basics, measurement and modelling of BRTF

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Outline

1. basics
   - introduction
   - photometrics reloaded
2. BRTF math
   - BRTF definition
3. gonio-photometers
   - incidence light
   - sample mount
   - detector system
4. BRTF data and models
   - example data BRTF
   - asymmetric in/out angular resolution
5. getting BRTF into *Radiance*
   - paths
   - BRTF models
   - example: model fits in 1994
   - what *Radiance* is missing

name

- BRTF = bidirectional reflection transmission function
- BSDF = bidirectional scatter distribution function
- Bxxx = .. whatever..

all the same quantity:

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all the same quantity:
scattering of light at a surface

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  5. compare materials by BRTF data

solid angle

- solid angle of an object as seen from point P:
  project object onto sphere with radius r around P
  $\Omega := \frac{\mathbf{A}_p}{r^2}$
- unit: *steradian* [sr]
- dimensionless, full sphere: 4π, hemisphere: 2π
- infinitesimal: $d\Omega$, finite: Ω or $\Delta\Omega$
- solid angle of a cone with opening angle α:
  $\Omega_{cone} = 2\pi\left(1 - \cos\frac{\alpha}{2}\right)$

basic unit:
power transported by electromagnetic radiation

as described within concept of *photometry*
(sometimes known as *radiance flux*)

radiant power

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three spectral flavours:

- spectrally integrated: *radiometric* [Watt]
- spectrally resolved: power per wavelength interval [Watt/nm]
- weighted by eye response and integrated: *photometric* [Lumen]

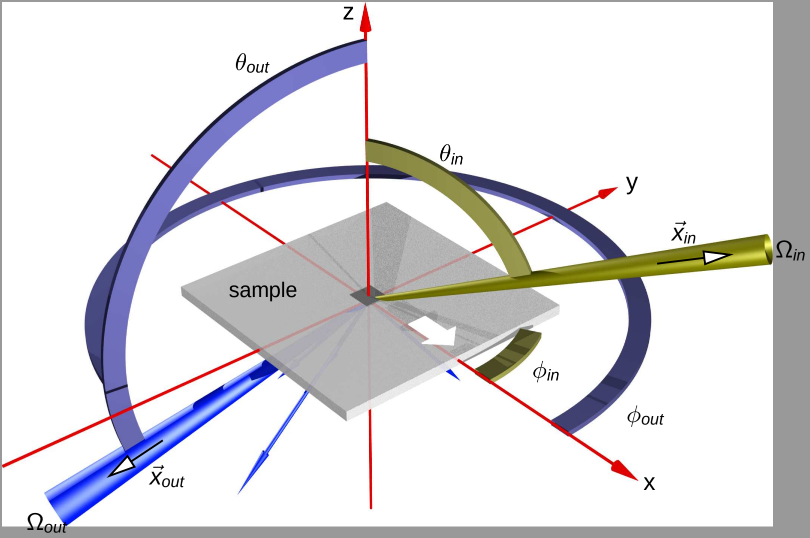
derived quantities

quantities used most often:

- radiant power per area: $\mathcal{E}$ [Watt/m2]
- radiant power per solid angle [Watt/sr] (*Radiant Intensity*)
- radiant power per solid angle and projected area, $\mathcal{L}(\vec{x})$, [Watt/(sr*m^2)] (*Radiance*)

... and equivalent photometric units

coordinate system



coordinate system

advantages of using these sample coordinates:

- standard polar coordinates
- one BRTF for front and back side of sample
- z-axis: surface normal
  x-axis: marked on sample
- direction written as $\vec{x}$ or (θ, ϕ)

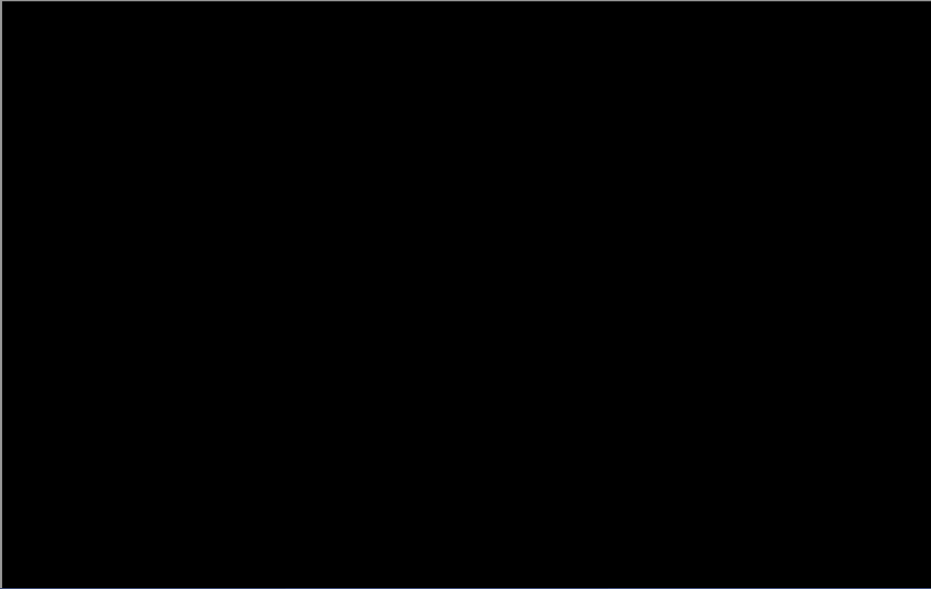
With incident light on the *front* surface: $\theta_{in} = (0^o ... 90^o)$:

- $\theta_{out} = (0^o ... 90^o)$ reflection,
  $\theta_{out} = (90^o ... 180^o)$ transmission.

