MONITORING LAND SURFACE SOIL MOISTURE FROM SPACE WITH IN-SITU SENSORS VALIDATION - THE HUNTSVILLE EXAMPLE

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ABSTRACT

Based on recent advances in microwave remote sensing of soil moisture and in pursuit of research interests in areas of hydrology, soil climatology, and remote sensing, the Center for Hydrology, Soil Climatology, and Remote Sensing (HSCaRS) conducted the Huntsville '96 field experiment in Huntsville, Alabama from July 1-14, 1996. We, researchers at the Global Hydrology and Climate Center's MSFC/ES41, are interested in using ground-based microwave sensors, to simulate land surface brightness signatures of those space borne sensors that were in operation or to be launched in the near future. The analyses of data collected by the Advanced Microwave Precipitation Radiometer (AMPR) and thc C-band radiometer, which together contained five frequencies (6.925, 10.7, 19.35, 37.1, and 85.5 GHz), and with concurrent in-situ collection of surface cover conditions (surface temperature, surface roughness, vegetation, and surface topology) and soil moisture content, would result in a better understanding of the data acquired over land surfaces by the Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission Microwave Imager (TMI), and the Advanced Microwave Scanning Radiometer (AMSR), because these spaceborne sensors contained these five frequencies. This paper described the approach taken and the specific objective to be accomplished in the Huntsville '97 field experiment.

Key **Words:** Soil moisture, Microwave remote sensing, In-situ sensors, Spaceborne imagers.

INTRODUCTION

Advancements of microwave remote sensing technology, such as a suite of space-borne active and passive microwave sensors become operational or to be operational in next few years, makes monitoring land surface soil moisture a possibility. On the other hand, recent advances in microwave researches indicated that both passive microwave and active microwave techniques have provided solid theoretical and experimental results that the top five cm of soil moisture can be measured from ground-based truck, aircraft and space platforms under a variety of environmental conditions and through a moderate vegetation cover (Engman, 1995). We, researchers at the Global Hydrology and Climate Center, are interested in the microwave sensors with frequencies corresponding to those current or near future space-borne active and passive microwave sensors (Wu, 1996). We also address several of the specific recommendations of the workshop attendees of a NASA's Office of Mission to Planet Earth (MTPE) sponsored workshop in 1994 on soil moisture (Wei, 1994). It is also consistent with the overall goals of MTPE Strategic Enterprise as it pertains to studies involving land-cover change, global productivity, and long-term climate variability.

At the same time, We are one of the research teams participated in the Huntsville '96 field experiment in microwave remote sensing of soil moisture in Huntsville, Alabama from July 1-14, 1996, sponsored by the Center for Hydrology, Soil Climatology, and Remote Sensing (HSCaRS). The remote sensing measurements were supported by soil profile instrument systems, gravimetric moisture measurements, and soil and vegetation characterization. Additionally, radiation, wind, air temperature, and relative humidity measurements were also included, Scientific objectives focused on defining the soil depth emitting and reflecting energy at various microwave wavelengths; characterizing temporal and spatial variability of surface moisture, and studying the capability of measuring moisture at different frequencies. Both Huntsville '96 and Huntsville '97 field experiments focus on a small-scale (plot-size) testbed with well equipped *in-situ* instruments and three microwave soil moisture remote sensing systems. Preliminary results of the Huntsville '96 field experiment will be presented in the American Meteorological Society's Annual Meeting on February 2-7, 1997 (Laymen et al., 1997). This paper, with encouraging findings of Huntsville '96 as the starting point, will address several issues for the Huntsville ' 97 field experiment:

1. We will conduct the well controlled concurrent active/passive microwave data collections, with similar frequencies of L-, C-, and X-band, over the testbed for a range of conditions.
2. To facilitate and to convert the Advanced Microwave Precipitation Radiometer (AMPR) to become suitable for ground-based applications, we will modify the AMPR system's hot and cold loads calibration subsystem and the data acquisition subsystem.

