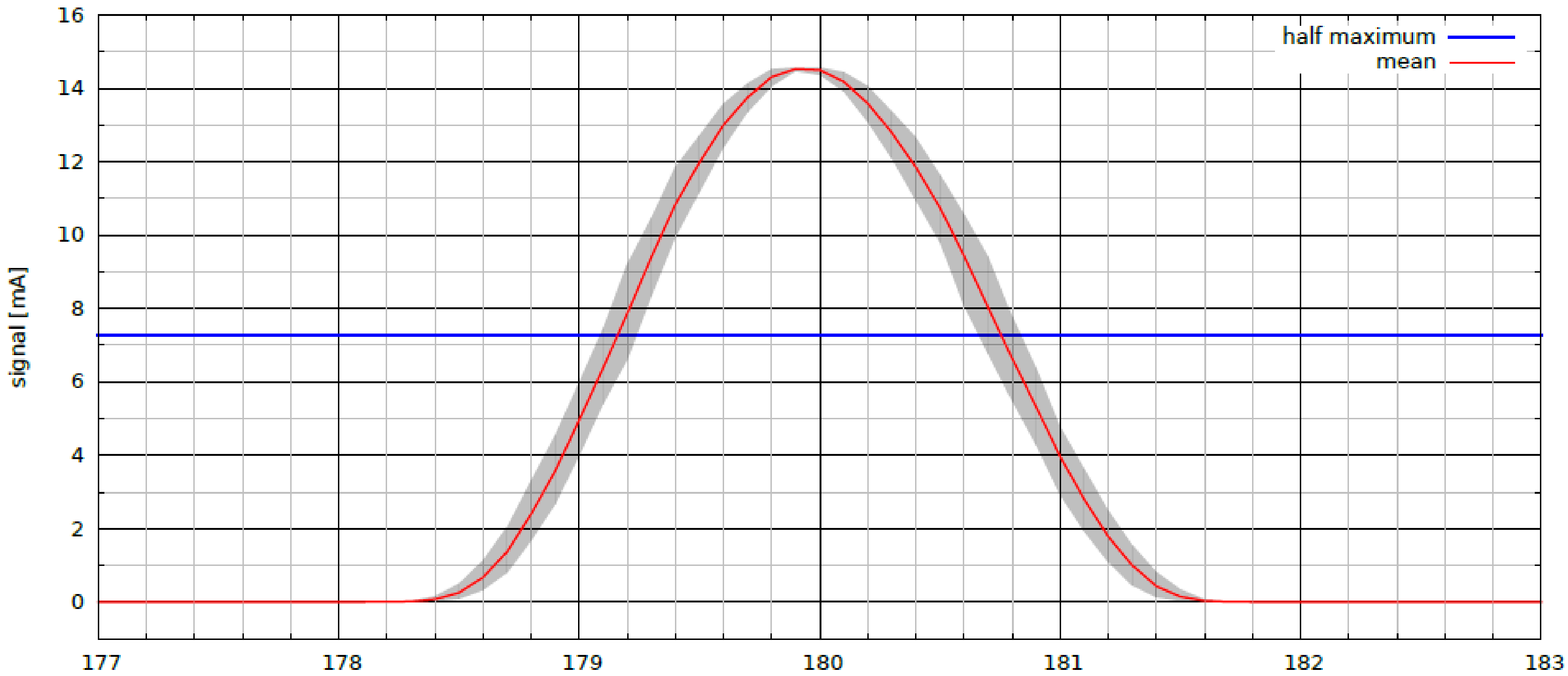
Left: Unobstructed beam

Right: Transmitted peak (fabric, normal incidence)

Image: HSLU

Focus on sample: Illumination profile

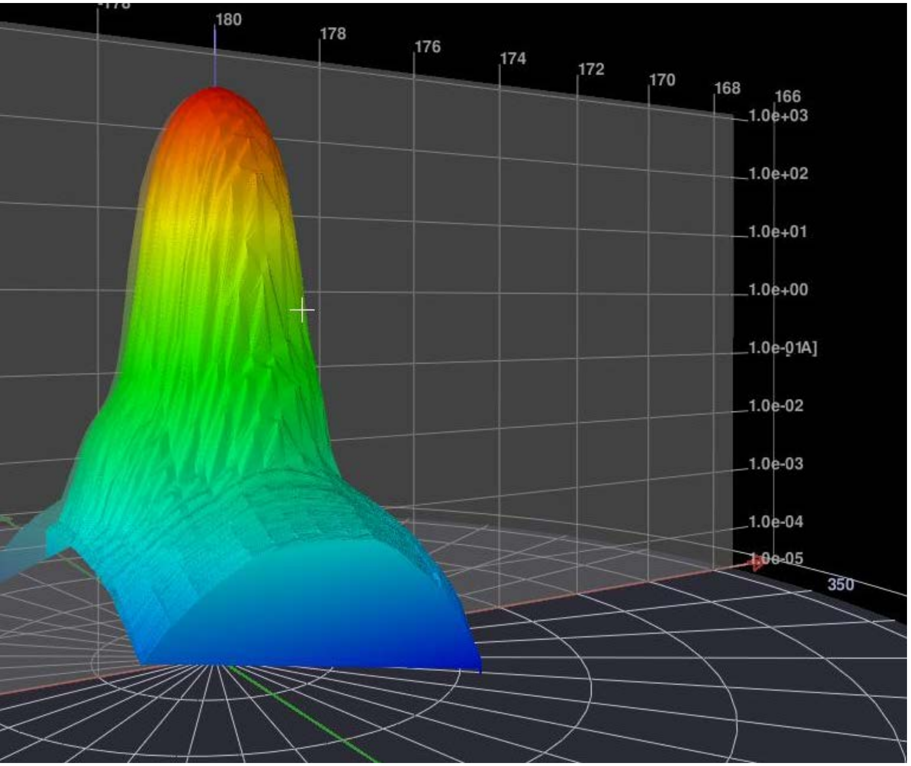


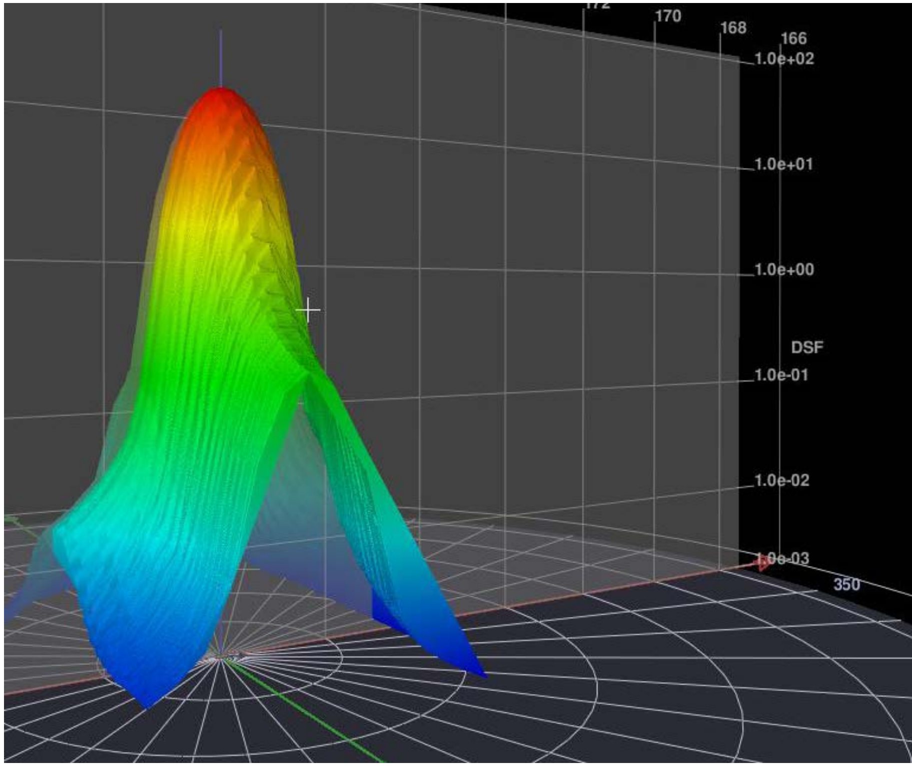


Useful if sample size is small, 10 mm diameter of illumination on sample at normal incidence, FWHM=1.5deg (about the resolution of tensor tree g7 in outgoing direction)

