Modeling Transmission of Microwaves Through Dynamic Vegetation

Joaquin J. Casanova, *Student Member, IEEE*, Jasmeet Judge, *Senior Member, IEEE*, and Miyoung Jang

***Abstract*—In this paper, we develop a model for estimating canopy opacity τ for sweet corn. We estimate the refractive index based upon moisture distribution in the corn during different stages of growth. The moisture distribution was observed during two season-long field experiments. We found that the moisture content decreased linearly as the height of the corn increased, with the distribution closer to Gaussian in the fruit region during reproductive stages. The τ obtained from our model was compared to that estimated using a widely used Jackson model. In general, our τ estimates were higher than those obtained using the Jackson model, with a root mean-square difference (rmsd) of up to 0.23 Np between the two models. The τ values were used in a microwave emission model at C-band, and the model estimates of brightness were compared with field observations. We found that the model brightness temperatures matched well with observations, with rmsd's of 5.13 and 4.88 K, using our model and the Jackson model for τ, respectively.**

***Index Terms*—Microwave propagation, remote sensing, vegetation.**

I. INTRODUCTION

MICROWAVE emission models for dynamic vegetation during the growing season require accurate estimation of canopy emission and attenuation. The nonscattering attenuation is described by canopy optical depth (τ) that primarily depends upon the distribution of moisture in the canopy. Several methods have been investigated for determining canopy optical depth. For example, Ulaby and Wilson [1] modeled τ of the wheat canopy as a uniform cloud of wet biomass with leaves and stems treated separately. In addition, polarization dependence was included for stem attenuation. Eom [2] developed a model for τ that is applicable to row-structured canopies, such as wheat or corn. The model accounts for azimuthal anisotropy in τ by modeling the canopy as a random collection of dielectric spheroids. This method matched well with observations but requires a computationally intensive solution of the radiative-transfer equation. Jackson and Schmugge [3] used the results of many studies and developed an empirical model for τ. In their model, τ is estimated as the product of a frequency-dependent constant b and water-column density (in kilograms per square meter) in the canopy. The Jackson model is flexible but has little physical basis, with b often used as a fitting parameter in emission models or estimated empirically [4]. England and Galantowicz [5] developed a refractive model for estimating optical depth of grass, which is based upon vertical profiles of moisture content within the grass canopy.

In this paper, we develop a canopy-opacity model for sweet corn. The refractive model developed by England and Galantowicz [5] was extended for sweet corn using observed moisture distribution during our fourth and fifth Microwave Water- and Energy-Balance Experiments (MicroWEX 4 and 5). In this paper, we describe the field experiments, measurements of canopy-moisture profiles, and the τ model. We compare the τ estimated by our model with that estimated using the Jackson model. The τ values obtained from the two approximations were used in a microwave emission model at C-band, and the model estimates of brightness were compared with field observations. Because our model involves a biophysically based approach, the methodology presented here can be extended to other vegetation types.

II. MICROWEX 4 AND 5

MicroWEXs are a series of experiments conducted by the Center for Remote Sensing at the University of Florida during growing seasons of corn and cotton [6]–[11]. The objective of the experiments is to understand microwave signatures of agricultural crops during different stages of growth. MicroWEX 4 was conducted during the sweet-corn growing season, which is from March 10 through June 2 in 2005 [9]. MicroWEX 5 was conducted during the subsequent corn season from March 9 through May 26 in 2006 [10]. Both experiments were conducted at the same 37 000-m^2 site in the University of Florida (UF), Institute of Food and Agricultural Sciences, Plant Science Research and Education Unit in Citra, FL. During the experiments, we observed microwave brightness (MB) at 6.7 GHz using the tower-mounted UF C-band Microwave Radiometer. Additional MB observations at 1.4 GHz were conducted during MicroWEX 5, using the UF L-band Microwave Radiometer. Concurrent measurements were made of micrometeorological and canopy parameters, soil-moisture and temperature profiles, and radiation and heat fluxes at the land surface during both experiments. Canopy parameters, such as biomass and height, were measured weekly during MicroWEX 4 and 5, as shown in Figs. 1 and 2. Vertical distribution of moisture in the canopy was measured five times during MicroWEX 4 and three times during MicroWEX 5 [12].

Manuscript received September 25, 2006; revised May 3, 2007. This work was supported in part by the NASA–New Investigator Program (00050655) and in part by the National Science Foundation Earth Science Directorate (EAR-0337277).

