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SURFACE SOIL MOISTURE MEASUREMENT WITH MICROWAVE RADIOMETRY†

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Abstract—Soil moisture is one of the few directly observable hydrologic variables that has an important role in water and energy budgets necessary for climate studies. At the present time there is no practical approach to measuring and monitoring soil moisture at the frequency and scale necessary for these large scale analyses. Current and near future satellite systems have failed to address this important question. Here, a solution utilizing passive microwave remote sensing is presented.

1. INTRODUCTION

There is growing recognition of the importance of soil moisture in the hydrologic cycle, especially as the scale of interest moves to regional and global problems. Soil moisture is one of the few directly observable hydrologic variables that plays an important role in water and energy budgets necessary for climate studies. At the present time there is no practical approach to measuring and monitoring soil moisture at the frequency and scale necessary for these large scale analyses. Current and near future satellite systems have failed to address this important question. A passive microwave sensing system could be used to measure and monitor surface soil moisture hydrology.

Microwave remote sensing offers four unique advantages over other spectral regions:

(1) the atmosphere is effectively transparent providing all-weather coverage (in the decimeter range of wavelengths);
(2) vegetation is semi-transparent allowing the observation of underlying surfaces (in the decimeter range of wavelengths);
(3) the microwave measurements are strongly dependent on the dielectric properties of the target which for soil is a function of the amount of water present;
(4) measurement is independent of solar illumination which allows day or night observation.

The real part of the complex dielectric constant of water in this spectral region is approx 80. The value for dry soil is around 3. This large contrast provides a basis for estimating the moisture for dielectric values between these two extremes.

The dielectric constant of the soil–water mixture is related to passive microwave observations of brightness temperature through the emissivity or reflectivity of the soil. Brightness temperature (the variable measured by the microwave radiometer) is related to soil emissivity subject to atmospheric (negligible), vegetation and surface features as shown in Fig. 1. These relationships are also dependent on wavelength, polarization and look angle.

2. AN OPTIMAL MICROWAVE RADIOMETER SYSTEM FOR SOIL MOISTURE SENSING

2.1. *Wavelength*

Of all the system design parameters, this is the most critical. There are several factors to consider:

(1) The dielectric constant of water decreases as wavelength decreases and this is reflected in the dielectric properties of wet soils. The effects of this decrease in the dielectric constant on the brightness temperature–soil moisture relationship are illustrated in Fig. 2 for the bare soil curve. Here the slope of the relationship between soil moisture and brightness temperature, the sensitivity, has been computed as a function of wavelength. The sensitivity is relatively constant down to a wavelength of 5 cm. Below this it drops off rapidly. A loss in sensitivity makes instrument error and other noise factors more important and will decrease our ability to accurately estimate moisture.

(2) Attenuation by vegetation increases as wavelength decreases. Vegetation can mask the soil from the sensor. A correction algorithm has been developed that requires the minimal amount of ancillary information on the vegetation canopy. In this approach the vegetation is treated as an attenuating layer that is described by its transmissivity. This transmissivity is

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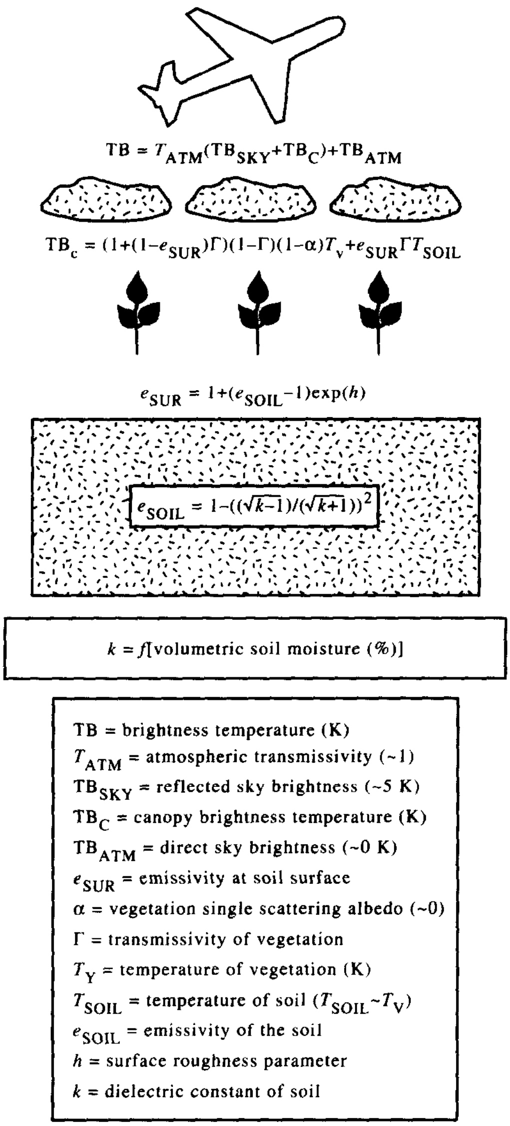

