Status of Microwave Soil Moisture Measurements with Remote Sensing

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Active and passive microwave remote sensing techniques have demonstrated their potential for measurements of soil moisture. However, the soil moisture response from them is coupled to vegetation and surface roughness effects, and therefore the interaction among all three needs to be understood. This paper reviews the progress made in the measurement of soil moisture and the factors such as vegetation and surface roughness that affect these measurements. The active techniques, particularly those employing synthetic aperture radar (SAR), provide opportunities for soil moisture studies over a large area, and various aircraft and space missions have been carried out to achieve them. Still, there are unresolved questions about deriving soil moisture from these missions, and research is underway to develop algorithms so that soil moisture information can be obtained on a local as well as a global basis.

INTRODUCTION

Soil moisture is an environmental descriptor that integrates much of the land surface hydrology and is the interface between the solid earth surface and the atmosphere. As important as this seems to our understanding of hydrology, the related ecosystem dynamics, and biogeochemical cycles, it is a descriptor that has not had widespread application in the modeling of these processes. The main reason for this is that it is a very difficult variable to measure, not at a point in time, but at a consistent and spatially comprehensive basis. The large spatial and temporal variability that soil moisture exhibits in the natural environment is precisely the characteristic that makes it difficult to measure and use in earth science applications. For the most part our understanding of the role of soil moisture in hydrology, ecosystems, and biogeochemistry has been developed from point studies where the emphasis has been on the variability of soil moisture with depth. Much of our failure to translate this point understanding to natural landscapes can be traced to a realization that soil moisture varies greatly in space but with no obvious means to measure the spatial variability. As a parallel consequence, most models have been designed around the available point data and do not reflect the spatial variability that is known to exist.

Recent advances in remote sensing technology have shown that soil moisture can be measured by a variety of techniques using all parts of the electromagnetic spectrum. However, microwave technology has the potential to be used from a space platform and has demonstrated the ability to quantitatively measure soil moisture under a variety of topographic and vegetation cover conditions. A number of experiments using truck-mounted sensors, aircraft, and spaceborne sensors have shown that a thin layer, on the order of 5 cm, of the soil can be accurately measured. Thus, because remote sensing is spatial in nature, it now provides us with a potential capability to make frequent and spatially comprehensive measurements of the near surface soil moisture. This paper reviews the status of microwave remote sensing of soil moisture and identifies problems as well as progress made in the development of algorithms.

MICROWAVE TECHNIQUES

Microwave techniques for measuring soil moisture include both the passive and active microwave approaches, with each having distinct advantages. The theoretical basis for measuring soil moisture by microwave techniques is based on the large contrast between the dielectric properties of liquid water and of dry soil.

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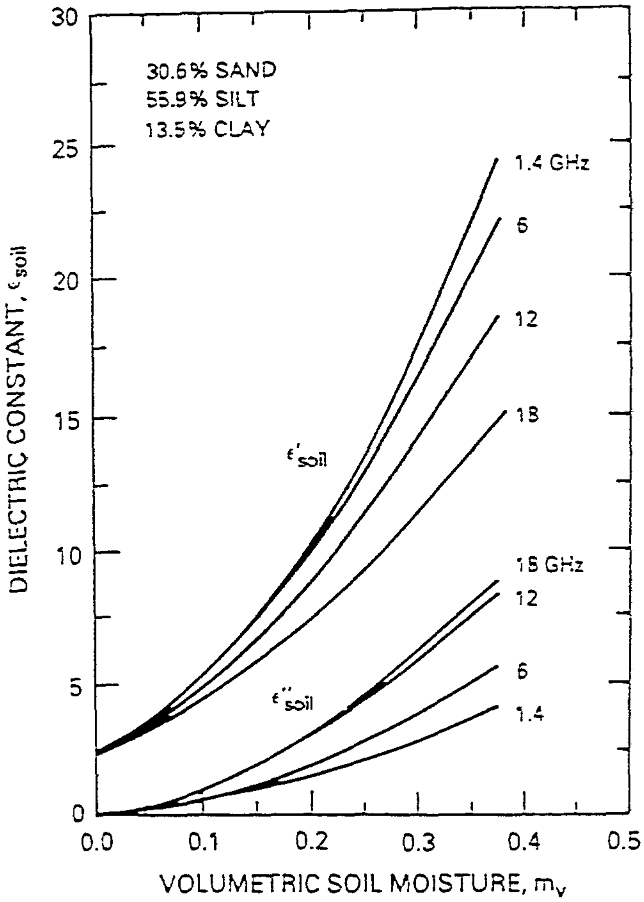

Figure 1. An illustration of the real (ε'_{soil}) and imaginary (ε''_{soil}) parts of the dielectric constant as a function of volumetric moisture content for a loamy soil measured at four frequencies (after Ulaby et al., 1986).

The large dielectric constant for water is the result of the water molecule's alignment of the electric dipole in response to an applied electromagnetic field. For example, at L-band frequency the dielectric constant of water is approximately 80 compared to that of dry soils, which is on the order of 3–5. Thus, as the soil moisture increases, the dielectric constant can increase to a value of 20, or greater (Schmugge, 1983). Figure 1 illustrates the change in real (ε'_{soil}) and imaginary (ε''_{soil}) part of dielectric constant for soil at several microwave frequencies. As the frequency increases, the real part decreases and the imaginary part (a measure of losses) increases with the increase of soil moisture.

