Journal of Quantitative Spectroscopy & Radiative Transfer 197 (2017) 141–153

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Analysis of polarized pulse propagation through one-dimensional scattering medium

Yong Zhang, Feng-Ju Yao, Ming Xie, Hong-Liang Yi *

School of Energy Science and Engineering, Harbin Institute of Technology, 92 West Dazhi Street, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 12 August 2016
Received in revised form
7 October 2016
Accepted 12 November 2016
Available online 15 November 2016

Keywords:
Transient vector radiative transfer
Polarization
Scattering
Natural element method

ABSTRACT

This paper analyzes the polarized light propagation in a one-dimensional scattering medium with the upper surface subjected to an oblique incident short-pulsed laser beam using the natural element method (NEM). The NEM discretization scheme for the transient vector radiative transfer equation (TVRTE) is presented in detail. The accuracy of the natural element method for transient vector radiative transfer in the scattering medium is assessed. Numerical results show that the NEM is accurate, and effective in solving transient polarized radiative problems. We examine a square short-pulsed laser transport firstly in the atmosphere with Mie scattering and then within aerosol scattering medium. We then investigate the transient polarized radiative transfer problem in the atmosphere-ocean system. The time-resolved signals and the polarization state of the Stokes vector are presented and analyzed. It is found that the scattering types of the medium make greatly influence on the transient transportation of the polarized light. Critically, the polarization states of the backward and forward scattered photons show significantly different time varying trends. For the two-layer system with dissimilar refractive index distributions, due to the total-reflection effect, the existence of a Fresnel interface significantly changes the polarization state of the light, and discontinuous distribution features are observed on the interface.

1. Introduction

The propagation of the polarized light pulses in scattering medium has attracted a lot of interest [1,2]. Optical imaging through clouds and fog, imaging in biological medium, and microwave detection in clutter can benefit from the additional information provided by the polarization characteristics. Monitoring the transient polarized features of forward- and the backward-scattering responses, for different angles of incidence and detection, may disclose some subtle details of the medium's internal structure or/and radiative properties [3,4]. For example, ultrafast optics have been used to enhance optical imaging and diagnosis. With this technique, a short light pulse is applied to the biological tissues, and the transmitted ballistic and quasiballistic photons that carry more information about biological tissue properties are extracted through various gating techniques [5]. Polarization propagation in the scattering medium is a complicated process. Many parameters, such as size, shape, refractive index, scattering properties of the medium, and incident polarization state play important roles in the scattering of light [6,7]. In order to fully understand the evolution of the polarization state in a scattering medium, as well as the time- and polarization-dependent distribution of light transmitted through the medium, the numerical study of the transient polarization radiation transfer is essential.

For the steady vector radiative transfer equation (SVRTE), many successful methods have been developed [8–17]. However, owing to its complexity, only a few studies have been reported that take into account both the polarization and the transient aspects of the radiative transfer equation (RTE). To solve the problem of polarized pulse propagation in random medium, Ishimaru et al. [2] used the discrete-ordinates method by expanding the Stokes vector in Fourier series. By using a Monte Carlo (MC) technique, Wang et al. [5] examined polarized light transmitting through randomly scattering medium with a polystyrene-microsphere solution. Sakami et al. [18] used the Discrete Ordinates (DO) method to investigate the propagation of a polarized pulse in random medium. Ilyushin et al. [19] applied the small angle approximation of the radiative transfer theory to study the propagation of the short light pulse in the scattering medium considering polarized effect. Yi et al. [20] developed a MC model with a combination of time shift and the superposition principle for solving transient vector radiative transfer in a scattering layer. Recent improvements to the understanding of polarized light scattering from aspherical particle scattering were developed by Brown and Xie [21]. Finally, Brown [22] also made significant leap in the community's

* Corresponding author.
E-mail address: yihongliang@hit.edu.cn.(H.-L. Yi)

http://dx.doi.org/10.1016/j.jqsrt.2016.11.005
0022-4073/

Nomenclature

$\mathbf{I}$	stokes vector $\mathbf{I}=(I, Q, U, V)^T$, W/(m^2 μm sr)
$\mathbf{I_0}$	stokes vector of the incident light
$\mathbf{I}_d$, $\mathbf{I}_c$	stokes vectors for the diffuse and direct radiation, respectively, W/(m^2 μm sr)
H	geometrical length of the domain, m
n	refractive index
N_θ, N_φ	numbers of discrete polar angle and azimuthal angle
$\bar{\bar{\mathbf{P}}}$	cattering matrix
$\bar{\bar{\mathbf{R}}}$	reflection matrix
$\mathbf{S}$	scattering source term, W m^{-2}
$\bar{\bar{\mathbf{Z}}}$	scattering phase matrix

Greek symbols

ϕ	shape function
φ	azimuthal angle
$\bar{\bar{\boldsymbol{\kappa}}}_e$	extinction matrix, m^{-1}
κ_s	single scattering coefficient, m^{-1}
μ	direction cosine of the polar angle
θ	polar angle
θ_0, φ_0	polar and azimuth angles of the incident light
ρ	reflection coefficient of the Lamberitian surface
$\mathbf{\Omega}$	unit direction vector of radiation

Subscripts

d	diffuse component for Stokes vector
c	collimated component for Stokes vector
w	boundary surface

Superscripts

T	transpose symbol
m, m'	index for direction

understanding of the linkages between geometry and symmetries of linear and circular polarization state backscattering relations for the laboratory and LIDAR environments. From the above studies, we can see that limited research work on the transient vector radiative transfer is available. Moreover, the propagation mechanism of polarized light pulses in the scattering medium has not been fully investigated. For example, the effects of various parameters, such as refractive index, scattering types of the medium, and incident polarization state on the behavior of temporal signals need to be examined in detail.

