KU LEUVEN

LIGHT&LIGHTING
LABORATORY

Modelling of light propagation in translucent materials

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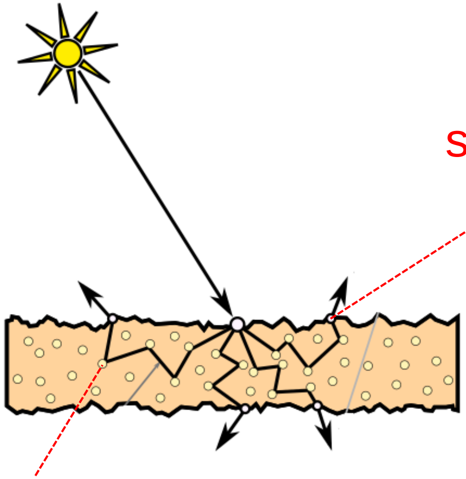
Translucent materials

- Light can partially pass.
- **Scattering** is happening.
- No clear/distinct images can be seen through them.



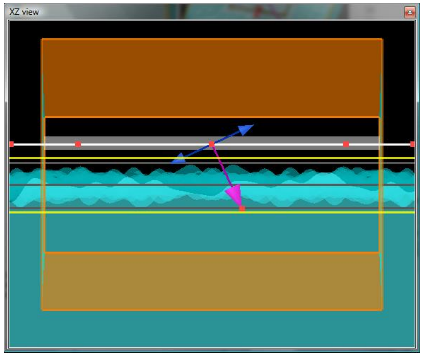
Surface scattering

Volume scattering

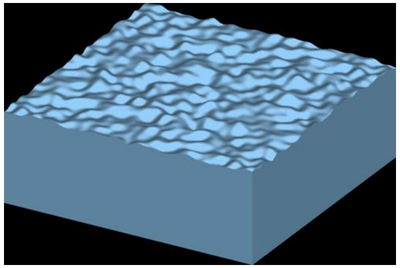
Translucent materials

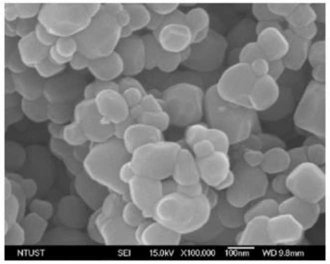
Model light propagation

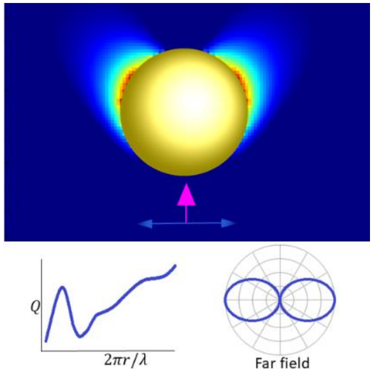
Option 1 : Propagating coherent EM fields



Problem 1 : A lot of accurate information is needed.







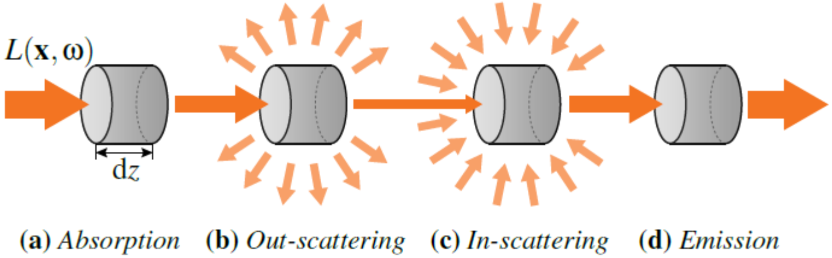
Problem 2 :Very time-consuming.

→ *Impractical for simulating large translucent objects !!!*

Option 2 : Propagating radiant flux

1) The radiative transfer equitation

- Models the redistribution of the radiance in a differential volume element due to absorption, scattering and emission.

