The L-Band PBMR Measurements of Surface Soil Moisture in FIFE

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Abstract—The NASA Langley Research Center’s L-band pushbroom microwave radiometer (PBMR) aboard the NASA C-130 aircraft was used to map surface soil moisture at and around the Konza Prairie Natural Research Area during the four intensive field campaigns of FIFE in May–October 1987. There was a total of 11 measurements over an area of 7 × 14 km during this period. One of the measurements was made on May 28 when soils were known to be saturated. This measurement was used for the calibration of the vegetation effect on the microwave absorption. Based on this calibration, the data from other measurements on other days were inverted to generate the soil moisture maps. A good agreement was found when the estimated soil moisture values were compared to those independently measured on the ground at a number of widely separated locations. There was a slight bias between the estimated and measured values, the estimated soil moisture on the average being lower by about 1.8%. This small bias, however, was accounted for by the difference in time of the radiometric measurements and the soil moisture ground sampling.

I. INTRODUCTION

During May–October 1987, four intensive field campaigns were conducted for the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) over a 15 × 15 km test site including the Konza Prairie Research Natural Area (KPRNA) [1]. The duration of these campaigns amounted to a total of 57 days, with each campaign lasting between 12–17 days. The objectives of FIFE are to obtain the necessary data to permit interpretation of satellite observations to infer climatologically significant land surface parameters. One of several major elements in this cooperative effort is soil moisture mapping of the test area. The L-band (21 cm wavelength) pushbroom microwave radiometer (PBMR) [2] aboard the NASA C-130 aircraft is the major sensor for the large-scale soil moisture mapping effort. A PRT-5 thermal infrared radiometer, the NS001 Thematic Mapper Simulator (TMS), and the Thermal Infrared Multispectral Scanner (TIMS) were also aboard the aircraft to monitor surface temperature variations and vegetation cover. Only the data from the PBMR and PRT-5 were used in the analysis reported in this paper.

A few PBMR flights were previously conducted over the Konza Prairie in June 1985 [3]. The results from these flights showed the effect of surface burn treatment on the L-band microwave emission. It appeared that the dead vegetation in the unburned region formed a highly absorptive layer which effectively masked the low microwave emission from the underlying wet soils. These results and most of the research efforts of the past [4, and references therein] were limited to studies of the effects of surface parameters, e.g., soil moisture, vegetation, and roughness on microwave emission. Recently, there have been some attempts to estimate soil moisture profiles from the radiometric measurements by both U.S. and Russian investigators [5]–[7]. The latter authors employed radiometers at wavelengths of 18 and 30 cm. The emphasis was to extend the soil moisture estimation from the near surface to depths of 0.5–1 m. The effect of vegetation on microwave absorption was assumed to be measurable and correctable.

An approach to estimate surface soil moisture (0–5 cm) from L-band radiometric measurements over a 7 × 14 km area is described in this paper. The effect of vegetation is calibrated and corrected for by the L-band radiometric measurements over the area on a day immediately following a heavy rainfall. The estimated soil moisture values at a number of locations are compared to those derived from the independent ground sampling. The average estimated soil moisture is found to be lower than that from the ground measurements by about 1–2%. The reason for this bias is also discussed in the paper.

II. THE MEASUREMENTS

The FIFE test site (Fig. 1) is located at and around Konza Prairie, a few kilometers south of Manhattan, Kansas, and covers a 15 × 15 km area approximately centered at the intersection of Highways 77 and 177 (39° 03' 46" N latitude, 90° 32' 20" W longitude). Most of the test site was covered with tall prairie grass. The KPRNA is located at the northwest quadrant of the test site. A number of watersheds in the KPRNA underwent different surface treatments by burning at different intervals over the years. The L-band PBMR measurements were made over half of the test site, as indicated by the rectangular box (7 × 14 km) in the figure. The PBMR has four beams pointing at ±8° and ±24° from the nadir, each having a beam width of about 16°. Thus the resulting swath width..
is about 1.2 times the height of the aircraft flight. The radiometric measurements were acquired at altitudes of 300 and 600 m. Twelve east-west flight lines at 600 m altitude covered the area shown by the rectangular box in Fig. 1. In addition, three short lines were flown at 300 m altitude over two adjacent watersheds, as indicated by the dotted lines within the box. The solid circles in the figure give the locations where soil moisture sampling was made, every other day, during each of the four intensive field campaigns (IFC). Those indicated by the letter "P" were the locations of ten portable automated weather stations (PAM) where the rainfall amount and surface air temperature were recorded every 15 min. The soil moisture samples were taken at the depths of 0-5 and 5-10 cm. Five soil samples were collected at each depth in these locations. A number of samples was also obtained for the estimation of bulk density in each of these locations. Weekly measurements of vegetation biomass were also taken at these locations.

