Radiometric sensitivity to soil moisture at 1.4 GHz through a corn crop at maximum biomass

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[1] Radiometric sensitivity to soil moisture at 1.4 GHz through a corn canopy at a maximum biomass of 8.0 kg m^{-2} (water column density of 6.3 kg m^{-2}) was much higher than expected. The magnitude of the measured sensitivity of horizontally polarized brightness temperature to the 0–3 cm volumetric soil water content was at least 1.5 K per 0.01 m^3 m^{-3} and could have been as high as 2.5 K per 0.01 m^3 m^{-3}. Vertically polarized brightness temperature was 0.5 K per 0.01 m^3 m^{-3} less sensitive than horizontally polarized brightness temperature. A widely used radiative transfer model that assumes a uniform distribution of vegetation in the canopy underestimated this soil moisture sensitivity at horizontal polarization by over 1 K per 0.01 m^3 m^{-3}. Given an appropriate emission model that correctly accounts for the differences in transparency between heterogeneous canopies (as compared to the wavelength) such as corn and relatively homogeneous canopies such as grass, it appears that there will be practical sensitivity to soil moisture through corn (and most, if not all, row crops) throughout the growing season. *INDEX TERMS:* 1866 Hydrology: Soil moisture; 6969 Radio Science: Remote sensing; 1894 Hydrology: Instruments and techniques; 6994 Radio Science: Instruments and techniques; *KEYWORDS:* field experiment, hydrology, microwave radiometry, radiative transfer, remote sensing, soil moisture

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1. Introduction

[2] Microwave radiometry, the measurement of naturally emitted microwave radiation, is sensitive to the presence of liquid water. When directed toward Earth's surface, microwave radiometry can reveal the the quantity and distribution of water stored in vegetation and the first few centimeters of the soil, key components of the water cycle. Brightness near 1.4 GHz has been identified as the optimum frequency for soil moisture remote sensing [*Njoku and Entekhabi*, 1996]. Future satellite radiometers [*Kerr et al.*, 2001] will for the first time make it possible to collect data detailing the land surface moisture state at temporal and spatial scales useful in hydrometeorology [*Entekhabi et al.*, 1999].

[3] Although the response to changes in soil water content has been well documented for several years [*Schmugge*, 1978; *Newton and Rouse*, 1980; *Wang et al.*, 1980; *Jackson et al.*, 1982; *Ulaby et al.*, 1983], there are still many questions about the effect of the overlying vegetation. Vegetation degrades the soil moisture signal by absorbing and scattering radiation emitted from the soil. As the canopy biomass increases, absorption and scattering also increase and the vegetation becomes less transparent. Absorption occurs because the imaginary part of the canopy's index of refraction is nonzero. This is primarily due to the presence of liquid water within the vegetation tissue. Scattering occurs in some vegetation because of water's large refractive index and the significant electrical size of the canopy constituents. The opacity of the canopy is commonly characterized by the canopy architecture and either the vegetation column density, the total mass of fresh vegetation per unit area, or simply the water column density, defined as the mass of liquid water within the vegetation per unit area [*Jackson and Schmugge*, 1991].

[4] It is generally assumed that brightness at 1.4 GHz is sensitive to soil moisture up to a certain level of vegetation canopy biomass. This level has not been clearly defined. Because corn can quickly grow to high levels of column density, and because it is commonly grown in many areas of the United States, many soil moisture remote sensing experiments have utilized corn as a prototype vegetation canopy. For example, *O'Neill et al.* [1996] reported a measurable sensitivity to soil moisture at a water column density of 4 kg m^{-2} in corn. *Ulaby et al.* [1983] found that a change of one percent gravimetric soil moisture produced a change in brightness temperature of 1.1 K for a water column density of approximately 5 kg m^{-2} in corn. On the other hand, *Brunfeldt and Ulaby* [1984] observed no difference between corn fields that either had metal screens placed at the soil surface, or had no screens, at the middle of

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the growing season. *Wang et al.* [1984] observed no sensitivity to soil moisture through a grass canopy with vegetation column density of 8 kg m^{-2}.

[5] Recall that the transparency of the canopy also depends on the type of vegetation. We hypothesize that the actual sensitivity to soil moisture in a corn canopy is different than that predicted by current models of microwave brightness that assume an even distribution of moisture throughout the canopy. The distribution, and not simply the amount of water in the canopy, is also important. For example, while *Wang et al.* [1984] observed no sensitivity to soil moisture through an 8 kg m^{-2} grass canopy at 1.4 GHz, a corn canopy of similar density but with water concentrated in stems and ears might be be sufficiently transparent to 1.4 GHz radiation to allow sensitivity to soil moisture.

[6] In this paper, we determine the radiometric sensitivity to soil moisture at 1.4 GHz through a dense corn canopy of 8 kg m^{-2}, the maximum biomass observed during a complete growing season, and the same density of the opaque grass canopy observed by *Wang et al.* [1984]. We accomplish this by analyzing time series measurements of 1.4 GHz brightness, soil moisture, and relevant micrometeorology, all of high temporal resolution. Our approach is unique: remote sensing studies typically replicate satellite measurements, in which discrete measurements are made at isolated points in time. Our method of integrating nearly continuous observations of brightness, micrometeorology, and soil state reveals how these variables change together as a result of their interdependencies. This method can be used to identify subtle physical processes that might otherwise be hard to find. We also compare the measured radiometric sensitivity with model predictions and other observations in the literature.

2. Measurements

[7] The experimental site, an 800 m (E–W) by 400 m (N–S) field in southeastern Michigan, was planted in corn during the summer of 2001. The field is unusually flat and uniform in terms of soil properties and, during that summer, was extremely uniform in vegetation. A picture of the experiment site is shown in Figure 1. The soil at the site was a silty clay loam of the Lenawee series (16.1% sand, 55.0% silt, 28.9% clay). The field was planted on April 29 and 30 (day of year 119 and 120), cultivated on June 11 and 12 (day of year 162 and 163), and harvested on October 17 and 18 (day of year 290 and 291). Average row spacing was 0.77 m. Plant density was 7.49 m^{-2}. Rows were planted E–W.

[8] To characterize the canopy, we measured leaf area index (LAI) as well as vegetation and water column densities periodically throughout the summer. Each LAI value was computed from the average of ten samples made with a leaf area meter, taken at random locations separated by 5 to 10 m within the field. Each sample was made using one above-canopy measurement and the average of three below-canopy measurements of the incident radiation: in the row and one third and two thirds of the way across the row space. The wet and dry masses of six randomly chosen plants were averaged to compute column densities.

[9] In a similar experiment the previous summer, we used a laser profiler to measure soil surface height standard deviation and correlation length. We estimated the change in roughness over the course of both the 2000 and 2001 growing seasons with measured precipitation and the model of *Zobeck and Onstad* [1987]. Soil surface height standard deviation varied from 28 mm in early July of 2001, to 25 mm during the middle of August, to 15 mm in early October. A correlation length of 85 mm measured the summer of 2000 was assumed to remain unchanged.

2.1. Radiometry

[10] Two radiometers (direct-sampling digital radiometers, custom-made by the Space Physics Research Laboratory at The University of Michigan), mounted on the hydraulic arm of a truck, recorded horizontally polarized (H-pol) and vertically polarized (V-pol) 1.4 GHz brightness (Figure 1). The radiometers were oriented at an incidence angle of $\theta = 35°$ and an azimuthal angle with respect to row direction of $\phi = 60°$ ($\phi = 0°$ defined as parallel to row direction). Along a line of sight at $\theta = 35°$, the radiometers were 10 m above the soil surface. The azimuthal angle was chosen to avoid any possible uniqueness that may be associated with $\phi = 0°$, 45°, or 90°. The truck was positioned within the field at the head of a "lane", a portion of the field that was not planted. The lane, 6 rows wide and approximately 250 m long, began at the eastern edge of the field and continued west. Antennae E and H plane half power beam widths were approximately 21°. Side lobe levels were below −20 dB. Each radiometer's footprint was approximately 40 m^2.

