MICROWAVE REMOTE SENSING OF SOIL WATER: RECENT ADVANCES AND ISSUES

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ABSTRACT. *Remotely sensed observations at microwave wavelengths are sensitive to spatio-temporal changes in near-surface soil water. This near-surface soil water information derived using various microwave techniques can be related to soil water in the root zone, one of the most critical parameters in agriculture, through hydrology/crop models. This article provides a brief review of approaches for using microwave observations and discusses some major challenges that still remain in using these observations for soil water studies.*

Keywords. *Crop models, Hydrologic models, Microwave remote sensing, Radar, Radiometry, Soil water.*

Soil water content in the root zone is arguably the most important parameter in agriculture. It is a primary driver for hydrological processes, including evapotranspiration, infiltration, runoff, and recharge, as well as a critical factor in crop growth and yield. Accurate estimate of water in the root-zone is essential for modeling hydrologic and nutrient fluxes and states in agricultural terrains and for modeling effects of water stress on crops. Remote sensing provides observations of hydrologic conditions at different spatio-temporal scales. There are two steps involved in utilizing remote sensing observations for root-zone soil water estimation in agricultural terrains. The first step is to use remote sensing observations to obtain surface/near-surface soil water information, and the second step is to vertically resolve or link this information to root-zone soil water through hydrology/crop models. Microwave remote sensing can be highly sensitive to soil water content in the upper few centimeters. Satellite-based microwave observations can provide spatial and temporal distributions of global soil water at spatial resolutions of hundreds of meters (radar) to tens of kilometers (radiometry), and temporal resolutions of twice daily (radiometry) to a several weeks (radar). This article focuses on recent advances and some major challenges in estimating root-zone soil water using microwave remote sensing observations of near-surface soil water.

MICROWAVE REMOTE SENSING OF SOIL WATER

Remotely sensed observations in the microwave region of the electromagnetic spectrum, particularly at wavelengths above the Debye relaxation of liquid water (~3 cm), are sensitive to liquid water content in the upper few centimeters of the soil (henceforth near-surface soil water). This sensitivity is due to a large difference between the refractive indices of dry soil and water at these wavelengths. The typical value of the index for a dry soil is about 2, while that of water is close to 9. In addition, the microwave observations are independent of solar radiation, clouds, and light rain, allowing for estimates of soil water during day and night and ignoring atmospheric effects (Ulaby et al., 1981). For soil water studies, observations at wavelengths around 20 cm are ideal for radiometric observations because the region falls among the lowest protected radio astronomy bands, with minimal cosmic and ionospheric radiation (see figure 5.9 in Ulaby et al., 1981). The electromagnetic radiation at these wavelengths has the further advantage of penetrating dense vegetation cover.

Microwave remote sensing involves two techniques: passive, where natural microwave emission or brightness temperature of a terrain is observed using a radiometer, and active, where backscattered/reflected power from a terrain is compared to the transmitted signal using a radar, as shown in figure 1. Brightness temperature (T_B) observed by radiometer is the sum of contributions from the sky (extraterrestrial and atmospheric, $T_{B\mathrm{sky}}$), the soil, ($T_{B\mathrm{soil}}$), and the vegetation ($T_{B\mathrm{veg}}$) (Ulaby et al., 1981), as shown in figure 1a. At the wavelength of 20 cm, $T_{B\mathrm{sky}}$ of 2 to 3 K is very small and is often ignored. $T_{B\mathrm{soil}}$ is a function of emissivity (e) and the effective temperature of the soil. Soil emissivity is given by $e = 1 - R$, where R is the hemispherical-directional reflectivity of the soil at microwave wavelengths. For a soil whose surface is smooth with respect to microwave wavelengths, R is the familiar Fresnel reflectivity, which is dependent on refractive index and incidence angle. This dependence of soil water on the index of refraction is the basis for microwave radiometry's sensitivity to soil water. $T_{B\mathrm{veg}}$ is a function of canopy temperature, opacity, and scattering properties.

