MICROWAVE REMOTE SENSING OF SOIL MOISTURE

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ABSTRACT

Because of the large contrast between the dielectric constant of liquid water and that of dry soil at microwave wavelength, there is a strong dependence of the thermal emission and radar backscatter from the soil on its moisture content. This dependence provides a means for the remote sensing of the moisture content in a surface layer approximately 5 cm thick. The feasibility of these techniques has been demonstrated from field, aircraft and spacecraft platforms. The soil texture, surface roughness, and vegetative cover affect the sensitivity of the microwave response to moisture variations with vegetation being the most important. It serves as an attenuating layer which can totally obscure the surface. Research has indicated that it is possible to obtain 5 or more levels of moisture discrimination and that a mature corn crop is the limiting vegetation situation.

INTRODUCTION

Since the early sixties, the meteorological and Landsat series of satellites have provided much data useful for water resources management. The sensors, on board these satellites, operated in the visible and infrared portions of the spectrum and were able to observe such parameters as snow cover and surface water areas, land use, and surface temperature. Unfortunately, these sensors are restricted by cloud cover and are limited in the hydrological parameters which they can observe. Variables such as soil moisture, snow water equivalent, snow wetness, precipitation distribution and timely observations of floods are not amenable to measurements by these shorter wavelength sensors.

The microwave portion of the electromagnetic spectrum offers potential for monitoring several of these parameters, and in particular, the one which is the subject of this paper, soil moisture. For purposes of this paper, the wavelength range from 0.3 cm to 50 cm will be considered the microwave portion of the spectrum and for soil moisture sensing, only those wavelengths longer than about 5 cm are particularly effective. An advantage of the microwave wavelengths for remote sensing is that there is very little atmospheric absorption of radiation at these wavelengths; thus, observations of the earth's surface can be made from aircraft or satellite altitudes with little or no atmospheric obscuration.

Electromagnetic radiation at these wavelengths is particularly effective for soil moisture sensing because of the large contrast between the dielectric properties of liquid water and those of dry soil. The large dielectric constant of water results from the alignment of the permanent electric dipole moment of the water molecule. The dielectric constant of water at the lower microwave frequencies is approximately 80 compared with 3 to 5 for dry soils; as a result, the dielectric constant of wet soils can reach values of 20 or more. This produces a range of soil emissivity from about 0.95 for dry soils to 0.6 or less for wet soils with changes of a corresponding magnitude in the soil's reflectivity.

In this paper we will present results indicating the current status of the use of microwave approaches for the remote sensing of soil moisture. Both active and passive microwave approaches will be discussed. The passive microwave approach (radiometry) involves the measurement of the thermal emission from the surface at microwave wavelengths. This emission depends on the temperature and emissivity of the surface medium. This is to be contrasted with the active microwave approach (radar) in which a pulse of microwave energy is transmitted by the sensor and the return or reflected signal is measured. The strength of the return depends on the surface roughness and dielectric properties of the terrain being studied, but not directly on the temperature of the medium. The Second Edition Manual of Remote Sensing, published by the American Society of Photogrammetry, gives very complete descriptions of both these approaches[1]. Another excellent reference is the series of books on Microwave Remote Sensing by Ulaby, Moore and Fung[2]. The methods of soil moisture determination are summarized in the review paper by Schmugge et al.[3].

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

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau} \tag{1}$$

where $i = \sqrt{-1}$, ω = angular frequency, ε_s is the low frequency ($\omega\tau < 1$) value of ε, ε_∞ is the high frequency ($\omega\tau > 1$) of ε, and τ, the relaxation time, is a measure of the time required for the molecule to align itself with an applied field. For water $\varepsilon_s \simeq 80$ while $\varepsilon_\infty \simeq 3.5$. 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[4] 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 1. 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 in sandy soils, and is less able to contribute to the soils dielectric properties.

The curves in Figure 1 are the results from an empirical model which estimates ε of soils as a function of moisture content developed by Wang and Schmugge[5]. As Hoekstra and Delaney[4] 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 $\varepsilon_x = \varepsilon_{ice}$ 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 and Schmugge[5], 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 texture data can be used to estimate the value of W_t for a soil. Thus, 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 characteristics is available. The frequency dependence is contained in the dielectric constant for water. At the present time, it is assumed that there is no frequency dependence of W_t within the microwave spectral region but this needs to be studied further.

Recall that the dielectric constants of the medium describe propagation characteristics for an electromagnetic wave in the medium. Therefore, they determine the emissive and reflective properties for a smooth surface and it is the observation of these properties which makes possible the remote sensing of soil moisture.

MICROWAVE SENSORS

These changes in surface emissivity and reflectivity can be observed by passive and active microwave sensors. The former are radiometers which measure the thermal emission from the ground at microwave wavelengths. The latter are radars which transmit a pulse of electromagnetic energy and then measure the backscattered return.

Microwave Radiometry

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

$$T_B = \tau(rT_{sky} + (1 - r)T_{soil}) + T_{atm} \qquad (2)$$

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 in 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. As mentioned in the introduction, the normal range of condition atmospheric effects are small at the longer wavelengths, e.g. T_{sky} = 5 to 6K at 1.42 GHz with 3K of it being the constant cosmic background radiation and τ is typically 0.98 - 0.99. Therefore, Equation (2) reduces to $T_B = e\ T_{soil}$ where T_{soil} is the effective radiating temperature of the soil and can be estimated from the soil temperature[6].

Measurement of this thermal emission requires very sensitive radiometers of the type used for radio astronomy. These consist of a large antenna, typically about one meter in size depending on the platform, and a very sensitive radio receiver. The size of the antenna determines the angular resolution of the radiometer which is approximately λ/D, where D is the size of the antenna. Thus, a one meter antenna at the 21 cm wavelength yield an angular resolution of about 1/5 of a radian or 12°. This dependence of the spatial resolution on the antenna size is a major factor in the potential use or radiometric systems from space. For example, a 1.4 GHz radiometer with a 10 meter antenna operating on a satellite in a 500 km orbit would have a spatial resolution of 10 km. With this type of resolution, it would be possible to resolve the soil moisture variations resulting from large rain systems.

The range of dielectric constants shown in Figure 1 will produce a change in emissivity from about 0.95 or dry soils to 0.60 or so for wet soils. This approximate range has been observed in field experiments where a radiometer is mounted on a tower and the observed brightness temperature can be compared with actual soil moisture measurements. An example of the results is given in Figure 2. Here normalized brightness temperatures at a wavelength of 21 cm (frequency = 1.42 GHz), i.e. measured brightness temperatures are divided by the physical temperature of the soil and are compared with soil moisture values for the 0 to 2 or 0 to 2.5 cm layer of the soil. The data were obtained for fields with sandy loam soils, one in California and the other in Maryland. The data illustrate the basic sensitivity of the microwave emissivity to soil moisture variations and one of the major limitations, i.e. the microwave sensors respond to surface layer (~ 2 to 5 cm thick) moisture variations. This is true for both active and passive sensors.