For passive microwave remote sensing of soil moisture from a bare surface, a radiometer measures the intensity of emission from the soil surface. This emission is proportional to the product of the surface temperature and the surface emissivity, which is commonly referred to as the microwave brightness temperature (T_B) and can be expressed as follows (Schmugge, 1990):

$$T_B = t(H)*[rT_{sky} + (1 - r, T_{soil}] + T_{atm}\,, \qquad (1)$$

where $t(H)$ is the atmospheric transmissivity for a radiometer at height H above the soil, r is the smooth surface reflectivity, T_{soil} is the thermometric temperature of the soil, T_{atm} is the average thermometric temperature of the atmosphere, and T_{sky} is the contribution from the reflected sky brightness. For typical remote sensing applications using longer microwave wavelengths (greater than 5 cm, which are better for soil moisture), the atmospheric transmission will approach 99%. The atmospheric, T_{atm}, and sky, T_{sky}, contributions are both less than 5°K, each of which are small compared to the soil contribution. Thus neglecting these two terms, Eq. (1) can be simplified to

$$T_B = (1 - r)T_{soil} = eT_{soil} \qquad (2)$$

where e = (1 – r) is the emissivity and is dependent on dielectric constant of the soil and the surface roughness. Thus over the normal range of soil moisture, a decrease in the emissivity from about 0.95 to 0.60 or lower can be expected. This translates to a change in brightness temperature on the order of 100°K. Though the relationship between emissivity and brightness temperature is linear (see Eq. 2), the soil moisture has a nonlinear dependence on reflectivity because the reflection coefficient $\mathcal{R}$ of the ground is related in a nonlinear way to the dielectric constant of the ground (ε). For horizontal polarization, the reflection coefficient is given by

$$\mathcal{R} = \frac{\cos\theta - \beta}{\cos\theta + \beta} \qquad (3)$$

where $\beta = (\varepsilon - \sin^2\theta)^{1/2}$ and θ is the angle of incidence. The expression for vertical polarization can be written in a similar way. The dielectric constant, ε, is a complex quantity and the empirical relationships between dielectric constant and soil moisture derived by Dobson et al. (1985) show that dielectric constant has a nonlinear dependence on soil moisture. However, even though the brightness temperature–soil moisture relation has a strong theoretical basis, most algorithms are empirical in that they depend on ground data for the relationship.

For the active microwave approach over a bare soil, the measured radar backscatter, σ_s^o, is related directly to soil moisture and is written in functional form as

$$\sigma_s = f(R, a, M_v) \qquad (4)$$

where R is a surface roughness term, a is a soil moisture sensitivity term, and M_v is the volumetric soil moisture. Although R and a are known to vary with wavelength, polarization, and incidence angle, there is no satisfactory theoretical model suitable for estimating these terms independently. Thus, as is the case for the passive microwave approach, the relationship between measured backscatter and soil moisture requires an empirical relationship with ground data, even for bare soils.

An additional approach for using soil moisture data derived with microwave approaches is through change

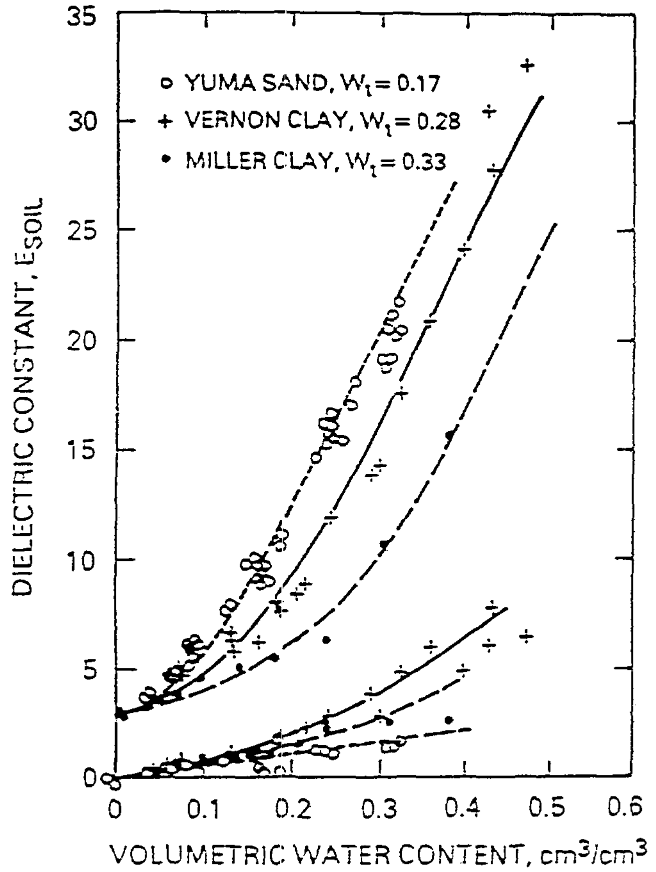

Figure 2. A comparison of laboratory measurements of the real and imaginary parts of the dielectric constant and model predictions (smooth curves) for three soils as functions of moisture content at a wavelength of 21 cm (after Wang and Schmugge, 1980). W_t denotes transition moisture.

