THE DEVELOPMENT OF A DIELECTRIC BASED SOIL MOISTURE SENSOR

By

GREGORY JAMES ARNOLD

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1990

Submitted to the Faculty of
the Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1992

THE DEVELOPMENT OF A DIELECTRIC

BASED SOIL MOISTURE SENSOR

Thesis Approved:

Thesis Adviser

Ronald L. Elliott

Glenn A. Kranzler

Thomas C. Collins
Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to thank Dr. Marvin Stone for serving as my major adviser. His insights to the problems encountered during this project were very helpful, and his willingness to let me choose the path of this research broadened my engineering knowledge. I would like to thank my other committee members, Dr. Ron Elliott and Dr. Glenn Kranzler, for their proofreading and suggestions. I would also like to thank all of the faculty at the Agricultural Engineering department for the help and information that they gave me during my graduate work.

I would like to thank the staff at the Ag Engineering Lab for machining and constructing the equipment used in this project. A special thanks goes to Gordon Couger. Although his job title is Senior Software Specialist, he also has a good understanding of digital and analog electronics. Without his help in the initial stages of the sensor development, this project would have been intensely difficult, to say the least.

I would like to acknowledge all of the people at the agronomy research stations in Oklahoma. These people supplied the soils for this study and their cooperation was greatly appreciated. I would also like to thank Dr. James West in the Electrical Engineering department at OSU for taking the time to explain transmission line methods. His knowledge was very helpful in developing the model used for the analysis of dielectric properties.

A special thanks goes to my wife, Jamie. She has been very understanding about my unique working hours, and she has been behind me every step of the way. Also, my parents, grandparents, and great grandparents have always stressed education, and I would like to thank all of them for their support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

NOMENCLATURE

α	Attenuation constant
β	Phase constant
ε'	Dielectric constant or real permittivity
ε''	Dielectric loss factor
ε^*	Complex permittivity
ε_o	Permeability of free space
γ	Complex propagation constant
j	$\sqrt{-1}$
κ'	Relative dielectric constant
κ''	Relative loss factor
κ^*	Complex relative permittivity
μ'	Real permeability
μ''	Magnetic loss factor
μ^*	Complex permeability
θ	Volumetric moisture content
ρ	Density
σ	Dielectric conductivity
$\tan(\delta)$	Loss tangent
ω	Radian frequency

CHAPTER I

INTRODUCTION

Background and Need

The moisture content of soil is an important property that impacts many agricultural processes including irrigation scheduling, water infiltration, water runoff, and evapotranspiration. Currently, irrigation scheduling is difficult to implement and requires extensive knowledge of particular crops and soil types. It is common and sometimes necessary to over-water a crop to ensure that enough water is applied. An economical and relatively accurate soil moisture sensor could aid in the efficient application of water, thus conserving valuable water resources and decreasing the expense of irrigation. In addition, the sensor could be used to aid in the development of new irrigation scheduling methods for different crops by monitoring soil moisture activity.

There are many other uses for soil moisture information, but some of the more obvious areas where soil moisture data could be applied are hydrology, meteorology, and off-road vehicle mechanics. Hydrologists utilize soil moisture information to determine the runoff, infiltration, and percolation from a rainfall event. Meteorologists can use large-scale soil moisture information to aid in weather prediction. Finally, off-road vehicle designers are interested in the trafficability properties of moist soils.

For the applications discussed, it is desirable to use *in situ* soil moisture sensors that have the potential to be remotely observed. There are many devices currently available to measure soil moisture content, including resistance blocks, tensiometers, and soil psychrometers. These types of sensors can be used in coordination with a datalogger to obtain soil moisture information, but the sensors have problems with long-term stability and portability. The resistance blocks must be calibrated for each soil in which they are placed, since the saline concentration directly affects the conductivity of the resistance block, and the degradation of the sensor over time changes its calibration curve. Tensiometers are limited by their inability to measure the entire range of soil moisture content, and they are sensitive to temperature gradients between their various parts. The soil psychrometer is an effective device for measuring the relative humidity of the soil, but the thermocouple junction it uses to condense and evaporate water droplets must be kept clean to achieve long-term stability.

In academic research, two popular methods for determining the moisture content of soil are neutron scattering and loss of weight during oven drying. Neutron probes give a good measure of moisture content, but the radioactive source is expensive to purchase and difficult to license. Also, since there is a radioactive source, the neutron probe should be supervised at all times, minimizing the possibility for remote sensing. The oven drying method to determine moisture content is accurate and serves as a reference standard, but it is destructive, laborious, and the time required is on the order of days.

It would be advantageous to have an *in situ* soil moisture sensor to make irrigation scheduling and other processes requiring soil moisture information easier to implement. Ideally, the sensor should provide real-time soil moisture information in any soil type and should be a stand-alone unit, capable of remote operation.

Objective

The objective of this research was to develop a prototype dielectric soil moisture sensor. This objective was met by first developing a database of dielectric properties for a wide textural range of soils and then designing a prototype sensor based on the results of the dielectric properties tests.

CHAPTER II

LITERATURE REVIEW

The underlying reason that dielectric methods work for determination of soil moisture content is that the relative dielectric constant for water is near 80 and the relative dielectric constant of dry soil ranges from 2 to 5. The effective dielectric constant of moist soil is then primarily a function of the soil water content. Also, since the dielectric constant of dry soil does not vary greatly between soil types, the dielectric constants for different soil types at a given moisture content should be nearly the same.

There have been several successful attempts at using dielectric properties to determine soil moisture content. Time domain reflectometry (TDR) is a method that determines the dielectric constant of soil by measuring the time difference between the reflections of an electromagnetic pulse applied to a coaxial (or other geometry) sample cell with soil as the dielectric medium. The reflections occur at the cable-sensor interface and at the end of the sensor. The length of the electrode geometry and the time difference between the reflections provide the information needed for calculating the velocity of the electromagnetic waves in the soil medium. From the velocity of the electromagnetic waves, the dielectric constant of the soil can be found. Topp et al. (1980) showed that with TDR, the dielectric constant could be correlated directly with volumetric water content using a "universal" calibration curve which is relatively independent of soil type and density. Grantz et al. (1990), Van Wesenbeeck and Kachanoski (1988), and Herkelrath et al. (1991) have successfully used time domain reflectometry to measure soil moisture in field experiments. Although TDR is effective for determining the soil moisture content, the high-frequency equipment that is needed for the TDR unit makes this method quite costly.

Another dielectric method for determining the soil moisture content is to measure the capacitance of an arbitrary capacitor geometry using soil as the dielectric medium. The capacitance is directly related to the dielectric constant and can be correlated with moisture content. This method is particularly attractive, because the soil capacitor may be used as an active element in an oscillator circuit. The output of the circuit can then be correlated with moisture content. Dean et al. (1987) used a capacitance method to determine the moisture content of soils. The sensor that was developed produced accurate results within a given soil type, but the results varied significantly for different soils. Most of the soil types used in their experiment were not common agricultural soils, and the experimental design of the sensor test was not detailed enough to make assumptions about the major differences in sensor response for unlike soils. Cherniak (1964) also developed a dielectric soil moisture sensor which uses a capacitance method. Included in his study are the effects that temperature and frequency have on the dielectric constant of water and a description of the electromagnetic mechanisms at work within a dielectric sensor.

Selig and Mansukhani (1975) provide an excellent review of literature on dielectric properties of soil and suggest that a good frequency range for using the soil dielectric constant to measure soil moisture is 1 MHz to 100 MHz. This range was recommended because the loss tangent is small enough to minimize the effects of soil conductivity and the dielectric constant is better correlated. They also made the important point that the dielectric methods have been shown to work well for determining volumetric moisture content, but not for mass-basis moisture content.

Hipp (1974) discussed the variations in dielectric properties of moist soils with frequency, moisture content, and density. He illustrated that in the radio frequency (RF) to microwave frequency range, the density dependence of the dielectric constant of moist soil decreases as frequency increases. He also provided a detailed description of the method he used for determining the dielectric properties with transmission line methods.

