Review of fritted and diffusing glass: measurement, modelling, and impact

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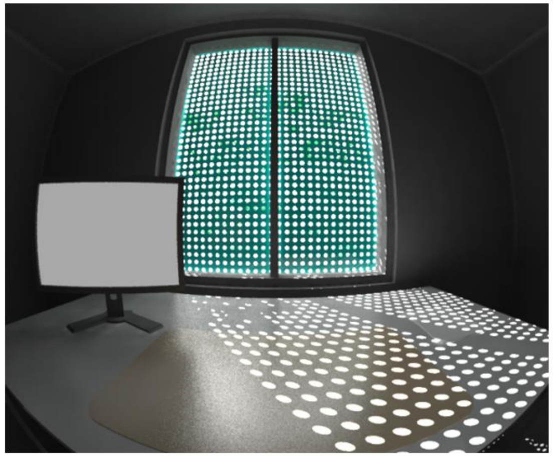
Introduction

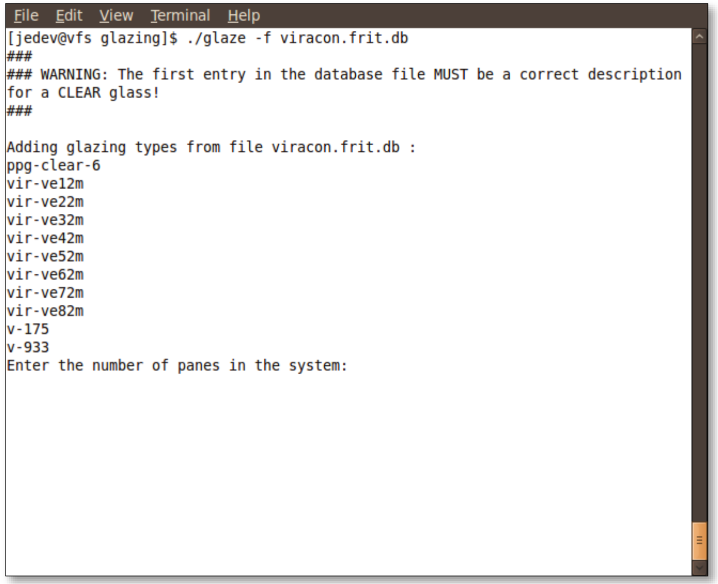
Modelling frit glass and patterns, a limited history



```
void trans open
0
0
7 1.0 1.0 1.0 0 0 1 1

void plastic plastic_bluegreen
0
0
5 0.000 0.723 0.666 0 0

void mixfunc perforated_s05_r25
6 plastic_bluegreen open uv_hole perforate.cal -s .05
0
1 0.25
```



perforate.cal

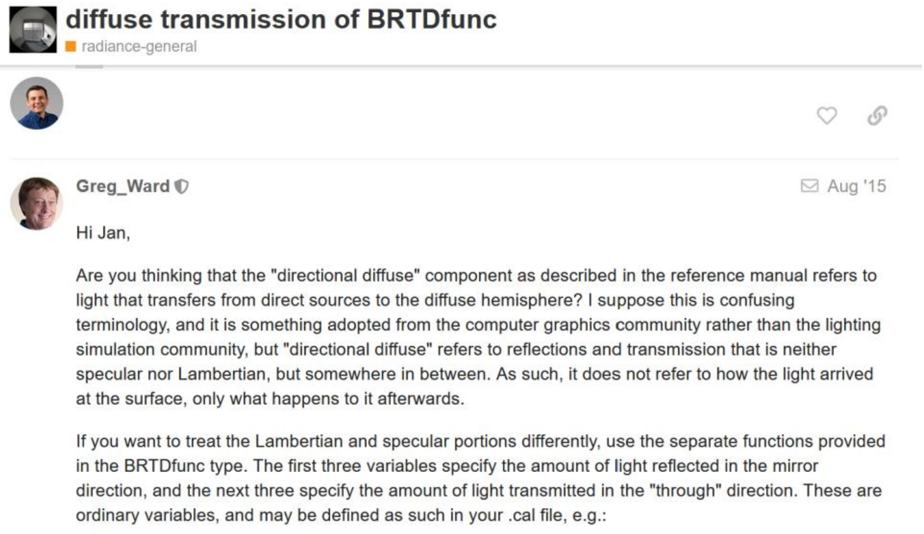
Georg Mischler, 1993
(UV version) Abel Boerema, 2004

glaze.csh script with manufacturer frit data

Jack de Valpine
Greg Ward

2009

Modelling frit glass and patterns, a limited history


diffuse transmission of BRTDfunc

radiance-general

Greg_Ward — Aug '15

Hi Jan,

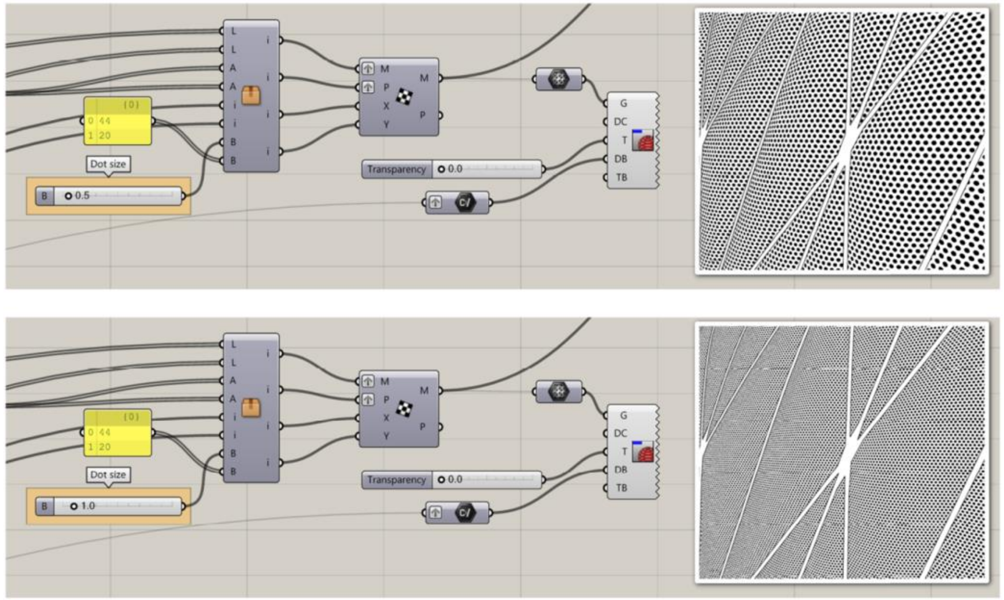
Are you thinking that the "directional diffuse" component as described in the reference manual refers to light that transfers from direct sources to the diffuse hemisphere? I suppose this is confusing terminology, and it is something adopted from the computer graphics community rather than the lighting simulation community, but "directional diffuse" refers to reflections and transmission that is neither specular nor Lambertian, but somewhere in between. As such, it does not refer to how the light arrived at the surface, only what happens to it afterwards.

If you want to treat the Lambertian and specular portions differently, use the separate functions provided in the BRTDfunc type. The first three variables specify the amount of light reflected in the mirror direction, and the next three specify the amount of light transmitted in the "through" direction. These are ordinary variables, and may be defined as such in your .cal file, e.g.:

Diffuse transmission of BRTDfuncs

Jan Wienold
Greg Ward

2015



colorpict automation for patterns

Mostapha Sadeghipour Roudsari
Anne Waelkens

2015

How to handle diffusion / scattering?

VIRACON®

800 Park Drive
Owatonna, MN 55060

800.533.2080
viracon.com

Performance Data Imperial **MAKEUP**

Transmittance		
Visible Light:	28%	
Solar Energy:	11%	
Ultraviolet (UV):	<1%	

1 3/8" (1.36" avg.) VRE35-4322 Insulating Laminated Glass
5/16" Pure Mid Iron VRE-4322 #2 with 40% V957
SUBDUED GRAY #2
1/2" Airspace - Argon
1/4" Pure Mid Iron
.060" clear PVB
1/4" Pure Mid Iron

Reflectance	
Visible Light-Exterior:	21%
Visible Light-Interior:	20%
Solar Energy:	35%

NFRC U-Value	
Winter	0.24 Btu/(hr x sqft x °F)
Summer	0.20 Btu/(hr x sqft x °F)

Shading Coefficient (SC)	0.18
Relative Heat Gain	39 Btu/(hr x sqft)
Solar Heat Gain Coefficient (SHGC)	0.16
Light to Solar Gain Ratio (LSG)	1.75

Viracon's Performance Data is center of glass data based on National Fenestration Rating Council's (NFRC) measurement standards and is calculated using Lawrence Berkeley National Laboratory's (LBNL) WINDOW 7 software.

Generated By: VIRACON\nicholasp

Page: 1 - Run at: 10/25/2021 2:45:41 PM

- This is not a diffusing frit, but it is typical of what is received from a manufacturer when specifying a frit.
- Total Tvis is present, but no indication of diffuse characteristics.
- For diffusing media, where do we get data from, and how do we model it in Radiance?

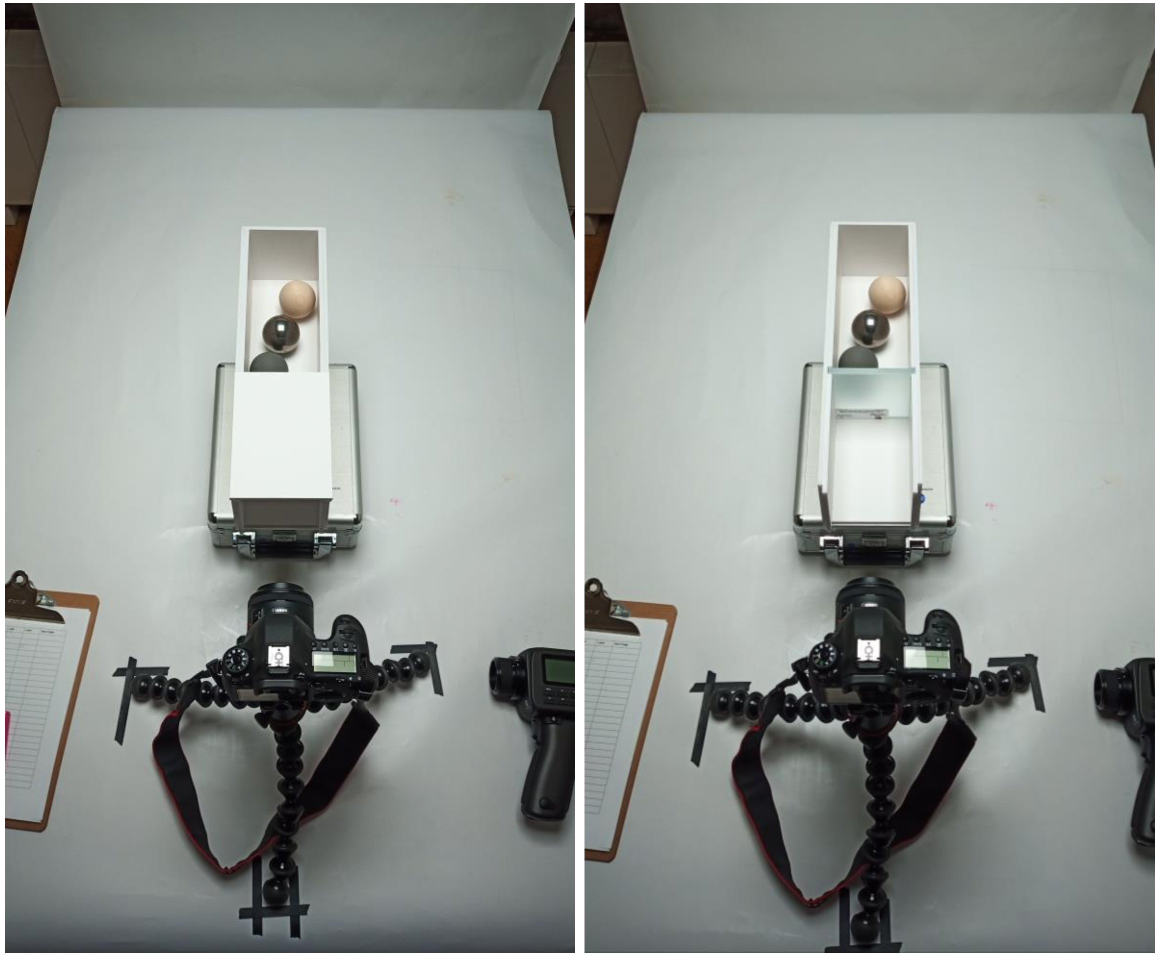
Goals

- Measure several diffusing frit media kindly provided by manufacturers.
- Model them 'simply' in Radiance.
- Test their effects in some reasonable daylight models.
  - Glare reduction – HDR renders / DGP calculations
  - UDIe >3000 lx reduction
- Document and learn from my mistakes.

Measurements

Cornell box-esque measurement setup

Setup overview



Top view / cover removed

- I built a box and filled it with three spheres at a known distance from the media.
- Took calibrated HDR photography in a constant light setting under a bright studio lamp.
- See Jakubiec, Inanici, Van Den Wymelenberg and Mahic papers for more details on HDR capture.

