Reprinted from

Symposium on Machine Processing of Remotely Sensed Data and Soil Information Systems and Remote Sensing and Soil Survey

June 3-6, 1980

Proceedings

The Laboratory for Applications of Remote Sensing

Purdue University
West Lafayette
Indiana 47907 USA

IEEE Catalog No.
80CH1533-9 MPRSD

SOIL MOISTURE SENSING WITH MICROWAVE RADIOMETERS

DR. THOMAS SCHMUGGE

NASA/Goddard Space Flight Center

I. ABSTRACT

The large difference between the dielectric constant of water and dry soils produces a strong dependence of the dielectric properties, and thus emissivity, of wet soils on their moisture content in the microwave ($50 \geqslant \lambda \geqslant 1$ cm) region of the electromagnetic spectrum. This change in emissivity with soil moisture content can be measured remotely with microwave radiometers. The variation of emissivity with soil moisture is dependent on the wavelength (λ) of observation, soil type, surface roughness and vegetative cover. These dependencies are discussed both theoretically and experimentally. Results obtained from aircraft and spacecraft platforms are presented which give a positive indication of the utility of this remote measurement technique.

II. INTRODUCTION

Microwave radiometric approaches for the remote sensing of soil moisture have been studied for more than 10 years. The sensitivity of the soil's emissivity to its moisture content has been demonstrated with radiometers operating from ground-based, aircraft and spacecraft platforms. This dependence of the soil's microwave emissivity on its moisture content is due to the large contrast between the dielectric properties of free water and those of dry soil. The large dielectric constant for water results from the alignment of the electric dipole moment of the water molecule in response to an applied field. At the longer microwave wavelengths ($\lambda \cong 10$ to 20 cm) the dielectric constant of pure water is approximately 80 compared with 3 to 5 for dry soils. Therefore, since the dielectric constant of a soil-water mixture is predominantly influenced by the amount of water in the mixture, as the moisture content of a soil increases its dielectric constant can reach values of 20 or more at $\lambda = 21$ cm. As a result, changes in soil emissivity are produced, varying from .95 for dry soils to 0.6 or less for wet soils.

Microwave radiometers measure the thermal radiation emitted by the soil. This radiation is generated within the volume of the soil and is dependent on the moisture (i.e. dielectric) and temperature profiles in the soil. The fraction of the upwelling radiation incident on the soil surface that is transmitted into the air will be determined by the dielectric properties of a thin transition layer at the surface. This fraction of upwelling radiation transmitted across the soil/air interface can be termed the emissivity of the soil. The dependence of the dielectric properties of this surface layer on its moisture content produces the sensitivity to soil moisture which is observed by microwave radiometers. Theoretical studies using a radiative transfer model for soils have indicated that this transition layer is on the order of a few tenths of a wavelength thick, i.e., 2 to 5 cm for a 21 cm wavelength. This result has generally been confirmed by observations with radiometers operating at this wavelength on both tower and aircraft platforms. This layer thus determines the primary soil moisture sampling depth. The relative thinness of this layer is a major limitation to remote sensing approaches.

In this paper the dependence of the relationship between emissivity and soil moisture on such things as soil texture, surface roughness, vegetative cover and nonuniform moisture and temperature profiles will be discussed from both the experimental and theoretical viewpoints.

In general the effect of the atmosphere is that of an attenuating layer which would reduce the sensitivity of an airborne or spaceborne radiometer to observe surface emissivity variations. However, at the wavelengths most useful for soil moisture sensing, i.e., greater than 10 cm, the atmospheric effects will be minimal and can be neglected and will not be discussed here.

III. MICROWAVE EMISSION FROM SOILS

A microwave radiometer measures the thermal emission from the surface and at these wavelengths the intensity of the observed emission is essentially proportional to the product of the temperature and emissivity of the surface (Rayleigh-Jeans approximation). This product is commonly referred to as brightness temperature (T_B). The value of T_B observed by a radiometer at a height h above the ground is

$$T_B = \tau(r\, T_{sky} + (1 - r)\, T_{soil}) + T_{atm} \qquad (1)$$

where r is the surface reflectivity and τ the atmospheric transmission. The first term is the reflected sky brightness temperature, which depends on wavelength and atmospheric conditions; the second term is the emission from the soil ($1 - r = e$, the emissivity); and the third term is the contribution from the atmosphere between the surface and the receiver.

The emissivity for a smooth surface with uniform soil moisture and temperature profiles can be calculated using the Fresnel equation of electromagnetic theory. Figure 1 presents values of the calculated emissivity for wet and dry sandy soils. The two

