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Direct retrieval of the shape of leaf spectral albedo from multiangular hyperspectral Earth observation data

Matti Mõttus [a,b,*], Miina Rautiainen [b]

[a] Tartu Observatory, Tõravere, Tartumaa, 61602 Estonia
[b] Dept. of Forest Resource Management, P.O. Box 27, FI-00014 University of Helsinki, Finland

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ABSTRACT

Physically-based retrieval of vegetation canopy properties from remote sensing data presumes a knowledge of the spectral albedo of the basic scattering unit, i.e. leaf. In this paper, we present a novel method to directly retrieve the spectral dependence of leaf single-scattering albedo of a closed broadleaf forest canopy from multiangular hyperspectral satellite imagery. The new algorithm is based on separating the reflected signal into a linear (first-order) and non-linear (diffuse) reflectance component. A limitation of the proposed algorithm is that the leaf single-scattering albedo $\omega(\lambda)$ is retrieved with an accuracy of a structural parameter (called a_0) which, in turn, depends on canopy bidirectional gap probability, ratio of leaf reflectance to transmittance, and distribution of leaf normals. The structural parameter (a_0) was found to depend on tree-level structural parameters, such as tree height and volume of a single crown, but not the amount of leaf area.

1. Introduction

Remote sensing data in the visible and near-infrared (VNIR) optical domains is a useful source of information for estimating biogeophysical variables of large vegetated areas. Among the parameters of interest are, for example, leaf area index, canopy cover, clumping index, fraction of absorbed photosynthetically active radiation, chlorophyll content, net primary production, canopy water stress, amount of forest fire fuel, and parameters describing tree crown geometry. Several successful inversion algorithms have been developed to retrieve various canopy variables from optical VNIR measurements (Liang, 2007). The shape of leaf spectral albedo is not directly on the traditional list of retrievable parameters; it can be considered an intermediate product carrying information about foliar biochemistry (e.g., Jacquemoud et al., 1996).

Retrieval of vegetation canopy properties from Earth observation data presumes knowledge of the spectral albedo of the basic scattering unit. Some a priori values may be used, but due to a continuously changing environment, leaf spectral albedos exhibit temporal fluctuation: a given plant species cannot be assumed to always have the same spectrum (e.g., Demarez et al., 1999). The limitations on determining leaf spectral albedo also form the limitations for the retrieval of other canopy parameters, e.g., LAI or canopy 3D structure. Thus, in truly robust algorithms, leaf spectral albedo should be retrieved from remote sensing data together with other canopy biophysical properties, i.e. it should not be assumed to be known in advance or to remain constant throughout different seasons. However, it is evident that the number of retrievable parameters is limited by the amount of available data that can be used as input to the inversion algorithm (Verstraete et al., 1996). One of the first studies on retrieving simultaneously several parameters, LAI and leaf reflectance, was carried out by Privette et al. (1996). While they succeeded in this task, the accuracy of retrieval was much better when one of the parameters was fixed. Fortunately, with the advent of multiangular remote sensing, more information is collected for each pixel and several canopy characteristics can, in theory, be inverted simultaneously (Diner et al., 1999).

Traditionally, when leaf reflectance properties or canopy structure was estimated from remote sensing data, a full canopy reflectance model was inverted. The studies ranging from the pioneering works of Goel and Strebel (1983) and Wu and Stahler (1994) to modern operational algorithms are far too numerous to be listed. The most recent review on inverting canopy reflectance models was written by Kimes et al. (2000) almost a decade ago. Since 2000, various success rates have been reported by using a plethora of physically-based models (Stenberg et al., 2008).

In this paper, we present a pioneer study on the theoretical background for the retrieval of the shape of leaf single-scattering albedo from multiangular, hyperspectral reflectance data. In an accompanying case study, we use the new algorithm to retrieve the leaf spectral albedos of two typical hemiboreal broadleaved tree species from CHRIS PROBA

* Corresponding author. Tartu Observatory, Tõravere, Tartumaa, 61602 Estonia.
E-mail addresses: matti.mottus@aai.ee (M. Mõttus), miina.rautiainen@helsinki.fi (M. Rautiainen).

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data. Finally, we discuss the limitations related to defining and measuring leaf spectral albedo with the proposed algorithm, possibilities on retrieving the magnitude of leaf albedo, and evaluate possible implications on the retrieval of other canopy parameters.

2. Theory

2.1. Splitting canopy reflectance into first and higher orders

Canopy reflectance R is defined as the ratio of radiance measured above a reflecting surface compared to the radiance produced by a perfectly reflecting Lambertian surface under the same illumination conditions (e.g., Widlowski et al., 2007). For a vegetation canopy, we can split the canopy-leaving radiance, and thus reflectance, into two components,

$$R(\Omega,\lambda) = R_F(\Omega,\lambda) + R_D(\Omega,\lambda), \tag{1}$$

where R_F is the contribution of first-order scattering (photons reaching the sensor after having interacted only once with the ground or a canopy element), R_D is the contribution of diffuse scattering (defined here as the rest of the atmospherically corrected signal contributed by higher-order photons, or photons that have scattered more than once below the canopy upper border), Ω denotes the view direction and λ wavelength.

Without any specification of the origin of the first-order component R_F (leaves, tree trunks, ground, etc.), we note that it depends only on the mean albedo of the (sunlit) objects and wavelength-independent bidirectional gap probability a. Thus, we may write that

$$R_F(\Omega,\lambda) = a(\Omega)\omega(\lambda). \tag{2}$$

This equation is used as the defining equation for $\omega(\lambda)$, the mean single-scattering albedo of objects that are both visible and sunlit. The physical interpretation of ω depends on the observed object. For example, for a closed (hemi)boreal forest canopy, $\omega(\lambda)$ as defined by Eq. (2) can be described as the mean leaf single-scattered albedo contaminated by the spectral albedo of non-leafy canopy material and understory vegetation. More generally, for closed forest canopies and off-zenith view and illumination angles where a satellite sensor sees almost exclusively green canopy elements, we assume that ω corresponds to the albedo of the basic canopy scattering unit and will hereafter be referred to as spectral leaf single-scattering albedo.

