

Soil Moisture and Rainfall Estimation Over a Semiarid Environment with the ESTAR Microwave Radiometer

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Abstract—The application of an airborne electronically steered thinned array *L*-band radiometer (ESTAR) for soil moisture mapping was investigated over the semiarid rangeland Walnut Gulch Watershed located in southeastern Arizona. During the experiment, antecedent rainfall and evaporation were very different and resulted in a wide range of soil moisture conditions. The high spatial variability of rainfall events within this region resulted in moisture conditions with distinct spatial patterns. Analysis showed a correlation between the decrease in brightness temperature after a rainfall and the amount of rain. The sensor's performance was verified using two approaches. First, the microwave data were used in conjunction with a microwave emission model to predict soil moisture. These predictions were compared to ground observations of soil moisture. A second verification was possible using an extensive data set collected the previous year at the same site with a conventional *L*-band push broom microwave radiometer (PBMR). Both tests showed that the ESTAR is capable of providing soil moisture with the same level of accuracy as existing systems. ESTAR instruments have the potential to satisfy application data requirements from spaceborne platforms.

I. INTRODUCTION

A number of recent investigations designed to study land surface hydrologic-atmospheric interactions have shown the potential of *L*-band passive microwave radiometry for measuring and monitoring surface soil moisture over large areas [1]. These studies have focused on the spatial information provided about soil moisture as well as flux variables that can be inferred through frequent temporal observation. Satisfying the data needs of these investigations requires the ability to map large areas rapidly. With aircraft systems this means a need for more beam positions over a wider swath on each flightline. For satellite systems the essential problem is resolution. Both of these needs are currently being addressed

through the development and verification of electronically steered thinned array radiometer (ESTAR) technology [2], [3]. In this study, the application of an ESTAR *L*-band radiometer for soil moisture mapping was investigated.

II. EXPERIMENT DESCRIPTION

The ESTAR instrument used in this study is described in [2] and [3]. It is an *L*-band radiometer operating at a wavelength of 21 cm with a capability of providing the equivalent of up to 8 beam positions within its $\pm 45^\circ$ field of view, which is twice the swath of the push broom microwave radiometer (PBMR). ESTAR has a nominal ground resolution of 0.2 of the altitude. For this experiment the ESTAR was installed on the NASA C-130 aircraft operated by the NASA Ames Research Center.

The site chosen for this study was a semiarid rangeland, the Walnut Gulch Watershed, located in southeastern Arizona which is operated by the USDA-ARS Southwest Watershed Research Center. This watershed has a relatively long history of detailed hydrologic measurements and associated analysis [4] and was the focus of a major interdisciplinary experiment in the summer of 1990 [5]. As part of that experiment multitemporal *L*-band radiometer data were collected using the PBMR [6] and a single swath system with 2.25 cm and 21 cm radiometers [7]. Extensive ground observations of soil moisture were collected in 1990 to validate the performance of these radiometers.

The seven flightlines flown during 1991 were also used in the 1990 experiment involving the PBMR [6]. This pattern resulted in contiguous coverage of an area approximately 5 km by 10 km at a ground resolution of 200 m. The 1991 flights were conducted on August 1 and August 3.

Ground data collection during this experiment consisted of gravimetric sampling of the surface 5 cm of the soil and the measurement of the 5 cm soil temperature within one hour of the aircraft overflights. Some surface temperatures were obtained with a hand held infrared thermometer. These data were collected at ten locations distributed over the area as shown in Fig. 1. Eight of these sites, numbers 1 through 8, were the same as those used in the 1990 studies [6].

