



A linear physically-based model for remote sensing of soil moisture using short wave infrared bands

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ABSTRACT

Technological advances in satellite remote sensing have offered a variety of techniques for estimating surface soil water content as a key variable in numerous environmental studies. Optical methods are particularly valuable for remote sensing of soil moisture since reflected solar radiation is the strongest passive signal available to satellites and thus observations at optical wavelengths are capable of providing high spatial resolution data. Since remote sensors do not measure soil water content directly, mathematical algorithms that describe the connection between the measured signal and surface water content must be derived. Here, we present a physically-based soil moisture retrieval model in the solar domain (350–2500 nm) that is based on the Kubelka–Munk two-flux radiative transfer theory. The model is designed to describe diffuse reflectance from a uniform, optically thick, absorbing and scattering medium. The theory suggests a linear relationship between a transformed reflectance and soil water content in the short wave infrared bands (e.g. band 7 of Landsat and MODIS satellites) providing an easy-to-use algorithm in these bands. Accuracy of this model was tested and preliminarily verified using laboratory-measured spectral reflectance data of different soils. Further studies on potentials and challenges of this model for large-scale application using optical satellites data remain a topic of ongoing research.

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1. Introduction

Surface soil moisture is a fundamental state variable controlling a wide range of processes occurring at the land–atmosphere interface including water infiltration and runoff, evaporation, heat and gas exchange, solute infiltration, erosion, etc. The importance of measuring and monitoring surface soil moisture at various spatial scales has been highlighted by many authors (e.g. Ochsner et al., 2013; Robinson et al., 2008; Vereecken et al., 2008; Wang & Qu, 2009).

Despite recent advances in electromagnetic (EM) sensing capability, whether ground-based (Jones, Wraith, & Or, 2002; Jones et al., 2005; Bogaen, Huisman, Oberdorster, & Vereecken, 2007; Vaz, Jones, Meding, & Tuller, 2013) or remotely deployed (de Jeu et al., 2008; Huisman, Hubbard, Redman, & Annan, 2003; Kornelsen & Coulbaly, 2013; Njoku, Jackson, Lakshmi, Chan, & Nghiem, 2003), accurate assessment of surface water content is still a challenging task due to complex spatiotemporal variability of soil moisture in addition to scaling issues (Brocca, Melone, Moramarco, & Morbidelli, 2010; Crow et al., 2012;

Landrum, 2013; Ojha, Morbidelli, Saltalippi, Flammini, & Govindaraju, 2014; Western, Grayson, & Blöschl, 2002; Western et al., 2004; Wu & Li, 2009).

The interaction of EM radiation with soils at various wavelengths has been shown to be significantly correlated with surface moisture content. Hence, various remote sensing (RS) methods have been developed in different regions of the EM spectrum. These methods may be classified into three major groups (Verstraeten, Veroustraete, & Feyen, 2008; Wang & Qu, 2009):

- i) **Optical methods.** Methods using optical (or solar domain) bands (wavelengths between 0.35 and 2.5 μm) in which the reflected radiation of the sun from the Earth's surface, known as reflectance, is measured (Ben-Dor et al., 2009). Reflectance is commonly formulated as a function of soil moisture content using empirical (regression) analysis (Wang & Qu, 2009).
- ii) **Thermal infrared methods.** Methods in which the thermal emission of the Earth (wavelengths between 3.5 and 14 μm) is measured (Wang & Qu, 2009). The estimation of surface soil moisture using remotely sensed thermal wavebands primarily relies on the use of soil surface temperature measurements, either singly by the thermal inertia method (Verstraeten, Veroustraete, van der Sande, Grootaers, & Feyen, 2006) or in combination with vegetation indices, for example using the so-

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called “triangle method” (Carlson, 2007; Carlson, Gillies, & Perry, 1994).

- iii) **Microwave methods.** Methods in which the intensity of microwave emission (wavelengths between 5 and 1000 mm) is measured. The fundamental basis of microwave RS of soil moisture is the large contrast between the dielectric properties of water (~ 81) and other soil constituents (< 4). As surface soil moisture content increases, the dielectric constant of the soil–water mixture increases significantly, and this change is readily detectable by microwave sensors (Njoku & Kong, 1977).

Microwave RS techniques have demonstrated the most promising ability for globally monitoring of soil moisture variations (e.g. Al-Yaari et al., 2014). Unlike the thermal and optical sensing, there is significant penetration into the soil at lower microwave frequencies. Measurements at these frequencies are not impeded by clouds or darkness (Njoku & Entekhabi, 1996). Most microwave models have a physical basis, although they commonly include some empirical (calibration) parameters to account for surface roughness which causes perturbation of the microwave signal (Shi et al., 2006).

Despite the benefits of microwave methods, optical and thermal methods are also essential in remote sensing of soil moisture, because of their capability for providing very high spatial resolution maps, especially when compared with the very coarse output of microwave sensors. Therefore, optical/thermal satellites data provide favorable means for downscaling (i.e. improving spatial resolution) microwave satellite estimates of soil moisture (Merlin, Walker, Chehbouni, & Kerr, 2008; Merlin et al., 2013; Piles et al., 2011).