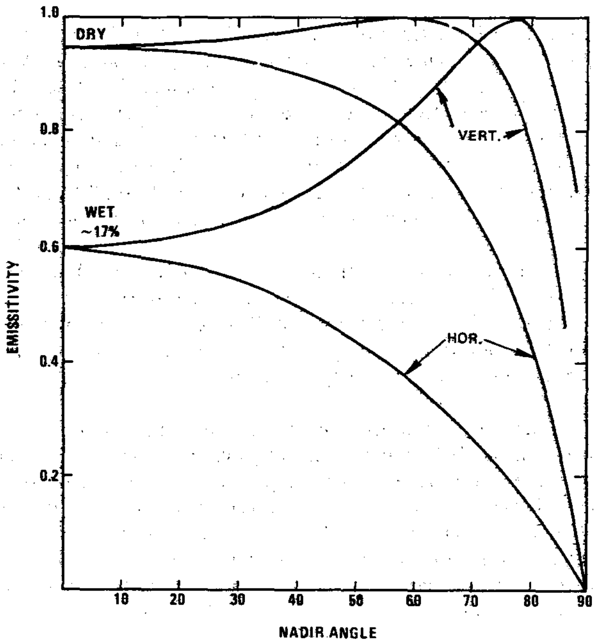

Figure 1. Emissivities calculated using the Fresnel equations for a smooth dielectric surface

two curves represent the horizontal and vertical polarizations of the emitted radiation. Horizontal polarization is that state in which the electric field of the wave is parallel to the emitting surface, while vertical polarization has an electric field component perpendicular to the surface. As incidence angle moves away from nadir the vertically polarized emissivity increases until it reaches 1.0 at what corresponds to the Brewster angle of physical optics. As a result, the difference in emissivity between wet and dry soils for vertical polarization decreases for off-nadir angles. For horizontal polarization the difference between wet and dry soils remains essentially constant with angle. Figure 2 presents results of field measurements conducted at the Beltsville Agricultural Research Center (BARC) verifying this behavior at wavelengths of 6 (C-Band) and 21 (L-Band) cm. These results were for a bare field with a relatively smooth surface in a wet condition, Figure 2a, and in a dry condition, Figure 2b. There is about a 70K difference in T_B for the 14% difference in the soil moisture.

A. DIELECTRIC PROPERTIES OF SOILS

As noted in the introduction it is the large dielectric constant (ϵ) for water as compared to those for the soil minerals which makes the microwave approaches useful for soil moisture sensing. The frequency dependence of the dielectric properties of water are described by a Debye relaxation spectrum given by

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau} \qquad (2)$$

where $i = \sqrt{-1}$, ω = angular frequency, ϵ_s is the low frequency ($\omega\tau \ll 1$) value of ϵ, ϵ_∞ is the high frequency ($\omega\tau \gg 1$) of ϵ, and τ, the relaxation time, is a measure of the time required for the

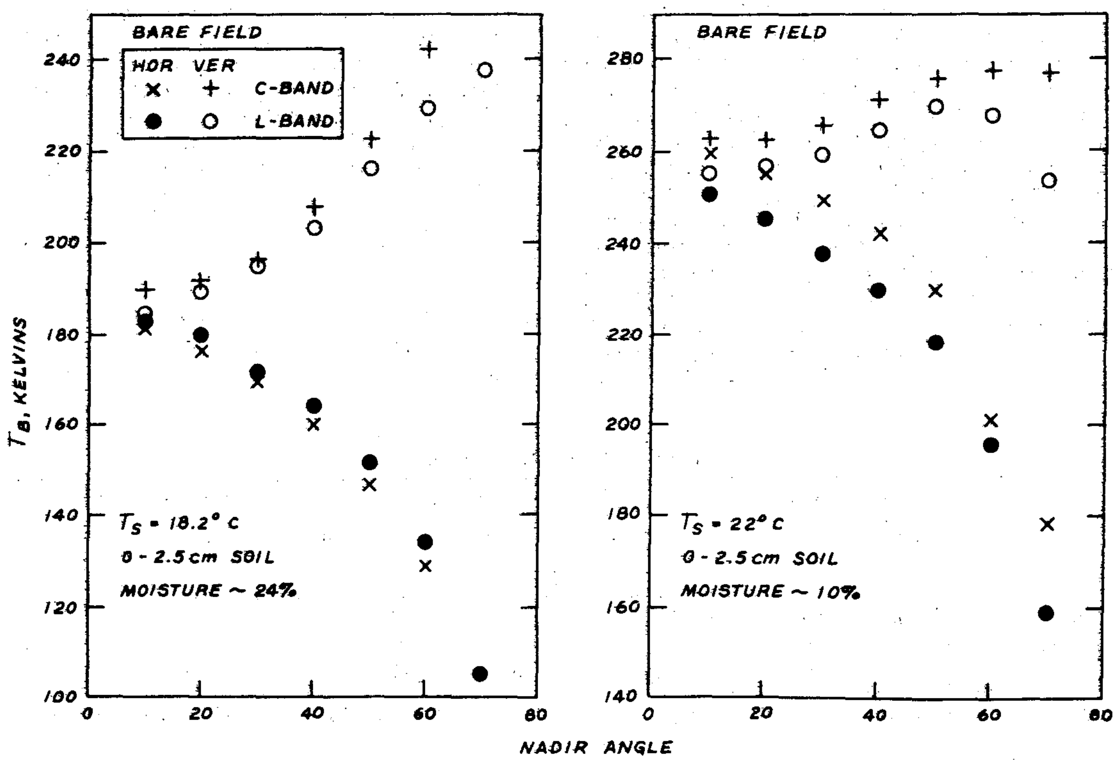

Figure 2. Results of field measurements at L-Band (λ = 21 cm) and C-Band (λ = 6 cm) for a bare field. At Beltsville Agricultural Research Center: (a) wet field; (b) dry field.

molecule to align itself with an applied field. For water $\epsilon_s \simeq 80$ while $\epsilon_\infty \simeq 3.5$. For liquid water $1/\tau \approx 10^{10}$ Hz while for ice $1/\tau \approx 10^3$. Thus if the frequency of the electric field oscillation is too high the dipole moment of the H_2O molecule will not become aligned and its dielectric contribution will be reduced to the high frequency value, ϵ_∞.

