Journal of Quantitative Spectroscopy & Radiative Transfer 112 (2011) 727–735

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Canopy spectral invariants. Part 1: A new concept in remote sensing of vegetation

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ARTICLE INFO

Keywords:
MODIS
MISR
Scale
Canopy structure
Canopy spectral invariants
Radiative transfer equation
Eigenvalues
Eigenvectors

ABSTRACT

The concept of canopy spectral invariants expresses the observation that simple algebraic combinations of leaf and canopy spectral reflectance become wavelength independent and determine two canopy structure specific variables – the recollision and escape probabilities. These variables specify an accurate relationship between the spectral response of a vegetation canopy to incident solar radiation at the leaf and the canopy scale. They are sensitive to important structural features of the canopy such as forest cover, tree density, leaf area index, crown geometry, forest type and stand age. This paper presents the mathematical basis of the concept which is linked to eigenvalues and eigenvectors of the three-dimensional radiative transfer equation.

1. Introduction

Interaction of solar radiation with the vegetation canopy is described by the three-dimensional radiative transfer equation [1,2]. The interaction cross-section that appears in this equation is treated as wavelength independent considering the size of the scattering elements (leaves, branches, twigs, etc.) relative to the wavelength of solar radiation [1]. Although the scattering and absorption processes are different at different wavelengths, the interaction probabilities for photons in vegetation media are determined by the structure of the canopy rather than photon frequency or the optics of the canopy. This feature results in unique spectrally invariant behavior for a vegetation canopy bounded from below by a non-reflecting surface: some simple algebraic combinations of the single-scattering albedo and canopy spectral transmittances and reflectances eliminate their dependencies on wavelength through the specification of two canopy structure specific spectrally invariant variables – the recollision and escape probabilities.

The recollision probability is the probability that a photon scattered from a phytoelement will interact within the canopy again [3] and is related to the maximum eigenvalue of the radiative transfer equation [4,5]. The escape probability is the probability that a scattered photon will escape the vegetation in a given direction [6]. These variables specify an accurate relationship between the spectral response of a vegetation canopy to the incident solar radiation at the leaf and the canopy scale and allows for a simple and accurate parameterization for the partitioning of the incoming radiation into canopy transmission, reflection and absorption at any wavelength in the solar spectrum. This result is essential to both modeling and remote sensing communities as it allows for the separation of the structural and radiometric components of the measured and/or modeled signal. The former is a function of canopy age, density and arrangement while the latter is a function of canopy biochemical behavior. Consequently, the canopy spectral invariants offer a simple and accurate parameterization of the shortwave radiation block in many global models of climate, hydrology, biogeochemistry, and ecology [7,8].

In remote sensing applications, the information content of spectral data can be fully exploited if the wavelength independent variables can be retrieved, for

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doi:10.1016/j.jqsrt.2010.06.014

they can be more directly related to structural characteristics of the vegetation canopy. This concept underlies the operational algorithm of global leaf area index, and the fraction of photosynthetically active radiation absorbed by vegetation developed for the moderate resolution imaging spectroradiometer (MODIS) and multi-angle imaging spectroradiometer (MISR) instruments of the Earth observing system (EOS) Terra mission [4,5]. The canopy spectral invariants have also been exploited in developing a 26 year leaf area index data record from multiple sensors [9,10]. Here we will discuss the theoretical basis of the concept and its potential utility for investigating the three-dimensional canopy structure from space measurements. In Part 2 [22], we will apply the concept to the classification of forest types from hyperspectral data.

2. Radiative transfer in vegetation canopies

Let $V \subset R^3$ and δV be the domain where radiative transfer occurs and its boundary, respectively. The domain V can be a shoot, tree crown, or a part of the vegetation canopy with several trees, etc. In remote sensing, V is a parallelepiped of horizontal dimensions X, Y and biome dependent height Z and represents a pixel in which a vegetation canopy is located [2,5]. The function characterizing the radiative field in V is the monochromatic intensity $I_\lambda(\boldsymbol{x},\Omega)$ depending on wavelength, λ, location $\boldsymbol{x}$ and direction Ω. Assuming no polarization and emission within the canopy, the monochromatic intensity distribution function is given by the boundary value problem for steady-state radiative transfer equation [1,2]:

$$LI_\lambda = S_\lambda I_\lambda, \tag{1}$$

$$I_\lambda(\mathbf{x}_\mathrm{B},\Omega) = \pi^{-1}\int_{\mathbf{n}_\mathrm{B}\cdot\Omega'>0} \rho_\lambda(\mathbf{x}_\mathrm{B},\Omega',\Omega) I_\lambda(\mathbf{x}_\mathrm{B},\Omega') \left|\mathbf{n}_\mathrm{B}\cdot\Omega'\right| d\Omega' + q_\lambda(\mathbf{x}_\mathrm{B},\Omega),$$
$$\mathbf{n}_\mathrm{B}\cdot\Omega < 0, \quad \mathbf{x}_\mathrm{B}\in\delta V. \tag{2}$$

