Monte Carlo modeling of the optical signature of satellite coatings

Agnès LECADRE-SCOTTO
2^{nd} year PhD student
ONERA, DPHY/ECM

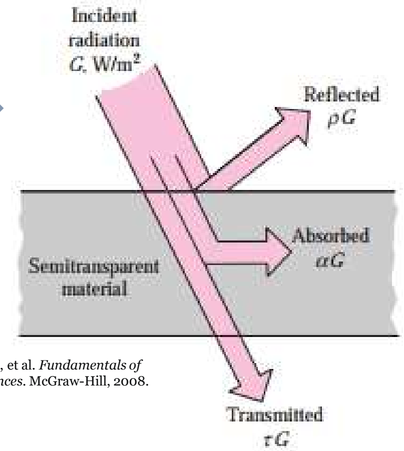
Thesis supervisors : Christophe Inguimbert (DPHY), Simon Lewandowski (DPHY), Romain Ceolato (DOTA)

Effects of the space radiation environment - Optical signature

Space environment

UV
electrons
protons
alpha particles
heavy ions

Chemical & structural modification lead to
Alteration of optical and thermal properties



Cf Cengel, Yunus A., et al. *Fundamentals of Thermal-Fluid Sciences*. McGraw-Hill, 2008.

$$\alpha + \rho + \tau = \mathbf{1}$$

ρ, τ = Optical Signature

Ageing

White paint

an example of a consequence:
thermal control

Ph.D aim :
Study of the optical signature as a function of the radiation dose per particle

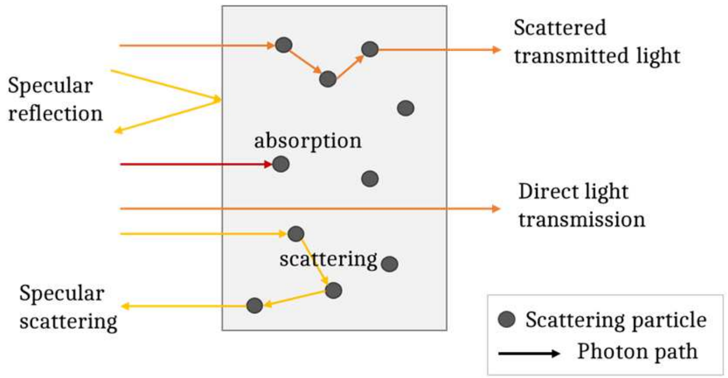
Objectives

- Modeling paint reflectance/transmitance between 250 and 2500 nm
- Ageing on SEMIRAMIS : (e-/ p+) spatial environment
- Comparison with before/after ageing spectrophotometer measurements

Outlines

- Monte Carlo radiative transfer code GEANT4
  - Physical parameters
  - Models
- Ageing of paint samples and components
- Measurements before and after irradiation to validate the model

Photon transport in a matter : Physical phenomena



Reflection/refraction

Absorption

Scattering

Paints : Composite material

Pigments
+
Polymer binding agent

Deposited on substrate

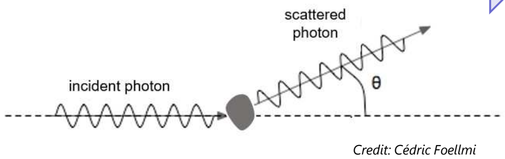
Photon transport in a matter : Physical phenomena
Parameters

Reflection/refraction → **Optical Indices** n, k

Absorption → **Absorption factor** $K = \frac{4\pi k}{\lambda}$
(attenuation coefficient)

Scattering → **Phase function**
→ **angular distribution model**

Size and shapes of scattering centers relative to wavelength



paint / substrate interface (roughness, specular/diffuse reflection model)

Retrieving of parameters controlling photon transport in paint

Refractive index
pigment (**ZnO**), binder (**PDMS**), substrates (**Aluminium, evaporated aluminium, suprasil)**

Absorption factor binder, substrate

Phase function pigment

Grain size pigment

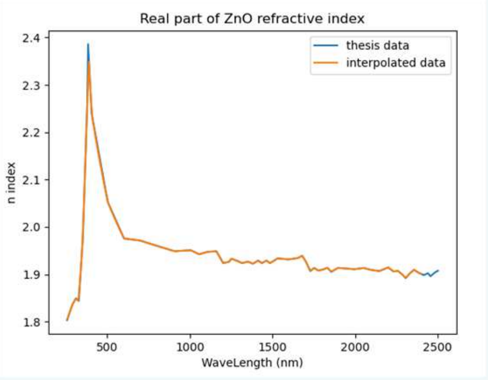
How can we retrieve all the ***physical parameters*** *that control photon transport in our paints?*

