



A symbolic approach for the identification of radiative properties



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ABSTRACT

A new Symbolic Monte Carlo (SMC) based on null-collision algorithms allows (1) overcoming the usually required knowledge of the optical thickness in SMC and (2) expressing radiative quantities as simple polynomials of the absorption and scattering coefficients. The proposed method can be applied to complex systems such as heterogeneous absorbing and scattering media in complex geometry. It opens new outlooks for the analysis and the identification of radiative properties in a wide range of radiative transfer applications in participating media.

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1. Introduction

The difference between Symbolic Monte Carlo (SMC) methods and standard Monte Carlo (MC) methods lies in the fact that some parameters are retained as symbolic variables in SMC, while scalar values are affected to all the problem's parameters in MC. Consequently, the output of SMC simulations is a functional in which the requested parameters appear explicitly. The symbolic approach thus differs from other more usual techniques, such as standard MC, for which scalar numerical outputs are obtained.

The SMC functional form is generally used to infer the parameters of interest, appearing as variables in the function, from measurements. Indeed, SMC makes the resolution of inverse problems easier, which may explain why it was initially called inverse Monte Carlo method [1]. SMC methods have been applied in various studies dedicated to inverse problems in remote sensing [2] or medical imaging [3,4]. In particular, SMC have been investigated by Dunn [5] and by Subramaniam and Mengüç [6] for inverse problems in radiative heat transfer.

It should be emphasized that SMC methods only solve the direct model, and are completely distinct from usual MC techniques developed for solving inverse problems such as Markov Chain Monte Carlo methods within the Bayesian framework [1,7]. The symbolic approach can be considered as a useful preliminary step toward the development of an efficient identification strategy. In radiative transfer problems, these identification methods combine spectroscopic measurements with radiation models, such as the

radiative transfer equation (RTE), in order to infer parameters such as the radiative properties, temperature or species concentrations [8]. Inverse problems for radiation concern many applications including optical tomography in medical imaging [9] or combustion diagnosis [10] among others. Inverse radiation methods have also been implemented for the identification of radiative properties in complex heterogeneous media such as porous and fibrous materials [11–15], or foams [16,17]. In these approaches, the inversion is performed by using an iterative procedure, where at each step, direct computations and measurements (of radiative fluxes, intensities) are compared.

The objective of this work is to propose a SMC algorithm that allows obtaining simple analytical forms (here polynomials) of radiative quantities as a function of radiative properties, and that can be applied in complex problems related to radiative transfer (in complex three-dimensional geometry, with absorption, scattering and/or reflective walls, etc.). The analytical form can then be used (1) to help in the choice of an inverse strategy by providing physical insights about the parameters which need to be identified and (2) to improve the efficiency of the inverse method. For instance, if a minimization technique is applied, the analytical forms of the radiative quantities are used as a solution of the direct model. Consequently, the numerical resolution of the direct model is not needed anymore at each iteration which significantly decreases the computational cost. This is particularly true in many radiative transfer applications where the numerical resolution of the radiative transfer equation (RTE), commonly used as direct radiation model, is computationally expensive [8].

Using SMC, Dunn [5] identified the scattering albedo in inhomogeneous media assuming isotropic scattering. Subramaniam and Mengüç [6] extended the approach to anisotropically

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scattering media, and identified the profile of the scattering albedo together with the asymmetry factor of the phase function. In these studies, the analysis is limited as it requires a precise knowledge of the optical thickness of the medium, making impossible the identification of absorption and scattering coefficients.

In the present work, a new symbolic approach is described that allows expressing radiative quantities (intensities, fluxes, source terms, etc.) as simple functions of the radiative properties of the medium (more specifically its absorption and scattering coefficients). This approach does not require any knowledge about the optical thickness. It opens new outlooks for the development of identification techniques of the radiative properties of participating media since the absorption and scattering coefficients can then be identified, which was not the case for previous SMC studies for which only the albedo was accessible.

The paper is structured as follows. In the second section, the principle of the method is introduced and the potential benefits for modeling and inverse analysis are highlighted. In the third and fourth sections, details of the proposed approach are given. It is shown to provide tractable multivariate polynomials of absorption and scattering coefficients. The developments focus on the absorption and scattering coefficients. The symbolic approach for the phase function parameters has already been discussed by Subramaniam and Mengüç [6], and their approach can be integrated without additional difficulties in the method proposed here. In the fifth section, an example of application in a heterogeneous medium is provided.

2. Principle

The objective of the present work is to propose a method for expressing radiative quantities as simple functions of absorption and scattering coefficients of complex participating media. Such functions present advantages in terms of analysis – for a better understanding of physical phenomena, experimentation design or optimization issues – and allow performing inversion procedures with efficiency. Fig. 1, for instance, displays the functional expression of radiative intensity I_η (at the exit of a homogeneous emitting, absorbing, and isotropically scattering slab of width L) as a function of the scattering optical thickness $\tau_{s,\eta} = \sigma_\eta L$.

