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How much light is internally reflected at the boundaries of translucent layers ?

Arthur Gautheron^{1,2}, Raphaël Clerc², Vincent Duveiller², Lionel Simonot³, Bruno Montcel¹ and Mathieu Hébert²

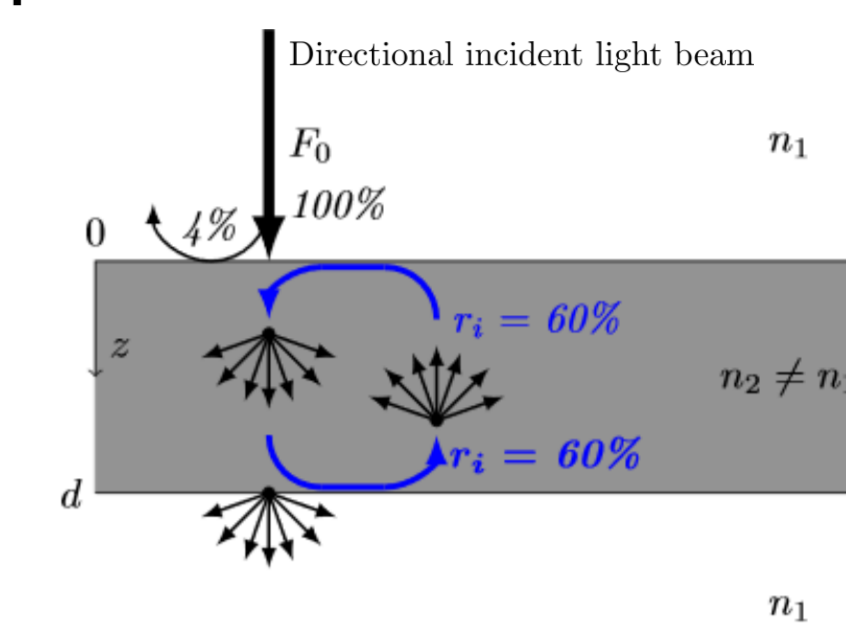
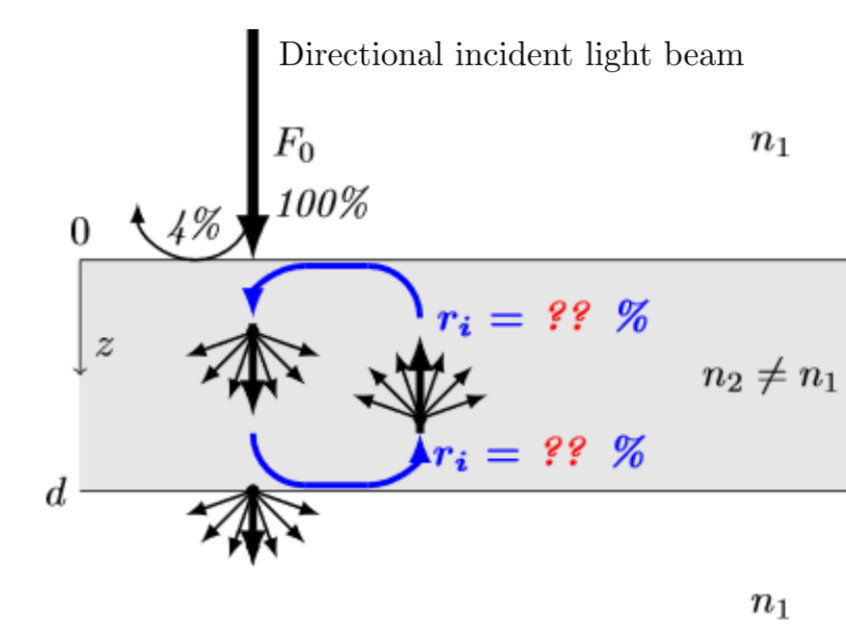
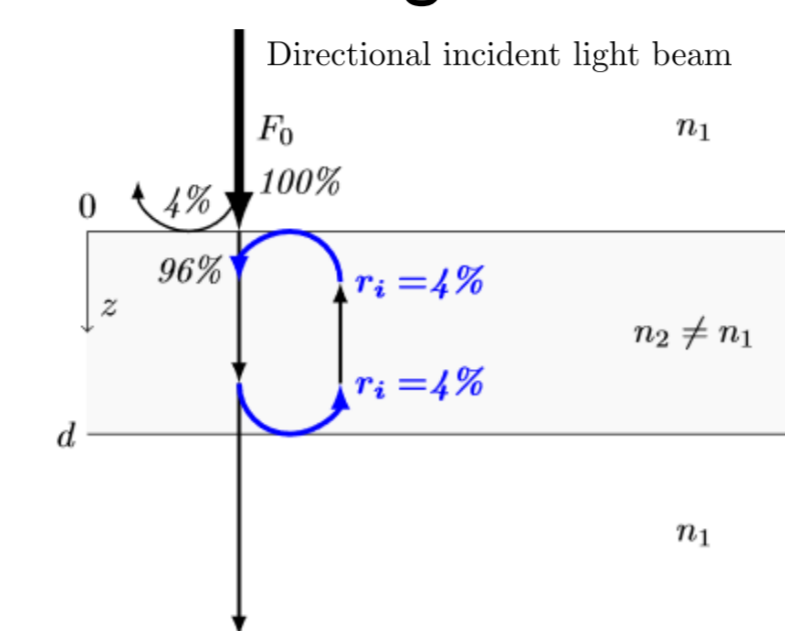
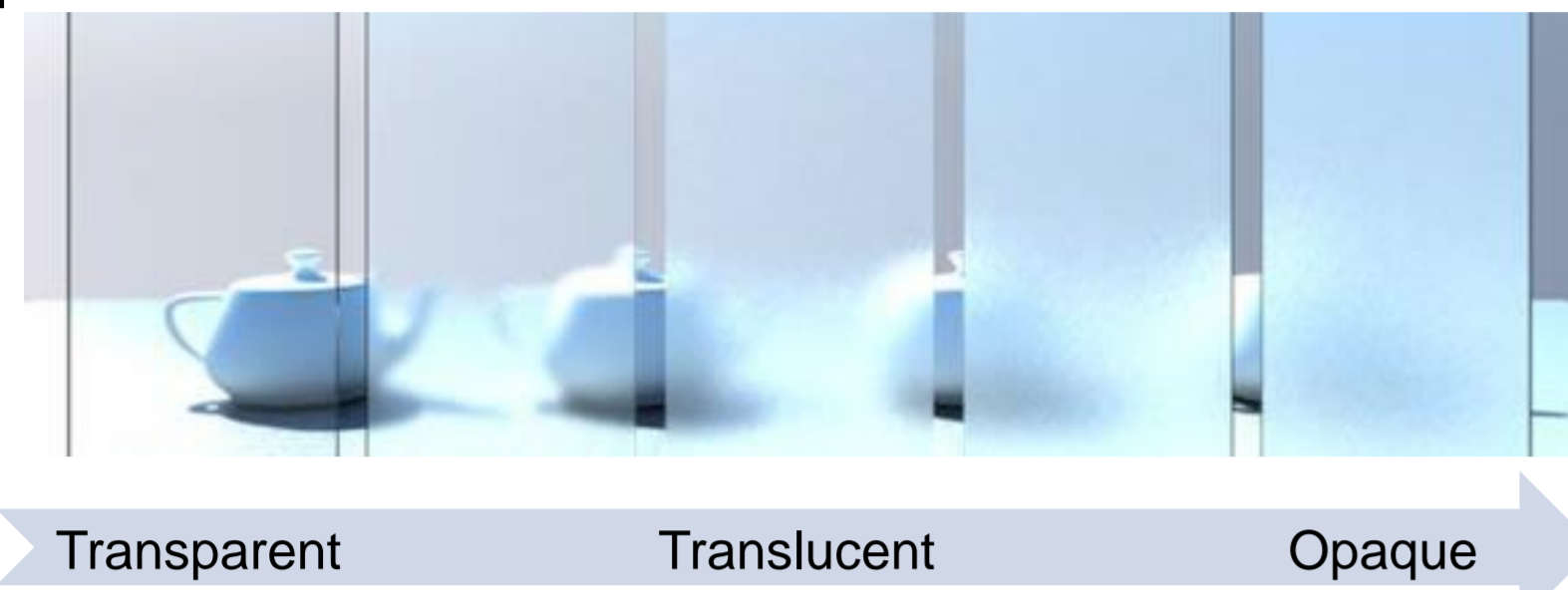
¹Univ Lyon, INSA-Lyon, Univ Claude Bernard Lyon 1, UJM-Saint Etienne, CNRS, Inserm, CREATIS UMR 5220, U1206, F69100, Lyon, France
²Univ Lyon, Univ Jean Monnet de Saint-Etienne, Institut d'Optique Graduate School, CNRS UMR5516 Laboratoire Hubert Curien, F42000, Saint-Etienne, France
³Univ de Poitiers, CNRS UPR 3346 Institut Pprime, F86962, Futuroscope Chasseneuil Cedex, France