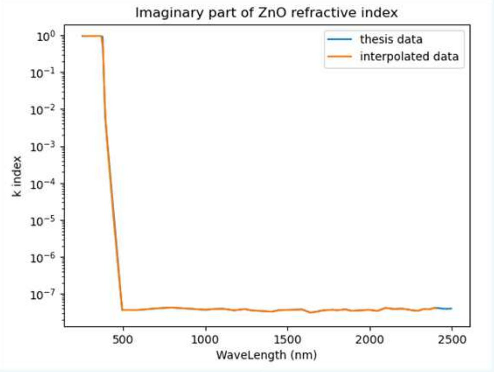
→ *Two methods :*

1. From litterature
2. From painted samples

White paint constituant and substrates data from litterature

- ZnO Refractive Index
  Carole Duvignacq Thesis

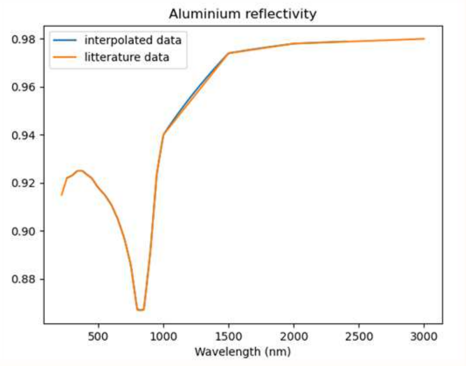


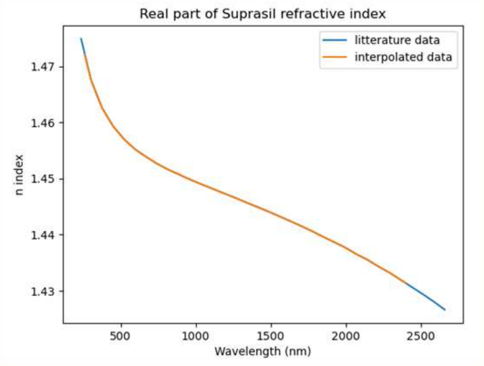


Grain size ZnO
→ particle size analyzer

Morphology ZnO
→ Holography

- Aluminium Reflectivity
- Suprasil Refractive Index



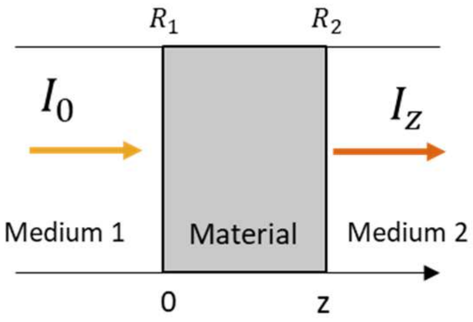


K_{att}^{PDMS} $K_{att}^{Suprasil}$

↓

Beer’s Law applied on suprasil and binder

Suprasil and binder attenuation coefficients – Beer's Law



Beer's Law + surface reflectivities

$$T = \frac{I_z}{I_0} = (1 - R_1)e^{-Kz}(1 - R_2)$$

K **: attenuation coefficient**

$$R_2 = \left(\frac{n_2 - n_{mat}}{n_2 + n_{mat}}\right)^2$$

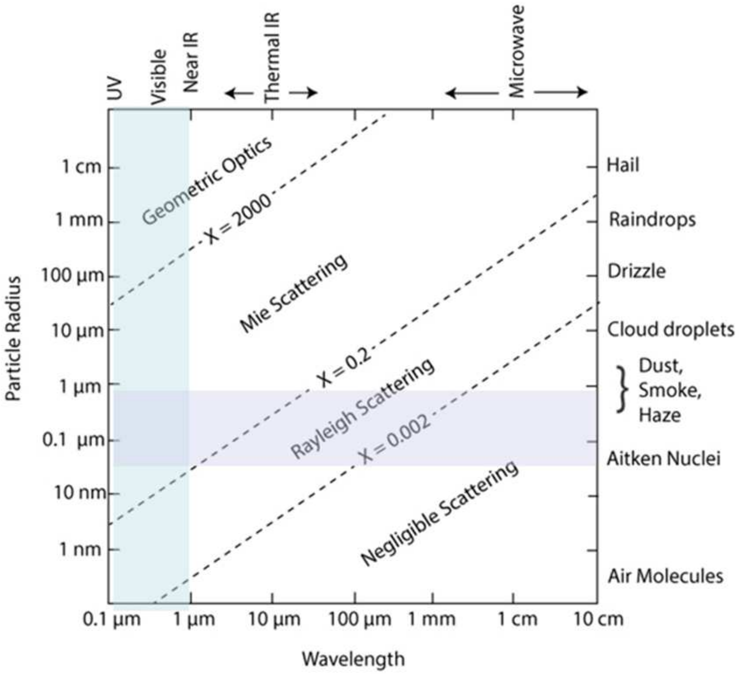
$$R_1 = \left(\frac{n_1 - n_{mat}}{n_1 + n_{mat}}\right)^2$$