Von Hippel (1961) also gave a detailed description of dielectric properties and their measurement. Dielectric fundamentals were presented, and a large database of dielectric properties for a diverse group of materials was included.

Nelson (1983) discussed a method of predicting the dielectric constant of particulate materials with equations that included the bulk density of the specific material. He showed that cube roots and square roots of the dielectric constants of particulate materials correlate nearly linearly with density. The choice of cube roots or square roots was dependent on the nature of the material under investigation. The materials used in the experiment were wheat, whole-wheat flour, and pulverized coal, and the cube root method fit those materials best. The use of a density correction factor may be necessary for determining the moisture content of soils, since the soil dielectric constant may be affected by soil bulk density. Although the materials used in his study are not particularly similar to moist soil, the methods used may provide a starting point for the development of a model that can be used with soil.

Ansoult et al. (1984) presented the statistical relationship between the dielectric constant and water content in a porous media. A model was developed to determine the absolute range of the dielectric constant given physical properties of the porous media. In a field application of a dielectric sensor, this research could provide a method of checking the sensor for faulty operation or other problems.

The literature contains many studies of soil dielectric properties in the RF to microwave frequency range, but literature that includes the development of a remote field sensor in these frequency ranges is less common. Birchak et al. (1974) developed a microwave probe to determine soil moisture content, but they required two different sensors for high and low moisture contents. Campbell (1988) tested the dielectric properties of a wide range of soils and investigated different methods of modeling the dielectric response of soils. Kraft (1987) presented a method of measuring the dielectric properties of soil and other geological materials in the 500 kHz to 5 MHz frequency range using a coaxial probe. Richards (1990) developed a fringe field capacitance sensor to determine the permittivity of moist soil in the 1 kHz to 20 kHz range.

CHAPTER III

MEASUREMENT OF SOIL DIELECTRIC PROPERTIES

The frequency range in which soil dielectric properties could be measured in this study was limited by the equipment available, which had a measurement frequency range of 400 kHz to 110 MHz. The measurement frequency range for this study was selected to be from 1 MHz to 100 MHz. An initial step in developing a dielectric soil moisture sensor is to determine the most suitable frequency in the 1 MHz to 100 MHz range for sensor operation. The most suitable frequency in this range is the frequency at which moisture content has the greatest relative effect on the dielectric constant and soil properties have the smallest relative effect on the dielectric constant.

Density and soil type have some effect on the dielectric constant of soil, but the effect for a wide range of soils was not known. Hipp (1974) discussed soil dielectric parameters as functions of frequency, density, and moisture, but the actual dielectric data for different soil types were limited. Two purposes were served by developing a database of dielectric properties for the soils being tested. The database documented the dielectric constant variations with frequency, soil type, density, and moisture content, and the database could likely be used to estimate the response of a prototype sensor in different soils.

Dielectric Properties of Materials

For a given electrode geometry - parallel plate, coaxial, or parallel wire - there are three electrical circuit elements at work: capacitance, inductance, and resistance. There are also three dielectric properties of materials which correspond to the magnitude of these circuit elements. They are permittivity, permeability, and conductivity, respectively. Of these properties, permittivity and conductivity are significantly affected by change in moisture content, and thus they are the properties of primary interest for this research.

Permittivity, ε^*, is a complex value which includes the real permittivity or dielectric constant (ε') and the complex loss factor (ε'').

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

The dielectric constant is proportional to the electrical capacity of a material, and the loss factor is proportional to the energy dissipated within the material. The relative permittivity, κ^*, is a ratio of the complex permittivity to free-space permittivity, ε_0. From this ratio, the relative dielectric constant, κ', and relative loss factor, κ'', arise.

$$\kappa^* = \kappa' - j\kappa'' \tag{2}$$

The conductivity, σ, is proportional to the loss within a dielectric medium and is directly related to the loss factor and radian frequency (ω) as shown in the following equation.

$$\sigma = \omega\varepsilon'' \tag{3}$$

The loss tangent, $\tan(\delta)$, is a dissipation factor, or a ratio of loss current to charging current. When the loss tangent is small, it indicates that capacitive reactance is larger than real resistance at the given frequency.

$$\tan(\delta) = \frac{\varepsilon''}{\varepsilon'} = \frac{\kappa''}{\kappa'} \tag{4}$$

Finally, the permeability, μ^*, has a real part, μ', which is related to the magnetization and an imaginary part, μ'', which is related to the magnetic losses in a coil.

$$\mu^* = \mu' - j\mu'' \tag{5}$$

As the dielectric constant affects the capacitance of a condenser, the permeability affects the inductance of a coil. Permeability has been shown to be near that of free space for most biological materials (Hipp, 1974), so its value is assumed constant in the analysis of the dielectric properties of soils.

Equipment

The laboratory dielectric properties tests were performed using a vector impedance meter, a coaxial sample cell, and a personal computer. A schematic of the equipment is shown in Figure 1. The impedance meter was linked to the coaxial cell by connecting the meter probe to the BNC connector on the cell. The personal computer, equipped with an IEEE-488 interface card, was coupled to the impedance meter by an IEEE-488 interface cable.

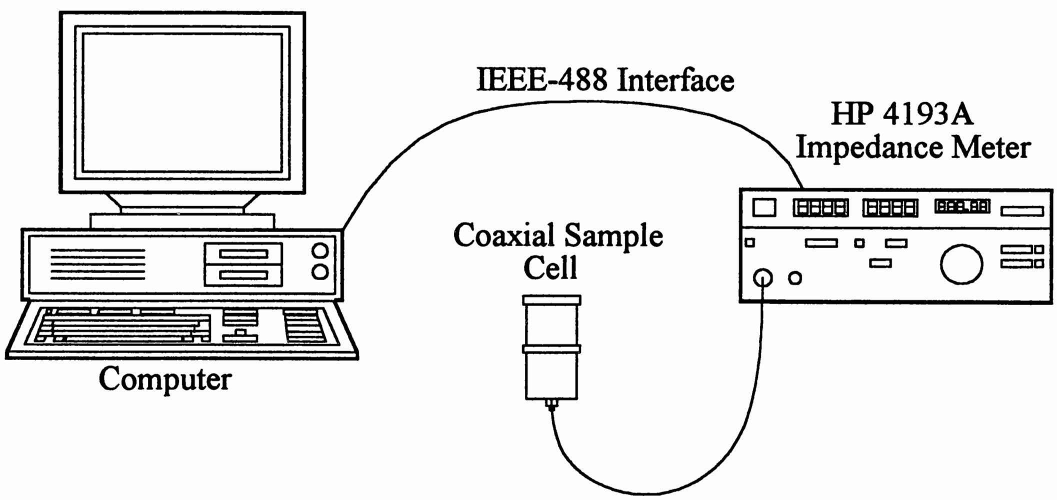

Figure 1. Schematic of equipment used for testing soil dielectric properties.

The equipment is controlled in the following manner. The computer sends a command through the IEEE-488 interface to set the measurement frequency of the impedance meter. The meter is given several seconds to stabilize, and then the computer sends another command to execute the impedance measurement of the coaxial cell. When the measurement is complete, the meter sends the impedance value back to the computer. The frequency and impedance data are then stored on the computer's hard disk drive. The control program in the computer then steps to the next frequency and repeats the above operations until all impedance measurements for the frequencies of interest have been performed. The following section gives a brief description of the equipment used for the dielectric properties tests.

Impedance Meter

A Hewlett Packard 4193A Vector Impedance Meter was used to measure the impedance of the coaxial cell. The meter displays the magnitude and phase of the device under test for frequencies from 400 kHz to 110 MHz. The magnitude was given in ohms, and the phase angle was given in degrees. The magnitude is multiplied by the cosine of the phase angle to yield real resistance and by the sine of the phase angle to yield complex reactance.

