UHF band attenuation through a corn canopy with crop growth

Richard Jay Cirone
Iowa State University

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UHF band attenuation through a corn canopy with crop growth

by

Richard Cirone

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Agricultural Meteorology

Program of Study Committee:
Brian Hornbuckle, Major Professor
Andy Vanloocke
Mark Westgate

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2019

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ABSTRACT

Soil moisture and vegetation remote sensing measurements can be inaccurate and/or misinterpreted in the US Corn Belt, specifically when considering seasonal variation in standing vegetation. A direct crop water measurement method was employed to assist in dry bias correction of soil moisture remote sensing, specifically to satellites SMOS and SMAP. A 433 MHz radio link was installed in a central Iowa corn field, shortly after planting, across a distance of 50 meters, for the purpose of measuring attenuation by crop water. This experiment ran until mid grain fill, development stage R3. Vegetation water column density increased from essentially 0 at planting to just above 4 kg/m$^2$ at R3. Received signal strength fell from -68 dBm to -86 dBm. The relationship between water column density and signal strength was significant, on the seasonal scale ($p = 3.6442 \times 10^{-5}, r^2 = 0.894$), with the signal dropping around 4 dBm per 1 kg/m$^2$ increase in water column density. At the V10 stage, vegetation contained on the order of 0.5 kg/m$^2$ more water in the morning than the afternoon. A response in received signal strength to this diurnal variation in crop water was not detected, however. The change in crop water could be too small to measure, or it may be masked out by signal noise, such as soil moisture, leaf wetness, or temperature effects on receiver efficiency. Crop water measurements by means of a radio link can monitor growth and development, and possibly scan for water stress. Crop water measurements can also assist in correcting SMAP and SMOS soil moisture measurements, which are inaccurate in the US Corn Belt, possibly due to seasonal vegetation.
CHAPTER 1. INTRODUCTION

In recent satellite missions, the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA) have each launched multiple microwave remote sensing satellites. Remote sensing is defined by measuring electromagnetic radiation with an antenna, and converting power received into a meaningful observation. Microwave radiation has a frequency of hundreds of megahertz to hundreds of gigahertz (wavelength of millimeters to around 1 meter), and is readily absorbed by groups of water molecules. The ESA launched SMOS (Soil Moisture and Ocean Salinity) in 2009. NASA launched SMAP (Soil Moisture Active Passive) in 2015. Both of these satellites operate in the L-band, on the long wavelength side of the microwave region, with wavelengths of 21 cm. Microwave remote sensing satellites which are tasked with observing Earth’s surface conditions, by means of measuring a microwave radiance, which is a function of surface temperature, surface reflectivity, optical depth above the surface which attenuates (weakens) the microwave, and vegetation temperature, if vegetation is present. One goal is to calculate surface reflectivity, as this variable indicates soil moisture and ocean salinity. Another goal is to find optical depth, the attenuation of the wave, as this provides insight on the medium above the surface, which is often vegetation. Because microwaves are absorbed (and sometimes scattered by) groups of water molecules, vegetation optical depth will increase proportionally with its water column density, the mass of crop water per ground area. Surface temperature and vegetation temperature are found by weather models.

Soil moisture measurements are erroneous over the US Corn Belt (Figure 1.1), where the surface is seen as drier than when measured in situ by around 7% volumetric (Walker, 2016). There are multiple possible sources of this error, which result from misinterpretations of soil surface roughness, soil clay fraction, radio frequency interference, and vegetation water column density. Vegetation water column density is likely variant on the diurnal scale, which would cause a difference in SMOS
and SMAP measured radiance between their 6 am and 6 pm overpasses. This study intends to quantify changes in crop water on the seasonal and diurnal scales, and the consequential change in attenuation of microwaves that travel through a vegetation canopy.

![Figure 1.1 SMOS measured soil moisture vs. South Fork Iowa River Soil Moisture Network (central Iowa) average, April – October 2013 – 2015.](image)

Experiments have been conducted to quantify microwave attenuation through a corn canopy. Hunt et al. (2011) set up cell phone towers in and around a corn field, which communicated with a commercial cell tower, and recorded signal strength. Towers in the corn field suffered more signal attenuation than those outside the field, as the signal passed through a greater volume of vegetation to reach the towers in the field. Ulaby et al. (1986) set up smaller scale microwave experiments in crop fields, and also observed that signal attenuation increases with distance traveled through the canopy, along with the water mass fraction of the vegetation. Because microwaves are absorbed and scattered by vegetation, optical depth is dependent on the water content of the vegetation, the distance the wave travels through vegetation, and incidence angle.
1.1 Motivation

The degree to which vegetation attenuates radiation is quantified by vegetation optical depth (VOD), which is known as \( \tau \) in microwave remote sensing literature. \( \tau \) also is proportional to the distance of the medium we look through, shown by (1.1), where \( \kappa_e \) (Np-m\(^{-1}\)) is extinction coefficient and \( d \) is distance the wave travels through the medium. The extinction coefficient is the sum the absorption coefficient (\( \kappa_a \)) and the scattering coefficient (\( \kappa_s \)), shown by (1.2). The absorption and extinction coefficients are functions of wavelength, temperature of the canopy, and salinity of the crop water (Ulaby et al., 1986). For SMAP and SMOS, the sensitivity to soil moisture decreases as VOD increases; the signal from the soil is attenuated as it goes through the crops, along with an increased brightness from the crops themselves. When corn is knee-high (\( \tau = 0.1 \) Np), brightness temperature, which is a measured surface temperature, decreases by 2.5 K per 1% increase in \( \theta_v \), volumetric soil moisture. When the canopy is full (\( \tau = 0.4 \) Np), brightness temperature decreases by 1.1 K per 1% increase in \( \theta_v \) (Hornbuckle et al., 2016).

\[
\tau = \kappa_e \cdot d \quad (1.1)
\]

\[
\kappa_e = \kappa_a + \kappa_s \quad (1.2)
\]

Soil moisture is the only reservoir of water which plants use for their growth. Plants uptake water through their roots, which is use photosynthesis to convert that water and carbon dioxide to carbohydrates; soil moisture must be greater than the wilting point for this to occur. Field operations are reliant on soil moisture too. If soil moisture is too high, farm equipment cannot navigate through the field for planting, fertilizing, harvesting, etc. Knowledge of soil moisture is relevant not only in the field of agriculture, but around the world. Heat will transfer through a wet soil more readily than a dry soil due to water’s high thermal conductivity, relative to air (Campbell and Norman, 1988). A wet soil’s water will also more readily evaporate, cooling the surface and by latent heat flux and adding water to the air. Due to soil moisture’s impacts on heat and water
fluxes, it is critical to know for numerical weather prediction, which provides forecasts for the entire world.

An alternate (yet related) motive for finding the attenuation through a crop canopy in relation to its water column density is monitoring of crop health. There are no current automated measurements of water column density in crop fields, on local or countywide scales. Permanent stations which measure crop water by radio links can monitor crops and validate SMOS and SMAP retrieved VOD. Water stress could be identified if attenuation is weak (crop is dry). Also, if the crop is healthy, development can be monitored by attenuation, as each development stage has a corresponding $\tau$. For corn, maximum $\tau$ is expected between the R2 and R3 stages, which occurs at 1000°C·day for hybrids which are planted in central Iowa (Hornbuckle et al., 2016). This ordinarily lines up with August in Iowa, shown by Figure 1.2 (Hornbuckle et al., 2016). Noting the maturity rating (how many vegetative stages the crop executes) is key, as the peak in $\tau$ may vary in stage and thermal time depending on maturity rating. More work is required on this study.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure12.png}
\caption{SMOS optical depth: raw values, 21 day running average, and Fourier smoothed curve at Kossuth county, IA in 2010.}
\end{figure}

It can also been seen that SMOS retrieved VOD is highly variable on the daily scale in Figure 1.2. Crop water column density is not expected to exhibit this noise pattern, when considering a single field or countywide average. This noise could be due to variation in soil surface roughness, soil
moisture, or other factors. A vegetation network consisting of field sites with radio links may be used to validate SMOS and SMAP measurements.