Other coordinates possible, use transformations.

demo

it's all easy ...



defining formula

Definition

$$\mathcal{L}_{out}(\vec{x}_{out}) = \int_{\vec{x}_{in}}^{\Omega_{in}=2\pi} BRTF(\vec{x}_{out}, \vec{x}_{in})\ \mathcal{L}_{in}(\vec{x}_{in})\ \cos(\alpha_{in})\ d\Omega_{in}$$

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- $BRTF_{void}(\vec{x}_{out}, \vec{x}_{in}) = \delta(\vec{x}_{out} - \vec{x}_{in}) / \cos(\alpha_{in})$, *Dirac Delta function*

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- $BRTFc(\vec{x}_{out}, \vec{x}_{in}) := BRTF(\vec{x}_{out}, \vec{x}_{in})\cos(\alpha_{in})$

approximate formula

$$\mathcal{L}_{out}(\vec{x}_{out}) = \int_{\vec{x}_{in}}^{\Omega_{in}=2\pi} BRTF(\vec{x}_{out}, \vec{x}_{in})\ \mathcal{L}_{in}(\vec{x}_{in})\ \cos(\alpha_{in})\ d\Omega_{in} \qquad (1)$$

- assume $\mathcal{L}_{in} > 0$ for small Ω_{in} around $\vec{x}^{*}_{in}$ only
- and assume $BRTF = const$ over Ω_{in}

approximate formula

$$\mathcal{L}_{out}(\vec{x}_{out}) = \int_{\vec{x}_{in}}^{\Omega_{in}=2\pi} BRTF(\vec{x}_{out}, \vec{x}_{in})\ \mathcal{L}_{in}(\vec{x}_{in})\ \cos(\alpha_{in})\ d\Omega_{in} \qquad (1)$$

- assume $\mathcal{L}_{in} > 0$ for small Ω_{in} around $\vec{x}^*_{in}$ only
- and assume $BRTF = const$ over Ω_{in}
- then, and only then

$$BRTF(\vec{x}_{out}, \vec{x}^*_{in}) \approx \frac{\mathcal{L}_{out}(\vec{x}_{out})}{\mathcal{E}_{in}} \qquad (2)$$

But:
This approximation is misleading and should be used with caution.

averaged BRTF

measured BRTF is always averaged over solid angles
of detector $\Delta\Omega_{out}$ and lamp $\Delta\Omega_{in}$:

$$\overline{BRTF}(\Delta\Omega_{in}, \Delta\Omega_{out}) := \frac{1}{\Delta\Omega_{in}\,\Delta\Omega_{out}} \int_{\vec{x}_{out}}^{\Delta\Omega_{out}} \int_{\vec{x}_{in}}^{\Delta\Omega_{in}} BRTF(\vec{x}_{out}, \vec{x}_{in})\; d\Omega_{in}\; d\Omega_{out} \tag{3}$$

consequences:

this limit measurement of BRTF features.
$\rightsquigarrow$ minimise $\Delta\Omega_{out}$ and $\Delta\Omega_{in}$

transmission values from BRTF

transmission τ from Ω_{in} into Ω_{out} is given by:

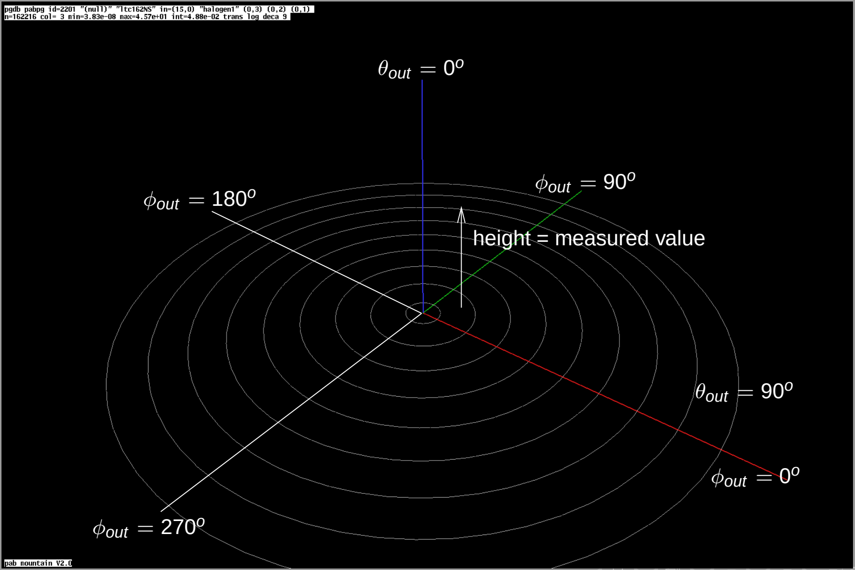
$$\tau(\Omega_{in},\Omega_{out}) = \frac{\int_{\vec{x}_{out}}^{\Omega_{out}} \left\{ \int_{\vec{x}_{in}}^{\Omega_{in}} BRTF(\vec{x}_{out},\vec{x}_{in}) \mathcal{L}_{in}(\vec{x}_{in}) \cos(\alpha_{in}) d\Omega_{in} \right\} \cos(\alpha_{out}) d\Omega_{out}}{\int_{\vec{x}_{in}}^{\Omega_{in}} \mathcal{L}_{in}(\vec{x}_{in})\ \cos(\alpha_{in})\ d\Omega_{in}} \quad (4)$$

Which for the *direct-hemispherical transmission* results in:

$$\tau_{dh}(\vec{x}_{in}) := \tau(d\Omega_{in}, 2\pi) = \int_{\vec{x}_{out}}^{2\pi} BRTF(\vec{x}_{out},\vec{x}_{in})\ \cos(\alpha_{out}) d\Omega_{out} \quad (5)$$

visualising BRTF 3D

for one incident direction (θ_{in}, ϕ_{in}), display one hemisphere:



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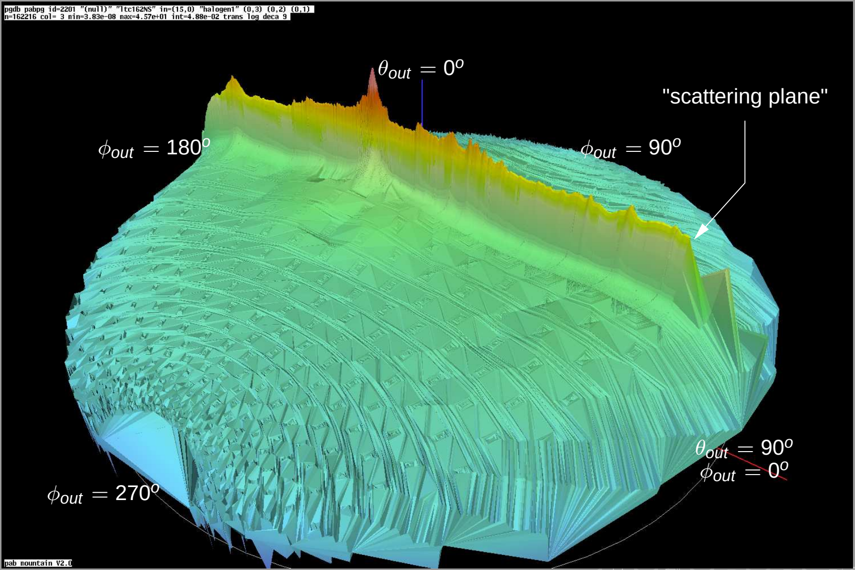
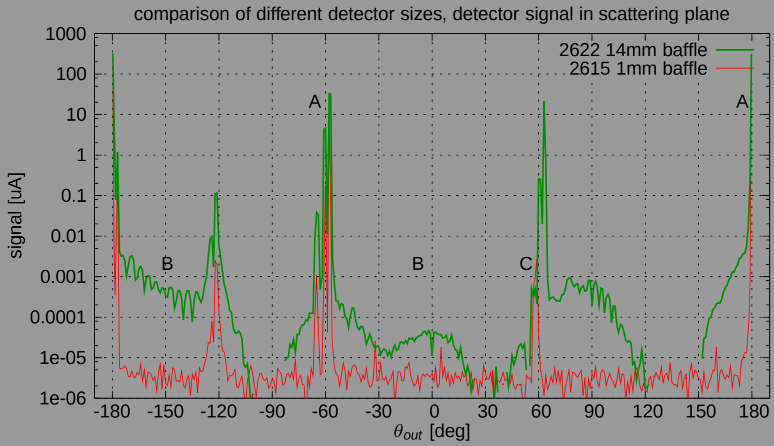