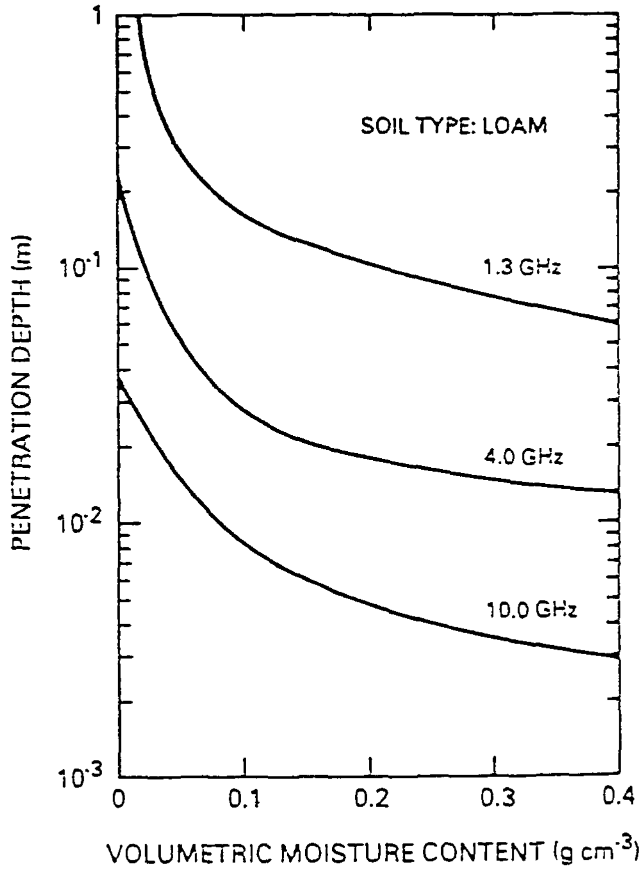

Figure 3. Penetration depth as a function of moisture content for three frequencies (after Ulaby et al., 1982).

detection. This approach can be used for both passive or active microwave data. The change detection method minimizes the impact of target variables such as soil texture, roughness, and vegetation because these tend to change slowly, if at all, with time.

SENSOR-TARGET INTERACTIONS

As discussed above, microwave techniques for measuring soil moisture have a strong theoretical basis. In addition, they are not limited to cloud-free and bare-soil conditions because the microwave approach can sense through cloud cover and, in many cases, through a vegetation canopy. Each of the two basic approaches, passive and active, offer different but distinct advantages. The differences being in their instrument characteristics and their interaction with the characteristics of the target.

There are a number of target and target-sensor characteristics that affect the measurement of soil moisture. These include the effects of soil texture, the depth of measurement, surface roughness, vegetation effects, and instrument parameters, such as incidence angle and frequency. Each of these are discussed in more detail below.

SOIL TEXTURE

Soil texture affects the microwave sensing of soil moisture in the way that the dielectric constant changes with the relative amounts of sand, silt, and clay in the soil. Figure 2 shows this effect with laboratory data and an empirical model developed by Wang and Schmugge (1980). However, it can be seen that this effect is relatively small, and given the overall accuracy of the methods and uncertainty in other factors, texture effects can be neglected for practical purposes.

MEASUREMENT DEPTH

The same principles control the depth of soil that is being measured by the microwave technique, whether it is passive, as discussed above, or active. In a series of careful field experiments with a C-band, HH polarization radar, Bruckler et al. (1988) showed experimental

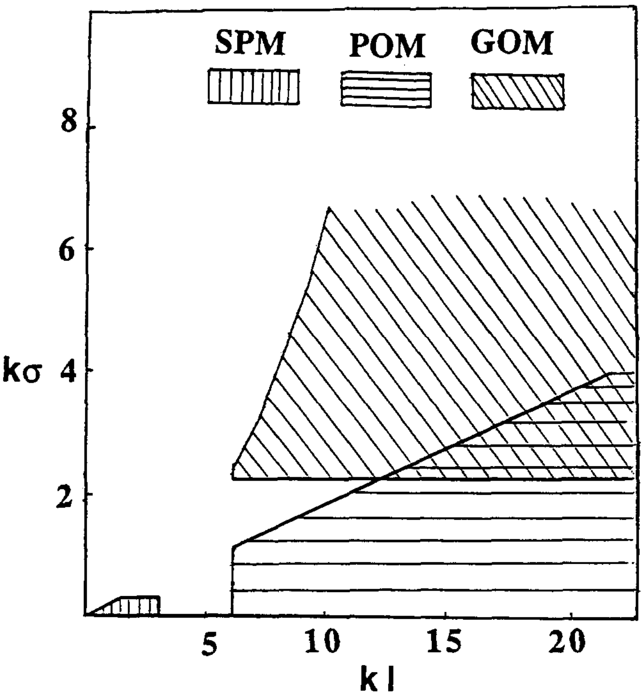

Figure 4. Regions of validity for different scattering models and roughness parameters (after Oh et al., 1992).

results of penetration depth compared with soil moisture that followed very closely to the theoretical curve for a uniform profile.

