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Utilizing Space-based Technology for Cotton irrigation Scheduling

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Abstract.

Accurate soil moisture content measurements are vital to precision irrigation management. Electromagnetic sensors such as capacitance and time domain reflectometry have been widely used for measuring soil moisture content for decades. However, to estimate average soil moisture content over a large area, a number of ground-based in-situ sensors would need to be installed, which would be expensive and labor intensive. Remote sensing using the microwave spectrum (such as GPS signals) has been used for measuring large area soil moisture contents. In our previous work we estimated surface soil moisture contents for bare soil using a GPS Delay Mapping Receiver (DMR) developed by NASA. However, the effect of vegetation was not considered in these studies. Hence the objectives of this study were to: 1) investigate the feasibility of using DMR to determine soil moisture content in cotton production fields; 2) evaluate the attenuation effect of vegetation (cotton) on GPS reflected signal. Field experiments were conducted during the 2013 and 2014 growing seasons in South Carolina. GPS antennas were mounted at three heights (1.6, 2.7, and 4.2 m) over cotton fields to measure GPS reflected signals (DMR readings). DMR readings, soil core samples, and plant measurements were collected about once a week and attenuation effect of plant canopy was calculated. Results showed that DMR was able to detect soil moisture changes within one week after precipitation events that were larger than 25 mm per day. However, the DMR readings were poorly correlated with soil volumetric water content during dry periods. Attenuation effect of plant canopy was not significant. For irrigation purpose, the results suggested that the sensitivity of GPS reflected signals to soil moisture changes needs to be further studied before this technology can be utilized for irrigation scheduling in cotton production.

Keywords.

Remote sensing, GPS, Soil volumetric moisture content, Irrigation

Introduction

Competition for limited water resources is one of the most critical issues currently affecting civilization. The ability to make more water available for domestic, agricultural, industrial and environmental uses will depend on better management of water resources, watersheds, and storm water runoff. Accurate soil moisture measurements are vital for improving agricultural management practices. The large contrast between the dielectric constants of water ($\epsilon_w \approx 80$) and dry soil ($\epsilon_s \approx 3-5$) at microwave frequencies has provided an opportunity to estimate soil moisture contents using microwave signals (Engman and Chauhan, 1995). The relative dielectric constant of soil medium (ϵ) is usually a complex number and is given as:

$$\epsilon = \epsilon' + j\epsilon'' \quad 1$$

where ϵ' is permittivity of soil medium, ϵ'' is the loss factor, and j is the imaginary unit ($\sqrt{-1}$). "Electromagnetically, a soil medium is, in general, a four-component dielectric mixture consisting of air, bulk soil, bound water, and free water" (Hallikainen et al., 1985). Various models have been used to establish the relationship between the complex dielectric constant of a soil-water mixture and soil volumetric water content (θ) (Wang and Schumge, 1980; Hallikainen et al., 1985; Dobson et al., 1985). The Wang and Schumge empirical model (1980) predicts the dielectric constant of soil over a soil moisture range between 0 and 0.5 $\text{cm}^3 \text{cm}^{-3}$ for different soil textures at two frequencies of 1.4 and 5 GHz. The Dobson model (Dobson et al., 1985) is a semi-empirical model, which utilizes soil volumetric water content and soil texture as inputs and predicts the dielectric constant of soil for various soil textures at wider range of microwave frequencies (1.4 to 18 GHz).

Soil moisture can be estimated from microwave frequencies using active or passive remote sensing. The active remote sensing technique utilizes radar, which transmits electromagnetic waves to the ground surface and measures the backscattered signals. The passive remote sensing, on the other hand, utilizes a radiometer, which measures thermal microwave emission from the soil surface (Njoku and Entekhabi, 1996). However, the microwave radiometer requires complex calibration and a large antenna to achieve high surface spatial resolution (Jackson & Schumge, 1992). Active remote sensing is further divided into monostatic or bi-static radar, depending on whether transmitting and receiving antennas are co-located. The backscattered signal measured by the active system and the thermal microwave emission measured by the passive system both depend on the dielectric constant of soil and thus are affected by soil volumetric water content. Active remote sensing has higher spatial resolution and is more sensitive to surface roughness and vegetation cover, compared to passive remote sensing (Engman and Chauhan, 1995). The limitations of both active and passive remote sensing are minimized in the NASA's Soil Moisture Active Passive (SMAP) mission by combining these two methods using a radar and a radiometer (Entekhabi et al., 2010).

