Now with 67% more phases!

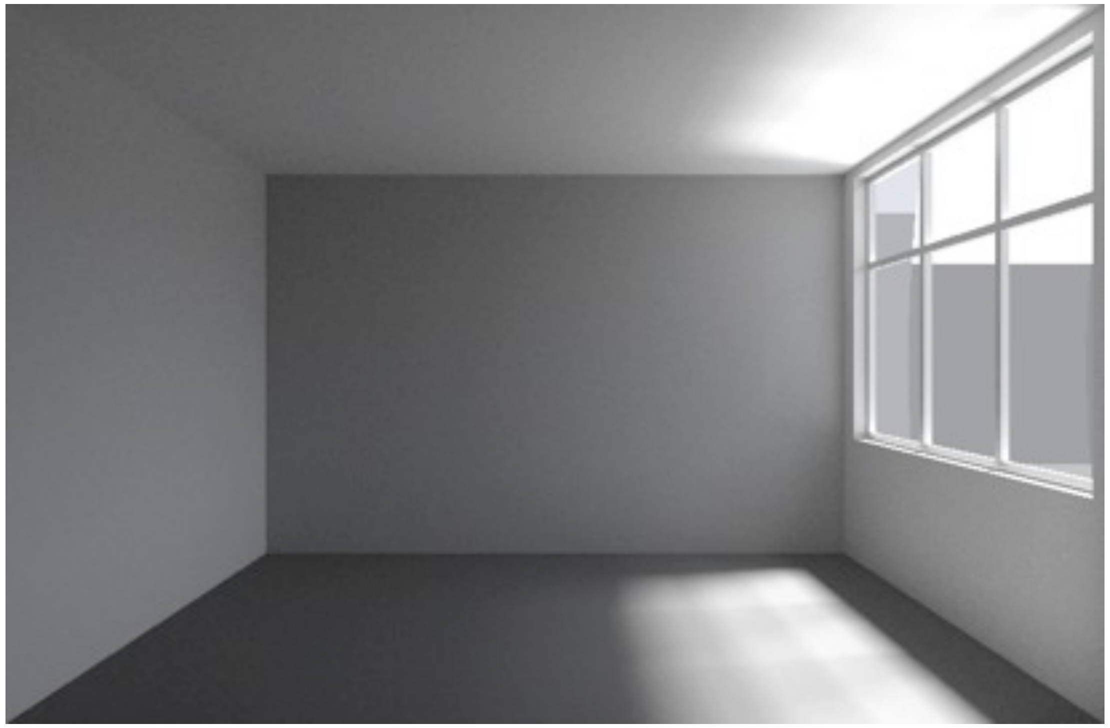
The 5-phase method

Andy McNeil, LBNL
Radiance Workshop
11 August 2013

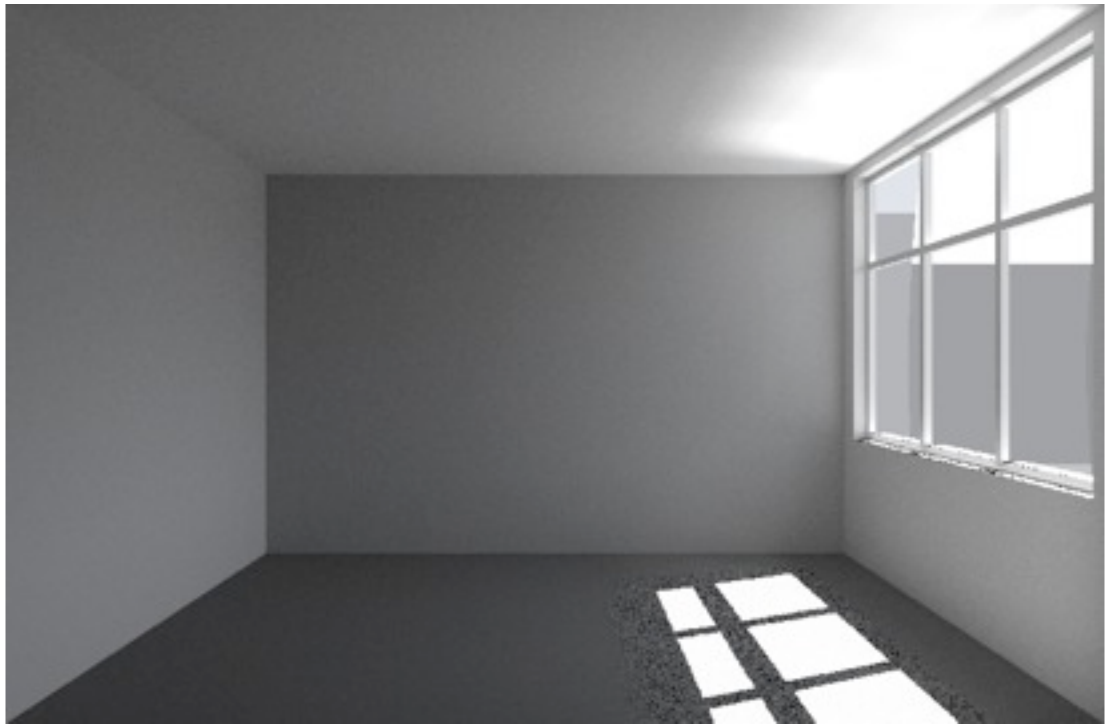
BERKELEY LAB
Lawrence Berkeley National Laboratory

Why do we need more %@#!$ phases?

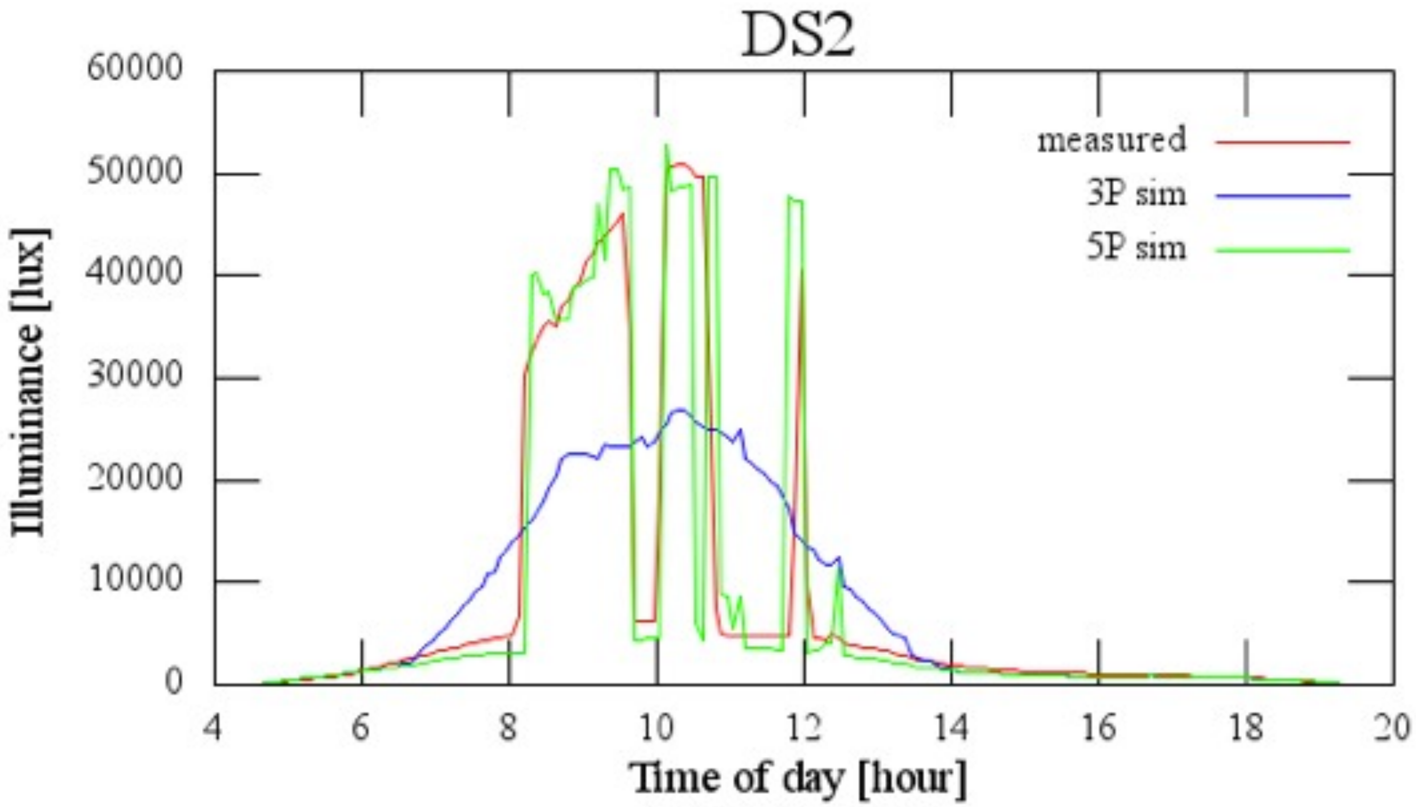
- The three-phase method disperses energy passing through the window.
- Particularly evident with direct solar component.
- Five-phase method uses high-resolution BSDF or actual BSDF geometry for direct solar component.



3-phase simulation result

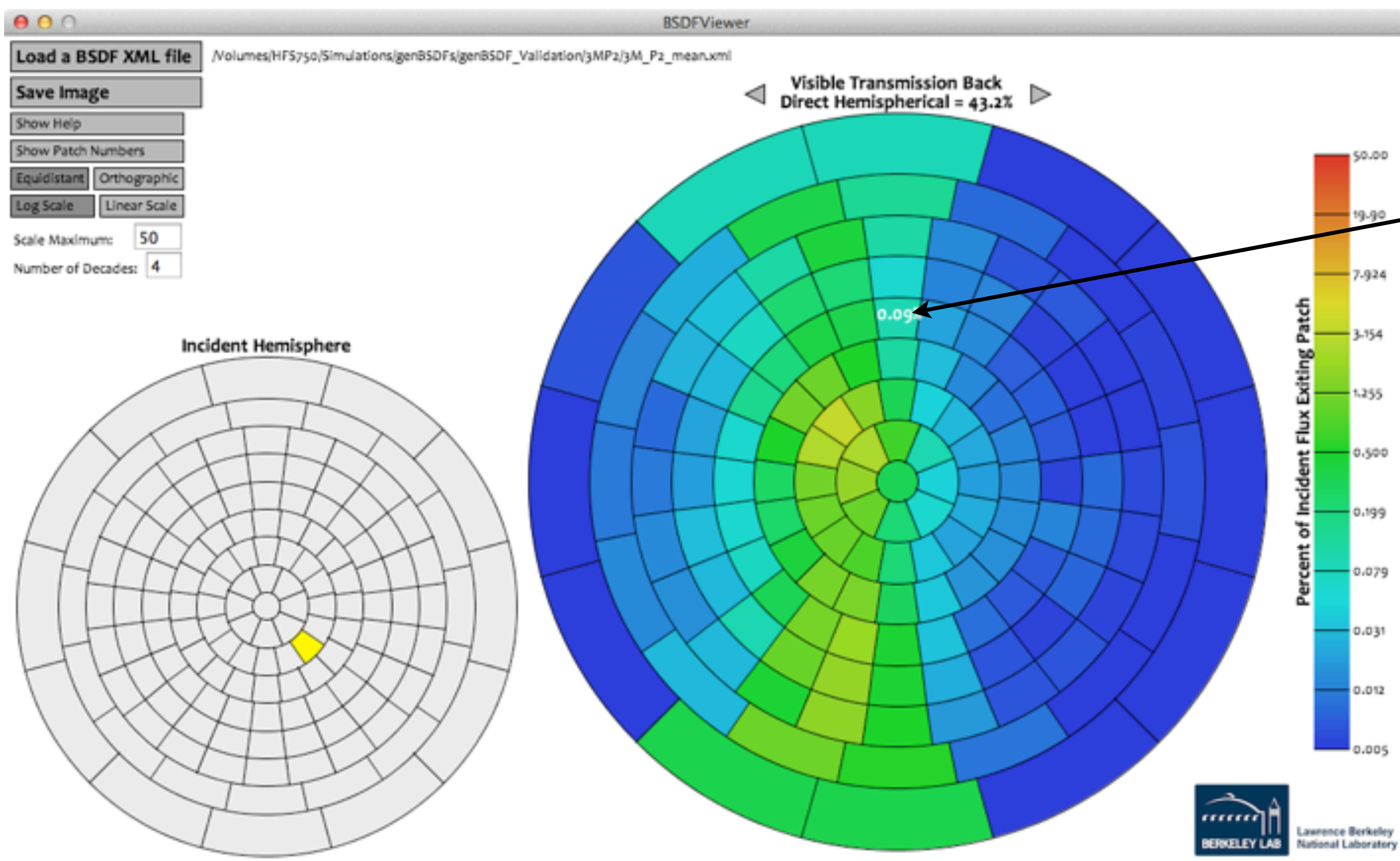


5-phase simulation result



Why can’t we do a daylight coefficient simulation with CFS?

- Sky is a glow material - stochastically sampled
- BSDF rays are emitted based on importance
- No deterministic rays for sun



- ~ 14 Reinhart patches to 1 Klems patch
- 0.09% / 43.2% from BSDF
- 6,720 ambient rays ~ 1 sample/ Reinhart patch.
- 0.09% of 100,000 lux = 90 lux

The Equations

The 3-Phase Equation:

$$I_{3ph} = VTDS$$

The 5-phase Equation:

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

Direct sun calculated using high-resolution BSDF or system geometry.

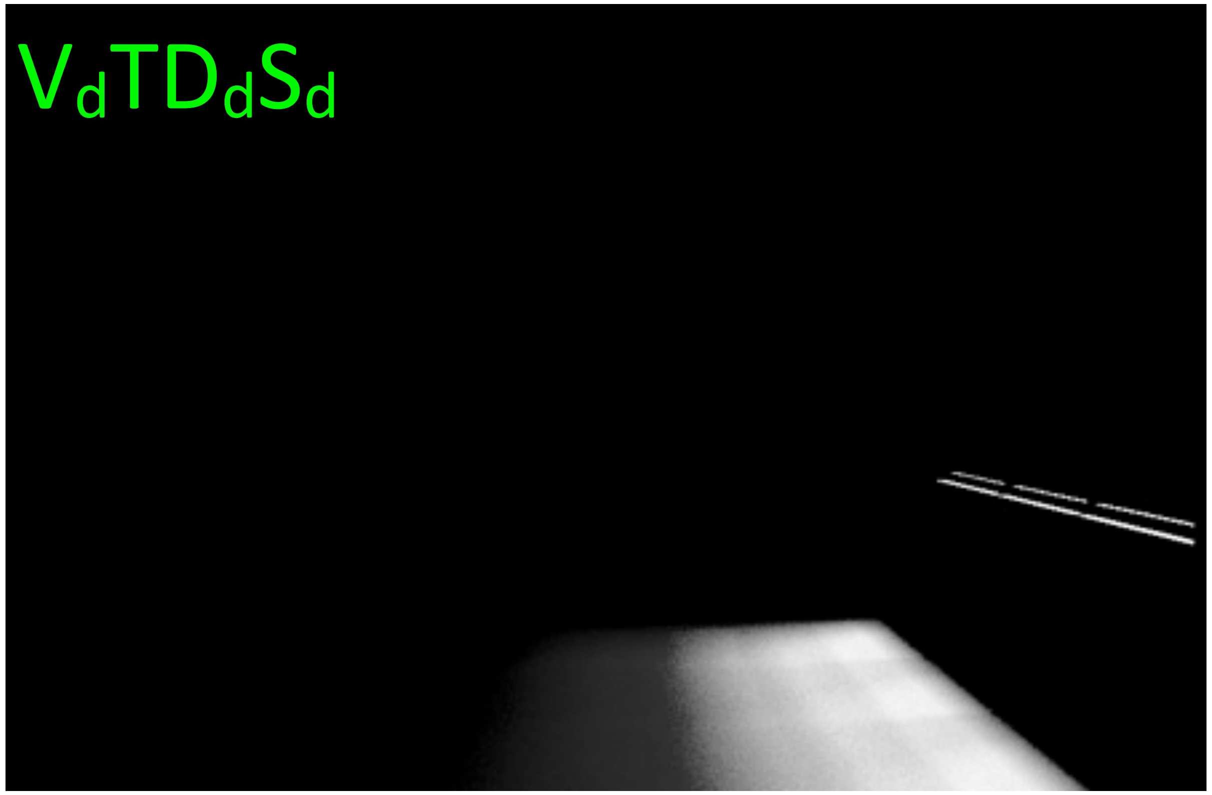
Direct sun component calculated using the 3-phase method.