[11] The radiometer data acquisition system measured the brightness temperature of both the antennae and internal reference loads at 2-min intervals. We used the sky (a brightness temperature between 5 and 10 K) as one calibration point. Absorber calibration at ambient temperature produced inconsistent results because of an inadequate absorber target. In its place we used the internal reference loads, which were maintained at a constant temperature of 293 K. The calibration procedure included a continual adjustment of the slope of the calibration line according to the observed changes in reference load brightness. These small changes in reference load brightness were the result of slow temperature changes in some radiometer components. Radiometer precision (standard deviation of brightness temperature measurements, and also often called NEΔT), is a function of random temperature fluctuations within the radiometer. Precision varied over the course of the summer. During the experiment described in this paper, brightness temperature precision at H-pol and V-pol was 0.5 K and 0.4 K, respectively. We estimate the accuracy of brightness measurements calibrated using the internal reference loads instead of an absorber to be ±2 K.

2.2. Micrometeorology

[12] A micrometeorological station was located approximately 150 m west of the truck at the approximate center of the field (Figure 1). We positioned an infrared (IR) thermometer, supported by the micrometeorological station tower, approximately 1 m above the canopy and pointed it at nadir. An identical IR thermometer underneath the canopy, approximately 20 cm above the ground and also pointed at nadir, measured the soil surface temperature. This soil IR thermometer was also near the micrometeorological station tower. These two sensors each have accuracy of $<\pm 0.7$ K and a precision of <0.1 K. Buried thermocouples

Figure 1. Experiment site on day of year 178. Truck-mounted radiometers appear in the foreground. A micrometeorological station tower can be seen in the background. See color version of this figure in the HTML.

and thermistors measured soil temperature at 1.5 and 4.5 cm, respectively, with an accuracy of ±0.3 K or less and a precision of <0.1 K. We also measured precipitation, wind speed and direction, relative humidity, air temperature, and downwelling solar and atmospheric radiation. A data logger recorded 20-min averages of micrometeorological variables sampled once every ten seconds.

2.3. Soil Moisture

[13] Planting and cultivation produce distinct localized soil topography in row crops such as corn. We reduced this topography to a binary representation of high (H) and low (L) elevations as a practical way to retain this unique row structure. An illustration of this pattern is shown in Figure 2. Although only 2 to 4 cm lower than H areas, L areas were distinct from the rest of the soil surface because of their higher water content (and resulting darker color), bulk density, and smoother surface. We sampled several rows with a metric tape measure to find the spatial fractions of H and L areas. We classified 21% of the surface as L.

[14] Time-domain reflectometry (TDR) instruments, placed at 1.5 cm and 4.5 cm below the soil surface in both H and L areas, measured volumetric water content. The sample volume of a TDR instrument has the shape of slightly flattened cylinder of length equivalent to the length of the transmission lines. The sensing volume extends slightly farther in the plane containing the two wires of the transmission line than in the perpendicular direction. According to calculations performed by *Knight* [1992], approximately 80% of the sensing volume is within a 2 cm radius, and slightly more than 90% within a 3 cm radius for the particular TDR instruments used in this experiment. *Baker and Lascano* [1989] found that a TDR instrument has a vertical resolution of approximately 3 cm when the TDR is oriented so that the plane containing the two wires of the transmission line is parallel to the soil surface. Hence the TDR placed at 1.5 and 4.5 cm measured the 0–3 and 3–6 cm layers, respectively. A total of twelve TDR instruments (three in H areas at 1.5 cm, three in H areas at 4.5 cm, three in L areas at 1.5 cm, and three in L areas at 4.5 cm), averaged to account for the spatial fractions of H and L areas, produced plot-scale 0–3 and 0–6 cm water content measurements. We spread the TDR instruments over an approximately 20 m^2 area near the micrometeorological station tower. We placed soil temperature instruments in a similar arrangement.

[15] We used several hundred hand-held impedance probe measurements of soil moisture made over the course of the summer to calibrate the nearly continuous TDR measurements of soil moisture at the micrometeorological tower. The 0–6 cm soil water content sampled by the impedance probe matched the sampling depth of the TDR measurements made at 1.5 and 4.5 cm. See Figure 3 for an illustration. TDR instruments were not placed directly on top of each other, but displaced horizontally in adjacent rows. On days we used the impedance probe, we collected 10 measurements in H areas and 10 measurements in L areas at 7 randomly chosen sites between the truck and the tower, for a total of 140 measurements per day. This procedure calibrated the TDR instruments in situ to the plot-scale near-surface soil moisture.

2.3.1. Impedance Probe

[16] An impedance probe (ThetaProbe ML2x, Delta-T Devices, Cambridge, UK) consists of four 6 cm sharpened stainless steel rods that protrude from a 40 mm diameter and 112 cm long PVC cylinder. It generates a 100 MHz electrical signal on an internal transmission line. When inserted into the ground, the four rods form another transmission line whose characteristic impedance depends on the refractive index of the soil, n_{soil}. Reflections at the interface between the internal transmission line and the rod array produce a standing wave. The voltage output, *V*, is a function of the voltage standing-wave ratio. The ThetaProbe ML2x has been carefully designed so that there is a linear relationship between *V* and n_{soil} [*Delta-T Devices Ltd.*, 1999]:

$$V = (n_{soil} - 1.1)/4.44. \tag{1}$$

Except for saline soils, the imaginary part of n_{soil} is small at 100 MHz and has been ignored in equation (1). Strong

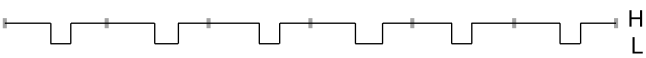

Figure 2. Soil topography reduced to a binary representation. Shaded rectangles represent rows of vegetation. Average row spacing was 0.77 m.

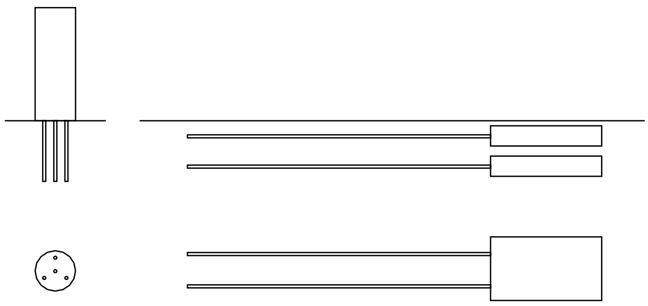

Figure 3. Orientation of impedance probe and TDR. (top) Side view. (bottom) Plan view. Drawn to scale.

linear relationships between n_{soil} and water content for many types of soils have been observed [*Topp et al.*, 1980; *Whalley*, 1993; *White et al.*, 1994; *Curtis*, 2001]. Hence

$$n_{soil} = a_0 + a_1 \theta_v. \quad (2)$$

Here a_0 and a_1 are constants and θ_v is volumetric water content.

[17] We calibrated our impedance probe to the soil at the site with gravimetric measurements of soil water content, made in both H and L areas. To make calibration samples, we used a metal scoop to remove a 5 cm by 5 cm by 6 cm = 150 cm^3 rectangular prism surrounding the holes left by the rods of the impedance probe. We also made bulk density measurements using the USDA-ARS excavation method. The calibration data are shown in Figure 4. For the silty clay loam soil at the site, a_0 = 0.9 and a_1 = 11. These values are significantly different from those established as standard calibrations for mineral soil (a_0 = 1.6 and a_1 = 8.4) and for organic soil (a_0 = 1.3 and a_1 = 7.7) [*Delta-T Devices Ltd.*, 1999]. The standard calibration line for mineral soil is also included in Figure 4. A higher value of a_1 is consistent with the findings of *White et al.* [1994], who found the slope of the line relating water content to the refractive index to increase with clay content (the clay fraction of the soil at the site was 28.9%). The standard deviation of the differences between the linear relationship and actual volumetric measurements shown in Figure 4 is approximately 0.02 m^3 m^{-3}. We chose to ignore any temperature dependence due to the variation of water's refractive index with temperature.

2.3.2. Time Domain Reflectometers

[18] Each TDR instrument (Water Content Reflectometers, model CS615 8221-07, Campbell Scientific, Logan, Utah) consists of a two-wire transmission line and a circuit board encapsulated within its epoxy head. The transmission line is 30 cm long, each wire has a radius of 1.6 mm, and the wires are separated by 3.2 cm. The circuit is essentially a bistable multivibrator that transitions from one voltage level to another. This transition, which occurs within a few nanoseconds, propagates down the length of the transmission line, is reflected by the open circuit at the end, and travels back to the sensor head. The reflected transition triggers the multivibrator to transition again, and the process is repeated. The output is a frequency-scaled square wave whose period corresponds to the length of time between the multivibrator's transitions, which corresponds to the time it takes the pulse to make a round trip on the transmission line.

