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Multifrequency passive microwave observations of soil moisture in an arid rangeland environment

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Abstract. A cooperative experiment was conducted by teams from the U.S. and U.S.S.R. to evaluate passive microwave instruments and algorithms used to estimate surface soil moisture. Experiments were conducted as part of an interdisciplinary experiment in an arid rangeland watershed located in the south-west United States. Soviet microwave radiometers operating at wavelengths of 2·25, 21 and 27 cm were flown on a U.S. aircraft. Radio frequency interference limited usable data to the 2·25 and 21 cm systems. Data have been calibrated and compared to ground observations of soil moisture. These analyses showed that the 21 cm system could produce reliable and useful soil moisture information and that the 2·25 cm system was of no value for soil moisture estimation in this experiment.

1. Introduction

The U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) and the Institute of Radioengineering and Electronics (IRE) of the Academy of Sciences of the U.S.S.R. conducted a series of aircraft experiments designed to evaluate the IRE instruments and algorithms in hydrologic applications. Measurements were made as part of the interdisciplinary MONSOON'90 (Kustas *et al.* 1991) experiment conducted during the summer of 1990 in the USDA ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona.

The IRE provided a multifrequency radiometer system. A unique feature of this system was that it provided data at two frequencies in the L band portion of the microwave spectrum. Based upon multifrequency information, the IRE has developed procedures for estimating several types of land surface variables. These include; surface soil moisture, profile soil moisture, depth to shallow groundwater table, soil salinity, and vegetation biomass (Chuklantsev and Shutko 1988, Mkrtchjan *et al.* 1988, Reutov and Shutko 1990, Shutko 1986). Of course, not all of these procedures will work under all conditions. The goal of this joint experiment was to provide a test environment for these methods and an independent evaluation of their effectiveness.

In addition to the IRE radiometers, ground observations of relevant physical parameters were collected concurrently. Ground samples of surface soil moisture were collected at the series of met stations that the radiometers covered. The NASA L band pushbroom microwave radiometer was also flown as part of the MONSOON'90 experiment.

2. Passive microwave radiometer description

The radiometer system supplied and operated by the IRE in this experiment utilized 3 wavelengths; 2·25, 21 and 27 cm. The 2·25 cm (X band) system utilized a waveguide-horn antenna assembly whereas the two L band radiometers had a dual microstrip antenna. The field of view (3 db) of the antennas was 35°, which yielded a ground resolution of 0·7 times the altitude for L band.

Antennas, radiometers, and data collection system were installed on an ARS operated twin-engine Aerocommander aircraft. Existing fuselage cutouts were used for installation of the antennas. ARS and NASA integrated the signals from the radiometers into an existing data collection system that supplied time code information and concurrent video coverage. Raw data were obtained every 0·02 seconds.

3. MONSOON'90 experiment

The study was conducted during the late summer when shifts in wind patterns in the south-west United States result in increased atmospheric moisture and some rainfall over an otherwise arid environment. The focus of MONSOON'90 was the study of the energy and water balance using various scales of ground measurements and multispectral aircraft and satellite remote sensing.

Vegetation in the study site consisted of a fairly uniform transition from sparse cover of shrubs to grass. Visual inspection of the cover indicated that it should have only a minimal effect on soil measurements at decimeter microwave wavelengths (Shutko 1986). Figure 1 illustrates the typical cover condition in the shrub-dominated portion of the watershed. The surface soils over the watershed consist primarily of coarse textured varieties, i.e., sandy loam, with high rock contents (>50 per cent by volume).

Drainage channels (called washes) are dry most of the time. Rainfall is usually associated with cellular thunderestorm activity and may result in flash floods. Following these events the soil normally dries quickly because of the high evaporative demand and the minimal vegetation cover.

The IRE instruments were flown over three flightlines at an altitude of 150 m between 8 and 9 am local time. The flightlines provided coverage of eight meteorological stations at which ground observations of soil moisture were collected. A summary of the flights and conditions during the experimental period is given in table 1.