Various active or passive systems are currently mounted on ground carriers, aircrafts, or spacecrafts for the purpose of soil moisture monitoring with different spatial resolutions. Over ground level, Schwank et al. (2005) mounted a radiometer operating at 1.4 GHz on a tower and compared radiometer readings with time-domain reflectometer (TDR) soil moisture readings at different growth stages of clover grass. An aircraft-mounted electronically scanned thinned array radiometer (ESTAR) was used to map soil moisture over the Little Washita watershed in Oklahoma (Jackson et al. 1995). While the Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001) and recently launched

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SMAP satellites (Entekhabi et al., 2010) provide soil moisture data on a global scale.

Recently, utilization of GPS signal for remote sensing of soil moisture has been demonstrated over various systems. Larson et al. (2008) utilized geophysical and geodetic intended GPS receivers for soil moisture retrieval with resolution of 300 m². A delay mapping receiver (DMR) using L1 GPS signal developed at NASA Langley Research Center was mounted on an aircraft (Masters et al., 2004; Katzberg et al., 2006) and tractor-mounted boom (Privette et al., 2011) for soil moisture measurement. The DMR system is compact in size and only uses low-gain antenna, giving advantages compared to radiometers and other remote sensing instruments (Grant 2006). In our previous work (Privette et al., 2011 and 2016), we estimated surface soil moisture contents for bare soils using a DMR. However, the effect of vegetation was not considered in these studies. Therefore, the objectives of this study were to : 1) investigate the feasibility of using a DMR to determine soil moisture content in a cotton field; and 2) evaluate the attenuation effect of vegetation (cotton) on GPS reflected signal. This information has potential application for site-specific irrigation management.

Material and Methods

Site Condition

Field experiments were conducted at the Edisto Research and Education Center (EREC) of Clemson University near Blackville, South Carolina, during the 2013 and 2014 cotton growing seasons. In 2013, the experiment was conducted in a cotton field equipped with a lateral variable rate irrigation system (Lateral Field, LF). In 2014, in addition to LF field, a separate field equipped with drip irrigation system was used (Drip Field, DF). Field LF was planted with cotton variety DP 1050 on May 22, 2013 and May 7, 2014. The DF field was planted to cotton variety PHY333WRF on May 27, 2014. During both years, plant density was 82,145 seeds per hectare with 96-cm row spacing. The DF field allowed testing the effect of different levels of vegetation on GPS reflectivity since cotton at this field was planted at a later date. The plot size at both fields was 7.6 m by 15.2 m. Both fields had the same soil type, Varina loamy sand (*Fine, kaolinic, thermic Plinthic Paleudults*).

Field Instrumentation

The DMR is a bi-static system, which uses two antennas with a zenith Right Hand Circularly Polarized (RHCP) antenna (3G15A-XS-1, Antcom, U.S.A.) viewing the sky and a nadir Left Hand Circularly Polarized (LHCP) antenna (3G15L-A-XS-1, Antcom, U.S.A.) viewing the ground. The DMR system utilizes a Zarlink GP2010/2021 chipset (Zarlink Semiconductors, Ottawa, Canada) which has two antenna inputs and, therefore, both the direct and reflected signals can be acquired.

In 2013, the antenna platform (including RHCP and LHCP GPS antennas) was mounted on the lateral VRI at the LF field (Figure 1). The platform was made of two layers of plastic board with one layer of aluminum sheet in between. In 2014, the platform was mounted on a high-boy sprayer (Figure 1) to allow reflectivity readings to be collected from the two fields at different heights. The DMR was connected to the two antennas through two separate coaxial cables. A GPS inline amplifier (LA-21-1575-100-S, Raven Industry) was used before connecting the coaxial cable to each antenna. The DMR was located inside the lateral VRI system control box in 2013 and inside the high-boy sprayer cab in 2014.



Figure 1. GPS antennas mounted on lateral VRI (left) and on a high-boy sprayer (right) during 2013 and 2014, respectively.

System Calibration and Resolution

The DMR records the signal strength of direct and reflected GPS signal from the RHCP and LHCP antennas, respectively. The instrument output, which is the ratio of strength of reflected signal to direct signal, can be used to estimate surface reflectivity. Hence, it is important to make sure the output difference of the two DMR channels is only due to ambient environment, rather than the circuitry noise. The two input channels inside the DMR were evaluated using a balanced RF power divider (Model PE2011, Pasternack Enterprises, Inc. Irvine, CA) and the signal-to-noise ratio (SNR) of each channel was recorded. In 2014, the system was also calibrated over a surface with known reflectivity, which was a circular plastic container (2.4 m diameter and 0.3 m deep) filled with water. The reflectivity of a water body is relatively constant ($\Gamma_s = 0.61$) at a temperature range from 20°C to 30°C and GPS satellite elevation angles between 50 and 90 degrees (Grant, 2006; Katzberg et al., 2006). The calibration factor (f_c), was calculated as described by Grant (2006):

$$f_c = \frac{\Gamma_s}{G_c} \quad 2$$

where G_c is reflectivity from DMR. This calibration factor accounts for noises such as variation in satellite power, instrument temperature, cables, and cable connectors (Grant 2006). It should be pointed out that this scale factor was unique for each satellite and day of data acquisition.

