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Optical measurement techniques for complex fenestration systems (CFS)

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Outline

- Optical properties
- Spectrophotometers
- Definition of BRDF, BTDF, BSDF
- Goniophotometer measurements
- Imaging system measurements
- Other methods
- Data representation
- Questions

How much

where

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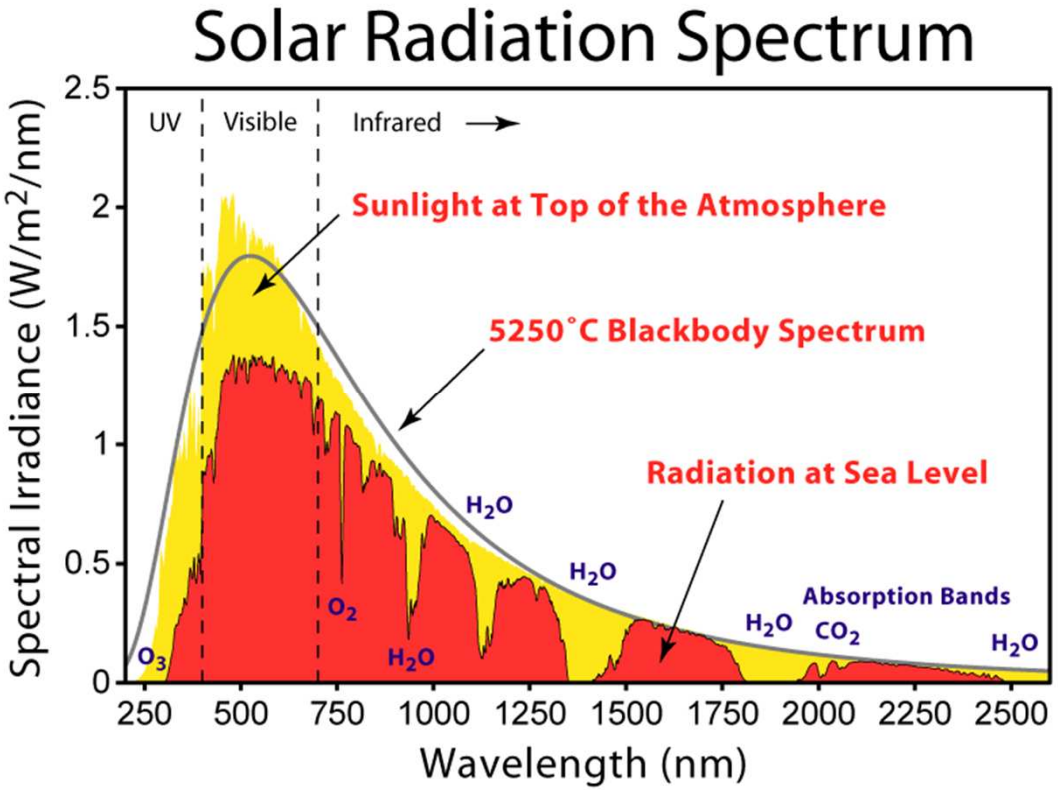
Examples of CFS

Direct-hemispherical properties

- Reflectance and transmittance
  - Wavelength
  - Angle of incidence
  - Polarization
  - Temperature, tension, magnetic field
- Direct-direct, specular
- Direct-diffuse, scattered-only
- Direct-hemispherical, total = ds+dd

Wavelengths of light

- Optical properties are λ dependent
- Light sources have different intensity at different λ
- Detectors have different sensitivity at different λ



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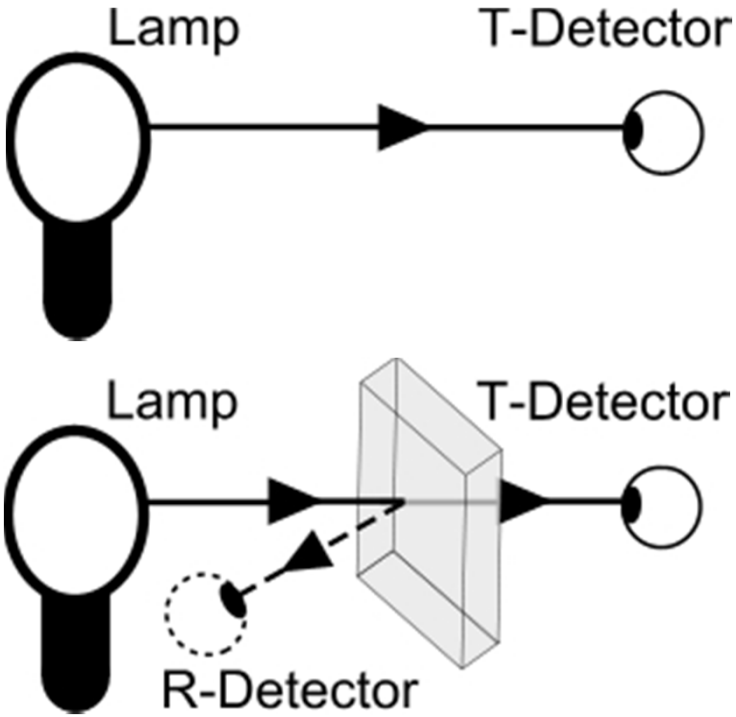
Measuring transmittance and reflectance