The authors are with the Center for Remote Sensing, Agricultural and Biological Engineering Department, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611 USA (e-mail: jcasa@ufl.edu; jasmeet@ufl.edu; miyoung@ufl.edu).

Digital Object Identifier 10.1109/TGRS.2007.902302

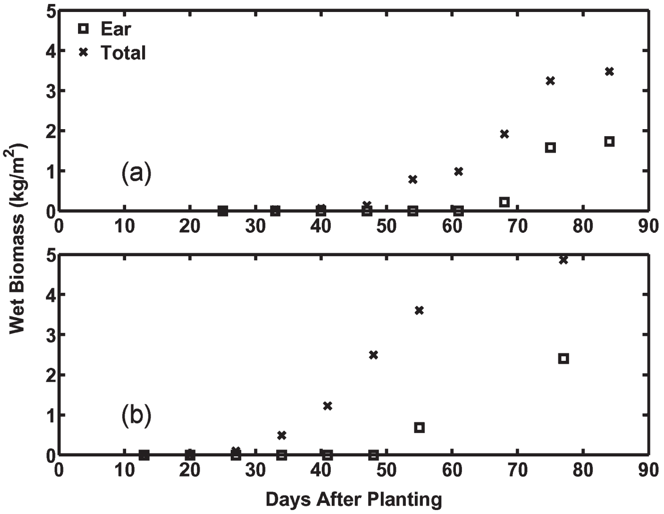

Fig. 1. Observations of total and ear wet biomass during (a) MicroWEX 4 in 2005 and (b) MicroWEX 5 in 2006.

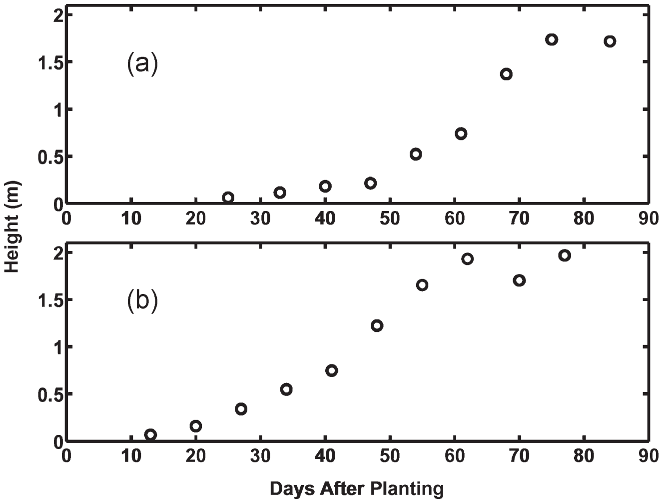

Fig. 2. Observations of canopy height during (a) MicroWEX 4 in 2005 and (b) MicroWEX 5 in 2006.

III. METHODOLOGY

A. *Moisture-Distribution Measurements*

Five measurements of moisture distribution were conducted during MicroWEX 4: May 12 (Day After Planting (DAP) 63), May 17 (DAP 68), May 26 (DAP 77), June 2 (DAP 84), and June 6 (DAP 88). The samples collected on DAP 63 and 88 consisted of plants in vegetative stage, i.e., before ear formation, while those collected on other days consisted of plants at various reproductive stages. Additional plant sample was obtained on DAP 88 to determine the density of wet vegetation (solid). Three measurements of moisture distribution were conducted during MicroWEX 5: April 10 (DAP 32), May 1 (DAP 53), and May 15 (DAP 67). The samples collected on DAP 53 and 67 consisted of plants in reproductive stages.

All representative plant samples were cut every 10 cm and weighed wet. The samples were dried at 70 °C for at least 48 h and weighed to obtain dry biomass. The samples on DAP 63, 2005 were cut every 5 cm to ensure that finer samples were not needed to obtain accurate moisture distribution. The density of vegetation material for each layer was measured by volume displacement in a graduated cylinder.

