Soil Moisture Mapping at Regional Scales Using Microwave Radiometry: The Southern Great Plains Hydrology Experiment

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Abstract—Surface soil moisture retrieval algorithms based on passive microwave observations, developed and verified at high spatial resolution, were evaluated in a regional scale experiment. Using previous investigations as a base, the Southern Great Plains Hydrology Experiment (SGP97) was designed and conducted to extend the algorithm to coarser resolutions, larger regions with more diverse conditions, and longer time periods. The L-band electronically scanned thinned array radiometer (ESTAR) was used for daily mapping of surface soil moisture over an area greater than 10,000 km² for a one month period. Results show that the soil moisture retrieval algorithm performed the same as in previous investigations, demonstrating consistency of both the retrieval and the instrument. Error levels were on the order of 3% for area integrated averages of sites used for validation. This result showed that for the coarser resolution used here that the theory and techniques employed in the algorithm apply at this scale. Spatial patterns observed in the Little Washita Watershed in previous investigations were also observed here. These results showed that soil texture dominated the spatial pattern at this scale. However, the regional soil moisture patterns were a reflection of the spatially variable rainfall and soil texture patterns were not as obvious.

Index Terms—Hydrology, microwave, remote sensing, soil moisture.

I. INTRODUCTION

The need for a suitable approach to the global measurement of soil moisture has been emphasized by the World Climate Research Program [1]. Under this program, the global energy and water cycle experiment (GEWEX) was created to study the “fast” component of the climate system. One of the objectives of the GEWEX Continental-Scale International Project (GCIP) is to improve the predictive capability of coupled hydrologic-meteorological models. In order to achieve this, an improved capability in modeling the large-scale soil moisture dynamics and its verification is essential.

A global soil moisture observing system has so far eluded us. This is due to the difficulty in implementing conventional measurement methods, which work well at the small scale, over large regions. Both technological issues and the inherent heterogeneity of the soil properties and land surface attributes are factors. As in the case of many geophysical variables, global measurement and interpretation of soil moisture might be best accomplished by a combination of ground-based and spaceborne techniques.

Microwave radiometry at long wavelengths can be used to measure and monitor surface soil moisture. The fundamentals of this approach are well established [2] and soil moisture retrieval algorithms have been verified using high resolution ground based experiments and aircraft observations [3].

A key issue in implementing this approach has been the inherent spatial resolution problem of long wavelength microwave radiometry at spacecraft. Antenna size is the only factor that we can change to improve resolution. However, increasing the antenna size introduces extremely difficult engineering problems that cannot be solved using conventional technologies. This has been a major reason for looking at innovative approaches such as synthetic aperture radiometry [4].

It should be noted that even if a synthetic aperture antenna, or any of the other alternatives under development, is used for soil moisture measurement that the spatial resolution will be on the order of 10–30 km. This resolution is coarse compared with sensors operating at visible wavelengths but it is compatible with other spaceborne microwave radiometers used for water vapor as well as current and future global climate models.

The primary objective of this investigation was to evaluate the performance of the soil moisture retrieval algorithm at coarser spatial resolution. This evaluation will provide a critical link in extrapolating previous high resolution results to the footprints of future satellites. As part of this, the spatial and temporal domains of the data collection were expanded to provide a more extensive test bed for the algorithm and the ESTAR instrument.
SGP97 was designed to address the objectives described above. The core of this project was the large scale aircraft soil moisture mapping. Based upon constraints, the experimental area mapped was ~10,000 km² (order of magnitude larger than previously observed) at a spatial resolution compatible with known data interpretation algorithms (~1 km). The spatial domain of the resulting data base is large enough that it may be useful in scaling up to projected satellite sized footprints (~10 km). The intent was to obtain nearly daily temporal coverage over a period of one month. Data were collected using an L band passive microwave mapping instrument called the electronically scanned thinned array radiometer (ESTAR) flown on a P3B aircraft operated by NASA’s Wallops Flight Facility.