Fig. 1. Schematic of a passive microwave emission model from land surfaces.

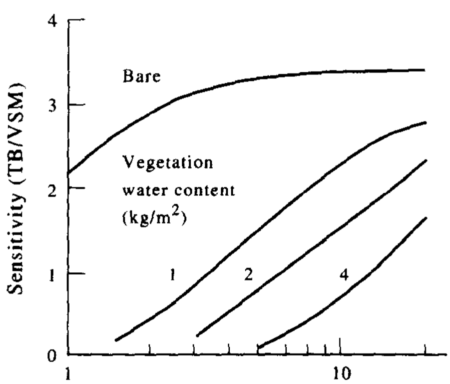

Fig. 2. Sensitivity of brightness temperature to soil moisture as a function of wavelength for bare and vegetated conditions (H polarization 10° look angle).

related to the optical depth of the canopy and as a first order approximation, optical depth was found to be a function of the water content of the vegetation and the structure of the plant for a particular sensor system[1,2]. If the cover type and vegetation water content (or a surrogate parameter such as a vegetation index) is known, the microwave observations can be adjusted to estimate moisture.

Figure 2 includes sensitivity curves for several values of the vegetation water content. For the same canopy and vegetation water content, the sensitivity is reduced as wavelength decreases. While sensitivity to the soil moisture for bare soil remained about the same down to a wavelength of 5 cm, when vegetation is present the loss of sensitivity is more rapid. These results very clearly illustrate why longer wavelengths are more desirable for soil moisture estimation and the lack of information when shorter wavelengths (< 5 cm) are used in the presence of vegetation.

(3) More ancillary vegetation information is necessary to estimate soil moisture at shorter wavelengths. Recent studies[3] have examined the effects of plant shape and wavelength on the vegetation model parameters. As the wavelength decreases the attenuation will increase. This means that sensitivity to vegetation water content increases. Also, as wavelength decreases, the variability of the vegetation parameter increases. This is due to the increase in importance of vegetation structure (and scattering phenomena) at shorter wavelengths. Accounting for vegetation at these shorter wavelengths will require the use of more sophisticated models and a great deal more information concerning the canopy.

(4) The depth of the soil layer that contributes to the measured brightness temperature increases with wavelength. Radiative transfer theory shows that the brightness temperature observed by a sensor is the integrated result of the dielectric properties in a layer that is dependent on the wavelength used. The thickness of this layer increases with wavelength.

The significance of this variation in the contributing depth, especially for hydrology and climate studies, can be illustrated in an example. Here, the same flightline was flown in the early morning on four consecutive days over a watershed in Arizona using an X (2.25 cm) and an L band (21 cm) radiometer. During this period of time the following climatic conditions occurred:

1 August: uniform rainfall in evening
2 August: sunny and hot
3 August: cloudy, rain near the beginning of line
4 August: sunny and hot

The radiometer data are summarized in Fig. 3. All of the climatic conditions are reflected in the L band data, however, at X band the day to day changes are rather small. The X band sensor does respond to the persistent wet spots (drainages) but barely responds to the daily changes. The reason for this is that the

