LINKING CHANGES IN DYNAMIC COTTON CANOPY TO PASSIVE MICROWAVE REMOTE SENSING

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2006
This document is dedicated to my wife, Tzu-Yi, Hsu and my parents, Jyue-Min Tien and Chi-Shih, Wu.
ACKNOWLEDGMENTS

First and foremost, I would like to thank my parents, Jyue-Min Tien and Chi-Shih, Wu, for their encouragement and dedication throughout the years of my graduate study in the United States. They have done everything imaginable to ensure my success. Acknowledgement also goes to my wife, Tzu-Yi Hsu, for her infinite love and support during the victories as well as defeats.

Credit is due Dr. Jasmeet Judge, my mentor, for her encouragement, advice, guidance, and endless patience. I would like to extend my gratitude to Dr. Wendy Graham and Clint Slatton of the University of Florida, Dr. Roger De Roo of the University of Michigan, and Dr. Wade Crow of the United States Department of Agriculture, for the ideas they provided as members of my supervisory committee. I would like to thank Mr. Larry Miller and Orlando Lanni for their technical support. I would also like to thank Tzu-yun Lin, Joaquin Casanova, and Mi-Young Jang, for their companionship during my field experiment. Thanks also go to the PSREU Research Coordinator, Mr. James Boyer, and his team for providing excellent management of the study fields.

Last but not least, I would like to express my appreciation to the National Aeronautics and Space Administration Earth System Science Fellowship program, which provides the financial support for my dissertation.
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Soil moisture is one of the most important variables in land-atmosphere processes. It determines how precipitation partitions into infiltration, surface runoff, and groundwater recharge. Additionally, soil moisture is important in partitioning the available energy into the latent and sensible heat fluxes at the land surface. The control of soil moisture is the key mechanism for the feedback mechanisms between land and atmospheric fluxes.

Accurate estimates of these land surface fluxes are essential for understanding and quantifying the global, regional, and local hydrological cycles. Even though the biophysics of moisture and energy transport is captured in most current Soil-Vegetation-Atmosphere-Transfer (SVAT) models that provide estimates of soil moisture, the computational errors accumulate over time and the model estimates diverge from reality. One promising way to significantly improve model estimates of soil moisture is by
assimilating remotely sensed data that are sensitive to soil moisture, for example, microwave brightness temperatures, and updating the model state variables.

The microwave brightness at low frequencies is very sensitive to soil moisture in the top few centimeters in most vegetated surfaces. Most of the passive microwave brightness experiments for soil moisture retrieval conducted in agricultural terrains have been short-term experiments that captured only parts of the growing season. Knowledge for the interactions between microwave brightness signatures and changes in soil moisture and temperatures for a dynamic agricultural canopy, such as cotton, is very important during the whole growing season. Microwave brightness (MB) models simulating the terrain emission provide the opportunity to relate microwave signatures to soil moisture information. An integrated SVAT and MB model provides the opportunity to direct assimilate microwave remote sensing observations.

The goal of this dissertation is to develop a MB model that can be used to simulate microwave brightness temperature (\(T_B\)) for the entire growing season of cotton. This MB model can be linked with existing SVAT models such as the Land Surface Process (LSP) model for the cotton growing season to allow assimilation of passive microwave observations.
CHAPTER 1
INTRODUCTION

Soil moisture is a key variable governing land-surface processes. It determines the amount of precipitation that contributes to infiltration, surface runoff, and groundwater recharge. Additionally, soil moisture is important in partitioning the available energy into the latent and sensible heat fluxes at the land surface. The control of soil moisture is the key mechanism for feedback mechanisms between land and atmospheric fluxes (Brubaker and Entekhabi, 1995; Entekhabi and Brubaker, 1995; Entekhabi et al., 1996).

Accurate estimates of these land surface fluxes are essential for understanding and quantifying the local, regional, and global hydrological pathways. Many numerical Soil-Vegetation-Atmosphere-Transfer (SVAT) models have been used for simulating the water and energy balance processes at the surface and in vadoze zone. Some examples of such models include, BATS (Dickinson et al., 1986), ISBA (Noilhan and Mahfouf, 1989), SSiB (Xue et al., 1991), VIC (Wood et al., 1992), SiSPAT (Braud et al., 1995), SWEAT (Burke et al., 1997), PATTERN (Mulligan, 1998), and LSP (Judge, 1999; Judge et al., 2003). SVAT models provide estimates of these fluxes to the Global Circulation Models (GCMs), to provide long- and near-term weather predictions (Roy et al., 2001; Pruski and Nearing, 2002; Schmidt and Glade, 2003; Shepherd and McGinn, 2003; Peres and DaCamara, 2004; Voldoire and Royer, 2004; Meier et al., 2005; Von Bloh et al., 2005; Kay et al., 2006a; Kay et al., 2006b). GCMs have also been used to investigate climate anomalies. The results from the GCM simulations demonstrated that soil
moisture anomalies are closely related to anomalies in estimation of runoff and evapotranspiration (ET) (Entekhabi et al., 1996).

Even though flux estimates in SVAT models are well represented and understood, the model estimates still diverge over time due to accumulated errors in numerical approximation, parameter estimation, and model initialization. One promising way to decrease the errors in flux estimates is to assimilate independent observations periodically into the SVAT models. Such data assimilation is based on a probabilistic framework that accounts for the uncertainty when combining different information sources, e.g., remotely sensed observations, in-situ measurements, and mathematical models (McLaughlin, 1995). McLaughlin (1995) discussed the early development in data assimilation for SVAT modeling. He concluded that remotely sensed observations could initiate dramatic changes in hydrologic practice. Microwave brightness observations provide complimentary data sources and can be used with in-situ measurements. Since then, a number of studies have been conducted using different observations and different assimilation approaches (McLaughlin, 1995; Reichle et al., 2001a; Reichle et al., 2001b; Margulis et al., 2002; McLaughlin, 2002; Reichle et al., 2002a; Reichle et al., 2002b; Aubert et al., 2003; Crow and Wood, 2003; Crow et al., 2003; Crow, 2003; Heathman et al., 2003; Montaldo and Albertson, 2003; Reichle and Koster, 2003; Houser et al., 2004; Margulis and Entekhabi, 2004; Reichle and Koster, 2004; Rodell and Houser, 2004; Walker and Houser, 2004; Berg et al., 2005; Crow et al., 2005a; Crow et al., 2005b; Dunne and Entekhabi, 2005; Gottschalck et al., 2005; Moradkhani et al., 2005; Ni-Meister et al., 2005; Reichle and Koster, 2005; Dunne and Entekhabi, 2006). Because data assimilation must balance information from different sources, proper representation
of uncertainty is essential (McLaughlin, 2002). Remotely sensed observations by the
space-borne, airborne, and ground-based sensors provide the possibility for data
assimilation in SVAT models at different spatial and temporal scales. Microwave
observations at low frequencies (< 10 GHz) are very sensitive to soil moisture in the top
few centimeters in most vegetated surfaces (Bruckler et al., 1980; Mo et al., 1980;
Newton and Rouse, 1980; Ulaby et al., 1981; Wang and Choudhury, 1981; Burke and
Schmugge, 1982; Schmugge, 1985; Schmugge et al., 1985; Ulaby et al., 1986; Jackson et
al., 1992; Jackson et al., 1993; Jackson et al., 1995; Jackson et al., 1998; Owe and van de
Griend, 1998; Laymon et al., 2001; Le Vine et al., 2001; Paloscia et al., 2001; Jackson et
al., 2002; Jackson et al., 2005; McCabe et al., 2005; Schwank et al., 2005; Wen et al.,
2005). The microwave observations, brightness temperatures \( (T_B) \), are estimated by a
Microwave Brightness (MB) model using the temperature and moisture properties of the
surface.

Recently studies have been conducted to develop SVAT models that are linked
with microwave emission or microwave brightness (MB) models. These integrated
models allow for assimilation of microwave observations (Judge et al., 1999; Burke et al.,
2001; Burke et al., 2002; Burke et al., 2003; Judge et al., 2003; Montaldo and Albertson,
2003; Burke et al., 2004; Demarty et al., 2005; Crow et al., 2005b). Figure 1-1 shows the
linkage between SVAT-MB models and data assimilation using remote sensing
observations. The SVAT models use weather data as forcing to estimate the moisture and
energy fluxes, and profiles of soil temperature and moisture in the vadoze zone. Using the
soil temperature and moisture profiles as inputs, MB models estimate brightness
temperatures \( (T_B) \) of the terrain. Data assimilation utilizes the differences between \( T_B \)
estimated by the MB model and those observed by remote sensing, along with the associated errors to minimize the uncertainty in $T_B$. Finally, by model inversion the optimized $T_B$ can be used to update the moisture and temperature profiles in the SVAT model.

Figure 1-1. Linkage between SVAT-MB models and data assimilation using remote sensing observations.

The goal of this dissertation is to develop a MB model that can be used to simulate microwave $T_B$ for the entire growing season of cotton as shown in the red box. This MB model can be linked with existing SVAT models such as the Land Surface Process (LSP) model for the cotton growing season to allow assimilation of passive microwave observations.

**Historical Development of Microwave Remote Sensing for Soil Moisture**

Microwave remote sensing provides observations that are independent of solar illumination and of cloudy and low precipitation conditions. Due to longer wavelengths,
microwaves also penetrate into the soil and vegetation canopy. There are two fundamental types of microwave sensing approaches: active and passive. Both types utilize the large contrast of the dielectric properties between the atmosphere and land to estimate microwave signatures from the terrains. Compared to passive microwave sensing, active sensing is more sensitive to the geometric and dielectric properties of the land surface (Ulaby et al., 1981).

Many ground-based, air-borne, and space-borne observations have been used for passive microwave remote sensing studies. Most of these studies involve retrieval of soil moisture and other surface variables using passive microwave observations. For example, Wigneron et al. (1996) used microwave observations at 1.4 (\(\lambda = 21\) cm) and 5 GHz (\(\lambda = 6\) cm) to monitor hydrological variables over agricultural land. Njoku and Li (1999) used passive microwave observations at 6 to 18 GHz (\(\lambda = 1.6\) to 5 cm) to retrieve land surface variables, e.g., soil moisture, vegetation water content, and surface temperature. Jackson (2001) studied the relation between brightness temperature at low frequency at 1.4 GHz (\(\lambda = 21\) cm) and soil moisture over the spatial resolutions of 800 m and 1600 m for the retrieval algorithms for the near-surface soil moisture. Calvet et al. (1996), Jackson and Le Vine (1996), Jackson (2001), Kerr et al. (2001), Njoku et al. (2002), Njoku et al. (2003), Drusch et al. (2004), and Crow et al. (2005a) used air- and space-borne passive microwave imagery at 1.4, 5.5, 6.9, and 36.5 GHz (\(\lambda = 21, 5.5, 4.4\), and 0.8 cm) to retrieve soil moisture in regional scales. They found that although the spatial resolution of the space-borne microwave observation is quite coarse (~50 km), it is still within the range of most regional hydrologic models. Parde et al. (2004) investigated the possibility of implementing a multiple parameter retrieval approach based on the ground-based L-
band \((f = 1.4 \text{ GHz or } \lambda = 21 \text{ cm})\) radiometer observations. Crosson et al. (2005a, 2005b) analyzed the parameter sensitivity of soil moisture retrievals at L-, C- and X-band \((f = 1.4, 6.7, \text{ and } 10 \text{ GHz or } \lambda = 21, 5.5, \text{ and } 3 \text{ cm, respectively})\) empirically using airborne radiometers. They concluded that the accuracy for model parameters in the current retrieval approach, using single-frequency and single-polarization retrieval algorithm, might not be able to meet the hydrologic requirements of the soil moisture retrieval from remote observations \((\pm 4 \% \text{ in volumetric soil moisture})\), given the spatial and temporal resolution of space-borne microwave radiometers. Davenport et al. (2005) analyzed the parameter sensitivity of soil moisture retrievals at L-band \((f = 1.4 \text{ GHz or } \lambda = 21 \text{ cm})\) theoretically using a simple zero-order MB model for a terrain consisting of a layer of vegetation canopy on top of a semi-infinite soil layer. Their findings showed that vegetation canopy properties produced the most uncertainty in soil moisture retrievals.

The low microwave frequencies are better for increased sampling depth and for reduced noise effects caused by the vegetation canopy and soil surface roughness. The sensitivity of \(T_B\) to soil moisture changes decreases with increasing vegetation. The soil contribution is attenuated significantly through the vegetation. Therefore, a better understanding of modeling emission from dynamic vegetation canopies during the growing season is required (Jackson et al., 1999; Njoku and Li, 1999; Ferrazzoli et al., 2000; Crosson et al., 2005a; Davenport et al., 2005).

**Dissertation Objectives**

This dissertation aims to understand the interactions between the passive microwave signatures, and soil and vegetation dynamics during a growing season of cotton. Cotton is one of the most important agricultural crops in the SE-US region in
terms of both acreage and economic value. It occupies about 13.2 million acres in this region with a related value exceeding $ 50 billion nationwide and supplies about 20% of the world output (US Cotton Market, 2002). Because it is increasingly an irrigated crop, its management influences water cycling significantly, including the changes in aquifer storage and recharge, and evapotranspiration (ET), causing changes in land-surface atmosphere exchange.

The dissertation focuses on the development of a physically based MB-Cotton model which simulates $T_B$ at C-band ($f = 6.7$ GHz; $\lambda = 4.4$ cm) during the entire growing season, and on comparison of the $T_B$ estimated by the MB-Cotton model to the $T_B$ observed by the University of Florida C-band Microwave Radiometer (UFCMR) during the Microwave, Water, and Energy Balance Experiments (MicroWEXs).

The research questions addressed in this dissertation include the following:

1. What are the accuracy and precision of the $T_B$ measurements used in this study? (Chapter 3)
2. What is the effective depth of C-band under different soil moisture conditions? (Chapter 4)
3. How well does the MB-Cotton model capture the observed brightness using soil moisture at 2 cm? (Chapter 5)
4. How well does the MB-Cotton model capture the observed brightness if the detailed soil moisture information is available for the effective depth? (Chapter 5)
5. Is scattering in the canopy important for simulating accurate $T_B$ when cotton reaches maturity? (Chapter 5)
6. How does the sensitivity of $T_B$ to soil moisture changes as cotton matures? (Chapter 6)

**Dissertation Format**

In this dissertation, Chapter 2 contains the description and observations made during the first, second, and third Microwave Water and Energy Balance Experiments (MicroWEX-1, 2, and 3). Chapter 3 contains the discussion for the radiometric calibration for the C-band microwave radiometer, UFCMR, using the calibration data
collected during the MicroWEXs. Chapter 4 includes the description of Microwave Brightness for the Cotton (MB-Cotton) model. Chapter 5 contains the model calibration for MB-Cotton model using data collected during MicroWEX-3. Chapter 6 includes the discussion of the sensitivity analysis of the modeled $T_B$ using MB-Cotton and observed $T_B$ to the changes in moisture and temperature during MicroWEX-1 and 3. Chapter 7 provides a summary of the results, original contributions, and recommendations for future research.
CHAPTER 2
MICROWAVE WATER AND ENERGY BALANCE EXPERIMENTS

This chapter contains the description of a series of field experiments, called Microwave, Water, and Energy Balance Experiments (MicroWEXs) and the observations during the experiments that are used in this dissertation. These experiments were conducted by the Center for Remote Sensing, Agricultural and Biological Engineering Department at the Plant Science Research and Education Unit, IFAS during growing seasons of cotton (MicroWEX-1 in 2003), corn (MicroWEX-2 in 2004), and cotton (MicroWEX-3 in 2004). The observations of microwave brightness of terrain, microwave absorber, and micrometeorological conditions collected during MicroWEX-1, 2, and 3 were used for microwave radiometer calibration in Chapter 3. The observations of vegetation and soil conditions, micrometeorological parameters, and terrain microwave brightness during MicroWEX-3 were used to calibrate the microwave brightness model for cotton (MB-Cotton) developed in Chapter 5 and to discuss the sensitivity of brightness temperatures to changing soil and vegetation conditions in Chapter 6.

The First Microwave Water and Energy Balance Experiment (MicroWEX-1)

Figures 2-1 and 2-2 show the location of the PSREU and the study site for the MicroWEX-1, respectively. The area of the study site was a 130 m X 75 m. A linear move system was used for irrigation. The cotton was planted on July 9 (Day of Year in 2003, DOY 190) at an orientation 60° from East as shown in Figure 2-3. The plant spacing was about 4 cm and the row spacing was 90 cm. Instrument installation took place on July 17 (DOY 198).
Figure 2-1. Location of PSREU/IFAS.

Figure 2-2. Location of the field site for MicroWEX-1 at the UF/IFAS PSREU where the MicroWEXs were conducted.
The instruments consisted of a ground-based microwave radiometer system and micrometeorological stations. The ground-based microwave radiometer system was installed at the middle of the north edge of the site facing south to avoid the radiometer shadow interfering with the field of view (see Figure 2-3). The micrometeorological station was installed at the center of the field and included soil moisture and temperature probes, soil heat flux plates, thermal infrared sensor, net radiometer, and raingauges. Two additional raingauges also were installed at the east and west edge of the radiometer footprint to capture the irrigation. Later, an eddy covariance system was installed at the northeast corner of the site on August 15 (DOY 227). Detailed descriptions of field observations and a field log during MicroWEX-1 can be found in the experimental data report (Tien et al., 2005) at Electronic Data Source of UF/IFAS Extension (http://edis.ifas.ufl.edu/AE288). Because the lack of soil moisture data due to lightening damage to the sensors during MicroWEX-1, observations during this experiment could only used for the microwave radiometer calibration (Chapter 3).

Figure 2-3. Layout of the sensors during MicroWEX-1.
Sensors

MicroWEX-1 had two major instrument subsystems: the ground-based University of Florida C-band Radiometer (UFCMR) and the micrometeorological subsystems, a collection of commercially available instruments.