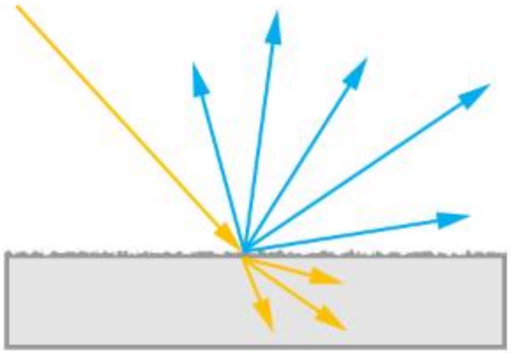


(a) *Absorption* **(b)** *Out-scattering* **(c)** *In-scattering* **(d)** *Emission*

$$(\vec{\omega} \cdot \nabla) L(\boldsymbol{x}, \vec{\omega}) = -(\mu_a(\boldsymbol{x}) + \mu_s(\boldsymbol{x})) L(\boldsymbol{x}, \vec{\omega}) + \mu_s(\boldsymbol{x}) \int_{4\pi} p(\boldsymbol{x}, \vec{\omega}', \vec{\omega}) L(\boldsymbol{x}, \vec{\omega}') + \ell_e(\boldsymbol{x}, \vec{\omega})$$

2) The rendering equation

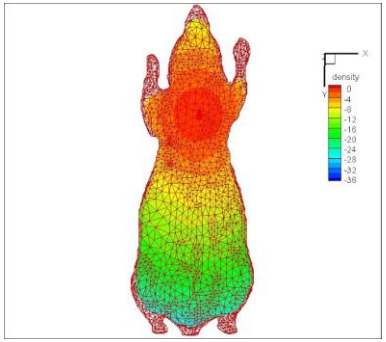
- Models the redistribution of the radiance at material interfaces.

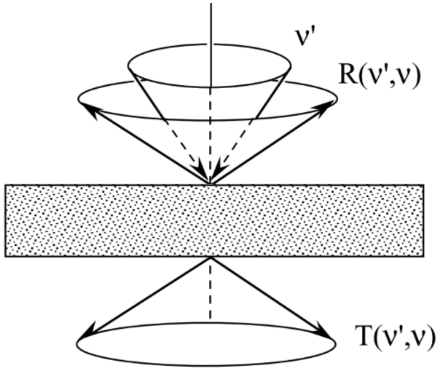


$$L_{out}(\boldsymbol{x}, \vec{\omega}') = \int_{4\pi} f_s(\boldsymbol{x}, \vec{\omega}, \vec{\omega}') L_i(\boldsymbol{x}, \vec{\omega}) |\cos\theta| \, d\omega$$

Numerical methods for solving these equations

- Finite-element methods →
- Monte-carlo path tracing
- Adding-doubling method →
- Kubelka-Munk model
- ………..

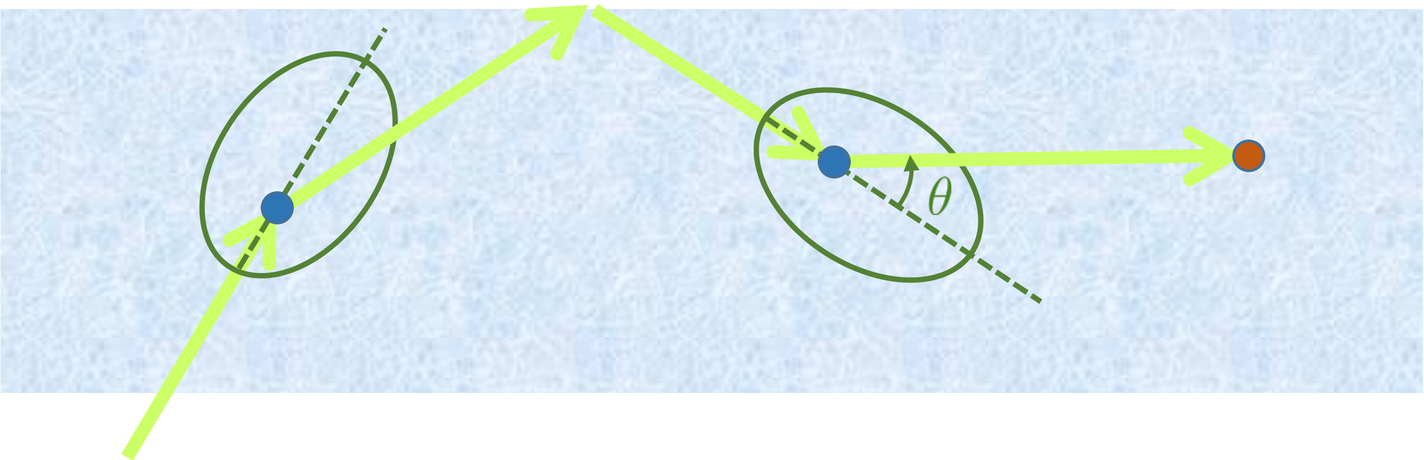




Optical modelling parameters

For volume & surface scattering

Homogeneous, isotropic materials with volume scattering



Volume scattering material properties :

