WORKSHOP ON BTDF MEASUREMENT

BTDF - measurand and sample types

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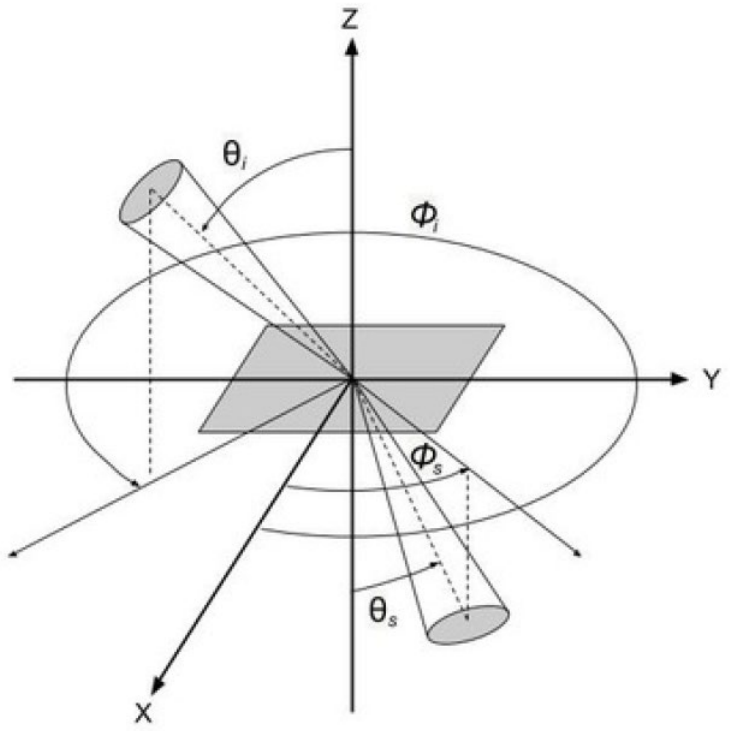
Outline

- Definition of BRDF
- Practical measurements of BTDF
- Uncertainty factors
- Applications
- Sample types

Bidirectional Transmittance Distribution Function (BTDF)

BTDF is a measure of the transmitted optical scatter of a material as a function of wavelength and direction

BTDF measurement geometry



from Butler *et al* 2019 *Metrologia* 56 065008

The BTDF is defined as the ratio of the transmitted radiance scattered by a sample ($L_{\tau s}$) in a specific direction to the incident irradiance on that sample (E_i):

$$BTDF = \frac{L_{\tau s}(\theta_i, \phi_i, \theta_s, \phi_s, \lambda)}{E_i(\theta_i, \phi_i, \lambda)} \quad [sr^{-1}]$$

BTDF definition

$$BTDF = \frac{L_{\tau s}\,(\theta_i, \emptyset_i, \theta_s, \emptyset_s, \lambda\,)}{E_i(\theta_i, \emptyset_i, \lambda\,)}$$

In a strict sense the definition requires:

- Negligible thickness
- No internal scattering
- Uniform incident beam
- Etc.

In practice the following formula is often used*:

$$BTDF \approx \frac{P_S/\Omega_S}{P_i \cos\theta_S}$$

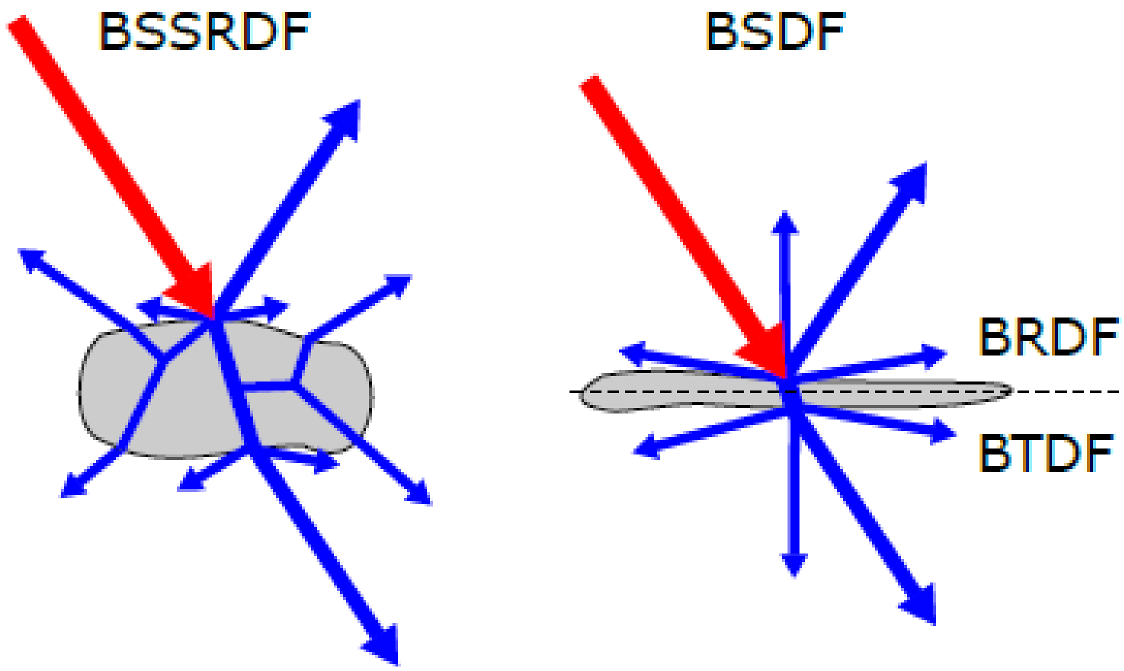
obtained by expressing $L_{\tau s}$ and E_i in terms of the incident and scattered radiant power (P_i, P_s) and the projected solid angle ($\Omega_s \cdot \cos\theta_s$).