A further example of the radiometer sensitivity is shown in Figure 3 where aircraft observations of the normalized brightness temperatures at 21 and 6 cm wavelengths are compared with surface measurement of soil moisture for native grass pastures in Oklahoma[7]. The non-linear behavior for the λ = 6 cm data imply that it is responding to the moisture in thinner layers at the surface. The high altitude data taken at 1500 or 3000 m agree very well with that obtained at the 300 m altitude.

On the basis of extensive field and aircraft experiments such as these, we have concluded that radiometers operating the 21 cm wavelength are the most effective for the passive remote sensing of soil moisture. They can operate at incidence angles within ± 30° off nadir with little change in sensitivity and thus can be scanned. For the off nadir observations, the horizontal polarization, i.e. where the electric fields of the wave has a component parallel to the surface is preferred. The particular wavelength of 21 cm was chosen because it is a radio astronomy quiet band, where there are no man-made sources of radiation being broadcast. Shorter wavelengths have less ability to penetrate vegetation and have a shallower sampling depth. While longer wavelengths would have greater penetration capability, they would have poorer spatial resolution and would be more subject to man-made interference.

Radar

An active microwave sensor or radar sends out a pulse of microwave radiation and then measures the return that is reflected back to it as represented in Figure 4. The intensity of this reflected signal is described by what is called the backscattering coefficient. An advantage of the radar is that the energy in the received pulses can be angularly separated into the return from different locations on ground. Thus, if the radar is on board an aircraft, it is possible to produce radar backscatter image of the ground.

Analogous to the optical reflectivity of terrain, the backscattering coefficient σ° (sigma zero) describes the scattering properties of terrain in the direction of the illuminating source. The scattering behavior of terrain is governed by the geometrical and dielectric properties of the surface (or volume) relative to the wave properties (wavelength, polarization, and angle of incidence) of the incidence illumination. Recall from Figure 1 that the dielectric constant of a soil-water mixture is strongly dependent on its water content. Thus, in general σ° of terrain is dependent on the soil moisture content of an effective surface layer whose thickness is governed by the properties of the terrain at the wavelength used; this thickness will be approximately the same for active and passive microwave approaches. In addition to this dependence on soil moisture content, however, σ° is also, in general, a function of the surface roughness and vegetation or snow cover (if not bare). The variations of σ° with soil moisture, surface roughness, incidence angle, vegetation cover and observation frequency have been studied extensively in ground based experiments conducted by scientists at the University of Kansas[8,9,10] using a truck mounted 1-18 GHz active microwave system. Some of their conclusions based on these investigations will be presented here.

Look angle and roughness effects. The dependence of backscatter intensity on surface roughness is represented schematically in Figure 4. Smooth surfaces behave as specular reflectors and therefore only have strong backscatter when the incidence angle is near zero. Rough surfaces, on the other hand, behave as isotropic scatterers and thus there is minimal angular variation. Depending on the wavelength, soil surfaces can display this range of behavior as is demonstrated in the plots of σ° versus angle presented in Figure 5 for five fields with essentially the same moisture content but with considerably different surface roughness. At the longest wavelength (1.1 GHz, Figure 5a), σ° for the smoother fields is very sensitive to incidence angle near nadir, i.e. specular behavior, while for the rough field σ° is almost independent of angle. At an angle of about 7°, the curves intersect and the effects of roughness are minimized. As the wavelength decreases, Figure 5b and 5c, all the fields appear rougher, especially the smooth field, and as a result, the intersection point of the five curves moves out to larger angles. At 4.25 GHz, the intersection occurs at 10°, and it was this combination of angle and frequency that yielded the best sensitivity to soil moisture independent of the soil's surface roughness. Based on these results, the following set of optimum parameters was determined: frequency = 4-5 GHz, $\theta = 7° - 17°$ from nadir, and horizontal transmit horizontal receive polarization[8].

SOIL TEXTURE

In the earlier discussion of the soil dielectric properties, the dependence on soil type or texture was pointed out and attributed to the differing soil particle surface areas. In the radiometric response to soil moisture this dependence is manifested by differing slopes of the emissivity versus soil moisture curves. Similarly, for the active microwave response there will be a dependence of the slope of the $\sigma°$ versus soil moisture curve on soil type. This is demonstrated in Figure 6a where the regression lines of $\sigma°$ versus soil moisture data are plotted for three different soils[10]. In this figure, the soil moisture values are expressed in volumetric units (g/cm^3) and the three soils have different shapes. When the soil moisture values are normalized by dividing by the 1/3 bar moisture content (field capacity), the slopes for the three soils are brought into relatively close agreement. This behavior was also observed in radiometric observations from aircraft[11] and field[12] platforms. This result implies that the microwave sensors are responding to the state of the water in the soil or perhaps to the amount of water above some critical level, e.g. the wilting point[13]. The use of the 1/3 bar moisture level as the normalizing factor is the first approach for explaining the soil texture effects and was developed on the basis of our understanding of the nature of the behavior of water in soils. We expect that there will be further refinements.

SOIL-MOISTURE SAMPLING DEPTH

The relationship between both the active and passive microwave responses and soil moisture content depends on the dielectric contrast across the air-soil interface. The question arises as to how thick a soil layer needs to be considered for determining the dielectric properties of the soil. Wilheit[14] determined theoretically that this transition layer is on the order of a few tenths of a wavelength thick. Experimentally this result is difficult to verify, but Newton et al.[15] have attempted to measure this thickness by comparing the dry-down curves for various soil layers with soil moistures predicted by radiometer observations at 1.4, 4.9, and 10.7 GHz (wavelengths: 21, 6.0, and 2.8 cm). They measured the moisture content for three layers (0-2 cm, 0-5 cm, and 0-9 cm) at the surface as functions of time and found that the soil moistures predicted by the two higher frequencies dried at about the same rate which was faster than that observed for the 0 to 2 cm layer, implying that these radiometers were responding to an even thinner layer at the surface. At 1.4 GHz, the drying rate was somewhere between that observed for the 0 to 2 cm and the 0 to 5 cm layer, indicating that at this frequency the sampling depth is in the 2 to 5 cm range of about two tenths of a wavelength. This is the reason for the different behaviors at 6 and 21 cm wavelengths seen in Figure 3.

VEGETATION EFFECTS

A vegetation layer covering the soil will absorb and scatter some of the microwave radiation incident on it. The absorption will be primarily due to the water content in the vegetation. The precise sources for the scattering are not understood at the present time and are the subject of much current research both experimental and theoretical.