$\mu_a(\lambda)$ - absorption coefficient

$\mu_s(\lambda)$ - scattering coefficient

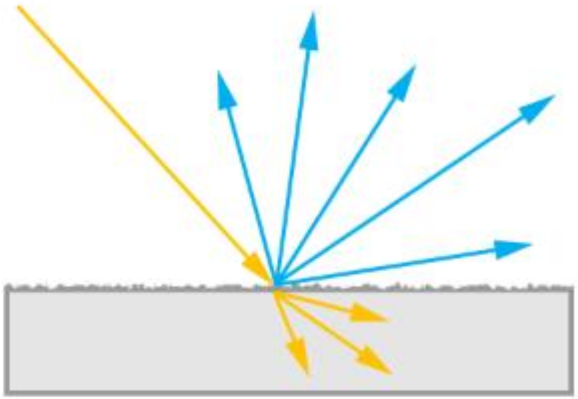
$p(\theta, \lambda)$ - scattering phase function

Materials with homogeneous surface scattering

Surface BSDF :

Proportionality factor of scattered radiance to the incident irradiance

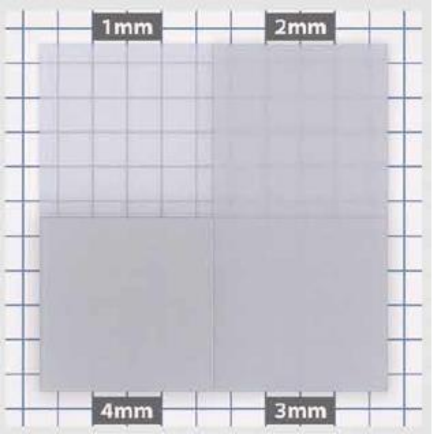
$$f_s(\overset{\lambda}{\cancel{\mathbf{x}}}, \vec{\omega}, \vec{\omega}') = \frac{L_{out}(\cancel{\mathbf{x}}, \vec{\omega}')}{E_{in}(\cancel{\mathbf{x}}, \vec{\omega})}$$



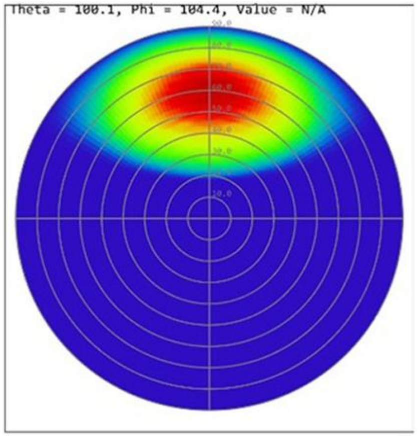
Knowing these properties allows accurate simulation models

$\mu_a(\lambda)$ $\mu_s(\lambda)$ $p(\theta, \lambda)$ $f_s(\vec{\omega}, \vec{\omega}', \lambda)$

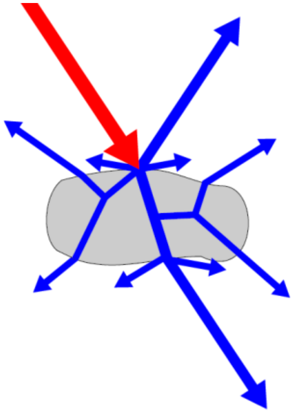
Appearance



Optical performance



BSSRDF



(Except some typical coherence effects e.g. speckle)

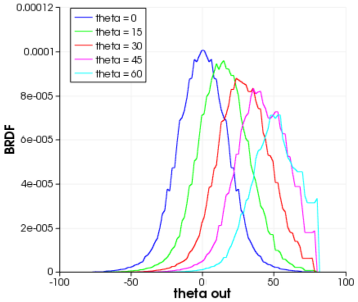
Parameter extraction

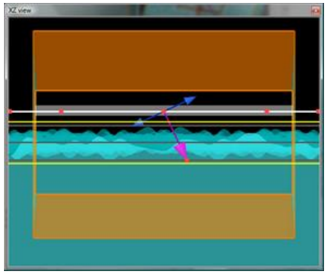
Acquiring accurate optical properties for flux models

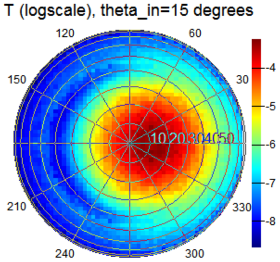
Option 1 : Use EM field modelling to calculate optical parameters for flux based methods

Example 1

- Surface BSDF can be found if accurate information is available.