3. Since the Special Sensor Microwave Imager (SSM/I) has been in operation nearly 10 years with its three (19.35, 37.1, 85.5 GHz) frequency-channels have been duplicated by the AMPR and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) have the 10.7 GHz frequency-channel and to be launched in 1997, we will collect the AMPR data, with site validation objective, to simulate the SSM/I and TMI sensors' land surface brightness temperatures, T_B, to get a better understanding and interpretation of these sensors' acquired data over land surfaces.
4. Since the Advanced Microwave Scanning Radiometer (AMSR) to be launched on the EOS PM-1 platform in the early 2000s have the lowest frequencies of 6.925 GHz, we will also conduct data collection using the 4-8 GHz step frequency C-band radiometer in the Huntsville '97 field experiment to simulate AMSR land surfaces brightness signatures.
5. Since the ground-based AMPR system is able to measure a half space, i.e. from nadir (looking directly downward from the boon) to zenith (looking directly upward) with 360 degree horizontal rotation, the measured sky and land surfaces brightness temperatures will be used to simulate the space borne microwave sensors' microwave signatures over land, the TRMM microwave imager in particular. During thunder storms or rain conditions, the upward looking AMPR will be able to collect rain rate over land just as the rain gage.
6. We will start developing the AMPR and C-band collected brightness temperature data bases for which the space borne microwave sensors' measurements over land surfaces would be validated.

TESTBED AND IN-SITU INSTRUMENTS

A research testbed was established at Alabama A&M University's Agricultural Research Station located about 20 km north of Huntsville, Alabama (Fig. 1). The testbed consisted of four plots about 50 x 60 m. Two plots were bare of vegetation and two others were vegetated. One of the vegetated plots had a tall fescue cover, whereas the other had a mixture of vegetation. A total of 110 soil cores (1 m) were extracted from the testbed on a 10 m grid for soil characterization. Soil of the grass-covered plot is classified as clay loam to silty clay loam, whereas the other plots are silt loam. Clay content increases with depth to 1 m in all plots from 24% to about 50'%.. Clay content is slightly higher in the grass plot. The organic matter content in the surface 15 cm is less than 2%. The configuration of the testbed will be the same in 97 experiment with cotton to replace the rough bare field.

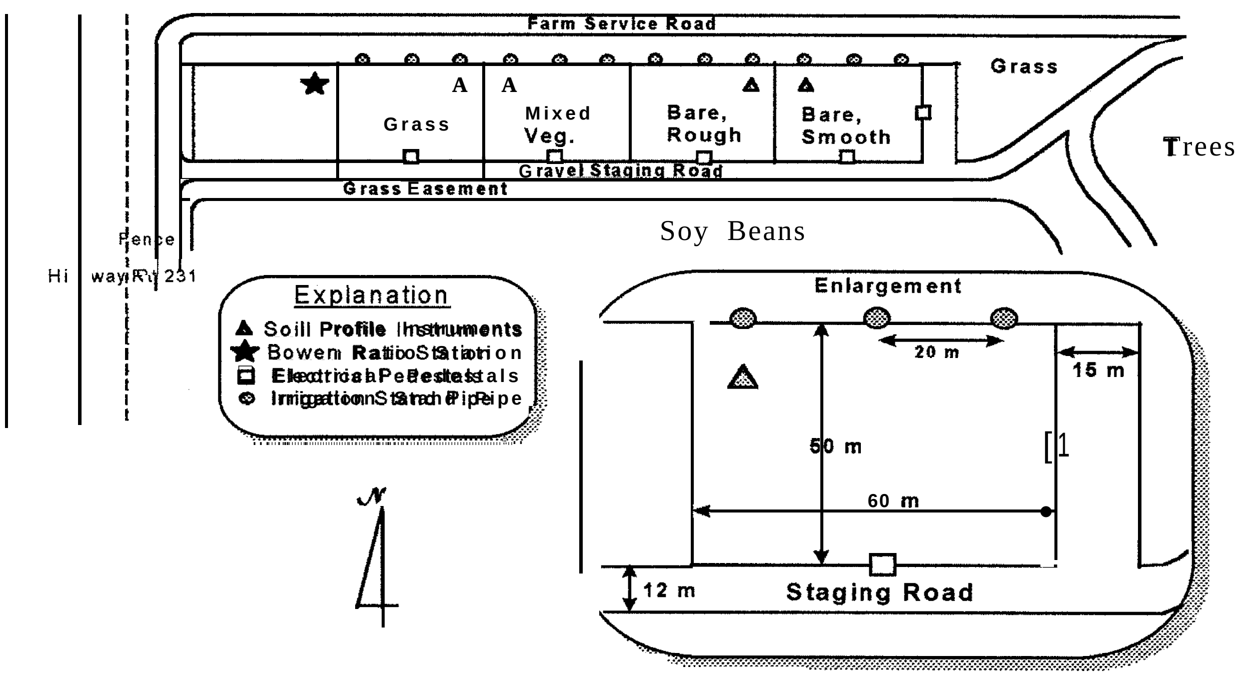

Figure 1. Diagram showing the layout of the testbed. Remote sensing instruments staged from the gravel road on the south side of the plots.