The relationship between emissivity and soil moisture depends on the dielectric contrast across the air–soil interface. Consequently, this results in some uncertainty as to exactly how thick the soil layer is for determining the dielectric constant. According to Wilheit (1975), the layer of soil would be on the order of a tenth of a wavelength or less. Mo et al. (1980) determined that the radiometric sampling depth is between 0.06 and 0.1 times the wavelength. In an experiment comparing dry-down measurements of soil layers at three frequencies, Newton et al. (1982) found that for L-band (21-cm wavelength) the sampling depth was about two-tenths of the wavelength. The fact of the matter is that measurement depth is not a constant, but is related to the moisture content, and to the operational frequency of the sensor. A reasonably good idea about the measurement depth can be obtained from penetration depth, δp inside the soil. This is given by

$$\delta p = k|Im(\sqrt{\varepsilon})| \quad (5)$$

where $k = 2\pi / \lambda$ is free space propagation constant, ε is dielectric constant of soil, *Im* denote the imaginary part and the vertical bars refer to the absolute value. The plot of penetration depth versus soil moisture for various frequencies is shown in Figure 3 (Ulaby et al., 1982).

SURFACE ROUGHNESS

Microwave signatures from the soil is related to the reflectivity of the surface, which if smooth can be calculated by the usual Fresnel equations. Smoothness in microwave terms is relative, as it is dependent on the wavelength. That is, a surface that is smooth for one wavelength, say a 21-cm L-band (1.4 GHz), may not be smooth for 6-cm C-band (4.9 GHz), and 2.8-cm X-band (10.7 GHz). The effect of a rough surface is to increase the surface emissivity and thus to decrease the sensitivity to soil moisture (Newton and Rouse, 1980).

Choudhury et al. (1979) have shown that surface roughness can affect the soil reflectivity r' in the following way:

$$r' = r\exp(-h\cos^2\theta), \quad (6)$$

where r is the smooth surface reflectivity, h is a roughness parameter ($= 4\,\sigma^2 k^2$) proportional to the root mean square (RMS) height variations of the soil surface, and θ is the incidence angle. It is important to note that in Eq. 6, the RMS height, σ, appears as squared in the exponential. Therefore, the value of reflectivity will decrease rapidly with the slight increase of σ. This is what makes reflectivity very sensitive to σ compared to soil moisture. It should be mentioned here that the roughness-reflectivity dependence issue is under a great deal of investigation, because relation (6) is violated under certain conditions of roughnesses and incidence angles. The tilled row structure (large scale regular surface variations) also affects the reflectivity of the surface. Such a surface can be viewed as a composite rough surface where small-scale random roughness is superimposed on the large scale surface variation. Wang et al. (1980) have used an empirical approach to study these effects. They also assumed the effect of random roughness to be independent of incident angle, that is:

$$r' = r\exp(-h) \quad (7)$$

More recent work on the effect of row structure on emissivity has been reported by Promes et al. (1988). It is shown there that for a row height to row spacing ration less than 0.2, an error in emissivity is less than 3%.

Theis et al. (1986) have demonstrated the possibility of using a multisensor approach for improving the estimates of soil moisture under field conditions. In this case, the effects of surface roughness were accounted for with scatterometer measurements. These were then used in a soil moisture equation that included terms related to the emissivity measured by the radiometer and to the scatterometer roughness term. Inclusion of the roughness term improved the r'^2 values from 0.22 and 0.65 for C-band and from 0.69 to 0.95 for L-band.

Although roughness may not be a serious limitation for passive sensors, at least for most natural surfaces, it is a major factor for radar. In many cases the effects of roughness may be equal or greater than the effects of soil moisture on the backscatter. Thus the soil moisture problem becomes one of determining the roughness effect independently so that a model can be inverted to yield a measure of soil moisture.

The role of surface roughness in soil moisture estimation for the active case needs to be understood through surface scattering processes. The theoretical work on surface scattering can be divided into three categories: The small perturbation model (SPM), the physical optics model (POM), and geometrical optics model (GOM). In a broad sense, the geometrical optics model is best suited for a very rough surface, the physical optics model is suitable for surfaces with intermediate scales of roughness, and the small perturbation model is suitable for surfaces with short correlation lengths (l). Figure 4 describes the regions of validity for the three models in terms of kl and $k\sigma$. The mathematical expressions to calculate surface backscatter using these models and their regions of validity in terms of RMS height, correlation length, and wavelength can be found in Ulaby et al. (1982). An examination of these surface backscattering expressions employing different scattering models shows that even though the backscatter increases due to the increase of surface roughness, the soil moisture sensitivity to backscatter diminishes due to a sharp rate of decrease in the value of reflectivity (see Eq. 6). As a result to two competing effects, the roughness effects overshadow the soil moisture effects.

These conclusions are based on theoretical expressions, and have not been tested by experiments. However, the empirical relations derived by Oh et al. (1992) that are based on experimental data, support the above conclusion. Furthermore, Oh et al. (1992) have shown that for the typical values of $k\sigma$ and kl, the results fall in an area outside of the various models' regions of validity (Figure 4). Consequently, most people have had little success using these models.

Based on the scattering behavior in limiting cases and experimental data, Oh et al. (1992) have developed an empirical model in terms of the RMS roughness height, the wave number and the relative dielectric constant. By using this model with multipolarized radar data the soil moisture content and the surface roughness can be determined. The key to this approach is the copolarization ratios (hh / vv) and cross-polarization ratios (hv / vv) are given explicitly in the terms of the roughness and the soil dielectric constant. Results from this model look very good and if further testing proves as valid, this approach will be a major step forward in determining soil moisture from radar backscatter. Moreover, this model appears to work well in the roughness domains in which the more classical methods have failed in the past.