This paper provides a detailed description of the SGP97 Hydrology Experiment and the ESTAR instrument and data. Brightness temperature data collection and processing methods are presented. The soil moisture retrieval algorithm is rigorously tested using ground observations. Brightness temperature and soil moisture image products are analyzed and interpreted.

II. STUDY REGION

The region selected for investigation is exceptionally well instrumented for surface soil moisture, hydrology, and meteorology research. Fig. 1 shows the location and general features. In selecting the region, three facilities were important. They were the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Little Washita watershed (LW) southwest of Chickasha, the USDA ARS Grazinglands Research Lab at El Reno (ER), and the Department of Energy Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) Central Facility (CF) near Lamont (see Fig. 1). The overall character of the SGP region is reflected in the false color composite image created from a Landsat Thematic Mapper (TM) data set collected on July 25, 1997 and is shown in Fig. 2.

This image is a combination of bands 2–4 as the blue, green, and red channels. Red areas in the image indicate vegetation. Whites and blues indicated bare soil and dormant or senescent vegetation. It should be noted that at the outset of SGP97 that all winter wheat was senescent. Wet field conditions in the

Fig. 1. Map of the SGP97 region and meteorological networks.
region delayed the harvest, especially in the northern portion of the SGP97 region.

The Little Washita Watershed is located in southwest Oklahoma in the Southern Great Plains region of the United States and covers an area of 603 km$^2$ (Fig. 1). The climate is classified as subhumid with an average annual rainfall of 75 cm. Within the watershed there are a total of 42 continuous recording rain gages distributed at a 5-km spacing over the watershed that are called the ARS Micronet system. The topography of the region is moderately rolling with a maximum relief less than 200 m. Soils include a wide range of textures with large regions of both coarse and fine textures. Land use is dominated by rangeland and pasture (63%) with significant areas of winter wheat and other crops concentrated in the floodplain and western portions of the watershed area.

Additional background information on the watershed can be found in [5].

The LW area has been the focus of related remote sensing experiments in 1992 [3] and 1994. Additional details can be found at the following world wide web site, http://hydrolab.arsusda.gov/.

The USDA ARS Micronet system provides hourly observations that include the following: rainfall, air temperature, humidity, and soil temperature (5, 10, 15, and 30 cm). At thirteen of these sites (Fig. 1), soil moisture at several depths (5, 10, 15, 20, 30, and 60 cm) is measured.

USDA ARS also operates the Grazinglands Research Laboratory at El Reno, OK. This consists of 24.3 km$^2$ of government operated grasslands ranging from winter wheat to natural prairie. The general region is dominated by winter wheat. Grasslands within the ER area were less intensively utilized than the private lands in the surrounding area. Soils are mostly silt loam.

The third facility that was used is the DOE ARM Central Facility. This area consists of a grassland and a winter wheat field side by side. This facility is extensively instrumented and a great deal of descriptive information can be found in [6]. The region surrounding the CF area is dominated by winter wheat and soils are mostly silt loam. The CF represents one location in the ARM CART network shown in Fig. 1. Included in this network are extended facilities (EF) which generally include profile soil moisture measurements every hour at depths of 5, 15, 25, 35, 60, 85, 125, and 175 cm.

In addition, the study region also falls within the domain of the Oklahoma Mesonet as shown in Fig. 1. All of the Mesonet locations provide extensive meteorological data and many also include profile soil moisture measurements. Soil moisture is recorded every half hour for depths of 5, 25, 60, and 75 cm. Additional details on the Oklahoma Mesonet can be found in [7].

III. ELECTRONICALLY SCANNED THINNED ARRAY RADIOMETER (ESTAR)

L band passive microwave radiometers are capable of providing surface soil moisture maps. Recent experiments such as Washita'92 [3] have demonstrated the capabilities of this approach.

The electronically scanned thinned array radiometer (ESTAR) is a synthetic aperture, passive microwave radiometer operating at a center frequency of 1.413 GHz (21 cm) and bandwidth of 20 MHz. For this experiment it was installed to provide horizontally polarized data. This instrument is the most efficient soil moisture mapping device currently available.