[19] The phase (propagation) velocity of an electromagnetic wave is $u_p = c/n'$ where c is the speed of light in a vacuum and n' is the real part of the refractive index. Waves propagating through a medium are also attenuated according to the magnitude of the imaginary part of the refractive index, n''. Waves travelling on a TDR transmission line, with Fourier components from the tens of MHz to several GHz, will exhibit dispersion due to the frequency dependence of the real and imaginary parts of the refractive index. The degree of dispersion depends primarily on two factors: the fraction and degree to which soil water is held, or "bound", to the soil matrix [*De Loor*, 1956; *Hoekstra and Doyle*, 1972]; and the bulk soil electrical conductivity [*Hoekstra and Delaney*, 1974]. Both effects are not well understood. Bulk soil electrical conductivity increases linearly with water content in most soils [*Rhoades et al.*, 1989]. There is still much debate on the nature of bound water [*Grant et al.*, 1957; *Wang*, 1980; *Dobson et al.*, 1985; *Or and Wraith*, 1999; *Hillhorst et al.*, 2001] and its effect on TDR measurements, particularly in clayey soils [*Dasberg and Hopmans*, 1992; *Dirksen and Dasberg*, 1993]. As a result, no universal calibration for TDR exists.

[20] TDR measurements are also affected by temperature. *Pepin et al.* [1995] noted that since the refractive index of pure water decreases with temperature below 1 GHz, soil moisture can be overestimated at higher soil temperatures. Using a simple refractive mixing model that did not take into account soil type, they found that the necessary temperature correction was not as great as predicted. For the soils tested, sand had the greatest change with temperature, while loam and peat had much less. *Persson and Berndtsson* [1998] also measured TDR temperature dependence, taking note of the temperature dependence of electrical conductivity. The soils with large surface areas, high clay contents, and high electrical conductivity had positive temperature correction factors. The other soils (which were mostly sands) had negative correction factors, as predicted by the temperature dependence of pure water. *Wraith and Or* [1999] measured TDR pulse travel time as a function of temperature for four soils. They found that high surface area and low water content are conditions favorable for an increase in measured travel time with increasing temperature and speculated there is a "release" of bound water with temperature in soils with low water contents and in soils with high surface areas.

[21] *Seyfried and Murdock* [2001] tested the CS615 model 8221-07 in air, water, sand, and three soils to evaluate its temperature dependence. They found that it is extremely precise. There is also a small but significant unique sensor bias that can be measured and corrected. Following their example, we corrected the raw pulse periods for an electronics temperature effect. Since three instruments were averaged together at each combination of H and L and depth, we ignored intersensor variability. We then fit the period, P, to the impedance probe measurements with a second-order polynomial using the method of least squares:

$$P = A + C_1 \theta_v + C_2 \theta_v^2. \quad (3)$$

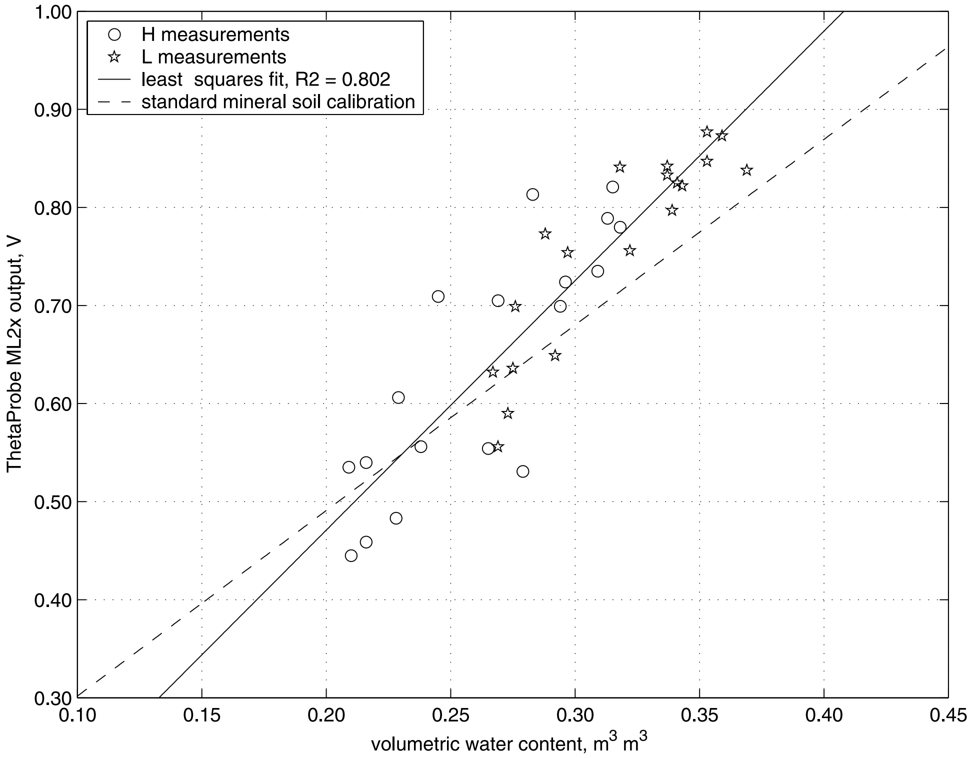

Figure 4. Impedance probe calibration. See color version of this figure in the HTML.

A, C_1, and C_2 are constants. A was forced to be 0.760 ms as found for oven-dry soil, independent of soil type.

[22] Measured temperature effects and a proposed temperature correction based upon the observations of *Seyfried and Murdock* [2001] are shown in Figure 5. The temperature dependency for sand is also shown. Note that it is slightly negative. Because of our soil's relatively high clay content, a negative temperature dependence was not expected. Two calibration curves for the TDR instruments are shown in Figure 6. In one calibration, we adjusted P with the proposed positive temperature dependence. In the other, we made no additional temperature correction to the period. Both calibration curves fit the data well. The standard calibration curves provided by the manufacturer for soils with low and high electrical conductivities are also included for comparison. When we applied the temperature correction in Figure 5 to the period, we found values of $A = 0.760$, $C_1 = -0.266$, and $C_2 = 6.986$ for equation (3). When we applied no temperature correction, the values of the parameters were $A = 0.760$, $C_1 = -0.295$, and $C_2 = 5.584$.

[23] A comparison of 0–6 cm volumetric soil water content measured by the impedance probe with the 0–6 cm volumetric soil water content measured by the TDR using both calibrations is shown in Figure 7. Taking into account the impedance probe calibration and the uniformity of the site, we estimate the accuracy of TDR measurements to be <0.02 m^3 m^{-3}. Our observations and the observations of *Seyfried and Murdock* [2001] suggest that their precision is <0.001 m^3 m^{-3}.

2.3.3. Evaluation of Approach

[24] Our soil moisture calibration procedure had two main strengths. First, we performed the calibration in situ, eliminating the need to transport soil cores into the laboratory. This avoided changes in soil structure and bulk density and automatically took into account the effects of small air gaps and other environmental factors that may have affected instrument performance. Second, we calibrated the TDR to the plot-scale soil moisture, not just the soil moisture at one isolated point. It is not possible to make TDR or impedance probe measurements within radiometer footprints without significantly altering the soil surface and changing soil surface roughness, an important variable. Instead, we made an effort to tie together measurements made in separate areas, and consequently at different scales. While the impedance probe and TDR instruments individually sample volumes of several cm^2, radiometer footprints cover areas of several m^2.