Cornell box-esque HDR measurements [1]


Vitro Starphire Velour, 2 Face


Vitro Starphire Opaque, 1 Face


Vitro Starphire Velour, 1 Face


Vitro Starphire Satin, 1 Face

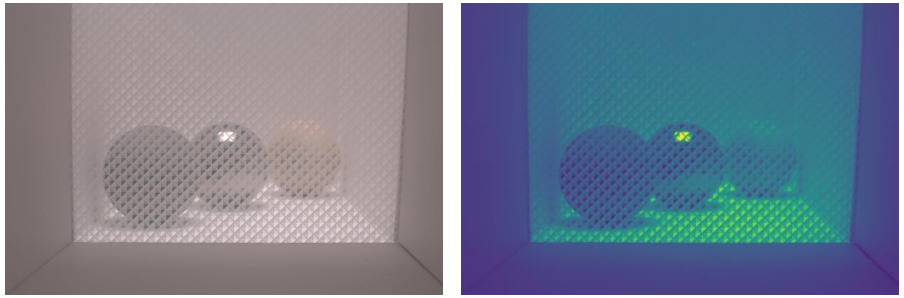

Vitro Starphire Satinlite, 1 Face

Cornell box-esque HDR measurements [2]

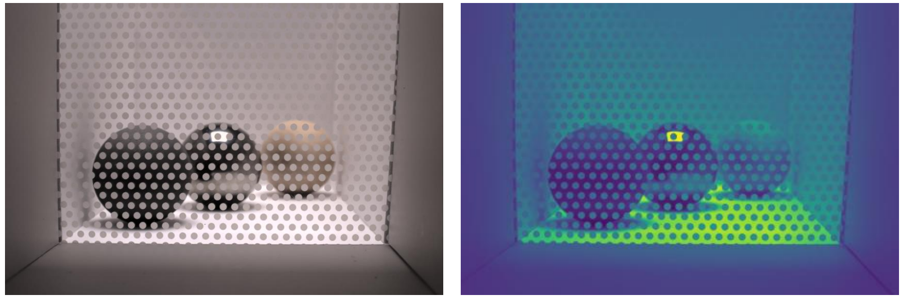
Vitro Starphire Bronze Satin, 1 Face

Vitro Starphire Grey Satin, 1 Face

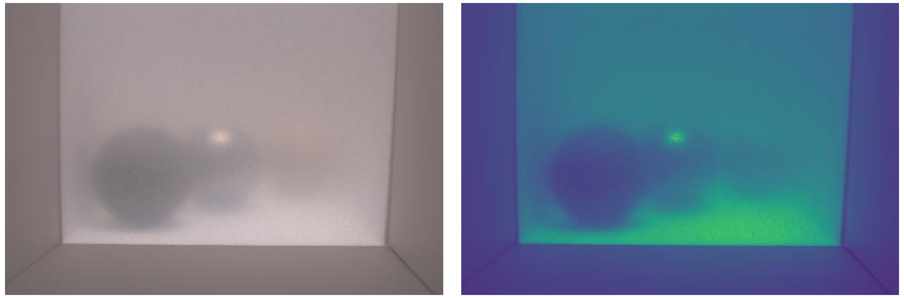
Cornell Box-esque HDR measurements [3]



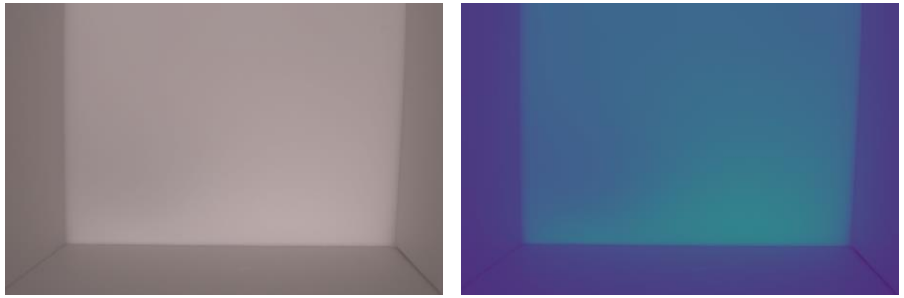
MMM SH2CSC Cut Glass



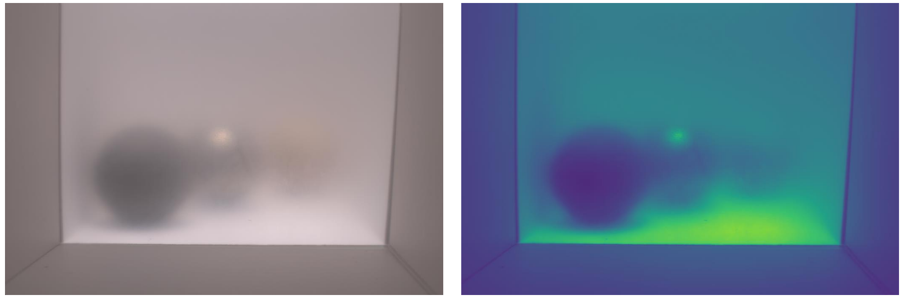
MMM SH2FGSK Shizuku White



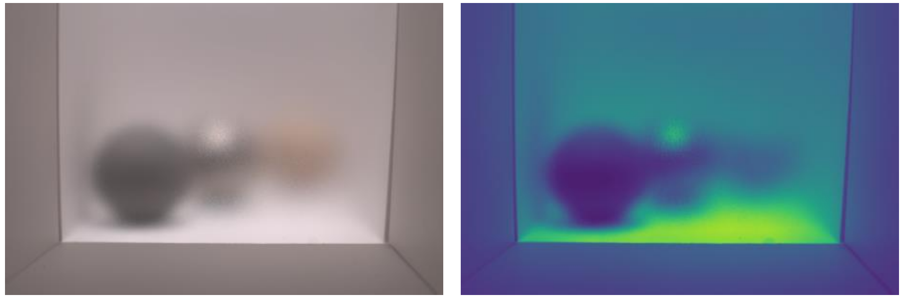
MMM 7725SA-324 Frosted Crystal Electrocut



MMM SH2MAMM Milky Milky

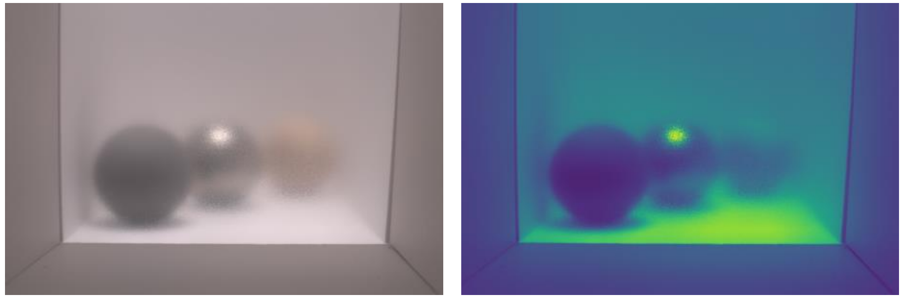


MMM SS7725SE-314 Dusted Crystal Electrocut

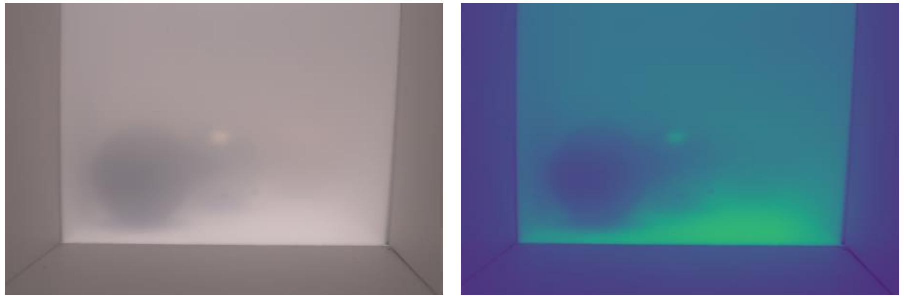


MMM SH2MACRx2 Mat Crystal x2

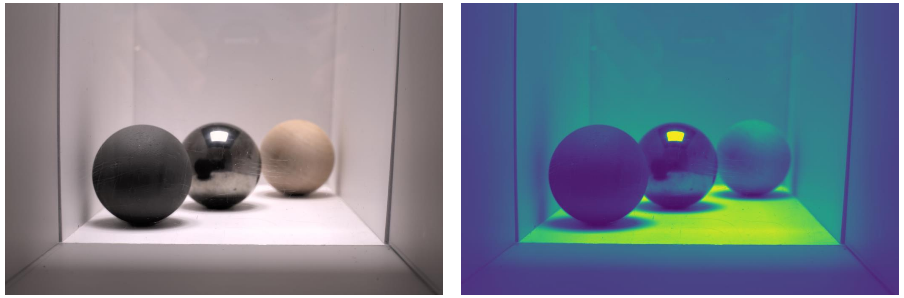
Cornell box-esque HDR measurements [4]



MMM SH2FNCR Fine Crystal



MMM SH2MAMC Milky White



Clear Acrylic

- There is a really wide range of diffusion levels available.

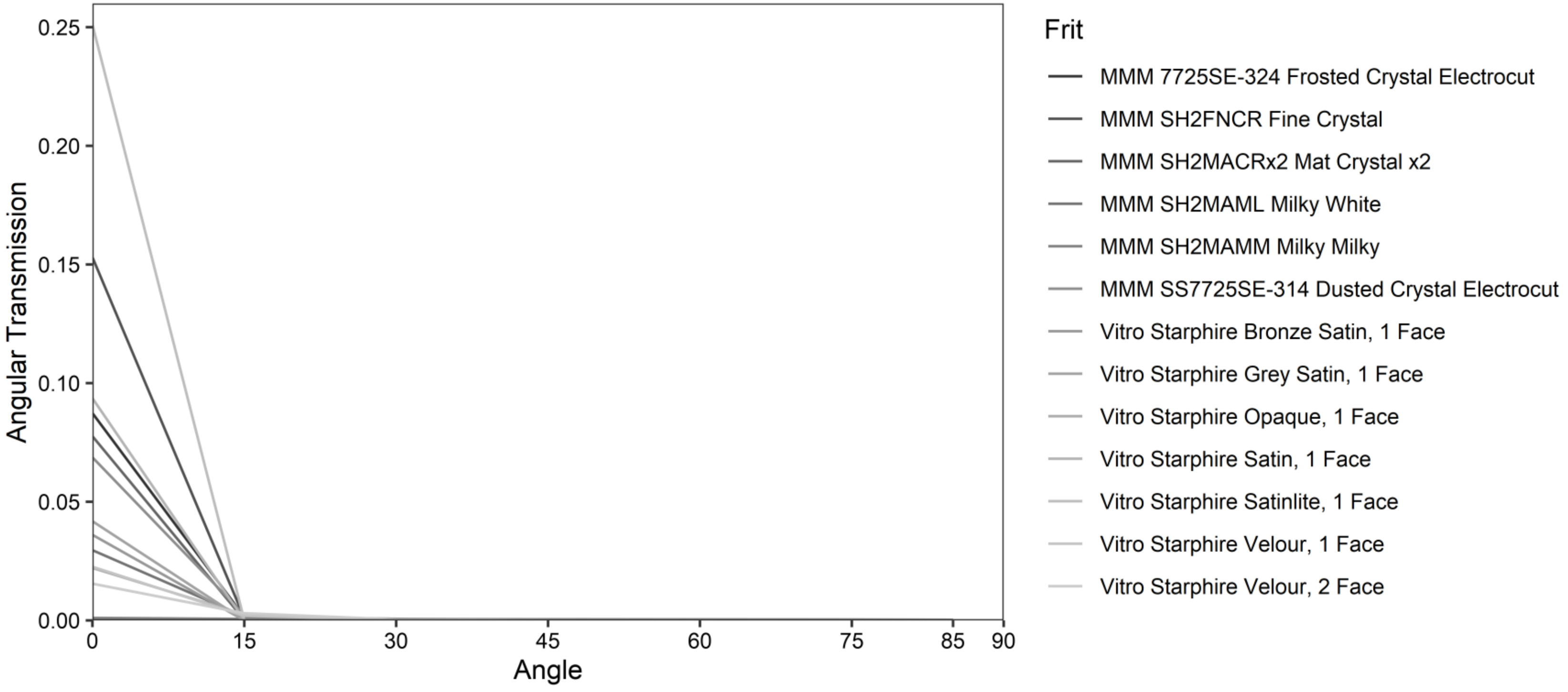
Angular measurement setup

Setup overview

Lights off with sample

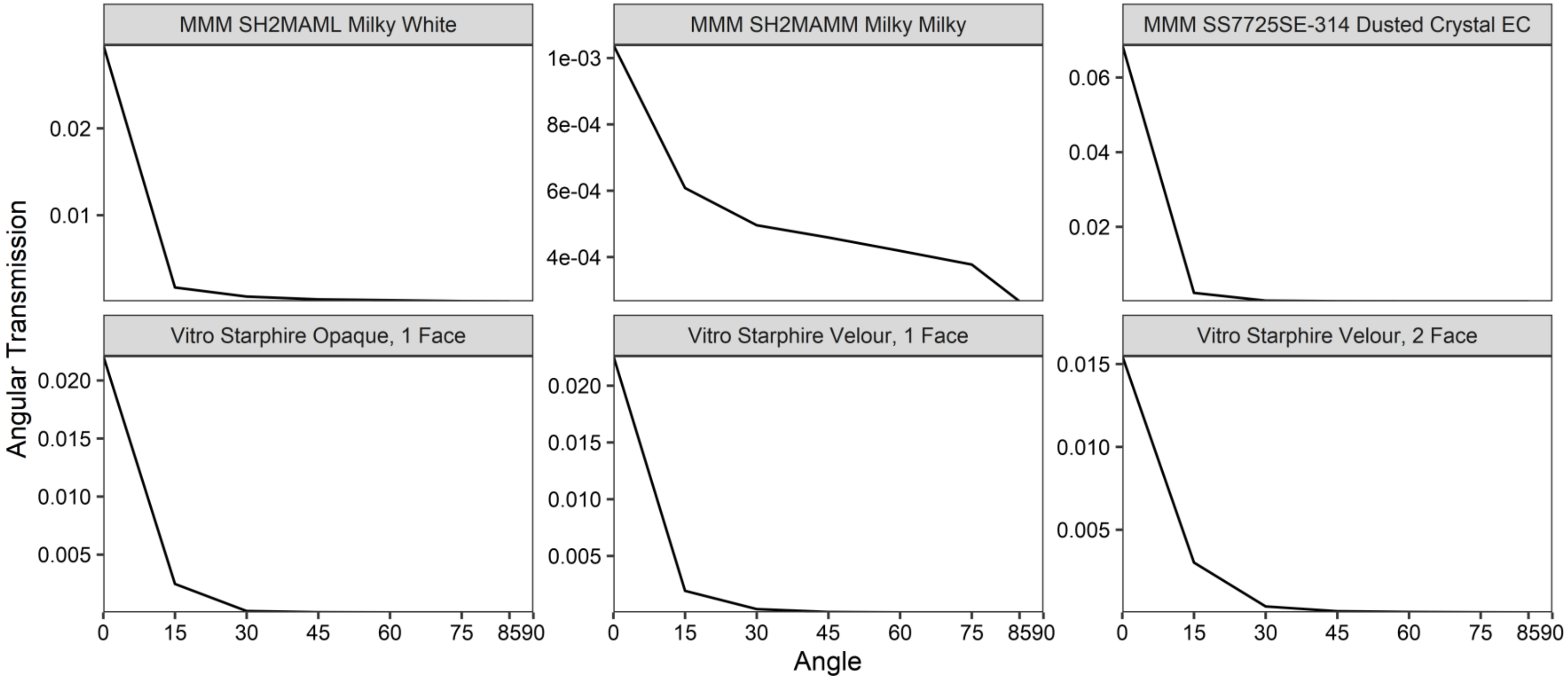
- I also measured the samples at some angular points with direct normal transmission from a spotlight.
- Measurements were at 15-degree increments and done with a handheld luminance meter.