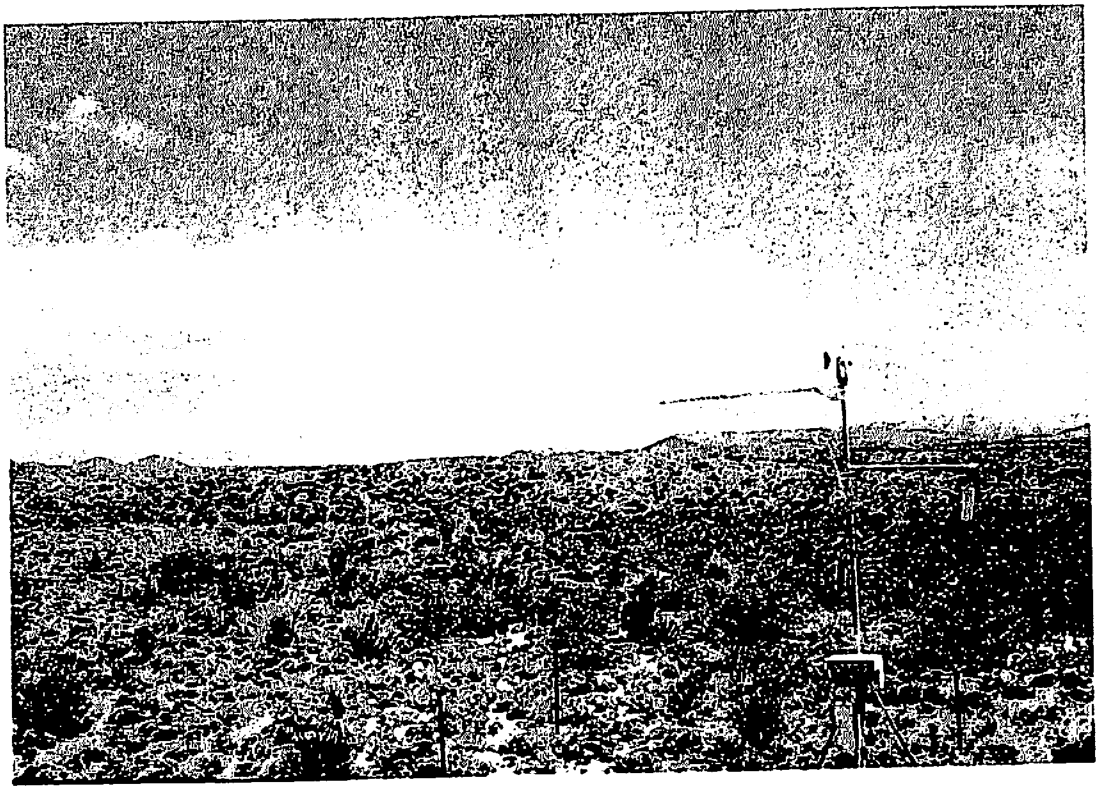

Figure 1. Photograph of typical vegetation cover conditions in the Walnut Gulch watershed.

4. Results and discussion

The bandwidth and selected wavelengths of the IRE radiometers resulted in a number of radio frequency interference problems (RFI) that had not been anticipated. Each wavelength was affected by noise to different extents. In almost all cases it was fairly simple to identify noisy data sets because the RFI caused a saturation of the signal.

At 27 cm the RFI was generally constant and saturated the sensor making the data unusable. Only when passing over land-water boundaries was a change detectable. The loss of this wavelength was unfortunate because data at this

Table 1. Walnut Gulch aircraft microwave flights.

Date	IRE data	Antecedent meteorological conditions
30 July	Yes	Dry
31 July	Yes	Dry
1 August	No	Dry
2 August	Yes	Heavy rainfall over entire area
3 August	Yes	Drying
4 August	Yes	Cloudy, rain over west end
5 August	Yes	Drying
6 August	Yes	Drying
7 August	No	Drying
8 August	No	Drying
9 August	Yes	Drying

wavelength are important in the IRE procedures for estimating geophysical parameters (Shutko 1986).

Data collected at 21 cm were subject to periodic and temporary sources of RFI that were attributable to the bandwidth, because data collected by the PBMR at the same wavelength showed no interference. It was determined that the primary source of RFI at this wavelength was a tethered radar balloon operating over the U.S.-Mexico border. This was a sweep-type radar that resulted in a sinusoidal pattern of RFI in the data. On 1 August during the same thunderstorms that produced rainfall at Walnut Gulch, the radar was hit by lightning and was out of operation for several days. During this period we were able to collect noise free data which fortunately included a large range of moisture conditions.

The 2·25 cm X band data proved to be the most free of RFI problems. There was only one localized geographical area where the signal was saturated. The same interference was observed every day at the same location.