Power received (P_r) by radar depends on the radar backscattering cross-section (σ^0) of the terrain. The cross-section is the sum of scattering from the soil surface (σ^0_{soil}), volume scattering from the vegetation (σ^0_{veg}), and scattering interaction between soil and vegetation (σ^0_{sv}) (Ulaby et al., 1981), as shown in figure 1b. The σ^0_{soil} is a function of the reflectiv-

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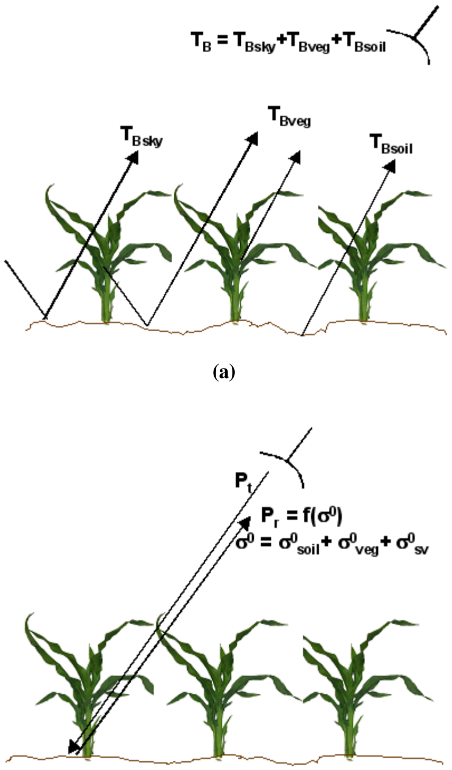

(a)

(b)

Figure 1. Components of microwave observations of an agricultural terrain: (a) passive (brightness temperature using a radiometer), and (b) active (power received using a monostatic radar).

ity of the soil and is highly sensitive to surface roughness. The σ^0_{veg} is a function of canopy opacity and geometry. For a mature crop, σ^0_{veg} could comprise a significant portion of σ^0.

Both the passive and the active techniques measure radiation quantities that are functions of the soil's index of refraction, and exhibit similar sensitivities to soil water (Du et al., 2000). However, because radar backscatter is highly sensitive to soil surface roughness and volume scattering within the vegetation, these effects produce a much larger dynamic range in σ^0 than that produced due to the effects of changes in soil water. This makes it difficult to recognize the contributions of soil water in the backscattered signal to obtain absolute soil water estimates. For this reason, the passive technique is more widely used for soil water studies and is discussed in greater detail in this article.

MICROWAVE OBSERVATIONS FOR SOIL WATER STUDIES

Three approaches are used to obtain near-surface soil water information from microwave observations. The first approach involves soil water retrieval through semi-empirical techniques. A widely used passive technique involves estimation of T_B using a semi-empirical model, where T_B is a function of microwave emissivity and effective temperature of the terrain (Kerr et al., 2001; Njoku et al., 2003; Wigneron et al., 2003; Drusch et al., 2004; Crow et al., 2005). Figure 2 shows an example of near-surface soil water derived using such a method, where observed T_B values were obtained from an airborne radiometer (Le Vine et al., 1994) at a wavelength of 20 cm with a spatial resolution of 200 m (Jackson et al., 1995). A widely used active technique involves developing simple regressions between observed soil water and σ^0 for test sites, and using the same relationship for "similar" terrain (e.g., Dubois et al., 1995; Biftu and Gan, 1999; Bindlish and Barros, 2000; Shoshany et al., 2000; Wickel et al., 2001; Oldak et al., 2003; Kelly et al., 2003; Thoma et al., 2006).