Our purpose in this paper is to solve the one-dimensional transient vector radiative transfer equation (TVRTE) by the natural element method (NEM), and carry forward research on the problem by revealing the physical behavior and characteristics of transient polarized radiative transfer in scattering medium. The NEM proposed by Braun and Sambridge [23] and Sukumar et al. [24] is a relatively new meshless Galerkin procedure based on the natural neighbour interpolation scheme, which in turn relies on the concepts of Voronoi diagrams and Delaunay triangulation to build Galerkin trial and test functions. Compared to the MLS approximation which is widely used in meshless method, some of the most important advantages of natural neighbor interpolants are the properties of interpolation of nodal data, ease of imposing essential boundary conditions, and a well-defined and robust approximation with no user-defined parameter on non-uniform grids. Most recently, we have developed the NEM for radiative heat transfer problems [25–27] in a multi-dimensional participating medium, including combined radiation and conduction heat transfer, transient scalar radiative transfer and scalar vector radiative transfer applications.

The outline of this paper is as follows. In the following section, the mathematical formulations of the TVRTE are introduced, and the NEM discretization for the TVRTE is given. In Section 3, the NEM solution for TVRTE in a slab filled with Mie scattering medium is examined to validate our code. Then the polarized radiative transfer problem in the one-dimensional atmosphere is studied. Mie scattering and aerosol scattering are considered, respectively. The transient polarized radiative transfer problems in the atmosphere-ocean system with Rayleigh scattering medium are then investigated. The time-resolved signals and the transient characteristics for the polarization state of the lights are presented and analyzed in detail. Finally, the conclusions are drawn in the last section.

2. Mathematical formulations

2.1. Transient vector radiative transfer equation

Consider polarized pulses of radiation obliquely incident on a plane-parallel slab containing scattering medium (see Fig. 1). A pulse beam is incident on the top boundary at a polar angle of θ_0 and azimuthal angle of φ_0. The incident radiation pulse having a peak Stokes vector of $\mathbf{I}_0$ travels with the speed of light c, and at any location in the medium, it remains available for the duration of the pulse-width t_p which is of the order of a nano-second. Based on the incoherent addition principle of Stokes parameters, the transient vector radiative transfer equation (TVRTE) for polarized monochromatic radiation in a homogeneous medium without considering thermal emission is written as [1]

$$\frac{n}{c_0}\frac{\partial \mathbf{I}(\mathbf{r},\mathbf{\Omega},t)}{\partial t}+\mathbf{\Omega}\cdot\nabla\mathbf{I}(\mathbf{r},\mathbf{\Omega},t)=-\bar{\bar{\boldsymbol{\kappa}}}_e\mathbf{I}(\mathbf{r},\mathbf{\Omega},t)+\frac{\kappa_s}{4\pi}\int_{4\pi}\bar{\bar{\mathbf{Z}}}(\mathbf{r},\mathbf{\Omega}'\to\mathbf{\Omega})\mathbf{I}(\mathbf{r},\mathbf{\Omega}',t)d\Omega' \quad (1)$$

where $\mathbf{I}=(I,\ Q,\ U,\ V)^{\mathrm{T}}$ (superscript T denotes transpose symbol) is the Stokes vector, in which I is the intensity, Q, U, and V describe the polarization state of the wave [28]; n is the refractive index of the medium; c_0 is the speed of light in vacuum; t is the time; $\mathbf{\Omega}=\mathbf{i}\xi+\mathbf{j}\eta+\mathbf{k}\mu=\mathbf{i}\sin\theta\cos\varphi+\mathbf{j}\sin\theta\sin\varphi+\mathbf{k}\cos\theta$ is the unit direction vector of radiation; $\mathbf{r}$ is the spatial coordinate vector; $\theta\,(0\le\theta\le\pi)$ and $\varphi\,(0\le\varphi\le 2\pi)$ are the polar angle and azimuthal angle, respectively; $\bar{\bar{\boldsymbol{\kappa}}}_e$ and κ_s are the extinction matrix (diagonal matrix) and the single scattering coefficient, respectively; $\bar{\bar{\mathbf{Z}}}$ is the scattering phase matrix for scattering from an incoming direction $\mathbf{\Omega}'$ to an outgoing direction $\mathbf{\Omega}$ which can be obtained by transforming the scattering matrix $\bar{\bar{\mathbf{P}}}$ [1].

For collimated irradiation, it is convenient to separate the modified Stokes vector into two parts, viz., the collimated Stokes vector $\mathbf{I}_c$ and the diffuse Stokes vector $\mathbf{I}_d$.

$$\mathbf{I}=\mathbf{I}_d+\mathbf{I}_c \quad (2)$$

where $\mathbf{I}_c$ is the Stokes vector of the residual collimated beam after extinction and $\mathbf{I}_d$ is the Stokes vector of the diffuse radiation that is scattered away from the collimated beam.

The collimated Stokes vector $\mathbf{I}_c$ obeys the Beer's law considering the effect of time:

$$\frac{n}{c_0}\frac{\partial \mathbf{I}(\mathbf{r},\mathbf{\Omega},t)}{\partial t}+\mathbf{\Omega}\cdot\nabla\mathbf{I}_c(\mathbf{r},\mathbf{\Omega},t)=-\bar{\bar{\boldsymbol{\kappa}}}_e\mathbf{I}_c(\mathbf{r},\mathbf{\Omega},t) \quad (3)$$