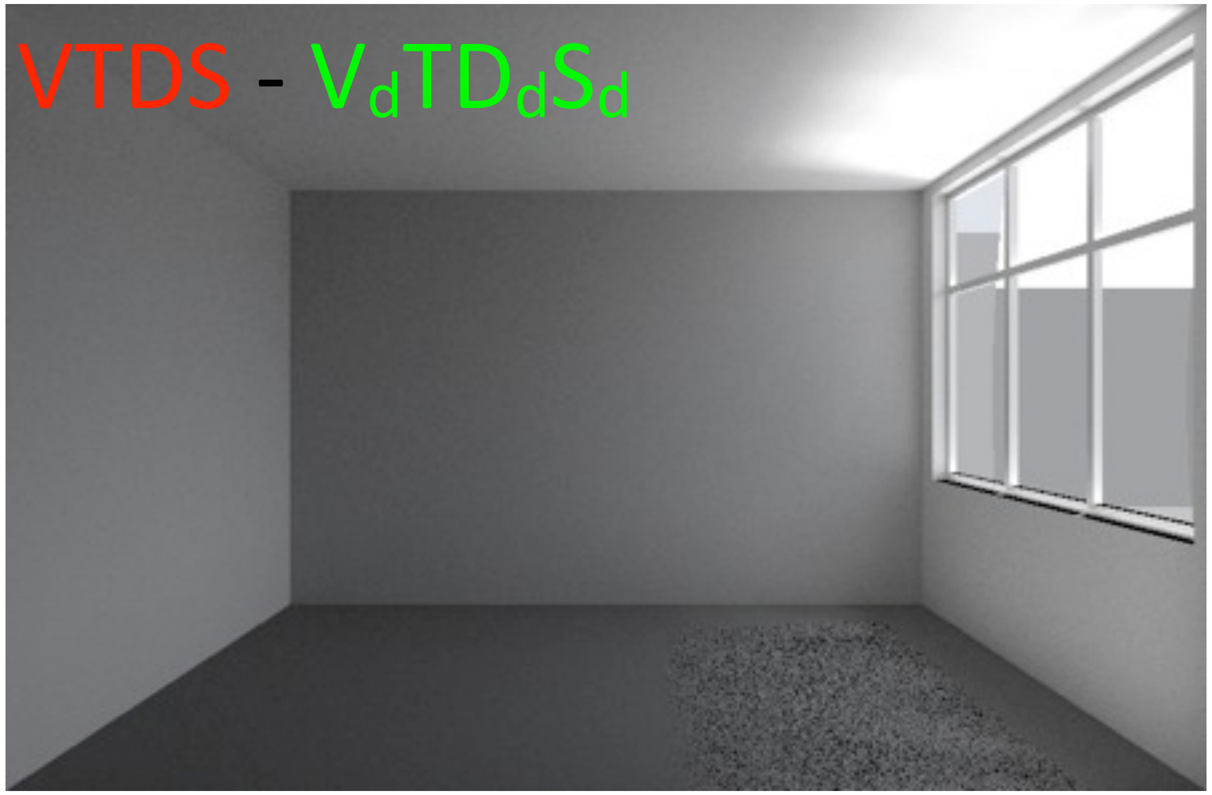
3-phase simulation.

$I_{5ph} = VTDS - V_dTD_dS_d + C_{ds}S_{sun}$

Graphically

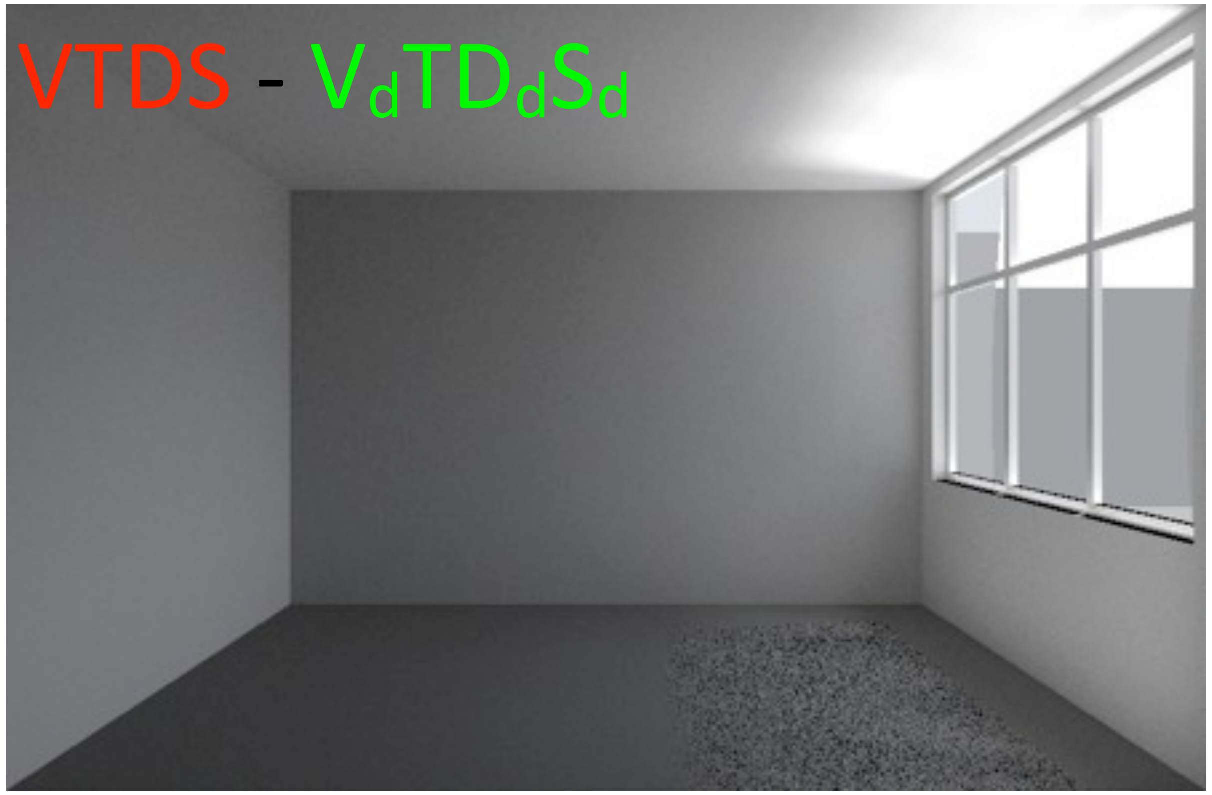
-



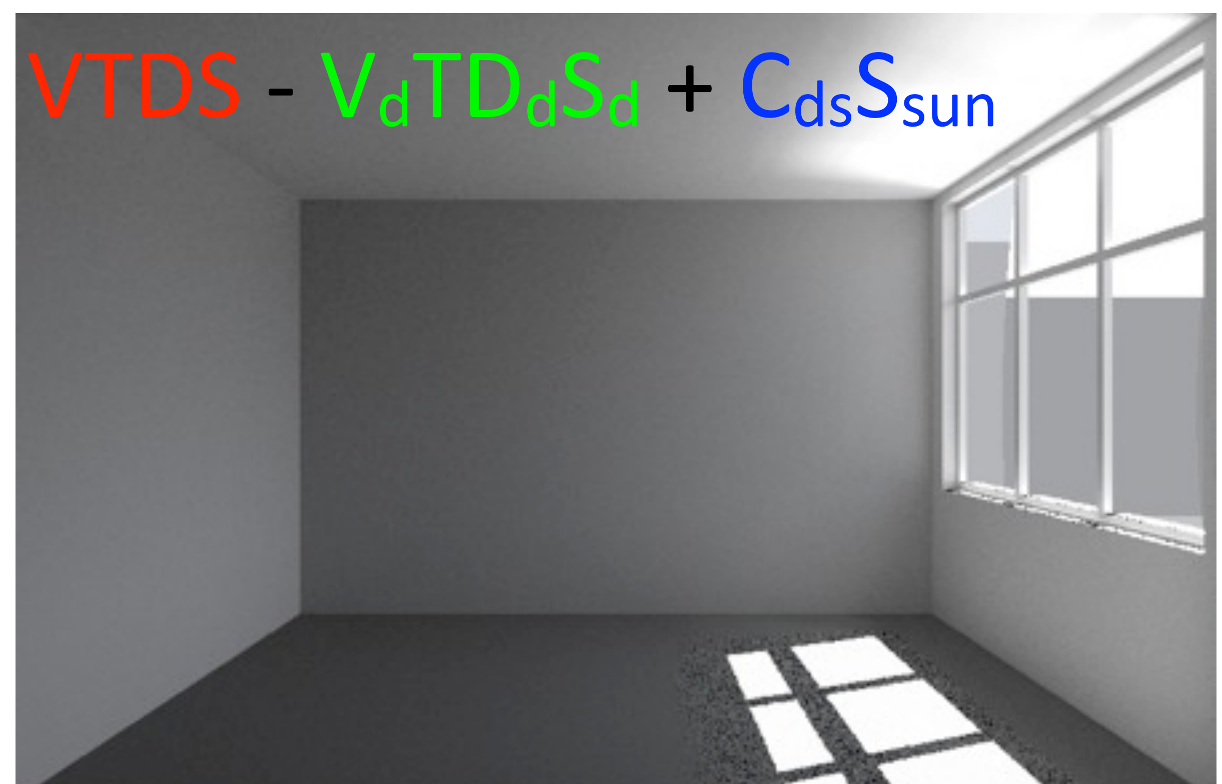


$I_{5ph} = VTDS - V_dTD_dS_d + C_{ds}S_{sun}$

Graphically



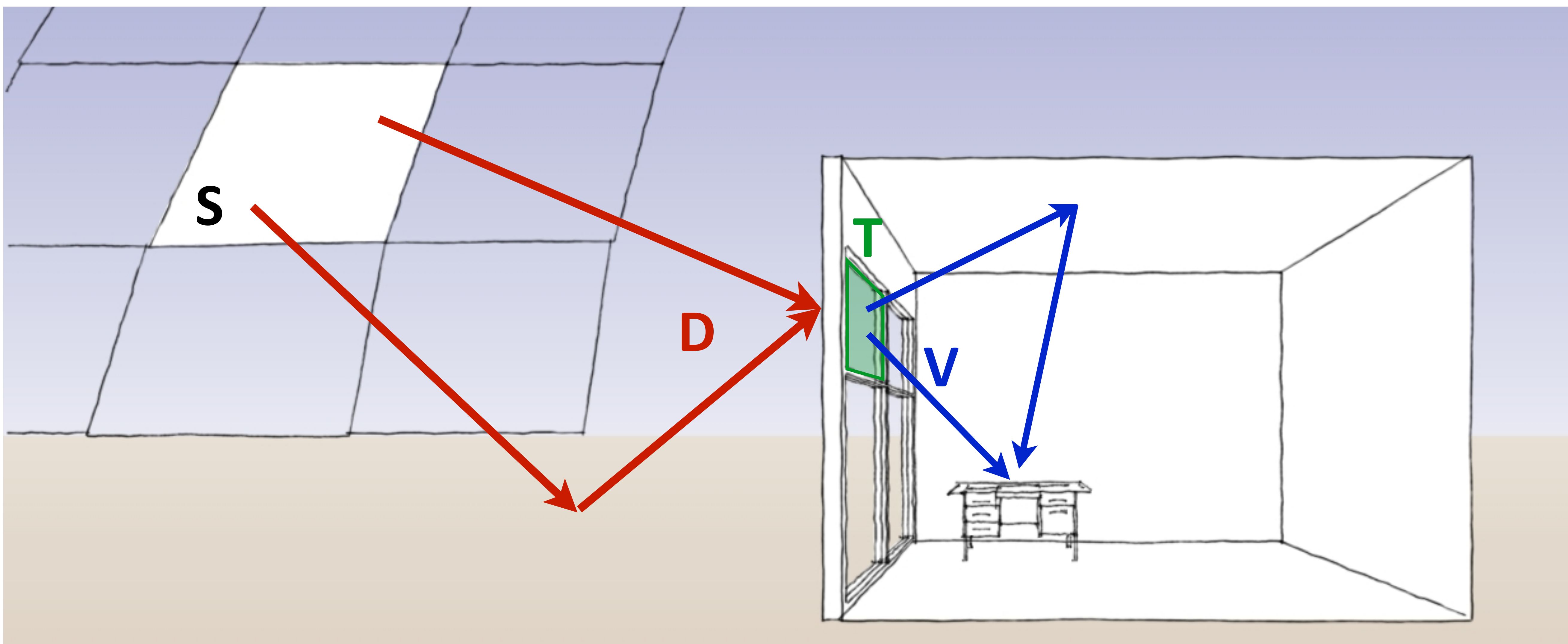
+



$I_{5ph} = VTDS - V_dTD_dS_d + C_{ds}S_{sun}$

First Term: 3-phase (review)

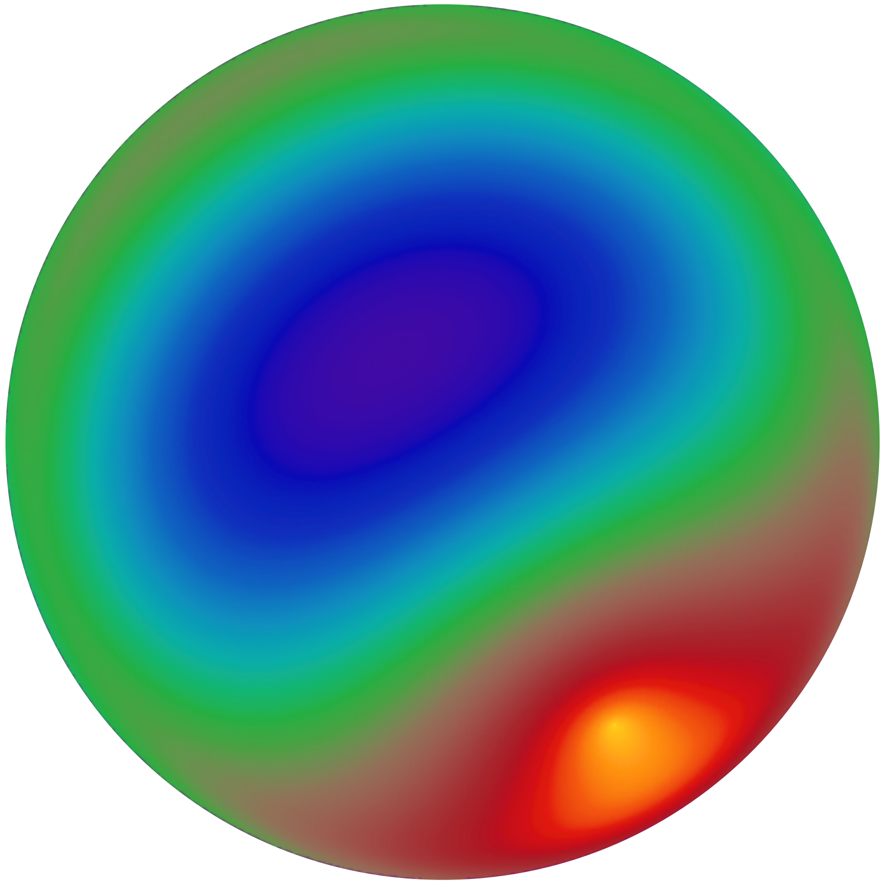
V = View Matrix (interior)
T = Transmission Matrix (BSDF)
D = Daylight Matrix (exterior)
S = Sky Matrix



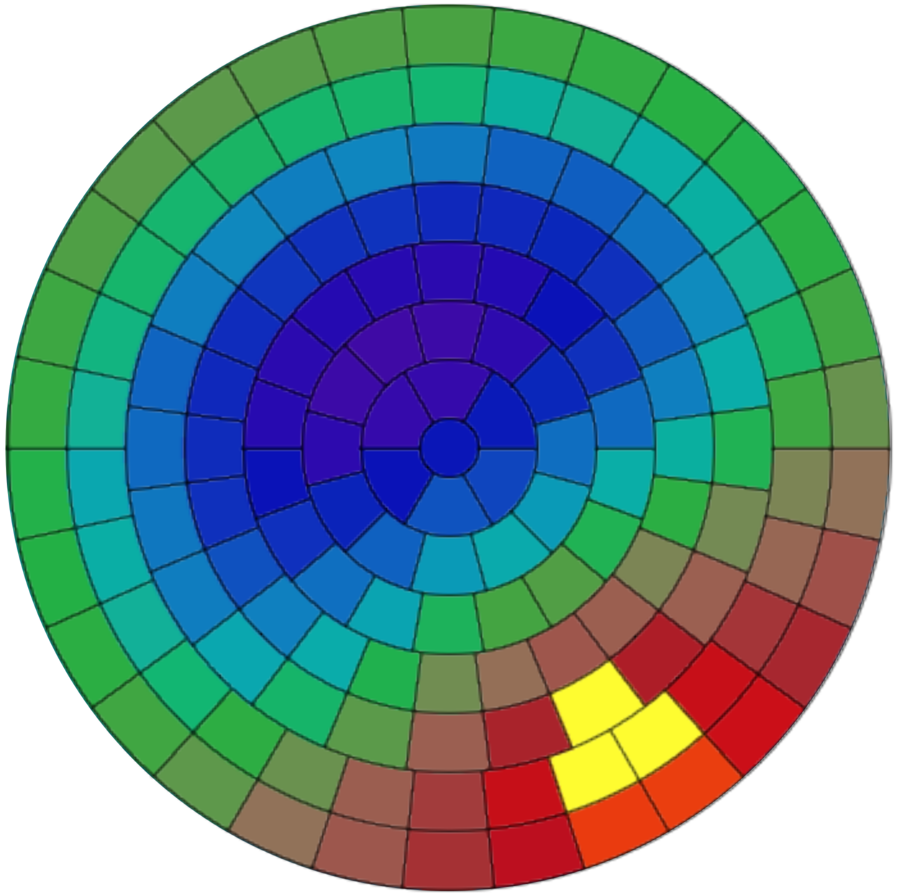
Sky matrix (S)

A sky vector contains average sky luminance in a discretized patch. A sky matrix is a series of sky vectors encompassing many time steps.