**University of Florida C-band Microwave Radiometer (UFCMR) System**

Microwave brightness temperatures at 6.7 GHz ($\lambda = 4.48$ cm) were measured every 30 minutes using the University of Florida’s C-band Microwave Radiometer system (UFCMR) (Figure 2-4 (a)). The radiometer system consisted of a dual polarized total power radiometer operating at the center frequency of 6.7 GHz housed atop a 10 m tower installed on a 16’ trailer bed. UFCMR was designed and built by the Microwave Geophysics Group at the University of Michigan (UM-MGG). It operated at the center frequency at 6.7 GHz that is similar to one of the center frequencies on the space-borne Advanced Microwave Scanning Radiometer (AMSR) aboard the NASA Aqua Satellite Program. Given the antenna beam width of 23° and the height between the antenna aperture and ground surface of 7.6 m, the size of the footprint was about 11 X 11 m². A rotary system was used to rotate the incidence angle of the UFCMR both for field observations and sky measurements. The terrain brightness temperatures were observed at an incidence angle of 55° matching that of the space-borne AMSR-E sensor. The radiometer was calibrated every two weeks with a microwave absorber as warm load and measurements of sky at zenith angles of 15°, 30°, 45°, and 60° as cold loads. The calibration of UFCMR will be discussed in detail in Chapter 3. Figure 2-4 (b) and (c) show the close-up of the rotary system and the antenna of the UFCMR, respectively. Table 2-1 lists the specifications of UFCMR.
Table 2-1. Radiometer specifications for UFCMR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna type</td>
<td>Potter Horn</td>
</tr>
<tr>
<td>Frequency</td>
<td>Center 6.7 GHz</td>
</tr>
<tr>
<td>Bandwidth 3 dB</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Beamwidth 3 dB</td>
<td>23° &amp; 21°, 21° &amp; 23°</td>
</tr>
<tr>
<td>Isolation</td>
<td>&gt; 27 dB</td>
</tr>
<tr>
<td>Polarizations</td>
<td>Sequential V/H</td>
</tr>
<tr>
<td>Noise Figure From</td>
<td>$T_{rec}$ 3.99 dB</td>
</tr>
<tr>
<td>RF gain</td>
<td>85 dB</td>
</tr>
<tr>
<td>NEDT 1 sec</td>
<td>0.71 K</td>
</tr>
<tr>
<td>NEDT 8 sec</td>
<td>0.25 K</td>
</tr>
<tr>
<td>First Side-lobe</td>
<td>47° from bore-sight -26 dB</td>
</tr>
</tbody>
</table>

Figure 2-4. University of Florida C-band Microwave Radiometer (UFCMR): (a) field setup, (b) front view showing the antenna, and (c) side view showing the rotary system.
Figure 2-5 shows the V- and H-pol brightness signatures observed by the UFCMR during MicroWEX-1. The T_B at H-pol were lower than that at V-pol early in the season and rapidly increased with the increasing contribution from the growing vegetation. The lowest T_B at H-pol was around 160 K on DOY 206.5 at the beginning of the season. The H-pol T_B reached to 260 K on DOY 240. The T_B at H-pol are more sensitive to changes in moisture than at V-pol for bare soil while V-pol primarily responds to soil temperature fluctuations at the incidence angle of 55°, close to Brewster angle at microwave frequencies (Ulaby et al., 1981). The difference in T_B at H- and V-pol before DOY 240 is primarily due to low emissivities at H-pol than those at V-pol, when the land surface is sparsely vegetated and the canopy contribution is minimal. The maximum difference between the T_B at two polarizations was 90 K.

Figure 2-5. Observed brightness temperatures at vertically (V-) and horizontally (H-pol) polarizations during MicroWEX-1.

The T_B at V- and H-pol converged on DOY 240, 50 days after planting corresponding to LAI of 1.4, plant water content (PWC) of 0.75 kg/m^2 (see Figure 2-35 and 2-36), and the canopy height of 80 cm (Figure 2-34). After DOY 240, a maximum difference of 10 K between the T_B at two polarizations was observed. The terrain T_B at
both polarizations were dominated by emission from the canopy. Most of the polarization dependent energy emitted from the soil was attenuated by the vegetation canopy and the observed $T_B$ were primarily due to emission from the canopy. The canopy emission was polarization independent because the moisture distribution within the canopy is statistically random at 6.7 GHz, resulting in similar $T_B$ at the two polarizations.

The most important goal for microwave radiometer operation is to maintain thermal control inside the radiometer to assure the measurement consistency. UFCMR uses a thermoelectric cooler (TEC) for thermal control of the Radio Frequency (RF) stages for the UFCMR. This is accomplished by the Oven Industries “McShane” thermal controller. McShane is used to cool or heat by a Proportional-Integral-Derivative (PID) algorithm with a high degree of precision at 0.01°C. The aluminum plate to which all the RF components are attached is chosen to have sufficient thermal mass to eliminate short-term thermal drifts. All components attached to this thermal plate, including the TEC, use thermal paste to minimize thermal gradients across junctions.

The majority of the gain in the system is provided by a gain and filtering block designed by the University of Michigan for the STAR-Light instrument (De Roo, 2003). The main advantage of this gain block is the close proximity of all the amplifiers, simplifying the task of thermal control. This gain block was designed for a radiometer working at the radio astronomy window of 1400 to 1427 MHz, and so the receiver is a heterodyne type with downconversion from the C-band RF to L-band. To minimize the receiver noise figure, a C-band low-noise amplifier (LNA) is used just prior to downconversion. To protect the amplifier from saturation due to out of band interference, a relatively wide bandwidth, but low insertion loss, bandpass filter is used just prior to the
amplifier. Between the filter and the antenna are three components: a switch for choosing polarization, a switch for monitoring a reference load, and an isolator to minimize changes in the apparent system gain due to differences in the reflections looking upstream from the LNA.

The electrical penetrations use commercially available weatherproof bulkhead connections (Deutsch connectors or equivalent). The heat sinks have been carefully located employing RTV (silicone sealant) to seal the bolt holes. The radome uses 15 mil polycarbonate for radiometric signal penetration. It is sealed to the case using a rubber gasket held down to the case by a square retainer.

The first electromechanical latching RF switch switches between H- and V-polarization. The second latching RF switch, switches between the analog signal from the first switch and the reference load. From here, the signal passes through an isolator, which limits the coherent interference of the receiver noise with itself as it is reflected by the switches. While this type of coherent interference occurs everywhere in the front end, the switches have different return loss depending on the switch position. The nearly equal temperatures of the isolator termination and the switches themselves insure that the sum of the noise generated by the switches and reflected by the switches is nearly constant with respect to switch position. The signal then passes thru a bandpass filter with a 6.7GHz center frequency, which protects the amplifier from saturation by out of band Radio Frequency Interference (RFI). A Low Noise Amplifier (LNA) is used to amplify the weak signals captured by the antenna, and thereby limits the contributions of downstream components to the receiver noise figure. A mixer takes the input from the LNA and a local oscillator to output a 1.4 GHz signal to the STAR-Lite block. After the
Power Amplifier and Filtering Block (the STAR-Lite back-end), the signal is passed through a Square Law Detector and a Post-Detection Amplifier. UFCMR is equipped with a Z-World BL1720 microcontroller that has responsibility for taking measurements, monitoring the thermal environment, and storing data until a download is requested. A laptop computer is used for running the user interface, named FluxMon, which communicates with the radiometer with a Radiometer Control Language (RadiCL). The radiometer is configured to maintain a particular thermal set point, and make periodic measurements of the brightness. Each measurement is a sequence of brightness observations of the reference load, then horizontal and vertical polarizations and then the reference load again. The data collected by the radiometer is not calibrated within the instrument, since calibration errors could corrupt an otherwise useful dataset. Figure 2-6 shows the block diagram of UFCMR.

Figure 2-6. Block diagram of the University of Florida C-band Radiometer (De Roo, 2003).
Micrometeorological Subsystems

The micrometeorological subsystems deployed during MicroWEX-1 includes eddy covariance system, net radiometer, thermal infrared sensor, soil moisture and temperature probes, soil heat flux plates, and the Florida Automated Weather Network station located at the PSREU (http://fawn.ifas.ufl.edu/).

Eddy covariance system

A Campbell Scientific eddy covariance system (Campbell Scientific, 1998a; Campbell Scientific, 1998b) was located at the southeast corner of the field (see Figure 2-7). The system included a CSAT3 anemometer and KH20 hygrometer. CSAT3 is a three dimensional sonic anemometer, which measures wind speed and the speed of sound on three nonorthogonal axes. Orthogonal wind speed and sonic temperature are computed from these measurements. KH20 measures the water vapor in the atmosphere. Its output voltage is proportional to the water vapor density flux. During MicroWEX-1, latent and sensible heat fluxes were measured every 30 minutes at the height of 2.1 m from the ground, with the CAST3 pointed at 209° with respect to the southwest direction. Figure 2-8 illustrates the raw latent (LE) and sensible heat fluxes (H) observed by the eddy covariance system during MicroWEX-1. Figure 2-9 and 2-10 show the horizontal wind speed and direction observed by the eddy covariance system during MicroWEX-1, respectively.

![Figure 2-7. Eddy covariance system.](image)
Figure 2-8. Latent (LE) and sensible heat fluxes (H) observed by the eddy covariance system during MicroWEX-1.

Figure 2-9. Horizontal wind speed observed by the eddy covariance system during MicroWEX-1.

Figure 2-10. Horizontal wind direction observed by the eddy covariance system during MicroWEX-1.
Net radiometer

A Kipp and Zonen CNR-1 four-component net radiometer (Campbell Scientific, 2006) was located at the center of the field to measure up- and down-welling short- and long-wave infrared radiation. The sensor consists of two pyranometers (CM-3) and two pyrgeometers (CG-3) as shown in Figure 2-11. The sensor was installed at the height of 2.5 m above ground and facing south. Figure 2-12 to 2-15 illustrates the up- and down-welling solar (shortwave) wave radiation, up- and down-welling far infrared (longwave) radiation, net total radiation, and solar albedo observed during MicroWEX-1, respectively.

Figure 2-11. Kipp and Zonen CNR-1 net radiometer.

Figure 2-12. Down- and up-welling solar radiation observed by CNR-1 during MicroWEX-1.
Figure 2-13. Down- and up-welling far infrared radiation observed by CNR-1 during MicroWEX-1.

Figure 2-14. Net total radiation observed by CNR-1 during MicroWEX-1.

Figure 2-15. Solar albedo observed by CNR-1 during MicroWEX-1.
Thermal infrared sensor

An Everest Interscience thermal infrared (TIR) sensor (4000.3ZL) was collocated with the net radiometer to observe skin temperature at nadir. Given that the sensor was installed at the height of 2.5 m and a field of view of 15°, the size of the footprint for the thermal infrared sensor was 66 cm by 66 cm. Figure 2-16 shows the surface thermal infrared temperature observed during MicroWEX-1. The data gap between DOY 219 and 290 is due to TIR sensor failure from condensation inside the sensor.

![Figure 2-16. Surface temperature observed by TIR sensor during MicroWEX-1.](image)

Soil moisture and temperature probes

Five standard Vitel Hydra soil moisture and temperature probes and five Campbell Scientific time-domain water content reflectometer (CS616) were used to measure soil volumetric water content (VSM) and temperature at depths of 4, 8, 12, and 20 cm within the rows every 15 minutes. The observations were duplicated at the depth of 4 cm near the root zone. Figure 2-17 and 18 show the volumetric soil moisture content observed by the Hydra and TDR probes, respectively. Figure 2-19 shows the volumetric soil moisture content observed at 4 cm in the middle of two rows and near the root area by the Hydra and TDR probes, respectively. The probes were installed ~1 m apart to avoid
interference. However, it should be bear in mind that the two locations of the VSM profile measured by the Hydra and TDR probes were separated by a distance of ~15 meters. During the late season, the VSM peaks at 8 cm were sometimes higher than those at 4 cm, for example, during the precipitation events on DOY 301, 323, 331, and 332; but sometimes lower than or equal to those at 4 cm, for example, during the precipitation events on DOY 309 and 348. This is mainly because of the heterogeneity of the infiltration due to the water interception by the spatially variable canopy. The VSM measured by the Hydra probes were higher than those measured by the TDR probes, while the diurnal variation of the VSM measured by the Hydra probes was less than those measured by the TDR probes. Figure 2-20 shows the soil temperatures observed by the Hydra probes. Figure 2-21 shows the soil temperatures observed at 4 cm in the middle of two rows and near the root area by the Hydra probes during MicroWEX-1. The data gap between DOY 215 and 302 was caused by damage to the Hydra probes due to lightening. After DOY 293, the TDR probes were installed alongside the Hydra probes to measure VSM at the same depths as those of TDR probes.

Figure 2-17. Volumetric soil moisture content (VSM) observed by Hydra probes during MicroWEX-1.
Figure 2-18. Volumetric soil moisture content (VSM) observed by TDR during MicroWEX-1.

Figure 2-19. Volumetric soil moisture content (VSM) at 4cm observed by the Hydra and TDR probes during MicroWEX-1.

Figure 2-20. Soil temperatures observed by the Hydra probes during MicroWEX-1.
Soil heat flux plates

Two Campbell Scientific soil heat flux plate (HFT-3) were used to measure soil heat flux at the depths of 4 and 8 cm, in row and near the root area, respectively. Figure 2-22 shows the soil heat fluxes observed during MicroWEX-1. The soil heat fluxes were high in the beginning of the season when the surface was mostly bare soil and cotton canopy had low biomass. As the canopy biomass increased, the soil heat fluxes decreased during the growing season.

Figure 2-21. Soil temperatures at 4 cm observed by Hydra probes during MicroWEX-1.

Figure 2-22 Soil heat fluxes observed by HFT-3 during MicroWEX-1.
Tipping buck raingauges

Four raingauges were used to collect precipitation and irrigation across the study site, as shown in Figure 2-3. Figure 2-23 and 2-24 shows the rainfall/irrigation at the east and west edge of the study site observed by the tipping bucket raingauge during MicroWEX-1, respectively.

![Figure 2-23. Rainfall/irrigation at the east edge of the study site observed by the tipping bucket raingauge during MicroWEX-1.](image)

![Figure 2-24. Rainfall/irrigation at the west edge of the study site observed by the tipping bucket raingauge during MicroWEX-1.](image)

Florida automated weather network (FAWN)

Data from one of the Florida Automated Weather Network (FAWN, 2006) sites were also available during the MicroWEX-1. Table 2-2 shows the parameters measured...
by FAWN. Figure 2-25 to 2-29 shows the air temperature, soil temperatures at 10 cm, net
radiation, relative humidity, and precipitation observed by FAWN during MicroWEX-1.

Table 2-2. Micrometeorological parameters measured by the FAWN station.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>°C, at 60 cm height</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>°C, at 10 cm depth</td>
</tr>
<tr>
<td>Rainfall</td>
<td>mm</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>W/m²</td>
</tr>
</tbody>
</table>

Figure 2-25. Air temperature observed by FAWN during MicroWEX-1.

Figure 2-26. Soil temperature at 10 cm observed by FAWN during MicroWEX-1.
Figure 2-27. Net radiation observed by FAWN during MicroWEX-1.

Figure 2-28. Relative humidity observed by FAWN during MicroWEX-1.

Figure 2-29. Rainfall observed by FAWN during MicroWEX-1.
Soil Sampling

Extensive soil sampling was conducted to provide additional information of the spatial distribution of the surface soil moisture, temperature, and surface roughness. The locations of the soil sampling sites are shown in Figure 2-3.

Gravimetric Soil Moisture

The gravimetric soil moisture (GSM) was sampled at 0-4, 4-8, 8-12, and 12-20 cm by a coring tool. The soil samples were weight when wet and then were oven-dried at 105°C for 24 hours. The inner diameter of the coring tool cylinder was 4.3 cm (d), the VSM and GSM of the soil samples were calculated as follows,

\[
VSM = \frac{s_w - s_d}{\pi (d/2)^2 L}
\]

\[
GSM = \frac{s_w - s_d}{s_d}
\]

where \(s_w\) and \(s_d\) are the wet and dry weights of a soil sample, \(L\) is the length of the coring tool section. Figure 2-30 and 2-31 show the volumetric soil moisture content derived by the gravimetric soil samples measured during MicroWEX-1.

Soil Temperature

A Max/Min waterproof digital thermometer from Forestry Supplier was used to measure the soil temperature at the depths of 2, 4, 8, and 16 cm at the same locations and time as the soil moisture sampling. The near surface soil temperature at the depth of 2 cm changed rapidly. This was primarily due to the fact that canopy cover was not uniform throughout the field. Figure 2-32 and 33 show the soil temperature observed during MicroWEX-1.
Figure 2-30. Observed volumetric soil moisture content (VSM) derived by the gravimetric soil samples during MicroWEX-1.

Figure 2-31. Observed volumetric soil moisture content (VSM) derived by the gravimetric soil samples near the UFCMR footprint during MicroWEX-1.
Figure 2-32. Observed soil temperatures during MicroWEX-1.

Figure 2-33. Observed soil temperatures near the UFCMR footprint during MicroWEX-1.
Vegetation Sampling

Vegetation properties such as stand density, row spacing, height, biomass, and LAI were measured weekly during the field experiment. The crop density derived from the stand density and row spacing was measured during the first two samplings since the cotton seeds were planted in the fixed spacing and the germination rate was over 90% throughout the field. The specific bi-weekly measurements included height, biomass, and LAI. In the early season, the first four vegetation samplings were conducted on seven spatially distributed sampling locations (Figure 2-3). The locations were chosen to characterize the spatial variability of the vegetation properties in the study site on July 29, July 31, August 8, and August 17 (DOY 210, 212, 220, and 229, respectively). After that, one vegetation sampling location was chosen to better represent the crop height within the radiometer footprint at least 30 meters from the field boundary.

Canopy Height

Crop height was measured by placing a measuring tape at the soil surface to average height of the crop. The height inside the UFMR footprint and at the vegetation sampling area were taken for each vegetation sampling. Figure 2-34 shows the crop height observed during MicroWEX-1.

Leaf Area Index (LAI)

LAI of the footprint was approximated by measuring 24 locations around the footprint every week. A Sunscan canopy analysis system was used for the first two LAI samplings. After August 24 (DOY 236), LAI was measured with a Li-Cor LAI-2000 in the inter-row region with 4 cross-row measurements. The LAI-2000 was set to average 4 locations into a single value so one observation was taken above the canopy and 4 beneath the canopy; in the row, ¼ of the way across the row, ½ of the way across the
row, and ¾ of the way across the row. This gave a spatial average for row crops of partial cover. Figure 2-35 shows the LAI observed during MicroWEX-1.

Figure 2-34. Canopy height inside the radiometer footprint observed during MicroWEX-1.

Figure 2-35. LAI inside the UFCMR footprint observed during MicroWEX-1.

Green and Dry Biomass

Each biomass sampling was conducted along one row. Along the row, a distance of one meter was recorded as the sampling length. The plants within this length were picked and put in plastic bags to prevent moisture loss. In the laboratory, the canopy samples were separated into leaves, stems, and bolls to measure their wet weights. The vegetation samples were put into paper bags and dried in an oven at 75°C for 48 hours. Then the
vegetation samples were removed from the oven and the dry weights were measured. The plant water content (PWC) then was calculated as:

$$PWC = B_w - B_d$$

(2.3)

where $B_w$ and $B_d$ are the green and dry biomass (kg/m$^2$), respectively. Figure 2-36 shows the green biomass and PWC observed during MicroWEX-1.

