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SOIL MOISTURE OBSERVATIONS USING MULTIFREQUENCY PASSIVE MICROWAVE SENSORS IN AN ARID RANGELAND ENVIRONMENT:A COOPERATIVE US-USSR EXPERIMENT

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1. INTRODUCTION

The U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) Hydrology Lab, the Remote Sensing Unit of the ARS Subtropical Experiment Station, and the Institute of Radioengineering and Electronics (IRE) of the Academy of Sciences of the USSR conducted a series of aircraft based experiments designed to evaluate the IRE instruments and algorithms in hydrologic applications. Measurements were made as part of the multidisciplinary MONSOON'90 experiment (Kustas et al., 1991) conducted during the summer of 1990 in the Walnut Gulch Watershed near Tombstone, Arizona.

The IRE provided a multifrequency radiometer system. A unique feature of this system is that it provides data at two frequencies in the L band portion of the microwave spectrum. Based upon this low-multifrequency information, the IRE scientists have developed algorithms for several types of land surface variables. These include; surface soil moisture, profile soil moisture, depth to shallow groundwater table, soil salinity, and vegetation biomass (Mkrtchjan et al., 1988 and 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. Performance of the radiometers was also evaluated using another L band passive microwave radiometer operated by NASA (pushbroom microwave radiometer - PBMR) which was also flown as part of the MONSOON'90 experiment.

Radiometer data collected during the experiment were first evaluated in terms of brightness temperature. Following the instrument verification, the data were used in the surface soil moisture prediction algorithms developed by the IRE and USDA and compared to ground observations of moisture.

2. PASSIVE MICROWAVE RADIOMETER

The radiometer system supplied and operated by the IRE in this experiment utilized 3 wavelengths: 2.25, 21, and 27 cm. ARS and NASA integrated the signals from the radiometers into an existing data collection system that supplied time code information and concurrent video coverage. Instrument calibration was attempted using a high emissivity target (eccosorb) and a low emissivity target (water). The expected brightness temperature range was used to adjust the radiometer signal to data system conversion that resulted in a system sensitivity of 1 degree Kelvin. Antennas, radiometers, and data collection system were installed on an ARS operated twin-engine Aerocommander Aircraft.

3. AIRCRAFT FLIGHTS AND CONDITIONS

Figure 1 shows the flightlines that were used by the Aerocommander and the locations of the intensive meteorological measurement stations. Each flightline was marked with targets that were visible on the videotapes. All IRE data was collected between 8 and 9 am local time. A summary of the flights and conditions during the experimental period is listed in Table 1.

Table 1. Walnut Gulch Aircraft Microwave Flights

Date	IRE Data	Antecedent Conditions
July 30	Y	Dry
July 31	Y	Dry
August 1	N	Dry
August 2	Y	Rainfall entire area
August 3	Y	Drying
August 4	Y	Cloudy, rain west
August 5	Y	Drying
August 6	Y	Drying
August 7	N	Drying
August 8	N	Drying
August 9	Y	Drying

4. RESULTS

The bandwidth and selected wavelengths of the IRE radiometers resulted in a number of radio frequency interference (RFI) problems that had not been anticipated. Each wavelength had its own source of noise which varied from minor to significant. In almost all cases it was fairly simple to identify bad data sets.

At 27 cm, the RFI was generally a constant source that dampened the signal to the point where it was unusable. The loss of this wavelength was unfortunate because data at this wavelength is important in the IRE algorithms and it should have provided information that has not been studied in the US.

Data collected at 21 cm were subject to periodic and temporary sources of RFI that are attributed to the this particular instrument, because PBMR data 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 US-Mexico border. This was obviously a sweep type radar that resulted in a sinusoidal pattern of RFI in the data. On August 1 during the same thunderstorms that produced rainfall at Walnut Gulch, the radar was hit by lightening and was inoperable for several days. During this period we were able to collect good noise free data which fortunately included the best range of moisture conditions. It may be possible at a later date to use appropriate filters to remove the RFI at this wavelength.