The effect of vegetation on radar backscatter expressed in natural units (m**2/m**2) is schematically represented in Figure 7 in terms of the backscatter coefficient σ_v° of the vegetation and the loss factor L for the vegetation.

From the analysis of extensive field data, the group at the University of Kansas has determined values for the σ_v° and the loss factor L of a number of different types of vegetation[16,17]. These results are presented in Figure 8 where curves representing the data for several types of vegetation are shown along with values of σ_v° and L. It is clear that corn has the largest backscatter. They found that σ_v° is dominant at low soil-moisture values, below about 50 percent of field capacity, but that in the range between 50 and 150 percent of field capacity, the measured σ° is dominated by the soil contribution with the absorption by the vegetation being cmpensated for by its backscatter.

In addition to scattering and absorption, for passive sensors the emission from the vegetation will be significant also. A model for the effects of vegetation on the microwave emission from soils is given in Figure 9. The radiation measured by a passive sensor can be expressed as the sum of three terms: the first is the emission from the soil reduced by the vegetation absorption, the second and third are the emissions from the vegetation, both direct and that reflected from the soil surface. Note that the last term will increase with increasing soil moisture thus partially counteracting the decrease from the first term. The factor ω is a single scattering albedo parameter for the vegetation and τ is the optical depth for the canopy. The canopy absorption is given by exp (τ). The values of ω and τ were found by a statistical fit to data obtained in field experiments[18]. The resultant values of τ for several observations over soybean, corn, and grass fields are given in Figure 10. These data show a linear dependence of τ on W, the plant water content. Mo et al. in the analysis of field radiometer data found that $\omega < 0.1$ and $\tau < 0.5$ for mature corn, soybeans, and grass fields. In a separate analysis of the same data, Jackson et al.[19] found that τ is a linear function of the plant water content with a proportionality factor = 0.11 for the water content expressed in kg/m**2. Aircraft data at the 21 cm wavelength over 2 meter corn fields in Kansas showed a 30 Kelvin range of brightness temperature between wet and dry conditions[20]. Analyses of these data showed similar values of ω and τ. Based on these observations, I estimate that a mature corn canopy will be the limiting vegetation condition for the remote sensing of soil moisture.

SPACECRAFT RESULTS

The flights of microwave sensors on recent satellites, e.g. Skylab, Seasat, and Nimbus 5, 6, and 7, have provided opportunities to do case studies on the remote sensing of soil moisture. The S-194 instrument on Skylab was a non-scanning 1.42 GHz radiometer with a 110 km field of view. With such coarse spatial resolution, it is difficult to compare directly the sensor response with in situ moisture measurements. However, there have been several indirect comparisons. Figure 11 shows a comparison of the Skylab brightness temperatures observed for several passes over the central plains of the United States with the Antecedent Precipitation Index (API). The error bars represent the standard deviation of the API values obtained for the 6 to 10 stations within each resolution element. Additional analyses of the Skylab data have been reported by McFarland[21], Wang[22], and Eagleman and Lin[23]. The The higher resolution of SAR on Seasat afforded the opportunity to compare the satellite observations directly with ground measurements. Blanchard et al.[24] did this for data over a site in the Oklahoma panhandle. They compared the digitally processed Seasat backscatter data with soil moisture for bare, alfalfa, and milo fields. They found a linear relation between σ° and soil moisture with a $r^2 = 0.7$. However, they found that the backscatter from corn fields, either cut or standing, was much stronger than that observed from the other fields and showed no sensitivity to soil moisture. This good correlation between satellite observations and soil moisture is very encouraging; however, the strong backscatter from corn and the inherent sensitivity to surface slope and roughness indicate the need for knowledge of the surface conditions before quantitative estimates of soil moisture can be inferred.

DISCUSSION AND CONCLUSIONS

The results presented here are examples of the progress that has been made in improving our fundamental understanding on the use of microwave remote sensors for the remote sensing of soil moisture. The next step in the process should be a demonstration of the capabilities of the sensors for determining surface soil moisture. An example of this type of result is given in Figure 12. Here 21 cm emissivities as measured by an airborne radiometer were used to estimate the 0 to 2.5 cm soil moisture and compared with the ground measurements for this layer. The data are from a series of nine flights over an agricultural area in Hand County, South Dakota[25]. The algorithm used to extract the soil moisture values was developed using calculated emissivities for actual soil-moisture profiles measured at the U.S. Water Conservation Laboratory in Phoenix, Arizona. The resulting emissivities versus soil moisture relationship was adjusted for estimated surface roughness and vegetation effects and then applied to the observed 21 cm emissivities to calculate soil moisture. The rms difference between the observed and calculated values was 4-5 percent. In an analysis of the ground data form these flights, Owe et al.[25] found that the average value of the coefficient of variation (CV is the standard deviation/mean) for the 0 - 2.5 cm layer was 0.25 with it being greater at the lower moisture levels. Thus, the rms difference observed in Figure 13 is comparable to the standard deviation observed in the ground measurements of soil moisture, particularly for the wetter cases.

As described here, remote sensing techniques can provide estimates of the soil moisture content for a surface layer about 5 cm thick. This depth is shallow compared to the 1 to 2 m rooting depth of many crops. Estimating the root-zone soil moisture from surface measurements has been studied using correlation techniques[26] and modeling studies[27] which assumed a moisture profile in hydraulic equilibrium. The conclusion from both approaches was that, if the water content of the surface 10 cm is known, the moisture content in the top meter could be calculated within acceptable limits, and that the lowest errors were obtained when the surface water contents were measured just before dawn. Using a similar technique, combined with airborne radiometric measurements of surface layer moistures, Kondratyev et al.[28] in the U.S.S.R. obtained large area estimates of the pre-planting moisture stored in the top one meter of the soil. This is an example of Soviet efforts to use the surface water content measurements to obtain information concerning the water status of the root-zone[29]. Efforts are continuing to improve our understanding of the relationship between surface and root zone moisture conditions for a wider range of climatic and crop conditions so that the potential of the remote sensing methods described in this paper can be fully exploited.

Alternatively, knowledge of the surface-layer moisture can be used to estimate moisture fluxes at the soil surface. These could then be used in water balance models to estimate the moisture in the profile. Barton[30] in Australia used soil moistures as determined with an airborne 2.8 cm radiometer in a model for determining evapotranspiration (ET) from grasslands. Bernard et al.[31] did the same sort of thing using simulated radar backscatter data. In the follow-up paper they verified the technique using field measurements with a radar system[32]. Both groups reported considerable success in estimating ET rates and the approach is being studied further.

