Remote sensing of soil moisture from an aircraft platform using passive microwave sensors

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ABSTRACT A series of experiments were conducted over several years using an aircraft platform to study the relationships between passive microwave data and surface soil moisture. Sensor systems included thermal infrared and multifrequency passive microwave instruments. Aircraft measurements were obtained concurrently with ground observations of soil moisture and land cover. Test sites included areas in both humid and semi-arid regions of the USA. Data analyses indicated that the basic cause and effect relationships between the sensor measurements and soil moisture can be extrapolated from theory and small scale tests to larger resolution elements observed by the aircraft. Pastures in different climatic regions showed similar responses. Vegetation canopy attenuation was verified. Based on these studies the optimal surface soil moisture sensor using passive techniques was a 21 cm wavelength radiometer.
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d'onde de 21 cm.

INTRODUCTION

Hydrological forecasts and agricultural water management decisions can be improved by timely and accurate observations of soil moisture. However, conventional measurements are impractical when frequent observations over large regions are required. For this reason, remote sensing techniques are being evaluated for soil moisture determination.

Previous research has shown that several sensor systems can be used to estimate surface soil moisture (Schmugge et al., 1980). Microwave systems appear to be the best suited to potential remote sensing applications because they provide a direct estimate of soil moisture, are extendable to satellite platforms, and are weather independent.

In this study, a series of experiments was conducted over a three-year period to determine the optimum passive microwave system for measuring surface soil moisture from an aircraft platform in several geographic areas. Multifrequency sensor system measurements from an aircraft were obtained concurrently with ground observations of soil moisture and land cover. Data analyses were conducted to determine the sensitivity of the relationship between soil moisture and passive microwave measurements considering the effects of canopy cover and geographic location and sensor system configuration.

TEST SITES AND GROUND SAMPLING

Data presented in this study were collected over the period 1976-1980 over sites in Florida, Oklahoma, and South Dakota. The majority of these data were collected between 1978 and 1980 in Florida and Oklahoma. Additional sites were evaluated in these studies; however, the data were unsuitable for analysis due to either inadequate ground sampling or sensor coverage.

Oklahoma test sites

Oklahoma test sites were small rangeland basins monitored by the USDA-ARS Southern Plains Watershed and Water Quality Laboratory near Chickasha, Oklahoma. Two flightlines covered a total of four rangeland (R5, R6, R7, and R8) or pasture basins which ranged in size from 8 to 18 ha. The rangeland basins were nearly adjacent and had similar silt loam soils.

Soil moisture samples were collected using a gravimetric technique for depth intervals of 0-2.5, 2.5-5, and 5-15 cm. Soil temperature measurements were obtained at depths of 2.5 and 15 cm. Gravimetric soil moisture data for each depth interval were converted to volumetric when combined with bulk density.

Flights were conducted on three dates in 1978: 1, 12 and 30 May. All these dates had relatively wet soil moisture conditions. To extend the analysis to a greater range of conditions, three additional flights were conducted in 1980 on 24 June, 14 August, and
9 September. Two of these dates were very dry and one was in the moderate range observed in 1978. Additional details of the sites and the data collected are presented in Jackson et al. (1980) and (1982a).

Florida test sites

The sampling locations in Florida were all in or west of the Taylor Creek Experimental Watershed, which is monitored by the USDA-ARS. They are in Okeechobee County just north of Lake Okeechobee.

Two flightlines were flown over the area on 30 November 1978, and 2 May, 22 May, and 13 June 1979. One flightline covered six orange grove sites each of which was about 40 ha (100 acres). Soils on this flightline were mostly fine sandy loams. A second flightline covered five pastures and two wooded sites with standing water. Soils were generally fine sands except for the two wooded sites.

Soil moisture samples were collected at eight points for each site. Data were obtained at four depth intervals: 0-2.5, 2.5-5, 5-10, and 10-15 cm. Gravimetric samples were gathered using an undisturbed core sampling device which yielded estimates of the bulk densities. Bulk density values in the 0-2.5 cm soil layer at these sites were low. Values in the orange grove sites average 1.02 g cm$^{-2}$ for the 0-2.5 cm layer and 1.38 g cm$^{-2}$ in the 2.5-5 cm layer. The pasture sites had an average bulk density of 0.87 gm cm$^{-3}$ in the 0-2.5 cm soil layer. Additional information on these test sites is presented in Jackson et al. (1981).

South Dakota test sites

Aircraft experiments were conducted on sites in Hand County, South Dakota, on nine dates covering the period of 1976-1978. Several pasture sites covered in these experiments were used in the current investigation. A total of five 400 by 400 m fields were studied; however, all fields were not sampled on each date.