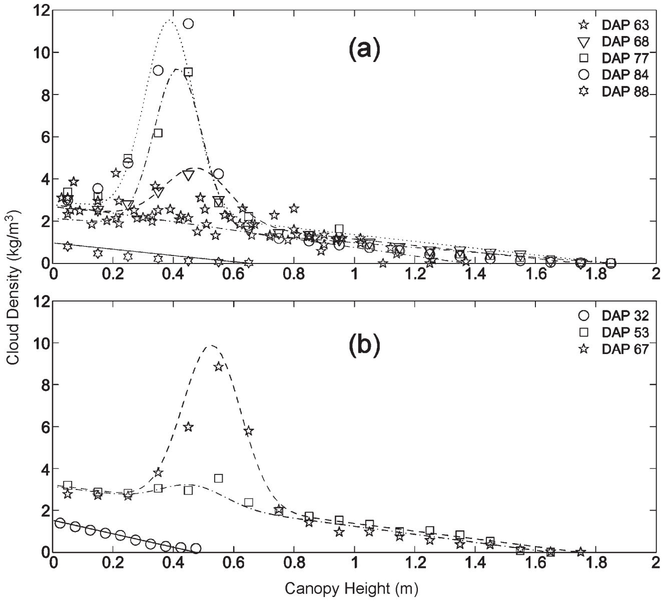

Fig. 3. Cloud densities measured during (a) MicroWEX 4 in 2005 and (b) MicroWEX 5 in 2006. The symbols and the lines represent the measurements and the best curve-fits, respectively.

Density of wet vegetation and air $\rho(z)$, which is called the cloud density, was calculated for each layer as a ratio of wet biomass of each layer and the thickness of the layer (10 cm). The mass of air is negligible. To obtain seasonal pattern, the cloud density of each layer was plotted as a function of height of the layer, shown in Fig. 3.

B. *Canopy Opacity*

The canopy opacity (τ) is estimated as [13], [14]

$$\tau = \int_0^h 2k_0\kappa(z)dz \tag{1}$$

where h is the canopy height (m), k_0 is the vacuum wavenumber (per meter), and $\kappa(z) = -\mathrm{Im}\{n_t(z)\}(Np/m)$ is the absorption coefficient of the canopy. $\mathrm{Im}\{n_t(z)\}$ is the imaginary part of the complex refractive index, estimated as the sum of volume fraction of components

$$n_t(z) = 1 + v_{\mathrm{wc}}n_{\mathrm{wc}}, \qquad v_{\mathrm{wc}} = \frac{\rho(z)}{\rho_s} \tag{2}$$

where v_{wc} is the volume fraction of the wet vegetation (in cubic meters per cubic meter), n_{wc} is the refractive index of the wet vegetation, and ρ_s is the density of wet vegetation (697.72 kg/m^3 in this paper [12]). Ulaby and El-Rayes' model [15] estimates n_{wc} as a function of frequency (6.7 GHz in this paper) and moisture mixing ratio (M_g). M_g is defined as the ratio of the weight of water in the canopy to the weight of wet canopy. Fig. 4 shows the mixing ratio during MicroWEX 4 and 5. In our model, we assume an isothermal canopy, so that, the

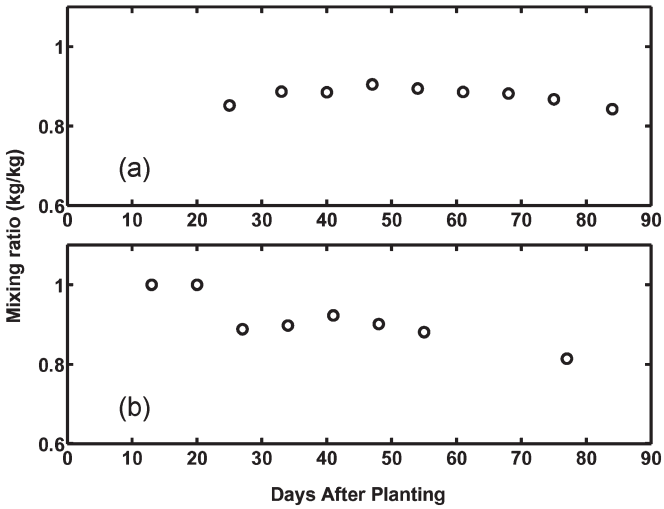

Fig. 4. Moisture mixing ratios measured during (a) MicroWEX 4 in 2005 and (b) MicroWEX 5 in 2006.

$\kappa(z)$ profiles can be integrated over the height of the canopy to obtain τ. The isothermal assumption was appropriate for a short sweet_corn canopy of 1.5 m. The absolute difference between the temperatures at the top and at the bottom of the canopy was < 4 K during the simulation period (see Section III-D).