As described in [5], vegetation cover of this watershed consists of sparse grass and desert shrub in the eastern and western portions of the study area, respectively. Wet biomass values in 1990 were typically 200–300 g/m² which should

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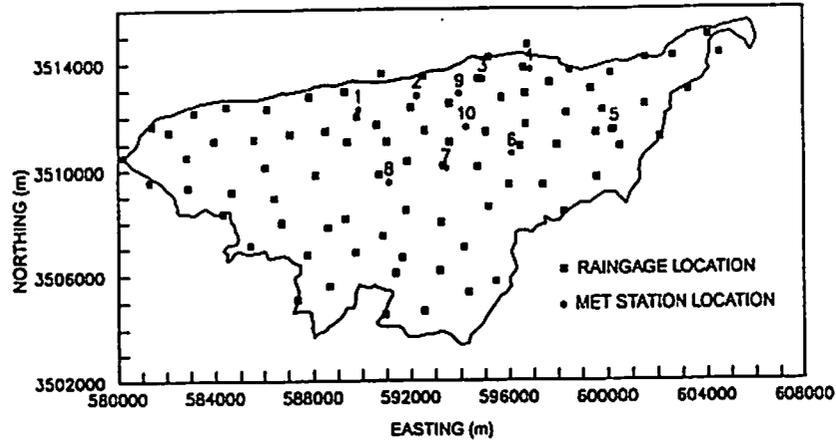


Fig. 1. The Walnut Gulch watershed showing the locations of all raingages and met station sampling sites.

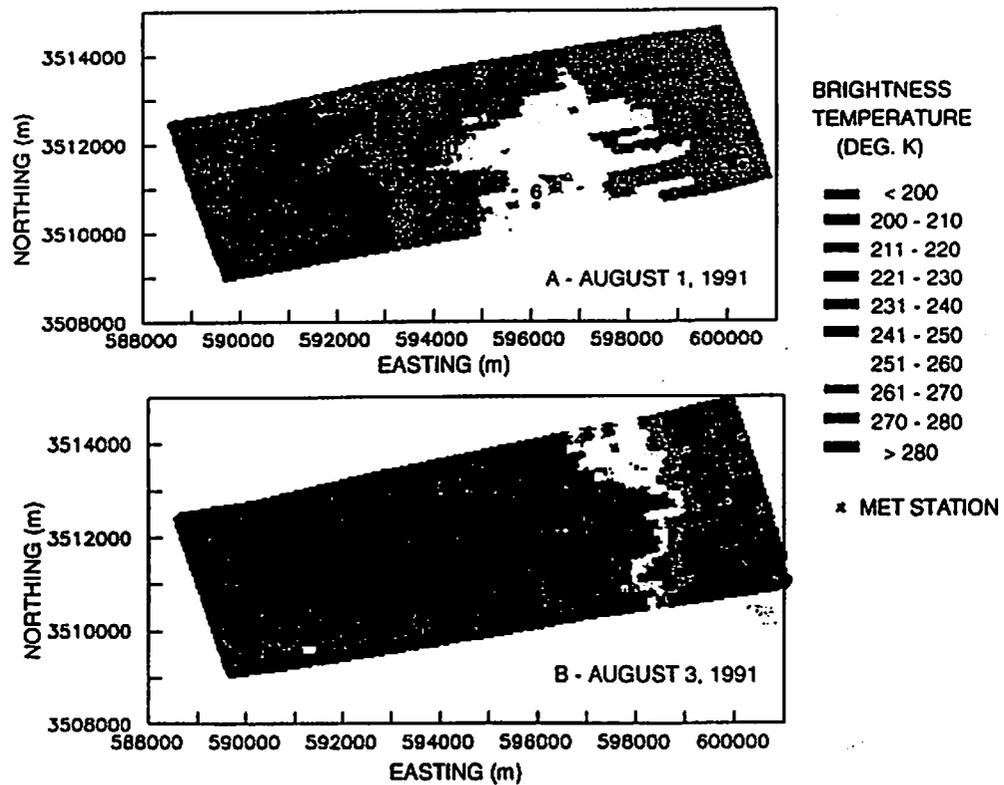


Fig. 2. ESTAR brightness temperature maps for the Walnut Gulch study area in degrees Kelvin; (a) August 1 and (b) August 3.

have minimal effects on the interpretation of the microwave brightness temperatures [8]. Surface soils are mostly sandy loams with varying rock fractions. A summary of the soil physical properties at the various ground sampling sites is presented in Table I.

III. BRIGHTNESS TEMPERATURE MAPS AND RAINFALL MAPPING RESULTS

Data collected using the ESTAR were processed to produce brightness temperatures at four beam positions which were identical to those of the PBM [6]. The resulting brightness temperature maps for the two 1991 dates are shown in Fig. 2. The two flights provided data over a wide range of brightness temperatures, even on a single date (August 3).

