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Multiple scattering analytical method for apparent characteristics in multilayer media

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ABSTRACT

A multiple scattering analytical method is developed to analyze the apparent characteristics of multilayer isotropic and anisotropic media in this work. The model to calculate the apparent directional radiative intensity in multilayer media is established. A monolayer infinite slab with different scattering phase functions is considered as an example to examine the accuracy of the proposed method. The results are compared with data calculated by a Monte Carlo method. Moreover, the radiative intensity as a function of apparent direction, under the assumption that rays are obliquely incident on the surface of participating media, is obtained. The influence of optical thickness on the apparent directional radiative intensity in multilayer anisotropic media is analyzed. The forward and backward scattering energy, which is not involved in the attenuation in the incident direction of light, dependence on optical thickness for different scattering orders is studied. These results advance the theory of multiple scattering, especially with respect to the total energy of forward and backward scattering. We provide theoretical and experimental data relevant for atmospheric research and target detection.

1. Introduction

Multiple scattering is a fundamental problem of radiative heat transfer in the participating media, which plays a pushing role in the fields of atmosphere and target detection [1]. The direction of propagation and magnitude of energy in transmitted light is influenced by scattering, resulting in different apparent directional radiative intensity distributions [2–4]. Scattering, apart from emission and absorption, must also be considered in isotropic and anisotropic media [5,6]. The energy of reflection, diffraction, and refraction are all classified as scattering energy [7,8]. Most objects are not perfectly opaque, but partially translucent. In translucent objects, incident rays undergo multiple scattering, which results in a complex light field. However, the light field within a scattering material sometimes cannot be measured directly [9,10]. The mechanism of light scattering and propagation is the basis of many applications, for instance, rendering, medical imaging, and material estimation [11]. Therefore, it is necessary to discuss the apparent characteristics of participating media with multiple scattering.

Recently, much work has been done on multiple scattering in participating media, and great progress has been made. Monte Carlo methods, discrete ordinate methods, the successive order of scattering method, finite-difference time-domain methods, and the T-matrix method were developed in the study of multiple scattering [12–16]. Considering multiple elastic scattering and Fresnel reflection, Sommersten et al. presented an algorithm based on discrete ordinate and Monte Carlo simulations for polarized radiative transfer in a vertically stratified system consisting of two plane-parallel media with different refractive indices. It included incident parallel-beam, isotropic radiation at the top of the upper medium and bidirectional reflection at the bottom of the lower medium [12]. Baran discussed the light scattering properties of naturally occurring ice crystals, which are found in cirrus. Current measurements of ice crystal size and shape were discussed and how these observations relate to current ice crystal models was reviewed [13,14]. The solution of a radiance field below inhomogeneous cloudy skies follows the modified theory of successive orders of scattering, which considers single-scattering radiances from broken clouds [15]. Stoll et al. developed a fast open-source code for determining the intensity and angular distribution of radiation transmitted through homogenous cloud cover [16]. The interaction of solar radiation with cloud particles is described by Mie scattering [17,18].

Multiple scattering in multilayer media have also been studied in the last few decades. Kokhanovsky et al. benchmarked results for vector atmospheric radiative transfer by comparing the discrete ordinate method, two Monte Carlo methods, the successive orders scattering method, and a modified doubling-adding technique [19].

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Nomenclature

a	transition variable related to angle, the value is 0 or 1
$I_1, I_2, \ldots, I_n$	radiative intensity of different scattering orders, W/sr
L	distance between two parallel planes, m
$L_0, L_1, \ldots, L_n$	transmission total distance of different scattering orders, m
$x_0, x_1, \ldots, x_n$	transmission path distance of different scattering orders, m

Greek symbols

$\alpha_1, \alpha_2, \ldots, \alpha_n$	zenith angle of different scattering orders, rad
$\beta_1, \beta_2, \ldots, \beta_n$	circumferential angle of different scattering orders, rad
$\kappa_{e\lambda}$	spectral extinction coefficient, m^{-1}
ω	scattering albedo
Φ	scattering phase function
Ω_0	initial solid angle, sr
Ω_s, Ω_i	scattering direction and incidence direction, respectively, rad
$\Delta\Omega_1$	outgoing solid angle of the first scattering, rad
θ	incident, scattering included angle, rad
τ	optical thickness, 1
Θ	included angle between incidence direction and scattering direction, rad

Subscripts

a,b	distance in different layers
i	angle label
1, 2,..., n	refer to the index of different scattering orders
λ	wavelength, μm
s	scattering direction