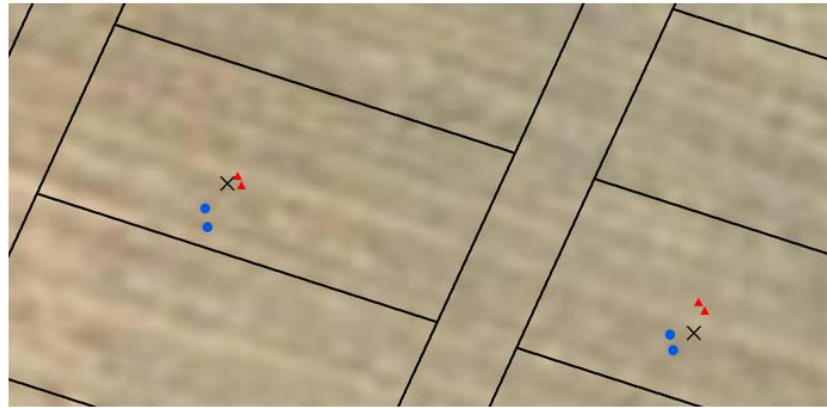
Before taking appropriate soil and plant samples in the field, it was necessary to calculate the resolution of the DMR signal. This resolution was calculated using equation 3 (Katzberg et al., 2006), assuming that the GPS reflection was specular, and that the reflectivity came from the First Fresnel Zone.

$$A = \pi \times \frac{\sqrt{h\lambda \sin \gamma}}{(\sin \gamma)^2} \times \frac{\sqrt{h\lambda \sin \gamma}}{\sin \gamma} \quad 3$$

where A is area (m^2) of First Fresnel Zone, h is height (m) of nadir antenna (LHCP antenna) above surface, γ is the elevation angle (degree) of satellite signal.

Data Collection

The satellites traverse an arc in the sky; therefore, during a data acquisition event, the apparent reflection point must then describe an arc on the ground. Since the repeat time for the satellites and their illumination is approximately twice per day (exactly twice per sidereal day), arc paths can be constructed based on the location of the GPS reflectometer (Privette et al., 2011). Using this method, the GPS receiver (DMR) was located in each plot in a way that the reflected arc paths would cross over predetermined locations inside the plots (Figure 2).



▲ Arc points on 2013/09/04 ● Arc points on 2013/09/09 × DMR positions □ Plot Plan

Figure 2. An example of predicted GPS reflected arc path with respect to locations of antenna platform.

In both years, data was collected about once a week, during cotton growing season. In 2013, the antenna platform was moved to a predetermined sampling location (reference point) in each experimental plot and the DMR data was collected for 20 minutes. Soil core samples and plant measurements were also collected from the predicted satellite reflection paths. Soil samples were taken at 10 and 20 cm depths and were analyzed for volumetric water content (VWC). Plant parameters such as leaf water potential and stomatal conductance were measured using Model 600 Pressure Chamber (PMS Instrument Company, USA) and SC-1 Leaf Porometer (Decagon Inc., USA), respectively. Similar procedure were followed in 2014, however, the DMR data was collected for 10 minutes per plot, and soil samples were taken from three depths (5, 10, and 15 cm). In addition, two randomly selected plant samples were taken and dried in oven at 65°C for 72 hours to obtain plant gravimetric water content (M_g).

Attenuation of GPS signal caused by plants was calculated as (Ulaby and Rayes, 1987):

$$L'_a(\theta) = \exp \left[\frac{4\pi}{3\lambda_0} V_l \varepsilon_l'' h_l \sec(\theta) \right] \quad 4$$

where $L'_a(\theta)$ is leaf loss factor due to canopy cover, V_l is biomass volume moisture content and is dimensionless, h_l is canopy height (m), ε_l'' is loss component of the dielectric constant of water containing leaves (dimensionless), λ is wavelength (m), θ is incidence angle and equal to $(90^\circ - \gamma)$.

The dielectric constant of plant (ε_l) was calculated using (Ulaby and Rayes 1987):

$$\varepsilon_l = \varepsilon_r + v_{fw} \varepsilon_f + v_b \varepsilon_b \quad 5$$

The reflectivity was then adjusted by the leaf loss factor due to canopy cover (Eq. 4) and calibration factor over water (Eq. 2):

$$G_{c_adjusted} = G_c \times f_c / L'_a \quad 6$$

For each successful data acquisition event in each plot, the DMR stored a series of txt files, including: DCOERR.txt (delay timing information), DEBUG.txt, DELYSUM.txt, DELYTIC.txt (reflected signal strength), DIRECT.txt (direct signal strength), NAVSTATE.txt (DMR position), RINEX2N.txt, and RINEX2O.txt. Satellite information was stored in the two RINEX files. Data was stored at every 0.1 second, named "tics". For each series of txt file obtained at each plot, a Matlab program developed by NASA was used to calculate average reflectivity during the sampling cycle (20 min in 2013 and 10 min in 2014). Linear regression was used to determine the correlation of reflectivity, either adjusted (in 2014) or not adjusted (in 2013), with volumetric water content of soil and crop stress parameters (stomatal conductance and leaf water potential).