![Figure 2-36. Green biomass and plant water content (PWC) observed during MicroWEX-1.](image)

The Second Microwave Water and Energy Balance Experiment (MicroWEX-2)

MicroWEX-2 was a similar experiment to MicroWEX-1 conducted during the corn growing season from March 17 (DOY 77) to June 3 (DOY 155) in 2004 (Judge et al., 2005). The study site was near that of MicroWEX-1, with an area of 183 X 183 m$^2$ (Figure 2-37).

During MicroWEX-2, the UFCMR were calibrated every two weeks. In this dissertation, only observations of sky brightness signatures, microwave absorber, and micro meteorological conditions were used to calibrate UFCMR and to investigate the accuracy and precision of the calibration in Chapter 3. Detailed descriptions of field observations and field log during MicroWEX-2 are given in the experimental data report.
The Third Microwave Water and Energy Balance Experiment (MicroWEX-3)

MicroWEX-3 was conducted utilizing the same study site as during MicroWEX-2 (Figure 2-37) during the growing season of cotton from June 16 (DOY 168) through December 21 (DOY 356) in 2004 (Lin et al., 2005). The crop spacing was about 8 cm and the row spacing was 76.2 cm. The instruments consisted of the UFCMR and micrometeorological stations (Figure 2-38). The UFCMR was deployed at the same incidence angle of 55° and height of 7.6 m as during MicroWEX-1. The observations were made every 15 minutes.
The micrometeorological stations included measurements of soil moisture and temperature profiles, surface thermal infrared temperature, down- and up-welling short- and long-wave radiation, soil heat flux, latent and sensible heat fluxes, and precipitation/irrigation depths. Detailed descriptions of field observation and field log for MicroWEX-3 can be found in the field data report (Lin et al., 2005) at Electronic Data Source of UF/IFAS Extension (http://edis.ifas.ufl.edu/AE361).

Figure 2-38. Layout of the sensors during MicroWEX-2 and 3.

The observations of sky brightness signatures, microwave absorber, and micrometeorological conditions collected during MicroWEX-3 were used for microwave radiometer calibration in Chapter 3. The field observations of soil surface temperature and soil temperature and moisture at depth of 2 cm during MicroWEX-3 were used to
develop and evaluate the microwave brightness model in Chapter 5, due to the lack of soil moisture data from lightening damage to the sensors during the MicroWEX-1. The observations of terrain brightness signatures, soil moisture, and temperature were also used to understand the sensitivity of brightness signatures to changing soil and vegetation conditions in Chapter 6. Figure 2-39 shows the observed $T_B$ during MicroWEX-3. The lowest $T_B$ at H-pol was around 120 K on DOY 205 in the early season. The H-pol $T_B$ reached to 260 K on DOY 245. The maximum difference between the $T_B$ at two polarizations was 110 K. The $T_B$ at V- and H-pol converged on DOY 262, 71 days after planting corresponding to LAI of 1.9, PWC of 0.60 kg/m² (see Figure 2-39, 2-44, and 2-46), and the canopy height and width of 60 and 50 cm, respectively (see Figure 2-42 and 2-43). After DOY 262, a maximum difference of 20 K between the $T_B$ at two polarizations was observed. Toward the late season during a period of 5 days from DOY 310 to 315, both $T_B$ at H- and V-pol decreased by ~15 K. This is because the decrease in Wc and LAI during the late season (Figure 2-43 and 2-44). Although the values of biomass and PWC still increased during this period mainly because the significantly increases of biomass and PWC in cotton bolls, those values decreased for leaves and stems (Figure 2-45 to 2-54). $T_B$ at both polarizations responded to the precipitation and/or irrigation in the whole growing season during MicroWEX-3. Figure 2-40 and 41 show the surface temperature, soil temperature and moisture at 2 cm observed during MicroWEX-3, respectively. Figure 2-40 shows the surface and soil temperatures at 2 cm observed by thermistor during MicroWEX-3. Figure 2-41 shows the volumetric soil moisture content (VSM) at 2 cm observed by the TDR probe during MicroWEX-3.
The data collected during vegetation sampling during MicroWEX-3 included canopy height and width, LAI, wet and dry weight of canopy components, leaves, stems, and bolls. Figure 2-42 to 2-44 show the canopy height, width, and LAI observed from four vegetation sampling areas during MicroWEX-3, respectively. Figure 2-45 and 46 shows the total biomass and PWC observed during MicroWEX-3, respectively. Figure 2-47 to 50 show the biomass for each component during MicroWEX-3. Figure 2-51 to 54 show the PWC for each component during MicroWEX-3. Table 2-3 lists the growth stages of the cotton planted during MicroWEX-3. Figure 2-55 shows pictures of growth stages of cotton. The detailed information about the growth and development of cotton can be found in Wright and Sprenkel (2005) and Ritchie et al. (2004).

Table 2-3 Growth stages of the cotton observed during MicroWEX-3.

<table>
<thead>
<tr>
<th>Growing Stage</th>
<th>Occurring Time (DOY in 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting</td>
<td>191</td>
</tr>
<tr>
<td>Emergence</td>
<td>195</td>
</tr>
<tr>
<td>Square formation</td>
<td>234</td>
</tr>
<tr>
<td>50 % Bloom</td>
<td>253</td>
</tr>
<tr>
<td>75 % Bloom</td>
<td>258</td>
</tr>
<tr>
<td>10 % Boll formation</td>
<td>272</td>
</tr>
<tr>
<td>40 % Boll formation</td>
<td>281</td>
</tr>
<tr>
<td>50 % Boll formation</td>
<td>288</td>
</tr>
<tr>
<td>Open boll</td>
<td>314</td>
</tr>
</tbody>
</table>

Figure 2-39. Observed brightness temperatures at vertically (V-) and horizontally (H-pol) polarizations during MicroWEX-3.
Figure 2-40. Surface and soil temperatures at 2 cm observed by thermistor during MicroWEX-3.

Figure 2-41. Volumetric soil moisture content (VSM) at 2 cm observed by the TDR probe during MicroWEX-3.

Figure 2-42. Canopy height observed during MicroWEX-3.
Figure 2-43. Canopy width observed during MicroWEX-3.

Figure 2-44. LAI observed during MicroWEX-3.

Figure 2-45. Green biomass observed during MicroWEX-3.
Figure 2-46. Plant water content (PWC) observed during MicroWEX-3.

Figure 2-47. Green biomass observed from NW area during MicroWEX-3.

Figure 2-48. Green biomass observed from NE area during MicroWEX-3.
Figure 2-49. Green biomass observed from SW area during MicroWEX-3.

Figure 2-50. Green biomass observed from SE area during MicroWEX-3.

Figure 2-51. Plant water content (PWC) observed from NW area during MicroWEX-3.
Figure 2-52. Plant water content (PWC) observed from NE area during MicroWEX-3.

Figure 2-53. Plant water content (PWC) observed from SW area during MicroWEX-3.

Figure 2-54. Plant water content (PWC) observed from SE area during MicroWEX-3.
Figure 2-55. (a) Square, (b) bloom, (c) boll, and (d) open boll of cotton.
CHAPTER 3
RADIOMETRIC CALIBRATION FOR C-BAND MICROWAVE RADIOMETERS

In this chapter, the calibration of UFCMR is described using widely used calibration techniques for ground-based C-band radiometers. The accuracy and errors associated with the UFCMR observations are also quantified.

Introduction

Ground-based microwave radiometers have been used extensively to measure upwelling terrain emission in the field experiments for hydrology, agriculture, and meteorology (Jackson and O’Neill, 1990; Jackson et al., 1997; Judge et al., 2001; Shi et al., 2002; Lemaitre et al., 2004; Schneeberge et al., 2004; Memmo et al., 2005). The total power radiometer is of the simplest designs compared to other designs such as the Dicke and noise injection (Ulaby et al., 1981; Skou, 1989). The stability and consistency of the relation between the output voltage and the antenna temperature, i.e. system gain and offset, are critical for radiometer operations. The system gain is highly sensitive to fluctuations in the physical temperature inside the radiometer requiring frequent calibration during the radiometer operation for reliable and accurate observations.

Many calibration techniques have been developed for microwave radiometers for space-borne and air-borne (Njoku et al., 1980; Ruf, 2000; Ruf and Li, 2003; Ruf et al., 1994; Ruf et al., 1995; Corbella et al., 2002; Bonnefond et al., 2003) and ground-based radiometers (Han and Westwater, 2000; Al-Ansri et al., 2002; Cimini et al., 2003; Deuber et al., 2004; Corbella et al., 2005; Pham et al., 2005; Goodberlet and Mead, 2006). In general, calibration techniques include observations of radiometer output voltages for
cold and hot targets with known brightness temperatures (Ulaby et al., 1981; Skou, 1989). For the radiometers operating at low frequencies away from the water vapor and oxygen absorption bands, such as C-band (6.7 GHz), commonly used cold targets are liquid nitrogen or the sky. Hot targets include microwave absorbers or matched load inside the radiometers. For a C-band ground-based microwave radiometer, the simplest calibration technique using the microwave absorber at ambient temperature as a hot target is called “external calibration” (EC). Another widely used calibration technique which utilizes the sky measurements at different angles to calculate the optical depth of the atmosphere and the brightness temperature of the sky is called “tipping curve calibration” (TC) (Han and Westwater, 2000; Cimini et al., 2003; Deuber et al., 2004). Either EC and TC can be used exclusively, or TC can be used to provide better estimate of the sky measurement for EC. Both these techniques are inconvenient and labor intensive to be performed frequently for long-term soil moisture studies using C-band ground-based radiometers. Moreover, the utility of TC at C-band can be hampered by the high atmospheric transparency at low microwave frequencies (Ulaby et al., 1981). Another technique, “internal calibration” (IC), uses an internal matched load as the hot target. This technique has been used for space-borne microwave radiometers, e.g. SMMR (Njoku et al., 1980), TMR (Ruf et al., 1994; Ruf et al., 1995), and JMR (Bonnefond et al., 2003), airborne radiometers (Corbella et al., 2002), and ground-based radiometers (De Roo, 2003; Pham et al., 2005; Goodberlet and Mead, 2006). Unlike EC and TC, IC can be performed faster than gain fluctuations. Furthermore, IC is neither sensitive to operator technique, nor to weathering of the delicate microwave absorber, nor does it require any additional hardware exclusively for the purpose of calibration. However, IC does not
account for the losses in the antenna and transmission lines before the internal switch used to observe the matched load.

In this section, the performance of IC is quantified and validated using EC and TC for long-term observations of soil moisture using ground-based C-band radiometers. The ground-based total power radiometer with similar design to the UFCMR, the C-band unit on the Truck Mounted Radiometer System 3 (TMRS-3); and the calibration experiments conducted in Alaska are described. Three different calibration techniques are summarized, and the consistency of the calibration among these techniques during the experiments are compared. The absolute accuracy of the brightness observations are evaluated by comparing the observed brightness temperatures of a lake with those obtained using a lake emission model.

C-band Radiometers

The UFCMR and TMRS-3C were both developed by the Microwave Geophysics Group at the University of Michigan (UM-MGG). Both are dual-polarized, unbalanced total power radiometers operating at the center frequency of 6.7 GHz, near the frequency of the Advanced Microwave Scanning Radiometer – EOS (AMSR-E) aboard the NASA Aqua Satellite. The UFCMR is mounted on a 10 m tower, whereas the TMRS-3C is mounted on the hydraulic arm of a Norstar truck, that can extend to 12 m. TMRS-3 consists of a suite of dual-polarized radiometers operating at 1.4, 6.7, 19, and 37 GHz mounted on an elevation positioner which allows for approximately 300° rotation in the elevation axis. A major difference between the UFCMR and TMRS-3C designs is the use of two receivers for V- and H-pol in TMRS-3C, compared to only one receiver in the UFCMR that switches between the two polarizations. Table I lists the specifications of the C-band radiometers.
Field Experiments

Microwave Water and Energy Balance Experiments (MicroWEXs)

MicroWEXs were conducted by the Center for Remote Sensing, Department of Agricultural and Biological Engineering, University of Florida, at the Plant Science Research and Education Unit (PSREU), IFAS, Citra, FL during the growing seasons of cotton (MicroWEX-1 (Tien et al., 2005) and -3 (Lin et al., 2005)) and corn (MicroWEX-2 (Judge et al., 2005)). During the MicroWEXs, the UFCMR measured microwave brightness temperatures every 15 minutes and was calibrated every two weeks. We conducted 10, 4, and 11 calibrations during the 140, 80, and 190 days of the MicroWEX-1, 2, and 3, respectively. Each calibration included measurements of sky at zenith angles of 15º, 30º, 45º, and 60º; of a microwave absorber at ambient temperature; and of a matched load inside the radiometer.

The Tenth Radiobrightness and Energy Balance Experiment (REBEX-10)

REBEX-10 was conducted by the UM-MGG from May 6 to July 1, 2004, at a site about 1 km north of Toolik Field Station on the North Slope of Alaska. In addition to conducting twice daily EC calibrations during REBEX-10, validation data was obtained by driving the Norstar truck to a beach on the NE shore of Toolik Lake, and extending the radiometer systems over the open water on June 21 (DOY 173) and 22 (DOY 174). The boom was extended to the West from the shore, in the direction of the smallest solid angle of land presented at the opposite shore of the lake. The calibration targets included sky, absorber, and lake surface. The sky measurements were recorded at zenith angles of 0º, 10º, 23º, 30º, 32º, 40º, and 55º. The lake surface measurements were obtained at incidence angles of 23º, 30º, 32º, 40º, and 55º. The lake temperature was measured once
on DOY 173 at 1502 hrs (AKDT) to be 13.7° C and on DOY 174 at 0342 hrs (AKDT) to be 10° C. These are expected to be extreme lake temperatures during this period.

**Calibration Methodology**

The relationship between the output voltage ($V_{out}$) and the antenna apparent temperature ($T_B'$) of a total power radiometer with a square-law detector such as the UFCMR and the TMRS-3C, can be expressed as follows:

$$T_B' = S \cdot V_{out} + I \tag{3.1}$$

where $S$ and $I$ are the slope and intercept of the calibration curve, respectively.

**External Calibration**

The calibration targets of EC included the microwave absorber at ambient air temperature and the sky measurement at zenith angle of 15° and 0° for UFCMR and TMRS-3C, respectively. The $S$ and $I$ are

$$S = \frac{(T_{B,sky} - T_{abs}) \cdot \eta + (T_{ant,sky} - T_{ant,abs}) \cdot (1 - \eta)}{V_{out,sky} - V_{out,abs}} \tag{3.2}$$

$$I = T_{B,sky} \cdot \eta + T_{ant,sky} \cdot (1 - \eta) - S \cdot V_{out,sky} \tag{3.3}$$

where $T_{abs}$ is the physical temperature of the absorber (K), $\eta$ is antenna efficiency, equal to 0.86 ± 0.01, as estimated in the laboratory using one-port measurements with a network analyzer, $T_{ant,sky}$ and $T_{ant,abs}$ are the physical temperatures of antenna during the sky and absorber measurements, respectively (K), and $V_{out,sky}$ and $V_{out,abs}$ are the output voltages during the sky and absorber measurements, respectively (volt). $T_{B,sky}$ (K) given by (Ulaby et al., 1981) is

$$T_{B,sky} = T_{B,atm}(\theta) + T_{extra} \cdot \exp(-\tau_0 \cdot \sec \theta) \tag{3.4}$$

and
\[ T_{B,\text{atm}} = \sec \theta \int_{-0}^{\infty} \kappa_a(z') \cdot T(z') \cdot \exp(-\tau(0,z') \cdot \sec \theta) \, dz' \]  

(3.5)

where \( T_{\text{extra}} \) is the extraterrestrial brightness temperature (K) which is \( \sim 2.7 \) K, \( \tau_0 \) is the total zenith opacity (Np), \( \theta \) is the zenith angle, \( \kappa_a \) is the atmospheric absorption coefficient (Np/m), \( T \) is the temperature profile (K), and \( \tau(0,z') \) is the optical thickness of the atmosphere between the surface and height \( z' \) (Np). Given the atmospheric temperature, pressure, and water vapor density, the sky brightness temperature can be calculated based on the 1962 U.S. Standard Atmosphere (Ulaby et al., 1981). At C-band, the sensitivity of sky brightness to changes in atmospheric conditions can be ignored due to the high atmospheric transparency (Ulaby et al., 1981).

The sources of error using EC include the measurement errors due to the antenna sidelobes, \( \varepsilon_{sl} \), the insertion loss variability of the radiometer switches, \( \varepsilon_{sw} \), and the uncertainty in the physical temperature measurements of the absorber, \( \varepsilon_{at} \). The effect of these errors using UFCMR and TMRS-3C will be discussed in later section.

**Tipping-Curve Calibration**

\( T_{B,\text{sky}} \) can be obtained by TC assuming a horizontally stratified atmosphere (Janssen, 1993) and (Han and Westwater, 2000) as

\[ T_{B,\text{sky}} = T_{\text{extra}} \cdot \exp(-A(\theta) \cdot \tau) + T_{\text{atm}} \cdot (1 - \exp(-A(\theta) \cdot \tau)) \]  

(3.6)

where \( A \) is the airmass at observation angle (\( \theta \)), \( \tau \) is the atmospheric opacity (Np), and \( T_{\text{atm}} \) is the mean atmospheric temperature (K). In a plane-stratified atmosphere, airmass \( A \) is defined as (Han and Westwater, 2000):

\[ A = \frac{1}{\sin \theta} \]  

(3.7)
For UFCMR and TMRS-3C, the antenna temperature is linearly related to the output voltage such that

\[
\frac{V_{\text{out,sky}} - V_{\text{out,abs}}}{V_{\text{out,abs}} - V_{\text{ofst}}} = \frac{T'_{A,\text{sky}} - T'_{A,\text{abs}}}{T'_{A,\text{abs}} - T_{\text{rec}}}
\]

(3.8)

where \(V_{\text{ofst}}\) is the system offset voltage when the system input noise temperature is zero K \((T_{\text{sys}} = T'_{A} + T_{\text{rec}})\), \(T'_{A,\text{sky}}\) and \(T'_{A,\text{abs}}\) are the apparent antenna temperatures for the sky and absorber measurements, respectively (K), and \(T_{\text{rec}}\) is the receiver noise temperature (K).