1.2 Field Setting

For reference, Figure 1.3 shows examples of corn at various stages during the growing season (Abendroth and Elmore, 2011). In this experiment, an ultra high frequency (UHF) microwave radio link was set up in the field just after corn emergence. At the time of experiment initiation, corn plants were in their V2 stage, weighing around 1 g with their tallest leaf reaching a height of 10 cm, so their absorption of wave power could be ignored. As the summer progressed, the plants grew through their vegetative stages up to V16, gathering crop water the whole way. By mid–July the plants transitioned into their reproductive stages, no longer growing taller, and developed ears. By the end of July, the plants were in their R2 (blister) stage, yet they only took up less than half of one percent of the volume in the field, as depicted by Figure 1.4. At this time just over half of the corn’s volume was water. The link remained until early August; at that time the corn was fully grown and its ears were at the R3 (milky) stage. Senescence, which entails a decrease in crop water column density, occurs in development stages R5 and R6, was not measured by this experiment.

Figure 1.3 Corn stages for the maturity group of my field site. Left three images are from this study. Right three images are from Iowa State University Extension and Outreach.
Electromagnetic radiation attenuates as electrical energy is converted to kinetic energy of molecules in the medium. As the microwaves pass through liquid water, groups of molecules orient their polarity with the electric field, taking energy from the wave, whether that be in the corn, leaf wetness, or elsewhere. Additionally, because crop water is saline, ions move along the electric field and attenuate the wave as well. Solids are much more rigid on the molecular scale than liquids, so they only weakly attenuate radiation. There is however a small attenuation coefficient from the dry matter in vegetation, along with some attenuation from water that is tightly bound to other molecules and acts electrically as ice (El-Rayes and Ulaby, 1987b). Since the antennas were omnidirectional, some of the radiation was reflected off the soil surface, which was then captured by the receiver.

Figure 1.4 The volume fractions of components above the soil on July 31st. Left: fractions for the whole field. Right: fractions for corn plants.

1.3 Non-Scattering Simplification

In order to model the power attenuation through a corn canopy, simplifications need to be made. Figure 1.5 represents vegetation and soil becoming simple geometric shapes, to the point that received power can be modeled. Here, the corn’s volume and air’s volume are considered as fractions of total volume, and one homogeneous effective medium attenuates the wave.
this model there is no scattering by the canopy, so all attenuation is due to absorption by the vegetation. This is a fair assumption when wavelength is much longer than particles or components in the medium. The soil, which is rough on the order of centimeters, has been flattened to simplify incidence angle of waves and reflectivity. Figure 1.5 also shows the ways radiation propagates in a radio link experiment, with some radiation traveling directly through the medium, while other incidence angles of radiation reflect off the soil, to be also captured by the receiver.

Figure 1.5  Top: realistic diagram of a radio link in a corn canopy. Bottom: Field simplified to allow for modeling.

In this model with scattering negated, VOD is simpler to find. Materials’ electrical properties are often expressed in terms of relative permittivity, \( \epsilon_r \), which has a real and imaginary component. Index of refraction is another frequency dependent way to describe electrical properties of a medium, which also has a real and imaginary component. The higher the imaginary component of the index of refraction the greater the absorption by the medium. At boundaries between mediums, the real components of indexes of refraction of the mediums determine the reflectivity and transmissivity.
(how much power is transmitted through). The index of refraction is the square root of the dielectric constant (1.3). The absorption coefficient, $\kappa_a$, can be found by (1.4), where $k_0$ is free space wave-number and $n''$ is the imaginary component of index of refraction. Free space wave-number is number of waves per meter in a vacuum, which can be found by (1.5), where $f$ is frequency and $c$ is the speed of light. Finally, combining these previous three equations with (1.1) gives a model for this new, non scattering $\tau$, which is (1.6). With this model, the imaginary index of refraction is to be the volume fraction corn times its index of refraction plus the volume fraction of air times its index of refraction. Because the index of refraction is 1 for air and the sum of the volume factions is 1, (1.7) finds the index of refraction of the effective medium, where $f_v$ is volume fraction of corn and $n_v$ is the complex index of refraction of corn.

\[
n = \sqrt{\epsilon_r} \quad (1.3)
\]

\[
\kappa_a = 2k_0 \cdot n'' \quad (1.4)
\]

\[
k_0 = \frac{2\pi \cdot f}{c} \quad (1.5)
\]

\[
\tau = \frac{4\pi \cdot f}{c} n'' d \quad (1.6)
\]

\[
n = f_v \cdot n_v + 1 - f_v \quad (1.7)
\]

I developed four hypotheses before the experiment to guide and focus this study. These hypothesis are formed from either physical laws, theories, or similar past experiments. Here stated are my original hypotheses, some of which were updated during or after the experiment.

1.4 Hypotheses
1.4.1 First Hypothesis: Signal Strength Decreases as Crop Water Increases

The premises of this hypothesis is simple; The higher the VOD, the more the wave is attenuated. This hypothesis was formed by radiometry models, and is backed up by related studies.

1.4.1.1 Cause of Decreased Signal Strength

At longer wavelengths than those used by SMAP and SMOS, such as at 69.3 cm which was used in this experiment, components of vegetation are much smaller than the wavelength, and scattering can be considered negligible. We did use vertically polarized radiation in this study, which is in the same direction as corn stems, so scattering will be kept in mind. It is worth noting that vertically polarized radiation couples strongly when it is parallel to a cylinder’s axis, which in this experiment the corn stalks are cylinders and the polarization is parallel to their axis (Ulaby et al., 1986).

At frequencies below 5 GHz, salinity plays a role in attenuation of radiation (Ulaby and Jedlicka, 1984). Corn fluid contains the potassium, magnesium, calcium, chlorine, nitrate, phosphate, sulfate, and sodium ions (Yasutake et al., 2009). The relaxation time for ions is longer than that of water molecules; it takes longer for ions to move along a varying electric field than it does for groups of water molecules to rotate and orient their polarity along an electric field. That is why frequencies above 5 GHz have periods too short for ions to accelerate to a significant velocity. Real and imaginary components are described by (1.8), where \( j \) is the square root of -1, \( \epsilon' \) real dielectric component, and \( \epsilon'' \) is the imaginary dielectric constant (El-Rayes and Ulaby, 1987a). Ionic conductivity is nearly linearly dependent with salinity, and contributes 1.27 Np/m to \( \kappa_a \) for corn, which has a salinity between 5 and 15 per mil (El-Rayes and Ulaby, 1987b).

\[
\epsilon_r = \epsilon' - j\epsilon''
\] (1.8)

Both the real and imaginary components of dielectric permittivity of vegetation increase with raised water content (Burke et al., 2004). Broadhurst (1970) found an \( \epsilon'' \) of 6 and 11 for bamboo leaves at 38\% and 63\% water mass, respectively at 23\degree C and 450 MHz. He also found tulip tree branches to have a \( \epsilon'' \) of 2.5 and 9 for water mass fractions of 30\% and 58\%. El-Rayes and Ulaby
(1987a) found dielectric constants of corn using a coaxial probe. They found the $\epsilon''$ to be 4.9 at a water mass fraction of 0.324 and an $\epsilon''$ of 20.5 for a water mass fraction of 0.835, at 0.4 GHz and 22°C. El-Rayes and Ulaby also determined corn stalk fluid has an $\epsilon''$ of 25. They then developed a relationship for a water mass fraction dependent complex dielectric constant, which considers free water in vegetation and bound water, which is held tightly by carbohydrates.

1.4.1.2 Timing of Enhanced Crop Water

Signal strength is expected to weaken as the crop gains water column density, the mass of water per ground area. $\tau$ in the longer microwave bands is greatest between the R2 and R3 stage, or at $1000^\circ$C · day for hybrids of corn planted in central Iowa (Hornbuckle et al., 2016). That is why this time of the season is expected to have the weakest signal strengths of all. A diurnal variation in crop water may also be present with transpiration only during daylight hours (Hypothesis 4), which is expected to align with a diurnal cycle in received signal strength. Hunt et al. (2011) observed a diurnal cycle in signal strength in a similar study, shown in Figure 1.6.