Using Eq. (1) to separate first- and higher-order scattering, the problem of describing the multiangular and hyperspectral distribution of canopy reflectance can be mathematically formulated as

$$R(\Omega_i,\lambda) = a_i(\Omega_i)\omega(\lambda) + b_i(\Omega_i,\lambda)D(\lambda), \quad i = 1,\ldots,N_\Omega, \tag{3}$$

where $D(\lambda)$ is the diffuse (multiply-scattered) flux reflectance and $b_i(\Omega_i,\lambda) = R_D(\Omega,\lambda)/D(\lambda)$ is a function describing the angular distribution of diffuse scattering. Instead of the wavelength λ, Eq. (3) contains directly two basic spectral parameters independent of the view angle Ω: $\omega(\lambda)$, or the spectral leaf albedo, and $D(\lambda)$, the diffuse spectral reflectance.

The shape of ω as a function of λ has been studied and modeled widely, and also measured directly (e.g., Combes et al., 2007). In addition, several public data bases of measured leaf spectra have been established as a part of extensive projects (e.g., LOPEX, FIFE MMR UNL, BOREAS). However, due to high natural complexity and temporal variability, leaf spectra for all species at all geographical locations cannot be assumed to be known exactly. Even for flat leaves, $\omega(\lambda)$ is not uniquely defined. The reflectance (and also transmittance) properties of a leaf are completely described only by the scattering phase function which depends on both the illumination and view angles relative to the direction of leaf normal. Thus, using only the leaf spectral albedo $\omega(\lambda)$ for each wavelength includes a set of implicit assumptions.

The defining equation for ω, Eq. (2), describes the single-scattering albedo as a function of the multiangular geometry. For leaves, this definition can be reformulated using the standard notation of canopy radiative transfer using the area scattering phase function $\frac{1}{\pi}\Gamma(\Omega'\rightarrow\Omega)$ (Ross, 1981):

$$\omega(\lambda) = \left\langle \frac{1}{\pi}\Gamma(\lambda,\Omega_S\rightarrow\Omega_i)\right\rangle_i, \tag{4}$$

where Ω_S is the illumination direction and Ω_i, $i = 1,\ldots,N_\Omega$ is the set of view directions. As the Gamma function is obtained by integrating over all possible leaf normal directions, ω defined by Eq. (4) can be expected to be a close approximation for the "true" leaf albedo, or flux reflectance, integrated over all view directions. The averaging in Eq. (4) can be omitted for Lambertian leaves with equal reflectances of both sides and a spectrally invariant reflectance-to-transmittance ratio. While the shape of the phase function of real leaves may be non-Lambertian, the differences are expected to be non-significant (Chelle, 2006).

If more than one light source is present and the non-Lambertian character of leaf scattering properties is taken into account, the averaging in Eq. (4) must be performed also over the set of illumination angles Ω_S. In the case of diffuse sky illumination, this corresponds to integration over the upper hemisphere. However, there is no reason to assume that under common illumination conditions, $\omega(\lambda)$ would depend heavily on the direction of incident photons (Ω_S in Eq. (4)) — the presence of diffuse incident flux does not affect the formulation of the problem.

The second term in the right hand side of Eq. (3), the diffuse spectral reflectance $D(\lambda)$, can be expected to be strongly and non-linearly related to $\omega(\lambda)$. $D(\lambda)$ cannot be measured directly and can only be obtained from a physically-based canopy reflectance model. Thus, it is difficult to use the retrieved $D(\lambda)$ for validation of the algorithm presented in this paper. While the shape of $D(\lambda)$ can be expected to contain valuable information on canopy structure, it is not analyzed here and only the possible approximations and applications are briefly discussed in Section 4.

Instead of trying to solve Eq. (3) with a full radiative transfer model, we will try to obtain the shape of the leaf albedo $\omega(\lambda)$ and leave the geometric factors a_i in Eq. (3) unknown. Similarly, instead of specifying the mechanisms producing diffuse scattering, we will try to find the proportion of diffuse scattering in each direction. Our algorithm utilizes directly the hemispherical-directional reflectance factors (HDRF's) without making any direct assumptions on the albedo of the vegetation canopy. Considering the above, it is reasonable to rewrite Eq. (3) as

$$\begin{aligned}
&R_0(\Omega_0,\lambda) = a_0(\Omega_0)\omega(\lambda) + b_0(\Omega_0,\lambda)D(\lambda)\\
&R_i(\Omega_i,\lambda) = \alpha_i(\Omega_i)a_0(\Omega_0)\omega(\lambda) + \beta_i(\Omega_i,\lambda)b_0(\Omega_0,\lambda)D(\lambda)\\
&\alpha_i(\Omega_i) = \frac{a_i(\Omega_i)}{a_0(\Omega_0)}\\
&\beta_i(\Omega_i,\lambda) = \frac{b_i(\Omega_i,\lambda)}{b_0(\Omega_0,\lambda)}\\
&i = 1,\ldots,N_\Omega - 1,
\end{aligned} \tag{5}$$

where Ω_0 is an arbitrarily chosen base direction. Now, the leaf reflectance spectrum will be described in terms of $a_0\omega$ and the parameters that need to be retrieved to obtain it include b_0D, α_i, and β_i. The physical meaning of the parameters α_i and β_i is easy to understand: α_i gives the ratio of first-order (or linear) scattering at