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A new look at decoupling of atmospheric radiative transfer and anisotropic surface reflection

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ABSTRACT

This paper presents a new approach for separating atmospheric radiative transport from the lower boundary condition in the case of one-dimensional problem. The approach allows for an exact analytical expression of the solution for an arbitrary surface reflectance. The solution has the form of linear combination of the standard problem solutions with illumination from both top and bottom of the atmosphere. The problem with illumination from below can be solved with existing radiative transfer codes by reversing the order of the atmospheric layers. The solutions for illumination from below are weighted with a surface resolving kernel that is specific for every lower boundary condition. The surface resolving kernel is defined by an integral equation of the Fredholm type. The solution for the Lambertian surface is also obtained in the framework of this approach. Different methods of solution for the surface resolving kernel are considered. The successive iterations of the integral equation for the surface resolving kernel are equivalent to the decomposition of the surface reflected radiance by the orders of reflection. Recipes for the cases when standard problems are solved with the methods of discrete ordinates and spherical harmonics are also considered.

1. Introduction

Remote sensing of non-Lambertian surfaces has applications in many fields of geoscience including correction of topographic effect [1], detection of oil film on seawater [2], retrievals of water inherent optical properties [3], estimates of leaf biochemical compounds [4], classification of biomes based on their directional signatures [5], snow cover research [6,7]. Another example of application sensitive to the directional nature of surface reflectance is retrievals of the surface albedo from satellite sensors in weather prediction [8,9] and climate research [10,11]. Directional anisotropy of surface reflectance is described with the bidirectional reflectance distribution function (BRDF) [12]. Retrieval of the BRDF from the satellite observations requires correction for atmospheric effect. So, it is desirable to express the solution of radiative transfer problem for the system "atmosphere+reflecting surface" through the solution of the pure atmospheric problem ("atmosphere+non-reflecting surface," this problem sometimes is referred to as a "standard problem") and reflecting properties of the surface. We will refer to such an expression as decoupling of atmospheric radiative transfer and anisotropic surface reflection.

Decoupling for the case of Lambertian surface was done decades ago [13,14]. This solution is widely used in the atmospheric radiative transfer calculations, see e.g. [15–18]. From mathematical perspective, the decoupling in the case of Lambetian surface is possible due to the independence of the surface reflected radiance on the direction. This property is not valid in the case of non-Lambertian surface. Existing attempts for the decoupling of the "atmosphere+non-Lambertian surface" problem are done by expanding surface reflected radiance by the number of reflections. Tanre et al. [19], see Eq. (8) there, expressed the surface reflected radiance in the form of sum of exact expression for single reflection and approximate expression for higher orders of interaction

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similar to that for the Lambertian surface. The exact expression for an arbitrary order of reflection from the surface was found in [20] along with formal sum of the infinite series. However, numerical evaluation of multiple reflections can be done only by accounting for the first several orders of reflection. The number of orders of reflection required to achieve a certain accuracy increases as atmosphere and/or surface becomes more reflective. Similar expression was used in [21], see Eqs. (8)–(10) and references therein, with implementation by the adding–doubling method.

In this paper, we will consider 1D radiative transfer problem for vertically heterogeneous atmosphere limited at the bottom by a uniform anisotropic reflective surface. Another way to account for all orders of interactions of radiation with the surface will be shown. We will also show the equivalence of the formal sum found in [20] and solution proposed here. Practical implementation of this approach with the discrete ordinates method and the spherical harmonics method will also be considered.

2. Radiative transfer problem

Let us consider a horizontally homogeneous atmosphere with an underlain uniform non-Lambertian surface illuminated at the top boundary with unidirectional light of given intensity I_0. Atmospheric conditions are described with the atmospheric optical thickness τ_t, the single scattering albedo $\Lambda(z)$, and the scattering phase function $\chi(z,\gamma)$. Radiance at altitude $\tau(z)$, in direction defined by the zenith and the azimuth angles θ and ϕ can be found as a solution of the radiative transfer equation (RTE)

$$\mu\frac{\partial I(\tau,\mu,\phi)}{\partial\tau}+I(\tau,\mu,\phi)=\Lambda(\tau)\int_0^{2\pi}d\phi'\int_{-1}^{1}d\mu'\,\chi(\tau,\mu',\mu,\phi'-\phi)I(\tau,\mu',\phi'), \tag{1}$$

supplemented with the boundary conditions:

$$I(\tau=0,\mu>0,\phi)=I_0\delta(\mu-\mu_0)\delta(\phi),\quad \mu_0>0. \tag{2}$$

$$I(\tau=\tau_t,\mu<0,\phi)=\int_0^{2\pi}d\phi'\int_0^{1}d\mu'\,\rho(\mu',|\mu|,\phi'-\phi)\mu' I(\tau_t,\mu',\phi'),\quad \mu<0. \tag{3}$$

The Z axis is pointed downward, so that the cosine of the viewing zenith angle (VZA), $\mu=\cos\theta$ is positive for downward direction, and negative for upward direction. Bottom boundary reflects the light with a known bidirectional reflectance distribution function [12] ρ.