Aperture synthesis is an interferometric technique in which the product (complex correlation) of the output voltage from pairs of antennas is measured at many different baselines. Each baseline produces a sample point in the Fourier transform of the scene, and a map of the scene is obtained after all measurements have been made by inverting the transform. ESTAR is a hybrid real and synthetic aperture radiometer which uses real antennas (stick antennas) to obtain resolution along-track and aperture synthesis (between pairs of sticks) to
obtain resolution across-track [4]. This hybrid configuration could be implemented on a spaceborne platform.

The effective swath created in the ESTAR image reconstruction (essentially an inverse Fourier transformation) is about ±45° wide at the half power points. The field of view is restricted to ±45° to avoid distortion of the beam but could be extended to wider angles if necessary. The image reconstruction algorithm in effect scans this beam across the field of view in 2° steps. The width of the synthesized beam is about 8–10°; hence, these data are not independent, since the beam at each data point overlaps its neighbors. Independent, contiguous beam positions can be achieved by averaging the response of several of these data points. Another approach, especially useful in a mapping mode, is to use all of the oversampled (i.e., not independent) observations and then to use a grid overlay to average the data. This is the procedure we chose to use for the SGP97 data. The final product is a time and geographically referenced series of microwave brightness temperatures at 0.25 s intervals.

Calibration of the ESTAR is achieved by viewing two scenes of known brightness temperature. By plotting the measured response against the theoretical response, a linear regression is developed that corrects for gain and bias. Scenes used for calibration include a black body and water. During aircraft missions, a black body is measured before and after the flight and a water target (lake) during the flight. Water temperature is measured or estimated.

The ESTAR instrument was flown on a P3B aircraft operated by the NASA Wallops Flight Facility. ESTAR was installed in the bomb bay portion of the aircraft during this mission [4]. Flights were conducted at an altitude of 7.5 km. The original flightline configuration called for four parallel lines (at 7.5 km) and a water calibration line (at 200 m over a lake). After reviewing the first day of data from the SGP97 mission, a problem with radio frequency interference (RFI) was found. This was a localized problem in an area at the same latitude as Oklahoma City. The source appeared to be associated with air traffic control radar at the Oklahoma City airport located directly east of the RFI area. This was a critical problem because the area affected included the El Reno study area. The flight plan was modified to include two east-west lines in this area (these are flown as a deviation in the last of the four long parallel lines). The line sequence is shown in Fig. 3. This reconfiguration, which involved reorienting the antenna to the source, eliminated the RFI.

An attempt was made to conduct the flights exactly the same way on a daily basis. For the most part this was accomplished, however, instrument, weather, and logistic constraints resulted in some deviations which are described in Table I.
In addition to the SGP97 region, a secondary study area was flown on selected dates. This area was part of the Cooperative Atmospheric Surface Exchange Study (CASES) located in Kansas. The flightlines for this area were flown after the standard SGP97 flightlines (Lines 8 and 9 in Fig. 3). Data were collected on four dates; June 20, July 2, July 12, and July 16.

Toward the end of the SGP97 mission, another instrument was operated that resulted in deviations in the flight plan. This was the Lidar Atmospheric Sensing Experiment (LASE) instrument [8]. For the most part, the deviations involved repeating selected flightlines.

IV. Soil Moisture Sampling

Collecting ground based soil moisture to validate the soil moisture retrieval algorithm was extremely important in this experiment. Numerous factors needed to be considered in designing the ground based sampling in order to make the results useful. The sampling strategy was influenced by logistic issues which include the existing and proposed locations of instrumentation, facility support, and site access. In addition, all surface samples had to be collected within a window of about 3 h with a limited number of people.

Sample coding utilized the area identification [Little Washita (LW), El Reno (ER), and Central Facility (CF)] and the sequential number within that area. Tables II–IV describe the set of gravimetric soil moisture sampling sites used in SGP97. These locations are shown in Figs. 4–6. Many of the sites used were also locations used by the three meteorological networks in the region. The network and its designation for the site are indicated in these tables.