Angular measurements – all fritted media



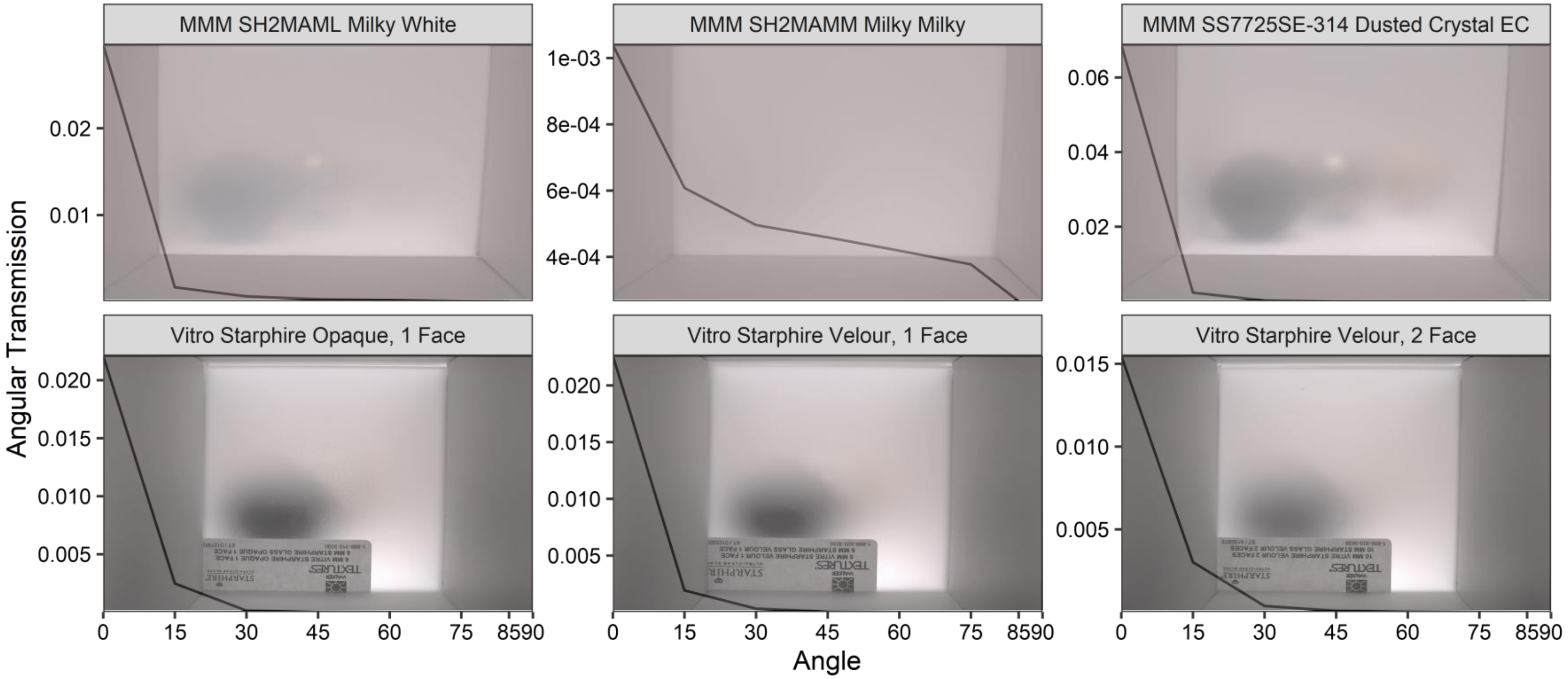
- Better angular resolution around the surface normal would be desirable.

Angular measurements – six most diffusing media



- Better angular resolution around the surface normal would be desirable.
- Still, some of the more diffusing media can be assessed in this way.

Angular measurements – six most diffusing media



- Better angular resolution around the surface normal would be desirable.
- Still, some of the more diffusing media can be assessed in this way.

Modelling fritted media

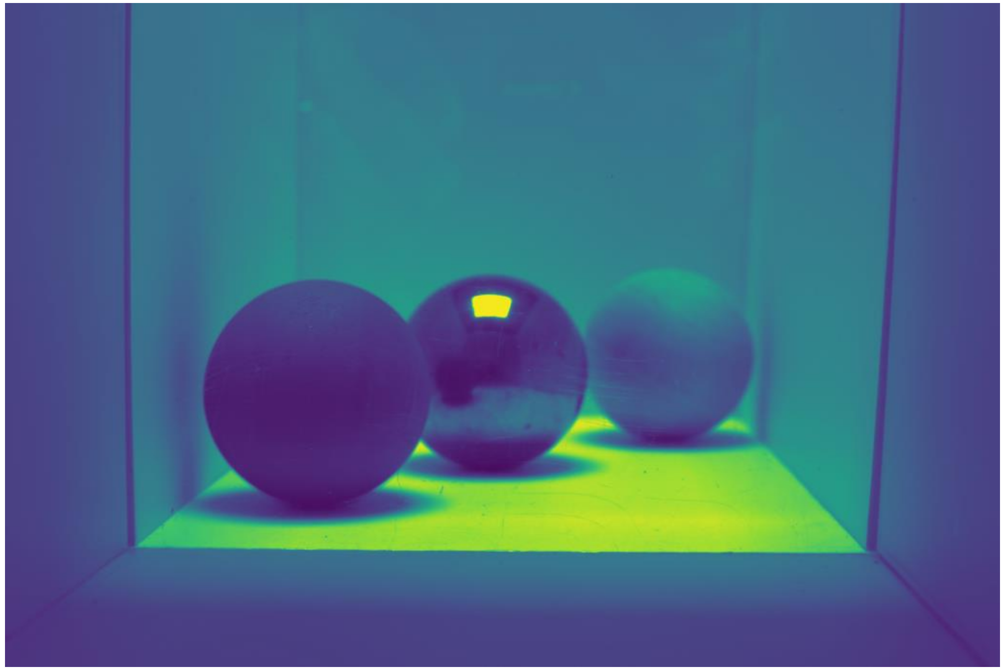
Model for rendering tests (clear acrylic)

HDR pcond -h

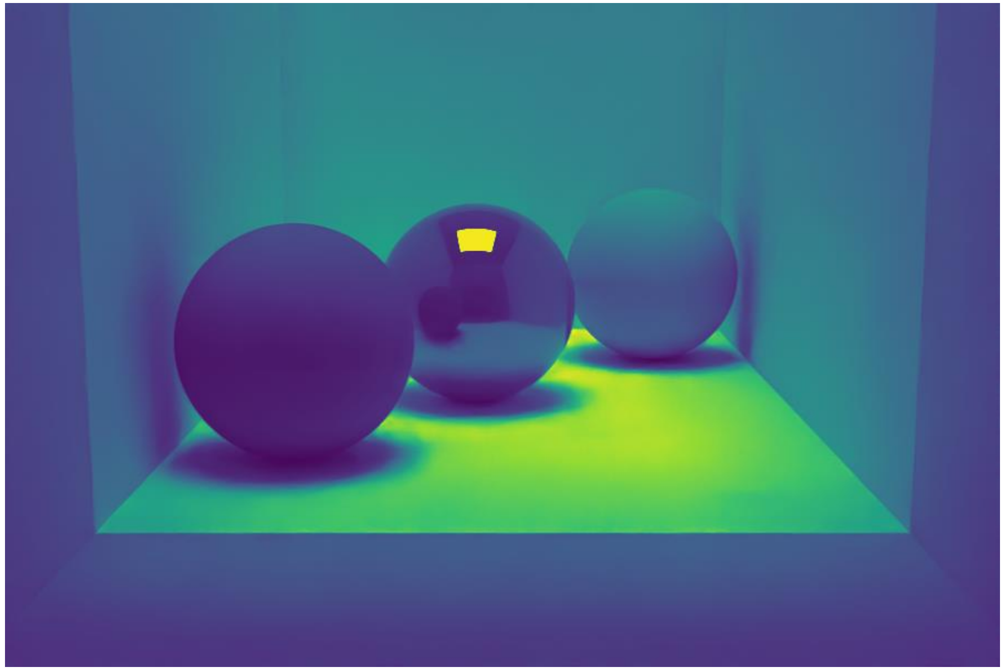
Render pcond -h

- Materials were measured with a Konica Minolta spectrophotometer.
- Light source is a glow material with the same direct normal luminance as the studio light.
- Colors are a bit off, but luminance levels are similar.

Model for rendering tests (clear acrylic)



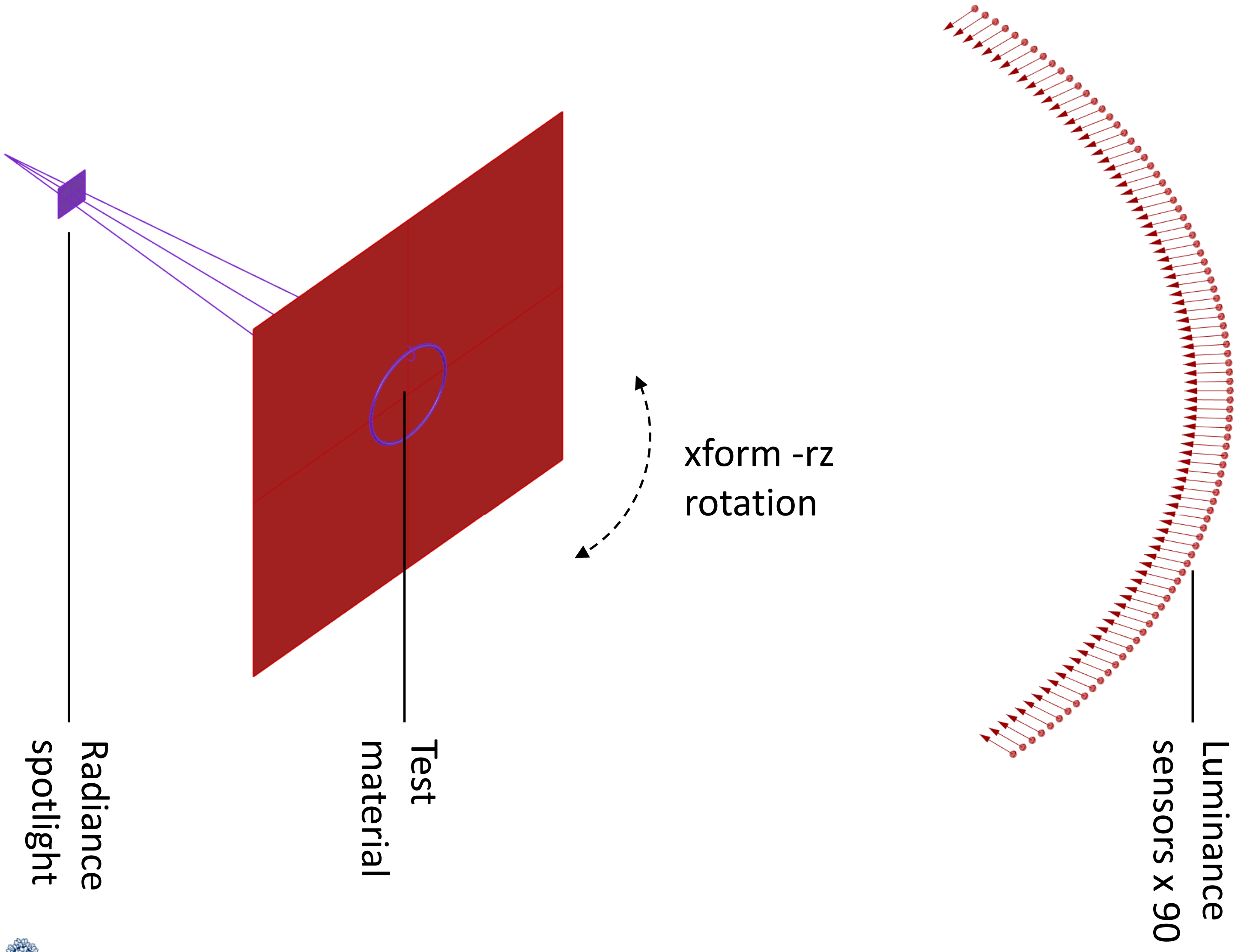
HDR



Render

- Materials were measured with a Konica Minolta spectrophotometer.
- Light source is a glow material with the same direct normal luminance as the studio light.
- Colors are a bit off, but luminance levels are similar.

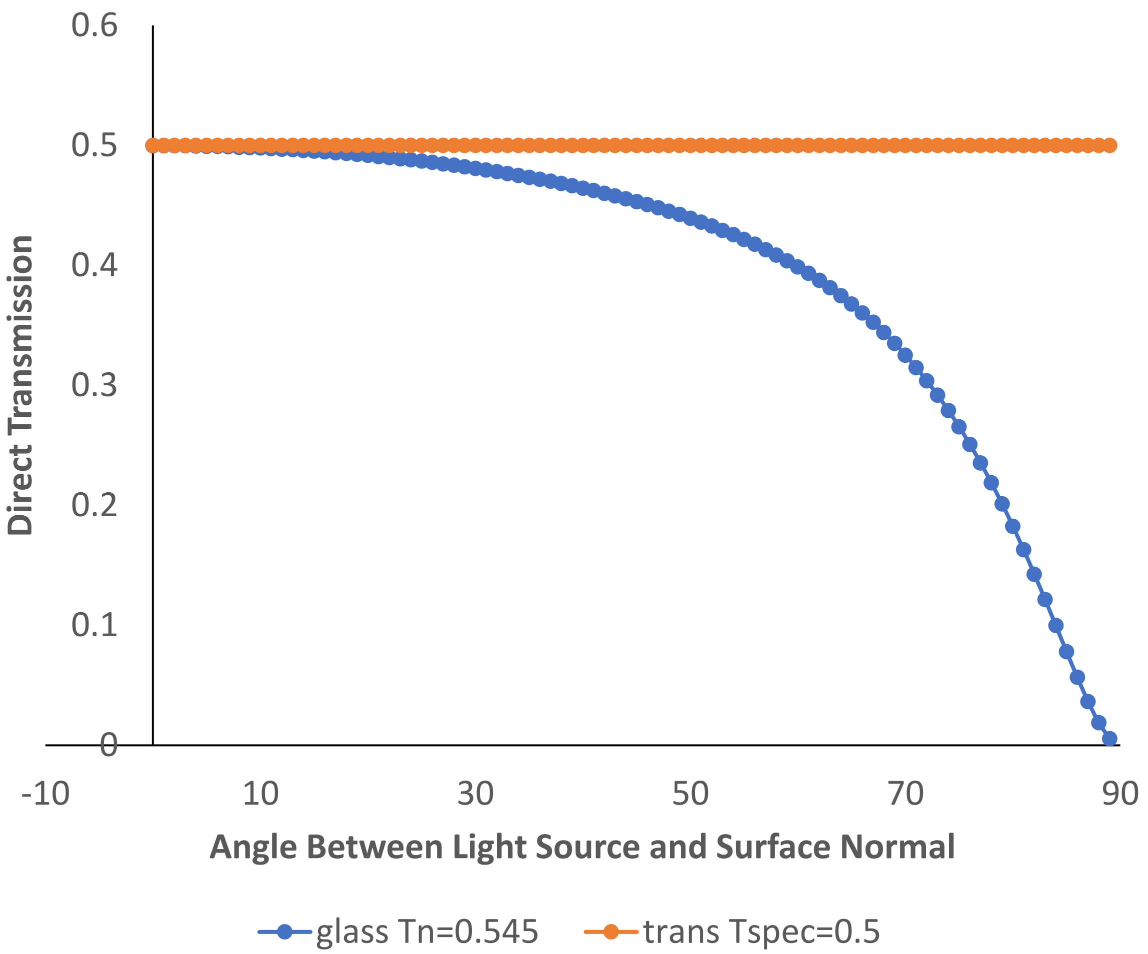
Virtual goniophotometer for angular tests



- The measurement setup was approximately recreated in Radiance using a spotlight, the receiving material, and an array of 90 angular luminance sensors.

- xform can be used to rotate the test material relative to the light source.