Image: HSLU

Focus on sample: Illumination & sample peaks

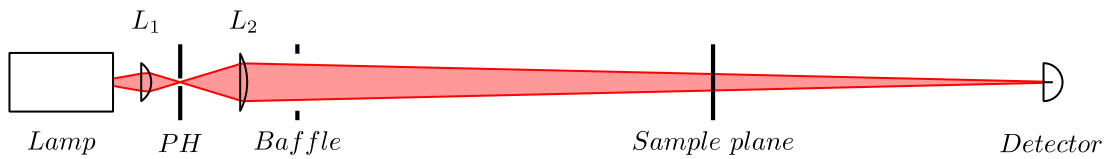


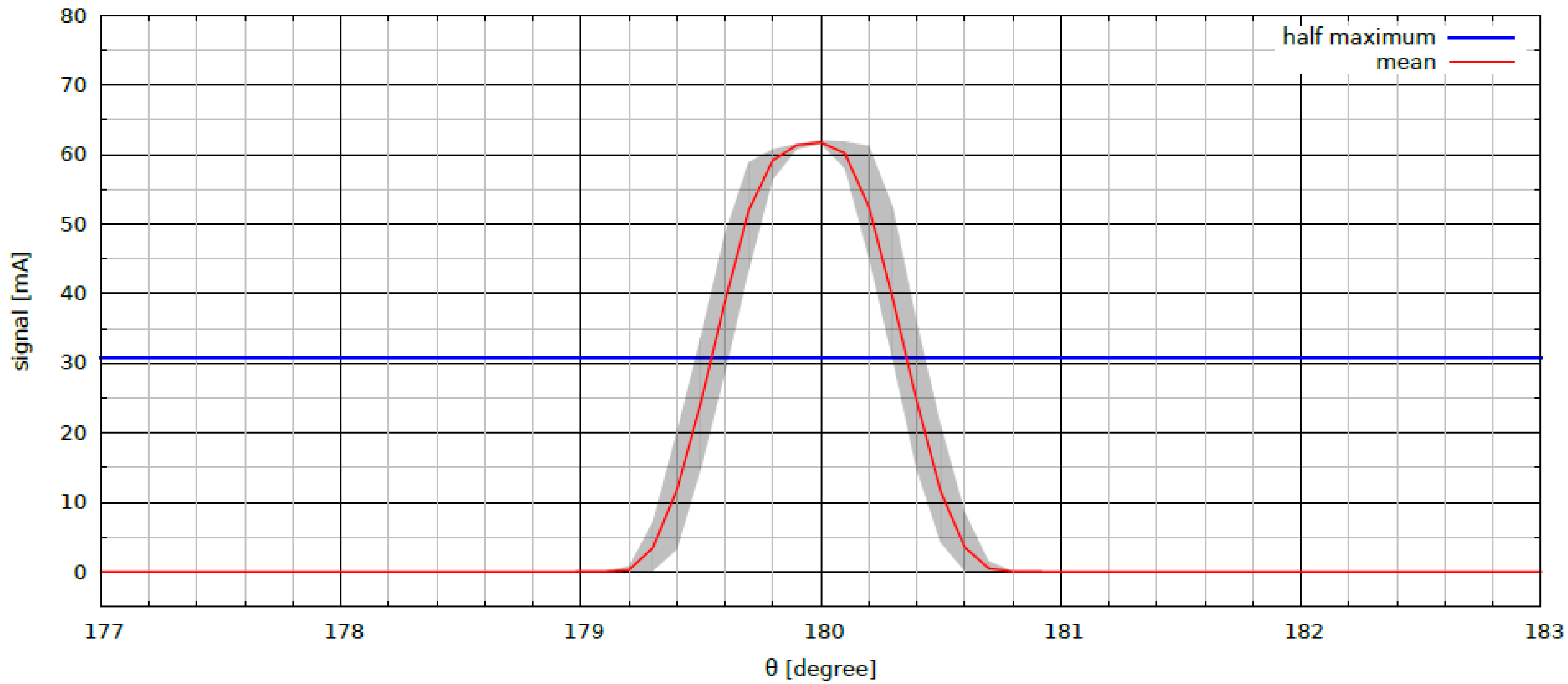


Left: Unobstructed beam
Right: Transmitted peak (fabric, normal incidence)

Image: HSLU

Focus at detector: Illumination profile

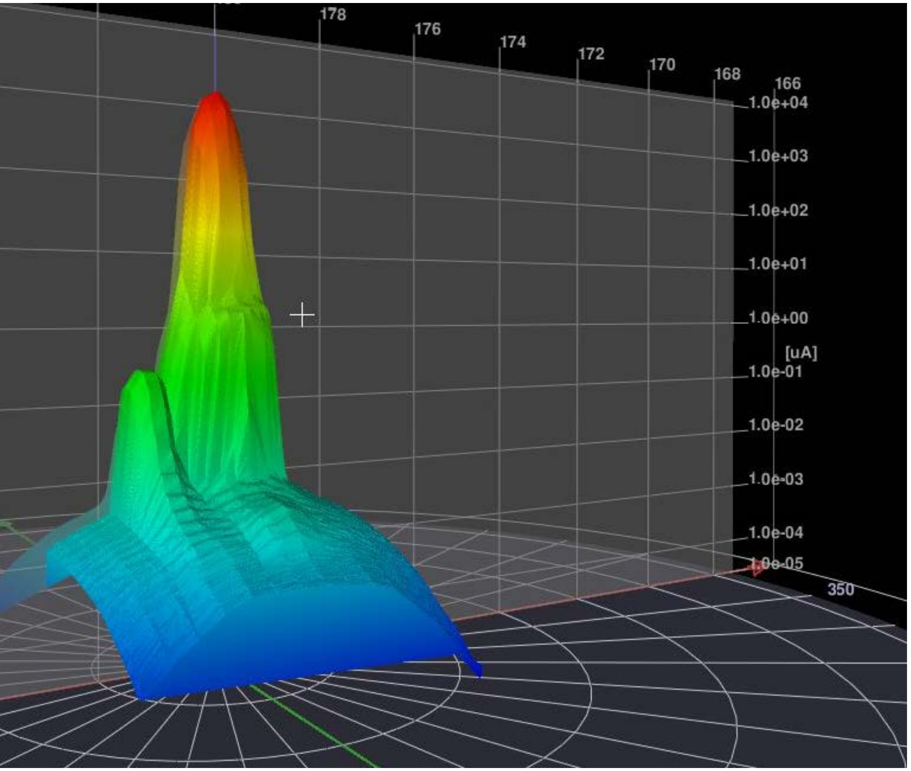


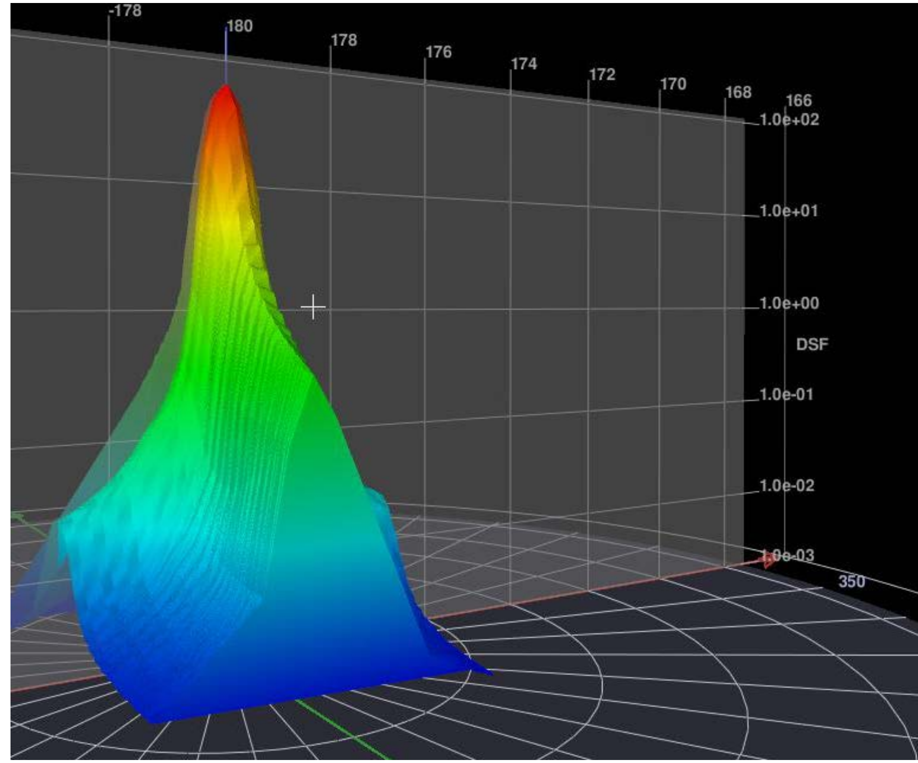


Highest directional resolution; requires dense sampling path else may miss peaks. Illuminated area on sample is about 20 mm so sample has to be large and structures on sample is limited to about 5 mm; FWHM is below 1°.

