Passive Microwave Remote Sensing of Soil Moisture

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ABSTRACT

The large dielectric constant of water at lower microwave frequencies causes a large change in the emissivity of soils as they become wet, from 0.95 when dry to less than 0.6 when wet. Numerous aircraft and field experiments have demonstrated that a 1.4 GHz (λ = 21 cm) radiometer is sensitive to moisture content of the surface soil layer for a wide range of vegetation conditions. This approach was studied in the Large Scale Field Experiments: HAPEX, FIFE and MONSOON 90 using an imaging microwave radiometer operating at a frequency of 1.42 GHz. During FIFE and Monsoon 90 a wide range of moisture conditions were present and it was possible to observe the drydown of the soil following heavy rains and to map its spatial variation. The quantitative agreement of microwave observations and ground measurements was very good. In HAPEX no significant rain fell and conditions were generally rather dry. Nevertheless, moisture variations due to irrigation were observed. In this paper we will present some results from the Monsoon 90 experiment.

KEYWORDS: microwave radiometers, soil moisture, dielectric constant

INTRODUCTION

Water stored in the soil serves as a reservoir for the evapotranspiration (ET) process on land surfaces. Therefore knowledge of the soil moisture content is important for partitioning the incoming solar radiation into latent and sensible heat components. There is no remote sensing technique which directly observes the amount of water in this reservoir. However microwave remote sensing at long wavelengths (λ > 10 cm) can give estimates of the moisture stored in the surface 5-cm layer of the soil. This approach is based on the large difference in the dielectric constant between water and dry soil (Schmugge, 1989 and Schmugge, 1986). Thus when water is added to dry soil the real part of the dielectric constant increases from about 3.5 to almost 30 for the wet soil. The resulting emissivity (ε) changes from 0.95 for a dry smooth soil to less than 0.6. This dependence of on moisture content has been observed with radiometers operating from tower, aircraft and spacecraft platforms. The sensitivity of ε to soil moisture depends on surface parameters such as roughness and vegetation cover and soil properties such as density and texture. The most important of these is vegetation cover, since it can totally mask the soil surface by absorbing radiation emitted from the soil surface and reemitting at its own temperature. At the 21-cm wavelength the amount of vegetation required for this screening is about 6 kg/m² in terms of its vegetation water content (Wv) (Jackson and Schmugge, 1991).

The NASA Push Broom Microwave Radiometer (PBMR) has demonstrated the capability of microwave sensors to map surface moisture variations during the Monsoon 90 and FIFE experiments. FIFE, the First ISLSCP Field Experiment, was conducted over a tall grass prairie in central Kansas between 1987 and 1989. Monsoon 90 was conducted over an arid watershed in southern Arizona during the summer of 1990. These two sites provided an interesting range of environmental conditions. In both experiments moisture contents ranged from very dry to saturated soil conditions. The correlations between the microwave response and soil moisture were very good. In this paper we will present only the results from the Monsoon 90 because the results from FIFE are available in the literature (Wang et al., 1989 and 1990).

1. DIELECTRIC PROPERTIES OF SOILS

The microwave remote sensing of soil moisture relies on the large contrast between the dielectric constant of water (= 80) and that of dry soil (= 3.5). This arises from the tendency of the electric dipole of the water molecule to...
align itself with the electric field at microwave frequencies. For ice the dielectric constant is large at low frequencies but because of the binding of the water molecule in the solid, the motion is inhibited at about 104 Hertz (Hz). For liquid water this reduction in the molecule’s ability to rotate does not occur until about 10^10 Hz or 10 GHz (1 GHz = 10^9 Hz) in the microwave range. The dielectric constant is important because it determines the propagation characteristics of an electromagnetic wave. These characteristics include the velocity of propagation, and the wavelength and absorption of energy in the medium. The square root of the dielectric constant is the index of refraction (n) for the material. The contrast in n at the boundary between two media which determines the reflection and transmission coefficients of an electromagnetic wave at the boundary.