Results and Discussion

System resolution and calibration

The resolution of the DMR system changes with satellite elevation angle and antenna height (Eq. 3). The DMR software is set to accept only high elevation angle satellites (greater than 60 degrees) to make the area of reflection specific to the area directly below the receiver (Katzberg et al., 2006). Therefore, the resolution of the DMR was calculated for elevation angles from 50 to 90 degrees. During 2013, when antennas (RHCP and LHCP) were mounted on the VRI at height of 4.16 m, the resolution of DMR ranged from 4.24 to 2.49 m², for satellite elevation angles of 50 to 90 degrees. During 2014, the antennas were mounted on the back of a high-boy sprayer and the height of antennas could change from 1.6 to 2.7 m. At height of 2.7 m, the resolution ranged from 2.75 to 1.61 m², for elevation angles of 50 to 90 degrees, while at height of 1.6 m, the resolution ranged from 1.97 to 0.55 m². The resolutions of DMR with elevation angle under different heights are shown in Figure 3. The plot size for both experimental fields (LF and DF) was large enough to exceed the DMR resolution.

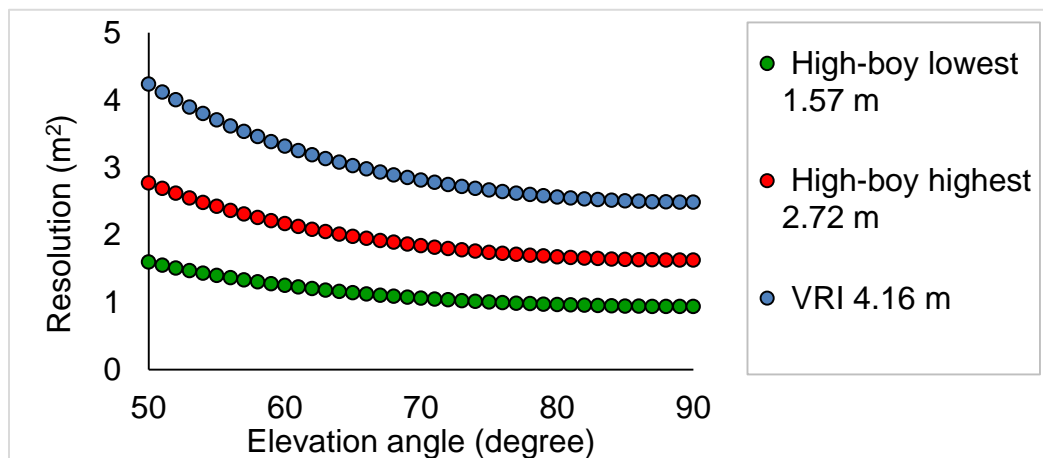


Figure 3. Resolution of DMR with elevation angle for antennas mounted at 1.57, 2.72, and 4.16 m.

As shown in Figure 4, the top and bottom channels of the DMR system had similar signal to noise ratio (SNR). There was a very strong correlation in SNR between the two channels ($R^2 = 0.94$ and slope of 1.03).

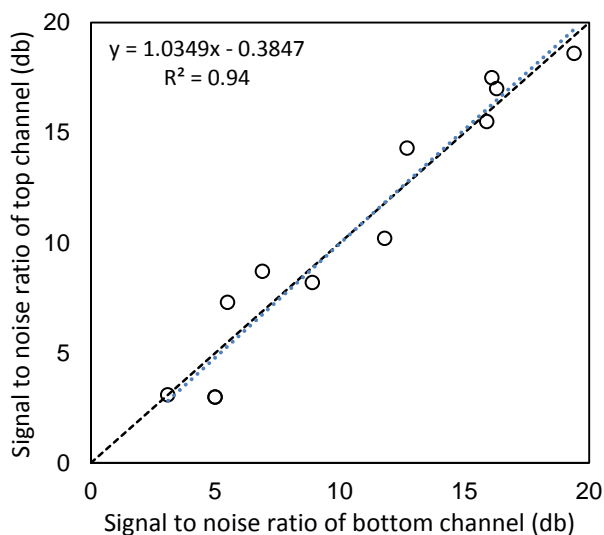


Figure 4 Signal to noise ratio of top and bottom channels of DMR.

