Effect of dew and intercepted precipitation on radar backscatter of a soybean canopy

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Effect of dew and intercepted precipitation on radar backscatter of a soybean canopy

by

Eric Scott Russell

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

Major: Agricultural Meteorology

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ABSTRACT

Soil moisture is a small but very active part of the hydrologic cycle. Recently many studies and reviews have been conducted on its impacts on climate change and short-term forecasting. Satellites could be used as a means for monitoring global soil moisture evolution. In November, 2009, the European Space Agency launched the first satellite dedicated to measuring soil moisture: Soil Moisture Ocean Salinity (SMOS). NASA is planning on launching its own satellite that will incorporate both a passive sensor (like SMOS) and an active sensor in hope of increasing the spatial resolution of the measurements. From September 23, 2008 (DOY266) through September 25, 2008 (DOY268), an aircraft equipped with both a passive and active sensor (PALS) flew over the Iowa Validation Site (IVS) making measurements of the soil moisture through a soybean canopy. At the same time, micrometeorological and soil data were collected. This research used the data from the active (radar) sensor to determine the effect of dew and intercepted precipitation upon the backscatter values. After the effect had been determined, the observed values were modeled and a correction for the dew was determined.

At this time in the season, the soybean canopy had begun senesence. Using the micrometeorological and soil data, an energy and water balance were performed on the IVS to determine if the senesence could be detected and to follow the changes within the field over the time period. It was determined that the water budget indicated a net storage over the system instead of the net loss that was anticipated.

The effects of the intercepted precipitation and dew were determined to have a significant effect upon the radar backscatter. The next step was to determine if this effect could be modeled and how much error it could cause. A semi-empirical backscattering model was used to do this. The model was fitted to the data collected at the IVS before being used to determine
what correction needed to be made for the dew effect. The dew correction used was twice the
dew amount added to the vegetation water content. This correction was not enough to fully
correct for the dew effect but did reduce the error from the dew.
CHAPTER 1. Introduction

1.1 Introduction

Soil moisture is an active part of the water cycle, even though it accounts for only a small fraction of the total amount of water on the earth. Because of its transient nature and potential climatological impact in many areas, it has garnered more attention recently [2]. Soil moisture position within the water cycle and its ability to regulate surface energy fluxes is most relevant [3, 4, 5, 2]. Soil moisture can be measured either at a point via time domain reflectometry, neutron probes, soil samples, or over a field (1 km$^2$) with cosmic rays (COSMOS) [6]. Both scales are static in their placement, measuring just the nearby soil. With the advent of the satellite and subsequent technology, larger scale transient measurements are being made using microwave radiometers and radars [7]. Unfortunately there has not been any evidence that microwave radar systems using only one frequency are capable of absolute detection of soil moisture at smaller scales [7]. However, change detection algorithms have been proposed to be used in concert with other measurements to estimate soil moisture [8].

Remote sensing can be defined as "the collection of information regarding an object of interest, conducted from some distance without actual contact with the object" [9]. It can be broken down into various categories either by approach (active vs passive) or by location within the electromagnetic spectrum (e.g. infrared, visible, or microwave). A passive remote sensing system relies on natural emission of radiation to make measurements. It does not emit any radiation but collects at the frequency of interest. Examples of a passive remote sensor include a camera or an infrared thermometer. Neither of these instruments emits radiation needed to make their respective measurements. An active remote sensing system does emit radiation toward the object of interest and measures the amount of radiation that is returned
to the sensor, e.g., a radar.

The different categories can be used together to narrow down what type of remote sensing is in use and give general information about strengths and limitations. For example, visible remote sensing (e.g., a camera) requires a visible light source to be effective. A microwave remote sensor relies on microwaves to 'see' the intended target. Not needing a light source to 'see' the intended target, microwave remote sensing can operate at any time in the day [10, 11]. Certain wavelengths are not affected by atmospheric conditions, and these are the ones used for soil moisture remote sensing.

Two frequency bandwidths are commonly used for microwave remote sensing of soil moisture: L-band and C-band. L-band is a range of frequencies between 1 GHz and 2 GHz and C-band is between 4 GHz and 8 GHz. L-band has an advantage over C-band and other higher frequency bandwidths because it is sensitive to soil moisture through higher vegetative water contents and has a deeper penetration depth into the soil [12]. L-band is also a protected bandwidth which should minimize any unwanted radio interference. It is currently in use on the Soil Moisture Ocean Salinity (SMOS) mission that is dedicated to measuring soil moisture using radiometry [13]. This is the same bandwidth that the planned Soil Moisture Active Passive (SMAP) will be using for both its planned radar and radiometer [12]. SMAP is currently scheduled for launch around 2014-2015. Six different applications have been identified that could benefit from the soil moisture and freeze/thaw measurements: weather and climate; droughts; floods; agriculture; human health; and national security [12]. The radar and radiometer data will be used together to create a higher resolution soil moisture product than what can be achieved by the radiometer alone because of the high dependence of radar backscatter to the vegetative canopy and soil surface [12].

The water within the soil changes the dielectric constant of the soil which in turn changes the measured signal. The base property of the soil that is measured is the dielectric constant of the soil. The soil's dielectric properties are based on the mixture of air, water and soil particles as well as the soil texture [10]. The dielectric constant is a combination of an imaginary and real component, of which in the context of a soil, the real part is much larger than imaginary
component so the imaginary component is sometimes ignored. The dielectric constant of the soil is dominated by the water within the soil matrix. When the soil moisture is higher than the wilting point for the particular soil type, the relationship between the dielectric constant and soil moisture is linear [14]. When the soil is at the wilting point, the water in the soil is 'bound' to the soil matrix, reducing it’s effect upon the electrical properties of the soil. Above the wilting point, water is not 'bound' to the soil matrix, but is 'free' and its contribution to the dielectric constant is not inhibited by a connection to soil particles. Because of the dependence of the reflectivity of the soil surface upon the dielectric constant of the water in the soil, the amount of radiation reflected back from the soil surface is dependent upon the water content of the soil.

Both active and passive remote sensing systems are polarized. The polarization of an electromagnetic wave is defined by the orientation of the electric component of the wave. Passive remote sensing measures emitted radiation and can separate it into horizontal or vertical polarizations. Polarizations for active sensors come in combinations because the polarization that the radar emits does not have to be the polarization that is measures. These combinations are HH, VV and HV or cross-polarization. The HV combination is generated because of the vegetation scattering. These polarizations can be measured at the same time if the system is capable [10].

Active remote sensing is also highly dependent upon the roughness of the soil surface [15]. Passive remote sensing is not as sensitive to soil roughness because it is only measuring naturally emitted radiation, not radiation that has 'bounced' off the surface. Empirical theoretical models have been developed to describe the soil surface but require specifying a surface roughness and other characteristics [7]. The roughness of a soil surface is defined as the root mean square of the standard deviation in the profile data [16]. This topic will be discussed further in depth in later sections of this work.

The characteristics of the vegetative canopy above the soil surface impart many different effects upon the radar backscatter. These include the water content of the canopy, the type of vegetation, and the distribution of the vegetation and its leaves and steams [17]. Unless using
a model that describes individual scatters within the canopy, semi-empirical models are used. In these models, the canopy is represented by the water content within the vegetative canopy. The semi-empirical model has the form of:

\[
\sigma^o = \sigma^o_{\text{canopy}} + \sigma^o_{\text{canopy+soil}} + \tau^2 \sigma^o_{\text{soil}} \tag{1.1}
\]

where \(\sigma\) represents the backscatter cross section of the canopy, soil, and the canopy-soil interactions and \(\tau\) is the attenuation due to the canopy. If the interaction term is neglected, then the model is defined as a 'water-cloud' model [18, 17, 19]. A 'water-cloud' model treats the water within the canopy as a uniform cloud with the water droplets being help in place by the canopy. The canopy backscatter contribution and extinction is dependent upon the water content of the canopy [20]. Therefore any changes in the canopy water content will change the attenuation of the radiation’s path through the canopy and the amount of backscatter coming from the canopy itself. These changes could come from the growth/senescence of the canopy and hypothetically from intercepted precipitation or dew. The influence of dew and intercepted precipitation on radar backscatter measurements is currently inconclusive [21].

A backscatter cross section of a scatterer is defined ”such that \(\sigma_b\) multiplied by the incident power density \(S_i\) would be equal to the total power radiated by an equivalent isotropic radiator” [22]. This is given by:

\[
\sigma_b = 4\pi R^2 \frac{S_s(\pi)}{S_i} \tag{1.2}
\]

where \(\sigma_b\) is the backscatter cross section, \(R\) is distance from the scatterer, \(S_i\) is the incident power, and \(S_s\) is the scattered power [22]. Simply, the backscatter cross section of an object is the ”effective scattering area” of an object that scatters radiation. To get the total backscatter from many objects in a location, it is the sum of all the backscatter cross sections. Backscatter is reported in values of decibels (dB). A dB is a ratio of power defined:

\[
P = 10\log_{10}\left(\frac{P_1}{P_2}\right) \tag{1.3}
\]

where \(P_1\) and \(P_2\) are the returned and incident powers, respectively [23].
There has been some research conducted on dew and intercepted precipitation impacts on passive microwave remote sensing. Though the impacts may not be exactly the same, the radiometer studies regarding water on the canopy can give a few clues as to what are possible changes to the backscatter measurements. Dew and intercepted precipitation have opposite effects on the brightness temperature over a maize canopy [24]. For a soybean canopy, the brightness temperature increases for both dew and intercepted precipitation, specifically for H-polarization (Hornbuckle, unpublished). Dew and intercepted precipitation change the amount of water within the vegetative canopy and the attenuation of the radiation is controlled by the vegetative canopy. Any changes in the vegetative canopy will change the amount of attenuation and scattering. Dense vegetation canopy and high water content reduce the sensitivity of the instrument to the soil moisture below, and a high enough water content (approximately 5 kg/m²) can mask the soil moisture completely [25, 12]. Extra water on the canopy can mask the soil moisture from the sensor, decreasing the sensitivity to the soil moisture and adding errors to the final value. The goal of this work is to determine if water on a soybean canopy (dew or intercepted precipitation) will cause errors in the soil moisture measurement and how to account for these errors.

1.2 Objectives and Hypotheses

The objective of this work is to answer the following questions:

- Can a water and energy balance be performed for the Iowa Validation Site (IVS) and is senescence able to be seen in a water balance?
- Does dew influence the radar backscatter values and is this influence significant?
- Can the dew influence on backscatter be modeled and how is dew best incorporated in the model?

The driving force behind the first question was the time period of the measurements, DOY266-DOY268 (September 23 - September 25, 2008). During this time, the soybean canopy was beginning to undergo senescence and the changing water content of the canopy does have
an effect upon the backscatter measurements [25]. Measurements of the canopy water content were taken and using the water balance could be another way to verify the measurements taken. If the water budget equation does balance then it is possible to account for the movement of water through the Iowa Validation Site. This would lend credence to the assumptions made when taking the measurements as well as show it is possible to account for water moving through a field using a mix of point and field averaged measurements.

Dew has been shown to impact measurements from microwave radiometers [24]. Similar electrical principles are at work when measuring naturally emitted radiation as artificially emitted radiation (radar). Both are dependent on the "electrical size" of the canopy as it can impact the scattering within the canopy [24]. The larger the scattering by the canopy, the lower the sensitivity to the soil moisture below as less radiation can reach the soil surface [26]. Lowering the sensitivity to changes in soil moisture could lower the accuracy of the measurements. If dew does make a significant impact on the observed backscatter values then converting from a backscatter value to a soil moisture value must take this impact into account. Intercepted precipitation also adds water to the overall canopy similar to dew and could have a similar effect. The wetter the canopy is, the more likely that these impacts will be observed.

The final question is only relevant if dew makes an impact on the backscatter measurements. Assuming that dew does make a significant impact upon the observed data, then the model must be adjusted in order to match those observations. To correct for any dew impact for passive remote sensing, the change is to add twice the amount of dew to the vegetative water content (Hornbuckle, unpublished). A similar method will be applied to the backscatter model to see if the same procedure can be used. Logic dictates that adjusting the vegetative water content for the presence of dew would be the solution to any impacts it may have. However, what the exact adjustment will be is unknown at present. It is also possible that the polarization will have an impact on how much of an adjustment needs to be made. The different polarizations are affected by the vegetation canopy differently and any dew adjustment might have to be polarization dependent [20].
CHAPTER 2. PALS Experiment

2.1 IVS Field

A comprehensive remote sensing observation and validation site has been outlined in previous work [27]. These observation sites were planned to be able to measure a large number of conditions simultaneously over a long period of time. The reasoning for such sites is that there are many different variables needed to ground-truth new remote sensing technologies and instruments. Remote sensing relies on ground-based validations over short periods of time and a site set up for long term measurements of ground variables would provide a long record of ground measurements to match the remotely sensed data. [27]. Three other areas of research which could be conducted with validation sites are in the areas of data assimilation, changing land use and in scaling of hydrologic variables [27]. A proposal submitted in 2005 to NASA’s Energy and Water Cycle Study outlined a 1 km$^2$ experimental validation site. The goal of the site was to instrument it with both in-situ and remote sensors to be able to measure the entire water cycle at multiple spatial scales over a long period of time, initially focusing on remotely sensed soil moisture.