Figure 1.6  Signal strength variation as measured by Hunt (2011) for seven radio links.
1.4.2 Second Hypothesis: Signal Strength Increases as Soil Moisture Increases

The reflectivity of soil increases with enhanced soil moisture. The portion of the signal that reflects off the soil will be larger when soil moisture is greater, adding to the received signal strength. Indirect effects of soil moisture are also apparent in the field system. Increased soil moisture means a higher thermal conductivity. This keeps vegetation warmer overnight and cooler during the day (Chen et al., 2013). Recall that dielectric constant of water is temperature dependent. Dew accumulation is also influenced by soil moisture; accumulated dew mass can be three times greater over a wet soil than a dry soil by means of distillation. Duration of dew is independent of soil moisture, however (Rowlandson, 2011).

1.4.3 Third Hypothesis: Signal Strength Decreases as Leaf Wetness Increases

This hypothesis was formed by radiometry models. Water drops in the medium the microwaves pass through will attenuate wave power.

1.4.3.1 Leaf Wetness Timing and Accumulation

Precipitation, irrigation, dewfall, dewrise, and guttation can all result in leaf wetness (Rowlandson, 2011). The field site in this study was not irrigated. Guttation is the process of leaf saps rising to the surface, and is enhanced in injured leaves. Guttation is small in magnitude relative to other forms of leaf wetness, and often it is not even modeled (Jacobs et al., 1994). Overnight, the surface of the canopy cools the fastest of anywhere in the field. Leaves will become colder than the air and the soil at some point during the night, as leaves will have less downwelling longwave radiation incident on them than the soil, yet leaves emit thermal radiation more effectively than air. The leaves may even cool to the dew point, at which time dewfall will occur. Dew can form on vegetation when the air temperature is above the dew point since the leaves are colder than the air overnight. In central Iowa, dew typically forms on corn when the air’s relative humidity is above 83% at heights between 1.5 and 2.0 m above the ground (Rowlandson et al., 2015). Distillation (dewrise) will increase dew accumulation when the soil is moist by soil evaporation and
condensation onto vegetation. Distillation can form on the top or bottom of leaves. Light winds aid in dew formation as they supply the control volume with additional moisture. Winds also heat the vegetation by a sensible heat flux, so faster winds suppress dew formation. The optimal 10 m wind speed for dew formation is between 1 and 4 m/s (Segal and Garratt, 1988). The most dew forms at two-thirds canopy height as that is where leaves are exposed to the atmosphere, yet most wind is blocked (Rowlandson, 2011). At a higher height in the canopy, there is less downwelling radiation from above vegetation, leading to higher leaves having cooler temperatures than lower leaves at night. The location of dew is relevant, as waves in different radio links travel through different heights in the canopy. Dew is at least 80% likely between 2:00 and 5:00 standard time on corn during the summer (Kabela et al., 2009). Dewfall rates can be as high as 0.06 mm/hr, with dewrise rates not exceeding 0.03 mm/hr (Segal and Garratt, 1988). Dewfall accumulation is rarely greater than 0.5 mm/night on corn (Chen et al., 2013). The rate of dew drying depends on the shape of the dew. Possible shapes are droplets, films, clustered droplets, and patches (Jacobs et al., 1994). Both sides of the leaf take the same amount of time to dry, and there is no difference in dew duration between 1/3 and 2/3 canopy height (Rowlandson, 2011). In a heavy dew event, more dew will collect in the collars and on the bottom of leaves (Kabela et al., 2009).

1.4.3.2 Impact of Leaf Wetness on Signal Strength

Leaf wetness, which could take the form of dew or intercepted precipitation, will act similarly to crop water in attenuating the microwaves, except without the effect of salinity. Another difference between this water and that in the crops is that this will change in response to atmospheric conditions much more quickly. The effect of dew on microwave radiance of vegetation is dependent on the type of vegetation. Brightness temperature of wheat, soybean, and grasses is known to increase with dew present (de Jeu et al., 2005). In corn, radiance decreases with increased dew (Hornbuckle et al., 2006). On the contrary, Hunt et al. (2011) found that signal strength at 2.4 GHz is unaffected by rain and leaf wetness.
1.4.4 Fourth Hypothesis: Crop Water is Greatest in the Mid Morning and Least in the Late Afternoon.

A similar experiment was conducted in 2016, where the signal strength was least in the mid morning and greatest in the late afternoon. The greatest rate of photosynthesis is during midday, at which time the crops are transpiring water at the greatest rate with the strongest solar radiation. Although stem water content is invariant with time of day, leaf water content is diurnally variable, especially in times of water stress (van Emmerik et al., 2017). During periods of water stress, water content of the leaves near the ear is far greater at 6 AM than 6 PM, while the highest and lowest leaves on the plant concur a much lesser diurnal variation (van Emmerik et al., 2017). Using cell phone signal through a known distance of a corn field, Hunt et al. (2011) found that the diurnal pattern of radio signal strength indicator (RSSI) was the same as what was believed to be water column density’s diurnal variation.
CHAPTER 2. METHODS AND PROCEDURES

2.1 Introduction

This experiment was conducted in a corn field during the summer of 2018, (42° 28'55.2" N, 93° 31'33.9" W). The main data collection period began June 1st and ended August 8th. It involved setting up a microwave radio link in the field to quantify attenuation due to crop water, along with other sensors for various environmental conditions. Vegetation was destructively sampled on a weekly basis for the purpose of finding water column density. The field site, which is named Coles Farm, is just east of Williams, IA. The experiment began just after emergence and continued until the R3 (milky fluid) stage. Table 2.1 shows the time periods for all data collected in the experiment. All automated instruments collected data June 1st through August 8th, so this is our range of dates of interest. A testing period preceded the experiment from March to mid–May, where all instruments except for the radios were tested, either for basal values or temperature sensitivity. All equipment was first tested in a laboratory setting in March. In April, soil moisture and temperature data was collected at the Williams field site (not yet planted) for the purpose of soil moisture sensor temperature calibration. In May, leaf wetness sensors were tested in a grassy area adjacent to a field just south of Ames, IA, for the purpose of comparing timing of leaf wetness and sensor wetness.

Table 2.1  Time periods of data. All dates 2018

<table>
<thead>
<tr>
<th>Data source</th>
<th>Begin Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logger Data</td>
<td>5/29</td>
<td>8/8</td>
</tr>
<tr>
<td>Radio Data</td>
<td>6/1</td>
<td>8/12</td>
</tr>
<tr>
<td>Flux Tower Data</td>
<td>6/1</td>
<td>8/14</td>
</tr>
<tr>
<td>Vegetation Data</td>
<td>5/29</td>
<td>8/7</td>
</tr>
</tbody>
</table>
2.2 CS616 Temperature Calibration

Soil moisture probes were the only instruments used which needed manual calibration. Campbell Scientific 616 soil moisture probes’ raw output is a period that depends on soil moisture and temperature. The steps for calibrating this period are the following:

1. Find a calibration equation between impedance (soil resistivity) measurements and volumetric soil moisture by comparing impedance voltage to sampled soil moisture.

2. Apply this equation to all impedance measurements and compare the average of those to 616 period at that time.

3. Account for the effect of temperature on CS616 period (Logsdon, 2018).

4. Apply this temperature calibration and period to soil moisture equation to 616 measurements at all times.

2.2.1 Impedance measurements to soil moisture

On 12 days during the experiment at Coles farm, soil samples were taken along with impedance measurements by a ML2x Theta Probe. The first three of these days were in April; the rest were in June or July. Four soil samples were taken each day, with a Theta Probe measurement just adjacent to the soil sample location as well. Impedance was also measured between 16 and 20 other points distributed around the experiment site on these twelve days as well. Volumetric soil moisture was calculated using bulk density and gravimetric soil moisture in equations 2.1, 2.2, and 2.3, where $\rho_B$ is bulk density, $M_D$ is mass of dry soil, $V_s$ is volume of all soil, $\theta_G$ is gravimetric soil moisture, $M_W$ is mass of water, $\theta_V$ is volumetric soil moisture, and $\rho_W$ is density of water (1000 kg/m$^3$).

$$\rho_B = \frac{M_D}{V_s} \quad (2.1)$$
\[ \theta_G = \frac{M_W}{M_D} \]  