*Also in various standards related to angle-resolved scattering measurements such as ISO 19986, ASTM E 2387 and SEMI ME1392

General cases

Bidirectional scattering distribution function (BSDF)

Bidirectional scattering-surface reflectance distribution function (BSSRDF)



from Frisvad *et al* 2020 *Computer Graphics Forum* 39.2, 729-755

Practical measurements of BTDF

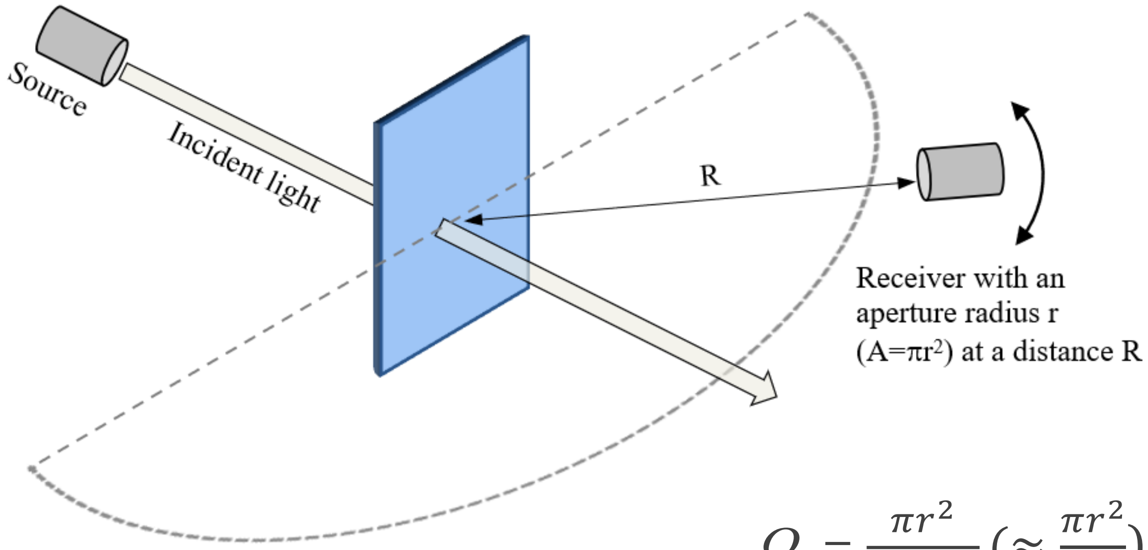
The sample is illuminated with a collimated beam and the amount of light scattered into a known solid angle is measured

$$BTDF = \frac{P_s}{P_i} \frac{R^2+r^2}{\pi r^2 \cos\theta_s}$$

For BTDF and samples with finite thickness (surface and bulk scattering), what is R?