The dielectric constant of soil increases from about 3 or 4 when dry to almost 30 when wet. While the range of variation is about the same for most soils, there are differences among the soils at the lower soil moistures. These arise from textural differences, i.e. the distribution of soil particle sizes. Wang & Schmugge (1980) observed that the initial water added to a soil is tightly bound to the particle surfaces and thus has dielectric properties somewhere between those of bound molecules in ice and those of freely rotating molecules in the liquid. Only after there are several layers of water on the particle surfaces does the water begin to behave like a liquid in its dielectric properties. Dobson et al. (1985) found that separation of the soil water into bound and bulk components depends on soil texture or, more directly, the specific surface area (SSA) of the soil. Their model treats the soil as a host medium of dry soil solids containing randomly distributed inclusions of bound water, bulk water and air. With such models it is possible to study the sensitivity of a soil’s dielectric properties to such factors as density, texture, salinity, etc. (e.g. Jackson and O’Neill, 1987).

This variation of the soil’s dielectric constant with moisture can produce a variation in the soil’s emissivity from 0.95 for dry soils to 0.6 or less for wet soils with changes of a corresponding magnitude for the soil reflectivity. These variations have been observed by both passive and active microwave sensors. Passive sensors (radiometers) observe the variations in the thermal emission from the soil due to emissivity changes (Schmugge, 1989 and Jackson and Schmugge, 1986). Active sensors (radars) transmit a pulse of electromagnetic energy and then measure the backscattered return, which is a function of the soil’s reflectivity (Dobson and Ulaby, 1986 and Bernard et al., 1981 and 1982). At microwave frequencies the capability to sense soil moisture remotely is limited to a surface layer about 5 cm thick and is affected by surface roughness and vegetation cover.

As part of a study of salinity effects on the soil’s emissivity Jackson and O’Neill (1987) made a careful series of field measurements over smooth loamy sand and compared the results with those expected from the dielectric constant models described above. Figure 1 illustrates that emissivity ranges from 0.6 for the wet soil (30 % volumetric soil moisture) to 0.9 for the dry soil (= 8% ). As shown in this figure the calculations from the two dielectric models agree with each other and with the data. Thus the basic sensitivity of microwave emissivity to soil moisture variations is well understood and the underlying theory is verified. The complications arise when factors as surface roughness and vegetative cover are added to the problem.

![Fig. 1 - Observed and predicted relationships between emissivity and volumetric soil moisture in the surface 0-2 cm layer for a bare, smooth, loamy sand soil at the 21-cm wavelength (L-band). From Jackson and O’Neill, 1987.](attachment:image.png)

2. MICROWAVE RADIOMETRY

A microwave radiometer measures the thermal emission from the surface, which at these wavelengths is proportional to the product of the thermodynamic temperature of the soil and the surface emissivity (Rayleigh - Jeans approximation to the Planck radiation law). This product is commonly called the brightness temperature (T_B). The brightness observed by a remote platform is represented schematically in Figure 2 where T_B is given by:
\[ T = \Gamma_{\text{atm}} (R \cdot T_{\text{sky}} + T_{\text{BC}}) + T_{\text{B atm}} \]

where \( \Gamma_{\text{atm}} \) is the atmospheric transmission from the ground to a radiometer platform and is typically about 99%; \( T_{\text{BC}} \) is the emission from the surface. In Figure 2, typical values of the various parameters at \( \lambda = 21 \text{ cm} \) are given. The first term is the reflected sky brightness which depends on atmospheric conditions, frequency and surface reflectance (R). For frequencies suitable for soil moisture sensing (\( \nu < 5 \text{ GHz} \)), \( T_{\text{sky}} \) and \( T_{\text{atm}} \) are small (<10K) and can generally be neglected. The major contribution to \( T_{\text{BC}} \) at 21-cm is the cosmic background radiation at 2.7 K, the atmospheric contribution is another 2 or 3K. Thus when multiplied by reflectivity of 0.4 for wet soil yields a reflected sky brightness of 1 or 2K. Thus the atmospheric contributions are negligible and we are left with the emission from the surface i.e., the second term, \( T_{\text{BC}} \), as the main contributor to \( T_{\text{B}} \). Thus equation (1) reduces to:

\[ T_{\text{B}} = T_{\text{BG}} \]

where

\[ T_{\text{BC}} = (1 + (1 - \varepsilon_{\text{surf}}) \Gamma) (1 - \Gamma) (1 - \alpha) T_{\nu} + \varepsilon_{\text{surf}} \Gamma T_{\text{soil}} \]  \( \text{(2)} \)

Here \( \Gamma \) is the transmissivity of the vegetation, \( \alpha \) is its single scattering albedo and \( T_{\nu} \) its temperature. \( T_{\text{soil}} \) is a measure of the intensity of the upwelling thermal radiation from the soil and is a weighted average of the soil temperature over the electromagnetic skin depth of the soil (Choudhury, et al., 1982). The emissivity \( \varepsilon_{\text{surf}} \), represents the fraction of this upwelling radiation which is transmitted into the air. This factor shows the primary sensitivity to soil moisture content. The critical question is: what is the thickness of the layer at the surface whose dielectric properties determine \( \varepsilon \), it is this thickness which determines the soil moisture sampling depth for microwave sensors. It has been established as a few tenths of a wavelength thick, or about 2 to 5 cm at the 21-cm wavelength (Wilheit, 1978, Newton, et al., 1983, and Wang 1987).

If we assume that \( T_{\nu} = T_{\text{soil}} \) which is the case for a full canopy or if the measurements are made during a period of uniform temperatures, such as predawn, and that \( \alpha = 0 \) which is the case at large, then Eq. (2) reduces to

\[ T_{\text{BC}} = (1 - (1 - \varepsilon_{\text{surf}}) \Gamma^2) T_{\text{soil}} \]

or

\[ \varepsilon_{\nu} = 1 - (1 - \varepsilon_{\text{surf}}) \exp (-2\tau) \]

(3')

where \( \varepsilon_{\nu} \) is the effective emissivity of the canopy and \( \Gamma^2 = \exp (-2\tau) \) with \( \tau \) the optical depth of the vegetation.

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**Fig. 2: Schematic of factors affecting the passive microwave emission from land surfaces.**
Thus vegetation reduces the sensitivity of the observed emissivity to soil moisture by the factor $\exp(-2\tau)$. In an analysis of many data sets Jackson and Schmugge (1991) found that

$$\tau = b W v$$

(4)

where $b$ is a plant dependent constant and $W v$ is the vegetation water content in kg/m$^2$. $b$ is approximately proportional to the frequency; at 21-cm it is about 0.1±0.03 for crops ranging from small grains or grasses to broadleaf plants such as maize or soybeans. From these results it is clear that longer wavelengths are preferable for soil moisture sensing and if the vegetation water content is known it should be possible to correct for vegetation effects.

Another perturbing effect or noise factor on the microwave emission from soils is surface roughness. Qualitatively, roughness decreases the reflectivity and thus increases the emissivity. A rough surface can be thought of as having an increased area through which it can emit thermal energy. Using a simple model Choudhury et al. (1979) have shown that the increase in the emissivity can be expressed as:

$$\Delta \varepsilon = R_0 \left[ 1 - \exp(-h) \right]$$

(5)

where $R_0$ is the smooth surface reflectivity and $h$ is an empirical roughness parameter which increases as the surface height variance increases and the horizontal correlation length decreases. The bare soil emissivity is then:

$$\varepsilon_{sr} = 1 - R_0 \exp(-h)$$

or

$$= 1 - (1 - \varepsilon_0) \exp(-h)$$

(6)