[25] One weakness of our calibration approach was its inability to determine whether a temperature correction was necessary. The three soils tested by *Seyfried and Murdock* [2001] occur in arid climates and all have high cation exchange capacities (CECs), or, in other words, high electrical conductivity. The electrical conductivity of the Lenawee silty clay loam at our experiment site was not measured. This soil, a fine, mixed, nonacid, mesic Mollic Epiaquept, exists in a humid climate in conditions which tend to wash out salts and produce low CECs. The mixed mineralogy also indicates that there is not one dominant type of clay that would favor a high CEC. Although its relatively high clay content favors a positive temperature dependence, the type of clay and its charge is equally important. We hypothesis that this soil has a slight positive temperature dependence, perhaps balanced by the negative free water change with temperature. We consider both calibrations in the following analysis. The

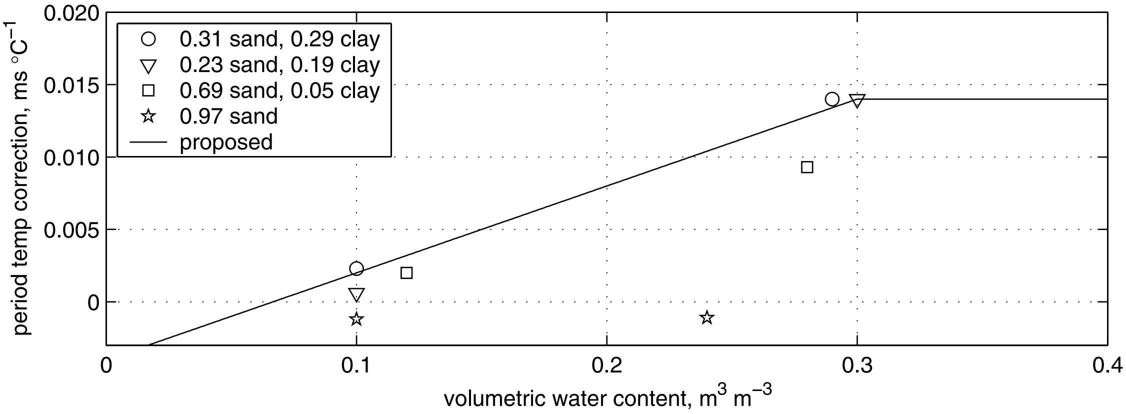

Figure 5. Proposed period temperature correction for the CS615 8221-07 TDR instrument based the work of *Seyfried and Murdock* [2001]. See color version of this figure in the HTML.

correct temperature dependence lies between these two extremes.

3. Observations

[26] Precipitation, 0–3 cm soil water content, vegetation IR temperature, soil IR temperature, soil temperature at 1.5 cm, V-pol 1.4 GHz brightness temperature, and H-pol 1.4 GHz brightness temperature for days of year 230 and 231 are shown in Figure 8. Day of year 230 corresponds to August 18 in the year 2001. At the time of these measurements the height of the corn canopy was 3.0 m, leaf area index was 4.8 m^2 m^{-2}, vegetation column density was 8.0 kg m^{-2}, and water column density was 6.3 kg m^{-2}. This column density was the highest that we observed during the summer.

[27] Before the rain event around 21:00 local daylight time (LDT) on day 230, soil moisture was very low and relatively constant. A diurnal change in H- and V-pol brightness in response to changes in soil and vegetation temperature is apparent. As temperatures increase, so does the microwave brightness.

[28] A distinct difference can be seen between the two calibrations of soil moisture. The temperature-corrected calibration has a much larger diurnal variation. Soil water content changes in response to temperature gradients [*Philip and de Vries*, 1957]. Water moves "down" a temperature gradient, from warmer regions to cooler regions. In the absence of precipitation, near-surface soil moisture should reach its daily maximum shortly after sunrise when the soil at the surface is cooler than the soil at depth, decrease during the day as the surface soil layer becomes warmer

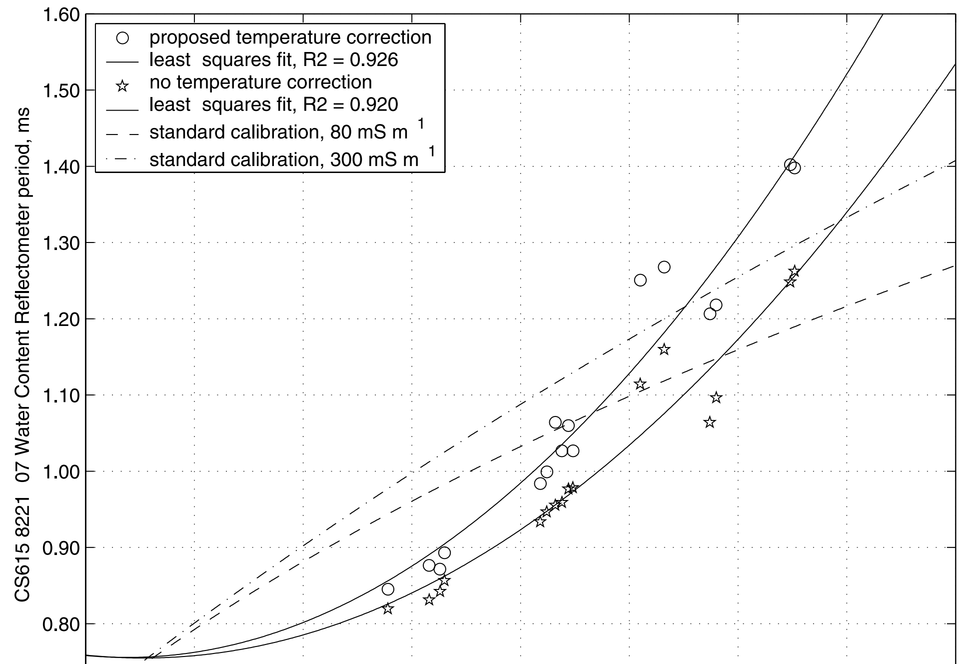

Figure 6. TDR instrument calibration. See color version of this figure in the HTML.

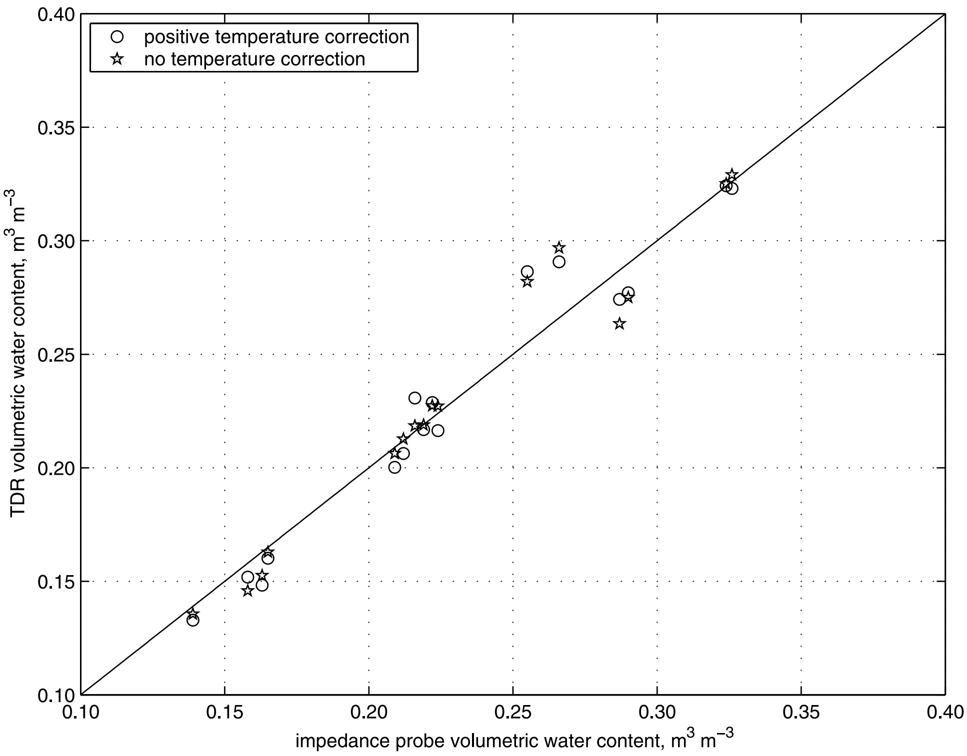

Figure 7. Comparison of 0–6 cm volumetric soil water content measured by the impedance probe with the average of 0–3 cm and 3–6 cm volumetric soil water content measured by TDR. See color version of this figure in the HTML.

than the underlying soil, and increase again during the night. The temperature-corrected measurement follows this pattern. The calibration with no temperature correction is π radians out of phase: the increase in temperature during the day produces a slight apparent increase in the measured water content. From these observations, it appears that this soil has a positive temperature dependence.

[29] The 21 mm rain event increased the 0–3 cm soil moisture by 0.09 m^3 m^{-3} (no temperature correction) and 0.08 m^3 m^{-3} (temperature–corrected). Vegetation IR temperature immediately decreased by almost 5 K, and soil IR temperature and soil temperature at 1.5 cm both began to drop. H- and V-pol brightness dropped sharply between 20:00 and 21:20 LDT, by 13.4 K and 10.3 K, respectively. In this and the following analysis, five adjacent measurements of H-pol brightness temperature and four adjacent measurements of V-pol brightness temperature have been averaged together in order to lower the uncertainty to approximately 0.2 K.