Image: HSLU

Focus at detector: Illumination & sample peaks





Highest directional resolution; requires dense sampling path else may miss peaks. Illuminated area on sample is about 20 mm so sample has to be large and structures on sample is limited to about 5 mm; FWHM is below 1°.

Image: HSLU

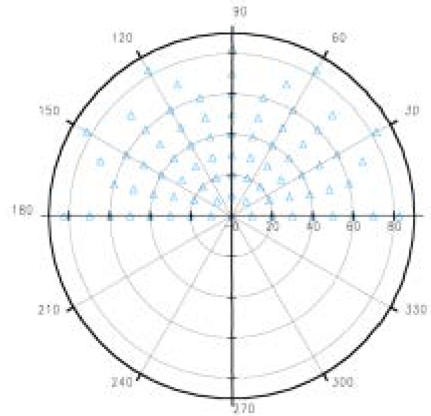
Focus on detector

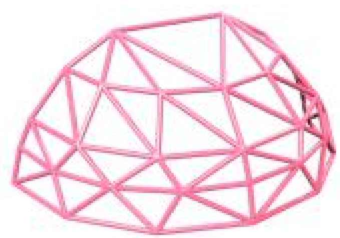
Sample roller shade fabric at the port of the goniophotometer (right) and transmitted and deflected light on the back wall of the HSLU lab (left).
Image: HSLU

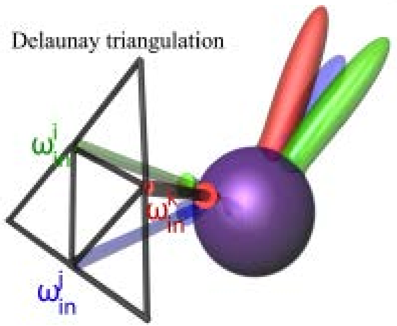
Step 2. Generate interpolant based on measured goniophotometer data

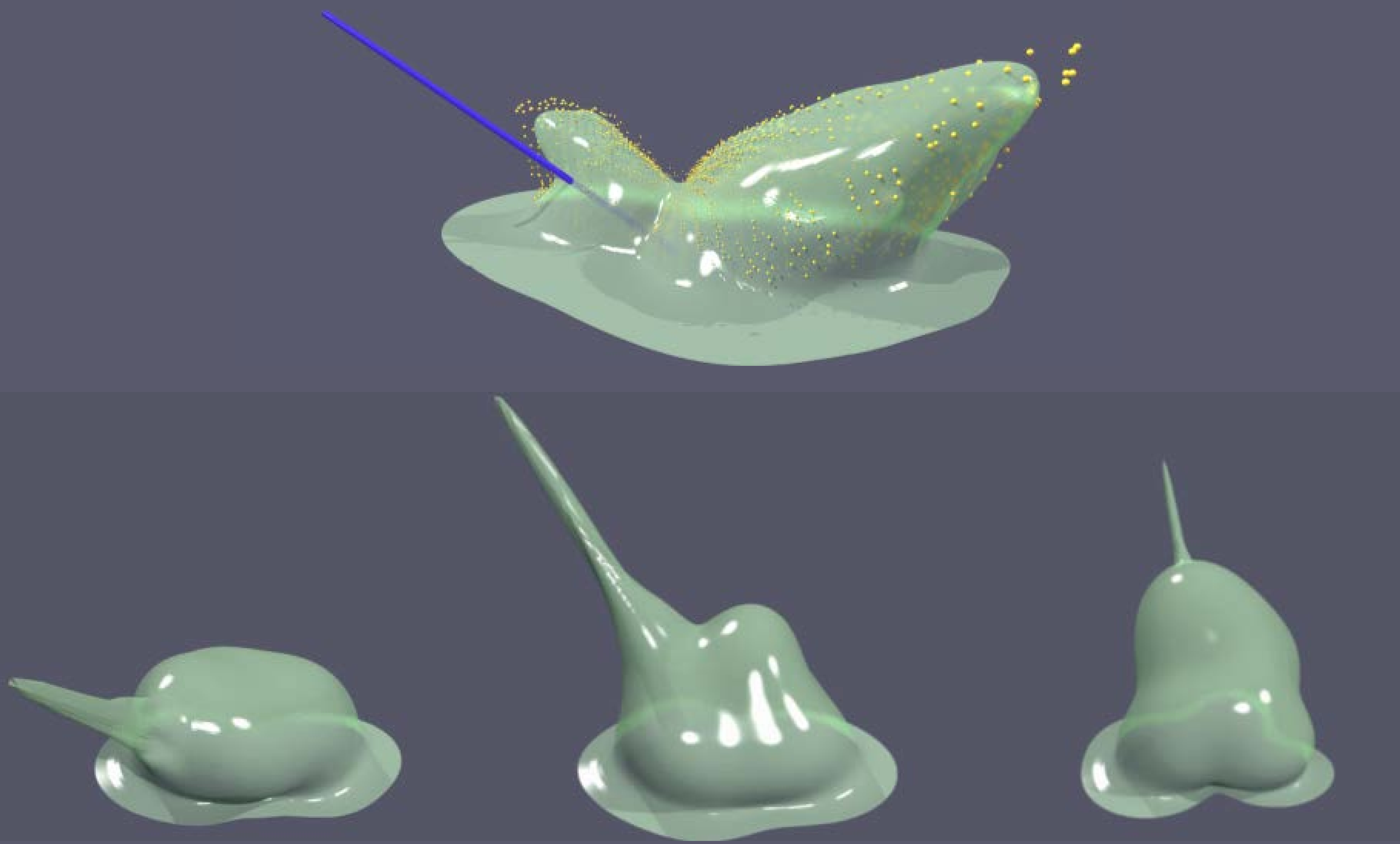
pabopto2bsdf -t {pgii data} > {interpolated radial basis func.sir}

- Generate a scattering interpolant representation (SIR) using *pabopto2bsdf*
  - Compute radial basis system (RBS): collection of 50-200 Gaussian lobes fit to outgoing measured data
  - Create a spherical Delaunay triangle mesh from measured incident directions
  - Use a Lagrangian mass transport plan along each Delaunay edge to transport RBS between vertices, using earth mover's distance (EMD) to minimize energy cost of transport







