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STATUS OF THE REMOTE MEASURE OF SOIL MOISTURE: A REPORT OF THE SSM/I PRODUCTS WORKING TEAM (SPWT)

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Moisture influences soil reflectivity and emissivity at all wavelengths so that, potentially, there are several remote sensing methods that might be used to infer moisture content or state. For example, soil wetness governs the albedo of bare soil (Idso, et al, 1975-a). However, remote sensing estimates of soil moisture that are based upon soil albedo would be of limited value because the dependence is specific to soil type, the inference would apply to only the upper millimeter of soil, and the method would not be applicable to the more interesting regions which have significant vegetation cover.

Radiobrightness is sensitive to soil moisture in prairie and agricultural land through the dominant influence of liquid water upon microwave emissivity. The Debye relaxation of liquid water (which is centered around 12 GHz at 280 K [Hasted, 1972]) causes the microwave emissivity of moist soil to increase monotonically with frequency. Consequently, the 1-30 GHz spectral gradient of soil radiobrightness is increasingly positive as moisture content increases. Single frequency estimates of moisture content are possible at frequencies below Debye relaxation if the thermal temperature of the soil is known or can be independently measured. In fact, single frequency estimates at 1-5 GHz are less prone to errors caused by volume scatter darkening in the vegetation canopy. Volume scatter darkening at the higher frequencies causes a negative bias in the 1-30 GHz spectral gradient (e.g., England, 1974 and 1975; and England, et al, 1991).

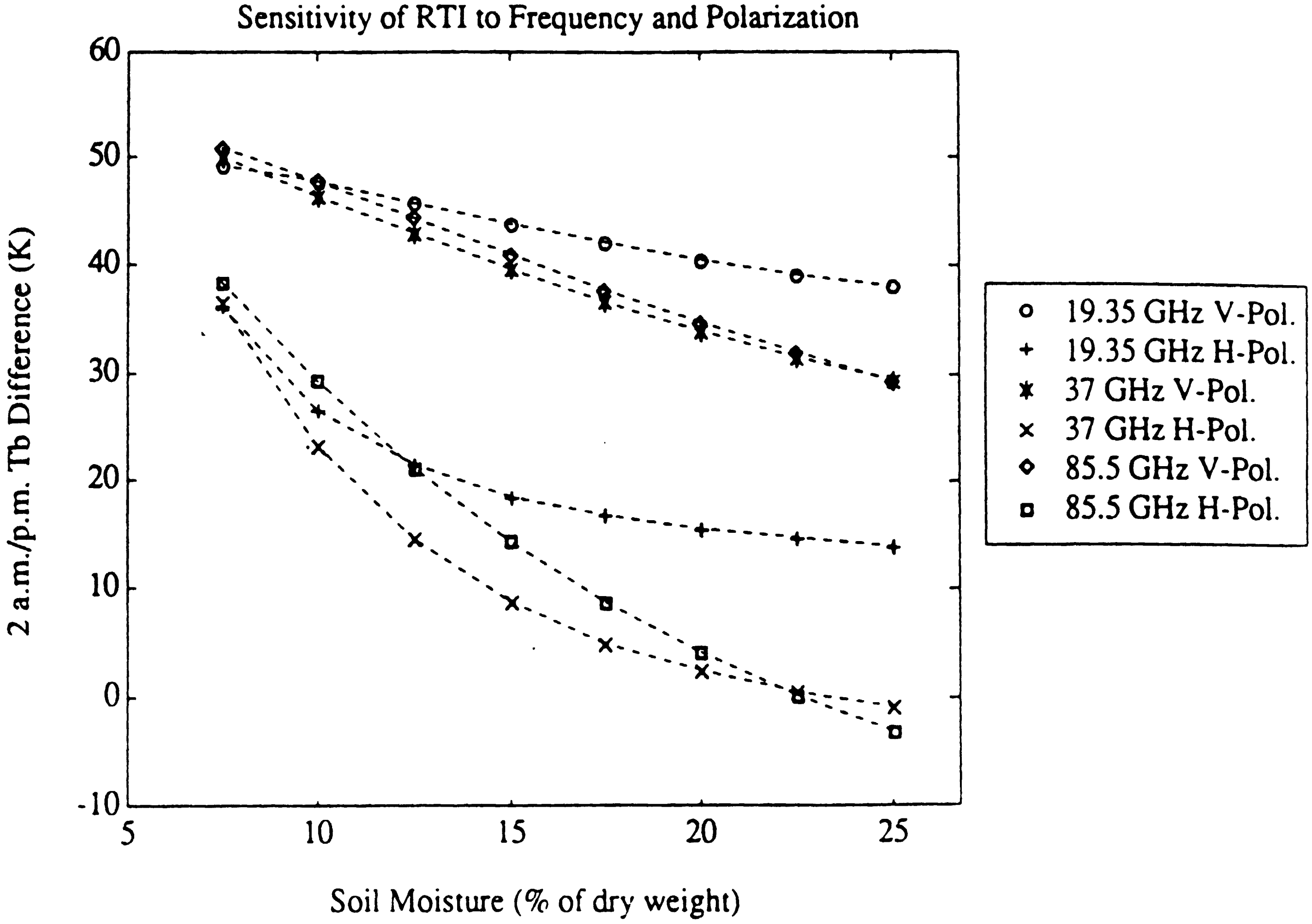
Vegetation constitutes the primary physical link between soil moisture and the atmosphere in northern prairie and in arctic tundra environments. Any correlation between soil moisture and humidity would involve the integrated moisture content from the soil's surface through the root zone of its vegetation, and would involve spatial scales which are smaller than the major drainage features (significantly less than 100 km). High sensitivity to root zone moisture in spectral measurements means frequencies of 5 GHz or less (e.g., Burke, et al, 1979; and Wang, et al, 1982), and moderate spatial resolution at frequencies below 5 GHz from satellite altitudes requires large antennas. This combination of frequency and spatial resolution from satellites has not been achieved with passive, imaging systems. For example, the lowest frequency and spatial resolution of the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) was 6.6 GHz and 150 km (Gloerson and Hardis, 1978), and that for the Defense Meteorological Satellite's Special Sensor Microwave/Imager (SSM/I) is 19.35 GHz and 43 km (Hollinger, et al, 1987). Above these frequencies, scattering by vegetation canopies certainly competes with soil moisture in governing the spectral gradient.

