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Modeling directional–hemispherical reflectance and transmittance of fresh and dry leaves from 0.4 μm to 5.7 μm with the PROSPECT-VISIR model

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ABSTRACT

Vegetation water content retrieval using passive remote sensing techniques in the 0.4–2.5 μm region (reflection of solar radiation) and the 8–14 μm region (emission of thermal radiation) has given rise to an abundant literature. The wavelength range in between, where the main water absorption bands are located, has surprisingly received very little attention because of the complexity of the radiometric signal that mixes both reflected and emitted fluxes. Nevertheless, it is now covered by the latest generation of passive optical sensors (e.g. SEBASS, AHS). This work aims at modeling leaf spectral reflectance and transmittance in the infrared, particularly between 3 μm and 5 μm, to improve the retrieval of vegetation water content using hyperspectral data. Two unique datasets containing 32 leaf samples each were acquired in 2008 at the USGS National Center, Reston (VA, USA) and the ONERA Research Center, Toulouse (France). Reflectance and transmittance were recorded using laboratory spectrometers in the spectral region from 0.4 μm to 14 μm, and the leaf water and dry matter contents were determined. It turns out that these spectra are strongly linked to water content up to 5.7 μm. This dependence is much weaker further into the infrared, where spectral features seem to be mainly associated with the biochemical composition of the leaf surface. The measurements show that leaves transmit light in this wavelength domain and that the transmittance of dry samples can reach 0.35 of incoming light around 5 μm, and 0.05 around 11 μm. This work extends the PROSPECT leaf optical properties model by taking into account the high absorption levels of leaf constituents (by the insertion of the complex Fresnel coefficients) and surface phenomena (by the addition of a top layer). The new model, PROSPECT-VISIR (VISible to InfraRed), simulates leaf reflectance and transmittance between 0.4 μm and 5.7 μm (at 1 nm spectral resolution) with a root mean square error (RMSE) of 0.017 and 0.018, respectively. Model inversion also allows the prediction of water (RMSE = 0.0011 g/cm²) and dry matter (RMSE = 0.0013 g/cm²) contents.

1. Introduction

The characterization of natural surfaces by remote sensing usually takes advantage of their optical properties in the atmospheric windows of the solar emission spectrum (0.4 μm to 2.5 μm, visible-near infrared to shortwave infrared, VNIR–SWIR) and the terrestrial emission spectrum (8 μm to 14 μm, thermal infrared, TIR). The 3–5 μm range (middle wave infrared, MWIR) where the radiance mixes fluxes both reflected and emitted by the surface has been little investigated, in some degree because of the complexity of the signal. Despite the development of multispectral and hyperspectral sensors covering all these wavelength domains in recent years, and their relevance to environmental studies, physical models for interpreting the 3–5 μm spectral radiance of Earth's surfaces are lacking (Boyd & Petitcolin, 2004). With several hundreds of narrow spectral bands in the infrared, the current generation of space sounders such as AIRS (Atmospheric InfraRed Sounder, Chahine et al., 2006) and IASI (Infrared Atmospheric Sounding Interferometer, Siméoni et al., 1999), mainly dedicated to the study of the Earth's atmosphere, have unequalled spectral resolution. Airborne sensors like AHI (Airborne Hyperspectral Imager, Lucey et al., 1998), SEBASS (Spatially Enhanced Broadband Array Spectrograph System, Kirkland et al., 2002), AHS (Airborne Hyperspectral Scanner, Sobrino et al., 2006) or FIRST (Allard et al., 2008) can also acquire hyperspectral images with a spatial resolution of a few meters. Both for surface and atmospheric studies, the interpretation of these measurements is

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difficult because vegetation covers about 65% of terrestrial surfaces and we know very little about the spectral optical properties of plant canopies in the infrared domain. In order to exploit properly such information, it is necessary to improve our understanding of these properties at different scales in this wavelength range.