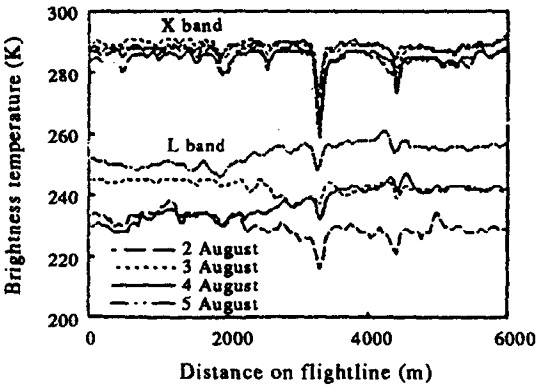

Fig. 3. Multitemporal–multifrequency aircraft radiometer observations of brightness temperature collected over the Walnut Gulch study site in August 1990[4].

layer it responds to dries out so quickly that it always appears "dry" to the sensor. This clearly illustrates the limited value of short wavelength sensors in providing hydrologic and meteorological information.

(5) Radio frequency interference (RFI) increases at wavelengths longer than 21 cm. The arguments presented suggest that the best wavelengths to use are the longest. However, RFI limits the specific regions that can be used and becomes more of a problem beyond the L band.

2.2. *Polarization*

The effects of polarization are illustrated in Fig. 4 where the sensitivity of the measurement is examined as a function of look angle at L band. Horizontal polarization is preferred because the sensitivity to moisture is higher throughout all look angles for both bare and vegetated fields.

2.3. *Look angle*

The ability to use as wide a range of look angles as possible is desirable in any mapping system and the effects of look angle are easily corrected for in the data interpretation algorithms. Figure 4 indicates that there are two competing factors at work that must be considered; the change in sensitivity with look angle and the increase in the path length through the vegetation. In this particular case, it appears that these two factors offset each other for horizontal polarization, other scenarios could be different. Based upon these considerations, the choice of look angle for horizontal polarization is not critical. However, there is a negative aspect of larger look angles. For a given sensor configuration, the size of the footprint will increase with look angle.

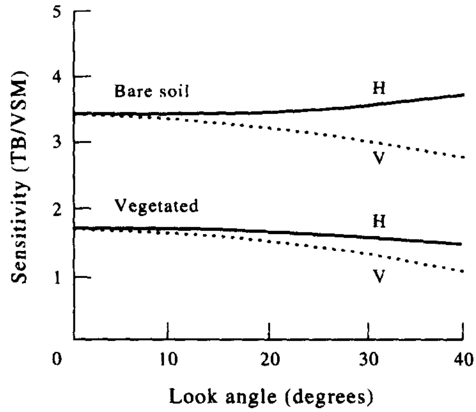

Fig. 4. Sensitivity of brightness temperature to soil moisture as a function of look angle for H and V polarizations (L band).

3. EXPERIENCES WITH AIRCRAFT AND SPACECRAFT RADIOMETERS

Concurrent with basic research, there has been an ongoing program of aircraft experimentation and a short lived Skylab experiment with an L band radiometer. Most of the aircraft data available for analysis comes primarily from two L band systems; a single beam system that was flown on a NASA P3 and C-130 aircraft from the mid 1970s until the early 1980s, and a pushbroom microwave radiometer (PBMR) configured for three or four beam positions that has been flown on NASA Skyvan, P-3 and C-130 aircraft since 1983. In addition to these sensors, a great deal of aircraft L band data has been collected by scientists in the U.S.S.R. which is summarized in[2].