C. MB Model

The MB model is a widely used τ–ω model [13]. The total brightness temperature of a terrain (T_B) is a sum of three contributions: $T_{\mathrm{Bs},p}$ (from the soil), $T_{\mathrm{Bc},p}$ (from the canopy), and $T_{\mathrm{Bsky},p}$ (from the sky)

$$\begin{aligned} T_{\mathrm{Bs},p} &= (1-r_p)T_{\mathrm{eff}}\exp(-\tau/\mu)\\ T_{\mathrm{Bc},p} &= T_c\left[1-\exp(-\tau/\mu)\right](1-\omega)\left[1+r_p\exp(-\tau/\mu)\right]\\ T_{\mathrm{Bsky},p} &= T_{\mathrm{sky}}r_p\exp(-2\tau/\mu) \end{aligned} \tag{3}$$

where p is the polarization, r_p is the reflectivity of the rough soil surface, T_{eff} is the effective radiating temperature of the soil calculated using the first-order approximation from [16] (in Kelvin), $\mu = \cos(\theta)$, where θ is the look angle (50° in this paper), T_c is the physical temperature of the isothermal canopy (in Kelvin), which is measured during the experiments, ω is the single scattering albedo, and T_{sky} is the sky brightness (assumed 5 K at C-band). In our model, r_p is based upon the semiempirical model of Wegmüller and Mätzler [17], with soil-roughness height of 0.0005 m [18]. Soil dielectric properties are determined using a four-component mixing model following Dobson *et al.* [19].

D. Model Comparison and Evaluation

Using the $\rho(z)$, we obtain τ for the MicroWEX 4 and 5 growing seasons. The estimates for τ are compared with those obtained using the Jackson model [3] as

$$\tau = bW_c \tag{4}$$

TABLE I

VALUES OF THE COEFFICIENTS IN (5) AND (6)

Coefficients	Values
a	2.054
b	-2.054
α_c	-114.32
α_d	5.87
α_e	-1.23
β_c	25.69
β_d	-1.37
β_e	0.34
γ_c	8.41
γ_d	0.29
γ_e	-0.07

where b is an empirical parameter, and W_c is the water content in the canopy (in kilograms per square meter).

We evaluate τ from our model and from the Jackson model in the MB model during the latter part of the MicroWEX 5 season. The MB model simulated T_B for ten days (DAP 42–52), with DAP 42–47 during vegetative growth and DAP 47–52 during ear formation. The canopy cover was 100% during the period of simulation. The MB model was driven with observed canopy and soil temperatures and moisture values.

IV. RESULTS AND DISCUSSION

A. Moisture-Distribution Function

As shown in Fig. 3, the cloud density function consists of two terms, a linear term representing the vegetative stage of the plant and a Gaussian term representing the moisture in the ear during the reproductive stages, as

$$\rho(z) = \frac{B_v}{h}(a+bh_n) + c\frac{B_e}{h}\exp\left[-\frac{1}{2}\left(\frac{h_n-d}{e}\right)^2\right] \tag{5}$$

where a, b, c, d, and e are fitted parameters, $h_n = z/h$ is the normalized height, and B_v and B_e are the wet biomass of vegetation (stem and leaves) and ear (in kilograms per square meter), respectively. Fig. 3 also shows the best curve-fits obtained for each sample. The parameters c, d, and e, governing the Gaussian term, were estimated as quadratic functions of dry biomass of the ear (D_{ear}) as

$$\begin{aligned} c &= \alpha_c + \beta_c D_{\mathrm{ear}} + \gamma_c D_{\mathrm{ear}}^2\\ d &= \alpha_d + \beta_d D_{\mathrm{ear}} + \gamma_d D_{\mathrm{ear}}^2\\ e &= \alpha_e + \beta_e D_{\mathrm{ear}} + \gamma_e D_{\mathrm{ear}}^2. \end{aligned} \tag{6}$$

Table I gives the values of a and b parameters and the coefficients in (6).