Such a site has been created and named the Iowa Validation Site (IVS) is located approximately 5 km southwest of Ames, IA. The IVS is a heavily instrumented 1 km$^2$ research agricultural field that is capable of remote sensing validation as well as other research regarding dew formation and duration, soil moisture, precipitation collection, and soil moisture. The IVS is planted with a soybean-maize rotation. In 2008, the IVS was planted with soybeans. The soil textures of the top 0.1 m of soil are predominantly clay loam and sandy clay loam. The average soil composition is 37% sand, 34% silt, and 29% clay. The wilting point is between 0.15 and 0.2 m$^3$/m$^3$ and field capacity is between 0.26 and 0.32 m$^3$/m$^3$ based off typical values
Figure 2.1 is a topographic map of the IVS field with the location of in situ measurements marked on it. Precipitation was measured at seven sites each with two tipping rain gauges, in and around the IVS. Two rain gauges were used at each site as a means of error correction and measurement agreement. Soil moisture was measured at depths of 15 mm, 45 mm, 150 mm, and 300 mm at sites 701, 703, 706, 709, 711, and 715. The measurements were made using time-domain reflectometry (TDR) probes buried in the soil. An eddy covariance (EC) tower was located at both site 706 and 705, which are about 200 meters apart from each other. Measurements made from the towers included: air temperature, relative humidity, latent and sensible heat fluxes and 3-component wind speed from a sonic anemometer.

Figure 2.1  Topographic map of the Iowa Validation Site (IVS) overlaid with the location of instruments and measurement locations. The markings refer to: precipitation (P), soil moisture (S), and eddy-covariance flux towers (F).
2.2 PALS Experiment

SMAPVEX08 (Soil Moisture Active/Passive Validation Experiment 2008) was an experiment that occurred in September and October of 2008 over the Delmarva Peninsula. The goal of SMAPVEX08 was to validate two new L-Band radiometers and test soil moisture retrieval algorithms for the upcoming SMAP satellite mission using an aircraft. On the way to the Delmarva Peninsula, the aircraft made a stop at the Iowa Validation Site for three days to make measurements. Measurements at the IVS were made using instruments both on the ground and from the airplane. The aircraft carried three different instruments, an infrared thermometer, a microwave radiometer and a microwave radar combination called PALS. The Passive/Active L-band sensor (PALS) is an aircraft mounted combination of a microwave radiometer and radar. The radiometer collects data in both horizontal (H) and vertical polarization (V) within the L-band at 1.4 GHz (21 cm wavelength). The radar is dual polarized and makes measurements in HH-, VV-, HV-, and VH-polarization combinations and operates at 1.26 GHz (24 cm wavelength). The PALS aircraft made overpasses of the Iowa Validation Site from September 23, 2008 (DOY266), through September 25, 2008 (DOY268). Multiple resolutions were collected for the radiometer but only one resolution (560 m by 420 m) was possible for the radar. Manual in situ measurements were also collected. On the third day, manual dew measurements were made in the morning using paper towels and had an equivalent depth of 0.75 mm. Vegetation water content was also recorded on the first and third day dropping from 2.3 kg/m$^2$ to approximately 1.2 kg/m$^2$. Soil roughness measurements were made on day 1 using an instantaneous laser profiler. Table 2.1 summarizes the daily means of field averaged values for precipitation, dew, vegetation water content and soil moisture.

Figure 2.2 illustrates the different flight paths that the aircraft took over the IVS field. Figures 2.3 through 2.5 show the actual points where the airplane made measurements over the IVS field for each of the three days. The flights stayed in the central and north part of the field where the bulk of the measurements were taken and to keep the entire footprint within the bounds of the IVS. DOY267 had the most passes and DOY266 had the least amount of passes over the field. Radiometer measurements were taken during every flight line shown.
Radar measurements were only taken during the 2A/2B flight line. The low resolution flight line covers about 30 percent of the field with one measurement. The timing of the overpasses will be discussed in later sections.

![Flight paths over the IVS field](image)

**Figure 2.2** Flight paths over the IVS field made by the PALS aircraft. The black outline shows the location of the IVS field and the boxes represent the area covered by a measurement at the altitude/resolution combination.

<table>
<thead>
<tr>
<th></th>
<th>September 23</th>
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<th>September 25</th>
</tr>
</thead>
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<td>18</td>
<td>10</td>
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<tr>
<td>Precipitation</td>
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<td>0 mm</td>
</tr>
<tr>
<td>Dew amount</td>
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<td>0.2730 m^3/m^3</td>
<td>0.2645 m^3/m^3</td>
</tr>
</tbody>
</table>

**Table 2.1** Table showing mean field quantities over the three experiment days along with the number of passes the aircraft made on the respective day. The first row shows the number of individual passes the aircraft made over the field.
Figure 2.3  Center point of footprint for all overpasses made on DOY266 over the IVS. The red circles represent the flights that were made in the west to east direction (B-passes) and the yellow circles represent the flights made in the east to west direction (A-passes). The underlying image is from DOY190, 2008.
Figure 2.4  Center point of footprint for all overpasses made on DOY267 over the IVS. The red circles represent the flights that were made in the west to east direction (B-passes) and the yellow circles represent the flights made in the east to west direction (A-passes). The underlying image is from DOY190, 2008.
Figure 2.5  Center point of footprint for all overpasses made on DOY268 over the IVS. The red circles represent the flights that were made in the west to east direction (B-passes) and the yellow circles represent the flights made in the east to west direction (A-passes). The underlying image is from DOY190, 2008.
2.3 Measurements

2.3.1 Day 1

The first day of the experiment was September 23, 2008 (DOY266). In the week leading up to this date, the IVS received no precipitation (see Figure 3.5) and the soil moisture was stable. The morning of DOY266 was clear. The aircraft began its passes over the IVS at 1339 UTC. The last overpass of the field was made at 1555 UTC. Figure 2.6 shows the soil moisture measured at 15 mm into the soil for the day at each site. There was almost no change in the soil moisture. The soybean canopy had stopped growing by the time the measurements were taken. Also on this first day, there was no measurable dew formation and the leaf wetness sensors were dry by 1200 UTC. On DOY266, the field was in a relative steady state. Three overpass sets, or groups of back and forth flights with very small time differences between each pass, were collected: R2, R4, and R6. The pass labels denote the following: the 'R' denotes radar, the number indicates what collection of passes it is from the first pass on DOY266, 'A' and 'B' denote the direction the airplane is flying, 'A' passes are from east to west and 'B' passes are west to east, and the final number indicates what individual pass it is in the set of passes in question.

Figure 2.7 shows the mean backscatter values for each individual overpass made on DOY266. Overlaid on top of the mean values is a linear fit. Each of the fitted lines has a negative slope indicating a decrease in backscatter over the course of the measurements with dB/hour changes of -0.006, -0.0085, and -0.0074 for VV, HH, and HV polarizations, respectively. The HH-polarization is the greatest in magnitude and HV polarization is the lowest. The large time gap between the first two measurements and the later ones is because during this time gap, the aircraft was making passes at lower altitudes for higher resolution radiometer data. Using the radar at lower altitudes produces aliased radar returns rendering the data useless. The statistical testing to determine if the means of both the individual passes and pass sets are significantly different was done using a paired t-test with $\alpha = 0.05$ Even with the large gap in time, the means of the first and last overpasses are not different at a statistically significant
level.

Table 2.2 shows the mean backscatter and standard deviations for the each individual pass along with the time of the overpass. The direction the aircraft is flying makes a difference on this day only when looking at the VV polarization. Using a t-test to compare the means of the passes flying in the A (east to west) and the B (west to east) directions, only the VV polarization indicates the A means and B means are different. Though they are statistically significantly different, looking at the means for the different directions, they are within 0.25 dB of each other, which is below the standard deviation of the means of each direction. Apart from the pass direction, the VV polarization means are not significantly different between any of the overpass sets. The HH polarization means of R4 and R6 are statistically significantly different from each other, however, the difference between the two means is only 0.22 dB. The cross-polarization means of R2 and R4 and then R4 and R6 are different but only because of the inclusion of pass R4B. Pass R4B is higher than any of the other cross-polarization pass means and is different enough to create the statistical significance. R2 and R6 on the other hand show no difference in their means.

<table>
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<tr>
<th></th>
<th>Time (UTC)</th>
<th>Mean HH</th>
<th>STD HH</th>
<th>Mean VV</th>
<th>STD VV</th>
<th>Mean HVpol</th>
<th>STD HVpol</th>
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Table 2.2 Means and standard deviations of each individual overpass for each polarization variant on DOY266.

### 2.3.2 Day 2

The second day of the experiment started with 12.87 mm of precipitation between the hours of 100 to 600 UTC. Figure 2.8 shows the recorded hourly precipitation averages over the
Figure 2.6  Soil moisture from 0 mm to 30 mm below the surface at 6 different sites within the IVS on DOY266.
Mean values for individual overpasses, DOY266

Figure 2.7  Mean backscatter for each individual pass for each polarization variant on DOY266. A linear fit line is overlaid the means.
7 different rain gauge sites in and around the IVS field. The leaf wetness sensors indicated a wet canopy from the precipitation up until 1700 UTC so all but the last set of overpasses would have seen a wet canopy. The precipitation caused a rapid increase in the measured soil moisture as seen in Figure 2.9. The soil moisture data is recorded in ten minute intervals and the large increase corresponds to the period of the largest hourly rainfall. By 0300 UTC, the soil moisture had reached a relative steady dry-down state after the initial increase and drainage due to the short but heavy precipitation. Conditions remained foggy and cloudy until late morning so the overpasses did not start until 1459 UTC and the last overpass set took place at 1725 UTC. The soil moisture is the biggest change between DOY266 and DOY267 though some precipitation could have been still sitting on the canopy as well. There were three sets of passes that took place this day: R8, R10, and R12.

Figure 2.10 shows the mean backscatter values for all the individual overpasses on DOY267. The individual pass means and standard deviations are shown in Table 2.3. Similar to DOY266, the time gaps between each grouping indicates an overpass set that is either not over the IVS or at an altitude that does not allow the radar to collect useable data. Unlike on DOY266, the change in the backscatter over the course of the day is not consistent between all three polarization variants. The change of the VV polarization is positive at $1.66 \times 10^{-4} \text{ dB hour}^{-1}$, indicating an increase in backscatter over the course of the measurements. The HH and HV polarizations are similar to one another, both negative and being two to three times larger than DOY266 at $-3.04 \times 10^{-4} \text{ dB hour}^{-1}$ and $-3.9 \times 10^{-4} \text{ dB hour}^{-1}$ respectively. This can be seen in Figure 2.10 as the VV and HH backscatter means converge and have a small amount of overlap. The mean of each pass set for the VV polarization increased 0.45 dB from the beginning to the end of the measurement period while the HH polarization decreased 0.94 dB. The HV polarization decreased 0.89 dB through the course of the measurements, and it also had a reduction in the spread of the individual pass means from 1.6 dB down to 0.68 dB. HH polarization also had a decrease in spread, but not as large, going from 1.28 dB to 0.903 dB. The VV polarization actually had an increase in the spread between the means, starting at 0.54 dB and increase to 0.89 dB.
Comparing the overpass sets to each other indicates a change in the backscatter means over the time period that the overpasses were flown. Passes R8 and R10 are not significantly different from each other, however, pass R12 is significantly different than both R8 and R10. This can partly be seen in Figure 2.10 when looking at the spread of values and the range they cover between each overpass set. The soil moisture during these overpasses is fairly stable as seen in Figure 2.9 but one of the leaf wetness sensors was still indicating a wet canopy through 1815 UTC. The other two leaf wetness sensors had been indicating dry since 1715 UTC and 1615 UTC so it is likely that the canopy was mostly wet for passes R8 and R10 while pass R12 was taken over a mostly dry canopy. Also, the wetness and drying of the canopy was likely heterogeneous which could account for the spread in the backscatter means for HH- and HV polarizations. The senescence of the soybean canopy could also be heterogeneous contributing to the overall heterogeneity of the entire IVS. As the canopy dried off and returned to a more homogeneous state, the HH and HV backscatter means decrease in range between individual pass means and the means themselves decreases. The VV-polarization does the reverse of the HH and HV-polarizations. The VV backscatter means increase and the spread between the means increases as well.

2.3.3 Day 3

The overnight period from DOY267 to DOY268 had clear skies which gave way to a heavy dew the next morning. Manual measurements were made just before 1300 UTC and recorded an average of 0.75 mm of dew. According to the leaf wetness sensors in the field, the dew did not dry off until 1500 UTC. Based off this timing, there was dew during the first set of overpasses (R14) but not during the second set (R15). The vegetation water content for the canopy was 1.3 kg/m$^2$. Figure 2.11 shows the soil moisture in the 0 mm to 30 mm layer of the soil. It remains fairly constant overnight and into the morning and then starts drying down a little quicker in the afternoon. During the period of the overpasses for the day (1354 UTC to 1632 UTC), at most sites, the soil moisture changed $< 0.01$ m$^3$/m$^3$ however at site 715, there is a small increase before sharp decrease. But on this day, the aircraft did not fly in
<table>
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<tr>
<th></th>
<th>Time</th>
<th>Mean HH</th>
<th>STD HH</th>
<th>Mean VV</th>
<th>STD VV</th>
<th>Mean HVpol</th>
<th>STD HVpol</th>
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Table 2.3  Means and standard deviations of each individual overpass for each polarization variant on DOY267. The pass labels denote the follow: the 'R' denotes radar, the number indicates which pass and what collection of passes it is from the first pass on DOY266, 'A' and 'B' denote the direction the airplane is flying, 'A' passes are from east to west and 'B' passes are west to east, and the final number indicates what individual pass it is in the larger collection of passes.
Figure 2.8 Precipitation on DOY267 start at midnight (0) through the entire day.
Figure 2.9  Soil moisture from 0 mm to 30 mm on DOY267 at 5 recording sites. Site 701 data is missing.
Figure 2.10  Mean backscatter for each individual pass for each polarization variant on DOY267. A linear fit line is overlaid the means.
the southern portion of the field so this change in soil moisture will not affect the backscatter measurements (see figure 2.5). Sites 701 and 703 both have relatively sharp decreases but not the same magnitude as site 715. With a small change in the soil moisture during the time of the overpasses, any change in the backscatter will be due to other changes such as the dew drying off. The naming convention for the overpass sets is the same as DOY266 and DOY267.