Phase function χ on the right-hand side of Eq. (1) is normalized with the condition

$$\int_0^{2\pi}d\phi'\int_{-1}^{1}d\mu'\chi(\tau,\mu',\mu,\phi'-\phi)=2\pi\int_0^{\pi}\chi(\tau,\cos\gamma)\sin\gamma\,d\gamma=1 \tag{4}$$

We will denote the solution of the problem defined by Eqs. (1)–(3) as $I^T_{nL}(\tau,\mu,\phi|\mu_0)$. Here superscript "$T$" stands for illumination of the atmosphere from its top, subscript "nL" stands for non-Lambertian. The solution depends on the cosine of the solar zenith angle (SZA) μ_0 as a parameter.

Let us also consider two other problems for the same atmosphere: illumination from either top or bottom of atmosphere with nonreflecting opposite boundary. The problems are stated with the RTE (1) and two sets of boundary conditions:

$$I(\tau=0,\mu>0,\phi)=I_0\delta(\mu-\mu_0)\delta(\phi),\quad \mu_0>0, \tag{5}$$

$$I(\tau=\tau_t,\mu<0,\phi)=0; \tag{6}$$

and

$$I(\tau=0,\mu>0,\phi)=0, \tag{7}$$

$$I(\tau=\tau_t,\mu<0,\phi)=\delta(\mu-\mu_s)\delta(\phi),\quad \mu_s<0. \tag{8}$$

Incident radiance for the case of illumination from the top coincides with that of the coupled problem but it is unitary ($I_0=1$) for the case of illumination from the bottom. We will denote the solution with boundary conditions (5) and (6) as $I^T_B(\tau,\mu,\phi|\mu_0)$ and the solution with boundary conditions (7) and (8) as $I^B_B(\tau,\mu,\phi|\mu_s)$. The superscripts there stand for the surface being illuminated and subscript "B" stands for black (no reflection on the opposite side).

The question we will answer in this paper is can the solution of the coupled atmosphere–non-Lambertian surface, $I^T_{nL}(\tau,\mu,\phi|\mu_0)$, be expressed through the solutions of pure atmospheric problems, $I^T_B(\tau,\mu,\phi|\mu_0)$ and $I^B_B(\tau,\mu,\varphi|\mu_s)$, and BRDF ρ?

3. Surface resolving kernel

3.1. Integral equation for SRK

To answer the question above, let us decompose the solution of the main problem $I^T_{nL}(\tau,\mu,\phi|\mu_0)$ into the radiance not interacting with the surface and the radiance reflected by the surface. The former is usually called "path radiance" and is given by $I^T_B(\tau,\mu,\phi|\mu_0)$. The reflecting surface can be considered as a source that depends on incoming radiance. The contribution of this source to the total reflected radiance for a single direction is given by $I^B_B(\tau,\mu,\phi|\mu_s)$. For this reason, the reflected radiance can be presented as a linear combination of $I^B_B(\tau,\mu,\phi|\mu_s)$ with different directions of incidence.

Remizovich et al. [22] considered homogeneous atmosphere with Lambertian underlain surface. They pointed out that the total signal at any atmospheric level τ can be represented as

$$I^T_L(\tau,\mu,\varphi|\mu_0)=I^T_B(\tau,\mu,\varphi|\mu_0)+\int_0^{2\pi}d\varphi'\int_0^{1}d\mu'\,f(\mu',\varphi')I^T_B(\tau_t-\tau,-\mu,\varphi-\varphi'|\mu'),$$

see Eq. (4.1) and discussion before it in that paper. It is easy to see that in the case of homogeneous atmosphere $I^T_B(\tau_t-\tau,-\mu,\varphi-\varphi'|\mu'>0)=I_0I^B_B(\tau,\mu,\varphi-\varphi'|-\mu')$; see discussion in Section 4.1 below. So, the integral term here is a linear combination of the solutions of the problem with illumination from below. An integral equation defining function f in that specific case was derived from the bottom boundary condition; see Eq. (4.2) in that paper. Their final result repeats expressions derived by van de Hulst [13] and Chandrasekhar [14] for the specific model of the atmosphere considered in that paper.

We will follow this approach and generalize it for an anisotropic reflecting surface under vertically