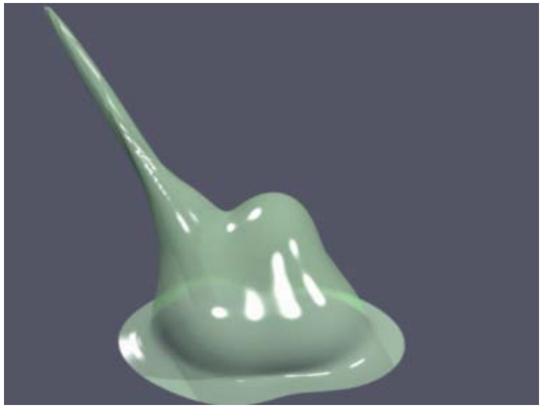


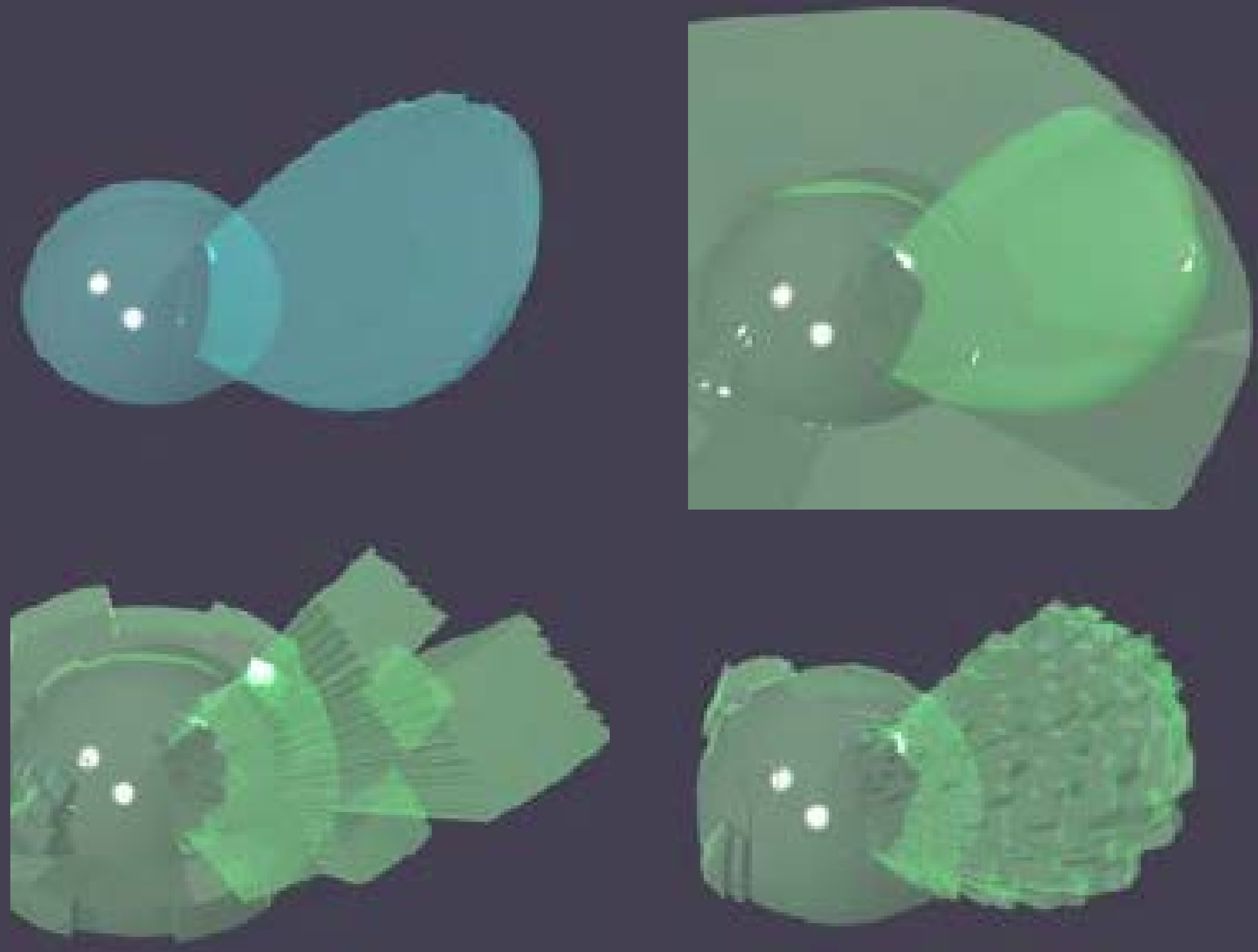
Ward, G., Kurt, M., Bonneel, N., 2012. A Practical Framework for Sharing and Rendering Real-World Bidirectional Scattering Distribution Functions, LBNL-5954E, Lawrence Berkeley National Laboratory, Berkeley, CA,

Step 3. Use interpolant to generate BSDF XML file

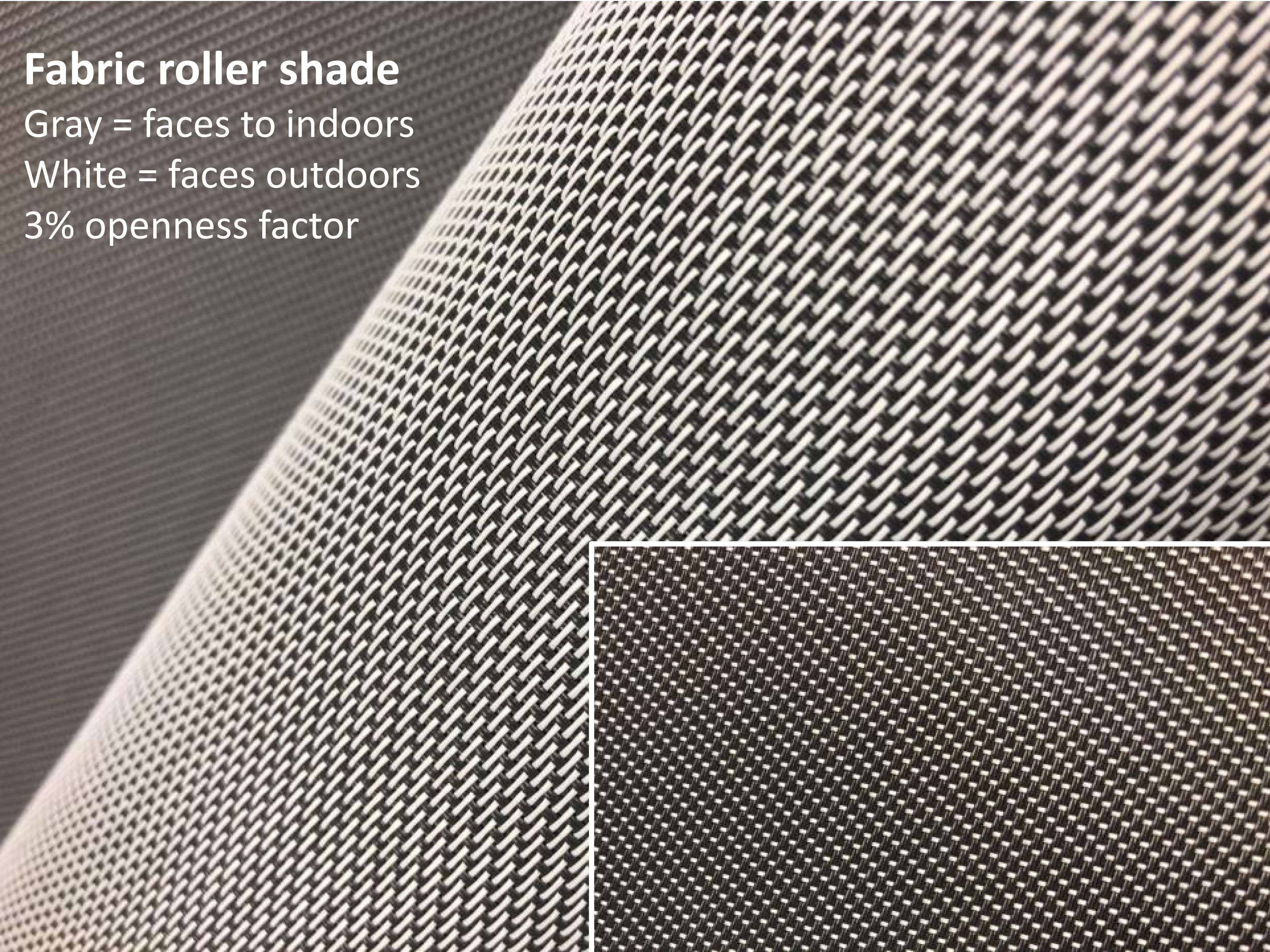
```
bsdf2ttree -g 6 {interpolated radial basis func.sir} > {tensor tree.xml}
```

- Use SIR interpolant to generate tensor tree BSDF at a defined resolution
  - - g 6 basis resolution ($2^{2 \cdot k}$ x $2^{2 \cdot k}$ where k=6; 4096 patches, 3° resolution)
  - If significant difference between target patch and adjacent patches, then send 64 sampling rays to compute a weighted average BSDF value for the target patch