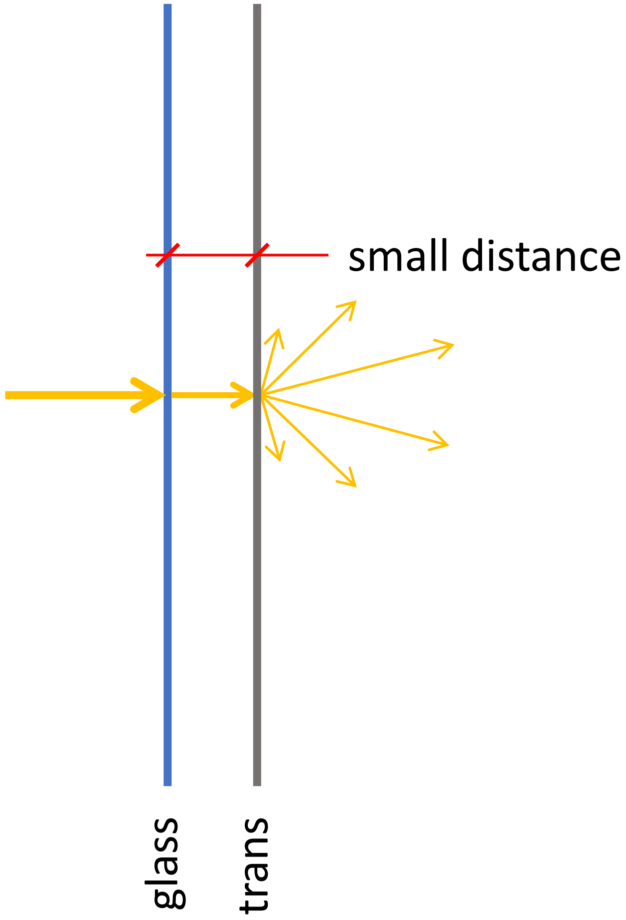
Lazy (or ‘innovative’) modelling approach



xform –rz angle

- A rough trans material with specular transmission can (probably) do a reasonable job of modelling the diffusion.
- BRTDfunc could do better, but is (very) convoluted to setup properly.
- <u>Problem</u>: trans materials don’t model angular transmission according to Fresnel.

Lazy (or ‘innovative’) modelling approach



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- BRTDfunc could do better, but is (very) convoluted to setup properly.
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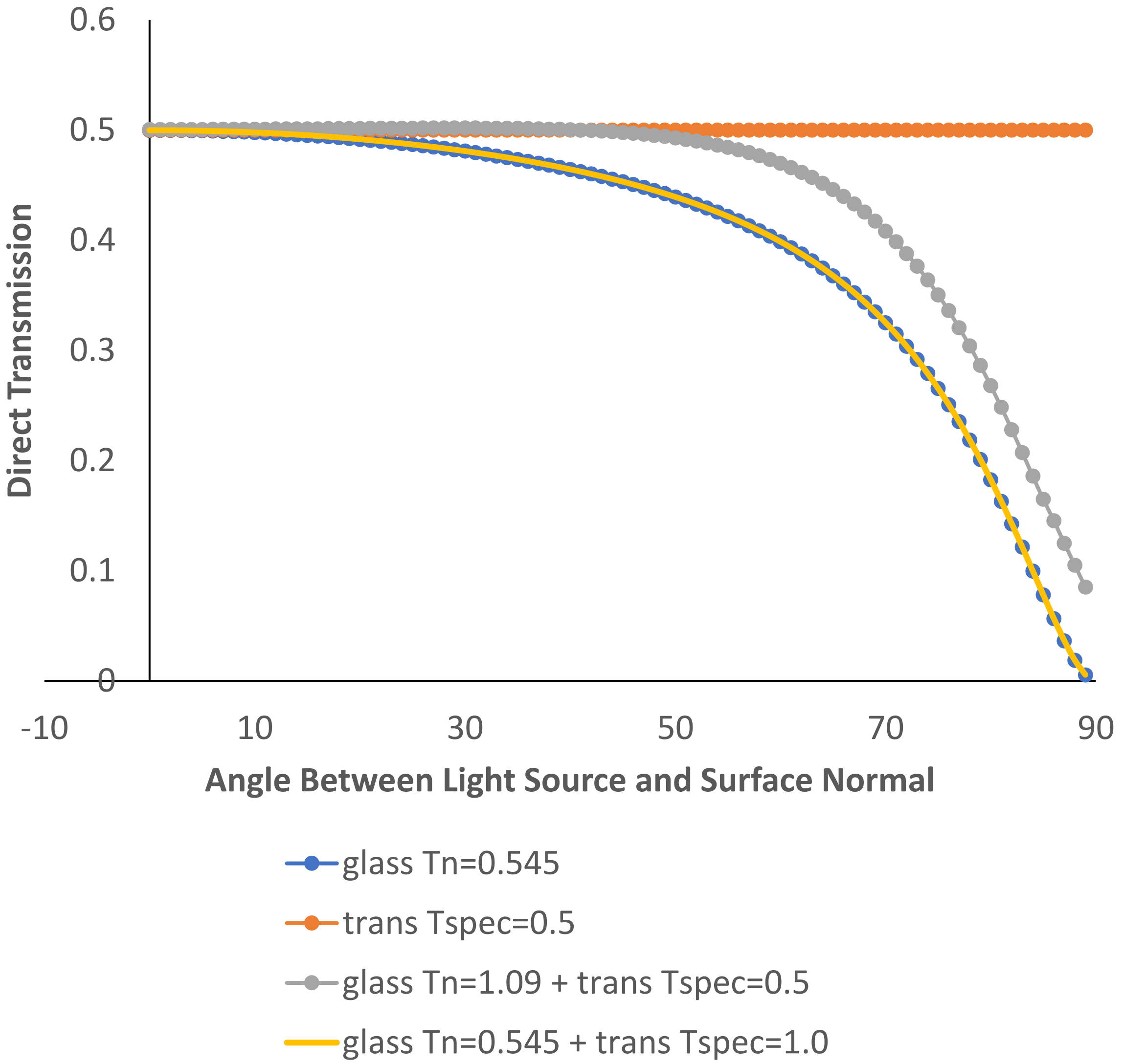
- Solution (?): Sandwich a glass with appropriate Tvis and a trans material together.

Lazy (or ‘innovative’) modelling approach



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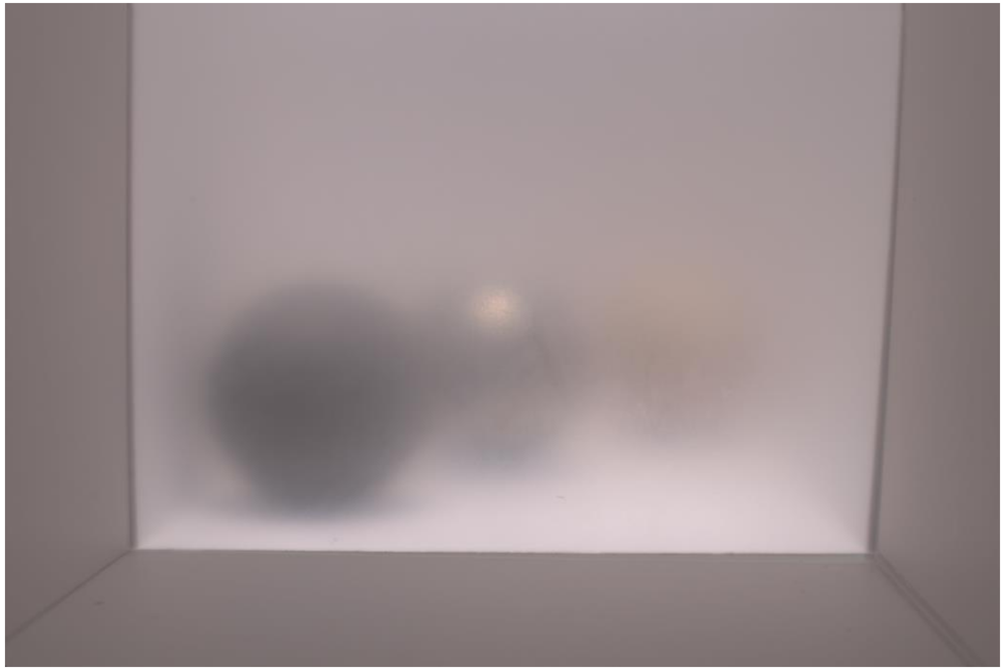
- Solution (?): Sandwich a glass with appropriate Tvis and a trans material together.

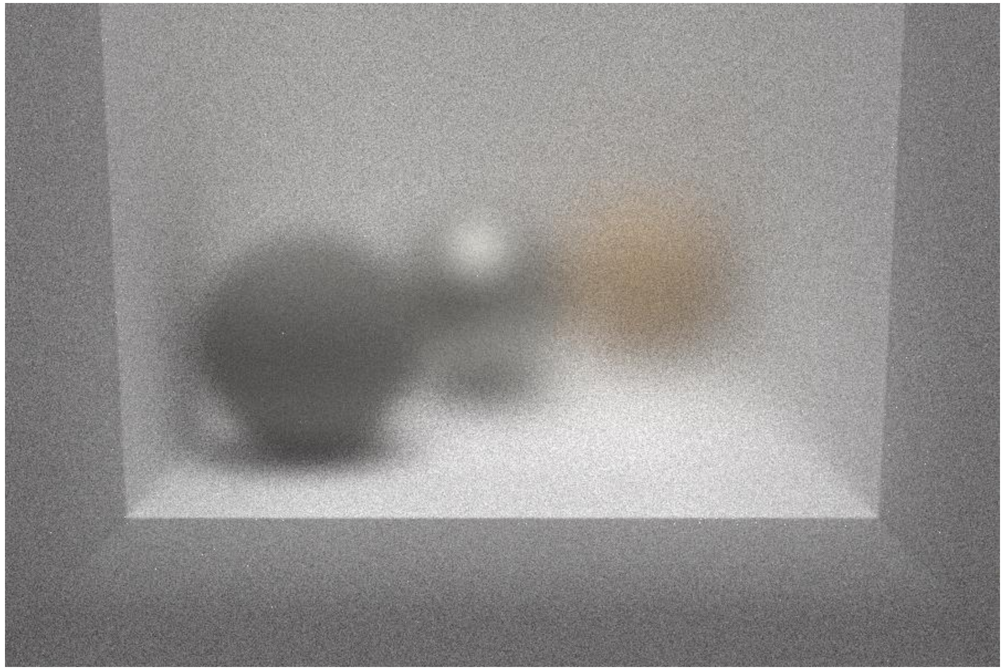
Rough trans can approximate the diffusing media

First pass!



HDR

MMM SS7725SE-314 Dusted Crystal EC



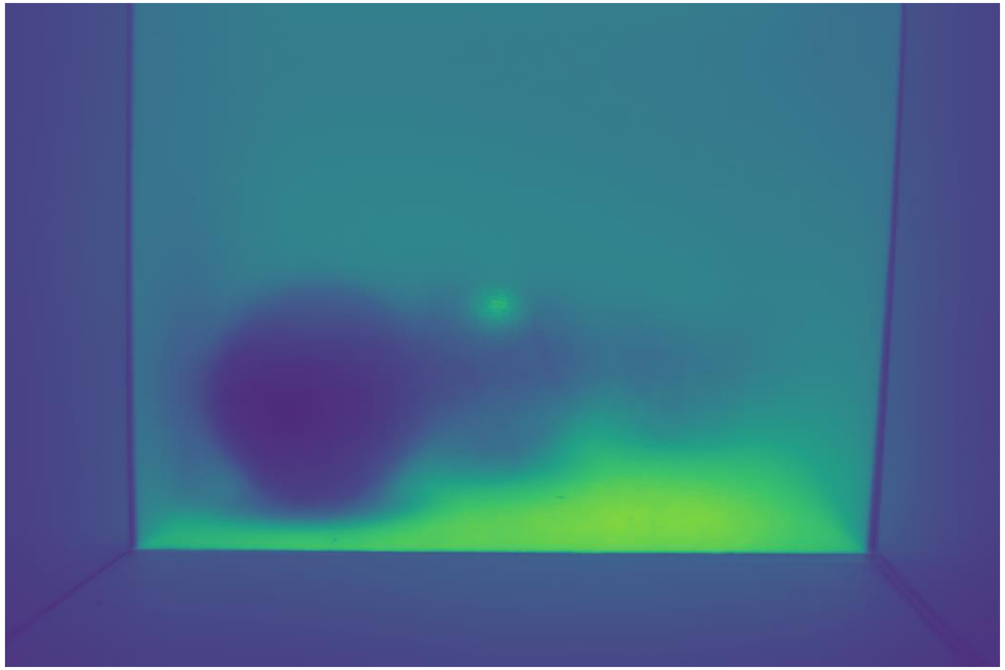
Render

Tvis = 0.75, Roughness = 0.075

- A rough trans material does a decent job of approximating the visual image through the glass.

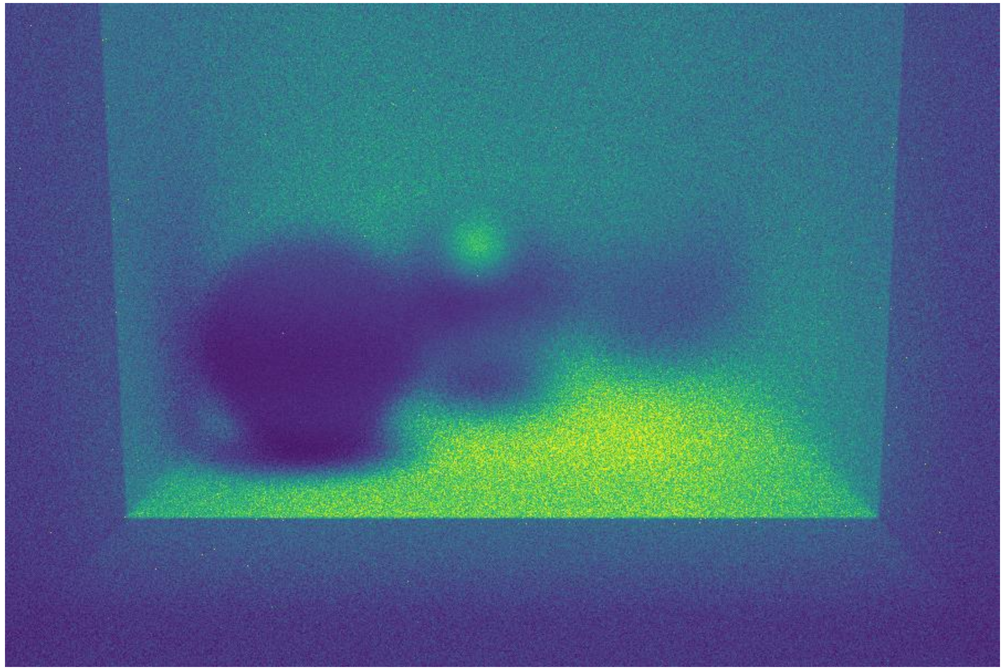
Rough trans can approximate the diffusing media

First pass!