The interest of expressing I_η as a functional is multiple. From a measured value of the radiative intensity, it is easy to identify graphically or analytically the scattering coefficient. Moreover, this figure provides another relevant information: the range of scattering optical thickness for which the identification is likely to be

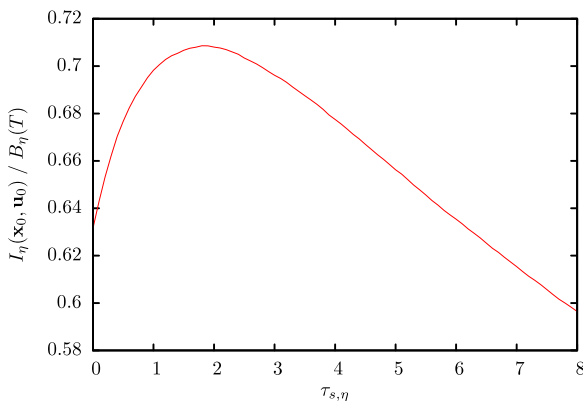


Fig. 1. Radiative intensity $I_\eta(\mathbf{x}_0, \mathbf{u}_0)/B_\eta(T)$ versus the scattering optical thickness $\tau_{s,\eta}$. $\mathbf{x}_0$ is located at the exit of the slab, and $\mathbf{u}_0$ is the outgoing normal at $\mathbf{x}_0$. The absorption optical thickness is $\tau_{a,\eta} = \kappa_\eta L = 1$ and the medium is isothermal. $B_\eta(T)$ is the blackbody intensity at temperature T of the medium.

accurate or not. For $\tau_{s,\eta} < 1$ and $\tau_{s,\eta} > 3$, the radiative intensity depends significantly on $\tau_{s,\eta}$. Therefore, the identification of the scattering coefficient can be implemented with confidence if a priori information indicates that the propagation medium is optically thin or thick. If no a priori information on the propagation medium is available, the information about the uniqueness of the solution is provided by the functional. Indeed, if the value of $I_\eta(\mathbf{x}_0, \mathbf{u}_0)/B_\eta(T)$ derived from measurements is for instance 0.68, two scattering optical thicknesses ($\tau_{s,\eta}$ may be close to 0.5 or close to 4) are solutions of the problem. For intermediate scattering optical thicknesses, i.e. $\tau_{s,\eta} \in [1, 3]$, the sensitivity of the radiative intensity to the scattering coefficient is weaker which has strong consequences for inversion. For instance, if the measured value of $I_\eta(\mathbf{x}_0, \mathbf{u}_0)/B_\eta(T)$ is around 0.7 with an uncertainty of 0.02 (relative uncertainty of 3%), it is impossible to conclude about which $\tau_{s,\eta}$ is solution in the interval $[0.5, 4]$.

All the elements of analysis given by the functional expression are in fact valuable to develop identification strategies.

Functional forms of radiative quantities can be obtained with SMC as shown in [5,6]. This method is based on the same principle as standard Monte Carlo methods. The only difference is that parameters (such as the absorption and scattering coefficients in our context) are retained under a symbolic form and are not used as “simple” numbers (see Chapter 7 from Ref. [1]). The quantities evaluated are therefore functions of the retained parameters, while in standard MC, scalars are computed according to a given set of parameter values. In practice, both algorithms are strictly equivalent: a large number of optical paths are randomly generated according to the statistical laws of radiative transfer, and radiative intensities or fluxes are then estimated from the average of samples, under their scalar (in standard MC) or functional forms (in SMC).

Among the statistical laws of radiative transfer in participating media, Beer's law turns out to be critical in SMC for radiative properties identification. Indeed, Beer's law is an exponential of the optical thickness depending on the absorption and scattering coefficients. Therefore, as far as absorption and scattering coefficients are involved, the functional form obtained with SMC remains a hardly tractable average of exponential functions (composed of as many nonlinear terms as Monte Carlo samples). It justifies probably why SMC has not been applied in the last two decades for inverse problems in radiative transfer.

However, in some cases, tractable functions of the absorption and scattering coefficients may be derived from radiative transfer models. For instance, let us consider the radiative transfer equation in the simple case of a non-scattering homogeneous medium

$$\frac{dI_\eta}{ds} = -\kappa_\eta I_\eta + \kappa_\eta B_\eta \quad (1)$$

and assume that there is no radiative source at location s_0 . The radiative intensity at location $s_j = s_0 + j\Delta s$ can be approximated, using finite differences with constant mesh size Δs , as:

$$I_\eta(s_j) = \kappa_\eta \Delta s B_\eta + \kappa_\eta \Delta s (1 - \kappa_\eta \Delta s) B_\eta + \dots + \kappa_\eta \Delta s (1 - \kappa_\eta \Delta s)^{j-1} B_\eta \quad (2)$$

This equation provides a polynomial function of the absorption coefficient and can be rewritten in a more compact form as:

$$I_\eta(s_j) = \sum_{i=0}^{j-1} a_i \kappa_\eta^i \quad (3)$$

Obviously in this simple case, the radiative intensity is known analytically and the polynomial expression has no real interest. Nevertheless, in more complex situations (with scattering, real geometries, heterogeneous media), such analytical solutions are no longer available and tractable expressions such as the polynomial equation (3) may be useful for analysis and identification.

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