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Review

Photon recollision probability in modelling the radiation regime of canopies — A review

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ABSTRACT

Nearly two decades ago, the idea of the 'spectral invariants theory' was put forth as a new tool to model the short-wave radiation absorbed or scattered by vegetation. The theory states that the amount of radiation absorbed by a canopy should to a great accuracy depend only on the wavelength and a wavelength-independent parameter describing canopy structure. The revolutionary idea behind this theory was that it would be possible to approximate vegetation canopy absorptance, transmittance and reflectance based on only the optical properties of foliage elements and the spectrally invariant parameter(s). This paper explains how this so-called spectral invariant is related to photon recollision probability and to canopy structural variables. Other spectral invariants were later introduced to quantify the directionality of canopy scattering. Moreover, the paper reviews the advances in the theoretical development of the photon recollision probability (p) concept and demonstrates some of its applications in global and local monitoring of vegetation using remote sensing data.

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1. Introduction

Physically-based remote sensing of vegetation relies upon accurate models of the canopy shortwave radiation budget, which quantitatively describe how the fractions of solar radiation absorbed, transmitted and reflected by the canopy are related to the optical and structural properties of the canopy and background. Optical properties comprise the scattering and absorption spectra of the vegetation elements, which vary with the wavelength, whereas the structural canopy descriptors are independent of wavelength, or *spectrally invariant*. The variable focused on in this review — the *photon recollision probability*, is not one of the input parameters to the classical three-dimensional radiative transfer (RT) equation for vegetation (Ross, 1981), but is closely related to the solution of this equation (Knyazikhin, Martonchik, Myneni, Diner, & Running, 1998).

The concept of recollision probability can be pictured by thinking of the radiative transfer as a stochastic process: When a photon interacts with an element in the canopy, the probability that it will be absorbed or scattered varies with the wavelength. However, once the photon has been scattered, the probability that it will collide with the canopy again depends only on the location of the scattering event and the direction it was scattered into. This recollision probability is a geometric quantity which, in geometric optics approximation, does not depend on the wavelength. One may define a canopy averaged mean photon recollision probability, which was shown to link together the optical properties at canopy and leaf level by a set of simple algebraic relationships (Smolander & Stenberg, 2005). The existence of a spectrally invariant '*p*-parameter' satisfying similar relationships was, however, first discovered and theoretically established by Knyazikhin et al. (1998). Only a clear interpretation of this parameter was still lacking at the time. The fact that the somewhat heuristic 'photon recollision probability'-approach was found to be coherent with physically-based radiative transfer started a new era in the application of the 'spectral invariants theory': the single parameter representing canopy structure had now been defined and thus could also be quantified.

Knyazikhin et al. (1998) put forth the idea of the 'spectral invariants theory' when developing the theoretical grounds of the MODIS algorithm for retrieval of the leaf area index (LAI) and the fraction of photosynthetically active radiation (fPAR). They proposed a revolutionary idea that it would be possible to approximate vegetation canopy absorptance, transmittance and reflectance using only the optical properties of foliage elements and one spectrally invariant parameter for each approximated canopy characteristic. The theory states that, knowing the leaf albedo (1-absorptance), canopy absorptance at any wavelength can be estimated with high accuracy from canopy absorptance at a reference wavelength. This property laid the foundation for the synergistic look-up-table (LUT) based algorithm developed by Knyazikhin et al. (1998), which has been successfully implemented in the retrieval of global leaf area index (LAI) from canopy reflectance data measured by the MODIS instrument.

This approach was contrary to many other lines of development where more complexity was favored in canopy radiation models. A couple of years later, several independent research lines in Boston University, University of Helsinki and University College London were investigating the spectral invariants theory and its applications. This paper reviews the advances in the theoretical concepts behind the spectral invariants and shows examples of various applications of the concept in global and local monitoring of vegetation using remote sensing data.

2. *p*-Theory

2.1. The concept of recollision probability

Knyazikhin et al. (1998) proposed that the unique positive eigenvalue of the radiative transfer equation can be expressed as the product of the leaf albedo and a wavelength independent parameter, and the name '*p*-theory' originates from the symbol they used for this canopy structural parameter. Empirical evidence for the spectral invariant behavior of the *p* parameter was provided later by Panferov et al. (2001) and Wang et al. (2003) based on the measured spectral reflectance and transmittance data of forest canopies. However, a clear interpretation of how *p* is related to the canopy structure, allowing it to be estimated from canopy structural measurements, was still missing. A step towards this goal was taken by Smolander and Stenberg (2005), who defined *p* as a conditional probability — the recollision probability, and in their simulation study derived tight relationships between *p* and LAI in model canopies. It was shown that, in addition to LAI, *p* is linked to the clumping of foliage.

Smolander and Stenberg (2005) were thus first to introduce the term recollision probability for *p*, which they defined as the probability by which a photon scattered from a phytoelement (leaf or needle) in a vegetation canopy will interact within the canopy again. The escape probability $(1 - p)$ correspondingly is the probability by which a scattered photon will escape the canopy. These probabilities are defined conditional to the photon having survived an interaction inside the canopy. The fraction of photons that enter the vegetation from above and are intercepted by elements in the canopy is called the *canopy interceptance* (i_0). The zero order (or *uncollided*) transmittance (t_0) in turn is the fraction of photons that are transmitted directly through gaps in the canopy: $t_0 = 1 - i_0$. In a canopy bounded underneath by a non-reflecting ('black') surface (Fig. 1), the transmitted photons will not interact within the canopy again. Under this condition, and assuming further that the *p* remains constant in successive interactions, canopy absorptance (a) at a specific wavelength (λ) is obtained as the sum of a geometric series:

$$a(\lambda) = i_0\left[(1-\omega_L(\lambda)) + \omega_L(\lambda)p(1-\omega_L(\lambda)) + \omega_L(\lambda)^2p^2(1-\omega_L(\lambda)) + \ldots\right] = i_0\frac{1-\omega_L(\lambda)}{1-p\omega_L(\lambda)}. \quad (1)$$

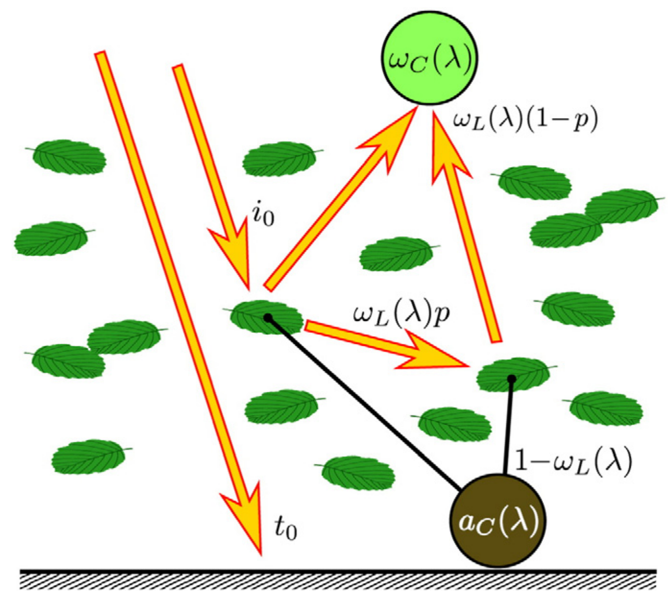

Fig. 1. Photons entering a canopy bounded below by black soil are first intercepted by leaves (i_0) or directly transmitted to and absorbed by the ground (t_0). The intercepted part is eventually absorbed (α_C) or scattered out from the canopy (ω_C) after one or multiple interaction and recollision events.

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