All data were georeferenced with the help of video coverage. The time was recorded when a ground control point was passed. Data were recorded 60 times a second which resulted in a measurement centred approximately every metre along the ground, based upon aircraft speed. Raw data, digital counts, are averaged for a period of time to reduce instrument noise. In this case the instrument was very stable even at 1 m spacing (no averaging). Figure 2 illustrates the effects of the length of the averaging period on the data trace for the L band sensor. The results obtained by averaging over a 10 m interval and a 40 m interval were nearly identical. When the

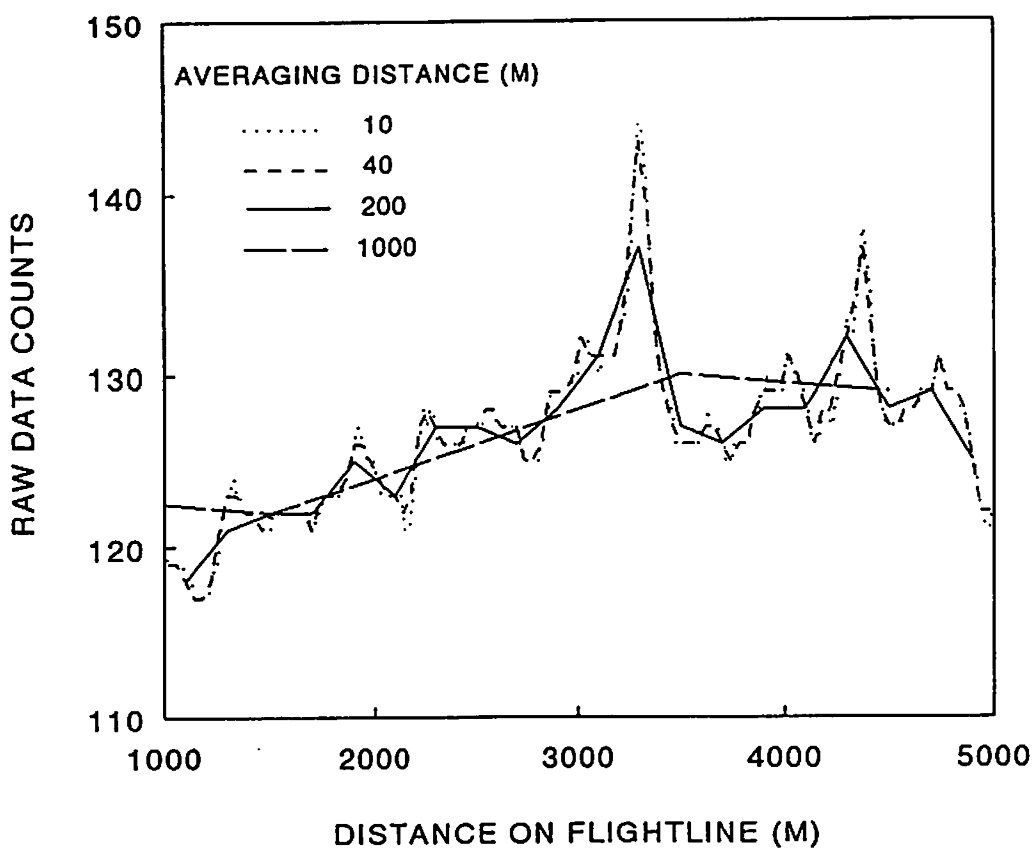

Figure 2. Effects of distance averaging on raw radiometer data, digital counts, patterns (*a*) X band and (*b*) L band.

distance is increased to 200 m, much of the spatial pattern was retained. However, the peaks begin to flatten out since the features that cause these are smaller than 200 m in size. Even at a 1000 m averaging the overall trends of the original data were retained. For this presentation, the data have been averaged to a 40 m spacing.

Calibration of the IRE radiometers consisted of comparing measured raw data counts for eccosorb, dry soil and water with brightness temperatures predicted based on previous experience (Shutko 1986). The calibration was then verified using L band data collected by the PBMR which was calibrated independently. Using the calibration equations, the brightness temperatures for each data set that was judged free of RFI were computed. The plots of brightness temperature versus distance along flightline 1 are shown in figure 3 for both 21 and 2·25 cm.

The most obvious feature of the brightness temperature graphs was the lack of temporal sensitivity in the 2·25 cm data. The dips in the curves on a given date correspond to drainages in the watershed which were wetter than the general area. These variations indicated that the sensor was responding to moisture variations in the depth of soil that determines its measured value. Based on previous research and theory (Jackson and Schmugge 1989, Shutko 1986), it was expected that this depth would be quite shallow. The results indicated that this layer dried out so quickly that the occurrence of rainfall on 1 and 3 August was barely detectable and suggests that the utility of 2·25 cm as a moisture sensor is very limited. Although it might be capable of indicating persistent patterns in wet or dry areas, it is unlikely that shorter-lived phenomena could be measured in areas with a high evaporative demand with an X band sensor. This would limit its utility in arid and semi-arid environments.