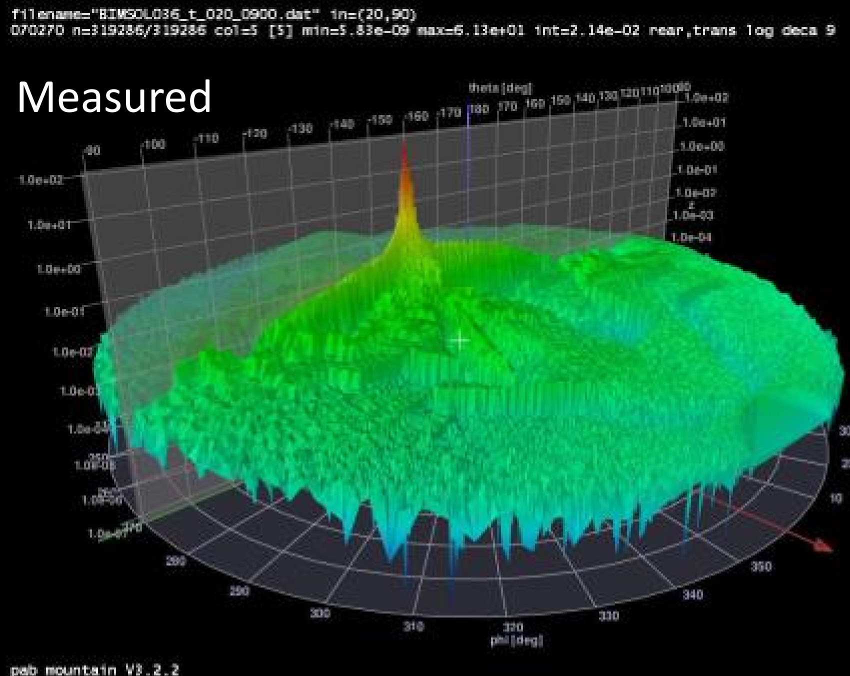


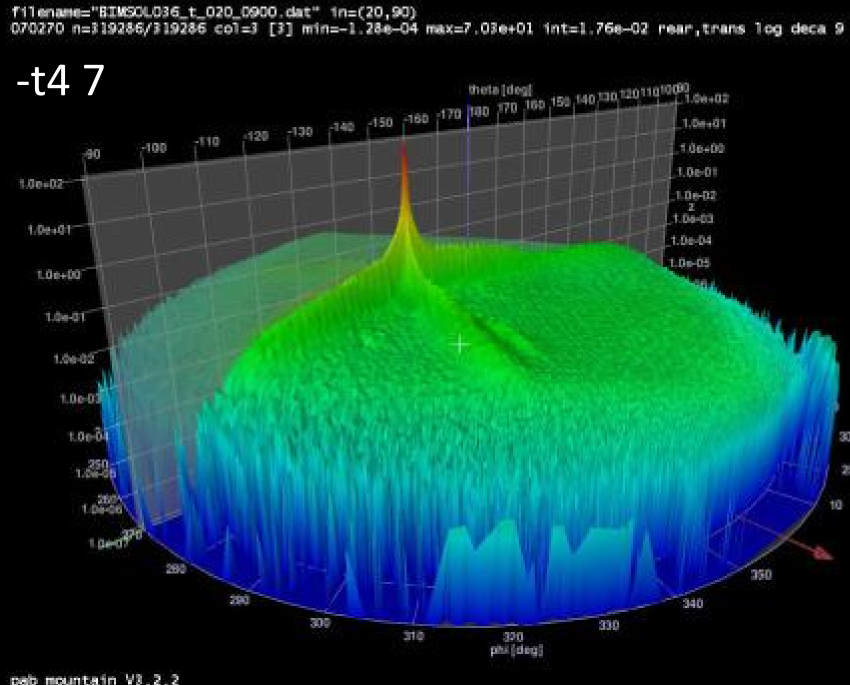
Clockwise: Original Ward-Geisler-Moroder-Dür BRDF model, Lagrangian interpolation, tensor tree representation, Klems representation
Solar Energy 160 (2018) 380-395

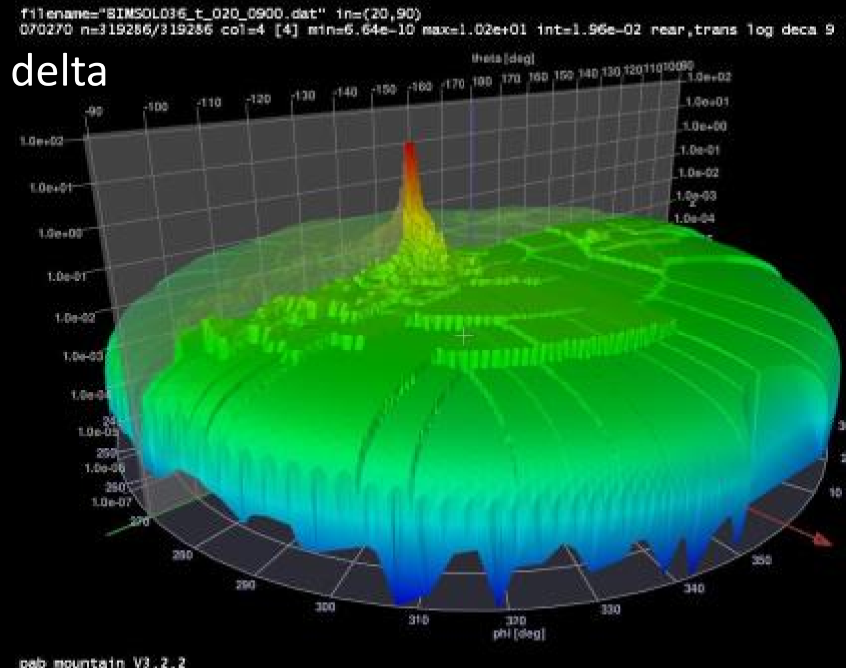

Fabric roller shade
Gray = faces to indoors
White = faces outdoors
3% openness factor

DSF=BTDF * cos(theta_s) distributions plotted for incident direction theta=20°, phi=90 ° (from outside) from measurement and model, as well as the absolute differences.

Images: HSLU







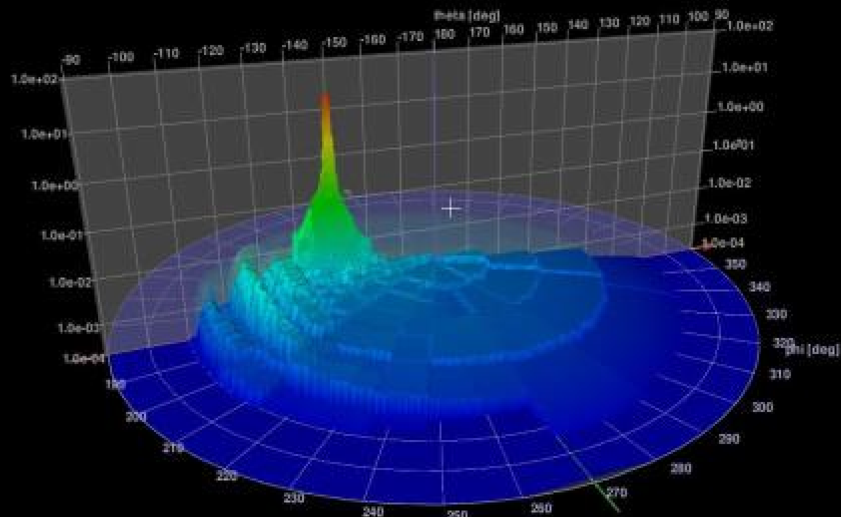
Anisotropic, isotropic, and sample orientation

	T_h	$BTDF_{max}$
Measured, phi=0	0.438	46.10
anisotropic g7 -t 97	0.426	7.84
isotropic g9, -t 97, phi=0	0.415	13.40
isotropic g9, -t 97, phi=90	0.402	21.00

HSLU: theta=30, phi=0 (pgII convention)
Th = hemispherical transmittance

filename="BIMSOL036DSF_t_0300_0000_t3_090.dat" in=(30,0)
137329 n=319292/319292 col=4 [4] min=4.20e-10 max=2.10e+01 int=2.25e-02 rear,trans log deca 9

-t3, phi=90



pab mountain V3.2.2

filename="BIMSOL036DSF_t_0300_0000_t4_000.dat" in=(30,0)
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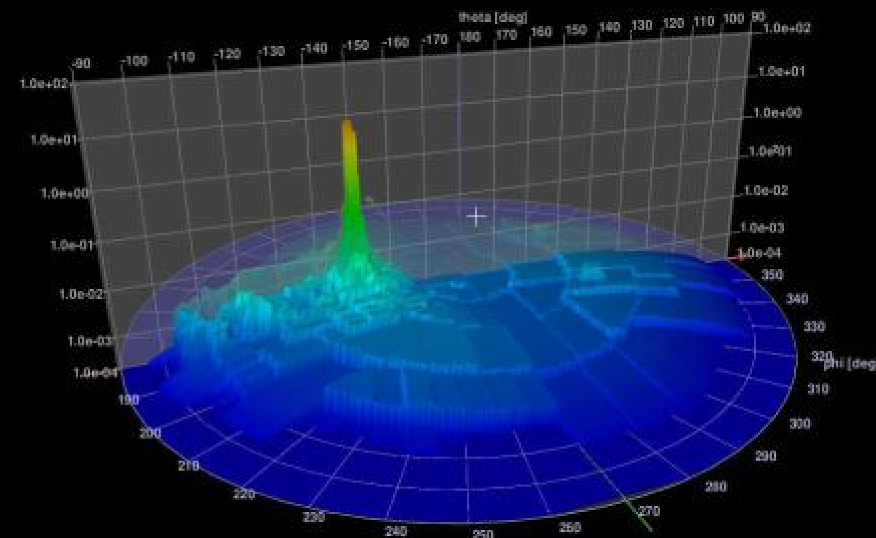
-t4