The X band data proved to be the most RFI free and provided very consistent observations. There was one localized geographical area where the signal was saturated. Outside of this spot, the X band data were considered to be very reliable.

Data were georeferenced using videotape coverage. Since the lines were flown at a nominal altitude of 150 m above ground level, the ground resolution at L band was 105 m. Data were recorded 60 times a second which resulted in a measurement centered approximately every meter on the ground. Typically, these raw data are integrated for a period of time to eliminate noise. In this case the instrument was very stable even at 1 meter spacing (no integration). Figure 2 illustrates the effects of the length of the integration time on the data trace. For both X and L bands, the results obtained by averaging over a 10 m interval and a 40 m interval are nearly identical. When the distance is increased to 200 m, much of the spatial pattern is retained. In large scale studies, the use of longer averaging intervals may be more useful in understanding the physical processes because it is unlikely that the small features that create the sharp peaks in the graphs will have any influence on large scale hydrology. For this presentation, the data have been averaged to a 40 m spacing.

Calibration of the IRE radiometers was performed using measured raw data counts for eccosorb, dry soil and water (targets with known emissivity values). This procedure resulted in a reasonable pattern of response in the data. The calibration was then verified using L band data collected by the PBMR.

Using the calibration equations, the brightness temperatures for each data set that was judged free of RFI were predicted. The plots of brightness temperature versus distance along flightline 1 are shown in Figure 3. The most obvious feature of this graph is the lack of temporal sensitivity in the X band data. The dips in the curves on a given date correspond to drainages in the watershed which are wetter than the surrounding area. These variations indicate that the sensor is responding to moisture variations in the depth of soil that determines its measured value. Based on previous research and theory, it was expected that this depth would be quite shallow at X band. What is a bit surprising is that this layer dries out so quickly that the occurrence of rainfall on the days preceding August 2 and 4 is barely detectable. This result suggests that the utility of X band for soil moisture sensing is very limited. It might be capable of indicating persistent patterns in wet or dry areas, however, it is unlikely that shorter lived phenomena could be measured in areas with high evaporative demand, which would eliminate arid and semiarid environments. One might argue that this wavelength might be useful in humid regions, however, another problem in using this wavelength is the significance of vegetation in masking the soil surface and obviously this is more important in humid areas.

Data collected at 21 cm (L band) show variation to moisture on any specific date and between dates. The depth of moisture contributing to this measurement, typically specified as 5 cm, is deep enough to track variations for several days following a rainfall event. Figure 3 illustrates several interesting features of the data. Preceding the flight on August 2, 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 period of high evaporative demand that resulted in a more or less uniform rise in the brightness temperatures over the area on August 3.

During the day preceding the August 4 flight, a cellular rainfall event occurred over the western end of the watershed and, in general, conditions did not favor evaporation over the study area. Both of these meteorological conditions are reflected in the August 4 data. On the western end of line 1, the brightness temperatures returned to the levels observed following the previous rainfall event (August 2 data). The patterns and levels of August 2 and August 4 match up remarkably on the western end of lines 1. Over the other portion of line 1, the eastern areas, the fact that there was little evaporative demand is reflected in the minor change in brightness temperature from the previous day.

Overall, the data show a wide dynamic range and indicate that changes related to meteorological factors are detectable if observed on a daily basis. In addition, there also appears to be a spatial consistency to the data that reflects the overall moisture condition independent of many sources of possible variation (i.e. topography, vegetation and soils). Obvious sources of variation such as the drainages do result in large deviations from the trend, however, the degree of spatial integration provided by the sensor appears to filter the other sources of variation into a meaningful pattern.

Soil moisture was predicted using both the IRE and USDA approaches. Both methods have similar foundations but differ in certain aspects, only the USDA approach is described here. These predictions were then tested using ground observations of surface soil moisture at specific sites.