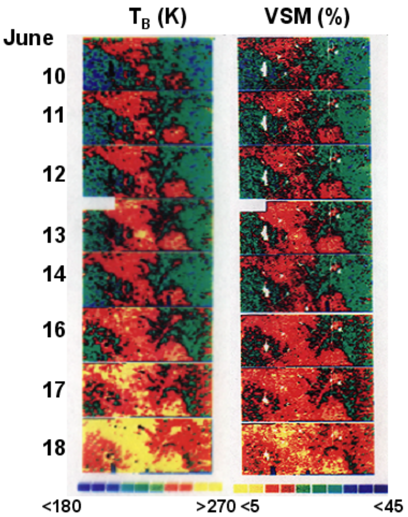

Figure 2. Airborne brightness temperatures at wavelength of 20 cm and derived soil water for the Washita '92 region in southwest Oklahoma (obtained from Jackson et al., 1995).

Such retrieved or derived near-surface soil water is often referred to as the soil moisture product or remotely sensed soil moisture. It is used in various hydrological or crop models for input, initialization, model evaluation, or for improvement of modeled estimates of water flux and transport, and hence root-zone soil water, through data assimilation (e.g., Entekhabi et al., 1994; Houser et al., 1998, Reichle et al., 2001, 2002; Crow and Wood, 2003; Moran et al., 2004; Drusch et al., 2005).

The second approach involves linking a microwave model with a hydrologic (e.g., Burke, 1997; Liou et al., 1999; Judge et al., 2007) or a crop model (e.g., Casanova et al., 2006), where the water and temperature profiles estimated by the latter models are used as inputs to the microwave model to estimate T_B. Because T_B is sensitive to near-surface water and temperatures, the hydrological and crop models are required to provide the microwave models with the profile estimates at high vertical resolution near the surface. Such linked models can be calibrated and evaluated using observations of T_B. This approach allows for improvement of modeled estimates of water flux and transport, and hence root-zone soil water, through assimilation of observed T_B rather than assimilation of the derived soil water product, following the first approach.

The third approach involves combined use of co-located/concurrent passive and active observations through various techniques (e.g., Chauhan and Lang, 1994; O'Neill et al., 1996; Chauhan, 1997; Njoku et al., 2002; Entekhabi et al., 2004; Zhan et al., 2006). Thus far, most of the techniques employing this approach use independent passive and active retrieval algorithms, as described for the first approach. The two soil water values thus derived are compared with one another (Entekhabi et al., 2004). In some techniques, active observations are used to calibrate or evaluate the vegetation scattering model to estimate canopy opacity and scattering, and passive retrieval algorithms use these estimates to obtain near-surface soil water (O'Neill et al., 1996).

CHALLENGES IN UTILIZING MICROWAVE OBSERVATIONS FOR SOIL WATER STUDIES

Even though significant technological and algorithmic advances have been made over the last three decades, major challenges still exist for more effective use of microwave remote sensing for soil water studies.

TECHNOLOGICAL CHALLENGES

Lack of satellite-borne radiometers operating at wavelengths (~20 cm) that are ideal for soil water studies is a major impediment to significant progress in the field. This lack of long-wavelength satellite radiometers is primarily due to the large antenna sizes required for these radiometers to achieve adequate spatial resolutions for climatological and hydrological applications (Ulaby et al., 1981; Leese et al., 2001). The longest wavelengths for satellite-based radiometers that can be used for soil water studies are 4.5 and 2.8 cm (AMSR-E) (Kawanishi et al., 2003), providing soil water estimates at an effective spatial resolution of 50 km. Of these, the observations at 4.5 cm near populated regions are corrupted by radio frequency interference from wireless communications.

Recent advances in aperture synthesis radiometry (LeVine et al., 1994) will enable satellite-based radiometric measurements with similar resolutions at longer wavelengths with a thinned array antenna. For example, the Soil Moisture Ocean Salinity (SMOS) mission by the European Space Agency, to be launched in 2008, will achieve 35 to 50 km spatial resolution at a wavelength of 20 cm, with approximately 4% of the number of elements required for a filled aperture array having the same spatial resolution (Kerr et al., 2001). In contrast, the spatial resolution of synthetic aperture radars is hundreds of meters (Moran et al., 2004) to achieve radiometric sensitivity equivalent to that of radiometers necessary for soil water studies.