For the most part, sampling was done on sites that were approximately a quarter section (0.8 km × 0.8 km) in size. In selecting the sites, an attempt was made to sample several adjacent sites that could be grouped into clusters. In addition, some sites were sampled solely to provide surface data at points that might be used to ultimately explore relationships between the surface measurements and the full profile of the soil. The full profile soil moisture data were available from the existing network site at which sampling was collocated.

Sites with “Full” sampling involved two transects separated by 400 m with a sample every 100 m resulting in 14 samples per site. Profile only sites required 9 samples collected over a 20 m x 20 m grid near the profile location. Sample location was not critical in the ESTAR investigation. The grid was used only as an aid in stratifying the distribution of samples.

A standardized tool was used to extract a sample of the 0–5 cm soil layer. Bulk density was sampled independently and used to convert the gravimetric soil moisture to volumetric soil moisture.
V. ESTAR DATA COLLECTION, CALIBRATION, AND PROCESSING

The goal in SGP97 was to collect data on every day possible during the one month aircraft deployment. Several factors work against achieving this goal; weather, aircraft constraints, and instrument problems. ESTAR flew more than 100 h during SGP97 and the wear and tear began to show on the instrument. On June 21, metal fatigue on a voltage regulator caused an instrument failure. It took several days to locate and repair the problem. On July 4, a switch failed and on July 10 a power supply wire broke and caused a short circuit. The data collected between July 7–10 is suspicious and may have been affected by this loose wire. Until this can be confirmed or ruled out, data collected during this period has been omitted from the data set.

During the SGP97 field campaign, a predetermined calibration for ESTAR was used to produce quick response images. Data were processed into an image product usually within twelve hours of collection. This product provided valuable information for mission planning and quality control. The first step in quality control was the review of the level and consistency of spatial and temporal features in these images.
Fig. 6. Test sites in the Little Washita (LW) area. Coordinates are UTM.

Additional details on calibration of the ESTAR instrument can be found in [4].

Post processing of the ESTAR data involved refining the calibration, georegistration using an on-board GPS receiver, RFI removal, and correction for incidence angle (images are normalized to nadir [3]). Several different data sets were evaluated for establishing the absolute calibration. These were based upon water data flown at various times during the study period. Following this, the alternatives were used to predict $T_B$ for the Little Washita watershed area. Results were compared to relationships that had been verified in the 1992 and 1994 experiments [3]. The data set consisted of an extensive set of water calibrations performed just prior to the field campaign.

Fig. 7 is a plot of $T_B$ versus soil moisture for the LW area. Data from both the previous and current investigations are plotted with the predicted relationship based upon the soil moisture retrieval algorithm. These results clearly demonstrate that the calibration for SGP97 is consistent with the 1992 experiments and the retrieval algorithm. The figure also shows that the ESTAR appears to have very high day to day consistency.

These data have also been reviewed for temporal consistency. It is possible that some instrument related drift can occur during the day and it is also possible that soil moisture and/or soil temperature may change enough during a flight that conditions may vary from the start to the end. Since we were interested in generating a snapshot of the region, the data were carefully reviewed for trends. During SGP97 the only time that such conditions were noted was preceding the instrument failure on July 10 (power supply wire) which resulted in the deletion of those days from further analysis.

An ESTAR data record consists of the time and $T_B$ values for each beam position at that point in time. Global Positioning System (GPS) data collected during flight were used to georegister the center beam position of each data record. Following this the aircraft pitch, roll, and yaw data were used to adjust the ground location of the center beam and all the footprint locations of that data record.

Criteria were established for identifying footprints that were contaminated with RFI. This was straightforward since RFI
VI. SOIL MOISTURE ALGORITHM

The Level 2 ESTAR images are the input to the soil moisture algorithm described in [3]. The algorithm is based on the inversion of the Fresnel reflection equation for horizontal polarization. For each pixel the following input data are required to apply the algorithm: soil temperature, vegetation type, vegetation water content, surface roughness, soil bulk density, and soil texture. Each of these inputs was generated as a plane of the GIS data base as described in the following sections.