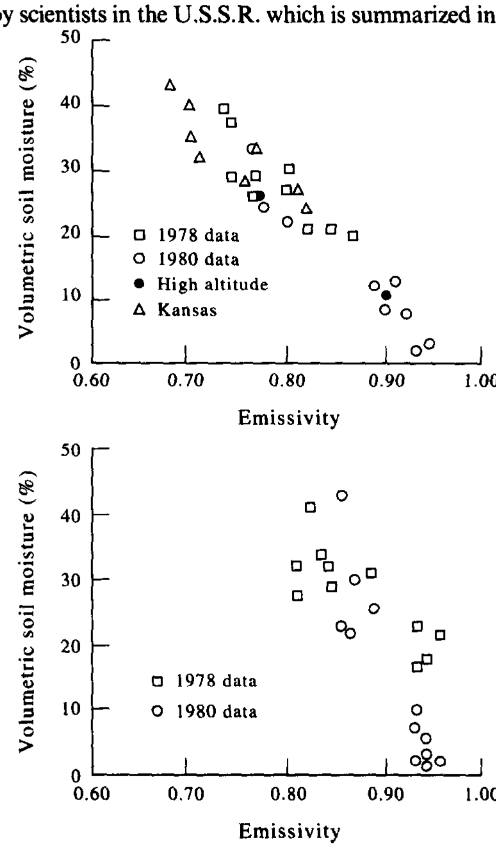

Fig. 5. Multitemporal aircraft observations of emissivity and volumetric soil moisture (0–5 cm) for rangeland sites from[5]: A–L band data and B–C band data.

The essential relationship between emissivity and surface soil moisture was verified early in the aircraft studies. An example of these results are reported in[5] for a multiyear experiment over rangeland watershed sites in Oklahoma. The data plotted in Fig. 5(a) show the L band observations. Fig. 5(b) is a plot of the C band observations collected simultaneously at nadir H polarization. These graphs illustrate an important point made previously concerning the loss in sensitivity in going from L to C band. The total range in observed emissivities has been nearly cut in half.

Figure 5(a) also includes data collected during 1980 at 10 times the baseline altitude which increased the sensor footprint size from 75 to 750 m. The high altitude observations appear to follow the same trend as the lower altitude data. Also plotted in Fig. 5(a) are data collected over similar sites in the Konza Prairie in 1985 as reported in[6].

Several large scale aircraft experiments have been conducted recently to study the temporal and spatial dynamics of surface soil moisture or emissivity in the context of hydrology[7]. The first such study was the HAPEX experiment conducted in France in 1986. Due to a limited range of observed conditions, these data have not been extensively processed. However, data from a second project, the 1987 FIFE program, has been extensively analyzed. As part of this project, an area 7 × 14 km was mapped a total of 11 times. The brightness temperature maps produced clearly reflected the antecedent meteorological conditions[8]. Comparisons with ground observations of surface soil moisture showed that moisture could be determined from the radiometer data after some calibration. Using the established relationship, soil moisture maps have been developed for selected watershed sites.

The FIFE results have awakened the interest of many researchers interested in the spatial and temporal dynamics of the surface soil moisture. Two additional hydrologic/meteorological experiments were conducted during the summer of 1990; MACHYDRO and MONSOON'90. MONSOON'90 [7] was conducted on the Walnut Gulch watershed, an arid rangeland site in southeast Arizona. Over a 10 day period a total of 6 mapping missions were conducted which included the full range of surface moisture conditions.

MACHYDRO[9] was conducted on a watershed site in Pennsylvania. Over a period of 9 days, five data flights were flown over a nominal 4 × 10 km area. This study area was quite different from the Walnut Gulch site. Here there were large variations in the vegetative cover.

Unfortunately, the database available from satellite platforms is quite limited. All of the spaceborne microwave radiometer systems to date have had poor resolution (Skylab L band) or short wavelengths (Nimbus ESMR and SMMR). However, even with these drawbacks investigators have been able to verify the basic ability to measure moisture from a satellite platform. In a recent investigation[10], data collected by the polar orbiting SSM/I at 3 very short microwave wavelengths were used to observe temporal patterns of the brightness temperature in Oklahoma following a large rainfall event. This instrument was able to track drying conditions over bare soil/stubble regions for several days following the rainfall. The results are better than might be expected at these wavelengths and clearly show the potential. On the other hand, over rangeland areas the sensitivity to moisture changes was completely eliminated. This second result makes it quite obvious why an L band sensor is needed.

Another problem with these investigations has been that little if any actual ground observations of soil moisture were collected. As a result investigators have used a soil moisture surrogate variable called the antecedent precipitation index (API) which incorporates the antecedent precipitation with a drydown pattern typical of the season and region.

