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Vegetation optical depth and scattering albedo retrieval using time series of dual-polarized L-band radiometer observations

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ABSTRACT

Passive microwave measurements have the potential to estimate vegetation optical depth (VOD), an indicator of aboveground vegetation water content. They are also sensitive to the vegetation scattering albedo and soil moisture. In this work, we propose a novel algorithm to retrieve VOD and soil moisture from time series of dual-polarized L-band radiometric observations along with time-invariant scattering albedo. The method takes advantage of the relatively slow temporal dynamics of early morning vegetation water content and combines a number of consecutive observations to estimate a single VOD. It is termed the multi-temporal dual channel algorithm (MT-DCA). The soil dielectric constant (directly related to soil moisture) of each observation is also retrieved simultaneously. Additionally, the method retrieves a constant albedo, thereby providing for the first time information on global single-scattering albedo variations. The algorithm is tested using three years of L-band passive observations from the NASA Aquarius sensor. The global VOD distribution follows expected gradients of climate and canopy biomass conditions. Its seasonal dynamics follow expected behavior based on precipitation and land cover. The retrieved VOD is closely related to coincident cross-polarized backscatter coefficients. The VOD and dielectric retrievals from MT-DCA are compared to those obtained from implementing the commonly used Land Parameter Retrieval Model (LPRM) algorithm and shown to have less high-frequency noise. There is almost as much variation in MT-DCA retrieved albedo between pixels of a given land cover class than between land cover classes, suggesting the common approach of assigning albedo based on land cover class may not capture its spatial variability. Globally, albedo appears to be primarily sensitive to woody biomass. The proposed algorithm allows for a more accurate accounting of the effects of vegetation on radiometric soil moisture retrievals, and generates new observations of L-band VOD and effective single-scattering albedo. These new datasets are complementary to existing remotely sensed vegetation measurements such as fluorescence and optical-infrared indices.

1. Introduction

Our ability to close the Earth's carbon budget and predict feedbacks in a changing climate depends on knowing where, when and how much carbon dioxide and water vapor is exchanged between the land surface and the atmosphere. Both these fluxes are intimately tied to vegetation: roughly 60% of global land evapotranspiration fluxes occur through plant-mediated transpiration (Schlesinger & Jasechko, 2014), and vegetation photosynthesis response to increasing CO_2 concentrations is the biggest carbon cycle feedback in climate models (Ciais et al., 2013; Schimel, Stephens, & Fisher, 2014). Microwave radiometric data at L-band are sensitive to both vegetation characteristics and soil moisture. In particular, radiometric observations are sensitive to vegetation optical depth (VOD). Passive soil moisture retrieving satellites at L-band like the NASA Soil Moisture Active Passive (SMAP) (Entekhabi et al., 2010), the ESA Soil Moisture and Ocean Salinity (SMOS) (Kerr et al., 2012), and the NASA/CONAE Aquarius-SAC/D (Le Vine, Lagerloef, Colomb, Yueh, & Pellerano, 2007) must properly account for the effect of VOD on observations in order to accurately retrieve soil moisture. Furthermore, microwave VOD estimates have previously been shown to be useful indicators for understanding vegetation state and variability, complementing the information provided by optical indices (Andela, Liu, van Dijk, de Jeu, & McVicar, 2013; Poulter et al., 2014; Zhou et al., 2014). VOD is also a potentially

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useful tool for crop monitoring (Patton & Hornbuckle, 2013) that could help detect crop water stress before optical sensors can (Van Emmerik, Steele-Dunne, Judge, & van de Giesen, 2014). VOD is directly proportional to total vegetation water content (VWC), with a constant of proportionality that is dependent on frequency and canopy structure. Since total VWC is related to biomass (it influences the amount of available storage for water), VOD has been used as an indicator of biomass in the past (e.g. Liu et al., 2015). However, since vegetation water content also varies depending on the soil water availability (even in the absence of changes in biomass), VOD can also be interpreted as an indicator of vegetation water content useful for studying plant responses to hydrologic stress.

The VOD measured by passive microwave sensors is an integrated measure of vegetation water content and structural effects. The total VOD is always less sensitive to the lower canopy layers than to the upper canopy layers, although the exact rate of attenuation of the microwave signal depends on the canopy. The rate of attenuation is also frequency-dependent (Ulaby, Moore, & Fung, 1986), although few studies have been done comparing the effect of frequency on the measured VOD. If differences in canopy penetration between observations at different frequencies are ignored, different satellites can be combined into a single long-term record of VOD (Owe, de Jeu, & Holmes, 2008; Liu, de Jeu, McCabe, Evans, & van Dijk, 2011). Such an existing record has been used as a vegetation indicator complementary to optical indices (Shi et al., 2008; Andela et al., 2013). VOD retrievals from recently launched L-band radiometers such as SMOS and SMAP could be used to extend long-term multi-frequency VOD records (Van der Schalie, Parinussa, et al., 2015). Additionally, vegetation water content, and thus the amount of plant stress inferred by measuring vegetation water content, generally varies throughout the canopy (e.g., Hellkvist, Richards, & Jarvis, 1974; Bohrer et al., 2005; Janott et al., 2011). Studies of vegetation water content based on remote sensing may thus be better served by using VOD from lower frequencies such as L-band, which attenuate less quickly and are more sensitive to lower canopy layers. Furthermore, the development of VOD datasets and of joint VOD and soil moisture retrieval algorithms at L-band is of interest because of the greater soil sensing depth of these frequencies.