A. Soil Temperature

The data collected as part of the Oklahoma Mesonet include observations of soil temperature at 10 cm under sod every...
TABLE V
ALGORITHM PARAMETER VALUES ASSIGNED TO LAND COVER CATEGORIES

<table>
<thead>
<tr>
<th>Category</th>
<th>Vegetation Parameter b</th>
<th>Vegetation Water Content (kg/m²)</th>
<th>Surface Roughness Parameter h</th>
<th>Soil Bulk Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>0.085</td>
<td>1.0</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Bare</td>
<td>0</td>
<td>0.0</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Corn</td>
<td>0.119</td>
<td>1.0</td>
<td>0.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Legume</td>
<td>0.085</td>
<td>Equation 1 or 2</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Pasture</td>
<td>0.095</td>
<td>Equation 1 or 2</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Trees</td>
<td>x</td>
<td>x</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Shrub</td>
<td>0.085</td>
<td>Equation 1 or 2</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Urban</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Water</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Wheat</td>
<td>0</td>
<td>0.0</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.119</td>
<td>0.5</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Pasture</td>
<td>0.085</td>
<td>Equation 1 or 2</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Legume</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Unclassified</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

TABLE VI
ALGORITHM PARAMETER VALUES ASSIGNED TO SOIL TEXTURES

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent Sand</th>
<th>Percent Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>Loamy Fine Sand</td>
<td>85</td>
<td>5</td>
</tr>
<tr>
<td>Fine sandy Loam</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Loam</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>Silt loam</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>Silty clay</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>Clay</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Pits, Quarries, Urban</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Sphagnum</td>
<td>55</td>
<td>35</td>
</tr>
<tr>
<td>Water</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

TABLE VII
SAMPLE SIZES FOR AVERAGES USED IN VALIDATION

<table>
<thead>
<tr>
<th>Site</th>
<th>ESTAR Pixels</th>
<th>Ground Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW</td>
<td>518</td>
<td>23</td>
</tr>
<tr>
<td>ER</td>
<td>54</td>
<td>15</td>
</tr>
<tr>
<td>CF</td>
<td>49</td>
<td>9</td>
</tr>
</tbody>
</table>

Fig. 9. Observed SGP97 soil moisture and brightness temperatures for clusters of test sites.

5 min. A standard reference time for each flight was selected, usually 10:00 and all stations available were used to compute the effective soil temperature following the method described in [9]. Then a grid resampling program was used to generate an 800 m data base of effective soil temperature for each day.

B. Vegetation Type

Vegetation type is used to define the functional form of the vegetation attenuation [10]. The SGP97 region is not very complex in terms of vegetation types. The data used are based on the land cover classification performed by Doriaawamy et al. [11]. They used satellite observations (Thematic Mapper, TM) to perform a land cover classification. On site surveys were used as part of this supervised approach. For each land cover/vegetation category a vegetation parameter, b, utilized in the retrieval algorithm was assigned based on published data. The TM data have a resolution of 30 m and in order to compute a value of b for each 800 m pixel the individual b values were averaged. Table V summarizes the values used.

C. Vegetation Water Content

For all vegetation besides the grass categories a fixed value of the vegetation water content (VWC) was used as shown
in Table V. For the grass and shrub categories there were three steps involved in estimating the VWC. First, vegetation characteristics were measured at various locations on the ground during the field campaign [12]. Next, normalized difference vegetation index (NDVI) values were computed for the entire region using the TM data collected on July 25, 1997. Values of the NDVI were extracted for all test sites and a relationship to the vegetation water content was established by optimizing a polynomial function. The equation is as follows

\[
VWC(\text{kg/m}^2) = 1.9134(\text{NDVI})^2 - 0.3215(\text{NDVI}).
\] (1)

Finally, for each TM pixel at 30 m the land cover, the NDVI, and (1) were used to estimate the vegetation water content. These were integrated to generate an 800 m pixel value and a data plane in the GIS.

