PLANT CHARACTERISTIC ESTIMATION USING SONAR, MULTISPECTRAL REFLECTANCE, AND ELECTROMAGNETIC RESPONSE

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
July 2006

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ACKNOWLEDGEMENTS

Foremost, I give thanks to God for giving me the courage to complete this degree and for the opportunity to work in an area for which I feel great passion. I would like to express great appreciation to my husband Fred and daughter Kristin for their patience, support, encouragement, and unending love. I thank my parents, John and Arline, for being my premier fans. And I thank my grandfather, Gus Boeckman, for instilling in me curiosity, intuition, enthusiasm, and work ethic and for his oil can that made me an agricultural engineer.

I would like to extend my sincere appreciation to my major advisor, Dr. Marvin Stone, for his time, guidance, encouragement and eminent example throughout my research. Appreciation is extended to Dr. John Solie and Dr. Niels Maness for their assistance and advice as members of my committee and as friends. I offer special thanks to Dr. Jerry Brusewitz for over thirty years of friendship, advice, and encouragement as an employer, instructor, advisor, committee member, and mentor.

Gratitude is extended to the Biosystems and Agricultural Engineering Department at Oklahoma State University for providing resources for this research and for providing the opportunity for continuance of my professional pursuits and research endeavors. To serve Oklahoma State University, the people of Oklahoma and the agricultural and engineering professions is a true honor.

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CHAPTER I

INTRODUCTION

Production agriculture, postharvest handling and food processing have become increasingly dependent on sensor technology for accurate, rapid measurement of physical and physiological properties of biomaterials. Traditional methods are time-consuming, destructive, and expensive. Therefore, research to develop and test new or improved methods of remote sensing biomaterial properties is essential for producers to maintain their position in the world market.

Remote sensing has become an environmental protection and remediation tool as well as a production diagnostic tool. Application of chemicals must be closely managed to prevent runoff and over- or under-application. With increases in fertilizer and chemical costs, producers must closely monitor application prescriptions and assess needs accordingly.

Physical property information necessary to make production and handling decisions include biomass, moisture content, chlorophyll content and concentration, and plant physical dimensions. The research presented in this dissertation includes three non-destructive sensing methods to determine these properties. The first section, Chapter Two, considers the use of an electromagnetic free-space system operating in the medium frequency range to estimate biomass water content and biomass. Chapter Three reports research using an ultrasonic distance sensor and a multispectral imaging system to estimate plant height, top profile surface area, and biomass. Chapter Four incorporates the findings in Chapter Three with several spectral indices to determine the optimum method of estimating chlorophyll content and concentration.

Each of these methods shows promise, when used in the proper context, to remotely estimate biomaterial characteristics. This investigation indicates some strengths and limitations in the use of reflectance based sensing for physiological property estimation and provides a scientific foundation for future research particularly in the area of radiofrequency and dielectric property sensing.

CHAPTER II

PLANT BIOMASS ESTIMATION USING DIELECTRIC PROPERTIES

ABSTRACT: An electrostatic free-space system acting as a parallel plate capacitor was designed and tested to estimate water content and biomass in situ using greenhouse grown spinach. The attenuation of the transmitted signal through the system was strongly correlated with water content and dry biomass (r^2 = 0.95) using 30.5 cm square plate antennae. Dry biomass estimates were accurate because sample moisture content was homogenous.

KEYWORDS: moisture content, biomass, radio frequency, electromagnetic, multipole

INTRODUCTION

Crop producers and agronomists when making management decisions desire estimation of plant biomass *in situ*. Biomass estimation facilitates accurate management decisions regarding chemical and fertilizer applications, estimation of yield, and post harvest handling of stover (Pordesimo et al., 2004). When nitrogen fertilizer is applied at rates in excess of that needed for maximum yield in cereal crops, nitrate leaching can be significant (Olson and Swallow, 1984; Raun and Johnson, 1995). Study of plant root systems and root surface sorption zones requires knowledge of plant biomass (Raun, 1997). Subsequently, a non-destructive method to quickly and accurately estimate plant biomass *in situ* may provide producers with essential information for making these production decisions.

Measurement of plant biomass via harvesting is destructive, expensive and time consuming (Reese et al., 1980). To address these complications, several techniques to assess plant biomass remotely and quickly have been developed. These techniques include vegetation indices to directly estimate biomass using empirical equations (Das et al., 1993; Guevara et al., 2002; Moges et al., 2004; Tucker, 1979), leaf area index (LAI) and intercepted radiation estimates integrated in crop simulation models such as the Monteith model (Asrar et al., 1985). However, the accuracy of these methods is confounded by dynamic atmospheric and agronomic factors (Serrano et al., 2000). In addition, some of the test methods are destructive, making them more costly, more time consuming and less desirable for producers.

Studies have shown that plant hydric status influences the efficiency of light conversion, a key variable for estimating dry matter production from solar radiation (Arsar et al., 1984; Steinmetz et al., 1990). To determine hydric status, plant water content has been estimated using gravimetric methods but, like the harvesting methods to determine biomass, these methods are destructive and time consuming. Additionally, only small area information is obtained. One method employed to gather information to directly estimate plant water content for a larger area has used radar. Radar response is sensitive to plant geometry, leading to inaccurate water content predictions (Ferrazzoli et al., 1992). Another method used to estimate plant water content, the use of passive radiometers, also lacks accuracy and the ability to sense large areas quickly (Wigneron et al., 1995).

Researchers have tested different techniques of using the dielectric properties of biomaterials to estimate water content. These studies include transmission line techniques such as waveguide (coaxial and free-space), impedance and cavity methods (Trabelsi and Nelson, 2003). Dielectric properties are, by definition, a measure of the polarizability of a material when subjected to an electric field (Von Hippel, 1954). For lossy materials, the relative complex permittivity, $\varepsilon = \varepsilon' - j\,\varepsilon''$, represents the dielectric properties. The dielectric constant, ε', describes the material's ability to store energy, the dielectric loss factor ε'', describes the material's ability to dissipate the electric field energy, and j is the imaginary root of -1 (Nelson, 1994; Trabelsi and Nelson, 2003). The dielectric properties of many materials depend on frequency, moisture content, bulk density, temperature, chemical composition, and the permanent dipole moments association with water and other constituent molecules (Nelson, 1973, 1981, 1983, 1984, 1991; Nelson and Stetson, 1976a; Von Hippel, 1954). The dielectric constant ε' has been calculated from the capacitance measurements through the system by the following equation (Equation 1) where C is the capacitance of the system with the sample and C_0 is the capacitance of the system with free space (Sacilik et al., 2006).

$$\varepsilon' = \frac{C}{C_0} \qquad (1)$$

Water is an influential factor due to its polar nature (ε' =80). Dielectric constants for biological materials are commonly less than 5. The other influencing factors are water related in that they translate into a change in the amount of water interacting with the electric field. The Debye model (Equation 2) describes the dielectric properties of liquid (non-bound) water (Debye, 1929; Hasted, 1973).

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau} \qquad (2)$$

where ε_∞ represents permittivity at frequencies so high that polarization due to molecular orientation does not occur, ε_s represents permittivity at zero frequency, ω is the angular frequency, and τ is the relaxation time. However, water in biomaterials exists both as liquid water and as water bound to the inner structure of the biomaterial. The dielectric properties of bound water lie somewhere between those of ice and those of liquid water depending on how tightly the water is bound. Therefore, testing of biomaterials has been conducted comparing potential difference measurements of elements with known permittivity to the test material or by correlating the transmission potential difference between two or more quantities of the same material with the water content, determined gravimetrically, of the test samples. These methods have been used by various researchers to determine the effect of moisture content, bulk density, temperature and frequency on the dielectric properties of cereal grains, oilseeds and other agricultural products (Berbert et al., 2002; Boldor et al., 2004; Jorgensen et al., 1970; Kim et al., 2002; Kim et al., 2003; Kraszewski and Nelson, 1991; Lawrence et al., 2001; Lawrence and Nelson, 1993; Lawrence et al., 1998a; Lawrence et al., 1998b; Nelson, 1965; Nelson and Lawrence, 1994; Nelson and Noh, 1992; Nelson and Stetson, 1976b; Noh and Nelson, 1989; Sokhansanj and Nelson, 1988; Stetson and Nelson, 1970; Trabelsi and Nelson, 2004).

A sensing system consisting of an electrostatic quadrupole has shown promise in estimating the water content of wheat spikes and stems *in situ* using dielectric interaction (Fechant et al., 1999a; Helbert et al., 2001b). Theoretical models of this system suggest that the response to the frequency of the injected current was optimum at 447 kHz (Helbert et al., 2001c). The difference between the emitted current and the received current was dependant on the dielectric properties of the plant material. The purpose of the system was to estimate plant development stages by detecting the water content difference between wheat spikes and stems. Coefficients of determination for the comparison of the estimated water content and the water content determined by gravimetric testing were 0.82 to 0.86 for spikes and stems, respectively (Helbert et al., 2001a). Free-space measurements such as those used by the Fechant and Helbert studies have the advantage of allowing transmission and reflection measurements without sample contact and with minimal sample preparation (Musil and Zacek, 1986). The relative complex permittivity ε may be determined using either the reflection coefficient or the transmission coefficient. Reflection coefficients require definition of a reference plane and are sensitive to surface characteristics. Transmission coefficient determination is not sensitive to specimen placement and is relative to the whole sample volume. This provides more representative information of the entire sample (Trabelsi and Nelson, 2003). Thus, for the study of crops *in situ*, free-space transmission measurement may be optimal. Previously mentioned studies have concentrated on harvested samples or specific plant segments. Research is also limited concerning the use of dielectric measurements in the medium radio frequency range (300 to 3,000 kHz) to estimate plant water content and biomass of plants in the field or moving bulk bioproducts,

With the purpose of developing a foundation for future sensor development in the area of dielectric property measurement *in situ*, it was proposed in this research that an electrostatic free-space system be tested to estimate plant water content. The frequency range of 300 kHz to 900 kHz was investigated. This frequency range was chosen in order to minimize ionic effects such as the Maxwell-Wagner effect (Kittel, 1996) and to reduce the interaction between the electromagnetic waves and the plant geometry (Fechant et al., 1999b). The Maxwell-Wagner effect exists in this frequency range but has been shown to be very weak (Fechant, 1996).

The attenuation, K, specific to the immediate dielectric properties of the material in the static sensing area was determined using the transmission measurements from a vector network analyzer (VNA) and Equation 23 (Von Hippel, 1954).

$$K = 10\log_{10}\left(\frac{P_0}{P(z)}\right) = 20\log_{10}\left(\frac{E_0}{E(z)}\right) \qquad (3)$$

where P_0 is the incident power at the transmitting antenna and P(z) is the power at the receiving antenna (distance z) after transmission attenuation due to the sensed area. E_0 and E(z) are the electric field intensities at the antennae. As the electromagnetic wave travels through the sensed area, the energy will be attenuated depending on the dielectric properties of the material. Since plants are a nonconducting material, ε' is the most influential on the change in *K* when the biomass enters the system. A positive *K* value would indicate a gain through the system while a negative *K* would indicate a loss (Agilent, 2000). It was proposed that, for a given sensing area and sensing system, a relationship between the water content of the sample and the difference, K_{sample}, in attenuation with plants in the systems and the free space system may be developed (Equation 4). The regression of this comparison may be used to estimate water content and biomass of the material being tested.

$$K_{sample} = K_{test} - K_{space} \qquad (4)$$

Subsequently, ε' was also correlated with the water content because of its influence on the attenuation *K* through the system.

Green-house grown spinach in flats was used as test material. Objectives for this study were:

- To determine if electromagnetic transmission response within the frequency range of 300 to 900 kHz can be used to detect volumetric moisture of spinach using the free-space system.

- To determine the optimum frequency within the proposed range for detecting volumetric moisture of spinach *in situ* using this system.
- To develop a relationship between the electromagnetic transmission attenuation, moisture content, and biomass of spinach plants for the given system.

METHODS AND MATERIALS

The electrostatic free-space system consisted of two antenna plates facing each other 60 cm apart. The antennae were connected to an Agilent Technologies 8712ET Vector Network Analyzer (VNA) using a 50-ohm cable with type-N connectors and a type-N to BNC adapter. One antenna transmitted the radiofrequency wave while the opposite antenna functioned as a receiver. The potential difference between the transmitted signal and the received signal in the frequency range of 300 and 900 kHz was measured at 1 kHz increments by the VNA. The potential difference between the antennae depends on the relative dielectric permittivity and the conductivity of the plant material. The dielectric permittivity has been shown to be inversely correlated to the moisture content of biomass (Fechant and Tabbagh, 1999; Helbert et al., 2001a). The complex permittivity of water is much greater than that of dry biomass ($\varepsilon'_{water} \approx 80$, $\varepsilon'_{drybiomass} \approx 3$). At 20°C, the relative dielectric constant for pure water is 80 compared to a dielectric constant of 1 in a vacuum. Thus water dominates the response of biomaterials to electromagnetic waves (Hasted, 1973). The functionality of the electrostatic free-space system was that of a parallel plate capacitor with the space between the antenna plates acting as the capacitive material. The equivalent electronic circuit is shown in Figure 1.

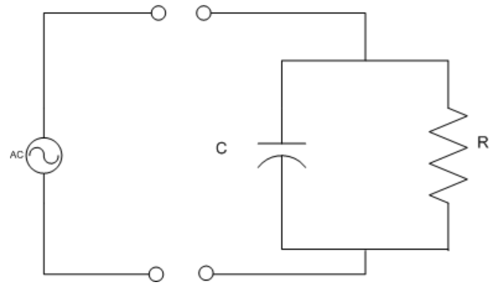

Figure 1. Equivalent circuit diagram for electromagnetic free space system.

The antennae were thin aluminum plates. Two sizes were tested: 12.7cm x 12.7cm x 0.32 cm and 30.5 cm x 30.5 cm x 0.32 cm. An insulated adapter was attached to the back of the plates to connect the cables leading to the network analyzer (Figure 2).

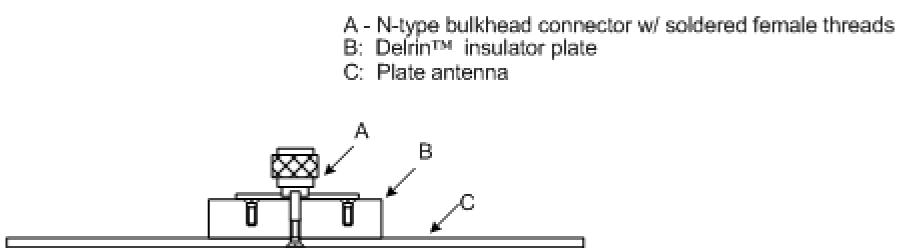

Figure 2. Cable attachment for plate antennae (drawing not to scale).

The plates were mounted on adjustable metal stands for testing and adjusted to a height of 50 cm from the ground to the center of the plate and 60 cm between faces of the plates Figure 3). ™The metal stands were kept outside of the sensing volume to prevent influence on the signal.

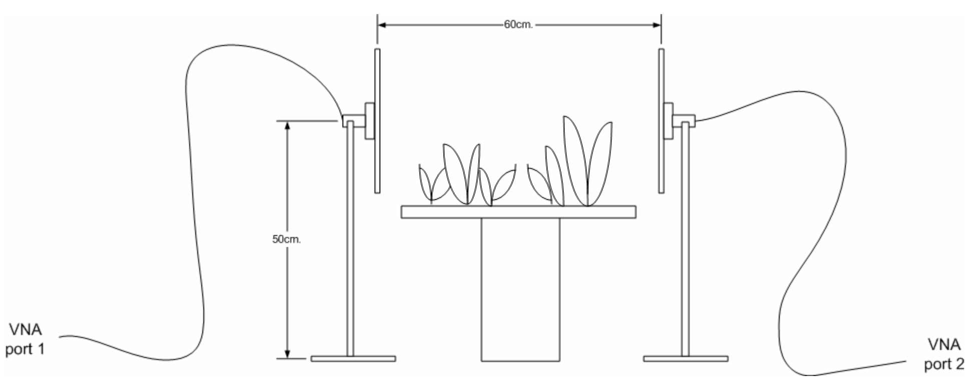

Figure 3. Sensing system layout (not to scale)

The height and plate dimensions were estimated using finite element analysis (FEA) in order to reduce the influence of the soil layer yet consider the necessary plant sensing area for various heights of plants from low growing crops such as spinach to taller crops such as wheat and rye. FEA was also used to estimate the distance between the antennae. The system was designed to sense a 1 m x 1 m x 0.60 m volume. A plastic platform placed in the middle of the space between the two antennae held the test specimens. To evaluate the nature of the wave and the presence of multiple reflections, a specimen of known water content was moved from the middle of the sensing area toward the receiving antenna and then toward the transmitting antenna. The modulus and phase were measured at each position. The results remained constant. The receiving antenna was rotated about its axis. The smallest angle of rotation produced a significant drop in signal indicating that the wave kept its original polarization after propagating through the specimen. Adjustments from the FEA estimated distances were not necessary.

Using the transmission logmag setting on the VNA, the modulus of the potential difference *K*, or $10 \cdot \log_{10}\left(\frac{P_0}{P(z)}\right)$ in db, was measured with open space between the antennae. The VNA was set to average 8 readings for each sample at 1 kHz intervals. Four different known samples of pure water (138, 183, 229, and 281 g) were introduced to validate the sensitivity of the system to changes in water content within the sensed volume. Signal attenuation was calculated by finding the difference between the *K* values of the system with open space and with a sample in the sensed area.

Flats of greenhouse grown spinach were used as sample biomaterial. The flats, injection molded trays 37.5 cm x 52.75 cm x 10.75 cm, with healthy plants were presented to the system, data were recorded over the stated frequency range with the

VNA, and a randomly chosen portion (approximately 10 percent) of the biomass was harvested at soil level, weighed and placed in an oven at 80°C for 48 hours for gravimetric determination of moisture content. This process was repeated until all of the vegetation in the flat had been harvested. Final data were collected with the flat void of vegetation. Attenuation was calculated and both water content and dry biomass were compared to the attenuation using statistical software.

To estimate the influence of soil moisture and vegetation outside the designed sensing space on the sensor response, spinach plants were placed below the lower limit of the design area. Data were recorded by the VNA as plants were sequentially removed. Samples were weighed and placed in an oven for gravimetric moisture content determination. Data with no plants in the sensing area were also recorded after all of the plants had been removed. The attenuation due to outside biomaterial was compared to the attenuation due to biomaterial within the designed sensing space. A reduced attenuation would indicate that the biomaterial outside the space has less influence on the system response.

RESULTS AND DISCUSSION

Known-quantity water samples

Results of the initial tests on known quantities of water revealed strong exponential correlation between the attenuation through the sensing system and the amount of water present ($r^2 = 0.99$) using the 30.5 cm antenna plates (Figure 4). The 30.5 cm antenna plates achieved stronger correlation with the water samples when compared to the response with the 12.7 cm plates ($r^2 = 0.99$ vs. 0.06). The response with the 12.7 cm plates was highly non-linear. FE Analysis suggests that the difference may be due to more edge losses in the smaller plates in the proximity of the sensed media (Figure 5a and b).

Graphs from 300 to 900 kHz were visually inspected to deduce the most responsive frequencies. Frequencies that exhibited the appropriate response to the different samples of water (attenuation positively correlating to water quantity) were analyzed with statistical software to locate the strongest correlation. The optimum frequency was 472 kHz (Figures 4 and 6).

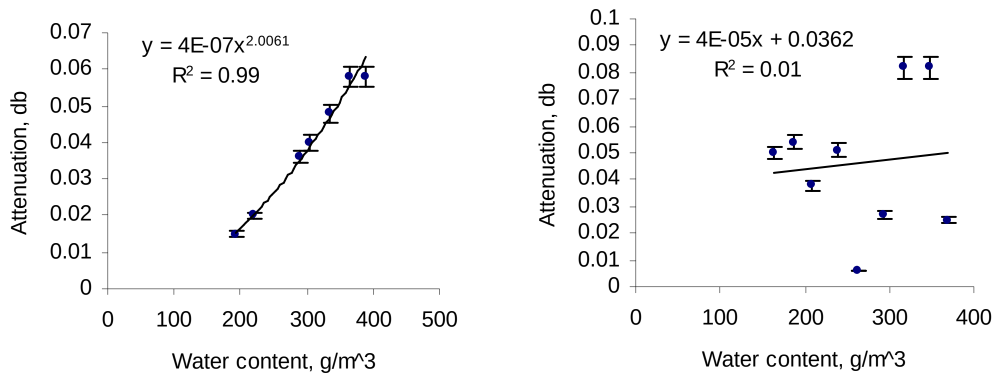

Figure 4. Signal attenuation compared to known water weights. 30.5 cm plates (l) and 12.7 cm plates (r) (Correlation calculated with 24 readings for each point. Averages are displayed for clarity.)

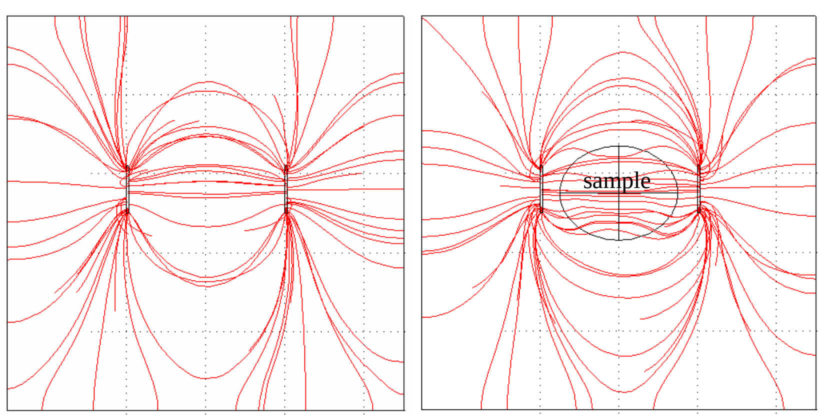

Figure 5a. FEA analysis of 12.7 cm plates without sample (l) and with sample (r) in sensing region used in free-space electromagnetic sensing system.

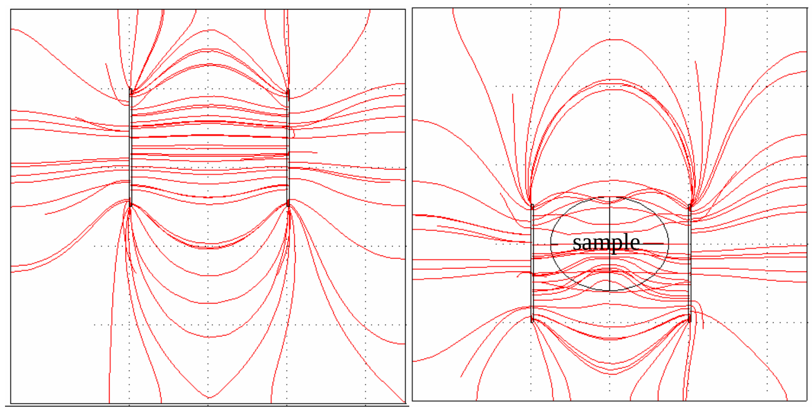

Figure 5b. FEA analysis of 30.5 cm plates without sample (l) and with sample (r) in sensing region used in free-space electromagnetic sensing system.

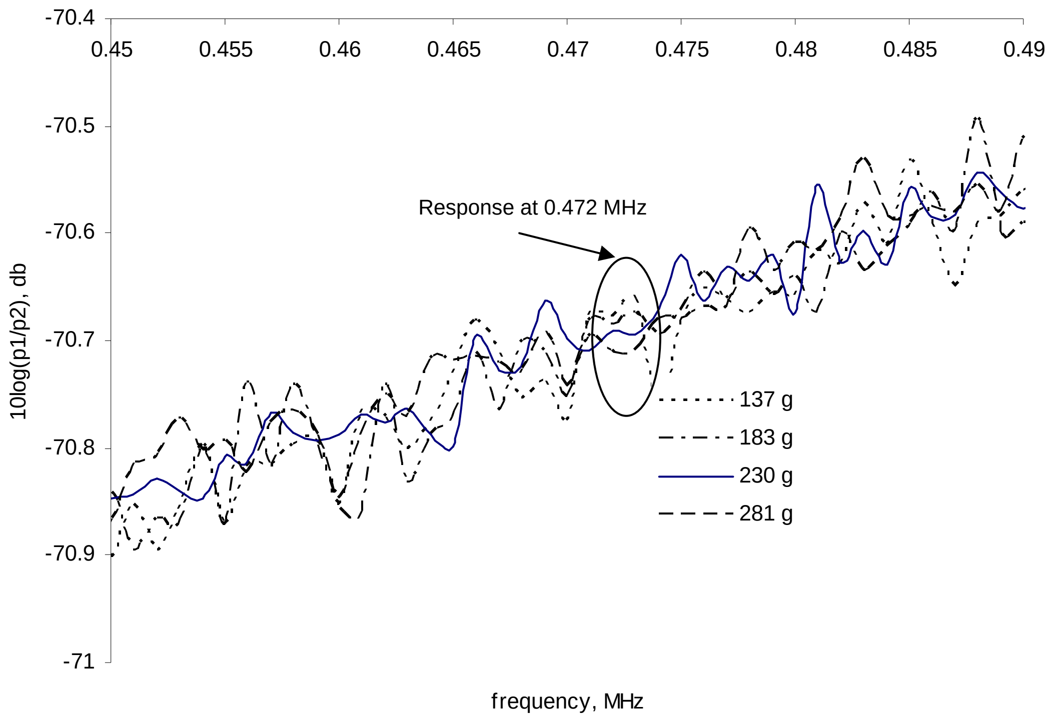

Figure 6. Example of transmission response versus frequency, indicating appropriate response to changes in known water samples.

Greenhouse-grown spinach samples

Data collected from the presentation of spinach in flats to the sensing system with the 30.5 cm antennae were analyzed to determine sensor response to the differences in biomass, thus water content differences, as biomass was sequentially removed from the flats. The leaves were void of excess moisture from irrigation. The data collected reflected the comparison of the signal introduced to the system at the first antenna plate, transmitted through the capacitive material (biomass), and received by the second antenna plate. The VNA stored this data as Transmission (K_{test}) = 10log(p1/p2). During post processing of the data, the attenuation, K_{sample}, was calculated by finding the difference between the transmission of the flat with no vegetation and with vegetation. Figure 7 shows the results comparing water content to signal attenuation ($r^2 = 0.95$) using the 30.5 cm plates. Figure 8 show the correlation to dry biomass determined by the gravimetric oven testing of the harvested biomass ($r^2 = 0.95$). The empirical linear equation using attenuation K_{sample} to predict water content of spinach within the sensing area using the system with the 30.5 cm plates was:

$$WC_{pred} = 178.57 K_{sample} - 51.32 \qquad (5)$$

where WC_{pred} is the predicted water content in grams. The empirical linear relationship to predict dry biomass in spinach using this system was:

$$M_{dry} = 19.72 K_{sample} - 6.72 \qquad (6)$$

where M_{dry} is the predicted dry biomass in grams.

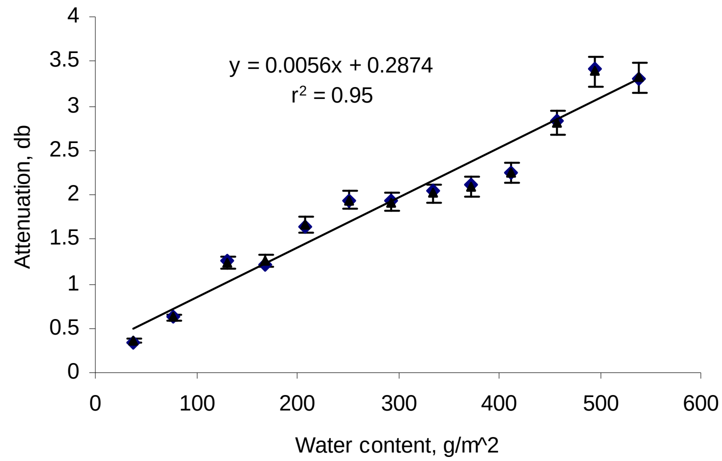

Figure 7. Comparison of signal attenuation to water content in greenhouse-grown spinach with 30.5 cm x 30.5 cm antenna plates. Each data point represents the average of 24 readings. Correlations were based on individual data.

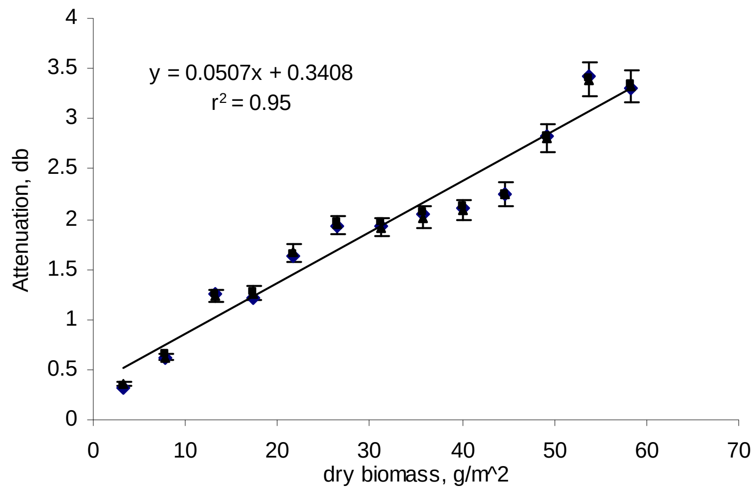

Figure 8. Comparison of signal attenuation to dry biomass in greenhouse-grown spinach with 30.5 cm x 30.5 cm antenna plates. Each data point represents the average of 24 readings. Correlations were based on individual data.

The same analysis conducted with the 12.7 cm x 12.7 cm antenna plates produced weaker correlations, shown in Figures 9 and 10 (r^2 = 0.73).

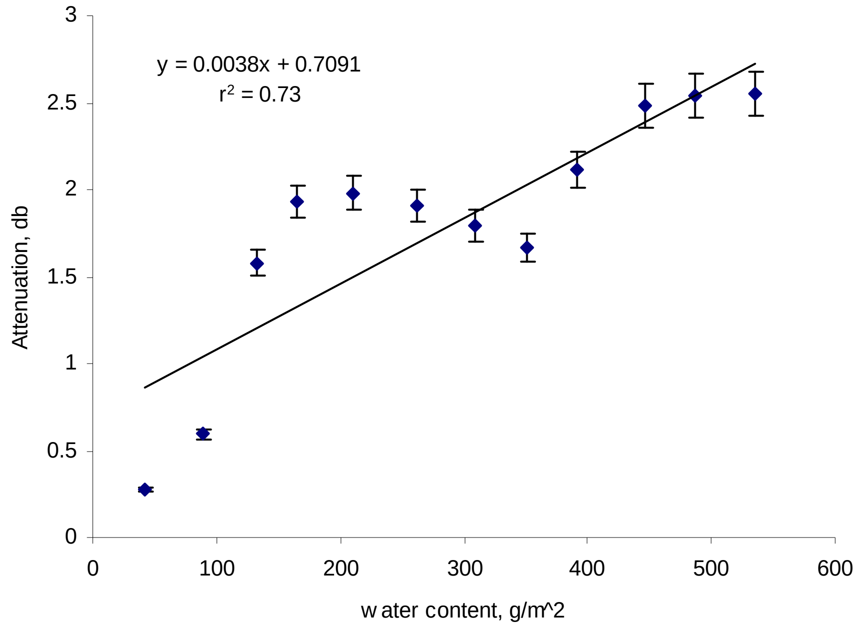

Figure 9. Comparison of signal attenuation to water content in greenhouse-grown spinach with 12.7 cm x 12.7 cm antenna plates. Each data point represents the average of 24 readings. Correlations were based on individual data.