In association with the three flight lines at 300 m altitude over the two small adjacent watersheds 1D and 2D, three ground transects were also established, along which soil moisture samples were collected in the top 5 cm layer at approximately 50 m intervals. The sampling locations were displayed as solid circles in an enlarged high-altitude photograph of the two watersheds (Fig. 2). Soil samples were generally acquired within ±1 h of the PBMR flights. Soil bulk density was measured once at each of these locations during the course of the experiment. The dashed line, 15, gives the approximate track of ground sampling locations during IFC 1, which was subsequently changed to track 16 for IFC 2-4. The aircraft flight lines followed the three tracks of ground sampling. Because the PBMR swath width is about 350 m at the 300 m flight altitude, each of the sampling locations was within the footprint of at least one of the four beams. The different appearance of the two watersheds was due to the fact that 1D is burned every year and 2D every other year (e.g., in 1984 and 1986). Thus, during the 1987 measurements, watershed 2D was covered with a mixture of new, fresh grass and dead grass from the previous year which stood about 0.7-1.0 m tall. The dead vegetation, when wet, turned out to be a good absorber of the microwave emission from the underlying soil [3], [8].

Fig. 3 gives a summary of the PBMR flights that took place during the four IFC's. There was a total of 11 days of measurements for both 600 and 300 m flight series, as indicated by the solid arrows. Four additional days of measurements were made at the 300 m altitude, as marked by the dashed arrows. The average values (cm) of daily rainfall over the test site are also shown in the figure for the entire experimental period. The average values were derived from the 10 PAM stations whose locations are indicated in Fig. 1. A fair amount of rain fell during each of the first three IFC's. Very little rainfall was observed after the third IFC, and the two last radiometric measurements were made over extremely dry soils. Thus the data
set collected by the PBMR covered a wide range (10-45\% by volume) of soil moisture conditions.

III. RESULTS

Three brightness temperature maps obtained from flights at 600 m altitude on May 28, May 30, and June 4 during the first IFC are shown in Fig. 4. The color scale was set at 5 K increments; the blue colors corresponded to low brightness temperatures ($T_b$); i.e., wet soils. As indicated in Fig. 3, the test site experienced a drying period following the heavy rainfall on May 27. The drying down of soils was clearly reflected in the brightness temperature maps where the observed $T_b$ values were generally low on May 28 and high on June 4. The soils were saturated with water on May 28, and yet the $T_b$ values measured over the area ranged from about 195 to 275 K. This large variation in $T_b$ was due to the effect of a detritus or thatch layer on the soil surface [3]. Watersheds in the Konza Prairie in the northwest quadrant of the test site were subjected to different surface treatments over the years. Some of them were burned at different yearly intervals, and the others were never burned. For the unburned watersheds, there was a gradual buildup of a layer of decayed vegetation over the soil surface. It was found [3] that this layer of material, when wet, acted as a good absorber of microwave energy, and thus, it behaved as a surface with a high emissivity at 1.4 GHz frequency. These areas have a high $T_b$ even though the soil is wet. Examples of such watersheds correspond to the higher $T_b$ regions in the upper left quadrant of the May 28 $T_b$ map in Fig. 4.

The 300 m altitude PBMR observations of the two adjacent watersheds in Fig. 2 have been analyzed and studied in some detail by Wang et al. [8]. The PBMR response to soil moisture variation in 1987 was very similar to that measured in 1985 under similar surface conditions. The calibration algorithm for the PBMR radiometry has not been modified since 1985, which demonstrated the stability of the instrument over these years. However, only the data collected in the first and fourth IFC’s of FIFE were used in the comparison to the 1985 measurements. The results of all 1987 measurements at 300 m altitude over these two watersheds are displayed in Fig. 5 where different symbols are used for observations in different IFC’s. These plots show the variation of normalized brightness temperature or effective emissivity ($\epsilon$) with the volumetric soil moisture ($W$) in the top 0-5 cm layer. $\epsilon$ is defined as the ratio of the brightness temperature measured by the PBMR to the surface temperature measured by the PRT-5 radiometer aboard the same aircraft. Each of the data points represents the average $\epsilon$ and $W$ values derived along a transect for each watershed using the appropriate PBMR beam.