[30] Interpreting the cause of this drop in brightness is complicated by several competing processes. First, an increase in soil moisture would tend to decrease the brightness. Second, a decrease in vegetation canopy temperature and soil temperature would also tend to decrease the brightness. Finally, the effect of an increase in canopy water content on the microwave brightness, due to intercepted precipitation, is not known. Liquid water on the canopy constituents would increase their dielectric constant and loss. On one hand, this would tend to increase the brightness temperature. A higher dielectric loss in the canopy would decrease the contribution of soil emission to the total brightness, but this decrease would be outweighed by the increase in emission from the vegetation due to an increase in the total water column density [*Ferrazzoli et al.*, 1992]. Conversely, volume scattering is significant in a corn canopy at 1.4 GHz [*Hornbuckle et al.*, 2003]. If the dielectric constant of the half-space is not significantly larger than the dielectric constant of the scattering layer (as in the case of a vegetation layer over a moist soil half-space) the presence of scatterers reduces the brightness temperature. This phenomena is called scatter darkening [*England*, 1975]. Hence an increase in canopy water would increase scattering within the canopy, which would tend to decrease the brightness.

[31] Immediately following the rain event there was a 1.5 K increase in the H-pol brightness temperature, from 262.0 K at 22:00 LDT on day 230 to 263.5 K at 6:00 LDT on day 231. This increase occurred while the 0–3 cm soil water content decreased by 0.01 m^3 m^{-3} (no temperature correction) as water infiltrated the soil. This increase in brightness was not consistent with changes in vegetation or soil temperatures during the same period. Vegetation IR temperature, soil IR temperature, and soil temperature at 1.5 cm all decreased by 0.8 K, 1.3 K, and 1.0 K, respectively. The increase in brightness temperature was also not likely to be caused by changes in water intercepted by the canopy, which would be expected to remain constant during the night. Between 21:00 to 6:00 LDT, relative humidity measured at 7.8 m remained between 94 and 97% and water vapor pressure actually decreased slightly, indicating little or no evaporation from the canopy. All of these changes occurred in the absence of solar radiative forcing, before

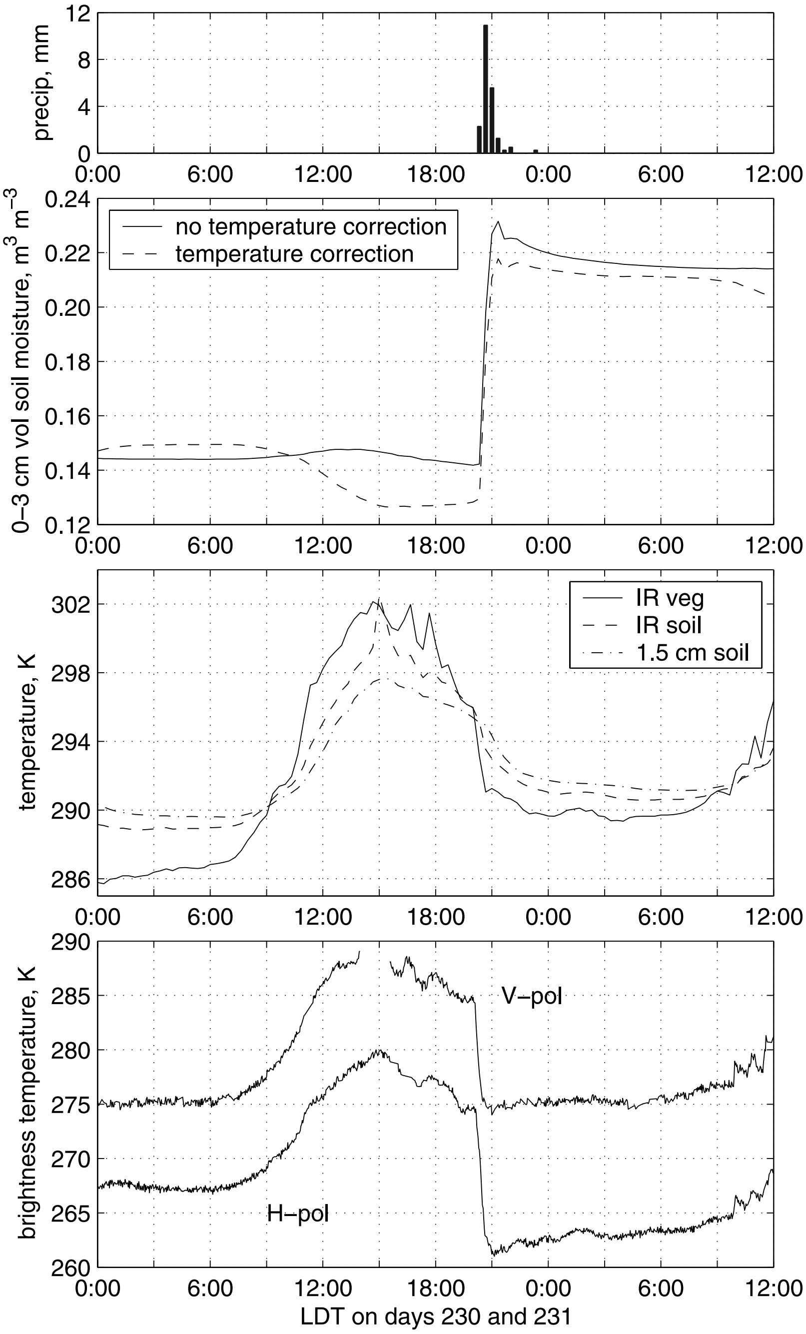

Figure 8. Precipitation, soil moisture, soil and vegetation temperatures, and 1.4 GHz brightness temperatures from 0:00 local daylight time (LDT) on day of year 230 to 12:00 LDT on day 231. See color version of this figure in the HTML.

the beginning of civil twilight at 6:18 LDT and sunrise at 6:48 LDT. The change in H-pol brightness temperature must then have been caused primarily by the change in soil moisture.

[32] According to these observations, the sensitivity of H-pol brightness temperature to volumetric soil moisture, S_H, was:

$$S_H = \frac{\Delta T_B}{\Delta VSM} = \frac{1.5\ \mathrm{K}}{-0.01\ \mathrm{m}^3\ \mathrm{m}^{-3}}, \\ = -1.5\ \mathrm{K\ per}\ 0.01\ \mathrm{m}^3\ \mathrm{m}^{-3}. \qquad (4)$$

This is a conservative estimate, given the changes in soil and canopy temperatures which tended to decrease the brightness temperature during this time period. V-pol brightness temperature increased by 1.0 K during this same time period, from 274.7 to 275.7 K, indicating a V-pol sensitivity to soil moisture of $S_V = -1.0$ K per 0.01 m^3 m^{-3}.

[33] The 0–3 cm soil water content and the difference between V-pol and H-pol brightness temperatures are shown in Figure 9. The change in the difference between the two polarizations after the rain event indicates a higher sensitivity to soil moisture at H-pol than at V-pol. Before the first rain event, the difference between V-pol and H-pol