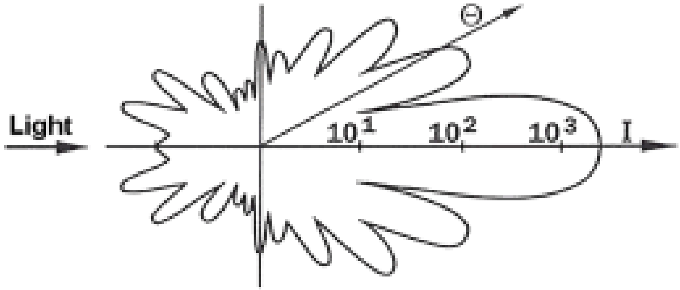






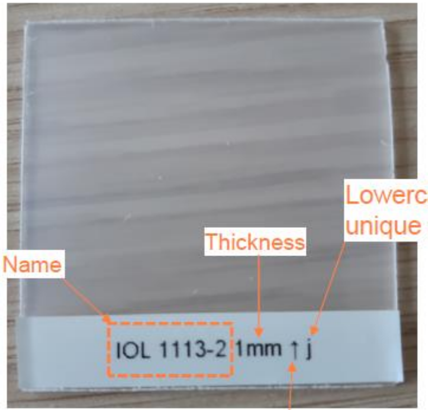
Example 2

- Volume scattering parameters can be found if accurate information is available.