2D cuts along scattering plane through 3D dataset
I prefer Cartesian plots over polar plots. example:



medium sized intermission

... questions to math part ?

next to come: gonio-photometers

light source types & parameters

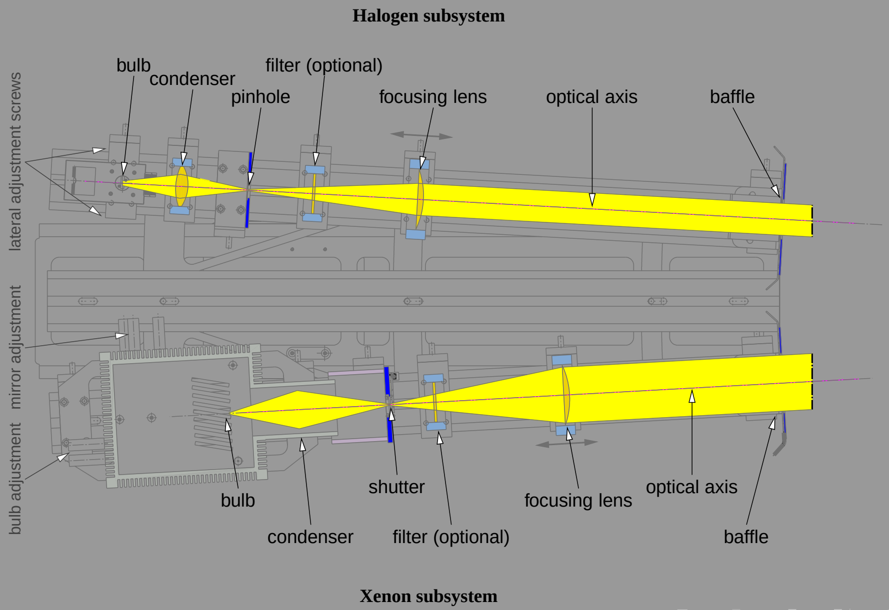
beam parameter	Halogen	Xenon	laser diode	gas laser
power	+	++	-	-
radiance	-	+	++	+++
noise	++	+	+	+
polychromatic	+	+	-	-
incoherent	+	+	-	-

choice depends on:

- sample type
- wavelength range
- detector type

in the following: lamps kept at fixed positions
alternative concepts: moving lamp, fixed sample

example: pgII lamp subsystem



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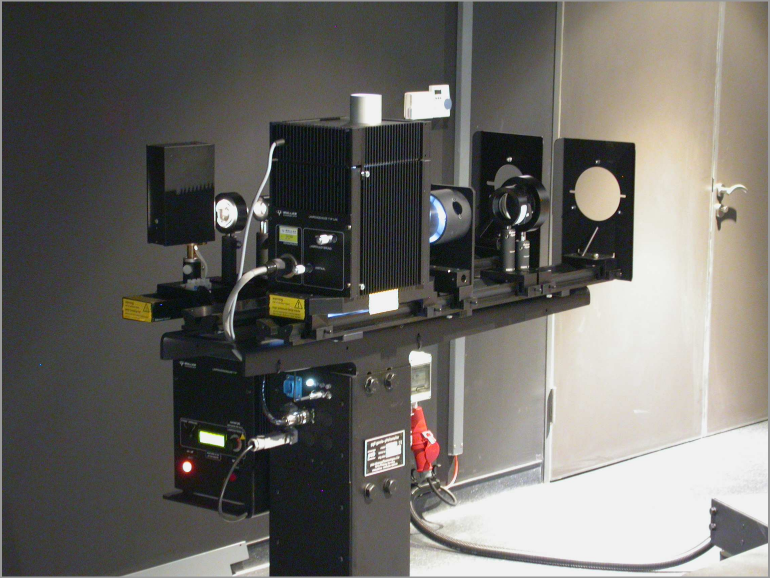
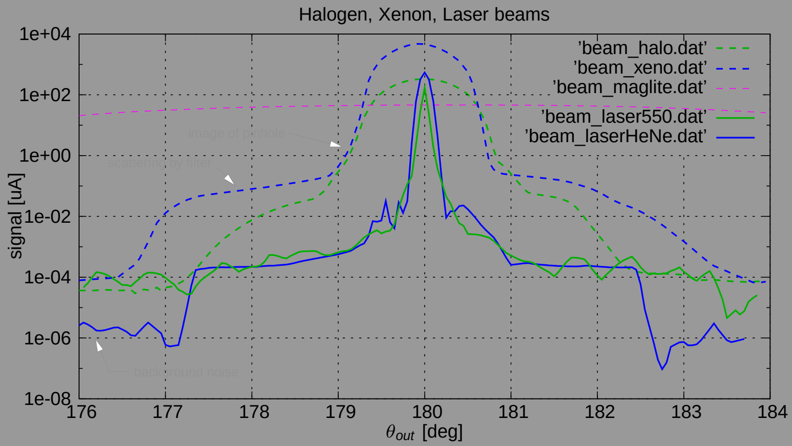


example: beam profiles



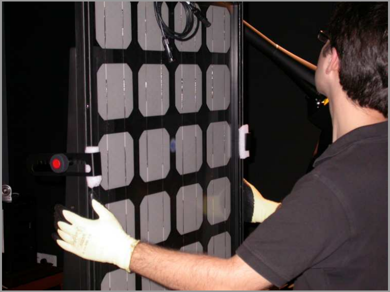
sample mount

- fixes sample (securely)
- adjusts for θ_{in}, ϕ_{in}
- $\rightsquigarrow$ two degrees of freedom
  manual adjustment or automatic
- minimal self-shadowing
- shading of stray light

