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Photon recollision probability in discrete crown canopies

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Abstract

The photon recollision probability in vegetation canopies, defined as the probability that a photon, after having interacted with a canopy element, will interact again, is a useful tool in remote sensing and ecological applications, enabling to link canopy optical properties at different wavelength and to estimate radiation absorption. In this work, a method is presented to estimate the photon recollision probability for horizontally homogeneous leaf canopies with arbitrary leaf angle distribution as well as for discrete crown canopies. The estimation is based on analytical approximation of the first-order recollision probability. Using the analytical solution of the two-stream equations of radiative transfer and Monte Carlo modeling, the first-order photon recollision probability is shown to slightly underestimate the mean recollision probability. Also, an approximation formula for the mean recollision probability in a horizontally homogeneous canopy is presented as a function of leaf area index. The method to calculate photon recollision probability in discrete crown canopies requires only the knowledge of total and between-crown canopy transmittance and is thus independent of the geometric-optical model used.

Keywords: Photon recollision probability; Geometric-optical reflectance model; Leaf inclination angle; Canopy transmittance

1. Introduction

Photon recollision probability in plant canopies is an active research topic in optical remote sensing of the vegetation covering extensive areas of our planet. It has emerged from physically-based algorithms to relate the structure and amount of plant cover to the quantitative measurements of the intensity of reflected radiation by various space- and airborne sensors. Physically-based models, although usually more computer-extensive and mathematically more complicated, are more robust and make a better use of available information compared with simple statistical approaches (Diner et al., 1999; Myneni et al., 1995), especially with the recent advent of hyperspectral and multi-angular remote sensing. The power and elegance of the photon recollision probability p, defined as the probability that a photon, after having interacted with a canopy element, will interact again, lies in both the ease of its practical application and its mathematical foundations.

In practical remote sensing, the photon recollision probability p can be used to partition incident radiative energy into reflected radiation and the fractions absorbed by the and soil and the canopy. It is nearly independent of the albedo of canopy elements, linking canopy properties at different wavelengths. Its spectral invariance also allows to derive this parameter from hyperspectral reflectance data (Wang et al., 2003). Mathematically, photon recollision probability is tightly linked with the eigenvalue problem of the radiative transfer equation, for which the theoretical basis was presented by Knyazikhin et al. (1998a, b) and Panferov et al. (2001). During recent years, several articles have been published on the application of canopy spectral invariants in estimating canopy reflectance (Disney et al., 2005; Rautiainen & Stenberg, 2005; Shabanov et al., 2003; Wang et al., 2003; Zhang et al., 2002, Mõttus et al., 2007). Recently, Huang et al. (2006) published a thorough article on the applications of p and the relevant mathematical definitions. The work by Huang et al. (2006) is frequently referred to in the current paper as it contains several definitions and important background information on the mathematical foundations of the problem.

Although photon recollision probability is a structural parameter, the relationship between p and measurable stand characteristics is unclear. The main purpose of this work is to

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illustrate which structural variables p depends on and to derive such relationships for leaf canopies. It should also be noted that in this manuscript, no attempts are made to evaluate neither the true spectral invariants (i.e., the coefficients pt_{bs}, pt_q, and pa in Knyazikhin et al. (1998a)) nor the eigenvalues of the radiative transfer equation in plant canopies. Canopy structure is introduced first by leaf angle distribution for horizontally homogeneous canopies and later by using a geometric presentation describing the stand as a collection of crown envelopes. In remote sensing applications, this approach is known as geometric-optical canopy modeling and initially, purely geometric considerations were used to derive the fractions of visible sunlit and shaded crown and ground areas (Li & Strahler, 1985). Later, to derive the brightnesses of the four components and to account for higher-order scattering, the optical properties of the crowns and the theory of radiative transfer have been utilized. The models taking into account the optical properties of the material filling the crown volume and multiple scattering became known as hybrid (or hybrid geometric-optical) models (e.g., Chen & Leblanc, 2001; Kuusk & Nilson, 2000; Leblanc & Chen, 2000; Nilson & Peterson, 1991; Li et al., 1995; Ni et al., 1999). Although some of these models can account for various levels of canopy structure (shoot, branch, whorl, crown, tree clusters, etc.), only leaf-level (effects of leaf orientation) and crown-level (effects of varying basic crown parameters) are discussed here.