E.g. via MIE theory

Example : Covestro samples



Sample Series Name

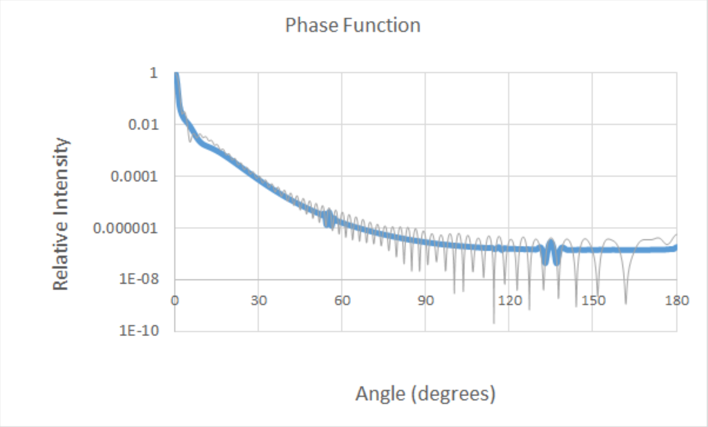
Thickness

Lowercase letter for unique assignment

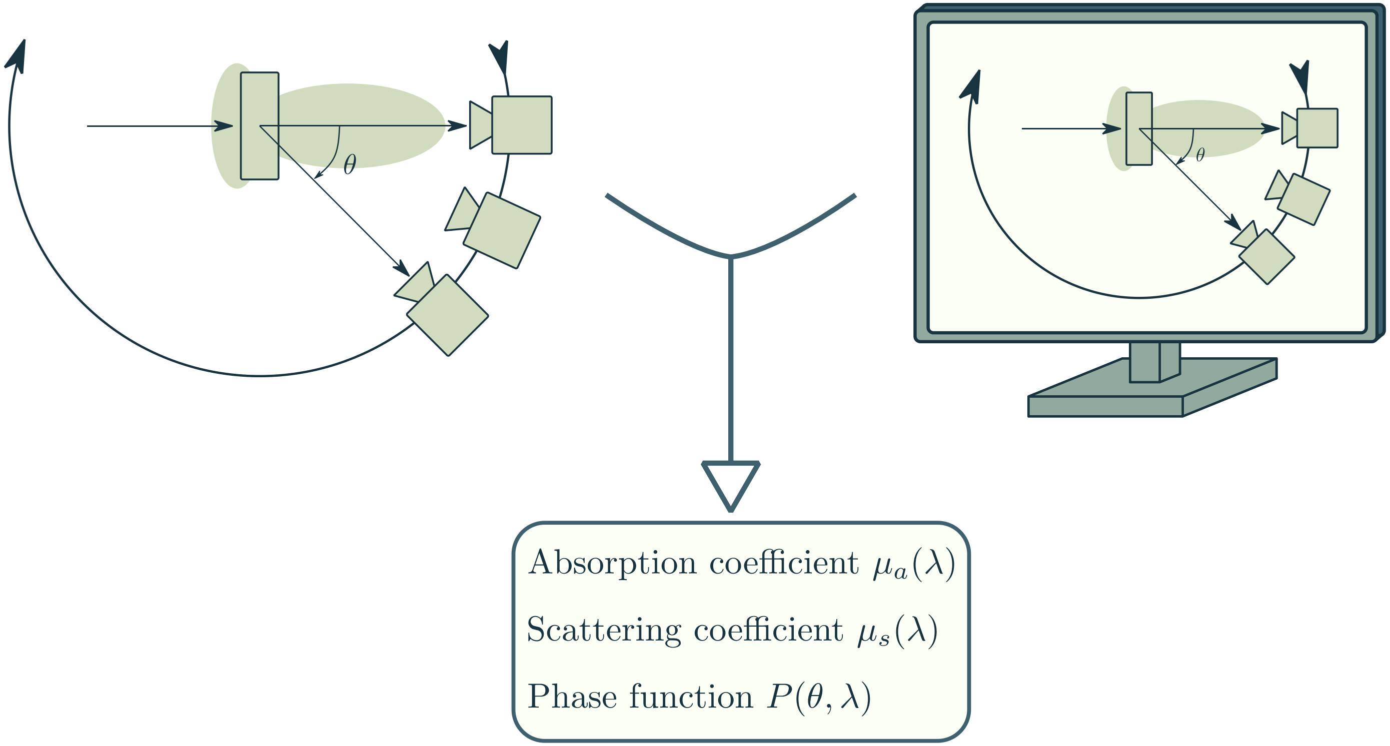
Flow Direction

Sample Series	Con-centration (mass-%)	Refractive Index (589nm)	D(10) (µm)	D(50) (µm)	D(90) (µm)
IOL1113-1	0.35%	1.42	1.4	1.9	2.6
IOL1113-2	1.75%	1.49	3.0	5.0	8.3

$$p(\theta,\lambda) = \frac{\int \mu_{s,D}(\lambda) \cdot p_D(\theta,\lambda) dD}{\int \mu_{s,D}(\lambda) dD}$$



