Satellite remote sensing applications for surface soil moisture monitoring: A review

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Abstract Surface soil moisture is one of the crucial variables in hydrological processes, which influences the exchange of water and energy fluxes at the land surface/ atmosphere interface. Accurate estimate of the spatial and temporal variations of soil moisture is critical for numerous environmental studies. Recent technological advances in satellite remote sensing have shown that soil moisture can be measured by a variety of remote sensing techniques, each with its own strengths and weaknesses. This paper presents a comprehensive review of the progress in remote sensing of soil moisture, with focus on technique approaches for soil moisture estimation from optical, thermal, passive microwave, and active microwave measurements. The physical principles and the status of current retrieval methods are summarized. Limitations existing in current soil moisture estimation algorithms and key issues that have to be addressed in the near future are also discussed.

Keywords surface soil moisture, monitoring, satellite, remote sensing

1 Introduction

Surface soil moisture is the water that is in the upper 10 cm of soil, whereas root zone soil moisture is the water that is available to plants, which is generally considered to be in the upper 200 cm of soil (http://www.ghcc.msfc.nasa.gov/landprocess/lp_home.html). Compared with the total amount of water on the global scale, this thin layer of soil water may seem insignificant; nonetheless, it is of fundamental importance to many hydrological, biological, and biogeochemical processes. The role of soil moisture in the top 1 to 2 m of the Earth’s surface has been widely recognized as a key variable in numerous environmental studies (Walker, 1999), including meteorology, hydrology, agriculture, and climate change (Topp et al., 1980; Jackson et al., 1987; Fast and McCorcle, 1991; Engman, 1992; Entekhabi et al., 1993; Betts et al., 1994; Saha, 1995; Su et al., 1995). Therefore, it is important to accurately monitor and estimate spatial and temporal variations of soil moisture.

Direct observations of soil moisture are currently restricted to discrete measurements at specific locations, and such point-based measurements do not represent the spatial distribution because soil moisture is highly variable both spatially and temporally (Engman, 1991; Wood et al., 1992) and are therefore inadequate to carry out regional and global studies (http://www.geotimes.org/may02/WebExtra0503.html). Technological advances in satellite remote sensing have offered a variety of techniques for measuring soil moisture across a wide area continuously over time (Engman, 1990). Researches in soil moisture remote sensing began in the mid 1970's shortly after the surge in satellite development. Subsequent research effort has occurred along many diverse paths, spanning most of the electromagnetic spectrum from optical to microwave region. Numerous researchers have shown that near-surface soil moisture content can be measured by optical and thermal infrared remote sensing, as well as passive and active microwave remote sensing techniques (Walker, 1999). The primary difference among these techniques are the wavelength region of the electromagnetic spectrum used, the source of the electromagnetic energy (Walker, 1999), the response measured by the sensor, and the physical relation between the response and the soil moisture content. Table 1 summarizes the relative merits of the different remote sensing techniques for surface soil moisture estimation.

As remote sensors do not measure soil moisture content...
directly, mathematical models that describe the connection between the measured signal and soil moisture content must be derived (de Troch et al., 1996). Usually, the forward model simulates the instrument’s response on the basis of relevant land surface parameters (Walker, 1999). A method is then developed for inverting the model by minimizing the residual error between the model simulated and sensor-measured values.

This review presents a comprehensive overview of the commonly used methodologies for soil moisture estimation, including their physical principles, advantages, and constraints from optical, thermal infrared, passive microwave, and active microwave measurements. Since the basic ideas inherent in the model inversion are similar no matter which spectrum domain the sensor uses, the overview of the model inversion approaches is only given in the passive microwave section.

### 2 Optical remote sensing for soil moisture estimation

Remote sensing of soil moisture content using the solar domain with wavelengths between 0.4 and 2.5 μm measures the reflected radiation of the sun from the Earth’s surface, known as reflectance (Sadeghi et al., 1984). Compared with microwave and thermal infrared domains that have been most commonly used for soil moisture estimation (Price, 1980; Wuthrich, 1994, Engman and Chauhan 1995, Jackson et al., 1995), little attention has been paid to the use of the solar domain (Liu et al., 2003). However, many investigations have shown that the solar domain also provides the capability for soil moisture estimation (Dalal and Henry, 1986; Schlesinger et al., 1996; Sommer et al., 1998; Leone and Sommer, 2000).

The effect of soil moisture on its reflectance has long been recognized by many scientists. Early in 1925, Angstrom found a decrease in reflectance when soil moisture increases in his measurements (Angstrom, 1925). Thereafter, familiar darkening of soil on wetting has been reported by other researchers (Curcio and Petty, 1951; Bowers and Hanks, 1965; Stoner and Baumgardner, 1980; Ishida et al., 1991). Several empirical approaches have been proposed to describe the connection between soil surface reflectance and moisture contents. Bowers and Smith (1972) observed a linear relationship between the absorption in a water absorption band and soil water content. A factor of about 2 for all soils except sands was employed by Jackson et al. (1976) to account for the reflectance reduction due to the increase of soil moisture content. By using absorbance values measured in the near-infrared, Dalal and Henry (1986) estimated soil moisture with accurate results over a range of soil samples. These empirical approaches, however, provide only a poor indication of soil moisture content, since the spectral characteristic of a soil also depends on numerous other factors, such as mineral composition, organic matter, soil texture, and surface roughness (Asner, 1998; Ben-Dor et al., 1999), causing wide variations when they are applied to other localities outside the calibration conditions.

Lobell and Asner (2002) developed a physical model to explain the soil reflectance variations due to moisture change based on their analysis of the reflectance for four different soils at various moisture contents. The soil reflectance at a particular wavelength is modeled as an exponential function of the volumetric soil moisture. Such nonlinear equations are representative of the physical processes underlying the relationship, i.e., Beer’s Law for absorption in random homogenous media (Liu et al., 2002). Since experiments performed by Lobell and Asner involved measuring soil reflectance under various moisture conditions, their model captures both the absorption and scattering effects of soil moisture (Dasgupta, 2007). Similar exponential models were proposed by Liu et al. (2002) to obtain a robust estimate of soil moisture.

Liu et al. (2003) analyzed 18 different soils that represent a large range of permanent soil characteristics and investigated the potential of estimating soil moisture

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