Meteorological conditions during the experimental period resulted in ground moisture values that produced the full range of brightness temperature observed the previous year [6]. Prior to the August 1 flight there was a localized rainfall event on July 30 that was centered between sites 5 and 6. An isohyetal map for the total event rainfall was produced using data collected by 85 raingages (see Fig. 1) distributed over the 150 km² watershed area and the result is shown in Fig 3(a). On August 2, prior to the second flight on August 3, there was a large cellular rainfall event that was centered near sites 1 and 2. The isohyetal map for this event is shown in Fig. 3(b). No rainfall occurred in the vicinity of site 5 on this date.

The brightness temperature patterns of Fig. 2 match the rainfall isohyetal patterns presented in Fig. 3 for the antecedent dates. The fact that an L-band radiometer detects whether or

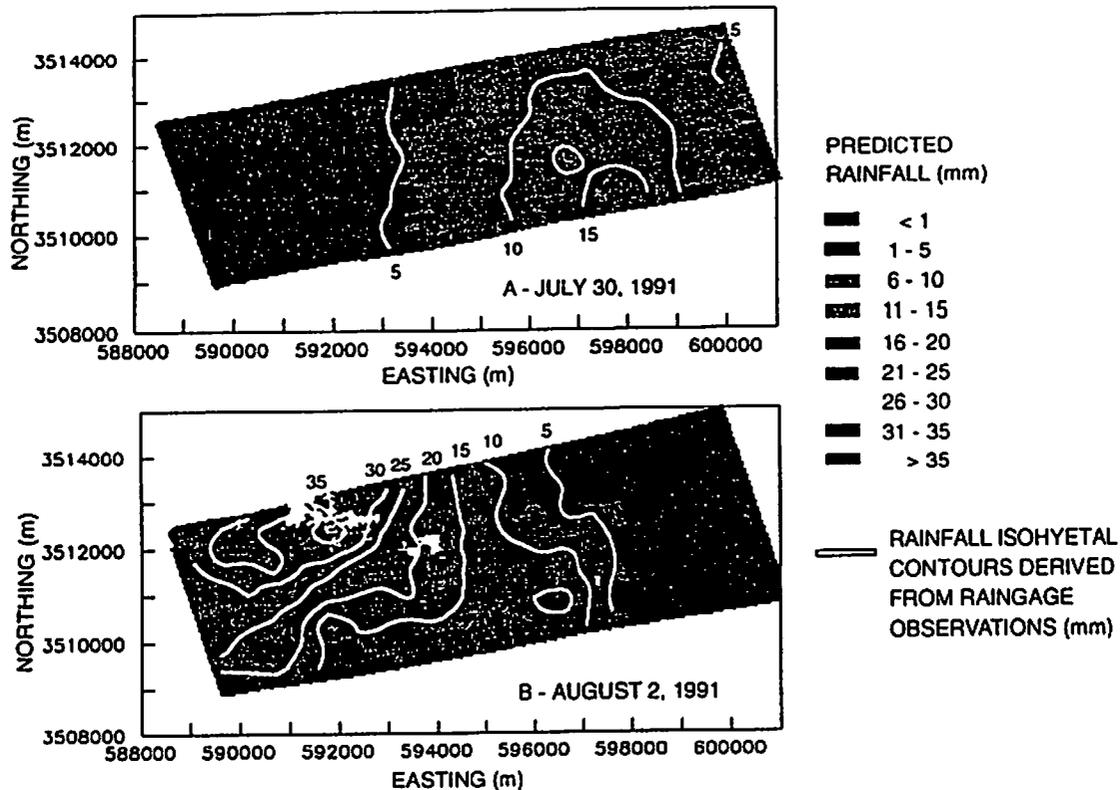


Fig. 3. Rainfall maps for Walnut Gulch study area. The isohyetal contour lines were derived from the observations made by the raingage network. The images were predicted from brightness temperatures observed after the event as described in the text. All values are in mm. (a) July 30 event and (b) August 2 event.