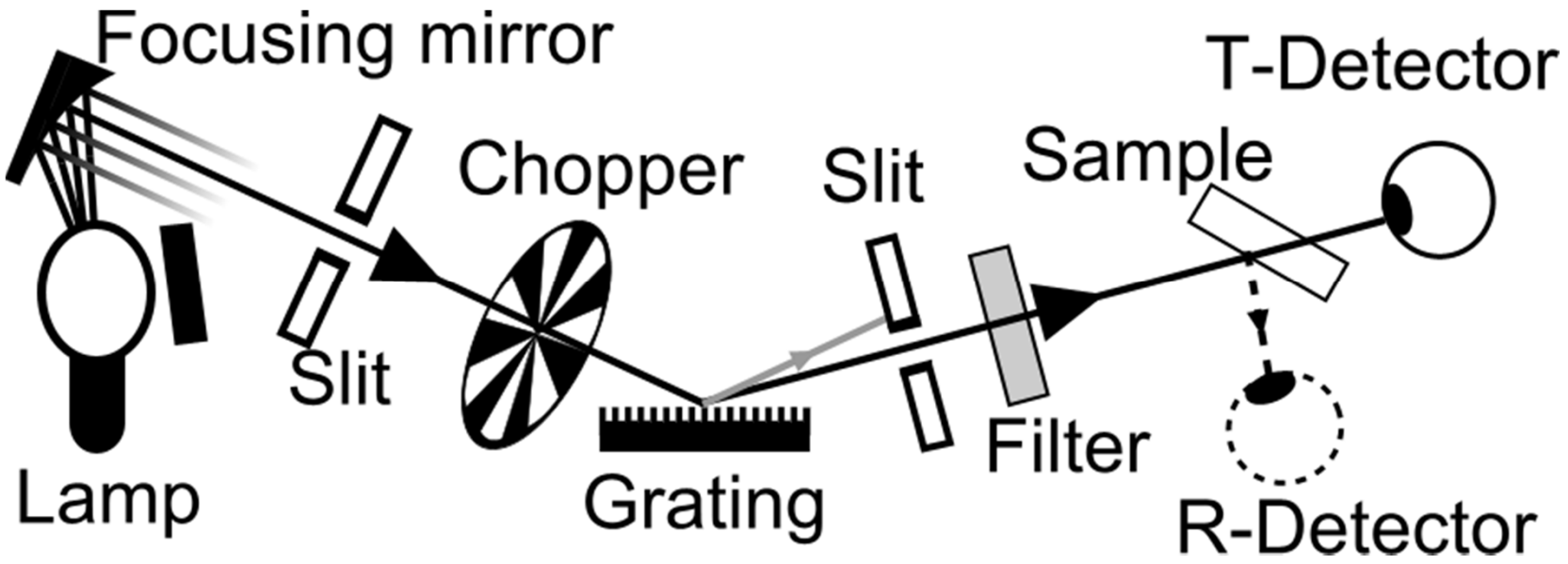
- Relative measurement between reference case of no sample and sample



T = Sample/Reference

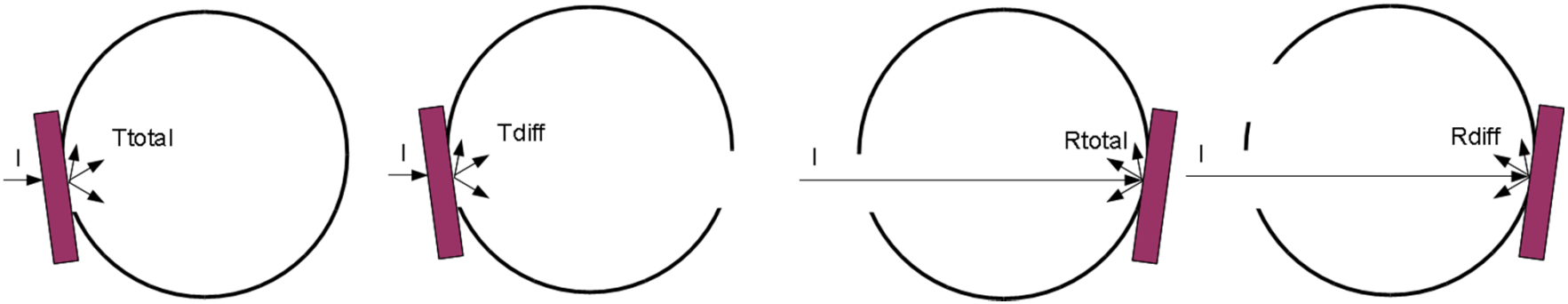
(world's easiest job)

Spectrophotometer



- Scanning spectrophotometer
- Optical multichannel analyzer is different

Definition of total, diffuse, specular

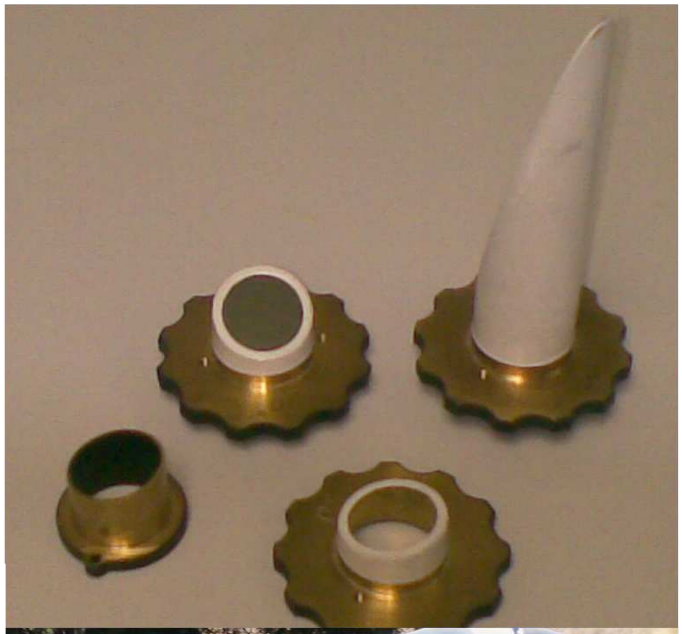


- Tdiff and Rdiff are obtained by opening a port and letting the specular component out.
- Tspec is calculated as Ttotal-Tdiff

hence, Tspec is instrument defined

Variable angle of incidence

- Still direct-hemispherical
- Characterization of fabrics with angle tubes
- Outdoor sphere
- Center mount for opaque samples