The IEEE-488 interface on the impedance meter allowed computer control of the signal frequency and a means of transferring the impedance data back to the computer for processing and storage on disk. Adapters to connect the meter probe to various test fixtures, including the BNC connector on the coaxial cell, were provided with the meter.

Coaxial Cell

The coaxial cell used to measure the dielectric properties was a modified version of the cell developed by Jorgenson et al. (1970). The cell consists of a center conductor, an outer conductor, a teflon ring that separates the upper and lower parts of the cell, a BNC connector, and a screw-on lid. For the cell used in this study, the primary differences from the cell designed by Jorgenson are that a BNC type connector is used as opposed to a N type connector and there is no series capacitor built into the lower portion of the cell. The cell was constructed of brass, and then the entire body and center electrode were silver plated to optimize the surface conductivity.

The characteristic impedance of the cell was designed to be 50 ohms and is actually 51.4 ohms. This design makes transmission line analysis simpler when using 50-ohm connections, because there is no unmatched impedance other than the soil sample impedance. A schematic of the coaxial test cell is shown in Figure 2.

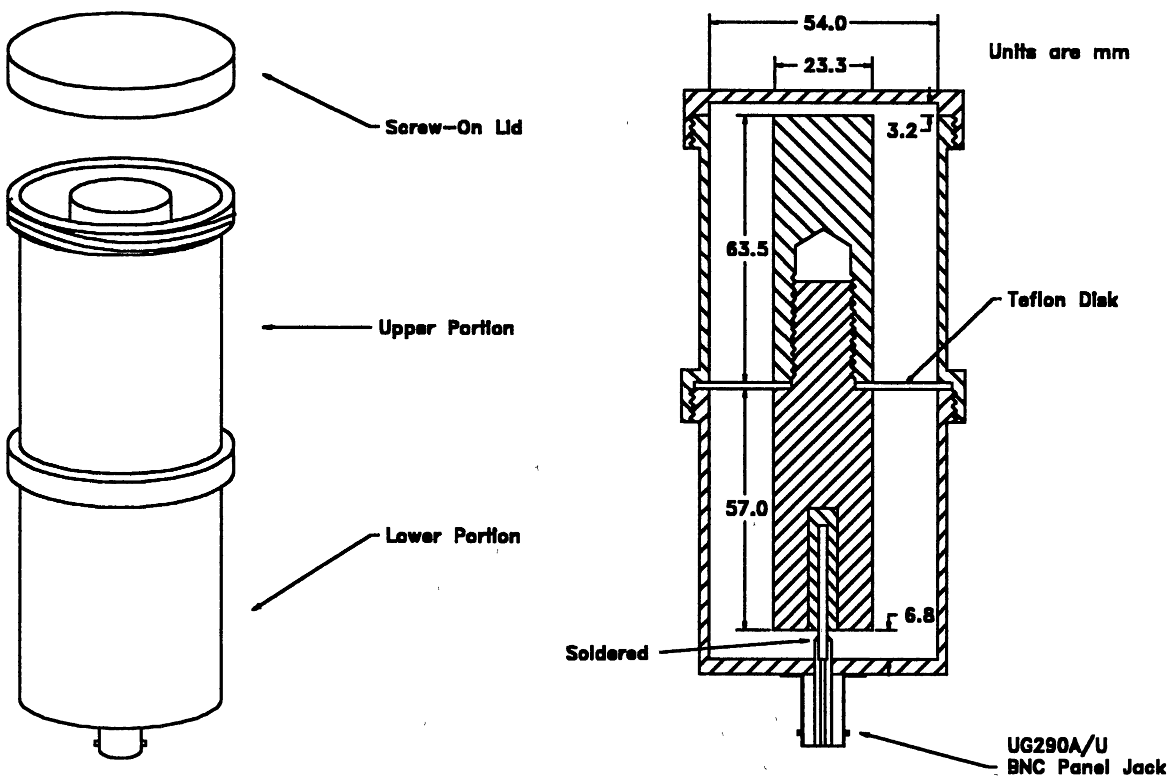

Figure 2. Schematic of the coaxial cell used to test the soils.

Personal Computer

The personal computer was used for measurement control, data acquisition, and data processing. An IEEE-488 interface card was used to control the impedance meter frequency and to transfer the data from the impedance meter to the personal computer. Computer programs were written for data acquisition and for converting the impedance data to dielectric properties data.

Procedure

Determining Dielectric Properties

Transmission line theory was used to calculate the dielectric properties, because the system being modeled behaved as both a lumped parameter circuit model and a distributed parameter circuit model, depending on the moisture content. The transmission line methods work for both conditions. For a lumped parameter circuit model, the device under test, in this case a coaxial line, is broken up into an equivalent circuit model where each electrical element is its own entity. For a coaxial cell with a lossy dielectric medium, it is generally represented by an inductor which is in series with a parallel capacitor-resistor combination. Once the model that approximates the frequency response of the actual circuit is developed, the impedance is separated into real and imaginary parts, and the dielectric properties are evaluated by using the coaxial cell geometry and the impedance equations for a resistor and a capacitor. The lumped parameter method is generally used for the analysis of dielectric properties when the wavelength is longer than the physical circuit. The physical circuit in this case is the coaxial cell containing an arbitrary dielectric medium.

At 100 MHz, the signal wavelength can approach the electrical length of the coaxial cell containing moist soil, depending on the moisture content of the soil. This condition occurs when the soil moisture content (dielectric constant) is large. When this is the case, the equivalent electrical circuit cannot be represented by a simple lumped circuit model. Rather, it behaves as a distributed circuit model. Since the analysis of a distributed circuit model greater than second order becomes difficult, transmission line theory (Cheng, 1983;

Von Hippel, 1961) was used to determine the dielectric properties of the soil. The advantages of using the transmission line method are that there is no requirement to model the coaxial cell as an equivalent circuit and the method works for lumped parameter and distributed parameter circuit models. The following discussion explains the transmission line methods used.

The general transmission line equation used to solve for the dielectric constant and conductivity is the input impedance equation:

$$Z_i = Z_o \frac{Z_L + Z_o \tanh \gamma\ell}{Z_o + Z_L \tanh \gamma\ell} \tag{6}$$

where

Z_i is the input impedance as seen by the impedance meter,
Z_o is the characteristic impedance of the transmission line,
Z_L is the load at the end of the transmission line or termination load,
γ is the complex propagation constant, and
ℓ is the length of the transmission line.

The characteristic impedance of a coaxial line depends on the properties of the dielectric medium and the inner and outer diameter of the coaxial conductors. The complex characteristic impedance of a coaxial transmission line is given as:

$$Z_o = \frac{j\omega\mu}{2\pi\gamma} \ln\frac{b}{a} \tag{7}$$

where

j is the square root of -1,
ω is the radian frequency,
μ is the permeability of the dielectric material,
γ is the complex propagation constant,
a is the inner conductor radius, and
b is the outer conductor radius.

The complex propagation constant, γ, is defined as:

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon')} \qquad (8)$$
$$= \alpha + j\beta$$

where

σ is the conductivity of the dielectric material,
ε' is the dielectric constant of the dielectric material,
α is the attenuation constant of dielectric material, and
β is the phase constant of dielectric material.

In the ideal case where the impedance measured is precisely the impedance of the sample under test and the method of circuit termination is exact, Equation 7 is sufficient to solve for the propagation constant. The propagation constant then provides the information needed to determine dielectric properties. In this case, the sample being tested occupies only the upper half of the coaxial cell, and the BNC connector introduces an unknown impedance. In order to determine the impedance of the upper portion of the cell, the impedance of the lower portion of the cell and the BNC connector must be removed from the measured impedance.

In order to obtain the impedance of the upper portion of the cell, the following method was used. (1) The electrical length of the entire coaxial cell and BNC connector was determined using air as the dielectric medium and an open-circuit termination. (2) The known conductor dimensions of the coaxial cell and the length of the sample portion of the cell were used to calculate the impedance of the upper portion of the cell. (3) The impedance of the upper portion of the cell was calculated by manipulating Equation 6. The following paragraphs operationally describe how these procedures were accomplished.