During 2014, the DMR was calibrated over a circular water body on different dates for different satellites. The calibration factor (f_c) ranged from 1.03 to 1.21 with standard deviation of 0.06. The daily average calibration factor was used to scale reflectivity collected on the corresponding date. Katzberg et al. (2006) reported DMR calibration factors ranging from 1.65 to 1.98 for data collected from an aircraft. The difference in calibration factor between the two studies might be due to differences in elevation of data collection.

Reflectivity and soil water contents

Figure 5 shows relationship between reflectivity measurements and soil VWC, collected at 10 and 20 cm, during 2013. The reflectivity data for 2013 was not adjusted by calibration factor or loss factor due to leaves. Reflectivity significantly correlated with VWC with linear relationship at 10 cm and 20 cm with R^2 equal to 0.34 ($P = 0.0004$) and 0.18 ($P = 0.0149$), respectively. As stated by Engman and Chauhan (1995), microwave signals, including GPS signal, can only accurately measure soil moisture of a thin layer of soil on the order of 5 cm. It is possible that the lower R^2 at 20 cm depth could be due to limitation of GPS signal penetration depth. It was noticed that, when VWC was low, the DMR was not able to detect changes in soil moisture (Figure 5). To further investigate this, data collected within one week following large rainfall events (daily rainfall exceeding 25.4 mm) were separated from other data points. For example, on Aug 20th, 2013, there was 26.5 mm of rainfall, and data sampled on 21st, 22nd, 26th, and 27th in August of 2013 were referred as “After Precipitation” points. Other data points were referred as “Dry” points. Figure 6 shows correlation of reflectivity to VWC after data was separated. Correlation of reflectivity with VWC was improved for measurements taken at 10 cm. However this was not true for VWC collected at 20 cm. Similarly, reflectivity was not significantly correlated with leaf water potential or stomatal conductance, as indicated by low R^2 of 0.04 and 0.02 ($P = 0.107$ and $P = 0.246$), respectively.

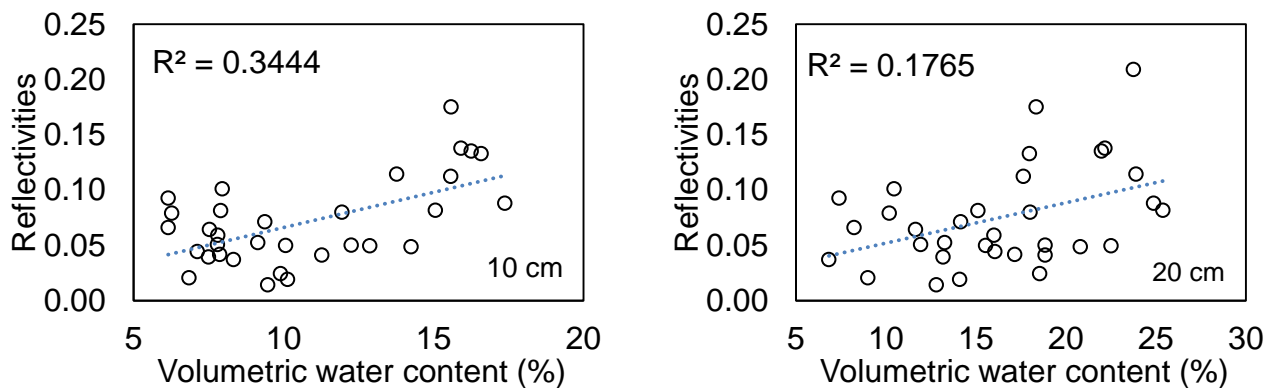


Figure 5. Correlations of reflectivity with volumetric water content of soil at 10 (left) cm and 20 cm (right) depths during 2013.