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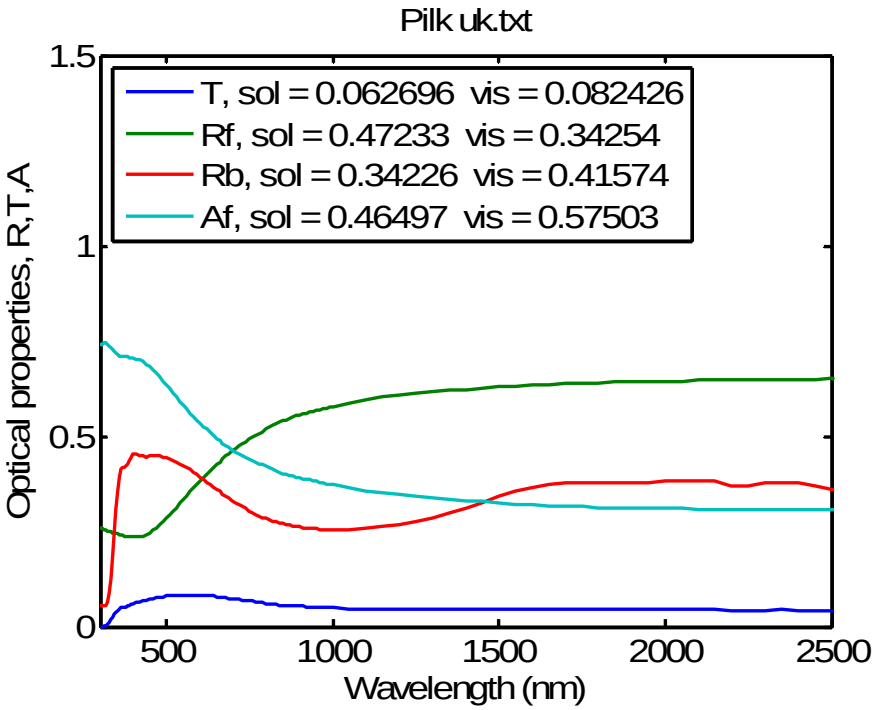
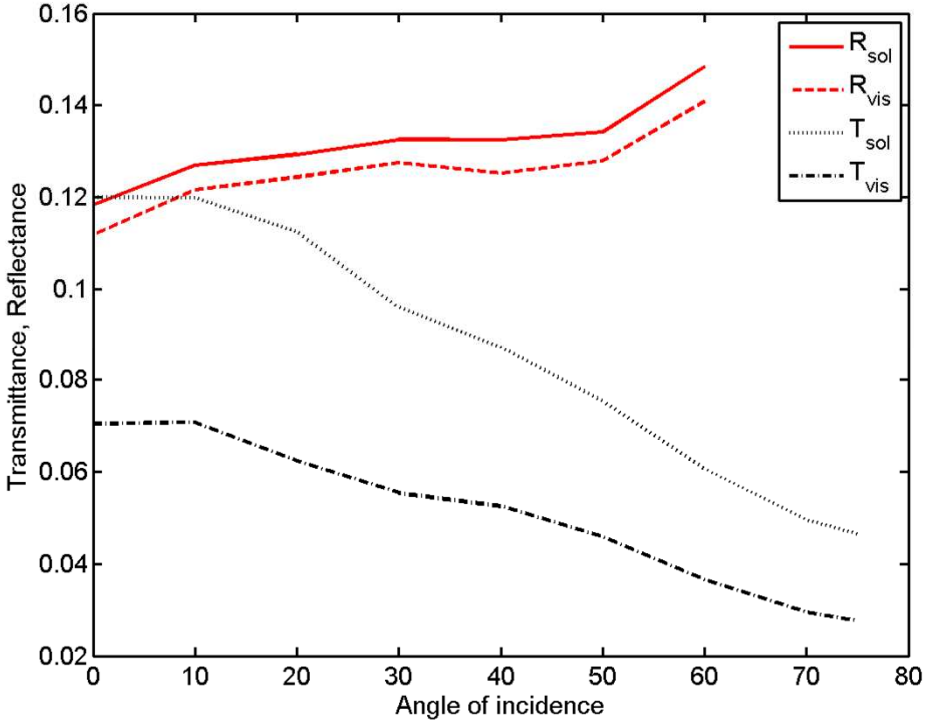
Examples of data





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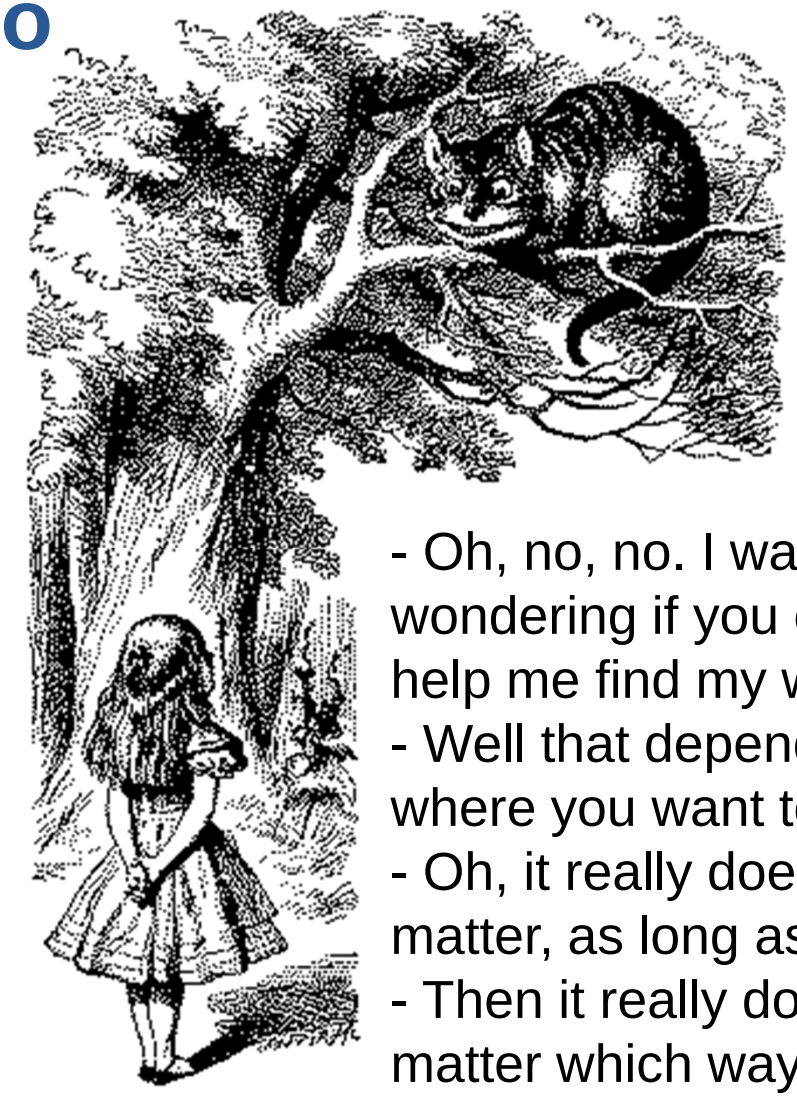
Where does light go

- Many applications require knowledge how much light goes in different directions
- Ratio is no longer useful since there is an infinite amount of outgoing directions



- Oh, no, no. I was just wondering if you could help me find my way.
- Well that depends on where you want to get to.
- Oh, it really doesn't matter, as long as...
- Then it really doesn't matter which way you go.