Several approaches exist for the simultaneous retrieval of vegetation optical depth and soil moisture that is necessary at L-band. Both variables can be simultaneously derived from a snapshot of measurements by using information from observations at both horizontal and vertical polarizations (Jackson, Hsu, & O'Neill, 2002; Meesters, de Jeu, & Owe, 2005). However, because the two polarizations are closely correlated, such a retrieval is sensitive to noise, as will be further explained in Section 2. If multi-angular data are available, such as in the case of SMOS, these can be used to further constrain the retrievals (Cui, Shi, Du, Zhao, & Xiong, 2015). Alternatively, observations from multiple overpasses can be combined into a single retrieval. Such a multi-temporal approach rests on the assumption that vegetation state as reflected in VOD is likely to change more slowly than soil moisture, and is constant over adjacent overpasses.

The use of a time series approach also allows for the retrieval of the single-scattering albedo, the amount of power scattered by the vegetation cover. The value of albedo is often assumed to be independent of polarization and constant as a function of land cover (Van de Griend & Owe, 1994; O'Neill, Chan, Njoku, Jackson, & Bindlish, 2012; Kerr et al., 2011). Its values are often close to zero (Wigneron et al., 2004). A correctly chosen effective value of the single-scattering albedo allows accounting for higher-order scattering effects, which are especially important over moderate to dense vegetation cover (Kurum et al., 2012). Many of the land-cover dependent values used in the literature are therefore in some sense fitting-parameters (Wigneron et al., 2004; Kurum, 2013). However, a land-cover dependent assignment is sensitive to errors in the land cover classifications, as well as to variations in albedo within a certain land cover type. A sensitivity study has shown that errors in assumed albedo add more uncertainty to single-incidence angle VOD and soil moisture retrievals than errors in soil and canopy temperature, soil roughness, or bias or noise in observed brightness temperature (Davenport, Fernandez-Galvez, & Gurney, 2005). The ability to retrieve albedo directly rather than relying on assumptions about its value may therefore significantly improve both VOD and soil moisture retrievals.

In this study, we introduce a new multi-temporal algorithm for simultaneous retrieval of vegetation optical depth, effective single-scattering albedo, and soil dielectric constant using dual-polarized single incidence-angle observations at L-band frequencies. The method is referred to as the multi-temporal dual channel algorithm (MT-DCA) and tested using three years of L-band passive observations from the Aquarius sensor. The paper is organized as follows. Section 2 motivates the need for a time series algorithm to avoid compensating errors when retrieving multiple parameters from a snapshot of dual-polarized observations. Section 3 describes the algorithm design. The testing methodology and datasets used in this paper are described in Sections 4 and 5, respectively. Retrieval results are shown in Section 6 and discussed in Section 7.

2. Algorithm motivation

2.1. Classical retrieval approach

Almost all radiometric soil moisture retrieval approaches are based on the so-called τ–ω model, a zeroth-order solution of the radiative transfer equations describing the emission of the land surface

$$\begin{aligned} T_{B_p} &= T_B^{soil} + T_B^{canopy} \\ &= T_s(1-r_p)\gamma + T_c(1-\omega)(1-\gamma)(1+r_p\gamma). \end{aligned} \quad (1)$$

The T_{B_p} is the brightness temperature at polarization p, which is either horizontal (H) or vertical (V), T_s is the effective land surface temperature, r_p is the rough surface reflectivity, and T_c is the canopy temperature. The quantity γ is the vegetation transmissivityand ω is the vegetation single-scattering albedo, the fractional power scattered by the vegetation.

The vegetation transmissivity γ accounts for attenuation of the emission through the vegetation layer. It is related to the vegetation optical depth,

$$\gamma = \exp\left(-\frac{\text{VOD}}{\cos\theta}\right), \quad (2)$$

where θ is the measurement incidence angle. When the VOD equals 0, there is no vegetation attenuation on the microwave emission from the soil and the corresponding γ is 1. The VOD increases with vegetation density; over dense vegetation, γ approaches 0 and the microwave emission is dominated by vegetation. VOD is commonly assumed to be linearly proportional to vegetation water content (Jackson & Schmugge, 1991; Van De Griend & Wigneron, 2004),

$$\text{VOD} = b \cdot VWC, \quad (3)$$

where the constant of proportionality b depends on the vegetation structure.

The rough surface reflectivity can be decomposed as $r_p = r_p^* \exp(-h\cos(\theta)^n)$, where r_p^* is the reflectivity of the flat (smooth) soil, h is the roughness parameter, which is assumed to be linearly related to the root-mean-square surface height of the soil surface, and n is an angular value (Ulaby & Long, 2014). The Fresnel equations relate r_p^* to the complex dielectric constant k of the soils, which is in turn governed by soil moisture and soil texture.

Most soil moisture retrieval algorithms rely on the same (or an equivalent) mathematical problem. In order to determine the vector of unknown parameters X from a set of observations, the mismatch