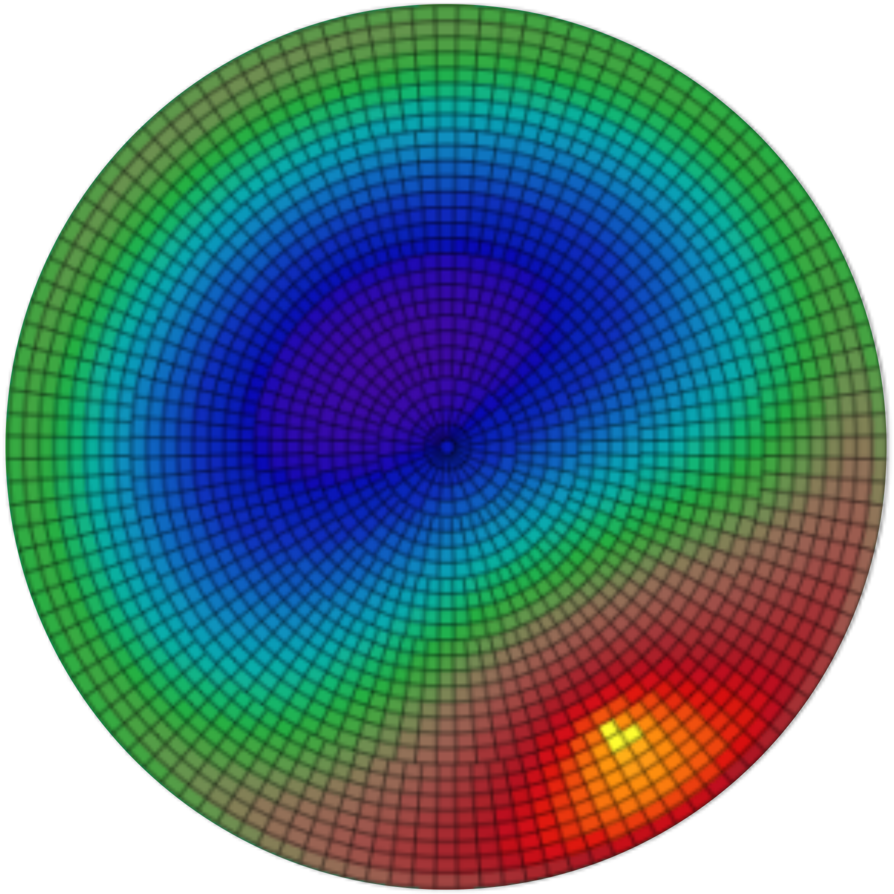
gendaymtx was recently added to Radiance to create a sky matrix from a *.wea weather data file.



Sky Luminance Gradient



Discretized Sky Luminance (Tregenza)



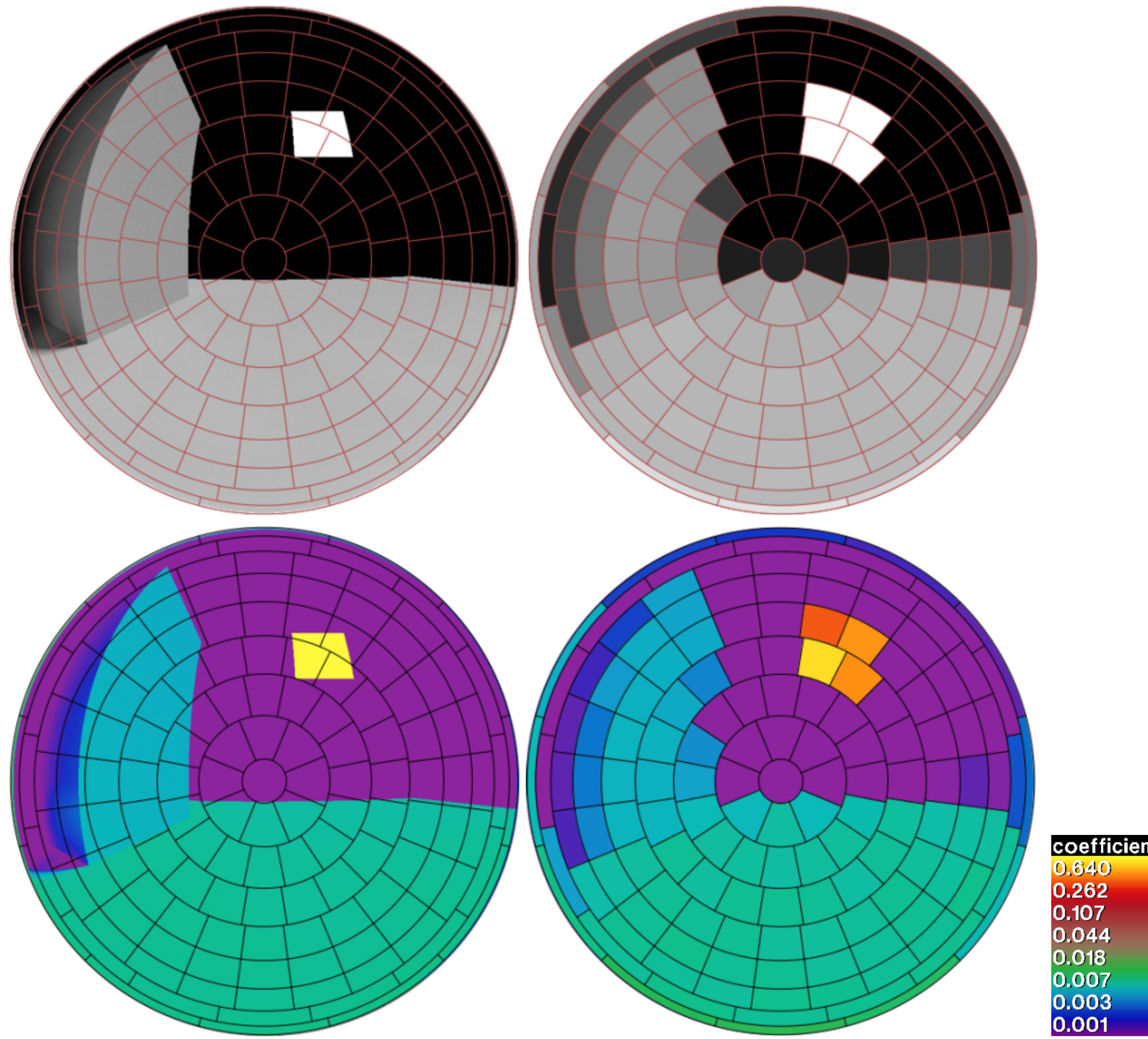
Discretized Sky Luminance (Reinhart MF:4)

$I_{5ph} = VTDS - V_dTD_dS_d + C_{ds}S_{sun}$

Daylight matrix (D)

The daylight matrix contains coefficients relating energy leaving sky patches with energy incident on a window in a klems directional bin.

An building with nearby obstruction

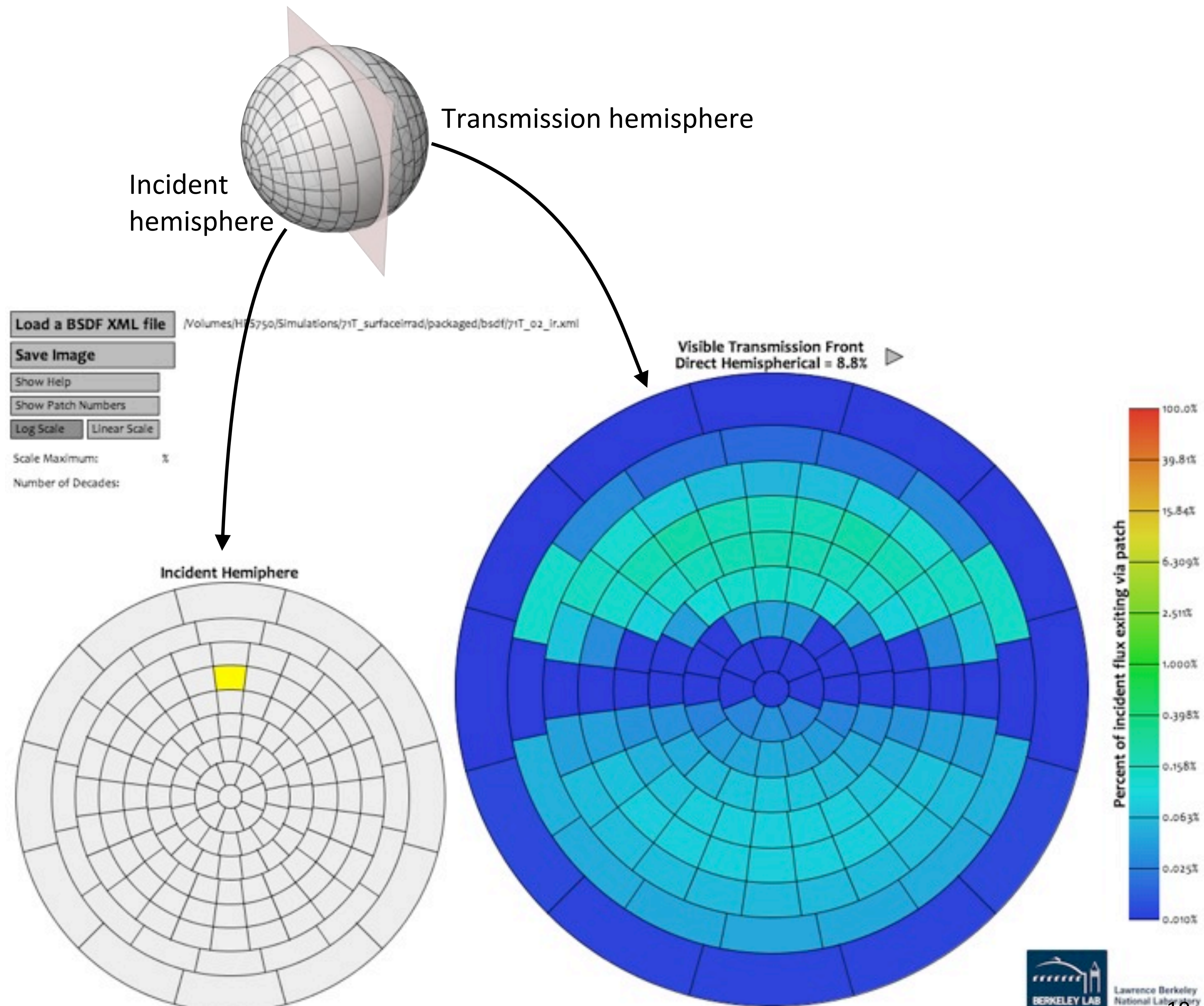


View through Klems screen

Depiction of Daylight matrix values for one sky patch.

Transmission matrix (T) / BSDF

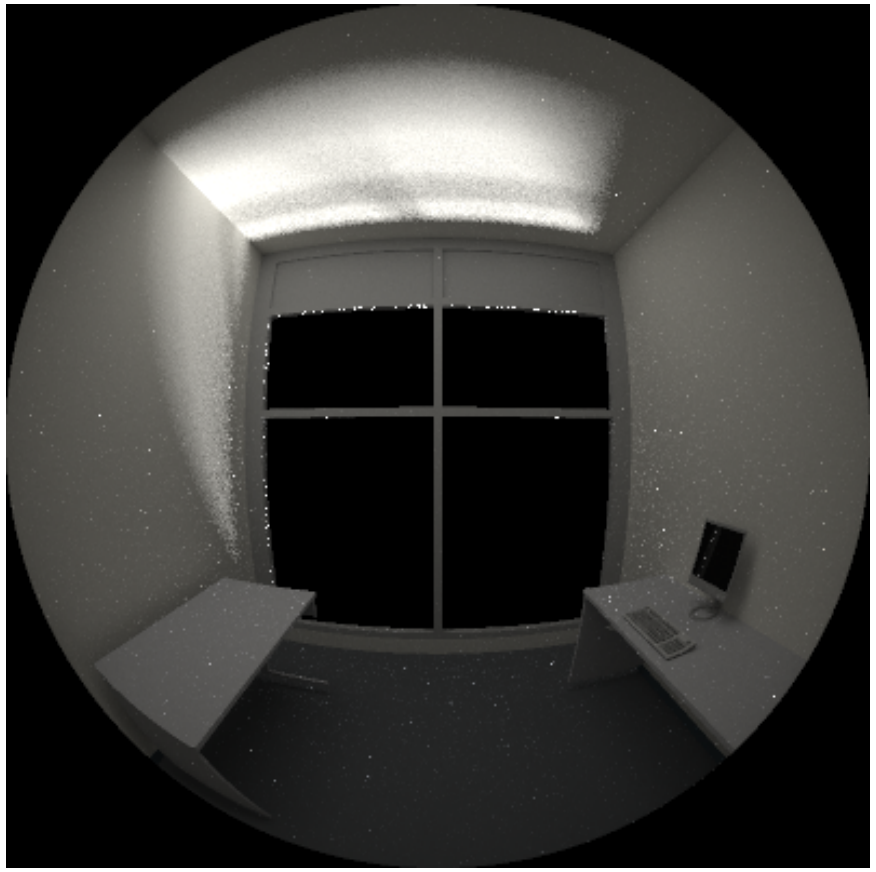
The transmission matrix contains coefficients relating energy incident on a window and energy leaving a window in Klems directional bins.

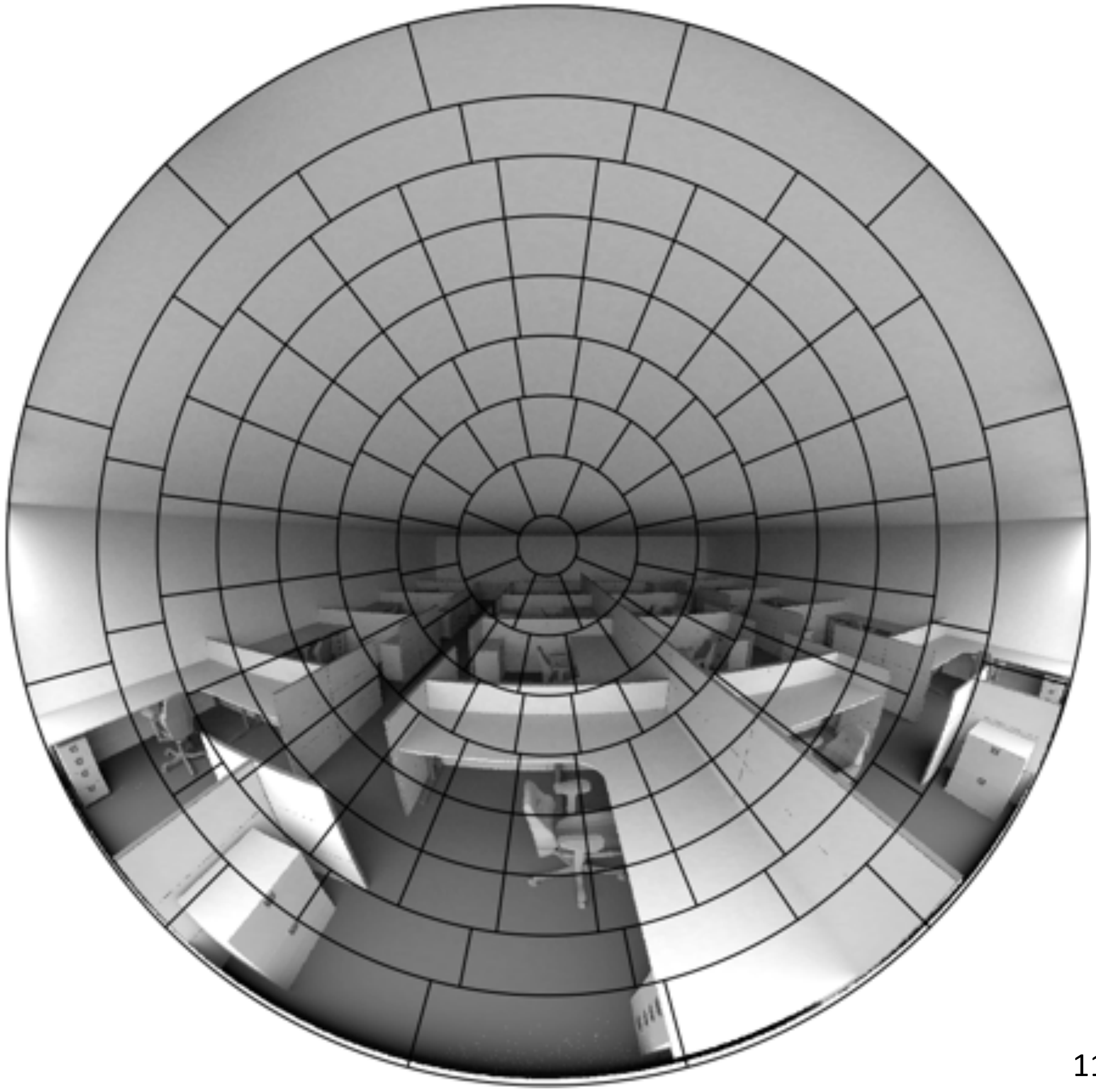


$I_{5ph} = VTDS - V_d T D_d S_d + C_{ds} S_{sun}$

View matrix (V)

The view matrix contains coefficients relating energy leaving a window in klems direction bins energy incident at a sensor point or image pixel.