Figure 2.12 shows the mean backscatter values for all the individual overpasses for DOY268. As with the two previous days, the time gap between the first set of overpasses and the last set of overpasses is when the airplane was collecting other data at a lower altitude and other field sites. Between pass R14 and pass R15, the dew on the canopy dried off. The LWS in the field indicated that the canopy was wet until approximately 1500 UTC. Table 2.4 lists the mean and standard deviation for each polarization combination for every individual pass on DOY268. The dry canopy yielded statistically significant lower backscatter values. The overall means of the R15 passes were at least 0.5 dB lower than of the R14 passes. The change in means are 0.5694 dB, 1.261 dB, 0.6764 dB for HH, VV, and HV polarizations respectively. This indicates that dew on the vegetative canopy does have an impact upon backscatter value since the soil moisture on this day did not change. Unlike DOY267, the direction the airplane was traveling did not make a difference on the mean backscatter values for DOY268.

### 2.3.4 Comparison of the Days

The differences in the means between individual passes and the sets of passes could be caused by the variation in incidence angle for each pass or location of the footprint. The location of the footprint in the field dictates what the ground conditions for the pass. But the variation of the incidence angle of the radar is very small (± 2 degrees, see Figure 3.2), the soil moisture is changing very slowly during the overpasses and any extremes in the field conditions would be averaged out given the size of the radar footprint. Given the lack of significant change in field conditions and the relatively low variability in the measurements, DOY266 is a good comparison for the next two days when there were significant changes to the soil moisture and canopy water content.
Figure 2.11  Soil moisture from 0 mm to 30 mm on DOY268 at all 6 recording sites.
Figure 2.12 Mean backscatter for each individual pass for each polarization variant on DOY268. A linear fit line is overlayed the means.
Table 2.4  Means and standard deviations of each individual overpass for each polarization variant on DOY268. The pass labels denote the follow: the 'R' denotes radar, the number indicates which pass and what collection of passes it is from the first pass on DOY266, ‘A’ and ‘B’ denote the direction the airplane is flying, ‘A’ passes are from east to west and ‘B’ passes are west to east, and the final number indicates what individual pass it is in the larger collection of passes.

Similarly to DOY266, on DOY267, the A direction and B direction passes are significantly different from each other. On DOY268, the direction of flight over the field did not have any significant impact upon the mean backscatter values. However, unlike DOY266, the DOY267 differences between the means are rather large. The smallest of these differences is in the VV polarization with the two means being -10.5 dB and -10.7 dB in the A and B direction respectively for a difference of 0.24 dB. This is less than a one percent change in soil moisture as a percent change in soil moisture is between 0.3-0.4 dB [28, 29]. The HH polarization had a difference of 0.77 dB with an A direction mean of -8.34 dB and in the B direction, -9.11 dB. The cross polarization difference was the largest with means of -19.0 dB for the A direction and -19.9 dB for the B direction and a difference between the two of 0.95 dB. The large difference between the pass direction is most likely due to the look direction of the radar. The radar ‘looks’ behind the aircraft at 40 degrees from nadir and slightly to the right of the airplane. Figure 2.13 is a simple schematic of the airplane flying over the field in each direction with an arrow pointing to the canopy as the radar would be looking at it. Even flying over the same portion of the field, the radar sees one side or the other of the canopy.
The overall means between DOY266 and DOY267 are significantly different from each other as expected. The soil moisture increased from DOY266 to DOY267 and this increase shows up in the radar backscatter data. From DOY266 to DOY267, the average soil moisture among the in situ sites increased 0.054 m$^3$/m$^3$ to 0.166 m$^3$/m$^3$ from DOY266 to DOY267 because of the precipitation. This is consistent with the increase of soil moisture from during just the DOY266 overpass times to the DOY267 overpass times. However during the three day period, the soybean canopy was senescing so the vegetative water content was decreasing. As will be seen in the next chapter, the range of vegetation water content values that are pertinent to the change in the canopy water content have a relatively small effect upon the overall backscatter. Also as expected, the mean backscatter values are significantly lower on DOY266 compared to DOY268.

When comparing between DOY267 and DOY268, a couple observations can be made. The first is the HH- and HV-polarization means are different between the two days; the VV-polarization means is not different. The biggest difference in the field conditions between the two days is the presence of dew in the morning of DOY268 which is picked up in the R14 overpasses but not the R15 overpasses. On DOY267, during the first two overpass sets (R8 and R10) the canopy was wet and in the process of drying off from the overnight rain but the R12 passes was over a mostly dry canopy. It is likely that the amount of dew on the canopy during the overpasses is different than the amount of intercepted precipitation collected by the canopy. As well at this time, the canopy was senescing. This would make the water content of the overall canopy different for each overpass set as the canopy dried off and the soybeans lost water and could account for some of the spread in the backscatter means. With only two overpasses over the IVS during the drying phase of the dew it is more difficult to compare to pass R15 later in the same day and to DOY267 where there are 6 passes per overpass set.

### 2.4 Water Balance and Senesence

A water and energy balance was done on the IVS to follow the path of the water moving through the field and determine if the dew and senescence were apparent. The canopy senesced
Figure 2.13  Look direction of the airplane depending on flight direction.
so quickly that the water balance was done to see if it could be used to verify the measured
the senescence. The two balances were completed using individual point measurements for the
entire field and were compared to using an average of all the point measurements to create
representative field characteristics. Through budget equations, the different components were
separated into their individual parts. These components make up the overall change through
the use of the laws of conservation. Much like balancing a checkbook, the inputs much match
the outputs or the system will not balance. The control volume for the two balances is the IVS
field through the soybean canopy and 0.06 m into the soil. The energy and water balances will
be focused upon the time period of DOY266 - DOY268. In order to do a water balance, the
energy balance must first be determined to be able to accurately calculate the evaporation from
the latent heat. Before being able to estimate the evaporation rate, the energy budget must
be closed. Once the energy balance is closed and evaporation estimates have been made, it is
then possible to do the water budget. Other objectives are to determine how accurate point
measurements are when used in a water balance for an entire field and to see if the senescence
of the soybeans creates an imbalance in the water budget or is seen in the water budget.

Equation (2.1) depicts the general form of a balance equation:

\[
\text{Change in storage} = \text{Inputs} - \text{Outputs} \quad (2.1)
\]

The change in the storage of the overall system is equal to the inputs of the desired variable
minus the outputs of the same variable out of the area of interest. When the change in storage
is zero, the system is in balance. Many water balance studies focus mainly on the energy
balance of the area of study because the energy balance determines the possible evaporation
within the field ([30, 31, 32, 33]). Unlike precipitation and soil moisture, evapotranspiration
(ET) is very difficult to directly measure and often gets estimated using a number of different
methods. The energy budget at the soil surface is:

\[
R_n - G = LE + H \quad (2.2)
\]

where \(R_n\) is the total net radiation, \(G\) is the ground heat flux, \(LE\) is the latent heat, and \(H\) is
the sensible heat, all in units of W m$^{-2}$. The latent heat value is of most concern for a water budget as it “is the rate of energy utilized in evapotranspiration” [9].

Latent heat cannot be directly measured but can be estimated and from there an ET amount can be calculated [33]. There are several ways of estimating the flux partitioning into the sensible and latent heat values. Most often used are: Bowen ratio, Priestley-Taylor, Penman-Monteith and eddy covariance (EC) ([34], [35]). Previous studies often used more than one method and compared the results to each other.

The water balance is more straightforward in its evaluation than the energy balance. The water budget is defined by:

\[(\Delta S + \Delta V) = (P + I) - (R + D + ET)\]  

(2.3)

where \(\Delta S\) is the change in soil moisture, \(\Delta V\) is the change in the water in the biomass, \(P\) is precipitation, \(I\) is irrigation, \(R\) is runoff, \(D\) is drainage out of the soil zone, and \(ET\) is evapotranspiration. After simplification based upon the time of the year, the water balance equation takes this form:

\[\Delta S + \Delta V = P - ET\]  

(2.4)

where ET is the combined evapotranspiration. The field used in this study is not irrigated and over the course of the study period, the soil did not reach saturation and flood, therefore runoff is negligible. D is assumed to be represented in \(\Delta S\) due to the depth of the soil moisture measurements. The \(\Delta V\) will represent the residual water that is not accounted for in the other terms.

Using equation (2.4) as the final calculation of the water balance, each variable had to be calculated. The change in the storage in the soil moisture (\(\Delta S\)) came directly from the TDR probes. The measurements were initially at 10 minute intervals, then averaged over an hour in order to match the rainfall data. Though the measurements were taken as point measurements, the volume of soil sampled by the probe is about 1.4 times the distance between the outside probes of the instrument [9]. With this fact in mind, the measurements made at 15 mm and
Figure 2.14 Change in soil moisture at site 709 for all measured depths starting DOY266 through DOY268.
45 mm were assumed to represent the soil volume 15 mm from their location. The measurement at 150 mm however, stretched this notion. Because of the decrease in the change in soil moisture with time, the measurement at 150 mm was used to represent the layer of soil between 60 mm to 225 mm. The 300 mm measurement was then used to represent the layer from 225 mm to 450 mm. The deepest measured point in the soil was assumed to be just above the infinite soil depth, where the soil moisture does not change over relatively short periods of time. Figure 2.14 shows the changes in soil moisture at the four depths for site 709. It can be seen that the measurement taken at 300 mm exhibits little change, while the two measurements taken near the soil surface exhibit the most change.

The second term on the left hand side of (2.4), \( \Delta V \), represents the residual of the water balance. It represents excess water that has either remained as storage within the system. The first term on the right hand side of the equation is the precipitation. The precipitation over the IVS has been discussed in the sections on the daily measurements (see Figure 2.8).

The second term on the right hand side of the water balance equation (2.4) is the evapo-transpiration term. The ET for the field was calculated from corrected values of latent heat reported by the two EC towers. Figures 2.15 and 2.16 show the radiation budgets for the two towers. The net radiation and latent heat peak on the third day of the time period for both towers. There are differences between the peak values for the two towers but they are consistent. The biggest differences show up in the ground heat flux over the three days and the peak value of the latent heat on the third day. Given the distance between the towers, the change in topography from site 706 to site 705, and the possible heterogeneity exhibited by a senescing soybean canopy, non-negligible differences between the two towers is not unreasonable. However, the radiation budget is not closed as evident in Figure 2.17. This figure shows the unaccounted for radiation through equation (2.1). Based off Figure 2.17, the eddy-covariance (EC) towers are underestimating the latent heat and sensible heat. This result has been reported in previous studies [36], [32].

Several reasons have been identified for why the energy budget from eddy correlation towers is not closed [37]. These reasons include the following: 1) The EC towers have a relatively small
Figure 2.15  Partitioning of radiation components at site 705 from the EC tower.
Figure 2.16  Same as figure 2.15 but at site 706.
Figure 2.17  Residual radiation from doing an energy balance at sites 705 and 706.
footprint and being close to the ground they possibly see the heterogeneity; 2) the interaction of eddies and turbulent fluxes can create instrument error; 3) with weak wind speeds, the tower itself may influence the turbulence that passes by the sensors; 4) the long averaging period of the sensors will dampen errors due to random fluxes but could measure other nonstationary events; and 5) errors due to distance between sensors, response time of the sensors and interference from the tower structure itself. Another possible source of error is the soil heat flux plate \((G)\) is buried in the soil where it could not be accurately reflecting the soil surface flux because of the heat storage of the soil [38]. The soil heat storage term also needs to be taken into account.

To get the amount of heat storage that is possible in the soil layer, the following equation is used:

\[
\Delta G = C_v \frac{\partial T}{\partial t} \delta z
\]  

(2.5)

where \(\Delta G\) is the heat storage in the soil \((w/m^2)\), \(C_v\) is the volumetric heat capacity of the soil \((J m^{-3} K^{-1})\), \(\delta z\) is the depth at which the soil heat flux plates are buried \((m)\), and \(\frac{\partial T}{\partial t}\) is change in the soil temperature within the layer per time \((K s^{-1})\) [38]. At the IVS, the soil heat flux plates were buried at a depth of 0.06 m. Soil temperature was measured at the same depths as soil moisture over 10 minute intervals. The volumetric heat capacity is estimated using:

\[
C_v = \phi_m \rho_m c_m + \theta \rho_w c_w
\]  

(2.6)

where \(\phi_m\) is the volume fraction of the soil minerals, \(\theta\) is the volumetric water content, \(\rho_m\) and \(\rho_w\) are the densities of the soil minerals and water, respectively, and \(c_m\) and \(c_w\) are the specific heats of the soil minerals and water respectively. Table 2.5 shows the values for each of the constants in equation (2.6). To determine the volume fraction of soil minerals, the bulk densities \(\rho_B\) in the top 10 cm of the soil were used. \(\rho_B\) for sites 705 and 706 are 1.34 g/m\(^3\) and 1.43 g/m\(^3\), respectively.

Figure 2.18 shows the heat stored in the top 0.06 m layer of the soil for site 706. Negative values indicate a loss of heat storage in the soil while positive values are an increase in the heat storage in the soil. The very large downward spike just after midnight on DOY267 coincides
Table 2.5 Constants used in calculation of the specific heat of the soil [1].

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_m$</td>
<td>$1 - \left( \frac{\rho_B}{\rho_m} \right)$</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>2650 $kg \ m^{-3}$</td>
</tr>
<tr>
<td>$c_m$</td>
<td>870 $J \ kg^{-1} \ K^{-1}$</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>1000 $kg \ m^{-3}$</td>
</tr>
<tr>
<td>$c_w$</td>
<td>4180 $J \ kg^{-1} \ K^{-1}$</td>
</tr>
</tbody>
</table>

with the rain event that night. The heat storage increases over the three days as the soil becomes wetter. The higher the water content, the more heat is capable of being stored because of water’s high heat capacity. Site 706 was the only site that the soil heat storage was calculated because it was the only site that had measurements of soil temperature and soil moisture. Using the bulk density from site 705 with the soil moisture and temperature from site 706 gives soil heat storage values that are nearly identical to site 706. The soil heat storage from site 706 will be used for both sites to correct the soil heat flux.