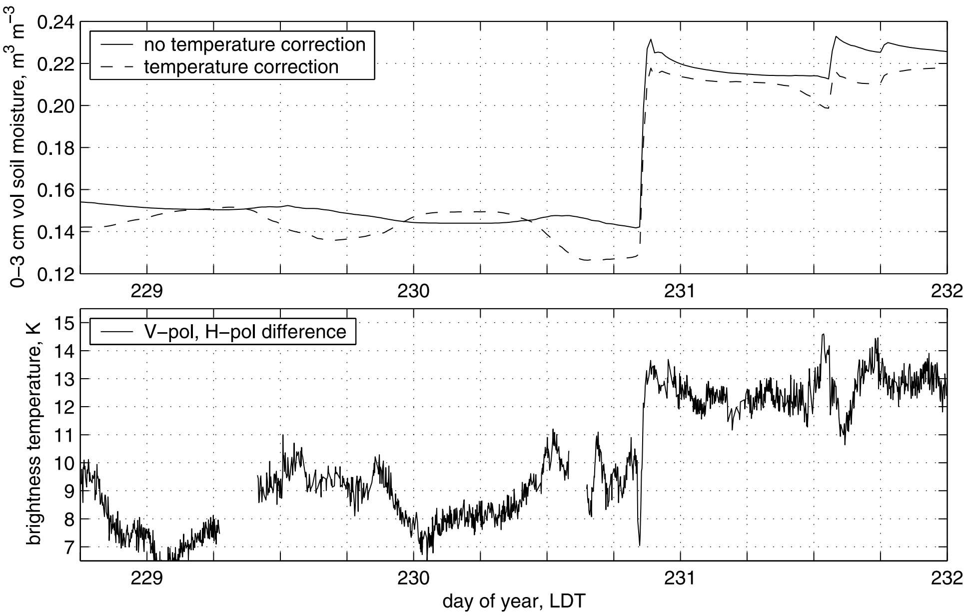

Figure 9. Soil moisture at 0–3 cm (both calibrations) and the difference between V-pol and H-pol brightness temperatures from 18:00 local daylight time (LDT) on day of year 228 to 0:00 LDT on day of year 232. See color version of this figure in the HTML.

brightness temperature during the early morning hours (0:00 to 6:00 LDT) on days 229 and 230 were, on average, about 8 K. After the rain event, H-pol was approximately 12 to 13 K lower than V-pol. This is consistent with the observed H-pol and V-pol sensitivities. If H-pol sensitivity is half a kelvin greater in magnitude than V-pol sensitivity, then a 0.08 to 0.09 m^3 m^{-3} change in soil moisture would lower the H-pol brightness temperature 4 to 5 K more than the V-pol brightness temperature, which is what we observed. The larger difference between V-pol and H-pol was maintained throughout day 231 when the soil was much wetter than it was on days 229 and 230. Two smaller precipitation events on day 231 also slightly increased the difference in V-pol and H-pol brightness.

[34] The temperature-corrected 0–3 cm soil moisture decreased by only 0.0047 m^3 m^{-3} between 22:00 and 6:00 LDT. This resulted in a sensitivity of -3.2 K per 0.01 m^3 m^{-3} at H-pol and -2.1 K per 0.01 m^3 m^{-3} at V-pol. Both of these sensitivities are close to that of bare soil [*Schmugge et al.*, 1986] and hence unrealistically high. The sensitivities we calculated for 0–6 cm soil moisture were even higher. From these observations, it appears that a small temperature correction to the TDR period is appropriate but only enough to produce the correct diurnal change. Otherwise the calibration with no temperature correction appears to closely match the actual soil moisture. The soil moisture sampling depth in our experiment appears to be closer to 3 cm than to 6 cm.

4. Analysis

[35] We found the precisions (standard deviations) of brightness temperature and soil moisture measurements to be 0.2 K and 0.001 m^3 m^{-3}, respectively. Measurements of a change in brightness temperature and a change in soil moisture would have precisions of:

$$\sigma_{\Delta T_B} = \sqrt{(0.2\ \text{K})^2 + (0.2\ \text{K})^2} = 0.28\ \text{K} \tag{5}$$

$$\begin{aligned}\sigma_{\Delta VSM} &= \sqrt{(0.001\ \text{m}^3\ \text{m}^{-3})^2 + (0.001\ \text{m}^3\ \text{m}^{-3})^2} \\ &= 0.0014\ \text{m}^3\ \text{m}^{-3}.\end{aligned} \tag{6}$$

The standard deviation of soil moisture sensitivity at both H- and V-pol, σ_S, can be found by using fractional standard deviations [*Beers*, 1962]. Define $\Sigma_S = \frac{\sigma_s}{\overline{S}}$, $\Sigma_{\Delta T_B} = \frac{\sigma_{\Delta T_B}}{\overline{\Delta T_B}}$ and $\Sigma_{\Delta VSM} = \frac{\sigma_{\Delta VSM}}{\overline{\Delta VSM}}$ as fractional standard deviations, where $\overline{S}$, $\overline{\Delta T_B}$, and $\overline{\Delta VSM}$ represent mean (expected) values. Given the form of equation (4), $\Sigma_S = \sqrt{(\Sigma_{\Delta T_B})^2 + (\Sigma_{\Delta VSM})^2}$. Hence:

$$\begin{aligned}\sigma_S &\approx \left|-1.5\ \text{K per m}^3\ \text{m}^{-3}\right| \\ &\quad \times \sqrt{\left[\frac{0.28\ \text{K}}{1.5\ \text{K}}\right]^2 + \left[\frac{0.00014\ \text{m}^3\ \text{m}^{-3}}{0.01\ \text{m}^3\ \text{m}^{-3}}\right]^2} \\ &= 0.35\ \text{K per m}^3\ \text{m}^{-3}.\end{aligned} \tag{7}$$

Here 1.5 K and 0.01 m^3 m^{-3} represent the observed changes in brightness temperature and soil moisture.

[36] We used a modeling approach to estimate the contribution of changing soil and vegetation temperature to the observed change in microwave brightness between 22:00 and 6:00 LDT. A vegetated surface can be modeled as a single isothermal layer of vegetation with diffuse boundaries over a soil half-space [*Jackson et al.*, 1982; *Mo et al.*, 1982; *Brunfeldt and Ulaby*, 1986; *Jackson and O'Neill*, 1990; *O'Neill et al.*, 1996; *Jackson et al.*, 1997; *Crosson et*

Table 1. Radiometric Sensitivity to 0–3 cm Volumetric Soil Moisture S[a]

	Raw Data	Vegetation Correction	Soil and Vegetation Correction
		Horizontal Polarization	
S_H[b]	−1.5	−2.1	−2.5
$S_{H,tc}$[c]	−3.2	−4.6	−5.4
		Vertical Polarization	
S_V	−1.0	−1.6	−2.0
$S_{V,tc}$	−2.1	−3.5	−4.4

[a]Values are in in K per 0.01 m^3 m^{-3}.
[b]No TDR temperature correction.
[c]Temperature-corrected TDR measurement.

al., 2002]. A solution of the radiative transfer equation can be written [*Hornbuckle et al.*, 2003]:

$$T_B = T_{Bsoil} + T_{Bcanopy\uparrow} + T_{Bcanopy\downarrow} \tag{8}$$

where

$$T_{Bsoil} = T_{soil}(1 - R_{soil})\Psi \tag{9}$$

$$T_{Bcanopy\uparrow} = (1 - \alpha)(1 - \Psi)T_{canopy} \tag{10}$$

$$T_{Bcanopy\downarrow} = (1 - \alpha)(1 - \Psi)T_{canopy}R_{soil}\Psi. \tag{11}$$

T_{Bsoil} represents the soil contribution to the total brightness temperature. $T_{Bcanopy\uparrow}$ and $T_{Bcanopy\downarrow}$ represent upwelling and reflected downwelling emission from the vegetation canopy, respectively. T_{soil} is the effective soil temperature; R_{soil}, an effective reflectivity of the soil surface; Ψ, the transmissivity of the vegetation layer; α, the single-scattering albedo; and T_{canopy}, the canopy temperature, defined as the average of soil and vegetation IR temperature. Sky brightness reflected by the land surface is neglected. R_{soil} is a function of volumetric water content. Ψ and α are determined primarily by the water content and structure of the canopy. T_{soil} closely matches soil temperature at 1.5 cm.

[37] We found the radiometric sensitivity to T_{canopy} by taking the derivative of equation (8):

$$\frac{d\,T_B}{d\,T_{canopy}} = (1 - \alpha)(1 - \Psi)[1 + R_{soil}\Psi]. \tag{12}$$

The variation of Ψ and α with canopy temperature has been ignored. Similarly, the radiometric sensitivity to T_{soil} is:

$$\begin{aligned}\frac{d\,T_B}{d\,T_{soil}} &= (1 - R_{soil})\Psi - T_{soil}\left[\frac{d\,R_{soil}}{d\,T_{soil}}\right]\Psi \\ &\quad + (1 - \alpha)(1 - \Psi)T_{canopy}\left[\frac{d\,R_{soil}}{d\,T_{soil}}\right]\Psi.\end{aligned} \tag{13}$$

We used the parameterization for corn developed by *Hornbuckle et al.* [2003], where the extinction coefficient, κ_e, was 0.289 at H-pol and 0.279 at V-pol, and α was 0.083 at H-pol and 0.050 at V-pol. We calculated the sensitivity to canopy temperature to be 0.64 K K^{-1} at H-pol and 0.63 K K^{-1} at V-pol for the conditions (soil moisture, soil and canopy temperature) observed in our experiment. Assuming that T_{soil} can be approximated by the soil temperature at 1.5 cm, we found the sensitivity to soil temperature to be 0.29 K K^{-1} at H-pol and 0.33 K K^{-1} at V-pol. Using these sensitivities, the change in H-pol brightness temperature between 22:00 and 6:00 LDT due only to soil moisture would have been approximately:

$$\begin{aligned}\Delta T_B &\approx 1.5\text{ K} + \left[1.0\text{ K} \times 0.6\text{ K K}^{-1}\right] + \left[1.3\text{ K} \times 0.3\text{ K K}^{-1}\right] \\ &= 2.5\text{ K}\end{aligned} \tag{14}$$

for a change of 1.0 K in T_{canopy} and a change of 1.3 K in soil temperature at 1.5 cm.