T = Transmittance

Measurements on **Suprasil** and **PDMS + Suprasil** samples

Spectrophotometer UV Vis-NIR PERKIN ELMER 1050

Light scattering in white paint



Optical photon 250-2500 nm

Pigment (~ 100nm radius)

MIE scattering

- Homogeneous sphere
- The size of the scattering particles is comparable to the wavelength

MIE scattering - Angular distribution

MIE phase function : infinite series solution

BHMIE Code – Python routine

Bohren & Huffman (1983)

Infinite series solutions not suitable to be included in the Monte Carlo simulation !

Henyey-Greenstein Approximation

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

Scattering anisotropy factor $g = \langle cos(\theta) \rangle$

Two-terms HG approximation

$$p_{HG}(g,\theta) = r\, p_{HG}(\theta_f, g_f) + (1-r)\, p_{HG}(\theta_b, g_b)$$

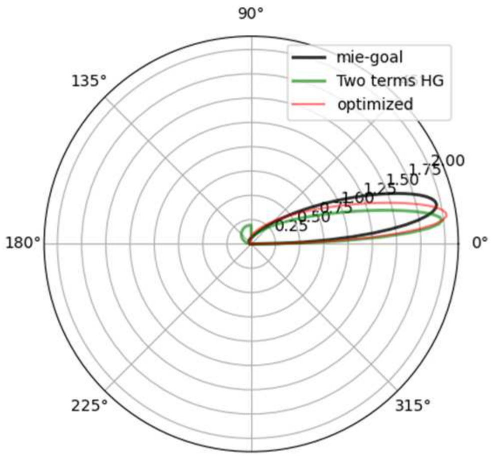
Forward and Backward scattering factor g_f and g_b

r **ratio** between forward and backward scattering

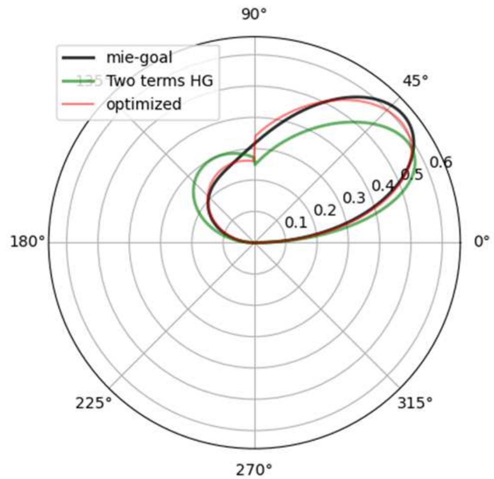
→ **To optimize**

Optimizing the parameters of the Henyey-Greenstein approximation

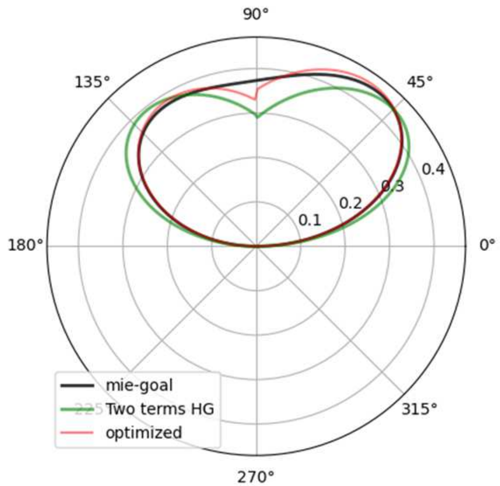
Optimization of g_f, g_b and ratio for each wavelength : **Genetic algorithm**



260nm



1002nm



2400nm

Photon transport in a matter : MONTE-CARLO on GEANT4

Physical parameters : inputs for radiative transfer code

MONTE-CARLO
Probabilistic method for photon transport

A true step length for a next physics interaction is randomly sampled using the **mean free path :**

$$L(E) = \frac{1}{\sum_i [n_i . \sigma(E, Z_i)]}$$

Number of atoms per volume of the i^{th} element n_i (m^{-3})