Option 2 : Fit simulation parameters to measurements

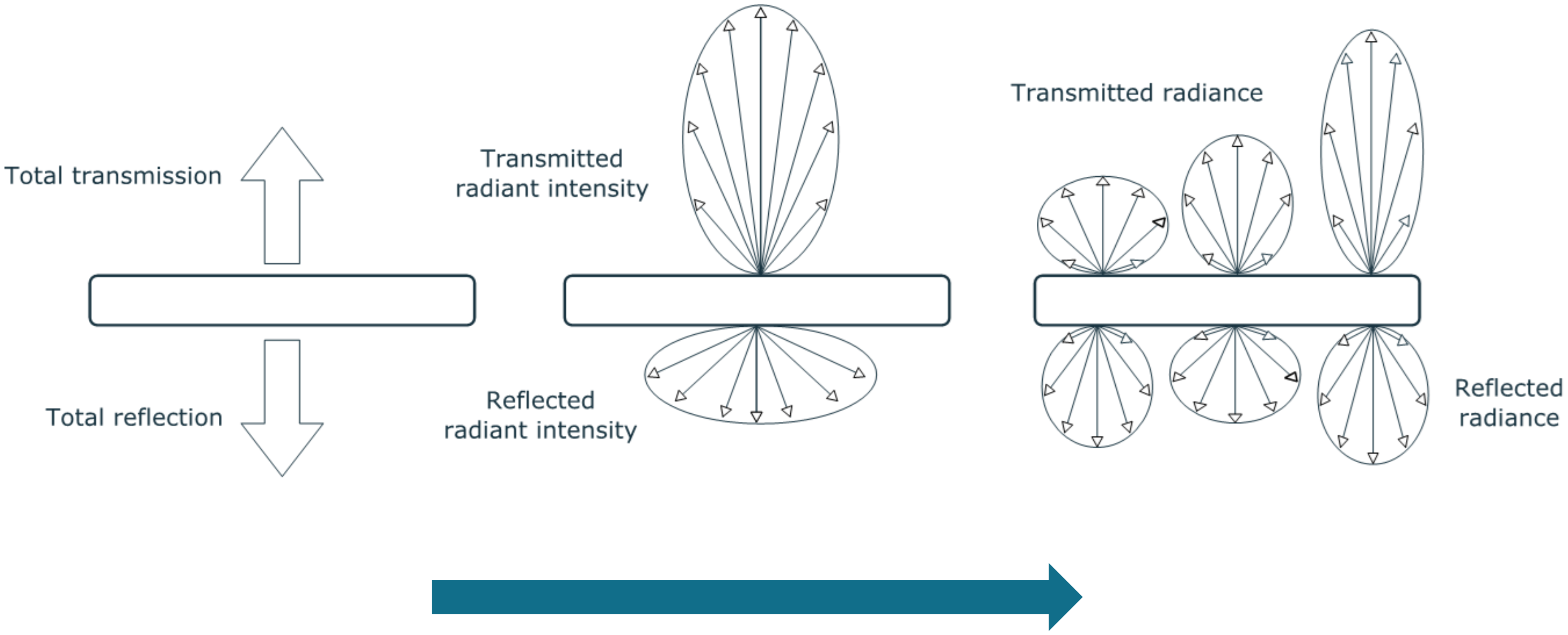


Absorption coefficient $\mu_a(\lambda)$

Scattering coefficient $\mu_s(\lambda)$

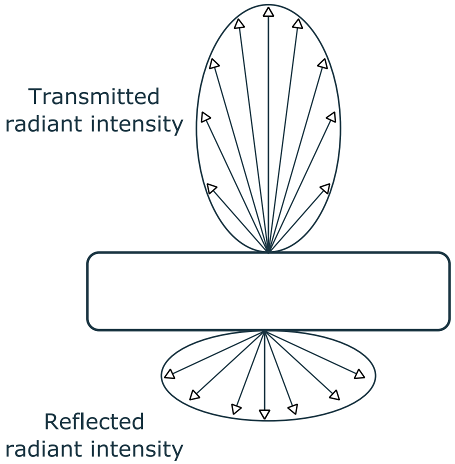
Phase function $P(\theta, \lambda)$

Fitting to various kinds of measurements

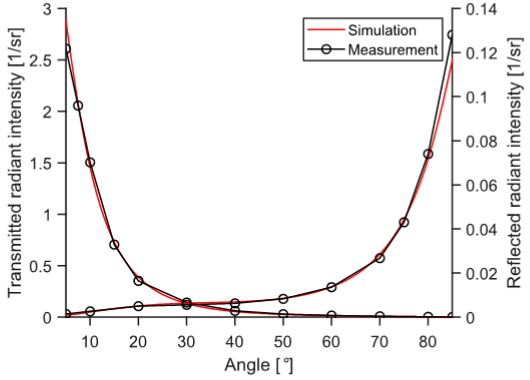


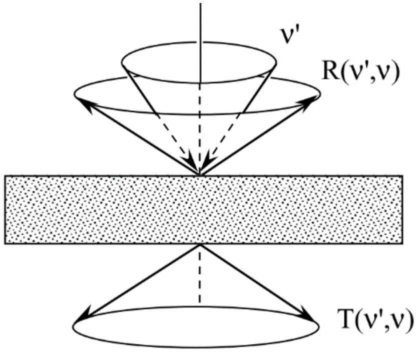
More accurate results can be obtained
if a more complete measurement of the scattered light is considered.