For an open circuit termination and a lossless line, the input impedance is given by the following equation:

$$Z_i = Z_O \coth(j\beta\ell) \qquad (9)$$

By rearranging Equation 9 and using simplifications for complex math functions, the electrical length of the cell and BNC connector can be represented as

$$\ell = \frac{1}{\beta}\cot^{-1}\left(\frac{j\,Z_i}{Z_O}\right) \qquad (10)$$

The electrical length of the air-filled coaxial cell and BNC connector was found for all test frequencies using Equation 10. The variables needed to determine the electrical length were either known or measured values. The characteristic impedance of the air-filled cell was found to be 51.4 ohms using Equation 7, and the characteristic impedance of the BNC connector was known to be 50 ohms. The phase constant for air was calculated using free-space dielectric properties in Equation 8. Finally, the input impedance was measured with the impedance meter.

Once the electrical length of the air-filled coaxial cell was known, the impedance of the BNC connector and the lower portion of the cell was calculated. This was done by subtracting the length of the sample portion of the cell from the electrical length, and then using this length in Equation 9. The transmission line equation was then altered to solve for the impedance of the upper portion of the coaxial cell where the sample under test was held. This is referred to as the interface impedance and is found by solving for the load impedance given the measured impedance:

$$Z_{int} = Z_O \frac{Z_{meas} - Z_O \tanh \gamma\ell}{Z_O - Z_{meas} \tanh \gamma\ell} \qquad (11)$$

where

Z_{int} is the impedance of the upper portion of the coaxial cell and
Z_{meas} is the impedance value obtained from the meter.

After the impedance of the sample portion of the coaxial cell was calculated, the complex propagation constant, $\gamma = \alpha + j\beta$, for the soil medium was found by using an iterative procedure in a computer program to solve the open circuit termination equation for impedance. This was done by using an open circuit termination in Equation 6 and by substituting the characteristic impedance with the contents of Equation 7. This allows the characteristic impedance to be expressed in terms of the dielectric properties, and the following equation results:

$$Z_{int} = \frac{j\omega\mu}{2\pi\gamma} \ln\frac{b}{a} \coth \gamma\ell \tag{12}$$

Once the propagation constant (attenuation factor and phase constant) is known, the assumption of free-space permeability allows the dielectric conductivity and dielectric constant to be calculated. The relative dielectric constant can then be derived from the ratio of the dielectric constant to the permittivity of free space. These properties are shown in the following equations:

$$\varepsilon' = \frac{\beta^2 - \alpha^2}{\omega^2\mu} \tag{13}$$

$$\sigma = \frac{2\alpha\beta}{\omega\mu} \tag{14}$$

$$\kappa' = \frac{\varepsilon'}{\varepsilon_o} \tag{15}$$

Without the assumption of free space permeability, additional measurements or different methods would be required to obtain the values for dielectric constant and conductivity. Tests that Hipp (1974) performed on two typical soils indicated that the assumption of free-space permeability is valid. However, problems could possibly arise if a soil with high iron content is encountered. An example calculation to determine the dielectric properties of a sample, given the impedance of the coaxial cell, is given in Appendix C.

Measurement Accuracy

In order to check the accuracy of measuring dielectric properties with the transmission line method, a test was performed using heptanol (C_7H_6O). This substance was used because there are published values for its dielectric properties over a wide frequency range (Buckley and Maryott, 1958). The heptanol was placed in the coaxial sample holder, and the impedance values for twelve frequencies in the 1 to 100 MHz range were recorded. The data were then processed using a computer program to obtain the dielectric properties. A comparison of the measured properties to the published properties is shown in Figure 3. The predicted values for the relative dielectric constant are a good approximation of the published values, but there is some deviation at higher frequencies. This may be partially explained by error in the measured length of the sample portion of the coaxial cell, but the purity of the heptanol is another possible reason for this deviation. Water vapor from the air may have been absorbed by the heptanol during testing, and residue inside the cell may have also affected the dielectric properties of the heptanol. As a standard method of giving bounds on the error, the probable error, e_p, is used. The probable error is defined as the standard deviation multiplied by 0.674. A range of the estimated value plus or minus e_p includes the true value 50 percent of the time (Doeblin, 1990). The measurement error for the dielectric properties is small. The standard deviation of the error for relative dielectric constant and relative loss factor are given in Table 1. As a result of the calibration test, the error associated with measuring the dielectric properties was considered negligible.

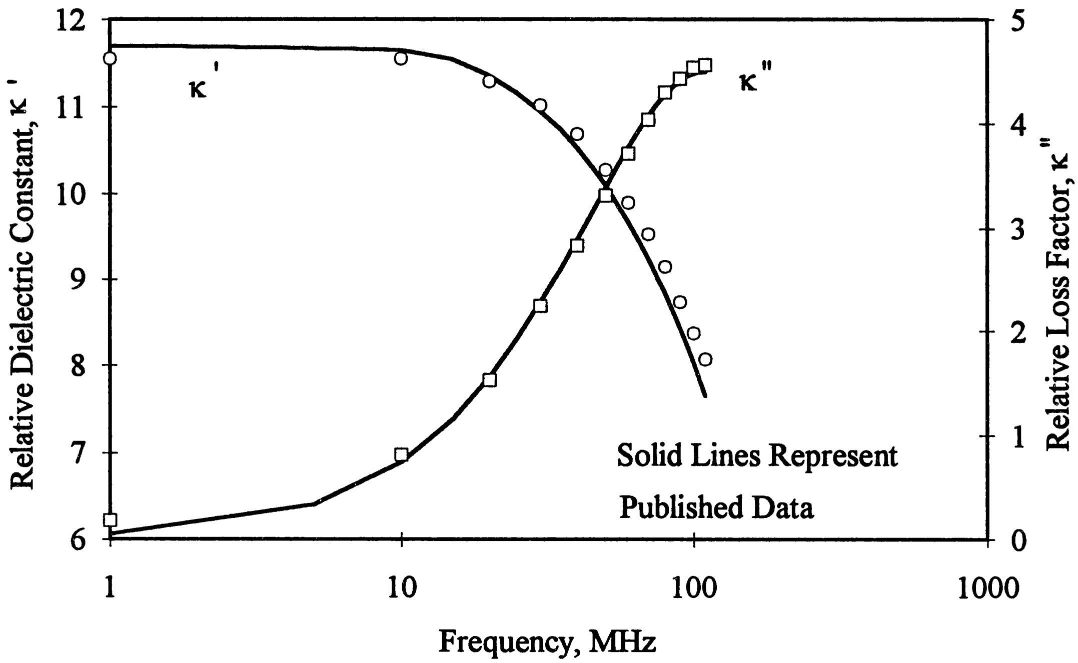

Figure 3. Comparison of published data with measured data for heptanol.

TABLE 1

CALIBRATION STATISTICS FOR HEPTANOL

Parameter	Relative Dielectric Constant	Relative Loss Factor
Standard Deviation	0.189	0.055
Probable Error	±0.127	±0.040

Soil Preparation

The purpose of the dielectric property tests was to determine the effect that volumetric moisture content, frequency, soil type, and density have on the dielectric properties of moist soils. Test parameters that could be reasonably set for all soils were frequency and volumetric moisture content at a given density. For this experiment, ten soils from various agronomy research stations in Oklahoma, three densities, and four volumetric moisture contents were selected. Volumetric moisture contents were centered around 0, 10, 20, and 30%. The soils were tested at four frequencies - 1, 10, 50, and 100 MHz. Particle size distribution tests were performed on the soils used in this experiment, and the results are presented in Appendix B, Table 10. Using the particle size distribution tests, the soils were classified into groups. Both the USDA and ISSS classifications (Hillel, 1982) for the soils are listed in Table 2. The USDA classification system was used for the soil groups listed in the thesis, but the ISSS classes are included in the table for readers familiar with this system.