VEGETATION COVER

The effect of vegetation is to attenuate the microwave emission from the soil; it also adds to the total radiative flux with its own emission. The degree to which vegetation affects the determination of soil moisture depends on the mass of vegetation and the wavelength. Barton (1978) used an aircraft-mounted 2.8-cm radiometer to measure soil moisture over bare soils and uniform grass cover. Although he demonstrated a strong relationship between brightness temperature and moisture for the bare fields, no relationship for the grass sites could be perceived.

In studies over bare soil and sorghum, Newton and Rouse (1980) found no sensitivity to soil moisture with the 2.8-cm measurements over the sorghum, but with the 21-cm data the radiometer was sensitive to soil moisture even under the tallest sorghum.

Basharinov and Shutko (1975) and Kirdiashev et al. (1979) studied a variety of crops in the USSR with wavelengths varying from 3 cm to 30 cm. For wavelengths greater than 10 cm, their results indicate that one can expect a decrease in sensitivity of about 10%–20% for small grains over what would be expected for bare soil. With broadleaf crops such as corn, the sensitivity could decrease by as much as 80% for wavelengths shorter than 10 cm, and 40% for a 30-cm wavelength. Thus, from these studies the wavelength effect can be seen, that is, a vegetation canopy is more transparent for longer wavelengths than for shorter wavelengths.

Jackson et al. (1982) developed a parametric approach based on a theoretical model proposed by Basharinov and Shutko (1975). This model treats the vegetation as an absorbing layer that can be quantified in terms of the water content of the vegetation by the following relationship:

$$M_v = 78 \cdot 9 - 78.4[1 + (e - 1)\exp(0.22W)], \qquad (8)$$

where M_v is the volumetric soil moisture (0–2.5 cm), e is the measured emissivity, and W is the water content of the vegetation (kg / m^2). Figure 5 illustrates the effect of vegetation on soil moisture. An additional advantage to the correction proposed by Jackson et al. (1982) is that all data needed in Eq. (8) can be measured with remote sensing.

Dead vegetation can also have an attenuating effect on the microwave emissions from the soil as was demonstrated by Schmugge et al. (1988). Aircraft experiments with an L-band push broom microwave radiometer over the Konza prairie grasslands showed that, for areas that had not been burned, a buildup of a thatch layer serves as a highly emissive layer above the soil, thus masking the emission of the soil itself. Where there was an absence of this thatch layer because of burning or graz-

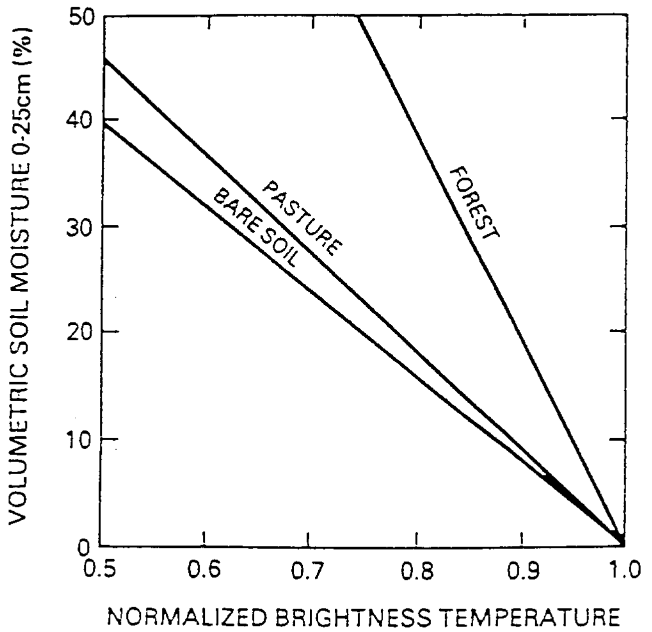

Figure 5. Relationships between normalized brightness temperature and soil moisture for bare soil and different types of vegetation; L band at HH - polarization at 10° (after Jackson et al., 1982).