Radar measures of soil moisture have been examined by, for example, Ulaby and Batlivala (1976), Blanchard and Chang (1983), Ulaby, et al (1986), and McDonald, et al (1988). When compared to imaging radiometers, operational satellite radars, like ESA's ERS-1, the Japanese JERS-1, and, eventually, the Canadian Radarsat, offer the advantages of much greater spatial resolution (typically a few tens of meters), and measurements that are, to first order, independent of thermal temperature. Their disadvantages include significantly greater cost for both the spaceborne system and for subsequent data processing. For our purposes, the significant difference between radar and imaging radiometers of the same frequency is that the radar backscatter signal is more strongly influenced by scattering in the vegetation canopy and by rough soil surfaces. For example, if canopy over soil is pictured as a scattering layer over a rough-surfaced halfspace, then a radar signal has to pass through the scattering layer at least twice in the process of being reflected from the soil. Radiation that is emitted from the soil must pass through the scattering layer only once. The difference is analogous to viewing an object through frosted glass when the light is on the viewer's side (radar), in contrast to viewing the object when the light is on the object side (radiometry).

Differences caused by surface roughness can be even more striking. For example, if a vegetation-free, moist soil were effectively a homogeneous, quasi-specular halfspace at the microwave wavelength, then there would be no backscatter of off-nadir radar for any moisture content, while radiobrightness would decrease monotonically with increasing wetness at all incidence angles. Generally, radar and microwave radiometry are complementary. Radar more effectively discriminates among plant canopies where there are differences among the scattering characteristics of leaves and their distributions. At the same frequency, radiometry is more usefully sensitive to soil moisture where increasing wetness causes the effective emissivity to decrease.