D. Surface Roughness

The technique used in the soil moisture algorithm for adjusting for surface roughness effects is based on [13]. For each land cover category, a roughness parameter was estimated based on previous investigations in this region. Values within each 800 m pixel were averaged to establish the surface roughness GIS data plane. Table V summarizes the values used.

E. Soil Bulk Density

For each land cover category a bulk density value was estimated based on samples collected as part of SGP97. Values
for each 30 m land cover pixel were averaged to establish the soil bulk density for the 800 m GIS data plane. Table V summarizes the values used.

F. Soil Texture

The algorithm utilizes the dielectric mixing model presented by Wang and Schmugge [14] and requires estimates of the percent sand and clay. A multilayer soil characteristics data set for the conterminous United States (CONUS-SOIL) has been developed at Penn State’s Earth System Science Center (ESSC) [15]. The state soil geographic database (STATSGO) developed by the USDA Natural Resources Conservation Service (NRCS) served as the starting point for CONUS-SOIL. One of the products available from this source is the soil texture classification of the surface soil on a 1 km grid. Based on soil texture samples and published data, percent clay and sand values were established for each soil texture category. Table VI summarizes the values used. The data were resampled to the 800 m grid to create two data planes (sand and clay) for the GIS.

VII. SOIL MOISTURE RESULTS

A. Algorithm Validation

Validation of the soil moisture retrieval algorithm was based on comparisons of ground based estimates of volumetric soil moisture and those derived from ESTAR data using the model. Georegistration of sensor footprints can never be more accurate than one half the footprint size. Since the sites were about the same size as the processed Level 2 ESTAR footprint, it isn’t possible to compare results at this scale. Therefore, our first level of comparison was for clusters of sites. The average of all $T_B$ values within a cluster was compared to the average of all the soil moisture samples within the same area. Fig. 9 is a plot of the observed soil moisture and $T_B$ values for all clusters.

Several of the clusters were winter wheat in various stages of harvest (CF3-6, ERIO-13, and LW21-23). The other clusters were all grassland. It should also be noted that the entire CF area was dominated by winter wheat, the ER area was mostly grassland, and LW was a mix of the two categories. Since the vegetation water contents of grasses is not very large, it is not surprising that the clusters within a given area show similar patterns. The relationships between soil moisture and $T_B$ follow well defined nearly linear trends expected from theory.

Another approach to the analysis of the data is to compare the average $T_B$ for each of the three areas (LW, ER, and CF) to the average soil moisture from all sites sampled in that area. The extent of the area that we averaged is defined by the ground sampling sites as shown in Figs. 4-6. The total number of ESTAR pixels and ground sampling sites used are summarized in Table VII.

The area averaged plots of soil moisture versus $T_B$ are shown in Fig. 10. Each of the areas has a unique functional relationship which is well defined. In addition to the strength of the trends, we also noted that the range of soil moisture conditions observed was large. The differences in the relationships between the areas makes sense in terms of the differences in the physical characteristics that affect the soil moisture and $T_B$ relationships.

Using a priori estimates of the characteristics of each area, the soil moisture algorithm was used to predict the soil moisture-$T_B$ relationship and the results are plotted in Fig. 10. These curves explain the behavior we observed in the data.

As noted in the discussion of the ESTAR calibration, it is possible to compare the SGP97 results for the LW area to those
collected in 1992 and 1994. These data are also included in Fig. 7 for comparison. Comparing the algorithm relationships to the observed data pairs strongly supports the retrieval algorithm and the consistency of ESTAR over a five year period.