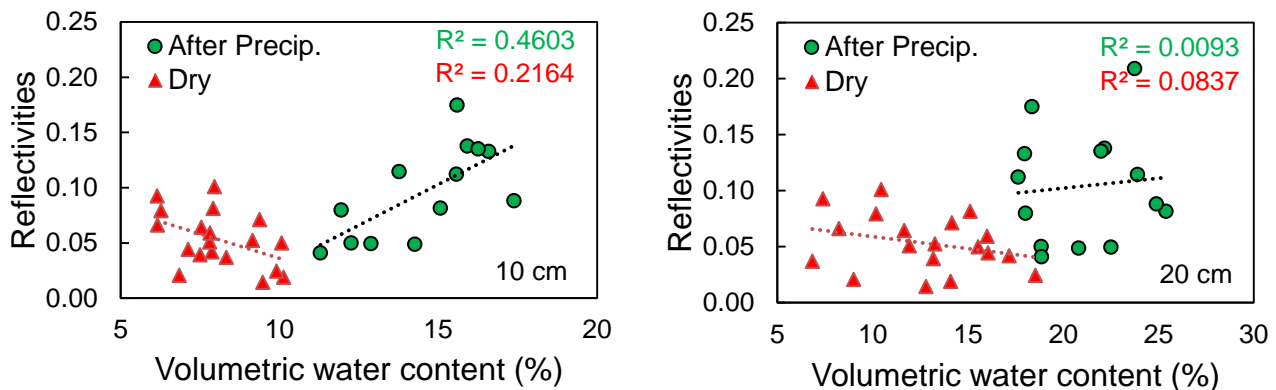
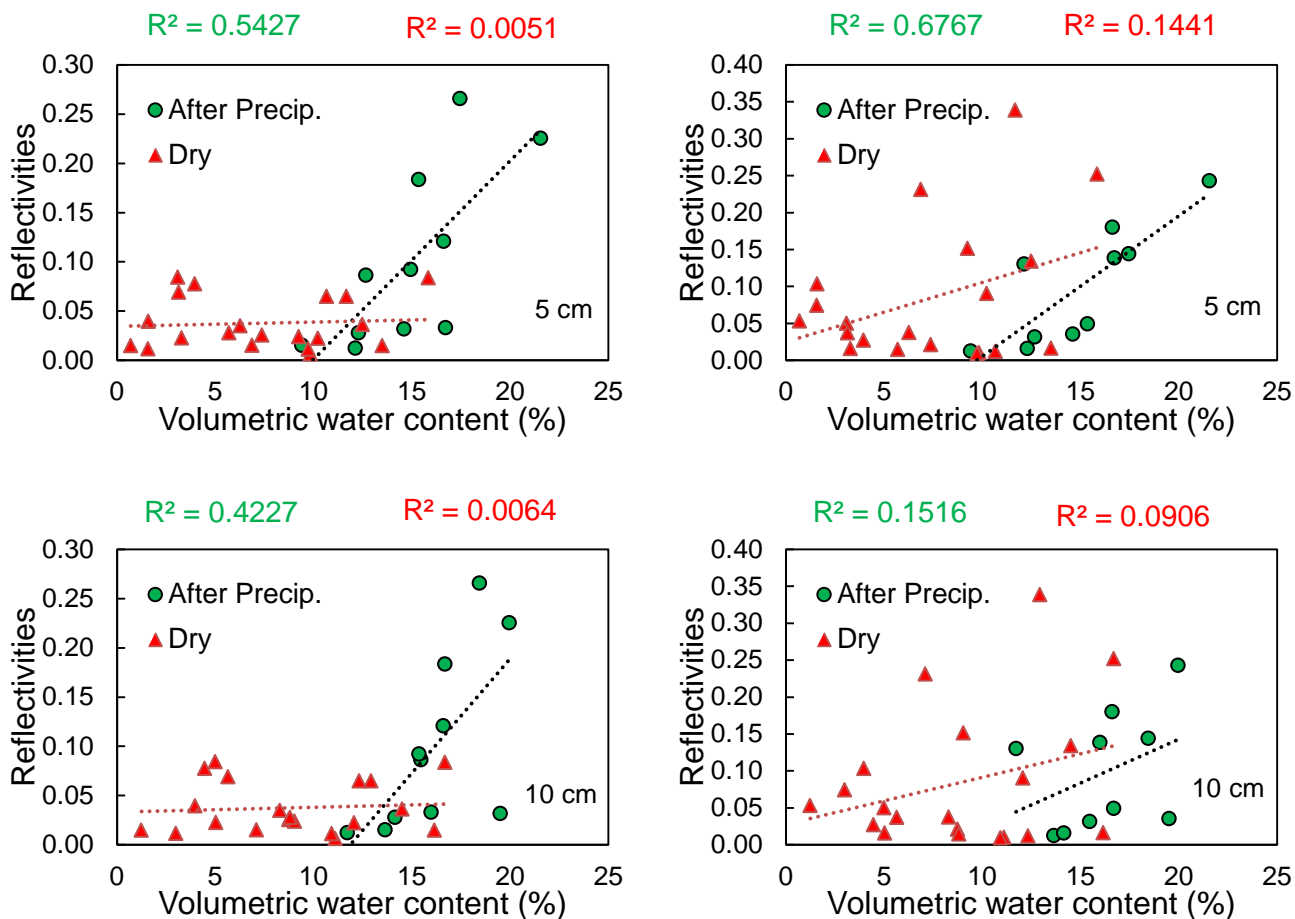


Figure 6. Correlations of reflectivity with volumetric water content of soil at 10 (left) cm and 20 cm (right) depths after data was separated during 2013.