B. Canopy Opacity

Fig. 5 shows the τ estimated using our model and the Jackson model with $b = 0.25$. The Jackson model estimates lower opacities throughout the growing season compared to those obtained using our τ model with root mean-square differences (rmsd's) between the two models of 0.16 Np during MicroWEX 4 and 0.23 Np during MicroWEX 5. However, the Jackson model

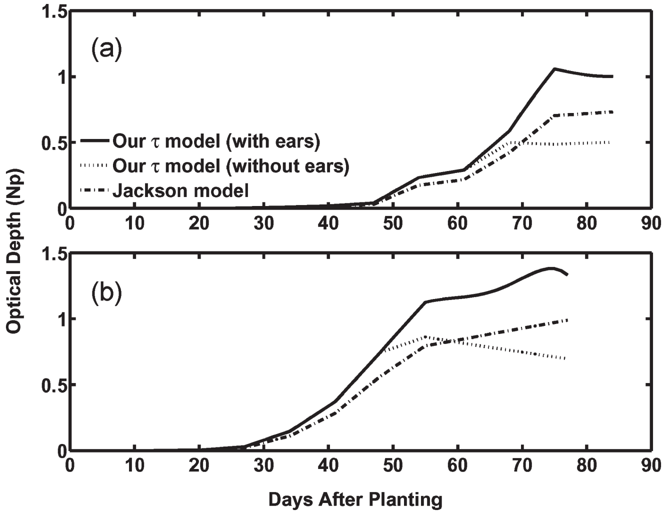

Fig. 5. Comparison of τ calculated using our τ model (with and without the Gaussian term) and that using the Jackson model during (a) MicroWEX 4 in 2005 and (b) MicroWEX 5 and 2006.

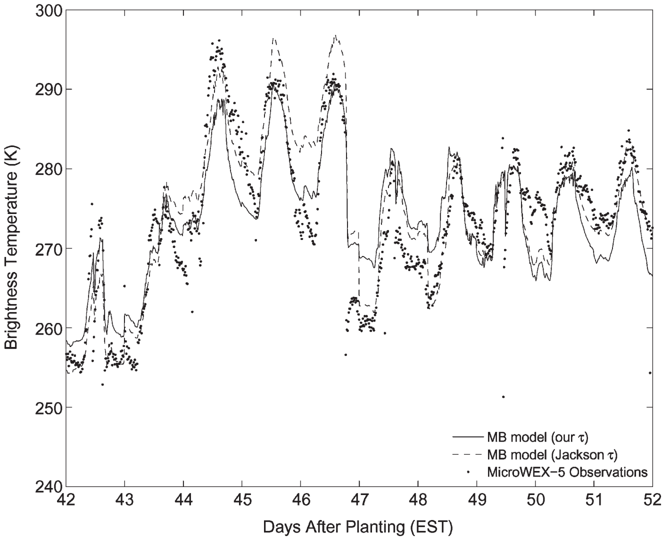

Fig. 6. Comparison of the observed T_B at H-pol during MicroWEX 5, those simulated by the MB model using τ from our model and from the Jackson model during late-season MicroWEX 5.

matched better with our model when the change in the moisture distribution that is due to ear formation was not included, with rmsd's of 0.10 Np during MicroWEX 4 and 0.11 Np during MicroWEX 5. The contribution of moisture in the ears to the optical depth is significant because they comprise a significant portion of the total biomass (see Fig. 1), with the increase in biomass primarily due to the growth of the ears once the corn reaches the reproductive stage. As a result, Fig. 5 shows a sharp increase in optical depth at the onset of ear development, at DAP 62 for MicroWEX 4 and DAP 47 for MicroWEX 5. By the end of the seasons, the optical depth is doubled when ears are included.

C. Microwave Brightness (MB)

TABLE II
RMSD's BETWEEN OBSERVED T_B DURING MICROWEX 5 AND THOSE ESTIMATED BY THE MB MODEL

τ model	RMSD (K)		
	DAP $<$ 47	DAP $\geq$ 47	DAP 42-52
Jackson (ω = 0.00)	5.84	12.50	9.74
Jackson (ω = 0.06 for DAP $\geq$ 47)	5.84	3.65	4.88
Our ω = 0.05 for 42<DAP<52	5.00	8.25	6.83
Our ω = 0.075 for DAP $\geq$ 47	5.00	5.22	5.13

Fig. 6 shows the comparison of the horizontally polarized (H-pol) T_B observed during MicroWEX 5 with those simulated by the MB model at C-band, with τ estimates made using our model and the Jackson model. The observed T_B increased during the drydown from DAP 42 to DAP 46.7 and then decreased by 30 K due to an irrigation event. The T_B at 6.7 GHz were sensitive to soil-moisture changes even when the canopy cover was 100% and biomass was 2.7 kg/m^2 (see Fig. 1).