In the preliminary analysis of the data for the ER area, we detected some bias when we used the same vegetation parameters as selected for the LW area in the previous studies in this region. It was observed during the experiment that the state of the grasslands in the ER area was different than other grassland sites encountered in the region. This is due to the fact that these are government owned lands that are managed quite differently from private lands. As a result, this area is not as intensively grazed and the grasses are taller and denser. There was also some thatch present on most of the ER grassland fields. The vegetation parameter $b$ for grasses is known to vary much more than that of other vegetation types [10].

Schmugge et al. [16] first observed what is referred to as the thatch effect in the 1985 experiments using an L band instrument in Kansas. It was observed that in grassland areas with thatch buildup on the soil surface that there was a decrease in the sensitivity of $T_B$ to changes in soil moisture. In subsequent analyses by Wang et al. [17] and [18], an attempt was made to interpret this effect quantitatively. The authors examined the vegetation water content, the vegetation parameter $b$, and the surface roughness parameter $h$ for areas with and without thatch. On the areas without thatch they were able to extract parameter values that were very reasonable as compared with previous results. For the areas with thatch, if they estimated vegetation water content from observations and used the $b$ parameter derived for the area without thatch it was necessary to triple the value of $b$ (an unrealistic result). In retrospect, we believe that there is an alternative approach to the problem that offers perhaps a better explanation. This would be to estimate the vegetation water content and $h$ a priori and then compute $b$. When we did this it yielded a value of $b$ which was twice as large as that observed on the areas without thatch. Based upon the points made above, the $b$ parameter value within the government operated portion of the ER area was increased.

An analysis of the observed NDVI versus vegetation water content data collected during the experiment [12] indicated that for the cover conditions in the ER area that beyond a certain value of vegetation water content the NDVI did not change. Since we were not able to accurately estimate the vegetation water content, this introduced error into the soil moisture estimates.

It is possible that part of the problem in applying the retrieval algorithm may be related to the fact that we are using NDVI values derived from observations made several weeks later in the summer (July 25, 1997). It is likely that by this time much of the tall grass had lost some of its water content and browned. This would result in lower values of NDVI than might have been obtained if sampling had been conducted concurrent with the aircraft mission. Low values of NDVI would in turn result in low estimates of the vegetation water content. Underestimating the vegetation water content would also lead to under predicting the soil moisture. Based on these considerations, the NDVI-vegetation water content function for the rangeland categories at El Reno was modified. Instead of the polynomial, an empirically derived piecewise function was used. This equation is

$$\begin{align*}
\text{IF NDVI} & \leq 0.5 \\
VWC(kg/m^2) &= 1.9134(NDVI)^2 - 0.3215(NDVI)
\end{align*}$$

If NDVI > 0.5

$$VWC = 4.2857(NDVI) - 1.5429.$$ (2)

Figs. 7, 9, and 10 are useful in evaluating the expected performance of the retrieval algorithm by comparing the observed data pairs to the algorithm relationship. In addition, we also compared the observed soil moisture and that predicted using the algorithm and GIS data bases for the three areas. These results are shown in Fig. 11. The standard errors of estimate are; LW = 2.1%, ER = 3.3%, and CF = 2.7%. The results are excellent and consistent with previous investigations [3]. The areas used are approximately the same size as could be achieved with a space platform sensor.
B. Soil Moisture Maps

Using the verified algorithm, we are then able to apply this and the ancillary data sets to each day of ESTAR data on a pixel by pixel basis. The resulting soil moisture maps are shown in Fig. 12.

There are four separate sequences of observations that will be referred to as: 1) June 18–20, 2) June 25–27, 3) June 29–July 3, and 4) July 11–July 16. In order to interpret these images, we need to consider the rainfall and physical characteristics of the region. In Fig. 13 the daily cumulative rainfall is plotted for three of the Mesonet locations near or within the three study areas. These values are at 10:00 local time for the previous 24 h. This corresponds to the nominal ESTAR overpass time.

The individual sequences of observations are generally drydowns, with the exception of 2. Spatial and temporal features in Fig. 12 are obviously related to the varying rainfall over the region. The northern portion received more rainfall than the south, however, the area around ER also had several large storms. Cumulative rainfall for the entire study period is plotted as an image in Fig. 14.

