Identification of radiative parameters of dense scattering media with polarization analysis

RIVIERE Nicolas[1], HESPEL Laurent[1]

[1] *Onera, Theoretical and Applied Optics Department*
Light Interaction with Matter, Imaging and detection Laser Systems Unit
2 avenue Edouard Belin, BP4025, 31055 Toulouse cedex 4, France
tel: +33 562 25 26 24, fax: +33 562 25 25 88, e-mail: nicolas.riviere@onera.fr

Abstract

Predicting the radiative properties of diluted scattering media and determining the BRDF-BTDF for dense scattering media require a good estimation of microphysical parameters such as particle size distribution. Polarized light scattering bears information that can favor the characterization of these media. Our study aims to introduce polarized data into the optimization scheme to find the optical thickness, the albedo, and the Mueller matrix. Direct 1D codes (adding-doubling) and 3D codes (Monte Carlo) have been developed to solve the polarized radiative transfer equation (VRTE). After a study of sensitivity, we adopt the inversion strategy. The optical thickness, albedo and others parameters which describe the Mueller matrix are identified recursively and coupled by optimization methods. The particle size distribution is then extracted from the Mueller matrix. After numerical validation of this concept, an experimental validation is conducted on reference media, using a specifically developed system (MELOPEE bench).

1 Introduction

Optical properties of scattering media are important for several applications like remote sensing, climatology, biomedical imaging, spray or paint coating... Considering absorbing and scattering made-man media, some effects as multiple scattering should be investigated. Three ways of study are possible: measurements, direct modeling by radiative transfer or electromagnetic methods, and identification of radiative parameters. In this paper, we choose an identification of the radiative parameters for spherical particles in cell or coating media. Simulation of scattering properties requires a good knowledge of the Particle Size Distribution (PSD), the shape or the optical indexes. Moreover, dense scattering and absorbing media can be affected by dependent effects. Therefore, direct modeling is quite difficult to perform. Radiative parameter identification is a useful tool to look into scattering media but a lot of works consider unpolarized data [1-2]. It generally implies the optical thickness (OT) to be known and functions which represent the scattering parameters to be simplified. Then, the identification is more difficult for high optical thickness. This paper's aim is to improve actual optimization schemes in order to develop a robust method and to analyze the contribution of polarized data to a better and simultaneous estimation of all the radiative parameters (OT, albedo and Mueller matrix).

2 Identification of radiative parameters

We already demonstrated that the polarization state after scattering gives information to characterize scattering media [3]. The Stokes-Mueller formalism is selected to describe the evolution of the polarization of the light. In fact, it uses real quadratic values directly measured by detectors. The degree of polarization is represented by the ratio between the second and the first elements of the scattered Stokes vector. During an optimization process, it allows to be free from the uniqueness of the solution when we consider a multiple scattering media.

2.1 Optimization principle

To represent the Mueller matrix (**M**) efficiently in an optimization scheme with limited CPU time, we consider particles randomly oriented. **M** can be describe by a Legendre polynomial decomposition where μ is the cosine of the quadratic angle.

$$\mathbf{M} = \begin{bmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{12} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & -M_{34} & M_{44} \end{bmatrix}, \; M_{ij} = \sum_{n=0}^{N} (2 \cdot n + 1) \cdot a_n \cdot P_n(\mu) \tag{1}$$

There is no assumption on particles but this method needs too many parameters to represent the Mueller matrix (*e.g.* 240 parameters if $r_g = \lambda$ for spherical particles). If optical indexes and particle morphology are known, a second way consists in building a base of scattering matrices against the radius. During the optimization, we make an integration over the PSD. It is a sum of log-normal distributions each represented by 3 parameters (f, r_g, s_g).

$$n(r) = \sum f \cdot \frac{1}{(2\pi)^{1/2} \cdot r \cdot \ln(s_g)} \cdot e^{-\frac{(\ln(r) - \ln(r_g))^2}{2 \cdot \ln^2 s_g}} \tag{2}$$

The general optimization scheme is described by Figure 1. First, we model the polarized scattered light using “direct” codes. We consider an heterogeneous and 1D media with N homogeneous layers. The Vectorial Radiative Transfer Equation (1D-VRTE) is solved by an adding-doubling method and a Fourier decomposition of the radiance [4]. We take into account the layers’ modification as the optical index. In this study, the method is limited to flat interfaces with unpolarized or linearly polarized incident beam. The approach is validated with referenced analytical data [5] and by comparison to data generated by a Monte Carlo model (3D). Then, we define an objective function to make a comparison between referenced (*e.g.* experimental) and simulated data. The minimization of this function is done by considering optimization methods (quasi-Newton or simulated annealing process).

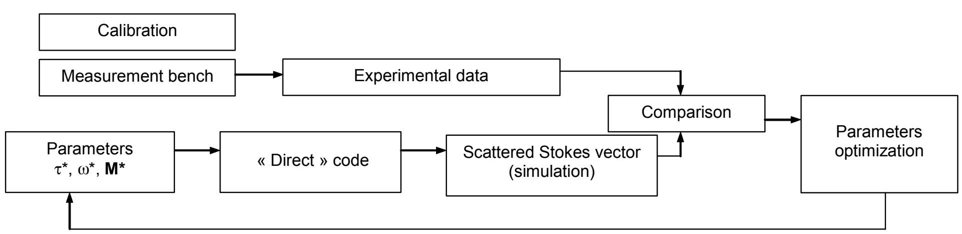

Figure 1: General optimization scheme.