The linear regression of the data points in each plot of the figure gives a result very similar to the one derived from the measurements during first and fourth IFC’s alone.
There is little scatter of the data points along the regression line in Fig. 5(a). This suggests that, for the burned watersheds of which ID is an example, the variation of vegetation biomass during the growing season does not have a significant effect on the microwave response to soil moisture. On the other hand, the regression slopes for the two watersheds are markedly different. In contrast to the ID watershed which is burned every year, the 2D watershed is burned only in every even number of years (e.g., 1984, 1986). The fully grown, but dead vegetation from the previous year (about 0.7-1.0 m tall) remained standing during the 1987 measurements. This layer of dead vegetation shows a strong microwave emission, and is apparently the main cause for the difference in the regression slopes. Most of the experimental area outside of KPRNA is burned every year.

To quantitatively understand the effect of vegetation on the observed microwave emission, we have replotted the data from Fig. 5 in Fig. 6, along with plots of the calculated variation of emissivity with soil moisture. These are given by the equation

$$ e = 1 + (e_0 - 1) \exp(-2\tau) $$

from Jackson et al. [10], where $\tau$ is the optical depth and $e_0$ is the bare soil emissivity:

$$ e_0 = 1 + (e_b - 1) \exp(-h) $$

with $e_b$ being the smooth surface emissivity and $h = 0.1$ the roughness factor. The value of $h$ used here is arbitrary and is based on a comparison of surface conditions to earlier experiments [3], [9]. We used a soil density value of 1.0 g/cm$^3$ for the calculations, which is at the upper end of the range of measured values which were between 0.8 and 1.0 g/cm$^3$. The soil texture was chosen to be silty clay loam, as determined from soil maps to be the prevalent texture. We could very well adjust these parameters to get a much better fit to the data, but it is clear that for the range of $\tau$ values chosen, the curves pretty well bracket the observations. In the next paragraph, we will show that these values are reasonable for the vegetation conditions encountered.

In Table I, we present biomass data obtained by the Natural Resource Ecology Laboratory of Colorado State University for five watersheds which represent the range of burn conditions encountered in FIFE. They include the 1D and 2D watersheds, plus two unburned watersheds about 1 km west of 1D, ID on a south-facing slope, and 4D on a north-facing slope. None of these four watersheds was grazed so burning is the only consumer of the dead biomass. The fifth watershed, 8B, is outside the KPRNA. It is burned every year and grazed by cattle. The values in the table are the average of 10-14 points along 250-400 m transects, generally east–west, across the watersheds. The standard deviations for these data range from 0.15 to more than 30% of the mean. The values are for the dry biomass of both the green and dead vegetation, the latter consisting of standing dead vegetation and the litter lying on the soil. As expected, the watersheds burned every year had no dead vegetation during the first 3 IFC's, 2D had standing dead vegetation, but no litter, while the unburned watersheds had both standing dead vegetation and litter. By comparing the amounts of dead vegetation for 2D and the unburned watersheds, we can estimate the amount of litter on the soil for these watersheds to be about 0.5 kg/m$^2$. The amount of water stored in the dead biomass depends on the period since the last significant rainfall.

Analysis of vegetation data from other sites in FIFE
showed that the dead vegetation can hold an amount of water equal to or slightly greater than its dry weight. For the green vegetation, the ratio of water to dry biomass was between 1 and 2, the latter being the case for the first two IFC’s. Thus, for the burned watersheds, the water content ($W_{\text{d}}$) of the green biomass was 0.3–0.5 kg/m$^2$. From Jackson et al. [10], we find that the optical depth of canopy is given by