The microwave remote sensing of soil moisture is at a threshold at the present time. Theoretical and experimental research over the past 10 to 15 years have pretty much defined the capabilities of the active and passive microwave approaches. Briefly summarized they are: the ability to measure the moisture content of a surface layer about 5 cm thick to a relative accuracy of between 10 and 20 percent; the measurement can be made under all weather conditions and through a light to moderate vegetative canopies, i.e. the limiting case appears to be a mature corn crop; and the factors of soil texture and surface roughness will introduce uncertainties into the soil moisture determinations. Before these systems are flown on spacecraft or even before ground studies are enlarged, it will be necessary to convince the management of the utility of such a remotely sensed soil moisture measurement. In closing, I think it is important to realize that remote sensing measurements will not provide as accurate or as deep a measurement of soil moisture as can be obtained by conventional in-situ measurements, but they do provide a means for getting repetitive measurements over large areas of the surface layer soil moisture condition, and thus these microwave approaches provide an unique opportunity to obtain previously unattainable information about the land surface.

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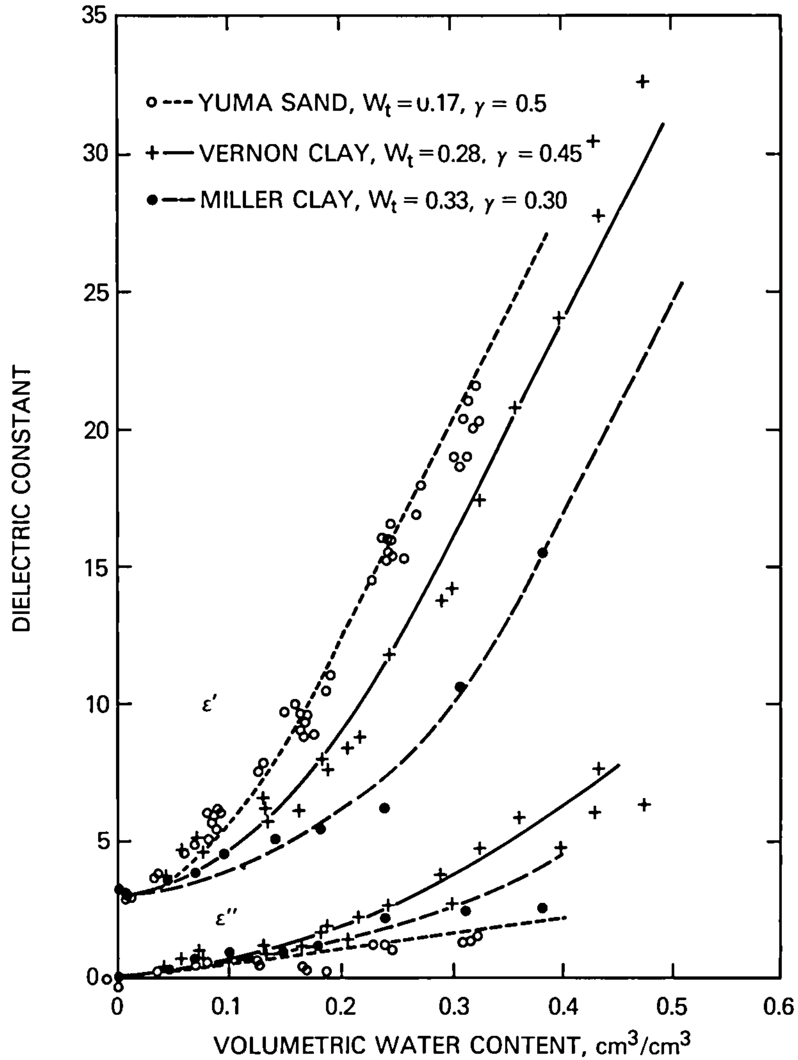


Figure 1. Laboratory measurements of the real and imaginary parts of the dielectric constant for 3 soils at a wavelength of 21 cm.

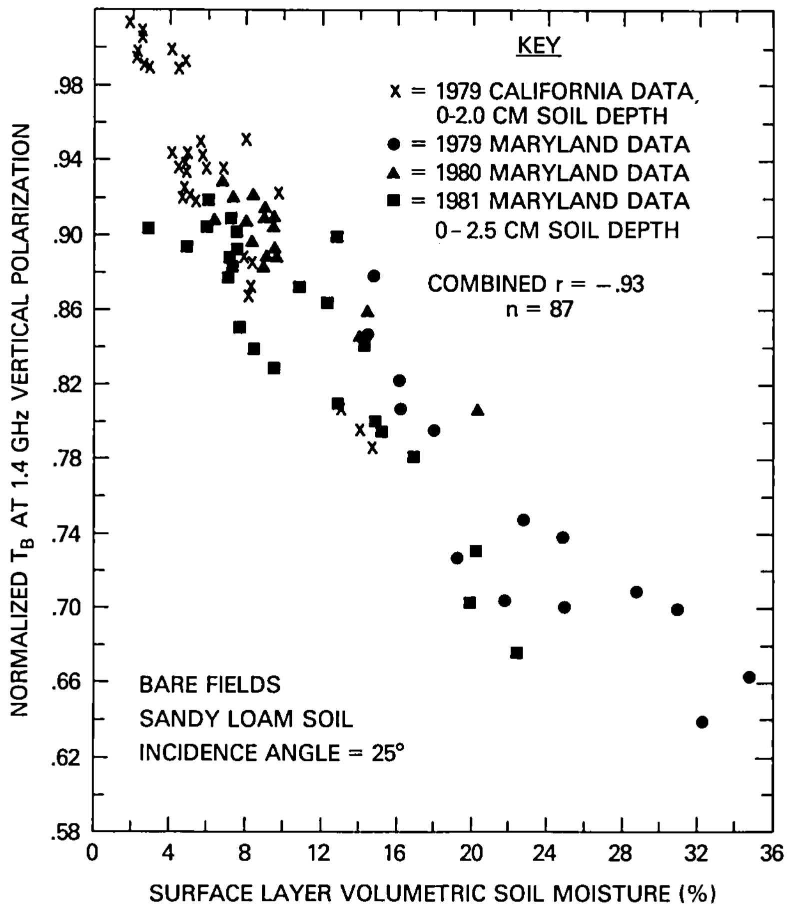


Figure 2. Observations of microwave emissivity from a tower.