When water is first added to a soil it will be tightly bound to the particle surface and will not be able to rotate freely. As more water is added the molecules are further away from the particle surface and are more free to rotate. After about 8 or 9 layers the molecules behave as free water and contribute significantly to the dielectric properties of the soil. In measurements of the dielectric properties of soils Hoekstra and Delaney[1] observed a frequency dependence similar to that expected by Equation (1) with the exception that the soil water has a range of relaxation times longer than that of liquid H_2O.

Laboratory measurements of the dielectric constant for three soils ranging from a sandy loam to a heavy clay at a wavelength of 21 cm are presented in Figure 3. The characteristics of the 3 soils are given in Table 1 along with calculated values of emissivity. For all three soils there is a region at low moisture levels where there is a slow increase in ϵ and above this region there is much steeper increase in ϵ with moisture content. It can be seen that the region of slowly increasing ϵ is greater for the clay soils than for the sandy loam. Due to the greater surface area present in the clay soils, more water is tightly bound to soil particles at a given moisture level than in sandy soils, and is less able to contribute to the soils dielectric properties.

The curves in Figure 3 are the results from an empirical model to develop an analytical expression for ϵ of soils as a function of moisture content.[2] As Hoekstra & Delaney[1] point out in their paper the dielectric behavior of water in soils is different from that in the bulk liquid phase, i.e., the tightly bound water has dielectric properties similar to those of ice while the loosely bound water has dielectric properties similar to those of the liquid state and the crossover occurs at the transition moisture W_t. This is the point where the slope of the dielectric constant curve changes. Therefore, to obtain the dielectric properties of the moist soil a simple mixing formula is used in which the components are the dielectric constants of the soil mineral (or rock), air and water (ϵ_x), with ϵ_x being a function of the water content, W_c, in the soil. At zero water content $\epsilon_x = \epsilon_{ice}$ and it increases linearly until the transition moisture W_t is reached, at which point ϵ_x has a value approaching that for liquid water. In Wang & Schmugge[2] the values of W_t were determined for 18 soils by a least squares fit to the data. These values of W_t are compared with values of the soils' wilting points (WP) calculated from the known soil textures. The correlation coefficient for W_t = 0.9 indicating that there is a strong dependence of W_t on WP and that testure data can be used to estimate the value of W_t for a soil.

The values of the emissivity presented in TAble 1 give an indication of the brightness temperature (T_B) to be expected for these soils. For example, since at W_c = 0.3 the range in emissivity is 0.14 or about a 45K range in T_B, this difference in the emission for wet soils should be easily observable.

Based on the above research, it appears that reasonable estimates of the dielectric constant for soils can be made both as a function of moisture content and microwave frequency if the knowledge of the soil texture or moisture characteristic is available. The frequency dependence is contained in the dielectric constant for water which is well understood.[5] It is assumed that there is no frequency dependence of W_t within the microwave spectral region.

IV. REMOTE SOIL MOISTURE DETECTION

A. RADIATIVE TRANSFER CALCULATIONS

Thermal microwave emission from soils is generated within the soil volume. The amount of energy generated at any point within the volume depends on the soil dielectric properties (or soil moisture) and the soil temperature at that point. As energy propagates upward through the soil volume from its point of origin, it is affected by the dielectric (soil moisture) gradients along the path of propagation. In addition, as the energy crosses the surface boundary it is reduced by the effective transmission coefficient (emissivity), which is determined by the dielectric characteristics of the soil transition layer near the surface.

The emission from the soil surface can be expressed as:

$$T_B = e\left[\int_{-\infty}^{0} T(z)\,\alpha(z)\exp\left(-\int_{z}^{0}\alpha(z')dz'\right)dz\right] = eT_{eff} \quad (3)$$

Table 1
Characteristics of Soils Represented in Figure 1

	Texture			Moisture Properties			Soil Emissivities*** at				
	Sand	Silt	Clay	WP*	FC**	W_t	W_c = 0	0.1	0.2	0.3	0.4
				in cm^3/cm^3			cm^3/cm^3				
Yuma Sand	100	0	0	.007	.07	.17	.92	.83	.69	.59	.53
Vernon Clay Loam	16	56	28	.19	.42	.28	.92	.86	.75	.64	.56
Miller Clay	3	35	62	.36	.63	.33	.92	.88	.81	.73	.63

*Calculated from equation based on regression analysis of the relationship between wilting point (WP) and soil texture for 100 representative soils.[2]

**Calculated from equation based on regression analysis of the relationship between field capacity (FC) and soil texture for 100 representative soils.[2]

***Calculated using the Fresnel Equations for reflectivity at a smooth surface.

where T(z) is the temperature profile and α(z) is the absorptivity as a function of depth which depends on moisture content. Results from numerical solutions to this equation have been presented by Njoku and Kong[6], Wilheit[7] and Burke et al.[8] These papers have included results which indicate that the models do a good job of predicting T_B for a smooth surface. One of the most significant results from these models is that the effective sampling depth (or transition layer) is on the order of only a few tenths of a wavelength.[7] Thus, for a 21-cm-wavelength radiometer this layer is about 2 to 5 cm.