TABLE I
WALNUT GULCH SAMPLING SITE SOIL PROPERTIES

Site	Sand (%)	Silt (%)	Clay (%)	Specific Surface Area (m^2/g)	Bulk Density (g/cm^3)	Rock Volume (%)
1	66	24	10	26	1.64	42
2	69	20	11	30	1.83	51
3	71	20	9	20	1.58	41
4	73	22	5	28	1.82	61
5	69	20	11	54	1.61	56
6	67	25	8	27	1.44	48
7	80	14	6	10	1.74	22
8	72	20	8	21	1.47	31
9	63	24	13	84	1.66*	10*
10	67	23	10	52	1.66*	30*

*Estimate based on visual field observations.

not there was rainfall is not surprising. There were, however, two interesting points observed in the data. The first was the fact that even 2 days after a rainfall event in a semiarid environment, the rainfall pattern can still be detected (August 1 ESTAR observations). The second feature of interest is that on the day following the large rainfall event of August 2 the sensor is able to discern the difference between areas that received 25 mm of rainfall and those that had 15 mm. This feature suggests that there is a great deal of quantitative rainfall information that can be extracted.

Schmugge *et al.* [6] examined the relationship between rainfall amount and brightness temperature in the Walnut Gulch watershed using the PBMR data collected in 1990. Using a set of data with uniformly dry antecedent conditions,

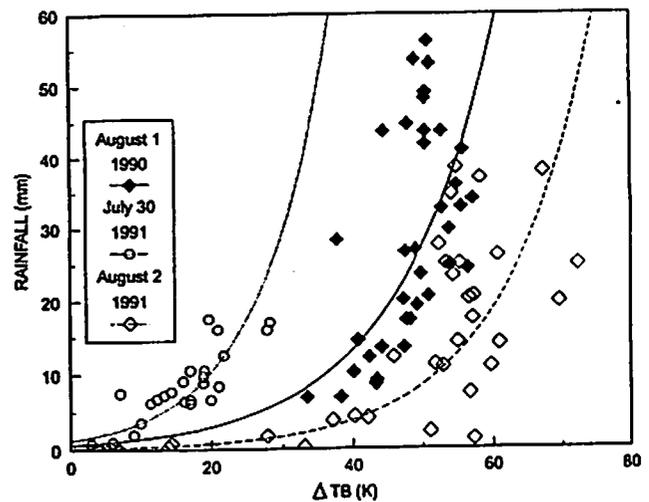


Fig. 4. Relationship between rainfall amount and the decrease in brightness temperature for Walnut Gulch rainfall events in 1990 and 1991.

the decrease in brightness temperature (ΔT_B) at raingage locations was correlated to the rainfall amount. These results are shown in Fig. 4. As shown here, an exponential model describes the relationship well. The r^2 value for this function was 0.68. In [6] it was noted that a functional relationship between brightness temperature and rainfall did not apply above 30 mm of rainfall. This result is probably related to soil limitations on infiltration resulting in runoff being carried offsite and concentrated in channels.

A similar analysis was performed for the 1991 events. Based on antecedent rainfall, it was assumed that prior to the events

that the entire watershed would be dry and have a brightness temperature of 280 K. Using this assumption, the observed brightness temperature for an area surrounding each raingage (30 gages on August 1 and 35 on August 3) was subtracted to obtain ΔT_B . These values are plotted in Fig. 4 versus the rainfall amounts. As in the case of the 1990 data, an exponential function describes the relationship well for both days, $r^2 = 0.83$ for the July 30–August 1 data and $r^2 = 0.79$ on for the August 2–August 3 data. The August 3 data set is especially interesting because observations over a larger range of rainfall amounts than in 1990 were available. The differences in the relationships for each date might be attributed to within storm rainfall intensity distributions and both the infiltration and the evapotranspiration that occurred between the rainfall and the microwave observations. These results are very interesting and warrant further study as additional data sets become available.