Soil moisture samples for depth intervals of 0-2.5, 0-5, and 0-10 cm were collected. Soils were generally loams and silt loams. Four to six samples were obtained on each 16 ha field. Since several of the pastures were longer than 400 m, the number of samples ranged up to 18 for a 1200 m long field.

REMOTE SENSING SYSTEMS

The NASA 929 (C-130B) aircraft was the sensor platform used in these experiments. A nominal altitude of 305 m (1000 ft) and a ground speed of 278 km h$^{-1}$ (150 knots) were chosen. The systems assessed in this study included cameras, a thermal infrared radiometer and multifrequency microwave radiometers.

Colour infrared photography was obtained by using a Zeiss 23 cm (9 in.) camera with Kodak 2443 film. A 15 cm (6 in.) focal length at the specified altitude resulted in a nominal scale of approximately 1:2000 on the photo products. Forward overlap of 10% was used.

Thermal infrared radiometer data were also obtained by using a Barnes precision radiation thermometer (PRT5) with a spectral range...
from 8 to 14 microns. This is a fixed beam sensor with a field view of 2°. The ground swath width at the flight altitude was 24 m (79 ft).

The multifrequency microwave radiometer (MFMR) is a collection of five separate radiometers operating over the frequency range 1.414-37 GHz. The characteristics of these radiometers are described in Table 1. The instruments are basically Dicke radiometers in which the incoming radiation is compared with internal reference sources at known temperatures to obtain the quantitative values of the brightness temperature (T_b) of the incoming radiation.

Look angles of 0° and 40° were used for the C, L, and K band radiometers. Horizontal and vertical polarization data were collected for the C and K bands and only horizontal polarization data for the L band.

RESULTS AND DISCUSSION

All microwave data used in these analyses are expressed as emissivity or normalized brightness temperatures. These values are computed by dividing observed brightness temperature by a weighted soil/canopy temperature (Choudhury et al., 1982). All soil moisture values are expressed in per cent by volume.

Oklahoma pasture sites analyses

A significant problem in remote sensing experiments is trying to control the site variables so that a particular factor can be studied. This is especially true in aircraft studies. One set of data which were collected in this series came as close as possible to maintaining homogeneous conditions over an extended period so that the effects of soil moisture could be evaluated.

Data were collected on four rangeland basins located near Chickasha, Oklahoma, on three dates in 1978 and three dates in 1980. Qualitative observations revealed some changes and differences in the pasture density; however, these differences were small. Surface roughness and topography were similar at all sites with R7 and R8

<table>
<thead>
<tr>
<th>System designation</th>
<th>Centre frequency (GHz)</th>
<th>Wave-length (cm)</th>
<th>Receiver bandwidth (MHz)</th>
<th>Antenna beam-width (°)</th>
<th>Swath width (m) for 305 m altitude: 0° look angle</th>
<th>40° look angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>L band</td>
<td>1.41</td>
<td>21.00</td>
<td>27</td>
<td>15</td>
<td>75</td>
<td>120</td>
</tr>
<tr>
<td>C band</td>
<td>5.00</td>
<td>6.00</td>
<td>50</td>
<td>6</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Ku band</td>
<td>18.00</td>
<td>1.67</td>
<td>200</td>
<td>6</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>K band</td>
<td>22.00</td>
<td>1.35</td>
<td>200</td>
<td>6</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Ka band</td>
<td>37.00</td>
<td>0.81</td>
<td>200</td>
<td>6</td>
<td>30</td>
<td>50</td>
</tr>
</tbody>
</table>
being slightly rougher due to erosion.

Figure 1 shows a plot of the 0-5 cm soil moisture vs. normalized brightness temperature for all observations in 1978 and 1980. It is obvious from this plot that a single line could be fitted to the scatter of points to describe the relationship for both years.

Based on this and water calibration data, we concluded that the microwave radiometers operated consistently between the two years.

To determine the optimal sensor configuration and the accuracy of these sensor systems on this group of watersheds, a linear regression function was applied to each system data set. The results, parameters and coefficients of determination are summarized in Table 2. The analysis was repeated for three soil moisture depths.

A review of these results shows that L band systems have a stronger linear relationship and are more sensitive to near-surface soil moisture than the C band systems (where sensitivity is based on the regression slope parameter). This is in agreement with the results of Wang et al. (1982) who observed a substantial decrease in sensitivity for grass covered fields at C band.