Between transparent and opaque : translucent material.

In a transparent medium, a directional beam remains directional. In an opaque diffusing layer, the directional beam becomes perfectly diffused. In translucent layers, the directional beam is scattered progressively along its path.

At the bordering interfaces of a layer of material, some light is internally reflected and goes back into the layer. The fraction of internally reflected light (represented by parameter r_i) strongly depends onto the angular distribution of the scattered light, with respect to the Fresnel reflectance formulae.

The main insight of this work is to show that the amount internally reflected light is not the same at the two boundaries, and it depends a lot on the thickness of the layer.



Not Scattering : $r_i = 4\%$

Weakly Scattering : $r_i = ??$

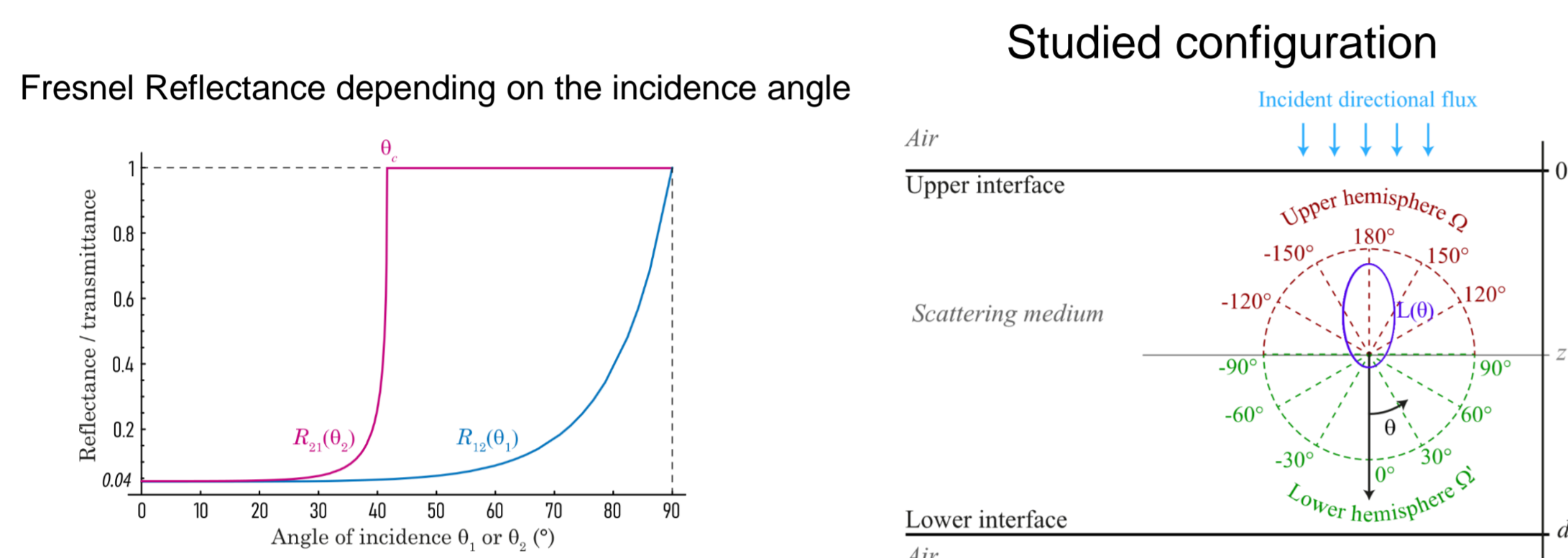
Strongly Scattering : $r_i = 60\%$

Methods

Solving the radiative transfer equation with bordering interfaces

To determine the fraction of internally reflected light, r_i , we need to know the angular distribution of light at the interface. For this, we will estimate it through a model of light scattering, by solving the RTE, finite element method.

The main parameters are: optical index n , absorption coefficient k , scattering coefficient s , anisotropy parameter g , etc. Another important parameter, little known, is the thickness d of the layer.



- Assumptions :
- Incident directional flux at normal incidence on the whole surface, featuring an azimuthal symmetry.
 - 1D geometry : physical quantities only depend on the depth z and zenithal angle θ .
 - Internal reflections at both sides of the directional light component