Cross Section per atom of the process

$$\sigma = \frac{number\ of\ interactions}{incident\ flow} \quad (m^2)$$

- **Probability of Absorption→** L_{abs}
- **Probability of Scattering →** L_{scatt}

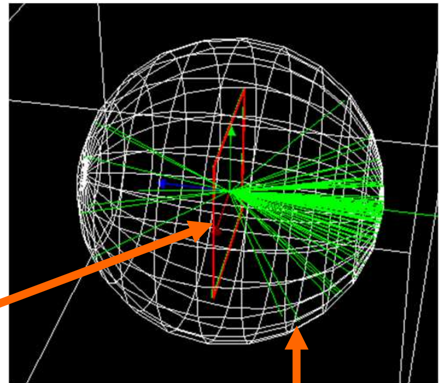
Development of an application with the GEANT4 optical module: IMOTEP

Simulation of photon transport step by step

- Particles and physicals process information
- Geometry and materials

coating layers + substrate

surface layer
layer 1
layer 2
layer 3
layer 4
substrate layer

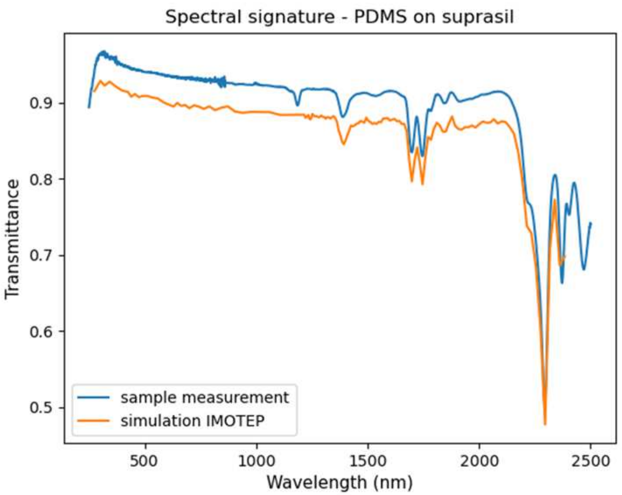


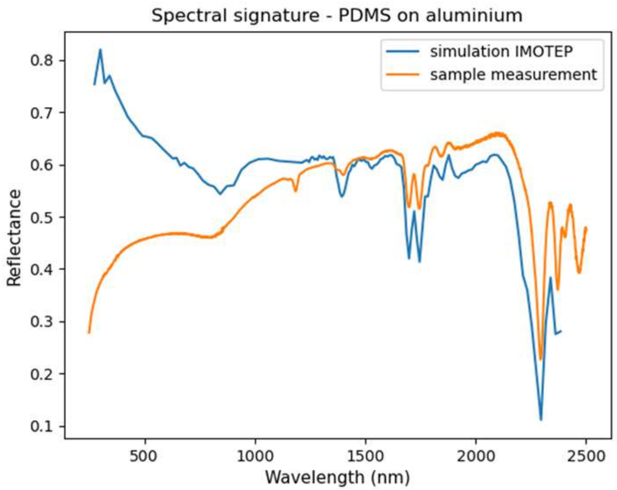
spherical detector

PRELIMINARY NUMERICAL RESULTS BEFORE IRRADIATION

Comparison with PDMS sample measurements

PDMS deposit thickness: 130µm





Huge difference for small wavelengths

4% difference

→ **Interface modeling between deposit and metal substrate to better define**

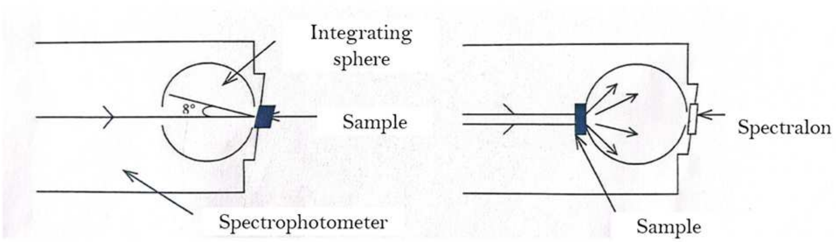
Experimental study of material degradation
Irradiation campaign : 240keV protons

1. Characterization
Reflectance and transmittance measurements :
Spectrophotometer UV-Vis-NIR: PERKIN ELMER 1050

2. Irradiation and in situ reflectance measurements on a vacuum chamber : SEMIRAMIS

Irradiation step	Fluence (p+/cm²)	Total fluence (p+/cm²)
1	1.10^{15}	1.10^{15}
2	2.10^{15}	3.10^{15}
3	2.10^{15}	5.10^{15}
4	2.10^{15}	7.10^{15}
5	3.10^{15}	10.10^{15}