TABLE 2

SOIL CLASSIFICATION ACCORDING TO PARTICLE SIZE DISTRIBUTION

Location	USDA Classification	ISSS Classification
Altus	Silty Clay Loam	Clay Loam
Chickasha	Silt Loam	Sandy Clay Loam
Ft. Cobb	Loamy Sand	Sand
Goodwell	Loam	Sandy Loam
Haskell	Silt Loam	Sandy Loam
Lahoma	Clay Loam	Sandy Clay Loam
Mangum	Sand	Sand
Perkins	Loam	Sandy Loam
Stillwater	Clay Loam	Sandy Clay Loam
Tipton	Loam	Sandy Loam

Since density is somewhat dependent on soil type, the following method was used for establishing the soil bulk density for each soil. (1) The soil was oven-dried for a period of 48 hours to remove virtually all of the moisture. (2) Oven-dried soil was poured into a container of known volume with only enough packing to settle the soil, and the density that resulted was recorded. (3) Dry soil was manually packed as tightly into the container as possible, and the resulting density was recorded. (4) The average of the minimum and maximum densities was used as the reference bulk density for that particular soil. This reference bulk density was rounded to the nearest tenth and used as one of the three density values. The other two densities used were 0.1 g/cc greater and less than the reference density. For example, if the reference density was 1.3 g/cc, the three densities used for that particular soil would be 1.2, 1.3, and 1.4 g/cc. The densities used for each soil type are given in Table 3.

TABLE 3

SOIL BULK DENSITIES FOR TESTS

	Soil Bulk Density in Grams Per Cubic Centimeter		
Location	Low	Reference	High
Altus	1.2	1.3	1.4
Chickasha	1.2	1.3	1.4
Fort Cobb	1.3	1.4	1.5
Goodwell	1.2	1.3	1.4
Haskell	1.1	1.2	1.3
Lahoma	1.1	1.2	1.3
Mangum	1.4	1.5	1.6
Perkins	1.2	1.3	1.4
Stillwater	1.2	1.3	1.4
Tipton	1.2	1.3	1.4

The soil samples were stored in sealed liter jars, using four jars per soil type (one for each moisture content). The following method was used to set the moisture content to the desired value. (1) Pour oven-dried soil into a container until there is enough soil volume to fill the coaxial test cell at least three times, and record the mass of the soil. (2) Use the reference density to compute a reference volume that the mass of soil must occupy to have the specified reference density. (3) Calculate the volume of water required to obtain the desired volumetric moisture content using the reference volume, and mix that volume of water into the soil by adding "layers" of soil and water. (4) Allow the soils at least five days to equilibrate. Also, during the equilibration period the containers were agitated to mix the soil and speed the moisture distribution. This method of setting the volumetric moisture content was adequate for all of the soil types used in this study, except for the Chickasha soil. The Chickasha soil was calculated to be at 37 percent volumetric moisture content rather than 30 percent volumetric moisture content. A possible explanation for the deviation is a measurement error when the water was added to the soil. Although the moisture content deviation shifts the data to a point where a direct comparison with other data is more difficult, the data are still valid for the Chickasha soil.

Since the volume of the coaxial cell is known, the reference density, initial water content, and the desired density can be used to calculate the mass of soil needed in the cell to obtain the desired density. This relation is given in the following equation.

$$m = \rho_d V + \frac{\rho_d}{\rho_r} \rho_w \theta_o V \tag{16}$$

where

m = mass of soil needed for desired density,
V = sample volume of the coaxial cell,
ρ_d = desired soil density,
ρ_r = reference soil density,
ρ_w = density of water, and
θ_o= soil volumetric water content.

A soil prepared using the above method should have the desired volumetric moisture content at the reference density. However, when the density deviates from the reference density, the resulting volumetric moisture content will be lower when the density is set to a value less than the reference density and higher when the density is set to a value greater than the reference density. The reason is that when an arbitrary amount of moist soil is placed into or taken out of the same volume, the amount of water within that volume increases or decreases, respectively.

This method of density variation was chosen over the use of individual containers, since the number of containers needed for the experiment would have tripled. Also, it was sufficient for the experiment to have the soil at either a constant volumetric moisture content or a constant density. Constant density was selected.

Soil Testing

The dielectric property tests were performed using the Hewlett-Packard 4193A vector impedance meter and the coaxial sample cell. The soils were placed in the coaxial cell and tested, and the resulting impedance data were then saved to a floppy disk. These data were then processed with another program to obtain the dielectric properties. Room temperature was recorded during the tests, and it remained between 24 and 25 C. Since the temperature change was small, and since the dielectric constant of moist soil is not extremely dependent on temperature (Cherniak, 1964), the effect of temperature on dielectric properties was not considered in the analysis of data.

The mass of soil needed in the coaxial cell in order to obtain the desired density was determined by using Equation 16 and the initial properties of the soil under observation. Once the mass of soil needed was known, the soil was packed into the cell. This task was broken into two parts. First, the cell was filled with half of the soil mass required and the soil was packed to a volume slightly greater than half of the sample portion of the cell.

Next, the remainder of soil was placed in the cell and packed until the soil was flush with the top of the cell. The soil-filled cell was then weighed to verify that the mass of soil added was correct. In the case where soil spilled over the edge of the cell during filling, soil was added to the cell until the problem was corrected. The instrument used for packing the soil was a piece of thick-wall plastic tubing. The inside and outside diameter of the tubing nearly matched the distance between the inner and outer conductors of the coaxial cell. The outside diameter of the tubing was slightly less than the diameter of the outer conductor, and the inside diameter of the tubing was slightly greater than the diameter of the inner conductor. These dimensions allowed the tubing to slide over the center conductor and pack the soil into the cell. After the soil was packed in the cell, the lid was screwed onto the cell, and the computer program to acquire the impedance data was executed. The impedance data were then processed at a later date by a different computer program which converted the impedance values to dielectric properties.

Following the impedance measurements, the soil was removed from the coaxial test cell and placed in a numbered metal container for drying. The mass of the empty container was recorded and the mass of the container plus the moist soil was recorded. After several of the soil-filled cans had accumulated, the soils were oven-dried for a 48-hour period at a temperature of 110 C, and the weight of each container plus dry soil was recorded. By using the weight of water in the soil and assuming a value of 1 gram per cubic centimeter for the density of water, the volume of water that occupied the soil was calculated. This volume of water was then used with the coaxial cell volume to arrive at the volumetric moisture content of the particular soil being investigated. The actual volumetric water content was then matched with the test data by using the numbered containers.

Discussion of Dielectric Property Tests

Frequency

The objectives of the dielectric property tests were to determine the effects of frequency, density, soil type, and moisture content on the dielectric constant of moist soils. The effect of frequency is quite easily seen in Figures 4-7. The data points at 1 MHz are very scattered, and although a relationship between moisture content and the dielectric constant can be seen, the predicted error associated with estimating the moisture content from a dielectric constant is large. The 10 MHz data of Figure 5 are less scattered than the 1 MHz data, but there is still considerable variance. The trend seen in the graphs is that for the 1 to 100 MHz frequency range, density and soil type have less effect on the dielectric constant at higher frequencies. Also, a desirable characteristic for a capacitance type of sensor is for the loss tangent (dielectric loss) to be small. Figure 8 shows that for 50 and 100 MHz the loss tangent is quite small compared to the 1 and 10 MHz data. In light of the results from the dielectric properties tests, the operating frequency for the prototype sensor was chosen to be near 100 MHz, and most of the following discussion applies to 100 MHz data.