Radiative Transfer Equation solved using Discrete Ordinates Method [5]

$$\mu \frac{dL}{d\tau}(\tau, \mu) = -L(\tau, \mu) + \frac{1}{2} \int_{-1}^1 p_0(\mu, \mu') L(\tau, \mu') d\mu'$$

Boundary Conditions at both interfaces include Fresnel reflections

L	Radiance ($\text{Wm}^{-2}\text{sr}^{-1}$)	τ	Optical Thickness ($\tau = (\mu_s + \mu_a)z$ where z is the depth of interest in cm)
μ_a	Absorption coefficient (cm^{-1})	ω_0	Albedo of the sample with $\omega_0 = \mu_s / (\mu_s + \mu_a)$
μ_s	Reduced scattering coefficient (cm^{-1})	p_0	Phase Function partially integrated
μ	cosine of the interest angle θ		

Diffuse Internal Reflectance

$$r_{id} = \frac{\int_0^{\pi/2} L_0(\pi - \theta) R_{21}(\theta) \sin(2\theta) d\theta}{\int_0^{\pi/2} L_0(\pi - \theta) \sin(2\theta) d\theta}$$

Similar formula for r'_{id} at bottom interface

Global Internal Reflectance

$$\text{Top Interface } r_{ig} = \frac{F_d}{F_d + F_N} r_{id} + \frac{F_N}{F_d + F_N} r_N$$

$$\text{Bottom Interface } r'_{ig} = \frac{F'_d}{F'_d + F'_N} r'_{id} + \frac{F'_N}{F'_d + F'_N} r'_N$$

F_d Diffused Flux
 F_N Directional Flux
 r_N Fresnel reflectance at normal incidence from the medium through air.
 x' Quantity referring to the bottom interface.

Validity of the 2- and 4-flux models with and without internal reflectance

Reflectance & Transmittance generated with RTE Solver for various thicknesses

Extraction of optical parameters with 4-flux RTE Model for a given thickness

Optical Parameters
Absorption coefficient k ,
scattering coefficient s

Conversion to 2-flux optical parameters
Absorption coefficient K , scattering coefficient S of the Kubelka-Munk model