Typically R is taken from the viewing side of the sample as this side defines the solid angle

Schematic of measurement set-up for BTDF



$$\Omega_s = \frac{\pi r^2}{R^2+r^2} \left(\approx \frac{\pi r^2}{R^2}\right)$$

Uncertainty factors

Using the measurement equation, the relative error in the measured BTDF can be expressed as (r<<R):

$$BTDF = f_s = \frac{P_s}{P_i}\frac{R^2+r^2}{\pi r^2 \cos\theta_s}$$

$$\frac{\Delta f_s}{f_s} = \sqrt{\left(\frac{\Delta P_s}{P_s}\right)^2 + \left(\frac{\Delta P_i}{P_i}\right)^2 + \left(\frac{2\Delta r}{r}\right)^2 + \left(\frac{2\Delta R}{R}\right)^2 + \left(\frac{1}{f_s}\frac{\partial f_s}{\partial \theta_s} - \tan\theta_s\right)^2 \cdot (\Delta\theta_s)^2}$$

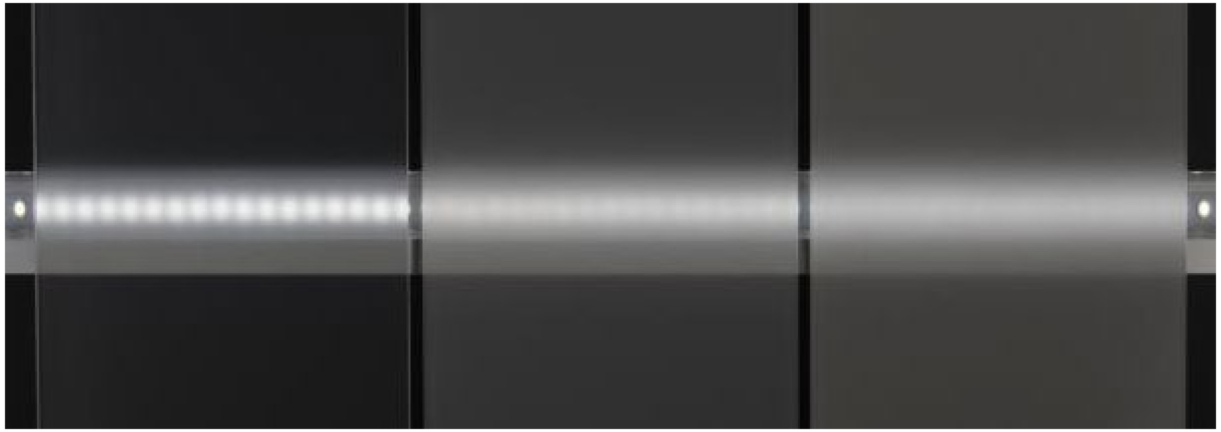
- ΔX is the estimated error in each component X (could be replaced with standard uncertainties u_x)
- Often each component includes several contributions to the error
- For example, ΔP_i could include detector non-linearity, repeatability (sampling), stray-light, wavelength error etc.

Applications of BTDF

BTDF measurements are of interest in fields such as

- Architecture (glazings, fenestration systems)
- Solar cell industry (increased efficiency by light trapping or reduced shadowing losses)
- Lighting (diffusers for luminaires, automotive lighting etc.)
- Satellite-based earth remote sensing (spectral radiance calibration)

Prismatic glazing (from www.glassform.com.au)



Luminaire diffusers for LED (from www.covestro.com)

BxDiff JRP 18SIB03

RI. SE

Sample types for BTDF

(Transmissive) diffuser:

- Optical element that scatter light (such that its spatial coherence is substantially reduced)

Diffusor type	Material / mechanism	Properties
Volume diffuser	Polytetrafluoroethylene (PTFE) Syntetic fused silica w air	Near lambertian Spectrally flat
Surface diffuser	Coated, grounded, frosted or sandblasted glass, random structure	Roughly circular shape, generally
Holographic*	Films, polymer-on-glass etc. Pseudo-random structures	Circular or elliptical scattering with gaussian profile
Engineered**	Films, polymer-on-glass etc. Designed structures	Non-Gaussian profile

*Replicated from a holographically recorded master (laser speckle). Pseudo random, non-periodic structures.

**Replicated from engineered master structures allowing for light management with independent control of both the distribution pattern and the intensity profile

Lambertian diffusers

- The relative transmittance follows Cos θ_s
- Constant BTDF ($1/\pi$ for a perfect diffuser)
- In practice, the more near-lambertian properties the lower the tranmittance