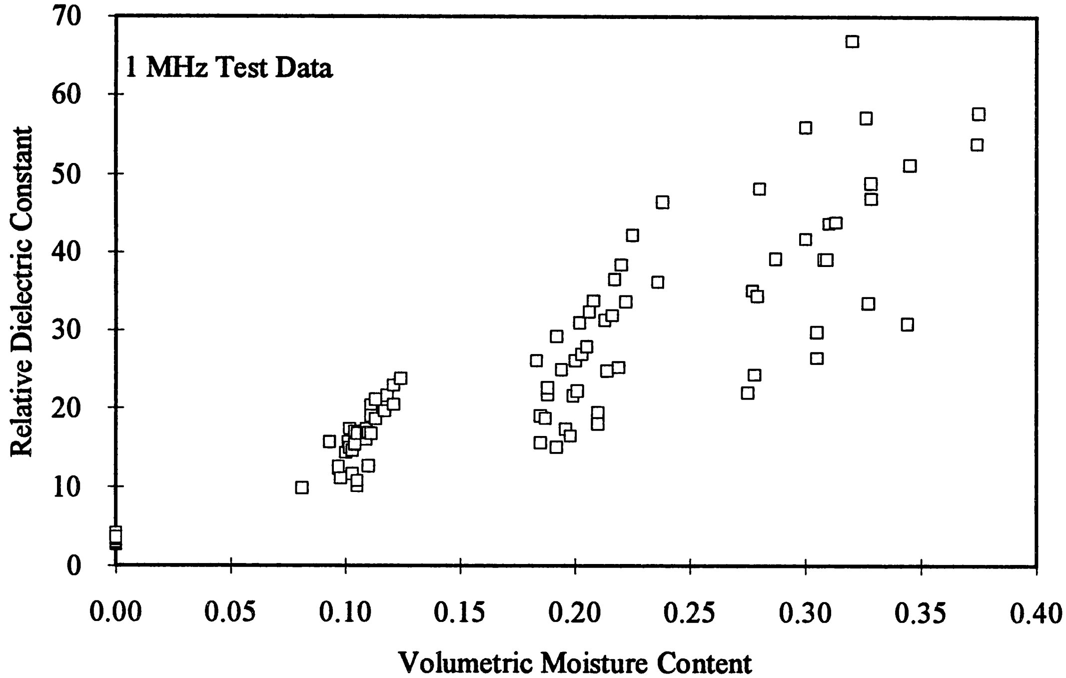

Figure 4. Relative dielectric constant for all soil types and densities at 1 MHz.

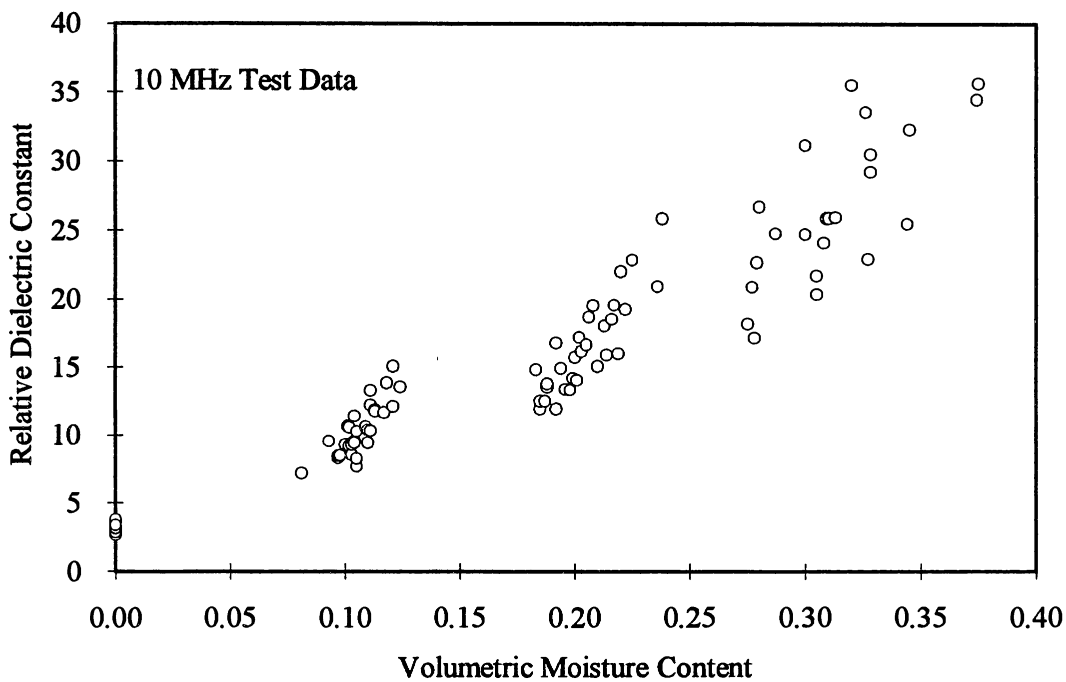

Figure 5. Relative dielectric constant for all soil types and densities at 10 MHz.

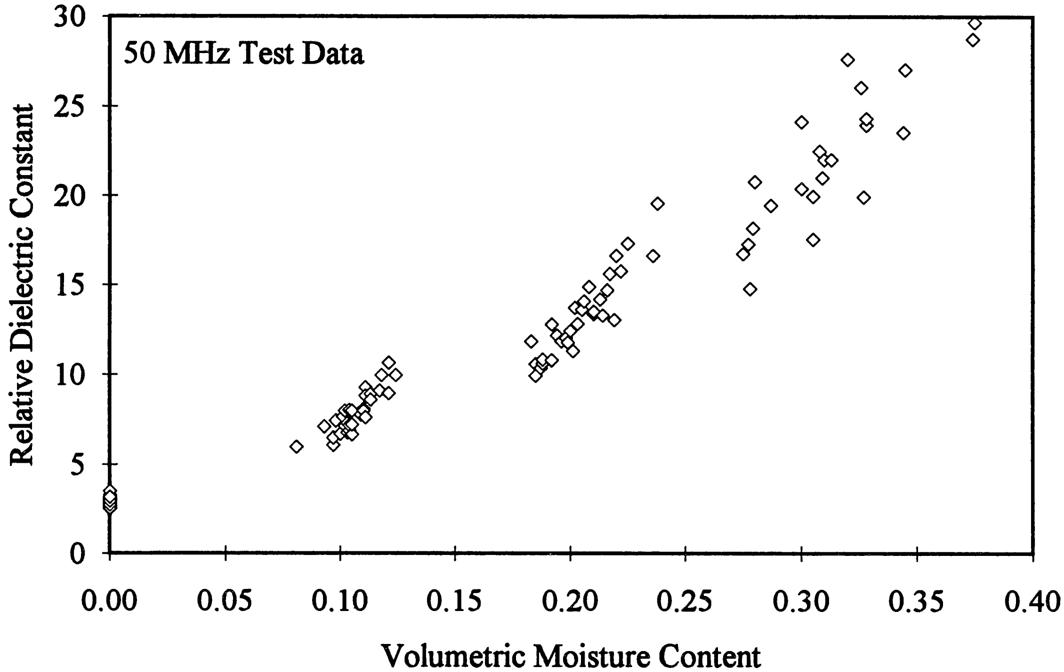

Figure 6. Relative dielectric constant for all soil types and densities at 50 MHz.