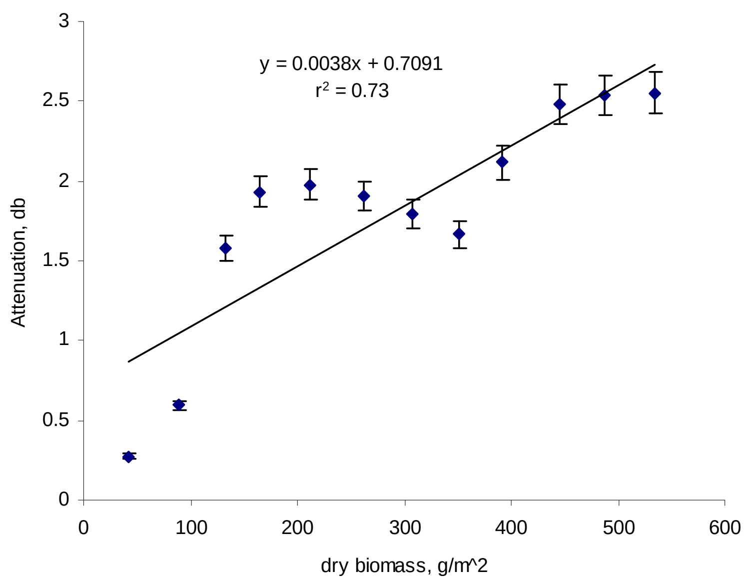

Figure 10. Comparison of signal attenuation to dry biomass in greenhouse-grown spinach with 12.7 cm x 12.7 cm antenna plates. Each data point represents the average of 24 readings. Correlations were based on individual data.

Review of the response for both sizes of plate antennae revealed a transition-shaped curve, which was more pronounced in the smaller antenna plate system. Other researchers have experienced this same tendency in free-space dielectric sensing systems when comparing moisture contents to sensor response (Eubanks and Birrell, 2001; Fechant and Tabbagh, 1999; Helbert et al, 2001a; Kabir et al, 1997; Nelson, 1994; Trabelsi and Nelson, 2003). The frequency of the system appears to be insignificant in the shape of this non-linear response. While strong correlations using a linear relationship were obtained in this research as well as the referenced research, the non-linear response should be noted in the design of a sensing system. In the case of the 30.5 cm x 30.5 cm plate system, response between 300 and 400 g water content did not coincide with the linear response at water content below and above this region. Fitting an extreme value cumulative transition curve to the data in Figure 6 resulted in a coefficient of determination of 0.95, $y = -49.4\exp\left(-\exp\left(-\frac{x - \ln(\ln 2) - 97.6}{160.1}\right)\right)$. The standard deviation was erratic in the range between 300 and 400 g water content. Fitted standard deviation for the transition curve was 0.22 indicating strong repeatability. One hypothesis for the curved nature of this response was the microscopic and macroscopic molecular structures as well as the chemical constituents in biomaterial (Kabir et al, 1997). In support of this hypothesis, other researchers have advanced the idea in soil moisture studies. Several mixture equations using the dielectric constant and electromagnetic response of soil and vegetation have been offered. The equation systems that determine a transition water content, θ_t, indicate that at moisture levels less than θ_t, water is tightly bound to the biomaterial particles by matric and osmotic forces (bound water). These water molecules do not polarize easily. As the water content increases beyond θ_t, the water is able to move more freely and this free water will have a dominant effect on the dielectric constant (Schmugge and Jackson, 1992; Van de Griend and Wigneron, 2004; Wang and Schmugge, 1980). Each biosystem has its own empirically determined θ_t and response both below and above θ_t dependent upon the antenna design, molecular constituents, temperature, and the gross frequency range of the sensing system. Results given in Figures 6 through 9 appeared to concur with these mixture equation systems. However, the results reported in this research reflected the change in water content within a volume, not within the biomass. The water content within the plants did not change. Plant material was removed, thus changing the water content within the sensed space. It may be hypothesized that standing wave interaction changed as the shape of the sensed biomaterial changed with plant (thus water content) removal. The important conclusion from this and cited research, however, was that designers should consider the response of the antenna system employed and determine the appropriate method of accommodating the varying response areas of this relationship in context with the sensed space or biomaterial.

Dielectric Constant Calculations

The dielectric constant ε' was determined using Equations 2, 3 and 7. The correlation between ε' and water content and dry biomass was strong ($r^2 = 0.94$) as shown in Figures 11 and 12. This indicated the system was responding appropriately to the capacitance of the biomaterial in the sample volume. Free space has an ε' close to 1 while more biomass should result in a positive regression with ε'. The correlation of ε' with biomass was as strong as the correlation of ε' with water content in this research because the water content was homogeneous throughout the sample. In samples with more variability in moisture content, the relationships of ε' with water content and biomass have the potential of being different. While water content can be directly estimated using this method, biomass estimates may be less accurate due to variability throughout the sample.

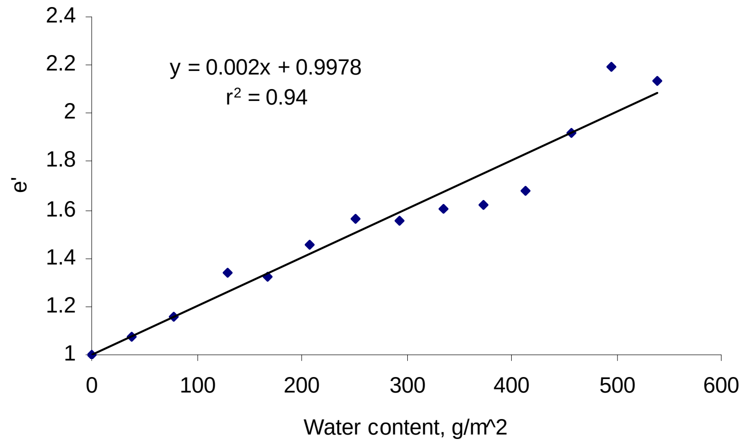

Figure 11. Dielectric constant *e'* compared to water content in greenhouse-grown spinach with 30.5 cm x 30.5 cm antenna plates. Each data point represents the average of 24 readings and calculations.

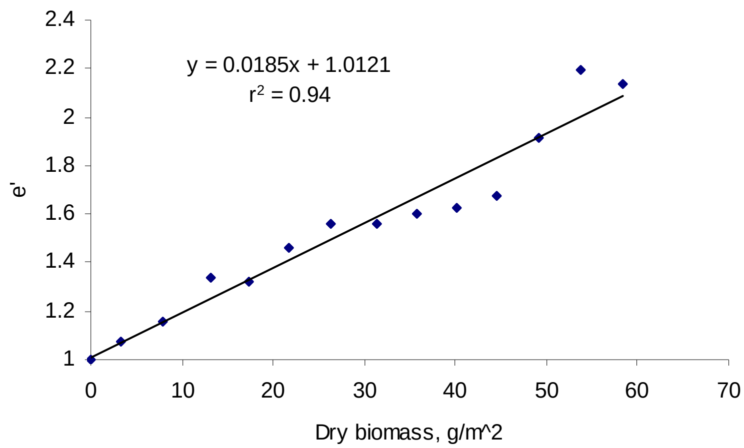

Figure 12. Dielectric constant *e'* compared dry biomass in greenhouse-grown spinach with 30.5 cm x 30.5 cm antenna plates. Each data point represents the average of 24 readings.

Biomass Outside the Sensing Area

Evaluation of the data collected with the known water samples outside the lower limit of the sensing space suggested that biomaterial and soil at the ground level had minimal influence on sensor results. Coefficients of determination with the known water samples and the plant material compared to the sensing system attenuation were 0.05 and

0.38, respectively, based on a linear relationship. The attenuation for plant material placed below the sensing area was 90 per cent less per gram of water than the attenuation for plant material within the sensing area (Figure 13). The apparent influence of soil and material outside of the sensing area was considered minimal.

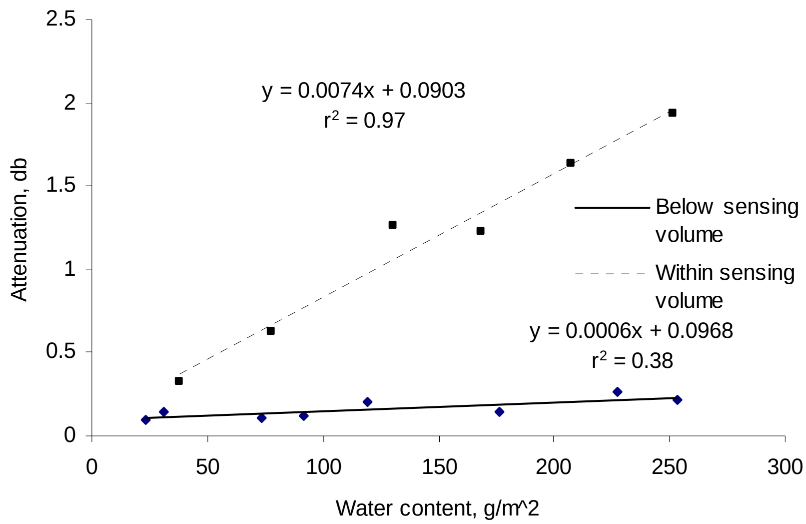

Figure 13. Response of sensing system to biomaterial water content within and outside of sensing volume using 30.5 cm antennae plates.

Correlation between the predicted and gravimetrically measured water content and biomass is shown in Figures 13 and 14 ($r^2 = 0.95$). The error in the prediction may be due to the uncertainty of gravimetric measurement, which is generally considered to be 5 per cent. The sensing system uncertainty included the uncertainty in determining the sensed area and the inaccuracies of the VNA. The estimation of water content outside of the sensing volume indicated an 8 % influence in response for the larger amounts of water in the sensing volume. VNA manufacturer's information reported a 1 % error in transmission tracking. The design of the system presented response as a difference in signal attenuation due to a change in dielectric properties within the same sensing area.

This reduced the liability of VNA calibration errors. Therefore, the error budget for the sensing system was approximately three percent more than the destructive method of gravimetric water content determination.

Figures 14 and 15 indicate the sensing system was within the estimated uncertainty expectations. The confidence and prediction intervals are based on a 95 percent confidence level.

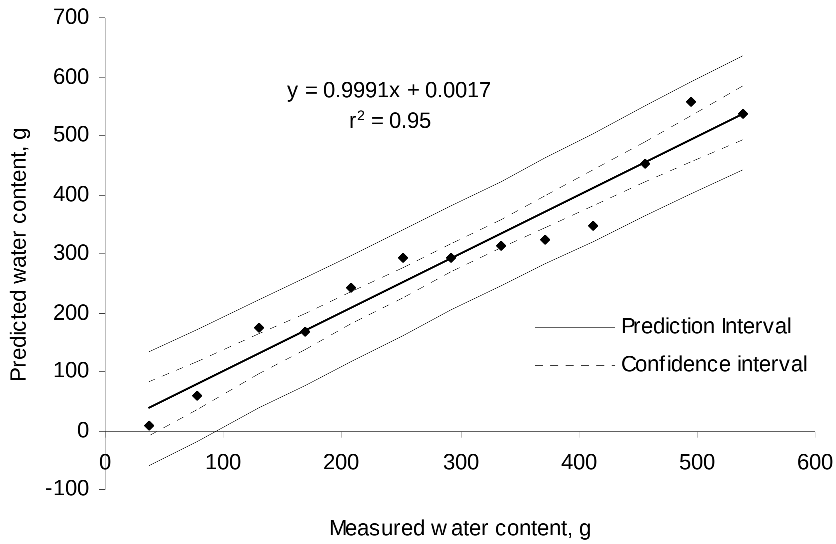

Figure 14. Comparison between predicted sensing area water content and gravimetrically determined water content using a linear relationship. (95% confidence and prediction intervals)

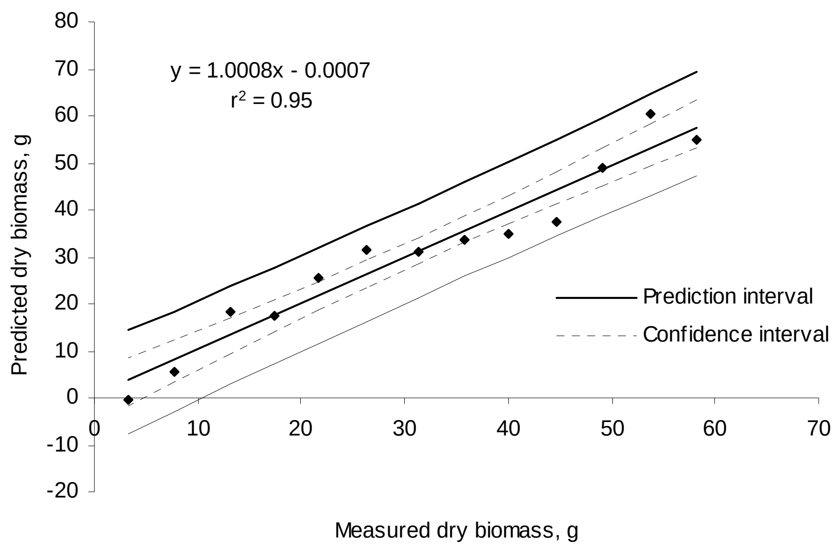

Figure 15. Comparison between predicted sensing area dry biomass and gravimetrically determined dry biomass using a linear relationship. (95% confidence and prediction intervals)

CONCLUSION

The electromagnetic free-space system showed promise for estimating plant water content given the results when tested with greenhouse-grown flats of spinach (r^2 = 0.95). The estimate of dry biomass was accurate in this study because the sample moisture content was homogeneous. In sample volumes with variable water content, less accuracy is expected.

Finite element analysis was used to estimate the initial design, which proved to be appropriate. Two sizes of antenna plates were tested based on the finite element analysis of response. The larger size, 30.5 x 30.5 x 0.32 cm, was the preferred design when compared to the smaller 12.7 x 12.7 x 0.32 cm plates. Testing of samples just outside of the expected sensing area of 1 m x 1 m x 0.6 m indicated only minimal response. Therefore, influence of soil moisture and operator proximity would be minimal.

It is important to note the transition curve in each of the sensor responses in this research. These curves indicated a region between 300 and 400 g water content that responded with a different slope when compared to the remainder of the range considered.

The next stage of design using this technique must include testing of the system using different kinds of biomaterial such as plants with different leaf profiles and other food products presented in bulk. The VNA should be replaced with a current source and potential difference detector for more portable field sensing. The design has the potential of being an inexpensive, accurate method of non-destructively estimating water content of biomaterials *in situ*. Through extensive testing, the potential exists to determine and quantify the presence of insects and foreign material.

References

Agilent. 2000. 8712ET and 8714ET RF Network Analyzers Users Guide. *Part No. 08714-90011*: Agilent Technologies.

Arsar, G., L. Hipps, and E.T. Kanemasu. 1984. Assessing solar energy and water use efficiencies in winter wheat: A case study. *Agric. For. Meteorol.* 31 (1984):47-58.

Asrar, G., E.T. Kanemasu, R.D. Jackson, and P. Pinter. 1985. Estimation of total above-ground phytomass production using remotely sensed data. *Remote Sens. Environ* 17 (1985):211-220.

Berbert, P., D. Queiroz, and E. Melo. 2002. Dielectric properties of common bean. *Biosystems Engineering* 83 (4):449-462.

Boldor, D., Sanders. T., and J. Simunovic. 2004. Dielectric properties of in-shell and shelled peanuts at microwave frequencies. *Trans. ASAE* 47 (4):1159-1169.

Das, D., K. Mishra, and N. Kalra. 1993. Assessing growth and yield of wheat using remotely-sensed canopy temperature and spectral indices. *Int. J. Remote Sens.* 14 (1993):3081-3092.

Debye, P. 1929. *Polar molecules*. New York: The Chemical Catalog Co.

Eubanks, J. and S. Birrell. 2001. Determining moisture content of hay and forages using multiple frequency parallel plate capacitors. Paper No. 01-1072. ASAE International Meeting, Sacramento, California.

Fechant, C. 1996. Realisation d'un quadripole de mesure in situ de la permittivite dielectrique des vegetaux. Premiere application a la determination du contenu en eau des epis de ble, Universite de Paris VI.

Fechant, C., J. Buis, and A. Tabbagh. 1999. In situ measurement of medium-frequency apparent permittivity using an electrostatic quadrupole. Application to the determination of the water content of wheat. *Meas. Sci. Technol.* 10 (1999):174-181.

Fechant, C., and A. Tabbagh. 1999. Laboratory measurement of the dielectric permittivity of vegetables at 430 kHz. Correlation between apparent permittivity of a set of wheat ears and their water content. *C. R. Acad. Sci. Paris* 327 (IIb):285-298.

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

Guevara, J.C., J.M. Gonnet, and O.R. Estevez. 2002. Biomass Estimation for native perennial grasses in the plain of Mendoza, Argentina. *Journal of Arid Environments* 50:613-619.

Hasted, J. 1973. *Aqueous Dielectrics*. London: Chapman and Hall.

Helbert, J., P. Boissard, and J. Buis. 2001a. Estimation of the vertical profile of the wheat crop water content with an electrostatic multipole. An experimental study. *Agronomie* 12 (2001):471-481.

Helbert, J., P. Boissard, and J. P. Buis. 2001b. A theoretical study of an electrostatic multipole to assess the horizontal and vertical distribution of the in situ water content of vegetation canopies. *Agronomie* 21 (2001):127-138.

Jorgensen, J., A. Edison, S. Nelson, and L. Stetson. 1970. A bridge method for dielectric measurements of grain and seed in the 50- to 250-MHz range. *Trans. ASAE* 43 (1):18-20, 24.

Kabir, M., K. Khalid, W. Daud, and S. Aziz. 1997. Dielectric properties of rubber wood at microwave frequencies measured with an open-ended coaxial line. *Wood and Fiber Science* 29(4):319-324.

Kim, D., J. Kim, S. Lee, and S. Noh. 2002. Measurement of grain moisture content using microwave attenuation at 10.5 GHz. *IEEE Transactions on Instrumentation and Measurement* 51 (1):72-77.

Kim, D., S. Lee, J. Lee, S. Noh, and M. Kim. 2003. On-line measurement of grain moisture content using RF impedance. *Trans. ASAE* 46 (3):861-867.

Kittel, Ch. 1996. *Introduction to solid state physics*. 7th ed. ed: John Wiley & Sons.

Kraszewski, A., and S. Nelson. 1991. Density-independent moisture determination in wheat by microwave measurements. *Trans. ASAE* 34 (4):1776-1783.

Lawrence, K., D. Funk, and W. Windham. 2001. Dielectric moisture sensor for cereal grains and soybeans. *Trans. ASAE* 44 (6):1691-1696.

Lawrence, K., and S. Nelson. 1993. Radio-frequency density-independent moisture determination in wheat. *Trans. ASAE* 36 (2):477-473.

Lawrence, K., S. Nelson, and P. Bartley. 1998a. Measuring dielectric properties of hard red winter wheat from 1 to 350 MHz with a flow-through coaxial sample holder. *Trans. ASAE* 41 (1):143-150.

Lawrence, K., W. Windham, and S. Nelson. 1998b. Wheat moisture determination by 1- to 110-MHz swept-frequency admittance measurements. *Trans. ASAE* 41 (1):135-142.

Moges, S., W.R. Raun, R. Mullen, K. Freeman, G.V. Johnson, and J. B. Solie. 2004. Evaluation of green, red, and near infrared bands for predicting winter wheat biomass,nitrogen uptake, and final grain yield. *Journal of Plant Nutrition* 27 (8):1431-1441.

Musil, J., and R. Zacek. 1986. *Microwave Measurement of Complex Permittivity by Free Space Methods and applications*. New York: Elsevier.

Nelson, S. 1965. Dielectric properties of grain and seed in the 1 to 50-mHz range. *Trans. ASAE* 8 (1):38-48.

Nelson, S. 1973. Electrical properties of agricultural products - A critical review. *Trans. ASAE* 16 (2):384-400.

Nelson, S. 1981. Review of factors influencing the dielectric properties of cereal grains. *Cereal Chem.* 58 (6):487-492.

Nelson, S. 1983. Observations on the density dependence of the dielectric properties of particulate materials. *J. Mircrowave Power* 18 (2):143-153.

Nelson, S. 1984. Estimation of permittivities of solids from measurements on pulverized or granular materials. In *Dielectric Properties of Heterogeneous Materials*. J. A. Kong. New York: Elsevier.

Nelson, S. 1991. Dielectric properties of agricultural products. *IEEE Transaction on Electrical Insulation* 26 (5):845-869.

Nelson, S. 1994. Measurement of microwave dielectric properties of particulate materials. *Journal of Food Engineering* 21:365-384.

Nelson, S., and K. Lawrence. 1994. RF impedance and dc conductance determination of moisture in individual soybeans. *Trans. ASAE* 37 (1):179-182.

Nelson, S., and S. Noh. 1992. Mathematical models for the dielectric constants of rice. *Trans. ASAE* 35 (5):1533-1536.

Nelson, S., and L. Stetson. 1976a. Frequency and moisture dependence of the dielectric properties of hard red winter wheat. *Journal of Agricultural Engineering Research* 21 (2):181-192.

Noh, S., and S. Nelson. 1989. Dielectric properties of rice at frequencies from 50 Hz to 12 GHz. *Trans. ASAE* 32 (3):991-998.

Olson, R., and C. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. *Soil Science Society of America Journal* 48:583-586.

Pordesimo, L.O., W.C. Edens, and S. Sokhansanj. 2004. Distribution of aboveground biomass in corn stover. *Biomass and Bioenergy* 26:337-343.

Raun, W.R. 1997. Indirect measures of plant nutrients. *Commun. In Soil Sci. Plant Anal.* 29:1571-1581.

Raun, W.R., and G.V. Johnson. 1995. Soil-plant buffering of inorganic nitrogen in continuous winter wheat. *Agronomy Journal* 87:827-834.

Reese, G.A., R.L. Bayn, and N.E. West. 1980. Evaluation of double-sampling estimators of subalpine herbage production. *Journal of Range Management* 33:300-306.

Sacilik, K. C. Tarimci, and A. Colak. 2006. Dielectric properties of flaxseeds as affected by moisture content and bulk density in the radio frequency range. *Biosystems Engineering* 93(2): 153-160.

Serrano, L., I. Filella, and J. Penuelas. 2000. Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. *Crop Science* 40 (May-June):723-731.

Schmugge, T. and T. Jackson. 1992. A dielectric model of vegetation effects on the microwave emission of soils. *IEEE Trans. Geosci. Remote Sensing* 30: 757-760.

Sokhansanj, S., and S. Nelson. 1988. Dependence of dielectric properties of whole-grain wheat on bulk density. *Journal of Agricultural Engineering Research* 39 (3):173-179.

Steinmetz, S., M. Guerif, R. Delecolle, and F. Baret. 1990. Spectral estimates of the absorbed photosynthetically active radiation and light-use efficiency of a winter wheat crop subjected to nitrogen and water deficiencies. *Int. J. Remote Sens.* 11 (1990):1797-1808.

Stetson, L., and S. Nelson. 1970. A method for determining dielectric properties of grain and seed in the 200- to 500-MHz range. *Trans. ASAE* 13 (4):491-495.

Trabelsi, S., and S. Nelson. 2003. Free-space measurement of dielectric properties of cereal grain and oilseed at microwave frequencies. *Measurement Science and Technology* 14:589-600.

Trabelsi, S., and S. Nelson. 2004. Microwave dielectric properties of shelled and unshelled peanuts. *Trans. ASAE* 47 (4):1215-1222.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens. Environ* 8 (19791):127-150.

Van de Griend, A. and J. Wigneron. 2004. The *b*-factor as a function of frequency and canopy type at H-polarization. *IEEE Transactions on Geoscience and Remote Sensing* 42(4): 786-794.

Von Hippel, A. R. 1954. *Dielectric Properties and Applications*. New York: John Wiley and Sons.

Wang, J. and T. Schmugge. 1980. An empirical model for the complex dielectric permittivity of soils as a function of water content. *IEEE Transactions on Geoscience and Remote Sensing* 18(4): 288-296.

Wigneron, J., A. Chanzy, J. Calvet, and N. Bruguier. 1995. A simple algorithm to retrieve soil moisture and vegetation biomass using passive microwave measurements over crop fields. *Remote Sens. Environ.* 51:331-341.

CHAPTER III

ULTRASOUND AND DIGITAL IMAGERY FOR ESTIMATING CROP BIOMASS

Abstract: Ultrasonic distance sensing has been used extensively to detect proximity and distance to objects. Digital imagery can be used to estimate vegetative coverage. The product of plant height resolved through ultrasound distance sensing and top view surface area determined through digital imaging analysis was used to estimate plant biomass. This study used ultrasound and digital imagery to estimate biomass in corn, snap beans, and spinach. Strong correlation was found between actual biomass and estimated biomass in corn and spinach. (r^2=0.85 and 0.84). Less accuracy was achieved in estimating bean biomass. NDVI alone and the product of NDVI and height were also considered as possible estimators of biomass.

Keywords: Plant biomass, ultrasound, height, NDVI, digital imagery, plant modeling

INTRODUCTION

The ability to estimate plant biomass may accurately facilitate product management decisions regarding chemical and fertilizer application, estimation of yield, and post harvest handling of (Pordesimo et al., 2004) Direct measurement of plant biomass via harvesting is destructive and expensive (Reese et al., 1980). A method of nondestructively estimating plant biomass *in situ* is desired by growers and researchers to assess plant status during production and prior to harvest. Timely estimation of biomass may provide opportunity for accurate remediation to improve yield and may reduce environmental impact during application of chemicals.

Plant characteristics have been estimated using the various remote sensing techniques (Price and Bausch, 1995; Wiegand et al., 1979). These techniques have the advantage of providing near instantaneous information about plants nondestructively

(Clevers, 1988). The ratio of reflectance in the near-infrared spectral bands to the reflectance in the red bands has been found to estimate biomass and is somewhat effective in normalizing the effect of soil background reflectance variation (Colwell, 1973)

Red and near-infrared spectral bands have been combined in a mathematical relationship to indicate the presence of chlorophyll and to minimize interference from other non-chlorophyll containing objects in the subject area (Rouse et al., 1974a). Normalized difference vegetation index (NDVI) has been used to estimate biomass and to determine the existence of chlorophyll-containing objects within a subject space (Nitsch et al., 1991; Rouse et al., 1974a). NDVI may be determined using the following formula:

$$NDVI = (\rho_{NIR} - \rho_{RED})/(\rho_{NIR} + \rho_{RED}) \qquad (1)$$

where: ρ_{NIR} = reflectance in the near-infrared band

ρ_{RED} = reflectance in the red spectral band

Plant height, biomass, vegetation coverage, and yield have been correlated with NDVI as well as with red and green spectral reflectance (Raun et al., 1999; Weckler et al., 2003; Yang and Anderson, 1996). NDVI has been adjusted for the soil background since NDVI is affected by soil brightness. The resulting index was a soil adjusted vegetation index (SAVI) (Huete et al., 1985). These indices were developed for the whole growing season. At specific growth stages, they may not provide accurate estimates of physical plant characteristics. Blackmer *et al.* (Blackmer et al., 1994) recommended interpreting the variability in chlorophyll meter readings relative to reference areas that were not nitrogen-limited in each field. In-field reference areas may help to normalize variation due to growth stages or environmental conditions. The nitrogen reflectance index (NRI) was proposed by Bausch and Duke (Bausch et al., 1996). This index requires a relationship for each growing season. The reflectance in the area of interest is normalized by the reflectance from a reference area where there is no nitrogen stress (Equation 2).

$$NRI = (\rho_{NIR}/\rho_G)_{\text{area of interest}}/(\rho_{NIR}/\rho_G)_{\text{reference}} \tag{2}$$

where: ρ_{NIR} = reflectance in the near-infrared band

ρ_G = reflectance in the green band

Bausch and Duke (1996) correlated NRI to the nitrogen sufficiency index (NSI) described by Peterson *et al.* (Peterson et al., 1993) and the total nitrogen percentage in the plant. The formula for NSI is:

$$NSI = (C_{av})_{\text{area of interest}}/(C_{av})_{\text{reference}} \times 100 \tag{3}$$

where: C_{av} = average chlorophyll meter readings in the subject area and in an area with no nitrogen limits

The relationship between NRI and NSI appeared to be a 1:1 correlation. NRI was successfully used to estimate plant nitrogen, spatial field variability, and prescription nitrogen application for maize (Bausch et al., 1996; Diker, 1998; Diker and Bausch, 1998). The ability of NRI and NSI to estimate leaf area index (LAI), dry matter and yield appears to be limited. NRI seems to depend on crop canopy type (Diker and Bausch, 2003). NRI was a better indicator of LAI at earlier growth stages in plants with a planophile canopy than an erectophile canopy. In the later growth stages, it was a better indicator of LAI in plants with an erectophile canopy.

Plant biomass has been segregated from different backgrounds in digital images using an adaptive neuro-fuzzy inference system (ANFIS) from MATLAB® 6.1 (Neto et al., 2003). Digital imaging processing techniques have been used to determine vegetation coverage (Lukina et al., 1999; Richardson et al., 2001; Ter-Mikaelian and Parker, 2000). Multispectral images have also been used to determine NDVI and exhibit strong correlation with NDVI from chlorophyll meters and reflectance based sensors (r^2= 0.97) (Weckler et al., 2003).

Ultrasonic distance sensors (UDS) have commonly been used for distance measuring and proximity in noncontact applications (Massa, 1999) and in industrial and agricultural storage tank level sensing. The speed of sound in air, taking into consideration the temperature of the air, can be used to determine distance (Equation 4) (Massa, 1999). Ultrasonic distance sensors typically emit a burst in the 40 kHz to 250 kHz frequency range and detect the reflection of the burst. The time between pulse emission and reflection detection is determined and a distance to the detected object can be calculated.

$$D=6505.5\left(t_1-t_0\right)\sqrt{1+\frac{T}{273}} \tag{4}$$

where: D = distance to object, m

T = temperature of air, °C

t_1 = time at which sonic wave is transmitted

t_0 = time at which sonic wave is received

For purposes of this study, three plant species (corn, spinach and snap beans) were chosen based on the different inherent biomass presentation of each crop. The authors hypothesize that the product of the top view surface area (TVSA) determined by the use of digital imaging and the height of the plant determined by ultrasonic distance sensing will provide an estimate of plant volume on a single plant scale. This proposed method is quite similar to the biomass estimation method of native perennial grasses using basal diameter and plant height (Guevara et al., 2002).

The purpose of this study is to investigate the correlation between plant biomass in three plant species (corn, snap beans, and spinach) and the estimate of plant volume using an ultrasonic distance sensor to estimate height and a digital imagining system to estimate vegetative coverage.