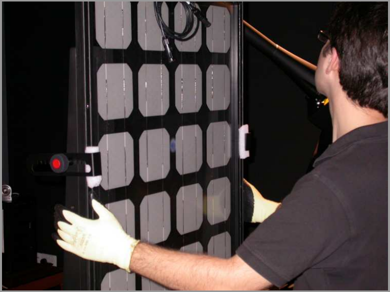
in the following: vertical sample mount assumed

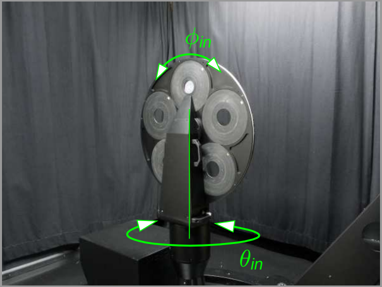
example sample mounts

example sample mounts

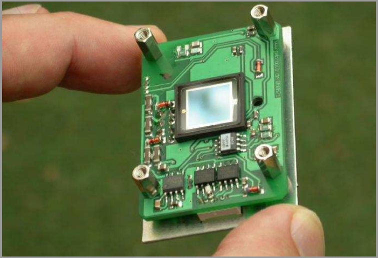


example sample mounts



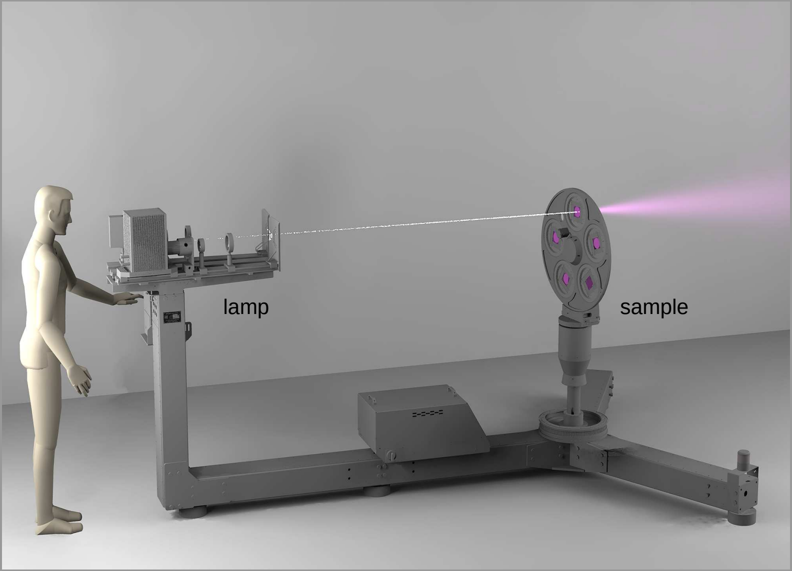


detector parameters



- material and wavelength: Si (VIS), InGaAs (IR), etc
- principle: photo-diode, etc
- sample rate: measurements / second: 1Hz to 1kHz
- noise: *noise equivalent BRTF*, lowest measurable BRTF
- dynamic range: 10^2 at least, 10^8 better

detector mechanics



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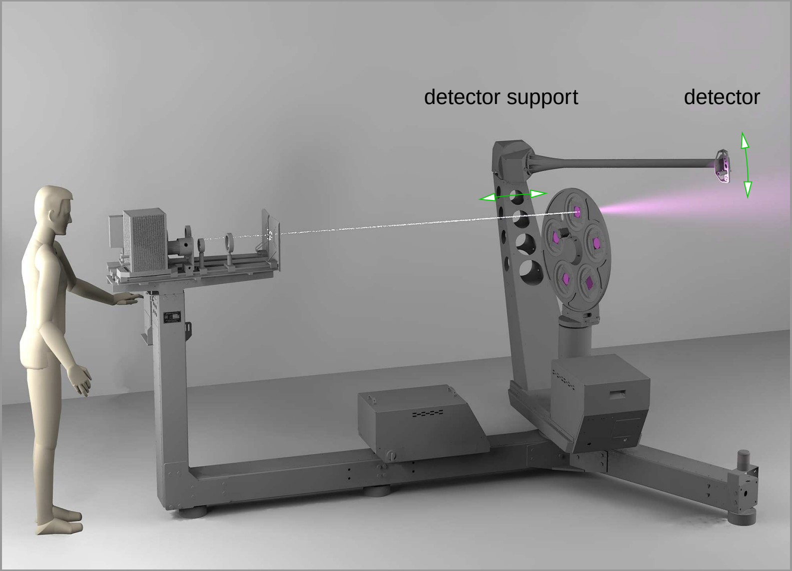
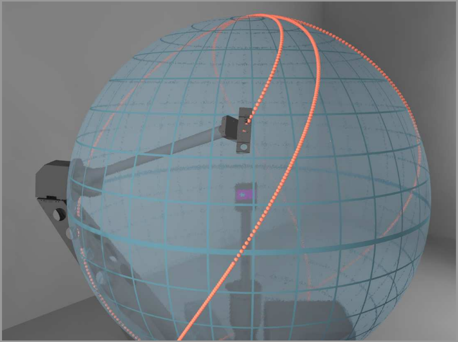


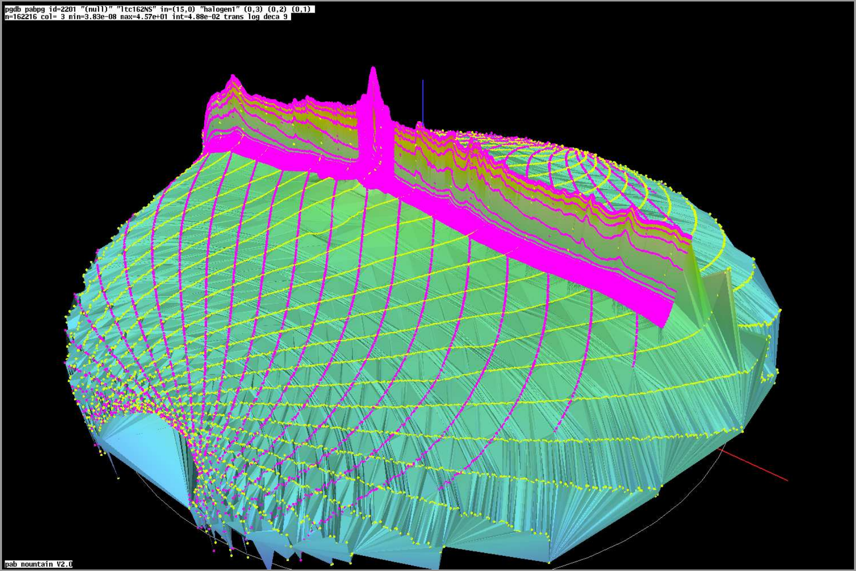
scanning gonio-photometer



measurements-on-the-fly:

- avoid start-stop-cycles
- need excellent sync between position and data-acquisition
- need fast detector

discrete BRTF values versus continuous function



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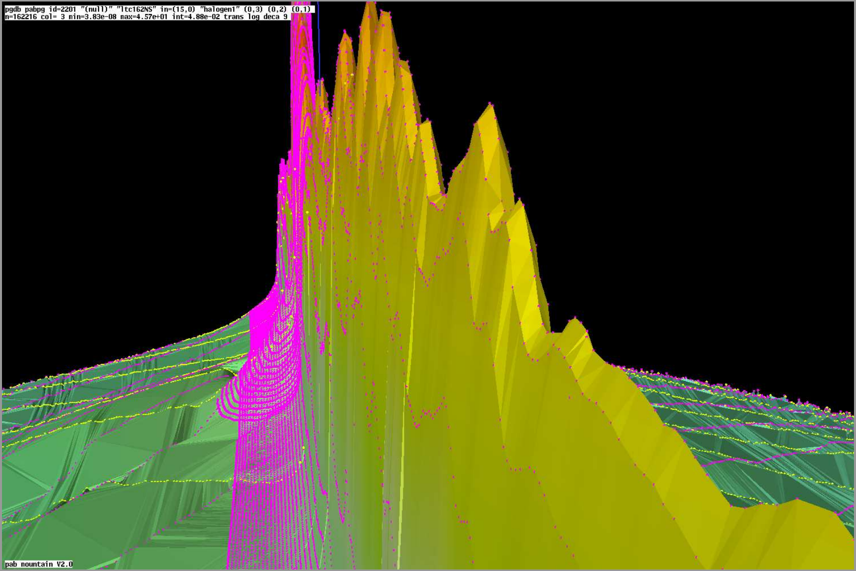

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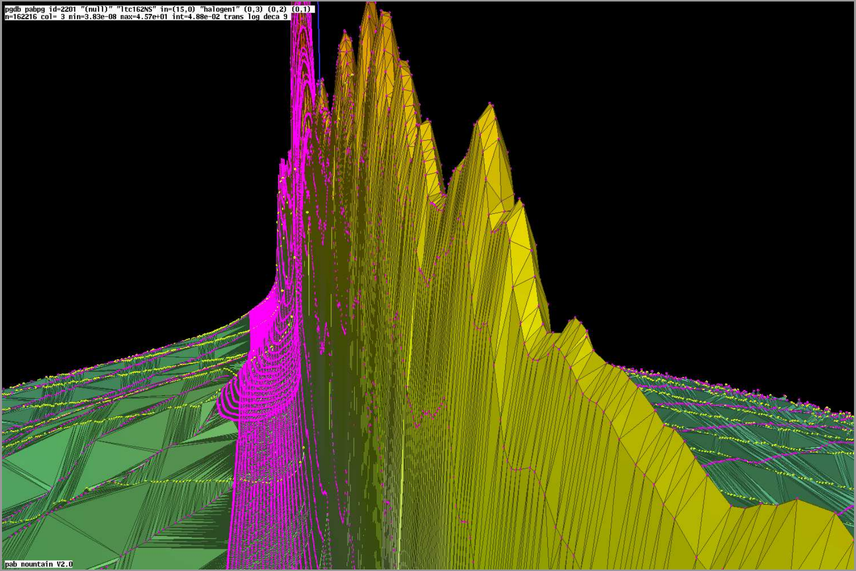
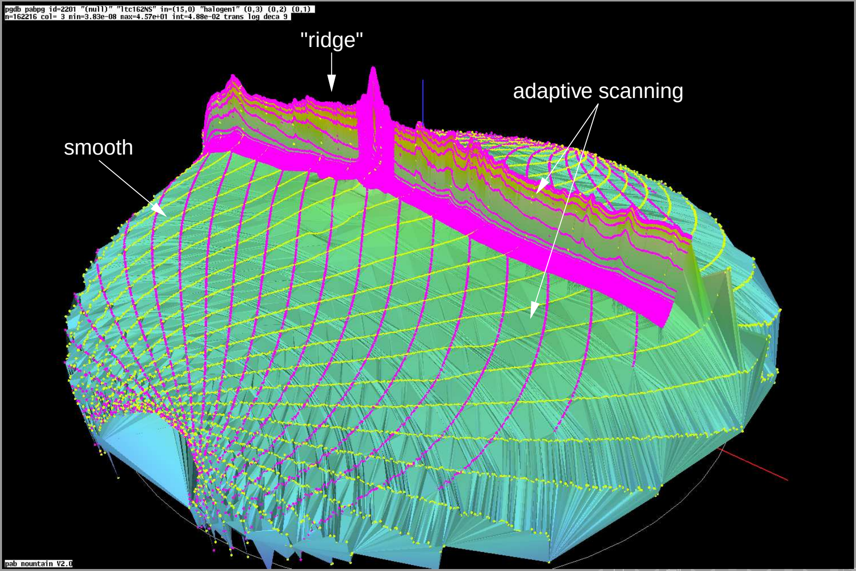


discrete BRTF values versus continuous function

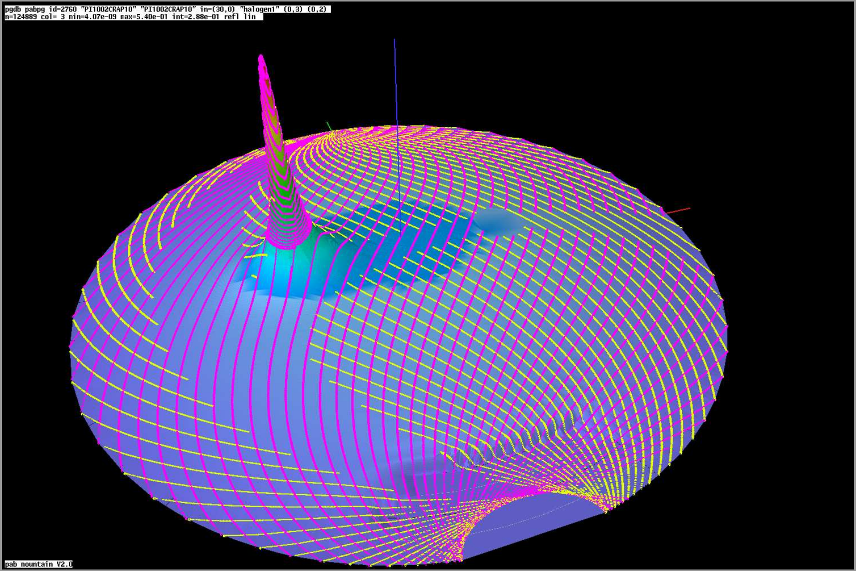
- in 3D, $f(x_i, y_i)$ data points
  do *not* define a unique surface
- Delaunay triangulation recommended
- triangulation used for interpolation and integration
- $\rightsquigarrow$ good triangulation vital for BRTF data processing

adaptive high angular resolution

BRTF consists of smooth areas and peaks/ridges:

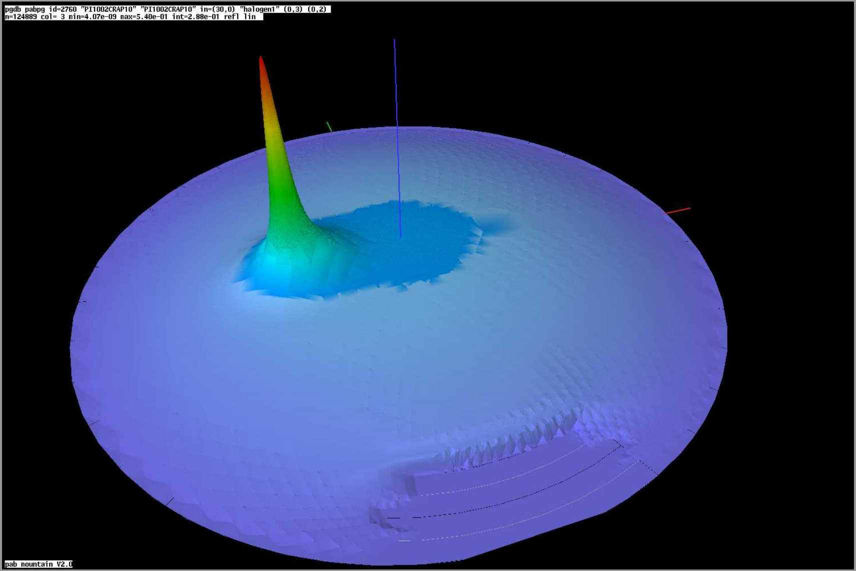


checking for measurement errors implicitly



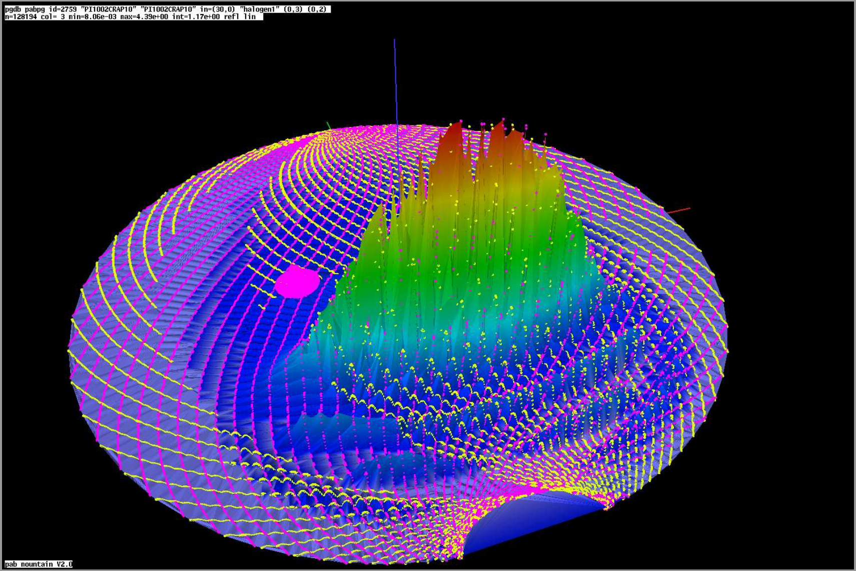
128109 data points all nicely smooth

checking for measurement errors implicitly



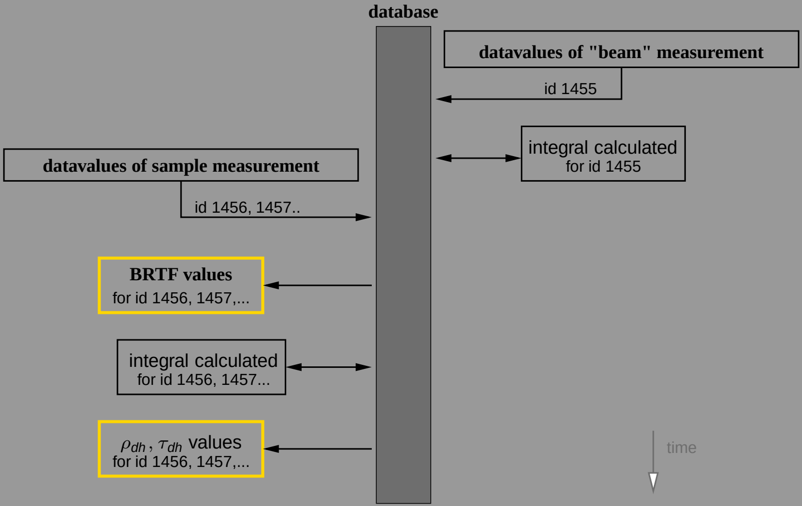
good.

checking for measurement errors implicitly



ceiling lights on, 100Hz noise, (see SPIE 2010 paper for more)

getting BRTF from raw data



getting BRTF from raw data

advantages of using unscattered beam as reference

- illuminated area and detector distance cancel out
- no reference samples needed
- sensor identical for reference measurement

imaging versus scanning gonio-photometers

alternative way of doing measurements:

imaging gonio-photometers

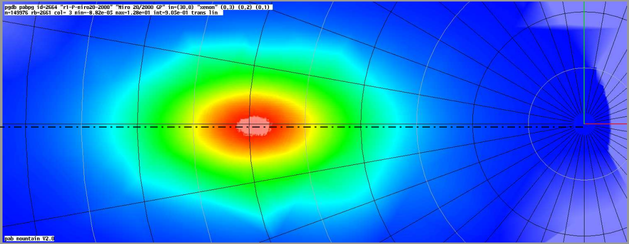
- + faster
- - more intermediate optics, not as general

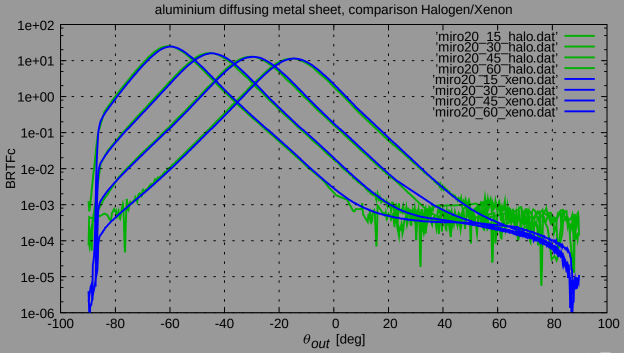
very short intermission

... questions to machine&measurement part ?