Recommendations for View matrix

- Use glow material for window geometry - improves sampling of large / nearby windows.
- Increase -ad substantially
- Set -lw to ad^{-1}

parameter	default setting	recommended*
ab	1	**9**
ad	350	**16,384**
lw	2.00E-03	**6.10e-5 (ad^{-1})**

* recommendations based on BRE validation space

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

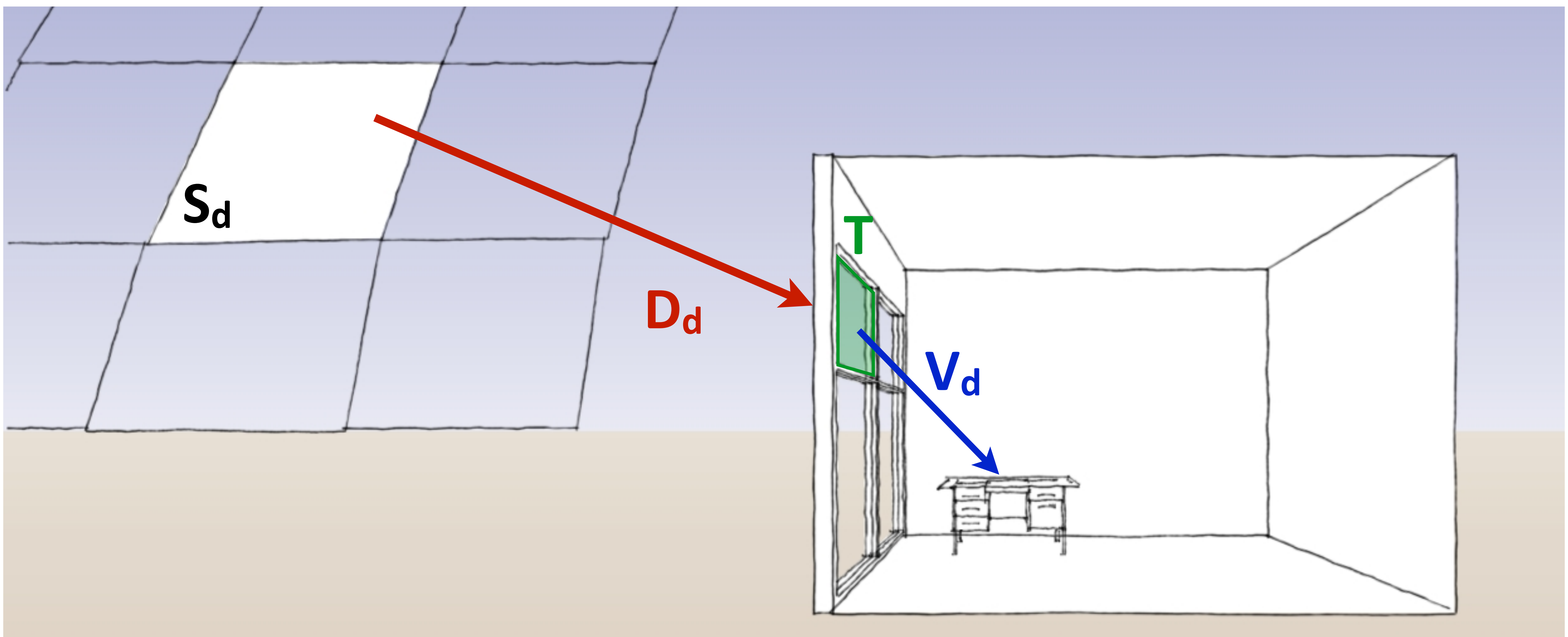
Second Term:
Direct component of 3-phase

V_d = Direct View Matrix (interior)

T = Transmission Matrix (BSDF)

D_d = Direct Daylight Matrix (exterior)

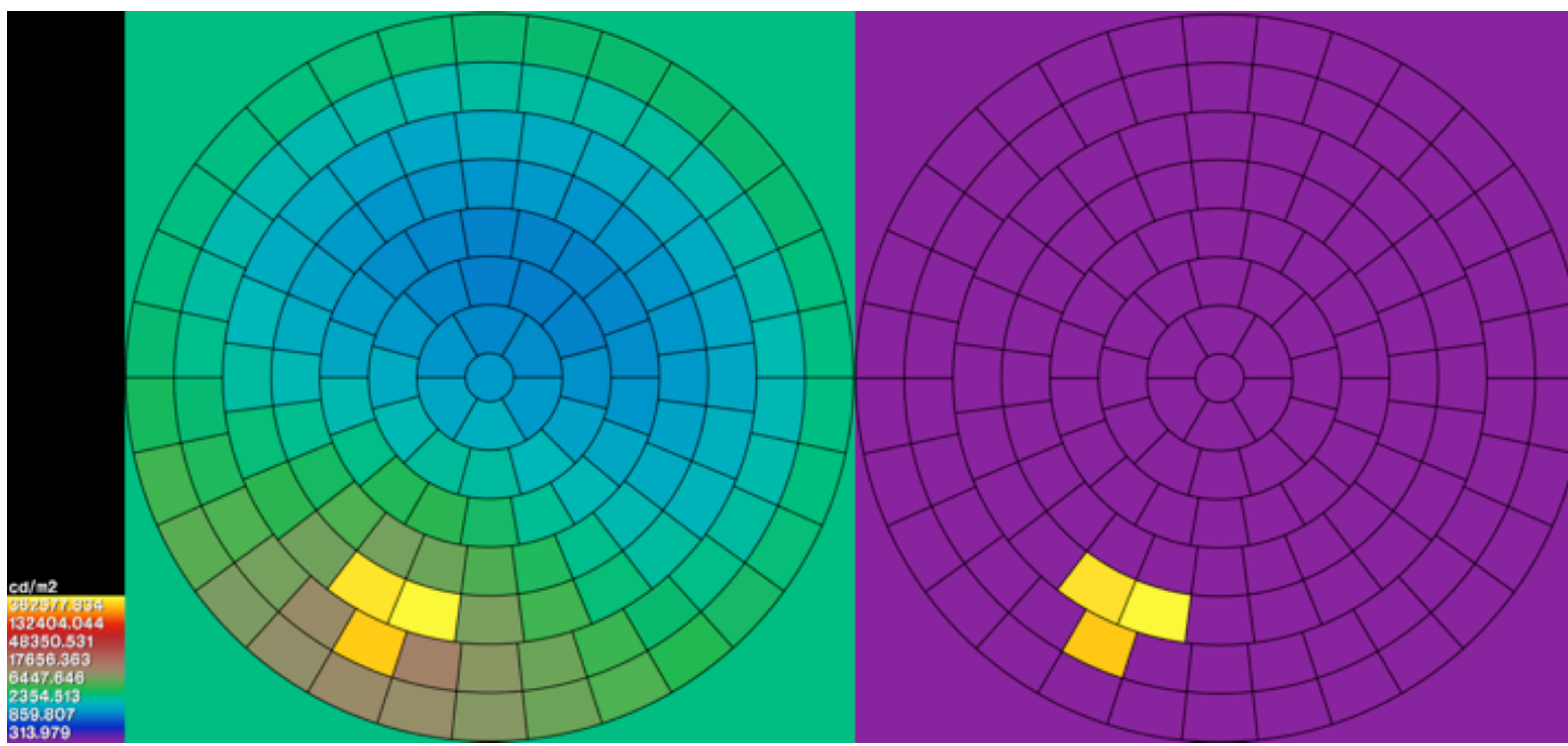
S_d = Direct Sky Matrix



Direct Sky Matrix (S_d)

The direct sky matrix contains only luminance from the sun.

gendaymtx has a -d option to generate a direct only sky matrix.



$I_{5ph} = VTDS - V_dTD_dS_d + C_{ds}S_{sun}$

Daylight matrix (Dd)

The daylight matrix contains coefficients relating energy leaving sky patches with energy incident on a window in a klems directional bin, without any external inter-reflection.

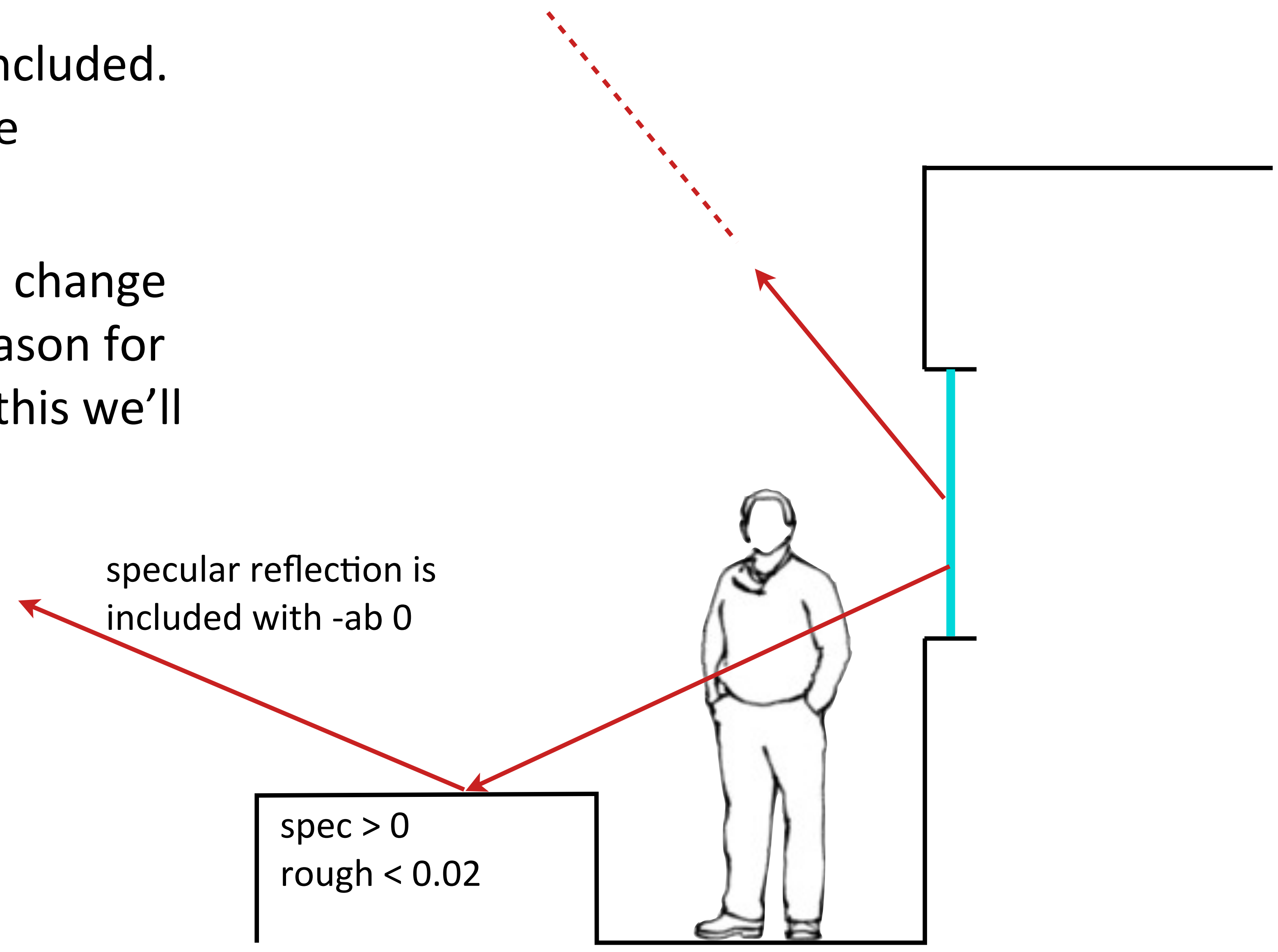
rcontrib is used with -ab 0

Even with -ab 0 specular reflections are included. This is not desired so materials need to be modified for this model.

So we create a material called 'black' and change materials of all geometry to black (the reason for using black will make sense later). to do this we'll use:

xform -m black geom.rad | oconv

genkelmsamp | rcontrib -ab 0



Direct View matrix (V_d)

The view matrix contains coefficients relating energy leaving a window in klems direction bins that is directly incident at a sensor point or image pixel.

rcontrib is used with -ab 1

As with the direct daylight matrix, specular reflections will be included (which is unwanted) so we'll have to change the materials in the model.

xform -m black geom.rad | oconv

rcontrib -ab 1

Third Term:
Direct sun component

C_{ds} = Sun Coefficient Matrix

S_{sun} = Sun Matrix

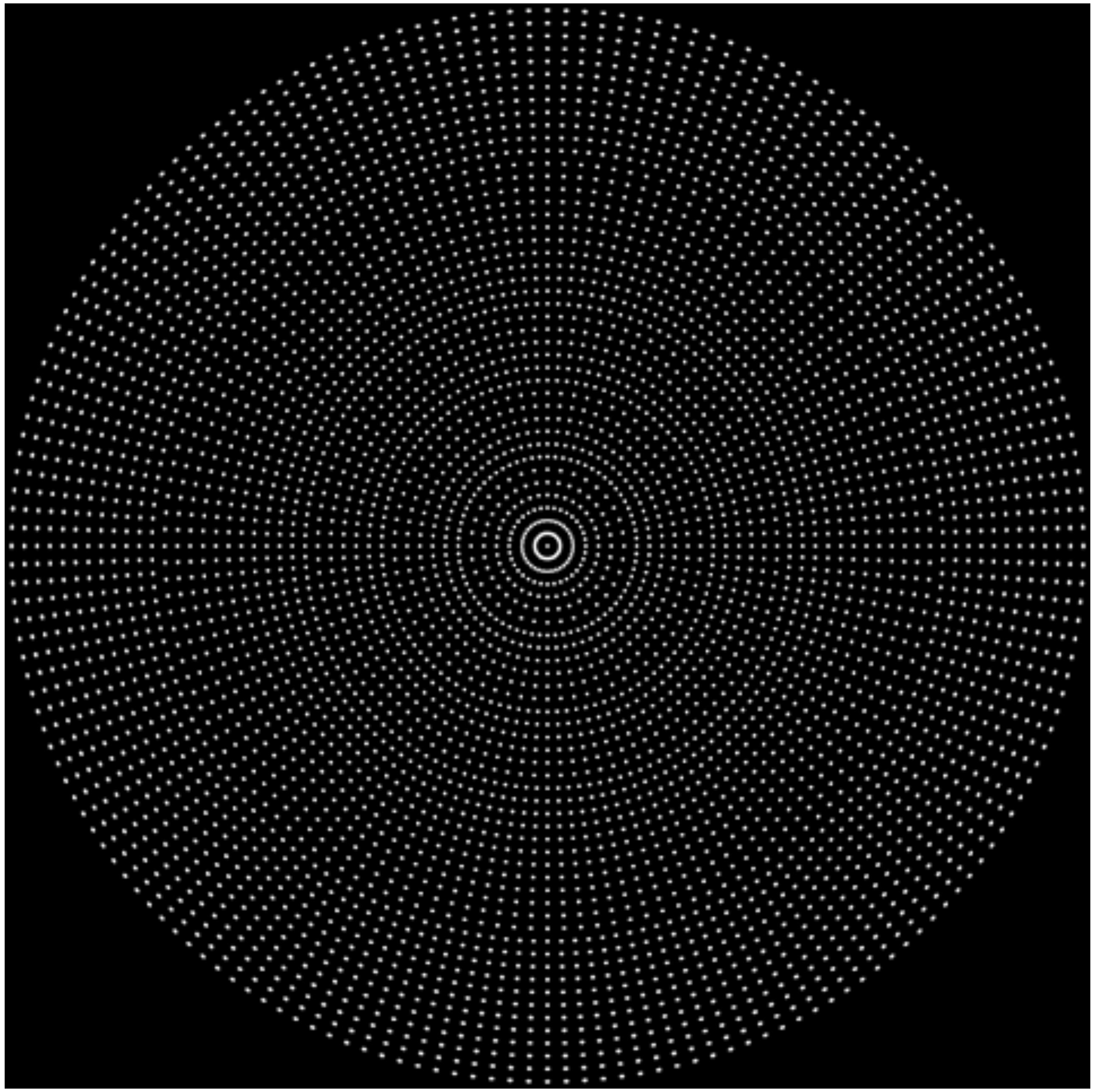
Generating suns

We need a radiance geometry file containing lots of suns centered in Reinhart sky patches.

- reinsrc.cal
- rcalc

echo void light solar 0 0 3 1e6 1e6 1e6 > suns.rad

```
cnt 5185 | rcalc -e MF:6 -f reinsrc.cal \
    -e Rbin=recno -o 'solar source sun 0 0 4 \
   ${ Dx } ${ Dy } ${ Dz } 0.533' >> suns.rad
```



Fisheye rendering looking up at a sky full of suns. These suns use the Reinhart MF:6 sky patches.