Intensity-based inverse adding-doubling (IAD)

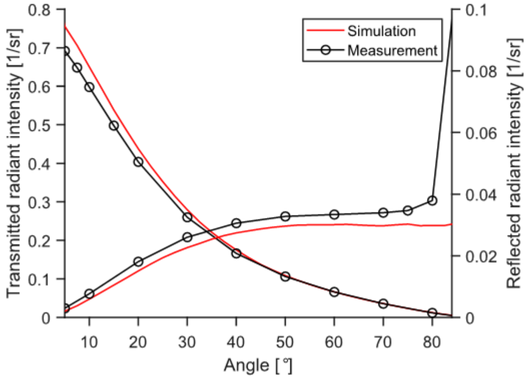


Fitted





Predicted



Correia, A., Hanselaer, P., Meuret, Y. (2019). Accurate and robust characterization of volume scattering materials using the intensity-based inverse adding-doubling method, *Modeling Aspects in Optical Metrology VII* (p. 110570N). SPIE

Parameter extraction

Main Challenges

Phase function models

Henyey-Greenstein (HG)

$$p_{\mathrm{HG}}(\theta) = \frac{1-g^2}{4\pi(1+g^2-2g\,\cos(\theta))^{3/2}}.$$

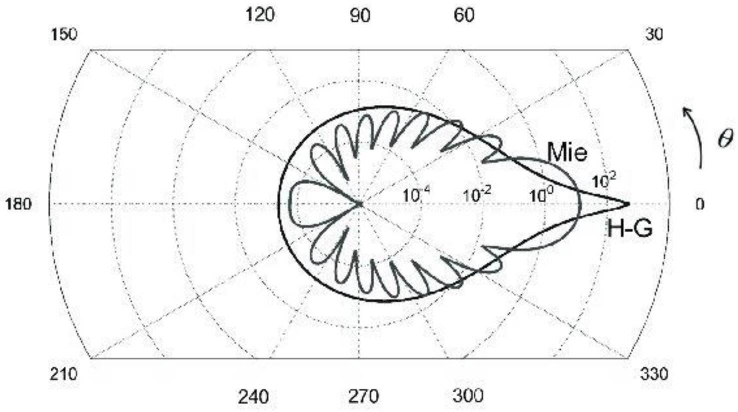
One-parameter phase function model

Gegenbauer Kernel (GK)

$$p_{\mathrm{GK}}(\theta) = K\cdot(1+g^2-2g\,\cos(\theta))^{-(\alpha+1)}$$

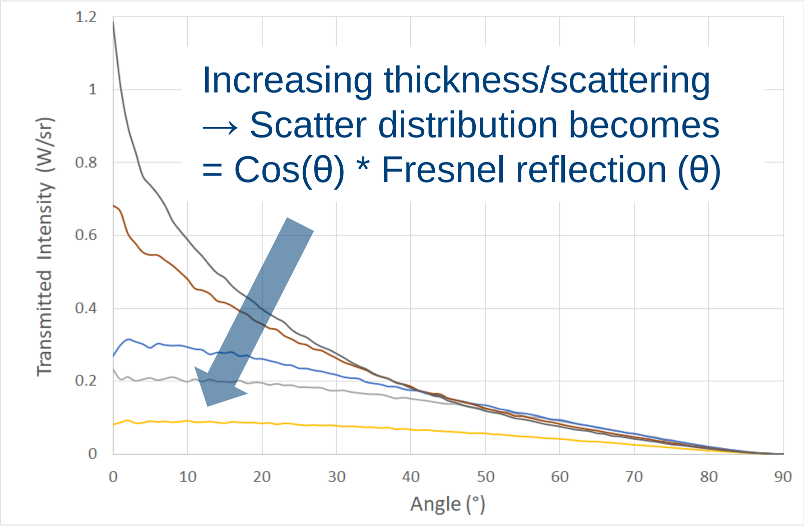
$$K = \alpha g\frac{(1-g^2)^{2\alpha}}{\pi[(1+g)^{2\alpha}-(1-g^{2\alpha})]}.$$