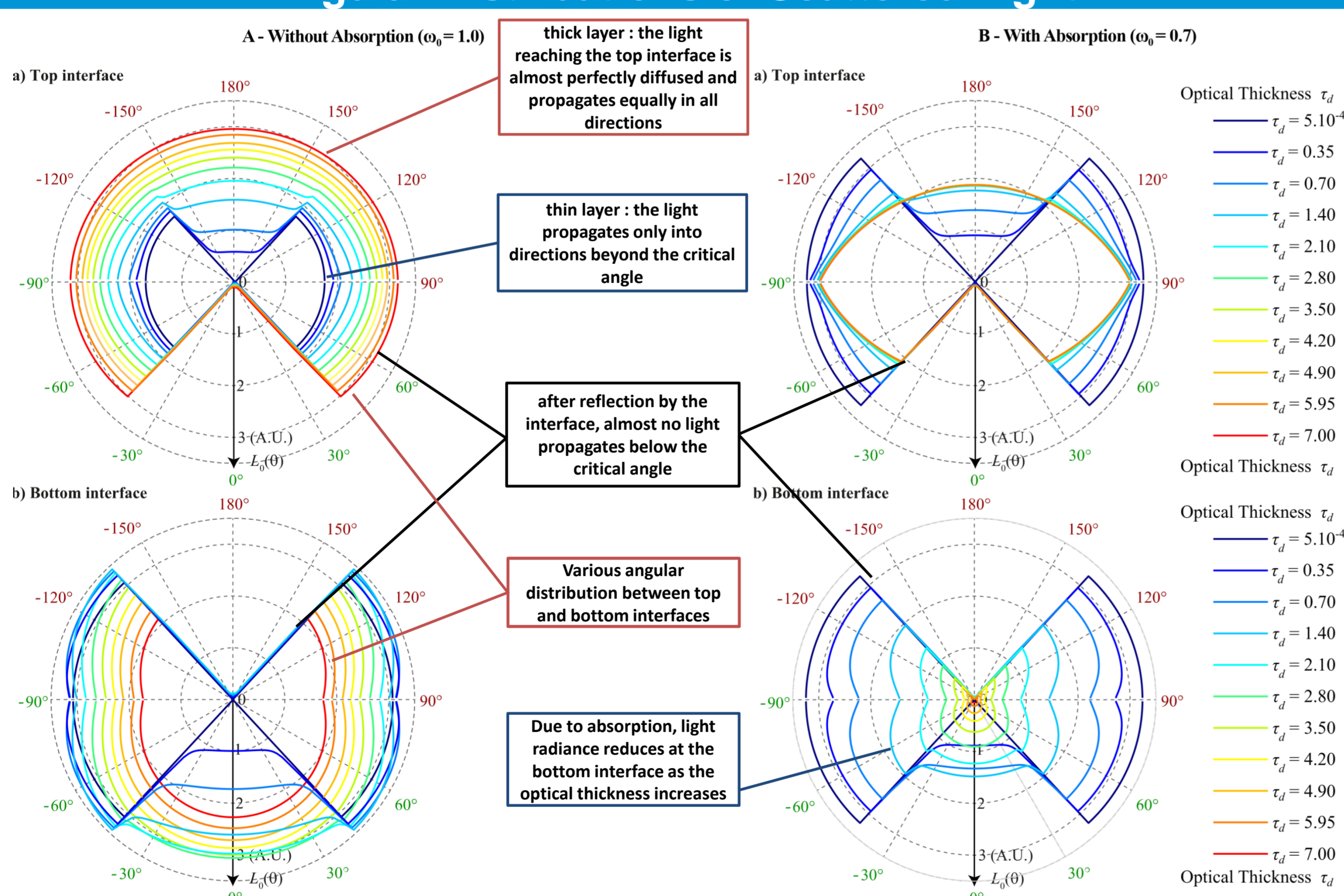
Reflectance & Transmittance generated by each 4-flux model (r_i 60%, r_i RTE)

Reflectance & Transmittance generated by each 2-flux model (r_i 0%, r_i 4%, r_i 60%, r_i RTE)