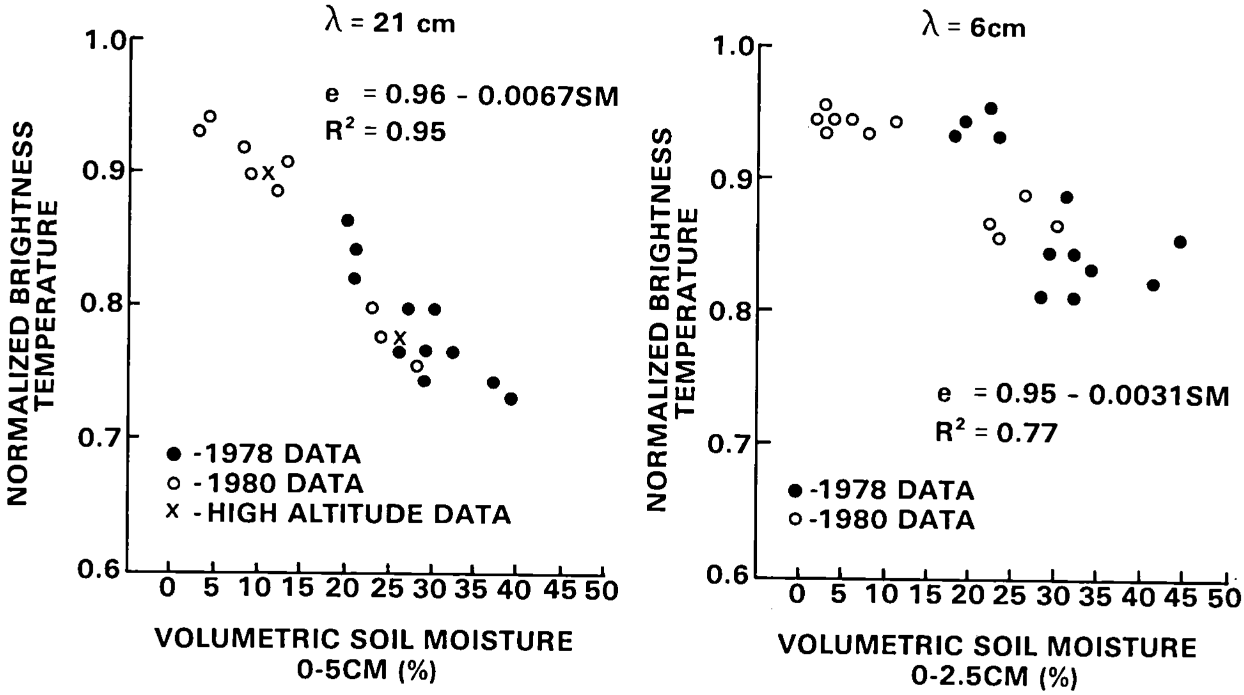


Figure 3. Observations of microwave emissivity at nadir from an aircraft at an altitude of 300 m.

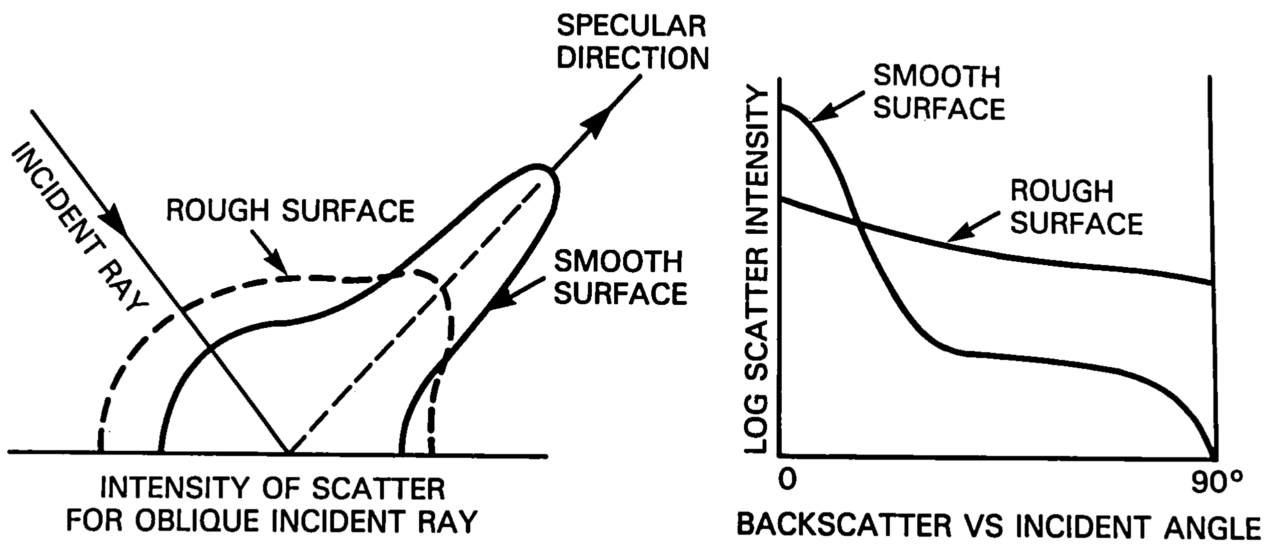


Figure 4. Schematic of radar intensity patterns showing the different behaviors of smooth and rough surfaces. The backscatter ($\sigma°$) is the intensity in the direction of incidence.