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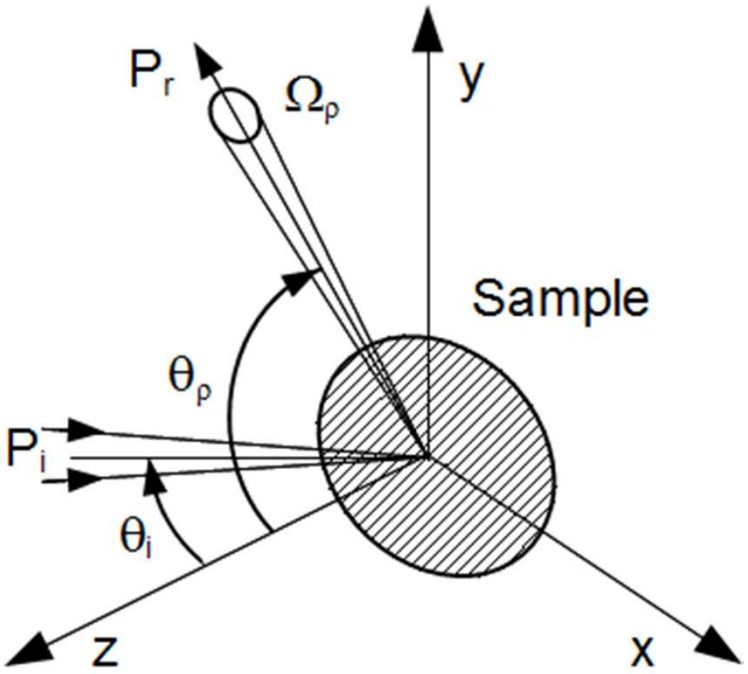
BRDF – The Bi-directional Reflectance Distribution Function

- Fred E. Nikodemus wrote “Directional Reflectance and Emissivity of an Opaque Surface” in 1965

$$\mathrm{BRDF}(\theta_i, \theta_\rho) = \frac{P_r/\Omega_\rho}{P_i \cos\theta_\rho}$$

- Not his definition but more useful for experiments



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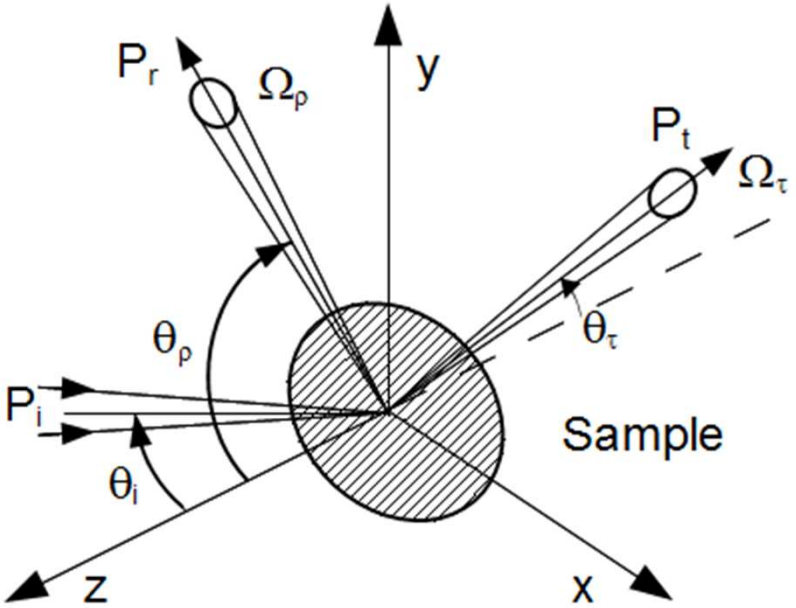
BTDF – Same thing for transmittance

- Transparent samples both BRDF and BTDF
- The combination is often denoted as BSDF (Scattering) or B(R/T)DF



- Definition of angle coordinates needed

Properties of the BSDF

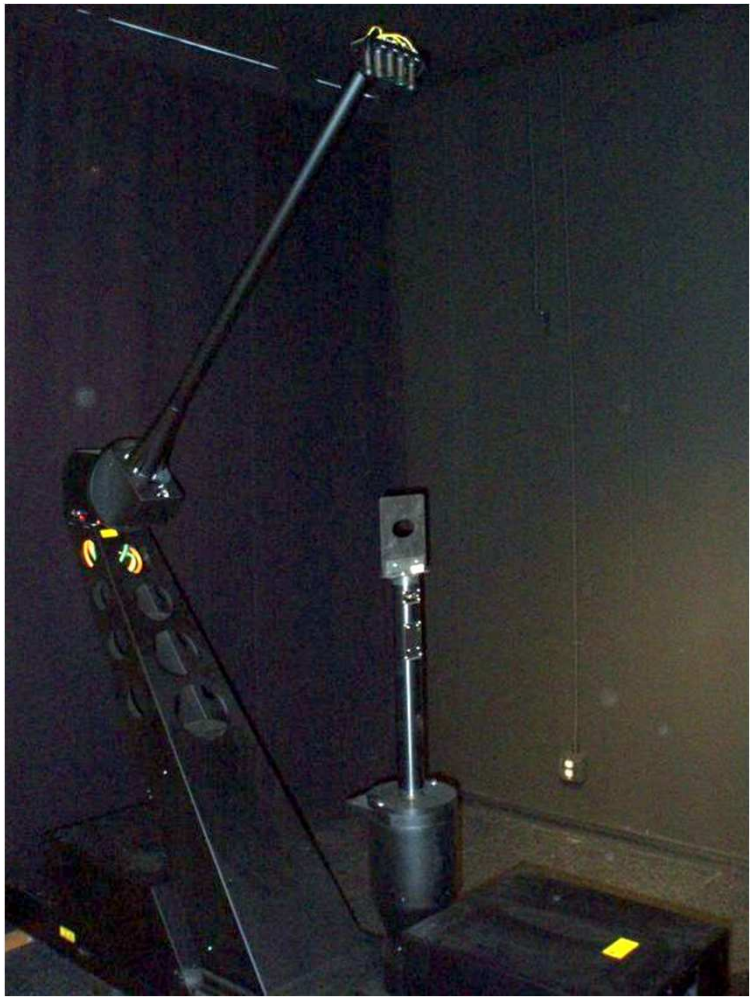
- Main parameters are incident and outgoing angles – continuous definition space
- Wave properties – wavelength (band), polarization state
- Sample properties – temperature, dirt