There are alternative methods for obtaining soil moisture from satellite imaging radiometers. Moisture increases the apparent thermal inertia of soil by increasing its thermal conductivity, density, and specific heat, and by daytime cooling through evapotranspiration and nighttime warming through condensation. That is, as the moisture content of soil increases, its day-night difference in thermal temperature tends to decrease, and, consequently, its day-night difference in radiometric brightness also decreases. These effects have been examined in the thermal infrared spectrum (e.g., Idso, et al, 1975-b; Reginato, et al, 1976; Price, 1980; Heilman and Moore, 1980; and Vleck and King, 1983), and were the basis of the Heat Capacity Mapping Mission (HCCM) (e.g., Heilman and Moore, 1981 and 1982), a thermal infrared experiment that, in part, used differences in the near-surface storage of moisture as a discriminator among different rock and soil types (Watson, 1975).

The thermal microwave day-night signature will exceed the equivalent thermal infrared signature because soil moisture reduces microwave emissivity, but increases (slightly) thermal infrared emissivity. While thermal infrared techniques more easily achieve higher spatial resolution, the reduced susceptibility to cloudiness favors a radiobrightness technique for time varying parameters like soil moisture. This radiobrightness technique, which we call Radiobrightness Thermal Inertia (RTI), uses the diurnal thermal pulse to probe the soil, and interprets the consequences of the thermal pulse through its influence upon near-surface thermal and emissive properties. The depth of penetration comes from the thermal pulse, while the radiometric sensitivity comes from consequent thermal and dielectric changes in the surficial soils. RTI is based upon diurnal predictions from the Michigan Cold Region Radiobrightness (MCRR/diurnal) model (England, et al, 1992). Predicted sensitivities of the RTI measure of soil moisture are shown in accompanying figure.



Potential sensitivity of RTI to soil Moisture (England, et al, 1992).

Vegetation will tend to mask both thermal infrared and microwave signatures. Diurnal variations of moisture within extensive plant canopies have complex effects upon radiometric signatures (e.g., Burke and Schmugge, 1982; and Wang, 1985). Similarly, there are diurnal changes in the vertical distribution of soil moisture. Njoku and O'Neill (1982) investigated the diurnal biases on a single frequency measure of soil moisture caused by diurnal variations in the effective emission depth at frequencies of 0.6-0.9, 1.4, and 10.7 GHz. At the SSM/I frequencies of 19.35, 37.0, and 85.5 GHz, penetration is slight, but such variations may be important. Vegetation effects are expected to be less severe in prairie regions where the vegetation is short or sparse, or when there is little moisture in the canopy. Because the signal in the thermal inertia measurement is the difference between day and night radiometric temperatures, an underlying dependence upon moisture should emerge through any bias caused by volume scattering if the masking effects of the canopy are relatively constant over time. In fact, day-to-night scattering effects are not fixed because canopy moisture varies. Such diurnal variations are to be included in the RTI model.

The RTI technique is particularly well suited to satellite remote sensing because it requires successive day and night observations. Sun-synchronous satellites overfly a region at nearly 12 hour intervals permitting just such measurements for properly phased orbits. For example, the overflight of the SMMR occurred at midnight and noon local solar time which are close to optimum times for observing day-night differences, but overflight of the current SSM/I occurs at approximately 6:00 a.m. and 6:00 p.m. which are particularly poor times because they correspond to thermal crossover rather than to thermal maxima and minima.

The RTI measure of soil moisture is, as yet, theory with a weak observational corroboration. The theory will be checked through a field experiment using our Tower Mounted Radiometer System (TMRS) -- an SSM/I equivalent that we have built. The experiment is planned for the University of Michigan's Matthaei Botanical Garden in Ann Arbor, MI, during July and August of 1992. The theory and the experimental hardware were developed under NASA grant NAGW-1983.

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