The functions for each date can be applied with the observed brightness temperatures (after computing ΔT_B as described above) to map the rainfall distribution. The resulting images are shown in Fig. 3 which also include the raingage isohyetal contours. Both methods of estimating the spatial distribution of rainfall show similar patterns on a given day, however, there are some differences. The contour lines in Fig. 3 were based on interpolation using available raingages so obviously there is a possibility for error. The most important point concerning these results is that the brightness temperature method yields the same basic results as those obtained using the raingages which suggests a potential approach to greatly enhancing our ability to estimate rainfall over large and remote areas that typically do not have raingage networks. Using a limited network a basic functional relationship could be established and then used with the T_B data. If the characteristics of this function can be related to event and local features the results could be extrapolated over very large regions.

IV. SOIL MOISTURE ESTIMATION AND MAPPING RESULTS

As stated at the outset, the primary goal of this experiment was the verification of the ESTAR instrument as a soil moisture sensor. The primary verification was provided by comparing the observed surface soil moisture with the values predicted using a previously established relationship [7] and the observed brightness temperatures at those sites. As described in [7] the predicted relationships are based on analyses of data collected in controlled condition experiments for a similar but not identical soil. This relationship is referred to as the BARC model since it was based on data collected over a ten year period at the Beltsville Agricultural Research Center. The differences are primarily related to the rock fraction which is higher for the Walnut Gulch area. The only study that has considered this parameter is one reported in [9]. In that study, it was suggested that changing the rock fraction could have two offsetting effects on the soil moisture–brightness temperature relationship. One effect would result from the fact that the dielectric properties of rocks are different from those of an equivalent volume of soil. The other effect results from the

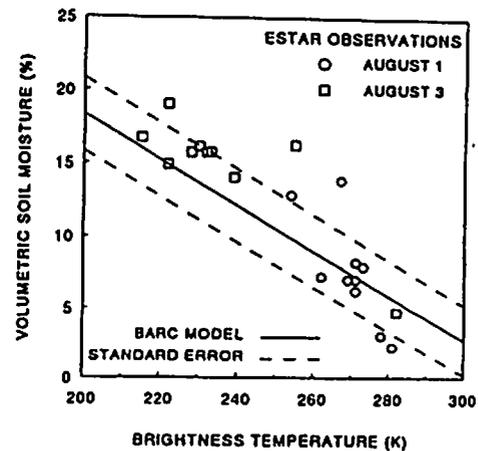


Fig. 5. Observed and predicted relationships of soil moisture and ESTAR brightness temperature. BARC model based on [9].

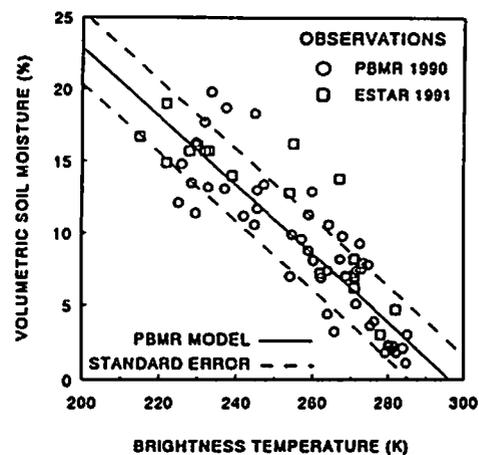


Fig. 6. Observed and predicted relationships of soil moisture and 1990 PBMR and 1991 ESTAR brightness temperature. PBMR model is a linear regression fit to the 1990 data.

fact that rock volume is correlated to the presence of surface rocks [5]. This results in increased surface roughness.

The *a priori* relationship from [7] and [9] is plotted in Fig. 5 along with the observed brightness temperature and soil moisture data from the 10 sampling sites in 1991. Using this model the standard error of estimate for the ESTAR observations was estimated as 2.9% soil moisture. This compares to a value of 2.5% obtained in [9] and leads to the conclusion that the ESTAR can be used to accurately estimate soil moisture.

The ESTAR data were also compared to the PBMR data collected in 1990. As described in [6], this was an extensive data set that covered a wide range of moisture conditions. Using the PBMR data, a linear regression equation was developed for the prediction of soil moisture from the brightness temperature. This curve and the PBMR data are shown in Fig. 6. The slope of this model is slightly different than the BARC model [9] and its standard error of estimate is 2.5%. When used to predict soil moisture from the ESTAR brightness temperatures, the error was determined to be 2.6% which was a marginal improvement over the BARC model.