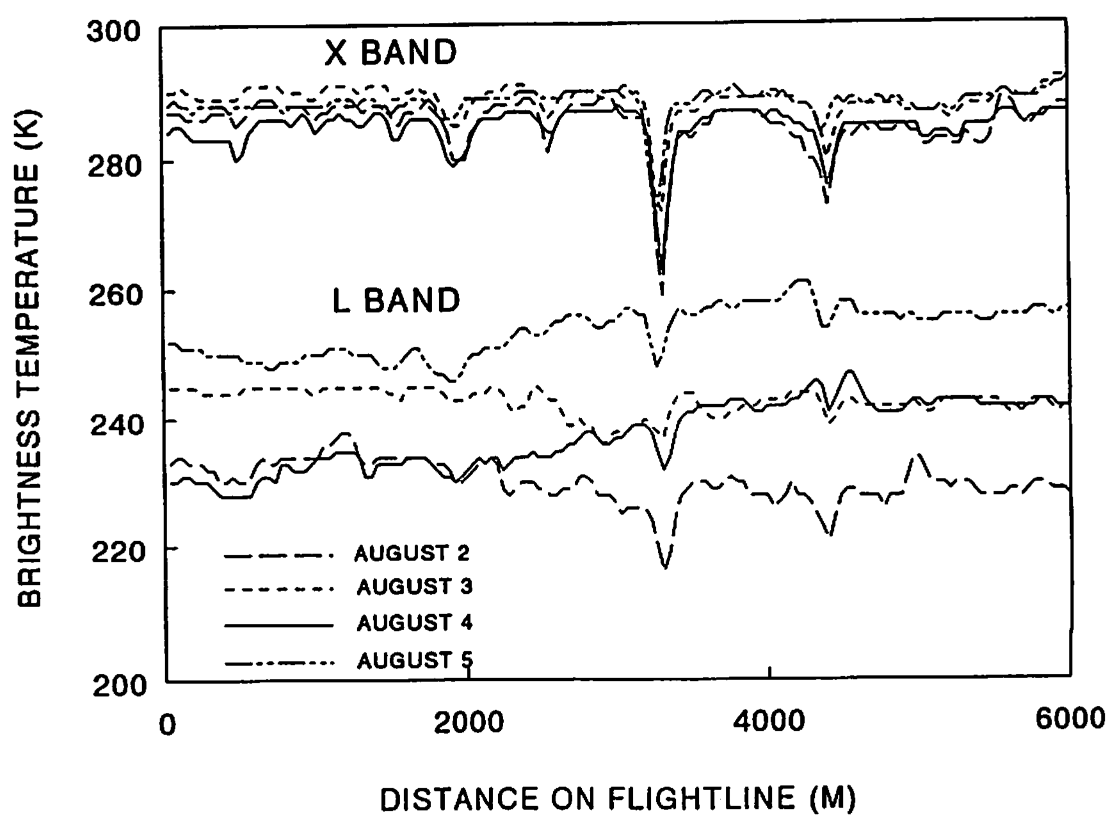

Figure 3. Microwave brightness temperature data collected on Walnut Gulch flightline 1 using (*a*) X band and (*b*) L band.

Data collected at 21 cm showed a response to soil moisture both along a flightline and between dates. The depth of soil contributing to this measurement, typically regarded as 5 cm (Jackson and Schmugge 1989), was deep enough to track moisture variations for several days following a rainfall event. Figure 3 illustrates several interesting features of the data. Preceding the flight on 2 August, there was a large rainfall event (> 3 cm) over the entire study area which resulted in low levels of brightness temperature. Following this there was a high evaporative demand that resulted in an increase in the brightness temperatures over the area on 3 August. During the evening hours of 3 August, a cellular rainfall event occurred over the western end of the watershed (the left hand side of figure 3) and, in general, conditions on that day did not favour evaporation over the study area. Both of these meteorological conditions are reflected in the 4 August data. On the western end of the study area, the brightness temperatures returned to the levels observed following the previous rainfall event of 1 August. The patterns and levels of 2 August and 4 August match up on the western end of flightline 1.

Over the eastern portion of the area, the fact that there was little evaporative demand was reflected in the minor change in brightness temperature between the 3 August and 4 August data. Between the 4 August and the 5 August flights, the conditions were favourable for high evaporative rates which resulted in an increase in brightness temperatures over all the lines.