The equations for \(S\) and \(I\) are the same as (3.2) and (3.3), with \(T_{B,\text{sky}}\) estimated by the radiative transfer equation using the least-square technique from 0 to 45°. The atmospheric temperature was approximated by the air temperature at the earth surface (Han and Westwater, 2000).

The sources of error using TC include \(\varepsilon_{\text{sl}}, \varepsilon_{\text{sw}}\), and \(\varepsilon_{\text{at}}\), similar to those in EC.

**Internal Calibration**

IC uses an internal matched load or a fixed temperature source inside the radiometer as the hot target. The cold target is the sky measurement at 15° for UFCMR and at 0° for TMRS-3C. The \(S\) and \(I\) using IC are

\[
S = \frac{T_{B,\text{sky}} \cdot \eta + T_{\text{ant,sky}} \cdot (1 - \eta) - T_{\text{cal}}}{V_{\text{out,sky}} - V_{\text{out,cal}}}
\]

(3.9)

\[
I = T_{\text{cal}} - S \cdot V_{\text{out,cal}}
\]

(3.10)

where \(T_{\text{cal}}\) is the physical temperature of the matched load (K), \(\eta\) is the antenna efficiency, \(V_{\text{out,cal}}\) is the output voltage at the matched load at \(T_{\text{cal}}\) (volt), and \(T_{B,\text{sky}}\) is estimated, similar to EC (Ulaby et al., 1981).
The sources of error using IC include the $\varepsilon_{sl}$ and $\varepsilon_{sw}$, similar to those in EC, the error due to the uncertainty in the antenna efficiency estimation, $\varepsilon_{ae}$, and the uncertainty in the physical temperature measurements of the internal load, $\varepsilon_{lt}$.

**Lake Emission Model (LEM)**

For an open, calm water surface, the brightness temperature observed by a microwave radiometer can be modeled as:

$$T_{B,p} = \Gamma_p \cdot T_{B,sky} + (1 - \Gamma_p) \cdot T_{water}$$  \hspace{1cm} (3.11)

where $\Gamma_p$ is the reflectivity at polarization $p$ and $T_{water}$ is the physical temperature of water (K). $T_{B,sky}$ is $\sim 5$ K for C-band. The reflectivity of the specular water surface is determined by the incidence angle (Rose et al., 2002) and the dielectric constant of the water. The empirical dielectric models for pure water can be found in Ulaby et al. (1986) and Meissner and Wentz (2004).

**Results and Discussion**

The calibration data from MicroWEXs and REBEX-10 provided a unique opportunity to compare the performance of two C-band radiometers with similar design in different environmental conditions. During each experiment, the radiometers were maintained at constant temperatures with 0.1 K standard deviation at the RF circuitry. Table II shows the means and the standard deviations of the calibration curves at H-pol during MicroWEXs and REBEX-10. These included 25 data points during MicroWEXs, as well as 80 points for EC and IC, and 2 points for TC during REBEX-10. IC produced the most consistent calibration curves in terms of the lowest standard deviations of the slopes, although the differences among the calibration techniques were not statistically significant.
Table 3-1. Mean and standard deviation of the slopes (S) and Intercepts (I) for the H-and V-pol calibration curve during MicroWEX-1 (MW-1) and REBEX-10 (RB-10).

<table>
<thead>
<tr>
<th>Unit: S [K/v] and I [K]</th>
<th>EC Mean</th>
<th>Std.</th>
<th>IC Mean</th>
<th>Std.</th>
<th>TC Mean</th>
<th>Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S H-pol MW-1</td>
<td>189.37</td>
<td>3.81</td>
<td>188.62</td>
<td>2.00</td>
<td>182.48</td>
<td>3.12</td>
</tr>
<tr>
<td>S H-pol RB-10</td>
<td>152.35</td>
<td>3.68</td>
<td>152.62</td>
<td>0.84</td>
<td>150.34</td>
<td>3.40</td>
</tr>
<tr>
<td>I H-pol RB-10</td>
<td>-69.18</td>
<td>5.38</td>
<td>-69.47</td>
<td>4.23</td>
<td>-65.70</td>
<td>6.68</td>
</tr>
<tr>
<td>S V-pol MW-1</td>
<td>175.52</td>
<td>5.06</td>
<td>174.56</td>
<td>6.94</td>
<td>167.04</td>
<td>6.38</td>
</tr>
<tr>
<td>S V-pol RB-10</td>
<td>157.36</td>
<td>5.92</td>
<td>156.41</td>
<td>3.37</td>
<td>152.05</td>
<td>1.94</td>
</tr>
<tr>
<td>I V-pol MW-1</td>
<td>-99.56</td>
<td>14.92</td>
<td>-98.84</td>
<td>16.67</td>
<td>-81.40</td>
<td>14.70</td>
</tr>
<tr>
<td>I V-pol RB-10</td>
<td>-19.52</td>
<td>2.64</td>
<td>-19.00</td>
<td>2.31</td>
<td>-17.28</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Fig. 3-1 to 3-4 show the gain fluctuations of the calibration curves for MicroWEXs and REBEX-10 at H-pol. Similar results also were found for V-pol. The mean absolute difference (MAD) between the slopes of EC and IC was 2.8 K/volt during MicroWEXs.

Figure 3-1. Slopes for the calibration curve at H-pol during MicroWEX-1. RMSE of EC = 1.20, TC = 1.84, and IC = 1.10 K/volt.
Figure 3-2. Slopes for the calibration curve at H-pol during MicroWEX-2. RMSE of EC = 1.12, TC = 1.43, and IC = 1.02 K/volt.

Figure 3-3. Slopes for the calibration curve at H-pol during MicroWEX-3. RMSE of EC = 1.12, TC = 1.43, and IC = 1.02 K/volt.
Figure 3-4. Slopes for the calibration curve at H-pol during REBEX-10. RMSE of EC = 1.20, TC = 1.84, and IC = 1.10 K/volt.

The difference between the slopes of TC and EC was 4.4 K/volt; and the difference between the slopes of TC and IC was 3.6 K/volt during MicroWEXs. The MADs for REBEX-10 were not calculated because there were only two TC measurements. During MicroWEXs, the EC and IC calibration curves were closer to each other, while TC produced slightly dissimilar results from EC and IC. This was primarily because at C-band, TC is based on multiple measurements with small differences in brightness temperatures ($T_B$) of the sky, compared to measurements at higher frequencies at which the differences are larger. Due to the high atmospheric transparency, the utility of TC at C-band was reduced. Applying the calibration curves over the output voltages for the terrains observed during MicroWEXs and REBEX-10, the MAD of the calibrated $T_B$ using the three calibration techniques was 1.14 K. Table 3-2 gives the root-mean-square errors (RMSE) estimates in the accuracy of observed $T_B$ using UFCMR and
TMRS-3C due to $\varepsilon_{ae}$, $\varepsilon_{sl}$, $\varepsilon_{sw}$, $\varepsilon_{at}$, and $\varepsilon_{lt}$ as mentioned in section IV. The RMSE of EC, TC, and IC are 1.20, 1.84, and 1.10 K/volt, respectively.

Table 3-2. RMSE estimation for the operation and calibration for UFCMR and TMRS-3C.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Source</th>
<th>Value (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{ae}$</td>
<td>Antenna Efficiency</td>
<td>$&lt; 0.14$</td>
</tr>
<tr>
<td>$\varepsilon_{sl}$</td>
<td>Antenna Sidelobe (Incidence angle 0° to 45°), H-pol</td>
<td>1.06 to 1.75</td>
</tr>
<tr>
<td>$\varepsilon_{sw}$</td>
<td>Radiometer Switch</td>
<td>$&lt; 0.25$</td>
</tr>
<tr>
<td>$\varepsilon_{at}$</td>
<td>Absorber Temperature Measurements</td>
<td>$&lt; 0.50$</td>
</tr>
<tr>
<td>$\varepsilon_{lt}$</td>
<td>Load Temperature Measurements</td>
<td>$&lt; 0.10$</td>
</tr>
</tbody>
</table>

To assess the accuracy of the calibration, the observed $T_B$ of a calm lake at different incidence angles between 20° to 55° during REBEX-10 was used to compare with the LEM modeled $T_B$. The RMSE due to antenna sidelobe during the lake observations decreases slightly as the incidence angle increases. Figure 3-5 illustrates the RMSE due to antenna sidelobe during lake observation. The RMSE due to antenna sidelobes during the lake observations were 0.28, 0.26, 0.25, 0.25, and 0.24 K at H-pol whereas those were 0.47, 0.39, 0.37, 0.31 and 0.26 K at V-pol at the incidence angles of 23°, 30°, 32°, 40°, and 55°, respectively. These RMSE are included in the error bars shown in Figure 3-6 and 3-7. Observed $T_B$ were compared with those of a smooth water surface simulated by LEM (Figure 3-6 to 3-7).

Figure 3-5. RMSE due to antenna sidelobe during the lake observations
Figure 3-6. Comparison of the brightness temperature differences ($\Delta T_B$) by observations and LEM at H-pol on DOY 173. The total RMSE in observations and simulation are 1.46, 2.02, and 1.39 for EC, TC, and IC, respectively.

Figure 3-7. Comparison of the brightness temperature differences ($\Delta T_B$) by observations and LEM at H-pol on DOY 174. The total RMSE in observations and simulation are 2.58, 2.73, and 2.54 for EC, TC, and IC, respectively.
Two dielectric models for pure water, Ulaby et al. (1986) and Meissner and Wentz (2004) were used. Figure 3-8 shows the dielectric constant of pure water simulated by two models at C-band. At C-band the MAD between the simulated LEM $T_B$ by two models were insignificant at $\sim 0.0095$ K. The uncertainty in the water temperature measurement was ± 3.0 K resulting in an RMSE of 0.8 and 2.3 K at H- and V-pol in the simulated $T_B$, respectively. The MAE between the observed and modeled $T_B$ at H-pol were 2.5 ±1.46, 3.9 ±2.02, and 2.4 ±1.39 K for EC, TC, and IC, respectively. The MAE between the observed and modeled $T_B$ at V-pol were 1.3 ±2.58, 2.4 ±2.73, and 1.3 ±2.54 K for EC, TC, and IC, respectively. For soil moisture applications, an accuracy of about 2 K at C-band is adequate (Calvet et al., 1996).
Conclusion

The calibration experiments during the MicroWEXs and REBEX-10 were designed to assess the calibration consistency of two C-band radiometers with similar design. The three most widely used techniques, EC, TC, and IC, were compared to understand their performance for long-term soil moisture studies using ground-based C-band radiometers. Even though IC produced the most consistent calibration curves, the differences among the three calibration techniques were not statistically significant. Applying the calibration curves over the output voltages observed during the MicroWEXs and REBEX-10, the MAD of the $T_B$ calibrated among the three calibration techniques was 1.14 K.

This chapter provides results to the first research question in Chapter 1: “What are the accuracy and precision of the $T_B$ measurements used in this study?” as follows: The absolute accuracy of calibration techniques was investigated by comparing the observed and modeled $T_B$ of a calm lake. The MAE between the observed and modeled $T_B$ at H-pol were $2.5 \pm 1.46$, $3.9 \pm 2.02$, and $2.4 \pm 1.39$ K for EC, TC, and IC, respectively. The MAE between the observed and modeled $T_B$ at V-pol were $1.3 \pm 2.58$, $2.4 \pm 2.73$, and $1.3 \pm 2.54$ K for EC, TC, and IC, respectively. Due to the high atmospheric transparency, the utility of TC at C-band is greatly reduced. Because IC was found to have an MAE of ~2 K that is suitable for soil moisture applications and was consistent during our experiments under significantly different environmental conditions, it can be used to augment less frequent calibrations obtained by the EC or TC techniques.
CHAPTER 4
MICROWAVE BRIGHTNESS MODEL FOR COTTON

In this chapter, the Microwave Brightness for Cotton (MB-Cotton) model developed to simulate the brightness temperature ($T_B$) for the whole growing season of cotton is described.

**Microwave Brightness Model for Cotton (MB-Cotton)**

Overall terrain emission of cotton is estimated as a linear combination of bare soil and vegetation canopy $T_B$ because the footprint is a mixture of bare soil and vegetation emission for row crops such as cotton (Figure 4-1):

$$T_{B,p} = (1 - C_c) \cdot T_{B,S,p} + C_c \cdot T_{B,C,p} \quad (4.1)$$

where $p$ is the polarization, $C_c$ is the fraction of canopy cover, $T_{B,S,p}$ and $T_{B,C,p}$ are the bare soil and canopy components, respectively.

![Figure 4-1. Schematic of the microwave brightness model for cotton.](image)
The Cc is the ratio of canopy width to row width.

\[
Cc = \frac{W_c}{W_r}
\]  \hfill (4.2)

**Bare Soil Component (TB_{B,S,p})**

The soil is modeled as a semi-infinite, horizontally uniform, and smooth surface medium. The bare soil component consists of emission from the atmosphere and soil layers as (Figure 4-1)

\[
TB_{B,S,p} = TB_{sky} \Gamma_p + T_{eff} (1 - \Gamma_p)
\]  \hfill (4.3)

where \(TB_{sky}\) is the downwelling atmospheric brightness temperature (K), \(\Gamma_p\) is the reflectivity of the soil at polarization \(p\), and \(T_{eff}\) is the effective physical temperature of the soil (K). At C-band, \(TB_{sky}\) is \(~5\) K. The reflectivity at vertical (\(\Gamma_v\)) and horizontal (\(\Gamma_h\)) polarizations are given by Fresnel equations (Ulaby et al., 1981):

\[
\Gamma_v (\theta) = \left| \frac{\varepsilon_{soil} \cos \theta - \sqrt{\varepsilon_{soil} - \sin^2 \theta}}{\varepsilon_{soil} \cos \theta + \sqrt{\varepsilon_{soil} - \sin^2 \theta}} \right|^2
\]  \hfill (4.4)

\[
\Gamma_h (\theta) = \left| \frac{\cos \theta - \sqrt{\varepsilon_{soil} - \sin^2 \theta}}{\cos \theta + \sqrt{\varepsilon_{soil} - \sin^2 \theta}} \right|^2
\]  \hfill (4.5)

where \(\theta\) is the incidence angle from zenith (see Figure 4-1), and \(\varepsilon_{soil}\) is the dielectric constant of the wet soil.

\(T_{eff}\) is estimated using Radiative Transfer equation (Ulaby et al., 1981) as (Figure 4-2):

\[
T_{eff} = T_{soil,Z_{eff}} \cdot \exp \left[ - \tau_s (0, Z_{eff}) \right] + \
\int_{Z_{eff}}^{0} \kappa_{\varepsilon_s} (z') T(z') \exp \left[ - \tau_s (0, z') \right] dz'
\]  \hfill (4.6)
where $T_{\text{soil},Z_{\text{eff}}}$ is the soil physical temperature at the depth of effective depth ($Z_{\text{eff}}$),

$\tau_s(0,Z_{\text{eff}})$ is the optical depth of the effective soil layer (Np), $\kappa_{e,s}$ is the power extinction coefficient of the soil medium (Np/m), and $T$ is the physical temperature of the soil (K).

Figure 4-2 shows the schematic of the $T_{\text{eff}}$ approximation.

\[ T_{\text{eff}} = T_{\text{eff},1} + T_{\text{eff},2} + T_{\text{eff},3} + T_{\text{eff},\infty} \]

\[ Z=0 \]

\[ \begin{array}{c}
\vdots \\
T_{\text{eff},1} & T_{\text{soil},1} & \varepsilon_{\text{soil},1} \\
\vdots & \vdots & \vdots \\
T_{\text{eff},2} & T_{\text{soil},2} & \varepsilon_{\text{soil},2} \\
\vdots & \vdots & \vdots \\
T_{\text{eff},3} & T_{\text{soil},3} & \varepsilon_{\text{soil},3} \\
\vdots & \vdots & \vdots \\
T_{\text{eff},\infty} & & \\
\end{array} \]

\[ Z=Z_{\text{eff}} \]

Figure 4-2. Schematic of $T_{\text{eff}}$ approximation.

The effective depth ($Z_{\text{eff}}$) of soil emission is approximated by the penetration depth of soil ($\delta_p$), which is calculated as (Ulaby et al., 1982) as:

\[ \delta_p = \frac{\lambda_0}{4\pi} \left| \text{Im}\left(\sqrt{\varepsilon_{\text{soil}}}\right) \right|^{-1} \quad (4.7) \]

where $\text{Im}$ represents the imaginary part of the quantity, $\lambda_0$ is the free-space wave length and $\varepsilon_{\text{soil}}$ is dielectric constant of the wet soil. The soil is modeled as a semi-infinite medium, with layered constitutive properties. The dielectric properties within a layer are assumed to be constant. The multiple reflections between the soil layers and volume scattering within the soil layers were assumed to be zero. Figure 4-3 shows the penetration depth, i.e. $Z_{\text{eff}}$ as a function of volumetric soil moisture content (VSM).

Because the values of observed VSM during the field experiments were between 5 and 35 % (Figure 2-17, 18, and 40), the effective depth at C-band for MB-Cotton model was determined to be 2 cm (Figure 4-3). $T_{\text{eff}}$ was calculated by integrating the emission from layered soil based upon their dielectric and thermal profiles from 0 to 2 cm.
Figure 4-3. Penetration depth at C-band as a function of volumetric soil moisture content using Equation 4.7.