In the Huntsville '96 field experiment (Laymon et al., 1997):

Soil samples for gravimetric moisture content were collected from the four experimental plots at random locations and occasionally on a 10 x 10 m grid. The soil was sampled at five depth intervals (0-1, *0-3,0-5,0-7,* and 0-10 cm) in the morning (~08:00) and at a single depth interval (0-5 cm) in the afternoon (~14:30). Standard procedures were used to analyze these samples. Soil bulk density of the upper 15 cm was determined using the excavation method developed by the U.S. Department of Agriculture. Bulk density samples were collected before irrigation (DOY1 83), two days after irrigation (DOY186, 187), and after a one week dry-down period (DOY194). Figure 2 shows the daily amount of precipitation (irrigation, rainfall) measured by distributed rain gages. Irrigation totaling 34.3 mm was applied on DOY184- 186. Two rain events occurred totaling 43.7 mm; 36.1 mm fell on DOY189-190 and 7.6 mm fell on DOY196 (Fig. 2). Irrigation was applied to bare and vegetated plots at slightly different times. Because gravimetric sampling is destructive, samples were only acquired from the northern half of the plots outside the area sampled by the remote sensing instruments. To evaluate potential errors resulting from sampling different halves of the plots, we conducted an assessment of the spatial variability of surface moisture for each plot. Results show that, in general, the variance in gravimetric moisture content was low. Peaks in variance occurred on two days for the rough bare plot and on three days for the mixed vegetation plot. For the most part, soil moisture behaved as expected in response to the two dominant wetting events (Fig. 3).

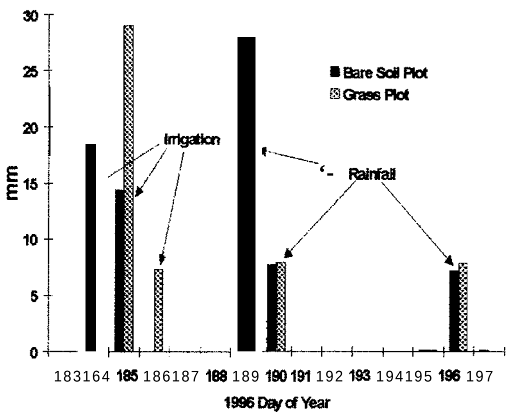

Figure 2. The daily amount of precipitation (irrigation, rainfall) measured by distributed rain gages.

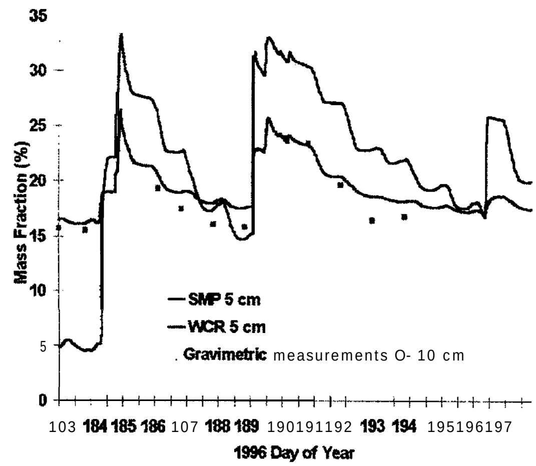

Figure 3. The soil water content.