HDR

MMM SS7725SE-314 Dusted Crystal EC

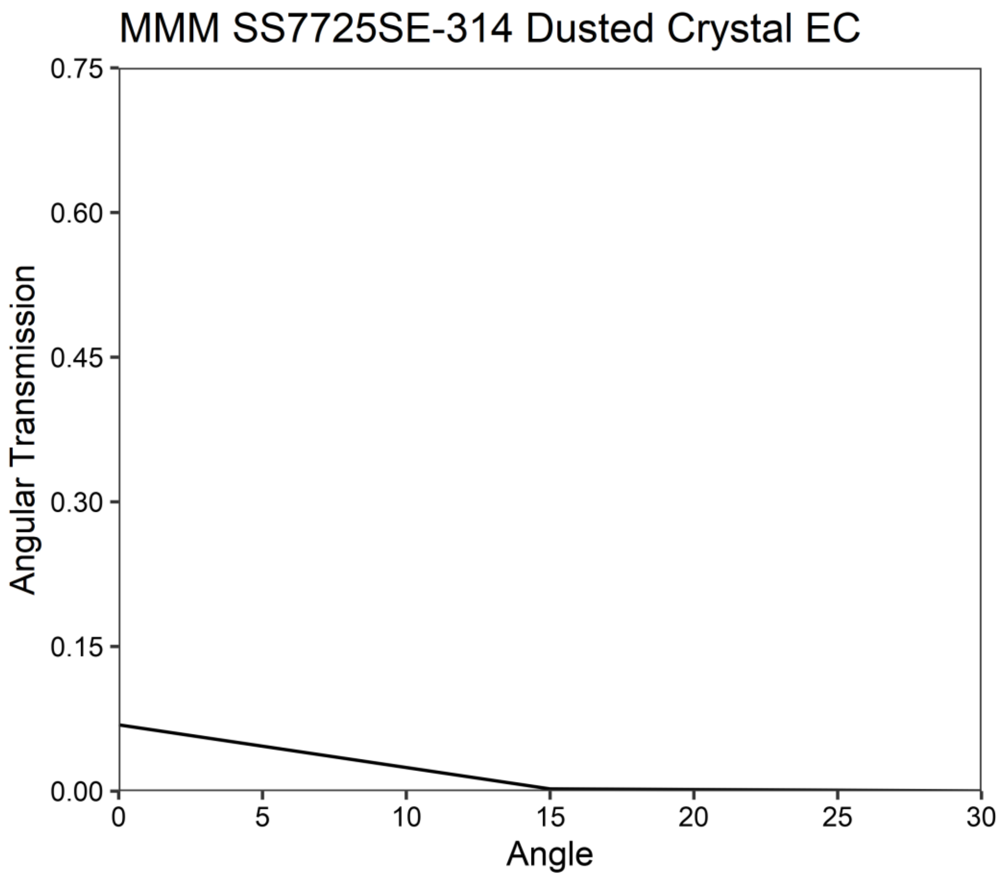


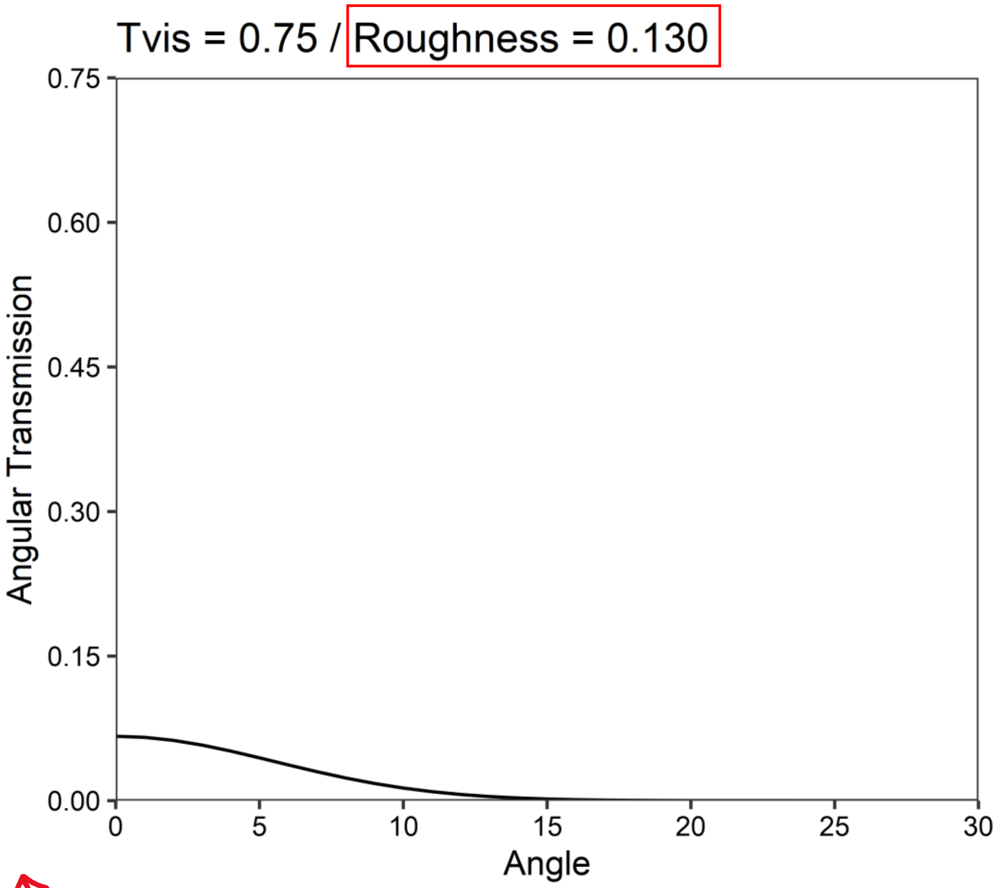
Render

Tvis = 0.75, Roughness = 0.075

Rough trans can approximate the diffusing media

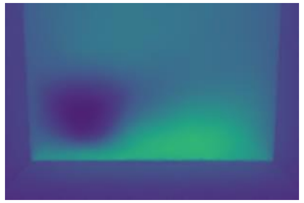
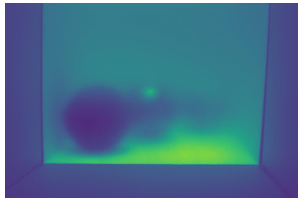
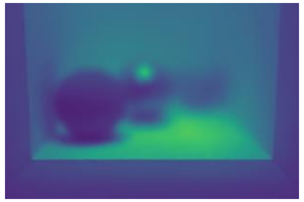
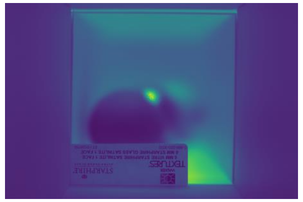
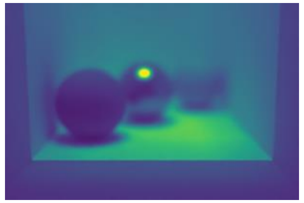
First pass!



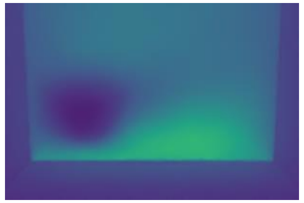
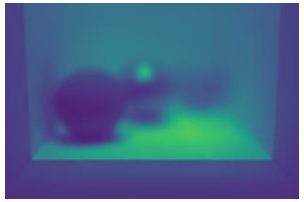
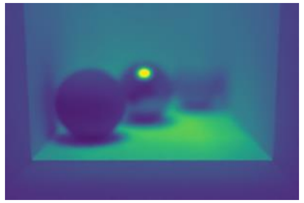


Don't use this solely to match data without more measurements!

Material models for four levels of diffusion

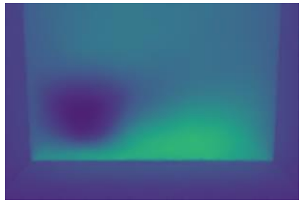
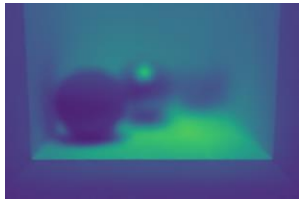
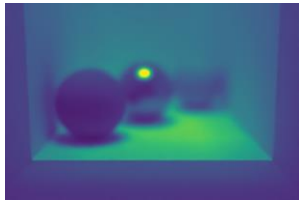
HDR Measure	Roughness	Transmissivity	Diffuse Frac.	Rendering
 MMM SH2MAMM Milky Milky	0.650	0.82	0.50	
 Vitro Starphire Velour, 2 Face	0.250	0.82	0.10	
 MMM SS7725SE-314 Dusted Crystal Electrocut	0.060	0.82	0.20	
 Vitro Starphire Satinlite, 1 Face	0.035	0.82	0.15	

Material models for four levels of diffusion

Roughness	Transmissivity	Diffuse Frac.	Rendering
0.650	0.82	0.50	
0.250	0.82	0.10	
0.060	0.82	0.20	
0.035	0.82	0.15	

```
void glass glass_surface
0
0
3 0.8275 0.8275 0.8275

void trans diffuse_65_50
0
0
7 1 1 1 0 0.65 1 0.50
```

Material models for four levels of diffusion

Roughness	Transmissivity	Diffuse Frac.	Rendering
0.650	0.82	0.50	
0.250	0.82	0.10	
0.060	0.82	0.20	
0.035	0.82	0.15	

```
void glass glass_surface
0
0
3 0.8275 0.8275 0.8275

void trans diffuse_65_50
0
0
7 1 1 1 0 0.65 1 0.50
```

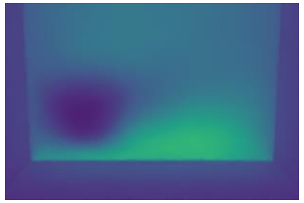
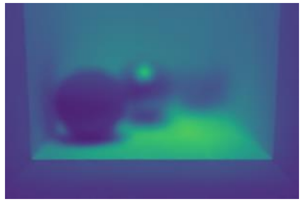
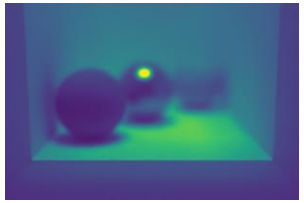
Use for offset dots

```
void mixfunc perforated
6 void diffuse_65_50 uv_hole
perforate_offset.cal -s .05
0
1 0.35685
```

Use for gradient dots

```
void mixfunc perforated
6 void diffuse_65_50 uv_hole_flip
perforate_offset_gradient.cal -s .05
0
2 0.6 1.25
```

Material models for four levels of diffusion

Roughness	Transmissivity	Diffuse Frac.	Rendering
0.650	0.82	0.50	
0.250	0.82	0.10	
0.060	0.82	0.20	
0.035	0.82	0.15	

```
void glass glass_surface
0
0
3 0.8275 0.8275 0.8275

void trans diffuse_060_80
0
0
7 1 1 1 0 0.060 1 0.80
```

Use for offset dots

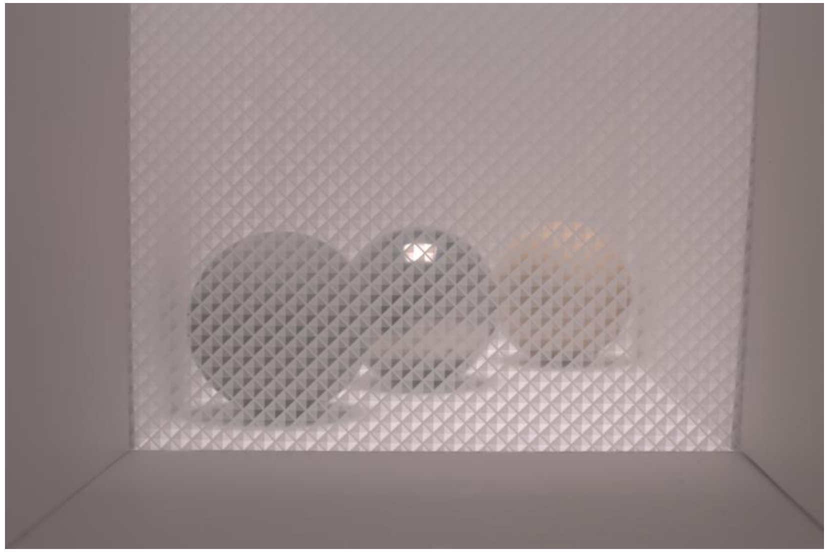
```
void mixfunc perforated
6 void diffuse_060_80 uv_hole
perforate_offset.cal -s .05
0
1 0.35685
```

Use for gradient dots

```
void mixfunc perforated
6 void diffuse_060_80 uv_hole_flip
perforate_offset_gradient.cal -s .05
0
2 0.6 1.25
```

A few thoughts on frit patterns

Patterns add further complexity



MMM SH2CSC Cut Glass

MMM SH2FGSK Shizuku White

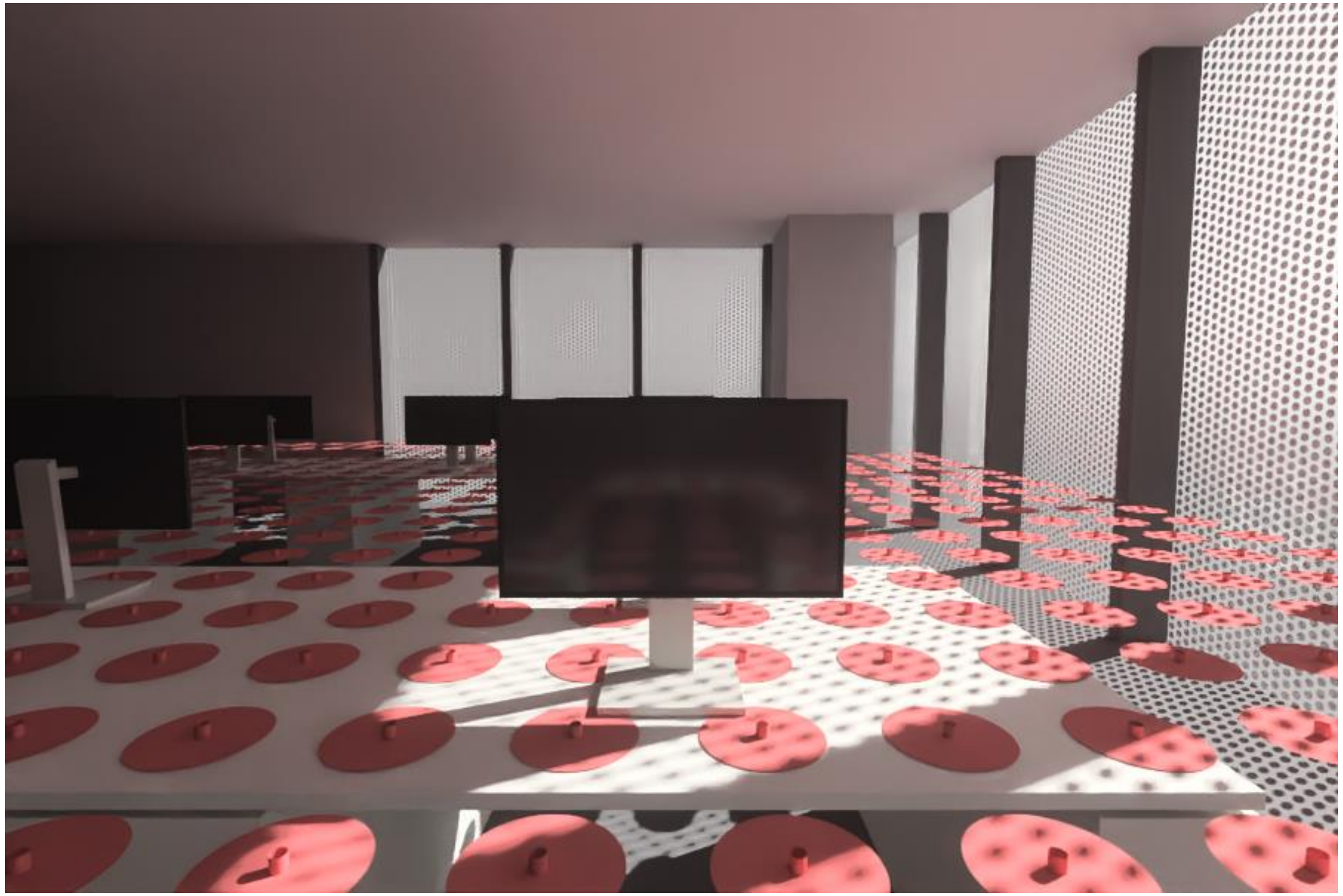
- Challenging to model specific patterns at scale. Gradients and images, too, are irksome.
- Wreaks havoc on some grid-based metrics such as ASE—annual sunlight exposure.