(2.2)

\[ \theta_V = \frac{\rho_B}{\rho_W} \theta_G \]  

(2.3)

Averaging the four Theta Probe voltages and volumetric soil moistures for each day gave 12 data points, each with a voltage and soil moisture (Figure 2.1). There is a weak relationship between soil moisture and measured voltage \((r^2 = 0.25)\). A much stronger voltage dependency on soil moisture was expected; the relationship may be weak because of averaging together four points in the field. That is why from this step on we will also consider the generalized calibration from the ML2x manual for a mineral soil. From this step, two equations relating Theta Probe voltage to soil moisture have been obtained, (2.4) and (equation 2.5), where \(V\) is the voltage of the Theta Probe, which comes from the ML2x manual.

\[ \theta_V = 0.0899V + 0.263 \]  

(2.4)

Figure 2.1 Theta probe measured voltage vs. volumetric soil moisture from samples. The green line represents the linear approximation for a mineral soil as specified by the ML2x manual.
\[ \theta_V = 0.529V - 0.0595 \]  \hspace{1cm} (2.5)

2.2.2 CS616 measurements to soil moisture

Using Equations 2.4 and 2.5, mean soil moisture was calculated from ML2x voltage across all points. This soil moisture was then plotted vs 3 cm deep CS616 period, obtaining a relationship by linear regression. CS616 period is against calculated soil moisture in Figure 2.2.

![Figure 2.2](image)

Figure 2.2 3 cm deep CS616 period averaged for the time period of soil sampling vs. soil moisture calculated from Theta Probe measurements. Soil sample points are using equation 2.4. Generalized calibration is using equation 2.5.

2.2.3 Temperature calibration

Four 3 cm deep thermocouples were installed in the soil, which measured the soil average temperature at that depth. Through a trial and error method, I subtracted from the period of the CS616s a certain constant times the temperature until the best linear relationship was made between period and soil moisture. This constant is 0.137 µs per °C, which resulted in an \( r^2 \) value of 0.95 between temperature calibrated period and soil moisture (Figure 2.3). From this step, we have obtained two equations for converting CS616 period to soil moisture: my calibration (equation
2.6) and the manual – assisted calibration (equation 2.7). In these equations, $P$ represents period in microseconds and $T$ represents 3 cm soil temperature in °C.

\[
\theta_V = 0.0052(P - 0.137T) + 0.1833
\]  

(2.6)

\[
\theta_V = 0.0303(P - 0.137T) - 0.5282
\]  

(2.7)

Figure 2.3 3 cm deep CS616 temperature adjusted period averaged for the time duration of soil sampling vs. soil moisture calculated from Theta Probe measurements. Soil sample points are using equation 2.4. Generalized calibration is using equation 2.5.

2.2.4 Applying the temperature calibration to all soil probe measurements

The temperature calibration will effectively reduce the soil moisture measured, to a greater effect with increased soil temperature. This temperature calibration is shown in Figure 2.4. The difference between temperature calibrated and uncalibrated soil moisture is shown in Figure 2.5, and contains calculations for soil moisture using soil samples and the ML2x manual. There is a much greater variation in soil moisture with the manual’s generalized calibration than using soil sampled in this experiment. With the experimental calibration, $\theta_V$ would be between 0.3 and 0.36
the entire experiment period, which is a range smaller than realistic. That is why we are treating the generalized temperature calibration soil moisture as the true soil moisture in this study.

Figure 2.4 3 cm deep CS616 temperature adjusted period averaged for mid June and temperature calibrated period.

2.3 Instrument Setup and Data Collection

Figure 2.6 shows a map for the layout of the experiment; instrument towers and walking paths are highlighted. All instruments except the radios were on either the east or west logger. All instruments collected data on 5 s intervals, which were averaged over 15 minutes. In situ measurements (corn size and mass) were taken roughly weekly with around 36 plants being sampled each day. Flux tower data from NLAE (National Lab for Agriculture and the Environment) was also on 15 minute averages, which were used for verification / quality control of my data. The Flux tower is located in the center of the field, and provides radiation and precipitation measurements.

2.3.1 Radio Link

The radio link was activated on June 1st and was decommissioned on August 12th. This radio link consisted of two towers, one with three transmitters at 433 MHz and one with a single receiver.
Figure 2.5  3 cm deep CS616 calculated soil moisture for mid June, temperature calibrated and uncalibrated.

The installation is shown in Figure 2.7. The transmitting tower is the one I am standing next to. These two towers were 50 m apart. A frequency of 433 MHz was selected because that corresponds to a wavelength of 69.3 cm, which is larger than the length of any component of the corn. This allows for the simplification model proposed in section 1.3 by means of neglecting scattering. This wavelength the microwave range, which is key in order to be attenuated by liquid water, yet field components emit weakly here. Figure 1.5 depicts a diagram of wave propagation in this experiment, where waves are attenuated as they travel through vegetation. On July 17th, the radios were adjusted to allow for an increased sensitivity and detection of weaker signals.

### 2.3.2 Soil Moisture

Time domain reflectometers (TDRs) measured soil moisture. A TDR is a waveguide with two prongs, which the wave travels between. The wave starts at the base of the TDR, propagates to the end, and then reflects and returns to the base. The time this cycle takes is measured as the period, which increases as index of refraction increases. A longer period indicates higher soil moisture in a mineral soil. Fourteen Campbell Scientific 616s were used, 8 at a depth of 3 cm and 6 at a depth
of 9 cm, in order to characterize the top 12 cm of the soil; 37% of power reaches a depth of 14 cm in damp soil at a wavelength of 69.3 cm. Also, an impedance probe was used, which measures the top 6 cm of the soil, and can be compared to soil moisture measured by the 3 cm deep TDR. Installation of these sensors began with digging a large portion of the soil out from behind the intended soil to measure. Then, a vertical face was cut into the soil and the prongs of the TDR were inserted into the soil, keeping the base of the sensor parallel to the ground. Figure 2.8 shows a TDR all the way inserted into the soil. Then, the removed soil was filled back from where it was dug out from, being compressed under the base of the CS616. Roughly weekly, soil samples were taken for the purpose of calculating a soil moisture from the period measured by the TDR. This involved taking 20 measurements of soil impedance with a ML2x and and four soil samples, which would be massed on site, dried, and massed again to find water and bulk mass.

2.3.3 Temperature Measurements

Soil temperature was measured by six copper type-T constantan thermocouples, three residing at each logger. Four thermocouples placed at a depth of 3 cm; two were at a depth of 9 cm.
Thermocouples, along with TDRs, were placed at both locally high (in row) and low (between rows) places in the field to represent the entire area of interest (Hornbuckle, 2003). Soil temperature was also measured by an infrared thermometer looking down at the soil from a height of 40 cm between rows. Another infrared thermometer was placed 3 m above the ground, looking down at the top to the corn canopy to measure crop skin temperature. Air temperature and humidity were measured by a HMP50 thermometer, which was kept at mid–canopy height (Figure 2.9).
2.3.4 Leaf Wetness

Timing and relative quantity of leaf wetness was determined with Decagon leaf wetness sensors. These dielectric sensors have a highly resistive plate which current passes through; circuitry on the plate being connected by an electrically conductive material such as impure water will reduce resistance and increase the output voltage. Leaf wetness sensors were angled 38° down from horizontal, facing north to prevent ultraviolet damaging, as specified by Rowlandson (2011) that sensors are to be oriented 30° to 45° down facing north in the northern hemisphere. Angling the sensors at a consistent declination with past experiments also produces a similar runoff and incidence angle when considering heat and water mass fluxes. Three sensors were located at a height of 83 cm, which is one-third the height the top of a fully grown corn canopy, which I consider to be 250 cm, which was estimated from previous field experiments. Three more sensors were elevated 167 cm, or two-thirds of full canopy height, as the greatest accumulations of leaf wetness are found here (Kabela et al., 2009). At each height of sensors, two sensors were facing up to measure dewfall and leaf wetness from rain and one sensor was facing down which does not measure rain. Guttation was not measured by leaf wetness sensors. Leaf wetness was at times measured in situ. This was preformed by weighing a freshly cut plant while taking care to not spill off the water on the leaves.
and stem. Then, the leaf wetness would be whipped off and dried with a towel if necessary. The plant would be weighed again and the decrease in mass was considered leaf wetness. This was only applicable when leaf wetness was present and the plant was small (V10 or earlier).