Although the spatial resolution of SMOS is adequate for climatological studies, it is too coarse for applications in agricultural hydrology at the field or farm scale (Leese et al., 2001). At these scales, soil water exhibits high temporal and spatial variability. Much research has been conducted in developing statistical techniques to upscale and downscale these observations (e.g., Reichle et al., 2001). Significant technological advances, either in hardware or in data processing, are needed to reduce the resolution by an order of magnitude for satellite microwave radiometry to be useful for agricultural applications.

CHALLENGES IN DEVELOPMENT AND VALIDATION OF ALGORITHMS

Theoretical relationships between microwave remote sensing and soil water are well understood. These have been tested through numerous combined ground-based and airborne field investigations for different terrain types at different spatial scales. However, the seasonal components of these relationships require further investigations because most of these experiments were short-term experiments and did not cover seasonal variations in dynamic vegetation. Understanding the microwave signature of crops and its sensitivity to soil water during growing seasons is critical to its utility in agriculture. Recently, several field campaigns called Microwave Water and Energy Balance Experiments (MicroWEXs) were conducted over corn and cotton to obtain season-long observations of T_B along with various water/energy balance and soil/vegetation parameters (Judge et al., 2005; Casanova et al., 2005; Tien et al., 2007). Such long-term extensive datasets are rare because very few ground-based and airborne radiometers exist in the U.S. and worldwide for development, calibration, and validation of microwave algorithms. Recently, Krajewski et al. (2006) conceptualized a remote sensing observatory in an effort to improve such infrastructure.

Even though active observations are difficult to use for absolute estimate of soil water, they can be used to provide high-resolution estimates of changes in soil water over similar vegetation conditions (Narayan et al., 2006). Algorithms that combine active and passive observations can significantly improve soil water estimates. They take advantage of the complementary nature of these observations, with radar's high spatial resolution and high sensitivity to vegetation, and radiometer's high sensitivity to soil water and low sensitivity to vegetation. Scarcity of combined active/passive observations at various spatio-temporal scales for development and testing of integrated algorithms has been a major hurdle.

Integration of hydrologic and microwave observations is another major challenge. Typically, "operational" models are employed to provide soil water estimates, e.g., NOAH (Pan and Mahrt, 1987) and CLM (Dai et al., 2003). These models are highly parameterized with simplified biophysics, often using non-physically based parameters, to reduce the computational demands. In addition, the vertical resolution in the soil is too coarse to fully utilize microwave observations that are highly sensitive to water and temperature distribution in the top few centimeters. In contrast, bio-physically based models that have high vertical resolution near the soil surface are more complex, computationally intensive, and are primarily used as diagnostic models for algorithm development and validation (e.g., Judge et al., 2003; Whitfield et al., 2006). They use a large number of parameters that need to be estimated using site-specific calibration. There is a strong need for a category of bio-physically based models that consist of physically meaningful, measurable parameters but are computationally efficient enough to be used operationally. Biophysical fidelity of these parameters is particularly essential to ensure that each of the linked/integrated models use the same definitions for shared inputs and parameters. Significant computational advances have led to development of novel methodologies to conduct sensitivity analyses and reduce the number of unconstrained parameters that need site-specific calibration (Gupta et al., 1999). Continued computational advances and collaborations of scientists with significantly different expertise is critical to achieve operational models that can be better integrated directly with microwave observations (T_B or σ^0) to obtain real-time estimates of root-zone soil water.

CONCLUSIONS

Microwave remote sensing is highly sensitive to water and temperature distribution in the top few centimeters of the soil. This near-surface sensitivity to soil water can be linked to root-zone soil water through hydrologic or crop models.

Even though both the active and passive techniques exhibit similar sensitivity to soil water, active signals are noisier due to scattering within the vegetation and are difficult to use to obtain absolute soil water estimates. Integrating active and passive observations utilizes the complementary nature of both the techniques and can provide better soil water estimates. Scarcity of ground-based and airborne active/passive sensors and lack of satellite-borne sensors with optimum wavelength and spatial resolution for soil water studies are major impediments to significant progress in the field, including development and validation of algorithms.

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