METHODS AND MATERIALS

Corn, snap beans and spinach were grown in flats in greenhouses. At the post-cotyledon stage, individual plants were randomly removed from the flats every other day for three weeks with growing media intact. This sampling schedule insured a range of size and maturity for the plants. Each plant was presented to an ultrasonic sensor via a turntable with a diameter of 0.91 m located 1.04 m below the fixed-position sensor. The turntable was allowed to travel two rotations at 3.04 m/min (1.06 rpm). Plants were removed from the turntable and placed under a multispectral camera mounted on a tripod at nadir with respect to the plant. Digital images were acquired and stored on a laptop computer. After ultrasonic distance sensor data were collected and the digital images acquired, the vegetative portions of the plants were harvested and weighed to the nearest 0.1 g. The wet biomass weight was recorded.

Ultrasonic sensing equipment

A Senix Ultra-SPA (Bristol, VA) ultrasonic distance sensor was used to gather distance measurements from the ultrasound unit to the plant. Specifications for the sensor are listed in Table 1.

Table 1. Specifications for Senix Ultra-SPA ultrasonic distance sensor

Environmental Conditions	Wet or high dust
Weight	0.9 kg
Temperature	Automatically compensates, -30 to +70 degrees C
Range	50 cm to 11 m
Transducer	Piezoelectric, 50 kHz
Measurement cycle	Adjustable using SoftSpan© software
Beam Angle	12 degrees nominal @ -3 db, conical
Sensitivity	Adjustable single turn potentiometer
Accuracy	Better than 1% of target distance
Repeatability	Nominal 0.1 % of range
Power	12-30 VDC at 60 ma
Resolution	.086 mm maximum; 12 bits over spanned distance and full output range 0-10 VDC or 0.20 ma
Communications	Serial RS-232, continuous output

The sensor was fixed to a stand over the turntable. The sensor triggered a pulse once every millisecond. The beam was conical with a total angle of 12° down at 3 db. The time between the emitted pulse and the detection of a reflected pulse was converted into a distance measurement by Senix's proprietary software, SoftSpan©. The ultrasonic distance sensor data were captured and saved as a text file on a laptop computer. Plant material was represented as an anomaly in the sensor's response when compared to the response from the bare turntable (Figure 1). Figure 2 provides an example of a spinach plant profile determined from the SoftSpan© generated text files.

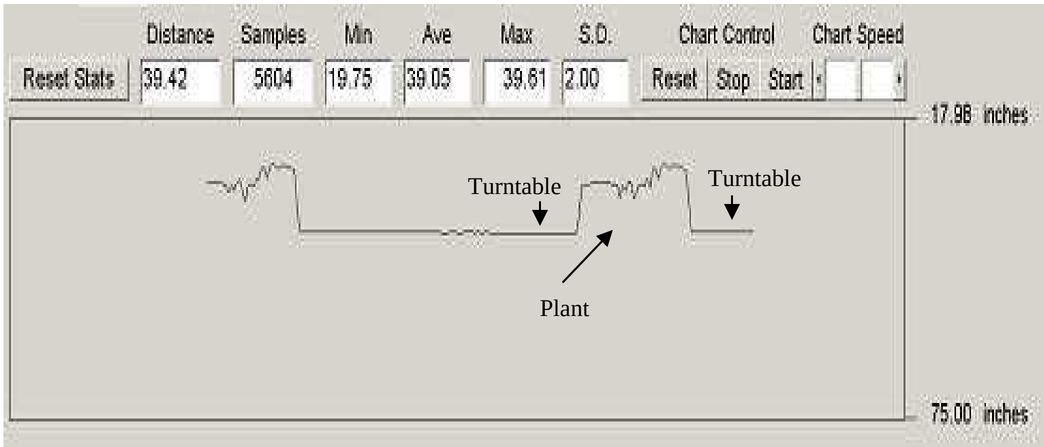

Figure 1. Ultrasound distance sensor response represented in SoftSpan© - Corn Plant

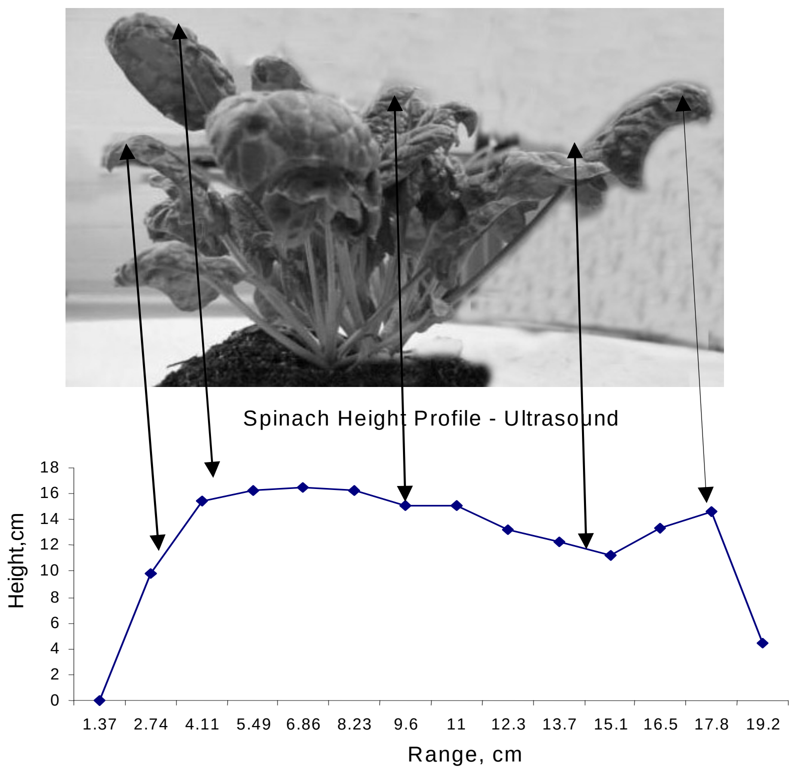

Figure 2. Ultrasound distance sensor profile – Spinach Plant

The ultrasonic distance sensor data were analyzed for each plant to determine the maximum and minimum distances from the sensor. The maximum distance represented the distance to the turntable while the minimum distance represented the distance to the tallest point in the plant. The difference between the maximum and minimum distances represented the maximum height of the plant including supporting soil and root area. Height attributed to soil and root area was subtracted to find the maximum height of the vegetative portion of the plant. An average height for each plant was also determined by considering the responses across the profile of the plant. Hand measurements were taken with a meter stick at 2.5 cm intervals across the profile of the plant to validate the ultrasonic sensor response.

CAMERA DESCRIPTION

A DuncanTech MS3100 multispectral camera (Auburn, CA) was configured to collect irradiance data in three narrow optical bands, 550, 670, and 780 nm ±10 nm FWHM, which correspond to green, red, and near-infrared bands respectively (Table 1.2). The camera system includes an RS232 communication interface to receive operation commands and configuration data for imagery control.

Table 2. Specifications for DuncanTech MS3100 multispectral camera

Imaging Device	3 ea. 1/2in Interline Transfer CCD
Resolution	1392 (H) x 1040 (V) x 3 sensors
Pixel Size	4.65 x 4.65 micron
Pixel Clock and Data Transfer Rate	14.318 MHz max.
Sensing Area	7.6 x 6.2 mm
Frame Rate	7.5 frames per second
Signal/Noise	60 dB
Electronic Shutter	1/8000 – 1/7.5 sec Independent control per channel
Control Input	RS-232 port
Operating Temp	0 – 65 degrees C
Operating Voltage	12 volts
Weight	1.62 kg

The image data is presented as digital pixel values through the digital video output controller. A frame grabber, National Instrument's PCI-1424, was installed in a

Dolch ruggedized laptop. A 14 mm focal length telecentric lens was used which provided sufficient image size to accommodate one plant at a distance of 1 m. The camera was placed on a tripod and the plant was lighted with external incandescent lighting. Reflectance for each band was obtained using Labsphere Reflectance Calibration Standard reflectance targets with nominal reflectance of 10%, 50%, 75%, and 99%. A calibration procedure developed by Weckler *et al.* (Weckler et al., 2002) was followed using industry standard reflectance targets. Images were converted into reflectance using the following equations:

$$\rho_{red} = \frac{I_{red}}{I_{red(calibration)}} \qquad (5)$$

$$\rho_{near\text{-}infrared} = \frac{I_{nir}}{I_{nir(calibration)}}$$

where:

I_{red} = reflected red light from the plot

I_{nir} = reflected near-infrared light from the plot

$I_{red(calibration)}$ = reflected red light from the calibration targets

$I_{nir\ (calibration)}$ = reflected near-infrared light from the calibration targets

An NDVI image was then generated using reflectance in the red and near-infrared bands as in Equation 6.

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \qquad (6)$$

where:

ρ_{NIR} = near-infrared irradiance

ρ_{RED} = red irradiance

Analysis of the multispectral images was accomplished using the image processing toolbox techniques of Matlab™ software. The IR and red reflectance pixel values were identified from the multispectral camera images. These values were used to calculate NDVI using Equation 6 above. The values of the pixels in the images that had an NDVI greater than zero represent plant material and were saved in a matrix. Values of pixels that had an NDVI less than zero represent background and were saved in a separate matrix. In the case of a single plant with no soil or plant material in the background, the pixels with a positive NDVI represent only the subject plant with no background interference. The plant material pixel values were averaged to find the average plant NDVI. Assigning a null value to the background pixels and a "one" to the plant material pixels binarized the image. The vegetation area was calculated using the "bwarea" command from the image processing toolbox applied to the binary image.

RESULTS

Plant Ultrasonic Distance Sensor Profiles

The coefficient of determination for the hand-measured height compared to the ultrasonic distance sensor estimated height was 0.87. Profiles of the same plant were 96 percent repeatable. Variations in plant beginning and ending points were due to a slight speed variation of the turntable caused by the weight of the sample.

The profiles of the spinach plants were compact with little variation in height. The corn and snap bean profiles showed great variation in height due to the erectophile canopy presentation in corn and the stems and vines in beans.

NDVI and Biomass Correlations

Considering only single plants and NDVI determined for only the plant material by digital image analysis, the coefficients of determination indicated a weak correlation of 0.15 for snap beans (Figure 3) while better for corn and spinach at 0.64 and 0.78 respectively. Each model was statistically significant ($p < 0.05$). A possible explanation for the low coefficient of determination in snap beans is the presentation of stems in the image. When the digital images were analyzed for stem area segregated from leaf material, a much lower NDVI resulted (NDVI < 0.300) while the leaf material less stems had an average NDVI greater than 0.500.

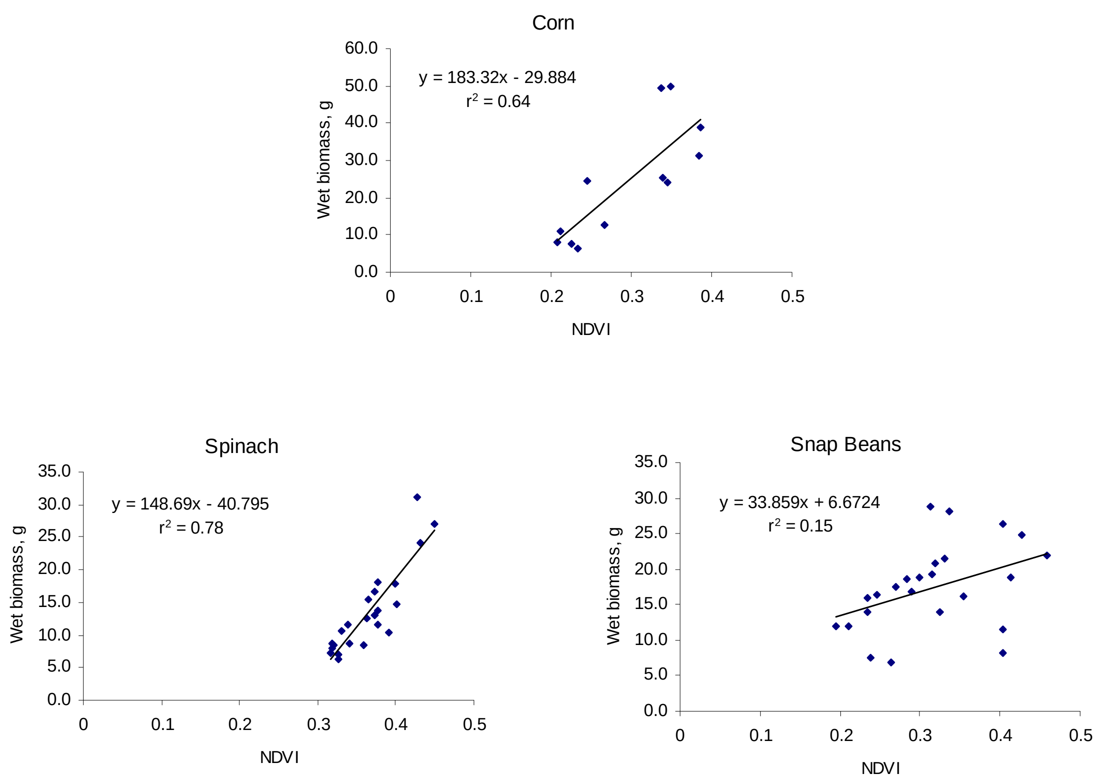

Figure 3. Measured biomass correlated with NDVI to estimate biomass

Because the NDVI was determined for plant material excluding background using the top surface view in the digital image, it was proposed that the NDVI be multiplied by the plant height as determined by the ultrasonic distance sensor to estimate a plant volume. This plant volume estimate was compared to the weighed wet biomass. Using the plant height as a multiplier for NDVI provided an improvement in biomass estimation in corn and in snap beans, while there was little improvement in the biomass estimate in spinach Figure 4). The results in snap beans remained inadequate to estimate biomass ($r^2 = 0.25$, $p = 0.0114$). Corn and spinach correlations were statistically significant with a p-value less than 0.001.

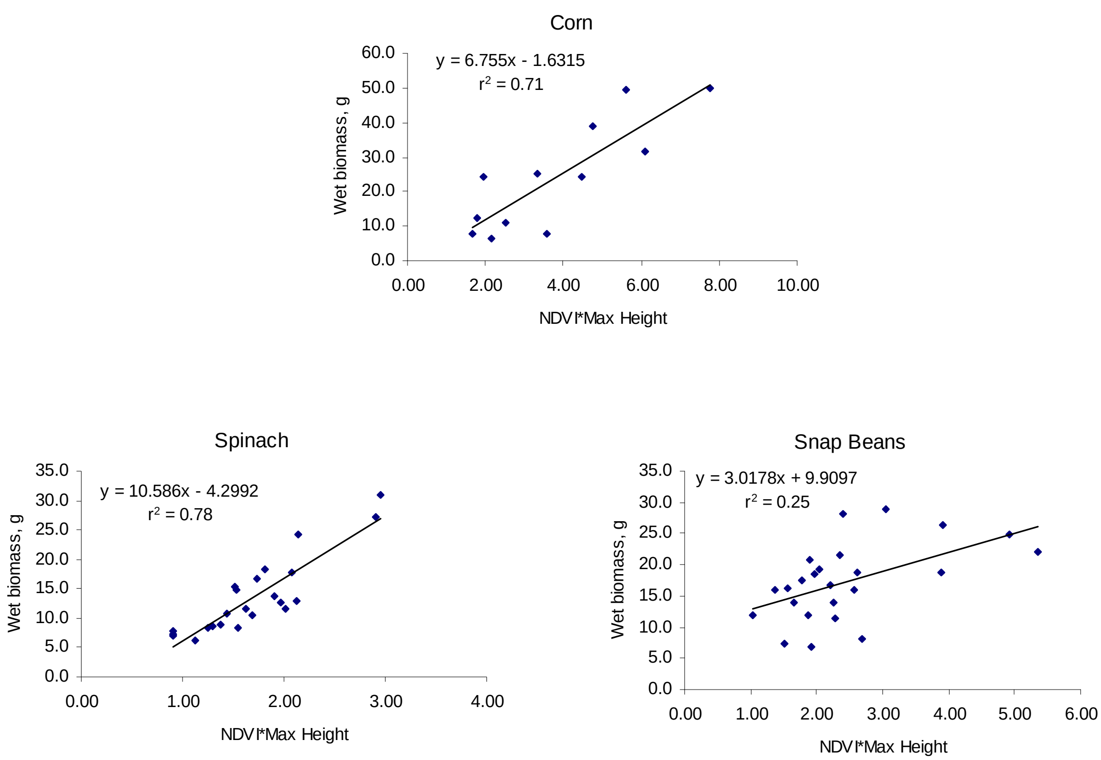

Figure 4. Measured biomass correlated with NDVI*plant maximum height to estimate biomass

Vegetative Coverage, Height Estimate and Biomass Correlations

To estimate plant volume, the vegetative coverage determined from the top surface area view digital image analysis was multiplied by the height estimate result from the ultrasonic distance sensor data. This product was compared to the measured wet biomass weights. The results are given in Figure 5. This method provided much improvement of results over using NDVI in the estimate, particularly in snap beans. Each model was statistically significant at $p < 0.0005$.

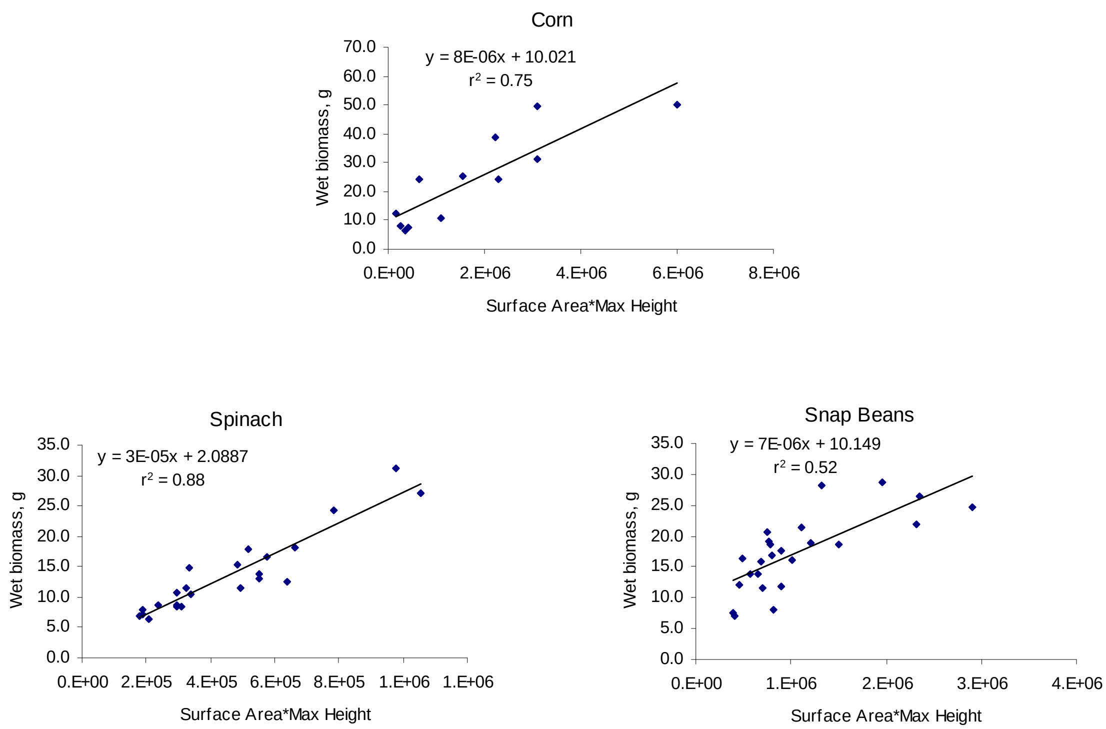

Figure 5. Measured biomass correlated with top view surface area*plant maximum height to estimate biomass

The same methods as above using both NDVI and vegetative coverage were repeated with the average height used as the height component instead of the maximum plant height. The results are shown in Figures 6 and 7. The product of the average plant height and the TVSA estimates provided a better biomass estimate in corn than using the maximum height in the calculations or using NDVI with height. However, in spinach and snap beans using the maximum height estimate and the vegetative coverage in the calculations provided a better estimate.

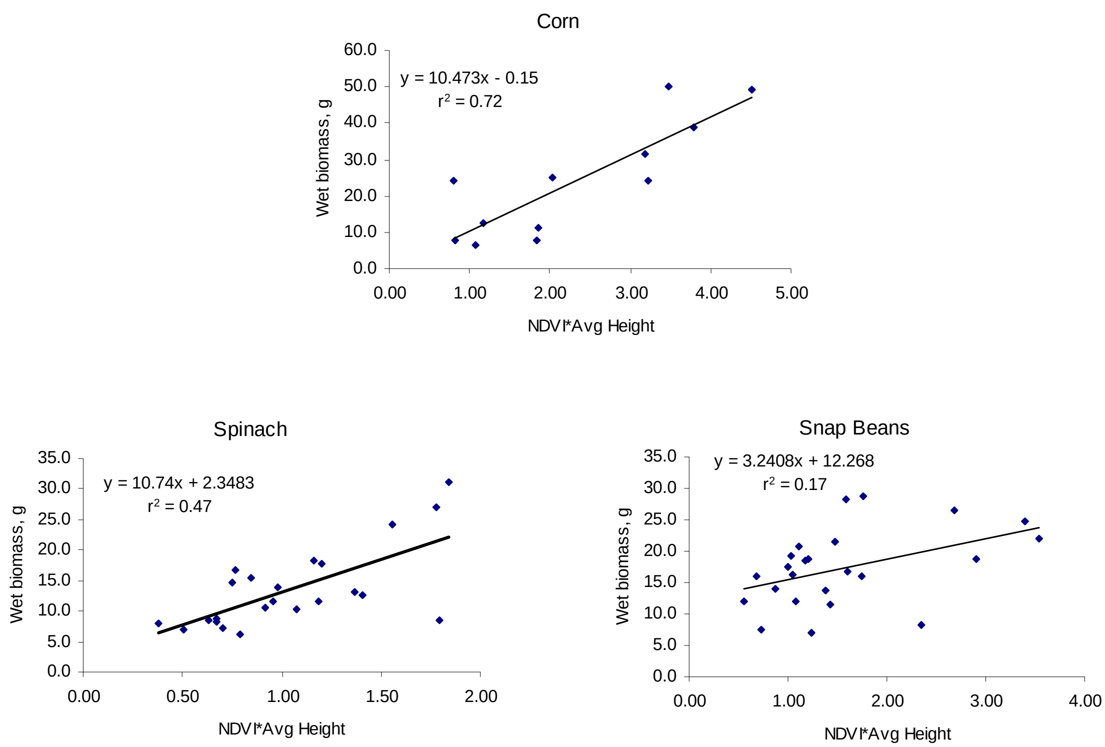

Figure 6. Measured biomass correlated with NDVI*plant average height to estimate biomass

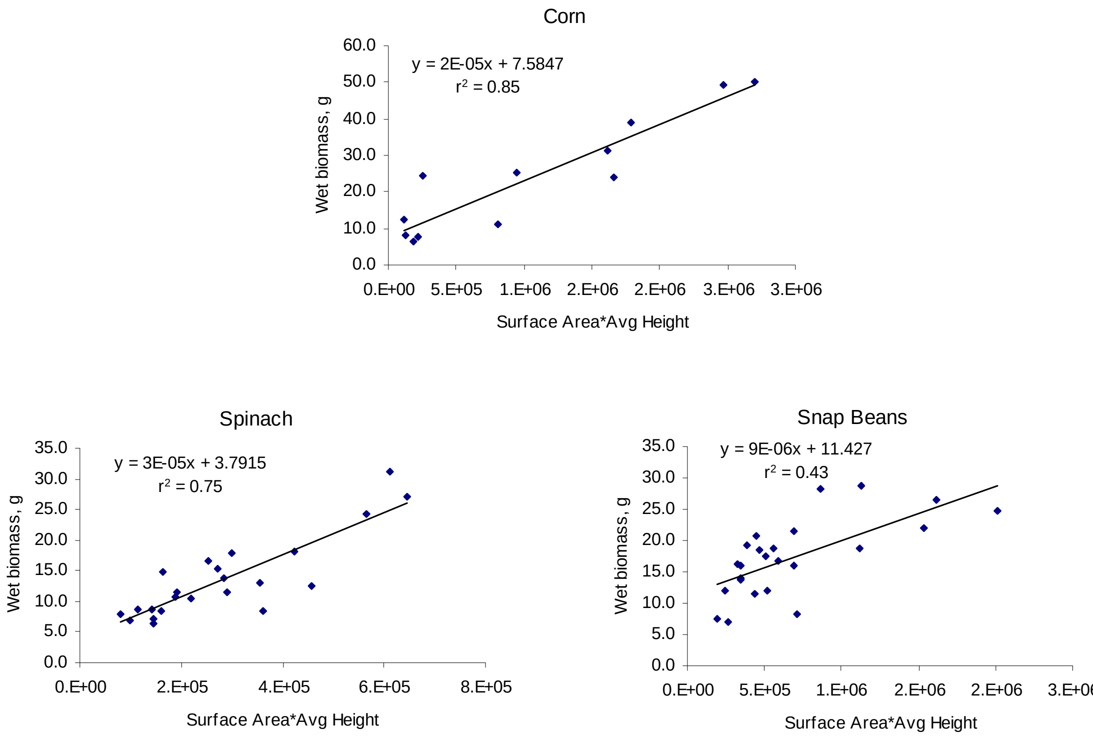

Figure 7. Measured biomass correlated with TVSA*plant average height to estimate biomass

Comparing the product of NDVI and estimated plant volume, found using the estimated height and vegetative coverage, to the weighed wet biomass provided a marginal improvement in the spinach and corn biomass estimates (r^2 = 0.88 and 0.76). There was no improvement in the estimate of biomass in corn and in snap beans. Table 3 summarizes the results of the biomass estimation methods mentioned above.

Table 3. Comparison of biomass estimation methods (coefficients of determination)

	NDVI	NDVI*Max Height	NDVI*Average Height	TVSA*Max Height	TVSA*Average Height	NDVI*TVSA*Max Height	NDVI*TVSA*Average Height
Corn	0.64	0.71	0.72	0.75	**0.85**	0.76	0.82
Spinach	0.78	0.78	0.47	**0.88**	0.76	**0.88**	0.80
Snap Beans	0.15	0.25	0.17	**0.52**	0.43	0.05	0.35

CONCLUSIONS

The product of ultrasonic sensor-based height estimates and top view surface area multispectral image data may provide an adequate estimate of individual plant biomass in corn and spinach (r^2 = 0.85 and 0.88). Coefficients of determination were lower with snap beans (r^2 = 0.52). This method provided an improvement over using NDVI to estimate biomass of single plants; for example: r^2 improved from 0.64 to 0.85 in corn. For corn, the most appropriate biomass estimate was found by using the product of the digital image top view surface area and the average plant height as derived from an ultrasonic distance sensor (r^2 = 0.82). In spinach, the product of the digital image top view surface area, NDVI, and the maximum plant height or the top view surface area and NDVI provided the best estimate (r^2 = 0.88). The product of the digital image top view surface area and the maximum plant height provided the best estimate of biomass in snap beans (r^2 = 0.52).

These positive results indicate that research should include investigation of dry biomass prediction, as well as nitrogen uptake and chlorophyll concentration estimates, using plant volume determined by ultrasonic distance sensing and digital image analysis of vegetation surface area.

REFERENCES

Bausch, W.C., H.R. Duke, and C.J. Iremonger. 1996. Assessment of plant nitrogen in irrigated corn. 3rd International Conference on Precision Agriculture. Minneapolis, MN.

Blackmer, T.M., J. S. Schepers, and G. E. Varvel. 1994. Light reflectance compared with other nitrogen stress measurements in corn leaves. *Agronomy J.* 86:934–938.

Clevers, J.G.P.W. 1988. The derivation of a simplified reflectance model for the estimation of leaf area index. *Remote Sensing of Environment* 25:53-69.

Colwell, J.E. 1973. Bidirectional spectral reflectance of grass canopies for determination of above ground standing biomass. PhD. University of Michigan, Michigan, USA.

Diker, K. 1998. Use of geographic information management systems (GIMS) for nitrogen management. PhD Thesis, Colorado State University, Fort Collins, CO, USA.

Diker, K., and W. C. Bausch. 1998. Mapping in-season soil nitrogen variability assessed through remote sensing. 4th International Conference on Precision Agriculture. St. Paul, MN.

Diker, K., and W.C. Bausch. 2003. Potential use of nitrogen reflectance index to estimate plant parameters and yield of maize. *Biosystems Engineering* 85 (4):437-447.

Guevara, J.C., J.M. Gonnet, and O.R. Estevez. 2002. Biomass Estimation for native perennial grasses in the plain of Mendoza, Argentina. *Journal of Arid Environments* 50:613-619.

Huete, A. R., R.D. Jackson, and D.F. Post. 1985. Spectral response of a plant canopy with different soil backgrounds. *Remote Sensing of Environment* 17:37-53.

Lukina, E.V., M. L. Stone, and W. R. Raun. 1999. Estimating Vegetation Coverage in Wheat Using Digital Images. *J. Plant Nutr*. 22 (2):341-350.

Massa, D.P. 1999. Choosing an ultrasonic sensor for proximity or distance measurement. *Sensors* (February).

Neto, J.C., G. E. Meyer, D. D. Jones, and A. J. Surkan. 2003. Adaptive Image Segmentation using a Fuzzy Neural Network and Genetic Algorithm for Weed Detection. Paper No. 033088. ASAE Annual International Meeting. Las Vegas, NV.

Nitsch, B.B., K. VonBargen, G.E. Meyer, and D. A. Mortensen. 1991. Visible near-infrared plant, soil and crop residue reflectivity for weed sensor design. Paper No. 91-3006. ASAE. St. Joseph, MI.

Peterson, T.A., T.M. Blackmer, D.D. Francis, and J.S. Schepers. 1993. Using a chlorophyll meter to improve N management. Lincoln: Cooperative Extension Institute of Agriculture and Natural Resources, University of Nebraska.

Pordesimo, L.O., W.C. Edens, and S. Sokhansanj. 2004. Distribution of aboveground biomass in corn stover. *Biomass and Bioenergy* 26:337-343.

Price, J.C., and W.C. Bausch. 1995. Leaf area index estimation from visible and near-infrared reflectance data. *Remote Sensing of Environment* 52:55-65.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 1999. In-Season Prediction of Potential Grain Yield in Winter Wheat Using Canopy Reflectance. *Agronomy Journal* 93 (2):131-138.

Reese, G.A., R.L. Bayn, and N.E. West. 1980. Evaluation of double-sampling estimators of subalpine herbage production. *Journal of Range Management* 33:300-306.

Richardson, M.D., D.E. Karcher, and L.C. Purcell. 2001. Quantifying turf grass cover using digital image analysis. *Crop Science* 41:1884-1888.

Rouse, J.W., R.H. Hass, J.A. Schell, D.W. Deering, and J.C. Harlan. 1974. Monitoring the vernal advancement of retrogradation of natural vegetation. Greenbelt, MD.

Ter-Mikaelian, M.T., and W. C. Parker. 2000. Estimating biomass of white spruce seedlings with vertical photo imagery. *New Forests* 20:145-162.

Thenkabail, Prasad S., Ronald B. Smith, and Eddy De Pauw. 2000. Hyperspectral Vegetation Indices and Their Relationships with Agricultural Crop Characteristics. *Remote Sensing of Environment* 71 (2):158-182.