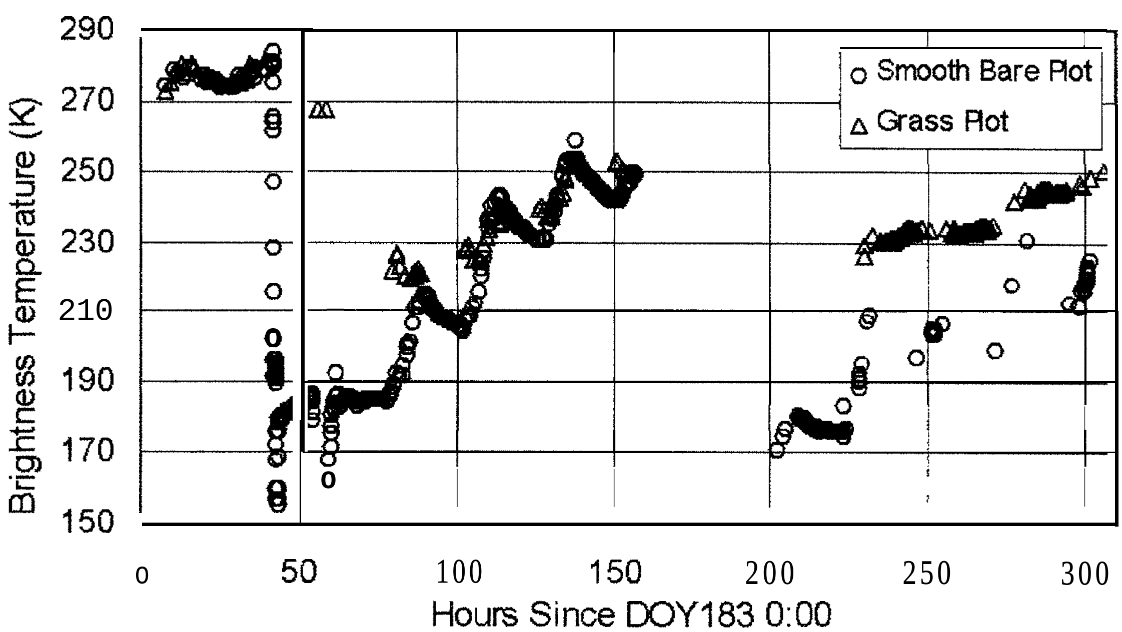

Figure 4. Time series of L-band microwave brightness temperature for the smooth bare and grass plots.

Surface soil moisture was about 7% as the experiment began. It rose rapidly to about 32% after the wetting events and dried slowly afterwards. Some differences in the moisture response among plots were observed. In order to obtain information required for application and testing of radiative transfer algorithms and land surface models, several vegetation properties were measured during the field experiment including vegetation height, wet and dry biomass, dielectric constant (for grass plot only), roughness of underlying soil, leaf dimension and orientation, and the angular distribution of stems and leaves. Except as noted, each variable was measured on both vegetated plots on several occasions during the two-week experiment period.

The microwave remote sensing data collected during this experiment lend themselves to an evaluation of the radiometer and radar performance in a) capturing the time-series of moisture change through two wetting and drying cycles, b) capturing the diurnal cycle of moisture change, c) comparison among various microwave wavelengths in a and b, and d) comparison of a through c as a function of different vegetation cover. At the outset of the experiment, microwave brightness temperatures (T_B) for the L and S bands were between 250° to 280° K for all plots (Fig. 4). After the initial wetting, T_B on the smooth bare plot dropped to 180° K. T_B on the vegetated plots only dropped by about 30° K (Fig. 4). T_B recovered to about 80% of its initial value in the four days prior to the second wetting on DOY 189. L-band T_B's are commonly higher than those of S-band. The magnitude of these differences varies for the different land cover conditions. The inter-band T_B's are most similar on the smooth bare plot and least similar on the grass plot.

In the Huntsville '97 field experiment:

The mode of the AMPR data collection and its close association with the C-band radiometer's data sets will be modified to better simulate the space borne microwave sensors' brightness signatures over land surfaces. The testbed and the *in-situ* instruments will stay the same as described in previous section; the field data collection scheme will also be the same.

TRUCK RADARS AND TRUCK RADIOMETERS

The Functionality and Operation ofMicrowave Soil Moisture Sensors

Three separate microwave remote sensing systems were deployed during the Huntsville '96 field experiment and also will be deployed next year, each with the capability to measure over multiple frequencies:

1. The S- (2.65 GHz) and L-band (1 .413 GHz) microwave radiometers (SLMR) with 15° beamwidth, 0.1° K radiometric resolution, and 1 sec. integration time were integrated into one system (Jackson et al., 1995). A step frequency (4 -8 GHz) C-band radiometer with six channels: 4.63, 5.06, 5.91,6.34, 6.77, 7.20 GHz 15° beamwidth, 0.1 K radiometric resolution, and one second integration time. The antennas of the SLMR were mounted to observe horizontal polarization. Data were acquired at a look angle of 15° from nadir and at a nominal height of 14 m. The radiometers sampled about 220 times each second. Each measurement was made using a 15 second integration time. An "autocollect" capability allowed us to leave the system unattended over a site for extended periods. This capability was utilized to collect data throughout the night, during irrigation, and at other times of interest. Measurements were made at each plot on nearly an hourly basis during the day throughout the experiment. The radiometers were placed in autocollect mode over the smooth bare plot at night during the first week and over the grass plot during the second week. Radiometers were calibrated over a pond at the research station before and after the experiment. An entire day was dedicated to cycling through absorber, sky and water measurements. Over water, measurements were made in 5° increments from 5° to 65°. Surface water temperature was measured throughout the day with three temperature sensors that were floating 2 cm below the pond surface.
2. The Advanced Microwave Precipitation Radiometer (AMPR) comprised another system (Spencer et al., 1994). AMPR is a 4-channel (10.7, 19.35, 37.1, 85.5 GHz) continuous scanning instrument previously deployed on the NASA ER-2 aircraft. The 3 dB beamwidths of the four channels are 8.0°, 8.0°, 4.2°, 1.8°, respectively. The reflector scans 90° while sampling 50 beam spots every 1.8° over 2.5 sees. After four scans, the reflector scans up to measure internal warm and cold calibration loads. The feed-horn is fixed with respect to the reflector, thus providing H and V polarization at opposite ends of the scan. Between the two scan extremes, the two polarization states are combined and are equal at the middle of the scan. The instrument was offset 45° from the other radiometers so that H polarization coincided with the look angle of the SLMR.
3. The third system was comprised of an L- (1.6 GHz), C- (4.75 GHz), and X-band (10.0 GHz) radar with 9°-120 beamwidth at 3 dB and 4 polarization combinations (O'Neill et al., 1995). The radars were deployed from another boom track and instrument control and data acquisition systems were operated

from the back of the truck. Radar data were acquired at two incidence angles as measured from nadir—at 15° for coincidence with the radio-meter measurements, and at 45° for vegetation modeling. The radar system used two modes of operation, "sweep" and "snapshot." In sweep mode, the radar boom was slowly rotated through 120° of azimuth in order to acquire a spatial average across the test plot. This was the standard mode during the day. In snapshot mode, the radar boom was stationary and a single radar footprint was imaged repeatedly over time. This mode was automated and used to collect data throughout the night. During the first week of the experiment, radar back-scatter measurements were made in sweep mode on all four test plots each day, with collection cycles initiated at 06:00, 10:00, and 14:00 hours local daylight time. At night, the radar truck was placed in autocollect snapshot mode over the Bare-smooth plot to acquire data coincident with the radiometers. After rain events, the radar truck staged at a single plot on a given day in order to get complete diurnal data for each plot. Hourly sweep data were collected between 08:00 and 16:00, and half-hourly snapshot data over night between 17:00 and 07:00.

The AMPR Modification for the Huntsville '97

To facilitate and to convert the AMPR system to become suitable for ground-based applications, it is necessary to modify its hot and cold loads calibration subsystem and the data acquisition subsystem

Hot and Cold Loads Calibration System: The AMPR is a total power radiometer. Because of this feature, a hot and cold loads are needed to conduct the system calibration by means of scanning through the hot and cold loads for every four scans of the one data acquisition cycle. Frequent comparison of the measured land surfaces brightness temperatures with respect to the hot and cold load temperatures requires constancy and a large spread of temperature between the hot and cold loads. The hot load was designed to heat up and keep it at a constant temperature of 320K. The cold load was originally designed to use the air temperature at 20km flight altitude of the ER-2. At that altitude the air flow through the cold load is usually well below freezing point of 210k. A 110K or more spread of temperature between the hot and cold loads is sufficient to do the calibration. When AMPR was ground based as it was used in the "Huntsville 96" field experiment, the above ground air temperature in July not only subject to day-night variation, the noon time temperature can exceed 25C (295 K). Without modification of AMPR cold load, the calibration system produce only 15K temperature spread instead of the 110K it needed. Therefore, we do need to modify the cold load by using a freezing system to cool it down to well below freezing point (21 OK) to make it comparable to the original design specification.