2.3.5 $M_w$, Mass of Water in Crops

Destructive sampling was the means for directly measuring the mass of crop water. First, plants were staged and height and stem diameter measurements were made for future reference. Plants were cut at their base, or just above their roots if visible, and then weighed as soon as possible, which on some days was within seconds as the scale was set up in the field. This was possible on days with calm to light winds; as wind lifts the scale weight readings become inaccurate. We employed a wind shield every time we weighed in the field to help block any light breezes. When corn was not weighed in the field, it was weighed in a trailer at the side of the field within 20 minutes of cutting. On June $^\text{th}$ plants were massed in the field, and then in the trailer around a half hour later, which is shown in Figure 2.10. This shows a mass decrease on the order of grams from when the plants were freshly cut in the field to when they were weighed in the trailer. A few large outliers exist, which are caused by wind error. Because this difference is only up to 10 g, we considered the measured mass the actual mass for all samples on all days, whether they were massed in the field or in the trailer. There are corn plants were then heated in 70°C driers for one week to find dry mass. Plants were sampled roughly weekly and between 30 and 36 plants were measured on days when we sampled. On June 6$^\text{th}$ and June 27$^\text{th}$, three plants were sampled each hour for twelve hours. There were two days of this study which a great number of corn plants were sampled: July 17$^\text{th}$ and August 7$^\text{th}$. July 17$^\text{th}$ featured sampling of 20 plants per hour from 10 am to 5 pm. On August 7$^\text{th}$ we sampled 30 plants per hour, from 10am to noon.

2.4 Leaf Wetness Sensor Testing

Twelve leaf wetness sensors were set up in a grassy patch adjacent to a newly planted (but not emerged) soybean field just south of Ames, IA, on May 8$^\text{th}$, 2018, arranged according to
Figure 2.10 Masses of the 36 sampled corn plants from June 19th. The elapsed time between the crops being weighed in the field and in the trailer is between 20 and 30 minutes.

Figure 2.11. The leaf wetness sensors were located around heights of one-third and two-thirds full canopy height and were angled 38° down, facing north, just as during the main experimentation period at Williams, IA. There were two main differences between this testing period and the main experiment. In the testing period, there were six sensors around both specified height and all sensors were face up. The testing period ran until May 18th, and sensors were visited on the mornings of May 10th and 16th to observe how the sensors dry off with time compared to grass, and also compare drying time with voltage reading. Measurements from May 10th are shown in Figure 2.12. The sensors were also visited overnight in the early morning hours of May 17th to observe dew formation timing in comparison from the grass to the leaf wetness sensors. Notably, the dew dries off the sensors before it does so for the grass. Dew also forms earlier on the grass than it does on the sensors. Overnight on May 17th, a light dew event occurred on the grass, which corresponded to only a very small voltage increase on the sensors, with little to no visible dew on the sensors. Some sensors output higher voltages than others at all times, on the order of 10 to 20 mV, which agrees with leaf wetness sensor documentation; Leaf wetness sensors all have different base voltages (Rowlandson, 2011). Voltages below 270 mV corresponded to dry sensors, which meant little to
no dew formed on vegetation. With voltage ranges from 270 to 300 mV, small drops of water were visible on the sensors, which corresponded to light dew on vegetation. Voltage ranges above 300 mV showed large drops on the sensors, which aligned with substantial dew on vegetation. Heavy dew events registered with voltages above 400 mV. These tests show there may be light dew present on vegetation, whether that be turf grass or a full maize canopy, even though the sensors register as dry. Also, the leaf wetness sensors may output an elevated voltage, even when there appears to be no dew.
Figure 2.12  Leaf wetness sensor test results from May 10th. Here, grass wetness is categorized as follows: 6 for all grass wet, 4 for some grass wet, 2 for only tall grass wet, and 0 for all grass dry.
CHAPTER 3. RESULTS

Environmental variables of interest were compared to received signal strength on the seasonal, daily, or diurnal scale. In cases where variables appear to correlate in time, they are plotted versus each other as well in a two sample student’s t-test. The overarching goal is determining the effect of crop water on signal strength, with other tests for calibration and determining the magnitude of noise factors. At some times certain radio transmitters were down, resulting in no signal being detected. At other times, the wave was attenuated to the point that the power received was so low that it was not detectable. That is why in some plots, there are lapses in recorded signal strength, while some radio link pairs were omitted in select plots all together. In all plots, error bars on water column density are to two standard error.

3.1 Introduction

All results shown pertain to at least one hypothesis. While the data collection method was consistent throughout the whole experiment period for all automated instruments, it was inconsistent for destructive crop measurements; sampling days occurred semi-regularly due to targeting dry days in order to avoid leaf wetness. The number of samples / rate of sampling varied by day depending on if we were attempting to see a hourly change in crop water and if additional tests were conducted. In the cases where diurnal plots are presented, anomalies are plotted, which are the difference between the value at that point in time and daily mean, averaged over the whole data collection period.

3.2 The Effect of Antenna Temperature on Signal Strength

Even before crops became significantly large (before the V6 stage) there is a diurnal variation in signal strength. This variation is suspected to be due to antenna temperature, and is plotted vs.
such in Figure 3.1. Early in the experiment period when crops are negligible, diurnal signal strength closely follows enclosure temperature. Figure 3.2 shows signal strength vs. receiver temperature for this time period, and it becomes clear that temperature affects receiver and/or transmitter efficiency. As all of the results of the study involve signal strength, be aware that the diurnal cycle in air temperature, and therefore enclosure temperature, may be the cause of hourly variations in signal strength.

3.3 Hypothesis 1

Signal strength decreases as crop water increases.

This hypothesis is tested for all three transmitter – receiver pairs. Crop water refers to the mass of water in vegetation (corn) tissue, which is expressed as water column density, the mass of water
per ground area above the soil. This hypothesis was analyzed on the seasonal scale, and a daily scale on days which many samples were taken or sampling spanned several hours of the day.

### 3.3.1 Seasonal Variation

A seasonal variation in received signal strength was evident, as shown by Figure 3.3. Signal strength decreases rapidly between stages V8 and V11 in the growing degree day range of 400 to 550°C. Meanwhile, water column density is increasing steadily from thermal time 200 to 700°C, which corresponds to development stages V5 and V16, respectively. These two variables are plotted against one another in Figure 3.4, showing a significant relationship and strong correlation ($p = 3.6442 \times 10^{-5}$, $r^2 = 0.894$). This result agrees with my original hypothesis. Received signal strength and water column density are the two variables of interest that varied the most seasonally.
3.3.2 Hourly Variation

On a select few days out of the growing season, we attempted to measure an hourly variation in water column density. On these days, we are assuming that the plants are not growing or increasing their dry mass appreciably. There may be a difference in size of the plants sampled between hours, though. This sampling bias was eliminated by the following three steps:

1. Find the mean dry mass for all plants sampled on that day.

2. Find the gravimetric water content (ratio of water mass to dry mass) of each plant sampled.

3. Calculate water mass of each plant, by multiplying its gravimetric water content by the daily mean dry mass.

4. Find each plant’s water column density by multiplying its calculated water mass by the planting density (plants per square meter of ground area).
5. Find mean water column density of plants sampled within an hour.

June 6th was the first day with several sampling hours, but water column density then was a mere 0.1 kg·m$^{-2}$, which is not great enough to noticeably reduce power received in this experiment, so results from this day are excluded from this portion of the study.

The next day when crops were measured over a long period of time was June 27th, when plants were at the V10 stage. This day featured sampling 3 plants on 12 separate hours, from 6:00 am to 5:00 pm CDT. Figure 3.5 shows the data for this sampling day. There was some dew in the morning on this day, which was measured by the whipping method, and is shown in the top two panels, and will be addressed in a later hypothesis. On this day, total water column density (including dew) was higher in the morning than in the afternoon, and signal strength decreased slightly throughout the day. This was a mostly cloudy day with light winds, and a high temperature of 29°C. Figure 3.6 shows that water column density and signal strength are not related on June 27th.
Figure 3.5  Leaf wetness reading (top), dew amount(second), water column density (including dew if any) (third), and received signal strength (bottom) for June 27th, 2018.