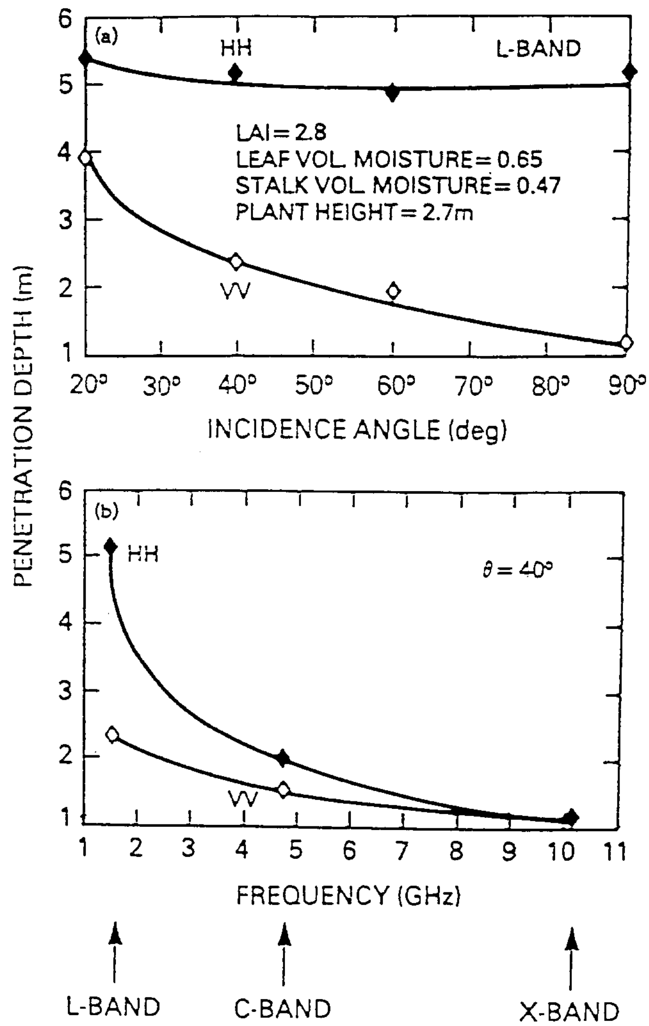

Figure 6. An illustration of the penetration depth of a corn canopy versus incidence angle for HH and VV polarization at (a) L-band, and (b) 40° (after NASA, 1988).

ing, the microwave sensitivity to soil moisture was as expected for bare soil.

Theis et al. (1984) demonstrated the use of visible and infrared data to calculate a perpendicular vegetation index (PVI), which in turn was used to correct the L-band emissivity determined with a passive microwave radiometer. They found as long as the PVI was less than 4.3, good results could be obtained. More recently, Jackson and Schmugge (1991) have analyzed a large amount of published data to verify previous findings. In addition, they have defined a vegetation parameter that is based on the optical depth of the canopy. This parameter appears to be inversely related to the wavelength and can represent four types of vegetation classes (leaf-dominated, stem-dominated, grasses, and trees and shrubs). Furthermore they speculate on how this parameter could be estimated using visible and near infrared satellite data in an operational sense. These studies point out the possibility of a total satellite remote sensing approach for soil moisture with a minimum amount of ground sampling.

As with the roughness case, the effect of vegetation on the active microwave sensing of soil moisture is greatly dependent on the instrument incidence angle, frequency, and polarization. These effects are illustrated in Figure 6 for a corn canopy. In the top half of Figure 6, it can be seen that the attenuation for the horizontal polarization is relatively weak, but the vertically polarized data are attenuated to a much greater degree because of their relationship to the canopy structure, which consists primarily of vertical stalks. The effect of frequency on penetration depth can be seen in the lower part of Figure 6. It is readily apparent that the penetration depth increases with a decrease in frequency or an increase in wavelength.

VEGETATED TERRAIN MODELING

With radar the effect of the vegetation canopy adds more complexity to the problem. Now to determine soil moisture, one must determine the soil roughness effects *and* the effects of the vegetation canopy, which is not a trivial exercise. One of the techniques that can help resolve these effects is the theoretical modeling of vegetated terrains. The modeling provides an insight into the interaction of microwaves with the vegetated terrains by describing vegetation and soil surface in terms of their microwave equivalents. With a set of parameters that are reasonable representatives of a particular vegetation,

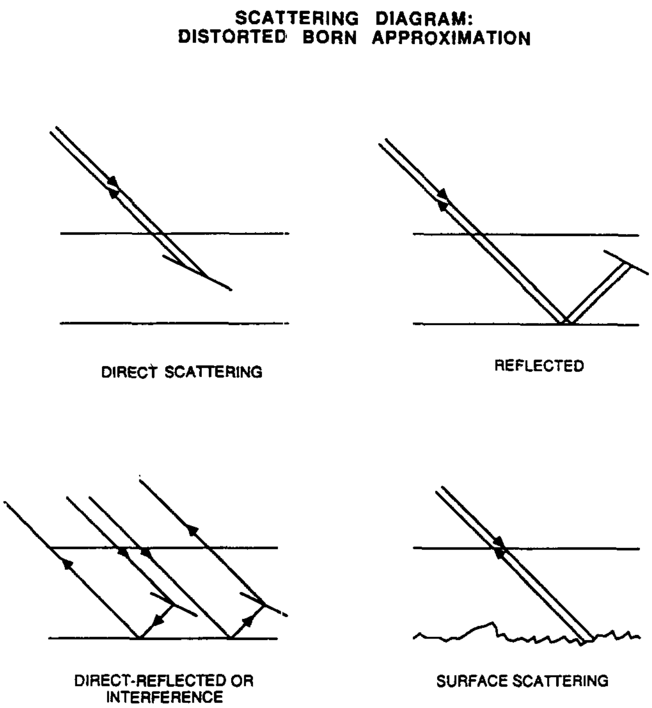

Figure 7. Dominant scattering mechanisms from a layer of vegetation.

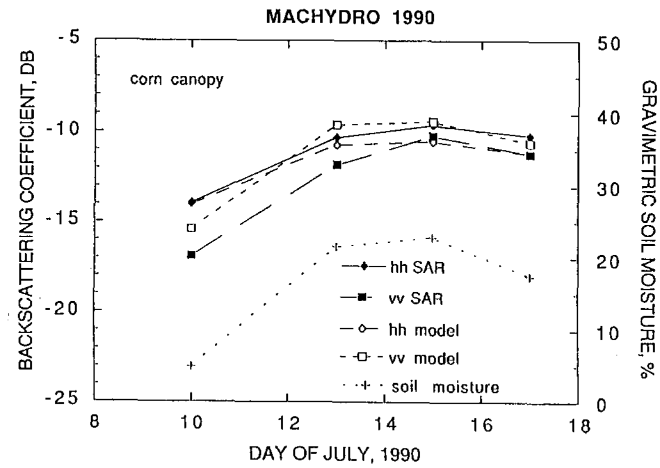

Figure 8. L-band AIRSAR data and modeling results from a corn field with varying soil moisture.

the modeling can help isolate the effects of vegetation and soil moisture on microwaves.