Using soil moisture and temperature profiles measured at the U.S. Water Conservation Laboratory,[9] values of T_B were calculated using the Wilheit[7] model. The measurements were made for a smooth bare field with an Avondale loam soil. Figure 4 presents results for dawn and mid-day soil profiles for a sequence of days following an irrigation. The T_B values are plotted vs moisture in various soil layers from 0 -1 cm to 0-10 cm. There is an obvious 10-15K difference between the dawn and mid-day results due to soil temperature changes with time for dry soil conditions. For the wet soil conditions the effect of soil temperature is masked by the mid-day dry-out of the increased soil moisture in the surface layer for the dawn condition. For the day profiles there is a dramatic drying of the surface cm or so of the soil. For example, the moisture content of the 0-1 cm layer dried from 16% to 11% to 8% on the fourth, fifth and sixth days after irrigation, producing a T_B increase from 200K to 240K during this period. Calculations at the 1.55 cm wavelength showed an even sharper increase in T_B from 217K on the fourth day to 275K on the fifth day, indicating that the moisture sampling depth at this wavelength is less than 1 cm. At the 21 cm wavelength there is generally a linear decrease of T_B with soil moisture in the 0-1 cm layer for both times of day. The T_B vs 0-2.5 cm and 0-5 cm soil moisture curves displayed a behavior similar to that which would be expected from the dielectric constant curves of Figure 1, i.e., a slow decrease of T_B out to the transition moisture W_t and then a more rapid decrease in T_B. The break in the 5 cm curve occurs at about 12%, the approximate value of W_t for this soil. This indicates that the soil moisture sampling depth is about 5 cm at the 21 cm wavelength.

If the calculated values of T_B are divided by T_{eff} of equation 3, the resultant emissivities for the dawn and mid-day profiles are in excellent agreement. Unfortunately, the moisture and temperature profiles are needed to calculate T_{eff}. However, it has been found that T_{eff} can be estimated by a linear combination of the surface temperature and an estimated deep soil temperature. This approach can be used in remote sensing applications to determine emissivities independent of soil temperatures.

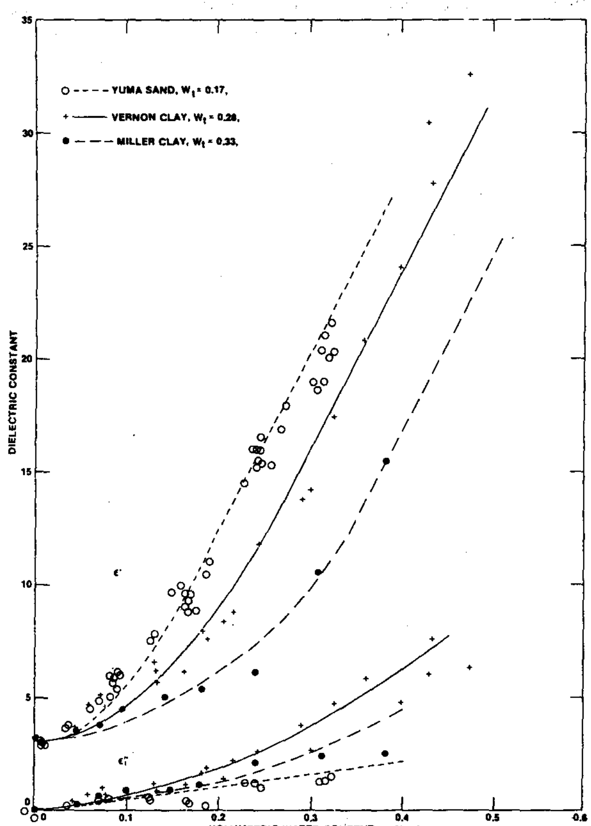

Figure 3. Laboratory measurements of the real and imaginary parts of the dielectric constant for three soils as a function of moisture content at a wavelength of 21 cm. The data for Yuma Sand and Vernon Clay Loam are from Lundien[3] and those for Miller Clay are from Newton.[4] The smooth curves are from an analytical model by Wang & Schmugge.[2]

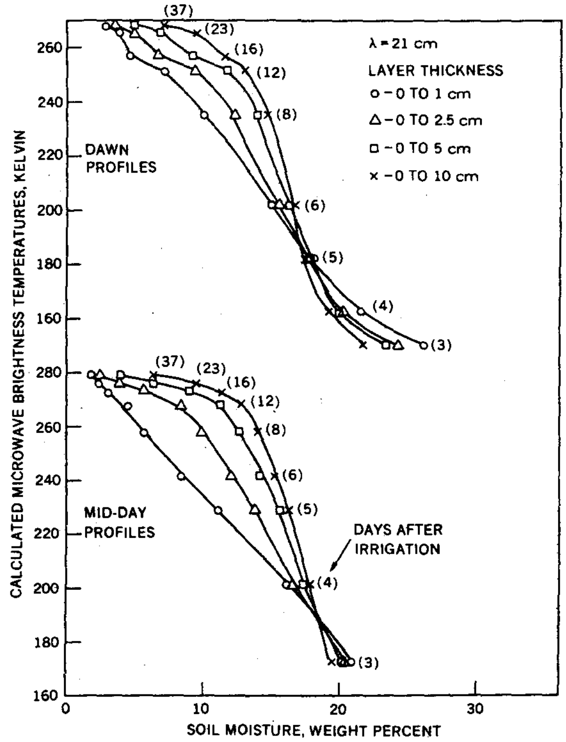

Figure 4. Calculated 21-cm brightness temperatures using soil moisture and temperature profiles measured at U. S. Water Conservation Laboratory in Phoenix, Arizona.[9]