Here L and S_λ are the streaming-collision and scattering linear operators defined as

$$LI_\lambda = \frac{1}{\sigma(\boldsymbol{x},\Omega)}\Omega\cdot\nabla I_\lambda(\boldsymbol{x},\Omega) + I_\lambda(\boldsymbol{x},\Omega),$$
$$S_\lambda I_\lambda = \frac{1}{\sigma(\boldsymbol{x},\Omega)}\int_{4\pi}\sigma_{s,\lambda}(\boldsymbol{x},\Omega'\to\Omega) I_\lambda(\boldsymbol{x},\Omega')d\Omega'.$$

The term ρ_λ is the bidirectional reflectance factor of the boundary δV, q_λ describes the radiation penetrating into V through the boundary δV, $\mathbf{n}_\mathrm{B}$ is the outward normal at $\mathbf{x}_\mathrm{B} \in \delta V$, and 4π denotes the unit sphere. The boundary source q_λ at points $\boldsymbol{x}_\mathrm{T}$ on the canopy top boundary is usually given by a mono-directional beam attenuated by the atmosphere, $c_\lambda\delta(\Omega-\Omega_0)$, and radiation scattered by the atmosphere $d_\lambda(\mathbf{x}_T,\Omega)$ (diffuse radiation), i.e., $q_\lambda(\mathbf{x}_T,\Omega) = c_\lambda\delta(\Omega-\Omega_0) + d_\lambda(x_T,\Omega), \quad \mathbf{n}_\mathrm{T}\cdot\Omega<0$.

The interaction cross-section, σ, and differential cross-section, $\sigma_{s,\lambda}$, are defined as [1,2]:

$$\sigma(\mathbf{x},\Omega) = u_\mathrm{L}(\boldsymbol{x})G(\mathbf{x},\Omega), \sigma_{s,\lambda}(\boldsymbol{x},\Omega'\to\Omega)$$
$$= u_\mathrm{L}(\boldsymbol{x})\frac{1}{\pi}\Gamma_\lambda(\boldsymbol{x},\Omega'\to\Omega)$$

where $u_\mathrm{L}(\boldsymbol{x})$ is the one-sided leaf area density distribution (in $\mathrm{m}^2/\mathrm{m}^3$), G is the geometry factor (dimensionless), and Γ_λ/π is the area scattering phase function (in sr^{-1}). The interaction cross-section is assumed to be strictly positive, i.e., $\sigma(\boldsymbol{x},\Omega) \geq \overline{\sigma} > 0$. This inequality is required to apply mathematical techniques developed by Vladimirov [11], which will be used in Sections 3 and 4. It should be noted however that this condition can be released [12]. We also assume that $\Gamma_{s,\lambda}(\boldsymbol{x},\Omega'\to\Omega) = \Gamma_{s,\lambda}(\boldsymbol{x},-\Omega\to-\Omega') = \Gamma_{s,\lambda}(\boldsymbol{x},\Omega\to\Omega')$. These symmetry properties provide sufficient conditions for the validity of the reciprocity principle [13].

Note that the interaction cross-section is a function of the direction of photon travel. Also, the differential scattering cross-section is not, as a rule, rotationally invariant, i.e., it generally depends on the absolute directions of photon travel Ω' and Ω, before and after scattering, respectively, and not just the scattering angle $\cos^{-1}(\Omega'\cdot\Omega)$. These properties make solving of the radiative transfer equation more complicated; for example, the expansion of the differential scattering cross-section in spherical harmonics cannot be used. In contrast to radiative transfer in atmosphere the interaction cross-section in vegetation canopies is wavelength independent. This spectral invariance results in various unique relationships, which, to some degree, compensate for difficulties in solving the radiative transfer equation due to the above-mentioned features of the extinction and the differential scattering cross sections.

The interaction and differential cross sections are related as

$$\int_{4\pi}\sigma_{s,\lambda}(\boldsymbol{x},\Omega'\to\Omega)d\Omega = \omega(\lambda,\boldsymbol{x},\Omega')\sigma(\boldsymbol{x},\Omega')$$

where ω is the single scattering albedo. For ease of analysis, we assume that the single scattering albedo does not depend on $\boldsymbol{x}$ and Ω'. It coincides with the leaf albedo in this case. In the vegetation canopy angular distribution of radiation scattered by an elementary volume is mainly determined by geometrical properties of phytoelements resident in the volume [1,2]. Therefore we assume that the differential cross-section normalized by the single scattering albedo does not depend on wavelength. The scattering operator rearranges to $S_\lambda=\omega(\lambda)S_0$.

The three-dimensional radiative transfer problem with arbitrary boundary conditions can be expressed as a superposition of the solutions of some basic radiative transfer sub-problems with purely absorbing boundaries [13]. Therefore we restrict our consideration to the case when $\rho_\lambda=0$. We also assume that the source function q_λ does not depend on wavelength, $q_\lambda=q_0$. In optical remote sensing, the incident solar radiation is proportional to a wavelength dependent scalar. The latter condition therefore can be met by normalizing the boundary value problem by this scalar. Under the conditions discussed in this section, the single scattering albedo $\omega(\lambda)$ is the only variable that imbues wavelength dependency to the solution of the radiative transfer equation in vegetation canopies.

The formulation of radiative transfer presented here underlies the retrieval technique for producing global leaf area index and fraction of photosynthetically active