Theoretical models of the relationship between the L band $T_B$ and surface soil moisture (determined by the Fresnel equation for smooth surfaces) indicate that the sensitivity of the instrument should be greater at 40° look angle than it is at 0°. On the other hand, studies by Jackson et al. (1982b), Wang et al. (1982), Ulaby et al. (1983) and Kirdiashev et al. (1979) have shown that the presence of vegetation generally reduces microwave sensitivity to soil moisture. Therefore, one might expect that as look angle increases and consequently the thickness of the viewed vegetation layer increases, that sensitivity would decrease going from 0° to 40°. The results
TABLE 2 Estimating normalized brightness temperature from soil moisture for rangeland basins, Oklahoma, 1978 and 1980

<table>
<thead>
<tr>
<th>Soil moisture parameter</th>
<th>Regression System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Intercepts</td>
</tr>
<tr>
<td>0-2.5</td>
<td>0.95 0.91</td>
</tr>
<tr>
<td></td>
<td>0.0059 0.0073</td>
</tr>
<tr>
<td></td>
<td>0.93 0.91</td>
</tr>
<tr>
<td></td>
<td>0.96 0.92</td>
</tr>
<tr>
<td></td>
<td>0.0067 0.0082</td>
</tr>
<tr>
<td>0-5</td>
<td>0.95 0.92</td>
</tr>
<tr>
<td></td>
<td>0.0079 0.0095</td>
</tr>
<tr>
<td>0-15</td>
<td>0.88 0.83</td>
</tr>
</tbody>
</table>

shown in Table 2 for L band indicate that the vegetation density of these pastures does not significantly affect the typical bare soil responses.

The effects of polarization can only be examined for C band, since there were no vertical polarization L band data. In general, the vertical polarization data have a stronger relationship at 0° and a weaker relationship at 40°; however, the accuracy of all the C band relationships is relatively low and precludes a conclusion.

Based upon these results it appears that the L band sensor operating at either 0° and 40° is the best system configuration for the remote sensing of surface soil moisture under low biomass or short vegetation conditions. The data cover a very wide range of soil moisture conditions and a linear function describes the relationship very well, based upon the coefficient of determination.

The coefficient of determination for the C band systems based on a linear regression is not a completely fair measure of these systems. Figure 2 is a plot of the C band data collected at 0° and horizontal polarization. Early investigators (Schmugge et al., 1974) have observed that the relationship between soil moisture and normalized brightness temperature at this and shorter wavelengths is not linear. A better descriptor is a flat line to some soil moisture with a linear function beyond that point. Our data show this trend.

The use of a nonlinear function to describe the relationship might result in an improved coefficient of determination; however, it would not mean that the C band sensor is very good for this application. A zero slope relationship from zero to about 20% soil moisture, as in this case, indicates that the sensor is not responsive to variations in this range. In contrast, the L band sensor is sensitive, as shown in Fig.1.

A possible problem with linear analysis of this type is the
Remote sensing of soil moisture

0.5 10 15 20 25 30 35 40 45

VOLUMETRIC SOIL MOISTURE 0-2.5CM (%)

FIG. 2 C band soil moisture data.

selection of an appropriate soil moisture sampling depth with which to compare the microwave measurements. It is quite likely that a shallower soil layer, such as 0-1 cm or 0-0.5 cm, is more directly related to the microwave response at C band (Wang et al., 1982). If the average soil moisture in this shallower depth were plotted against the microwave data in Fig. 2, a more linear fit might result. However, since our intent is to find the sensor most sensitive to soil moisture in the deepest depth possible, L band still appears to be a better choice than C band.

Along the same line of thought, we considered the relationship between the soil moisture in several soil layers and the microwave response, emphasizing the L band system at a 0° look angle. The coefficient of determination values in Table 2 suggest that the strongest relationship exists between the microwave data and the 0-5 cm soil layer. However, the other two thicknesses also show a fairly strong relationship.

One reason why we do not see marked differences in these statistics is that in a pasture there is generally a good surface cover with a well-developed root system. Under these conditions, evaporation of soil moisture is controlled by transpiration, and, if the root system is not extremely different over the near surface depths, the soil moisture will tend to be fairly uniform with depth. This situation will change after smaller rainfall events, when near-surface soil moisture gradients may form.

We are seeking the most sensitive relationship and it appears that sensitivity increases with depth. However, we must also consider the accuracy. Based upon these two factors, it appears that the L band response is determined primarily by the 0-5 cm soil layer moisture.

Another factor that we considered in these experiments was the effect of the sensor footprint on the soil moisture-microwave
relationship. On two flight dates in 1980, data were collected at higher altitudes, 1500 and 3000 m, over the rangeland basin group. At these altitudes the ground resolutions for L band were 375 and 750 m, respectively, at a $0^\circ$ look angle. Soil moisture values from the four basins were averaged and plotted vs. the normalized brightness temperatures among the low-altitude data in Fig. 1. Fortunately, two very different soil moisture conditions were observed. These results fall right in the range of the low altitude data and suggest that the relationships can be extended to higher altitudes and larger footprints.