Data Acquisition System: The AMPR system was originally designed and manufactured by MSFC for airborne (ER-2), large area coverage, and very long automated data acquisition flight times, its data acquisition system with very burdensome flight data included is not suitable to be used in the ground-based AMPR system. Lesson learned from the "Huntsville 96" microwave soil moisture measurement field experiment indicates a completely different data acquisition system is needed for the ground-based AMPR system. The switch-on completely automated data acquisition scheme, used in the past or future AMPR ER-2 borne flight missions, was designed to meet the requirement of ER-2 platform, because there is only one man pilot. The pilot have no time to pay attention to his pay load instruments for which AMPR is just one part of the whole pay load. Therefore, all sensors on ER-2 platform must be fully automated; the pilot turn on the instruments and forget about it during the flight mission. For the ground based AMPR we will have an operator to operate the system and he shall decide how to conduct the measurement, e.g. measuring the soil moisture of a test plot every 15 minutes or every hour to see its change. We do not need to measure soil moisture or whatever parameters all the times. We will implement a controllable data acquisition scheme and make it operable on and off by the operator and at the same time keep the hot and cold load calibration system running all day long to maintain constancy of the Calibration temperature. This scheme can be made by using a separated power source for the calibration system. Computer programs will be developed and used to operate the data acquisition system and with operator interactive or interfacing capabilities.

THE AMPR AND C-BAND RADIOMETER'S ROLE IN SOIL MOISTURE SENSING

It is believed that by using the AMPR and the C-band radiometer will result in a better understanding of the data acquired over land surfaces by the Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission Microwave Imager (TMI), and the Advanced Microwave Scanning Radiometer (AMSR).

A modification of the AMPR subsystems as described in previous section by itself will have the following benefits:

1. The developed truck-mount ground-based AMPR system provides a better position to participate in the "Huntsville 97" field experiments, because ER-2 borne AMPR are very costly.

2. *The* three frequencies of Tom Jackson's microwave system, and four frequencies of the AMPR system to be used to collect microwave brightness temperature signatures (in 1.4, 2.65, 4 - 8, 10.7, 19.35, 37.1, and 85.5 GHz) over the Huntsville '97's selected test-plots would provide a better understanding of soil moisture over these test-plots.
3. On the other hand, since the Advanced Microwave Scanning Radiometer (AMSR) to be launched on the EOS PM-1 platform in 2000 have the lowest frequencies of 6.925 GHz, using the 4-8 GHz step frequency C-band radiometer to collect data in the Huntsville '97 field experiment will enable us to simulate AMSR's land surfaces brightness signatures.

CONCLUSION

In the Huntsville '96 field experiment, three frequencies of Tom Jackson's microwave system, and four frequencies of the AMPR system were used to collect microwave brightness temperature signatures (in 1.4, *2.65,* 4 *-7, 10.7, 19.35, 37.1,* and *85.5* GHz) over three test-plots of bare soil, alfalfa, and grass, respectively. A quick look of the collected data indicated that significant decrease of brightness temperature was caused by the increase of soil moisture which is in agreement with the theory. A team work approach of the Huntsville '96 field experiment resulted in a valuable data sets and the follow on analyses would provide a better understanding of soil moisture over that three test-plots. Analyses of the AMPR collected data together with concurrent in-situ collection of surface cover conditions (surface temperature, surface roughness, vegetation, and surface topology) and soil moisture content, would result in a better understanding of the data acquired over land surfaces by the Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission Microwave Imager (TMI), and the Advanced Microwave Scanning Radiometer (AMSR), because the AMPR and the C-band radiometer contained four frequencies (6.925, 10.7, 19.35,37.1, and 85.5 GHz) of these spaceborne sensors.

ACKNOWLEDGMENTS

This work was supported Grant No. NCCW-0084 from the National Aeronautics and Space Administration (NASA), Washington, DC. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U. S. Government. Acknowledgment is given to the Center for Hydrology, Soil Climatology, and Remote Sensing (HSCaRS) support staff. Contribution from HSCaRS the Department of Plant, Soil and Animal Sciences and the Agricultural Experiment Station, Alabama A&M University, Normal, AL 35762. Journal No. 346.

Acknowledgment is also given to Drs. M-Y Wei, Jim Arnold, Roy Spenser, and Tom Jackson for the fruition of using the Advanced Microwave Precipitation Radiometer in Huntsville '96 experiment.

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