Most of the microwave models have been constructed by replacing the vegetated regions with a random medium whose statistical characteristics are related to physical quantities of the medium. The random modeling techniques divide naturally into two types: continuous and discrete. In the continuous case, the random medium is modeled by assuming that its dielectric constant or permittivity is a random process whose moments such as the mean and correlation function, are known. The continuous models were introduced to treat the problems in turbulence (Tatarski, 1971), but later on they have been employed for vegetation modeling (Fung and Fung, 1977; Tsang and Kong, 1979).

In the discrete case, on the other hand, the medium is viewed as a collection of dielectric scatterers whose position and orientation statistics are given. In the case of vegetation, this might be the individual leaves and stems that comprise the plant. Using this approach, the solution is expressed in terms of scattering cross-section of the individual scatterers. The advantage of the discrete approach is that the results are expressed in terms of quantities (plant geometry and orientation statistics) that are easily related to the biophysical properties of individual plants. The discrete model approach for a random layer of vegetation was first used by Du and Peake (1969) to compute the attenuation through a layer of leaves. Later Lang (1981), Karam and Fung (1983), Ulaby et al. (1990), etc. have used them to develop more rigorous theoretical models for backscattering from a layer of vegetation over a soil surface. Over the years, the discrete scatter approach seems to have gained favor as a preferred approach for vegetation modeling.

To compare the modeling results (using discrete random media technique) with radar, the model cross-sections from individual scatterers such as leaves and stems are converted to backscattering cross-section per unit area from a layer of leaves, stems, etc. The distorted Born method has been used to compute backscattering per unit area. Based on this approach (see e.g., Chauhan et al., 1994 and references there), the radar backscatter from the layer of vegetation is composed of four principal components: direct, reflected, direct-reflected and surface scattering terms (Figure 7). The information about soil moisture is contained in the last three terms. The reflected term is usually very small because the wave hits the ground twice (see Figure 7). If the surface is very rough, the direct-reflected wave gets lost in the vegetation, therefore, the soil moisture information will only be contained in the surface scattering term. If, however, the surface is flat, the surface scattering term will be small, then direct-reflected term will have most of the information about the soil moisture. Therefore, depending on the surface characteristics, the soil moisture information can be retrieved either from surface or from direct-reflected term.

As an example of modeling, Figure 8 describes the model behavior to the changing soil moisture. The soil moisture and AIRSAR data were collected as a part of the MACHYDRO experiment in Pennsylvania in 1990. As shown in Figure 8, the model gives a reasonably close agreement with the AIRSAR data collected under varying soil moisture conditions (Chauhan et al., 1994).

Table 1. Errors in Estimated Parameter Values (after Njoku and Kong, 1977)

Profile		*Error in Parameter Vector p − p**			
Moisture	*Temperature*	$p_1 - p_1^*$	$p_2 - p_2^*$	$p_3 - p_3^*$	$p_4 - p_4^*$
1	1	−0.017	−4.88	0.00345	−0.959
1	2	0.071	21.02	0.0105	2.937
1	4	0.023	3.38	0.0019	
1	5	−0.073	−18.12	−0.0084	−2.308
2	1	−0.042	−10.04	−0.004	−0.943
2	2	0.021	18.1	0.0097	2.369
2	4	0.001	−0.86	0.00031	
2	5	0.011	−9.55	−0.0071	−1.726
3	1	0.045	4.33	0.00012	0.3
3	2	−0.093	3.96	0.0045	0.585
3	4	0.023	−0.64	0.00021	
3	5	0.031	−9.63	−0.0061	−1.057
4	1	0.044	5.84	0.0038	0.877
4	2	0.011	−8.795	−0.0067	−1.273
4	4	0.041	−3.56	−0.0016	
4	5	−0.009	9.45	0.0062	1.2849

INVERSION TECHNIQUES AND SOIL MOISTURE

An inverse problem makes use of measured brightness temperature or radar backscatter data as input to an algorithm designed to produce estimates of variables of interest, that is, soil moisture in the present case. The relationship between geophysical parameters and measured parameters is complicated, which makes the problem ill-posed. In such problems, a small error in the data can produce a large error in the solution. A number of techniques based on either increasing the information contents of the system, for example, statistical inversion (Njoku and Kong, 1977), neural networks (Benediktsson et al., 1990), etc., or restricting the solution space of the problem, for example, Twomey-Phillips method (Chauhan and Lang, 1989) and Twomey–Tikhonov method (Twomey, 1963) etc., have been proposed. All of the above methods have achieved limited success and pose numerical instabilities to the solutions of the retrieved parameter obtained from active or passive devices.