The USDA approach to predicting the soil moisture attempts to integrate the physical basis of the relationship between the passive microwave emission from soils and soil moisture with practical trade-offs in terms of data requirements (Jackson and Schmugge, 1989). The procedure used consists of the following steps:

1. Computation of emissivity from measured brightness temperature using observed soil and thermal infrared data.
2. Correction for vegetation using vegetation type and water content information.
3. Surface roughness correction using observed surface height variations.
4. Soil moisture estimate based on the assumption of Fresnel equation conditions in the surface 5 cm adjusted for soil texture.

In this particular study, it was necessary to consider another variable. In the Walnut Gulch watershed, the levels of soil rock content were quite high (ranging from 30 to 70% in the surface 5 cm). A recent investigation by Jackson et al. (1991) considered the effects of rock content on the soil moisture-emissivity relationship and was incorporated here. That study showed that the most important factor to consider was that the presence of rocks eliminates a specific volume of the soil that can vary in its dielectric properties as a function of soil moisture. This means that a soil with no rocks and a field water holding capacity of 30% would exhibit a range of 30% soil moisture and the same soil with 50% rock content would only have a 15% range. The net result is that the possible range of resulting soil emissivity is decreased.

The emissivity-soil moisture relationship employed here is that proposed in Jackson et al. (1991) as being representative of coarse textured soils for a wide range of conditions. Based on observed conditions and previous investigations, no vegetation correction was applied because of its low percentage cover and water content. Figure 4 shows the predicted soil moisture values for flightline 1.

Predicted values for the general areas of the met stations were extracted and compared to the ground observations of surface soil moisture. These results are summarized in Figure 5 and indicate fairly good agreement between the point measurements and the radiometer estimates. Reasons for the differences between the two methods will be evaluated in the future, however, it is most likely that the major cause is the difference in the spatial scale of the techniques.

5. SUMMARY

A series of aircraft remote sensing experiments was conducted to evaluate a multifrequency microwave radiometer package for estimating soil moisture and other variables. Meteorological conditions in the Walnut Gulch Watershed during the MONSOON 90 experiment were excellent for these investigations. Unfortunately, local radio frequency interference resulted in the loss of data at the longest microwave wavelength and the analysis focused on data collected at traditional wavelengths. Analysis to date have shown that the IRE radiometers are stable and consistent. Results of brightness temperature analyses showed that X band data is useless in monitoring soil moisture in this environment. However, the L band (21 cm) radiometer data clearly tracked the meteorological conditions. Initial comparisons to ground point samples of soil moisture indicate good performance. Additional studies are underway to expand the data base by cleaning up noisy data sets, comparing the USDA and IRE methods for estimating soil moisture, and conducting in-depth analysis of the microwave and ground observations at the met sites.

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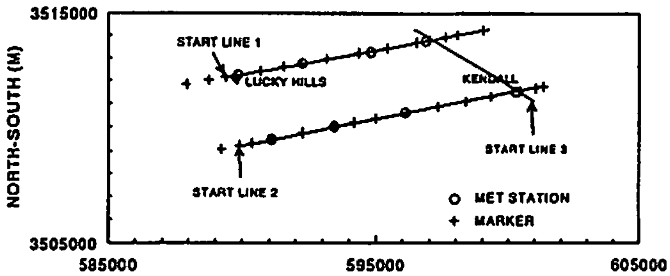

Figure 1. Walnut Gulch Watershed study area flightlines and meteorological stations.