2.2 Sensitivity analysis

This section aim is to determine the domain of validity for an objective function used in the optimization process. The analysis is restricted to spherical particles and to two polarized data of interest witch are the BRDF-BTDF ($\mu.I$) and the degree of linear polarization (*DOLP* or *Q/I*). The study is performed considering a non polarized incident radiance ($\vec{L}_{inc} = (1,0,0,0)^T$) and an incident vector collimated with the normal of the surface ($\mu_{inc} = 1$). Both polarized data ($\mu.I$ and *Q/I*) are invariant for all azimuth planes. The normalized sensitivity coefficient is proportional to the scattered-Stokes-vector derivative and is defined by Eq. (3). This value is calculated for each interest parameters described above.

$$C_{S,normalized} = \frac{x_j}{L_{scattered,i}} \cdot \frac{\partial L_{scattered,i}}{\partial x_j} \quad (3)$$

Then, it may be deduced a restricted angular range (*cf.* Table 1) where the objective function of each parameter should be done. The originality of our study is that all angular ranges are not dependent on each other in order to steer clear of parameters dependence in the optimization process. The BRDF-BTDF is used to make the objective function depending on the albedo whereas the degree of depolarization is used for the OT determination.

Table 1: angular range.

	OT	Albedo	PSD (r_g)
$\mu . I$ reflected	-	-0.75<μ<-0.25	-1<μ<-0.75
$\mu . I$ transmitted	-	0<μ<0.25	0.75<μ<1
Q / I reflected, if albedo ~ 1	-0.5<μ<0 if OT<1.5	-	-
	-1<μ<-0.5 if OT>1.5	-	-
Q / I reflected, if albedo $\neq 1$	-0.5<μ<0	-	-
Q / I transmitted	-	-	0.75<μ<1

The global objective function F is a sum of functions defined for each parameter: $F = \alpha_{OT} \cdot F_{OT} + \alpha_{\omega} \cdot F_{\omega} + \alpha_{PSD} \cdot F_{PSD}$. This conditioning problem advantage is that the optimization is improved. Nevertheless, we must weight the sum in the global objective function (α_i).

2.3 Numerical validation of the optimization

Referenced data are generated by numerical models. First, each objective function is validated and then the global objective function is tested. Parameters are identified with less than 10% of accuracy.

However, some limits appear in this approach. For high OT it is more difficult to retrieve the albedo or the PSD (*cf.* Figure 3a). Furthermore, the particle optical index should be known. The error is quite equal to 50% when the optical index is set to 1.65 instead of 1.58 for latex particles. In fact, phase functions are mainly affected by its value. Considering measurement noise simulated by a standard deviation, the OT is well optimized but the albedo is more difficult to be assessed (*cf.* Figure 3b).

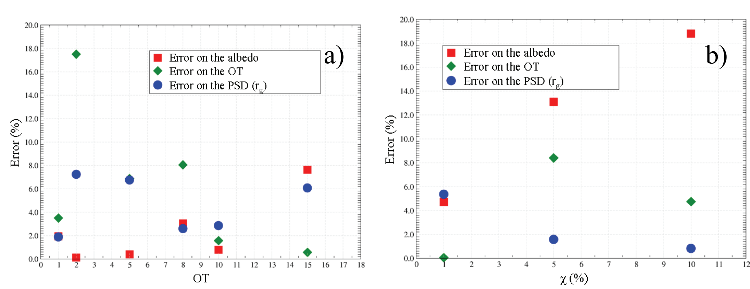

Figure 3: Error on the retrieved parameters according to the value of the OT (a) and to the standard deviation parameter χ (b).

3 Optimization based on experimental data

We intend also to validate experimentally the method. A polarized light scattering measurement setup based on the work of Kuik *et al*. [6] was developed. This automated setup could measure in the incident plane both the polarized BRDF-BTDF and the degree of linear polarization on a cross polarized way. Direct measurements of the optical thickness on a dedicated way are also available. The calibration is done using referenced materials like spectralon or calibrated latex particles into an analysis cell. This part of our study will be explained in detail during the oral session. A first experimental validation is performed with latex particles into an analysis cell (r_g = 530 nm). The albedo is assumed to be equal to 1 (no absorption). The measured OT on the dedicated experimental setup is equal to 2.1. The retrieved values after optimization on the 3 parameters (OT, albedo and PSD) are displayed on Table 2.

Table 2: Retrieved values of the OT, the albedo and the PSD.

	OT	Albedo	PSD (r_g)
Retrieved values	2.13	0.96	0.517 nm
Error	4%	4%	3%

5 Conclusion and perspectives

To conclude, this approach involves a good efficiency of the optimization scheme with limited CPU time. Moreover, we have verified the identification method sturdiness for several perturbing phenomenon even for a high optical thickness. The inverse approach has been assessed by numerous numerical simulations in order to determine its validity domain. The retrieved parameters accuracy derived from the optimized outputs is less than 10%. A numerical validation of this concept is actually performed with non-spherical particles. All of these results will be presented in the oral session. We also intend to expend the experimental validation of this method on scattering media made of non-spherical particles. Calibrated media made of non-spherical particles will then be used in the future.

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