Example: 40% coverage offset dots

```
void plastic white_dots
0
0
5 0.7 0.7 0.7 0.0 0.0

void mixfunc perforated
6 void white_dots uv_hole perforate_offset.cal -s .05
0
1 0.35685
```

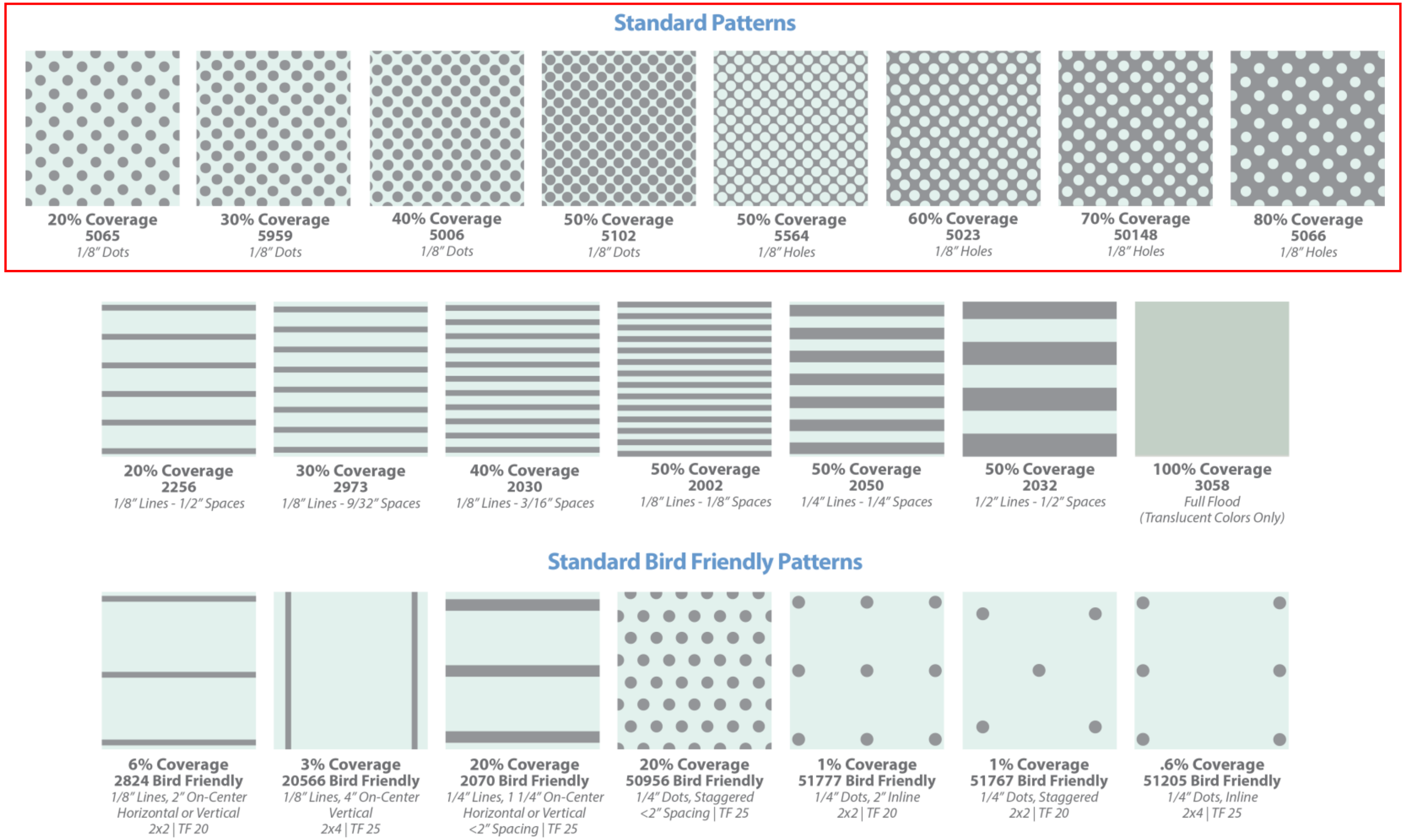
```
{
    perforate_offset.cal

    A perforation function for mixfuncs with offset holes  for planar sufaces.
    Foreground is solid, background the holes.

    The relative hole size to a U,V division is determined by A1.
    -s is a scaling parameter.

    J. Alstan Jakubiec, 2023 - Added UV staggering of holes
    Built upon the work of: Abel Boerema 2004, n.a.v.Georg Mischler 30. 04. 1993
}


{uv coordinate mapping}
un = mod(U, 1) - 0.5;
vn = mod(V, 1) - 0.5;

{separate rules for alternating U coordinates}
even_odd = mod(U, 2) - 1.0;

{even holes}
even = if(sqrt(un*un + vn*vn) - A1, 1, 0);

{odd holes, need to be joined to work with the planar U,V subdivisions}
odd_top = if(sqrt(un*un + (vn+0.5)*(vn+0.5)) - A1, 1, 0);
odd_bottom = if(sqrt(un*un + (vn-0.5)*(vn-0.5)) - A1, 1, 0);

{final holes}
outofcirc = if(even_odd, even, and(odd_top, odd_bottom));

uv_hole = outofcirc;
```

Example: 40% coverage offset dots



- Now with a 0.3 m spacing sensor grid imposed upon the scene (red circles with protruding cylinder point locations).
- With 40% coverage, it is pretty random whether a sensor is covered or not.
- Are these areas not sunlit? According to an hourly ASE calculation, they are not. According to an occupant, probably they are.
- For annual calculations, it doesn't make sense to use a pattern like this.
- It is better to area-weight the effect of your frit, whether it be translucent or opaque.

Example: 40% coverage offset dots



https://www.viracon.com/printing/

Example: gradient offset dots (bottom to top)

```
void plastic white_dots
0
0
5 0.7 0.7 0.7 0.0 0.0

void mixfunc perforated
6 void white_dots uv_hole perforate_offset_gradient.cal -s .05
0
2 0.75 1.75
```

```
{
	perforate_offset_gradient.cal

	A perforation function for mixfuncs with offset holes for planar sufaces.
	A new parameter controls the circle radius as a function of distance along the surface.
	Foreground is solid, background the holes.

	The relative hole size to a U,V division is determined by A1.
	The distance along the V-axis in world units where the circle radius is 0 is determined by A2.
		For example, 1.5 means the circles radius goes to 0 1.5 [units] up the surface.
	-s is a scaling parameter.

	Use uv_hole for bottom-to-top gradients.
	Use uv_hole_flip for top-to-bottom gradients.

	J. Alstan Jakubiec, 2023 - Added UV staggering of holes and V-gradient
	Built upon the work of: Abel Boerema 2004, n.a.v.Georg Mischler 30. 04. 1993
}

{uv coordinate mapping}
un = mod(U, 1) - 0.5;
vn = mod(V, 1) - 0.5;

{separate rules for alternating U coordinates}
even_odd = mod(U, 2) - 1.0;

{shifting radius along V-axis}
dist_v = if(A2 - V/S, A2 - V/S, 0);
radius = if(dist_v, A1 * (dist_v / A2), 0);
dist_v_flip = if(A2 - V/S, 0, abs(A2 - V/S));
radius_flip = A1 * (dist_v_flip / A2);

{even holes}
even = if(sqrt(un*un + vn*vn) - radius, 1, 0);
even_flip = if(sqrt(un*un + vn*vn) - radius_flip, 1, 0);

{odd holes, need to be joined to work with the planar U,V subdivisions}
odd_top = if(sqrt(un*un + (vn+0.5)*(vn+0.5)) - radius, 1, 0);
odd_bottom = if(sqrt(un*un + (vn-0.5)*(vn-0.5)) - radius, 1, 0);
odd_top_flip = if(sqrt(un*un + (vn+0.5)*(vn+0.5)) - radius_flip, 1, 0);
odd_bottom_flip = if(sqrt(un*un + (vn-0.5)*(vn-0.5)) - radius_flip, 1, 0);

{final holes}
outofcirc = if(even_odd, even, and(odd_top, odd_bottom));
outofcirc_flip = if(even_odd, even_flip, and(odd_top_flip, odd_bottom_flip));

uv_hole = outofcirc;
uv_hole_flip = outofcirc_flip;
```

Example: gradient offset dots (top to bottom)

```
void plastic white_dots
0
0
5 0.7 0.7 0.7 0.0 0.0

void mixfunc perforated
6 void white_dots uv_hole_flip perforate_offset_gradient.cal -s .05
0
2 0.6 1.25
```

```
{
     perforate_offset_gradient.cal

     A perforation function for mixfuncs with offset holes for planar sufaces.
     A new parameter controls the circle radius as a function of distance along the surface.
     Foreground is solid, background the holes.

     The relative hole size to a U,V division is determined by A1.
     The distance along the V-axis in world units where the circle radius is 0 is determined by A2.
          For example, 1.5 means the circles radius goes to 0 1.5 [units] up the surface.
     -s is a scaling parameter.

     Use uv_hole for bottom-to-top gradients.
     Use uv_hole_flip for top-to-bottom gradients.

     J. Alstan Jakubiec, 2023 - Added UV staggering of holes and V-gradient
     Built upon the work of: Abel Boerema 2004, n.a.v.Georg Mischler 30. 04. 1993
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{uv coordinate mapping}
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{separate rules for alternating U coordinates}
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dist_v = if(A2 - V/S, A2 - V/S, 0);
radius = if(dist_v, A1 * (dist_v / A2), 0);
dist_v_flip = if(A2 - V/S, 0, abs(A2 - V/S));
radius_flip = A1 * (dist_v_flip / A2);

{even holes}
even = if(sqrt(un*un + vn*vn) - radius, 1, 0);
even_flip = if(sqrt(un*un + vn*vn) - radius_flip, 1, 0);

{odd holes, need to be joined to work with the planar U,V subdivisions}
odd_top = if(sqrt(un*un + (vn+0.5)*(vn+0.5)) - radius, 1, 0);
odd_bottom = if(sqrt(un*un + (vn-0.5)*(vn-0.5)) - radius, 1, 0);
odd_top_flip = if(sqrt(un*un + (vn+0.5)*(vn+0.5)) - radius_flip, 1, 0);
odd_bottom_flip = if(sqrt(un*un + (vn-0.5)*(vn-0.5)) - radius_flip, 1, 0);

{final holes}
outofcirc = if(even_odd, even, and(odd_top, odd_bottom));
outofcirc_flip = if(even_odd, even_flip, and(odd_top_flip, odd_bottom_flip));

uv_hole = outofcirc;
uv_hole_flip = outofcirc_flip;
```
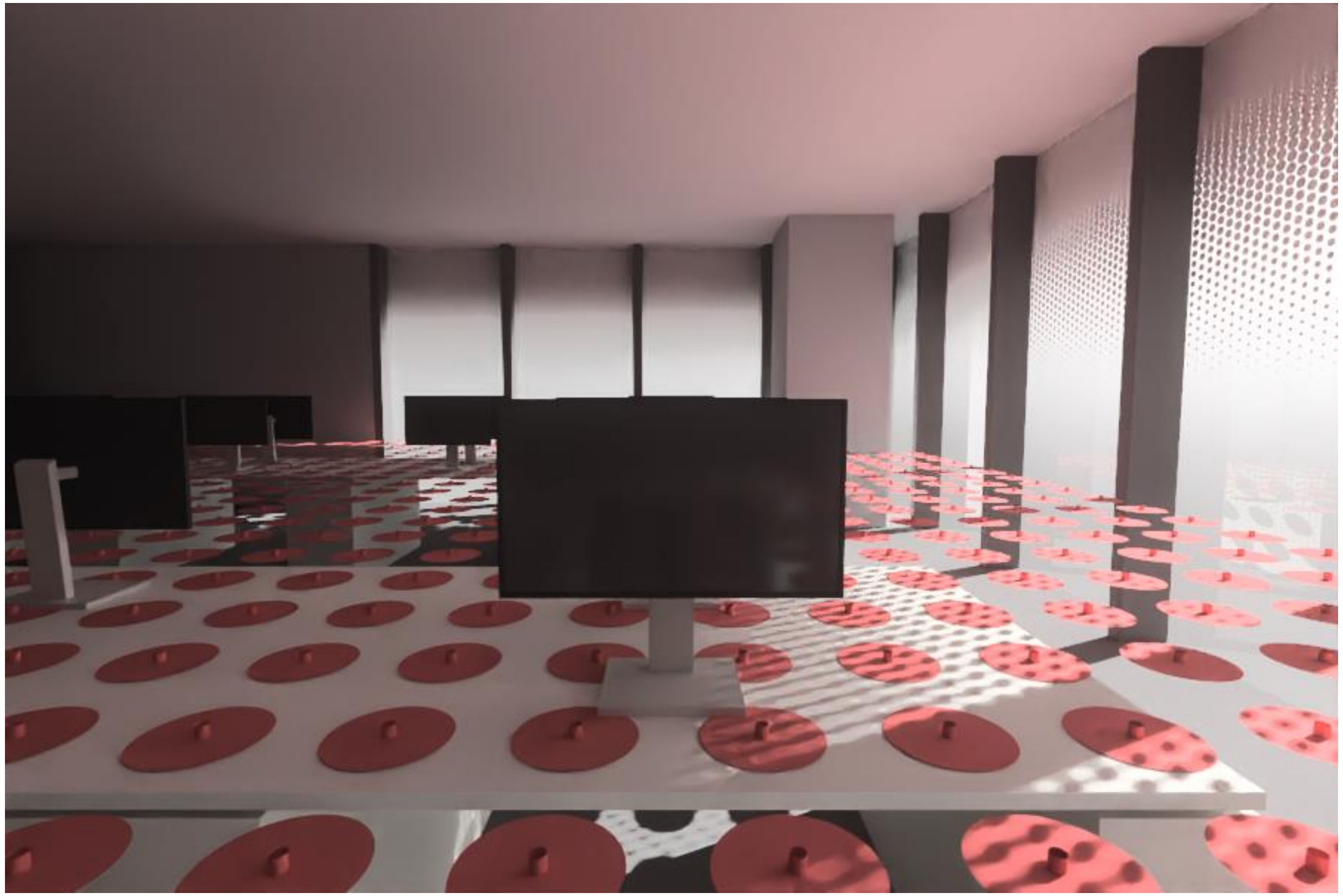

Example: gradient offset dots (top to bottom)



- More complexity here, because the spatial distribution of the light level change is not uniform.
- Options:
  - Split your glass proportionally into two materials.
  - Run as-is. At least the probability of sensors being struck decreases with distance appropriately.