Superscripts

0	radiative intensity index in radiation transfer
m_1	the outgoing direction

Mukaigawa et al. proposed a new method to analyze light transport in homogeneous scattering media. Their method includes two steps. First, single and multiple scattering are separated by projecting high-frequency stripe patterns. Then, multiple scattering was decomposed into each bounce component based on the light transport equation. The light field for each bounce was recursively estimated [20]. Aberle et al. studied the effects of multiple scattering in the Rayleigh-Gans range and the application of light scattering in dye-sensitized solar energy materials [21,22]. A new semi-discretization method has been proposed to calculate the energy storage [23–25]. Moosmüller et al. studied the simple analytical relationships of the Ångström constants for aerosol attenuation, absorption, scattering and single scattering albedo [26]. A fast expansion algorithm was developed to simulate multiple scattering in optical systems and multiple scattering processes in the hypersphere [27,28]. Monte Carlo methods were used to calculate the multiple scattering of polarized light [29,30]. A practical algorithm for multiple light scattering has been developed in pure scattering vacuum adiabatic plates and variable refractive index media [31–35]. The continuous-order scattering method is developed to compute multiple scattering in different media, such as broken clouds, and blood [36,15,37–39].

In our previous paper [40], we proposed a multiple scattering analysis method (MSAM), and established the radiative model to calculate the apparent directional radiative intensity distribution. The distribution of radiative intensity was discussed in different scattering orders, and compared with the Monte Carlo method. However, the model did not take into account obliquely incident of light or multilayer media. In the actual transmission of light, oblique incidence and multilayer media are more realistic and include more information. Therefore, this paper develops the radiative intensity model for oblique angles of incidence. A multilayer model is established and the radiative intensity of a two-layer medium is calculated. The apparent characteristics of the directional radiative intensity distribution in multilayer participating media is analyzed.

2. Method and model

The model of apparent directional radiative intensity distribution of oblique incidence is established. Considering the change of the circumferential direction, the radiative intensity model of the oblique incident medium is builded firstly. Moreover, a two-layer model of isotropic media is discussed.

2.1. Monolayer media

The model that rays are obliquely incident on the surface of a one-dimensional infinite slab is adopted in the following. As Fig. 1 shows, first-order scattering in participating media is considered. The radiative intensity of incident rays is $I_{\lambda,0}$, the solid angle is Ω_0, and the thickness of the slab is L_0. As shown in Fig. 1, the direction of incident rays is $(\alpha_0, 0°)$ (i.e., zenith angle is α_0, circumference angle is 0°). Rays propagate in the L_1 direction, which the zenith angle is α_1 and the circumferential angle is β_1. L_1 is a function of integration parameter x_0. By calculating the path $L_0/\cos\alpha_0$ integral according to Ref. [40], the total spectral radiative intensity in the direction of zenith angle α_1 can be expressed as Eq. (1).

$$I_{\lambda,1}^{m_1} = I_{\lambda,0} \cdot \Omega_0 \cdot \kappa_{e\lambda} \cdot \omega \cdot \Phi_\lambda(\Omega_i, \Omega_s) \cdot \int_0^{L_0/\cos\alpha_0} \exp(-\kappa_{e\lambda} \cdot x_0) \times \exp(-\kappa_{e\lambda} \cdot L_1) \cdot dx_0/4\pi \tag{1}$$

Here, $\Phi_\lambda(\Omega_i, \Omega_s)$ is the scattering phase function. Ω_i and Ω_s are the incident direction and scattering direction, respectively. The outgoing direction is represented as m. As shown in Fig. 1(a), the exit zenith angle α_1 is acute, rays are emitted from the lower side of the slab. When the exit zenith angle α_1 is obtuse, rays are reflected from the back of the slab shown in Fig. 1(b). The corresponding path length L_1 is given by Eq. (2). The variable a_1 can be obtained referring to Ref. [40].

$$L_1 = a_1 L_0/\cos\alpha_1 - (x_0 \cdot \cos\alpha_0)/\cos\alpha_1 \tag{2}$$

Second-order scattering is discussed in the following based on the above first-order scattering process. As shown in Fig. 2, zenith angle and circumferential angle of first-order scattering is α_1 and β_1, respectively. And zenith angle and circumferential angle of second-order scattering is α_2 and β_2, respectively. The radiative intensity at zenith angle α_2 is shown in Eq. (3). The prime represents the radiative intensity in a certain direction. The total spectral radiative intensity in the direction of zenith angle α_2 can be expressed as Eq. (4).