B. VEGETATION EFFECTS

A vegetative canopy acts as an absorbing layer which absorbs some of the upwelling radiation from the soil and also emits radiation at its own temperature. The magnitude of the effect depends onthe amount of vegetation and the wavelength of observation. A thick canopy would approximate a Lambertian black body, i.e., it would have an emissivity close to one and show no angular or polarization effects. Basharinov and Shutko[10] and Kirdiashev et al,[11] have reported on observations made in the USSR over the 3 to 30-cm wavelength range for a variety of crops. Their results indicate that for small grains and grasses the sensitivity to soil moisture is 80 to 90% of that expected for bare ground at wavelengths greater than 10 cm. Broad leaf cultures, like mature corn or cotton, transmit only 20-30% of the radiation from the soil at wavelengths shorter than 10 cm and about 60% at the 30-cm wavelength. They observed 30 to 40% sensitivity for a forest at the 30-cm wavelength, although they did not mention the type or height of trees.

In Figure 5 results from the BARC experiments for grass covered fields are presented at the 6 (C-band) and 21 (L-band) cm wavelengths. Data for two grass heights are presented: 30 cm in Figure 5a and 12.5 cm in Figure 5b. There is little or no change of T_B with angle observed at the 6 cm wavelength for the 30 cm tall grass and T_B is about that which was observed for the dry field in Figure 2. Also, there is little difference between the values obtained at different polarizations, as would be expected for a thick canopy. The 21 cm results display angular and polarization effects similar to those seen in Figure 2 for the bare fields. However, T_B has increased: the 30 cm grass field has the same moisture content as the wettest of the two bare fields, but T_B = 220K compared to 190K for the bare field. In comparison a dry field would be expected to have T_B = 270K. Thus, the dynamic range between wet and dry fields is reduced by the presence of vegetation from 80K to abut 50K. Similarly, the polarization difference at $\theta = 40°$ is reduced from 38K to 21K. Both of these factors indicate that for a field with a dense 30 cm grass cover, sensitivity to soil moisture was reduced to about 60% of the bare soil case, which is a little less than the transmissivity reported by the Russians. The quantification of vegetation in terms of wavelength and biomass parameters is a near term objective of our field research program.

C. ROUGHNESS EFFECTS

The results presented in Figures 3 & 4 were for fields with relatively smooth surfaces. Field measurements made at Texas A&M University[4] indicate that roughening the surface increases soil emissivity. Figure 6 presents the results at 21 cm wavelength for three surface roughnesses, classified as smooth, medium rough and rough and having RMS height variations of 0.9, 2.6, and 4.3 cm respectively. The solid symbols are the measured values and the open symbols are calculated values for the same profile. The range of T_B between wet and dry decreases from about 120K for the smooth field to 80K for medium rough and 40K for the rough field.

Qualitatively this increase in emissivity can be attributed to the increase in the soil surface area that interfaces with the air and