To correct for possible errors in the latent and sensible heat flux values, two closure schemes have been developed [36]. The two closure schemes are the ‘residual closure’ and ‘Bowen ratio closure’. Both methods have assumptions about the correctness of the measurements made by the EC towers. The residual closure method assumes that the net radiation, sensible heat, and ground heat flux are measured accurately. The latent heat flux is found from this method by solving the energy balance for latent heat as the residual. The Bowen ratio is the ratio between the sensible and latent heat fluxes. The Bowen ratio (BR) closure method assumes that only the net radiation and ground heat flux are measured accurately and $H$ and $LE$ are underestimated but the Bowen ratio is accurately measured and adjustments to $H$ and $LE$ are made accordingly [36]. The Bowen ratio closure method is recommended due to the similarity of latent and sensible heat about the roughness layer [36]. This study therefore used the same Bowen ratio closure to close the energy balance.

The Bowen ratio was calculated between the hours of 1500 UTC and 1900 UTC for each day as this was deemed the most stable period in the flux values. Also during this period is when the latent and sensible heat fluxes are at their maximum. An average of the Bowen ratio
Figure 2.18  Soil heat storage at site 706 for DOY266-DOY268.
Figure 2.19  Bowen ratio values based off unclosed radiation budget at sites 705 and 706.
during that time period was used to correct latent and sensible heat values. The Bowen ratios for each tower are shown in Figure 2.19. The overnight periods were left out of the Bowen ratio closure because of the large variations seen overnight from DOY267 to DOY268 and errant data points that were removed as in the case of overnight from DOY266 to DOY267. The daytime periods for all three days remain mostly stable but by the third day have decreased as the partitioning of radiation favored latent heat more than sensible heat. Table 2.6 shows the average Bowen ratios used in closing the energy budget.

<table>
<thead>
<tr>
<th>Day of Year</th>
<th>Site 706</th>
<th>Site 705</th>
</tr>
</thead>
<tbody>
<tr>
<td>266</td>
<td>1.03</td>
<td>3.96</td>
</tr>
<tr>
<td>267</td>
<td>1.36</td>
<td>1.11</td>
</tr>
<tr>
<td>268</td>
<td>1.23</td>
<td>0.50</td>
</tr>
<tr>
<td>Average for three days</td>
<td>1.21</td>
<td>.74</td>
</tr>
</tbody>
</table>

Table 2.6 Bowen ratio values used in forcing closure on the energy budget.

To correct the latent and sensible heat values, the following equations were used:

\[ D = (R_n - G) - (LE + H) \]  

(2.7)

where D is the residual radiation. The Bowen ratio is used to determine how much of the residual radiation is added to the latent heat value and the rest of the residual radiation is added to the sensible heat. The change in the latent heat value is:

\[ \Delta LE = \frac{D}{1 + BR} \]  

(2.8)

This equation will give the corrected latent heat values. The \( \Delta LE \) is then added to the measured value of latent heat from the EC tower to get the ’actual’ latent heat. The change in the sensible heat is \( D - \Delta LE \). This will close the energy budget so when the new values are input into equation (2.7), the right and left sides equal each other. Figures 2.20 and 2.21 are the same as Figures 2.15 and 2.16, but show the new energy budget after closure has been applied.

Once the energy budget was closed, from the latent heat values, ET could be calculated directly. The following equation was used:
Figure 2.20 Radiation partitioning at site 705 after BREB closure has been forced.
Figure 2.21  Same as figure 2.20 but at site 706.
\[ ET = \frac{LE \times M}{\lambda \times \rho_w} \tag{2.9} \]

where ET is the evapotranspiration in millimeters, \( M \) is the molar mass of water (18.02 g/mol), \( \rho_w \) is the density of water in g/m\(^3\) and \( \lambda \) is the latent heat of vaporization of water (44 kJ/mol).

The ET is then converted to a per hour value. Once evapotranspiration was calculated from the latent heat values, using equation (2.4), the water balance could be calculated.

Thirty water balances were calculated by using each combination of the tower data and the soil moisture data. The same field average precipitation data was used for every individual balance. By combining each EC tower with every soil moisture site, the variation between the sites and field characteristics are able to be seen. Also, because of the possible heterogeneity of the IVS field due to the senescing soybean canopy, as well as the change in topography throughout the field, doing individual water balances for each site helps show where sinks and sources of evaporation and soil moisture storage are. The three soil depth layers used were: 0-60 mm, 0-225 mm, and 0-450 mm. After 450 mm, there is no change in the soil moisture storage having reached a depth in the soil where no changes occurred over the study period.

From this data, the water balance was calculated for the three days at an hourly time step by using equation (2.4). A final mean storage value for each site at each layer was then calculated by averaging the value given based off each tower’s ET amount. From here, an average storage value for each layer using the values for the five different soil moisture sites can be used as an estimate for the total water balance over the entire IVS field.

Table 2.7 shows the daily evaporation amounts based off of (2.9) after the energy budget has been closed and the potential evaporation (PE) amounts using the Penman-Montheith equation. The two sites are within about 0.4 mm of each other over the three days for the total evaporation. There is a difference in evaporation between the two sites on DOY266. The Bowen ratios (Table 2.6) for the sites on DOY266 also are not very close which creates a disparity in the amount of the residual radiation being added to the latent versus sensible heat terms. A similar thing is happening for DOY268 though the difference between the two sites is less compared to DOY266. The residual radiation on DOY266 for both sites are similar to each
other (Figure 2.17) however, the measured latent heat values differ up to 126 W m\(^{-2}\) during the day. The difference of DOY266 evaporation values stem from their measured latent heat values being different. The potential evaportaions for this day are close in value with site 705 being lower similar to the actual evaporation. Closing the energy budget increased both sites latent heat values, with site 705 getting a slightly bigger increase (3 W m\(^{-2}\) to 13 W m\(^{-2}\)). The reverse occurs on DOY268, with site 705 having the higher latent heat and lower Bowen ratio than site 706. This leads site 705 to have the higher evaporation on DOY268, being approximately 1 mm higher. DOY267 is the most similar day when comparing the latent heat and Bowen ratio values, and which leads to similar evaporation values. This day had reported cloud cover for most of the day, limiting the amount of direct solar radiation which kept down the potential evaporation values compared to the two other days. The difference between the two latent heat values could be because of difference in the vegetative canopy, soil type and texture, and instrument orientation.

<table>
<thead>
<tr>
<th></th>
<th>Site 705</th>
<th>Site 705 PE</th>
<th>Site 706</th>
<th>Site 706 PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY266</td>
<td>0.35</td>
<td>6.57</td>
<td>1.87</td>
<td>6.84</td>
</tr>
<tr>
<td>DOY267</td>
<td>1.02</td>
<td>3.62</td>
<td>0.89</td>
<td>3.76</td>
</tr>
<tr>
<td>DOY268</td>
<td>2.73</td>
<td>5.52</td>
<td>1.71</td>
<td>5.27</td>
</tr>
<tr>
<td>Mean</td>
<td>1.37</td>
<td>5.23</td>
<td>1.49</td>
<td>5.29</td>
</tr>
<tr>
<td>Total</td>
<td>4.10</td>
<td>15.71</td>
<td>4.47</td>
<td>15.87</td>
</tr>
</tbody>
</table>

Table 2.7 Daily total evaporation and potential evaporation (PE) rate based off the sum of the hourly evaporation rates (mm/hour) for each day.

Even though the amount of evaporation may not agree between the two sites, the shapes of the graphs for each site do agree well. Figure 2.22 shows the hourly and running sum evaporation amounts. The negative values of the hourly evaporation represent when condensation could be occurring. The condensation could manifest itself as dew on the soybean canopy. As expected, the peak for evaporation occurs around midday at each site for each day. Comparing the running sums for each site, they exhibit the same trends in time. The previously discussed differences in the latent heat values can be seen in the plots of the evaporation amounts.

Figure 2.23 shows the changes of the layer equivalent depth soil moisture for each site at each layer as well as the total change. For all the sites but 711, the 60 - 225 mm depth had
Figure 2.22  Hourly (top) and running sum (bottom) based off the latent heat values at sites 705 and 706. The top graph is the hourly evaporation amounts and the running sum is the bottom graph.
Figure 2.23 Change in soil moisture through each layer at each site from start of DOY266 to end of DOY268.

The most overall change over the three days. The raw measurement change was always smaller at the 150 mm measurement point than the two measurements above (15 mm and 45 mm) but because the 60 - 225 mm layer is much larger than the 0 - 30 mm and 30 - 60 mm layers, the available storage is larger. Though the top two points respond the quickest, the layer over which they respond has a much smaller amount of possible storage compared to the deeper assumed layers. Mean overall change in soil moisture for the field for the three days over the 0 - 450 mm depth is 6.6 mm.

Disagreement between the sites as to the final change in storage for the field was expected as each site encompasses different soil characteristics. Site 703 is in a depression in the field as is site 715 and should generally be wetter. Site 709 is located on a hill top in the field and should be the driest location. Sites 706 and 711 are on the upper and lower parts of a downward slope, respectively, and should fall in between sites 703, 715 and 709. Also, there are at least six different soil types within the IVS field with different drainage characteristics depending upon the location within the field and the surrounding topography (Sally Logsdon, personal communication). The sites used for this study incorporate much of the variability
within the field so by combining the different sites together, statements about the overall field can hopefully be made.

Table 2.8 shows the results from the water balance. Three different layers were examined to see how large of a contribution they make to the overall water balance. From Table 2.8, it can be seen that if just the top 60 mm of the soil is used for the change in soil moisture storage then not all the change can be captured. The deeper the assumed depth used for the soil moisture storage term, the more complete the water balance becomes. Each individual site does not balance to zero but the mean of the three sites with data at 300 mm is an increase of 1.59 mm assuming a layer of 0 - 450 mm soil storage depth. If just the top 60 mm are used, there is 5.38 mm of increase into the storage of the system and for 0 - 225 mm layer, the increase decreases to 2.44 mm. All the sites regardless of depth indicate an increase in the amount of water within the IVS control volume.

<table>
<thead>
<tr>
<th>Site</th>
<th>0 - 60 mm</th>
<th>0 - 225 mm</th>
<th>0 - 450 mm</th>
<th>P - θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 703</td>
<td>3.76</td>
<td>0.96</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td>Site 706</td>
<td>5.49</td>
<td>1.69</td>
<td>1.69</td>
<td>5.98</td>
</tr>
<tr>
<td>Site 709</td>
<td>5.85</td>
<td>1.56</td>
<td>0.43</td>
<td>4.72</td>
</tr>
<tr>
<td>Site 711</td>
<td>5.43</td>
<td>3.78</td>
<td>2.65</td>
<td>6.94</td>
</tr>
<tr>
<td>Site 715</td>
<td>6.37</td>
<td>4.2212</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td>Mean</td>
<td>5.38</td>
<td>2.44</td>
<td>1.59</td>
<td>5.88</td>
</tr>
</tbody>
</table>

Table 2.8 Final system storage (mm) over the three days for each individual soil moisture site at the three different layer depths. The last column is the difference between the precipitation and soil moisture from 0-450 mm.

From Table 2.8, there is a lot of variation in the end result of the water balance. Looking at the 0 - 60 mm soil layer, precipitation dominates the water balance results because there is not a lot of potential storage at this layer. Based off these results, there would be an increase of 5.38 mm of water into the entire field over the three days. As seen in Figure 2.14 the soil moisture changes down through a depth of at least 300 mm, though the amount decreases to almost zero by the time this layer is reached. Adding in another layer below the top 60 mm, the local conditions at each site start making a more obvious impact. Each site has its own soil type, texture and topography. The heterogeneity between the sites in their characteristics will cause each site to respond differently to any precipitation. Looking at the individual sites
shows that adding in the 225 mm to 60 mm layer can change the end storage over 4 mm. Adding in the deepest soil layer accounts for even more of the storage. The assumption was made that with the depths of the measurements made, all the measurable change in the soil moisture would be detected. If this assumption is true, then the 0-450 mm water balance residual represents the change in the final system storage. Through this analysis, there is an increase in water in the IVS of on average, 1.59 mm.

Each soil moisture site is different because of the aforementioned differences in the specific characteristics at that site. At the same time, assumptions about the amount of evaporation and precipitation were also made. The precipitation is assumed to be uniform across the field as the average of all seven rain gauges within the field. The evaporation was also assumed to be uniform based off either the 705 or 706 EC tower. It is possible that the evaporation is different depending on the portion of the field due to the denseness of the vegetation canopy and the soil moisture content. Assuming that the soil moisture measurements did capture all the soil storage and the precipitation was uniform over the IVS, and then the amount of evaporation needed to balance the equation can be determined. This is what is seen in the last column of Table 2.8. Sites 703 and 715 were not determined because of the missing data at the lowest depth so the entire soil column water storage could not be determined. On average, the amount of evaporation needed to completely balance the water in the IVS is 5.88 mm. Referring back to Table 2.7, only approximately 4.3 mm of evaporation took place. This leaves 1.58 mm of water that is unaccounted for in the balance equation.

This extra water could have drained even lower than the 300 mm sensor as Figure 2.14 shows a small change in the soil moisture at this depth. However, these changes would have to account for more than two times the amount of water. In the balance equation, it was assumed that none of the precipitation ran off the IVS but it is possible that some water did run off the field and would not have been detected by any of measurements that were made. Instrument error is the final possibility as to why the equation did not balance. The EC tower measurements when it’s raining are not usable because the instruments are wet. The two deeper soil moisture layers consist of a larger volume than what the sensors are generally assumed to
be able to measure so some soil column storage may be missed through this assumption.