Figure 3.8  Mean signal strength plotted vs water column density for July 17th, 2018.
July 17th was the next day with sampling over several hours, which featured VT and R1 crops. On this day 20 plants were sampled per hour, from 10:00 am to 5:00 pm central time (Figure 3.7). On this day, there was work on the radios, so all radio link data before 1:00 pm is inaccurate. Additionally, the top link was down for this day. On July 17th, water column density was somewhat lower in the late afternoon than the rest of the day. The signal strength does not change significantly though on this day. The weather on this day was seasonally warm with calm winds. Figure 3.8 shows that water column density and signal strength are not related on this day.
Figure 3.7 Water column density (top) and received signal strength (bottom) for July 17th.

Figure 3.9 Water column density (top) and received signal strength (bottom) for August 7th.
The third large quantity sampling day, which was also the last sampling day of the experiment, was August 7th, when R3 crops were measured. On this day we collected 30 plant samples an hour, spanning only 10:00 am to noon. This day sampling was in a different location; we took plants from the line that the radios measure. This could result in an increased signal strength, except that field workers were also in the transmission line and attenuating the waves. Figure 3.9 shows the water column density and signal strength for August 7th. Water column density remains constant while signal strength decreases slightly during this two hour span. There was rain on this morning, before the sampling period. Leaf wetness was minimal by the sampling hours, though. The bottom link was dampened to the point that it was not detectable on this date. Although we can see water column density varying by hour, it may not be varying enough to cause a notable change in power received, as depicted by Figure 3.10. There is not even an observable change in signal strength after sampling in Figure 3.11, as signal on the morning August 8th is of nearly identical to that on August 7th before sampling.
3.4 Second Hypothesis

Signal strength increases as soil moisture increases.

Soil moisture plays a role in that it affects signal reflectivity. The power of the reflected signal may either add or subtract from power received, depending on the difference in phases of the direct and soil – reflected signals. That is why this hypothesis has since been updated. Soil moisture was first compared to signal strength on the diurnal scale, and then on the daily scale, focusing on days with rapid increases in soil moisture (rain).

3.4.1 Diurnal variation

Soil moisture increases steadily overnight until late morning, until midday into the evening when soil moisture decreases (Figure 3.12). This is true at depths of both 3 cm and 9 cm. Soil moisture is around the daily mean value overnight and in the early afternoon at these depths.
Soil moisture varies by around 1% volumetric at a 9 cm depth and by 1.5% volumetric at a 3 cm depth diurnally. Signal strength follows a similar diurnal pattern, maxing out in the morning and reaching a minimum in the late afternoon. Received signal strength varies by 1 to 2 dBm diurnally. This pattern may be due to temperature dependent efficiency of the antennas rather than a soil moisture dependence. Signal strength anomaly is plotted vs soil moisture anomaly in Figure 3.13, showing a fairly good positive correlation ($p = 2.67 \times 10^{-21}$, $r^2 = 0.617$) at a 3 cm depth and a less clear relationship at a lower depth of 9 cm ($p = 5.09 \times 10^{-8}$, $r^2 = 0.236$). These results uphold my original hypothesis.

Figure 3.12  Soil moisture anomaly (top) and received signal strength anomaly (bottom) for the entire experimental period.
Figure 3.13  Soil moisture diurnal anomaly vs. signal strength diurnal anomaly at a 3 cm depth (top) and at a 9 cm depth (bottom), data points at every 15 minutes, considering the entire experimental period.
3.4.2 Hourly Variation

Hourly variations in soil moisture are analyzed on days with rain, as those are the days with rapid increases in soil moisture. To omit the effect of crops, we will only consider days within the first two weeks of the experiment in this area of the study. The first example of a rainy day is June 2\textsuperscript{nd}, when rain showers occurred the morning after equipment installation. The soil moisture and signal strength received are shown in Figure 3.14, when 3 cm soil moisture increased from 0.24 to 0.29 volumetric. Simultaneously, the signal strength of the middle link increase by 2 dBm while the strength of the bottom link decreases by 1 dBm. The top link is unaffected by this increase in 3 cm soil moisture. When the 3 cm depth soil moisture drops below 26\% volumetric, the signal strength returns to its value before the rain had occurred.

The next rain event was on June 6\textsuperscript{th}, when two rain bursts occurred; one in the morning and one in the evening (Figure 3.15). The middle link’s signal again increases once 3 cm soil moisture increases, as does the bottom link’s signal strength decreases. Again, the top link is unaffected by
Figure 3.15  Leaf wetness (top), soil moisture (middle) and received signal strength (bottom) during and around a rain event on June 6th.

changing soil moisture. On this day however, received signal strength returns to its original value before precipitation within two hours of increasing.

The final rain analysis was for June 14th, depicted by Figure 3.16, when 3 cm depth soil moisture began to exceed 9 cm soil moisture. In the early morning, a light shower occurred. Later in the morning, one of the heaviest rain events of the season occurred, increasing 3 cm soil moisture from 23% to 38% volumetric. Middle link signal strength increases by 2 dBm in the morning shortly after the heavy rain and remains elevated for 5 hours. Bottom link signal strength is decreased by 2 dBm during the same time period. The top link is again unaffected.

For each of these three cases, the middle link shows an increased received signal strength shortly after an increase in soil moisture, before returning to its pre-rain value a few hours later. The bottom link’s signal strength is decreased by roughly the same magnitude as the middle link’s is increased, for the same time periods. The top link’s signal strength is invariant with soil moisture. The ground – reflected component of the signal is coherent with direct one for all three links.
Figure 3.16  Leaf wetness (top), soil moisture (middle) and received signal strength (bottom) during and around a rain event on June 14th.

The ground-reflected power is out of phase with the direct one, to a different degree for each link; some links may be constructively interfering, some may be destructively interfering. The spikes in leaf wetness are around two hours before changes in signal strength; signal strength is varying in coordination with increased soil moisture much more closely. This eliminates the possibility of this soil moisture dependent variation in signal strength actually being from increased leaf wetness from intercepted precipitation.

3.5 Third Hypothesis

Signal strength decreases as leaf wetness increases.

Leaf wetness is characterized by the water on (not in) plants, which can take the form of droplets or films of water. Leaf wetness was detected by leaf wetness sensors, along with being measured directly by finding the mass with a scale in a few select cases (see Figure 3.5 for an example of
this), by means of whipping off dew and re-massing plants. Leaf wetness sensors are oriented in various ways, some facing upwards (as denoted by a “U” in figure legends) or downwards (denoted by a “D”), and being at one-third fully grown canopy height (labeled with “1/3”) or two-thirds height (“2/3”).

3.5.1 Diurnal

![Diurnal Leaf Wetness & Signal Strength Cycle](image)

Figure 3.17 Diurnal cycle of leaf wetness output voltage (top) and diurnal anomaly of received signal strength (bottom).

By plotting diurnal cycles of leaf wetness variation and signal strength in Figure 3.17, it is not apparent that signal strength would decrease as leaf wetness increases. Leaf wetness is greatest around sunrise, and least in the afternoon. Those are the times at which signal strength is highest and lowest, respectively. There is a false relationship between leaf wetness and signal strength, shown in Figure 3.18, which does not consider other field variables. Perhaps leaf wetness plays only a small role in attenuation; water column density from leaf wetness is much lesser than that from vegetation, at least on June 27th, shown by Figure 3.5. Notably, the diurnal cycle is larger for
Figure 3.18  Mean leaf wetness diurnal anomaly vs. signal strength diurnal anomaly, data points at every 15 minutes, considering the entire experimental period.

leaf wetness sensors at two-thirds canopy height than those at one-third canopy height. Also, the diurnal cycle is much larger for leaf wetness sensors facing up than down. To take a closer look at the effect of leaf wetness on microwave attenuation, we need to compare days where leaf wetness is variable, yet other environmental variables are similar.
3.5.2 Daily

This hypothesis was tested on a daily scale by comparing subsequent days’ signal strength, some with dew and some without dew. The number of cases for this was limited, however, because nearly every morning during the experimental period had dew. Times of appreciable rain (on the order of millimeters) were left out of this study, in order to keep soil moisture from spiking. The first couple of days where these conditions are met are June 28th through June 30th, shown in Figure 3.19, when dew was present on the mornings of the 28th and 29th, but not the 30th. During these days which featured dew in the morning, signal strength is decreasing steadily for all three radio links. Then on the dry (dew-less) morning, signal strength levels off or even slightly increases. There is no clear relationship between leaf wetness and signal strength on the weekly scale, represented by Figure 3.20.
Figure 3.20  Mean leaf wetness diurnal anomaly vs. signal strength diurnal anomaly, data points at every 15 minutes, for the period in late June, plotted by Figure 3.19.