Table 1 shows an example of soil moisture retrieved from a brightness temperature model data set (Njoku and Kong, 1977). The temperature data has been generated through an emission model for different soil moisture profiles. In Table 1, p_1, is the true value of soil moisture and p_1^*, is the estimated value using inversion algorithm. The error in soil moisture inversion ($p_1 - p^*_1$) is tolerable. However, in an actual experiment, the data that is gathered by an active or passive sensor has the noise embedded into the data because of system and atmospheric contamination. Therefore, the simple and easy-to-use inversion algorithm as proposed by Njoku and Kong (1977) may yield poor estimates of the parameters. More rigorous methods that are based on restricting the solution space by using iterative procedures can be helpful. Following one of such techniques, Chauhan and Lang (1989) have achieved reasonable success in inverting vegetation parameters from model backscatter multipolarization data by adding a random noise up to 50%. The application of this algorithm to the experimental data for the soil moisture estimation is in progress.

FUTURE MICROWAVE REMOTE SENSING OF SOIL MOISTURE

The previous sections have discussed the basis of microwave remote sensing for soil moisture and presented a discussion of various target-sensor interactions. As promising as microwave remote sensing for soil moisture appears to be, the future for using microwave data for operational use is somewhat uncertain. For the next few years, researchers will be limited by the lack of suitable data. Currently the ERS-1 SAR from the European Space Agency and the JERS-1 SAR from the Japanese are the only operational active microwave satellite sensors with frequencies suitable for soil moisture. Although these instruments should provide valuable data sources for extending our knowledge of SAR for measuring soil moisture, to date very little data have been available for this purpose. Fortunately there have been some intensive and science-driven aircraft experiments conducted in the last several years (e.g., FIFE, MACHYDRO '90, WASHITA '92, etc.) and these data are beginning to become available to the scientific community. These should be invaluable for providing sample data for developing and testing algorithms as well as answering some of the target-sensor questions.

Looking ahead to when there may be more microwave sensors on orbiting platforms, one confronts the basic differences between passive and active instruments and the intended use of the data. Comparing the instruments simplistically, the active sensors have the capability to provide high spatial resolution data (on the order of tens of meters) but their sensitivity to soil moisture may be confused more by roughness, topographic features, and vegetation than the passive systems. On the other hand, the passive systems, although less sensitive to target features, can provide spatial resolutions only on the order of tens of kilometers. One then must consider how the data will be used. Meteorological and climate models currently use computationl cells on the order of 10–100 km, which may be well within the capacity of future passive systems. However, if one is interested in more detailed hydrologic process studies and partial area hydrology, the passive data would appear to be of little use. It is in this context that the active systems appear promising. For example, existing and planned SARs can provide at least 20–30 m resolution over a swath width of 100 km. Some SARs also have the capability of a scanning mode (SCANSAR) to cover a much wider swath (300–500 km) at a reduced resolution (250 m). Future space launch manifests include several SARs but no passive systems other than the MIMR will have frequencies low enough to be useful for soil moisture.

RESEARCH NEEDED

Although it appears that there will be some microwave measurements available in the future, there are a number of research questions that must be addressed before these data are valuable on a routine basis. Most of the following comments will apply directly to the SAR because it appears these data will be the first that we have to work with. However, to a certain degree (in many cases a lesser degree), these needs also apply to the passive systems.

There is a need to develop algorithms to extract volumetric soil moisture directly from the microwave measurement (backscatter coefficient or brightness temperature). To do this, the target characteristics of vegetation and surface roughness will have to be parameterized. As discussed previously, there is great progress being made in these areas but much more needs to be done. Connected directly to this need is a need to better understand the effects of surface roughness on the measured microwave response with respect to incidence angle, azimuth angle, wavelength, and polarization. New methods to measure surface roughness need to be explored. The dual frequency Δk radar technique has been quite effective to measure sea-surface roughness (Schuler et al., 1991). Implementation of this technique to soil surfaces can provide accurate measure of roughness over a very large scale. Also, there is a need to understand the effect of the vegetation canopy on the microwave response. Vegetation variables include the geometry for the individual plant as well as the canopy as a whole, the water content (and perhaps the biochemical makeup) of the plant, and its stage of growth. Microwave variables would include the incidence angle, and azimuth angle, wavelength, and polarization. Some difficult problems such as soil moisture estimation from rocky soil, effects of discontinuous canopy or vegetation clumps on soil moisture estimation, etc., also need to be addressed.

There is a need to investigate the use of change detection algorithms for determining the relative soil moisture of an area and whether or not this information can be useful for hydrologists. Change detection should minimize the influence of target variables such as roughness and vegetation, at least over short time intervals. With change detection it is assumed that the only target change occurring is the soil moisture. Thus, any measured changes in T_B or σ^0 can be related directly to changes in soil moisture. Fortunately, both the brightness temperature and backscatter relationships with soil moisture are approximately linear. There is also a reasonable basis for expecting change detection methods to provide adequate data for agricultural and hydrologic applications if the data are collected from a long-term orbiting platform. Long-term (multiseason or year) data will establish the upper (wet) and lower (dry) limits for the change algorithm.

There is a need to develop software procedures for correcting the effects of terrain on the microwave response. Active microwave (SAR) is especially sensitive to this. This includes foreshortening, layover, and local incidence angle effects. Also, a potential issue is the relative accuracy of the Digital Elevation Map (DEM) data with respect to the spatial resolution of the microwave data and the potential effect of subpixel variability on the measured signal.

There is also a need to investigate the potential for polarimetric SAR and its potential for extracting target information such as the surface roughness and vegetation characteristics. Studies of this technique need to be carried out with carefully conceived ground data collection programs.

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