The hourly instantaneous values for the water balance are shown in Figure 2.24. Apart from the rain event, the hourly instantaneous values vary near zero for the entire period. This means that the movement of water in and out of the field is being captured and in balance. The large upward spike at the start of the second day indicates that the soil moisture response to the rain occurred across an hour break. The largest amount of precipitation occurred over the hour break. At site 711, the large upward then downward spike may indicate a delay in the soil response to the precipitation. Site 711 does not follow the same pattern that sites 706 and 709 do, showing a lot more variation and some relatively high magnitude peaks in the latter portion of the period. Figure 2.25 shows the running sum of the $\Delta V$ term from (2.4). The plots compare the running sum between the hourly evaporation amounts of the two EC towers. The difference between the two evaporation rates becomes evident quickly. The precipitation event is noticeable as the rise in the running sum after 00:00 UTC. The running sum maintains at this new level for most of the rest of the time period with some diurnal variation. During the day, water exits the system through evaporation and can be seen as the curve slightly decreases during the daytime for both DOY267 and DOY268. The slight increase at night between DOY267 and DOY268 is evidence of some condensation occurring, most likely in the form of dew. Comparing the curves between each graph shows good agreement in the shape between the two EC tower sites at each soil moisture site. Comparing between sites 706 and 709, the magnitudes of the peaks and valleys are very similar even though the actual curves for site 709 are shifted downward. Site 711 has another maximum just before 00:00 UTC between DOY267 and DOY268 in addition to the increase leading up to the precipitation on DOY266. On DOY266, the soil moisture data indicates a drydown at the deepest soil layer which when translated to an equivalent depth can become relatively large. The second maximum that is observed after the precipitation is because of an increase in the soil moisture in the deepest soil layer (225 mm-450 mm). This pattern is not observed at the other two sites.

The water balance over a senescing soybean canopy was investigated in this study. In the water balance equation used, only the evaporation amounts were not measured directly and
Figure 2.24 Hourly change in the water balance for the IVS through the three days.
Figure 2.25  Running sum of the change in the water balance over the IVS the time period.
had to be estimated from other measurements. Latent heat values from two eddy covariance
towers spaced within 200 meters of each other were used to estimate evaporation. The energy
budget for both the towers had to be closed to minimize possible errors, most importantly
the possibility of large underestimation. The energy budget was closed by assuming that the
Bowen ratio from both towers was correct and then correcting the latent and sensible heat
values to mimic the Bowen ratio. Different depths of soil moisture storage were used to identify
at what depths the largest impacts were made on the overall system storage. All layers had
similar storage amounts, but the depth of the layer over which the change occurred varied. The
smaller layers near the surface had more change over shorter time periods than the deeper and
bigger layers where smaller changes in the storage occurred over a longer time.

The evaporation estimates were different for DOY266 and DOY268 between the two sites,
but were similar for DOY267. Why these differences occur is uncertain but possible reasons
include the heterogeneous nature of the canopy and soil surface, fetch direction and length and
instrument error due to rain and dew conditions. However, the total evaporation amounts over
the three days at the two sites were within 0.5 mm of each other. The storage of the system
as a whole indicated an increase in the amount of water stored in the IVS. Why there was
an increase in sotrage and not a decrease in water stored as expected could be the result of
many different assumptions that were applied in order to do the analysis. Soil moisture storage
increased from the rain event and then responded to it over time. Evaporation increased on
DOY268 as more water was available in the system for evaporation. Given the present data,
how much of the latent heat was from evaporation at the soil surface as opposed to coming
from the senescing canopy cannot be determined, partly due to the increase in system storage.
Though subsurface evaporation measurements were taken, the measurements were taken from
3 mm to 27 mm, not the soil surface. This does not allow for measurements of evaporation
at the soil surface, which can be done by EC towers[34]. While data is available below the
soil surface, the EC towers’ measurements of latent heat also include radiation that went into
transpiring water from the vegetative canopy as well as the soil surface. Partitioning out the
fraction of radiation that went to the soil surface and how much was intercepted by the canopy
was not done and estimates made would be very difficult to verify.
CHAPTER 3. Model Description and Fit

3.1 Background of the Model

The orientation of the stems and leaves within the canopy can change how the radiation is scattered [39]. Many different approaches have been used to model and correct for the effects of vegetation upon the backscatter of a microwave radar. These different approaches include trying to describe the interaction of radiation upon the stems and leaves of the crop canopy ([39],[40]), the use of a water-cloud model ([17],[41]), and a semi-empirical model that lies in between in terms of complexity [20]. Six scattering mechanisms need to be considered and modeled. They are:

1. Direct backscatter from the soil surface.
2. Direct backscatter from the vegetation.
3. Single bounce off the ground.
4. Double bounce off the ground.
5. Scattering back and forth from the vegetation without hitting the ground.
6. Scattering between the plant stem and ground.

Mechanism 5 is not significant for use in L-band and mechanism 6 is important when using C-band, but not in L-band[39]. An earlier model did not include mechanism 5 and 6 but instead treated the soybean leaves as flat disks and the stems as perfect cylinders [40]. Good agreement between the ground truth and modeled data was found except at the very early stages of soybean development [40].
A less complex model in its treatment of the canopy is the water-cloud model. The water-cloud model treats the vegetation canopy similar to a cloud of liquid water droplets [18][17][41]. Using the canopy as the basis for the cloud, the density of the moisture in the canopy is simply the height of the canopy divided by the water content of the plants. This simplifies the model greatly as individual equations for the scattering from leaves and stems do not have to be calculated and the canopy can be treated as one 'big leaf'. Now, instead of trying to model an individual canopy's characteristics, knowing the height of the vegetation and its water content is all that is needed. However, the water-cloud model only takes into account the backscatter from the canopy and the soil and neglects any soil-canopy interactions. The water-cloud model has the form of:

$$\sigma^0 = \sigma^0_{\text{canopy}} + \tau^2 \sigma^0_{\text{soil}}$$

(3.1)

where $\sigma^0_{\text{canopy}}$ and $\sigma^0_{\text{soil}}$ represent the backscatter cross-section of the canopy and soil surface, respectively, and $\tau$ is the vegetation transmissivity. Within the definition of $\sigma^0_{\text{canopy}}$ are empirical fitting parameters dependent on the vegetation type. Instead of treating the canopy as one 'big leaf' as is normally done, a correction term can be incorporated for the overlap within a canopy based off the canopy's characteristics [17]. As with all semi-empirical backscattering models, the water-cloud model has to be calibrated and fitted to the specific canopy and frequency being used [17][41].

However, the total backscatter has been described in another model as the sum of the backscatter from the soil surface, the vegetation, and interactions between the soil and canopy [12]. A small step up in complexity from the water-cloud model adds in the interactions between the the vegetation canopy and the soil surface. Figure 3.1 shows the different pathways that radiation can take within a soybean canopy that are significant to the total backscatter [20]. The left panel shows the direct backscatter from the canopy (1) and the canopy-ground (single bounce) backscatter (2). The right panel shows ground-canopy-ground (double bounce) backscatter (3) and the direct backscatter from the soil surface (4). From the list of the six different scattering mechanisms, the first four are used in this model. The model was developed
using a truck-mounted microwave radar during the summer with a relatively dry canopy with a maximum vegetative water content of 0.97 kg/m$^2$ [20]. To help simplify the model, the water column density of the canopy ($m_w/h$) was used instead of a more complex approximation for the backscatter cross-section of the canopy and canopy-ground. The model was able to match the data collected and predict the vegetative water content with an $R^2 > 0.9$ [20].

It was decided to use a semi-empirical model that included the first four scattering mechanisms to adapt to the IVS field using the data collected during the PALS experiment. The model was first described in [20]. The next section will outline the model equations in more detail followed by an overview of the model parameters and a brief discussion of how each could affect the model output. The last portion of this chapter will describe empirically fitting the model to the data collected at the IVS field and evaluate its performance.

There are four distinct paths for the radiation to follow through the canopy. They are:

1. Direct backscatter from the canopy (3.2)

2. Radiation that scatters off the ground then canopy or off the canopy then off the ground
and out the canopy (GC) (3.3)

3. Scattering from the ground to the canopy, back to the ground and out of the canopy (GCG) (3.4)

4. Direct backscatter from the soil surface (3.5)

The equations for the backscattering components are:

\[ \sigma_{pq}^o = \frac{\sigma_{pq1} \cos \theta}{\kappa_p + \kappa_q} (1 - T_p T_q) \]  
(3.2)

\[ \sigma_{pq2}^o = 2 T_p T_q (\Gamma_p + \Gamma_q) h \sigma_{pq2} \]  
(3.3)

\[ \sigma_{pq3}^o = \sigma_{pq1} T_p T_q \Gamma_p \Gamma_q \]  
(3.4)

\[ \sigma_{pq4}^o = \sigma_{pq3} T_p T_q \]  
(3.5)

Where \( \Gamma_p \) is the p-polarized Fresnel reflectivity of the ground, \( \theta \) is the incidence angle in radians, \( T_p \) is the p-polarized transmissivity through the canopy, \( \kappa_p \) is the p-polarized extinction coefficient due to the canopy, \( \sigma_{pq1} \) and \( \sigma_{pq2} \) are the backscattering cross sections of the canopy for the direct canopy and bistatic backscatter components, respectively, and \( \sigma_{pq4}^o \) is the backscatter coefficient of a bare soil surface.

The model is the combination of the four components shown above.

\[ \sigma_{pq}^o = \sigma_{pq1}^o + \sigma_{pq2}^o + \sigma_{pq3}^o + \sigma_{pq4}^o \]  
(3.6)

Inserting the four equations for the components, the model is:

\[ \sigma_{pq}^o = \frac{\sigma_{pq1} \cos \theta}{\kappa_p + \kappa_q} (1 - T_p T_q) + 2 T_p T_q (\Gamma_p + \Gamma_q) h \sigma_{pq2} + \sigma_{pq1} T_p T_q \Gamma_p \Gamma_q + \sigma_{pq3} T_p T_q \]  
(3.7)

Substituting and then distributing across terms:
\[
\sigma_{pq}^o = \frac{\sigma_{pq1} \cos \theta}{\kappa_p + \kappa_q} - \frac{\sigma_{pq1} \cos \theta (T_p T_q)}{\kappa_p + \kappa_q} - \frac{\sigma_{pq1} \cos \theta (T_p T_q)(T_p T_q)\Gamma_p \Gamma_q +}{\kappa_p + \kappa_q} \sigma_{pq1} \cos \theta \kappa_p + \kappa_q (T_p T_q) + 2T_p T_q(\Gamma_p + \Gamma_q)h \sigma_{pq2} + \sigma_{pq2}^o T_p T_q
\]

Combining and pulling out like terms:

\[
\sigma_{pq}^o = \frac{\sigma_{pq1} \cos \theta}{2\kappa_{pq}}(1 - T_{pq}^2 + T_{pq}^2 \Gamma_p \Gamma_q - T_{pq}^4 \Gamma_p \Gamma_q) + T_{pq}^2(2(\Gamma_p + \Gamma_q)h \sigma_{pq2} + \sigma_{pq2}^o) (3.8)
\]

Factoring and rearranging yields:

\[
\sigma_{pq}^o = a_{bias}(\frac{\sigma_{pq1} \cos \theta}{2\kappa_{pq}}(1 - T_{pq}^2)(1 + T_{pq}^2 \Gamma_p \Gamma_q) + T_{pq}^2(2(\Gamma_p + \Gamma_q)h \sigma_{pq2} + \sigma_{pq2}^o)) (3.9)
\]

Defining the terms in equation 3.9:

\[
T_{pq} = \exp^{\kappa_{pq}h \sec \theta} (3.10)
\]

\[
\sigma_{pq1} = \frac{a_2 m_w}{h} (3.11)
\]

\[
\sigma_{pq2} = \frac{a_3 m_w}{h} (3.12)
\]

\[
\kappa_{pq} = a_4 \sqrt{\frac{m_w}{h}} (3.13)
\]

\[
\Gamma_p = \Gamma_{po} \exp^{[-(2ks \cos \theta)^2]} (3.14)
\]

where \(a_2, a_3, a_4\) are empirically fitted parameters, \(h\) is the height of the canopy in meters, \(m_w\) is the vegetative water content, \(k\) is the wave number, \(\Gamma_{po}\) is the Fresnel reflectivity of a specular surface, and \(s\) is the soil surface roughness in meters.
3.1.1 Model Parameters

The measurements discussed in the previous chapter are needed both as boundary conditions for the model (3.9) and to test and validate it. Some of the input parameters are static in that they will not change and can be set as constants (e.g. frequency of the radar). Other parameters are changing over time and the variation must be taken into account (e.g. vegetative water content). Table 3.1 lists all the input variables that are needed to run the model separated into constants and variable conditions. The only constant in Table 3.1 that could potentially change is the soil roughness. Soil roughness will be discussed in a later section as to why it is considered a constant. The height of the canopy will effectively be a constant as the study period is only three days long during while the canopy has begun senescence. Over the course of the growing season, it will change until the final peak value is reached. Deep soil temperature was taken at a layer deep enough within the soil that it did not change. All the other constants are functions of the radar.