Weckler, P. R., J. B. Solie, M. L. Stone, R. Jayasekara, and C. N. Washmon. 2002. Airborne collection of NDVI data on winter wheat in Oklahoma. Paper No. 021081. ASAE Annual International Meeting. Chicago, IL.

Weckler, P.R., N.O. Maness, C.L. Jones, R. Jayasekara, M.L. Stone, D. Chrz, and T. Kersten. 2003. Remote Sensing to Estimate Chlorophyll Concentration Using Multi-Spectral Plant Reflectance. Paper No. 031115. 2003 ASAE Annual International Meeting. LasVegas, NV.

Wiegand, C.L., A.J. Richardson, and E.T. Kanemasu. 1979. Leaf area index estimates for wheat from Landsat and their implications for evapotranspiration and crop modeling. *Agronomy Journal* 74:677-683.

Yang, C., and L.G. Anderson. 1996. Determining within-field management zones for grain sorghum using aerial videography. 26th International Symposium on Remote Sensing of Environment. Vancouver, BC, Canada.

CHAPTER IV

CHLOROPHYLL ESTIMATION USING MULTI-SPECTRAL REFLECTANCE AND HEIGHT SENSING

ABSTRACT: Chlorophyll concentration relates strongly to the photosynthetic potential of a plant and subsequently to physiological and metabolic status of the plant. Chlorophyll is an indirect indicator of nitrogen status and is used in optical reflectance-based variable rate chemical application technology. This research investigated a non-destructive method of determining chlorophyll content and concentration at the individual plant level in spinach. A multi-spectral imaging system was used to determine spectral reflectance and to estimate top-view surface area. An ultrasonic distance sensor provided vegetation height estimates. Surface area estimates and height data were combined to estimate plant biomass. The relationships between reflectance, estimated biomass, and laboratory measured chlorophyll content and concentration were investigated. The product of biomass estimate and normalized difference vegetative index ($NDVI_{680}$) provided the best estimate of chlorophyll content per plant ($R^2 = 0.91$) while estimates of chlorophyll concentration per unit leaf mass were less accurate ($R^2 = 0.30$).

Keyword: Multispectral, reflectance, NDVI, spinach, biomass, ultrasound, sonar, chlorophyll content, chlorophyll concentration.

INTRODUCTION

Chlorophyll content, which is related to the nitrogen concentration in green vegetation, is significant to managing chemical and fertilizer application as an indicator of photosynthetic activity (Haboudane et al., 2002). Fertilizer in excess of plant needs may result in surface runoff and pollution of lakes and streams (Daughtry et al., 2000; Howarth and Stanwood, 1994). The ability to accurately estimate plant chlorophyll content and concentration may provide growers with valuable information to allow estimation of crop yield potential and to make decisions in nitrogen (N) management. Chlorophyll content (C_{CONT}) is defined as the chlorophyll mass per unit ground surface area or per plant. Chlorophyll concentration (C_{CONC}) is defined as the chlorophyll mass per unit mass of plant material. Both chlorophyll content and concentration provide valuable information about plants. C_{CONT} may be used to evaluate the overall photosynthetic capacity or productivity of the plant canopy. C_{CONC} may be an indicator of plant physiological status or level of stress (Blackburn, 1998a).

Chlorophyll a and b and carotenoids concentrations correlate to the photosynthetic potential of a plant and give some indication of the physiological status of the plant (Danks et al., 1983; Gamon and Surfus, 1999; Young and Britton, 1990). Estimates of pigment concentrations may provide evaluative information about the spatial and temporal dynamics of plant stress (Schepers et al., 1996; Serrano et al., 2000). Researchers have posed many methods of using spectral reflectance at the leaf and canopy levels to detect and quantify pigment contents, particularly chlorophyll and carotenoid contents, in plants. One approach has been to detect the reflectance in individual narrow spectral bands around 680 and 800 nm (Blackburn, 1998a,1998b; Carter and Knapp, 2000; Serrano et al., 2000). Wood, *et al.*(Howarth and Stanwood, 1994) applied transmittance spectrometry to corn plant leaves and used the 430 nm wavelength where transmittance is high and the 750 nm wavelength where transmittance is low to detect chlorophyll a and b in corn. They found strong correlation between chlorophyll measurements and nitrogen concentration. In contrast, Sembiring, *et al.* (Raun, 1998) used reflectance spectrometry and found that indices using wavelengths between 705 and 735 nm and between 505 and 545 nm were good predictors of biomass but not good predictors of nitrogen and phosphorus concentration in winter wheat.

Another approach has been to use spectral indices or ratios that attempt to minimize the effects of background interference, leaf surface interactions and environmental interference (Colwell, 1973; Nitsch et al., 1991; Rouse et al., 1974b; Serrano et al., 2000). Daughtry, *et al.* (2000) considered the effects of background reflectance, chlorophyll concentration, leaf area index (LAI) and their interactions in relationship to the reflectance at 550, 670, 700, and 801 nm, and several indices including the ratios of NIR and red reflectance, NIR and green reflectance, red normalized difference vegetative index (NDVI), green NDVI, modified chlorophyll absorption in reflectance, soil-line vegetation index and optimized soil-line vegetation index in corn to estimate leaf chlorophyll concentration. Analysis of variance was used to assess the fraction of the variation in correlation that could be attributed to background reflectance, chlorophyll concentration, LAI, and the interactions of each independent variable. This research concluded that the ratios of spectral vegetation indices were linearly related to leaf chlorophyll concentration over a wide range of foliage cover and background reflectance. Blackburn *et al.* (Blackburn and Steele, 1999; Blackburn, 2002) concluded that no single spectral approach or selection of wavelengths will have the strongest relationship with pigment concentrations under all circumstances. There is a need to investigate the potential of different approaches in different vegetation types.

Broge and Leblanc (Broge and Leblanc, 2000) considered the capability of broad band and hyperspectral vegetation indices to estimate canopy chlorophyll density and green leaf area index. They concluded that canopy architecture played an important role, along with other external factors, in the usefulness of spectral indices. Pinter, *et al.* (Pinter Jr. et al., 1990) compared satellite, aircraft and ground observations of cultivated soil, cotton, and wheat to investigate the bidirectional reflectance factor of different surfaces. The reflectance factors varied with sensor, target, wavelength interval and viewing and illumination geometry. Percentage cover, the density of biomass, the architectural arrangement of plant parts, and solar zenith and azimuth angles modified reflectance.

Scanning light detection and ranging (LIDAR) instruments have been used to directly measure spatial variations in forest canopy height and other aspects of the canopy vertical structure (Lefsky et al., 1999a; Lefsky et al., 1999b). LIDAR systems estimate the distance between the sensor and an object by measuring the time taken for a burst of laser light to travel from the sensor to the object and back to the sensor (Wehr and Lohr, 1999). LIDAR is typically used onboard an aircraft. Blackburn (Blackburn, 2002) used LIDAR to remove canopy gap areas from images gathered with an airborne spectrographic imaging system and to quantify pigment concentrations per unit leaf mass and per unit ground area for broad-leaved deciduous and coniferous evergreen forests. This study also evaluated the use of LIDAR imagery to increase the accuracy of the imaging system's spectral models. This technique showed promise by improving the relationships between the "red edge" wavelength reflectance and pigment concentrations per unit leaf mass for coniferous trees but less promise with the analysis of deciduous trees.

In an effort to remotely estimate dimensional characteristics, digital imaging processing techniques have been used to determine vegetation coverage (Lukina et al., 1999; Richardson et al., 2001; Ter-Mikaelian and Parker, 2000; Weckler et al., 2003). Multispectral images have also been used not only to determine vegetative coverage, but also to determine normalized difference vegetative index (NDVI). NDVI calculated from these images exhibited strong correlation with NDVI from chlorophyll meters and a reflectance-based sensor (Weckler et al., 2003).

Ultrasonic distance sensors (UDS) have commonly been used for distance measuring and proximity in non-contact applications (Massa, 1999) and in industrial and agricultural storage tank level sensing. UDS emit a burst of sound in the 40 kHz to 250 kHz frequency range and measure the time taken for the sound to travel to an object and back to the sensor. Combined with a multi-spectral imaging system estimate of top view surface area vegetative coverage (Weckler et al., 2003), biomass can be estimated non-destructively at the single plant level (Jones et al., 2004).

Weckler, *et al.* (Weckler et al., 2003) determined that NDVI was strongly correlated with plant biomass, vegetative coverage, and chlorophyll content per unit ground area in spinach (r^2 = 0.94, 0.98, and 0.92, respectively). However, correlation with chlorophyll concentration per unit plant mass was weak (r^2 = 0.38). Kersten (Kersten, 2002) also concluded that the correlation between NDVI and C_{CONC} in spinach was weak. This research included field grown spinach with various fertilizer application rates and plant spacing. The findings of Lukina, *et al.* (Lukina et al., 1999) and Sembiring,*et al.* (Raun, 1998) were confirmed regarding NDVI readings producing a more accurate estimate of C_{CONT} than of C_{CONC}. The studies of Weckler, *et al.* (Weckler et al., 2003) concurred. Strong correlation was found between NDVI and C_{CONC} when plants were segregated by maturity. No global correlation was found and no regression commonalities existed between data at different maturity levels.

Much research has investigated the possibility of assessing chlorophyll concentration using reflectance-based remote sensing. However, little evidence exists for an encompassing technique applicable to a number of plant species. The objectives of this study are to:

- select wavelengths or indices that provide the best estimate of chlorophyll content and concentration in spinach,
- combine estimated plant biomass data with reflectance data from a multi-spectral imaging system to quantify, at single plant level, chlorophyll content and chlorophyll concentration
- assess the feasibility of reflectance-based sensing to estimate chlorophyll concentration in spinach

MATERIALS AND METHODS

Spinach was grown in flats in a greenhouse. Two flats were given no additional post emergence fertilizer, two flats were given fertilizer at the amount recommended to achieve best growth considering the ambient light and temperature conditions, and two flats were given twice the amount of fertilizer used to achieve maximum growth. This fertilizer regime endeavored to provide varying biomass and chlorophyll levels. Water was applied consistently throughout the flats to limit water stress and limit variation due to water stress.

Six weeks after planting, 25 plants were randomly removed from the flats. Each plant placed on a turntable and rotated into the field-of-view of a Senix Ultra-SPA (Bristol, VA) ultrasonic distance sensor (UDS). Turntable diameter was 0.91 m and the turntable was located 1.04 m below the fixed-position sensor (Table 1). UDS data were analyzed according to the procedure outlined in Jones *et al.* (Jones et al., 2004) The UDS was fixed to a stand directly above the turntable. The turntable traveled two rotations at 1.06 rpm. Plant tangential velocity was 3.04 m/min. The sensor triggered a pulse once every millisecond. The conical beam had a total angle view of 12° where signal was greater than 3 db. The test environment temperatures were maintained at 21° ± 2°C. The time between the emitted pulse and the detection of a reflected pulse was converted into a distance measurement by Senix's proprietary software, SoftSpan©. The UDS data were captured and saved as a text file on a laptop computer. The distance between measurements was 1.6 cm.

Table 1. Specifications for Senix Ultra-SPA ultrasonic distance sensor

Environmental Conditions	Wet or high dust
Weight	0.9 kg
Temperature	Automatically compensates, -30 to +70 degrees C
Range	50 cm to 11 m
Transducer	Piezoelectric, 50 kHz
Measurement cycle	Adjustable using SoftSpan© software
Beam Angle	12 degrees nominal @ -3 db, conical
Sensitivity	Adjustable single turn potentiometer
Accuracy	Better than 1% of target distance
Repeatability	Nominal 0.1 % of range
Power	12-30 VDC at 60 ma
Resolution	0.086 mm maximum; 12 bits over spanned distance and full output range 0-10 VDC or 0.20 ma
Communications	Serial RS-232, continuous output

The UDS data were analyzed for each plant to determine the maximum and minimum distances from the sensor. The maximum distance represented the distance to the turntable from the UDS while the minimum distance represented the distance to the tallest point in the plant. The difference between the maximum and minimum distances represented the maximum height of the plant including supporting soil and root area. Height attributed to soil and root area was subtracted to find the maximum height of the vegetative portion of the plant. Hand measurements were taken with a meter stick at 2.5 cm intervals across the profile of the plant to validate the UDS response.

Plants were removed from the turntable and placed under a DuncanTech MS3100 multispectral camera (Auburn, CA) mounted on a tripod at nadir with respect to the plant (Table 2). Plants were illuminated with incandescent lighting. The MS3100 camera was configured to collect irradiance data in three narrow optical bands, 550, 670, and 780 nm ±10 nm full width half maximum (FWHM), which correspond to green, red, and near-infrared bands, respectively. A 14 mm focal length telecentric lens was used which provided sufficient image size to accommodate one plant at a distance of 1 m.

Table 2. Specifications for DuncanTech MS3100 multispectral camera

Imaging Device	3 ea. 1/2in Interline Transfer CCD
Resolution	1392 (H) x 1040 (V) x 3 sensors
Pixel Size	4.65 x 4.65 micron
Pixel Clock and Data Transfer Rate	14.318 MHz max.
Sensing Area	7.6 x 6.2 mm
Frame Rate	7.5 frames per second
Signal/Noise	60 dB
Electronic Shutter	1/8000 – 1/7.5 sec Independent control per channel
Control Input	RS-232 port
Operating Temp	0 – 65 degrees C
Operating Voltage	12 volts
Weight	1.62 kg

Reflectance for each band was obtained using a multi-step reflectance calibration standard (model SRT-XX-050, Labsphere Inc., New Sutton, NH) with nominal reflectance of 10%, 50%, 75%, and 99%. Images were converted into reflectance using the following equations:

$$\rho_{red} = \frac{I_{red}}{I_{red(cal)}}$$
$$\rho_{near\text{-}infrared} = \frac{I_{nir}}{I_{nir(cal)}} \qquad (1)$$

where: I_{red} = reflected red light from the view

I_{nir} = reflected near-infrared light from the view

$I_{red(cal)}$ = reflected red light from the calibration targets

$I_{nir\ (cal)}$ = reflected near-infrared light from the calibration targets

Digital images were acquired and stored on a laptop computer. An NDVI image was generated using reflectance in the red and near-infrared bands as in Equation 2.

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \qquad (2)$$

where: ρ_{NIR} = near-infrared irradiance

ρ_{RED} = red irradiance

The images were analyzed using the image processing toolbox of Matlab™ software (The Math Works, Inc, Natick, MA). The IR and red reflectance pixel values were identified from the multispectral camera images. These values were used to calculate NDVI using Equation 2 above. Each pixel with an NDVI value greater than 0 and less than 0.05 was eliminated to remove soil NDVI from the analysis. The values of the pixels remaining with an NDVI greater than zero represented plant material and were saved in a matrix. Values of pixels that had an NDVI less than zero represented background and were saved in a separate matrix. In the case of a single plant with no soil or plant material in the background, the pixels with a positive NDVI represent only the subject plant with no background interference. The plant material pixel values were averaged to find the average plant NDVI. The image was binarized by assigning a null value to the background pixels and a “one” to the plant material pixels. The vegetation area was calculated using a subroutine from the image processing toolbox applied to the binary image.

After UDS data were collected and the digital images acquired, the vegetative portions of the plants were harvested, weighed, and placed in zippered bags and on ice for transport to the lab. Laboratory chlorophyll analysis were conducted according to Inskeep and Bloom (Inskeep and Bloom, 1985). Data were analyzed using SAS software (SAS, 1999). The following spectral bands, ratios or indices were evaluated as estimators of plant properties (Table 3):

Table 3. Estimators used for investigation comparisons.

Estimator	Equation*
R_{Green}	Reflectance at 550 nm ±10 nm
R_{Red}	Reflectance at 670 nm ±10 nm
R_{NIR}	Reflectance at 780 nm ±10 nm
NIR/RED	Ratio of reflectance at 780 and 670 nm ±10 nm
NIR/GREEN	Ratio of reflectance at 780 and 550 nm ±10 nm
$NDVI_{670}$	$NDVI=\frac{(R_{780}-R_{670})}{(R_{780}+R_{670})} \quad (1)$
$NDVI_{550}$	$NDVI=\frac{(R_{780}-R_{550})}{(R_{780}+R_{550})} \quad (2)$

***Subscript wavelengths represent a bandwidth of ±10 nm.**

Chlorophyll content was defined as:

$$C_{CONT} = C_{CONC} \bullet W \qquad (3)$$

where: C_{CONT} = chlorophyll content (mg/plant)

C_{CONC} = chlorophyll concentration (mg/kg biomass)

W = plant biomass (kg)

Plant biomass was estimated by multiplying the top view surface area derived from the multi-spectral camera images and the plant height estimates from data (Equation 4).

$$W_{EST} = A_{MS} \bullet H_{UDS} \qquad (4)$$

where: W_{EST} = estimated plant biomass

A_{MS} = surface area estimate from camera (pixels)

H_{UDS} = estimated plant height from UDS (cm)

RESULTS

Biomass Estimation

Biomass estimates were found to be strongly correlated with actual plant biomass (wet weight) (R^2 = 0.88) (Figure 1). The linear regression equation from this comparison was used to provide estimated biomass (g/plant) for further reflectance calculations and comparisons.

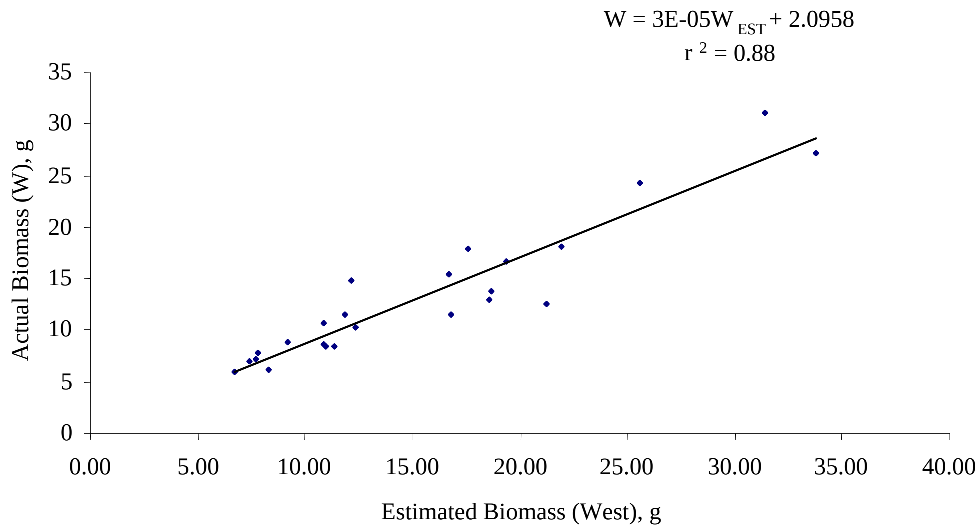

Figure 1. Actual biomass compared to estimated biomass

Chlorophyll Content (C_{CONT})

Reflectance values at 550, 670, and 780 nm were used to derive the ratios and indices listed in Table 2.3. Ratios and the reflectance at 550, 670, and 780 nm were compared to the laboratory-determined C_{CONT} (Table 4). $NDVI_{670}$ provided the strongest correlation with C_{CONT} with an R^2 of 0.75 (Figure 2).

Table 4. Comparison of actual plant properties to plant property estimator.

Estimator	**Coefficients of Determination (R^2)***		
	Chlorophyll Content (mg/plant) vs. estimator	**Chlorophyll Content vs. estimator • biomass estimate**	**Actual Chlorophyll Concentration (mg/kg) vs. Chlorophyll Concentration estimate**
R_{Green}	0.21	0.87	0.01
R_{Red}	0.10	0.86	0.01
R_{NIR}	0.58	0.90	0.10
NIR/RED	0.15	0.90	0.28
NIR/GREEN	0.05	0.89	0.30
$NDVI_{670}$	0.75	0.91	0.03
$NDVI_{550}$	0.40	0.89	0.25

*All linear regressions were statistically significant, $p<0.01$

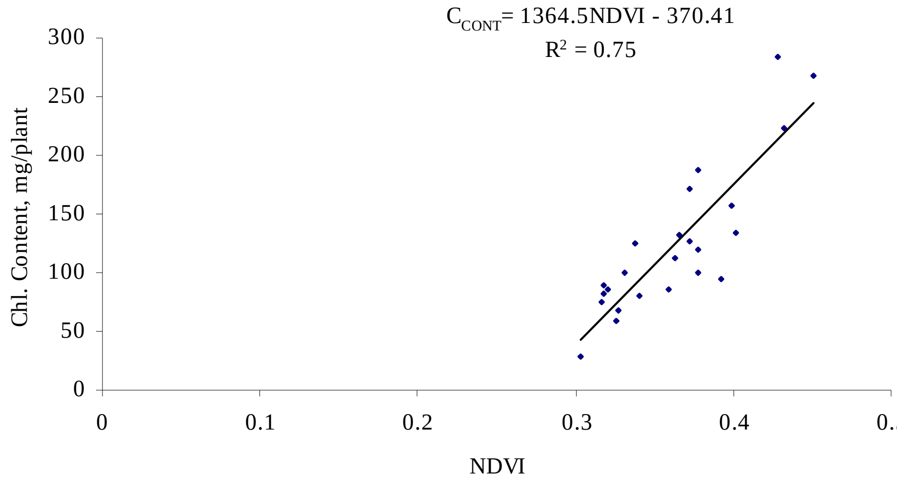

Figure 2. Actual chlorophyll content, mg/plant compared to $NDVI_{670}$.

$NDVI_{670}$ was divided by the biomass estimates as suggested by Kersten's research (Kersten, 2002). Little improvement resulted in the correlation with C_{CONT} (R^2 = 0.76). When $NDVI_{670}$ was multiplied by the biomass estimates, correlation with C_{CONT} improved (R^2 = 0.91). Each of the ratios was multiplied by the biomass estimates (Table 4). While each correlation strengthened, $NDVI_{670}$ was the most effective at estimating C_{CONT} (Figure 3).

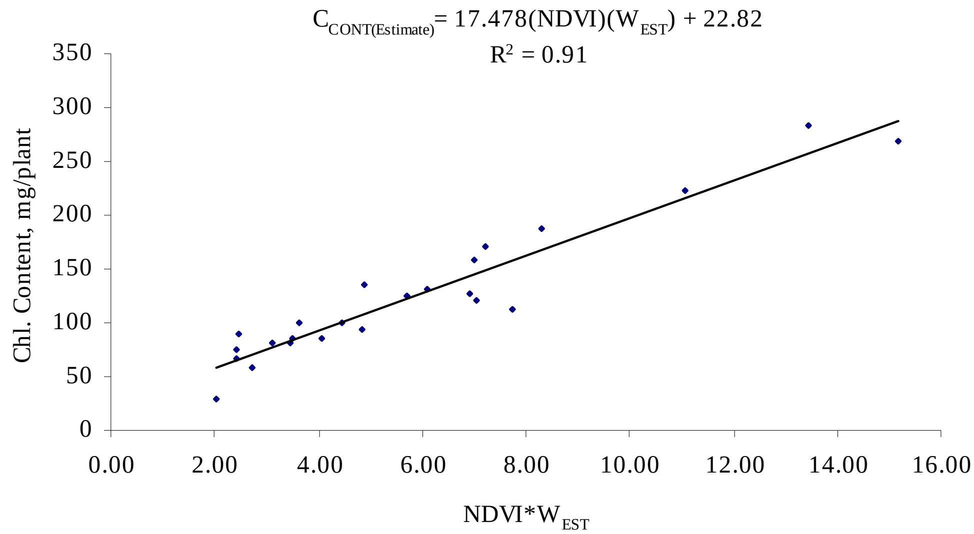

Figure 3. Actual chlorophyll content, mg/plant, compared to the product of $NDVI_{670}$ and biomass estimates.

Chlorophyll Concentration (C_{CONC})

$C_{CONT(Estimate)}$ was calculated using the linear regression equation for each of the ratios or bands. Substituting $C_{CONT(Estimate)}$ for C_{CONT}, Equation 3 was used to calculate $C_{CONC(Estimate)}$. These estimates were compared to the laboratory data for C_{CONC} (Table 4). The strongest correlation was found using $C_{CONT(Estimate)}$ from NIR/Green data ($R^2 = 0.30$) (Figure 4). This correlation might be conversely interpreted as suggesting chlorophyll concentration is responsible for reducing 30 percent of the variation in the NIR/Green reflectance ratio and other factors are responsible for the remaining 70 percent of the variation in the regression. This data suggests that chlorophyll concentration plays a smaller role in the regression of the spectral indices and ratios considered in this research when compared to other factors such as biomass. Because of the minimal response to chlorophyll concentration, other methods of plant property estimation such as fluorometric chlorophyll analysis may be more appropriate in estimating subtle differences in chlorophyll concentration.

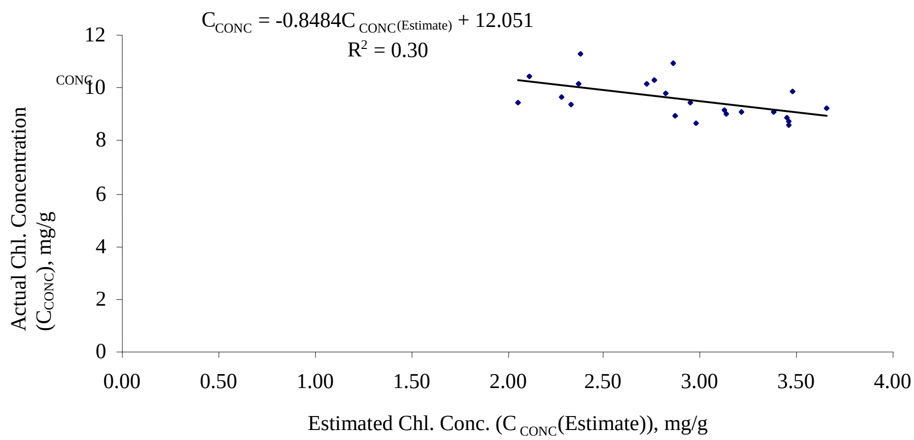

Figure 4. Actual plant chlorophyll concentration, mg/g, compared to estimated chlorophyll concentration.

Conclusion

- $NDVI_{670}$ multiplied by estimated biomass appears to provide the best estimate of chlorophyll content in spinach (R^2 =0.91) of the indices tested in this study.
- Multiplying reflectance ratios and indices by estimated biomass improved chlorophyll content estimations, mg/plant (increasing R^2 from 0.75 to 0.91 for $NDVI_{670}$).
- Reflectance-based remote sensing may not be the best method for estimating the plant pigment concentrations (chlorophyll a and b). Chlorophyll concentration, mg/kg, showed weak correlation with all considered reflectance indices and ratios. These results concur with Weckler (2003), Kersten (1999), Blackburn

(1999, 2002), and Sembiring (1998). Although still a weak estimation of chlorophyll concentration, NIR/Green showed the strongest correlation with an R^2 of 0.30.

References

Blackburn, G. A. 1998a. Quantifying chlorophylls and carotenoids from leaf to canopy scales: an evaluation of some hyper-spectral approaches. *Remote Sensing of Environment* 66:273-285.

Blackburn, G. A. 1998b. Spectral indices for estimating photosynthetic pigment concentrations: a test using senescent tree leaves. *Int. J. Remote Sens.* 19:657-675.

Blackburn, G. A., and C. M. Steele. 1999. Towards the remote sensing of Matorral vegetation physiology: relationships between spectral reflectance, pigment, and biophysical characteristics of semiarid bushland canopies. *Remote Sensing of Environment* 70:278-292.

Blackburn, George Alan. 2002. Remote sensing of forest pigments using airborne imaging spectrometer and LIDAR imagery. *Remote Sensing of Environment* 82 (2-3):311-321.

Broge, N. H., and E. Leblanc. 2000. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. *Remote Sensing of Environment* 76:156-172.

Carter, G.A., and A.K. Knapp. 2000. Leaf optical properties in higher plants: linking spectral characteristics to stress and chlorophyll concentration. *American Journal of Botany* 88 (4):677-684.

Colwell, J.E. 1973. Bidirectional spectral reflectance of grass canopies for determination of above ground standing biomass. PhD., University of Michigan, Michigan, USA.

Danks, S. M., E. H. Evans, and P.A. Whittaker. 1983. Structure Function and Assembly. In *Photosynthetic Systems*. New York: Wiley.

Daughtry, C. S. T., C. L. Walthall, M. S. Kim, E. Brown de Colstoun, and J. E. McMurtreyIII. 2000. Estimating Corn Leaf Chlorophyll Concentration from Leaf and Canopy Reflectance. *Remote Sensing of Environment* 74 (2):229-239.

Gamon, J. A., and J. S. Surfus. 1999. Assessing leaf pigment content and activity with a reflectometer. *New Phytologist* 143:105-117.

Haboudane, D., J.R. Miller, N. Tremblay, P.J. Zarco-Tejada, and L. Dextraze. 2002. Integrated narrow-band vegetation indices for prediction of cropy chlorophyll content for application to preceision agriculture. *Remote Sens. Environ.* 81 (2002):416-426.

Howarth, M.S., and P.C. Stanwood. 1994. Extracting 3-D information using 2-D images of seeds. *Computers and Electronics in Agriculture* 10 (1994):175-188.

Inskeep, W. P., and P. R. Bloom. 1985. Extinction coefficients of chlorophyll *a* and *b* in N, N-dimethylformamide and 80% Acetone. *Plant Physiology* 77:483-485.

Jones, C.L., N.O. Maness, M.L. Stone, and R. Jayasekara. 2004. Sonar and Digital Imagery for Estimating Crop Biomass. Paper No. 043061. ASAE/CSAE Annual International Meeting. Ottawa, Ontario, Canada.

Kersten, T. D. 2002. Remote sensing based method for estimating chlorophyll concentration in spinach. Masters, Biosystems and Ag. Engineering, Oklahoma State University, Stillwater.

Lefsky, M. A., W. B. Cohen, S. A. Acker, G. G. Parker, T. A. Spies, and D. Harding. 1999a. Lidar Remote Sensing of the Canopy Structure and Biophysical Properties of Douglas-Fir Western Hemlock Forests. *Remote Sensing of Environment* 70 (3):339-361.

Lefsky, M. A., D. Harding, G. G. Parker, and H. H. Shugart. 1999b. Lidar remote sensing of forest canopy and stand attributes. *Remote Sens. Environ.* 67:83-98.

Lukina, E.V., M. L. Stone, and W. R. Raun. 1999. Estimating Vegetation Coverage in Wheat Using Digital Images. *J. Plant Nutr.* 22 (2):341-350.

Massa, D.P. 1999. Choosing an ultrasonic sensor for proximity or distance measurement. *Sensors* (February).

Nitsch, B.B., K. VonBargen, G.E. Meyer, and D. A. Mortensen. 1991. Visible near-infrared plant, soil and crop residue reflectivity for weed sensor design. Paper No. 91-3006. ASAE. St. Joseph, MI.

Pinter Jr., P. J., R. D. Jackson, and M. S. Moran. 1990. Bidirectional reflectance factors of agricultural targets: a comparison of ground-c aircraft- and satellite-based observations. *Remote Sens. Environ.* 32:215-228.