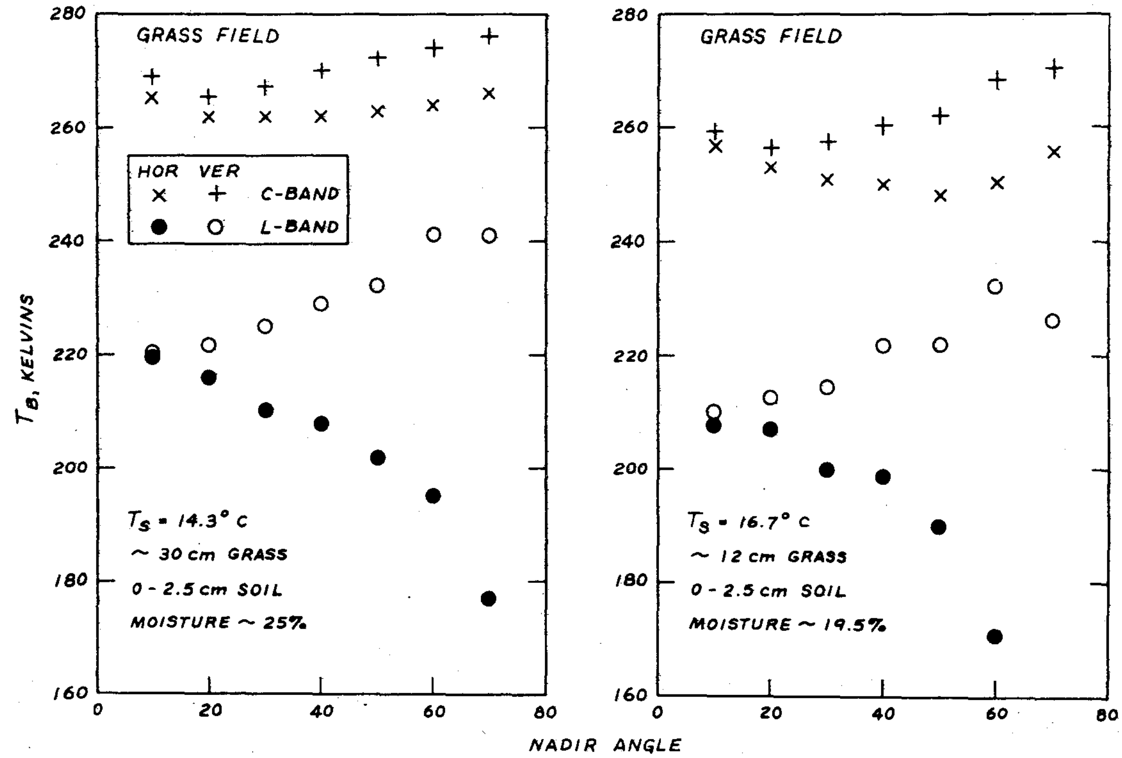

Figure 5. Results of field measurements at L-Band (λ = 21 cm) and C-Band (λ = 6 cm) for a grass covered fields: (a) 30 cm grass; (b) 12 cm grass.

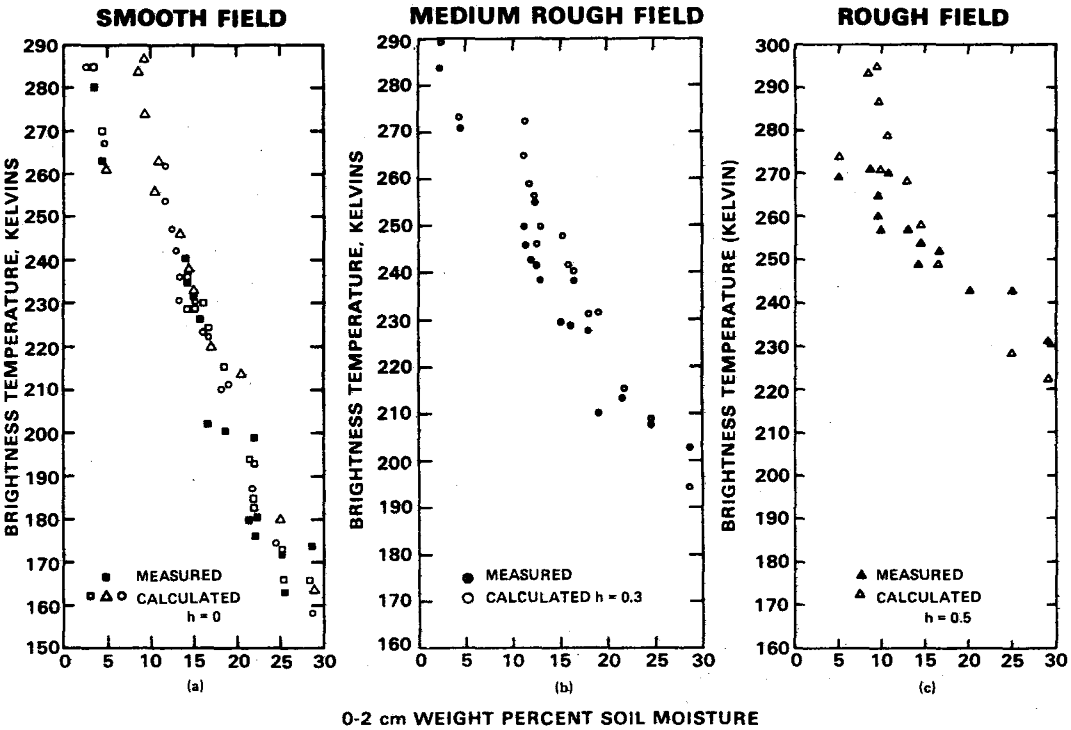

Figure 6. Comparison of calculated and measured values of T_B at $\lambda = 21$ cm for fields with three levels of surface roughness. Measurements were made from the truck mounted at Texas A&M University.[4] In Figure 6a the calculations were done for the profiles observed in all three fields.[12]

thus can transmit the upwelling energy. Quantitatively Choudhury et al.[12] have shown that surface roughness increases the emissivity by an amount

$$\Delta e = r_o \,(1 - \exp(-h)) \qquad (4)$$

where r_o is the reflectivity for the smooth surface and h is an empirically determined roughness parameter which is proportional to the rms height variations of the surface with h = 0 for a smooth surface. For dry fields since $r_o \leq 0.1$, the effect of increased surface roughness on observed soil emissivity will be small, while for wet fields with $r_o = 0.4$, the effect is correspondingly larger. Thus, in Figure 6 there is little difference in T_B among the three fields for dry conditions, with most of the T_B data at moisture levels $\leq$ 5% falling between 270 and 280K. However, for the 30% moisture condition there is approximately a 60K difference between smooth and rough field results. In Figure 6 the open symbols are the values calculated using the Wilheit radiative transfer model. The values of h used in the calculation ranged from 0 for the smooth field to 0.5 for the rough field. The good agreement that is found in general indicates the validity of these models for T_B estimates. Results from aircraft overflights of irrigated agricultural fields in the Phoenix, Arizona area gave values of h in the range of .4 to .6 for furrowed fields. At the present time it is still necessary to determine h empirically. Neither the geometry of soil surfaces nor the physics of radiation scattering from these surfaces is sufficiently well known to calculate h from first principles.