$$\tau = 0.11 * W_{\text{d}} = 0.035 - 0.06$$

which is somewhat less than the $\tau$’s found in the results of the emissivity calculations shown in Fig. 6. From Fig. 6(a) for a 1D watershed, the observations fall between the curves with $\tau$ values of 0.05 and 0.1. For the 2D watershed, the water content of the green vegetation in IFC 2 is about 0.5 kg/m$^2$, and for the dead, it is about 0.3 kg/m$^2$ for a total of 0.8 kg/m$^2$, yielding a $\tau$ value of 0.1. As seen in Fig. 6(b), the data fall between curves having values of 0.1 and 0.2. The data for the wettest IFC (2) are mostly above the curve. Thus, it appears that with a roughness value of $h = 0.1$, the $\tau$ values required to bracket the data are slightly larger than those predicted from the surface biomass measurements, but still within reason. However, the important point here is that the theory predicts the type of behavior we are seeing in the FIFE data, and that the range of biomass variation seen in the four IFC’s (about a factor of 2) does not significantly affect the slope of the regression line we used to extract the soil moisture values in the next section.

IV. SOIL MOISTURE ESTIMATION

Based on the regression results of Fig. 5, the emission model calculations, and the PBMR measurements, it is possible to derive the soil moisture contours and study the temporal variation of soil moisture patterns for the 1D and 2D watersheds [8]. To estimate soil moisture from the PBMR measurements for regions beyond these two watersheds required either the establishment of similar regressions to Fig. 5 or an independent measurement of vegetation biomass and the associated effect of microwave absorption for these regions. Both of these requirements are not available. However, the soil moisture estimation for these regions could be made with two reasonable assumptions. First, following the heavy rainfall on May 27, the soils of the experimental area are saturated ($W = 43\%$) during the PBMR measurements on May 28. The variations in the measured $T_b$’s at different regions are largely due to the effect of vegetation cover. Second, the lines of regressions between $e$ and $W$ from different locations all intersect at a common point at $e = 0.892$ and $W = 10.7\%$ determined by the two regression equations in Fig. 5. The first assumption is justified on a gross scale based on the distribution of $W$ shown in Fig. 7 that was obtained from the ground samples of May 28. Fig. 7(a) and (b) showed the histograms of $W$ collected from the 1D and 2D watersheds, while Fig. 7(c) gave the same for samples collected from other locations indicated in Fig. 1. Each sample in Fig. 7(c) is, in turn, the average of five soil moisture samples collected around a given station. The saturated value of 43% was chosen based on the average of samples from widely separated locations (Fig. 7(c)).

The second assumption is based on the previous experimental observations [10], [11] that the slope of the regression between $e$ and $W$ for vegetation-covered soils becomes smaller when compared to that for bare soils. The point of intersection occurs at the dry end of the two regression lines of different slopes. Thus, between the intersection point determined from Fig. 5 and the effective emissivity measured by PBMR on May 28, a linear relationship between $e$ and $W$ can be determined at any location. The derived relationship is then used to estimate $W$ at that location from other days of radiometric measurements. This process is applied to the pixels in the PBMR image, except for the regions unburned for many years where the radiometer has little sensitivity to soil moisture variation.

### Table I

**Dry Biomass Results in kg/m$^2$**

<table>
<thead>
<tr>
<th>IFC-1</th>
<th>IFC-2</th>
<th>IFC-3</th>
<th>IFC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>Dead</td>
<td>Green</td>
<td>Dead</td>
</tr>
<tr>
<td>1D</td>
<td>0.161</td>
<td>0.0</td>
<td>0.280</td>
</tr>
<tr>
<td>2D</td>
<td>0.154</td>
<td>0.223</td>
<td>0.245</td>
</tr>
<tr>
<td>1B</td>
<td>0.104</td>
<td>0.723</td>
<td>0.212</td>
</tr>
<tr>
<td>1AD</td>
<td>0.080</td>
<td>0.588</td>
<td>0.145</td>
</tr>
<tr>
<td>øø</td>
<td>0.133</td>
<td>0.0</td>
<td>0.277</td>
</tr>
</tbody>
</table>

**Remarks**

- Burned every year
- Not grazed
- Burned every two years
- Not grazed
- Unburned
- Not grazed
- Burned every year
- Grazed
Fig. 8 shows the distribution of estimated $W$ in the top 5 cm layer for three different days. The top two plots obtained on May 30 and June 4 are associated with the drying-down period in the first IFC. The bottom plot obtained on October 6 in the fourth IFC corresponds to a dry-soil condition after a long period where no significant rainfall was observed. A few white regions in the plots are associated with either the densely wooded areas along streams or the areas which have not been burned for a number of years. These are the regions of little PBMR sensitivity where surface soil moisture estimation is not attempted. The three plots in the figure give examples of estimated surface soil moisture maps that might be expected from measurements of a typical $L$-band radiometer. A verification of the estimation is made through comparisons to independent ground soil moisture samplings at a number of locations indicated in Fig. 1. These comparisons are presented in Figs. 9 and 10.