$I_{5ph} = VTDS - V_dTD_dS_d + C_{ds}S_{sun}$

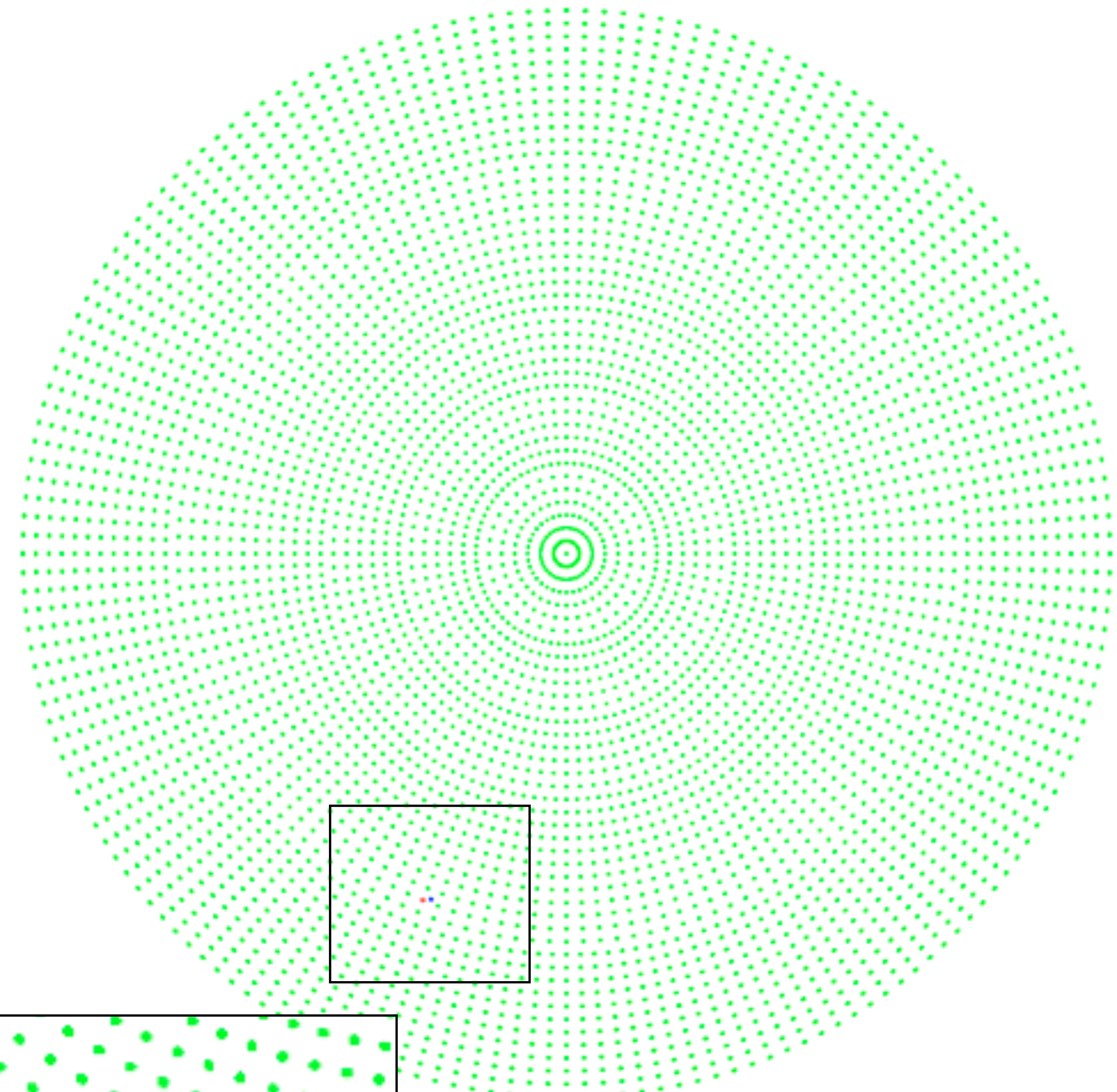
Sun Matrix

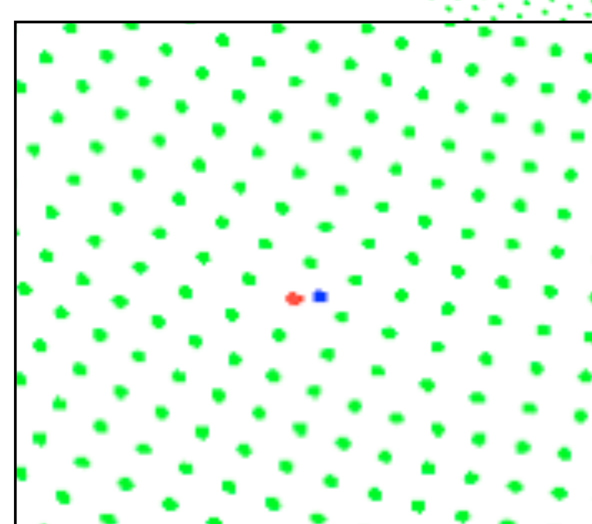
The sun matrix used in the third term of the 5-phase equation.

gendaymtx has a secret option for creating the sunmatrix:

**gendaymtx -m 6 -5 -of city.wea **
> city_direct_m6.smx

- Closest sun position is used per timestep (one position instead of three patches).
- A factor is included to compensate for the solid angle of reinhart patch vs. angular source.





blue - actual timestep sun position
red - sun position used in calculation
difference = 1.15°

Direct Sun Coefficient Matrix - sensor points

Fenestration Model:

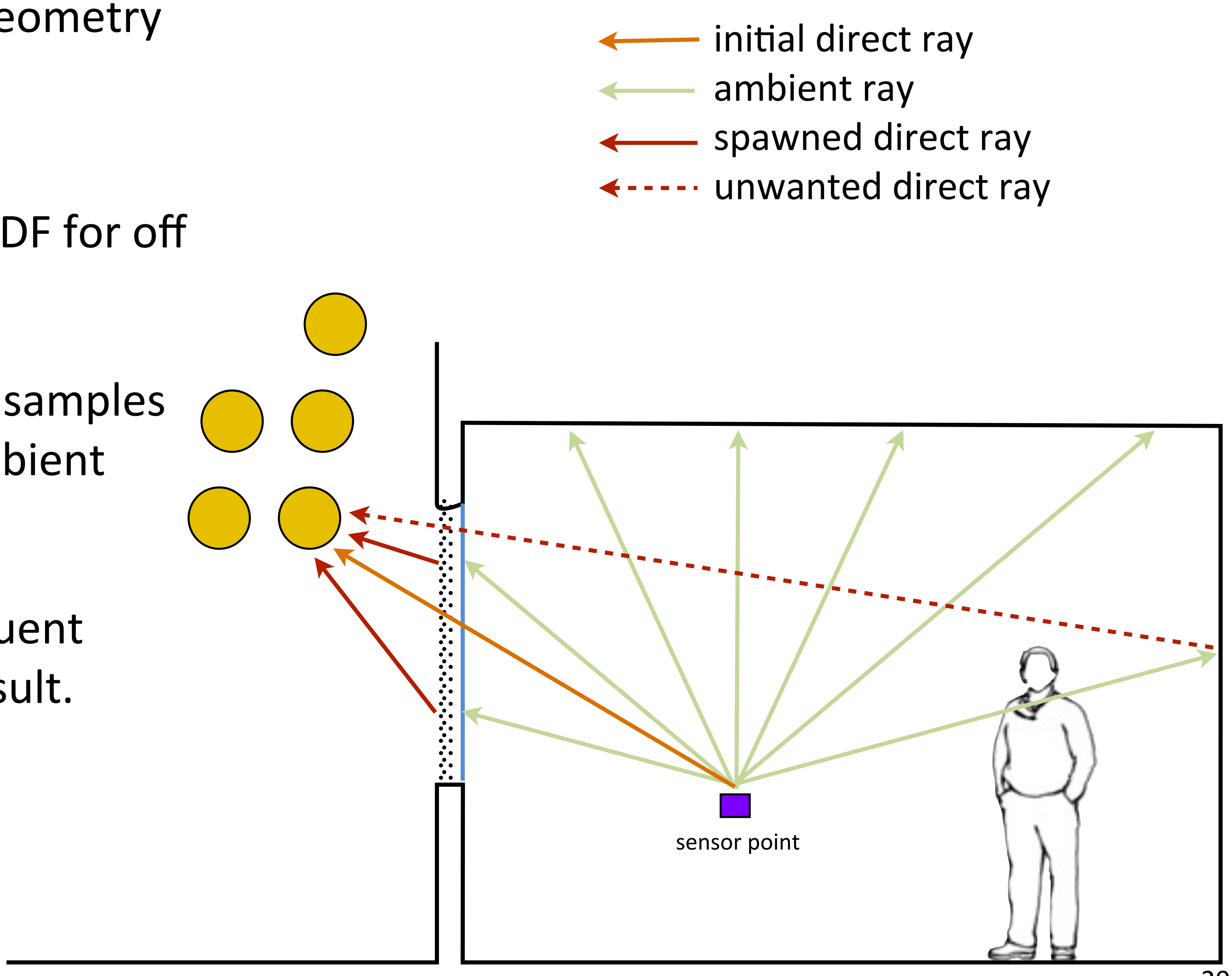
- Klems BSDF + Proxied geometry
- Tensor Tree BSDF + Proxied geometry
- Tensor Tree BSDF w/o proxied geometry

All Black Materials:

We want ambient rays to sample the BSDF for off angle transmission: **-ab 1**

When an ambient sample is sent, direct samples are sent from the termination of the ambient rays: **we don't want this behavior**

All-black geometry prevents the subsequent direct sample rays from affecting the result.



Direct Sun Coefficient Matrix - renderings

Preventing unwanted rays gets more complex with renderings - a black model produces a black luminance rendering.

Step 1 - generate a illuminance coefficient rendering with black model:

vwrays | rcontrib -i

Step 2 - generate a material reflectance map - each pixel is equal to the material reflectance divided by pi:

rpict -av 0.31831 0.31831 0.31831

Step 3 - multiply step 1 times step 2.

This workaround assumes all reflectances are lambertian

This is terribly awkward. I'm still looking for a better way...

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

Putting it all together

```
dctimestep view.vmx  T.xml  daylight.dmx  city.smx  >  1term.dat
dctimestep view_direct.vmx  T.xml  daylight_direct.dmx  city_direct.smx  >  2term.dat
dctimestep suncoefficient.mtx  city_ds.smx  >  3term.dat

rlam -if3 i_3ph.dat i_ds3ph.dat i_ds5ph.dat  |  \
     rcalc -if9 -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-$6+$9' \
     -e '$1=179*(.265*r+.670*g+.065*b)' | \
     awk '{printf("%f\t",$1);if(NR%8760==0) printf("\n")}' > illum.txt
```

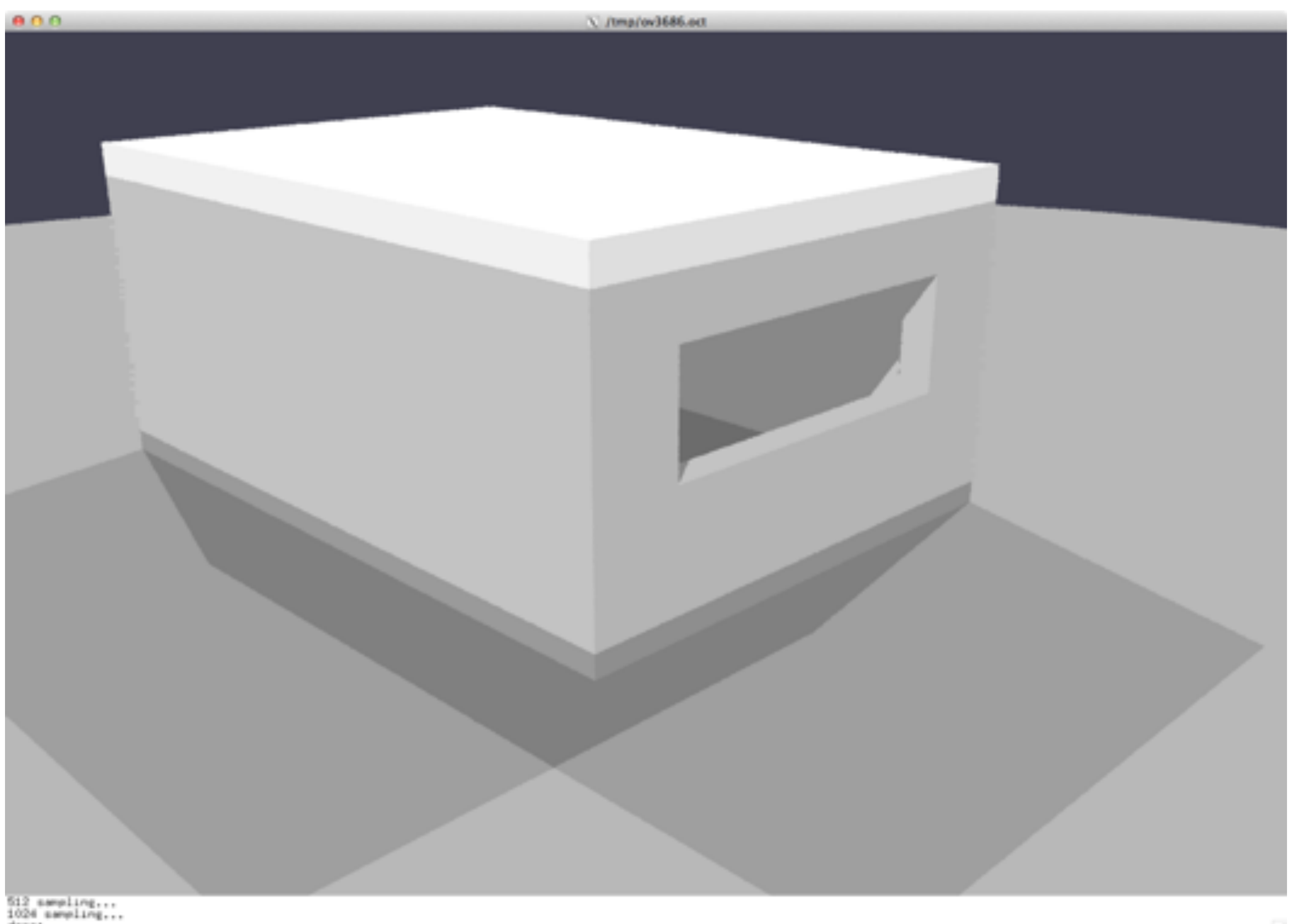
Again, kinda messy.

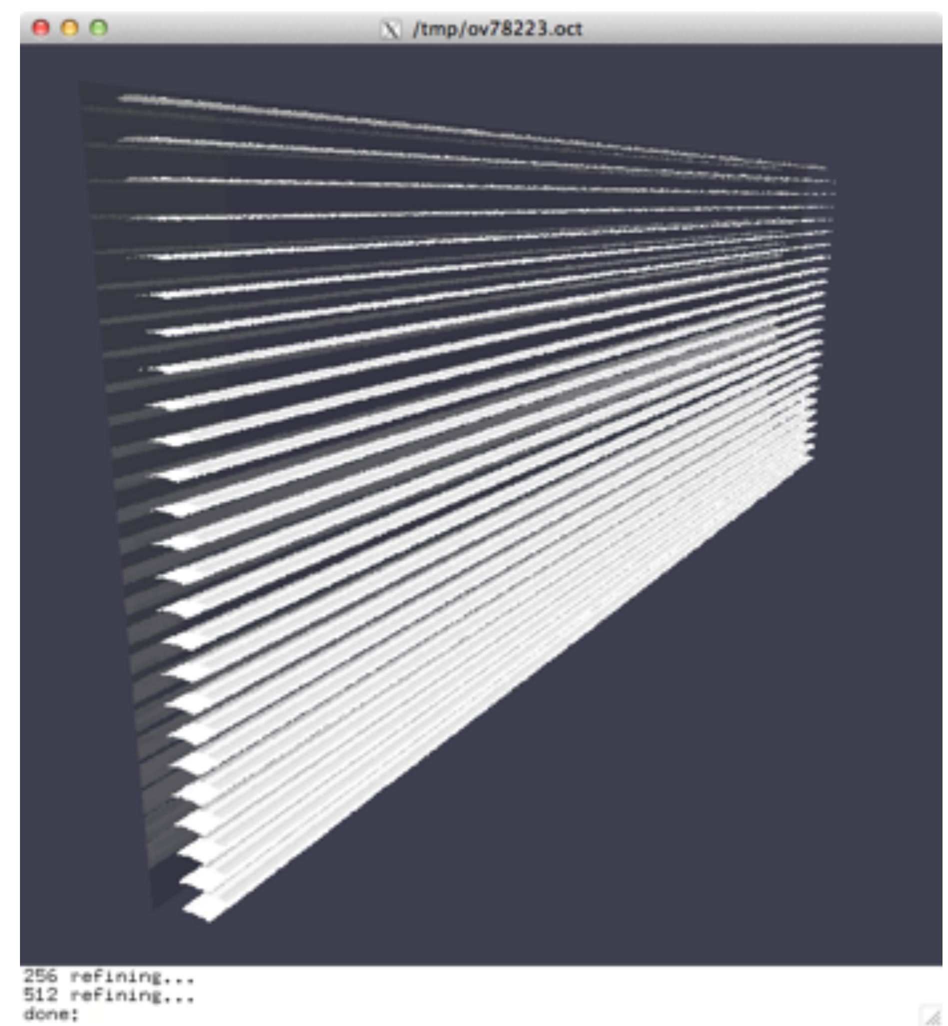
Does you head hurt? Mine does.

An Example

Using the model from Axel's tutorial

Fenestration: clear glazing with venetian blinds.