3. Final measurements
Air reintroduction - Spectrophotometer PERKIN ELMER 1050

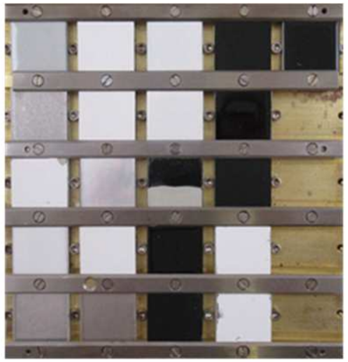


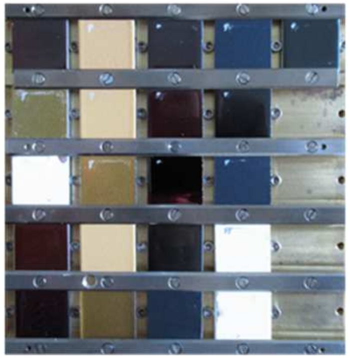
PU *Aluminium*	**White paint PDMS / ZnO** *Aluminium*	**White paint PU / ZnO** *Aluminium*	**Black paint PDMS / carbon black** *Aluminium*	**Black paint PU / carbon black** *Aluminium*
PDMS *Aluminium*	**White paint PDMS / ZnO** *Aluminium évaporé*	**White paint PU / ZnO** *Evaporated Aluminium*	**Black paint PU / carbon black** *Evaporated Aluminium*	
ZnO *Evaporated Aluminium*	**PDMS** *Evaporated Aluminium*	**PU** *Evaporated Aluminium*	**Black paint PDMS / carbon black** *Evaporated Aluminium*	
White paint PU / ZnO *Suprasil*	**White paint PDMS / ZnO** *Suprasil*	**Black paint PU / carbon black** *Suprasil*	**ZnO** *Aluminium*	
PU *Suprasil*	**PDMS** *Suprasil*	**Black paint PDMS / carbon black** *Suprasil*	**ZnO** *Suprasil*	

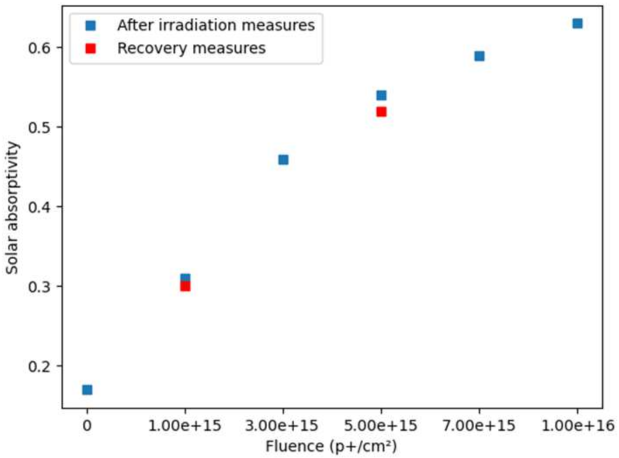
Sample mapping

EXPERIMENTAL RESULTS

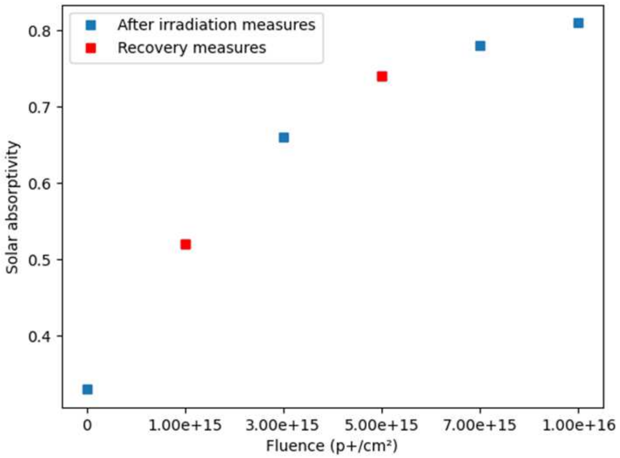
Degradation and solar absorptivity







PDMS/ZnO white paint on aluminum



PU/ZnO white paint on aluminum

AkzoNobel

→ Solar absorptivity increases with ageing

Perspectives

Experimental study :

- Exploit experimental results from the 240 keV protons campaign
- Plan a new irradiation campaign: 45 keV protons, electrons 400 keV

Modeling - GEANT4 parameters :

- Determine the optical indices and particle sizes of my white paint samples
- Better describe the interface between the metal substrate and the dielectric layer
- Determine the optical signature of paint
- Degradation laws