Example: gradient offset dots (top to bottom)

Glare reduction tests

Limited assessment through renderings

Six Materials

1. Clear glass
2. Opaque white 70%
3. 0.650 roughness trans
4. 0.250 roughness trans
5. 0.060 roughness trans
6. 0.035 roughness trans

See previous pages

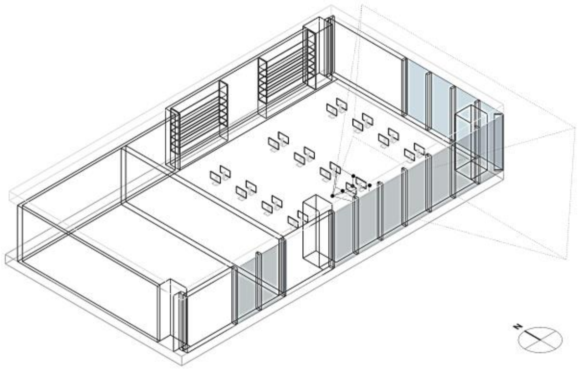
X

Three Patterns

1. Full coverage
2. 40% dots
3. Top-to-bottom gradient

X

One Model



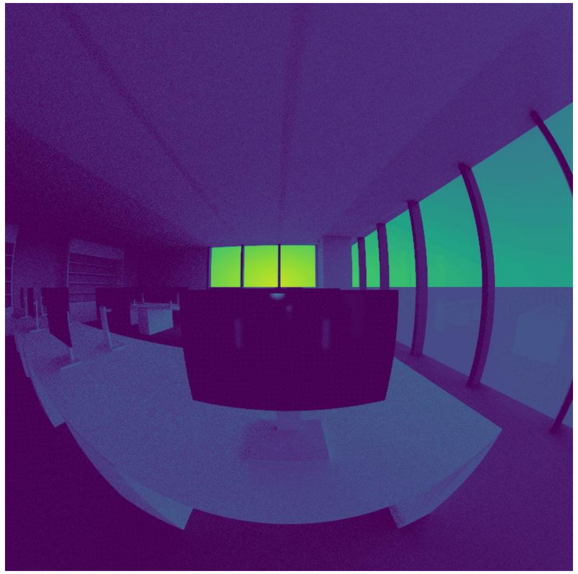
X

One day, ½ hourly

1. September 17, 6:00-19:00 (Toronto TMYx, Perez sky, clear day)

→ DGP evaluations from HDR renderings

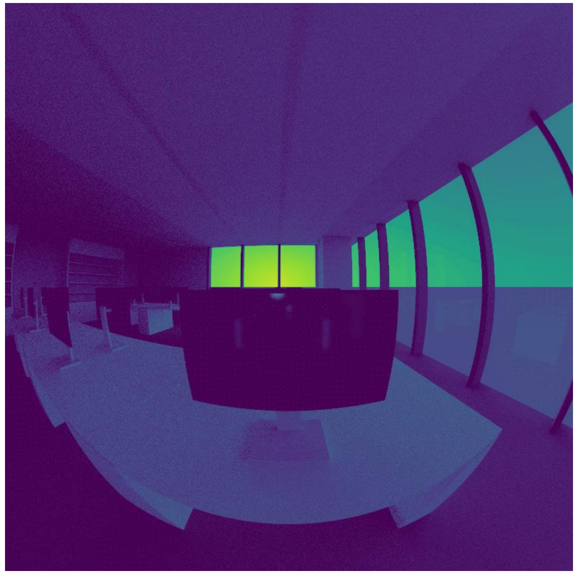
Example rendered outputs



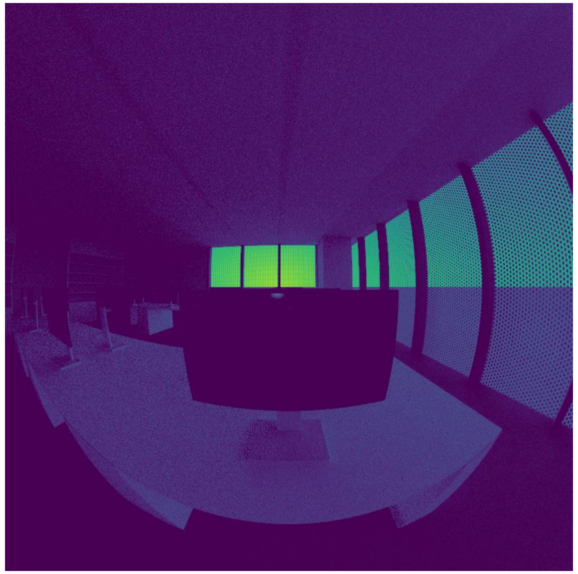
Full Glass, Tn = 0.82

Luminance, cd/m^2 1 100 1,000 10,000

Example rendered outputs

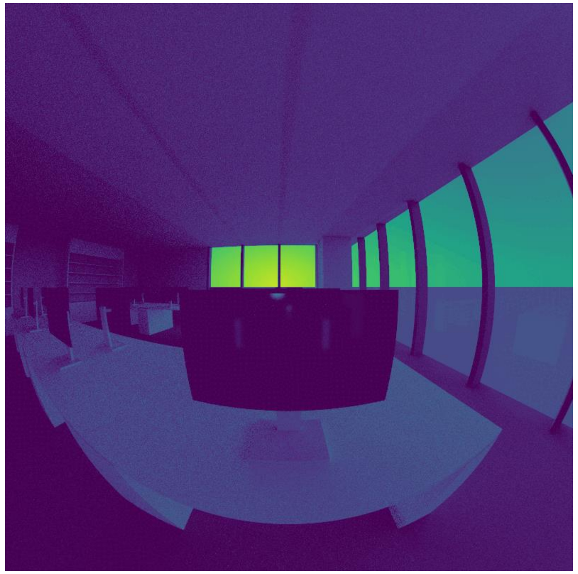


Full Glass, Tn = 0.82

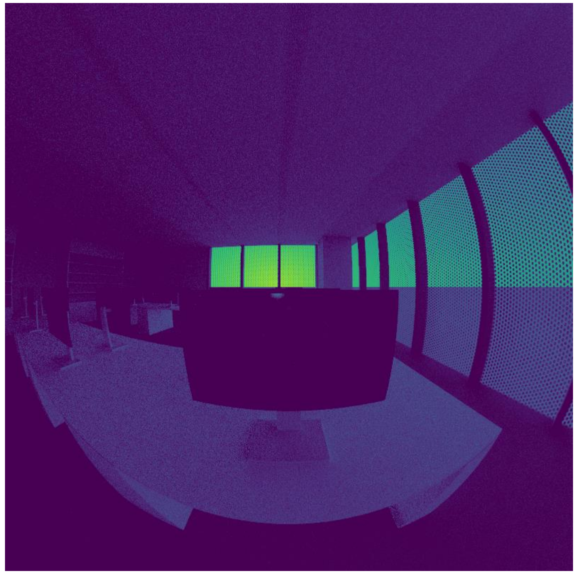


Offset, Opaque White

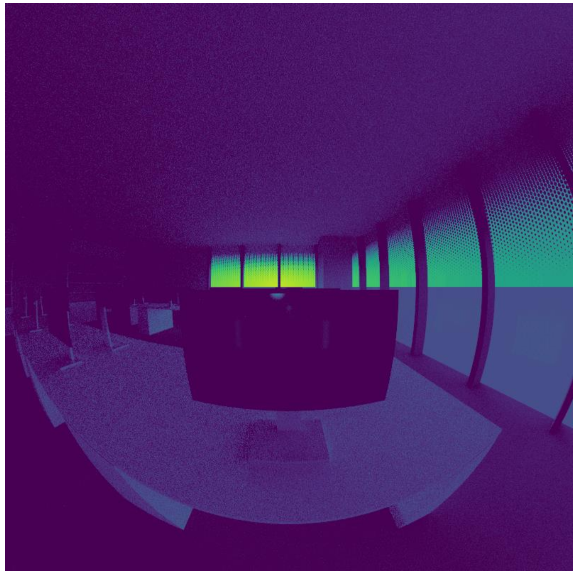
Example rendered outputs



Full Glass, Tn = 0.82



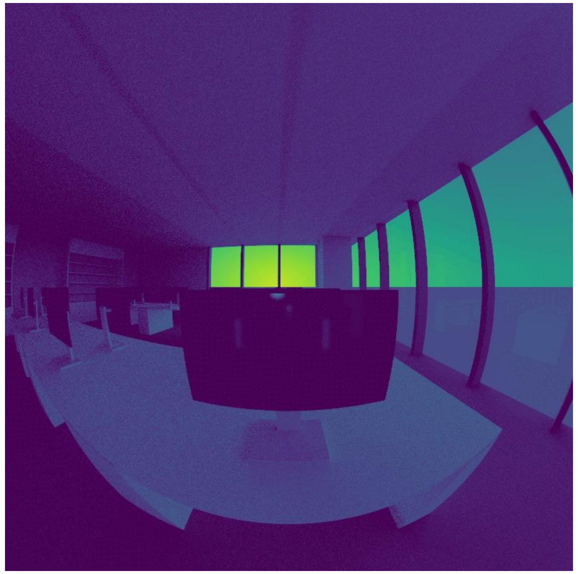
Offset, Opaque White



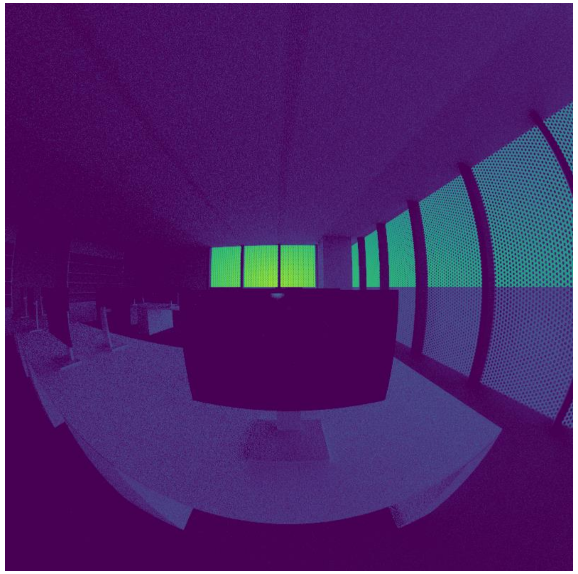
Gradient, Opaque White

Luminance, cd/m^2

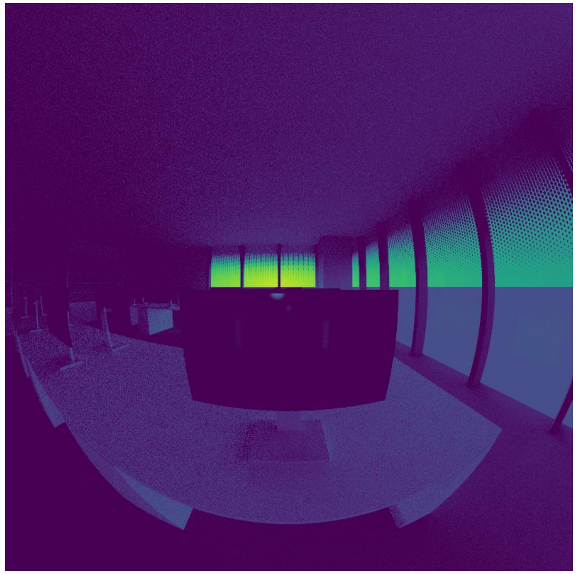
Example rendered outputs



Full Glass, Tn = 0.82



Offset, Opaque White

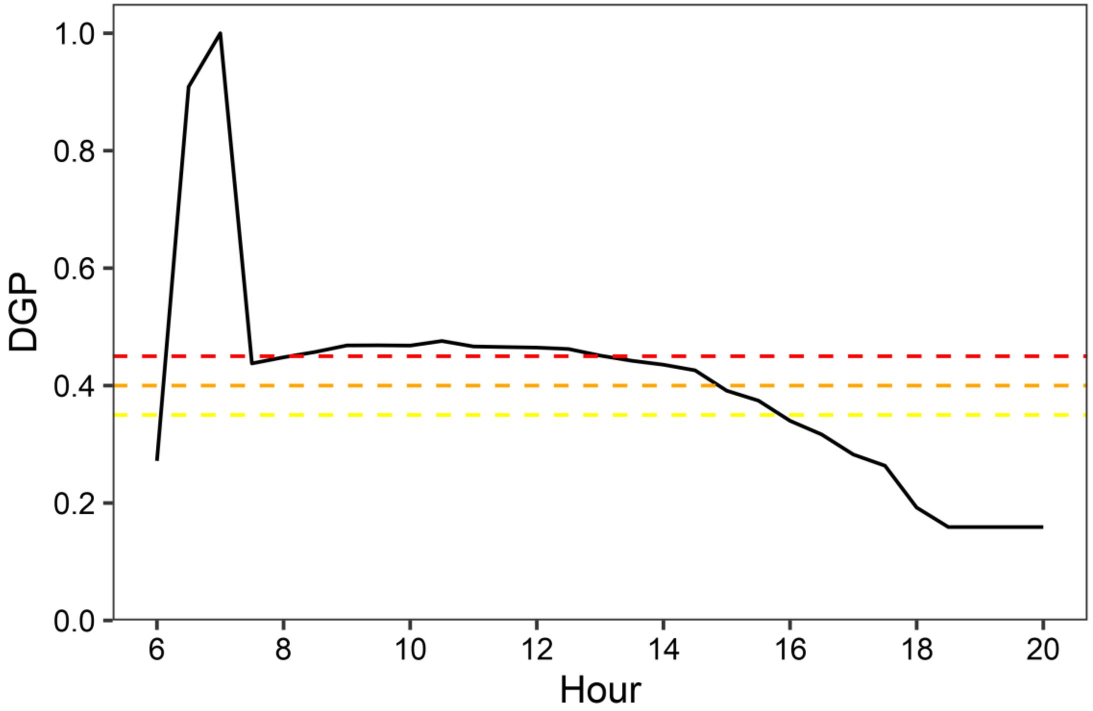


Gradient, Opaque White

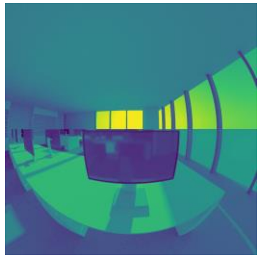
Full, trans roughness=.250
Vitro Starphire Velour, 2 Face

Luminance, cd/m^2

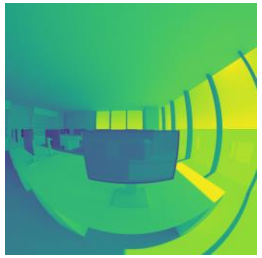
Baseline, full clear glass Tn = 0.82, DGP



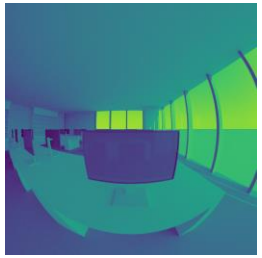
- Strong peaks of DGP occur in the morning with levels hovering around 0.45 (disturbing) from 7:30 until 13:00.