Hereaus HOD® – High Purity Fused Silica Diffusor

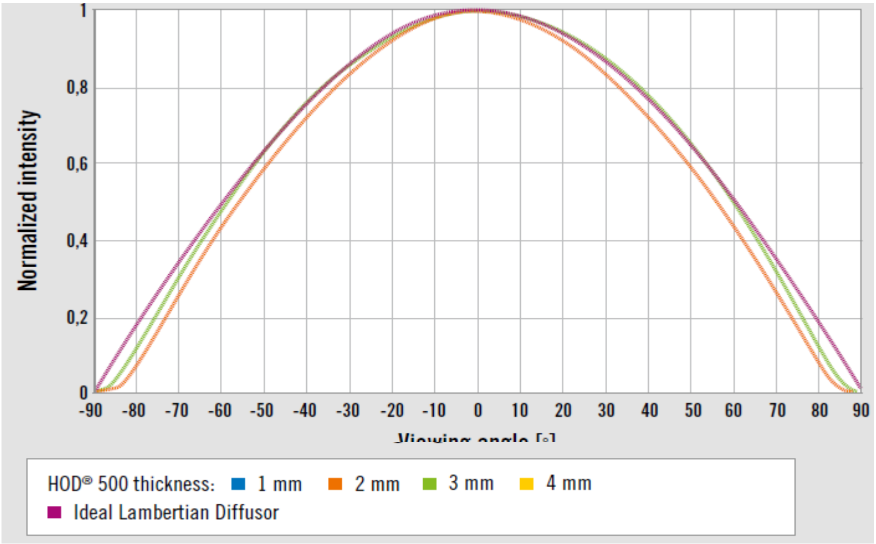
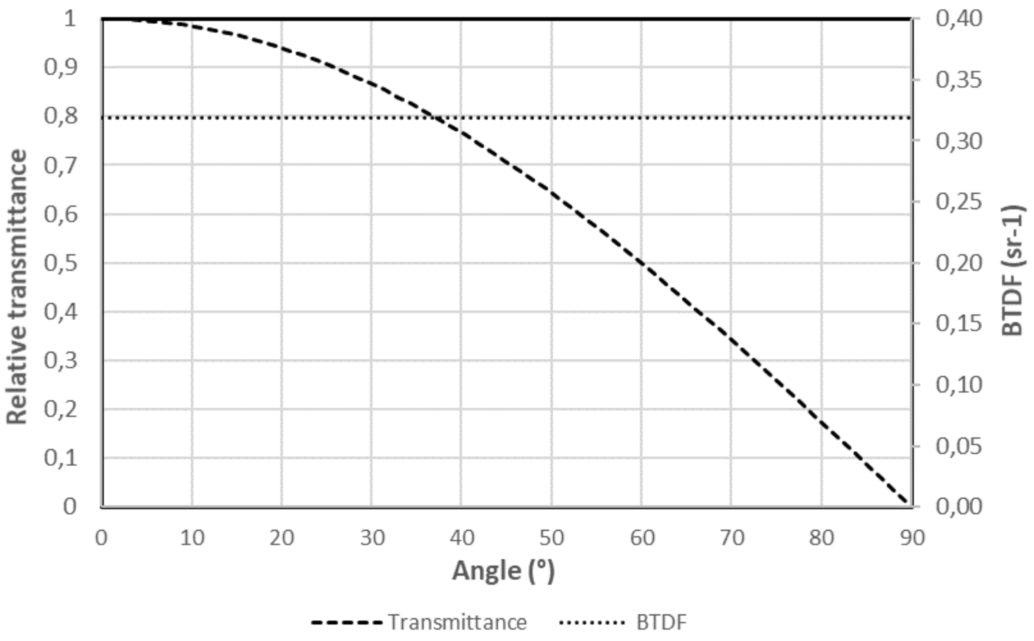