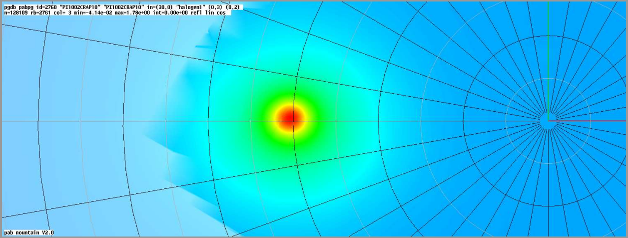
next to come: BRTF data &models

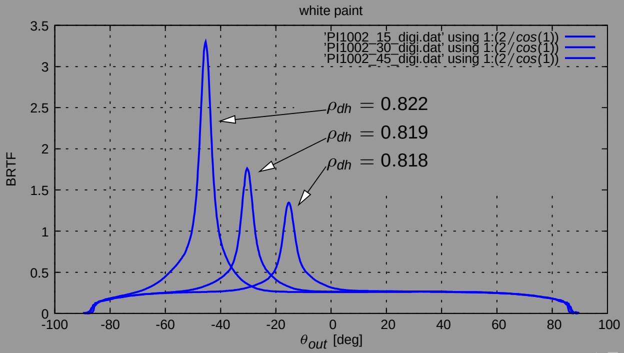
example: aluminium



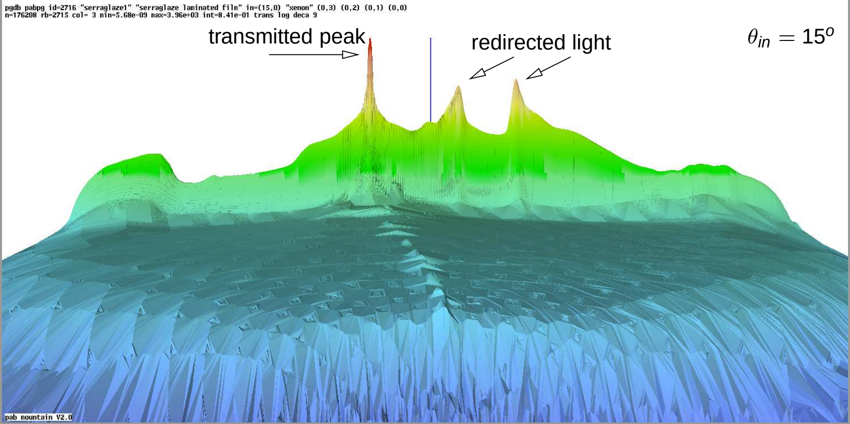


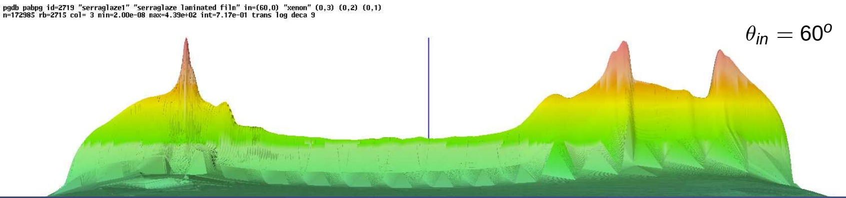
example: white paint





example: light redirecting, Serraglaze





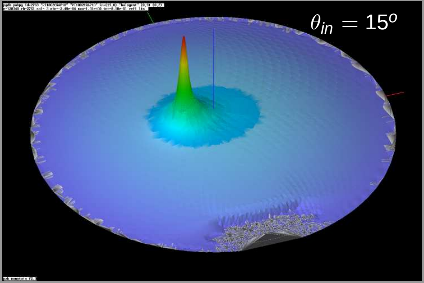
both sides are *not* symmetric:

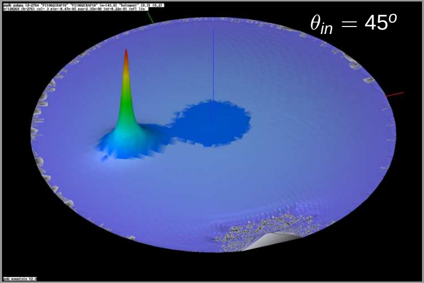
- outgoing side:
  adaptive, high resolution (0.1^o)
- incident side:
  low resolution (10^o)

since:

Theorem
in most cases the topology of a BRTF does not change between $\vec{x}_{in}$ and $\vec{x}_{in} + \Delta$, for small Δ (e.g. 20^o)

topology of a BRTF





- structure ("topology") of BRTF remains the same for Δ
- shape *parameters* change:
  peak position, peak height, peak width, background level
- $\rightsquigarrow$ intermediate θ_{in} are predictable.
- $\rightsquigarrow$ measurements of finely resolved θ_{in} are redundant
- $\rightsquigarrow$ don't waste time and data with these
  think of a good interpolation method

getting BRTF into *Radiance*

problems to solve while importing data:

- interpolation between outgoing directions $\vec{x}_{out}$: triangulation, etc

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fitting parameter of function to BRTF data

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- fit $f_{a_1 \ldots a_N}(\theta_{out}, \phi_{out})$ to one dataset of incident direction $\vec{x}_{in}$

note: see chapter 5 in author's 1995 dissertation (in German)

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- standard Levenberg-Marquardt method not 100% robust

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choice of model function

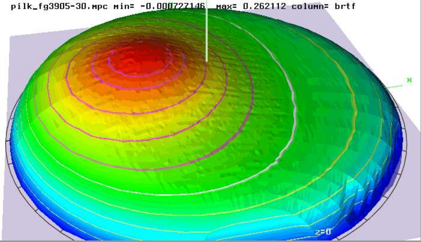
- internal to *Radiance* (e.g. `trans`)