A small value for single-scattering albedo (ω) was included in the MB model when using our τ estimates. The value of 0.05 before ear formation (DAP 47) and 0.075 after DAP 47 provided the least rmsd (see Table II).

In the Jackson model, $b = 0.25$, which is similar to the literature-based values for corn [4], provided the lowest rmsd. Typically, ω is set to zero in the Jackson model [3], but we found that the T_B using the Jackson model was overestimated after ear formation, with an rmsd of 12.50 K. Including $\omega = 0.06$ after ear formation when the Jackson model reduced the rmsd to 3.65 K, as shown in Table II. The values of ω needed to provide the least rmsd, for both τ models were small, < 0.1, implying that single scattering is sufficient to provide realistic T_B estimates for the mature sweet-corn canopy and multiple scattering is not needed. The overall rmsd between observed T_B and the modeled T_B, using the two τ models, were similar, with 5.13 K for our model and 4.88 K for the Jackson model (see Table II).

V. CONCLUSION

We develop a refractive model for vegetation opacity of growing sweet corn based upon moisture distribution in the canopy. The moisture content decreased linearly as height of the corn increased, but the distribution was closer to Gaussian in the fruit region during the reproductive stages. The τ obtained from our model estimated higher values than the Jackson model, with an rmsd between the two of up to 0.23 Np. The τ values obtained from the two approximations were used in a microwave-emission model at C-band, the model estimates of T_B matched well with observations using both τ values, with similar rmsd's. Because our model involves a biophysically based approach, the methodology presented here can be extended to other vegetation types.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their helpful comments, O. Lanni and L. Miller for providing engineering support during MicroWEX 4 and 5, J. Boyer and his team at the Plant Science Research and Education Unit for land and crop management, and K.-J. Tien and T.-Y. Lin for their help in data collection.

REFERENCES

[1] F. Ulaby and E. Wilson, "Microwave attenuation properties of vegetation canopies," *IEEE Trans. Geosci. Remote Sens.*, vol. GRS-23, no. 5, pp. 746–753, Sep. 1985.

[2] H. J. Eom, "A thermal microwave emission model for row-structured vegetation," *Int. J. Remote Sens.*, vol. 13, no. 16, pp. 2975–2982, 1992.

[3] T. Jackson and T. J. Schmugge, "Vegetation effects on the microwave emission of soils," *Remote Sens. Environ.*, vol. 36, no. 3, pp. 203–212, 1991.

[4] A. A. Van de Griend and J. Wigneron, "The b-factor as a function of frequency and canopy type at H-polarization," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 4, pp. 786–794, Apr. 2004.

[5] A. England and J. Galantowicz, "Moisture in a grass canopy from SSM/I radiobrightness," in *Proc. 2nd Tropical Symp. Combined Optical-Microw. Earth and Atmos. Sensing*, Atlanta, GA, Apr. 1995, pp. 12–14.

[6] K. J. Tien, J. Judge, O. Lanni, and L. Miller. (2003). *Field Observations During the First Microwave Water and Energy Balance Experiment (MicroWEX-1): From July 17–December 16, 2003*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular 1470. [Online]. Available: http://edis.ifas.ufl.edu/AE288

[7] J. Judge, J. Casanova, T. Lin, K. Tien, M. Jang, J. Judge, O. Lanni, and L. Miller. (2004). *Field Observations During the Second Microwave Water and Energy Balance Experiment (MicroWEX-2): From March 17–June 3, 2004*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular 1480. [Online]. Available: http://edis.ifas.ufl.edu/AE360

[8] T. Y. Lin, J. Judge, K. Tien, J. Casanova, M. Y. Jang, O. Lanni, and L. Miller. (2004). *Field Observations During the Third Microwave Water and Energy Balance Experiment (MicroWEX-3): From July 16–December 21, 2004*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular 1483. [Online]. Available: http://edis.ifas.ufl.edu/AE361

[9] J. Casanova, T. Lin, M. Jang, K. Tien, J. Judge, O. Lanni, and L. Miller. (2005). *Field Observations During the Fourth Microwave Water and Energy Balance Experiment (MicroWEX-4): From March 10–June 14, 2005*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular No 1482. [Online]. Available: http://edis.ifas.ufl.edu/AE362