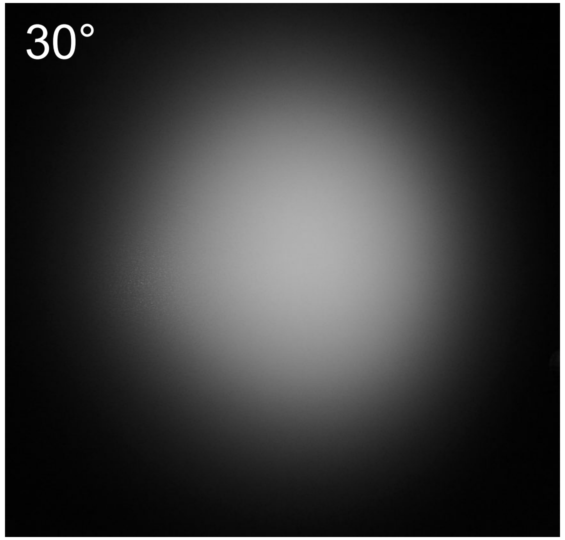
Diagram from HOD® data sheet

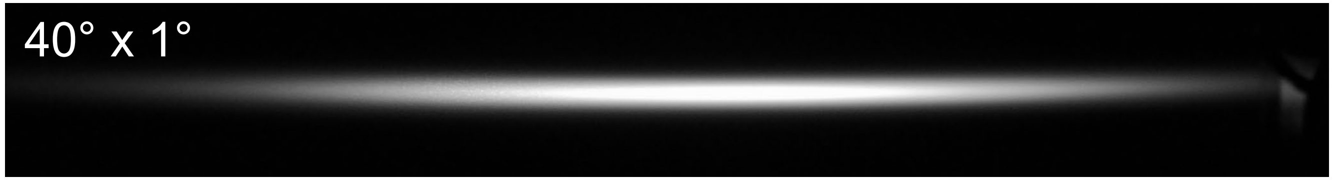
Perfect lambertian diffuser

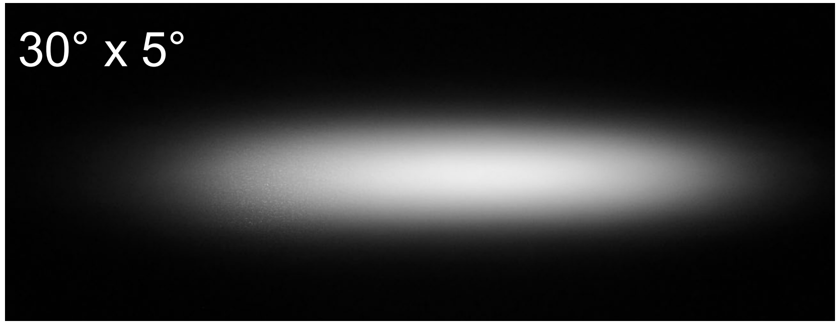


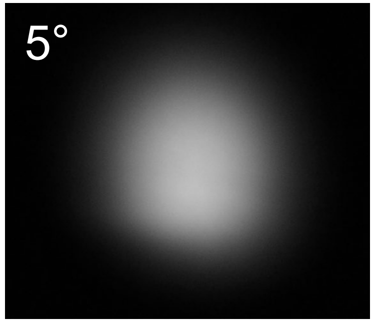
Examples of other diffusor types

Holographic diffusers

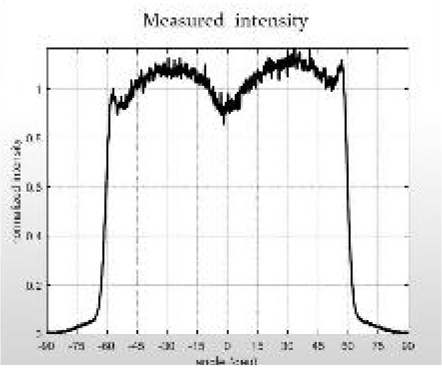


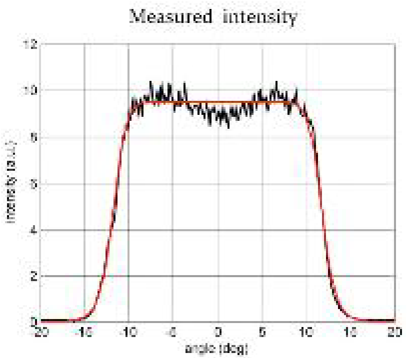




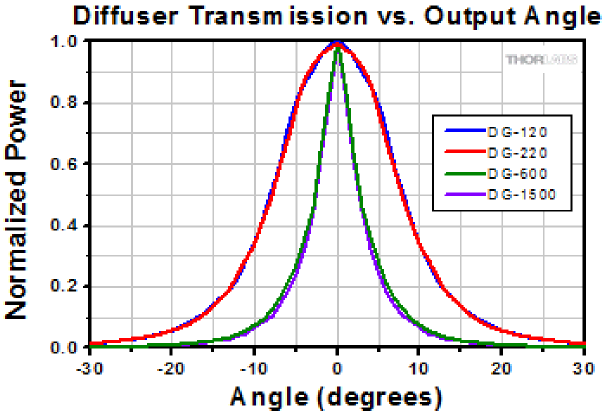


Engineered diffusers (from RPC Electronics)





Ground glass diffusers (from Thorlabs)



Some useful references

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- F.O. Bartell, E.L. Dereniak, and W.L. Wolfe, “The theory and measurement of bidirectional reflectance distribution function (BRDF) and bidirectional transmittance distribution function (BTDF),” Proc. SPIE 257, 154-160 (1981)
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- Stover, John C. and Society of Photo-optical Instrumentation Engineers, *Optical scattering : measurement and analysis,* SPIE Optical Engineering Press Bellingham, Wash., USA 2012