Raun, W.R., G.V. Johnson, H. Sembiring, E.V. Lukina, J.M. LaRuffa, W.E. Thomason, S.B. Phillips, J.B. Solie, M.L. Stone and R.W. Whitney. 1998. Indirect measure of plant nutrients. *Commun. In Soil Sci. Plant Anal.* 29:1571-1581.

Richardson, M.D., D.E. Karcher, and L.C. Purcell. 2001. Quantifying turfgrass cover using digital image analysis. *Crop Science* 41:1884-1888.

Rouse, J.W., R.H. Hass, J.A. Schell, D.W. Deering, and J.C. Harlan. 1974. Monitoring the vernal advancement of retrogradation of natural vegetation.*NASA/GSFC*. Greenbelt, MD.

SAS/STAT Procedures Release 8.02. Statistical Analysis System Institute, Cary, N. Carolina.

Schepers, J. S., T. M. Blackmer, W. W. Wilhelm, and M. Resende. 1996. Transmittance and reflectance measurement of corn leaves from plants with different nitrogen and water supply. *J. Plant Physiol.* 148:523-529.

Serrano, L., I. Filella, and J. Penuelas. 2000. Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. *Crop Science* 40 (May-June):723-731.

Ter-Mikaelian, M.T., and W. C. Parker. 2000. Estimating biomass of white spruce seedlings with vertical photo imagery. *New Forests* 20:145-162.

Weckler, P.R., N.O. Maness, C.L. Jones, R. Jayasekara, M.L. Stone, D. Chrz, and T. Kersten. 2003. Remote Sensing to Estimate Chlorophyll Concentration Using Multi-Spectral Plant Reflectance. Paper No. 031115. 2003 ASAE Annual International Meeting. LasVegas, NV.

Wehr, A., and U. Lohr. 1999. Airborne Laser Scanning - an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing* 54:68-82.

Young, A., and G. Britton. 1990. Carotenoids and stress. In *Stress Responses in Plants: Adaptation and Acclimation Mechanisms*. R. G. Alscher and J. R. Cumming. New York: Wiley-Liss.

CHAPTER V

CONCLUSION

This research involving the non-destructive estimation of plant physical and physiological characteristics *in situ* considered three distinct methods: reflectance-based sensing, ultra-sound distance sensing, and radiofrequency wave interaction with plant dielectric properties. Each method exhibited strengths when applied appropriately and challenges for future sensor development.

Radiofrequency wave interaction in the middle frequency range (300 to 3,000 kHz) was tested using a free-space plate antenna system and greenhouse-grown spinach as biomaterial. This sensing system design was essentially a parallel plate capacitor with the space between the plate antennae acting as the dielectric capacitive material. The change in the dielectric constant of this space was correlated with the moisture content of the biomaterial since water has a large dielectric constant compared to dry biomaterial. The dielectric response due to a change in water content is remarkable when compared to changes in dry biomaterial. However, knowing the gross moisture content range for a crop facilitated the estimation of dry biomass from sensing the amount of water content in the space. Two sizes of aluminum plate antennae were tested, 12.7 cm x 12.7 cm x 0.32 cm and 30.5 cm x 30.5 cm x 0.32 cm. The height and separation distances were estimated using finite element modeling software. Response of the original design was observed using finite element analysis. Laboratory testing using spinach as a test crop indicated the 30.5 cm square plate antennae responded with a higher level of accuracy when estimating water content. The response was significant with a coefficient of determination of 0.95 for a linear response. The data for all tests indicated a fourth order response which concurs with other cited research. The non-linear correlation improved the coefficient of determination to 0.97 when estimating water content using the larger plates.

Development of a portable unit would be particularly valuable and the system should be tested in production fields. An anticipated challenge is interference from surrounding biomaterial. The size and placement of the plate antennae should be specific for the biomaterial considered. Future research in this area should include testing the system using other crops such as corn with a different plant structure. This research should also be extended to include harvested products such as grain and seeds and value-added packaged products such as herbs and nutraceutical extractions. It is expected that this technology may be used to identify pest infestation in stored products.

This would reduce some of the processing time in determining a plant height profile. Also, a laser beam may provide more accuracy than ultrasound because of the small beam divergence (typically < 1 mrad half angle) compared to the sonic beam of the ultrasound unit (< 8 deg half angle??).

Ultrasonic distance sensors provided estimates of plant height. These estimates, combined with top surface area estimates from a multispectral imaging system, provided strong correlation with biomass, kg/plant, in spinach and corn but weaker correlation in snap beans. Beans presented a challenge for the system because stems make up approximately 50 percent of the plant’s weight but much less of the surface area. Future research in this area should include the use of an ultrasound sensor with a smaller beam divergence angle. Also, a laser beam may provide more accuracy than ultrasound because of the small beam divergence compared to the sonic beam of the ultrasound unit.

Additionally, multispectral imaging requires a finite processing time after the image is acquired. Therefore, future research should propose a method of on-the-go image processing that would include the height information from the ultrasound unit or laser beam reflection with the binarized pixel count of the image to estimate plant biomass. In the case of viney plants such as beans, this method might be successful with the integration of a weighted neural network to assign more weight to areas with small pixel counts for the stems and less weight to the large pixel count areas for the leaves.

Each of the above methods provided strong correlations with biomass. The radiofrequency method has the added advantages of not being geometry sensitive at the medium frequency range considered in this research and the stacked arrangement of leaves does not confound the results. The disadvantage compared to ultrasound and multispectral sensing is that any water present on the exterior of the sample material will have a larger influence on the results.

The combination of the biomass estimate from the ultrasound and multispectral imaging systems and NDVI calculated from the imaging system data provided strong correlation with chlorophyll content in spinach. However, the estimate of chlorophyll concentration was weaker. Reflectance-based sensing using ambient light may not be sensitive enough to respond to subtle changes in chlorophyll concentration. A scanning laser beam light source may provide more sensitive estimates in future research. Combining the dimensional estimates with NDVI did improve the estimation of chlorophyll content compared to past research results using only NDVI calculations.

A summary of suggested future research in these areas includes:

Radiofrequency system:

- Test other plants such as corn with the existing system
- Construct field-ready system and test in crop production fields
- Test on harvested grain and seed to estimate moisture content and pest infestation.
- Test on moving biomaterials such as grain or seedlings on a conveyor.

Ultrasound and imaging system to estimate biomass:

- Consider the use of narrow beam ultrasound or laser beam to determine plant height.
- Develop immediate response imaging processing software that integrates height estimates with binarized pixel count from the image.

Ultrasound and imaging system to estimate chlorophyll content and concentration:

- Consider the use of scanning laser beam to estimate plant dimensions and calculate NDVI.
- Include ultrasound or laser distance estimation with existing reflectance-based sensing equipment for variable rate technology.
- Consider use of a light transmittance system for chlorophyll concentration estimation instead of a reflectance based system.

While many areas of research showed promise, the most fertile area for future research consideration is the use of radiofrequency to determine specific quality characteristics or indicators in biomaterial because of its independence of geometry and spectral reflectance properties, its ability to consider interlaced or stacked sample material, and its ability to provide immediate results from large or multiple samples without requiring extensive data processing.

APPENDIX A

ELECTROSTATIC FREE-SPACE SENSOR

KNOWN WATER WEIGHT SENSOR RESPONSE

30.5 CM X 30.5 CM PLATE ANTENNAE

0.3 TO 1.1 MHZ

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.3	-72.593	-72.585	-72.605	-72.594	-72.569
0.301	-72.583	-72.596	-72.576	-72.511	-72.564
0.302	-72.584	-72.59	-72.639	-72.615	-72.584
0.303	-72.56	-72.603	-72.581	-72.673	-72.579
0.304	-72.624	-72.585	-72.632	-72.725	-72.577
0.305	-72.525	-72.501	-72.485	-72.483	-72.579
0.306	-72.508	-72.561	-72.545	-72.412	-72.555
0.307	-72.437	-72.547	-72.496	-72.512	-72.563
0.308	-72.47	-72.457	-72.474	-72.531	-72.476
0.309	-72.447	-72.482	-72.526	-72.455	-72.482
0.31	-72.481	-72.49	-72.483	-72.496	-72.566
0.311	-72.391	-72.45	-72.481	-72.44	-72.477
0.312	-72.44	-72.476	-72.449	-72.455	-72.449
0.313	-72.519	-72.409	-72.381	-72.479	-72.406
0.314	-72.348	-72.39	-72.489	-72.465	-72.362
0.315	-72.393	-72.322	-72.332	-72.428	-72.474
0.316	-72.326	-72.313	-72.374	-72.457	-72.396
0.317	-72.277	-72.317	-72.385	-72.367	-72.377
0.318	-72.297	-72.291	-72.354	-72.45	-72.373
0.319	-72.299	-72.36	-72.358	-72.359	-72.312
0.32	-72.236	-72.365	-72.305	-72.324	-72.345
0.321	-72.25	-72.291	-72.255	-72.252	-72.312
0.322	-72.28	-72.273	-72.277	-72.3	-72.322
0.323	-72.293	-72.299	-72.249	-72.297	-72.317
0.324	-72.188	-72.299	-72.289	-72.287	-72.321
0.325	-72.209	-72.22	-72.312	-72.217	-72.254
0.326	-72.204	-72.194	-72.259	-72.203	-72.259
0.327	-72.236	-72.205	-72.232	-72.234	-72.21
0.328	-72.216	-72.114	-72.196	-72.301	-72.241
0.329	-72.087	-72.143	-72.179	-72.21	-72.136
0.33	-72.125	-72.185	-72.167	-72.189	-72.191
0.331	-72.151	-72.127	-72.135	-72.114	-72.199
0.332	-72.124	-72.125	-72.054	-72.165	-72.174
0.333	-72.14	-72.078	-72.092	-72.079	-72.128
0.334	-72.113	-72.093	-72.011	-72.031	-72.113
0.335	-72.112	-72.127	-72.056	-72.111	-72.087
0.336	-72.072	-72.127	-72.074	-72.079	-72.163
0.337	-72.052	-72.045	-71.993	-72.04	-72.129
0.338	-72.043	-72.046	-72.044	-72.132	-72.069
0.339	-72.016	-72.03	-72.044	-71.965	-72.083
0.34	-71.962	-71.98	-72.045	-72.102	-72.077
0.341	-71.93	-72.06	-71.97	-71.957	-72.007
0.342	-72.001	-71.992	-71.918	-72.025	-72.039
0.343	-71.936	-71.951	-71.996	-71.996	-72.02
0.344	-71.968	-71.973	-71.99	-72	-71.931

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.345	-71.895	-71.937	-71.984	-71.988	-72.051
0.346	-71.91	-71.94	-71.935	-71.907	-71.981
0.347	-71.913	-71.932	-72.015	-71.944	-71.936
0.348	-71.897	-71.867	-71.883	-71.953	-71.951
0.349	-71.874	-71.921	-71.921	-71.953	-71.918
0.35	-71.86	-71.88	-71.872	-71.917	-71.963
0.351	-71.881	-71.907	-71.872	-71.795	-71.903
0.352	-71.848	-71.876	-71.881	-71.895	-71.811
0.353	-71.833	-71.835	-71.841	-71.853	-71.899
0.354	-71.868	-71.831	-71.833	-71.793	-71.917
0.355	-71.798	-71.846	-71.821	-71.876	-71.878
0.356	-71.778	-71.834	-71.858	-71.807	-71.828
0.357	-71.785	-71.807	-71.774	-71.864	-71.801
0.358	-71.734	-71.795	-71.759	-71.78	-71.77
0.359	-71.753	-71.785	-71.784	-71.729	-71.806
0.36	-71.752	-71.778	-71.741	-71.778	-71.778
0.361	-71.748	-71.705	-71.788	-71.752	-71.801
0.362	-71.753	-71.693	-71.764	-71.739	-71.795
0.363	-71.745	-71.745	-71.705	-71.771	-71.774
0.364	-71.744	-71.758	-71.688	-71.726	-71.704
0.365	-71.648	-71.691	-71.714	-71.757	-71.754
0.366	-71.725	-71.703	-71.682	-71.692	-71.739
0.367	-71.646	-71.706	-71.636	-71.722	-71.684
0.368	-71.615	-71.663	-71.838	-71.628	-71.61
0.369	-71.669	-71.641	-71.634	-71.688	-71.637
0.37	-71.574	-71.603	-71.607	-71.596	-71.66
0.371	-71.586	-71.625	-71.646	-71.703	-71.605
0.372	-71.585	-71.623	-71.584	-71.653	-71.577
0.373	-71.581	-71.518	-71.59	-71.581	-71.641
0.374	-71.594	-71.597	-71.603	-71.606	-71.632
0.375	-71.516	-71.558	-71.552	-71.51	-71.591
0.376	-71.503	-71.517	-71.6	-71.594	-71.577
0.377	-71.526	-71.526	-71.548	-71.542	-71.547
0.378	-71.509	-71.491	-71.492	-71.589	-71.555
0.379	-71.537	-71.544	-71.454	-71.507	-71.541
0.38	-71.541	-71.518	-71.477	-71.506	-71.555
0.381	-71.545	-71.536	-71.484	-71.555	-71.477
0.382	-71.439	-71.5	-71.448	-71.497	-71.535
0.383	-71.512	-71.493	-71.505	-71.499	-71.489
0.384	-71.481	-71.485	-71.485	-71.482	-71.501
0.385	-71.477	-71.484	-71.557	-71.464	-71.575
0.386	-71.416	-71.49	-71.492	-71.47	-71.486
0.387	-71.375	-71.419	-71.373	-71.434	-71.495
0.388	-71.437	-71.476	-71.413	-71.498	-71.453
0.389	-71.397	-71.438	-71.448	-71.413	-71.483
0.39	-71.364	-71.383	-71.395	-71.432	-71.411

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.391	-71.412	-71.395	-71.397	-71.426	-71.443
0.392	-71.392	-71.358	-71.392	-71.404	-71.371
0.393	-71.376	-71.302	-71.335	-71.409	-71.416
0.394	-71.351	-71.414	-71.345	-71.371	-71.423
0.395	-71.308	-71.33	-71.31	-71.373	-71.38
0.396	-71.318	-71.327	-71.386	-71.36	-71.445
0.397	-71.304	-71.34	-71.289	-71.329	-71.341
0.398	-71.327	-71.327	-71.322	-71.331	-71.368
0.399	-71.312	-71.356	-71.341	-71.288	-71.333
0.4	-71.335	-71.353	-71.353	-71.295	-71.287
0.401	-71.244	-71.197	-71.246	-71.341	-71.24
0.402	-71.294	-71.338	-71.351	-71.317	-71.26
0.403	-71.265	-71.249	-71.404	-71.309	-71.27
0.404	-71.29	-71.25	-71.194	-71.197	-71.288
0.405	-71.198	-71.202	-71.237	-71.284	-71.241
0.406	-71.165	-71.202	-71.164	-71.182	-71.256
0.407	-71.246	-71.201	-71.3	-71.256	-71.206
0.408	-71.266	-71.239	-71.21	-71.189	-71.23
0.409	-71.165	-71.195	-71.22	-71.242	-71.215
0.41	-71.126	-71.104	-71.255	-71.202	-71.233
0.411	-71.236	-71.165	-71.137	-71.203	-71.184
0.412	-71.127	-71.151	-71.226	-71.219	-71.16
0.413	-71.137	-71.185	-71.162	-71.242	-71.208
0.414	-71.145	-71.147	-71.168	-71.158	-71.19
0.415	-71.151	-71.176	-71.149	-71.142	-71.151
0.416	-71.166	-71.132	-71.126	-71.218	-71.191
0.417	-71.118	-71.151	-71.142	-71.055	-71.1
0.418	-71.159	-71.112	-71.168	-71.103	-71.183
0.419	-71.052	-71.135	-71.126	-71.101	-71.138
0.42	-71.108	-71.11	-71.092	-71.108	-71.122
0.421	-71.031	-71.111	-71.115	-71.062	-71.084
0.422	-71.055	-71.047	-71.116	-71.119	-71.149
0.423	-71.06	-71.067	-71.081	-71.12	-71.058
0.424	-71.104	-71.037	-71.028	-71.099	-71.115
0.425	-70.993	-71.04	-71.067	-71.076	-71.16
0.426	-71.043	-71.076	-71.107	-71.063	-71.02
0.427	-71.035	-71.055	-70.984	-71.071	-71.063
0.428	-71.053	-71.017	-71.004	-71.002	-71.107
0.429	-71.041	-70.992	-71.063	-71.068	-71.112
0.43	-70.972	-70.984	-70.987	-71.031	-71.12
0.431	-70.98	-70.943	-71.037	-70.995	-71.046
0.432	-71.009	-71.004	-71.018	-71.033	-71.052
0.433	-70.97	-71.012	-71.003	-70.983	-71.009
0.434	-70.928	-70.999	-71.023	-70.953	-70.989
0.435	-70.961	-70.972	-70.994	-70.977	-70.981
0.436	-70.96	-70.97	-70.969	-70.922	-71.02
0.437	-70.936	-70.944	-70.989	-70.954	-70.967

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.438	-70.935	-70.932	-70.987	-70.955	-70.961
0.439	-70.911	-70.88	-70.95	-70.943	-70.914
0.44	-70.975	-70.945	-71.029	-70.937	-70.917
0.441	-70.928	-70.923	-70.96	-70.961	-70.948
0.442	-70.923	-70.907	-70.918	-70.885	-70.936
0.443	-70.917	-70.907	-70.891	-70.942	-70.943
0.444	-70.915	-70.881	-70.897	-70.915	-70.905
0.445	-70.934	-70.929	-70.869	-70.873	-70.919
0.446	-70.886	-70.939	-70.912	-70.891	-70.884
0.447	-70.908	-70.841	-70.888	-70.843	-70.917
0.448	-70.825	-70.926	-70.815	-70.879	-70.782
0.449	-70.862	-70.853	-70.906	-70.819	-70.935
0.45	-70.87	-70.848	-70.841	-70.901	-70.857
0.451	-70.818	-70.844	-70.896	-70.853	-70.807
0.452	-70.808	-70.828	-70.866	-70.895	-70.876
0.453	-70.772	-70.839	-70.872	-70.857	-70.867
0.454	-70.803	-70.847	-70.801	-70.797	-70.884
0.455	-70.794	-70.808	-70.872	-70.872	-70.823
0.456	-70.823	-70.814	-70.74	-70.818	-70.745
0.457	-70.776	-70.768	-70.818	-70.815	-70.826
0.458	-70.766	-70.785	-70.741	-70.797	-70.845
0.459	-70.788	-70.793	-70.796	-70.794	-70.783
0.46	-70.848	-70.788	-70.856	-70.852	-70.801
0.461	-70.788	-70.769	-70.862	-70.768	-70.848
0.462	-70.751	-70.776	-70.741	-70.771	-70.775
0.463	-70.771	-70.763	-70.833	-70.8	-70.75
0.464	-70.716	-70.787	-70.787	-70.774	-70.781
0.465	-70.719	-70.798	-70.77	-70.729	-70.816
0.466	-70.715	-70.697	-70.711	-70.681	-70.747
0.467	-70.72	-70.728	-70.766	-70.711	-70.735
0.468	-70.73	-70.724	-70.702	-70.754	-70.723
0.469	-70.69	-70.663	-70.711	-70.738	-70.747
0.47	-70.742	-70.698	-70.753	-70.774	-70.736
0.471	-70.696	-70.71	-70.682	-70.675	-70.721
0.472	-70.711	-70.69	-70.685	-70.678	-70.669
0.473	-70.709	-70.695	-70.673	-70.66	-70.758
0.474	-70.679	-70.671	-70.695	-70.772	-70.77
0.475	-70.68	-70.619	-70.672	-70.682	-70.71
0.476	-70.669	-70.663	-70.636	-70.651	-70.715
0.477	-70.669	-70.631	-70.66	-70.663	-70.684
0.478	-70.595	-70.645	-70.636	-70.673	-70.729
0.479	-70.635	-70.62	-70.657	-70.656	-70.628
0.48	-70.608	-70.674	-70.64	-70.658	-70.689
0.481	-70.616	-70.555	-70.674	-70.617	-70.634
0.482	-70.584	-70.628	-70.599	-70.628	-70.623
0.483	-70.531	-70.598	-70.634	-70.571	-70.611
0.484	-70.584	-70.63	-70.613	-70.611	-70.641

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
0.485	-70.584	-70.559	-70.594	-70.532	-70.591
0.486	-70.576	-70.584	-70.563	-70.59	-70.61
0.487	-70.58	-70.583	-70.597	-70.65	-70.63
0.488	-70.554	-70.544	-70.494	-70.591	-70.606
0.489	-70.579	-70.562	-70.602	-70.585	-70.607
0.49	-70.511	-70.577	-70.59	-70.561	-70.592
0.491	-70.518	-70.555	-70.592	-70.553	-70.583
0.492	-70.496	-70.499	-70.557	-70.565	-70.551
0.493	-70.543	-70.513	-70.501	-70.52	-70.532
0.494	-70.486	-70.563	-70.539	-70.519	-70.588
0.495	-70.513	-70.535	-70.453	-70.499	-70.555
0.496	-70.472	-70.521	-70.53	-70.554	-70.543
0.497	-70.464	-70.504	-70.461	-70.541	-70.512
0.498	-70.448	-70.504	-70.507	-70.498	-70.568
0.499	-70.470	-70.459	-70.538	-70.506	-70.543
0.5	-70.455	-70.465	-70.505	-70.488	-70.497
0.501	-68.753	-68.721	-68.77	-68.82	-68.79
0.502	-68.733	-68.735	-68.777	-68.723	-68.81
0.503	-68.725	-68.795	-68.738	-68.786	-68.769
0.504	-68.729	-68.727	-68.699	-68.724	-68.741
0.505	-68.715	-68.718	-68.721	-68.758	-68.758
0.506	-68.726	-68.641	-68.681	-68.739	-68.726
0.507	-68.743	-68.695	-68.7	-68.699	-68.681
0.508	-68.683	-68.652	-68.686	-68.645	-68.726
0.509	-68.671	-68.669	-68.667	-68.637	-68.688
0.51	-68.649	-68.676	-68.645	-68.634	-68.709
0.511	-68.605	-68.673	-68.607	-68.652	-68.685
0.512	-68.663	-68.599	-68.668	-68.622	-68.677
0.513	-68.662	-68.589	-68.598	-68.654	-68.644
0.514	-68.61	-68.604	-68.592	-68.629	-68.651
0.515	-68.579	-68.613	-68.638	-68.631	-68.642
0.516	-68.572	-68.576	-68.568	-68.613	-68.608
0.517	-68.53	-68.568	-68.559	-68.555	-68.565
0.518	-68.558	-68.583	-68.589	-68.586	-68.611
0.519	-68.536	-68.518	-68.51	-68.544	-68.606
0.52	-68.522	-68.545	-68.555	-68.549	-68.655
0.521	-68.526	-68.516	-68.525	-68.505	-68.558
0.522	-68.559	-68.556	-68.559	-68.563	-68.558
0.523	-68.509	-68.552	-68.5	-68.549	-68.535
0.524	-68.504	-68.493	-68.511	-68.501	-68.552
0.525	-68.487	-68.48	-68.521	-68.516	-68.511
0.526	-68.45	-68.498	-68.536	-68.447	-68.517
0.527	-68.448	-68.509	-68.49	-68.499	-68.517
0.528	-68.47	-68.525	-68.549	-68.458	-68.558
0.529	-68.475	-68.45	-68.47	-68.435	-68.458
0.53	-68.434	-68.45	-68.463	-68.452	-68.503
0.531	-68.46	-68.457	-68.454	-68.45	-68.459
0.532	-68.391	-68.427	-68.417	-68.459	-68.466

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.533	-68.394	-68.437	-68.376	-68.373	-68.441
0.534	-68.397	-68.353	-68.432	-68.392	-68.423
0.535	-68.384	-68.425	-68.423	-68.435	-68.455
0.536	-68.35	-68.422	-68.378	-68.415	-68.422
0.537	-68.369	-68.423	-68.405	-68.364	-68.414
0.538	-68.36	-68.383	-68.375	-68.383	-68.414
0.539	-68.328	-68.362	-68.309	-68.399	-68.369
0.54	-68.299	-68.333	-68.396	-68.369	-68.35
0.541	-68.356	-68.28	-68.325	-68.331	-68.367
0.542	-68.295	-68.296	-68.346	-68.349	-68.345
0.543	-68.307	-68.372	-68.391	-68.314	-68.379
0.544	-68.302	-68.309	-68.318	-68.293	-68.36
0.545	-68.311	-68.305	-68.324	-68.352	-68.329
0.546	-68.333	-68.297	-68.275	-68.28	-68.337
0.547	-68.301	-68.257	-68.291	-68.307	-68.321
0.548	-68.3	-68.298	-68.29	-68.307	-68.331
0.549	-68.276	-68.262	-68.265	-68.299	-68.319
0.55	-68.278	-68.321	-68.283	-68.24	-68.315
0.551	-68.326	-68.24	-68.17	-68.192	-68.391
0.552	-68.246	-68.369	-68.285	-68.248	-68.146
0.553	-68.227	-68.239	-68.269	-68.272	-68.28
0.554	-68.21	-68.273	-68.257	-68.274	-68.267
0.555	-68.202	-68.236	-68.24	-68.243	-68.242
0.556	-68.264	-68.176	-68.21	-68.217	-68.254
0.557	-68.236	-68.31	-68.246	-68.211	-68.258
0.558	-68.187	-68.2	-68.237	-68.244	-68.243
0.559	-68.19	-68.198	-68.182	-68.228	-68.246
0.56	-68.219	-68.189	-68.197	-68.183	-68.259
0.561	-68.163	-68.17	-68.208	-68.218	-68.214
0.562	-68.216	-68.195	-68.187	-68.184	-68.24
0.563	-68.147	-68.157	-68.172	-68.14	-68.196
0.564	-68.109	-68.192	-68.256	-68.161	-68.142
0.565	-68.181	-68.193	-68.127	-68.147	-68.188
0.566	-68.116	-68.093	-68.165	-68.132	-68.172
0.567	-68.114	-68.19	-68.126	-68.195	-68.196
0.568	-68.161	-68.222	-68.137	-68.138	-68.18
0.569	-68.174	-68.12	-68.111	-68.197	-68.138
0.57	-68.135	-68.155	-68.118	-68.174	-68.146
0.571	-68.097	-68.086	-68.122	-68.132	-68.187
0.572	-68.075	-68.083	-68.094	-68.126	-68.171
0.573	-68.072	-68.138	-68.062	-68.138	-68.151
0.574	-68.097	-68.108	-68.109	-68.086	-68.136
0.575	-68.08	-68.102	-68.137	-68.115	-68.121
0.576	-68.096	-68.068	-68.047	-68.115	-68.131
0.577	-68.067	-68.091	-68.133	-68.06	-68.117
0.578	-67.999	-68.033	-68.069	-68.072	-68.111

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.579	-68.067	-68.115	-68.097	-68.071	-68.099
0.58	-68.004	-68.042	-68.064	-68.058	-68.084
0.581	-68.03	-68.042	-68.057	-68.062	-68.098
0.582	-68.031	-68.085	-68.048	-68.091	-68.087
0.583	-68.022	-68.038	-68.065	-68.01	-68.095
0.584	-68.058	-68.056	-68.041	-68.03	-68.093
0.585	-68.017	-68.026	-68.027	-68.054	-68.057
0.586	-68.012	-68.047	-68.028	-68.067	-68.058
0.587	-68.021	-67.996	-68.052	-68.055	-68.052
0.588	-67.975	-67.947	-68.075	-67.982	-68.038
0.589	-68.021	-67.99	-67.958	-68.01	-68.005
0.59	-67.937	-67.98	-68.029	-68.053	-68.021
0.591	-67.963	-68.051	-67.971	-68.046	-68.019
0.592	-67.962	-67.972	-67.998	-67.999	-68.008
0.593	-68.007	-67.995	-67.973	-67.989	-68.003
0.594	-67.964	-67.998	-67.993	-67.98	-68.018
0.595	-67.957	-67.948	-67.994	-68.011	-67.962
0.596	-68.001	-67.951	-67.98	-67.926	-68.018
0.597	-67.886	-67.941	-67.964	-67.95	-67.966
0.598	-67.91	-67.97	-67.951	-67.96	-67.988
0.599	-67.938	-67.908	-67.945	-67.915	-67.98
0.6	-67.936	-67.909	-67.958	-67.937	-67.937
0.601	-67.917	-67.911	-67.933	-67.948	-67.959
0.602	-67.919	-67.922	-67.916	-67.948	-67.942
0.603	-67.911	-67.918	-67.906	-67.946	-67.948
0.604	-67.876	-67.866	-67.942	-67.91	-67.979
0.605	-67.912	-67.961	-67.921	-67.898	-67.942
0.606	-67.915	-67.896	-67.901	-67.944	-67.899
0.607	-67.783	-67.99	-67.948	-67.826	-67.815
0.608	-67.99	-67.774	-67.901	-67.928	-67.804
0.609	-67.918	-67.861	-67.896	-67.874	-67.914
0.61	-67.889	-67.876	-67.911	-67.909	-67.877
0.611	-67.878	-67.83	-67.88	-67.934	-67.888
0.612	-67.832	-67.835	-67.853	-67.905	-67.909
0.613	-67.877	-67.853	-67.852	-67.858	-67.89
0.614	-67.803	-67.839	-67.852	-67.862	-67.872
0.615	-67.852	-67.836	-67.864	-67.845	-67.879
0.616	-67.839	-67.86	-67.85	-67.845	-67.863
0.617	-67.834	-67.821	-67.809	-67.854	-67.85
0.618	-67.81	-67.842	-67.849	-67.86	-67.843
0.619	-67.792	-67.808	-67.822	-67.813	-67.848
0.62	-67.823	-67.845	-67.857	-67.831	-67.839
0.621	-67.804	-67.805	-67.834	-67.79	-67.843
0.622	-67.781	-67.833	-67.798	-67.832	-67.852
0.623	-67.779	-67.82	-67.827	-67.84	-67.861
0.624	-67.77	-67.788	-67.804	-67.837	-67.819