Changes in soil moisture due to drainage/drying after a rainfall event are obvious in the CF area for sequences 1, 3, and 4. Large amounts of rain and homogeneous cover conditions make it relatively easy to detect the changes in soil moisture. In the ER area, the temporal change in the spatial distribution is also readily observed.

The temporal and spatial distribution of rainfall dominate the spatial soil moisture patterns. In previous investigations [3] the spatial structure of the soil texture was found to be an important factor in soil moisture patterns. To examine this we first looked at the LW area that had been used in these previous investigations. We extracted the same exact area used in Washita'92 from the SGP97 data base. For this analysis we are using brightness temperature rather than soil moisture. In addition, we have resampled the raw data to the same pixel resolution used in 1992 (200 m). Note that the raw data have a resolution of about 400 m, therefore, when resampled to 200 m the images will appear a bit blurry.

A representative image generated for the Washita'92 area is shown in Fig. 15. The spatial pattern of brightness temperature is identical to that observed in 1992. Certain features such as the triangular area in the west (senescent winter wheat on silt loam soils), the hotter area in the center (grasslands with sandy soils), and the colder linear feature in the east are replicated consistently. The drying sequences in this area were uninterrupted with the exception of number 2. One difference between the 1997 and the 1992 data sets is that the rainfall in 1992 was uniform and in 1997 there were larger amounts to the south and west (see Fig. 14).

This analysis shows that soil texture effects are present in the 1997 data set at a smaller extent. To examine this issue on a regional basis we start by looking at the vegetation and soils over the region. The TM image shown in Fig. 2 can be
used to gain a sense of vegetation distribution. The whites and blues are indicative of bare soils and senescent vegetation and the reds indicate green vegetation. The regional soil map is shown in Fig. 16.

In examining Fig. 16, we observe that the region is dominated by a single soil texture, silt loam (38%). There are several horizontal bands of coarser soils. Comparing Figs. 2 and 16 we observe a direct correspondence in spatial features. Winter wheat is planted on soils that can hold enough water for growth, otherwise the land cover is grass. Some features in the soil moisture images show a consistent spatial pattern through the various soil moisture levels.

VIII. SUMMARY

Microwave radiometry at long wavelengths can be used to measure and monitor surface soil moisture. A key issue in implementing this approach has been the inherent spatial resolution problem of long wavelength microwave radiometry at spacecraft altitudes. Synthetic aperture radiometry can solve this problem with spatial resolutions on the order of 10–30 km.

A major objective of this investigation was to evaluate the extension of high resolution soil moisture retrieval algorithms to coarser resolutions. To answer this question, a large scale field experiment called the Southern Great Plains 1997 (SGP97) Hydrology Experiment was conducted. An L band passive microwave sensor was used to map surface soil moisture over 10,000 km² for one month.

The field campaign resulted in an excellent data set for analysis. The ESTAR instrument performed very well at the high altitudes flown. Meteorological conditions were also excellent. Significant spatially variable rainfall events were mixed with drydown sequences.

Calibration of the ESTAR was verified using ground observations and results of previous experiments in this region. An established soil moisture algorithm was implemented using ancillary data bases. This algorithm was validated using ground observations at several scales. Error levels were nominally 3% which was consistent with previous investigations. Some problems were encountered with both the ESTAR data (RFI) and the algorithm (grass thatch) in the El Reno area. Corrections to these problems were found.

The soil moisture images show consistent spatial structure. In SGP97, this structure as dominated by rainfall distribution with soil texture and vegetation levels having a secondary effect. Smaller scale analysis of the Little Washita area replicated earlier studies both in algorithm performance and in spatial soil moisture patterns.

Results clearly demonstrated the performance of both the ESTAR instrument and the soil moisture retrieval. The fact that the results match up so well with the 1992 and 1994 experiments is of particular significance. It was concluded that the algorithms can be extrapolated from higher resolution ground experiments to satellite scales.

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REFERENCES

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