Both the vertical and horizontal scales of the roughness affect the emissivity. Values of $h$ range from 0 for a smooth field to about 0.5 for a very rough field (Choudhury et al., 1979). For dry fields with $R_0 < 0.1$, $\Delta \varepsilon$ will be small, = 0.02, while for wet fields with $R_0 = 0.4$ and the increase in emissivity will be larger, $\Delta \varepsilon = 0.16$. The effect will be to decrease the sensitivity of the observed microwave emission to soil moisture. In practice it has been found that $h = 0.1$ to 0.2 so that the decrease in sensitivity given by $\exp(-h)$ is on the order of 10 to 20%. As a result we conclude that the major perturbing factor affecting radiometer measurements for soil moisture detection is the amount of vegetation cover, since it can completely destroy the sensitivity to moisture variations for sufficiently thick covers. This will occur at the 21-cm wavelength for vegetation water contents in excess of 6 kg/m$^2$.

The result of these two perturbing factors can be expressed as:

$$\varepsilon = 1 + (\varepsilon_0 - 1) \exp(-h - 2\tau)$$

(7)

where $\varepsilon_0$ is the smooth soil emissivity. Thus without a priori knowledge of either roughness or vegetation amount it will not be possible to separate the effects of these two factors in an experiment.

3. LARGE SCALE FIELD EXPERIMENTS

With this background it is possible to apply this approach to map surface soil moisture in large scale field experiments and thus to establish its utility for determination of surface fluxes. Here we discuss results from the most recent of three such experiments.

The radiometric data were acquired with an L-band ($\nu = 1.42$ GHz; $\lambda = 21$-cm) pushbroom microwave radiometer (PBMR) aboard the NASA C-130 aircraft. The PBMR has four horizontally polarized beams pointing at $\pm 8^\circ$ and $\pm 24^\circ$ from nadir. Each beam has a full width at half maximum power of about 16$^\circ$ so that the total swath is about 1.2 times the aircraft flight altitude (Harrington and Lawrence, 1985). Additional instruments aboard the aircraft are the PRT-5 thermal infrared radiometer, the NS001 Thematic Mapper Simulator and the Thermal Infrared Multispectral Scanner (TIMS).

3.1 Monsoon 90

The Monsoon 90 experiment was conducted during the summer of 1990 at an arid watershed in south central Arizona in the US (Kustas et al., 1991). The purpose was to observe moisture fluxes in an arid climate during a drying period after a rain and to verify the role of remote sensing in determining these fluxes. The site selected is the well instrumented Walnut Gulch Experimental Watershed operated by the Southwest Watershed Research Center of the USDA Agricultural Research Service in southeastern Arizona. The region has 250-500 mm of annual precipitation with the majority falling during a summer “monsoon season” in July and August. This period was chosen for the experiment. Vegetation at the site is mostly sparse shrubs and desert grasses. There is a transition in the dominant vegetation types and density across the watershed. The eastern upland part of the watershed is classified as desert grassland, while the western part is classified as a desert steppeshrub community. The biomass measured at the met sites ranged from 0.1 to 0.5 kg/m$^2$ at seven of the sites with the eighth having slightly more than 1 kg/m$^2$. The near surface soils are coarse in texture, ranging from sandy loams to gravelly loamy sands.
A series of 6 PBMR flights was completed between 31 July (day 212) and 9 August (day 221) of 1990 at an altitude of 600 m. To provide complete coverage of the study area, 7 flight lines were set up separated by 500 m, as shown in Figure 3. They lie roughly in an E-W direction. On day 220 (8 Aug) only the outermost lines (#1 & #7) were flown; these lines provided coverage of the met sites. The flights were generally between 9 and 11 AM (local standard time, or 16 to 18 GMT). Volumetric soil moisture for the surface 5 cm of the soil was measured at these sites on a daily basis (Amer et al., 1993). The measurements were made gravimetrically and converted to volumetric values using measured soil bulk densities. The study period was characterized as very dry before the first flight on July 31 (day 212) with soil moisture < 5%, followed by up to 5 cm of rain on August 1 over most of the study area, as shown in Figure 4. Thus there was a significant decrease (50 to 60 K) in observed T_B during the next flight on August 2 (day 214) due to increases up to 20% in soil moisture. The succeeding flights on 4, 5, 8 and 9 August (days 216, 217, 220, and 221, respectively) showed the effects of some lighter rains and the subsequent drydown of the study area. On day 221 the values of TB rose to almost their pre-rain values.