There have been a number of other investigations that have shown that shorter wavelength satellite systems could be used to estimate moisture related variables[11–14]. These types of investigations have shown encouraging results, however, the results must be interpreted with some caution because they usually deal with a very limited geographical region and typically only those with light vegetation covers. Under such conditions it isn't unusual for the shorter wavelength systems to provide some useful information.

4. SURFACE SOIL MOISTURE ALGORITHM

The starting point in the algorithm is the calibrated output (brightness temperature) from the sensor. The first step in soil moisture estimation is the categorization of the ground element with regard to cover conditions. The surface must be identified as to whether it is land or water. The land categories are further divided into: forest/dense vegetation, snow/ice, broadleaf vegetation, stalk dominated vegetation or bare soil. Vegetation and land cover types not suitable are thus eliminated from further processing. These data do not have to be collected concurrently and an update every 2 weeks is adequate.

The second step in the algorithm is the correction for atmospheric moisture. Although the correction at L band is generally small, conditions involving heavy cloud cover and rain need to be identified. Cloud cover and order of magnitude rainfall data are readily available at an appropriate scale as standard meteorological satellite products.

Computation of the surface emissivity is the third step of the algorithm. Emissivity is computed by dividing the brightness temperature by the physical temperature of the target. Emissivity is not sensitive to this temperature estimate and, therefore, any one of a number of data sources can be used. The one limitation is that the data should be obtained as closely as possible in time to the microwave data.

The next step of the algorithm involves the elimination of vegetation and surface roughness effects. The correction for vegetation is based on the previously described algorithm that requires an estimate of vegetation water content. This parameter (or a surrogate such as green biomass) can be estimated using vegetation indices and an observation frequency of 2 weeks would be adequate. Surface roughness effects would depend on regional land management and crop calendar information which would have to be assembled, on a one time basis, from other sources.

The final step involves taking the soil emissivity, the result of the processing described above, and estimating soil moisture. This relies on first inverting the Fresnel equations to determine an effective dielectric constant for the surface layer and then using dielectric mixing model relationships and soil texture properties to estimate moisture. The soil texture properties are available on a global basis at appropriate scales.

5. SPATIAL RESOLUTION

Using existing fixed beam antenna technology, ground resolution is proportional to the wavelength and altitude and inversely proportional to the antenna size. The arguments presented in previous sections specified the wavelength at 21 cm. The altitude will also be fixed within a certain range for polar orbiting satellites, nominally 500 km. Therefore, the only design variable available for improving resolution is the antenna size. Size and mass are limited by launch vehicle and construction restrictions. For an L band system nominal resolution from a spacecraft altitude would be 50–100 km. This resolution is too coarse for all but a few global applications.

The problem of resolution using long wavelength passive microwave sensors has been the focus of recent research. A promising solution has been developed that is based on alternative antenna technology called electronically scanned thinned array radiometry, ESTAR[15]. This approach achieves better ground resolution by synthesizing a larger filled array antenna with an array of distributed elements that are of low volume and mass, thus overcoming the launch and construction constraints. A ground resolution of 10 km could be achieved based on known design constraints. Verification has been conducted using an aircraft prototype of this instrument[16].

6. SUMMARY

In the preceding sections various aspects of passive microwave remote sensing of soil moisture have been discussed. Important points relative to the operational use of this approach as a source of information for hydrologic analysis are summarized below.

(1) Microwave sensing allows all-weather and time of day observation.
(2) It provides a direct measurement of a moisture related soil property.
(3) The optimal wavelength for observations is 21 cm (L band).
(4) Aircraft experiments over several years and a range of conditions have shown the consistency and reliability of this approach.
(5) The data interpretation algorithm is well understood and operational techniques could be implemented with existing or proposed ancillary satellite data.
(6) New and potentially more valuable data (i.e. evaporation and infiltration properties of soils) might be extracted if a reliable multitemporal observational system was available.
(7) Through the use of new antenna technologies such as ESTAR, it will be possible to obtain data at a useful resolution from a spacecraft altitude.

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