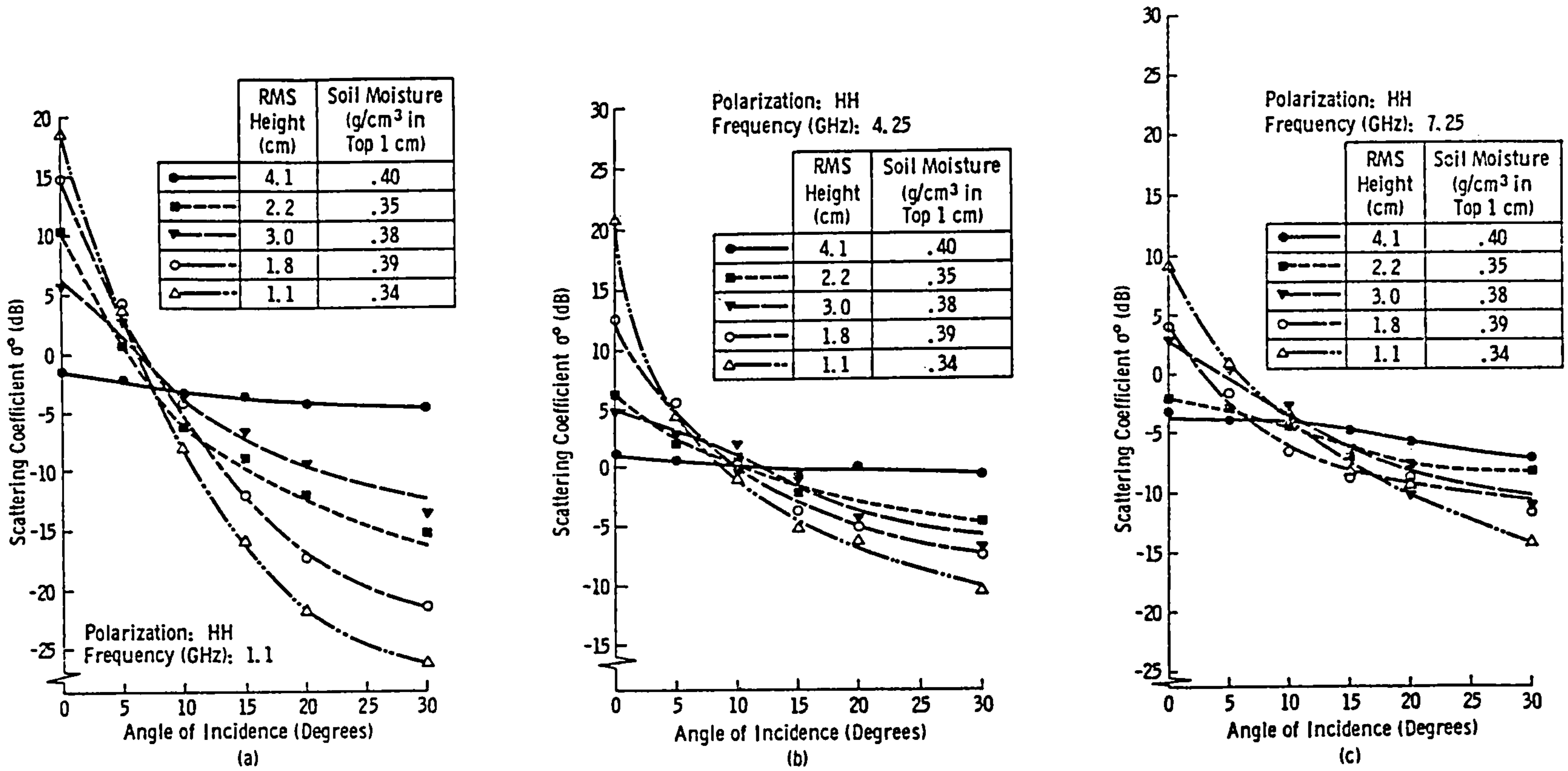


Figure 5. Angular variation of σ° in dB for 5 wet fields having RMS surface height variations as indicated. The measurements were made from a tower at the University of Kansas.

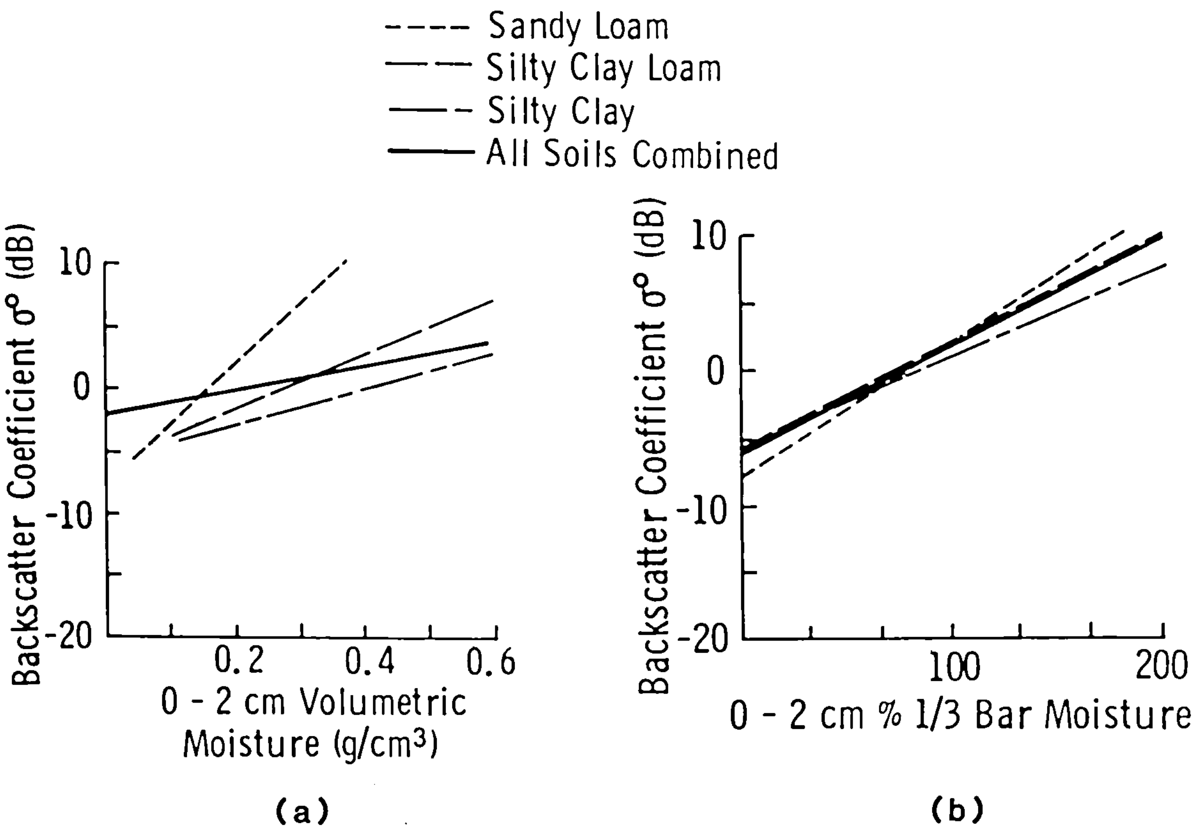
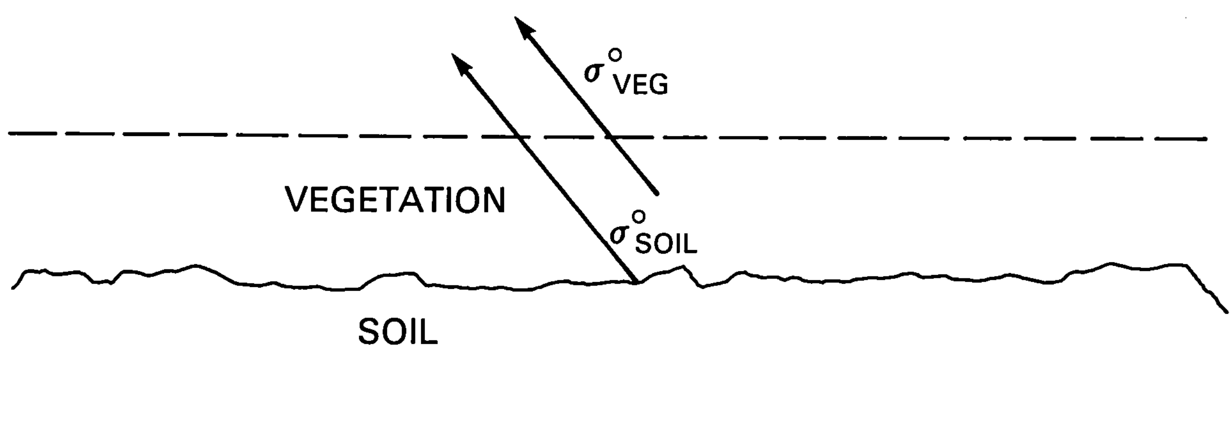


Figure 6. Regression results of tower measurements of σ° vs. soil moisture.



$$\sigma^{\circ}_{CANOPY} = \sigma^{\circ}_{VEG} + \sigma^{\circ}_{SOIL}/L^2$$

Figure 7. Schematic representation of the sources of radar backscatter from vegetated soils, where L is the canopy loss factor.