Famous BRDF values

- **$1/\pi$** – A surface of constant BRDF of $1/\pi$ for all outgoing angles will have a direct-hemispherical reflectance of 1. Constant BSDF values are called Lambertian
- **2** – BRDF-values can be larger than one without violating energy conservation
- **-1** – BRDF-values lower than 0 are not physical

Goniophotometer approach

- We put a small detector covering a space angle Ω at a given outgoing angle we detect P_r. By knowing P_i we can directly calculate the BRDF.



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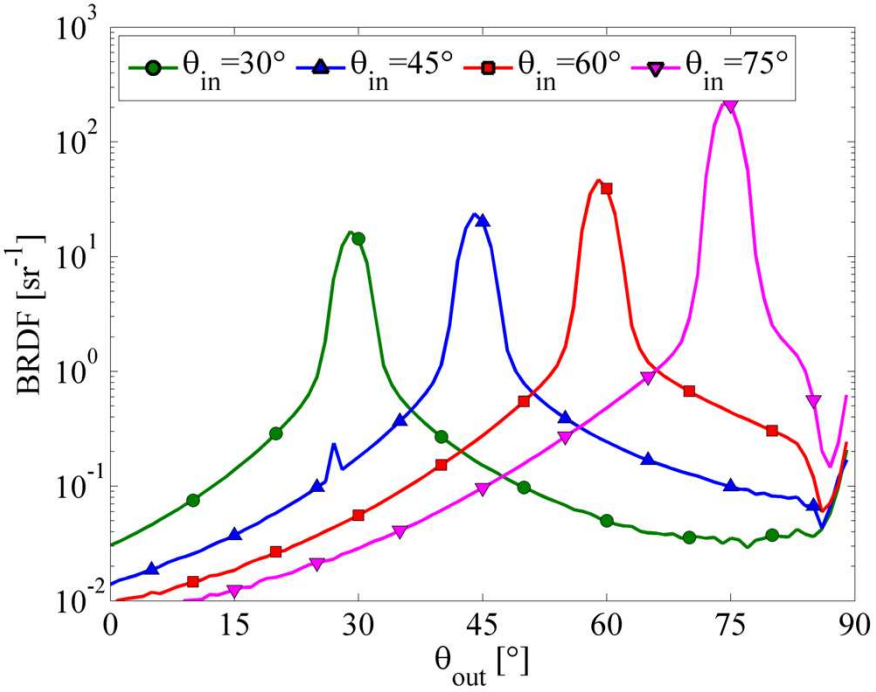
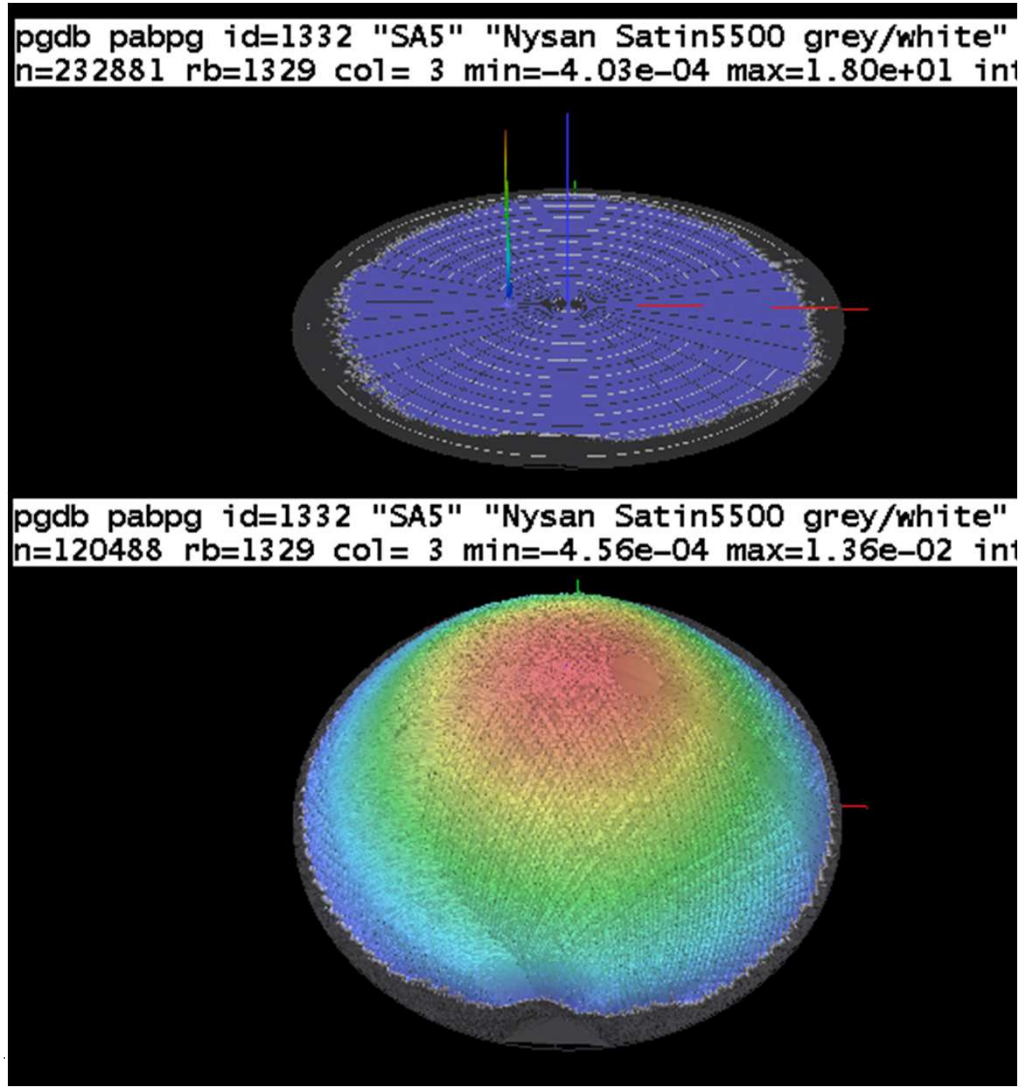
Examples of data