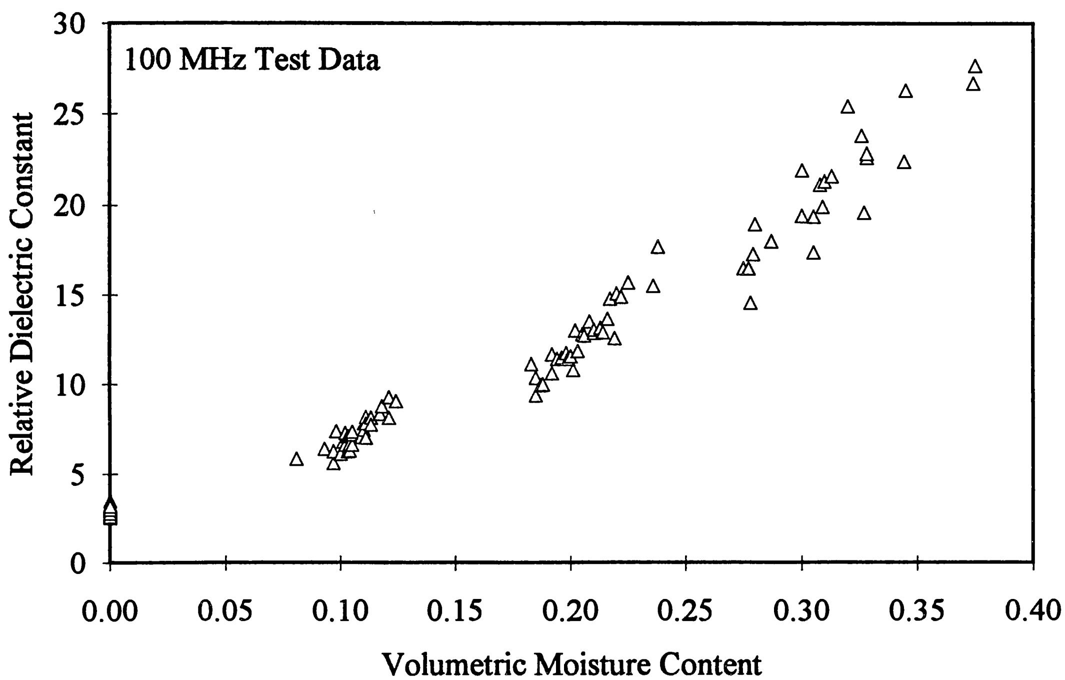

Figure 7. Relative dielectric constant for all soil types and densities at 100 MHz.

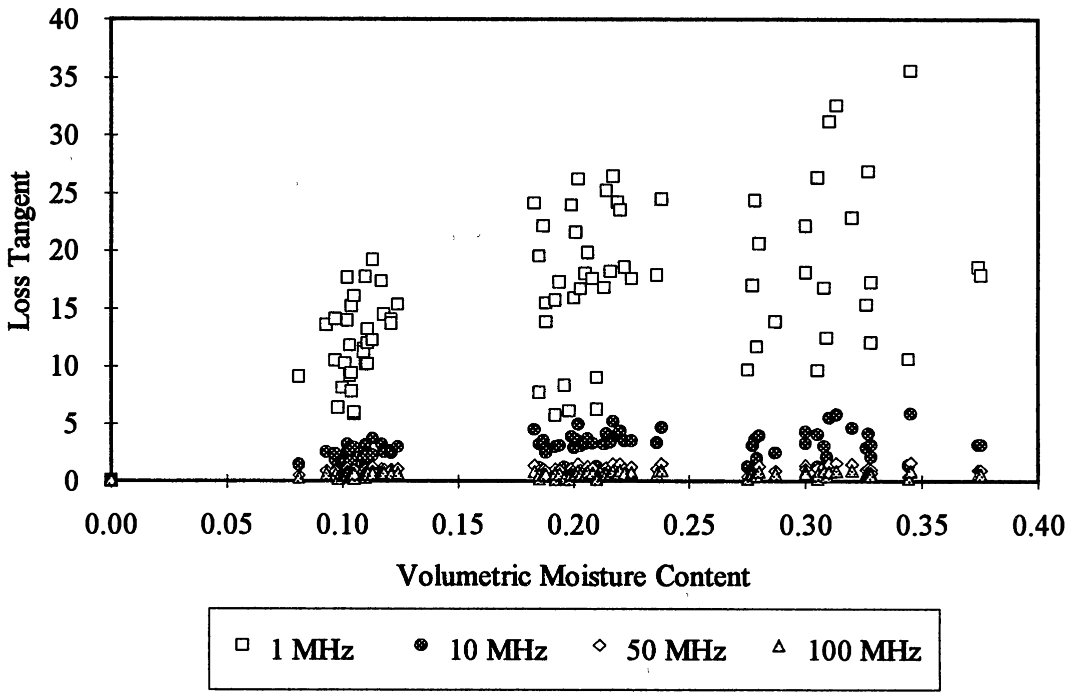

Figure 8. Loss tangent values at different frequencies for all soils and densities.

Soil Type and Density

As shown in Figure 9, the regression curve for the relative dielectric constant at 100 MHz, as related to volumetric moisture content for all of the data taken in this experiment, can be well represented by the following equation:

$$\kappa' = 3.03 + 0.261\theta + 0.0100\,\theta^2 \qquad r^2 = 0.978 \qquad (17)$$

where

κ' = relative dielectric constant and
θ = the volumetric moisture content.

The relationship has a high coefficient of determination, but the variance for this model increases with moisture content. A possible reason is the varying degree of electro-chemical activity in different soils. Clay exhibits strong electro-chemical reactions when moisture is added (Hillel, 1982), and the percentage of clay in a moist soil could affect its dielectric properties.

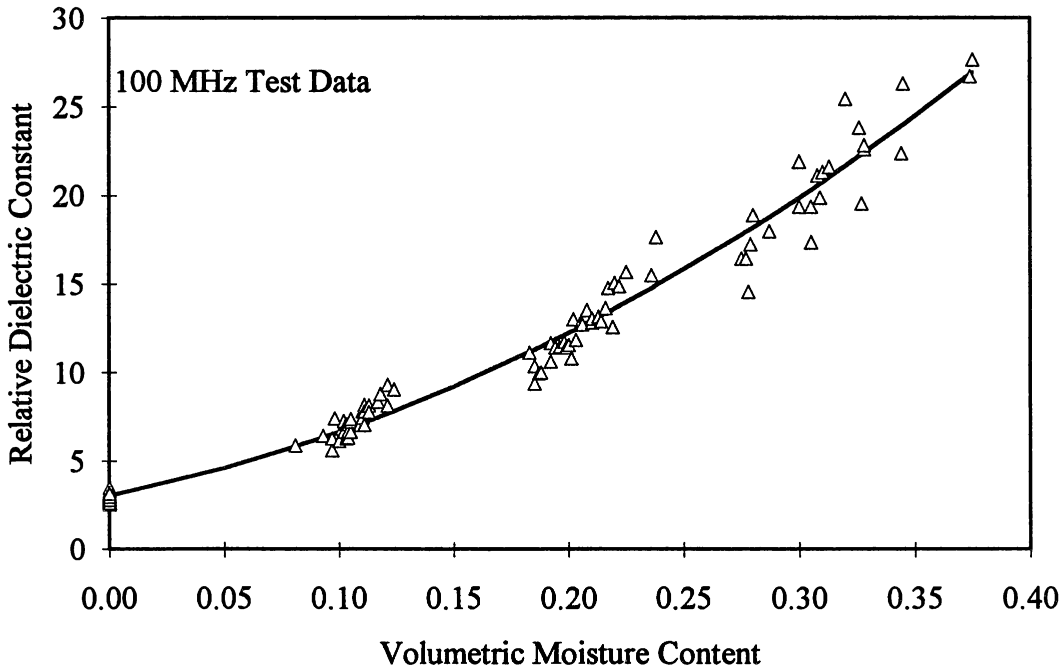

Figure 9. Regression of the 100 MHz data using all densities and all soil types.

Within a particular soil type, the error is considerably reduced. The soils were placed into groups of similar soil texture, as shown in Table 4. All of the soils are grouped under their USDA classification name, with the exception of the Fort Cobb soil. The Fort Cobb soil was placed in the same group as the Mangum soil because the difference between the soils in the particle size distribution tests was small.

TABLE 4

SOIL GROUPS OF SIMILAR TEXTURE

Group	Location	USDA Classification
Clay Loam	Lahoma	Clay Loam
Clay Loam	Stillwater	Clay Loam
Loam	Goodwell	Loam
Loam	Perkins	Loam
Loam	Tipton	Loam
Sand	Fort Cobb	Loamy Sand
Sand	Mangum	Sand
Silty Loam	Chickasha	Silty Loam
Silty Loam	Haskell	Silty Loam
Silty Clay Loam	Altus	Silty Clay Loam

The sensor results for the different groups are shown in Figures 10 through 13. The regression equations and the coefficients of determination for the four soil groups are given as follows:

Clay Loam $\kappa' = 3.00 + 0.271\theta + 0.00989\theta^2$ $r^2 = 0.985$ (18)

Loam $\kappa' = 3.04 + 0.251\theta + 0.0109\theta^2$ $r^2 = 0.989$ (19)

Sand $\kappa' = 3.01 + 0.295\theta + 0.00763\theta^2$ $r^2 = 0.994$ (20)

Silty Loam $\kappa' = 3.02 + 0.201\theta + 0.0108\theta^2$ $r^2 = 0.974$ (21)

where

κ' = relative dielectric constant and
θ = volumetric moisture content.