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.625	-67.815	-67.773	-67.779	-67.815	-67.835
0.626	-67.776	-67.767	-67.812	-67.764	-67.851
0.627	-67.784	-67.776	-67.799	-67.771	-67.823
0.628	-67.748	-67.754	-67.769	-67.769	-67.774
0.629	-67.772	-67.791	-67.779	-67.762	-67.811
0.63	-67.775	-67.782	-67.752	-67.764	-67.797
0.631	-67.71	-67.793	-67.786	-67.745	-67.808
0.632	-67.725	-67.727	-67.73	-67.793	-67.778
0.633	-67.732	-67.748	-67.736	-67.775	-67.837
0.634	-67.773	-67.761	-67.75	-67.751	-67.779
0.635	-67.773	-67.787	-67.732	-67.75	-67.79
0.636	-67.713	-67.774	-67.753	-67.751	-67.764
0.637	-67.752	-67.755	-67.75	-67.722	-67.794
0.638	-67.717	-67.734	-67.719	-67.725	-67.748
0.639	-67.765	-67.727	-67.732	-67.743	-67.76
0.64	-67.74	-67.736	-67.705	-67.724	-67.755
0.641	-67.719	-67.733	-67.724	-67.745	-67.769
0.642	-67.738	-67.705	-67.719	-67.743	-67.73
0.643	-67.692	-67.7	-67.709	-67.693	-67.759
0.644	-67.759	-67.746	-67.695	-67.744	-67.738
0.645	-67.706	-67.695	-67.697	-67.709	-67.744
0.646	-67.675	-67.701	-67.693	-67.702	-67.728
0.647	-67.668	-67.719	-67.721	-67.717	-67.753
0.648	-67.691	-67.67	-67.681	-67.687	-67.7
0.649	-67.699	-67.711	-67.672	-67.697	-67.71
0.65	-67.696	-67.67	-67.715	-67.681	-67.733
0.651	-67.701	-67.691	-67.66	-67.681	-67.743
0.652	-67.674	-67.66	-67.693	-67.697	-67.696
0.653	-67.69	-67.665	-67.708	-67.667	-67.709
0.654	-67.664	-67.701	-67.682	-67.679	-67.727
0.655	-67.65	-67.701	-67.699	-67.684	-67.698
0.656	-67.678	-67.691	-67.663	-67.655	-67.677
0.657	-67.636	-67.68	-67.684	-67.662	-67.665
0.658	-67.65	-67.635	-67.634	-67.669	-67.654
0.659	-67.635	-67.695	-67.621	-67.638	-67.669
0.66	-67.656	-67.666	-67.65	-67.666	-67.689
0.661	-67.639	-67.652	-67.626	-67.647	-67.697
0.662	-67.624	-67.684	-67.624	-67.672	-67.703
0.663	-67.644	-67.661	-67.668	-67.64	-67.732
0.664	-67.615	-67.664	-67.682	-67.638	-67.666
0.665	-67.617	-67.648	-67.661	-67.644	-67.651
0.666	-67.647	-67.652	-67.652	-67.661	-67.678
0.667	-67.634	-67.639	-67.635	-67.642	-67.675
0.668	-67.64	-67.655	-67.624	-67.638	-67.667
0.669	-67.647	-67.608	-67.641	-67.609	-67.621
0.67	-67.654	-67.631	-67.611	-67.644	-67.675

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.671	-67.652	-67.622	-67.65	-67.618	-67.646
0.672	-67.64	-67.624	-67.606	-67.646	-67.652
0.673	-67.597	-67.578	-67.61	-67.601	-67.651
0.674	-67.614	-67.591	-67.648	-67.612	-67.643
0.675	-67.643	-67.604	-67.598	-67.637	-67.643
0.676	-67.599	-67.603	-67.631	-67.591	-67.651
0.677	-67.625	-67.571	-67.614	-67.642	-67.641
0.678	-67.601	-67.622	-67.577	-67.621	-67.638
0.679	-67.585	-67.586	-67.612	-67.606	-67.607
0.68	-67.612	-67.614	-67.586	-67.605	-67.637
0.681	-67.576	-67.615	-67.577	-67.629	-67.637
0.682	-67.576	-67.624	-67.63	-67.609	-67.652
0.683	-67.567	-67.608	-67.592	-67.608	-67.67
0.684	-67.575	-67.546	-67.595	-67.647	-67.649
0.685	-67.636	-67.55	-67.549	-67.646	-67.626
0.686	-67.564	-67.587	-67.643	-67.623	-67.66
0.687	-67.599	-67.571	-67.565	-67.592	-67.619
0.688	-67.554	-67.586	-67.618	-67.601	-67.609
0.689	-67.578	-67.589	-67.585	-67.623	-67.611
0.69	-67.596	-67.574	-67.577	-67.593	-67.597
0.691	-67.592	-67.598	-67.631	-67.616	-67.597
0.692	-67.59	-67.582	-67.598	-67.582	-67.636
0.693	-67.584	-67.641	-67.618	-67.612	-67.605
0.694	-67.605	-67.555	-67.592	-67.602	-67.616
0.695	-67.613	-67.589	-67.561	-67.588	-67.611
0.696	-67.53	-67.582	-67.611	-67.59	-67.583
0.697	-67.567	-67.574	-67.569	-67.577	-67.591
0.698	-67.593	-67.589	-67.614	-67.597	-67.603
0.699	-67.596	-67.557	-67.608	-67.559	-67.622
0.7	-67.608	-67.622	-67.595	-67.585	-67.593
0.701	-65.999	-66.002	-66.014	-65.986	-66.023
0.702	-65.966	-65.998	-65.99	-66.009	-66.013
0.703	-65.996	-66.008	-65.991	-65.994	-66.025
0.704	-65.946	-65.9	-65.987	-66.037	-66.082
0.705	-65.925	-65.944	-66.008	-66.055	-65.972
0.706	-65.974	-65.948	-65.962	-66.02	-65.998
0.707	-65.983	-65.958	-65.992	-65.982	-66.015
0.708	-65.949	-65.931	-65.993	-65.981	-65.979
0.709	-65.939	-65.935	-65.936	-65.981	-65.993
0.71	-65.951	-65.949	-65.919	-65.965	-65.959
0.711	-65.962	-65.913	-65.955	-65.988	-65.99
0.712	-65.908	-65.942	-65.952	-65.925	-65.998
0.713	-65.927	-65.932	-65.931	-65.963	-65.983
0.714	-65.905	-65.904	-65.927	-65.928	-65.944
0.715	-65.91	-65.922	-65.926	-65.99	-65.934
0.716	-65.869	-65.884	-65.921	-65.914	-65.925

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.717	-65.903	-65.908	-65.918	-65.927	-65.938
0.718	-65.88	-65.926	-65.897	-65.9	-65.937
0.719	-65.882	-65.91	-65.893	-65.932	-65.955
0.72	-65.903	-65.905	-65.909	-65.932	-65.927
0.721	-65.896	-65.897	-65.902	-65.916	-65.93
0.722	-65.879	-65.861	-65.916	-65.886	-65.934
0.723	-65.857	-65.846	-65.896	-65.877	-65.917
0.724	-65.862	-65.851	-65.853	-65.925	-65.929
0.725	-65.887	-65.907	-65.819	-65.833	-65.771
0.726	-65.956	-65.838	-65.839	-65.814	-65.842
0.727	-65.858	-65.862	-65.864	-65.852	-65.91
0.728	-65.86	-65.873	-65.864	-65.859	-65.849
0.729	-65.842	-65.858	-65.844	-65.857	-65.852
0.73	-65.841	-65.795	-65.871	-65.869	-65.929
0.731	-65.847	-65.821	-65.817	-65.839	-65.882
0.732	-65.825	-65.822	-65.855	-65.843	-65.883
0.733	-65.815	-65.808	-65.828	-65.845	-65.872
0.734	-65.79	-65.83	-65.846	-65.862	-65.867
0.735	-65.799	-65.819	-65.866	-65.835	-65.843
0.736	-65.838	-65.79	-65.814	-65.828	-65.858
0.737	-65.79	-65.795	-65.823	-65.837	-65.85
0.738	-65.817	-65.834	-65.785	-65.806	-65.857
0.739	-65.777	-65.798	-65.8	-65.818	-65.861
0.74	-65.738	-65.733	-65.822	-65.802	-65.842
0.741	-65.926	-65.89	-65.799	-65.765	-65.84
0.742	-65.75	-65.73	-65.771	-65.811	-65.789
0.743	-65.799	-65.782	-65.77	-65.818	-65.819
0.744	-65.776	-65.789	-65.789	-65.765	-65.841
0.745	-65.788	-65.799	-65.808	-65.804	-65.805
0.746	-65.764	-65.725	-65.788	-65.84	-65.874
0.747	-65.767	-65.747	-65.755	-65.788	-65.829
0.748	-65.768	-65.778	-65.776	-65.8	-65.791
0.749	-65.753	-65.747	-65.774	-65.783	-65.821
0.75	-65.735	-65.746	-65.742	-65.776	-65.786
0.751	-65.734	-65.74	-65.729	-65.817	-65.796
0.752	-65.741	-65.778	-65.78	-65.763	-65.787
0.753	-65.724	-65.75	-65.757	-65.783	-65.799
0.754	-65.728	-65.76	-65.78	-65.754	-65.776
0.755	-65.662	-65.714	-65.753	-65.749	-65.769
0.756	-65.71	-65.723	-65.725	-65.765	-65.775
0.757	-65.739	-65.711	-65.735	-65.75	-65.772
0.758	-65.701	-65.712	-65.734	-65.768	-65.77
0.759	-65.689	-65.753	-65.777	-65.748	-65.76
0.76	-65.647	-65.699	-65.817	-65.772	-65.671
0.761	-65.703	-65.721	-65.78	-65.699	-65.756
0.762	-65.732	-65.709	-65.736	-65.707	-65.75
0.763	-65.691	-65.706	-65.679	-65.723	-65.727

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.764	-65.73	-65.689	-65.676	-65.7	-65.757
0.765	-65.677	-65.707	-65.721	-65.729	-65.722
0.766	-65.725	-65.669	-65.719	-65.72	-65.739
0.767	-65.718	-65.693	-65.7	-65.7	-65.734
0.768	-65.663	-65.68	-65.687	-65.729	-65.737
0.769	-65.655	-65.706	-65.692	-65.706	-65.714
0.77	-65.687	-65.672	-65.695	-65.686	-65.698
0.771	-65.662	-65.668	-65.698	-65.689	-65.72
0.772	-65.688	-65.684	-65.681	-65.683	-65.725
0.773	-65.651	-65.705	-65.685	-65.711	-65.741
0.774	-65.658	-65.683	-65.617	-65.668	-65.744
0.775	-65.679	-65.523	-65.699	-65.631	-65.678
0.776	-65.64	-65.719	-65.661	-65.724	-65.704
0.777	-65.635	-65.684	-65.654	-65.695	-65.7
0.778	-65.662	-65.678	-65.702	-65.674	-65.729
0.779	-65.664	-65.654	-65.626	-65.664	-65.703
0.78	-65.636	-65.713	-65.685	-65.681	-65.664
0.781	-65.633	-65.487	-65.552	-65.634	-65.856
0.782	-65.563	-65.685	-65.65	-65.629	-65.681
0.783	-65.631	-65.659	-65.679	-65.667	-65.705
0.784	-65.606	-65.664	-65.649	-65.69	-65.699
0.785	-65.663	-65.609	-65.604	-65.615	-65.712
0.786	-65.639	-65.653	-65.707	-65.708	-65.629
0.787	-65.631	-65.626	-65.633	-65.663	-65.686
0.788	-65.643	-65.637	-65.637	-65.644	-65.674
0.789	-65.633	-65.625	-65.622	-65.66	-65.706
0.79	-65.609	-65.65	-65.651	-65.655	-65.653
0.791	-65.641	-65.645	-65.653	-65.617	-65.659
0.792	-65.621	-65.63	-65.621	-65.634	-65.686
0.793	-65.628	-65.586	-65.612	-65.635	-65.668
0.794	-65.639	-65.612	-65.633	-65.634	-65.653
0.795	-65.628	-65.615	-65.637	-65.597	-65.694
0.796	-65.594	-65.621	-65.623	-65.627	-65.668
0.797	-65.609	-65.612	-65.621	-65.647	-65.657
0.798	-65.6	-65.626	-65.604	-65.622	-65.678
0.799	-65.603	-65.618	-65.622	-65.641	-65.648
0.8	-65.584	-65.605	-65.657	-65.612	-65.651
0.801	-65.603	-65.599	-65.601	-65.627	-65.629
0.802	-65.605	-65.603	-65.644	-65.645	-65.63
0.803	-65.585	-65.63	-65.602	-65.621	-65.641
0.804	-65.609	-65.652	-65.595	-65.629	-65.62
0.805	-65.619	-65.597	-65.578	-65.619	-65.658
0.806	-65.594	-65.617	-65.608	-65.635	-65.67
0.807	-65.625	-65.612	-65.626	-65.624	-65.651
0.808	-65.562	-65.6	-65.635	-65.628	-65.616
0.809	-65.564	-65.559	-65.579	-65.604	-65.631
0.81	-65.578	-65.592	-65.624	-65.645	-65.616

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.811	-65.61	-65.6	-65.596	-65.626	-65.657
0.812	-65.589	-65.576	-65.59	-65.595	-65.62
0.813	-65.581	-65.584	-65.578	-65.581	-65.634
0.814	-65.613	-65.578	-65.583	-65.607	-65.654
0.815	-65.583	-65.6	-65.615	-65.634	-65.644
0.816	-65.584	-65.56	-65.607	-65.635	-65.645
0.817	-65.57	-65.558	-65.605	-65.615	-65.653
0.818	-65.555	-65.603	-65.591	-65.588	-65.595
0.819	-65.556	-65.541	-65.573	-65.574	-65.631
0.82	-65.576	-65.584	-65.584	-65.619	-65.626
0.821	-65.594	-65.551	-65.583	-65.627	-65.626
0.822	-65.579	-65.597	-65.577	-65.583	-65.623
0.823	-65.577	-65.606	-65.601	-65.608	-65.655
0.824	-65.577	-65.587	-65.595	-65.609	-65.605
0.825	-65.581	-65.597	-65.597	-65.591	-65.629
0.826	-65.569	-65.568	-65.599	-65.642	-65.613
0.827	-65.557	-65.597	-65.581	-65.578	-65.62
0.828	-65.595	-65.543	-65.583	-65.593	-65.61
0.829	-65.59	-65.57	-65.576	-65.589	-65.623
0.83	-65.56	-65.558	-65.566	-65.644	-65.58
0.831	-65.558	-65.53	-65.626	-65.629	-65.56
0.832	-65.549	-65.552	-65.609	-65.593	-65.597
0.833	-65.569	-65.598	-65.594	-65.584	-65.632
0.834	-65.569	-65.59	-65.549	-65.569	-65.644
0.835	-65.581	-65.55	-65.553	-65.589	-65.587
0.836	-65.565	-65.551	-65.589	-65.603	-65.62
0.837	-65.589	-65.539	-65.578	-65.604	-65.602
0.838	-65.57	-65.587	-65.58	-65.592	-65.586
0.839	-65.57	-65.58	-65.569	-65.576	-65.602
0.84	-65.56	-65.573	-65.588	-65.567	-65.618
0.841	-65.561	-65.566	-65.588	-65.616	-65.637
0.842	-65.562	-65.553	-65.579	-65.572	-65.621
0.843	-65.525	-65.535	-65.582	-65.585	-65.612
0.844	-65.566	-65.547	-65.595	-65.57	-65.589
0.845	-65.564	-65.556	-65.565	-65.568	-65.636
0.846	-65.582	-65.579	-65.535	-65.594	-65.604
0.847	-65.534	-65.539	-65.56	-65.616	-65.609
0.848	-65.569	-65.574	-65.579	-65.581	-65.591
0.849	-65.578	-65.532	-65.584	-65.562	-65.647
0.85	-65.577	-65.542	-65.556	-65.601	-65.609
0.851	-65.598	-65.575	-65.559	-65.595	-65.602
0.852	-65.559	-65.554	-65.596	-65.575	-65.598
0.853	-65.564	-65.541	-65.539	-65.577	-65.687
0.854	-65.561	-65.552	-65.59	-65.575	-65.61
0.855	-65.575	-65.592	-65.56	-65.586	-65.617
0.856	-65.56	-65.555	-65.567	-65.603	-65.61
0.857	-65.558	-65.557	-65.558	-65.581	-65.592

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.858	-65.545	-65.587	-65.584	-65.575	-65.645
0.859	-65.601	-65.58	-65.555	-65.611	-65.61
0.86	-65.573	-65.544	-65.573	-65.578	-65.621
0.861	-65.562	-65.532	-65.595	-65.584	-65.618
0.862	-65.592	-65.554	-65.579	-65.614	-65.596
0.863	-65.557	-65.575	-65.578	-65.59	-65.643
0.864	-65.582	-65.564	-65.606	-65.574	-65.608
0.865	-65.576	-65.567	-65.578	-65.581	-65.584
0.866	-65.577	-65.59	-65.59	-65.604	-65.621
0.867	-65.548	-65.55	-65.56	-65.604	-65.634
0.868	-65.565	-65.578	-65.635	-65.597	-65.639
0.869	-65.579	-65.582	-65.592	-65.593	-65.625
0.87	-65.565	-65.56	-65.55	-65.611	-65.616
0.871	-65.582	-65.54	-65.586	-65.644	-65.611
0.872	-65.583	-65.565	-65.621	-65.583	-65.609
0.873	-65.566	-65.602	-65.591	-65.572	-65.629
0.874	-65.549	-65.541	-65.565	-65.592	-65.648
0.875	-65.566	-65.502	-65.596	-65.593	-65.64
0.876	-65.55	-65.601	-65.593	-65.601	-65.635
0.877	-65.584	-65.611	-65.567	-65.568	-65.632
0.878	-65.579	-65.552	-65.583	-65.6	-65.616
0.879	-65.571	-65.609	-65.55	-65.559	-65.646
0.88	-65.592	-65.613	-65.589	-65.596	-65.64
0.881	-65.606	-65.558	-65.597	-65.645	-65.615
0.882	-65.578	-65.576	-65.593	-65.611	-65.597
0.883	-65.577	-65.578	-65.598	-65.619	-65.639
0.884	-65.601	-65.601	-65.604	-65.592	-65.645
0.885	-65.622	-65.617	-65.617	-65.587	-65.641
0.886	-65.629	-65.583	-65.572	-65.609	-65.689
0.887	-65.617	-65.586	-65.58	-65.574	-65.6
0.888	-65.58	-65.609	-65.596	-65.64	-65.624
0.889	-65.624	-65.584	-65.627	-65.608	-65.628
0.89	-65.584	-65.601	-65.591	-65.622	-65.652
0.891	-65.606	-65.589	-65.646	-65.637	-65.662
0.892	-65.613	-65.606	-65.605	-65.638	-65.652
0.893	-65.582	-65.593	-65.623	-65.604	-65.644
0.894	-65.618	-65.601	-65.627	-65.62	-65.656
0.895	-65.571	-65.616	-65.619	-65.62	-65.656
0.896	-65.598	-65.579	-65.638	-65.634	-65.67
0.897	-65.628	-65.645	-65.603	-65.629	-65.757
0.898	-65.593	-65.61	-65.669	-65.634	-65.655
0.899	-65.611	-65.636	-65.613	-65.652	-65.679
0.9	-64.187	-64.192	-64.225	-64.226	-64.244
0.901	-64.169	-64.193	-64.176	-64.205	-64.261
0.902	-64.193	-64.213	-64.185	-64.24	-64.235
0.903	-64.197	-64.189	-64.199	-64.216	-64.23
0.904	-64.185	-64.214	-64.185	-64.193	-64.241

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.905	-64.208	-64.193	-64.208	-64.177	-64.241
0.906	-64.146	-64.175	-64.2	-64.207	-64.253
0.907	-64.186	-64.184	-64.179	-64.216	-64.231
0.908	-64.191	-64.192	-64.197	-64.208	-64.219
0.909	-64.172	-64.183	-64.176	-64.208	-64.225
0.91	-64.183	-64.172	-64.181	-64.178	-64.246
0.911	-64.171	-64.168	-64.173	-64.173	-64.217
0.912	-64.181	-64.176	-64.158	-64.211	-64.249
0.913	-64.131	-64.163	-64.195	-64.176	-64.215
0.914	-64.165	-64.131	-64.164	-64.165	-64.171
0.915	-64.145	-64.192	-64.173	-64.156	-64.198
0.916	-64.168	-64.158	-64.126	-64.193	-64.2
0.917	-64.148	-64.201	-64.164	-64.195	-64.191
0.918	-64.217	-64.174	-64.185	-64.195	-64.203
0.919	-64.161	-64.187	-64.161	-64.176	-64.229
0.92	-64.145	-64.153	-64.175	-64.167	-64.201
0.921	-64.151	-64.187	-64.183	-64.16	-64.203
0.922	-64.173	-64.156	-64.154	-64.181	-64.184
0.923	-64.162	-64.178	-64.172	-64.14	-64.193
0.924	-64.157	-64.141	-64.148	-64.161	-64.175
0.925	-64.174	-64.147	-64.155	-64.187	-64.177
0.926	-64.149	-64.151	-64.133	-64.183	-64.186
0.927	-64.146	-64.153	-64.155	-64.162	-64.217
0.928	-64.147	-64.162	-64.186	-64.159	-64.206
0.929	-64.156	-64.134	-64.159	-64.128	-64.18
0.93	-64.156	-64.157	-64.139	-64.149	-64.202
0.931	-64.132	-64.154	-64.163	-64.127	-64.154
0.932	-64.124	-64.182	-64.139	-64.169	-64.119
0.933	-64.158	-64.165	-64.151	-64.146	-64.202
0.934	-64.166	-64.153	-64.17	-64.153	-64.192
0.935	-64.164	-64.124	-64.139	-64.132	-64.179
0.936	-64.129	-64.149	-64.127	-64.195	-64.141
0.937	-64.203	-64.113	-64.145	-64.128	-64.244
0.938	-64.133	-64.152	-64.172	-64.109	-64.21
0.939	-64.13	-64.15	-64.128	-64.147	-64.173
0.94	-64.138	-64.143	-64.087	-64.159	-64.127
0.941	-64.135	-64.131	-64.124	-64.126	-64.169
0.942	-64.134	-64.128	-64.157	-64.143	-64.211
0.943	-64.164	-64.121	-64.157	-64.139	-64.163
0.944	-64.145	-64.137	-64.131	-64.11	-64.203
0.945	-64.122	-64.107	-64.131	-64.15	-64.169
0.946	-64.133	-64.125	-64.131	-64.18	-64.157
0.947	-64.155	-64.143	-64.165	-64.143	-64.172
0.948	-64.116	-64.164	-64.136	-64.137	-64.179
0.949	-64.116	-64.135	-64.142	-64.145	-64.155
0.95	-64.157	-64.145	-64.146	-64.152	-64.196
0.951	-64.134	-64.095	-64.135	-64.133	-64.207

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.952	-64.103	-64.147	-64.135	-64.124	-64.154
0.953	-64.105	-64.152	-64.16	-64.159	-64.208
0.954	-64.114	-64.133	-64.138	-64.133	-64.186
0.955	-64.131	-64.151	-64.134	-64.156	-64.154
0.956	-64.12	-64.134	-64.124	-64.182	-64.159
0.957	-64.179	-64.136	-64.159	-64.14	-64.213
0.958	-64.149	-64.159	-64.143	-64.167	-64.194
0.959	-64.057	-64.119	-64.275	-64.269	-64.283
0.96	-64.155	-64.194	-64.142	-64.147	-64.144
0.961	-64.151	-64.129	-64.161	-64.175	-64.202
0.962	-64.15	-64.19	-64.147	-64.121	-64.178
0.963	-64.146	-64.143	-64.176	-64.173	-64.224
0.964	-64.155	-64.139	-64.11	-64.186	-64.122
0.965	-64.175	-64.099	-64.167	-64.22	-64.168
0.966	-64.141	-64.158	-64.165	-64.17	-64.201
0.967	-64.151	-64.138	-64.147	-64.171	-64.189
0.968	-64.138	-64.166	-64.124	-64.164	-64.21
0.969	-64.153	-64.148	-64.154	-64.154	-64.224
0.97	-64.149	-64.151	-64.17	-64.176	-64.18
0.971	-64.129	-64.167	-64.156	-64.161	-64.179
0.972	-64.156	-64.169	-64.164	-64.184	-64.214
0.973	-64.15	-64.168	-64.169	-64.16	-64.213
0.974	-64.159	-64.161	-64.15	-64.175	-64.215
0.975	-64.142	-64.205	-64.115	-64.174	-64.19
0.976	-64.176	-64.181	-64.165	-64.172	-64.22
0.977	-64.152	-64.102	-64.273	-64.124	-64.233
0.978	-64.164	-64.154	-64.164	-64.159	-64.206
0.979	-64.166	-64.173	-64.155	-64.189	-64.224
0.98	-64.163	-64.172	-64.154	-64.185	-64.23
0.981	-64.206	-64.242	-64.135	-64.202	-64.203
0.982	-64.21	-64.193	-64.196	-64.206	-64.259
0.983	-64.159	-64.201	-64.185	-64.16	-64.189
0.984	-64.193	-64.164	-64.156	-64.239	-64.23
0.985	-64.116	-64.199	-64.237	-64.25	-64.235
0.986	-64.187	-64.178	-64.179	-64.183	-64.229
0.987	-64.175	-64.183	-64.194	-64.18	-64.251
0.988	-64.164	-64.198	-64.199	-64.196	-64.246
0.989	-64.207	-64.184	-64.202	-64.217	-64.277
0.99	-64.178	-64.18	-64.221	-64.204	-64.24
0.991	-64.223	-64.212	-64.185	-64.221	-64.248
0.992	-64.17	-64.21	-64.237	-64.206	-64.259
0.993	-64.183	-64.209	-64.208	-64.196	-64.219
0.994	-64.177	-64.204	-64.195	-64.241	-64.269
0.995	-64.195	-64.202	-64.199	-64.203	-64.256
0.996	-64.185	-64.222	-64.233	-64.173	-64.256
0.997	-64.204	-64.234	-64.235	-64.244	-64.278
0.998	-64.244	-64.224	-64.25	-64.247	-64.265

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
0.999	-64.213	-64.204	-64.263	-64.28	-64.279
1	-64.213	-64.225	-64.23	-64.212	-64.231
1.001	-64.215	-64.206	-64.222	-64.254	-64.267
1.002	-64.247	-64.243	-64.272	-64.253	-64.274
1.003	-64.247	-64.216	-64.241	-64.24	-64.287
1.004	-64.238	-64.267	-64.274	-64.235	-64.266
1.005	-64.236	-64.25	-64.227	-64.253	-64.31
1.006	-64.221	-64.251	-64.264	-64.267	-64.275
1.007	-64.285	-64.229	-64.339	-64.311	-64.314
1.008	-64.252	-64.282	-64.279	-64.271	-64.305
1.009	-64.246	-64.278	-64.291	-64.276	-64.28
1.01	-64.217	-64.236	-64.239	-64.276	-64.294
1.011	-64.307	-64.306	-64.273	-64.299	-64.389
1.012	-64.293	-64.287	-64.284	-64.286	-64.312
1.013	-64.221	-64.297	-64.276	-64.303	-64.321
1.014	-64.281	-64.317	-64.269	-64.302	-64.28
1.015	-64.25	-64.289	-64.323	-64.318	-64.324
1.016	-64.318	-64.307	-64.307	-64.3	-64.331
1.017	-64.278	-64.276	-64.302	-64.31	-64.346
1.018	-64.28	-64.318	-64.302	-64.318	-64.341
1.019	-64.283	-64.281	-64.35	-64.351	-64.342
1.02	-64.35	-64.284	-64.273	-64.258	-64.419
1.021	-64.283	-64.296	-64.309	-64.371	-64.347
1.022	-64.322	-64.333	-64.329	-64.336	-64.355
1.023	-64.276	-64.341	-64.355	-64.336	-64.37
1.024	-64.316	-64.337	-64.372	-64.319	-64.404
1.025	-64.34	-64.333	-64.342	-64.347	-64.379
1.026	-64.321	-64.325	-64.361	-64.333	-64.42
1.027	-64.347	-64.317	-64.348	-64.36	-64.394
1.028	-64.344	-64.358	-64.359	-64.354	-64.398
1.029	-64.35	-64.346	-64.334	-64.325	-64.386
1.03	-64.362	-64.358	-64.377	-64.373	-64.391
1.031	-64.37	-64.357	-64.341	-64.383	-64.387
1.032	-64.359	-64.395	-64.392	-64.402	-64.423
1.033	-64.358	-64.38	-64.351	-64.36	-64.411
1.034	-64.378	-64.379	-64.407	-64.41	-64.458
1.035	-64.36	-64.405	-64.412	-64.43	-64.423
1.036	-64.394	-64.411	-64.425	-64.431	-64.448
1.037	-64.38	-64.418	-64.435	-64.397	-64.433
1.038	-64.443	-64.408	-64.411	-64.391	-64.438
1.039	-64.423	-64.385	-64.412	-64.406	-64.477
1.04	-64.394	-64.429	-64.44	-64.442	-64.485
1.041	-64.425	-64.412	-64.462	-64.463	-64.493
1.042	-64.444	-64.416	-64.44	-64.46	-64.48
1.043	-64.428	-64.436	-64.455	-64.467	-64.462
1.044	-64.435	-64.419	-64.436	-64.472	-64.49
1.045	-64.436	-64.475	-64.473	-64.478	-64.476

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
1.046	-64.466	-64.471	-64.454	-64.488	-64.496
1.047	-64.467	-64.478	-64.48	-64.489	-64.508
1.048	-64.473	-64.479	-64.462	-64.514	-64.509
1.049	-64.48	-64.479	-64.513	-64.525	-64.533
1.05	-64.494	-64.501	-64.51	-64.521	-64.559
1.051	-64.439	-64.442	-64.554	-64.448	-64.517
1.052	-64.498	-64.478	-64.545	-64.507	-64.557
1.053	-64.488	-64.523	-64.51	-64.507	-64.543
1.054	-64.521	-64.525	-64.551	-64.537	-64.595
1.055	-64.516	-64.526	-64.542	-64.558	-64.568
1.056	-64.53	-64.536	-64.536	-64.551	-64.601
1.057	-64.566	-64.526	-64.568	-64.576	-64.646
1.058	-64.535	-64.535	-64.575	-64.529	-64.596
1.059	-64.546	-64.584	-64.569	-64.576	-64.628
1.06	-64.555	-64.565	-64.567	-64.593	-64.615
1.061	-64.577	-64.575	-64.584	-64.579	-64.652
1.062	-64.587	-64.6	-64.538	-64.606	-64.652
1.063	-64.607	-64.635	-64.627	-64.644	-64.653
1.064	-64.569	-64.573	-64.62	-64.602	-64.631
1.065	-64.605	-64.585	-64.634	-64.61	-64.664
1.066	-64.588	-64.631	-64.59	-64.555	-64.691
1.067	-64.6	-64.629	-64.636	-64.629	-64.682
1.068	-64.608	-64.638	-64.643	-64.65	-64.715
1.069	-64.638	-64.665	-64.652	-64.676	-64.69
1.07	-64.649	-64.697	-64.675	-64.702	-64.702
1.071	-64.647	-64.694	-64.659	-64.687	-64.711
1.072	-64.672	-64.681	-64.679	-64.652	-64.698
1.073	-64.669	-64.706	-64.696	-64.711	-64.741
1.074	-64.668	-64.656	-64.715	-64.703	-64.755
1.075	-64.705	-64.731	-64.726	-64.716	-64.755
1.076	-64.723	-64.767	-64.755	-64.735	-64.773
1.077	-64.72	-64.723	-64.801	-64.737	-64.778
1.078	-64.753	-64.807	-64.785	-64.766	-64.799
1.079	-64.71	-64.734	-64.752	-64.751	-64.79
1.08	-64.724	-64.758	-64.764	-64.781	-64.817
1.081	-64.749	-64.749	-64.771	-64.787	-64.804
1.082	-64.762	-64.792	-64.764	-64.783	-64.839
1.083	-64.839	-64.794	-64.823	-64.792	-64.847
1.084	-64.749	-64.832	-64.772	-64.825	-64.819
1.085	-64.785	-64.826	-64.818	-64.82	-64.835
1.086	-64.822	-64.809	-64.794	-64.827	-64.836
1.087	-64.867	-64.784	-64.878	-64.862	-64.856
1.088	-64.844	-64.861	-64.782	-64.885	-64.79
1.089	-64.852	-64.852	-64.845	-64.876	-64.899
1.09	-64.848	-64.853	-64.853	-64.868	-64.898
1.091	-64.855	-64.851	-64.851	-64.906	-64.885
1.092	-64.888	-64.876	-64.876	-64.887	-64.935