In this regard, thermal approaches have received more attention than optical. Although thermal RS methods are powerful and have been developed based on physical rationale, the methods are often empirical and depend on local meteorological conditions, such as wind speed, air temperature, and humidity (Nemani, Pierce, Running, & Goward, 1993), and thus measurement results vary temporally and with land cover types (Czajkowski, Goward, Stadler, & Waltz, 2000). In other words, the relationship between soil moisture and surface temperature is highly dependent on atmospheric conditions. Therefore, in most cases these methods require ground measurements for calibration of the empirical fitting parameters (Yang, Wu, Shi, & Yan, 2008).

This limitation motivated us to revisit the optical RS technique to potentially develop a physically-based method with minimal calibration requirements. We aimed to balance between physical significance and practical application, where such a model is lacking among existing optical RS methods.

In terms of physical significance, three classes of optical models may be distinguished in the literature. The first class includes simple regression models for formulating soil moisture–reflectance relationship (Liu et al., 2002; Liu et al., 2003; Lobell & Asner, 2002; Muller & De'camps, 2000; Nolet, Poortinga, Roosjen, Bartholomeus, & Ruessink, 2014; Persson, 2005; Skidmore, Dickerson, & Schimmelpennig, 1975; Zhu, Wang, Shao, & Horton, 2011). Although such models are established based on a physical understanding of the impact water has on the soil spectrum from light absorption and refraction at the water–mineral interfaces, they commonly contain physically meaningless empirical parameters and thus require soil information a priori in order to be solved (i.e. calibration). Models such as that of Whiting, Li, and Ustin (2004) may be distinguished as a second category having a stronger physical basis than the first group. Such models are based on a fit to a continuum of the soil water absorption bands, which are directly related to the amount of water in the surface soil layer. In that sense, these models relate the water content to a physical optical property rather than the change in reflectance at one wavelength and the observation is potentially independent of the soil type (Haubrock, Chabrilat, Lemmertz, & Kaufmann, 2008). Models introduced by Twomey, Bohren, and Mergenthaler (1986), Bach and Mauser (1994) and

Philpot (2010) are among a few models in the third class which were fully formulated based on physics of radiative transfer. These models usually suffer from difficult-to-determine input information.

We could also consider an additional class of models being developed nowadays based on machine learning techniques such as artificial neural networks and support vector machine (Hassan Esfahani, Torres-Rua, Jensen, & McKee, 2015; Zaman, McKee, & Neale, 2012). Commonly considering both optical and thermal bands, these models provide powerful tools for inferring surface soil moisture in complex/heterogeneous media (e.g. rough vegetated surfaces). However, these models are fully black-box with no physical origin and hence require a vast database for calibration and even then are limited to site-specific applications.

In the following, we present a simple model with physically definable parameters based on the Kubelka and Munk (1931) theory of reflectance. This model combines the benefits of both the first and third classes simultaneously, as it is in the form of a simple regression model, but is derived directly from a radiative transfer model and its parameters can be obtained either from fitting or from direct measurement. As an added advantage, and supported by both theory and experimental data, the proposed model reduces to a linear model at short wave infrared (SWIR) wavelengths offering a straightforward method for RS of soil moisture in these bands.

2. Theoretical considerations

2.1. Kubelka–Munk theory

Kubelka and Munk (1931) (KM hereinafter) developed a simple theory describing radiative transfer in an absorbing and scattering layer, considering a downward and an upward light propagation flux (I and J , respectively), perpendicular to the layer (Fig. 1). The diffuse (volume) reflectance could then be modeled incorporating both absorption by soil particles and water films and light scattering due to differences in the refractive index between soil particles and the surrounding water and air. The KM model can be derived directly from the radiative transfer equation (Sandoval & Kim, 2014; Thennadil, 2008) and thus has a good physical basis underlying its simplicity.

The KM model assumes that: (i) the layer exhibits infinite lateral extension (so that edge effects can be neglected), (ii) the light absorbing and scattering particles are uniformly distributed in the layer, (iii) particle dimensions are much smaller than the layer thickness, d , and (iv) the whole layer is homogeneously illuminated with a monochromatic diffuse light source (Ciani, Goss, & Schwarzenbach, 2005).

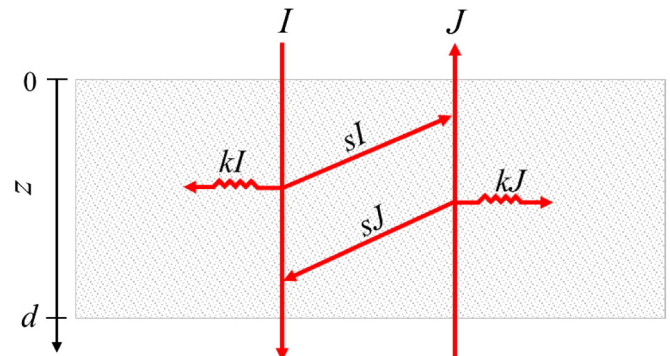


Fig. 1. Visualization of the Kubelka–Munk model, where I and J are the two light fluxes in opposite directions and k and s are the absorption and scattering coefficients, respectively (after Ciani et al., 2005).

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