Based upon the above, the BARC model was chosen for application because it provided a mostly *a priori* method.

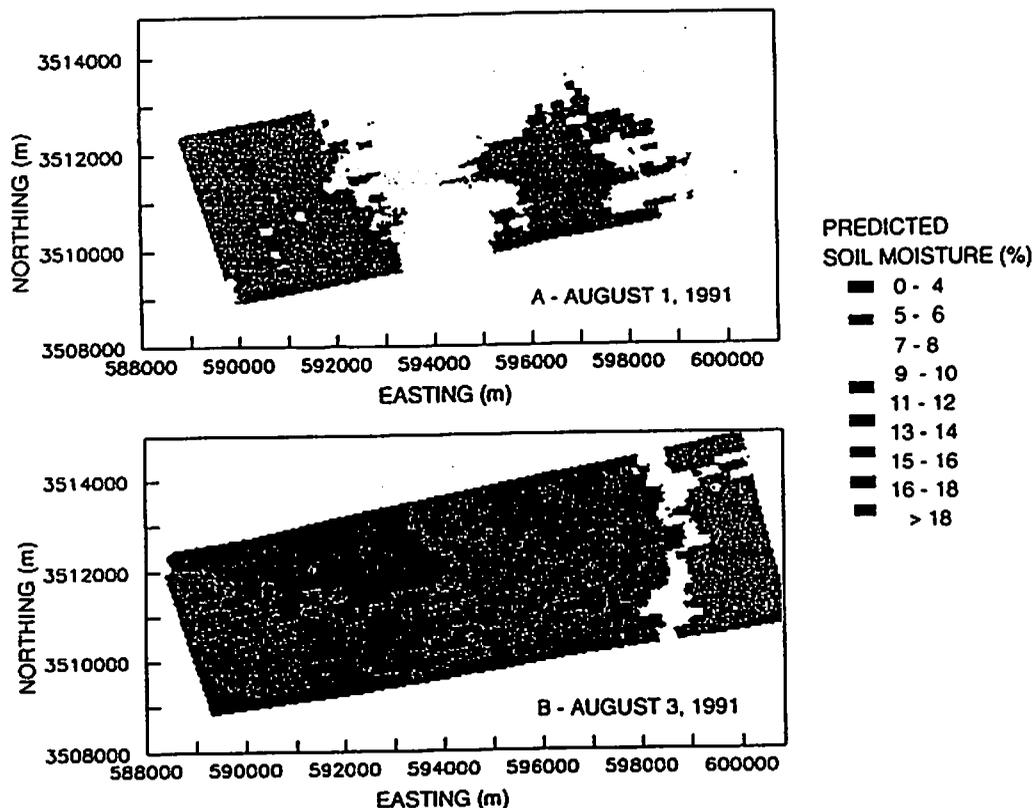


Fig. 7. Surface soil moisture maps for the Walnut Gulch watershed predicted using brightness temperature and BARC model; (a) August 1 and (b) August 3.

Using this model and the brightness temperature maps, a soil moisture map was produced for each date. These results are shown in Fig. 7.

V. SUMMARY

The ESTAR *L*-band radiometer was evaluated for soil moisture mapping applications over the semiarid rangeland Walnut Gulch Watershed located in southeastern Arizona. Antecedent rainfall and evaporation for the data flights were very different and resulted in a wide range of soil moisture conditions with distinct spatial patterns. Relationships between rainfall and brightness temperature were observed that further supported results obtained in other studies. These results show the potential of using an *L*-band radiometer to augment sparse raingage networks. Microwave brightness temperature data were used in conjunction with an *a priori* microwave emission model to predict soil moisture and compared to ground observations of soil moisture. A second verification was conducted using an extensive data set collected the previous year at the same site with the PBMR radiometer. Both tests showed that the ESTAR is capable of providing soil moisture with the same level of accuracy as existing systems. ESTAR has the potential of satisfying application data requirements and spacecraft limitations. These results show that it is capable of providing the necessary data for soil moisture applications.

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