	Known Water Weight Samples, g				open air
	281.2	229.29	182.97	137.72	0
Transmission, Format: Log Mag					
Freq(MHz)	dB	dB	dB	dB	dB
1.093	-64.879	-64.907	-64.923	-64.892	-64.962
1.094	-64.906	-64.888	-64.898	-64.932	-64.979
1.095	-64.888	-64.91	-64.922	-64.925	-64.966
1.096	-64.92	-64.919	-64.942	-64.959	-64.973
1.097	-64.934	-64.95	-64.936	-64.964	-65.003
1.098	-64.942	-64.946	-64.945	-64.99	-64.995
1.099	-64.982	-64.997	-64.947	-64.973	-65.009
1.1	-64.966	-64.994	-64.989	-64.992	-65.002

APPENDIX B

ELECTROSTATIC FREE-SPACE SENSOR

PLANT SAMPLE RESPONSE

30.5 CM X 30.5 CM PLATE ANTENNAE

0.3 TO 0.5 MHZ

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.3	-65.086	-65.023	-65.589	-66.138	-66.293	-66.415	-66.485	-66.51	-66.796	-67.143	-67.153	-67.759	-68.14	-68.422
0.301	-65.022	-64.987	-65.548	-66.146	-66.295	-66.4	-66.572	-66.474	-66.734	-67.127	-67.092	-67.797	-68.068	-68.398
0.302	-65.05	-64.972	-65.571	-66.133	-66.263	-66.358	-66.476	-66.428	-66.723	-67.135	-67.095	-67.789	-68.013	-68.372
0.303	-65.065	-64.969	-65.495	-66.152	-66.34	-66.28	-66.374	-66.421	-66.664	-67.178	-67.243	-67.665	-68.072	-68.361
0.304	-65.069	-64.937	-65.6	-66.047	-66.186	-66.352	-66.435	-66.415	-66.724	-66.996	-67.145	-67.657	-67.964	-68.349
0.305	-65.029	-64.919	-65.543	-66.117	-66.234	-66.339	-66.422	-66.422	-66.655	-67.073	-67.107	-67.662	-68.031	-68.36
0.306	-65.013	-64.933	-65.482	-66.074	-66.197	-66.286	-66.372	-66.388	-66.67	-67.074	-67.096	-67.717	-67.939	-68.334
0.307	-64.982	-64.897	-65.477	-66.101	-66.171	-66.276	-66.371	-66.372	-66.642	-67.025	-66.97	-67.668	-67.894	-68.288
0.308	-64.974	-64.891	-65.497	-66.059	-66.143	-66.271	-66.32	-66.372	-66.637	-67.057	-67.01	-67.663	-67.968	-68.26
0.309	-64.966	-64.877	-65.449	-66.036	-66.176	-66.265	-66.34	-66.361	-66.619	-67.02	-67.035	-67.685	-67.924	-68.255
0.31	-64.923	-64.851	-65.466	-66.017	-66.14	-66.256	-66.319	-66.35	-66.599	-66.994	-66.996	-67.587	-67.911	-68.236
0.311	-64.932	-64.847	-65.421	-65.962	-66.171	-66.202	-66.305	-66.321	-66.595	-66.973	-67.01	-67.591	-67.869	-68.236
0.312	-64.884	-64.812	-65.411	-65.955	-66.11	-66.217	-66.268	-66.287	-66.567	-66.975	-67.005	-67.546	-67.894	-68.23
0.313	-64.909	-64.787	-65.375	-66.013	-66.148	-66.189	-66.265	-66.242	-66.602	-66.918	-66.948	-67.584	-67.852	-68.201
0.314	-64.875	-64.828	-65.37	-65.963	-66.116	-66.148	-66.28	-66.285	-66.523	-66.952	-66.969	-67.578	-67.849	-68.207
0.315	-64.884	-64.739	-65.381	-65.945	-66.057	-66.125	-66.233	-66.236	-66.537	-66.936	-66.969	-67.542	-67.85	-68.19
0.316	-64.848	-64.742	-65.324	-65.917	-66.103	-66.135	-66.254	-66.225	-66.561	-66.885	-66.943	-67.522	-67.797	-68.131
0.317	-64.844	-64.752	-65.325	-65.903	-66.03	-66.156	-66.176	-66.197	-66.481	-66.886	-66.922	-67.552	-67.741	-68.197
0.318	-64.808	-64.72	-65.313	-65.916	-66.008	-66.134	-66.216	-66.213	-66.49	-66.868	-66.875	-67.516	-67.801	-68.162
0.319	-64.792	-64.71	-65.29	-65.883	-66.007	-66.094	-66.21	-66.179	-66.477	-66.873	-66.865	-67.487	-67.732	-68.105
0.32	-64.762	-64.716	-65.279	-65.879	-65.974	-66.101	-66.144	-66.205	-66.459	-66.842	-66.827	-67.433	-67.787	-68.107
0.321	-64.775	-64.692	-65.255	-65.854	-65.959	-66.071	-66.147	-66.173	-66.452	-66.834	-66.797	-67.44	-67.737	-68.078
0.322	-64.758	-64.666	-65.275	-65.84	-65.95	-66.056	-66.16	-66.126	-66.414	-66.807	-66.802	-67.436	-67.711	-68.064
0.323	-64.755	-64.646	-65.228	-65.833	-65.914	-66.014	-66.116	-66.144	-66.401	-66.816	-66.773	-67.478	-67.701	-68.063
0.324	-64.727	-64.644	-65.238	-65.769	-65.9	-66.011	-66.114	-66.119	-66.395	-66.766	-66.762	-67.399	-67.698	-68.037
0.325	-64.7	-64.615	-65.202	-65.723	-65.888	-65.998	-66.105	-66.094	-66.354	-66.763	-66.77	-67.476	-67.704	-68.028

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.326	-64.724	-64.623	-65.207	-65.767	-65.892	-66.032	-66.087	-66.098	-66.366	-66.745	-66.749	-67.385	-67.61	-68.047
0.327	-64.679	-64.578	-65.176	-65.765	-65.952	-65.951	-66.084	-66.041	-66.313	-66.749	-66.734	-67.362	-67.63	-68.001
0.328	-64.702	-64.591	-65.178	-65.72	-65.86	-65.946	-66.063	-66.084	-66.354	-66.748	-66.7	-67.33	-67.636	-68.003
0.329	-64.615	-64.564	-65.137	-65.72	-65.876	-65.943	-66.043	-66.048	-66.287	-66.695	-66.701	-67.295	-67.612	-67.942
0.33	-64.633	-64.546	-65.118	-65.694	-65.865	-65.925	-66.05	-66.013	-66.31	-66.666	-66.708	-67.356	-67.617	-67.96
0.331	-64.621	-64.518	-65.123	-65.687	-65.814	-65.918	-66.001	-66.041	-66.283	-66.634	-66.684	-67.288	-67.584	-67.911
0.332	-64.618	-64.535	-65.1	-65.671	-65.861	-65.885	-65.976	-65.993	-66.276	-66.644	-66.656	-67.284	-67.616	-67.898
0.333	-64.574	-64.504	-65.065	-65.703	-65.847	-65.867	-65.998	-65.974	-66.239	-66.68	-66.631	-67.232	-67.555	-67.887
0.334	-64.583	-64.476	-65.097	-65.648	-65.788	-65.874	-65.967	-65.966	-66.222	-66.633	-66.607	-67.254	-67.602	-67.891
0.335	-64.557	-64.501	-65.065	-65.625	-65.788	-65.875	-65.989	-65.944	-66.234	-66.638	-66.629	-67.237	-67.534	-67.891
0.336	-64.554	-64.451	-65.038	-65.622	-65.757	-65.827	-65.954	-65.935	-66.205	-66.583	-66.655	-67.235	-67.486	-67.856
0.337	-64.532	-64.477	-65.009	-65.589	-65.759	-65.814	-65.936	-65.904	-66.228	-66.552	-66.58	-67.22	-67.493	-67.859
0.338	-64.557	-64.454	-65.026	-65.567	-65.726	-65.807	-65.877	-65.919	-66.188	-66.542	-66.605	-67.163	-67.481	-67.826
0.339	-64.51	-64.428	-65	-65.602	-65.698	-65.77	-65.873	-65.93	-66.179	-66.546	-66.54	-67.194	-67.523	-67.826
0.34	-64.51	-64.396	-64.984	-65.528	-65.692	-65.794	-65.881	-65.881	-66.185	-66.521	-66.576	-67.185	-67.46	-67.82
0.341	-64.453	-64.405	-64.985	-65.553	-65.697	-65.79	-65.882	-65.854	-66.159	-66.56	-66.523	-67.167	-67.442	-67.783
0.342	-64.488	-64.392	-64.965	-65.537	-65.705	-65.789	-65.816	-65.862	-66.17	-66.526	-66.532	-67.162	-67.434	-67.809
0.343	-64.477	-64.364	-64.937	-65.504	-65.673	-65.78	-65.843	-65.845	-66.15	-66.513	-66.492	-67.135	-67.408	-67.777
0.344	-64.42	-64.336	-64.952	-65.477	-65.637	-65.749	-65.819	-65.833	-66.06	-66.48	-66.511	-67.151	-67.415	-67.786
0.345	-64.438	-64.349	-64.926	-65.518	-65.626	-65.712	-65.799	-65.863	-66.097	-66.464	-66.487	-67.094	-67.404	-67.731
0.346	-64.394	-64.31	-64.922	-65.473	-65.615	-65.693	-65.769	-65.776	-66.067	-66.47	-66.457	-67.106	-67.371	-67.728
0.347	-64.399	-64.318	-64.903	-65.463	-65.596	-65.686	-65.801	-65.788	-66.088	-66.46	-66.444	-67.117	-67.416	-67.699
0.348	-64.364	-64.293	-64.904	-65.455	-65.543	-65.671	-65.764	-65.802	-66.061	-66.444	-66.443	-67.063	-67.346	-67.7
0.349	-64.379	-64.297	-64.882	-65.427	-65.607	-65.662	-65.774	-65.769	-66.034	-66.406	-66.456	-67.082	-67.297	-67.726
0.35	-64.36	-64.235	-64.868	-65.396	-65.54	-65.638	-65.773	-65.756	-66.05	-66.427	-66.424	-67.071	-67.316	-67.628
0.351	-64.329	-64.236	-64.825	-65.43	-65.544	-65.645	-65.706	-65.706	-65.984	-66.361	-66.421	-67.024	-67.381	-67.662
0.352	-64.334	-64.262	-64.839	-65.393	-65.523	-65.634	-65.722	-65.703	-65.95	-66.385	-66.425	-67.037	-67.316	-67.652
0.353	-64.303	-64.249	-64.8	-65.385	-65.54	-65.633	-65.711	-65.699	-65.984	-66.369	-66.38	-67.007	-67.307	-67.646

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.354	-64.279	-64.23	-64.783	-65.391	-65.509	-65.589	-65.663	-65.701	-65.978	-66.344	-66.373	-66.991	-67.234	-67.601
0.355	-64.288	-64.196	-64.801	-65.371	-65.504	-65.61	-65.661	-65.655	-65.953	-66.323	-66.334	-66.972	-67.263	-67.607
0.356	-64.278	-64.196	-64.778	-65.354	-65.486	-65.558	-65.685	-65.643	-65.97	-66.315	-66.362	-66.95	-67.262	-67.573
0.357	-64.272	-64.169	-64.756	-65.315	-65.493	-65.534	-65.686	-65.646	-65.934	-66.313	-66.31	-66.981	-67.231	-67.595
0.358	-64.265	-64.144	-64.743	-65.327	-65.447	-65.54	-65.636	-65.628	-65.938	-66.295	-66.356	-66.92	-67.228	-67.549
0.359	-64.217	-64.143	-64.718	-65.317	-65.443	-65.566	-65.634	-65.637	-65.867	-66.252	-66.33	-66.927	-67.248	-67.555
0.36	-64.225	-64.14	-64.744	-65.334	-65.449	-65.513	-65.63	-65.62	-65.895	-66.254	-66.265	-66.907	-67.192	-67.518
0.361	-64.21	-64.115	-64.708	-65.29	-65.413	-65.491	-65.611	-65.599	-65.844	-66.259	-66.308	-66.893	-67.202	-67.523
0.362	-64.222	-64.134	-64.685	-65.269	-65.405	-65.489	-65.598	-65.584	-65.893	-66.26	-66.259	-66.881	-67.156	-67.496
0.363	-64.149	-64.098	-64.737	-65.309	-65.454	-65.468	-65.581	-65.547	-65.857	-66.22	-66.273	-66.901	-67.193	-67.498
0.364	-64.184	-64.1	-64.646	-65.233	-65.395	-65.46	-65.577	-65.575	-65.855	-66.246	-66.264	-66.886	-67.112	-67.505
0.365	-64.167	-64.061	-64.653	-65.224	-65.366	-65.455	-65.549	-65.562	-65.83	-66.246	-66.212	-66.858	-67.14	-67.482
0.366	-64.144	-64.07	-64.661	-65.222	-65.357	-65.446	-65.546	-65.5	-65.825	-66.213	-66.205	-66.848	-67.149	-67.469
0.367	-64.159	-64.032	-64.63	-65.185	-65.384	-65.387	-65.534	-65.494	-65.782	-66.259	-66.265	-66.771	-67.083	-67.444
0.368	-64.093	-64.019	-64.608	-65.185	-65.341	-65.444	-65.497	-65.522	-65.805	-66.196	-66.199	-66.801	-67.084	-67.425
0.369	-64.086	-64.02	-64.623	-65.137	-65.272	-65.387	-65.51	-65.538	-65.779	-66.147	-66.165	-66.832	-67.08	-67.451
0.37	-64.104	-64.025	-64.608	-65.19	-65.307	-65.399	-65.487	-65.495	-65.762	-66.14	-66.16	-66.764	-67.09	-67.431
0.371	-64.098	-64.001	-64.553	-65.142	-65.303	-65.378	-65.473	-65.477	-65.771	-66.124	-66.123	-66.785	-67.095	-67.399
0.372	-64.081	-63.979	-64.571	-65.154	-65.271	-65.402	-65.451	-65.491	-65.754	-66.102	-66.117	-66.765	-67.045	-67.378
0.373	-64.056	-63.996	-64.571	-65.121	-65.261	-65.349	-65.464	-65.462	-65.746	-66.129	-66.139	-66.766	-67.04	-67.414
0.374	-64.047	-63.985	-64.526	-65.098	-65.253	-65.353	-65.457	-65.472	-65.712	-66.12	-66.079	-66.735	-67.011	-67.355
0.375	-64.036	-63.941	-64.543	-65.111	-65.266	-65.313	-65.418	-65.433	-65.721	-66.084	-66.079	-66.735	-67.03	-67.358
0.376	-64.071	-63.926	-64.514	-65.119	-65.218	-65.357	-65.383	-65.441	-65.715	-66.079	-66.11	-66.751	-67.04	-67.389
0.377	-64.016	-63.92	-64.514	-65.092	-65.247	-65.323	-65.373	-65.409	-65.656	-66.047	-66.069	-66.701	-66.944	-67.312
0.378	-63.987	-63.919	-64.487	-65.09	-65.225	-65.305	-65.382	-65.394	-65.674	-66.076	-66.079	-66.691	-66.994	-67.364
0.379	-63.997	-63.897	-64.509	-65.08	-65.214	-65.264	-65.373	-65.381	-65.678	-66.033	-66.061	-66.645	-66.96	-67.32
0.38	-63.99	-63.883	-64.492	-65.037	-65.187	-65.272	-65.391	-65.375	-65.647	-65.995	-66.038	-66.634	-67.009	-67.303
0.381	-63.954	-63.864	-64.464	-65.03	-65.142	-65.236	-65.353	-65.319	-65.627	-66.029	-66.043	-66.647	-66.918	-67.331

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.382	-63.949	-63.883	-64.459	-65.029	-65.154	-65.253	-65.328	-65.336	-65.621	-66.001	-66.053	-66.638	-66.939	-67.243
0.383	-63.924	-63.848	-64.426	-65.019	-65.122	-65.224	-65.316	-65.32	-65.644	-66.001	-66.02	-66.622	-66.916	-67.257
0.384	-63.935	-63.835	-64.453	-65.002	-65.127	-65.188	-65.327	-65.291	-65.585	-66.025	-65.978	-66.573	-66.917	-67.267
0.385	-63.956	-63.838	-64.401	-64.971	-65.134	-65.256	-65.316	-65.284	-65.617	-66.003	-65.878	-66.64	-66.921	-67.252
0.386	-63.964	-63.789	-64.437	-64.939	-65.138	-65.226	-65.363	-65.367	-65.56	-65.955	-65.9	-66.549	-66.87	-67.233
0.387	-63.882	-63.831	-64.408	-64.951	-65.115	-65.184	-65.264	-65.303	-65.594	-65.979	-65.933	-66.56	-66.873	-67.206
0.388	-63.871	-63.798	-64.357	-64.947	-65.082	-65.187	-65.279	-65.276	-65.565	-65.955	-65.956	-66.544	-66.87	-67.206
0.389	-63.862	-63.798	-64.372	-64.941	-65.086	-65.157	-65.259	-65.242	-65.543	-65.931	-65.934	-66.557	-66.849	-67.183
0.39	-63.855	-63.772	-64.33	-64.937	-65.069	-65.182	-65.235	-65.239	-65.547	-65.906	-65.926	-66.528	-66.833	-67.199
0.391	-63.86	-63.775	-64.371	-64.922	-65.088	-65.178	-65.24	-65.232	-65.52	-65.907	-65.896	-66.556	-66.837	-67.156
0.392	-63.835	-63.745	-64.344	-64.922	-65.044	-65.138	-65.22	-65.251	-65.505	-65.908	-65.916	-66.554	-66.786	-67.159
0.393	-63.85	-63.736	-64.284	-64.907	-65.025	-65.105	-65.198	-65.231	-65.523	-65.892	-65.911	-66.522	-66.799	-67.127
0.394	-63.827	-63.717	-64.341	-64.893	-65.05	-65.133	-65.192	-65.218	-65.504	-65.896	-65.887	-66.523	-66.806	-67.108
0.395	-63.783	-63.71	-64.285	-64.893	-65.027	-65.098	-65.203	-65.223	-65.491	-65.874	-65.883	-66.474	-66.771	-67.182
0.396	-63.827	-63.718	-64.293	-64.861	-65.001	-65.094	-65.197	-65.207	-65.48	-65.812	-65.848	-66.509	-66.756	-67.124
0.397	-63.8	-63.693	-64.294	-64.857	-64.986	-65.095	-65.19	-65.188	-65.469	-65.818	-65.841	-66.501	-66.753	-67.101
0.398	-63.81	-63.69	-64.237	-64.848	-64.985	-65.036	-65.168	-65.185	-65.461	-65.833	-65.844	-66.472	-66.751	-67.099
0.399	-63.737	-63.657	-64.283	-64.837	-65.006	-65.046	-65.179	-65.219	-65.43	-65.828	-65.832	-66.474	-66.724	-67.067
0.4	-63.793	-63.703	-64.268	-64.829	-64.992	-65	-65.162	-65.162	-65.419	-65.799	-65.822	-66.403	-66.709	-67.083
0.401	-63.755	-63.658	-64.236	-64.806	-64.936	-65.037	-65.13	-65.125	-65.4	-65.836	-65.831	-66.451	-66.737	-67.069
0.402	-63.748	-63.66	-64.22	-64.78	-64.961	-65	-65.125	-65.117	-65.396	-65.812	-65.8	-66.459	-66.683	-67.09
0.403	-63.723	-63.623	-64.222	-64.788	-64.92	-65.04	-65.122	-65.112	-65.398	-65.764	-65.782	-66.395	-66.717	-67.035
0.404	-63.72	-63.624	-64.21	-64.79	-64.937	-64.987	-65.086	-65.09	-65.385	-65.799	-65.796	-66.396	-66.672	-67.037
0.405	-63.695	-63.686	-64.199	-64.819	-64.866	-65.006	-65.132	-65.125	-65.382	-65.811	-65.743	-66.374	-66.689	-67.049
0.406	-63.699	-63.579	-64.202	-64.785	-64.938	-64.982	-65.081	-65.111	-65.369	-65.715	-65.777	-66.369	-66.65	-67.009
0.407	-63.667	-63.568	-64.177	-64.736	-64.859	-64.984	-65.076	-65.065	-65.358	-65.743	-65.747	-66.383	-66.673	-66.998
0.408	-63.681	-63.577	-64.175	-64.727	-64.873	-64.95	-65.066	-65.079	-65.316	-65.699	-65.723	-66.358	-66.635	-66.993
0.409	-63.666	-63.604	-64.162	-64.723	-64.864	-64.979	-65.077	-65.027	-65.342	-65.71	-65.753	-66.373	-66.638	-66.987

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.41	-63.646	-63.586	-64.151	-64.747	-64.85	-64.957	-65.065	-65.04	-65.304	-65.689	-65.722	-66.313	-66.622	-66.958
0.411	-63.626	-63.553	-64.148	-64.681	-64.891	-64.925	-65.003	-65.015	-65.312	-65.687	-65.748	-66.309	-66.621	-66.959
0.412	-63.634	-63.552	-64.137	-64.702	-64.856	-64.91	-65.026	-65.013	-65.301	-65.668	-65.687	-66.305	-66.616	-66.963
0.413	-63.64	-63.547	-64.12	-64.708	-64.841	-64.912	-65.018	-65.021	-65.267	-65.68	-65.721	-66.328	-66.587	-66.918
0.414	-63.595	-63.526	-64.122	-64.683	-64.831	-64.91	-64.993	-64.995	-65.289	-65.66	-65.721	-66.312	-66.562	-66.963
0.415	-63.618	-63.511	-64.082	-64.691	-64.827	-64.878	-64.957	-64.993	-65.293	-65.644	-65.646	-66.248	-66.58	-66.903
0.416	-63.607	-63.511	-64.109	-64.693	-64.797	-64.891	-64.98	-64.968	-65.267	-65.637	-65.64	-66.275	-66.547	-66.876
0.417	-63.575	-63.513	-64.087	-64.656	-64.798	-64.868	-64.981	-64.984	-65.267	-65.636	-65.649	-66.269	-66.582	-66.898
0.418	-63.557	-63.489	-64.07	-64.623	-64.812	-64.844	-64.977	-64.964	-65.266	-65.633	-65.626	-66.237	-66.555	-66.88
0.419	-63.577	-63.48	-64.065	-64.617	-64.773	-64.831	-64.962	-64.964	-65.236	-65.618	-65.646	-66.248	-66.51	-66.893
0.42	-63.586	-63.469	-64.05	-64.628	-64.759	-64.869	-64.934	-64.933	-65.217	-65.624	-65.643	-66.223	-66.506	-66.857
0.421	-63.544	-63.447	-64.046	-64.631	-64.734	-64.851	-64.935	-64.929	-65.222	-65.625	-65.615	-66.27	-66.521	-66.888
0.422	-63.526	-63.451	-64.048	-64.616	-64.743	-64.811	-64.943	-64.938	-65.199	-65.571	-65.606	-66.25	-66.481	-66.844
0.423	-63.536	-63.433	-64.038	-64.61	-64.732	-64.814	-64.932	-64.891	-65.188	-65.611	-65.58	-66.202	-66.508	-66.825
0.424	-63.512	-63.401	-64.023	-64.585	-64.711	-64.822	-64.966	-64.899	-65.219	-65.524	-65.548	-66.248	-66.506	-66.863
0.425	-63.492	-63.418	-64.015	-64.6	-64.728	-64.783	-64.912	-64.89	-65.157	-65.53	-65.556	-66.195	-66.506	-66.825
0.426	-63.508	-63.443	-63.957	-64.605	-64.702	-64.75	-64.836	-64.903	-65.137	-65.578	-65.595	-66.135	-66.471	-66.829
0.427	-63.489	-63.399	-64.006	-64.578	-64.692	-64.782	-64.889	-64.886	-65.146	-65.518	-65.539	-66.177	-66.46	-66.817
0.428	-63.466	-63.387	-64.012	-64.587	-64.689	-64.808	-64.873	-64.866	-65.149	-65.581	-65.528	-66.167	-66.447	-66.761
0.429	-63.48	-63.394	-63.948	-64.521	-64.668	-64.754	-64.876	-64.859	-65.14	-65.536	-65.532	-66.159	-66.428	-66.787
0.43	-63.459	-63.403	-63.97	-64.569	-64.663	-64.771	-64.857	-64.871	-65.068	-65.499	-65.515	-66.116	-66.409	-66.765
0.431	-63.459	-63.351	-63.96	-64.544	-64.663	-64.716	-64.846	-64.828	-65.131	-65.522	-65.505	-66.126	-66.4	-66.806
0.432	-63.451	-63.363	-63.942	-64.512	-64.641	-64.738	-64.838	-64.843	-65.1	-65.516	-65.512	-66.158	-66.418	-66.771
0.433	-63.441	-63.359	-63.929	-64.503	-64.647	-64.753	-64.817	-64.836	-65.114	-65.506	-65.529	-66.14	-66.423	-66.757
0.434	-63.416	-63.346	-63.916	-64.496	-64.618	-64.731	-64.82	-64.832	-65.095	-65.497	-65.471	-66.121	-66.341	-66.746
0.435	-63.431	-63.345	-63.93	-64.477	-64.623	-64.707	-64.794	-64.837	-65.077	-65.497	-65.499	-66.108	-66.364	-66.744
0.436	-63.406	-63.331	-63.894	-64.506	-64.615	-64.685	-64.816	-64.808	-65.101	-65.462	-65.48	-66.123	-66.362	-66.74
0.437	-63.394	-63.335	-63.905	-64.466	-64.615	-64.682	-64.786	-64.794	-65.099	-65.461	-65.451	-66.08	-66.366	-66.723

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.438	-63.383	-63.309	-63.905	-64.458	-64.611	-64.679	-64.774	-64.801	-65.063	-65.431	-65.456	-66.078	-66.356	-66.703
0.439	-63.401	-63.293	-63.883	-64.473	-64.597	-64.685	-64.751	-64.802	-65.045	-65.43	-65.435	-66.09	-66.35	-66.707
0.44	-63.377	-63.287	-63.88	-64.453	-64.609	-64.677	-64.753	-64.769	-65.041	-65.428	-65.443	-66.043	-66.329	-66.699
0.441	-63.384	-63.254	-63.855	-64.455	-64.575	-64.661	-64.767	-64.773	-65.033	-65.416	-65.453	-66.051	-66.338	-66.67
0.442	-63.34	-63.3	-63.859	-64.418	-64.567	-64.652	-64.736	-64.757	-65.054	-65.407	-65.437	-66.025	-66.339	-66.654
0.443	-63.342	-63.273	-63.865	-64.392	-64.595	-64.638	-64.733	-64.711	-65.023	-65.403	-65.426	-66.039	-66.333	-66.696
0.444	-63.349	-63.244	-63.841	-64.414	-64.556	-64.613	-64.737	-64.73	-65.008	-65.41	-65.38	-66.041	-66.302	-66.639
0.445	-63.355	-63.257	-63.821	-64.43	-64.534	-64.649	-64.724	-64.687	-65.012	-65.397	-65.403	-66.001	-66.326	-66.658
0.446	-63.316	-63.237	-63.819	-64.429	-64.528	-64.624	-64.73	-64.714	-64.999	-65.373	-65.393	-66.011	-66.303	-66.656
0.447	-63.342	-63.218	-63.812	-64.383	-64.536	-64.589	-64.713	-64.7	-64.988	-65.386	-65.369	-65.992	-66.328	-66.634
0.448	-63.332	-63.227	-63.811	-64.386	-64.508	-64.585	-64.695	-64.73	-64.994	-65.422	-65.335	-66.009	-66.248	-66.609
0.449	-63.305	-63.207	-63.809	-64.359	-64.518	-64.598	-64.693	-64.726	-64.978	-65.329	-65.32	-65.984	-66.277	-66.63
0.45	-63.306	-63.202	-63.77	-64.366	-64.543	-64.583	-64.664	-64.692	-64.972	-65.34	-65.377	-65.973	-66.266	-66.624
0.451	-63.294	-63.194	-63.793	-64.377	-64.476	-64.584	-64.664	-64.678	-64.956	-65.36	-65.327	-65.968	-66.261	-66.603
0.452	-63.29	-63.194	-63.799	-64.382	-64.458	-64.566	-64.662	-64.686	-64.955	-65.343	-65.37	-65.988	-66.275	-66.6
0.453	-63.296	-63.217	-63.752	-64.346	-64.48	-64.595	-64.672	-64.669	-64.932	-65.333	-65.33	-65.958	-66.226	-66.592
0.454	-63.271	-63.172	-63.756	-64.332	-64.461	-64.563	-64.663	-64.658	-64.95	-65.301	-65.305	-65.948	-66.267	-66.604
0.455	-63.336	-63.199	-63.774	-64.361	-64.47	-64.527	-64.623	-64.67	-64.94	-65.293	-65.372	-65.945	-66.298	-66.662
0.456	-63.282	-63.183	-63.74	-64.325	-64.47	-64.563	-64.641	-64.631	-64.911	-65.284	-65.315	-65.935	-66.217	-66.522
0.457	-63.24	-63.165	-63.758	-64.334	-64.443	-64.517	-64.637	-64.611	-64.9	-65.294	-65.315	-65.902	-66.202	-66.562
0.458	-63.243	-63.153	-63.722	-64.309	-64.459	-64.504	-64.614	-64.627	-64.895	-65.29	-65.287	-65.918	-66.198	-66.561
0.459	-63.233	-63.146	-63.712	-64.281	-64.406	-64.518	-64.615	-64.599	-64.912	-65.271	-65.282	-65.911	-66.198	-66.574
0.46	-63.218	-63.139	-63.71	-64.28	-64.422	-64.535	-64.641	-64.614	-64.878	-65.25	-65.249	-65.897	-66.23	-66.558
0.461	-63.197	-63.115	-63.707	-64.254	-64.434	-64.506	-64.587	-64.62	-64.876	-65.318	-65.317	-65.92	-66.187	-66.53
0.462	-63.198	-63.13	-63.71	-64.266	-64.395	-64.527	-64.57	-64.587	-64.869	-65.268	-65.266	-65.884	-66.186	-66.538
0.463	-63.208	-63.094	-63.687	-64.263	-64.395	-64.48	-64.566	-64.57	-64.853	-65.21	-65.234	-65.886	-66.167	-66.506
0.464	-63.185	-63.127	-63.685	-64.255	-64.387	-64.47	-64.574	-64.602	-64.878	-65.233	-65.256	-65.89	-66.155	-66.52
0.465	-63.206	-63.106	-63.681	-64.253	-64.386	-64.478	-64.539	-64.553	-64.841	-65.22	-65.256	-65.847	-66.137	-66.483