[10] J. Casanova, F. Yan, K. Tien, J. Judge, O. Lanni, and L. Miller. (2007). *Field Observations During the Fifth Microwave Water and Energy Balance Experiment (MicroWEX-5): From March 9–May 26, 2006*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular 1514. [Online]. Available: http://edis.ifas.ufl.edu/AE407

[11] F. Yan, J. Casanova, K. Tien, J. Judge, O. Lanni, and L. Miller. (2007). *Field Observations During the Sixth Microwave Water and Energy Balance Experiment (MicroWEX-6): From June 19–October 31, 2006*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular 1515. [Online]. Available: http://edis.ifas.ufl.edu/AE409

[12] J. Casanova, M. Jang, and J. Judge. (2006). *Vertical Distribution of Moisture in a Sweet Corn Canopy During MicroWEX-4*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular 1492. [Online]. Available: http://edis.ifas.ufl.edu/AE395

[13] F. Ulaby, R. Moore, and A. Fung, *Microwave Remote Sensing Active and Passive*, vol. I. Norwood, MA: Artech House, 1981.

[14] F. Ulaby, R. Moore, and A. Fung, *Microwave Remote Sensing Active and Passive*, vol. III. Norwood, MA: Artech House, 1986.

[15] F. Ulaby and M. El-Rayes, "Microwave dielectric spectrum of vegetation—Part II: Dual-dispersion model," *IEEE Trans. Geosci. Remote Sens.*, vol. GRS-25, no. 5, pp. 550–557, Sep. 1987.

[16] A. England, "Radiobrightness of diurnally heated, freezing soil," *IEEE Trans. Geosci. Remote Sens.*, vol. 28, no. 4, pp. 464–476, Jul. 1990.

[17] U. Wegmüller and C. Mätzler, "Rough bare soil reflectivity model," *IEEE Trans. Geosci. Remote Sens.*, vol. 37, no. 3, pp. 1391–1396, May 1999.

[18] M. Jang, K. Tien, J. Casanova, and J. Judge. (2005). *Measurements of Soil Surface Roughness During the Fourth Microwave Water and Energy Balance Experiment: From April 18–June 13, 2005*, Center for Remote Sensing, Univ. Florida. UF/IFAS EDIS website, Tech. Rep. Circular 1483. [Online]. Available: http://edis.ifas.ufl.edu/AE393

[19] M. Dobson, F. Ulaby, M. Hallikainen, and M. El-Rayes, "Microwave dielectric behavior of wet soil—Part II: Dielectric mixing models," *IEEE Trans. Geosci. Remote Sens.*, vol. GE-23, no. 1, pp. 35–46, Jan. 1985.

Joaquin J. Casanova (S'06) received the B.S. degree in agricultural and biological engineering from the University of Florida, Gainesville, in 2006, where he is currently working toward the Master's degree.

Mr. Casanova is a member of the American Geophysical Union and American Society of Agricultural and Biological Engineers.

Jasmeet Judge (S'94–M'00–SM'05) received the Ph.D. degree in electrical engineering and atmospheric, oceanic, and space sciences from the University of Michigan, Ann Arbor, in 1999.

She is currently the Director of the Center for Remote Sensing and an Assistant Professor with the Agricultural and Biological Engineering Department, Institute of Food and Agricultural Sciences, University of Florida (UF), Gainesville. She is a Faculty Advisor of the UF Student Chapter of the Society of Women Engineers. She is an Associate Editor of the *Transactions of the American Society of Agricultural and Biological Engineers* and *Applied Engineering in Agriculture*. Her research interests are microwave remote-sensing applications to terrestrial hydrology, including modeling of microwave signatures, energy, and moisture interactions at the land surface and in the vadose zone for different terrain types and data assimilation.

Dr. Judge is a member of the American Geophysical Union, American Society of Agricultural and Biological Engineers, American Society of Civil Engineers, and Sigma Xi.

Miyoung Jang received the B.S. degree in electrical engineering and the M.E. degree in applied physics and electrical engineering from Ajou University, Suwon, South Korea, in 2000 and 2002, respectively, and the M.E. degree in agricultural and biological engineering, with a minor in electrical engineering, from the University of Florida, Gainesville, in 2005.