Figure 3.21  Leaf wetness voltage output (top) and received signal strength (bottom) for July 10th – July 13th, 2018.
The next and only other available sample of days in the experimental period which meet the criteria for comparing dew days to dry days are July 10th to July 13th. The mornings of July 10th and 11th had dew, mainly higher up in the canopy, while the mornings of the 12th and 13th did not (Figure 3.21). Here, we again see received signal strength decreasing by day when there is dew in the morning, but only for the middle link. Then, the middle link’s signal strength levels off for the dry days. The bottom link’s signal is so weak it is not detectable on the days with dew, but then returns on the dry days. The top link’s signal appears to be indifferent to the occurrence of dew during these days. Again, there is no distinct relationship between leaf wetness and signal strength on the weekly scale (Figure 3.22).
3.6 Fourth Hypothesis

Crop water is greatest in the mid morning and least in the late afternoon.

More data is required to test this hypothesis, as plants were not measured at night. The hope was to solve for crop water column density at all times of the day from signal strength, but the diurnal variation in water column density is not large enough to produce a detectable change in signal strength. It is noteworthy that gravimetric water content of corn is greater in the morning than the late afternoon from 3.3.2, and assuming that dry mass is not changing appreciably over the course of one day, water column density of crops is greater in the morning than in the afternoon.
CHAPTER 4. SUMMARY AND DISCUSSION

The summer of 2018 provided near ideal growing conditions for corn in Central Iowa; no water stress or other damages were detected. Like any field experiment, sources of human error were present and assumptions were made in order to preform calculations. At times equipment failed and data was not collected. Some hypotheses were updated to accommodate for new findings and interpretations. In summary, this experiment differed from those in the past, as the antennas in this study were entirely within the canopy for most of the experiment, and an incidence angle near 90° was used.

4.1 Growing Conditions

A cold first two-thirds of April prevented any notion of planting during the month. Even when the end of April became mild, 3 cm soil temperatures dipped below 10°C daily and remained too wet for field operations. May was warm, but featured frequent rain at the start. My field site was not planted until May 17th. In Iowa’s changing climate, rain is becoming more common in the spring, making planting difficult. The number of days each year that are ideal for planting are decreasing with climate change. As a result of the late planting, the farmer of my field decided to plant an earlier maturing hybrid, one which grows only 16 leaves, in order to increase the likelihood of the crop reaching maturity before the end of the growing season. The downside of planting this hybrid is that ears will be slightly smaller.

Although the field was planted late, thermal time was made up for by a hot end of May. High temperatures often exceeded 30°C and low temperature were just below 20°C from late May into June. By June 19th the crop was at stage V8, and by mid–July the crop was in its reproductive stages. Table 4.1 shows development of the crop at select days of the year. By the end of the growing season (mid October), the crops had certainly matured to their fullest.
Table 4.1  Thermal time and development stage of corn by date at this study’s field. Many of dates shown are also sampling days.

<table>
<thead>
<tr>
<th>Date</th>
<th>5/18</th>
<th>5/24</th>
<th>6/6</th>
<th>6/19</th>
<th>6/27</th>
<th>7/6</th>
<th>7/17</th>
<th>8/7</th>
<th>9/13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Time ($\degree C$)</td>
<td>0</td>
<td>50</td>
<td>221</td>
<td>397</td>
<td>488</td>
<td>609</td>
<td>761</td>
<td>1002</td>
<td>1424</td>
</tr>
<tr>
<td>Development Stage</td>
<td>Planting</td>
<td>VE</td>
<td>V4</td>
<td>V8</td>
<td>V10</td>
<td>V14</td>
<td>R1</td>
<td>R3</td>
<td>R6</td>
</tr>
</tbody>
</table>

The soil was moist at planting, but soon dried out slightly with a series of hot, sunny days. Soil moisture did not fall into a damaging range to the crops though, as 9cm deep it remained above 25% volumetric at the beginning of the season. Soil moisture jumped up in late June with frequent rain once again, and was above 35% volumetric for most of the second half of the month. Some fields in the state with potholes and ponded water suffered losses, especially in soybean fields, but our field site was not damaged by flooding. July was mostly dry, but did feature a few rain events. 9 cm soil moisture was above 30% volumetric at the start of the month, but fell to around 22 % by the end of the month, which is still much above the threshold of drought. A Canisteo soil is present at the location in the field of the experiment, which is a loam soil (Survey, 2015). According to Campbell and Norman (1988), a loam soil’s wilting point, the soil moisture when vegetation can no longer suck up water, is below 15% volumetric. More rain at the experiment’s conclusion brought soil moisture back above 30% volumetric.

4.2  Experimental Errors

This experiment was not without its errors. The largest source of error may be a result of the receiver’s limited sensitivity. Some transmissions were too weak after attenuation to detect. These weak transmissions were not accounted for in the 15 – minute average of signal strength. In the case where some transmissions were lost, the signal strength was represented by only the strongest waves, artificially raising the 15 – minute average signal strength. This could be the reason why in Figure 3.3 that even as water column density continues to increase in the middle of the experiment, received signal strength remains constant. The receiver was sensitive to signals stronger than -95 dBm before July 17th, when an adjustment was made to increase the sensitivity to
sense signals as weak as -110 dBm. Antenna efficiency may vary with temperature, see Figure 3.1, which shows the diurnal anomaly in receiver enclosure temperature and signal strength during the first two weeks of the experiment (to omit crops). Times of rain are omitted from this calculation as well. These two variables are in strong negative correlation, shown by Figure 3.2. The slope of this linear regression is signal strength decreasing by 0.015 dBm for every 1° C increase in temperature, which equates to a 0.225 dBm diurnal cycle, with a diurnal temperature variation of 15° C, which was often observed. Diurnal variation in signal strength became around 10 times larger than this once vegetation was full; antenna efficiency cannot explain the entire diurnal variation in signal strength. This correlation may be the result of temperature’s effects on dielectric properties of soil and small amounts of vegetation, but the extent of these effects on signal strength are still yet to be modeled.

Another source of error results from field operations, which knocked down and killed some plants within the radio link on July 14th. Around 7% of the plants in our link were knocked down, reducing planting density from 8.33 to 7.72 plants per square meter of ground area. These knocked over plants were then dead and disconnected from the soil until they were cleaned up on July 17th, and their electrical effects are unknown. Another source of error was inconsistent time between cutting of plant and weighing for fresh mass. Plants were weighed in the field whenever possible, but some days winds prevented this and plants were weighed around 20 minutes later in a trailer beside the field. Some drying and mass loss may occur during this time.

### 4.3 Hypotheses

In this section, my four hypotheses are analyzed, and potentially revised again. Results are compared to those in related studies when possible.
4.3.1 First Hypothesis

Signal strength decreases as crop water increases.

While seasonal result uphold this hypothesis, diurnal results do not support this hypothesis. Notably, a 0.5 kg · m$^{-2}$ change in water column density is visible to the radio link on the seasonal scale, but not when this variation in water column density occurs in one day. Other factors may be diurnally variant, which mask out this detection of this hypothesis on this time scale.