The power extinction coefficient was equal to the absorption coefficient of the soil medium because the volume scattering within soil layers was assumed to be zero, $\kappa_{e,s} = \kappa_{a,s} (\text{Np/m})$ calculated as (Ulaby et al., 1981),

$$
\kappa_{e,s}^* = \frac{4\pi}{\lambda_0} \left\{ \frac{\mu_r \varepsilon_r'}{2} \left[ \left( 1 + \left( \frac{\varepsilon_r''}{\varepsilon_r'} \right)^2 \right)^{1/2} - 1 \right] \right\}^{1/2}
$$

where $\lambda_0$ is the free-space wavelength, $\mu_r$ is the relative permeability, $\varepsilon'_r$ and $\varepsilon''_r$ are the real and imaginary part of the complex dielectric constant. $\tau_s$ is defined as (Ulaby et al., 1981):

$$
\tau_s (z', z) = \int_{z}^{z'} \kappa_{e,s}^*(z) dz
$$

At C-band, the dielectric property of soil layer can be treated as dielectric mixture including soil particles, air, bound water, and free water using the soil dielectric model developed by Dobson et al. (1985).

$$
\varepsilon_{\text{soil}} = v_s \varepsilon_s + v_a \varepsilon_a + v_{bw} \varepsilon_{bw} + v_{fw} \varepsilon_{fw}
$$
where $\varepsilon$ is the dielectric constant, $v$ is the volumetric content, and the subscripts $s$, $a$, $bw$, and $fw$ denote soil particle, air, bound water, and free water, respectively, and $\alpha$ is the adjustable factor ($\alpha = 0.65$ from Ulaby et al., 1986). For the soil of particle density around 2.65 g/cm$^3$, the dielectric constant are $\varepsilon_s = 4.7$, $\varepsilon_a = 1$, $\varepsilon_{bw} = 3.3$ (Dobson et al., 1985). The dielectric constant of free water is simulated by the Debye equation (Ulaby et al., 1986).

$$
\varepsilon_{fw} = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + j 2 \pi f \tau} \tag{4.11}
$$

where $\varepsilon_\infty$ and $\varepsilon_0$ are the high-frequency limit and static dielectric constants of pure water, $f$ is the electromagnetic frequency (Hz), $\tau$ is the relaxation time of pure water (s), and $j$ is $\sqrt{-1}$. The real and imaginary parts of the pure water dielectric constant can be written as:

$$
\varepsilon'_{fw} = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (2 \pi f \tau)^2} \tag{4.12}
$$

$$
\varepsilon''_{fw} = \frac{2 \pi f \tau (\varepsilon_0 - \varepsilon_\infty)}{1 + (2 \pi f \tau)^2} \tag{4.13}
$$

The high-frequency limit dielectric constant of pure water is found to be a constant, $\varepsilon_\infty = 4.7$ (Lane and Saxton, 1952) whereas the static dielectric constant of pure water is a function of the water physical temperature, $T_w$ ($^\circ$C) and simulated by (Klein and Swift, 1977)

$$
\varepsilon_0 = 88.045 - 0.4147 T_w + 6.295 \times 10^{-4} T_w^2 + 1.075 \times 10^{-5} T_w^3 \tag{4.14}
$$

The soil surface is modeled as a smooth-surfaced dielectric layer whose reflectivity at vertical ($\Gamma_v$) and horizontal ($\Gamma_h$) polarizations are given by Fresnel equations (Ulaby et al., 1981).
Recently, Mironov et al. (2004) developed a new dielectric model for soil in the microwave band from 0.6 to 18.0 GHz. The key point of their soil dielectric model is to use the complex dielectric constant directly as a function of volumetric soil moisture. The model also provided a more sophisticated method to account for the values of bound water fraction and dielectric constant. The soil complex dielectric constant values modeled by Mironov et al. (2004) model match well with the soil complex dielectric constant modeled by the Dobson et al. (1985) model. The comparison was done on silty clay soil with texture are of 5.02 % sand, 47.60 % silt, and 47.38 % clay. This soil is different from the soils at the study site with 92 % sand. The difference between the dielectric constants simulated by two models for the sandy soils at study site should be even smaller. At 6.7 GHz, the differences between the complex dielectric constants predicted by the two models were ~1.0 for real and imagery parts between soil volumetric moisture content of 10 and 30 %.

**Vegetation Component (T_{B,C,p})**

The canopy is modeled as dielectric cloud above the soil of width and thickness as canopy width and height, respectively. The canopy component, T_{B,C,p} in Equation 4-1, can be expressed as (Figure 3-1):

\[
T_{B,C,p} = T_{B,p}^{Sky} + T_{B,p}^{Soil} + T_{B,p}^{Canopy}
\]  

(4.15)

where \(T_{B,p}^{Sky}\), \(T_{B,p}^{Soil}\), and \(T_{B,p}^{Canopy}\) are the terms for sky, soil, and vegetation emission, respectively. The sky emission term accounts for downwelling atmospheric brightness temperatures (\(T_{B,sky}\)), attenuated through the canopy, reflected at the canopy-soil interface, and attenuated through the canopy again.

\[
T_{B,p}^{Sky} = T_{B,sky} \Gamma_p \left[ \exp\left( -2 \tau_c \right) \right]
\]  

(4.16)
where τ_c is the optical depth of the vegetation canopy (Np). The soil emission term accounts for the contribution from the soil brightness temperature emitted at the canopy-soil interface and attenuated by the canopy.

\[ T_{B,p}^{\text{Soil}} = T_{\text{eff}} \left( 1 - \Gamma_p \right) \exp(-\tau_c) \]  \hspace{1cm} (4.17)

\( T_{B,p}^{\text{Canopy}} \) accounts for the emission from the vegetation canopy in the upward and downward directing within the canopy.

\[ T_{B,p}^{\text{Canopy}} = T_{\text{canopy}} \left[ 1 - \exp(-\tau_c) \right] \left[ 1 + \Gamma_p \exp(-\tau_c) \right] \]  \hspace{1cm} (4.18)

where \( T_{\text{canopy}} \) is the effective canopy physical temperature (K) and \( \tau_c \) is the optical depth of the canopy (Np) calculated as (Ulaby et al., 1981):

\[ \tau_c (z', z) = \int_{z'}^{z} \kappa_{e,c} (z) dz \]  \hspace{1cm} (4.19)

where \( \kappa_{e,c} \) is the power extinction coefficient of the vegetation canopy (Np/m).

The vegetation canopy is treated as a two-component mixture including vegetation materials and air as host. Assuming there is no volume scattering in the vegetation canopy, the power extinction coefficient can be calculated using Equation (4.8). The dielectric constant of the vegetation canopy is modeled using the Dual-dispersion model (Ulaby and El-Rayes, 1987).

\[ \varepsilon_c = \varepsilon_r + v_{fw} \left[ 4.9 + \frac{75.0}{1 + f f / 18} - j \frac{22.86}{f} \right] + v_{bw} \left[ 2.9 + \frac{55.0}{1 + (j f / 0.18)^{0.5}} \right] \]  \hspace{1cm} (4.20)

where \( \varepsilon_r \) is the non-dispersive residual component, \( f \) is the electromagnetic frequency (GHz), and \( v_{fw} \) and \( v_{bw} \) are the free and bound water fraction in the vegetation canopy. These variables are empirically related to the gravimetric moisture content of the vegetation canopy (M_g) (Ulaby and El-Rayes, 1987).
The canopy dielectric properties were derived assuming the canopy is composed of vegetative materials only. This might lead to an overestimation in the canopy attenuation. Empirical dielectric models, such as England and Galantowicz (1995), estimating canopy dielectric constant based upon the volume fraction of wet vegetative materials may provide a better approximation.

**Summary**

In this chapter, the MB-Cotton model was developed based upon radiative transfer equation to simulate the brightness temperatures for a growing season of cotton. MB-Cotton model simulated overall terrain emission as a mixture of bare soil and canopy emissions. The proportion of canopy emission is determined by the fraction of canopy cover whereas the rest of the emission is contributed by the bare soil emission. The soil is modeled as a semi-infinite, horizontally uniform, and smooth surface medium. The soil at the effective depth is divided into three layers at the depths of 0.5, 0.5, and 1.0 cm from the surface. The dielectric property of the soils is modeled using literature-based model (Dobson et al., 1985). The cotton canopy is modeled as a rectangular dielectric cloud of width and thickness as canopy width and height. The dielectric property of the canopy is modeled using empirical model developed for vegetation constituents.

This chapter provides results to the second research question in Chapter 1, *What is the effective depth of C-band under different soil moisture conditions?* as follows:

\[
\varepsilon_r = 1.7 - 0.74M_g + 6.16M_g^2 \tag{4.21}
\]

\[
v_{fw} = M_g \left(0.55M_g - 0.076\right) \tag{4.22}
\]

\[
v_{bw} = \frac{4.64M_g^2}{1 + 7.36M_g^2} \tag{4.23}
\]
For sandy soil under the soil moisture conditions (5 to 35 %) observed during MicroWEXs, the effective depth of C-band is from 2.3 (5 %) to 0.7 cm (35 %).
CHAPTER 5
MODEL EVALUATION

In this chapter, the evaluation of the MB-Cotton model developed in Chapter 4 for a growing season of cotton is described. The growing season is divided into three stages, viz. early, mid, and late, based upon the phenological stages of cotton ranging from germination to mature canopy. The input variables for the MB-Cotton model are discussed, including the vegetation properties, surface temperature, and soil moisture and temperature profiles simulated by the Land Surface Process (LSP) model and observed soil moisture and temperature during MicoWEX-3. Finally, the $T_B$ simulated by the MB-Cotton model are compared to those observed for the dry down periods during MicroWEX-3 to evaluate the results.

Input Variables

The forcing for the MB-Cotton model can be categorized into soil and vegetation variables. Two simulations were conducted; the first using input soil variables from field observations from MicroWEX-3 and second using input soil variables from estimations by an SVAT model called, Land Surface Process (LSP) model. The field observed soil variables included surface thermal infrared temperature, volumetric soil moisture (VSM) and temperature at depth of 2 cm (see Figure 2-40 and 41). The LSP model estimated variables included surface temperature at 0.05 cm, VSM and temperature profiles at depths of 0.25, 0.76, and 1.26 cm (Figure 5-1). A brief description of the LSP model and its preliminary calibration results used in this dissertation are provided below.
Input Variables for Soil

**MicroWEX-3 field observations**

Figure 2-40 and 41 shows the thermal infrared temperature, volumetric soil moisture (VSM) and temperature at depth of 2 cm for the input variables for soil to the MB-Cotton model.

**Land Surface Process (LSP) model**

The LSP model was developed by the Microwave Geophysics Group at the University of Michigan to simulate coupled one-dimensional energy and moisture transport at the land surface and in the vadose zone when forced with observed weather (Liou and England, 1998; Judge et al., 1999; Judge et al., 2003).

The governing equations for the energy and moisture balance are given as (Judge et al., 2003):

\[
\frac{\partial X_m}{\partial t} = -\nabla \cdot \bar{q}_m
\]  
\[
\frac{\partial X_e}{\partial t} = -\nabla \cdot \bar{q}_e
\]
where \( X_m \) and \( X_e \) are the total moisture and energy contents per unit volume, (kg/m\(^3\) and J/m\(^3\)), respectively, and \( q_e \) and \( q_m \) are the moisture and energy fluxes (kg/s·m\(^2\) and J/s·m\(^2\)), respectively.

The soil profile is defined with layers of different thermal and hydraulic properties. The thickness of each soil layer increases exponentially with depth. A block-centered, forward-time finite difference scheme is used to calculate the moisture and temperature profiles. The model forcings include micrometeorological parameters, e.g. air temperature, relative humidity, downwelling short- and long-wave radiation, irrigation/precipitation, and wind speed. The initial conditions of the temperature and moisture profiles are obtained from the MicroWEX-3 observations. The upper boundary conditions for moisture and energy fluxes are given by the energy and moisture balance at surface as:

\[
\bar{q}_m(z = 0) = \rho_l \left(D_c - E_s - E_{tr} - R\right) = \rho_l \left(D_c - E_{sr} - R\right)
\]

\[
\bar{q}_e(z = 0) = R_{ns} - H_s - L_s
\]

where \( \bar{q}_m(z = 0) \) and \( \bar{q}_e(z = 0) \) are the moisture and energy fluxes at the upper boundary, \( \rho_l \) is the density of liquid water (kg/m\(^3\)), \( D_c \) is the rate of drainage (= total precipitation or irrigation – interception by the canopy) from the canopy (m/s), \( E_s \) is the rate of evaporation from the soil (m/s), \( E_{tr} \) is the rate of transpiration from the soil (root zone) (m/s), \( R \) is runoff (m/s), \( R_{ns} \) is the net radiation absorbed by the soil (W/m\(^2\)), and \( H_s \) and \( L_s \) are the sensible and latent heat fluxes from the soil, respectively (W/m\(^2\)). Moisture and energy fluxes at the lowest boundary conditions are set to gravity drainage and uniform energy flux, respectively. Table 5-1 shows the physical and hydraulic properties of soil and Table 5-2 shows the canopy parameters used in the LSP model (Yan et al., 2006).
Figure 5-2 and 5-3 show the temperature and moisture profiles estimated by the LSP model during MicroWEX-3, respectively.

Table 5-1. The physical and hydraulic properties of soil used in the LSP model (Yan, 2006).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_{ob}$</td>
<td>Bare soil roughness length</td>
<td>0.01 (m)</td>
</tr>
<tr>
<td>$\varepsilon_s$</td>
<td>Soil IR emissivity</td>
<td>0.98</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Pore-size index</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Psi_0$</td>
<td>Air entry pressure</td>
<td>0.076 (of m H$_2$O)</td>
</tr>
<tr>
<td>$K_{sat}$</td>
<td>Saturated hydraulic conductivity</td>
<td>$1 \times 10^{-4}$ (m/s)</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>Wilting point</td>
<td>0.0051 (m$^2$/m$^3$)</td>
</tr>
<tr>
<td>$\varphi_{sa}$</td>
<td>Sand fraction</td>
<td>0.894 (m$^3$/m$^3$)</td>
</tr>
<tr>
<td>$\varphi_{si}$</td>
<td>Silt fraction</td>
<td>0.034 (m$^3$/m$^3$)</td>
</tr>
<tr>
<td>$\varphi_c$</td>
<td>Clay fraction</td>
<td>0.071 (m$^3$/m$^3$)</td>
</tr>
<tr>
<td>$\varphi_o$</td>
<td>Organic fraction</td>
<td>0.0 (m$^3$/m$^3$)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Porosity</td>
<td>0.34 (m$^3$/m$^3$)</td>
</tr>
</tbody>
</table>

Table 5-2. The canopy parameters used in the LSP model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$</td>
<td>Leaf angle distribution parameter</td>
<td>1.00</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Leaf reflectance</td>
<td>0.3</td>
</tr>
<tr>
<td>$\varepsilon_c$</td>
<td>Canopy emissivity</td>
<td>0.98</td>
</tr>
<tr>
<td>$c_d$</td>
<td>Canopy drag coefficient</td>
<td>0.15</td>
</tr>
<tr>
<td>$i_w$</td>
<td>Canopy wind intensity factor</td>
<td>0.60</td>
</tr>
<tr>
<td>$l_w$</td>
<td>Leaf width</td>
<td>0.05 (m)</td>
</tr>
<tr>
<td>$F_b$</td>
<td>Base assimilation rate</td>
<td>$-0.2 \times 10^{-7}$ (kgCO$_2$/m$^2$/s)</td>
</tr>
<tr>
<td>$\varepsilon_{photo}$</td>
<td>Photosynthetic efficiency</td>
<td>$11.4 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Figure 5-2. Surface and soil temperature profiles in the top 2 cm simulated by the Land Surface Process (LSP) model during MicroWEX-3.
Figure 5-3. Soil moisture profiles in the top 2 cm simulated by the Land Surface Process (LSP) model during MicroWEX-3.

**Input Variables for Vegetation**

The vegetation variables for both the simulations were obtained from the biweekly vegetation samplings during MicroWEX-3. Among the four sampling areas, the NW site was found to be the most representative to the vegetation properties in the footprint of UFCMR. The variables include canopy height ($H_c$), canopy gravimetric water content ($M_g$), and canopy cover ($C_c$). $M_g$ was calculated as ratio of weight of water in the canopy to weight of dry vegetation. $C_c$ was calculated as ratio of canopy width to row width (equation 4.2). The observations during MicroWEX-3 were interpolated to provide the MB-Cotton model with inputs at every fifteen minutes, matching the temporal frequency of the other inputs. The interpolation used statistical models in the form of

$$Y = Y_{max} \cdot [1 - \exp(\beta \cdot t)]$$

(5.5)

where $Y$ is the interpolated variable, $Y_{max}$ is the maximum value of the variable observed during the season. $Y_{max}$ was equal to the average of the last four data points from the vegetation sampling during MicroWEX-3. $\beta$ is the regression coefficient, and $t$ is number of days since emergence. The 95% confidence interval ($\delta$) on the nonlinear least squares parameter, $\beta$ given the residuals and the Jacobian matrix at the solution for $M_g$ and $C_c$.
using equation (5.5) were 0.0195 and 0.0312, respectively. However, the $\delta$ values for $H_c$ was small at $10^{-5}$, suggesting that the nonlinear fit using equation (5.5) was inadequate.

To simplify the nonlinear fit, a cubic spline method was used instead (see Figure 5-4(a)).

Table 5-3 shows the regression coefficients and $R^2$ values of the empirical models for $C_c$ and $M_g$. Figure 5-4 shows the observed and interpolated vegetation input variables. The values of $H_c$ and $C_c$ were calculated as the mean of four measurements for each sampling location, while the values of $M_g$ were the sum of the $M_g$ in leaves, stems, squares, and bolls.

Table 5-3. Regression coefficients $\beta$ and $Y_{\text{max}}$ values for the canopy cover ($C_c$) and gravimetric water content of canopy ($M_g$) empirical models.

<table>
<thead>
<tr>
<th></th>
<th>$\beta$</th>
<th>$Y_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_c$</td>
<td>0.0205</td>
<td>0.8766</td>
</tr>
<tr>
<td>$M_g$</td>
<td>0.0337</td>
<td>2.2324</td>
</tr>
</tbody>
</table>

Figure 5-4. Input variables for vegetation: (a) Canopy height ($H_c$), (b) canopy cover ($C_c$), and (c) gravimetric water content of cotton ($M_g$) observed during MicroWEX-3. Error bars show one standard deviation around the mean values.
Dielectric Properties for Soil and Vegetation

The dielectric properties of the soil and vegetation were estimated by the four-component mixing model and dual-dispersion model as shown in equation (4.9) and (4.19), respectively. Figure 4-2 shows the effective depth ($Z_{\text{eff}}$) at C-band as a function of volumetric soil moisture content (VSM) using the mixing model. Minimum soil moisture observed during simulation period was 5% so that the maximum $Z_{\text{eff}}$ was \sim 2.0 cm for the simulation period.

Evaluation Methodology

The simulation period of the MB-Cotton model started on DOY 196 (July 14) and ended on DOY 314 (November 9) in 2004. The simulation was conducted during the dry down periods only, beginning at 24 hours after irrigation or precipitation events.

The growing season was divided into sub-seasons based upon the phenological stages of the cotton canopy (Chapter 2). The early season started with germination on DOY 196 to squares formation on DOY 234. The mid season was from DOY 234 to 50% boll formation on DOY 288. The late season was between DOY 288 to the last day of simulation on DOY 314 with 12% of the bolls opened (Figure 2-55).