Overall, the data show a wide dynamic range and indicate that changes in soil moisture related to meteorological factors are detectable if observations are made on a daily basis. In addition, there appears to be a spatial consistency to the data that reflects the moisture over the entire area independent of many sources of possible variation (i.e., topography, vegetation and soils). Obvious sources of variation such as the drainage channels do result in large deviations from the area average.

Surface soil moisture can be predicted using passive microwave L band based techniques developed by both the IRE and the USDA (Shutko 1986, Jackson and Schmugge 1989). The results presented here follow procedures described in Jackson and Schmugge (1989). The only new factor that had to be considered was the effect of the unusually high rock volume fractions in the soil surface layer.

A recent investigation (Jackson *et al.* 1991) showed that the most important impact that an increased rock fraction has is to reduce the possible range of soil moisture. Since the soil texture and rock volume fractions observed in Walnut Gulch are very similar to those reported in Jackson *et al.* (1991), the emissivity-soil moisture relationship developed in that study (basically a linear regression) was used here and is plotted in figure 4. Based on observed conditions and previous investigations (Jackson and Schmugge 1989), no vegetation correction was applied because of the low percentage vegetation cover and water content.

Ground sampled soil moisture at each meteorological station was then plotted versus the observed L band microwave emissivity. Emissivity was computed by dividing the brightness temperature by ground sampled soil temperature values (Jackson and Schmugge 1989). These results are summarized in figure 4 and indicate a correlation between the ground measurements and the radiometer estimates of soil moisture since most of the data fall within one standard deviation of the model regression line. Reasons for the differences between the estimated and sampled values of soil moisture are still being evaluated. It is most likely that the major causes were the differences in the spatial and temporal scales of the two techniques.

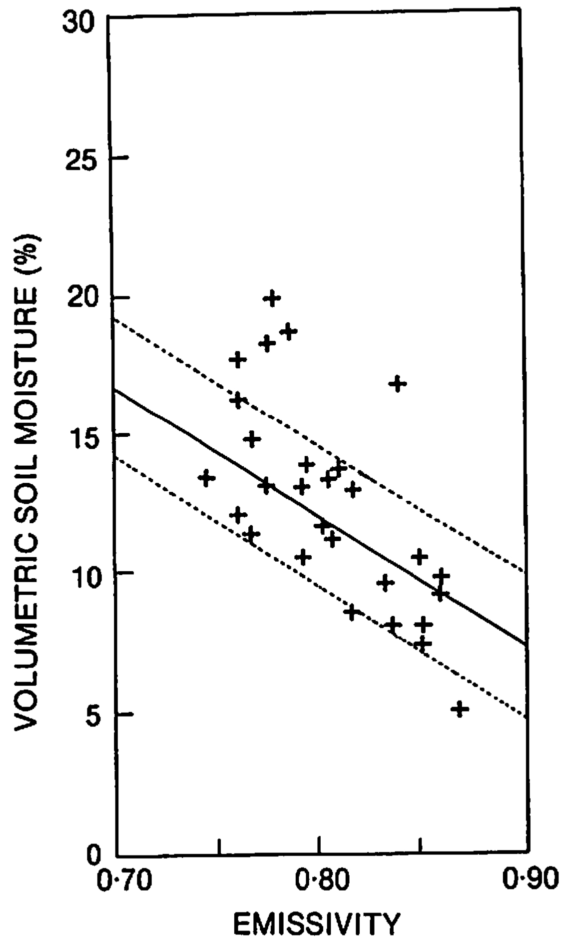

Figure 4. Soil moisture-emissivity relationship for the Walnut Gulch study site showing ground sampled and microwave estimated surface moisture. The solid line is the regression model and the dashed lines are the standard error.

5. Conclusions

A series of aircraft remote sensing experiments were conducted to evaluate a multifrequency microwave radiometer package for estimating soil moisture. Unfortunately, local radio frequency interference resulted in the loss of data at 27 cm, and so the analysis focused on data collected at 2·25 and 21 cm wavelengths. Analyses to date have shown that the IRE radiometers were stable and consistent. Results of brightness temperature analyses clarly showed that X band data would be of little value in monitoring soil moisture in this environment. However, the L band radiometer data clearly responded to the soil moisture. Initial comparisons with ground point samples of soil moisture indicate a high correlation. Further work is in progress to filter noisy data sets, compare USDA and IRE methods for estimating soil moisture, and to investigate in more detail differences between the microwave and ground observations at the meteorological sites.

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