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Pros and cons of goniophotometer

Pros

- Intuitive
- High, variable, angle-resolution
- Modular with respect to sources and detectors
- Can handles some inhomogeneities in the sample

Cons

- Slow
- Retroreflection is hard
- P_s often << P_i
- Large instrument to obtain far field

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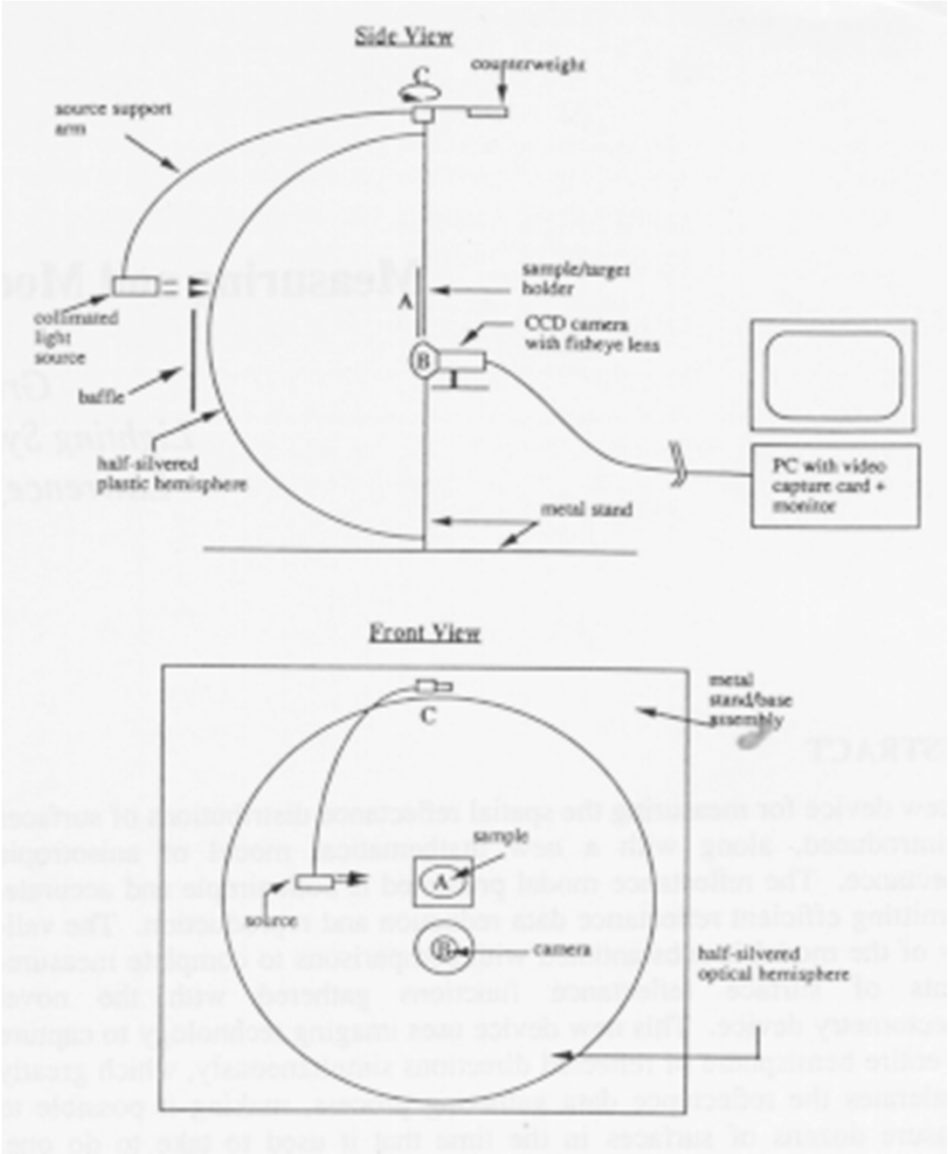
Imaging approach

- Key is a semitransparent specular hemisphere or hemiellipsoid
- Sample in one focal point and a camera with a fisheye lens in the other



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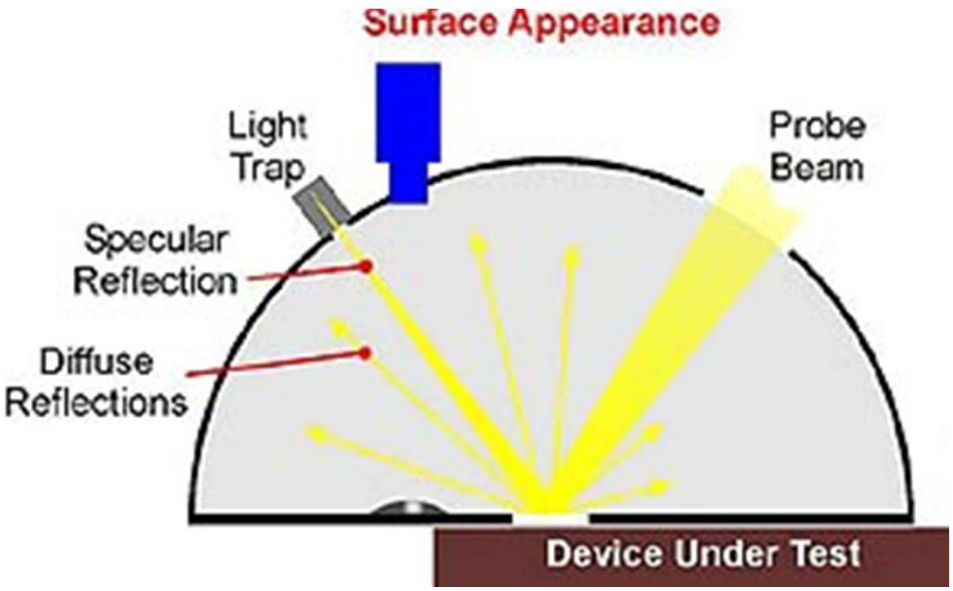
Imaging approach take 2