[38] Soil moisture sensitivities that we calculated using raw data and data corrected for simultaneous changes in vegetation and soil temperatures, for both TDR calibrations, are listed in Table 1. The sensitivities we calculated using temperature-corrected TDR measurements are unreasonably high. When we used TDR measurements with no temperature correction, we found a consistent difference of 0.5 K%$^{-1}$ between H-pol and V-pol sensitivities. This is consistent with the observed difference between V-pol and H-pol brightness temperature before and after the precipitation event in Figure 9.

5. Conclusion

[39] We observed a robust sensitivity of 1.4 GHz brightness temperature to changes in 0–3 cm volumetric soil moisture through a corn canopy with a water column density of 6.3 kg m^{-2} and vegetation column density of

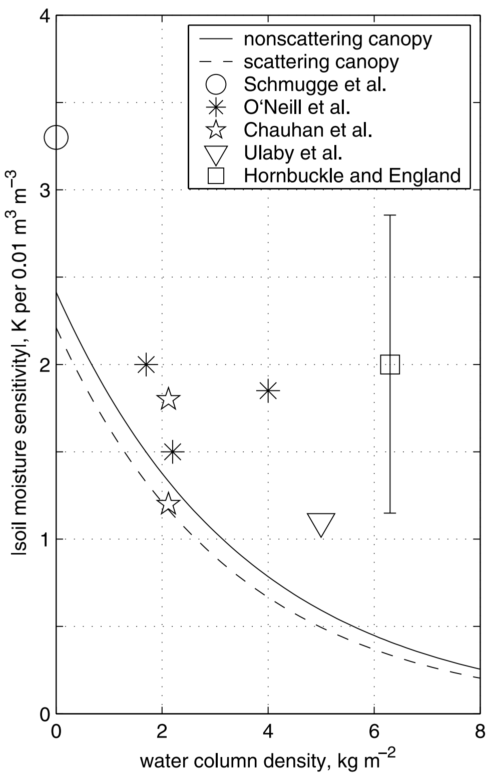

Figure 10. Measured and modeled sensitivity of H-pol 1.4 GHz brightness temperature to volumetric soil moisture through corn as a function of water column density. See color version of this figure in the HTML.

8.0 kg m^{-2}, the highest density observed during a full growing season. At H-pol the sensitivity was at least -1.5 K per 0.01 m^3 m^{-3}. If the sensitivity of brightness temperature to changes in vegetation and soil temperatures as predicted by a radiative transfer model are correct, H-pol sensitivity could be as large as -2.5 K per 0.01 m^3 m^{-3}. At V-pol, the magnitude of the sensitivity to soil moisture is 0.5 K per 0.01 m^3 m^{-3} less than at H-pol.

[40] H-pol soil moisture sensitivity (1) predicted by the radiative transfer model (equation (8)) for nonscattering vegetation (such as a grass canopy, α = 0); (2) predicted by equation (8) for scattering vegetation (a corn canopy, α = 0.083); (3) reported through corn from aircraft platforms [*Chauhan et al.*, 1994; *O'Neill et al.*, 1996; *Ulaby et al.*, 1983]; (4) for bare soil, established by many field experiments both from both airplane platforms and tower/truck-mounted radiometers [*Schmugge et al.*, 1986]; and (5) reported in this paper is plotted in Figure 10. A hypothetical change in soil moisture from 0.15 to 0.25 m^3 m^{-3} was used in the model calculations represented by the solid and dashed lines. The error bar on our measurement takes into account the uncertainty as calculated in equation (7) and the uncertainty resulting from changes in canopy (equation (12)) and soil (equation (13)) temperature. Modeled sensitivity is much less than that reported for bare soil because our soil was rough while the reported bare soil sensitivity includes soils with much smoother surfaces, and as a result, higher sensitivities to soil moisture. The soil moisture sensitivity reported in this paper is significantly higher than that predicted by the model described in section 4.

[41] It is apparent that both the amount of water in the canopy (water column density), and its distribution play an important role in determining soil moisture sensitivity. *Wang et al.* [1984] observed no sensitivity to soil moisture at 1.4 GHz in a grass canopy of equivalent vegetation column density as our corn canopy. For grass canopies, the water column density is typically half of the vegetation column density [*Dahl et al.*, 1993]. For our corn canopy, the water column density was nearly 80% of the vegetation column density. Of the 6.3 kg of water per m^2, we measured 1.2 kg in leaves, 3.4 kg in stems, and 1.7 kg in ears. Despite the presence of more water, we found the radiometric sensitivity to be higher than reported by *Wang et al.* [1984]. Hence heterogeneous canopies (with respect to the wavelength) such as field corn in which a large amount of the moisture is concentrated in stems and fruit appear more transparent than relatively homogeneous canopies such as grass where the water is more evenly spread over the entire canopy volume.

[42] The increased sensitivity to soil moisture could be because the canopy is in fact more transparent (a larger transmissivity, Ψ) than predicted, or because the radiative transfer model employed did not account for reflections between the canopy and the soil surface. *Hornbuckle et al.* [2003] found that volume scattering is significant in corn. Enhanced backscatter from scattering canopies has been observed in radar experiments [e.g., *Ulaby et al.*, 1986]. There may be a similar effect in radiometry. Radiation scattered by the vegetation could reflect off of the soil surface and hence increase sensitivity to soil moisture. Using the data presented in this paper, we cannot determine which mechanism, either higher transparency or volume scattering, or both, is correct, but both are possible.

[43] We expected radiometric measurement of soil moisture to be limited by column density. Research performed by other investigators has lead to the postulation that there is a point in the growing season at which the canopy becomes effectively opaque. Conversely, we have shown that with an appropriate emission model, ancillary data of sufficient accuracy (such as vegetation temperature and column density), and a typical microwave radiometer precision (NEΔT) of 1 K, microwave radiometry will be able to detect changes in soil moisture of less than 0.02 m^3 m^{-3} at all stages of corn development (growth, maturity, and senescence). This emission model must: have the correct sensitivity to soil and vegetation temperature; account for the differences in transparency between corn and grass-like canopies and/or an enhancement of soil moisture sensitivity through volume scattering; and possibly address the effect of water on the canopy. Given such an emission model, it appears that there will be practical sensitivity to soil moisture through corn (and most, if not all, row crops) throughout the growing season.

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References

Baker, J. M., and R. J. Lascano (1989), The spatial sensitivity of time-domain reflectometry, *Soil Sci.*, *147*, 378–384.

Beers, Y. (1962), *Introduction to the Theory of Error*, Addison-Wesley-Longman, Reading, Mass.

Brunfeldt, D. R., and F. T. Ulaby (1984), Measured microwave emission and scattering in vegetation canopies, *IEEE Trans. Geosci. Remote Sens.*, *22*, 520–524.

Brunfeldt, D. R., and F. T. Ulaby (1986), Microwave emission from row crops, *IEEE Trans. Geosci. Remote Sens.*, *24*, 353–359.

Chauhan, N. S., D. M. Le Vine, and R. H. Lang (1994), Discrete scatter model for microwave radar and radiometer response to corn: Comparison of theory and data, *IEEE Trans. Geosci. Remote Sens.*, *32*, 416–426.

Crosson, W. L., C. A. Laymon, R. Inguva, and C. Bowman (2002), Comparison of two microwave radiobrightness models and validation with field measurements, *IEEE Trans. Geosci. Remote Sens.*, *40*, 143–152.