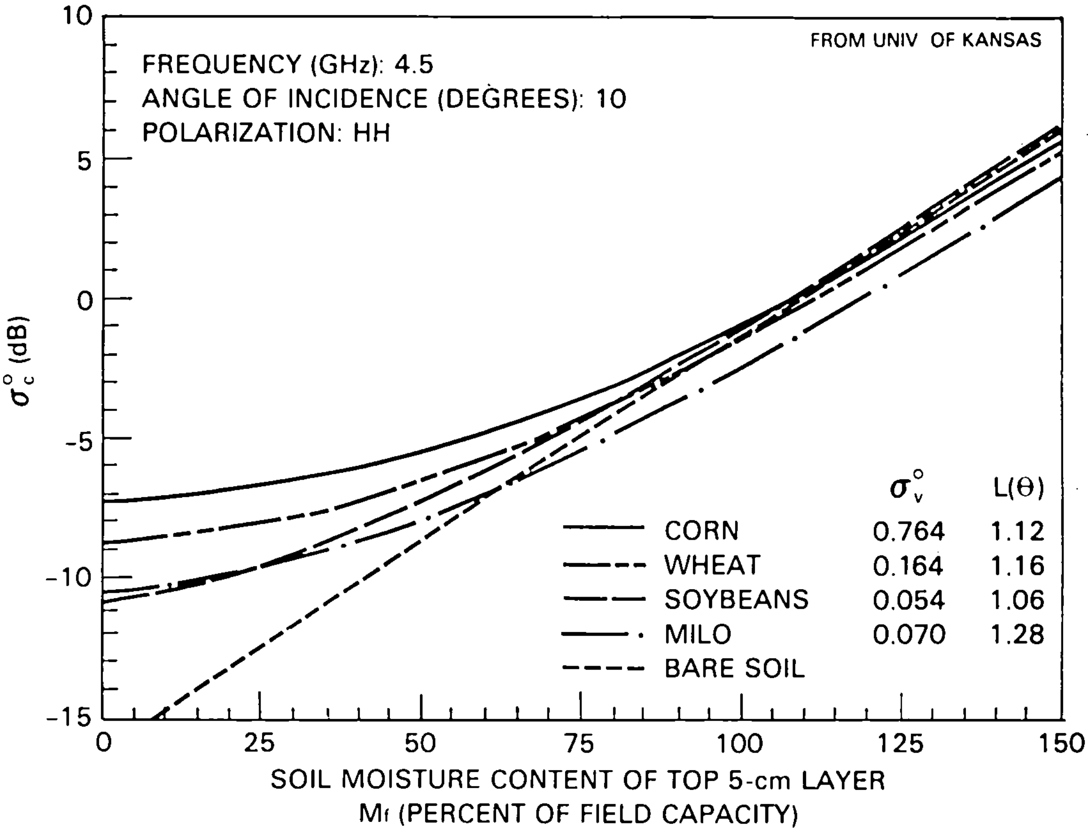
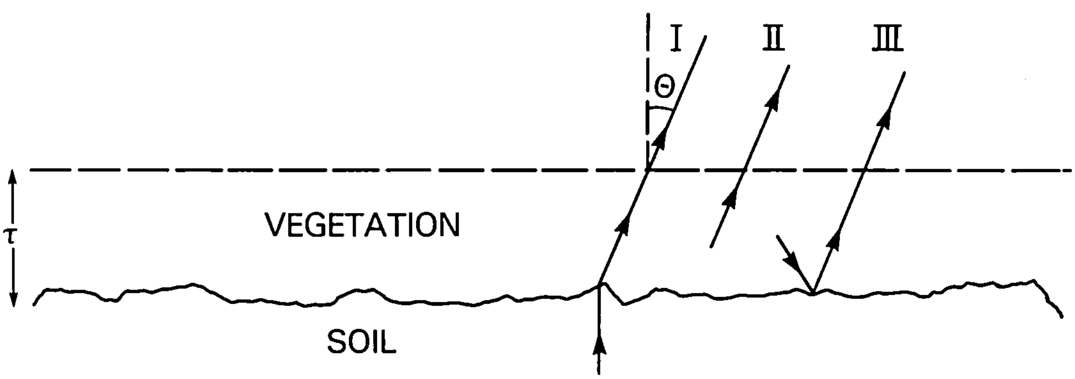


Figure 8. Variation of tower measurements of σ° for 4 crops.



$$T_B^{H,V} = \varepsilon_S^{H,V}\ T_{eff}\ e^{-\tau/\cos\Theta} \qquad \mathrm{I}$$

$$+ (1 - \omega)\ T_V\ [1 - e^{-\tau/\cos\Theta}] \qquad \mathrm{II}$$

$$+ (1 - \omega)\ T_V\ [1 - e^{-\tau/\cos\Theta}]\ R_S\ e^{-\tau/\cos\Theta} \qquad \mathrm{III}$$

Figure 9. Schematic representation of the sources of microwave emission for a vegetated soil. For comparison L = *exp* $(+\tau)$.

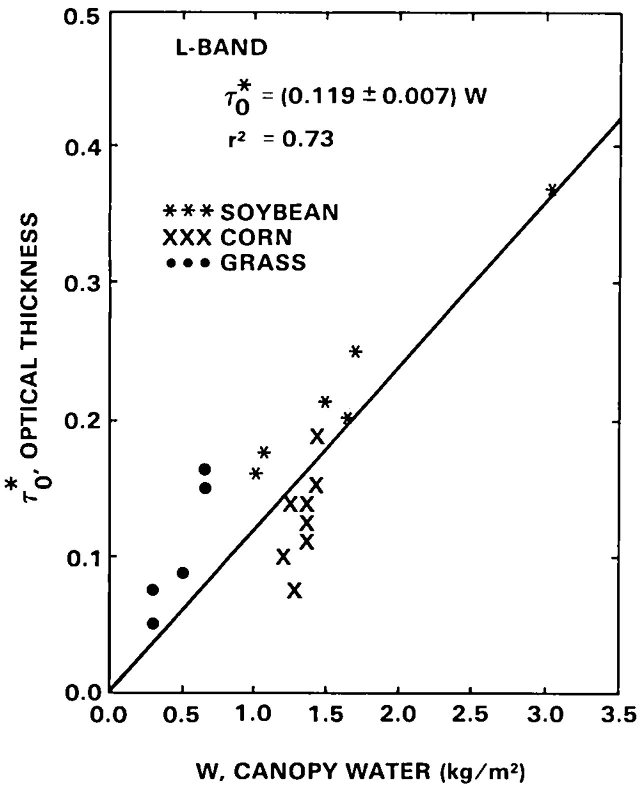


Figure 10. Variation of optical depth (τ) with canopy water content for 3 crops. Results from tower measurements at 2 km.