Two-parameter phase function model

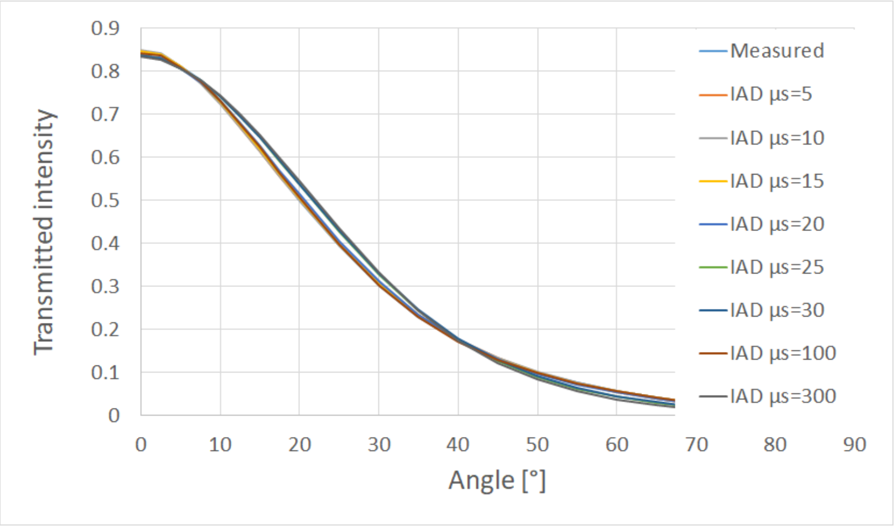


Similarity theory

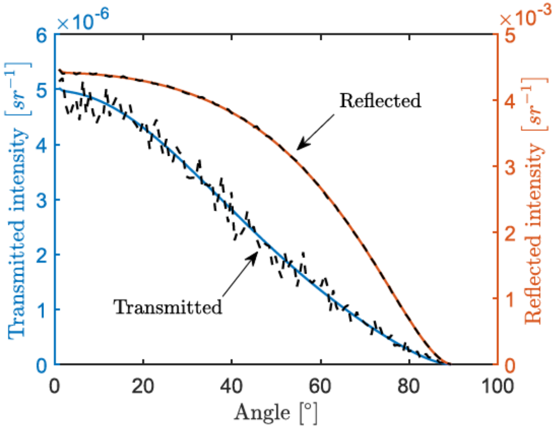
- For deeply-scattering geometries, one can derive multiple parameter-sets that produce indistinguishable images or optical performance.

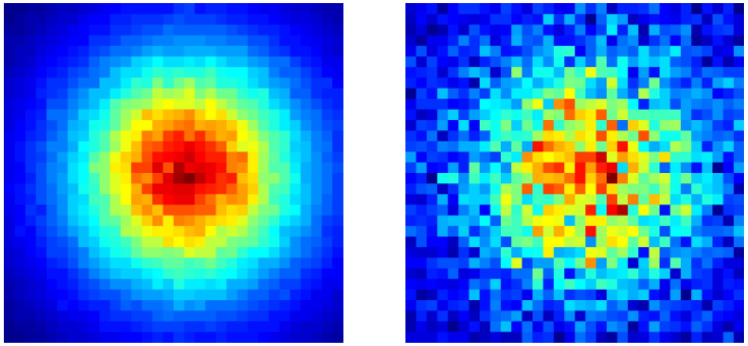


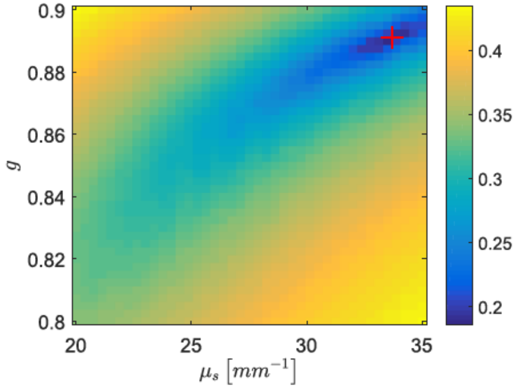
Increasing thickness/scattering
→ Scatter distribution becomes
= Cos(θ) * Fresnel reflection (θ)



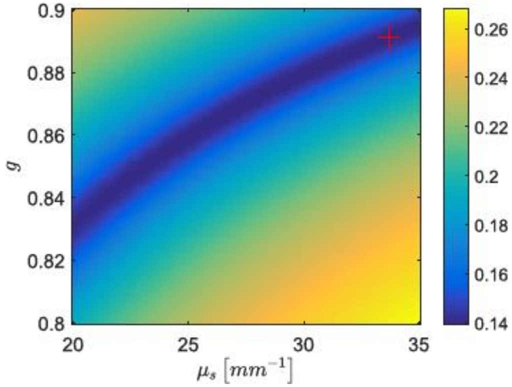
Impact of measurement accuracy !







Fitting error to radiant intensity without measurement noise



Fitting error to radiant intensity with measurement noise

Correia, A., Hanselaer, P., Cornelissen, H., Meuret, Y. (2017). Radiance based method for accurate determination of volume scattering parameters using GPU-accelerated Monte Carlo. *Optics Express*, *25*(19), 22575–22586

BTDF fitting results for Covestro Samples