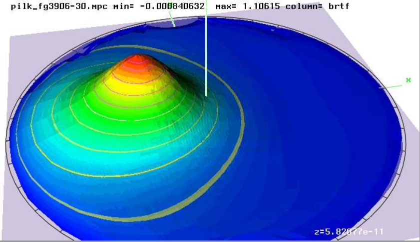
$$BRTF_{trans} = \frac{a_6\,(1 - a_7)}{\pi} + \frac{a_6\,a_7}{\pi a_5^2\,\sqrt{\cos(\theta_{in})\cos(\theta_{out})}} \exp[(2\,\cos(\theta_{half}) - 2)/a_5^2] \quad (6)$$

- external (example)

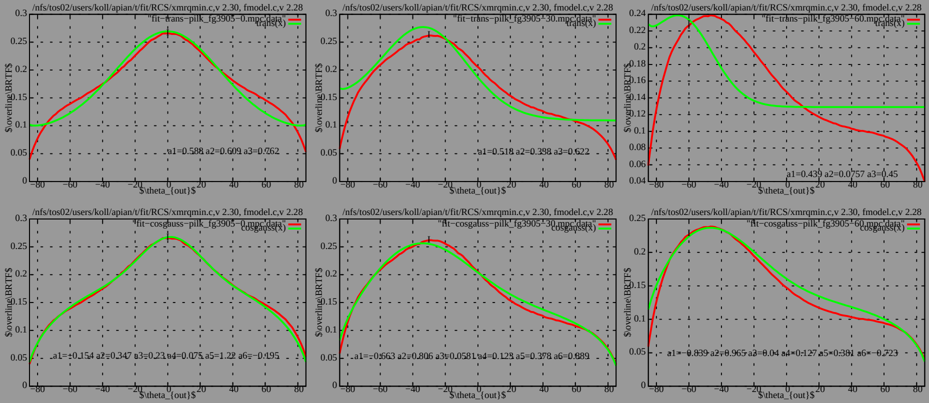
$$\begin{aligned} BRTF_{cosgauss} &:= a_1 + a_2(\cos\theta)^{a_3} + a_4 \exp(-\beta^2\,a_5) \quad (7)\\ \beta &:= \arccos[\cos(\theta)\cos(\alpha_{in} + a_6) - \sin(\theta)\cos(\phi_{out})\sin(\alpha_{in} + 10a_6)]\\ \theta &:= \pi - \theta_{out} \end{aligned}$$

example: fits to Pilkington fg3905, fg3906 in 1994



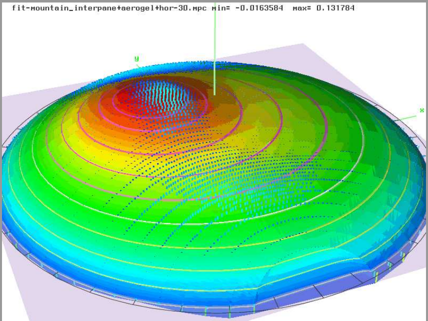


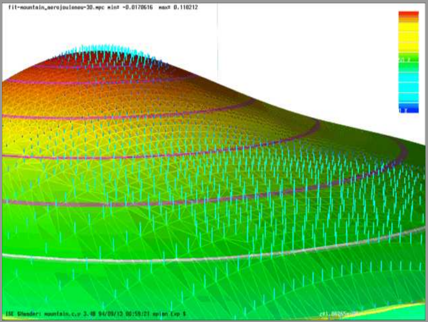
polymer/glass sandwich glazing,
forward scattering, ”milky” glazing



note: see chapter 6 in author's 1995 dissertation for details

fg3905 model comparison, off scattering-plane

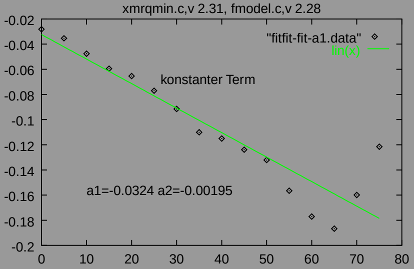


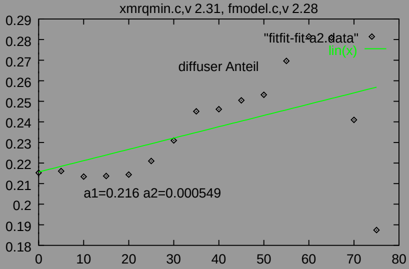


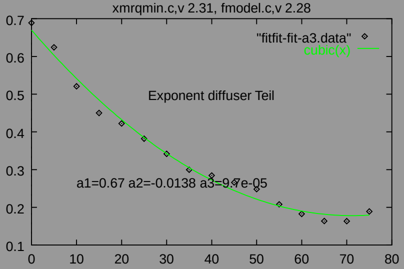
deviation between model and data shown as spikes

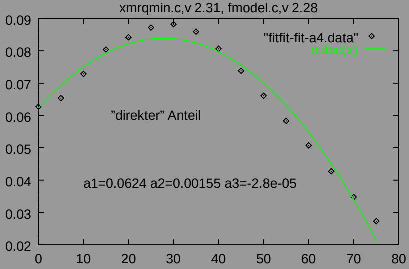
fitting is done for all outgoing directions (not just in-plane)
model may deviate outside the scattering plane

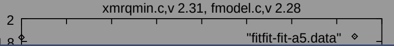
example: Aerogel model, parameter variation

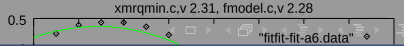












conclusions for *Radiance* models

- current models don’t match measured data well

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- current models don't match measured data well
- better built-in models or cal-files seem worth considering

- cal file support for photon-map (and ambient calcs)
  $\rightsquigarrow$ support for general BRTF models

all these features require changes to the rendering core

$\rightsquigarrow$ non trivial work. But would be *very* useful in practice.

what *Radiance* is missing

- cal file support for photon-map (and ambient calcs)
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- BRTF import using non-fixed-grid data

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what *Radiance* is missing

- cal file support for photon-map (and ambient calcs)
  ⇝ support for general BRTF models
- BRTF import using non-fixed-grid data
- way to add internal models in a modular way

all these features require changes to the rendering core

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links

latest papers on pgII gonio-photometer & links:

- "Experimental validation of bidirectional reflection and transmission distribution measurements of specular and scattering materials,"
  SPIE 2010, Brüssel, http://dx.doi.org/10.1117/12.860889
- "New scanning gonio-photometer for extended BRTF measurements"
  SPIE 2010, San Diego, http://dx.doi.org/10.1117/12.854011
- currently installed pgII gonio-photometers:
  SERIS Singapore, LBNL Berkeley, pab Freiburg, industrial client Europe
- pgII gonio-photometer webpage:
  http://www.pab.eu
- author's 1995 Phd: http://www.pab-opto.de/pers/phd/

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...thanks

last slide.

- physics is fun
- happy rendering
- thank you for joining workshop and thanks for your attention