This article is structured as follows. An approximation for p is derived by expansion of an analytical solution of the radiative transfer equation valid for canopies with horizontal leaves in Taylor series. Later, this approximation is extended to homogeneous canopies with arbitrary leaf angle distribution and to heterogeneous stands. In the final section, the approximations are compared with results of Monte Carlo simulations.

2. Theory and models

2.1. Photon recollision probability

Let us take a similar approach for determining the photon recollision probability p as that used by Smolander and Stenberg (2005). We start with the law of conservation of energy for a canopy bounded by a black surface,

$$T_0 + A + S = 1, \tag{1}$$

where T_0 is canopy direct transmittance (the fraction of incident radiation transmitted by the canopy without any interactions), A is canopy absorption (the fraction of incident radiation absorbed by the canopy), and S is canopy scattering (the fraction of incident radiation exiting the canopy after at least one interaction with canopy elements). Let us now define the normalized canopy absorption A/I_0 and the normalized canopy scattering S/I_0 , where $I_0=1-T_0$ is the fraction of incident radiation intercepted by the canopy. Instead of the normalized canopy absorption A/I_0 used by Smolander and Stenberg (2005), we will use, for the sake of clarity of later derivations, the normalized canopy scattering S/I_0. Writing this quantity as a sum of components contributed by various scattering orders yields

$$S/I_0 = \omega_L q_1 + \omega_L p_1 \omega_L q_2 + \omega_L p_1 \omega_L p_2 \omega_L q_3 + \ldots$$
$$= \sum_{i=1}^{\infty} \left\{ q_1 \prod_{j=1}^{i=1} p_j \right\} \omega_L^i, \tag{2}$$

where p_i is the conditional probability that a photon, after having interacted with canopy elements i times, will interact at least once again (or photon recollision probability of order i), $q_i=1-p_i$ is the conditional probability that a photon, after having interacted with canopy elements i times, will escape from the canopy without any further interactions, and ω_L is the single-scattering albedo of canopy elements. Further it will be assumed that the canopy consists of just one type of elements with a single ω_L value. These elements will be called "leaves", although in practical applications, the basic units used in radiative transfer modeling might be shoots or needles. The share of trunks, branches, flowers, etc. will be ignored. If the leaf scattering phase function is wavelength-independent, the photon recollision probabilities p_i are independent of the leaf single-scattering albedo ω_L.

If $p_i \equiv p$, or the recollision probability does not depend on the scattering order i, and using Eq. (1), we will arrive at the photon recollision probability equation proposed by Smolander and Stenberg (2005),

$$A/I_0 = \frac{1-\omega_L}{1-p\omega_L}. \tag{3}$$

If the recollision probabilities p_i are not equal to each other, Eq. (3) may be used as an approximation assuming the differences between the various p_i's are not large by defining a mean recollision probability p. Depending on the definition of p, it may be a function of the leaf single-scattering albedo, $p=p(\omega_L)$. However, to use Eq. (3) for relating canopy absorption at different wavelengths, it is preferable to perform the averaging to obtain a mean photon recollision probability that is independent of ω_L and describes the scattering process for the whole spectrum. Two methods to perform such averaging were presented by Mõttus et al. (2007). The algorithm shown by them to be more appropriate of the two is used in the current study. Thus, from here onwards, the symbol p will denote the mean photon recollision probability that is independent of ω_L calculated by fitting Eq. (3) to modeled absorption at different wavelengths.

2.2. Recollision probability as a power series

Eq. (2) can be viewed as a power series of the leaf single-scattering albedo ω_L. Thus, if we can obtain from some other source another power series of ω_L to calculate normalized canopy scattering, we can use it to derive the recollision probabilities p_i. Such series can be constructed by expanding a solution of the radiative transfer equation (e.g., Knyazikhin & Marshak, 1991) into a Taylor series. More specifically, as Eq. (1) is written for a canopy above a totally absorbing surface, we need