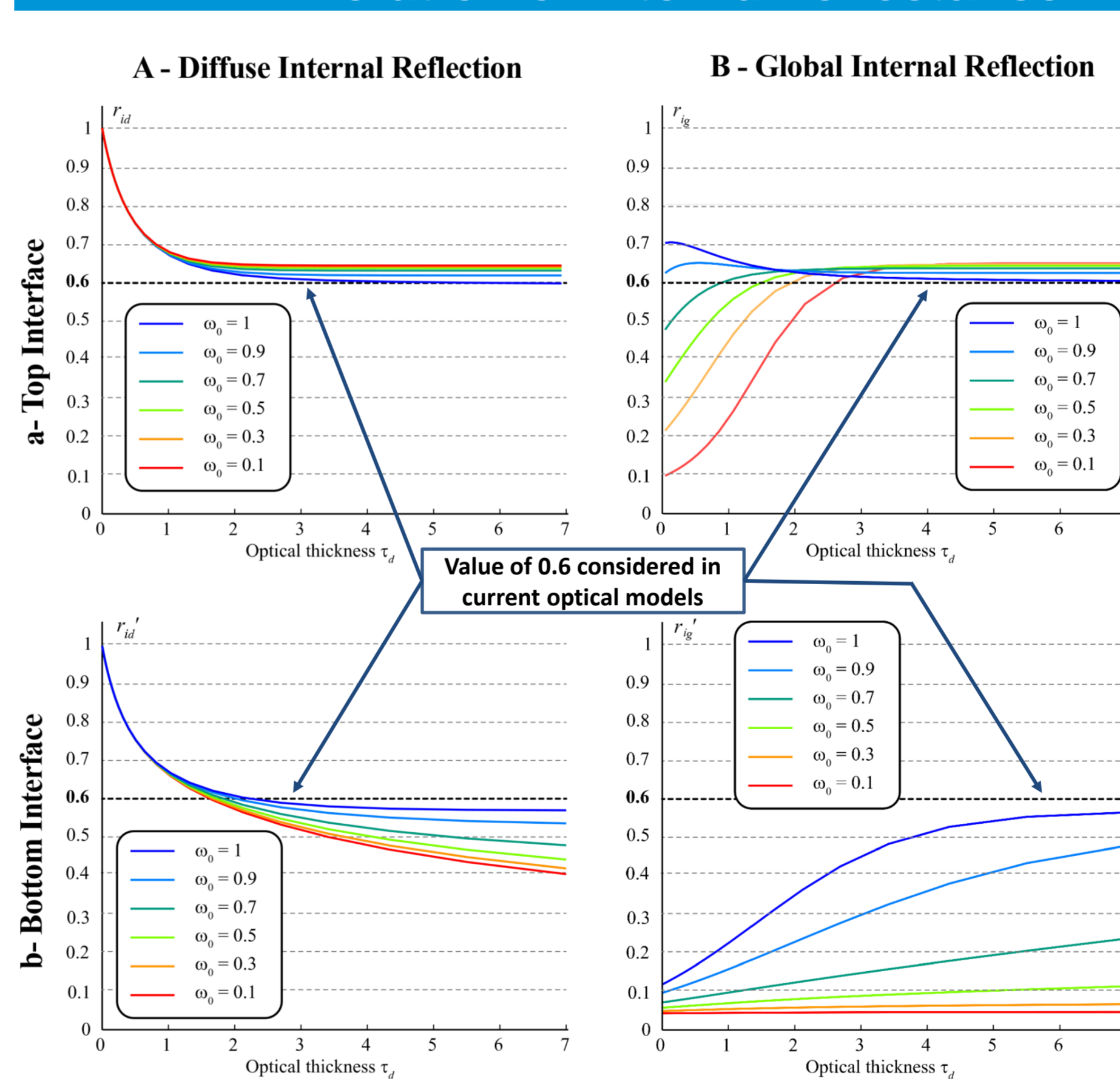
Comparison with Ground Truth

Results and Discussion

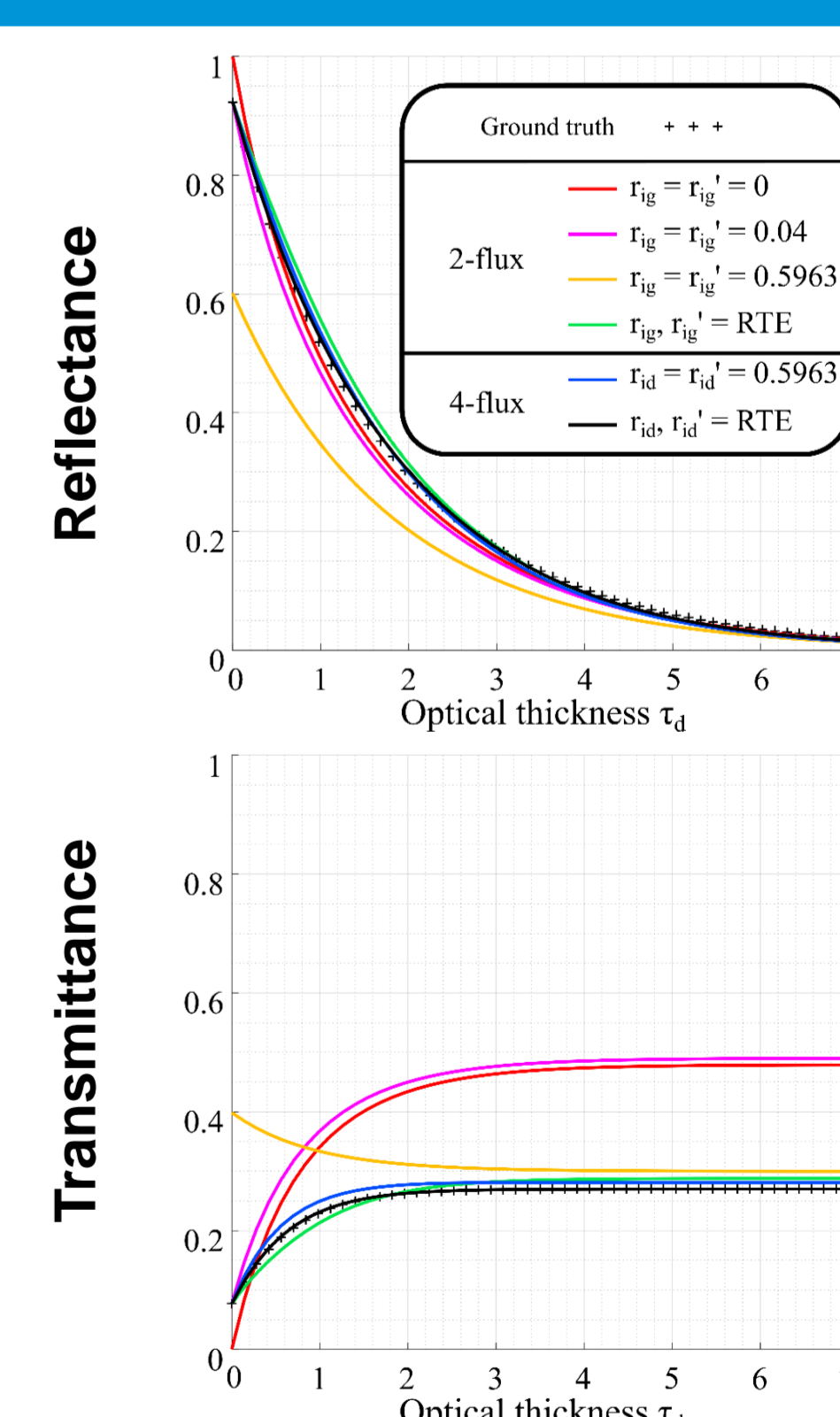
Angular Distributions of Scattered Light



Evolution of internal reflectance



Validity of the 2- and 4-flux models with and without internal reflectance



- Internal reflectance equal to its Lambertian light can lead to significant errors (up to 100%) for 2-flux models when dealing with translucent materials.
- The internal reflectance value varies a lot with optical thickness and absorption.
- Parameter extraction with 2- and 4-flux models can be significantly improved using the internal coefficient calculated using the radiative transfer equation.

A full description and results of this study are described in [4] and an Optic Express article.

Acknowledgments

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Contact: arthur.gautheron@creatis.insa-lyon.fr

Perspectives

- Lookup Table creation to optimize parameters extraction with Kubelka-Munk and Diffusion Approximation Models
- Evaluation of its impact on the estimation of chromophore concentration in biological tissues
- Evaluation of its impact on the measurement correction due to biological tissues

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