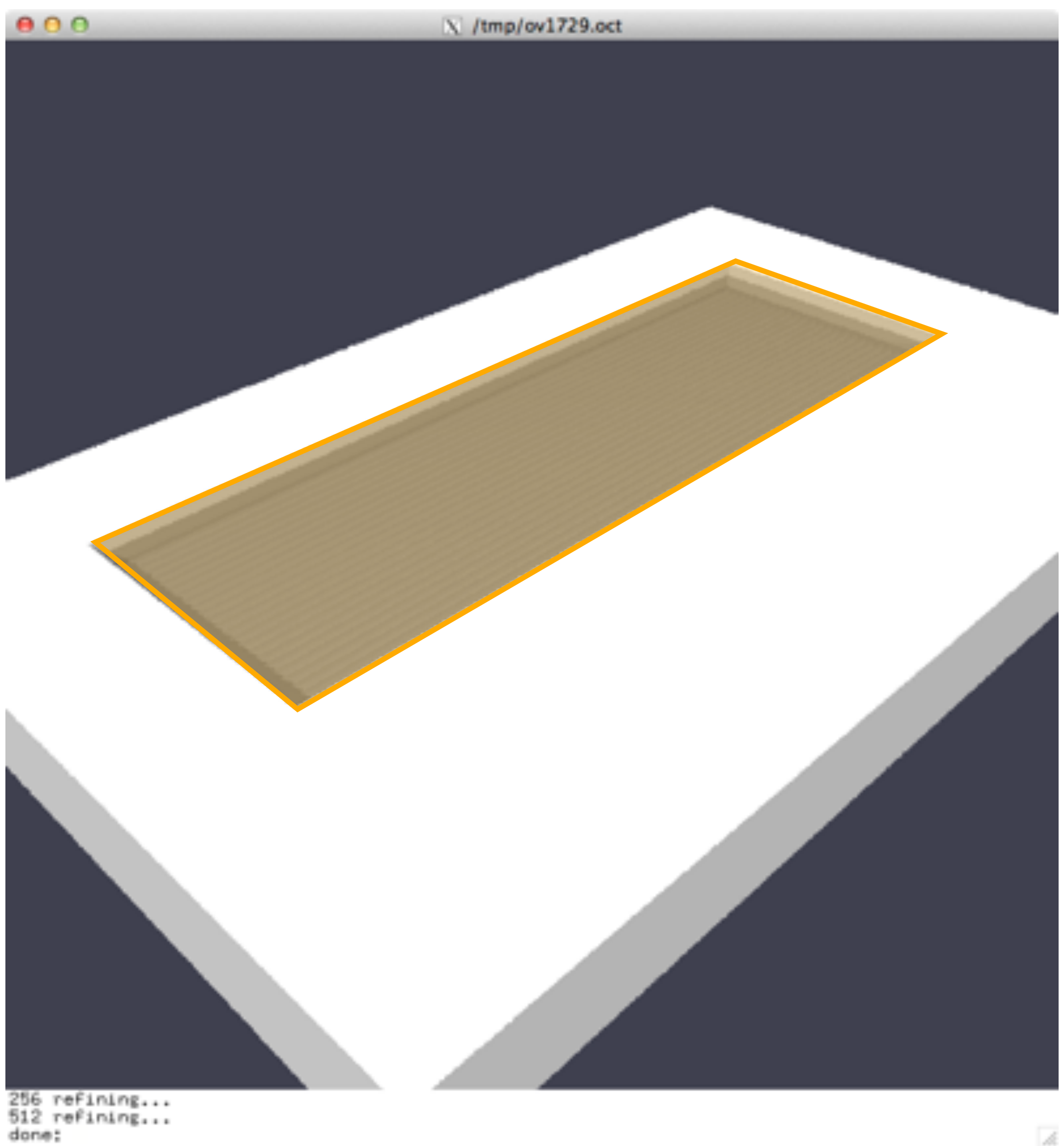
Creating BSDFs

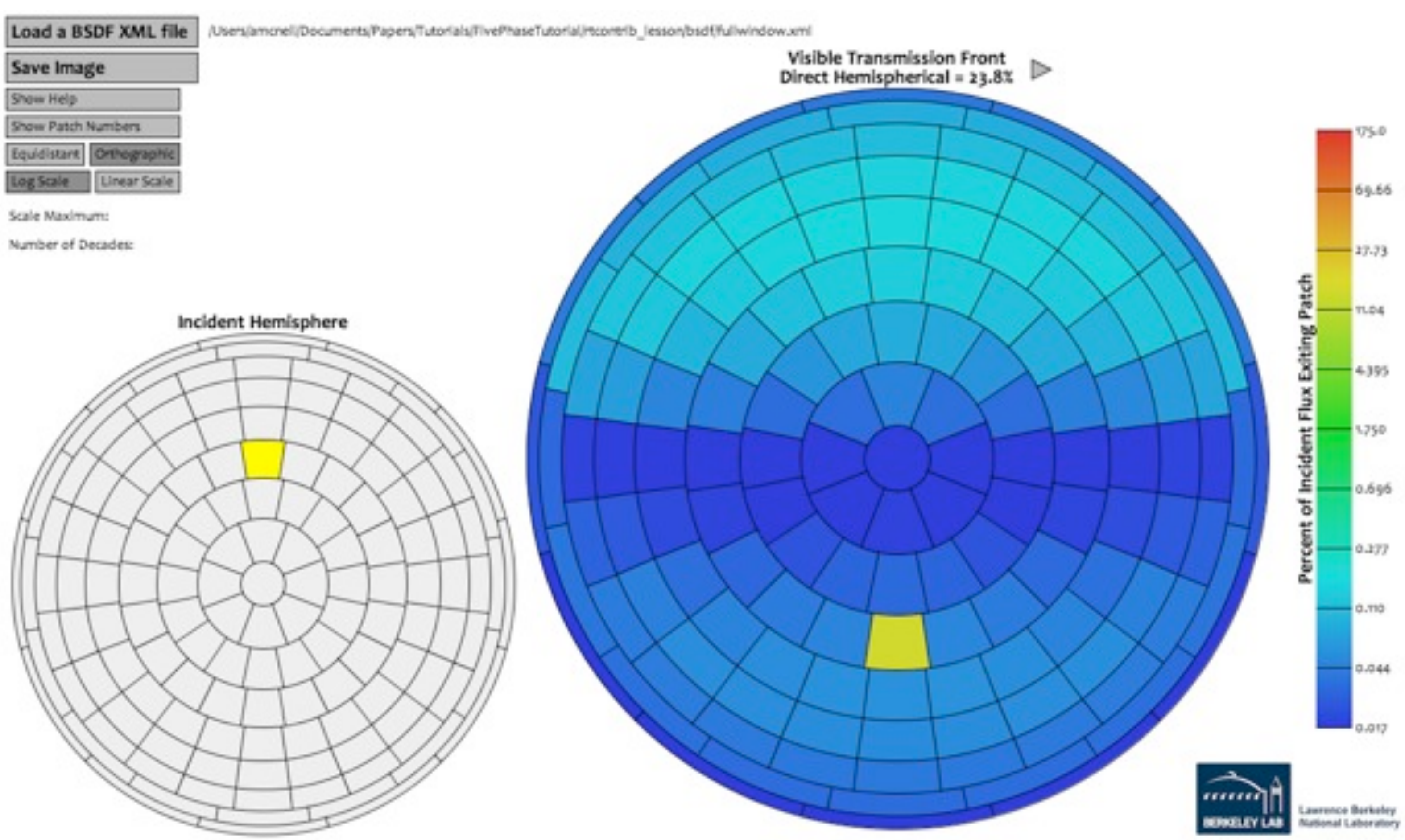
genBSDF +f +b -geom meter **-dim 0.5 3.5 1 2 -.3 0** -t4 5 bsdf/fullwindow.rad > bsdf/fullwindow_t45.xml

bsdf2klems bsdf/fullwindow_t45.xml > bsdf/fullwindow_klems.xml   (converts tensor tree to klems)

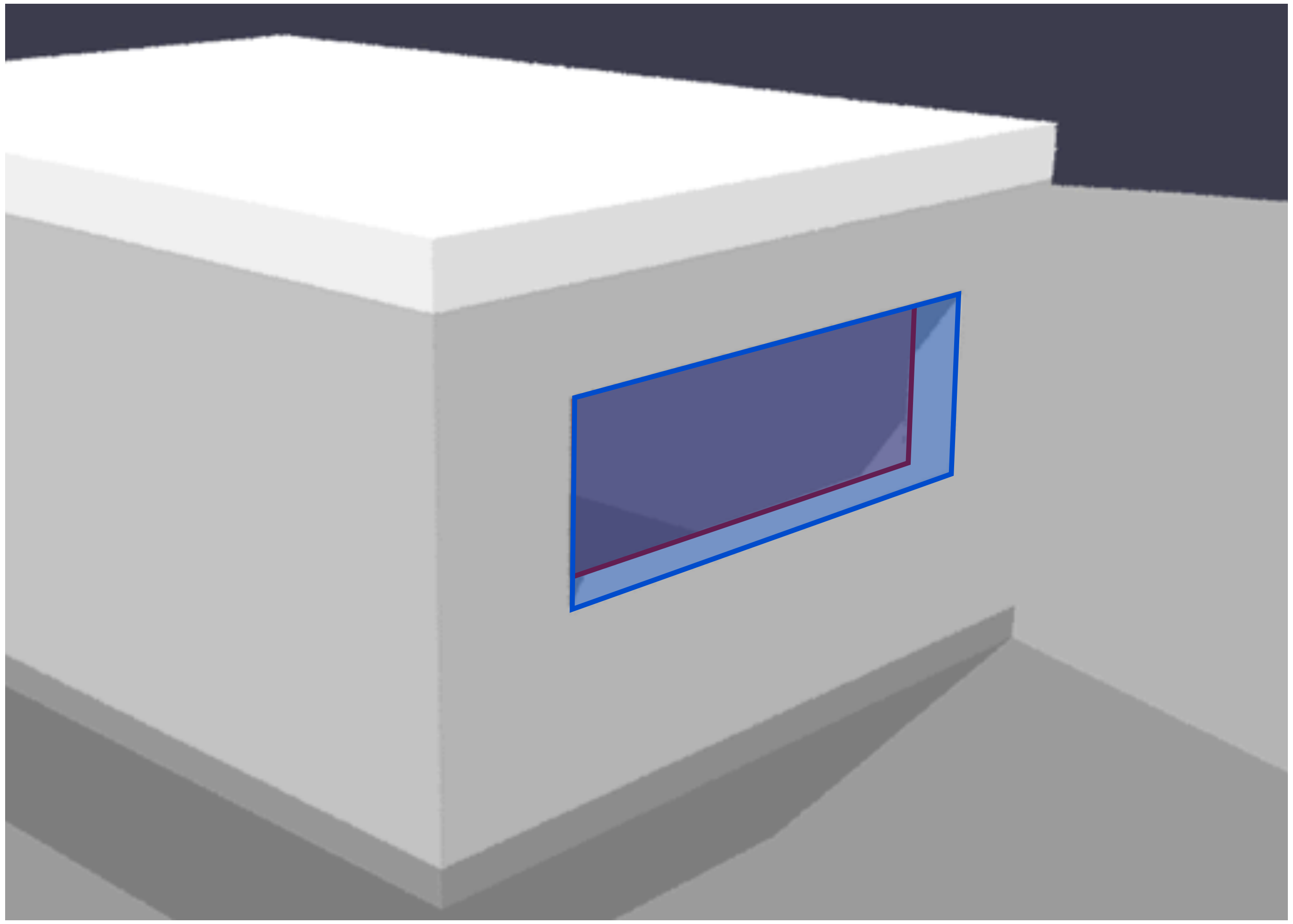
or

genBSDF -n 4 +f +b -geom meter **-dim 0.5 3.5 1 2 -.3 0** bsdf/fullwindow.rad > bsdf/fullwindow_klems.xml





Create view matrix and daylight matrix surfaces



```
#objects/viewmtxsurf.rad
void glow viewsurf
0
0
4 1 1 1 0

viewsurf polygon inside
0
0
12    0.5   0   1
      0.5   0   2
      3.5   0   2
      3.5   0   1
```

```
#objects/daymtxsurf.rad
void glow daymtxsurf
0
0
4 1 1 1 0

daymtxsurf polygon outside
0
0
12    0.5   0   1
      0.5   0   2
      3.5   0   2
      3.5   0   1
```

The view matrix surface will play double duty as the BSDF surface:

```
#objects/glazing_bsdf.rad
void BSDF BSDFproxy
6 0.24 bsdf/fullwindow_t45.xml 0 0 1 .
0
0

BSDFproxy polygon inside
0
0
12    0.5   0   1
      0.5   0   2
      3.5   0   2
      3.5   0   1
```

Generating View Matrices - sensor points

View Matrix:

```
oconv materials/testroom.mat objects/* skies/sky_white.rad objects/viewmtxsurf.rad \
      objects/daymtxsurf.rad > octs/model_3ph.oct

rcontrib < data/photocells.pts -f klems_int.cal -b kbinS -bn Nkbins -m viewsurf \
      -I+ -ab 10 -ad 65536 -lw 1.52e-5 octs/model_3ph.oct > matrices/viewmatrix.vmx
```

Direct View Matrix:

```
xform -m black objects/testroom_Swall.rad objects/testroom.rad objects/ground.rad  |   \
   oconv materials/testroom.mat - objects/viewmtxsurf.rad objects/daymtxsurf.rad \
      > octs/model_black.oct

rcontrib < data/photocells.pts -f klems_int.cal -b kbinS -bn Nkbins -m viewsurf \
      -I+ -ab 1 -ad 65536 -lw 1.52e-5 octs/model_black.oct > matrices/viewmatrix_direct.vmx
```

Generating Daylight Matrices

Daylight Matrix:

```
genklemsamp -c 1000 -vd 0 -1 0 objects/daymtxsurf.rad | \
    rcontrib -c 1000 -ab 2 -ad 1024 -e MF:1 -f reinhart.cal -b rbin -bn Nrbins -m sky_glow \
        octs/model_3ph.oct > matrices/daylightmatrix.dmx
```

Direct Daylight Matrix:

```
genklemsamp -c 1000 -vd 0 -1 0 objects/daymtxsurf.rad | \
    rcontrib -c 1000 -ab 0 -e MF:1 -f reinhart.cal -b rbin -bn Nrbins -m sky_glow \
        octs/model_black.oct > matrices/daylightmatrix_direct.dmx
```

Generating Sun Coefficient Matrix - sensor points

First the suns:

```
echo void light solar 0 0 3 1e6 1e6 1e6 > skies/suns.rad

cnt 5185  |  rcalc -e MF:6 -f reinsrc.cal -e Rbin=recno \
    -o 'solar source sun 0 0 4 ${ Dx } ${ Dy } ${ Dz } 0.533' >> skies/suns.rad
```

Then the octree:

```
xform -m black objects/testroom_Swall.rad objects/testroom.rad objects/ground.rad \
    | oconv materials/testroom.mat - objects/glazing.rad objects/venetianblind.rad \
        objects/glazing_bsdf.rad skies/suns.rad > octs/model_suns.oct
```

Finally the Coefficient Matrix:

```
rtcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5  -dc 1 -dt 0 -dj 1 -st 1 -ss 0 -faf  \
    -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m solar \
    octs/model_suns.oct > matrices/directsun.dsmx
```

Generating Sky Matrices

First convert an epw file to wea:

```
epw2wea skies/USA_CA_Oakland.Intl.AP.724930_TMY3.epw skies/OakLand.wea
```

Then the three sky matrices:

Normal sky matrix:

```
gendaymtx -of skies/OakLand.wea > matrices/OakLand.smx
```

Direct only sky matrix:

```
gendaymtx -of -d skies/OakLand.wea > matrices/OakLand_direct.smx
```

Direct sun sky matrix

```
gendaymtx -5 -d -m 6 -of skies/OakLand.wea > matrices/OakLand_direct_m6.smx
```

Obtaining a result

First term:

```
dctimestep -n 8760 -if matrices/viewmatrix.vmx bsdf/fullwindow.xml  \
    matrices/daylightmatrix.dmx matrices/OakLand.smx > i_3ph.txt
```

Second term:

```
dctimestep -n 8760 -if  matrices/viewmatrix_direct.vmx bsdf/fullwindow.xml  \
    matrices/daylightmatrix_direct.dmx matrices/OakLand_direct.smx > i_ds3ph.txt
```

Third term:

```
dctimestep -n 8760 -if matrices/directsun.dsmx matrices/OakLand_direct_m8.smx \
   > i_ds5ph.txt
```