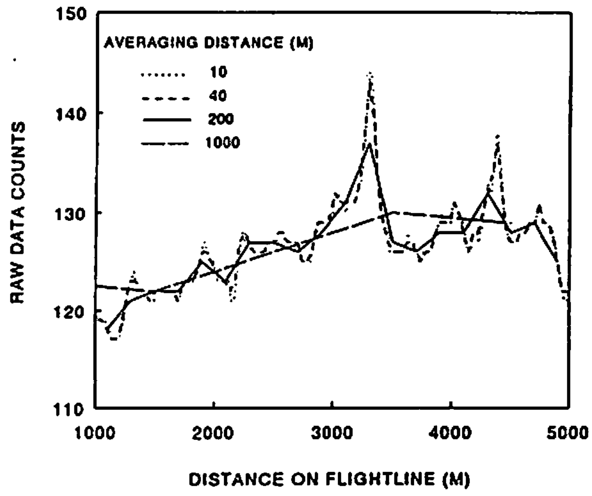

Figure 2. Effects of distance averaging on radiometer data patterns for L band.

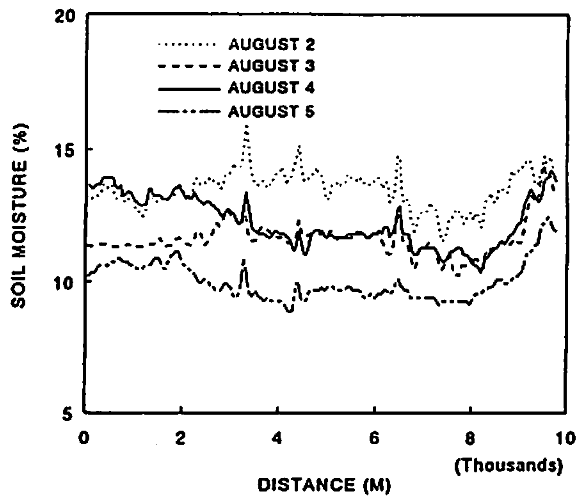

Figure 4. Volumetric soil moisture predicted using USDA method on Walnut Gulch line 1.

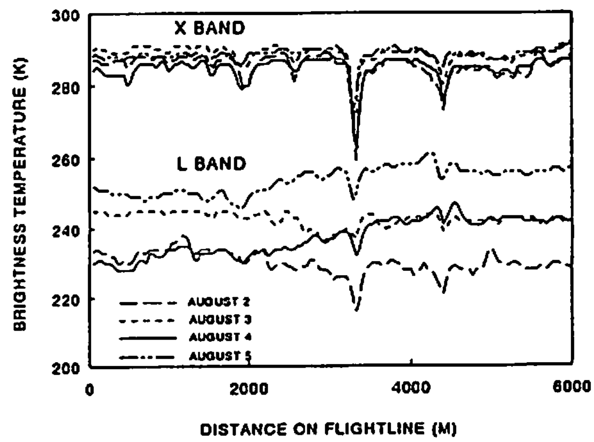

Figure 3. Microwave brightness temperature data collected on line 1.

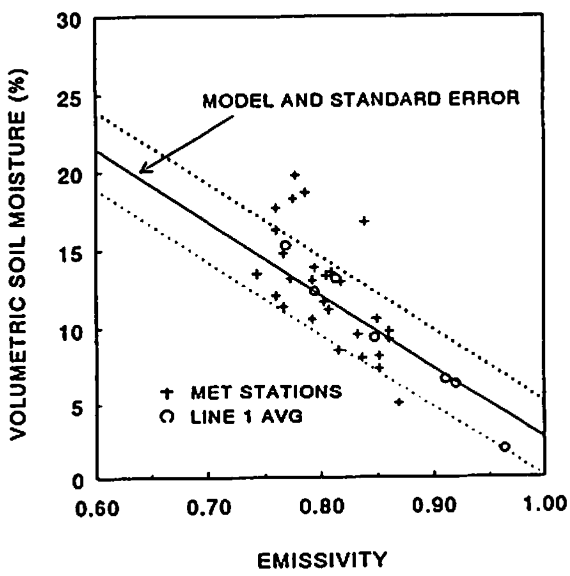

Figure 5. Comparison of ground sampled and remotely sensed estimates of soil moisture.