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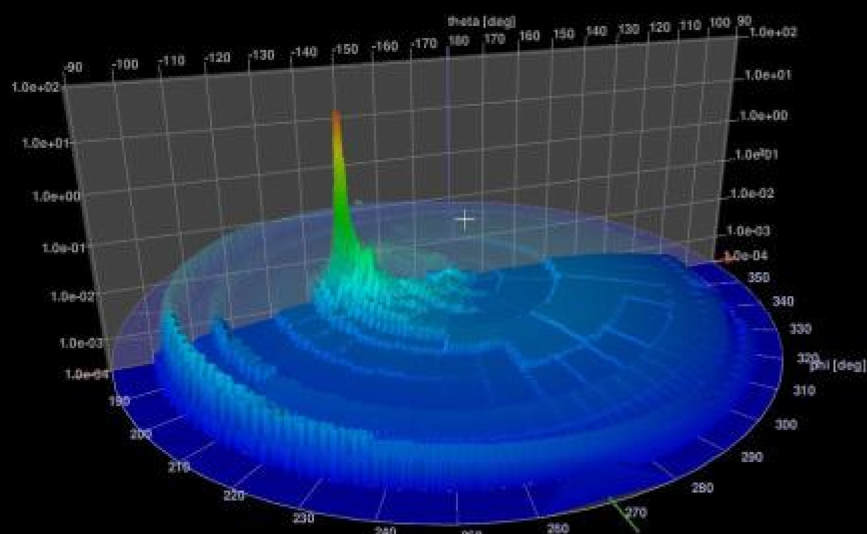
137329 n=319292/319292 col=4 [4] min=1.57e-10 max=1.34e+01 int=1.82e-02 rear,trans log deca 9

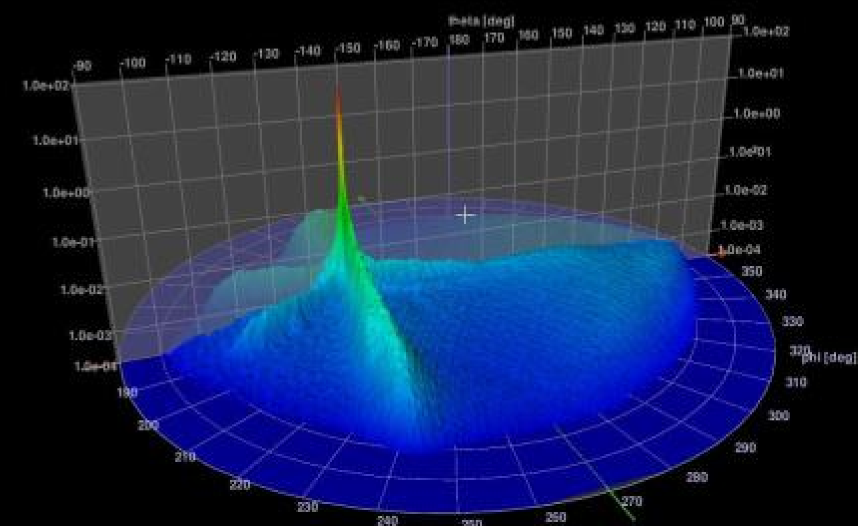
-t3, phi=0



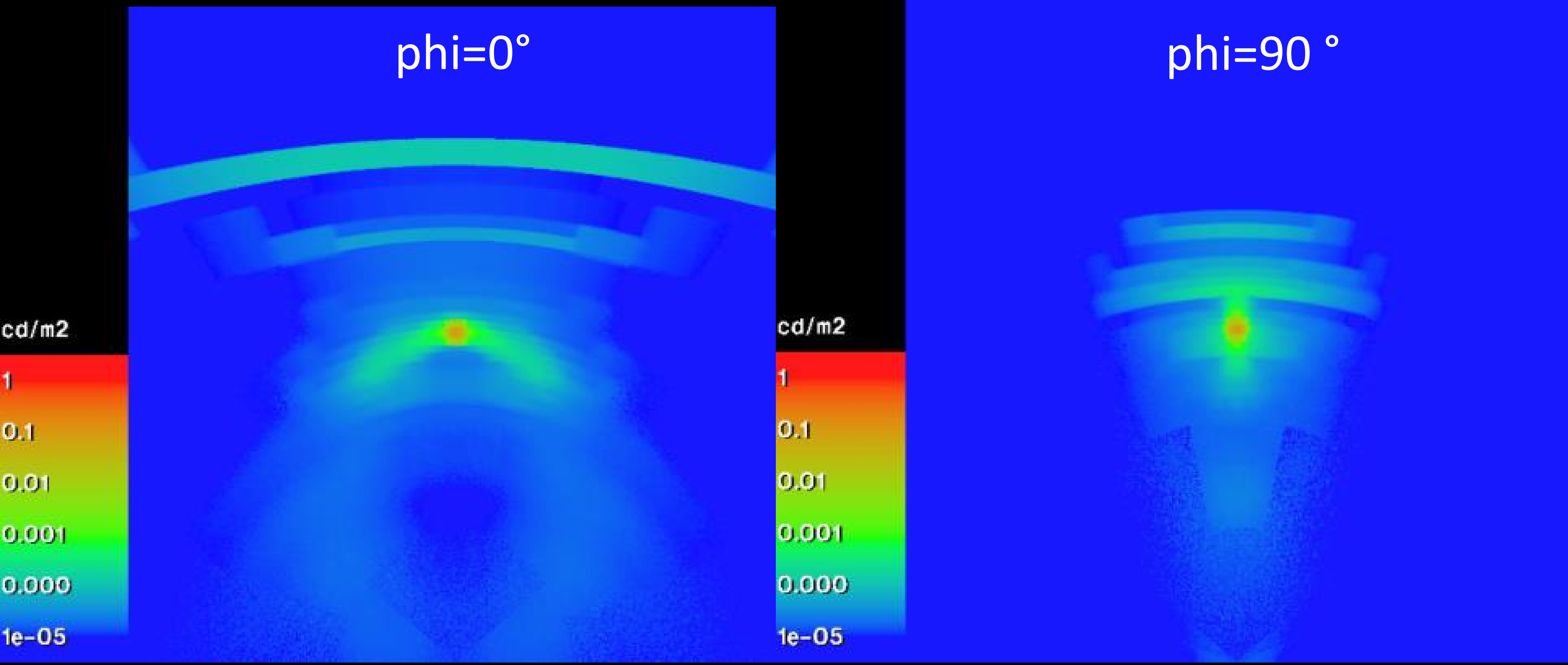
pab mountain V3.2.2

filename="BIMSOL036DSF_t_0300_0000_t4_000.dat" in=(30,0)
137329 n=319292/319292 col=3 [3] min=-1.29e-04 max=4.61e+01 int=1.48e-02 rear,trans log deca 9

Measured data



pab mountain V3.2.2



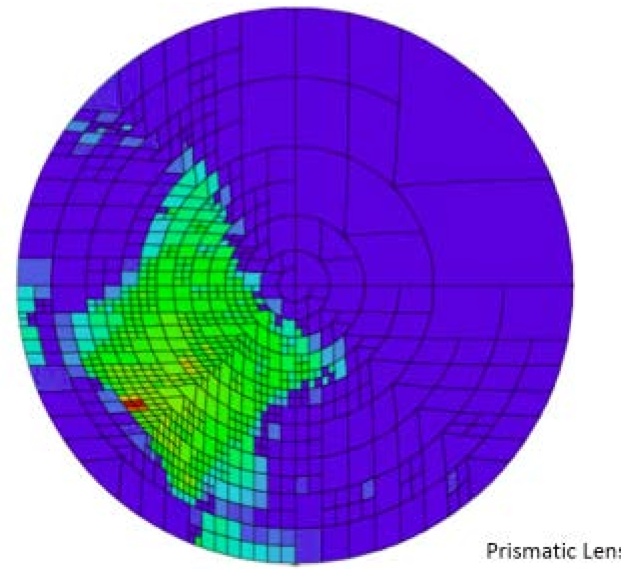
Rendering anisotropic materials as an isotropic material:

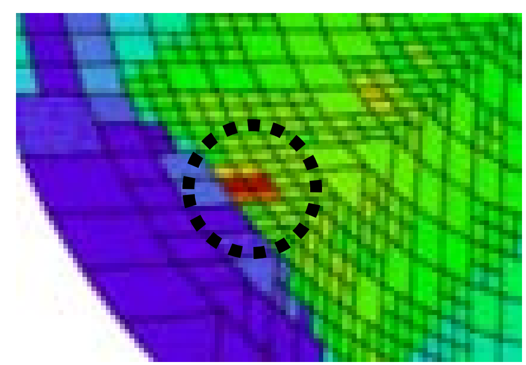
Affects orientation of glare sources, depending on phi angle assumed for the tensor tree XML.