D. AIRCRAFT AND SATELLITE EXPERIMENTS

Significant improvements in the understanding of the effects of individual scene parameters on the relationship of brightness temperature to soil moisture have been achieved using ground-based measurements acquired during controlled experiments. However, demonstration of the potential of passive microwave sensors for estimating soil moisture on an operational basis must be performed with aircraft and spacecraft sensors that integrate large areas of natural, non-idealized terrain. A series of aircraft experiments performed over the last several years by a number of investigators have demonstrated the sensitivity of microwave radiometers to soil moisture in agricultural terrain. Skylab and Nimbus satellites have also provided significant results for very large areas of integration.

An example of radiometer data acquired from an aircraft is given in Figure 7.[13] Here the infrared and 21-cm brightness temperatures are plotted as a function of distance along a track over the northern end of the Imperial Valley. This flight path is of particular interest because it includes data over the Salton Sea and the uncultivated desert east of the agricultural target area. These data indicate the range of brightness temperatures to be observed over such a combination of surfaces, that is, 96K over water, ~180 to 200K over the wet test fields, and 280K over the desert and dry fields. The range in T_B obtained with the microwave radiometer (~180K) is much larger than the 10K range of the infrared data over the same target areas, indicating a greater

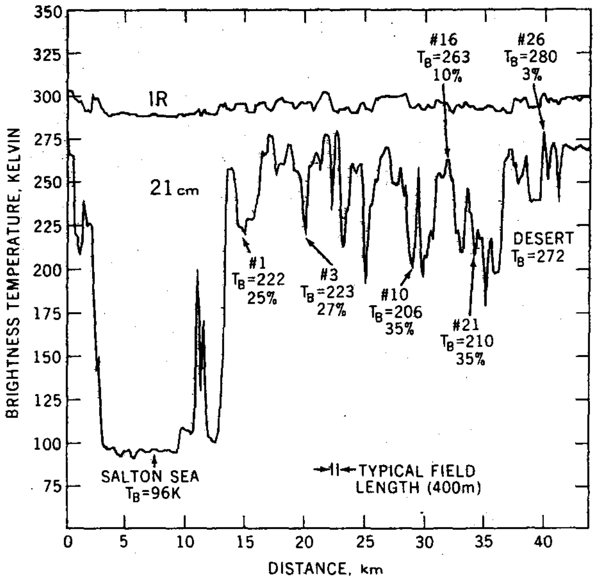

Figure 7. Thermal infrared (10 to 12 μm) and microwave (21-cm) brightness temperature versus distance for a flight path at the north end of Imperial Valley. The 21-cm brightness temperatures and measured soil moistures are indicated for several of the fields. Data were obtained with the NASA CV-990 aircraft flying at an altitude of 600 m.[13]

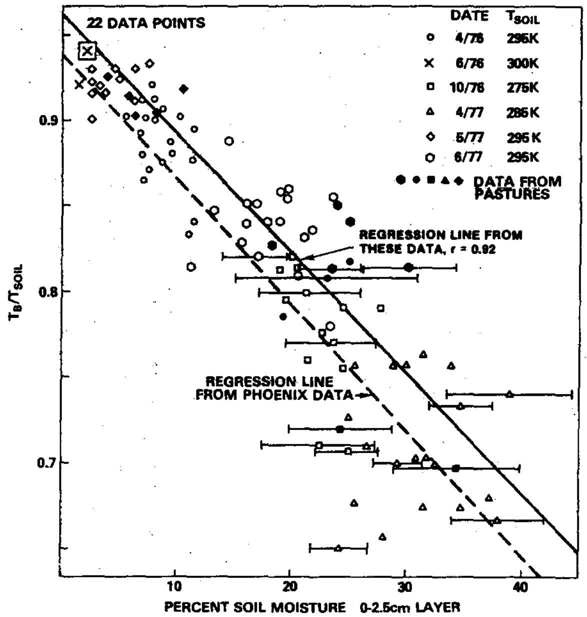

Figure 8. Observations made with a 21 cm radiometer at nadir incidence angle on board the NASA P-3A aircraft flying at an altitude of 300 m. The test site is in Hand County, South Dakota.

potential for microwave sensitivity to variations in soil moisture. The brightness temperatures of the individual fields were determined by averaging data acquired during the 3-s interval that the aircraft was over each field. These T_B values were compared with ground measurements of soil moisture typically made at four points in each field. The correlations between T_B and soil moisture in the top 2.5 cm were generally greater than 0.8.