As mentioned earlier, the maximum $Z_{\text{eff}}$ at C-band with given soil moisture field condition was 2.0 cm. Smaller values of $Z_{\text{eff}}$ are expected during the dry down periods when VSM was between 10 to 20%. For example, when VSM is 20%, $Z_{\text{eff}}$ is \sim 1.0 cm (Figure 4-2). The closest measurement of VSM to the surface was at 2 cm during MicroWEX-3. This observation measures an average VSM between 1 and 3 cm. Continuous monitoring VSM at depths < 2 cm are not feasible using soil moisture probes that are currently available. Because $Z_{\text{eff}} = \sim 2.0$ cm, detailed soil moisture and temperature profiles in the top 2 cm are very crucial for accurate simulation of $T_B$ at C-
band because of its high temporal variation. To investigate this issue further, two simulations were conducted with the MB-Cotton model. First with observed VSM and temperature at 2 cm and second with estimated VSM and temperature profiles in the top 2 cm by the LSP model (Figure 5-2 and 5-3). The $T_B$ from these two simulations were compared with field observed $T_B$ during MicroWEX-3 (see Figure 2-39).

**Results and Discussion**

**The Early Season**

For the early season, the MB-Cotton model was run for 39 days from DOY 196 (July 14) through 234 (August 21) in 2004. The biomass and plant water content of the canopy were less than 0.4 and 0.3 kg/m$^2$, respectively (Figure 2-45 and 2-46). The cotton was heavily irrigated and there were seven dry down periods. Table 5-4 shows the start and end times for these dry down periods.

Table 5-4. The start and end times of the dry down period in the early season during MicroWEX-3.

<table>
<thead>
<tr>
<th>No</th>
<th>Start Time</th>
<th>End Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
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</tr>
<tr>
<td>7</td>
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</tr>
</tbody>
</table>

**Comparison using VSM and temperature from LSP**

Figure 5-6(a) shows the simulated and observed $T_B$ at H-pol using LSP estimated soil moisture and temperature profiles during the early season. Overall, the MB-Cotton model captured the phases of the diurnal variation well, as seen in Figure 5-6(a). Figure 5-6(b) to (c) shows the VSM, surface temperatures, and soil temperatures simulated by the LSP model and observed during MicroWEX-3, respectively.
Figure 5-6. Comparison of the simulated and observed $T_B$ at H-pol at 6.7 GHz using (a) 0-2 cm LSP simulated soil temperature and moisture as inputs to the MB-Cotton model, (b) the 2 cm observed and 0 to 2 cm LSP simulated VSM, (c) the observed and LSP simulated surface temperatures, and (d) the 2 cm observed and 0 to 2 cm LSP simulated soil temperatures during the early season of MicroWEX-3.
The \( T_B \) simulated by the MB-Cotton model matched well with the observed \( T_B \) during the first 11 hours of dry down with mean absolute differences (MAD) and root mean square differences (RMSD) of 3.2 and 3.6 K, respectively (Table 5-5). During the dry down periods from DOY 203 to 219, the MB-Cotton model estimated the phases well, but the estimated \( T_B \) were higher by \( \sim 15 \) K than the observed \( T_B \) during the day. The \( T_B \) from the MB-Cotton model matched well with observations during the night. This could be due to the underestimation of the VSM by the LSP model during the day by \( \sim 4 \) % (see Figure 5-6(b)). During the last two dry downs on DOY 230 and 233, the MB-Cotton model matched the observed \( T_B \) well during the day with low MAD and RMSD, whereas the model overestimated the observed \( T_B \) by \( \sim 20 \) K during the night. This could be due to the underestimation in VSM by the LSP model during the night by \( \sim 6 \) % during this period (see Figure 5-6(b)).

Table 5-5. Mean absolute differences (MAD) and root mean square differences (RMSD) using MicroWEX-3 measurements at 2 cm (2 cm) and LSP estimations between 0 and 2 cm (0-2 cm) during the dry down in the early season during MicroWEX-3.

<table>
<thead>
<tr>
<th>No.</th>
<th>MAD (K)</th>
<th>RMSD (K)</th>
<th>MAD (K)</th>
<th>RMSD (K)</th>
</tr>
</thead>
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<td>LSP: 0-2 cm</td>
<td>LSP: 0-2 cm</td>
<td>MicroWEX: 2 cm</td>
<td>MicroWEX: 2 cm</td>
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<td>6.2</td>
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<td>11.5</td>
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</tr>
</tbody>
</table>

Comparison using observed VSM and temperature at 2 cm

Figure 5-7 shows the simulated \( T_B \) at H-pol using field observed soil temperature and moisture at 2 cm and those observed during the early season. Overall, the amplitudes of diurnal variation were significantly underestimated by the MB-Cotton model. The
diurnal amplitudes of the observed $T_B$ were $\sim$60, 40, and 20 K, respectively; whereas the diurnal amplitude of the $T_B$ simulated was only $\sim$15 K. This underestimation of diurnal amplitude is primarily because of the misrepresentation of VSM profile in the effective depth, $Z_{\text{eff}}$. Because $Z_{\text{eff}} < 1\text{cm}$ when VSM is greater than 20 % (Figure 4-3), using VSM at 2 cm as input does not provide realistic soil moisture distribution from 0 to 1 cm necessary to estimate diurnal amplitude in $T_B$ simulation to those observed (see Figure 5-6(b)).

![Figure 5-7](image_url)  
Figure 5-7. Comparison of the simulated and observed $T_B$ at H-pol at 6.7 GHz during the early season of MicroWEX-3 using 2 cm field observed soil temperature and moisture as inputs to the MB-Cotton model.

During the early season, the average values of MAD and RMSD between observed and simulated $T_B$ using 0 to 2 cm soil moisture and temperature estimated by LSP were 6.9 and 8.5 K, respectively; whereas average values of MAD and RMSD between observed and simulated $T_B$ using 2 cm soil moisture and temperature measurements were 7.5 and 9.3 K, respectively.

**The Mid Season**

For the mid season, the MB-Cotton model was run for 55 days from DOY 234 (August 21) through 288 (October 14). During this period, formation of cotton square began on DOY 234 and bolls formation began on DOY 253. About 40 and 50 % of
cotton bolls forming were observed on DOY 281 and 288, respectively. Figure 5-8 shows the cotton canopy at the beginning and end of this period. The vegetation properties increased significantly (Figure 2-42 to 2-45). The biomass and plant water content of the canopy components, leaves and stems increased from DOY 234 and achieved maximum values on ~DOY 273, whereas the biomass and plant water content (PWC) of squares and bolls kept increasing from ~0.4 to 1 kg/m² (Figure 2-47 to 2-54). The crop was irrigated five times and several precipitation events occurred, resulting in eleven dry down periods in the mid season. Table 5-6 shows the start and end times of these dry down.

Table 5-6. The start and end times of the dry down period in the mid season during MicroWEX-3.

<table>
<thead>
<tr>
<th>No</th>
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<th>End Time</th>
</tr>
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<tr>
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<td>286.6</td>
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</table>
Comparison using VSM and temperature from LSP

Figure 5-9(a) shows the simulated and observed $T_B$ at H-pol using LSP estimated soil temperature and moisture profiles at 0 to 2 cm as model inputs during the mid season, from DOY 234 and DOY 288 when ~50% of the bolls were formed. Overall, the phases of the $T_B$ estimated by the MB-Cotton model matched well the phases of the observed diurnal variations. During the first two dry downs, the model overestimated the $T_B$ compared to the observed $T_B$ by average of 6 K. This could be caused by an overestimation in canopy emission due to an overestimation in gravimetric water content ($M_g$) of the vegetation (Figure 5-4(c)) during this period. $M_g$ was calculated using the total water content in the canopy without accounting for the distribution of moisture in different components. The effective depth of the canopy, only a few cm, is very sensitive to the optical depth ($\tau$) of the canopy. As the cotton square formation begins, usually underneath the leaves, the emission from the canopy could be more complicated and using one effective $\tau$ may not be realistic. Although the assumption of canopy cloud model with homogeneous dielectric properties was a good approximation for cotton canopy, information about the distribution of the moisture in different components of the canopy as the reproductive stages began would help to improve the accuracy of simulation during this period. As bolls formation began on DOY 258, the model estimated the phases and amplitudes of the diurnal variations very well during the third dry down period as suggested by the values of MAD and RMSD of 4.0 and 5.3 K, respectively (Table 5-7). After DOY 262 until the end of the mid season, the MB-Cotton model matched the observed $T_B$ well during the day by the average MAD and RMSD of 6.3 and 7.2 K, respectively. But the model underestimated the observed $T_B$ at night by ~8 K.
Figure 5-9. Comparison of the simulated and observed $T_B$ at H-pol at 6.7 GHz using (a) 0-2 cm LSP simulated soil temperature and moisture as inputs to the MB-Cotton model, (b) the 2 cm observed and 0 to 2 cm LSP simulated VSM, (c) the observed and LSP simulated surface temperatures, and (d) the 2 cm observed and 0 to 2 cm LSP simulated soil temperatures during the mid season of MicroWEX-3.
Table 5-7. Mean absolute differences (MAD) and root mean square differences (RMSD) using MicroWEX-3 measurements at 2 cm (2 cm) and LSP estimations between 0 and 2 cm (0-2 cm) during the dry down in the mid season during MicroWEX-3.

<table>
<thead>
<tr>
<th>No.</th>
<th>MAD (K) 0-2 cm</th>
<th>RMSD (K) 0-2 cm</th>
<th>MAD (K) 2 cm</th>
<th>RMSD (K) 2 cm</th>
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<td>2.9</td>
<td>3.5</td>
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<td>3.2</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>4.3</td>
<td>5.7</td>
<td>5.9</td>
</tr>
<tr>
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<td>7.3</td>
<td>8.4</td>
<td>10.0</td>
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<tr>
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<td>8.4</td>
<td>7.2</td>
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</tr>
<tr>
<td>11</td>
<td>3.9</td>
<td>4.6</td>
<td>8.2</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Because $C_c$ was ~0.6 during this period, i.e. the bare soil cover fraction was 0.4, the signal from the bare soil fraction was overestimation by ~6 % in VSM by the LSP model (Figure 5-9(b)). Figure 5-9(c) shows the comparison between the surface temperatures observed by the thermal infrared (TIR) sensor and simulated by the LSP model. During the night, the observed surface temperatures were higher than those simulated by the LSP model by ~4 K.

**Comparison using observed VSM and temperature at 2 cm**

Figure 5-10 shows the simulated and observed $T_B$ at H-pol using field observed soil temperature and moisture profiles at 2 cm as model inputs during the mid season.

Between DOY 240 and 245, the MB-Cotton model captured the phases and amplitudes of diurnal variation. After DOY 253, the model consistently underestimated the observed $T_B$ by ~15 K. This could be because the soil at 2 cm was consistently wetter than that at 0 to 1 cm during this time by ~6 % (Figure 5-9(b)).
Figure 5-10. Comparison of the simulated and observed $T_B$ at H-pol at 6.7 GHz during the mid season of MicroWEX-3 using 2 cm field observed soil temperature and moisture as inputs to the MB-Cotton model.

During the mid season, the average values of MAD and RMSD between observed and simulated $T_B$ using 0 to 2 cm soil moisture and temperature profiles simulated by the LSP model were 5.7 and 6.7 K, respectively; whereas average values of MAD and RMSD between observed and simulated $T_B$ using 2 cm soil moisture and temperature measurements were 6.8 and 7.6 K, respectively. During the mid season, the assumption of non-scattering canopy cloud model is valid because the mean values of the simulated $T_B$ using both field observations and LSP estimations as inputs were less or equal to that of the observed $T_B$.

The Late Season

For the late season, the MB-Cotton model was run for 27 days from DOY 288 (October 14) through 314 (November 9). During this period, cotton bolls began to open on DOY 292. On DOY 314, about 12% of the cotton bolls were opened. Figure 5-11 shows the cotton canopy during the third sub-season. During this period, the crop height and width reached constant values of ~1.0 and 0.6 m, respectively (Figure 2-42 and 2-43). The biomass and plant water content kept increasing (Figure 2-45 and 2-46). This is because the biomass of the cotton boll increased exponentially in the late season (Figure
There was no irrigation applied to the crop during the late season. Table 5-8 shows the start and end times of the dry down periods in the late season.

![Cotton canopy in the late season](image)

Figure 5-11. Cotton canopy in the late season. The photo was taken on DOY 306 (November 1).

Table 5-8. The start and end times of the dry down period in the late season during MicroWEX-3.

<table>
<thead>
<tr>
<th>No</th>
<th>Start Time</th>
<th>End Time</th>
</tr>
</thead>
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</table>

**Comparison using VSM and temperature from LSP**

Figure 5-12(a) shows the simulated and observed $T_B$ at H-pol using LSP estimated 0 to 2 cm soil temperature and moisture as model inputs during the late season. Between DOY 288 and 294, the MB-Cotton model matched the phases and amplitudes of diurnal variation of the observed $T_B$ well and average values of MAD and RMSD were 5.1 and 5.8 K, respectively (Table 5-9). Starting from DOY 295 until the end of season, the model matched the observed $T_B$ well during the night fairly well. But the model overestimated the observed $T_B$ during the day by an average of ~10 K.
Figure 5-12. Comparison of the simulated and observed $T_B$ at H-pol at 6.7 GHz using (a) 0-2 cm LSP simulated soil temperature and moisture as inputs to the MB-Cotton model, (b) the 2 cm observed and 0 to 2 cm LSP simulated VSM, (c) the observed and LSP simulated surface temperatures, and (d) the 2 cm observed and 0 to 2 cm LSP simulated soil temperatures during the late season of MicroWEX-3.
Table 5-9. Mean absolute differences (MAD) and root mean square differences (RMSD) using MicroWEX-3 measurements at 2 cm (2 cm) and LSP estimations between 0 and 2 cm (0-2cm) during the dry down in the mid season during MicroWEX-3.

<table>
<thead>
<tr>
<th>No.</th>
<th>MAD (K)</th>
<th>RMSD (K)</th>
<th>MAD (K)</th>
<th>RMSD (K)</th>
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<td>2 cm</td>
<td>2 cm</td>
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<td>8.9</td>
<td>4.4</td>
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</table>

The average MAD and RMSD during this period were 5.8 and 7.3 K, respectively (Table 5-9). This is primarily because the LSP model underestimated the VSM at 0 to 2 cm during the day by ~3 % (Figure 5-12(b)). This might be due to the unrealistic representation of the moisture transport in LSP model process at night when the cotton canopy begins to senesce. If the VSM profiles estimated by LSP model could be improved significantly, the accuracy of $T_B$ simulation should improve as well.

**Comparison using observed VSM and temperature at 2 cm**

Figure 5-13 shows the simulated and observed $T_B$ at H-pol using field observed soil temperature and moisture at 2 cm as model inputs during the late season. During DOY 288 to 294, the MB-Cotton model captured the phases of the diurnal variation. However, the model underestimated the diurnal amplitude by ~10 K. This is because the underestimation in VSM measured at 2 cm when the cotton canopy was mature. During the period of three days after the beginning of formation of open bolls (DOY 295) and when ~10 % of the cotton bolls were opened (DOY 307), the model captured the phases and amplitudes of the diurnal variation very well. The MAD and RMSD during this period were 2.4 and 3.2 K, respectively. During DOY 309 and 315, the model captured the phases of the diurnal variation of the observed $T_B$. But the amplitudes were
underestimated from DOY 312 to DOY 315. This is because $C_c$ was underestimated. Toward the end of season due to the defoliation, defoliation decreased the density of leaves in cotton canopy. Therefore, the contribution from bare soil emission increased because of less extinction of the radiation emitted from the bare soil underneath the canopy. The accuracy of canopy emission could be improved by a better representation of $C_c$. An empirical function that relates the $C_c$ to LAI would account for the overestimation of $C_c$ toward the end of the season when the density of the leaves decreases.

![Figure 5-13. Comparison of the simulated and observed $T_B$ at H-pol at 6.7 GHz during the late season of MicroWEX-3 using 2 cm field observed soil temperature and moisture as input to the MB-Cotton model.](image)

During the late season, the average values of MAD and RMSD between observed and simulated $T_B$ using 0 to 2 cm soil moisture and temperature profiles simulated by the LSP model were 5.5 and 6.9 K, respectively; whereas average values of MAD and RMSD between observed and simulated $T_B$ using 2 cm soil moisture and temperature measurements were 4.0 and 5.1 K, respectively. During the late season, the non-scattering canopy cloud model is also applicable to cotton canopy because the mean values of the simulated $T_B$ using both inputs were smaller than that of the observed $T_B$. 
The Complete Growing Season

Based upon the results found from the previous sections for early, mid, and late seasons, 0 to 2 cm LSP estimated soil temperatures and moisture profiles were used for simulation from the beginning of the season to DOY 294. Due to the underestimation in VSM by the LSP model after DOY 196, the observed VSM and temperature at 2 cm were used for the MB-Cotton model simulation for the rest of season. Figure 5-14 shows the comparison of the observed $T_B$ and simulated $T_B$ using 2 cm measured temperature and VSM and 0 to 2 cm temperature and moisture profiles estimated by the LSP model before DOY 196 for the whole growing season.

Figure 5-14. Comparison of the observed and simulated $T_B$ at H-pol using 2 cm measured temperature and VSM and 0 to 2 cm temperature and moisture profiles estimated by the LSP model before DOY 196 during the whole season of MicroWEX-3.

For the whole season, during the dry down period, using LSP estimated temperature and moisture profiles at 0 to 2 cm produced the MAD and RMSD between the simulated and observed $T_B$ were 5.1 and 6.3 K, respectively. The canopy scattering was not significant for the cotton canopy at C-band. During the infiltration, MB-Cotton model using LSP estimated temperature and moisture profiles at 0 to 2 cm overestimated the $T_B$ in the early and mid seasons. During the late season, the MB-Cotton model
overestimated the observed $T_B$. This was primarily because the infiltration process in the LSP model was yet to modified for sandy soils.

**Conclusion**

In this chapter, the MB-Cotton model was evaluated for a growing season. The whole growing season was divided into three sub-seasons based upon the phenological stages. The field observed VSM and temperature at 2 cm were used as inputs to the MB-Cotton model as well as those at 0 to 2 cm estimated by the LSP model. To evaluate the results, the simulated $T_B$ were compared to the $T_B$ observed for the dry down periods during MicroWEX-3. The MB-Cotton model was evaluated only during the dry down periods primarily because the infiltration process in the LSP model was yet to modified for sandy soils.