Fig. 9 shows the temporal variations of $W$ for two flux stations 16 and 4. The locations of these stations are indicated by the latitudes and longitudes. The ground measured $W$ values, which are acquired every other day during the IFC's, are shown by the solid lines. The PBMR estimated $W$ values are denoted by the open circles. A few of these estimated $W$ values are also derived from measurements at 300 m altitude. During the first three IFC's, the soils are mostly wet, while in the last IFC the soils are extremely dry following a long spell of little or no rainfall.
ments were made after 11:30 AM local time. On the other hand, the ground soil moisture sampling was done in the morning for some stations and in the afternoon for other stations. When these two groups of stations were separated, the histograms for the two corresponding $W$s are shown in Fig. 11. They were markedly different, showing a time of day bias. Following a similar argument based on the statistics [12], it can be shown that the bias for the histogram in Fig. 11(a) for the morning samples is significantly different from zero, while that in Fig. 11(b) for the afternoon samples is not different from zero at a 99% confidence level [12]. This strongly suggests that the bias observed in Fig. 9(a) is mostly caused by the loss of surface soil moisture in the time interval between ground sampling and airborne radiometric measurements.

V. DISCUSSION

The distribution of the ground-measured soil moisture from the flux stations shown in Fig. 7(c) gives a standard deviation of 2.05%, which is less than the 5.5% derived for the 1D and 2D watersheds in the same figure. This is due to the fact that each sample itself in Fig. 7(c) is the average of five samples taken within a 5 m radius of a flux station. It can be shown that the statistics are comparable for the three groups of soil moisture data if each original sample is given equal weight. This implies that there is a significant variation in the spatial distribution of soil moisture, even in a relatively small region a few tens of meters in size. A radiometer like PBMR, which has a footprint of about 150–200 m at 600 m flight altitude, clearly cannot resolve such a small-scale soil moisture variation. It gives an estimation of average soil moisture for the footprint.

The approach used above for the estimation of surface soil moisture does not require independent measurements of the vegetation parameters to take care of the microwave absorption effect [9], [10]. The trade-off is the need for one set of radiometric measurements over wet soils with known moisture content so that we can assume...
a spatially uniform soil moisture distribution over the area of measurements. The assumption of a uniform surface soil moisture value of 43% on May 28 for the area mapped by the PBMR is perhaps oversimplified. In our ground sampling of 1D and 2D watersheds associated with the 300 m altitude flights, we found that soils in the regions of steep slope were generally drier by a few percent in comparison to other regions of the watersheds. This implies that an initial bias may exist in our approach of soil moisture estimation for some regions. As a result, the estimated soil moisture may be persistently higher or lower than the actual value for some regions of the mapped area. A comparison between the estimated and ground-measured soil moisture values has been made at each of the other available stations besides those two in Fig. 8. A few of those stations do show some bias in one direction or another throughout the whole period of measurements. However, only a few data points per station are available for the comparison; the bias cannot be categorized as being statistically significant.

VI. CONCLUSION

A number of radiometric measurements were made with the airborne L-band pushbroom microwave radiometer over and around the Konza Prairie Natural Research Area during the four intensive field campaigns of the First ISLSCP Field Experiment. An attempt was made to utilize these measurements for the estimation of surface volumetric soil moisture (0-5 cm). It depended strongly on a successful calibration of the vegetation effect on microwave emission from soils. This calibration was accomplished by the radiometric measurements on a day when the soils were saturated with water and by assuming a uniform surface soil moisture which was determined by ground sampling. Based on the information derived from this calibration, the radiometric measurements from all the other days were inverted to soil moisture values. The estimated values compared favorably to those independently measured on the ground at a number of widely separated locations. There was a bias of about 1.8% soil moisture. But this small bias could be accounted for by the difference in time of the radiometric measurements and ground sampling.

REFERENCES


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