Curtis, J. O. (2001), Moisture effects on the dielectric properties of soils, *IEEE Trans. Geosci. Remote Sens.*, *39*, 125–128.

Dahl, P., J. Judge, and A. W. England (1993), Vertical distribution of biomass and moisture in a prairie grass canopy, *Tech. Rep. RL 902*, Univ. of Mich. Radiat. Lab., Ann Arbor.

Dasberg, S., and J. W. Hopmans (1992), Time domain reflectometry calibration for uniformly and nonuniformily wetted sandy and clayey loam soils, *Soil Sci. Soc. Am. J.*, *56*, 1341–1345.

De Loor, G. P. (1956), Dielectric properties of heterogeneous mixtures, Ph.D. thesis, Univ. of Leiden, Leiden, Netherlands.

Delta-T Devices Ltd. (1999), Theta probe soil moisture sensor user manual type ML2x, Cambridge, U. K.

Dirksen, C., and S. Dasberg (1993), Improved calibration of time domain reflectometry soil water content measurements, *Soil Sci. Soc. Am. J.*, *57*, 660–667.

Dobson, M. C., F. T. Ulaby, M. T. Hallikainen, and M. A. El-Rayes (1985), Microwave dielectric behavior of wet soil—part II: Dielectric mixing models, *IEEE Trans. Geosci. Remote Sens.*, *23*, 35–46.

England, A. W. (1975), Thermal microwave emission from a scattering layer, *J. Geophys. Res.*, *80*, 4484–4496.

Entekhabi, D., et al. (1999), An agenda for land surface hydrology research and a call for the second international hydrological decade, *Bull. Am. Meteorol. Soc.*, *80*, 2043–2058.

Ferrazzoli, P., S. Paloscia, P. Pampaloni, G. Schiavon, D. Solimini, and P. Coppo (1992), Sensitivity of microwave measurements to vegetation biomass and soil moisture content: A case study, *IEEE Trans. Geosci. Remote Sens.*, *30*, 750–756.

Grant, E., T. Buchanan, and T. Cook (1957), Dielectric behavior of water at microwave frequencies, *J. Chem. Phys.*, *26*, 156–161.

Hillhorst, M. A., C. Dirksen, F. W. H. Kampers, and R. A. Feddes (2001), Dielectric relaxation of bound water versus soil matric pressure, *Soil Sci. Soc. Am. J.*, *65*, 311–314.

Hoekstra, P., and A. Delaney (1974), Dielectric properties of soils at UHF and microwave frequencies, *J. Geophys. Res.*, *79*, 1699–1708.

Hoekstra, P., and W. Doyle (1972), Dielectric relaxation of surface adsorbed water, *J. Colloid Interface Sci.*, *36*, 513.

Hornbuckle, B. K., A. W. England, R. D. De Roo, M. A. Fischman, and D. L. Boprie (2003), Vegetation canopy anisotropy at 1.4 GHz, *IEEE Trans. Geosci. Remote Sens.*, *41*(10), 2211–2223, doi:10.1109/TGRS.2003.817192.

Jackson, T. J., and P. E. O'Neill (1990), Attenuation of soil and microwave emission by corn and soybeans at 1.4 and 5 GHz, *IEEE Trans. Geosci. Remote Sens.*, *28*, 978–980.

Jackson, T. J., and T. J. Schmugge (1991), Vegetation effects on the microwave emission of soils, *Remote Sens. Environ.*, *36*, 203–212.

Jackson, T. J., T. J. Schmugge, and J. R. Wang (1982), Passive microwave remote sensing of soil moisture under vegetation canopies, *Water Resour. Res.*, *18*, 1137–1142.

Jackson, T. J., P. E. O'Neill, and C. T. Swift (1997), Passive microwave observation of diurnal surface soil moisture, *IEEE Trans. Geosci. Remote Sens.*, *35*, 1210–1222.

Kerr, Y. H., P. Waldteufel, J.-P. Wigneron, J.-M. Martinuzzi, J. Font, and M. Berger (2001), Soil moisture retrieval from space: The soil moisture and ocean salinity (SMOS) mission, *IEEE Trans. Geosci. Remote Sens.*, *39*, 1729–1735.

Knight, J. H. (1992), Sensitivity of time domain reflectometry measurements to lateral variations in soil water content, *Water Resour. Res.*, *28*, 2345–2352.

Mo, T., B. J. Choudhury, T. J. Schmugge, J. R. Wang, and T. J. Jackson (1982), A model for microwave emission from vegetation-covered fields, *J. Geophys. Res.*, *87*, 11,229–11,237.

Newton, R. W., and J. W. Rouse, Jr. (1980), Microwave radiometer measurements of soil moisture content, *IEEE Trans. Antennas Propag.*, *28*, 680–686.

Njoku, E. G., and D. Entekhabi (1996), Passive microwave remote sensing of soil moisture, *J. Hydrol.*, *184*, 101–129.

O'Neill, P. E., N. S. Chauhan, and T. J. Jackson (1996), Use of active and passive microwave remote sensing for soil moisture estimation through corn, *Int. J. Remote Sens.*, *17*, 1851–1865.

Or, D., and J. M. Wraith (1999), Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: A physical model, *Water Resour. Res.*, *35*, 371–383.

Pepin, S., N. J. Livingston, and W. R. Hook (1995), Temperature-dependent measurement errors in time domain reflectometry determinations of soil water, *Soil Sci. Soc. Am. J.*, *59*, 38–43.

Persson, M., and R. Berndtsson (1998), Texture and electrical conductivity effects on temperature dependency in time domain reflectometry, *Soil Sci. Soc. Am. J.*, *62*, 887–893.

Philip, J. R., and D. A. de Vries (1957), Moisture movement in porous materials under temperature gradients, *Eos Trans. AGU*, *38*, 222, 232.

Rhoades, J. D., N. A. Manteghi, P. J. Shouse, and W. J. Alves (1989), Soil electrical conductivity and soil salinity: New formulations and calibrations, *Soil Sci. Soc. Am. J.*, *53*, 433–439.

Schmugge, T. J. (1978), Remote sensing of surface soil moisture, *J. Appl. Meteorol.*, *17*, 1549–1557.

Schmugge, T. J., P. E. O'Neill, and J. R. Wang (1986), Passive microwave soil moisture research, *IEEE Trans. Geosci. Remote Sens.*, *24*, 12–22.

Seyfried, M. S., and M. D. Murdock (2001), Response of a new soil water sensor to variable soil, water content, and temperature, *Soil Sci. Soc. Am. J.*, *65*, 28–34.

Topp, G. C., J. L. Davis, and A. P. Annan (1980), Electromagnetic determination of soil water content: Measurements in coaxial transmission lines, *Water Resour. Res.*, *16*, 574–582.

Ulaby, F. T., M. Razani, and M. C. Dobson (1983), Effects of vegetation cover on the microwave radiometric sensitivity to soil moisture, *IEEE Trans. Geosci. Remote Sens.*, *21*, 51–61.

Ulaby, F. T., R. K. Moore, and A. K. Fung (1986), *Microwave Remote Sensing: Active and Passive*, vol. 3, Artech House, Norwood, Mass.

Wang, J. R. (1980), The dielectric properties of soil-water mixtures at microwave frequencies, *Radio Sci.*, *15*, 977–985.

Wang, J. R., J. C. Shiue, and J. E. McMurtrey III (1980), Microwave remote sensing of soil moisture content over bare and vegetated fields, *Geophys. Res. Lett.*, *7*, 801–804.

Wang, J. R., J. C. Shiue, S. L. Chuang, R. T. Shin, and M. Dombrowski (1984), Thermal microwave emission from vegetated fields: A comparison between theory and experiment, *IEEE Trans. Geosci. Remote Sens.*, *22*, 143–150.

Whalley, W. R. (1993), Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content, *J. Soil Sci.*, *44*, 1–9.

White, I., J. H. Knight, S. J. Zegelin, and G. C. Topp (1994), Comments on "Considerations on the use of time-domain relflectometry (TDR) for measuring soil water content" by W. R. Whalley, *Eur. J. Soil Sci.*, *45*, 503–508.

Wraith, J. M., and D. Or (1999), Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development, *Water Resour. Res.*, *35*, 361–369.

Zobeck, T. M., and C. A. Onstad (1987), Tillage and rainfall effects on random roughness: A review, *Soil Tillage Res.*, *9*, 1–20.

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