- Lambertian hemisphere
- Sample in one focal point and a curved mirror camera in the other
- Camera takes picture of the curved mirror



Pros and cons of imaging systems

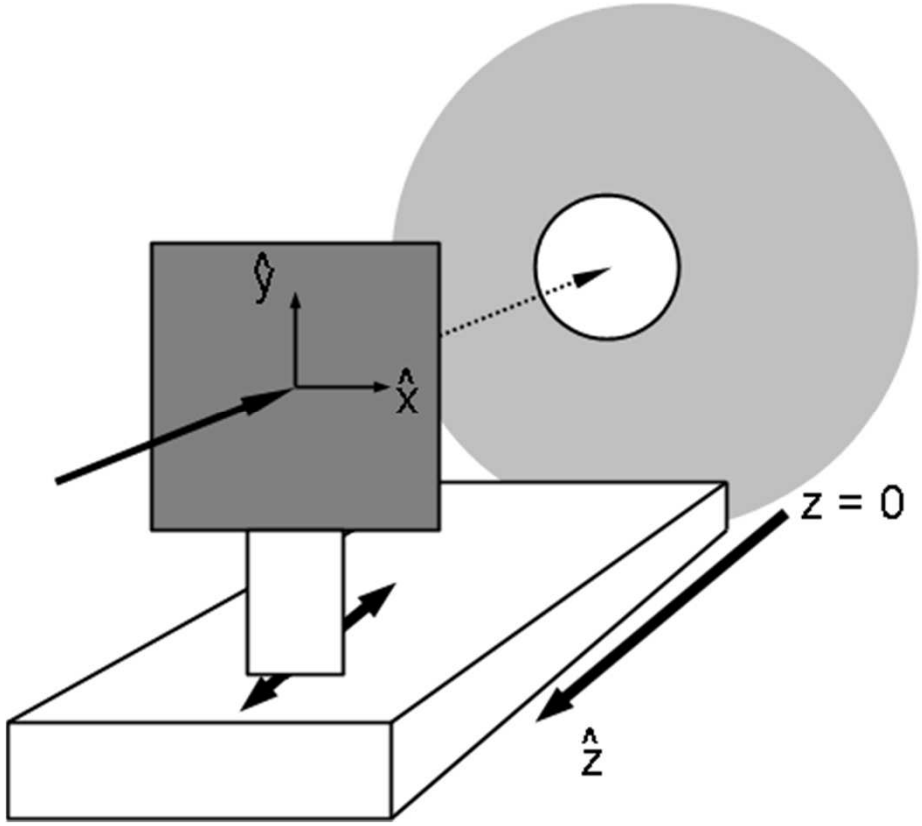
Pros

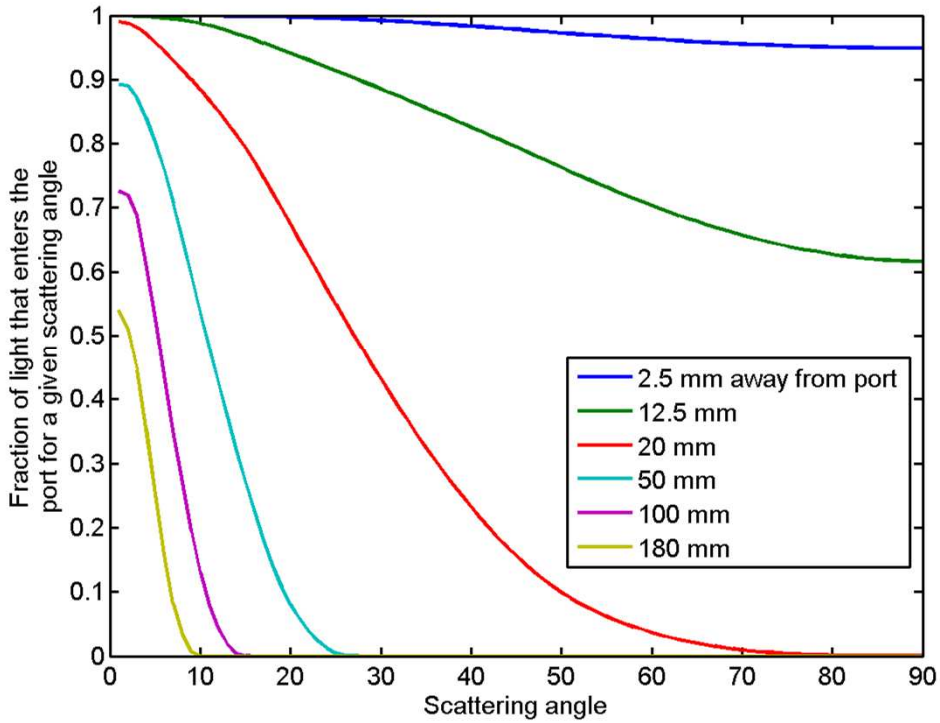
- Very fast
- Measures same outgoing angles every time

Cons

- CCD cameras
  - Dynamic range
  - Calibration is hard
- Large instrument to obtain far field
- Depth of field at focal points

Other methods - pullback





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Pros and cons of pullback method

Pros

- Cheap if you already have a spectrophotometer
- Spectral resolution

Cons

- Only near normal AoI
- Only isotropic
- Reflectance is hard
- Numerical solution is not good for BTDFs with large derivatives

Other methods

Bench-top spectrophotometers

In-situ detectors

Cons

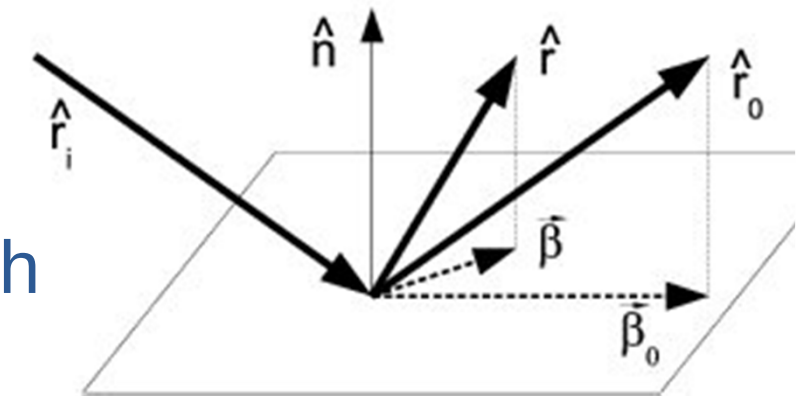
- Extrapolation of data
- Inaccuracy

Data representation

- Continuous function
  - Probability density function
  - Cumulative distribution function
- Discrete values
  - Variable or fixed space
  - Association of space angle with measured values