In the variable column, incidence angle comes directly from the radar data and will be examined in section 3.2.1. The desired incidence angle was set but it is not completely constant and the small variation will be taken into account. Soil surface temperature was measured directly and given the timing of the overpasses, it will not remain constant. Because of senescence, the vegetative water content was also decreasing over the three days. As discussed previously, attempts to use a water balance to help quantify this change were discussed. The final variable that will have to be considered is soil moisture. The soil moisture changed markedly over the field site through the three days and the impact that the change in soil moisture has upon the backscatter will be discussed. Table 3.2 shows the values that will be used to test the sensitivity of the model to variations among the variable parameters. The values chosen are the means from DOY266 rounded to one significant digit except for the soil surface temperature, which was rounded to the nearest whole kelvin.
Table 3.1  List of all the inputs into the backscatter model separated into constant and variable parameters.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar frequency</td>
<td>Soil moisture</td>
</tr>
<tr>
<td>Polarization</td>
<td>Incidence angle</td>
</tr>
<tr>
<td>Fitting parameters</td>
<td>Soil surface temperature</td>
</tr>
<tr>
<td>Wave number</td>
<td>Vegetative water content</td>
</tr>
<tr>
<td>Soil roughness</td>
<td></td>
</tr>
<tr>
<td>Deep soil temperature</td>
<td></td>
</tr>
<tr>
<td>Canopy height</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2  List of the values of the variable parameters to be used to test the sensitivity of the model to individual variables.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Test Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_2 - a_4 )</td>
<td>1</td>
</tr>
<tr>
<td>Incidence Angle</td>
<td>40°</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>0.2 m³/m³</td>
</tr>
<tr>
<td>Vegetative Water Content</td>
<td>2 kg/m²</td>
</tr>
<tr>
<td>Soil Surface Temperature</td>
<td>292 K</td>
</tr>
</tbody>
</table>

3.2  Factors Influencing the Model

3.2.1  Incidence Angle

The incidence angle that the radar is operating at changes during the flights. This is due to movement of the airplane. The incidence angle is centered on 40 degrees as was what the radar was set at but it is not a constant value. The standard deviation of the incidence angle over the combined three days is only 0.6643 degrees. The standard deviation for any single day does not vary more than 0.75 of a degree. The maximum angle over the three days is 41.46 degrees and minimum is 38.28 degrees and mean is 40.06 degrees. Figure 3.2 is a histogram of the incidence angles for each of the three days. Note the highest occurring incidence angles congregate around 40 degrees. A change in the incidence angle can alter the field of view of the radar slightly and change the amount of the field within the footprint. The vegetation scattering at larger incidence angles is larger and reduces the backscatter’s sensitivity to the soil moisture [41]. The higher the incidence angle, the more field could be seen but also results in a less direct measurement and vice versa for a lower incidence angle. When the incidence
angle reaches 50 degrees over a vegetation canopy, the sensitivity to soil moisture decreases to where it no longer plays a role in the overall backscatter [39]. The incidence angle shows up in the model in three different aspects. Incidence angle shows up explicitly in equation (3.2). It also shows up in the definitions for the transmissivity through the canopy (equation (3.10)) and in the reflectivity of the soil surface (equation (3.14)). Finally, it is in the soil surface backscatter model. Even in all these locations in the model, because of the very small range reported here, its impact will be negligible on the final result.

When running the model over this range of incidence angles using the values in Table 3.2, the backscatter value changes between the maximum and minimum incidence angle is different depending on which polarization combination is used. The percent changes are 10.09 %, 9.31 %, and 8.032 % for horizontal, vertical and cross polarizations respectively. The mean change over the three combinations is 9.144 %. Though this may seem like a very large change in backscatter value, these values were calculated without the model being fitted to any data and the change in backscatter per degree was only 0.0056 dB. This shows the model is sensitive to a change in the incidence angle, which is what was expected. Using the fitting values from [20], the percent change in the backscatter value based off just the incidence angle is less than 1 % for both the cross and horizontal polarizations, but almost 4 % for the vertical polarization pair.

### 3.2.2 Soil Surface Temperature

The surface temperature of the soil exhibits the expected diurnal cycle as seen in Figure 3.3. The mean soil surface temperature ($T_{sfc}$) over the three days is 19.70 degrees Celsius with a range from 299.48 K down to 287.25 K. The $T_{sfc}$ peaks shortly after 1200 on all three days and reaches its minimum a little after 1100 UTC. During the overpass times in the morning, $T_{sfc}$ is increasing quite dramatically during the warming period of the day. On DOY266 and DOY268, $T_{sfc}$ is increasing at a rate of 1.45 K per hour. On DOY267, $T_{sfc}$ is increasing at a more modest rate of 1.08 K per hour. The cooling slope of the curve is not quite as steep as the warming curve, even just taking in account the initial decrease and not the overnight period. The cooling rates are 0.89 K, 0.98 K, and 0.75 K per hour respectively for DOY266-DOY268.
Figure 3.2  Frequency of occurrence of incidence angles for all three days. Each bar is approximately 0.25 degrees in width. Day 1 corresponds to DOY266.
With the dielectric constant of the soil possibly being affected by a change in the soil surface temperature but this effect should be negligible [14].

As a check to see how much a change in soil surface temperature affects the model, it was run using the values in table 3.2 except with $T_{sfc}$ being varied over the aforementioned temperature range. The change from the maximum to the minimum backscatter values were only 0.72 %, 0.63 %, and 0.30 % for HH-, VV-, and cross-polarizations respectively with a mean of 0.62 %. The change in the real part of the soil dielectric constant is 3.41 % which is much larger than the amounts previously reported, however that was with subfreezing temperatures and partially frozen water in the soil [14]. Given only an average of 0.55 % change over a greater than 10 K range, a mean value of $T_{sfc}$ during the time period of the overpasses for each will be used.

3.2.3 Roughness

On DOY266, an instantaneous-profile laser scanner was used to identify the roughness of the soil surface on the west end of the Iowa Validation Site (IVS) Been Field. The scanner has a vertical resolution of 0.1 mm and a horizontal resolution of 1 mm, with a grid area of 1392 mm by 870 mm. The scanner apparatus was placed in between soybean rows with the longer portion parallel with the rows and the shorter profile perpendicular to the rows. The spacing between the soybean rows was 30 inches, or 760 mm. Given these dimensions, the profiler will capture the effects of the row spacing across a single row. Three scans over the same location were taken in a short time. The first scan was taken with the laser apparatus traveling away from its starting location, the second with the scanning apparatus returning to its initial starting location, and the third where the soil surface was cleared of organic matter and debris. Due to the nature of the instrument, some errors are inherent in the collection. The largest of these is the effect of shadowing of the laser beam from material on the soil surface. This can lead to missing and bad data points. These scans will be referred to as scanaway (SA), scantoward (ST), and clearedscan (CS) respectively. The differences between the three scans are the direction in which they were taken (ST and SA) from the initial starting point
Figure 3.3  Mean soil surface temperature over the IVS starting DOY266 through DOY268.
of the laser and if the soil under the profiler was cleared of plant litter (SA/ST vs. CS). The raw data from the scans had to be converted to a digital elevation model through the use of previously made calibration measurements.

Soil roughness is described as the random variation of the microterrain within a field [16]. This roughness can be attributed to tillage of the field, erosion, and raindrop impact. To achieve the random roughness, a linear best fit line was calculated for each row and each column to take into account the mean slope [16]. The best fit line was then subtracted from the initial raw data leaving the random portion of the height. The standard deviation (STD) of the residuals was then taken using the root mean squares method and plotted. Roughness was also determined by using a quadratic fit as opposed to a linear fit. Using a quadratic fit did not make a significant difference in the perpendicular roughness value. A two-sample t-test ($\alpha = 0.05$) was used to determine the possible difference and significance of the means from the two fits. The differences in the means were statistically significant at a p-value $<< 0.05$ but row-parallel quadraticaly determined roughness was within 0.1 mm - 0.2 mm of the linearly fit roughness. However, the row-perpendicular means using a quadratic fit were 0.5 mm to 0.7 mm lower than using a linear fit. Both roughness determination methods will be used in the backscatter model to compensate possible error in choosing one method over the other.

Figure 3.4 shows the standard deviations of the detrended (both linear and quadratic) parallel to row and perpendicular to row heights from the CS data. The change in roughness in between the crop rows is variant, with small and large changes between any two data points and no overall pattern to the roughness. The difference in the roughness between the two detrending techniques can be seen, particularly in two locations, near the beginning of the scan and near the end of the scan. In some locations, the two roughness’s line up very well with each other. Perpendicular to the crop rows, there is evident structure, with the roughest portion being in the middle with the lowest roughness on the edges of the crop row. The biggest difference between the two detrended (results from) methods can be seen in the very middle of the scan which corresponds to the middle of the row. Apart from a few other small spots where the two lines diverge, they match well, owing to very similar roughness values. The other two scans (SA
Figure 3.4 Random roughness for CS. Row-parallel roughness, top; row-perpendicular roughness, bottom.
and ST) both exhibit similar behavior, though they are not pictured here. The perpendicular roughness was expected to show more structure than the row parallel roughness because it is perpendicular to the soybean row. Multiple factors can contribute to this structure. Tractor wheels travel along the paths between rows and these spaces do not get disturbed as much as where the crops are planted. Also, the plants and leaves shield the soil underneath them from direct impact of rain, washing out some of the more variant erosive effects.

Table 3.3 shows the mean standard deviations for the random roughness of each scan both parallel and perpendicular. The change between the standard deviations depending on the scan is fairly small, as expected, with the changes being attributed to random error and shadowing effects impeding data collection. The CS-row roughness is quite a bit lower than the SA and ST roughness. This can be attributed to the clearing away of any non-soil contaminants in the path of the laser scanner. The ST column random roughness STD is much higher than either the CS or SA roughness STD. Why this occurred is possibly due to the direction the scan took place and shadowing effects of the laser by particles and aggregates on the soil surface. Another difficulty regarding the different scans is what should be considered 'soil roughness' and what isn't. Is soil roughness just the soil or should anything on the soil surface (eg. plant material) be considered part of the overall roughness? Seen in Table 3.3, the CS roughness is much lower when looked at parallel to the row, but similar to SA when looking perpendicular to the row. However, the maximum and minimum roughness values for CS are lower than the other two scans. This shows that even though the overall roughness may be comparable between the three scans, clearing the soil surface of plant litter and other non-soil objects reduces the maximum roughness of the soil surface and that non-soil components on the soil surface add to the overall roughness, particularly at the maximum of the roughness.

Comparing the mean STD of the roughness’s calculated here against previously published results shows that the roughness from the IVS is smaller. Other measurements with a laser profiler over profile lengths of 2 m, 4 m, and 8 m resulted in STD’s on the order of 1cm-5cm respectively [42]. Their measurements were taken in November and February on bare fields that exhibited various degrees of roughness. The profile taken at the IVS was only 1.4 m long.
whereas the shortest profile in [42] was 2 m, and as the profile length increases, the more likely multiscale processes are taking place (e.g., overall field terrain) [42].

Other laser profiler measurements taken at the end of August in a fully planted field resulted in roughness values of 1.0 cm-4.5 cm [43]. Another study took profiles at a length of 1.6 m with a 2 mm resolution and reported roughness values from 0.5 cm to 2 cm [44]. The values from these studies are higher than what was measured at the IVS, but were also taken earlier in the year when the field is likely to be rougher. Two factors have large impacts upon the soil roughness: tillage and rainfall [16]. Important to the roughness later in the year is rainfall. Rainfall on the surface of the soil will erode and smooth out the soil surface. From May 1st, 2008 until September 23rd, 2008 when the profiles were taken, approximately 728 mm of rain fell on the IVS field. Figure 3.5 shows the daily rainfall upon the IVS field starting from day of year (DOY) 121 (May 1st) through DOY 266 (September 23). Over the summer there were mixes of dry and wet periods with a few heavy rainfalls exceeding 40 mm in a day.

The backscatter coefficient from radar data of a soil surface is dependent upon two parameters: soil moisture and soil roughness. Soil roughness is difficult to model because it changes throughout the year due to both natural and anthropogenic forces. Multiple models have attempted to depict soil surfaces for their use with radar backscatter but are limited in their usage [44]. In radiometry measurements, soil roughness is only a small part of the influencing factors on the measured brightness temperature. But in radar measurements, soil roughness is almost as important as that of the soil moisture itself [45]. All ways of measuring soil surface roughness have errors associated with them, either disturbing the soil surface itself (meshboard), or issues with laser reflection form the ground and plant material (laser profiler) [45].

Figure 3.6 shows the height of each data point in the data matrix for the clearedscan set. Even in this small of a profile after a summer of rainfall and erosion smoothing out the soil, there still exists a large amount of roughness. If profiles were taken in other places within the field, they would look markedly different but likely have similar roughness values. As previously discussed, with the amount of rainfall received and the lateness in the season of the profile, the soil surface will have smoothed considerably from earlier in the summer. Using a simple model,
Figure 3.5  Daily rainfall totals for the IVS between May 1, (DOY 121) and September 23 (DOY266) when the soil surface roughness profile was taken.
Figure 3.6  Height profile for clearedscan (CS). X-axis is across row values, y-axis is down row values. Scale on right in mm.
the ratio between the roughness before and after a set period of rainfall can be determined [16]. The decrease in roughness from DOY 121 until DOY 266 is about 13 percent of the initial roughness. Inverting this ratio to get an approximate value for the initial roughness of the field yields a starting roughness of about 41.02 mm. With this marked decrease in roughness over the summer and because no other profiles were taken within the field, the assumption will be made that the soil surface roughness is similar across the whole field regardless of the larger-scale topography.

<table>
<thead>
<tr>
<th>Scan/Direction</th>
<th>Scanaway (SA)</th>
<th>Scantoward (ST)</th>
<th>Clearedscan (CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel Row Roughness</td>
<td>4.82</td>
<td>4.74</td>
<td>4.08</td>
</tr>
<tr>
<td>Perpendicular Row Roughness (mm)</td>
<td>5.21</td>
<td>6.42</td>
<td>5.30</td>
</tr>
<tr>
<td>Max/Min Parallel Row (mm)</td>
<td>11.93/1.33</td>
<td>14.6/1.28</td>
<td>10.6/0.82</td>
</tr>
<tr>
<td>Max/Min Perpendicular Row (mm)</td>
<td>9.90/0.00</td>
<td>9.59/0.09</td>
<td>8.65/0.00</td>
</tr>
<tr>
<td>Parallel Row STD (mm)</td>
<td>2.18</td>
<td>2.30</td>
<td>1.95</td>
</tr>
<tr>
<td>Perpendicular Row STD (mm)</td>
<td>2.00</td>
<td>1.55</td>
<td>1.81</td>
</tr>
</tbody>
</table>

Table 3.3 Mean standard deviation of random roughness.