During 2014, reflectivity measurements were adjusted by average calibration factors obtained on different dates. For antenna height of 1.6 m, reflectivity correlated with VWC collected at 5, 10, and 15 cm with R^2 of 0.30 ($P = 0.0015$), 0.24 ($P = 0.0053$), and 0.27 ($P = 0.0031$), respectively. For antenna height of 2.7 m, reflectivity correlated with VWC at 5, 10, and 15 cm with R^2 of 0.17 ($P = 0.0236$), 0.08 ($P = 0.129$), and 0.17 ($P = 0.0226$), respectively.

During the period of data sampling in 2014, there was heavy rainfall on Sep 9th (27.4 mm), Sep 17th (36.9 mm), and Sep 21st (21.4 mm). Data collected between Sep 9th and Sep 26th was separated as “After Precipitation” points. Similar to 2013, correlation of reflectivity with VWC improved after separating data points in two groups (Figure 7). For antenna height of 1.6 m, reflectivity correlated with VWC collected at 5, 10, and 15 cm with R^2 of 0.54 ($P = 0.0097$), 0.42 ($P = 0.0303$), and 0.45 ($P = 0.0233$), respectively. For antenna height of 2.17 m, reflectivity correlated with VWC collected at 5, 10, and 15 cm with R^2 of 0.68 ($P = 0.0035$), 0.15 ($P = 0.0266$), and 0.45 ($P = 0.0335$), respectively. Similar to 2013, reflectivity was less correlated with VWC collected during “Dry” periods (Figure 7). The increase in R^2 values for wetter soils agrees with previous finding by Grant (2006) who concluded that at least some precipitation was required in order to use reflected GPS signal to measure soil moisture. Similarly, Katzberg et al. (2006) found that DMR was able to detect soil moisture changes within 12 hours of rainfall.



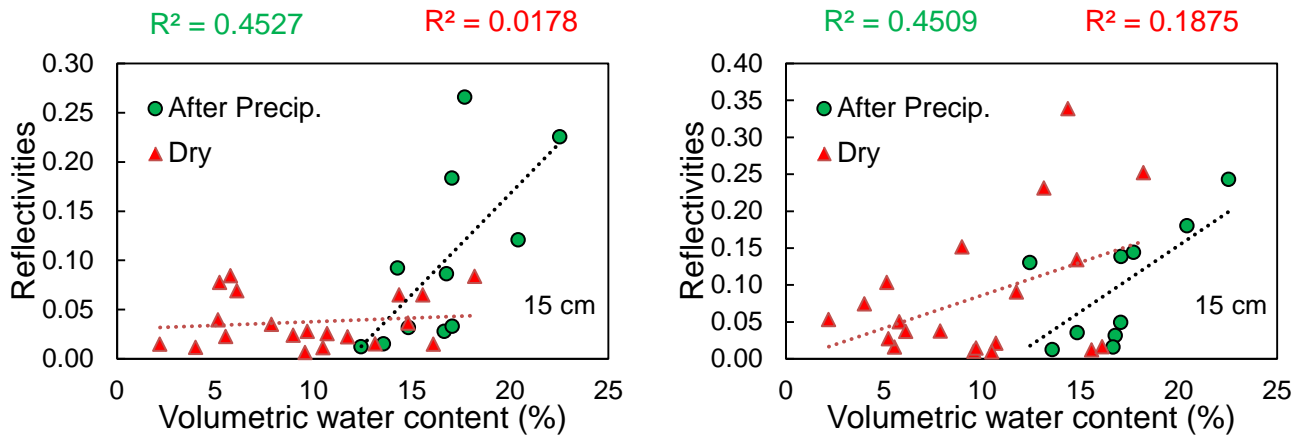


Figure 7. Correlations of reflectivity measured at 1.6 m (left panel) and 2.7 m (right panel) with volumetric water content of soil at 5 cm, 10 cm, and 15 cm depths during 2014.

Attenuation effects of vegetation

Gravimetric water content of cotton plant (M_g) was in the range of 0.6 to 0.85. Both real (ϵ') and imaginary components (ϵ'') of Dielectric constant (ϵ) of cotton plant increased with M_g (Figure 8). Figure 9 shows leaf loss factor increased as volumetric water content of cotton leaves increased.

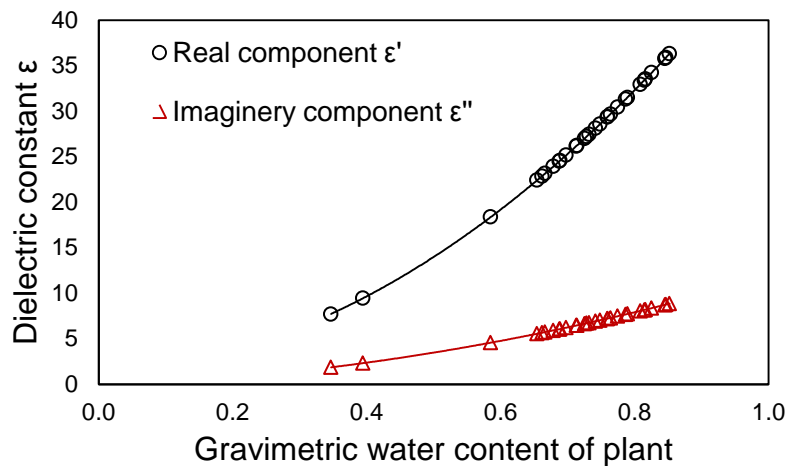


Figure 8. Relationship of dielectric constant with gravimetric water content of cotton.