Continuous Function – Data fitting

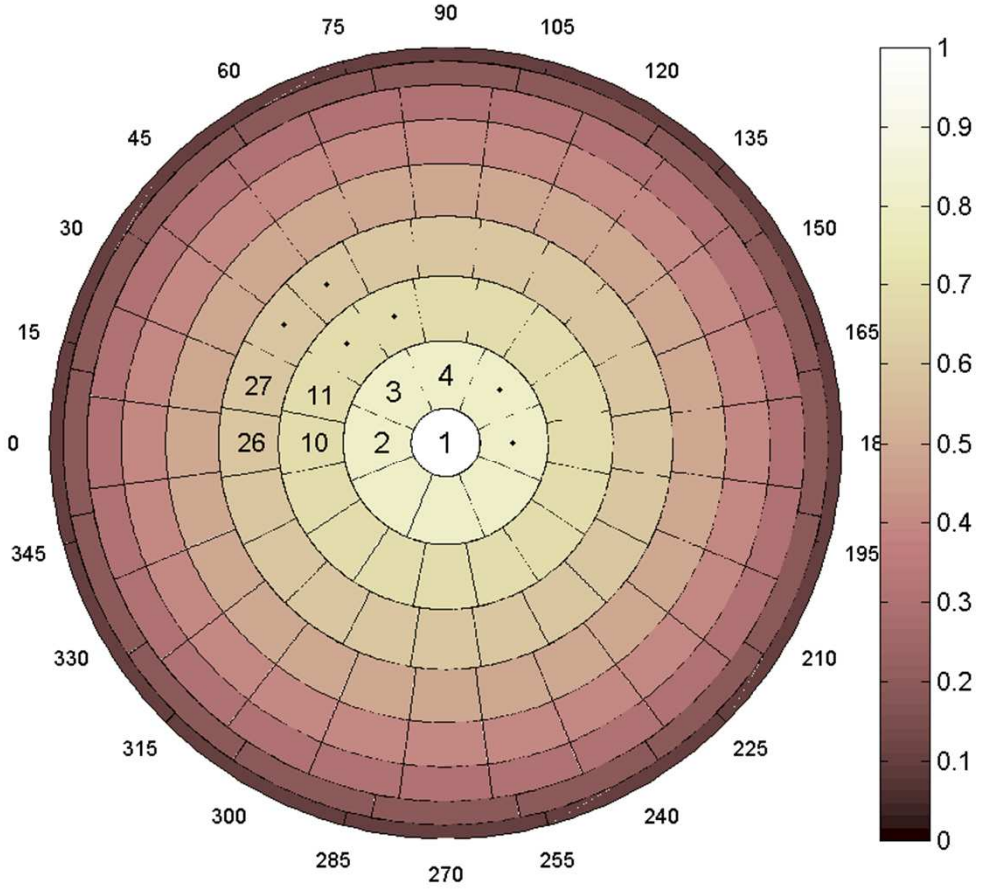
- Lambertian and Super-Lambertian
  - Convenient
- ABg-like
  - Scattering vector approach



- Any function that is representative of your sample

Discrete values – Klems basis

- Fixed space
- Clearly defined solid angle for each value
- Similar to Tregenza



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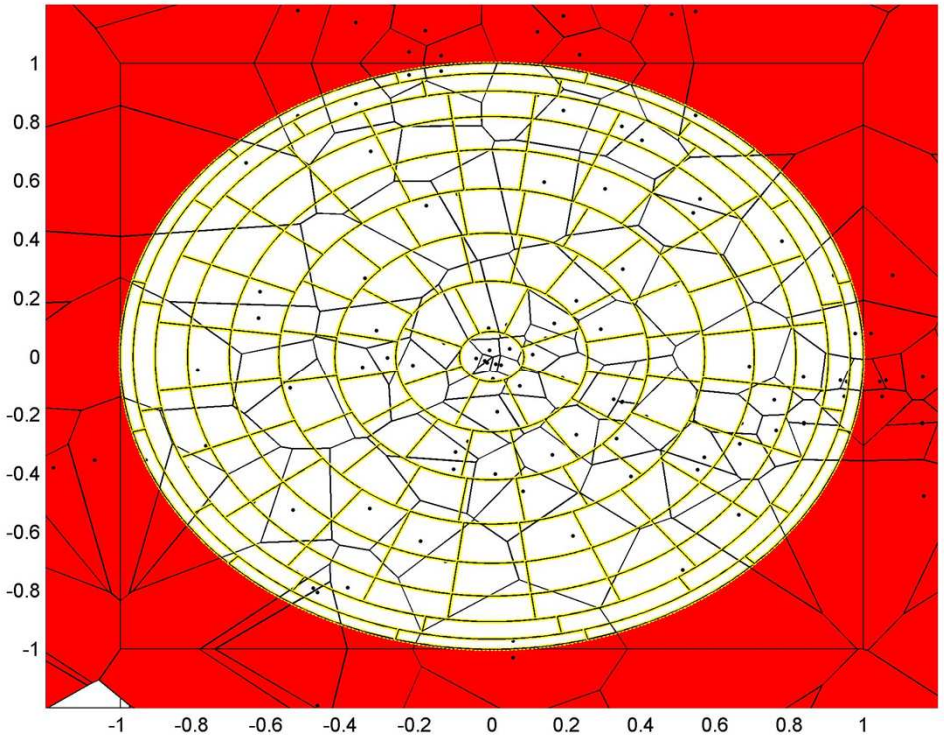
Binning data into fixed coordinate system

- Voronoi diagram to associate an area with each point
- Match against target coordinate system



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Summary

- Different ways to measure different properties that are relevant
- Direct-hemispherical versus BSDF
- Helpful to know end use

Questions?

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