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.466	-63.186	-63.07	-63.672	-64.236	-64.387	-64.499	-64.569	-64.58	-64.834	-65.258	-65.237	-65.854	-66.152	-66.511
0.467	-63.146	-63.075	-63.647	-64.237	-64.366	-64.457	-64.602	-64.557	-64.854	-65.225	-65.242	-65.859	-66.125	-66.484
0.468	-63.151	-63.082	-63.644	-64.229	-64.34	-64.458	-64.548	-64.549	-64.792	-65.233	-65.188	-65.849	-66.148	-66.52
0.469	-63.146	-63.062	-63.641	-64.239	-64.346	-64.44	-64.533	-64.541	-64.814	-65.207	-65.249	-65.845	-66.108	-66.473
0.47	-63.137	-63.059	-63.632	-64.207	-64.351	-64.432	-64.546	-64.548	-64.844	-65.204	-65.198	-65.827	-66.105	-66.483
0.471	-63.128	-63.04	-63.638	-64.219	-64.339	-64.441	-64.522	-64.53	-64.8	-65.205	-65.178	-65.796	-66.132	-66.462
0.472	-63.146	-63.032	-63.619	-64.205	-64.342	-64.394	-64.522	-64.515	-64.806	-65.224	-65.184	-65.82	-66.12	-66.446
0.473	-63.113	-63.023	-63.641	-64.213	-64.341	-64.411	-64.537	-64.522	-64.793	-65.174	-65.174	-65.801	-66.123	-66.435
0.474	-63.101	-63.045	-63.6	-64.176	-64.33	-64.391	-64.502	-64.504	-64.778	-65.144	-65.19	-65.783	-66.076	-66.454
0.475	-63.091	-63.035	-63.6	-64.203	-64.306	-64.366	-64.462	-64.507	-64.809	-65.174	-65.151	-65.79	-66.076	-66.416
0.476	-63.099	-63.023	-63.611	-64.166	-64.319	-64.402	-64.469	-64.476	-64.777	-65.159	-65.178	-65.77	-66.07	-66.415
0.477	-63.09	-63.003	-63.587	-64.163	-64.303	-64.391	-64.477	-64.494	-64.763	-65.153	-65.156	-65.792	-66.059	-66.417
0.478	-63.087	-62.984	-63.577	-64.18	-64.296	-64.382	-64.487	-64.474	-64.767	-65.155	-65.133	-65.753	-66.056	-66.416
0.479	-63.066	-63.001	-63.584	-64.159	-64.273	-64.348	-64.442	-64.434	-64.755	-65.131	-65.157	-65.743	-66.076	-66.409
0.48	-63.07	-62.981	-63.583	-64.136	-64.265	-64.353	-64.452	-64.471	-64.733	-65.097	-65.109	-65.748	-66.024	-66.344
0.481	-63.062	-62.985	-63.588	-64.135	-64.283	-64.355	-64.433	-64.463	-64.709	-65.129	-65.121	-65.733	-66.033	-66.371
0.482	-63.062	-62.955	-63.544	-64.118	-64.263	-64.352	-64.458	-64.476	-64.719	-65.11	-65.115	-65.759	-66.03	-66.367
0.483	-63.031	-62.958	-63.555	-64.113	-64.248	-64.339	-64.422	-64.429	-64.702	-65.11	-65.104	-65.751	-65.998	-66.362
0.484	-63.034	-62.969	-63.55	-64.104	-64.248	-64.343	-64.404	-64.414	-64.718	-65.092	-65.112	-65.715	-66.019	-66.369
0.485	-63.056	-62.927	-63.517	-64.094	-64.224	-64.31	-64.416	-64.413	-64.688	-65.084	-65.067	-65.724	-66.003	-66.341
0.486	-63.019	-62.944	-63.535	-64.093	-64.238	-64.313	-64.401	-64.43	-64.678	-65.082	-65.092	-65.697	-65.996	-66.336
0.487	-63.016	-62.935	-63.508	-64.082	-64.225	-64.295	-64.384	-64.393	-64.71	-65.042	-65.047	-65.714	-65.992	-66.313
0.488	-63.018	-62.915	-63.517	-64.059	-64.205	-64.315	-64.38	-64.407	-64.69	-65.048	-65.075	-65.706	-65.977	-66.319
0.489	-62.997	-62.917	-63.492	-64.069	-64.196	-64.267	-64.402	-64.388	-64.68	-65.063	-65.075	-65.684	-65.981	-66.349
0.49	-63.016	-62.898	-63.504	-64.093	-64.199	-64.292	-64.396	-64.352	-64.675	-65.05	-65.054	-65.664	-65.937	-66.311
0.491	-62.989	-62.911	-63.481	-64.079	-64.227	-64.301	-64.379	-64.382	-64.649	-65.055	-65.047	-65.652	-65.95	-66.316
0.492	-62.982	-62.898	-63.478	-64.048	-64.186	-64.269	-64.363	-64.375	-64.645	-65.023	-65.042	-65.668	-65.933	-66.297
0.493	-62.991	-62.893	-63.484	-64.068	-64.168	-64.276	-64.369	-64.375	-64.639	-65.036	-65.063	-65.663	-65.93	-66.297

	full	1st removal	2nd removal	3rd removal	4th removal	5th removal	6th removal	7th removal	8th removal	9th removal	10th removal	11th removal	12th removal	empty flat
sample weight, g	596.86	549.41	505.96	457.42	412.54	370.2	324.49	278.21	228.87	185.91	143.5	85.28	41.21	0
Transmission, Format: Log Mag														
Freq(MHz)	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
0.494	-62.971	-62.87	-63.461	-64.036	-64.172	-64.256	-64.364	-64.368	-64.625	-65.013	-65.013	-65.657	-65.919	-66.289
0.495	-62.987	-62.878	-63.469	-64.035	-64.145	-64.243	-64.349	-64.343	-64.63	-65	-65.031	-65.639	-65.921	-66.261
0.496	-62.951	-62.87	-63.459	-64.022	-64.175	-64.234	-64.353	-64.346	-64.635	-65.018	-65.037	-65.649	-65.91	-66.287
0.497	-62.978	-62.847	-63.427	-64.018	-64.15	-64.247	-64.348	-64.352	-64.6	-64.946	-65.004	-65.633	-65.961	-66.261
0.498	-62.947	-62.837	-63.429	-64.004	-64.188	-64.232	-64.346	-64.31	-64.571	-64.965	-64.981	-65.639	-65.932	-66.27
0.499	-62.917	-62.843	-63.421	-64.017	-64.151	-64.214	-64.342	-64.341	-64.611	-64.965	-64.967	-65.618	-65.889	-66.261
0.5	-62.905	-62.837	-63.422	-63.977	-64.135	-64.208	-64.307	-64.286	-64.562	-64.965	-64.994	-65.603	-65.871	-66.227

APPENDIX C

ELECTROSTATIC FREE-SPACE SENSOR

PLANT SAMPLE GRAVIMETRIC AND ATTENUATION DATA

30.5 CM X 30.5 CM PLATE ANTENNAE

flat status	wet plant material, g	dry biomass, g	water content, g	Response at 472 kHz		Attenuation, db		Predictions		e'
				Rep 1	Rep2	Rep 1	Rep2	dry biomass, g	water content, g	
full flat	596.86	58.27	538.59	-63.146	-63.066	3.3	3.343	54.90	537.96	2.14
1st removal	549.41	53.79	495.62	-63.032	-63.001	3.414	3.408	60.62	558.32	2.19
2nd removal	505.96	49.2	456.76	-63.619	-63.584	2.827	2.825	49.04	453.50	1.92
3rd removal	457.42	44.61	412.81	-64.205	-64.159	2.241	2.25	37.48	348.86	1.68
4th removal	412.54	40.05	372.49	-64.342	-64.273	2.104	2.136	34.78	324.39	1.62
5th removal	370.2	35.85	334.35	-64.394	-64.348	2.052	2.061	33.75	315.11	1.60
6th removal	324.49	31.27	293.22	-64.522	-64.442	1.924	1.967	31.23	292.25	1.56
7th removal	278.21	26.37	251.84	-64.515	-64.434	1.931	1.975	31.36	293.50	1.56
8th removal	228.87	21.64	207.23	-64.806	-64.755	1.64	1.654	25.63	241.54	1.46
9th removal	185.91	17.43	168.48	-65.224	-65.131	1.222	1.278	17.38	166.89	1.32
10th removal	143.5	13.21	130.29	-65.184	-65.157	1.262	1.252	18.17	174.04	1.34
11th removal	85.28	7.79	77.49	-65.82	-65.743	0.626	0.666	5.63	60.46	1.16
12th removal	41.21	3.34	37.87	-66.12	-66.076	0.326	0.333	-0.29	6.89	1.08
empty flat	0	0	0	-66.446	-66.409	0	0			1.00

APPENDIX D

ELECTROSTATIC FREE-SPACE SENSOR

PLANT SAMPLE GRAVIMETRIC AND ATTENUATION DATA

12.7 CM X 12.7 CM PLATE ANTENNAE

flat status	wet plant material, g	dry biomass, g	water content, g	Response at 472 kHz		Attenuation	
				Rep 1	Rep2	Rep 1	Rep2
full flat	587.54	52.54	535	-81.589	-81.559	2.554	2.554
1st removal	534.05	47.42	486.63	-81.589	-81.559	2.554	2.554
2nd removal	489.53	43.32	446.21	-81.603	-81.629	2.484	2.484
3rd removal	429.22	38.21	391.01	-81.951	-81.998	2.115	2.115
4th removal	385.06	34.32	350.74	-82.218	-82.449	1.664	1.664
5th removal	338.42	30.24	308.18	-82.367	-82.32	1.793	1.793
6th removal	287.72	25.44	262.28	-82.124	-82.207	1.906	1.906
7th removal	231.24	20.24	211	-82.224	-82.134	1.979	1.979
8th removal	180.83	15.88	164.95	-82.244	-82.181	1.932	1.932
9th removal	145.06	12.66	132.4	-82.599	-82.534	1.579	1.579
10th removal	96.99	8.54	88.45	-83.55	-83.519	0.594	0.594
11th removal	45.84	4.04	41.8	-83.615	-83.839	0.274	0.274
empty flat	0	0	0	-83.973	-84.113	0	0

APPENDIX E

ELECTROSTATIC FREE-SPACE SENSOR

OUT OF SENSING RANGE TEST

30.5 CM X 30.5 CM PLATE ANTENNAE

Samples below designed sensor range					
flat status	wet plant material, g	dry biomass, g	water content, g	Response at 472 kHz	Attenuation, db
full	193.81	74.5	119.31	-69.72	0.199
1	151.57	59.65	91.92	-69.793	0.126
2	119.69	46.43	73.26	-69.812	0.107
3	60.4	29.07	31.33	-69.77	0.149
4	39.04	15.3	23.74	-69.819	0.1
5	0	0	0	-69.919	0

Samples within designed sensor range					
flat status	wet plant material, g	dry biomass, g	water content, g	Response at 472 kHz	Attenuation, db
full	278.21	26.37	251.84	-64.515	1.931
1	228.87	21.64	207.23	-64.806	1.64
2	185.91	17.43	168.48	-65.224	1.222
3	143.5	13.21	130.29	-65.184	1.262
4	85.28	7.79	77.49	-65.82	0.626
5	41.21	3.34	37.87	-66.12	0.326
6	0	0	0	-66.446	0

APPENDIX F

GRAVIMETRIC, ULTRASOUND AND MULTISPECTRAL CAMERA DATA

SNAP BEANS

sample ID	wet biomass, g	NDVI	max height, cm	average height, cm	NDVI*max height	NDVI*avg height	surface area*max height	surface area*avg height	NDVI*max height*surface area	NDVI*avg height*surface area
p1nw	11.53	0.4032	5.65	3.55	2.28	1.43	694441.50	436840.13	279998.81	176133.94
p2nw	8.14	0.4044	6.62	5.79	2.68	2.34	816775.60	714594.53	330304.05	288982.03
p1w	19.25	0.3145	6.45	3.27	2.03	1.03	769743.00	390241.80	242084.17	122731.05
p2w	18.74	0.4133	9.43	7.03	3.90	2.91	1505028.00	1122413.60	622028.07	463893.54
p5w	21.97	0.4577	11.70	7.72	5.36	3.53	2323737.00	1533848.48	1063574.42	702042.45
p6w	18.52	0.2839	6.90	4.11	1.96	1.17	789843.00	470992.02	224236.43	133714.63
p5nw	26.39	0.4026	9.70	6.66	3.91	2.68	2348952.00	1611888.71	945688.08	648946.40
p6nw	16.30	0.246	6.37	4.24	1.57	1.04	495528.67	330145.00	121900.05	81215.67
p7w	24.80	0.4268	11.55	7.97	4.93	3.40	2910369.00	2007440.67	1242145.49	856775.68
p8w	20.77	0.3192	5.93	3.47	1.89	1.11	757854.00	443367.69	241907.00	141522.97
p7nw	16.10	0.3536	7.27	4.95	2.57	1.75	1009948.40	687554.77	357117.75	243119.37
p8nw	13.86	0.3245	6.92	4.24	2.25	1.38	570789.28	349518.31	185221.12	113418.69
p10w	28.15	0.3364	7.16	4.70	2.41	1.58	1320447.20	866847.77	444198.44	291607.59
p9nw	18.79	0.2984	8.77	4.03	2.62	1.20	1216223.60	559546.06	362921.12	166968.55
p10nw	21.51	0.3301	7.16	4.46	2.36	1.47	1113022.00	693393.36	367408.56	228889.15
p12w	17.53	0.2704	6.61	3.71	1.79	1.00	903983.60	506988.86	244437.17	137089.79
p11nw	12.00	0.2097	4.95	2.67	1.04	0.56	454553.55	245091.60	95319.88	51395.71
p12nw	15.97	0.235	5.83	2.92	1.37	0.69	686599.10	343888.40	161350.79	80813.77
p13w	28.79	0.3126	9.78	5.64	3.06	1.76	1958151.60	1129476.35	612118.19	353074.31
p14w	13.89	0.2343	7.10	3.70	1.66	0.87	660229.00	344224.72	154691.65	80651.85
p13nw	6.97	0.2636	7.27	4.71	1.92	1.24	406712.88	263627.87	107209.52	69492.31
p14nw	11.92	0.1945	9.57	5.54	1.86	1.08	891636.90	515967.70	173423.38	100355.72
p15nw	7.46	0.2387	6.30	3.07	1.50	0.73	390058.20	190014.07	93106.89	45356.36
p15w	16.84	0.2887	7.64	5.57	2.21	1.61	805790.80	587309.70	232631.80	169556.31
p16w	13.73	0.3463	9.98	6.69	3.46	2.32	1299096.60	871314.59	449877.15	301736.24

APPENDIX G

GRAVIMETRIC, ULTRASOUND AND MULTISPECTRAL CAMERA DATA

CORN

sample ID	wet biomass, g	NDVI	max height, cm	average height, cm	NDVI*max height	NDVI*avg height	Surface area*max height	surface area*avg height	NDVI*max height*surface area	NDVI*avg height*surface area
c3nw	6.47	0.2325	9.30	4.61	2.16	1.07	364485.60	180591.14	84742.90	41987.44
c4nw	7.97	0.2086	8.01	3.95	1.67	0.82	265155.03	130901.68	55311.34	27306.09
c3w	24.12	0.3459	12.91	9.30	4.47	3.22	2302498.50	1659156.61	796434.23	573902.27
c4w	31.42	0.3852	15.84	8.26	6.10	3.18	3090859.20	1612224.10	1190598.96	621028.72
c5nw	7.80	0.2263	15.84	8.13	3.58	1.84	433889.28	222612.68	98189.14	50377.25
c6nw	12.48	0.2661	6.69	4.40	1.78	1.17	171504.84	112798.40	45637.44	30015.65
c5w	11.02	0.2115	11.85	8.77	2.51	1.85	1085329.65	803027.37	229547.22	169840.29
c7w	38.93	0.3864	12.28	9.79	4.74	3.78	2240240.40	1785859.39	865628.89	690056.07
c8w	25.19	0.3391	9.86	6.01	3.34	2.04	1545752.20	942156.35	524164.57	319485.22
C9W	49.35	0.3364	16.73	13.39	5.63	4.50	3085346.60	2468738.33	1037910.60	830483.57
c12w	49.96	0.3498	22.16	9.96	7.75	3.48	6013204.64	2702233.58	2103418.98	945241.31
c13nw	24.31	0.2449	7.94	3.27	1.94	0.80	629808.74	259181.37	154240.16	63473.52

APPENDIX H

GRAVIMETRIC, ULTRASOUND AND MULTISPECTRAL CAMERA DATA

SPINACH

sample ID	wet biomass, g	NDVI	max height, cm	average height, cm	NDVI*max height	NDVI*avg height	surface area*max height	surface area*avg height	NDVI*max height*surface area	NDVI*avg height*surface area
sh1	15.36	0.3659	4.15	2.316	1.52	0.85	485301.00	270833.04	177571.64	99097.81
sh2	14.78	0.401	3.81	1.8675	1.53	0.75	334598.01	164005.72	134173.80	65766.29
sh3	11.49	0.377	5.33	3.139167	2.01	1.18	324266.54	190980.62	122248.49	71999.69
sh4	24.22	0.4321	4.97	3.598421	2.15	1.55	782526.50	566571.39	338129.70	244815.50
sh5	13.84	0.378	5.06	2.599091	1.91	0.98	552096.60	283586.81	208692.51	107195.81
sh6	27.14	0.4503	6.47	3.9555	2.91	1.78	1054868.80	644904.72	475007.42	290400.60
sh7	17.84	0.3986	5.2	3.0125	2.07	1.20	516692.80	299334.05	205953.75	119314.55
sh8	31.06	0.4284	6.89	4.304737	2.95	1.84	978173.30	611143.49	419049.44	261813.87
sm1	6.27	0.3262	3.43	2.4275	1.12	0.79	206479.14	146130.65	67353.50	47667.82
sm2	12.62	0.3636	5.42	3.877647	1.97	1.41	639126.40	457252.14	232386.36	166256.88
sm3	7.24	0.3166	2.84	2.212143	0.90	0.70	186707.28	145430.70	59111.52	46043.36
sm4	8.39	0.3588	4.29	5.01	1.54	1.80	308747.01	360564.69	110778.43	129370.61
sm5	10.39	0.392	4.29	2.752	1.68	1.08	340351.44	218332.67	133417.76	85586.41
sm6	8.6	0.3177	4.1	1.999286	1.30	0.64	293244.30	142994.91	93163.71	45429.48
sm7	7.01	0.3265	2.77	1.541538	0.90	0.50	177656.72	98868.11	58004.92	32280.44
sm8	8.34	0.3207	3.91	2.105	1.25	0.68	295795.41	159245.36	94861.59	51069.99
sm9	18.19	0.3778	4.8	3.075	1.81	1.16	661824.00	423981.00	250037.11	160180.02
sm10	11.49	0.338	4.8	2.828235	1.62	0.96	491136.00	289385.04	166003.97	97812.14
sm11	13	0.3722	5.71	3.67	2.13	1.37	550261.28	353670.56	204807.25	131636.18
sm12	7.86	0.3179	2.83	1.185455	0.90	0.38	189015.70	79176.51	60088.09	25170.21
sm13	16.64	0.3723	4.67	2.052143	1.74	0.76	576698.30	253419.12	214704.78	94347.94
sm14	10.68	0.3316	4.33	2.762727	1.44	0.92	293677.92	187379.21	97383.60	62134.95
sm15	8.77	0.3401	4.06	1.979091	1.38	0.67	237148.66	115600.68	80654.26	39315.79

APPENDIX I

MATLAB CODE

DETERMINING NDVI AND SURFACE AREA FROM MULTISPECTRAL IMAGES

% This program will calculate the NDVI for each images

```
I1=imread('c1.tif');                    % read the image
I2=imcrop(I1);                          % crop the image

IR=I2(:,:,1);                           %IR band
RED=I2(:,:,2);                          %RED band
GREEN=I2(:,:,3);                        %GREEN band
figure
subplot(2,2,1),imshow(I2)               %Display the images
title('Original image')
subplot(2,2,2),imshow(IR)
title('IR')
subplot(2,2,3),imshow(RED)
title('RED')
subplot(2,2,4),imshow(GREEN)
title('GREEN')
pixval on

%....................Display histograms for each band.........................
figure,imhist(IR)
title('IR histogram')
figure,imhist(RED)
title('RED histogram')
figure,imhist(GREEN)
title('GREEN histogram')

% .......................Calculate NDVI of the image........................
NDVI=(double(IR)-double(RED))./(double(IR)+double(RED));
figure,imshow(NDVI)
pixval on


%...................Calculate average NDVI & leaf area....................
% NDVI values of the vegetation is all positive,
% we can separate vegetation and the background using NDVI
% Determines the indices(k & l ) of array elements that meet a given logical condition
k=find(NDVI>0);
l=find(NDVI<0);

%....................Calculate average NDVI...............................
Average_NDVI=mean2(NDVI(k))

% Assign the values to the matix using k & l indices
NDVI(l)=0;
NDVI(k)=1;
figure,imshow(NDVI,[])

%........................Calculate average leaf area.......................
Area_vegetation=bwarea(NDVI)
```

APPENDIX J

REFLECTANCE DATA FOR CHLOROPHYLL CONTENT AND CONCENTRATION ESTIMATES

SAMPLE	NIR	Red	Green	$NDVI_{Green}$	NIR/Green	NIR/Red	$NDVI_{RED}$
sh1	80.04	105.77	117.72	0.2177	0.68	0.76	0.37
sh2	69.39	81.24	98.91	0.2061	0.70	0.85	0.40
sh3	74.86	102.37	103.74	0.2086	0.72	0.73	0.38
sh4	87.30	101.01	127.86	0.2727	0.68	0.86	0.43
sh5	71.62	106.88	124.37	0.2104	0.58	0.67	0.38
sh6	85.73	109.26	134.75	0.214	0.64	0.78	0.45
sh7	73.16	94.40	108.79	0.2224	0.67	0.78	0.40
sh8	77.58	107.745	131.31	0.2043	0.59	0.72	0.43
sm1	63.30	103.06	118.35	0.1209	0.53	0.61	0.33
sm2	70.09	105.22	128.49	0.142	0.55	0.67	0.36
sm3	65.91	112.76	132.28	0.1424	0.50	0.58	0.32
sm4	70.59	109.25	123.39	0.1747	0.57	0.65	0.36
sm5	73.25	97.92	112.80	0.221	0.65	0.75	0.39
sm6	56.50	97.34	129.56	0.107	0.44	0.58	0.32
sm7	71.45	110.10	131.25	0.1451	0.54	0.65	0.33
sm8	66.29	115.98	132.01	0.1234	0.50	0.57	0.32
sm9	75.97	118.75	144.82	0.1714	0.52	0.64	0.38
sm10	64.26	104.94	114.53	0.1308	0.56	0.61	0.34
sm11	74.57	115.55	136.71	0.1313	0.55	0.65	0.37
sm12	62.46	101.16	111.88	0.123	0.56	0.62	0.32
sm13	74.52	117.91	140.20	0.19	0.53	0.63	0.37
sm14	65.69	86.21	104.88	0.1355	0.63	0.76	0.33
sm15	71.09	96.75	102.37	0.1775	0.69	0.73	0.34
Sm16	49.57	65.37	80.71	0.103	0.61	0.76	0.30

APPENDIX K

CHLOROPHYL ANALYSIS AND ESTIMATION

sample	chlorophyll concentration, mg/kg	measured biomass, g	chlorophyll concentration, mg/g	chlorophyll Content, mg/plant	surface area, pixels	max. height, in.
sh1	8602.38	15.36	8.60	132.13	116940.00	4.15
sh2	9117.90	14.78	9.12	134.76	87821.00	3.81
sh3	8735.69	11.49	8.74	100.37	60838.00	5.33
sh4	9225.46	24.22	9.23	223.44	157450.00	4.97
sh5	8697.89	13.84	8.70	120.38	109110.00	5.06
sh6	9892.30	27.14	9.89	268.48	163040.00	6.47
sh7	8857.43	17.84	8.86	158.02	99364.00	5.20
sh8	9121.98	31.06	9.12	283.33	141970.00	6.89
sm1	9379.81	6.27	9.38	58.81	60198.00	3.43
sm2	8953.88	12.62	8.95	112.99	117920.00	5.42
sm3	10407.17	7.24	10.41	75.35	65742.00	2.84
sm4	10152.89	8.39	10.15	85.18	71969.00	4.29
sm5	9035.86	10.39	9.034	93.88	79336.00	4.29
sm6	9473.81	8.60	9.474	81.47	71523.00	4.10
sm7	9626.80	7.01	9.67	67.48	64136.00	2.77
sm8	10178.66	8.34	10.18	84.89	75651.00	3.91
sm9	10303.58	18.19	10.30	187.42	137880.00	4.80
sm10	10926.25	11.49	10.927	125.54	102320.00	4.80
sm11	9786.31	13.00	9.79	127.22	96368.00	5.71
sm12	11320.18	7.86	11.32	88.98	66790.00	2.83
sm13	10268.10	16.64	10.27	170.86	123490.00	4.67
sm14	9427.00	10.68	9.43	100.68	67824.00	4.33
sm15	9191.18	8.77	9.19	80.61	58411.00	4.06
sm16	4681.33	6.03	4.68	28.23	30949.00	5.00

biomass, pixels-in	Est. Biomass from Regression, g	NDVI*est. biomass	Chl. Content estimate	Chl. Concentration* Biomass^{-1} estimate	NDVI*biomass^{-1} estimate
485301.00	16.65	6.09	129.33	7.77	0.02
334598.01	12.13	4.87	107.86	8.89	0.03
324266.54	11.82	4.46	100.73	8.52	0.03
782526.50	25.57	11.05	215.94	8.44	0.02
552096.60	18.66	7.05	146.09	7.83	0.02
1054868.80	33.74	15.19	288.38	8.55	0.01
516692.80	17.60	7.01	145.41	8.26	0.02
978173.30	31.44	13.47	258.24	8.21	0.01
206479.14	8.29	2.70	70.08	8.45	0.04
639126.40	21.27	7.73	157.99	7.43	0.02
186707.28	7.70	2.44	65.41	8.50	0.04
308747.01	11.36	4.08	94.05	8.28	0.03
340351.44	12.31	4.82	107.14	8.71	0.03
293244.30	10.89	3.46	83.31	7.65	0.03
177656.72	7.43	2.42	65.19	8.78	0.04
295795.41	10.97	3.52	84.31	7.69	0.03
661824.00	21.95	8.29	167.76	7.64	0.02
491136.00	16.83	5.69	122.24	7.26	0.02
550261.28	18.60	6.92	143.84	7.73	0.02
189015.70	7.77	2.47	65.97	8.49	0.04
576698.30	19.40	7.22	149.04	7.68	0.02
293677.92	10.91	3.62	86.03	7.89	0.03
237148.66	9.21	3.13	77.57	8.42	0.04
154745.00	6.74	2.04	58.54	8.69	0.05

	r^2	Equation
Actual Biomass vs. Estimate Biomass	0.88	3E-05x + 2.0958
Chlorophyll Content/plant vs estimated Chlorophyll Content		
NIR/RED	0.15	296.8x-80.906
NIR/Green	0.05	184.13x+15.663
NDVI(green)	0.40	877.31x-25.093
Green	0.21	1.8855x-102.57
Red	0.11	1.6863x-48.73
NIR	0.58	5.7723x-283.11
NDVI(red)	0.75	1364.5x-370.41
Chlorophyll Content/plant vs. Biomass estimate		
NIR/RED	0.91	296.8x-80.906
NIR/Green	0.90	0.0004x+22.864
NDVI(green)	0.89	0.001x+43.335
Green	0.87	2E-6x+31.169
Red	0.86	2E-6+26.713
NIR	0.90	3E-6x+32.831
NDVI(red)	0.91	17.478x+22.82
Actual Chlorophyll Concentration vs. Estimated Chlorophyll Concentration		
NIR/RED	0.04	4e-6x+10.895
NIR/Green	0.03	-(4e-6)x+10.616
NDVI(green)	0.000004	-9e-8x+9.3978
Green	0.22	5e-8x+6.1959
Red	0.30	8e-8x+5.3436
NIR	0.05	4e-8x+7.9101
NDVI(red)	0.08	-0.7574x+15.569

VITA

Carol Lynn Cassel Jones

Candidate for the Degree of

Doctor of Philosophy

Thesis: PLANT CHARACTERISTIC ESTIMATION USING SONAR, MULTISPECTRAL REFLECTANCE, AND ELECTROMAGNETIC RESPONSE

Major Field: Biosystems Engineering

Biographical:

Personal Data: Born in Oklahoma City, Oklahoma, on August 15, 1956, the daughter of John L. and Arline C. (Boeckman) Cassel. Married to Fred E. Jones. One daughter, Kristin Katherine Stephens, born on December 15, 1984.

Education: Graduated from Edmond High School, Edmond, Oklahoma, in May 1974; received Bachelor of Science degree in Agricultural Engineering from Oklahoma State University, Stillwater, Oklahoma, in December 1977. Completed the requirements for the Doctor of Philosophy degree with a major in Biosystems Engineering at Oklahoma State University, July 2006.

Experience: Undergraduate research assistant for Dr. Gerald Brusewitz, Oklahoma State University Agricultural Engineering Department; Design Engineer, Worthington Pump Company, Shawnee, Okla.; Office Engineer, W. L. Somner, Inc., Oklahoma City, Oklahoma; Coordinator, Wheatbelt Educational Partnership, Dover, Okla.; Career Resource Network Manager, Oklahoma CareerTech, Stillwater, Okla.; and Research Engineer, Biosystems and Agricultural Engineering, Oklahoma State University

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Name: Carol L. Jones Date of Degree: July, 2006

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: PLANT CHARACTERISTIC ESTIMATION USING SONAR, MULTISPECTRAL REFLECTANCE, AND ELECTROMAGNETIC RESPONSE

Pages in Study: 120 Candidate for the Degree of Doctor of Philosophy

Major Field: Biosystems Engineering

Scope and Method of Study:

The goal of this study was to design, test and validate three methods of remotely estimating plant physical and physiological characteristics. A free-space parallel plate electrostatic sensing system operating at medium radio frequency range was used to estimate water content and plant dry biomass. An ultrasound distance sensing system and a multispectral imaging system was used to directly estimate plant height and top view surface area and indirectly estimate plant biomass. NDVI was calculated from the multispectral imaging system data. Combining NDVI with the plant height and top view surface area estimates, a correlation was observed between plant biomass, chlorophyll content and chlorophyll concentration.

Findings and Conclusions:

Plant water content and dry biomass of greenhouse grown spinach were estimated using a free-space electrostatic sensing system ($r^2 = 0.95$)

Ultrasonic sensor-based height estimates and top view surface area multispectral image data provided plant biomass estimates in corn and spinach ($r^2 = 0.85$ and 0.88). Estimates for snap beans were not as convincing ($r^2 = 0.52$).

Combining biomass estimates from the height and surface area data obtained by the ultrasonic distance sensor and the multispectral imaging system with $NDVI_{670}$ calculated from reflectance data from the imaging system provided strong correlations with chlorophyll content in spinach ($r^2 = 0.91$). This was an improvement from the chlorophyll content estimates using only $NDVI_{670}$. Correlations with chlorophyll concentration were weak. The strongest correlation was found using the reflectance ratio, NIR/Green ($r^2 = 0.30$).

ADVISER'S APPROVAL: Dr. Marvin L. Stone