Another example of aircraft data is presented in Figure 8. Here the results from 6 flights during 1976 and 1977 over a Hand County South Dakota test site are compared with the regression results for data obtained over the Phoenix and Imperial Valley areas in 1973 and 1975. The agreement between these independent experiments is very good. In each case the correlation between soil moisture and observed T_B was $\geqslant .85$. These data were for a range of surface conditions including fallow fields, wheat, alfalfa and pasture. The scatter in the aircraft data presented in Figure 8 arises from a number of sources, one of which is surface roughness as demonstrated in Figure 6, another is the uncertainty of ground measurements. The standard deviation of the ground measurements is represented by the error bars in Figure 8. The number of samples ranged from 6 to 29 depending on the length of the fields. This difficulty of making accurate ground measurements has hampered the determination of the accuracy of remote sensing techniques.

Studies of the Nimbus-5 satellite Electrically Scanning Microwave Radiometer (ESMR) data at 1.55 cm wavelength have shown that it has limited applicability for soil moisture sensing.[14,15] The limitation is primarily caused by a vegetative canopy over the soil. For situations where there is a significant amount of bare ground the ESMR brightness temperature has shown significant correlations with soil moisture. These situations arise in agricultural areas before the crops are planted and during the early stages of growth.

The Earth Resources Experiment Package (EREP) on board Skylab contained a 21-cm radiometer. This sensor was non scanning with a 115 km field of view between half power points. With this coarse spatial resolution, it would be difficult to directly compare sensor response and soil moisture measurements. However, there have been two reports of indirect comparisons. McFarland[16] showed a strong relationship between the Skylab 21-cm brightness temperatures and the Antecedent Precipitation Index (API) for data obtained during a pass starting over the Texas and Oklahoma panhandles and proceeding southeast toward the Gulf of Mexico.

Eagleman and Lin[17] carried the analysis of the Skylab data a step further and compared the brightness temperature with estimates of the soil moisture over the radiometer footprint. The soil moisture estimates were based on a combination of actual ground measurements and calculations of the soil moisture using a climatic water balance model. They obtained a correlation of 0.96 with data obtained during five different Skylab passes over Texas, Oklahoma and Kansas. This result is very good considering the difficulty of obtaining soil moisture information over a footprint of such a size and considering the fact that the brightness temperature was averaged over the wide range of cultural conditions that occurred over the area.

V. CONCLUSIONS

The possible use of the moisture dependence of soil emissivity in remote sensing of soil moisture has been described in this paper. A method for estimating a soil's dielectric properties from its texture and moisture content has also been discussed. Radiative transfer model calculations were presented which indicated that the soil moisture sampling depth was approximately a quarter of a wavelength, or about 5 cm at $\lambda = 21$ cm, and that soil temperature effects were important but can be parameterized in terms of the surface temperature and deep soil temperature.

Field measurement results were presented which indicated the degree to which sensitivity to soil moisture was reduced by vegetative cover and surface roughness. The vegetation effects for grass covered fields were shown to be substantial at $\lambda = 6$ cm but tolerable at the 21 cm wavelength, i.e., 50% sensitivity remained at the longer wavelength. Surface roughness also tends to mask true soil moisture conditions having its greatest effect for wet soil conditions. Observations at $\lambda = 21$ cm indicate that emissivity can be increased due to surface roughness by 0.2 for very wet soils versus only 0.02 for dry soils, resulting in decreased sensitivity of microwave emissivity to soil moisture variations. To effectively deal with the problem of surface roughness it will be necessary to learn more about the range of roughnesses which occur in nature. This may be done from knowledge of land use characteristics or through the possible use of polarization difference measurements. Roughness degrades the integrity of the surface; as a result, polarization differences will be decreased and may be used to categorize roughness magnitudes.

Observations from aircraft and spacecraft platforms at $\lambda = 21$ cm have demonstrated the sensitivity of microwave radiometers to soil moisture for a wide range of surface conditions. They are in general agreement with the results from field measurements and model calculations.

Based on results from the various measurement programs and model calculations it appears that observations at the longer wavelengths ($\lambda \geq 10$ cm) are necessary for soil moisture sensing. This conclusion is based on the greater sampling depth and the better vegetation penetration capabilities possible at the longer wavelengths. A drawback is the limitation the longer wavelengths impose on spatial resolution. The angular beamwidth ($\Delta\theta$) for a microwave antenna is diffraction limited and can be estimated by:

$$\Delta\theta \cong \lambda/d \text{ in radians,}$$

where d is the size of the antenna. The spatial resolution which can be obtained is proportional to the altitude of the sensor platform. The Skylab radiometer had a 1 m antenna operating at $\lambda = 21$ cm yielding an angular resolution of 1/5 radian, which combined with the spacecraft altitude accounts for the poor spatial resolution of the sensor. Therefore, much larger antennas will be required to obtain suitable resolutions, e.g. a 10 m antenna at $\lambda = 21$ cm would yield 10-20 km spatial resolution from spacecraft altitudes. This resolution is on the spatial scale of the rain cells producing soil moisture variations in nature. The placement of antennas of this size is feasible with current technology, and such a system currently under study in NASA. Thus, the possibility exists for obtaining from space repetitive measurements of surface soil moisture over large areas within the next decade.

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Dr. Schmugge received his Ph.D. in Solid State Physics from the University of California at Berkeley in 1965. From 1964 to 1970 he was an Assistant Professor of Physics at Trinity College in Connecticut. Since 1970 he has been with the Applications Program at the Goddard Space Flight Center studying the use of microwave radiometric approaches for earth resource applications, primarily in the areas of soil moisture and snow sensing.