4.3.1.1 Seasonal Variation

On the season scale, signal strength is decreasing in a significant relationship with water column density ($p = 3.6442 \times 10^{-5}, r^2 = 0.894$). Signal strength decreased from -69 dBm to -85 dBm with growth and development of the crop. This direct measurement method is comparable to those by Ulaby et al. (1986), who found corn’s maximum attenuation was 15 dB at an incidence angle of 52° and a frequency of 1.5 GHz. Hunt et al. (2011) also found a similar magnitude of attenuation, with RSSI dropping from -89 to -102 dBm with the growth of corn at 2.4 GHz. From bare soil to the V11 stage, signal strength may be directly proportional to water column density. After this point in development, the stem becomes similar in electrical size to the wavelength (70 cm) and scattering complicates this relationship. Overall, seasonal crop water and signal strength measurements support the first hypothesis.

4.3.1.2 Diurnal Variation

Diurnally, signal peaks mid – morning and decreases to a minimum in the afternoon. This is seen on all three radio links. Considering timing of transpiration, the opposite pattern is expected. This pattern is amplified by water stress; the plants in this experiment were not stressed. Diurnal signal strength pattern should mimic that of water column density, but it does not in this study (Hunt et al., 2011). The amplitude of this diurnal variation is around 0.5 dBm, which agrees with the findings of Hunt et al. (2011). This may be the result of the antenna efficiency’s dependence on temperature. Warm temperatures are experienced in the afternoon, which is the time of the weakest
signal. Plants were measured to have a decreasing water column density into the afternoon, but signal strength on such days remained constant or slightly weakened. It is possible that the diurnal change in crop water is too small to measure with these radios. The slope of linear regression line in Figure 3.4, considering the seasonal change in water column density and signal strength, indicates a 4 dBm decrease for each 1 kg · m\(^{-2}\) increase in water column density. A 0.5 kg · m\(^{-2}\) decrease in water column density decrease during the course of the day relates to a 2 dBm increase in signal strength. This was not observed on long sampling days, which may be attributed to noise factors.

4.3.2 Second Hypothesis

**Signal strength is affected by soil moisture.**

Soil moisture plays a role as some power is emitted towards the ground, which reflects off the soil and is incident on the receiver. Wet soils have a higher reflectivity than dry soils, which is also SMOS and SMAP’s means of soil moisture detection. This is relevant because soil reflectivity determines the strength of the wave that has been reflected off the ground. The antennas are omnidirectional with the nulls at nadir, and an angle of 2.3° is between the direct and ground – reflection signal on the middle link, with similar angles between the two components of interest on the top and bottom links. At a difference in angles this small, we are assuming the same power is emitted to both the direct signal and the ground – reflection signal. The power of these two signals is not simply additive; that would require these two waves to be in phase. The differences in path-length are small in this experiment in terms of electrical size, assuming the signal travels 14 cm into the soil before it reflects. Assuming there is no phase change at reflection, for the bottom link the difference is 3.2 cm (0.046λ); for the middle link the difference is 5.2 cm (0.075λ); the top link features a path-length difference of 7.5 cm (0.11λ). Because the difference in phase of these path-lengths are less than 0.25λ, all radio link pairs should be constructively interfering. The waves appear to be somewhat in phase for the middle link, while they appear to be deconstructively interfering for the bottom link (out of phase) when considering section 3.4.2. The top link appears unaffected by soil moisture, so its direct and ground – reflected signal may be one-quarter phase apart. This
inconsistency in coherency pattern could be the result of scattering by small vegetation, possibly by rainfall that has run off the leaves onto the stem, or that the depth the signal travels into the soil is misjudged. Signal strength is affected by soil moisture mostly at the onset of increased soil moisture, but not afterwards. This could be the result of soil moisture right at the surface (or ponded water) playing a large role or precipitation itself influencing signal strength. In any sense the signal is not always strengthening with increasing soil moisture, yet it is affected by soil moisture in some way in most cases, leading to the revision of this hypothesis. Antenna and soil geometry appear to play a role when considering this hypothesis.

4.3.3 Third Hypothesis

**Signal strength decreases as leaf wetness increases.**

Dew was most common between 2 am and 8 am daylight time. This does not correspond to the timing of minimum signal strength, which is in the afternoon. Leaf wetness is not the most important factor influencing signal strength. On June 27th, dew amount on plants was measured. Water column density of dew was around 0.05 kg/m², as compared to that of corn which was around 2.5 kg/m². Mass of dew on any given plant this morning was around 5 grams, while water mass per plant was around 300 g. Signal strength did not increase with dew drying. Knowledge of leaf area index, which was not measured, is necessary to convert between leaf wetness sensor voltage and dew water column density. To find the mass of dew on leaf wetness sensors, one can use equation 4.1, where \( m_d \) is mass of dew and \( V \) is sensor voltage in mV (Gerlein-Safdia et al., 2018). Using this equation for dew amount on June 27th, there was around 0.21 g of dew on the top side of the leaf wetness sensors. A conversion factor for mass of dew per leaf area may be necessary between leaf wetness sensors and real leaves; twice the mass of dew per leaf area can be seen on oak leaves than leaf wetness sensors (Gerlein-Safdia et al., 2018).

\[
m_d = 1.105 \times 10^{-3} V - 0.3126 \quad (4.1)
\]
On select series of days, some with dew and some without, the days with dew featured steadily falling signal strengths. During dry days, signal strength became steady or even increased slightly on the weekly scale. The fact that power received is slightly stronger on dry days which follow days with dew, or the suspension of decreasing signal strength seasonal trend is a result which supports this hypothesis. Dew can be an indicator of the trend in signal strength, but we don’t see a diurnal cycle in signal strength which is dependent on it.

4.3.4 Fourth Hypothesis

**Crop water is greater in the mid morning than in the late afternoon.**

This hypothesis was consistent across my long sampling days, especially on June 27th and July 17th. This hypothesis was updated as the time of day with the least crop water cannot yet be determined, as that would require sampling over all hours of the day and night. Hunt et al. (2011) found that crop water is greatest in the early morning and least in the afternoon, by radiometric means similar to this experiment. The diurnal cycle in water content of the leaves is greater in times of water stress, but plants in this field were not stressed this summer (van Emmerik et al., 2017). Water content of stems and leaves separately was not found. Burke et al. (2004) found that stem diameter will fluctuate with sap flow, but a significant variation of stem diameter throughout the course of a day was not found.

4.4 Closing Remarks

Although the seasonal effect of addition of crop water on attenuation is apparent, multiple frequently variable mediums and surfaces make quantifying the diurnal change in crop water by a radio link difficult. Soil moisture near the surface is variable in a matter of minutes with rainfall, and over the course of a day with drying / water resurfacing to drier soil above. Reflection off the soil introduces a source of uncertainty: coherency. Distances waves travel and wavelength will determine whether this is constructive or deconstructive coherency, and the electrical size of the difference in path-lengths is smaller at longer wavelengths. To calculate the phases, distances must
be measured exactly, potentially with lasers. The depth which the wave travels into the soil before reflecting must also be accounted for, which increases with wavelength. Also, reflectivity increases with soil moisture. It would be much easier to have only one signal travel from transmitter to receiver. This could be accomplished by having the antenna’s null pointed at the soil, aligning equipment with the Brewster angle, or by placing an absorptive wiring on the soil, to absorb nearly all microwave radiation sent there.

We are not certain on the effect of leaf wetness on signal strength in this experiment. It appears to have no immediate effect, but can influence the daily trend in signal strength. To find the true effect of leaf wetness, all other variables must be eliminated. To do so, a fake corn canopy would be created, potentially with PVC pipe for stems and leaf wetness sensors for leaves. Then, leaf wetness would be initiated, either by a fog machine or spray bottle. A radio link could then measure the effects of leaf wetness. To find the amount of dew on the canopy, leaf area index measurements are essential, along with a relationship between leaf wetness sensor voltage and water mass per corn leaf area. Leaf area index instruments can provide this, or every leaf can be run through a Li-Cor area meter, or even traced onto graph paper.

Modeling received signal strength can provide a comparison between crop water and crop water at an expected development stage / water content. This is useful for monitoring crop growth and health. Ulaby et al. (1986) states that corn can be modeled electrically by leaves above stalks. The height of the boundary between stalks and leaves is still undetermined. Additional crop models such as APSIM are available for calculating crop water, given planting parameters and weather conditions. There is still work to be done regarding finding optimal antenna setup to eliminate noise factors, but eventually a radio link vegetation network, or even private use for monitoring one’s own crops, is possible.
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