This chapter provides results to the third research question mentioned in Chapter 1 follows: Third question: **“How well does the MB-Cotton model capture the observed brightness using soil moisture at 2 cm?”** During the early season between emerging and square forming, the $T_B$ simulated by the MB-Cotton model using 2 cm soil moisture and temperature measurements matched the phases of the observed $T_B$. The average values of MAD and RMSD between the observed and modeled $T_B$ were 7.5 and 9.3 K, respectively. During the mid season, although the model captured the phases of diurnal variation, the model underestimated the diurnal amplitudes. The average values of MAD and RMSD were 6.8 and 7.6 K, respectively. During late season, the model captured the phases and amplitudes of the diurnal variation very well. The average values of MAD and RMSD were 4.0 and 5.1 K, respectively. Based upon the average values of sensitivities of $T_B$ to changes in VSM assuming uniform vertical distribution of VSM (see Chapter 6), the $T_B$ simulated by the MB-Cotton model using 2 cm soil moisture and
temperature measurements produced an error of ~2 % in VSM during the early and mid season, while the errors reduced to ~1 % during the late season.

The chapter also provides the Fourth question: “**How well does the MB-Cotton model capture the observed brightness if the detailed soil moisture information is available for the effective depth?**” Based upon the results of model evaluation during the early season, the accuracy of MB-Cotton model simulation could be improved by calibrating the underestimation in VSM estimated by the LSP model of ~4 % during the day and ~6 % during the night. Because $T_B$ at C-band is not sensitive to changes in VSM during the mid and late seasons, the accuracy of MB-Cotton model simulation did not improve significantly using detailed VSM between 0 and 2 cm during these time.

Forth question: “**Is scattering in the canopy important for simulating accurate $T_B$ when cotton reaches maturity?**” as follows: Based upon these results of comparison between modeled and observed $T_B$, the volume scattering is not significant in mature cotton canopy at C-band. Because the mean values of the simulated $T_B$ using both field observations and LSP estimations as inputs were less or equal to that of the observed $T_B$, inclusion of scattering will further decrease the model estimates of $T_B$. 
CHAPTER 6
SENSITIVITY ANALYSIS OF BRIGHTNESS TEMPERATURE TO CHANGES IN SOIL MOISTURE

In this chapter, the sensitivity of $T_B$ to changes in soil moisture and temperature for a growing season of cotton were investigated. Observations from MicroWEX-1 and 3 were used to discuss changes in these sensitivities with growing cotton. Because $T_B$ is a complex function of moisture and temperature distributions, the empirical relationships for plant water content (PWC) versus gravimetric water content ($M_g$), canopy height ($H_c$), and canopy cover ($C_c$) collected during MicroWEX-3 were utilized so that the MB-Cotton model described in Chapter 4 could be used to calculate sensitivities due to changes only in moisture or temperature as PWC increases. These simulated sensitivities were compared with those observed during MicroWEX-3 for the growing season. Finally, the simulated and observed sensitivities during MicroWEX-3 were compared to the observed sensitivities during MicroWEX-1.

**MicroWEX-3 Season**

**Simulated Sensitivity Using MB-Cotton Model**

The sensitivities of $T_B$ to changes in VSM using MB-Cotton model can be found by taking the partial derivative of equation (4.1) with respect to VSM as:

$$\frac{\Delta T_{B,p}}{\Delta VSM} = (1 - C_c) \cdot \frac{\Delta T_{B,S,p}}{\Delta VSM} + C_c \cdot \frac{\Delta T_{B,C,p}}{\Delta VSM}$$

(6.1)

The first term or the bare soil term can be expressed in detail as:

$$\frac{\Delta T_{B,S,p}}{\Delta VSM} = T_{B,sky} \cdot \frac{\Delta \Gamma_p}{\Delta VSM} + \frac{\Delta T_{eff}}{\Delta VSM} \cdot (1 - \Gamma_p) - T_{eff} \cdot \frac{\Delta \Gamma_p}{\Delta VSM}$$

(6.2)
and the second term or the canopy term can be expressed as:

$$\frac{\Delta T_{B,C,p}}{\Delta VSM} = \frac{\Delta T_{Sky}}{\Delta VSM} + \frac{\Delta T_{Soil}}{\Delta VSM} + \frac{\Delta T_{Canopy}}{\Delta VSM}$$  \hspace{1cm} (6.3)

where

$$\frac{\Delta T_{Sky}}{\Delta VSM} = T_{B,sky} \cdot \exp(-2\tau_c) \cdot \frac{\Delta \Gamma_p}{\Delta VSM}$$  \hspace{1cm} (6.4)

$$\frac{\Delta T_{Soil}}{\Delta VSM} = \exp(-\tau_c) \cdot \left\{ \frac{\Delta T_{eff}}{\Delta VSM} \cdot (1-\Gamma_p) - T_{eff} \cdot \frac{\Delta \Gamma_p}{\Delta VSM} \right\}$$  \hspace{1cm} (6.5)

$$\frac{\Delta T_{Canopy}}{\Delta VSM} = [1 - \exp(-\tau_c)] \cdot \left\{ T_{canopy} \cdot \exp(-\tau_c) \cdot \frac{\Delta \Gamma_p}{\Delta VSM} \right\}$$  \hspace{1cm} (6.6)

Here, the vegetation properties, such as $\tau_c$ and $T_{canopy}$ were assumed to be independent of the changes in VSM. Also, $\Delta T_{eff}/\Delta VSM$ is zero under isothermal condition.

Because PWC is independent of vegetation type, it is a widely used canopy variable to express the sensitivity of $T_B$. The values of PWC are not directly used in the MB-Cotton model, but they can be empirically related to the input vegetation variables ($M_g, C_c$, and $H_c$). Figure 6-1 (a), (b), and (c) show the relationships between the vegetation properties to $C_c$ from vegetation sampling data and regression models. The correlation between $M_g$ was linear until $C_c = 0.45$. Then constant $M_g$ was observed from $C_c = 0.45$ to 1.0. A similar trend was also observed for the correlation between $H_c$ and $C_c$ whereas a plateau occurred after $C_c = 0.7$. A linear relationship was used between $C_c$ and PWC because PWC did not reach a constant value as $C_c$ increased. Table 6-1 shows the R-square values for $M_g$ and $C_c$ (Figure 6-1(a)), $H_c$ and $C_c$ (Figure 6-1(b)), and PWC and $C_c$ (Figure 6-1(c)).
$M_g = 4.92C_c \ (C_c \leq 0.45); \ M_g = 2.21 \ (C_c > 0.45)$

$H_c = 1.30C_c \ (C_c \leq 0.7); \ H_c = 0.91 \ (C_c > 0.7)$

$PWC = 1.35C_c$

Figure 6-1. Relationships between the vegetation properties derived using data collected during MicroWEX-3.

Table 6-1. R-square ($R^2$) values for the fits for the relationships between $M_g$, $H_c$, and $PWC$ versus $C_c$.

<table>
<thead>
<tr>
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<th>$R^2$</th>
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</thead>
<tbody>
<tr>
<td>$M_g$-$C_c$</td>
<td>0.3893</td>
</tr>
<tr>
<td>$H_c$-$C_c$</td>
<td>0.8711</td>
</tr>
<tr>
<td>$PWC$-$C_c$</td>
<td>0.4779</td>
</tr>
</tbody>
</table>

$T_B$ at H- and V-pol were calculated with incremental increases in VSM during the growing season as $PWC$ increased from 0 (bare soil) to 1.2 kg/m$^2$. The incremental increases in VSM ranged from dry (5 %) to saturated soil (35 %). The soil layers and
vegetation canopy were isothermal at 300 K, similar to the average effective temperature observed during MicroWEX-3. The VSM was assumed to be constant at the effective depth ($Z_{\text{eff}}$), 0 to 2 cm, for the sensitivity of $T_B$ to changes in effective temperature calculation. The cotton canopy was assumed to consist of uniformly distributed dielectric materials. A set of input data was generated for the MB-Cotton model described in Chapter 4. The model simulated the H- and V-pol $T_B$ with incremental increases in VSM as PWC increased from 0 (bare soil) to 1.2 kg/m$^2$ ($C_c = 0.9$). The sensitivities of $T_B$ to changes in VSM was calculated as:

$$
\frac{\Delta T_{B,p}}{\Delta VSM} = \left| \frac{T_{B,p,2} - T_{B,p,1}}{VSM_2 - VSM_1} \right|
$$

(6.7)

where $T_{B,p,1}$ and $T_{B,p,2}$ are the brightness temperatures calculated by the MB-Cotton model using soil moisture values of $VSM_1$ and $VSM_2$, respectively. The incremental increases from $VSM_1$ to $VSM_2$ ranged from 5-6, 10-11, 20-21, 30-31 and 35-36 % as the range observed during MicroWEX-3.

The sensitivities of $T_B$ to changes in $T_{\text{eff}}$ was calculated as:

$$
\frac{\Delta T_{B,p}}{\Delta T_{\text{eff}}} = \left| \frac{T_{B,p,2} - T_{B,p,1}}{T_{\text{eff},2} - T_{\text{eff},1}} \right|
$$

(6.8)

where $T_{B,p,1}$ and $T_{B,p,2}$ are the brightness temperatures calculated by the MB-Cotton model using soil temperature values of $T_{\text{eff},1} = T_{\text{canopy},1} = 300$ K and $T_{\text{eff},2} = T_{\text{canopy},2} = 301$ K, respectively. To calculate the sensitivity of $T_B$ to changes in $T_{\text{eff}}$, the VSM profile was constant at 20 %.

Figure 6-2 and 6-3 show the sensitivities of the $T_B$ at H- and V-pol to changes in soil moisture over the growing season as estimated by the MB-Cotton model.
Figure 6-2. Sensitivity of the model brightness temperatures to changes in volumetric soil moisture (VSM) at different plant water content (PWC) at H-pol. For this simulation, $T_{\text{canopy}} = T_{\text{eff}} = 300$ K.

Figure 6-3. Sensitivity of the model brightness temperatures to changes in volumetric soil moisture (VSM) at different plant water content (PWC) at V-pol. For this simulation, $T_{\text{canopy}} = T_{\text{eff}} = 300$ K.
The TB are the most sensitive to soil moisture changes in bare soil conditions and when the soil is dry. The sensitivity decreases linearly with increasing soil wetness for H-pol, whereas the decrease is not linear for V-pol (see Figure 6-2 and 6-3). The sensitivity of the TB at H-pol was 5.6 K/\% for dry soil (VSM = 5-6 %) and the sensitivity decreased to 1.5 K/\% for saturated soil (VSM = 35-36 %). The sensitivity of the TB at V-pol was low at 1.6 K/\% for very dry soil, increased to its maximum of 2.0 K/\% at VSM = 20-21 \%, and decreased to 1.7 K/\% for VSM = 35-36 \% (see Figure 6-3). The sensitivity was maximum at 20 \% VSM because the reflectivity at V-pol is a second order function of dielectric property of the soils (see equation (4.4)), with the smallest value of emissivity occurring at VSM = 20 \%. As the PWC increases, the sensitivities of TB at H- and V-pol decrease linearly. This is primarily because of the linear empirical relationships shown in Figure 6-1. The sensitivity of the TB to soil moisture decreased significantly to less than 1.0 K/\% for both polarizations when vegetation water content is > 1.1 kg/m\(^2\). Finally, it should be noted that the sensitivity curves shown in Figure 6-2 and 6-3 were derived from the experimental data. Therefore, the simulated sensitivity of TB to changes in VSM is diminished when \(C_c = 1\).

Figure 6-4 to 6-6 show the sensitivity of modeled TB to changes in effective physical temperature of bare soil (\(T_{\text{eff}}\)) as VSM increases from 5 to 35 \% when PWC = 0, 0.5, and 1.2 kg/m\(^2\), which are the average PWC values observed during the early, mid, and late season during MicroWEX-3. The sensitivity of TB to changes in \(T_{\text{eff}}\) is obtained by calculating the differences between the TB at the \(T_{\text{eff}}\) of 300 and 301 K for 5 to 35 \% VSM. When PWC = 0 kg/m\(^2\), the sensitivity of TB to \(T_{\text{eff}}\) is < 0.75 K/K with the sensitivity decreasing to 0.51 K/K at H-pol.
Figure 6-4. Sensitivity of brightness temperatures to effective physical temperature of soil ($T_{\text{eff}}$) for bare soil condition, i.e. PWC = 0 kg/m$^2$.

Figure 6-5. Sensitivity of brightness temperatures to effective physical temperature of soil ($T_{\text{eff}}$) for PWC = 0.5 kg/m$^2$.

Figure 6-6. Sensitivity of brightness temperatures to effective physical temperature of soil ($T_{\text{eff}}$) for PWC = 1.2 kg/m$^2$. 
At V-pol, the sensitivity of $T_B$ to $T_{\text{eff}}$ is < 0.99 K/K with the sensitivity decreasing to 0.93 K/K (see Figure 6-4). When PWC = 0.5 kg/m$^2$, the sensitivity of $T_B$ to $T_{\text{eff}}$ is < 0.85 K/K with the sensitivity decreasing to 0.71 K/K at H-pol. At V-pol, the sensitivity of $T_B$ to $T_{\text{eff}}$ is < 0.99 K/K with the sensitivity decreasing to 0.95 K/K (see Figure 6-5). When PWC = 1.2 kg/m$^2$, the sensitivity of $T_B$ to $T_{\text{eff}}$ is < 0.97 K/K with the sensitivity decreasing to 0.95 K/K at H-pol. At V-pol, the sensitivity of $T_B$ to $T_{\text{eff}}$ is < 0.99 K/K (see Figure 6-6). As PWC increases, the sensitivities of $T_B$ to $T_{\text{eff}}$ and $T_{\text{canopy}}$ increase because the terrain emission is dominated by the canopy emission, which is independent upon VSM.

**Observed Sensitivity**

Figure 6-7 shows the close up of $T_B$ and VSM during a part of the early season. Between DOY 204 and 214, the values of LAI and PWC were < 0.5 and 0.0 kg/m$^2$, respectively (Figure 2-44 and 2-46) and both crop height and width of 5 cm (Figure 2-42 and 2-43). On DOY 205.6, the $T_B$ at H- and V-pol decreased by 100 K and 80 K, respectively. The decreases in $T_B$ corresponded to an increase in the VSM of 12 % at 2 cm depth. Another series of irrigation events occurred from DOY 209 to 211. During this period, corresponding to an average increase in VSM by 10 %, the decreases in $T_B$ at H- and V-pol were 97 and 42 K, respectively. Because $T_B$ is a function of both $T_{\text{eff}}$ and VSM, a part of the observed decrease in $T_B$ is due to a sudden change in $T_{\text{eff}}$. The decrease in $T_{\text{eff}}$ during these irrigation events was ~2 K. Based upon the sensitivities of $T_B$ to $T_{\text{eff}}$ simulated by the MB-Cotton model (Figure 6-4), thus resulted in the decrease in $T_B$ at H- and V-pol of ~1.5 and 2.0 K, respectively. Accounting for the decreases in $T_{\text{eff}}$ by the MB-Cotton model, the average values of $\Delta T_B/\Delta VSM$ at H- and V-pol during the early season were 8.8 and 5.3 K/%, respectively.
Figure 6-7. Response of brightness temperatures at V- and H-pol to the soil moisture changes at 2 cm during the early season.

Figure 6-8 shows the close up of $T_B$ and VSM during a part of the mid season. Between DOY 253 and 256, the values of LAI and PWC were ~1.5 and 0.5 kg/m², respectively (Figure 2-44 and 2-46) and crop height and width of 60 and 50 cm (Figure 2-42 and 2-43), respectively. On DOY 253.6, an irrigation occurred that increased VSM at 2 cm by 8%. The decreases in $T_B$ at H- and V-pol corresponding to this event were 26 and 20 K, respectively. The decrease in $T_{eff}$ was ~1 K, resulted in the decrease in $T_B$ at H- and V-pol were 0.85 and 0.99 K, respectively. Therefore, the values of $\Delta T_B/\Delta VSM$ at H- and V-pol were 3.1 and 2.3 K, respectively.

Figure 6-8. Response of brightness temperatures at V- and H-pol to the soil moisture changes at 2 cm during the mid season.
Figure 6-9 shows the close up of $T_B$ and VSM during a part of the late season. Between DOY 299 and 303, the values of LAI and PWC were \(\sim 2.2\) and \(1.2\) kg/m\(^2\), respectively (Figure 2-44 and 2-46) and crop height and width of 90 and 70 cm (Figure 2-42 and 2-43), respectively. On DOY 300.6, the VSM at 2 cm increased by 13 \% due to irrigation. The observed $T_B$ at H- and V-pol decreased by 26 and 24 K, respectively. The decrease in $T_{eff}$ was \(\sim 2\) K, resulted in the decrease in $T_B$ at H- and V-pol were \(\sim 1.9\) and 2.0 K, respectively. The values of $\Delta T_B/\Delta VSM$ at V- and H-pol were 1.9 and 1.7 K, respectively.

The sensitivities of $T_B$ derived from the MB-Cotton model at PWC = 0 kg/m\(^2\) was 5.6 K/\% at H-pol and 1.6 K/\% at V-pol for VSM = 5-6 \%, which is the typical value observed before irrigation during MicroWEX-3. The observed $T_B$ was more sensitive to the changes in soil moisture than the modeled $T_B$. This is because of the simulated sensitivity values were based upon instantaneous VSM changes for a uniformly distributed VSM profile, whereas the observed sensitivity values were calculated using 15 minutes $T_B$ observations. Therefore, instead of a uniform vertical VSM distribution at the effective depth (\(\sim 2\) cm for C-band, see Chapter 4), there is sharp gradient of moisture.
within the top 2 cm for sandy soil during infiltration, which might be needed for accurate sensitivity simulation using MB-Cotton model.

During the mid season when LAI and PWC were ~1.5 and 0.5 kg/m², the modeled sensitivities at H- and V-pol were 2.8 and 1.0 K/%, respectively. The modeled sensitivities matched the observed sensitivities. The differences between the observed and modeled sensitivities were of an average of 0.8 K/%. The better agreement between the simulated and observed values is because the overall terrain emission was dominated by the canopy emission, which is VSM independent as the canopy developed.

During the late season when the PWC was at 1.2 kg/m², the sensitivities of the modeled TB to the changes in soil moisture were at average values of 0.6 K/% at H-pol and 0.2 K/% at V-pol. But the observed sensitivities were ~2.0 K/%. This is primarily because the contribution from the bare soil emission increased when the density of the leaves decreased due to defoliation. Therefore, the MB-Cotton model might slightly overestimate the canopy emission due to the assumption of uniformly distributed dielectric materials in the canopy. Thus, Cₖ should be slightly lower than it was assumed. The results suggested that the TB at both polarizations at C-band are still sensitive to VSM at 2 cm during the whole growing season.