It is interesting to note that one of the earliest papers on leaf optical properties, published by Brown & Escombe (1905), addresses the question of radiative energy exchanges between plant leaves and their surrounding environment. Nevertheless, the first reflectance spectra of plant leaves in the infrared are published long after by Gates & Tantraporn (1952) who noticed that adult leaves reflect more light between 3 μm and 25 μm than juvenile leaves, which are very different in terms of phenology, morphology and anatomy. However, Wong & Blevin (1967) and Salisbury (1986) found relatively little spectral variation with senescence in the 8–14 μm domain. Salisbury & Milton (1988) and Elvidge (1988), who respectively measured leaf directional–hemispherical reflectance in the 2.5–13.5 μm and 2.5–20 μm regions, point out that the main effects occur at wavelengths shorter than 6 μm when a leaf is thoroughly dried, and that there is no significant influence of drying in the 8–14 μm region, where reflectance is more species dependent. Narayanan et al. (1991) confirmed that leaf reflectance does not vary with water content to a noticeable degree in the 9–11 μm wavelength region. They also showed that reflectance starts to increase at water contents far greater than the wilting point. The foregoing works suggest that the 3–5 μm atmospheric window may be a useful wavelength range to study vegetation water content, in contrast to the 8–14 μm window that may be more relevant to differentiating plant species. In addition, Salisbury et al. (1994) mention that Kirchhoff's law applies to most opaque materials, i.e., that emissivity $\varepsilon(\lambda)$ is related to directional–hemispherical reflectance $\rho(\lambda)$ by the relation $\varepsilon(\lambda)=1-\rho(\lambda)$. Thus, Salisbury and Elvidge's datasets form the first and, to date, the only open libraries of leaf emissivity. In most publications, the range from 0.95 to 0.98 is considered as an accepted order of magnitude for leaf emissivity in the 8–14 μm region. Ribeiro da Luz (2006) and Ribeiro da Luz & Crowley (2007, 2010) recently investigated leaf optical properties in the thermal infrared by completing a comprehensive work between 8 μm and 14 μm. They show that reflectance is linked to leaf surface properties and that plant species identification can be achieved using leaf spectral signatures. Leaf transmittance $\tau(\lambda)$ in the thermal infrared is generally supposed to be negligible. The only measurements of leaf reflectance and transmittance spectra between 0.3 μm and 25 μm that we know of were published by Gruninger et al. (1992). They state that a leaf cannot be regarded as an opaque medium between 4 μm and 5 μm, i.e., a leaf transmits part of the incoming radiation. In accordance with Kirchhoff's law the emissivity should then be calculated by the relation $\varepsilon(\lambda)=1-\rho(\lambda)-\tau(\lambda)$ (DeWitt & Nutter, 1988). For instance the emissivity of a leaf whose reflectance and transmittance equal 0.134 and 0.179 at 5 μm should be $0.687=1-0.134-0.179$ and not $0.866=1-0.134$. Olioso et al. (2007) who analyzed integrated emissivities acquired on drying plant canopies or drawn from the ASTER spectral library (http://speclib.jpl.nasa.gov/), emphasize the need for better knowledge of leaf optical properties in the infrared as a function of water content. The dataset of Fabre et al. (in press) containing reflectance spectra of cherry, sorghum, and sunflower leaves at different stages of drying is one of the first that directly link leaf optical properties to leaf water content in the 2.5–15 μm wavelength domain. However to date, the scarcity of experimental measurements and the complexity of the phenomena involved discouraged the development of a leaf optical properties model over this wavelength range.

The PROSPECT model (Jacquemoud & Baret, 1990; Féret et al., 2008) currently simulates the reflectance and transmittance spectra of plant leaves in the reflected solar energy domain as a function of their biochemical content (photosynthetic pigments, water, and dry matter) and a structure parameter that controls multiple scattering within the mesophyll. The model extension to longer wavelengths, beyond 2.5 μm, requires measurements of continuous spectra of leaves that display a wide range of anatomy and water content. As mentioned above, there is a lack of such data. The first part of this paper provides the background needed to understand leaf optical properties and presents a dataset of leaf reflectance and transmittance spectra acquired over the 0.4–14 μm wavelength region along with associated water and dry matter contents. Next, the physical bases of the extended version of PROSPECT, named PROSPECT-VISIR, are detailed and discussed. PROSPECT-VISIR consists of the introduction of the Fresnel complex coefficients and the addition of a top layer. The last section develops the calibration and verification of the model using this dataset.

2. Background

2.1. Leaf structure

Angiosperm leaves are made of one to several mesophyll layers sandwiched between the upper and lower epidermis. The epidermis is covered by a cuticle and an epicuticular wax layer of varying thickness, which tends to modify the surface roughness (Riederer & Müller, 2006; Ribeiro da Luz & Crowley, 2007). While most of the cells of the epidermis and mesophyll are ~20 μm in diameter, the wax particles are 1 μm (Ribeiro da Luz, 2005). Fig. 1 shows the anatomical structure of a typical dicot leaf, the mesophyll of which is specialized in two distinct tissues, the palisade and spongy mesophylls. This structure plays a major role in leaf optical properties as explained below.

2.2. Reflectance spectroscopy

The interpretation and modeling of VNIR–SWIR, MWIR and TIR reflectance spectra need a quick review of some physical processes. It is critical to list the main parameters that determine the spectral variation of reflectance: the complex refractive index $\tilde{n}(\lambda)=n(\lambda)+i\kappa(\lambda)$, where $n(\lambda)$ is the refractive index and $\kappa(\lambda)$ is related to the absorption coefficient at wavelength λ, the cell or particle size D and cell/particle arrangement in the mesophyll. Considering typical values of 20 μm for D in plant leaves, the laws of geometric optics apply in the whole 0.4–14 μm domain. Then, the total scattered light corresponds to the sum of the surface reflected light and the light that is first refracted and then transmitted out of the particles (Appendix A). Fig. 2 illustrates the interactions between incident light and spherical particles. Pathways (1) and (2) stand for rays that undergo only surface reflection, i.e., that never penetrate the particles. Due to surface roughness, they may be reflected in any direction, regardless of the direction of incident radiation. They are called specular rays in contrast with volume rays that are transmitted through one or more particles. Pathways (3) and (4) show that volume rays may also exit the mat surface at any angle. According to the absorption properties of the medium, the total reflectance displays a predominant surface scattering or volume scattering, which produce spectral features that have symmetric shapes. Vincent & Hunt (1968) explain that a strong absorption (opaque region) induces a maximum of specular reflectance and a minimum of volume reflectance (Appendix B). The prevalence of one behavior over the other actually depends both on the absorption level and on the size and arrangement of the particles. The cavity effect, which results from multiple reflections between surface asperities, reduces the fraction of specular reflectance compared to volume reflectance. Although the laws of physics apply in the whole optical domain, these effects change from the VNIR–SWIR to the MWIR, and from the MWIR to the TIR, due to fluctuations of the absorption coefficient and the size parameter $X=\pi D/\lambda$. Some of these effects that do not occur or have little apparent influence on VNIR–SWIR reflectance cannot be neglected in the MWIR and TIR (e.g.