**Canopy cover effects**

Experiments conducted in Florida included mostly pasture, forest, and orange grove sites on basically the same soil types. It has been observed in previous research by Jackson et al. (1982b) that the effect of increasing canopy cover on soil emission is a decrease of microwave sensitivity to soil moisture changes. Larger soil moisture changes are needed in the presence of vegetation canopy to produce the emissivity change observed over bare soils.

Data from the Florida experiment were grouped into two categories, pasture and trees, and were statistically analyzed. Figure 3 is a plot of the L band data at a look angle of $0^\circ$ vs. the 0-5 cm volumetric soil moisture. Although there is a great deal of scatter, the discrimination of the trends for the two groups is apparent. Microwave data obtained over pasture sites show sensitivity to soil moisture, while the tree sites all produce the same microwave response regardless of the underlying soil moisture, which included a
considerable range of values.

Linear regression results are summarized in Table 3, using only the 0-5 cm volumetric soil moisture. Pasture site results indicate that a linear function explains a significant portion of the variance of the data for L band systems. C band results indicate that vegetation of this density attenuates the sensitivity to the point where the trend is not significant. This lack of sensitivity at C band implies that the difference between the Florida and Oklahoma pastures is due to the increased biomass observed for the Florida pastures, which was qualitatively verified at both locations.

**TABLE 3** Estimating normalized brightness temperature from 0-5 cm soil moisture for Florida pasture and tree sites

<table>
<thead>
<tr>
<th>Regression parameter</th>
<th>System</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>L</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0^\circ)</td>
<td>(40^\circ)</td>
<td>(0^\circ)</td>
</tr>
<tr>
<td><strong>PASTURE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.97</td>
<td>0.96</td>
<td>0.96</td>
<td>0.95</td>
</tr>
<tr>
<td>Slope</td>
<td>0.0041</td>
<td>0.0052</td>
<td>0.0006</td>
<td>0.0009</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.62</td>
<td>0.64</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>TREES</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.90</td>
<td>0.90</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Slope</td>
<td>0.004</td>
<td>0.0006</td>
<td>0.0005</td>
<td>0.0001</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Results of the tree canopy cover regression indicate no sensitivity to soil moisture variations. These results may seem strange for the citrus orchards where the aerial photographs indicate that there is a considerable amount of space between the rows of trees. However, we must recall that the photograph is made in the visible portion of the spectrum, i.e. at wavelengths almost a million times shorter than the microwave observations. As a result, the orchard canopy behaves almost as uniform vegetation rather than a mixture of low and high emissivity targets.

Data for other canopy types on similar soils were too sparse to allow comparison. Pasture site data from Oklahoma and South Dakota sites were primarily from areas with silt loam soils. Florida pastures were in areas with sandy soils and high organic levels. Pastures in Florida had a greater biomass than those in South Dakota and Oklahoma based on visual observations.

Vegetation effect theory states that increasing the biomass should result in a decreased microwave sensitivity to soil moisture (Jackson et al., 1982b). Comparing the L band data at a 0\(^\circ\) look angle for the pasture sites shows that, in general, the microwave data are less
responsive to moisture variations in the denser Florida sites than in the South Dakota and Oklahoma sites. Figure 4 illustrates this point. Regression parameters for each state are summarized in Table 4.

Some caution must be exercised in direct comparisons between the three test sites because differences in soil type and organic matter content may be influencing the results. Schmugge (1980) showed that a silt loam soil would have a smaller slope to its linear regression than a sandy soil. Thus, the sandy Florida sites, if bare, should have a steeper regression slope than the silt loam soils in Oklahoma and South Dakota. If soil type differences were the only factor to consider, then the effect of the denser Florida pastures in decreasing microwave sensitivity to soil moisture would probably be greater than a comparison of the regression lines in Fig. 4 now indicates. However, the Florida sites were also characterized by soils with high organics and very low bulk densities, which tend to increase the water-holding capacity of the soil. Since a

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sites:</th>
<th>South Dakota</th>
<th>Oklahoma</th>
<th>Florida</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td></td>
<td>0.99</td>
<td>0.96</td>
<td>0.97</td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td>0.0068</td>
<td>0.0067</td>
<td>0.0041</td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td>0.90</td>
<td>0.95</td>
<td>0.62</td>
</tr>
</tbody>
</table>
sandy loam with high organics could "act" like a loamy soil with low organics, soil type information alone is not sufficient to normalize data from different test sites in order to analyse the microwave response to soil moisture. Additional work by a truck mounted system on the effects of soil organics and bulk density is needed before such a comparison can truly be accurate.

REFERENCES