3.2.4 Vegetative Water Content

In the model, the vegetation is treated as a mass of water per unit area of the canopy (kg/m²). The scattering from the vegetation canopy itself is impacted by more than just the vegetative water content (Mᵥ), but is also a function of the size of the leaves and stems in the canopy and their distribution in size, shape and orientation [17],[46]. Attempts to model the individual scattering of the leaves and stems of the plants have been undertaken and been successful [40], [46], [39]. However, these models are very complex and require a large number of input parameters and details about the specific field sites in order to run them. Though they produce accurate results and can better relate the backscatter to the plant geometry, there are two limitations: accurately representing the specific canopy and the complexity of the mathematics due to a large number of variables [17].

Within the model, Mᵥ shows up in three different expressions, which are the direct backscatter cross section, the bistatic cross section, and the canopy extinction coefficient. Mᵥ is in every component of the model as part of the transmissivity through the canopy (3.10) and depending
upon which individual component, possibly as part of the backscattering cross section. In the
two backscatter cross section terms (3.11 and 3.12), \( M_v \) is treated as the density of the water in
the canopy per a unit volume of the canopy. However, as part of the canopy extinction equa-
tion, the square root of the density is used. Figure 3.7 shows the effect changing the vegetation
water content from 0 up to 2.5 kg/m\(^3\) while using the parameters in table 3.2 across the three
different polarizations. As \( M_v \) increases, so does the overall backscatter, but the increase is
large at first and then slows down the higher \( M_v \) is. The only notably difference between the
three polarizations is at the very low end of the water content values. Apart from the initial
difference, the curves of the graph mirror each other and start converging on each other at
the higher \( M_v \) values. The increase in backscatter the higher \( M_v \) is was expected based upon
results from [20] and [25] though [25] uses leaf area index as a proxy for the water content of
the vegetation.

To get a better picture of how a change in \( M_v \) affects the modeled backscatter, each backscat-
tering mechanism was plotted with an increasing \( M_v \) in figure 3.8. All four components have
a dependence on \( M_v \). The shape of the curves for the first three mechanisms start off similar
but on different locations. When the different polarizations are introduced, the three combina-
tions mirror each other for both the GCG and CG backscatter, but not in either of the direct
backscatter plots. For the canopy direct backscatter, all three of the polarizations are equal.
This was expected because no term within equation 3.2 has a polarization dependency. What
was unexpected is for the soil direct backscatter, the cross-polarization and VV-polarization
were equal. The expectation was that apart from the direct canopy backscatter, the com-
ponents would have similar behavior because they all are polarization dependent due to the
inclusion of the Fresnel reflectivity term in each equation. In terms of the order of the curves
for the CG and GCG components, the cross-polarization values being between the HH and VV
values was expected. The HH-polarization as the largest of the three variants follows the data
collected from the PALS aricraft where the HH-polarization produced the largest backscatter
values.

After \( M_v \) reaches values greater than 0.25 kg/m\(^2\), the GCG backscatter starts to decrease.
Looking at equation 3.4, this is not a surprising result as the transmissivity term decreases quicker than the backscatter cross section can increase to make up for the increases attenuation. Similar to the GCG backscatter component, the CG backscatter as a whole decreases the backscatter but it’s decrease doesn’t start to occur until after \( M_v \) reaches values of 0.5 kg/m\(^2\) and it starts at a higher value initially. That the value of \( M_v \) where the CG backscatter starts to decrease is doubled that of the GCG term is not coincidence. The mechanics of the two terms are very similar but the CG backscatter only makes one forward trip and one return trip through the canopy whereas the CGC backscatter makes four trips through the vegetation. The first trip it enters the canopy, the second is on its way back out of the canopy then it is scattered back into the canopy before it is scattered back out of the canopy so the vegetation has twice the opportunity to attenuate the radiation.

The soil backscatter also shows a decrease in its contribution to the overall backscatter value with a slightly steeper slope at the lower \( M_v \) values and lessening the higher the \( M_v \). Once the vegetation reaches a certain value, the sensitivity to the soil moisture lessens to a point where the backscatter is no longer sensitive to it [25] [17]. If the curve for the soil direct backscatter was extend out to higher \( M_v \) values, it would eventually flatten out and the whole soil backscatter contribution would be masked by a dominating signal from the vegetation canopy.

The final of the four terms is the direct backscatter from the canopy. This is the only term out of the four that shows an increase as the water in the canopy increases. Physically this the expected result, as the density of the water and subsequently, the size of the plant increases, it is able to scatter more of the radiation. After plugging in the backscatter cross section and transmissivity equations into equation 3.2, keeping the incidence angle constant, the direct canopy backscatter becomes a function of the square root of the water density in the canopy \((\sqrt{\frac{M_v}{h}})\) and \((1 - T_pT_q)\). Both terms of the equation increase the backscatter of the canopy. The column density will increase slowly as the water contained in the canopy increases meaning a fuller canopy and because of the correlation between leaf area index and \( M_v \), more foliage [25]. As \( M_v \) increases the transmissivity must decrease, but since the transmissivity is the fraction of
the radiation actually penetrating the canopy, the lower the transmissivity, the more radiation that must be initially scattered by the top of canopy. This effect is described as \((1 - T_p T_q)\) in equation 3.2.

### 3.2.5 Soil Moisture

Soil moisture indirectly affects the final backscatter value. As the soil moisture changes, the dielectric constant of the soil changes [14]. The dielectric constant of the soil is dominated by the water within the soil matrix. So as the soil moisture increases, the Fresnel reflectivity will also increase [14]. Because of the dependence of the Fresnel reflectivity (equation 3.14) upon the dielectric constant of the water in the soil, the amount of radiation reflected back from the soil surface is dependent upon the water content of the soil. The Fresnel reflectivity is directly proportional to the terms where the radiation interacts with the ground (equations 3.3, 3.4, and 3.5). Given a direct relationship with each term, as the Fresnel reflectivity increases (via a soil moisture increase), the backscatter value should increase as well.

The model was run using the values from table 3.2 as in the previous sections. Figure 3.9 shows the effect of increasing soil moisture upon the overall backscatter at each polarization variant. The range of the overall backscatter is relatively small when compared to the range exhibited by varying the vegetative water content. As seen in the aircraft data and in the previous section, the HH-polarization has the largest values while the HV-polarization has the smallest values. The increase in the backscatter for all three polarizations is close to being linear though the dB per percent change in soil moisture is different for each. HH-polarization increases the quickest at a rate of 0.243 dB per a 1 percent change in soil moisture. The HV-polarization has the slowest increase at 0.1163 dB per a 1 percent change in soil moisture. VV-polarization is a little lower than the HH-polarization at 0.2195 dB per a 1 percent change in soil moisture.

Figure 3.10 shows the impact on increasing soil moisture has on the four components of the backscatter model. A change in \(\theta\) has no effect upon the direct canopy backscatter as there is no soil interaction within that term. The largest of the terms that include the soil moisture is the
Figure 3.7 Backscatter values for vegetative water contents from $0.0 \frac{kg}{m^2}$ to $2.5 \frac{kg}{m^2}$ using the values from table 3.2.
Figure 3.8 Breakdown of each of the four components of the model. The four panels are: the direct backscatter from the canopy in the top right, CG backscatter on the top left, GCG backscatter on the bottom left, and backscatter from the soil on the bottom right.
Figure 3.9  Backscatter values for soil moisture ranging from $0.0 \text{ m}^3/\text{m}^3$ to $0.4 \text{ m}^3/\text{m}^3$ using the values from table 3.2
Figure 3.10  Breakdown of each of the four components of the model using the same values as Figure 3.9.
canopy-ground (3.3). The GCG backscatter and the direct soil backscatter both are of similar value. The amount of increase of backscatter with increasing $\theta$ is largest at lower $\theta$ values and starts to level off the higher $\theta$ is. Consistent with the vegetative water content, breaking the model into its four components, the order of polarizations from largest to smallest changes from the full model for both the GC and GCG backscatter. The HH polarization remains the largest value, but when broken down, the VV polarization has the smallest values. However, the HH- and VV polarizations are identical and are 2 dB larger than the HV-polarization when considering the soil direct backscatter.

3.2.6 Soil Moisture and Vegetative Water Content

The two parameters in the model that vary within the field that affect the backscatter measurement are the soil moisture and the vegetative water content. These two parameters can vary simultaneously within the field potentially making it difficult to determine which parameter created the change in the backscatter. To determine the combination of $\theta$ and $M_v$ that would create the largest and smallest backscatter values, the model was run over the range of both $\theta$ and $M_v$ values used in the previous two sections. Varying both variables at the same time will show what combination of $\theta$ and $M_v$ will produce maximum and minimum backscatter values and how the four components interact with each other.

Figure 3.11 shows the results of the full model while varying the two variables at the same time. As expected, the backscatter is at a minimum when $(\theta, M_v)$ is (0,0) and is at a maximum at (0.4, 2.5). As seen in the previous section, as the soil moisture increases, the backscatter values will increase due to the direct relationship to the Fresnel reflectivity. Increasing the vegetative water content also produces an increase in the backscatter value while showing up in both the attenuation term and describing the backscattering cross-section of the canopy. The gradient of the backscatter is the largest at the lower values of $\theta$ and $M_v$ and the closer to the maximum value, the less change with changing parameters. Interestingly enough, the contours of Figure 3.11 are more closely in tune with the changes in $M_v$ than with $\theta$. Because the backscatter cross-sections of the vegetation canopy interactions have not being fitted in this
run, they are at a maximum and possibly overpowering the soil moisture change. When the backscatter cross-sections for the canopy are used, it is expected that the gradient will be more even as \((\theta, M_v)\) increases and the change will be less dependent upon the canopy characteristics. Also to note is there multiple combinations of \(M_v\) and \(\theta\) for a single backscatter value. The fitting parameters will be implemented into the model in the next section in order to fit the model to the data collected at the IVS.

The direct canopy backscatter only varies with changes in the vegetative water content so any changes in \(\theta\) produces no change in the backscatter values. The remaining three components do depend on both \(M_v\) and \(\theta\). The bistatic term minimizes at \((0,0)\) similar to the full backscatter. The bistatic term does not maximize where it would be expected at high soil moisture and high vegetative water content but at high soil moisture and relatively low vegetative water content as seen in Figure 3.12. In equation (3.3), the higher the \(\theta\) value, the larger the contribution to the backscatter the term will make, whereas \(M_v\) works both for and against the overall backscatter. The larger \(M_v\) is, the larger contribution from the canopy to the term but also the larger the attenuation due to the canopy. The three polarizations have similar shapes to their graphs but the range of backscatter values for each differs. The GCG term (equation (3.4) behaves similar to the bistatic term. In both equations, the canopy adds and attenuates the radiation. The attenuation is larger in the GCG term from the radiation interacting with the canopy more than once during its path and the GCG term is always smaller than the bistatic term. The two terms maximize at similar values of \(\theta\) and \(M_v\) and have similar shapes though the values are different.

The direct soil backscatter is dependent on the vegetative water as the source of attenuation so as \(M_v\) increases, the soil backscatter decreases and that is seen in Figure 3.14. Unlike the other two components, the soil backscatter does not maximize at \((0,0)\) but at \((0.4, 0)\) where there is no attenuation and the dielectric constant of the soil is the highest due to the highest water content.
Figure 3.11 Modeled backscatter using the full model over changing $\theta$ and $M_v$ for all the polarizations.
Figure 3.12 Modeled backscatter of the bistatic backscatter over changing $\theta$ and $M_v$ for all the polarizations.
Figure 3.13 Modeled backscatter of the GCG backscatter over changing $\theta$ and $M_v$ for all the polarizations.
Figure 3.14  Modeled backscatter of the direct soil backscatter over changing $\theta$ and $M_v$ for all the polarizations.
3.3 Fitting the Model

3.3.1 Fit to Iowa Validation Site

Fitting the model to the IVS field occurred in two parts. The first was to adjust \(a_2 - a_4\) then to adjust \(a_{bias}\) [20]. Table 3.4 show the combinations of the three fitting parameters with their respective polarizations from [20].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HH</th>
<th>VV</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_2)</td>
<td>0.0</td>
<td>0.0025</td>
<td>0.0</td>
</tr>
<tr>
<td>(a_3)</td>
<td>0.132</td>
<td>0.0605</td>
<td>0.0351</td>
</tr>
<tr>
<td>(a_4)</td>
<td>0.126</td>
<td>0.0</td>
<td>0.125</td>
</tr>
</tbody>
</table>

Table 3.4 Backscattering cross-section fitting parameters.

The fitting parameters change the dynamics of the model by eliminating terms as some of the values are zero. Analysis started by taking equations (3.2 - 3.5) and inputting the fitting parameters to see which equations were no longer contributing to the overall backscatter for each polarization. Two equations are eliminated from the final model through this analysis. The two equations are (3.2) and (3.4). Equation (3.4) is dependent upon equation (3.2) so if there is no contribution to the backscatter directly from the canopy, then there is no contribution from the GCG term. For all three polarizations, the bistatic backscatter was determined to be so dominant of a scattering mechanism that at HH and HV polarizations, there is no direct canopy backscatter. Though not at zero, the dominance is also felt in the VV polarization as \(a_2\) is small compared to \(a_3\). As for \(a_4\) for VV polarization, it equals zero so the transmissivity becomes 1 through equation (3.10) and eliminates the direct canopy term and thusly, the GCG term. This allows the soil backscatter to dominate over the bistatic backscatter. At HH polarization, neither the bistatic not soil backscatter dominates while at HV polarization, the bistatic term is the dominant term. Using these fitting parameters, VV was determined to have the best fit followed by HV and then HH polarization [20].