A false color representation of the brightness temperature maps for 4 of the flights is presented in Figure 5. The moisture conditions were dry (2 to 5%) before the first flight on day 212 and the resulting values of T_B ranged from 270 to 280 K. After the heavy rain on day 213 T_B decreased to 220 to 230K, as seen in the image for day 214 in Figure 5. With the data in this format it was possible to relate the change in T_B to the rainfall amounts at each rain gage. As illustrated in Figure 6, there is a linear decrease in TB with rain amounts up to about 25 or 30 mm. For rainfall above that level the soil apparently is saturated and no further decrease in T_B is observed. We believe that the moisture in the surface 0 to 5 cm layer had stabilized to values between 15 and 20% by the time of the flight on day 214.

By correlating values of T_B with ground measurements of soil moisture, a linear relation between the two was established with an R^2 > 0.9. With this relation soil moisture maps were derived from the T_B maps. Examples from the eastern portion of the watershed are given in Figure 7 for days 212, 214, 216 and 217. The spatial patterns qualitatively follow either the topography or soil patterns. The availability of data on successive days enabled us to evaluate the change in moisture storage and to compare it with estimates of the evapotranspiration flux at the met sites. Figure 8 shows a contour plot of the "ET" flux derived using this approach. The values are generally between 3 and 4 mm, which is about 1 mm less than observed at the met sites. This discrepancy is probably due to our neglect of fluxes through the lower boundary of 0 to 5-cm soil layer, i.e. any recharge from below.
Fig. 5 - PBMR images of 21-cm brightness temperatures for 4 days over the Walnut Gulch Watershed during Monsoon 90. The sites of the 8 meteorological stations are indicated by the X’s. Note that the region with heaviest rainfall ( > 50 mm) in Figure 4 corresponds to the lowest brightness temperature region in the day 214 image.
is possible to use this surface soil moisture information together with a priori knowledge of the soils and their typical moisture profiles in order to estimate moisture stored in the root zone of the soil (Mkrtchian et al., 1988; Kostov, 1992). This technique has been used in irrigation scheduling.

A remaining analysis task with these data sets is the development of a means to correct for vegetation using remotely sensed data. Approaches using various vegetation indices from visible and near infrared data will be considered. However we recognize that these approaches may not provide vegetation water content for thick and dense vegetation conditions. In the future, methods involving microwave polarization difference (Choudhury et al., 1989, Paloscia and Pampaloni, 1988 and 1992) at the higher frequencies should be investigated. In this case the absorption of the microwave emission from the soil by the vegetation at shorter wavelengths reduces the polarization difference at off-nadir observations.

This reduction can be used to estimate vegetation water content. The first opportunity to test this will be with data acquired during HAPEX-SAHEL experiment conducted in Niger during the late summer of 1992 where both the PBMR and the French multifrequency radiometer, PORTOS (Chanzy et al., 1992), were flown on several joint flights.

Fig. 6 - Comparison between the brightness temperature difference $T_b(212) - T_b(214)$ and the corresponding rainfall amounts.

**DISCUSSION**

These experiments have demonstrated that it is possible to map the spatial variation of surface soil moisture with a long wavelength microwave radiometer. Experiments in Bulgaria and the former Soviet Union have shown that it
SOIL MOISTURE CONTOURS DAY 214

Fig. 7 b)

SOIL MOISTURE CONTOURS DAY 216

Fig. 7 c)
Fig. 7 d)

Fig. 8 - Contour plot of the estimated "ET" on day 216 for the same area covered in Figure 7.
REFERENCES