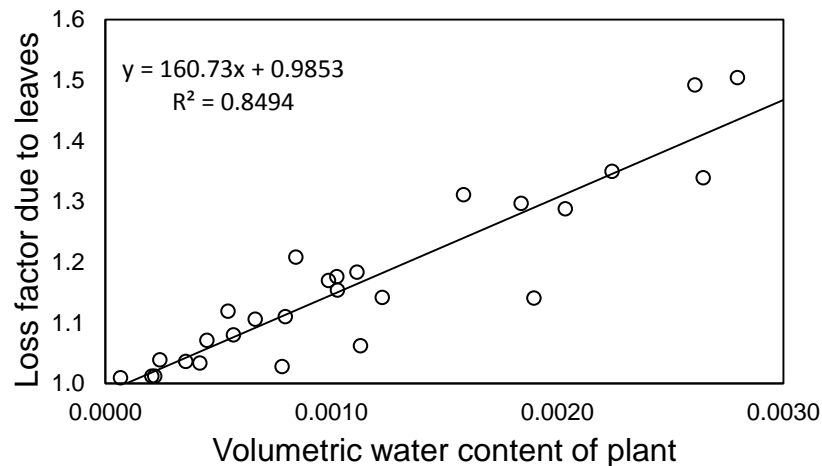


Figure 9. Relationship of loss factor with volumetric water content of cotton.

The effect of attenuation to GPS reflectivity caused by cotton canopy was accounted for by multiplying the original reflectivity by the loss factor due to leaves. It should be pointed out that the attenuation of GPS signal due to cotton stalks would be insignificant in this study, since only satellites at high elevation angles were selected by the DMR software, which makes the signals almost parallel to plant stalks (Grant, 2006). After adjustment, the relationship between adjusted reflectivity and VWC improved only for antenna height of 2.7 m, especially for soil depths of 10 and 15 cm (Table 1). Katzberg et al. (2006) also evaluated the effect of vegetation attenuation on GPS signal using equation from Ulaby and Rayes (1987). He concluded that, after attenuation caused by vegetation was accounted for, the mean error of the dielectric constant estimated from GPS reflectivity decreased, but the standard deviation increased.

Table 1. Summary of coefficient of determination for reflectivity measurements with volumetric water content of soil.

Year	Height ¹ (m)	Depth ² (cm)	Original Reflectivity		Adjusted Reflectivity	
			After Precipitation	Dry	After Precipitation	Dry
2013	4.2	10	0.46	0.22	/	/
2013	4.2	20	0.01	0.08	/	/
2014	1.6	5	0.54	0.01	0.51	0.00
2014	1.6	10	0.42	0.01	0.41	0.00
2014	1.6	15	0.45	0.02	0.42	0.02
2014	2.7	5	0.68	0.14	0.65	0.16
2014	2.7	10	0.15	0.09	0.24	0.11
2014	2.7	15	0.45	0.19	0.61	0.21

¹Height refers to distance of antenna platform to ground surface.

²Depth refers to distance of soil core samples took from ground surface.

Conclusion

This study was conducted to investigate the feasibility of using DMR to determine soil moisture content in cotton production fields and to evaluate the attenuation effect of vegetation (cotton) on GPS reflected signal. Results showed that DMR was able to detect soil moisture changes within one week after precipitation events that were larger than 25 mm per day. However, the DMR readings were poorly correlated with soil volumetric water content during dry periods. The DMR was evaluated using a RF power divider and the result showed that the top and bottom channels of the system produced similar signal to noise ratio. In addition, calibration results over water showed a small variation in calibration factor (1.14 ± 0.06), which indicated that noise of the system was stable throughout the experiment. The dielectric constant of cotton, both real and imaginary components increased with gravimetric water content of cotton. In addition, the loss factor due to leaves increased with volumetric water content of cotton. However, attenuation effect of plant canopy was not significant. After applying loss factors to reflectivity, the correlations between reflectivity and actual soil moisture content improved only for measurements made for antenna height of 2.7 m. For irrigation purpose, the results suggested that the sensitivity of GPS reflected signals to soil moisture changes needs to be further studied before this technology can be utilized for irrigation scheduling in cotton production.

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