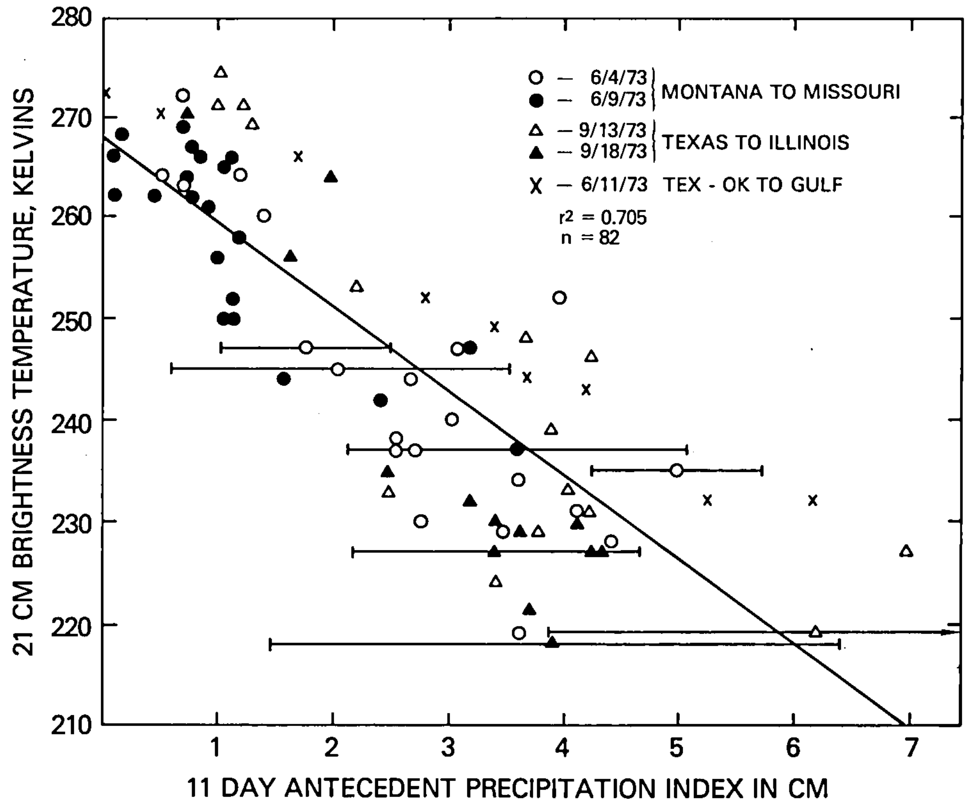


Figure 11. Satellite observations of T_B versus API.

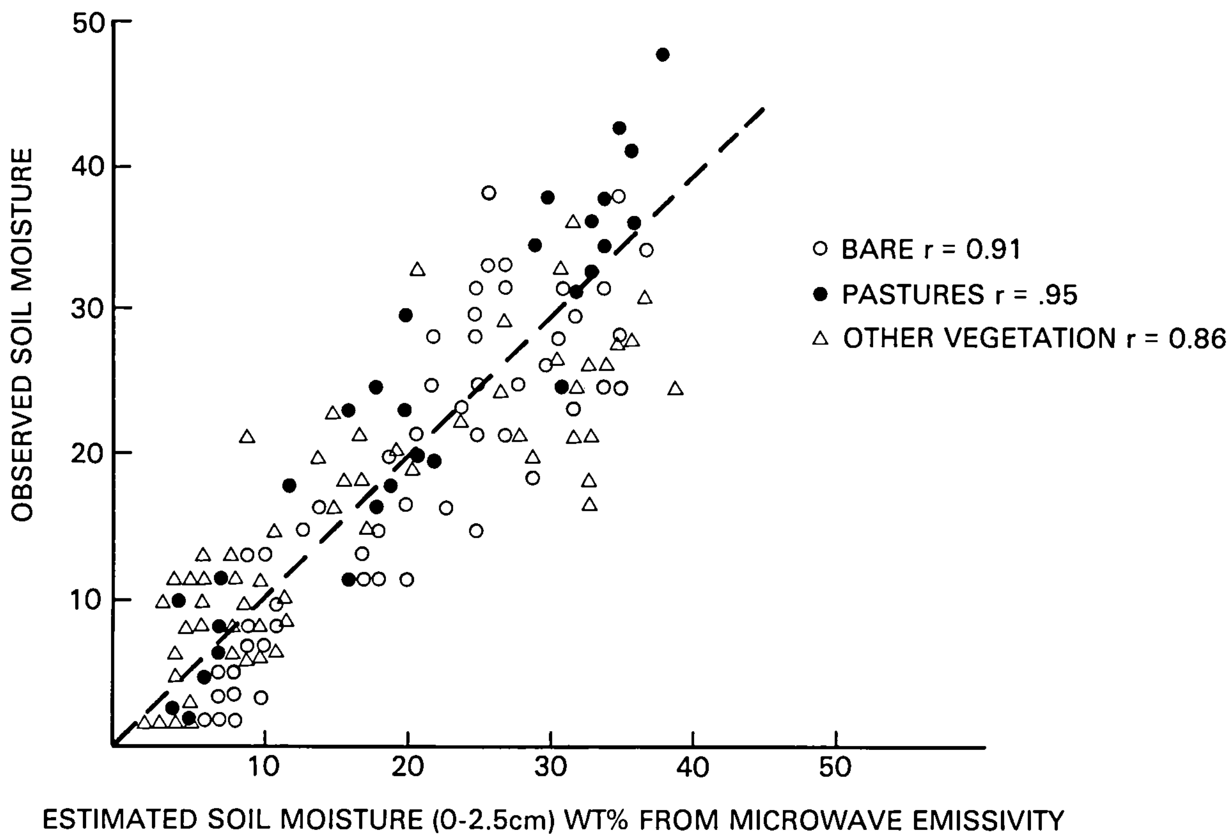


Figure 12. Comparison of measured and estimated values of soil moisture.