Images: HSLU

Step 4. Generate image using the five-phase method with peak extraction

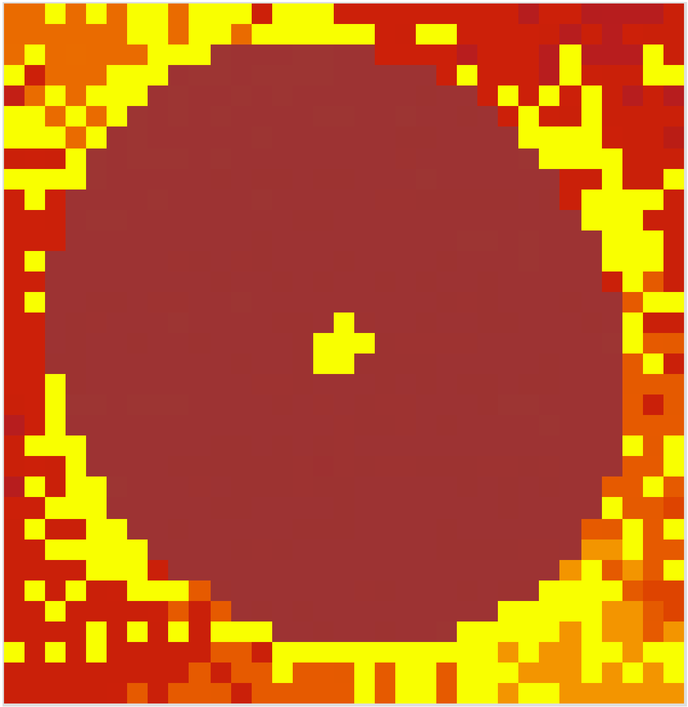
- What is "peak extraction"?
  - Detect when there is a strong peak near the "through" specular direction
  - If the magnitude of this peak relative to the surrounding BSDF is greater than 1.5 times the brightness of the sum of the surround then,
  - Replace the peak with a pure specular calculation for view rays and during shadow testing where all energy from direct component goes into the peak of 0.5°



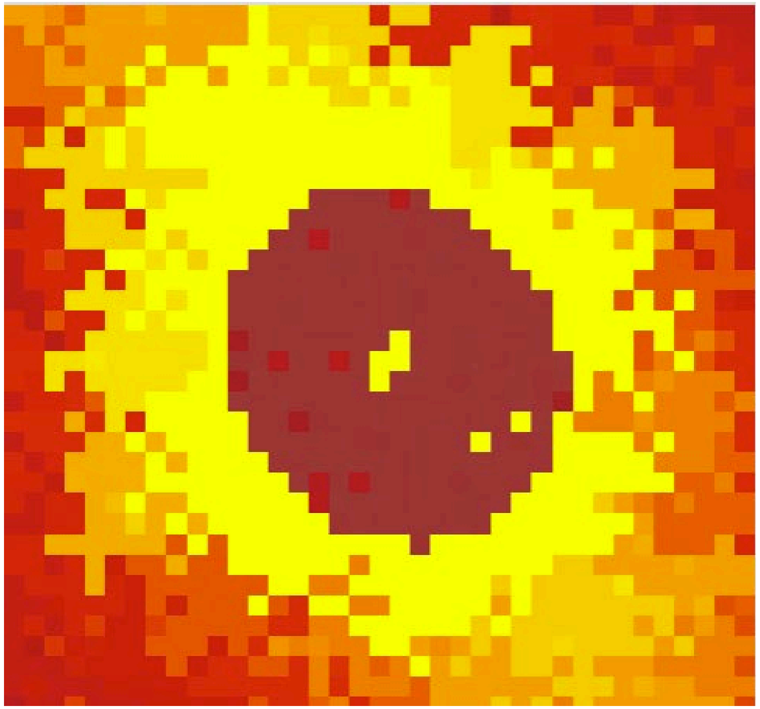


Peak is searched within a radius of 2-3 times the max resolution

Which resolution to use to properly trigger peak extraction?



-t3 6



-t3 7

Use of –t3 6 triggers peak extraction more reliably than higher-resolution tensor trees

- All energy from direct component goes into the peak of 0.5°
- Surrounding circumsolar region (dark red) shows luminance of the diffuse component

Perforated metal mesh

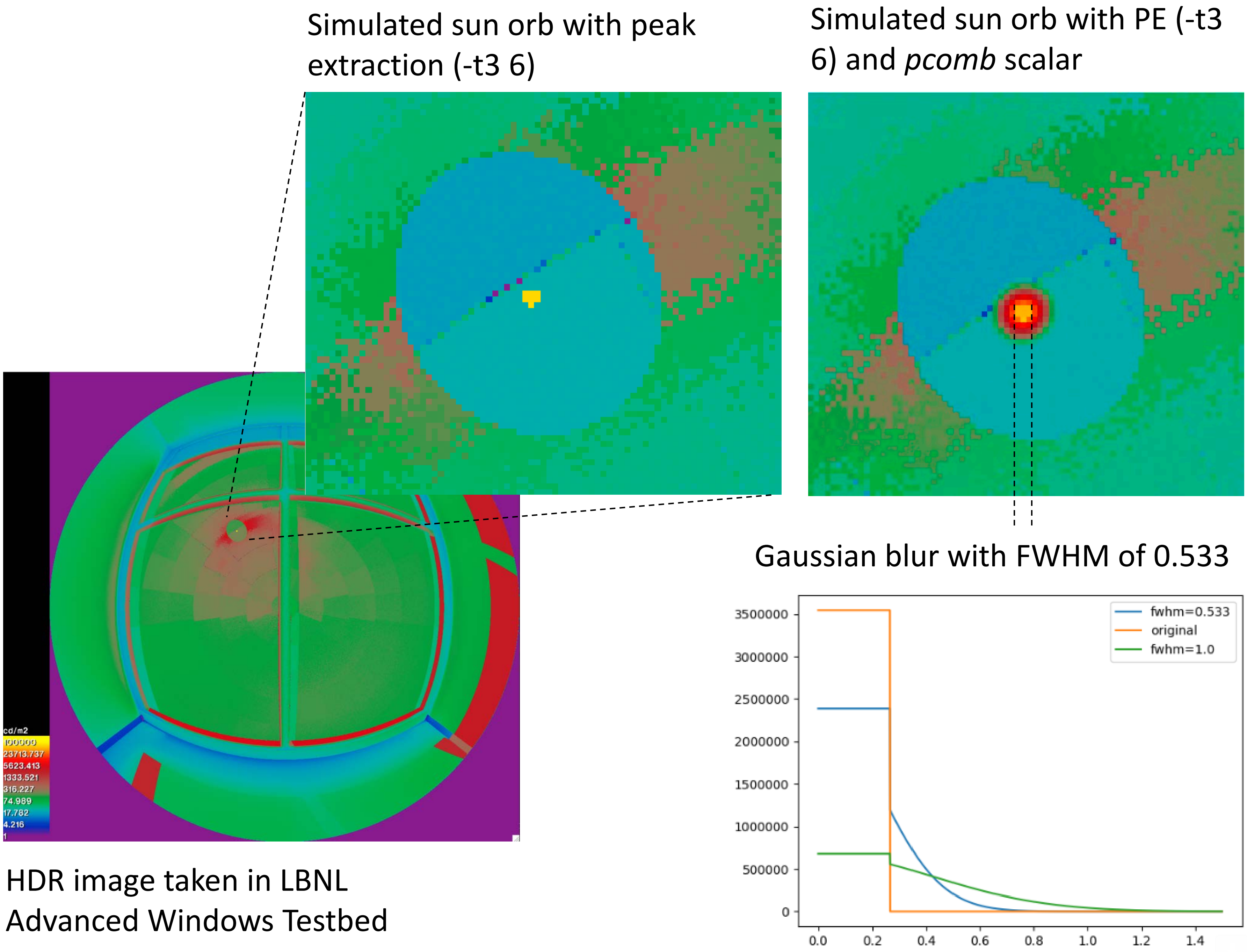
```
void aBSDF shade01
5 tensor_tree.xml 0 0 1 .
0
0
```

Daylighting film with redirected and specular components

Step 5. DGP: Post-process image using peak scalar to simulate optics of camera lens

- DGP is based on HDR images correlated to human subject responses
- Reduce contrast across sun luminance and circumsolar region using peak veiling scalar with *pcomb*
- Basis for scalar
  - scattering within camera lens,
  - forward scattering from fabric that was within the solid angle of the PE algorithm