7:00



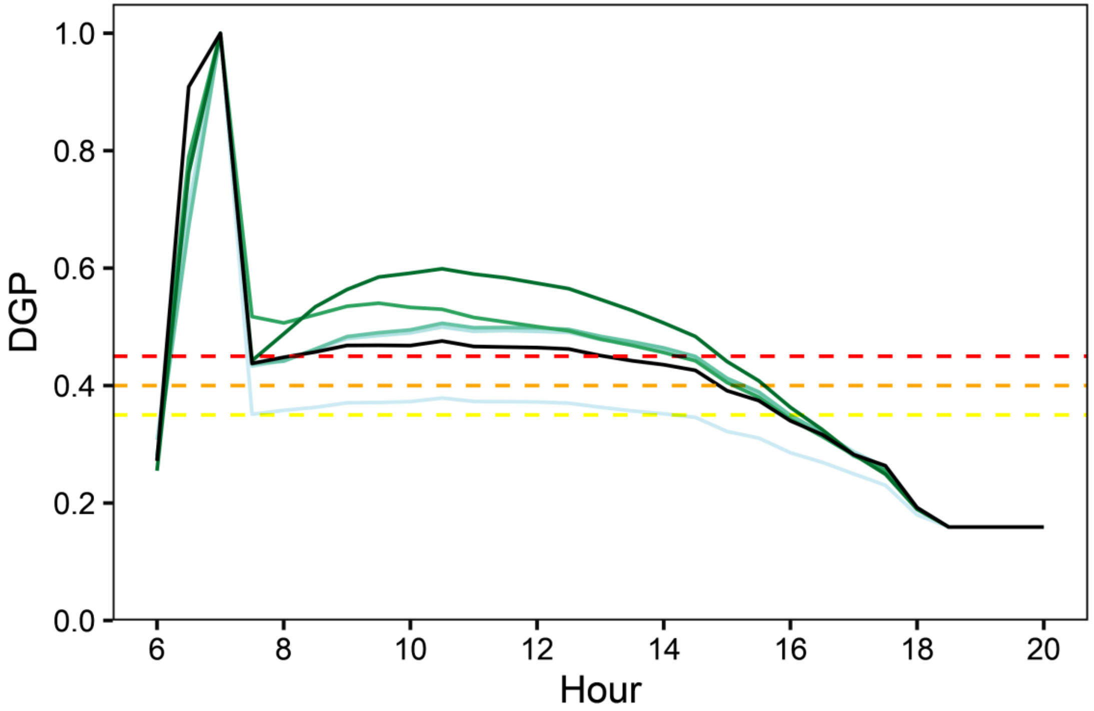
12:00



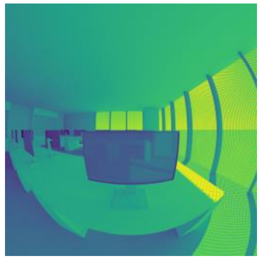
17:00

Luminance, cd/m²

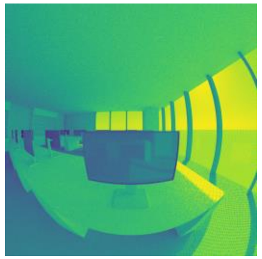
Offset, 40% coverage dots



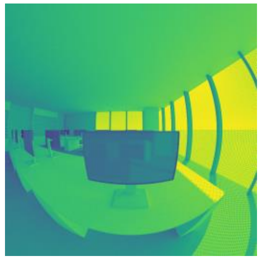
- In all cases, diffusing frit makes the glare problem worse according to DGP.
- Opaque white dots brings glare down to perceptible levels (~0.35) when the sun is not directly in the field of view.



10:30
Opaque white

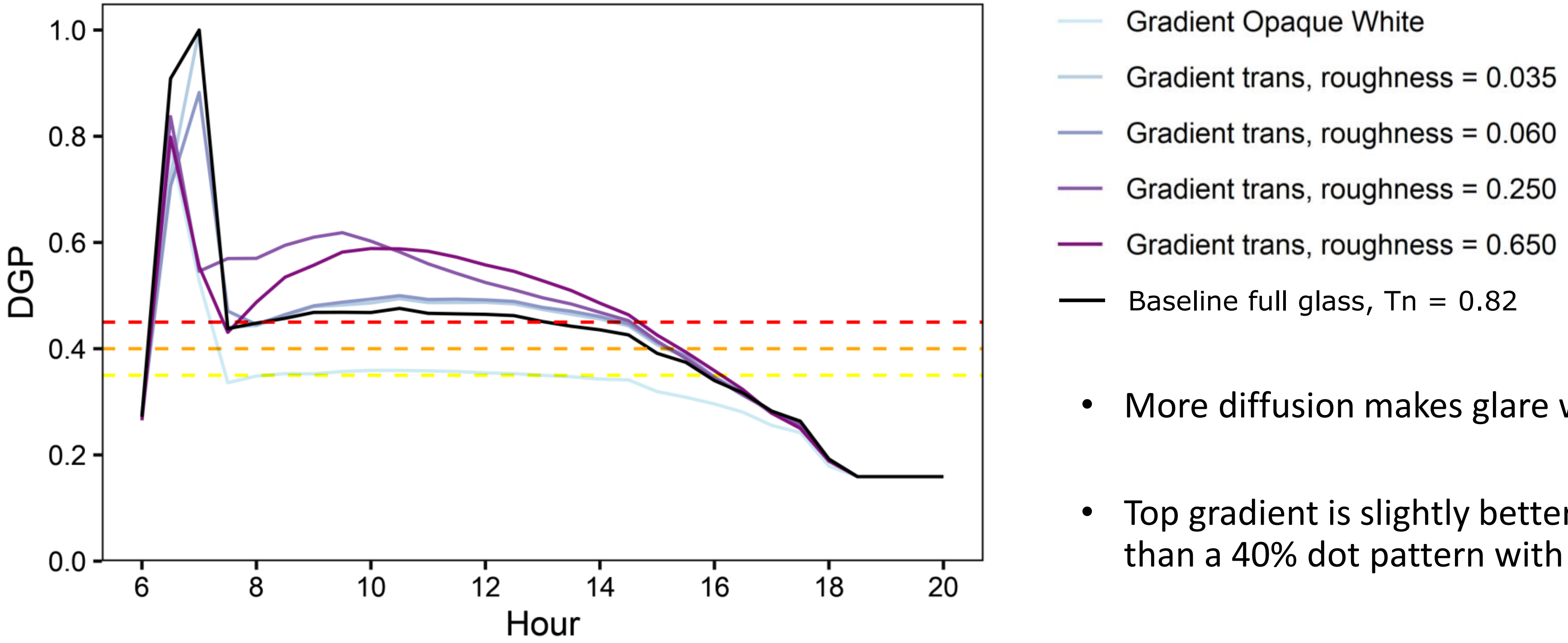


10:30
rough = 0.060

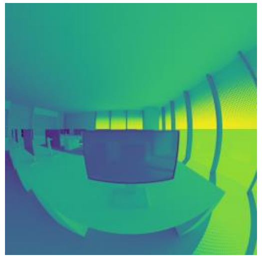


10:30
rough = 0.650

Gradient from top of glass

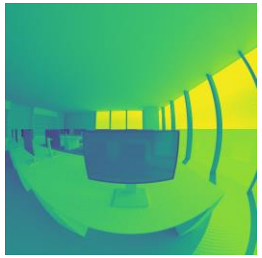


- More diffusion makes glare worse throughout the day.
- Top gradient is slightly better at improving glare perception than a 40% dot pattern with an opaque frit.



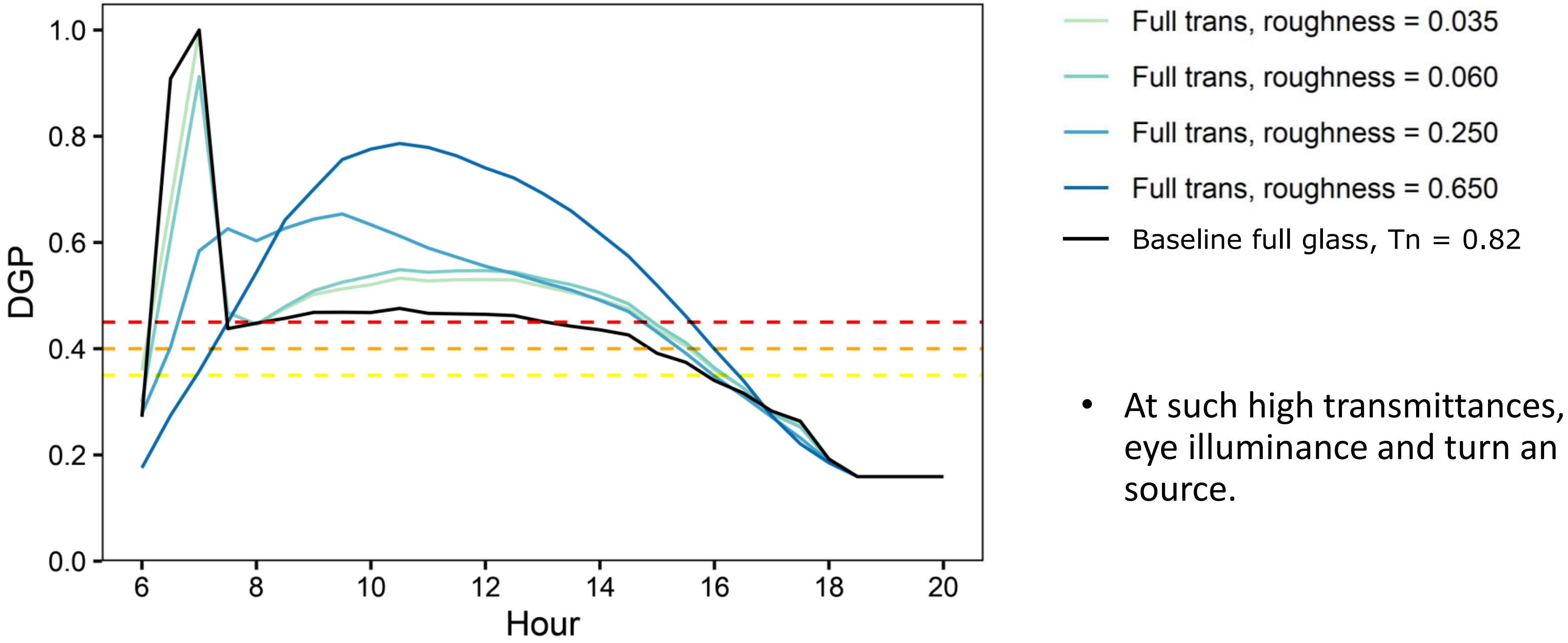
10:30
Opaque white

10:30
rough = 0.060

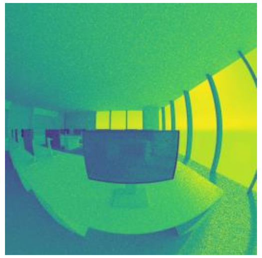


10:30
rough = 0.650

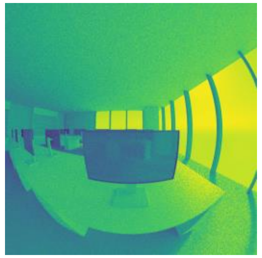
Full coverage of diffusing frit



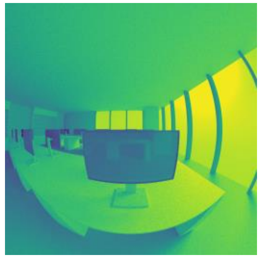
- At such high transmittances, diffusion can increase vertical eye illuminance and turn an entire façade into a glare source.



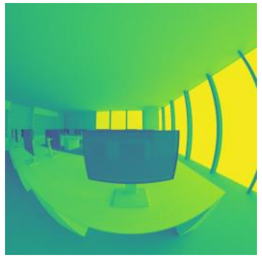
10:30
rough = 0.035



10:30
rough = 0.060



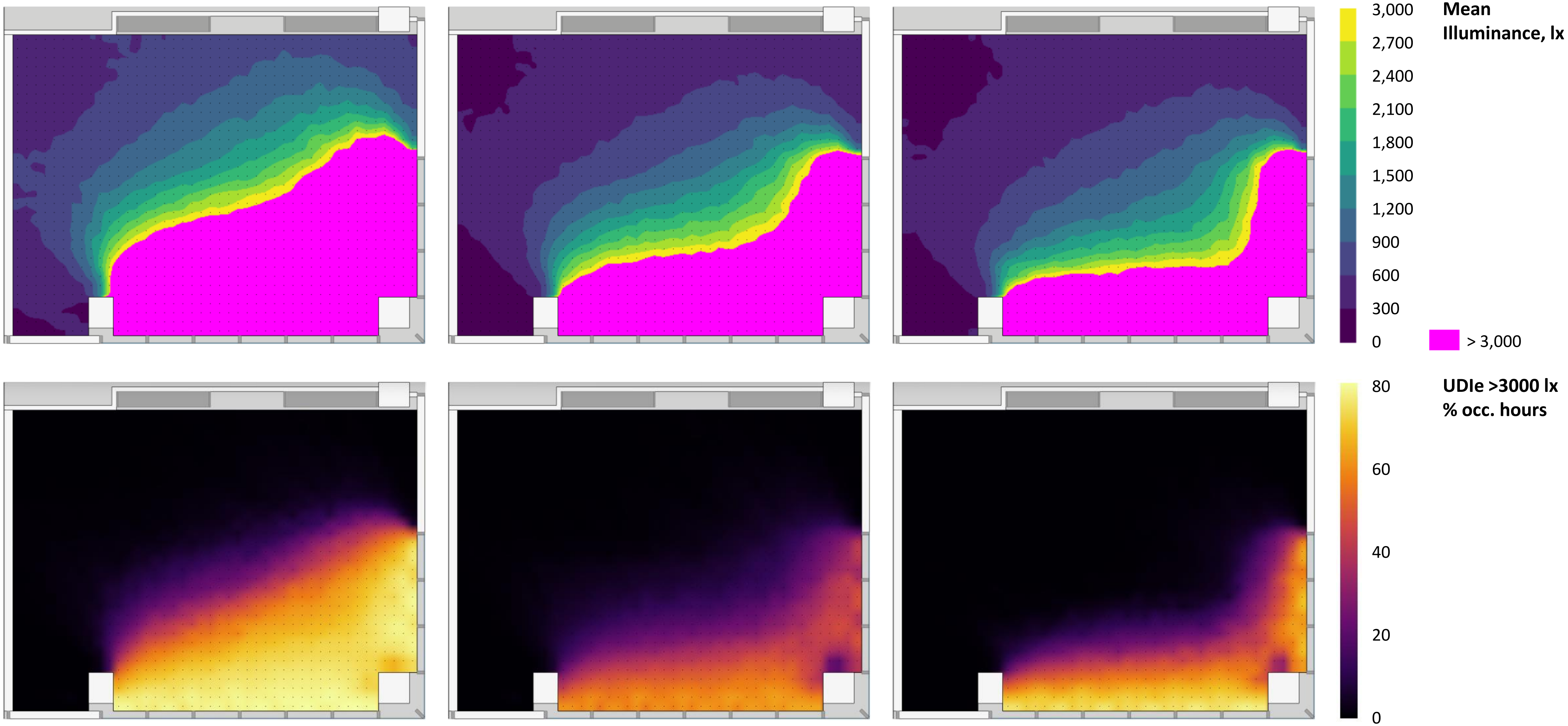
10:30
rough = 0.250



10:30
rough = 0.650

Luminance, cd/m²

Influence on annual mean illuminance, UDIe



Full Glass, Tn = 0.82 **Offset, Opaque White** **Gradient, Opaque White**

Caveats

- *"There is one additional caveat to the above formulas. If the roughness is greater than zero and the reflected ray,* $R(\overrightarrow{P_s}, \hat{r})$*, intersects a light source, then it is not used in the calculation. Using such a ray would constitute double-counting, since the direct component has already been included in the source sample summation."*

  - Greg, in materials.pdf

  - I think this means that reflections of sources won't be found when using trans materials to approximate diffusion. Reflected glare off urban buildings won't be considered, for example.
  - In my tests, specular reflections from glow sources are only found with shadow testing off.

- Angular distribution is impossible to get fully correct without proper measurements using a goniophotometer. See http://www.pab.eu/gonio-photometer/demodata/bme/gallery.html.

Sincere thanks to…

3M

VIRACON®
GLASS IS EVERYTHING™

Vitro®
Architectural Glass

Oldcastle BuildingEnvelope®
A CRH COMPANY

- For providing me samples to use in teaching that led to this presentation.

Thank you!

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University of Toronto & Solemma, LLC

Files are on GitHub, if they are of interest

https://github.com/C38C/RW2023_Frit