Obtaining a result - combining the terms

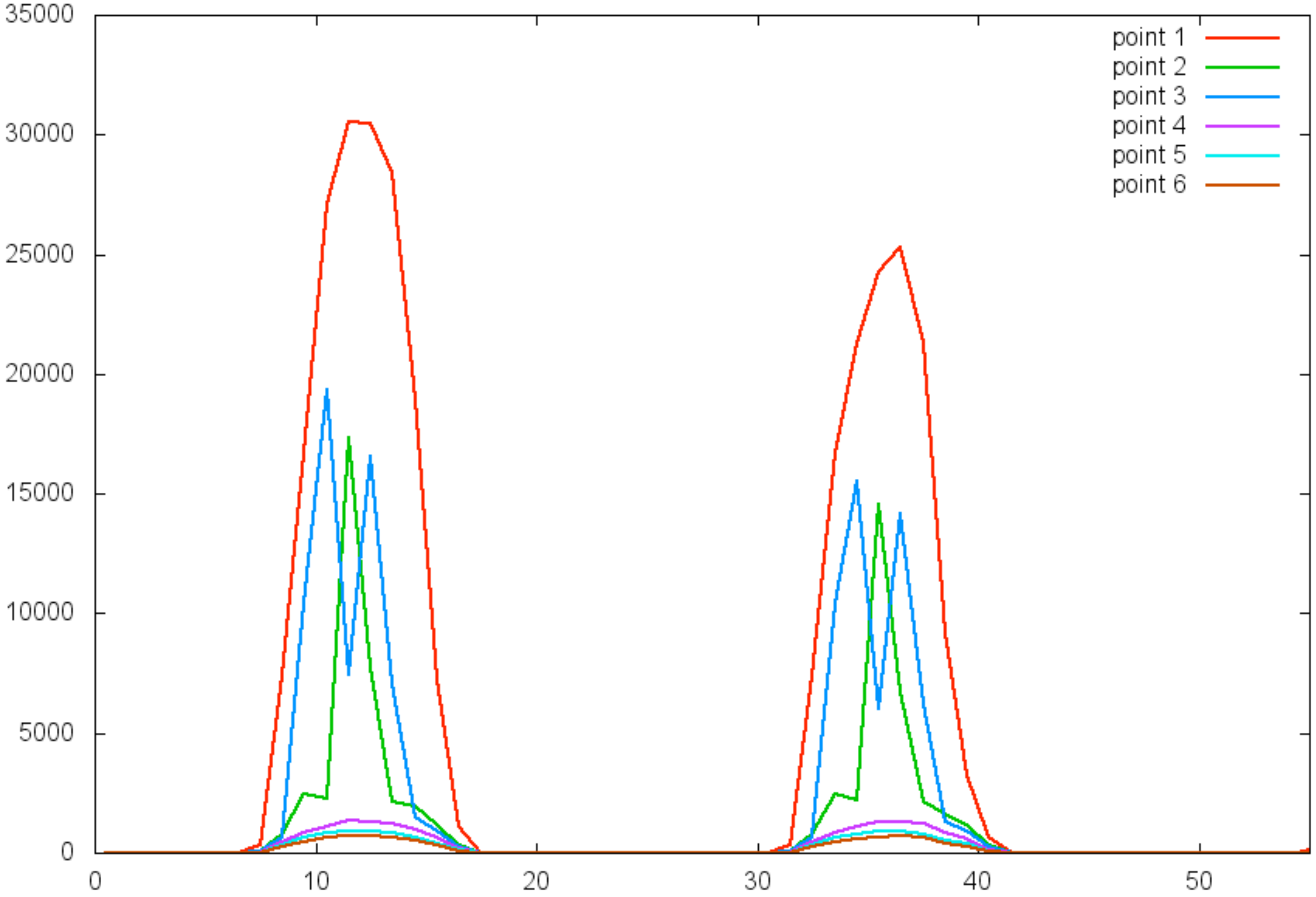
Creating unformatted binary data files:

```
tr -s '\t\r\n ' '\n' < i_3ph.txt | rcalc -of -e '$1=$1' > i_3ph.dat

tr -s '\t\r\n ' '\n' < i_ds3ph.txt | rcalc -of -e '$1=$1' > i_ds3ph.dat

tr -s '\t\r\n ' '\n' < i_ds5ph.txt | rcalc -of -e '$1=$1' > i_ds5ph.dat
```

Combining the files and doing the calculation:

```
rlam -if3 i_3ph.dat i_ds3ph.dat i_ds5ph.dat | \
    rcalc -if9 -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-$6+$9' \
        -e '$1=179*(.265*r+.670*g+.065*b)' | \
    awk '{printf("%f\t",$1);if(NR%8760==0) printf("\n")}'  > illum.txt
```

And Finally an illuminance result



Generating View Matrices - Renderings

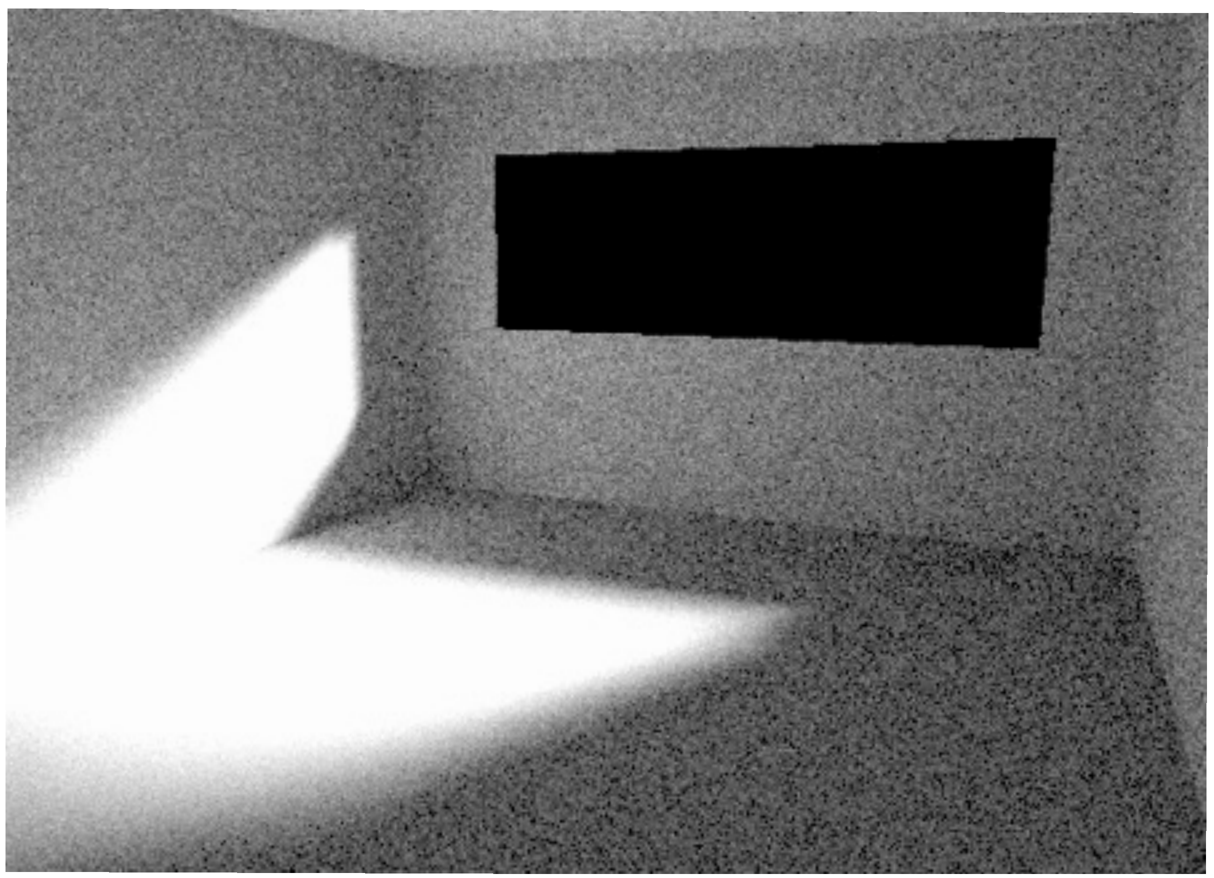
View Matrix:

```
vwrays -vf views/back.vf  -ff -x 500 -y 500 \
       | rcontrib `vwrays -vf views/back.vf  -x 500 -y 500 -d` -ffc -fo -o viewpics/back_%03d.hdr \
           -f klems_int.cal -b kbinS -bn Nkbins -m viewsurf -ab 10 -ad 65536 -lw 1.52e-5 \
           octs/model_3ph.oct
```

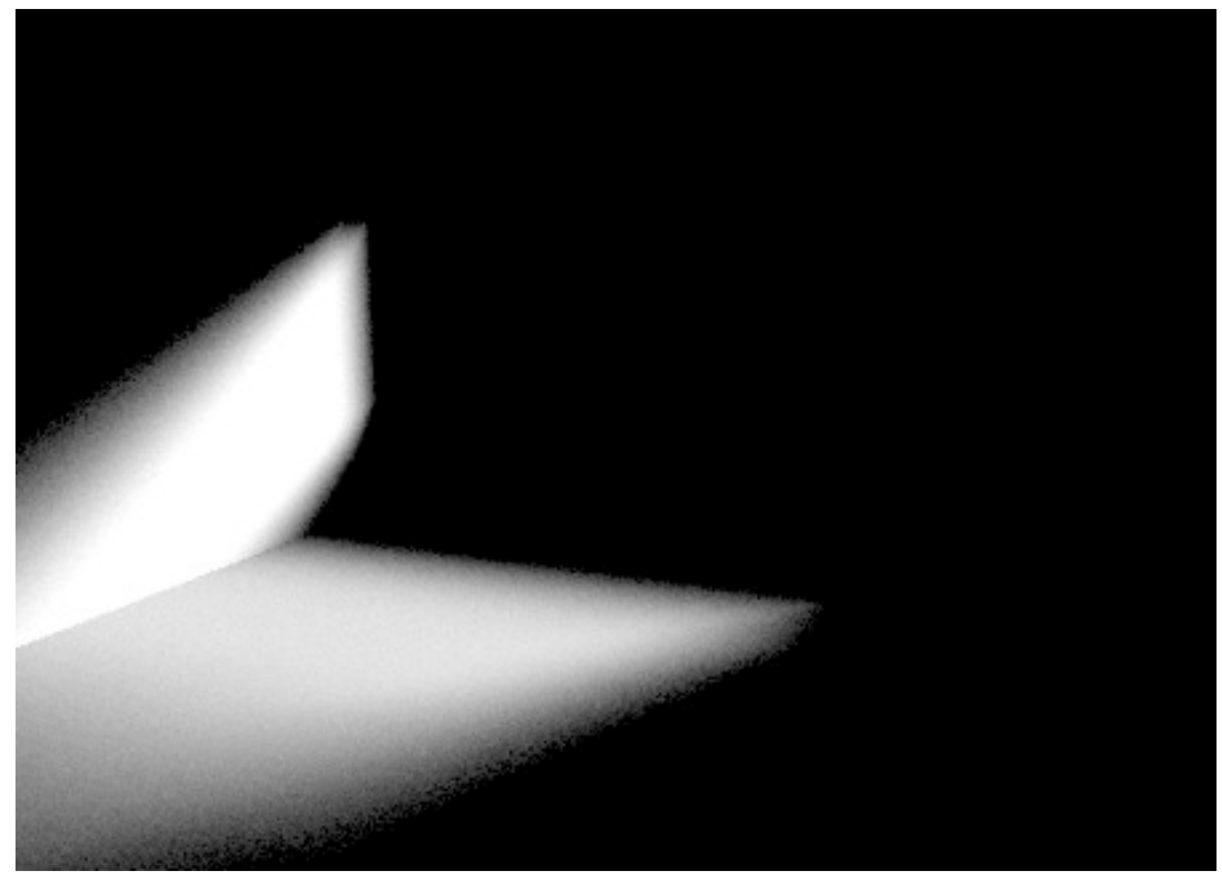
Direct View Matrix:

```
vwrays -vf views/back.vf  -ff -x 500 -y 500 \
       | rcontrib `vwrays -vf views/back.vf  -x 500 -y 500 -d` -ffc -fo -o viewpics_dir/back_%03d.hdr \
                 -f klems_int.cal -b kbinS -bn Nkbins -m viewsurf \
                 -ab 1 -ad 65536 -lw 1.52e-5 octs/model_black.oct
```

Rendered View Matrix - example



View Matrix



Direct View Matrix

Generating Sun Coefficient Matrix - Renderings

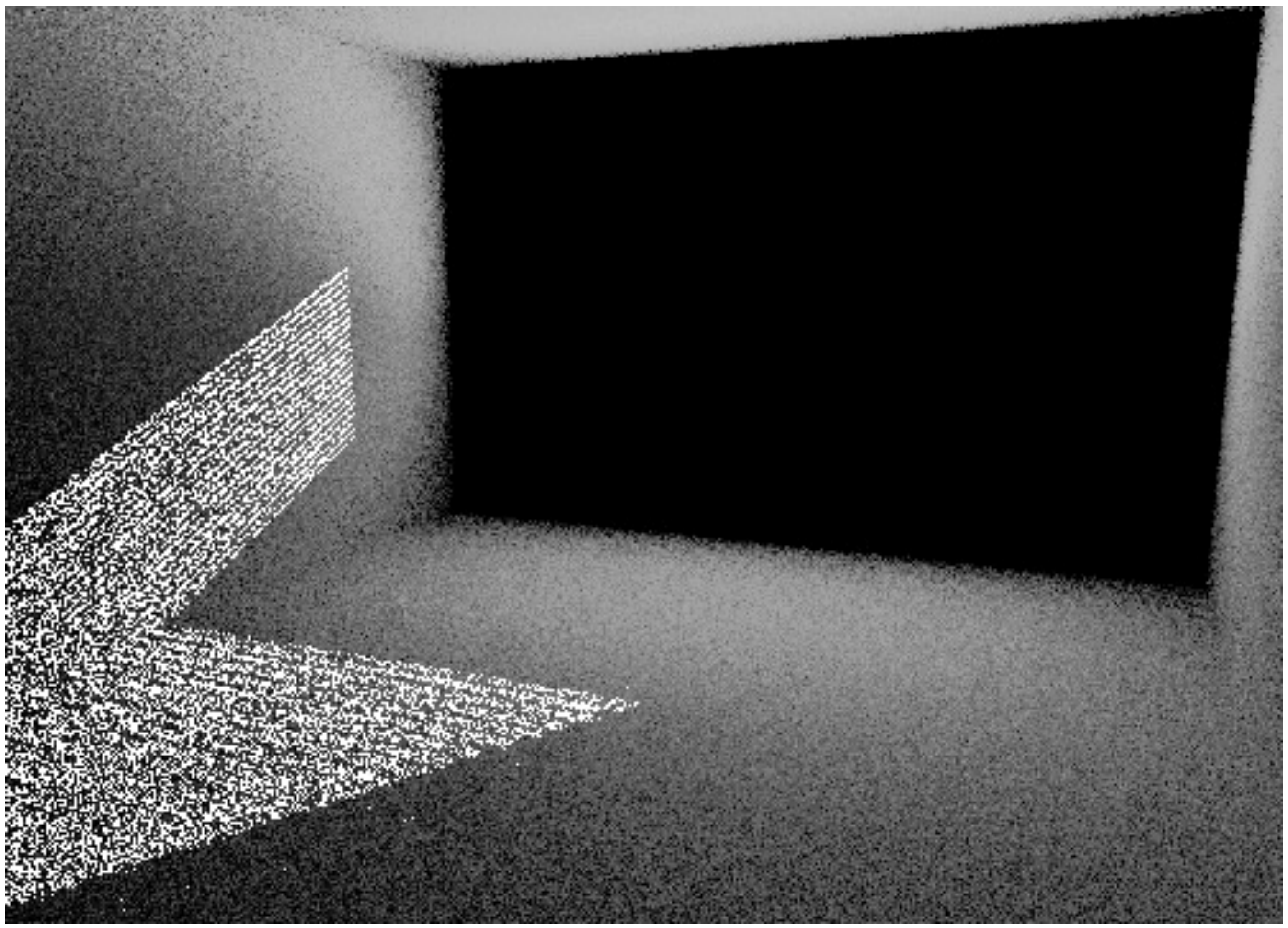
First the coefficient renderings:

```
ulimit -n 9999
vwrays -ff -vf views/back.vf -x 500 -y 500 \
    | rcontrib `vwrays -vf views/back.vf -x 500 -y 500 -d` -ffc -fo -o viewpics_ds/back_%04d.hdr \
        -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m solar -i -ab 1 -ad 1000 -lw 1e-3 \
        octs/model_suns.oct
```