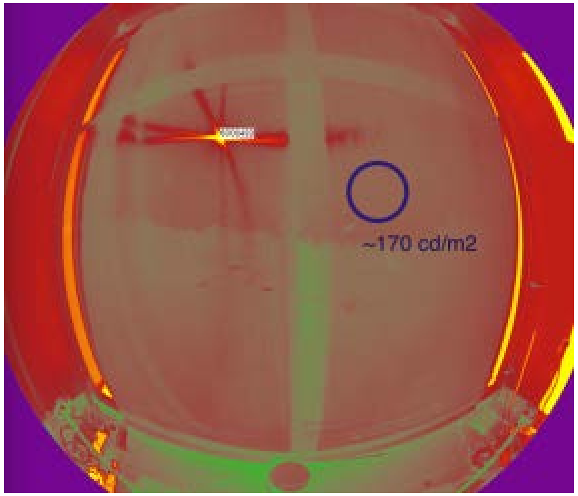
Image: EPFL


Simulated sun orb with peak extraction (-t3 6)
Simulated sun orb with PE (-t3 6) and *pcomb* scalar
Gaussian blur with FWHM of 0.533
cd/m2
100000
23713.737
5623.413
1333.521
316.227
74.989
17.782
4.216
1
HDR image taken in LBNL Advanced Windows Testbed
fwhm=0.533
original
fwhm=1.0
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

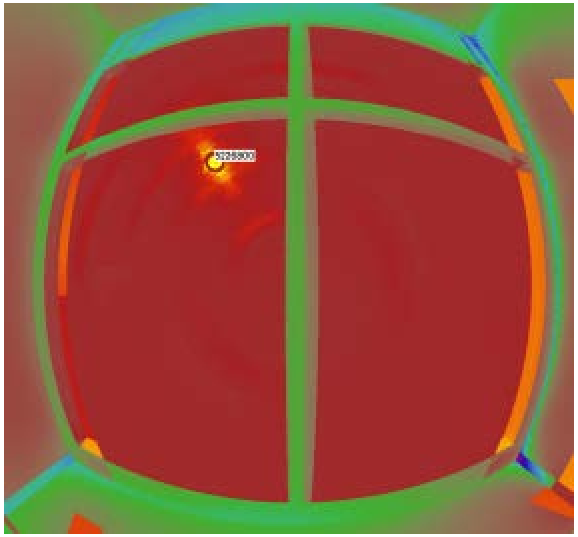
Step 6. Use *evalglare* to determine DGP

```
evalglare -vta -vv 180 -vh 180 view1.hdr
```

- Skycam luminance data
- Image size: 1000x1000 pixels
- Glare sources:
  - Lpixel is greater than 5 times Lscene-avg
  - Sun source pulled out as a separate glare source (Lpixel > 50,000 cd/m^2)



Camera photo in testbed



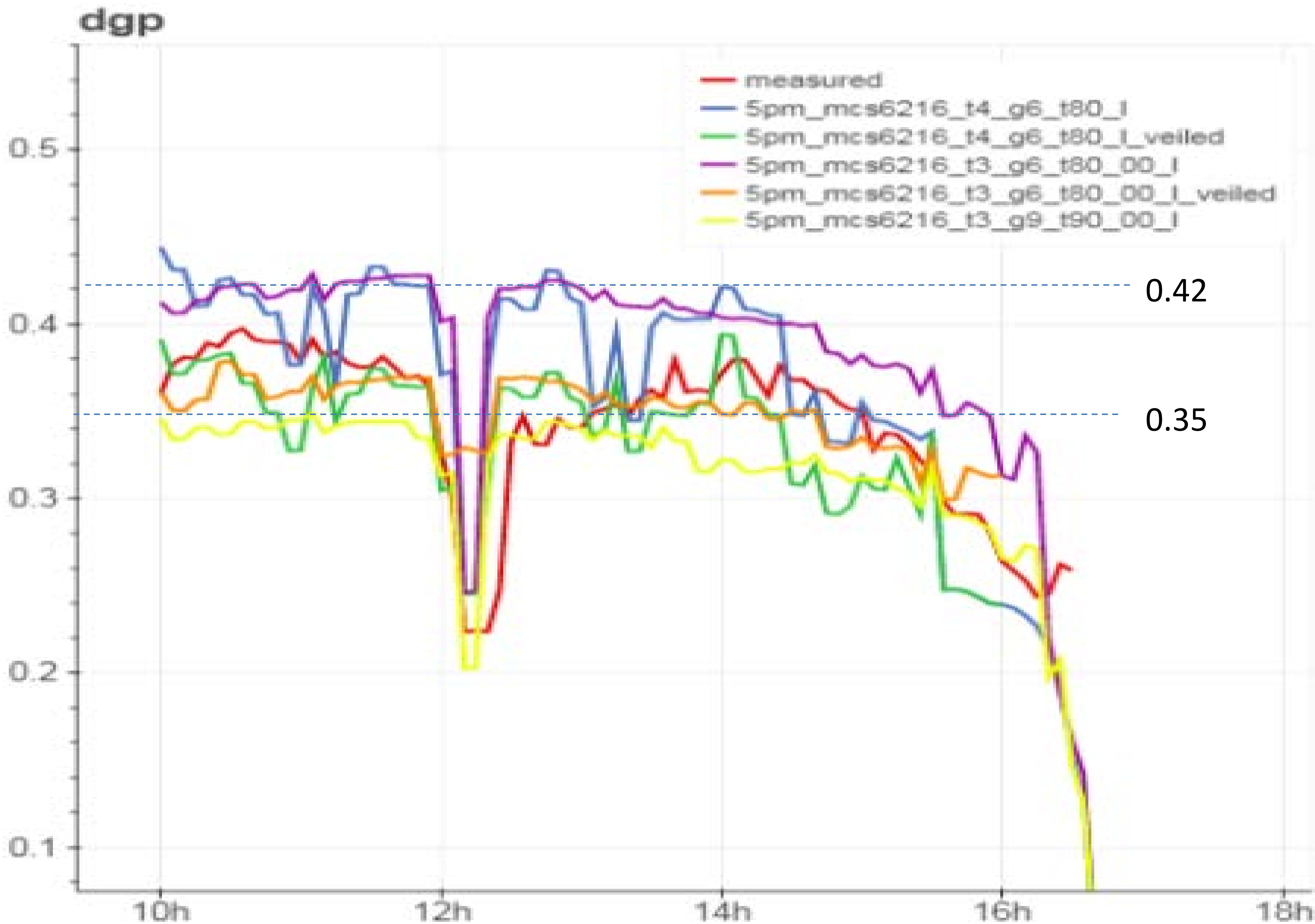
Rendering

Step 7. Compare simulated DGP to field measured DGP and assess error

$$DGP = c_1 \cdot E_v + c_2 \cdot \log(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{a_1} \cdot P_i^2}) + c_3$$

- Field measured HDR image capture
  - Neutral density filter
  - 7-8 exposures under stable sky conditions
  - Vertical illuminance measured at the camera lens
  - No pixel saturation

LBNL Advanced Windows Testbed


dgp
measured
5pm_mcs6216_t4_g6_t80_l
5pm_mcs6216_t4_g6_t80_l_veiled
5pm_mcs6216_t3_g6_t80_00_l
5pm_mcs6216_t3_g6_t80_00_l_veiled
5pm_mcs6216_t3_g9_t90_00_l
0.42
0.35
0.5
0.4
0.3
0.2
0.1
10h
12h
14h
16h
18h

DGP error

	rmse	rmse(%)
anisotropic_3deg_80	0.0416	11.6%
anisotropic_3deg_80_veil	0.0316	8.8%
isotropic_3deg_80	0.0489	13.6%
isotropic_3deg_80_veil	0.0196	5.5%
isotropic_0.3deg_90_noPE	0.0363	10.1%

How critical is accuracy for:

Product differentiation through rating and labeling

New product development

Design decisionmaking

National Fenestration Rating Council

Attachments Energy Rating Council
AERC

NFRC National Fenestration Rating Council® CERTIFIED	World's Best Window Co. Millennium 2000+ Vinyl-Clad Wood Frame Double Glazing • Argon Fill • Low E Product Type: **Vertical Slider**
ENERGY PERFORMANCE RATINGS	
U-Factor (U.S./I-P) **0.35**	Solar Heat Gain Coefficient **0.32**
ADDITIONAL PERFORMANCE RATINGS	
Visible Transmittance **0.51**	Air Leakage (U.S./I-P) **0.2**
Condensation Resistance **51**	—

Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. NFRC does not recommend any product and does not warrant the suitability of any product for any specific use. Consult manufacturer's literature for other product performance information. www.nfrc.org

Conclusions to date

- Pilot study helped us identify several critical measurement and modeling parameters that are important to get right
- We need to confirm generality of this full workflow for generating and validating BSDFs based on measured PG-II data
- Simpler, empirically-derived models derived from this more extensive workflow are a likely cost-effective alternative for generating high-resolution BSDFs
- More work to be done within IEA SHC Task 61!

Congratulations, Greg, on the Velux Award!

Depiction of my 30-year relationship with Greg Ward (Greg = Hobbes)

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