**MicroWEX-1 Season**

The canopy biomass observed during MicroWEX-1 was higher than MicroWEX-3, which was a typical cotton crop (see Figure 2-36 and 2-45 in Chapter 2). Because the canopy width data during the field experiment were not available during MicroWEX-1, the model sensitivities simulated by the MB-Cotton could not be computed correctly. Thus only the observed sensitivities during MicroWEX-1 are discussed. The sensitivities simulated by the MB-Cotton model from the previous section are used to account for the
effect due to changes in $T_{\text{eff}}$. This section provides opportunity for the inter-seasonal comparison of the observed sensitivities of $T_B$ to changes in VSM from MicroWEX-1 and 3.

Figure 6-10 shows the close up of $T_B$ and VSM during a part of the early season. The $T_B$ at both polarizations responded to the precipitation and/or irrigation in the early growing season. For example, the $T_B$ at V- and H-pol decreased by 40 K and 70 K, respectively, on DOY 205.5, corresponding to an increase in the VSM of 25 % at 4 cm depth. During the increase in VSM, from 12 % to 36 %, the soil temperature at 4 cm decreased by $\sim$2 K. The $\Delta T_B/\Delta T_{\text{eff}}$ for initial VSM of $\sim$12 % were 0.48 and 0.89 K/% at H- and V-pol, respectively (Figure 6-4). This would result in a $\Delta T_B/\Delta \text{VSM}$ of 1.5 and 2.8 K/% at V- and H-pol, respectively. An intermediate response of about 15 K at V-pol and 20 K at H-pol on DOY 206.5 was observed for an increase of $\sim$10 % in volumetric soil moisture. Accounting for the $\sim$2.0 K decreased in $T_{\text{eff}}$, the values of $\Delta T_B/\Delta \text{VSM}$ for DOY 2065.5 were 1.3 and 1.9 K/% at V- and H-pol, respectively. Similar responses were also observed on DOY 212.5 and 213.8 corresponding to an increase of about 15%.

![Figure 6-10](image-url)

Figure 6-10. Response of brightness temperatures at V- and H-pol to the soil moisture changes at 4 cm during the early season.
Figure 6-11 shows the close up of TB and VSM during a part of the late season. In the late season, when the TB were dominated by emission from vegetation canopy, the sensitivity of the TB to the soil moisture diminished. The TB at both polarizations were less sensitive to the change in soil moisture. The TB did not respond significantly to increases of 20, 10, and 20 % on DOY 302, 310, and 323, respectively.

**Comparison Between MicroWEX-1 and 3 Seasons**

Table 6-2 shows the simulated and observed values of sensitivity during MicroWEX-1 and 3. Both observed TB responded to changes in VSM in the early seasons during MicroWEX-1 and 3. However, the values of observed $\Delta T_B/\Delta VSM$ at two polarizations were considerably higher during MicroWEX-3 than those during MicroWEX-1. Higher values of the observed sensitivities during MicroWEX-3 than those during MicroWEX-1 were because the measured VSM was at 2 cm during MicroWEX-3 whereas the measured VSM was at 4 cm during MicroWEX-1, recall that $Z_{eff}$ at C-band is $\sim$2 cm for the given VSM conditions. Therefore, TB at C-band is less sensitive to changes in VSM at 4 cm than to changes in VSM at 2 cm. The higher sensitivity values during the early season in MicroWEX-3 are also due to a drier field.
condition during the field experiment. During the late season, observed $T_B$ at both polarizations responded to the precipitation and/or irrigation during MicroWEX-3, whereas there was no sensitivity of $T_B$ to changes in VSM during MicroWEX-1. This is because the cotton was under typical agricultural practice of the application of growth regulators that prevented the canopy width growing from exceeding the row width during MicroWEX-3. The canopy biomass during MicroWEX-1 was higher and the canopy cover achieved unity very early in the season, as the cotton was not managed with typical growth regulators. The $T_B$ at C-band are still sensitive to changes in VSM with $PWC = 1.2 \text{ kg/m}^2$. Thus, it is still possible to use $T_B$ at C-band observations to retrieve soil moisture even during the late season of cotton.

<table>
<thead>
<tr>
<th></th>
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<th>MicroWEX-3</th>
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<tr>
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<td>Simulated (K/%)</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>V-pol</td>
<td>H-pol</td>
<td>V-pol</td>
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</tr>
</tbody>
</table>

**Conclusion**

In this chapter, the MB-Cotton model described in Chapter 4 was used to simulate sensitivities of $T_B$ to changes in VSM during the growing season of MicroWEX-3 when $PWC$ increased from 0 to 1.2 kg/m$^2$. Because $T_B$ is a function of both $T_{eff}$ and VSM, a part of the observed decrease in $T_B$ observed is due to a sudden change in $T_{eff}$. Therefore, the MB-Cotton model was used to simulate the change in $T_B$ due to changes in $T_{eff}$ under different $PWC$ conditions. The sensitivities observed during MicroWEX-3 were discussed and the modeled sensitivities were compared to the observed sensitivities. The sensitivities observed during MicroWEX-1 were also discussed and compare the
observed values between MicroWEX-1 and 3 were compared. The results suggested that
the TB at both polarizations at C-band are still sensitive to VSM at 2 cm during the whole
growing season.

This chapter provides results to the sixth research question in Chapter 1 “How
does the sensitivity of TB to soil moisture changes as cotton mature?” as follows:
During MicroWEX3, the observed sensitivities of TB at H-pol decreased from 8.8 to 1.9
K/%, while those at V-pol decreased from 5.3 to 1.7 K/%. The TB at C-band are sensitive
to changes in VSM during the whole growing season of cotton. The modeled sensitivities
using MB-Cotton were lower than the observed values and decreased from 5.6 K/%% at H-
pol and 1.6 K/%% at V-pol to less than 1 K/%% at both polarizations in the late season. Thus,
TB at C-band can be used in data assimilation for the growing season of cotton to improve
estimates of moisture and energy fluxes by the LSP model.
CHAPTER 7
CONCLUSIONS

In this chapter, the results and contributions from this dissertation are summarized and recommendations for future research are provided.

Summary

This dissertation provides important insights into microwave brightness modeling for dynamic vegetation and into sensitivity of the brightness temperatures to changes in soil moisture. The major objective of the research was to develop a microwave brightness model at C-band (6.7 GHz) for the entire growing season of cotton (one of the dominant agricultural crops in the southeastern region of the U. S.) and calibrate it using the data collected during field experiments.

Two extensive field experiments were conducted, namely MicroWEX-1 and 3. The goal of MicroWEX-1 and 3 were to investigate the interactions between the microwave brightness signatures, land surface conditions, energy components, and hydrologic processes for the whole growing season of cotton. A variety of data were collected during MicroWEX-1 and 3, including $T_B$ at C-band, soil moisture and temperature profiles, soil heat flux, surface thermal infrared temperature, upwelling and downwelling solar and longwave radiation, latent and sensible heat fluxes, and precipitation and irrigation. MicroWEX-1 and 3 are unique datasets that can be used for various inter-disciplinary studies. The data are available in the UF/IFAS website (http://edis.ifas.ufl.edu).

The observed $T_B$ were collected using the UFCMR. To assess the accuracy for the $T_B$ observations by the UFCMR during our field experiments, microwave radiometer
calibration experiments were conducted in Florida during MicroWEXs and in Alaska during REBEX-10 using two C-band radiometers with nearly identical design. The three most commonly used calibration techniques for microwave radiometers, IC, EC, and TC, were tested. Accuracy of the measured $T_B$ was evaluated using a lake emission model. The results suggested that IC produced the most consistent and accurate $T_B$. The MAE between the measured and simulated $T_B$ was $\sim 2$ K, which is suitable for soil moisture studies.

A MB-Cotton model based upon the radiative transfer equation was used to simulate the $T_B$ emitted from the terrain, which is a dynamic mixture of bare soil and cotton canopy. The bare soil emission was modeled as the emitted radiation from a specular, horizontally semi-infinite, vertically multiple-layered, non-scattering dielectric medium. The cotton canopy was modeled as an emissive, non-scattering dielectric cloud with homogeneous dielectric properties. The dielectric properties of the bare soil and canopy were obtained from literature-based dielectric mixing and dispersion models, respectively. $T_B$ at H-pol simulated by the MB-Cotton model developed in this dissertation were calibrated against the observed $T_B$ during MicroWEX-3 for the whole growing season. To investigate the effect of a dynamic cotton canopy, the simulation period for the complete growing season was divided into three sub-seasons, based upon the phenological stages. The soil moisture and temperature at 2 cm measured during the field experiment as well as the soil moisture and temperature profiles at 0 to 2 cm estimated by the LSP model were used as inputs to the MB-Cotton model to show the importance of detailed soil moisture and temperature information at 0 to 1 cm for $T_B$ simulation.
During the early season, the MB-Cotton model captured the phases of the diurnal variation well using the 0 to 2 cm soil moisture and temperature profiles estimated by the LSP model. The $T_B$ simulated by the MB-Cotton model matched well with the observed $T_B$ during first dry down period. The MB-Cotton model estimated the phases well for the rest of dry downs and matched well with observations during the night, although the model overestimated the observed $T_B$ by $\sim$15 to 20 K during the day. This could be due to the underestimation of the VSM by the LSP model by $\sim$4 and 6 %, respectively. Overall, the amplitudes of diurnal variation were significantly underestimated by the MB-Cotton model using the observed 2 cm soil moisture and temperature as inputs. The diurnal amplitudes of the observed $T_B$ during the three day dry down periods were $\sim$60, 40, and 20 K, respectively; whereas the diurnal amplitude of the simulated $T_B$ was only $\sim$15 K. The underestimation of diurnal amplitude is primarily because the strong diurnal variation in of vertical VSM distribution within the top 2 cm. Using VSM at 2 cm as input does not represent the soil moisture distribution from 0 to 1 cm realistically during dry downs in the early season. The average values of MAE and RMSE between observed and simulated $T_B$ using 0 to 2 cm LSP estimations were 6.9 and 8.5 K, respectively. The MAE and RMSE between the observed and simulated TB using 2 cm field measurements were higher at 7.5 and 9.3 K, respectively.

During the mid season, the MB-Cotton model captured the phases of observed diurnal variations well using the LSP estimated 0 to 2 cm soil moisture and temperature profiles. During the first two dry downs when cotton square formation began, the model overestimated the observed $T_B$ by $\sim$12 K during the day and $\sim$8 K during the night. This could be caused by the overestimation in canopy emission due to a slightly
overestimation in $M_g$ of the vegetation. As bolls formation began, the model estimated the phases and amplitudes of the diurnal variations very well. For the rest of the mid season, the MB-Cotton model matched the observed $T_B$ well during the day, although the model slightly underestimated the observed $T_B$ at night by $\sim$8 K. This is due to the overestimation in VSM by $\sim$6 %. During the mid season, the MB-Cotton model captured the phases and amplitudes of diurnal variation well. However, for the rest of the mid season, the model consistently underestimated the observed $T_B$ by $\sim$15 K. This could be that the soil at 2 cm was consistently wetter than that at 0 to 1 cm during this time. The average values of MAE and RMSE between observed and simulated $T_B$ using 0 to 2 cm soil moisture and temperature profiles simulated by the LSP model were 5.7 and 6.7 K, respectively; whereas average values of MAE and RMSE between observed and simulated $T_B$ using 2 cm soil moisture and temperature measurements were 6.8 and 7.6 K, respectively. The assumption of non-scattering canopy cloud model is valid because the mean values of the simulated $T_B$ using both field observations and LSP estimations as inputs were smaller than that of the observed $T_B$.

During the late season until the open boll formation began, the MB-Cotton model matched the phases and amplitudes of diurnal variation of the observed $T_B$ very well using 0 to 2 cm soil moisture and temperature profiles. For the rest of the late season, the model matched the observed $T_B$ well during the night fairly well, although the model overestimated the observed $T_B$ during the day by an average of $\sim$10 K. This is primarily because the LSP model underestimated the VSM at 0 to 2 cm during the day by $\sim$3 %. If the VSM profiles estimated by LSP model could be improved significantly, the accuracy of $T_B$ simulation will be improved as well. Until the open boll formation began in the late
season, the MB-Cotton model captured the phases of the diurnal variation using the observed 2 cm soil moisture and temperature as inputs. However, the model underestimated the diurnal amplitude by ~10 K. The model captured the phases and amplitudes of the diurnal variation very well when ~10 % bolls were opened. For the rest of the late season, the model captured the phases of the diurnal variation of the observed $T_B$. But the amplitudes were underestimated due to the underestimation in $C_c$. The accuracy of canopy emission could be improved by a better representation of $C_c$ using an empirical function relating the $C_c$ to LAI. The average values of MAE and RMSE between observed and simulated $T_B$ using 0 to 2 cm soil moisture and temperature profiles simulated by the LSP model were 5.5 and 6.9 K, respectively; whereas average values of MAE and RMSE between observed and simulated $T_B$ using 2 cm soil moisture and temperature measurements were 4.0 and 5.1 K, respectively. The non-scattering canopy cloud model is also valid during the late season.

To investigate the sensitivities of $T_B$ to changes in VSM, the MB-Cotton model was used to simulate sensitivities of $T_B$ to changes in VSM during the growing season of MicroWEX-3. The MB-Cotton model was used to simulate the change in $T_B$ due to changes in $T_{eff}$ under different PWC conditions. The modeled sensitivities were compared to the observed sensitivities during MicroWEX-3. Finally, the sensitivities observed during MicroWEX-1 were used to compare the observed values between MicroWEX-1 and 3. During MicroWEX-3, the observed $T_B$ at both polarizations were more sensitive to the changes in VSM than the modeled $T_B$. This is because of the simulated sensitivity values were based upon instantaneous VSM changes for a uniform vertical distribution in VSM, whereas the observed sensitivity values were calculated
using 15 minutes $T_B$ observations. There is sharp gradient of moisture within the top 2 cm for sandy soil during infiltration, which might be needed for accurate sensitivity simulation using MB-Cotton model. The observed sensitivities during MicroWEX-1 were lower than those observed during MicroWEX-3. Because $Z_{\text{eff}}$ at C-band is $\sim$2 cm for the given VSM conditions, $T_B$ at C-band is less sensitive to changes in VSM at 4 cm. During the late season in MicroWEX-1, the sensitivities of $T_B$ at both polarizations diminished. This is because the canopy biomass during MicroWEX-1 was higher and the canopy cover achieved unity very early in the season as cotton was not managed with typical growth regulators. The $T_B$ at C-band are still sensitive to changes in VSM with $PWC = 1.2 \, \text{kg/m}^2$. Thus, it is still possible to use $T_B$ at C-band observations to retrieve soil moisture even during the late season of cotton.

**Contributions**

The major contributions of this dissertation are the development, calibration, and sensitivity analysis of the dynamic MB model for the whole growing season of cotton. The MB model can be extended for row crops without any significant volume scattering inside the canopy.

Another significant contribution is to the extensive dataset collection during MicroWEX-1 and 3 including $T_B$ at C-band, micrometeorological data, and vegetation sampling for two growing seasons of cotton ($\sim$120 days each). These high temporal frequency datasets are very unique for land surface process, crop growth modeling, and microwave remote sensing studies.
Recommendations for Future Research

In this section, several recommendations to improve data collection during field experiments and to improve modeling $T_B$ are provided. Some of the recommendations lead to improvement of our knowledge to the near surface moisture and energy processes.

Improvements in Data Collection during Field Experiments

Several improvements were made from MicroWEX-1 to MicroWEX-3. First was automated processing of raw data in real-time immediately after download. This had significant impact on quality control of the dataset by identifying sensor malfunction in a more timely manner, and decreasing the data gaps.

Second, the vegetation sampling protocol was significantly improved and standardized for MicroWEX-3. The protocol was approved by agronomists and is available on the web (http://edis.ifas.ufl.edu). In spite of improvements from MicroWEX-1 to MicroWEX-3, several areas could still be improved, which include

1. Detailed data for the cotton canopy, such as the spatial distributions of the branches, leaves, squares, and bolls is needed for better microwave brightness model development and calibration. Also, more frequent LAI, biomass, canopy dimension observations are needed during the early growing season.
2. The field observations of VSM and temperature profiles are needed for 0 to 1 cm soil depth at high temporal frequency for MB-Cotton and LSP model calibration. The VSM observation closest to the surface for these experiments were taken at 2 cm using currently available soil moisture sensors. The importance of 0 to 1 cm VSM for accurate simulation of diurnal variation in $T_B$ at C-band was demonstrated in this dissertation in Chapter 5.

Improvements in Brightness Modeling using the MB-Cotton Model

The calibration of the MB-Cotton model could be improved by using VSM at 0 to 1 cm. Although the LSP estimated 0 to 1 cm VSM data were used for calibration, the results suggested that the LSP model overestimated the diurnal amplitude in the 0 to 1 cm
VSM. This is primarily because there was no available field observed data for VSM at 0 to 1 cm for LSP model calibration. Future research linking the MB-Cotton model to the LSP model will benefit from a robust calibration for 0 to 1 cm VSM estimated by the LSP model.

Research efforts are also needed for significant improvement to the LSP calibration during the late season, which would lead to improve the overestimation in the amplitude of diurnal variation of $T_B$ simulated by the MB-Cotton model.

The calibration of the MB-Cotton model was only applied to the periods during dry down. Future research for model calibration/validation during infiltration is needed for continuous simulations. Research efforts are underway to investigate the changes in microwave brightness signatures during irrigation and precipitation.

Finally, the estimates of dielectric constant of soil-water mixture should be improved through an experiment of dielectric property measurements for sandy soil. The dielectric model for wet soil used in this dissertation was calibrated using only five types of soils (Dobson et al., 1985). The highest sand content of these soil types was only ~50 % compared to the 92 % sand observed in MicroWEXs. A recently developed empirical dielectric model was calibrated using soil with sand content of only ~5 % (Mironov et al., 2004). However, the differences of the modeled dielectric constant of the wet soil between the dielectric model developed by Dobson et al. (1985) and Mironov et al. (2004) at C-band were less than 2 at both real and imaginary parts for sandy loam soils (sand = 51 %). They concluded that the differences would be even smaller for sandy soils because most of the uncertainty was introduced by the fraction of bound water. A
laboratory experiment of dielectric property measurements for sandy soil would verify
and extend the applicability of the currently existing dielectric models.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Kai-Jen Calvin Tien was born in Taipei, Taiwan. He received his bachelor’s degree from the Department of Agricultural Engineering at the National Taiwan University in 1999. He received his master’s degree from the Department of Agricultural and Biological Engineering at the University of Florida in 2001. For his master’s thesis, Calvin Tien conducted research in land use/land cover classification and change detection using optical and thermal remote sensing observations obtained from satellites. In the fall of 2001, he began his Ph.D. studies in microwave remote sensing. After six years of research, he graduated from the University of Florida with a Doctor of Philosophy in agricultural and biological engineering.