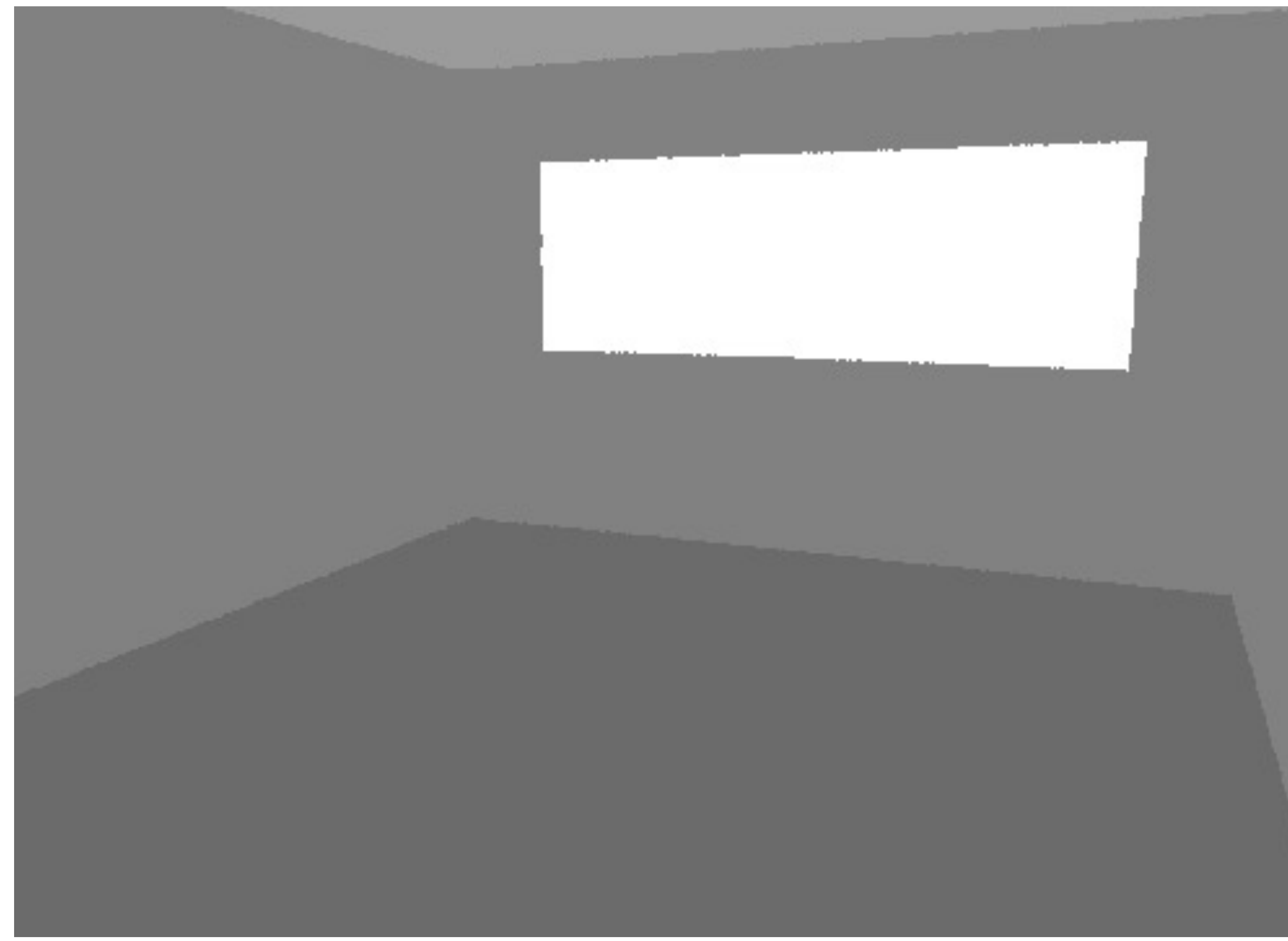
Then the material map rendering:

```
rpict -x 500 -y 500 -vf views/back.vf -av 0.31831 0.31831 0.31831 -aa 0 octs/model_3ph.oct \
    > materialmap.hdr
```

Sun Coefficient Rendering Example



Sun Coefficient Rendering



Material Map Rendering

Obtaining a result - Renderings

First term:

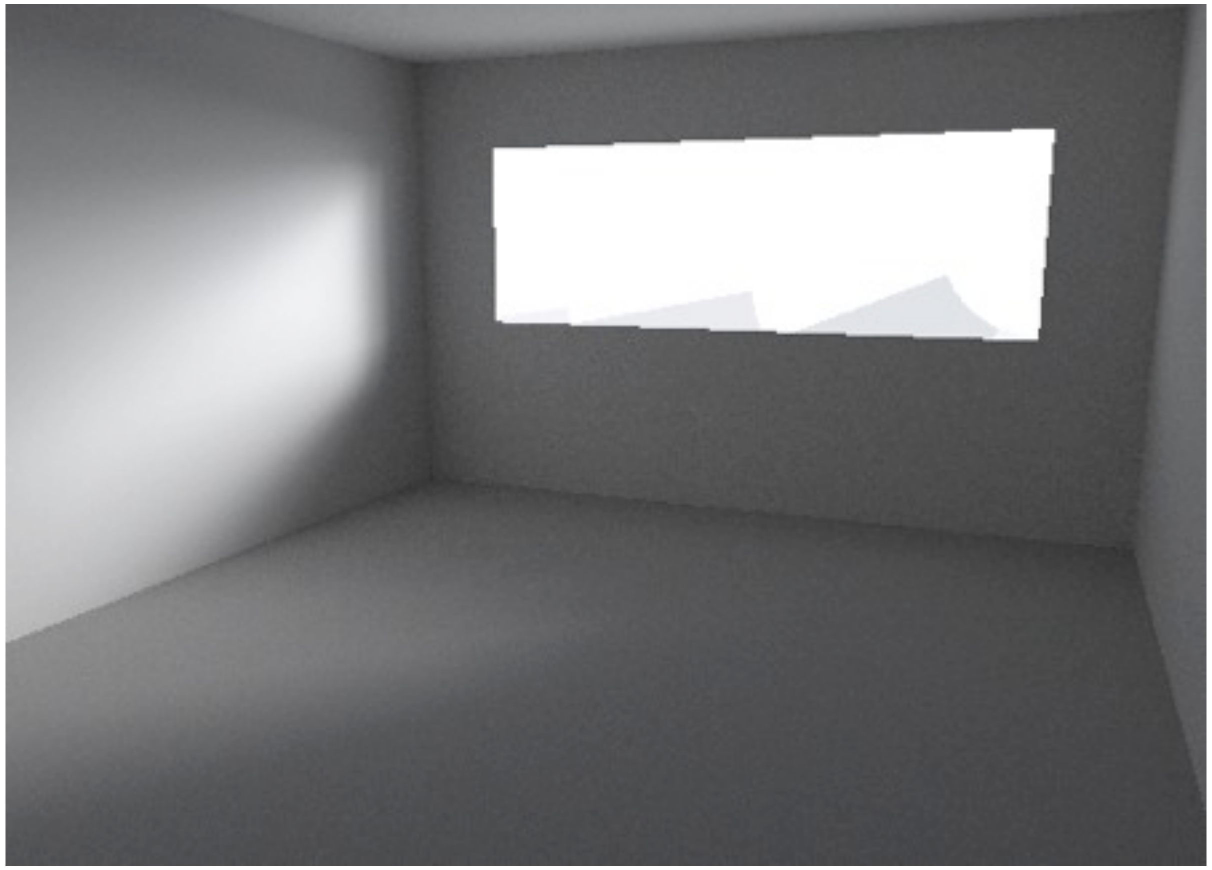
```
dctimestep -n 8760 -if -o hourlypics/back_%04d.hdr viewpics/back_%03d.hdr \
    bsdf/fullwindow.xml matrices/daylightmatrix.dmx matrices/OakLand.smx
```

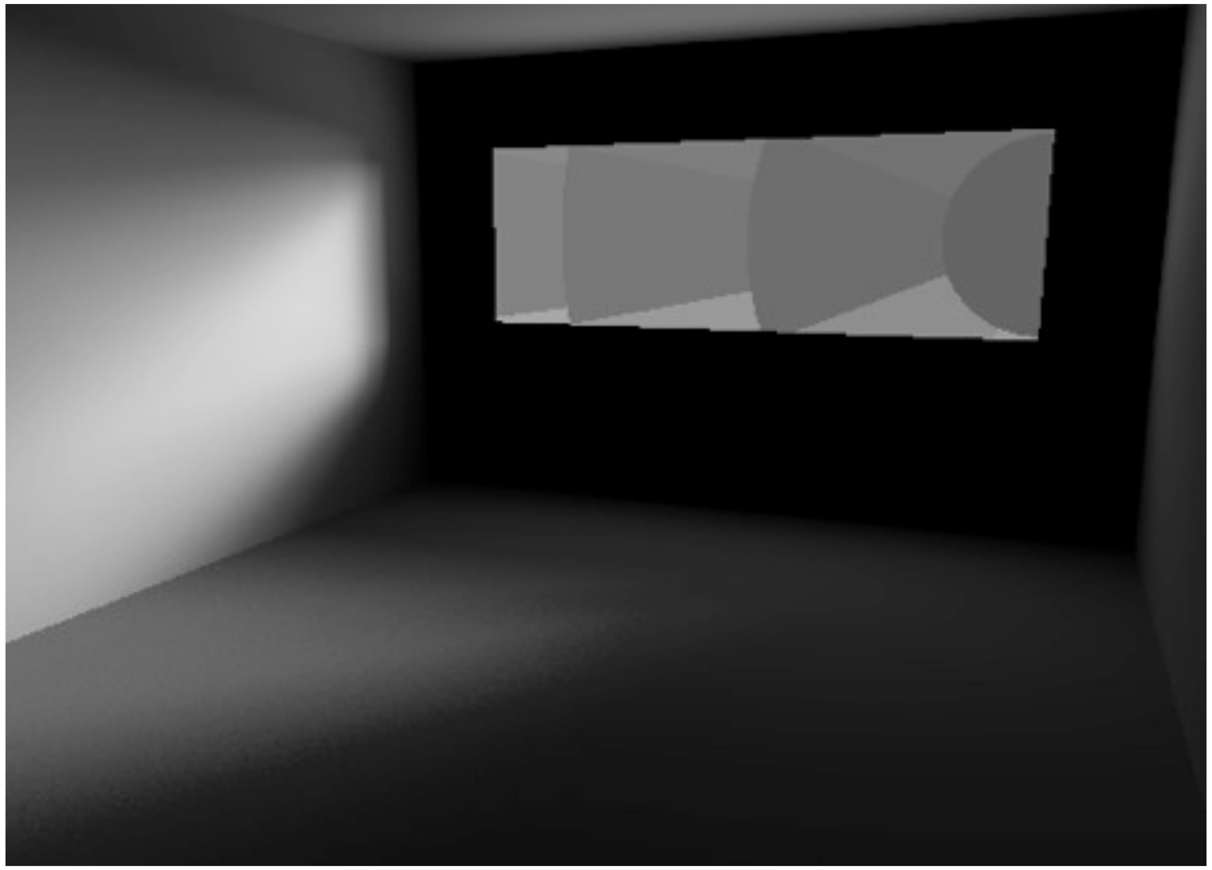
Second term:

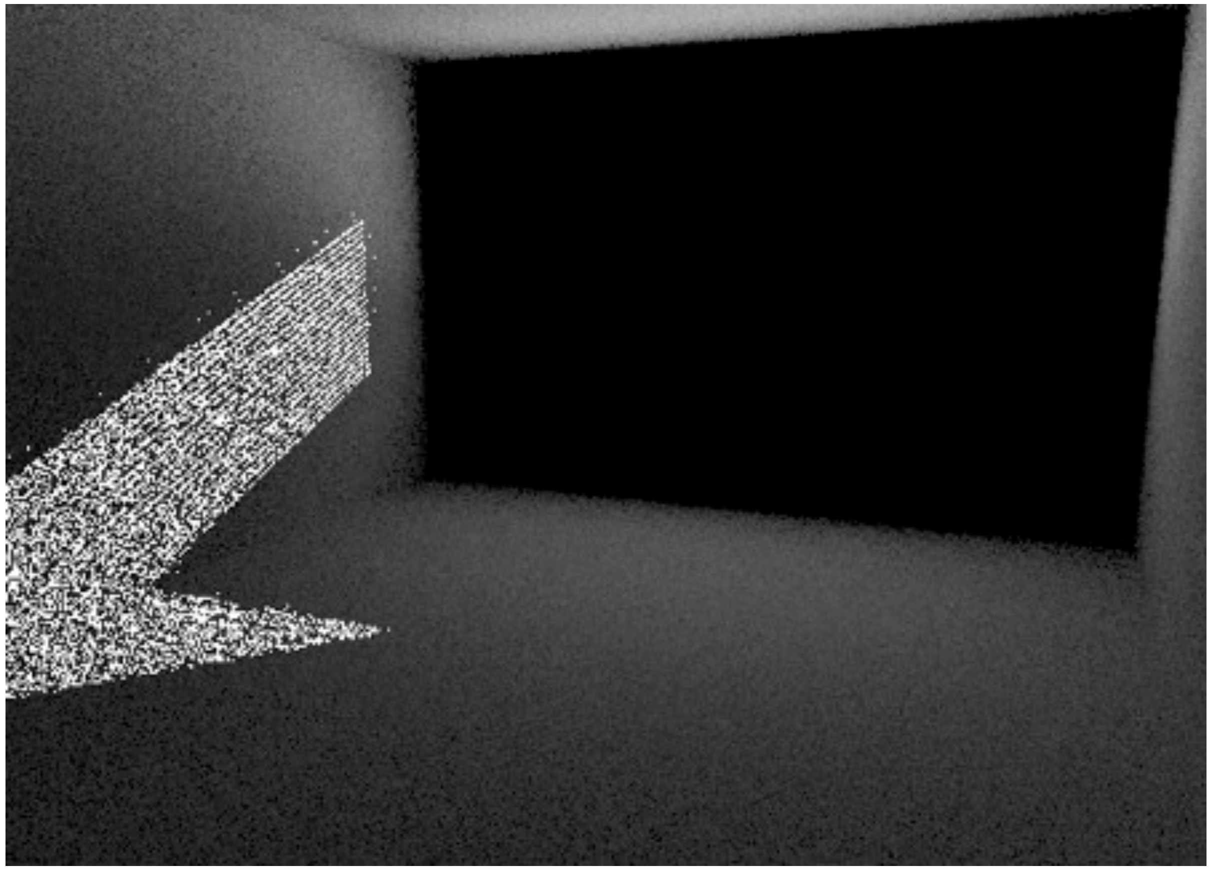
```
dctimestep -n 8760 -if -o hourlypics_dir/back_%04d.hdr viewpics_dir/back_%03d.hdr \
    bsdf/fullwindow.xml matrices/daylightmatrix_direct.dmx matrices/OakLand_direct.smx
```

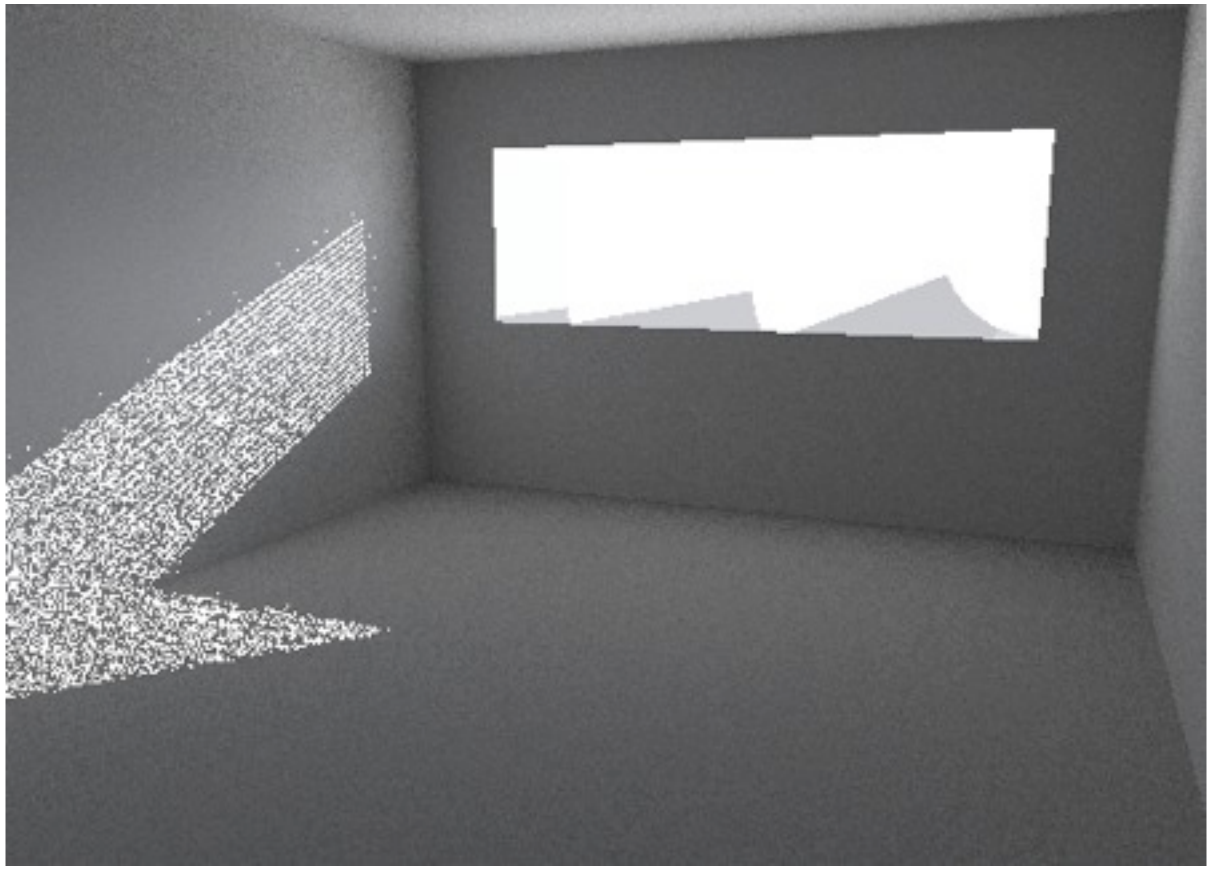
Third term:

```
dctimestep -n 8760 -if -o hourlypics_ds/back_%04d.hdr viewpics_ds/back_%04d.hdr \
    matrices/OakLand_direct_m6.smx
```


First Term (three-phase result)


Second Term


Third Term


Five-phase Result

What does the future hold?

- Five-phase simulation
  - Integration in DAYSIM - providing support for CFS
  - Openstudio/COMFEN other tools - via DAYSIM
  - Scripting / command line? - only for super hardcore (I'd rather not...)
- BSDF Data
  - Unhappy with the lack of independent testing for BSDF?
  - LBNL will start to offer BSDF measurement services for a fee to help kick start the industry.