To fit the model to the data collected within the IVS, a very simple fit was used. Excluded from equation (3.9) at the front of the model is \(a_{bias}\). This term was introduced in order to correct the model output because the soil backscatter model was developed for a bare soil, not
for a soil with a vegetative canopy above it and should be a constant value [20]. The $a_{bias}$ term was used here to fit the model to the data from the aircraft overpasses. Because it is a model correction term and not a physically based fitting parameter, it is possible to find an $a_{bias}$ for each day and each polarization. This means that there are possibly nine different $a_{bias}$ values depending upon the day and polarization. Each polarization fell within a different range of values so an universal $a_{bias}$ cannot obtained, but one for each polarization could be (Table 3.5). The daily $a_{bias}$ values were then averaged over the three days in order to get a single value for each polarization.

<table>
<thead>
<tr>
<th>DOY266</th>
<th>HH</th>
<th>VV</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY267</td>
<td>7.58x10^{-11}</td>
<td>7.83x10^{-12}</td>
<td>1.59x10^{-19}</td>
</tr>
<tr>
<td>DOY266</td>
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<td>2.49x10^{-10}</td>
<td>9.68x10^{-19}</td>
</tr>
<tr>
<td>DOY268</td>
<td>2.42x10^{-9}</td>
<td>3.77x10^{-10}</td>
<td>2.89x10^{-18}</td>
</tr>
<tr>
<td>mean</td>
<td>3.65x10^{-9}</td>
<td>2.11x10^{-10}</td>
<td>1.34x10^{-18}</td>
</tr>
</tbody>
</table>

Table 3.5 $a_{bias}$ values for each polarization and day.

To test the fit of the model to the observed data, the field average soil moisture for each overpass was determined based off the mean time the aircraft was over the IVS. This was used in conjunction with the vegetative water content for the specific day and the $a_{bias}$ of the polarization of interest. The calculated backscatter values were then compared to the observed means for each overpass. This was done using both the $a_{bias}$ that was determined for each day and polarization combination as well as the average $a_{bias}$ over the three days. Comparing the $a_{bias}$ values between each day to the mean created the expectation that the closer the daily $a_{bias}$ was to the mean, the better the model would fit the data. From here, if the $a_{bias}$ is higher than the mean value, it is likely the model will over predict the backscatter and if the $a_{bias}$ is lower than the mean value, it could under predict the backscatter. Even with a possibility of over and under predicting the backscatter values, the model is expected to follow the pattern of the observed data, increasing in backscatter when the soil moisture increases due to the precipitation. However, the vegetative water content is also changing over the time period and may contribute to the over and under prediction of the backscatter.

Figures 3.15 through 3.17 show the modeled backscatter values using both the daily bias
values and the average bias value plotted with the observed individual pass means. As expected, the daily $a_{bias}$ model values fit the observed values well. Using the three day averaged $a_{bias}$ value, the model does not have as big of a range between the different days and conditions. It over predicts for the first day but matches the second and third day fairly well. What is not captured by the model is the possible dew influence seen in the first two passes on DOY268. Looking more closely at DOY268, the model under predicts the first two pass backscatter values. These first two passes were taken while the canopy was wet with dew. For a microwave radiometer, it was determined that twice the dew amount can be added to the vegetative water content to correct for any effects it has on the measurement (Hornbuckle, unpublished). This was done for the backscatter model to determine if the same dew impact is seen. Dew is considered 'free' water in the canopy because it is not bound to a plant. 'Free' water has a larger effect upon the backscatter values than bound water does because it is not directly connected with other material.

Doubling the amount of dew and adding to the vegetative water content did shift the modeled backscatter values closer to the observed values (Figure 3.18), but still underpredicted them. Even though the model under predicts the backscatter, it does move the model values closer to the observed values. To make the modeled backscatter values match the observed backscatter for the two passes with dew on the canopy, the dew must be tripled to quadrupled. This assumption would mean that dew has a large effect on the overall backscatter from the canopy. It would also mean that any water on the canopy (intercepted precipitation) would also have a very large effect upon the backscatter. The drawback from increasing the dew by larger amounts could make the vegetation water content exceed 5 kg/m$^2$ which would start masking the sensitivity to the soil moisture. DOY267 had a wet canopy through the first two passes for that day. Assuming that any water on the canopy affects the backscatter, it would mean the vegetative water content of the canopy would have to augmented any day that is rained or there was dew. The model does estimate the mean backscatter for the days with water on the canopy. But it does not capture the dew effect. Capturing this effect is of most concern for the HH polarization because of the magnitude of the increase of the backscatter due to the
dew. This magnitude decreases when looking at VV polarization and even a little more for HV polarization. However, because of the magnitude of the spread is the largest on DOY268 for HH polarization, the modeled mean value for that day is actually the closest to the observed only 0.18 dB too high. The other two polarizations under predict the mean backscatter at 0.25 dB and 0.33 dB too low for VV and HV polarizations respectively. Table 3.6 has the modeled mean departures from the observed means for DOY266 and DOY267. The model over predicts the mean observed backscatter on DOY266 for all polarizations. This day had the driest soil moisture but the highest vegetative water content (excluding dew/precipitation) but a dry canopy. DOY267 and DOY268 were similar in soil moisture and vegetative water content and both had wet canopies. The $a_{bias}$ is more in tune with the last two days than the first day. Another possible explanation for the models insensitivity to the change in soil moisture and vegetative water content is the change in soil moisture offsets the change in vegetative water content. Figure 3.11 shows that the same backscatter value can result from multiple combinations of soil moisture and vegetative water content. It is possible the changes measured over the period have confused the model in this way.

The sensitivity of the backscatter to a change in soil moisture is between 0.3-0.4 dB per percent change in volumetric soil moisture [28, 29]. From the data in Table 3.6, the error ranges from under a percent to just over four percent departures from the observed means. The accuracy goal for SMAP is ± 4 % when vegetation water content is below 5 kg m$^{-2}$ [12]. This corresponds to between ± 1.2-1.6 dB error. All but one mean (HH on DOY266) are within the higher range and if the lower range is used, only two means are outside the error range (VV on DOY266). For the dew correction, it decreases the mean error from 0.81 dB to 0.52 dB. This change translates into an almost one percent increase in the accuracy of the final derived soil moisture.

The model itself is truncated from its initial form as per the fitting parameters discussed earlier so any effects on the canopy are damped in the bistatic scattering term and any direct canopy effects are not involved. The direct canopy backscatter is affected the most by any change of the canopy and would be the term that would be most sensitive to dew and inter-
cepted precipitation. The fitting parameters used were fitted to a canopy that never exceeded 1.0 kg/m$^2$ water content [20]. It could be that if the canopy were not as dry, $a_2 - a_4$ could have been different and more canopy interaction would be present in the model. If this is the case then the dew and intercepted precipitation response could potentially be seen.

<table>
<thead>
<tr>
<th></th>
<th>HH</th>
<th>VV</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY266</td>
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<td>-1.43</td>
<td>-0.93</td>
</tr>
<tr>
<td>DOY267</td>
<td>0.37</td>
<td>0.07</td>
<td>-0.14</td>
</tr>
<tr>
<td>DOY268</td>
<td>0.18</td>
<td>-0.25</td>
<td>-0.33</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.38</td>
<td>-0.54</td>
<td>-0.47</td>
</tr>
</tbody>
</table>

Table 3.6 Difference between the mean observed backscatter values and the mean modeled backscatter using the average $a_{bias}$
Figure 3.15  Modeled and observed backscatter values over DOY266-DOY268. Top plot shows the modeled backscatter using average soil moisture and vegetative water content for the pass time and a daily averaged $a_{bias}$ with the observed plotted as circles and a line running between the daily mean observed backscatter. Bottom plot is the same as the top plot except the $a_{bias}$ is an average the daily values. The first group of points is from DOY266, the second is from DOY267, and the third is from DOY268.
Figure 3.16 Modeled and observed backscatter values over DOY266-DOY268. Top plot shows the modeled backscatter using average soil moisture and vegetative water content for the pass time and a daily averaged $a_{bias}$ with the observed plotted as circles and a line running between the daily mean observed backscatter. Bottom plot is the same as the top plot except the $a_{bias}$ is an average the daily values. The first group of points is from DOY266, the second is from DOY267, and the third is from DOY268.
Figure 3.17 Modeled and observed backscatter values over DOY266-DOY268. Top plot shows the modeled backscatter using average soil moisture and vegetative water content for the pass time and a daily averaged $a_{bias}$ with the observed plotted as circles and a line running between the daily mean observed backscatter. Bottom plot is the same as the top plot except the $a_{bias}$ is an average of the daily values. The first group of points is from DOY266, the second is from DOY267, and the third is from DOY268.
Figure 3.18 Modeled and observed backscatter values for DOY268. The model includes the correction for the dew for the first two points and returns to observed vegetative water content for the remaining values.
CHAPTER 4. Discussion and Conclusions

Three overarching questions were asked at the beginning of this work:

- Can a water and energy balance be performed for the IVS and is senescence able to be seen in a water balance?
- Does dew influence the radar backscatter values and is this influence significant?
- Can the dew influence on the backscatter be modeled and how is dew incorporated in the model?

Each question was investigated using data collected over the same time period over the IVS. With the analysis, each question can now be answered. An energy balance was performed on the IVS and the results indicate that it was successful in describing the net radiation’s partitioning to the different fluxes. Before this conclusion was reached, the energy budget had to be closed via a combination of accounting for the soil heat storage and the residual radiation from the measurements. After the budget was forced closed, it gave confidence that the energy budget within the IVS can be accurately described and the latent heat values could be used to estimate the evaporation from the IVS. The evaporation within the field was the only variable within the water balance that was not measured directly as it had to be estimated from the latent heat which was closed using the Bowen ratio. The soil moisture and precipitation were measured directly. When the water balance was preformed, it was determined that there was an average of 1.59 mm of storage within the field. Some of the too much unaccounted for water could have been runoff which was assumed to be zero. Other possibilities that may account for some of this water may be from errors associated with the measuring of the precipitation within the field and with the EC towers in measuring the surface fluxes.
The water balance showed that there was an increase in the amount of water storage within the IVS over the three day period. Because of the possible increase in storage in the field over the three days, it would mask any exiting of water that is not captured within the evaporation and soil moisture storage term. The senescence reported over the three day period was 1.4 kg/m² (equivalent to mm) from DOY266 to DOY268. The intercepted precipitation and dew dry-off are assumed to be captured in the evaporation term via the latent heat. Yes, a water and energy balance can be conducted over the IVS. Were both able to balance? No. The assumptions of no run off or drainage and all the precipitation infiltrated the soil and the combination of point and field averaged measurements used together may have contributed to this fact.

Dew and intercepted precipitation influence the radar backscatter as measured by the PALS overpasses. Both DOY267 and DOY268 had a wet canopy for some of the overpasses. Both times, the overpasses that coincided with the leaf wetness sensors indicating a wet canopy, the radar backscatter was significantly different than when the canopy was designated dry. However, dew and intercepted precipitation had different effects upon the radar backscatter depending upon the polarization of interest. Intercepted precipitation both increased and decreased the observed radar backscatter, causing an increase in the backscatter for HH and HV, but a decrease for VV-polarization. On DOY267, both R8 and R10 overpasses were during the wet canopy time period and R12 was over a dry canopy. Looking at Table 2.3 and Figure 2.10, the radar backscatter values increased for VV-polarization while for HH- and HV-polarization, it decreased as the canopy dried.

Dew also has a polarization dependence on the impact it makes to the radar backscatter measurements. The polarization affects the magnitude of the change, not whether the backscatter increases or decreases. For all polarizations, dew increased the observed backscatter significantly. Pass R14 was down while the canopy was still wet with dew though in the drying phase of the dew. R15 was taken well after the canopy was indicated to be dry based on the leaf wetness sensors. For each polarization, the observed backscatter decreases for R15 from R14 (see Figure 2.12) while no other variable that affected the backscatter changed. The VV polarization means had the largest change from the R14 to R15 with HH and HV having
similar changes. This is opposite of dew’s effect on the passive measurement of soil moisture below a soybean canopy, which is an increase in brightness temperature (Hornbuckle, unpublished). An increase in brightness temperature indicates a possible decrease in soil moisture while an increase in the radar backscatter indicates a possible increase in soil moisture.

Dew was incorporated into the backscatter model by adding twice the amount of dew to the vegetative water content. The modeled values shifted closer to the observed values with this method but still under predicted the observed values. Increasing the water content to account for dew could detract from the model’s value as it shifts the dominating factor away from the soil and to the vegetation canopy. As noted in the introduction, there does exist a threshold above which the vegetation reduces the sensitivity to soil moisture changes and at a high enough water content, masks the soil completely. Seen in Figure 3.8, the soil moisture contribution to the backscatter decreases and slowly start leveling off but is lower than the contribution to the backscatter from the other terms. Anything larger than the doubling of the dew and adding to the vegetation water starts pushing the vegetation water content high enough that it will begin to decrease the soil moisture sensitivity. At the same time, assumptions about the relative impact of dew on the canopy can start becoming unreasonable.

Does dew and intercepted precipitation make an impact on the observed radar backscatter of soil through a soybean canopy? Yes. Is it possible to model the impact dew has on the backscatter? Yes, but it might not be as simple as doubling the dew amount and adding it to the vegetative water content. The data collected and presented here only had two passes over a soybean field during the drying phase of the dew event. This dew event was reported to be a fairly heavy dew as well. More measurements during the middle of the growing season when the vegetative water content is more stable could reduce some of the errors of the measurements and help show the dew effects. More measurements would also span more soil moisture conditions which would help show the sensitivity of the backscatter to changes in the soil moisture. More dew events and different dew amounts could also show if the impact on the backscatter is dependent upon the dew amount and what the right increase of the vegetative water content is to account for it. Measurements of the amount of intercepted precipitation would be used
to determine if the dew correction applies to that situation as well. Future measurements over different crop types apart from soybeans can help determine if the impact reported here is consistent across all row crops or if different crops are impacted differently.
BIBLIOGRAPHY