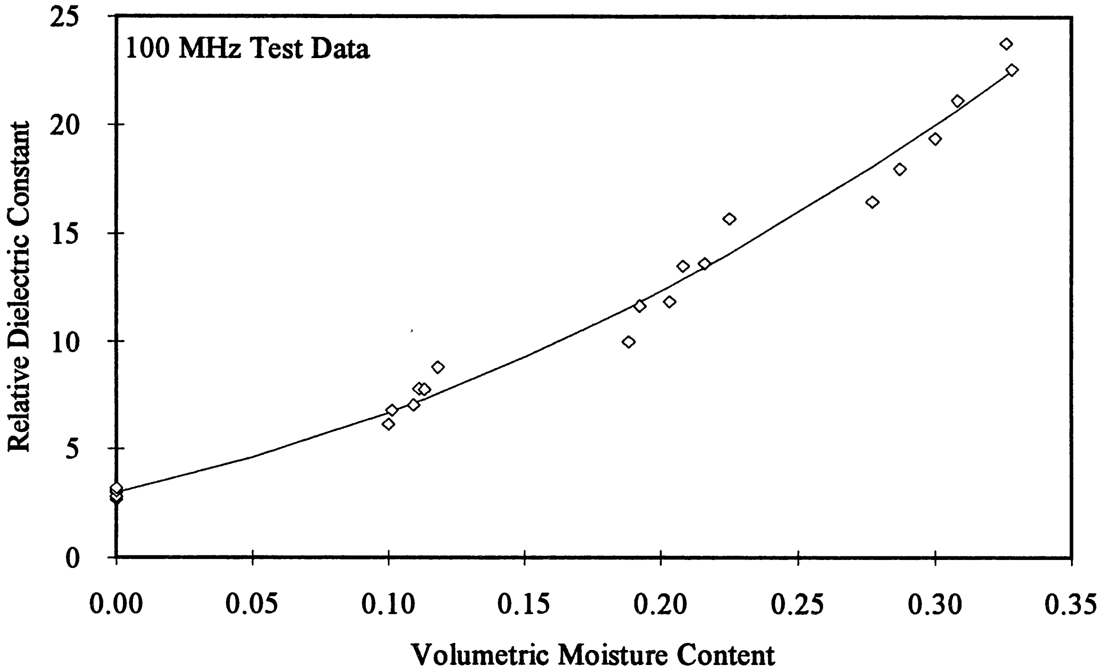

Figure 10. Relative dielectric constant for the clay loam group at 100 MHz.

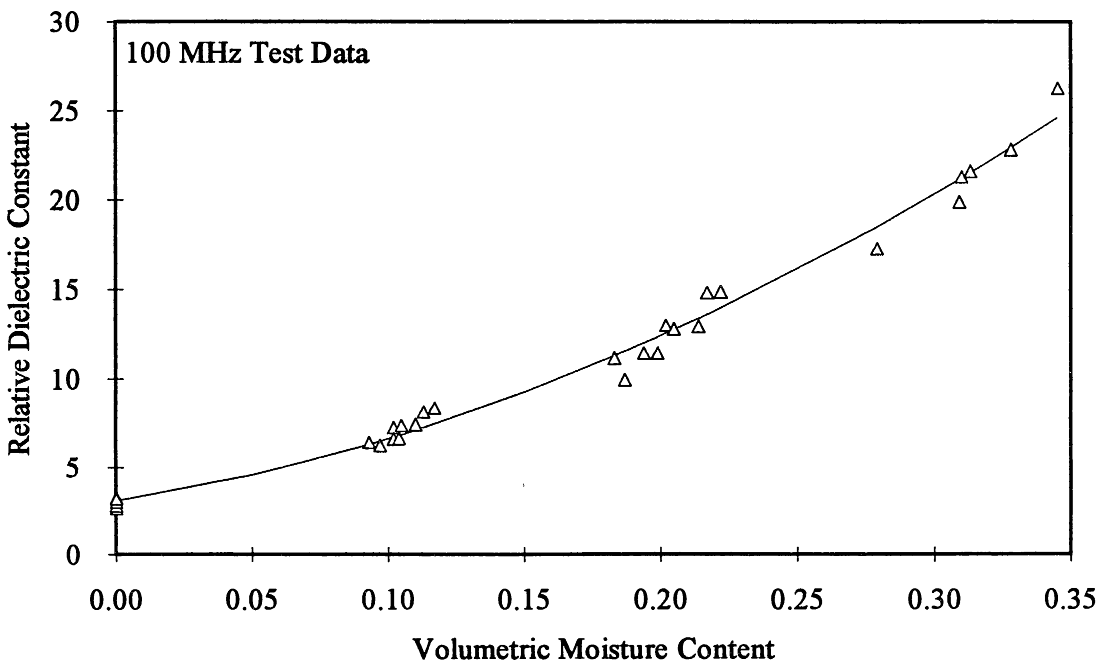

Figure 11. Relative dielectric constant for the loam group at 100 MHz.

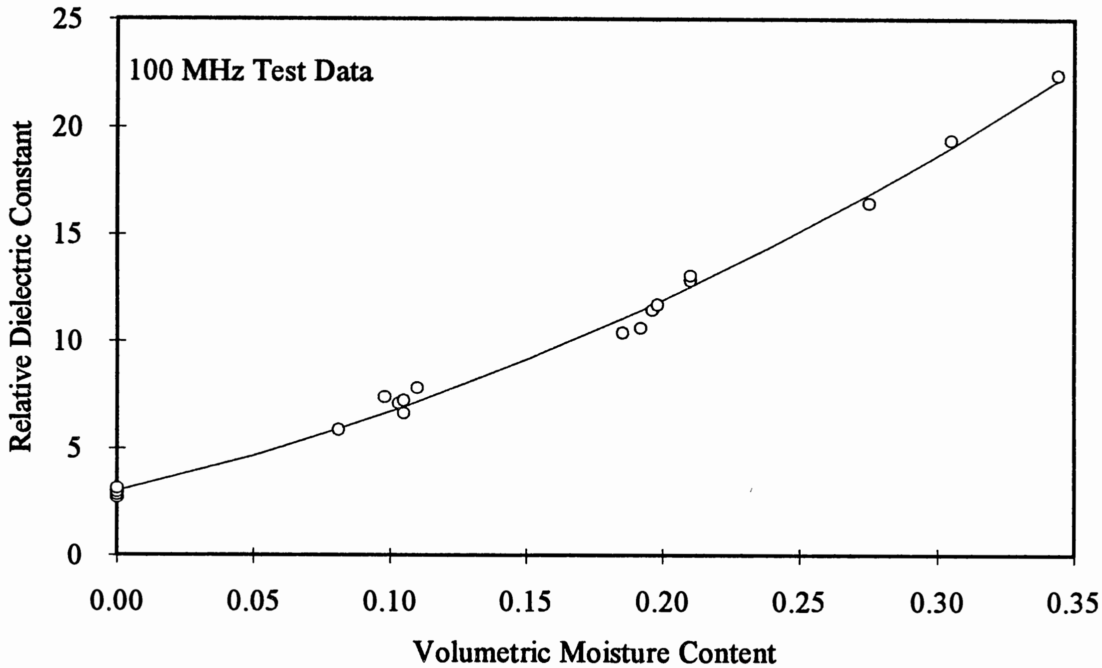

Figure 12. Relative dielectric constant for the sand group at 100 MHz.

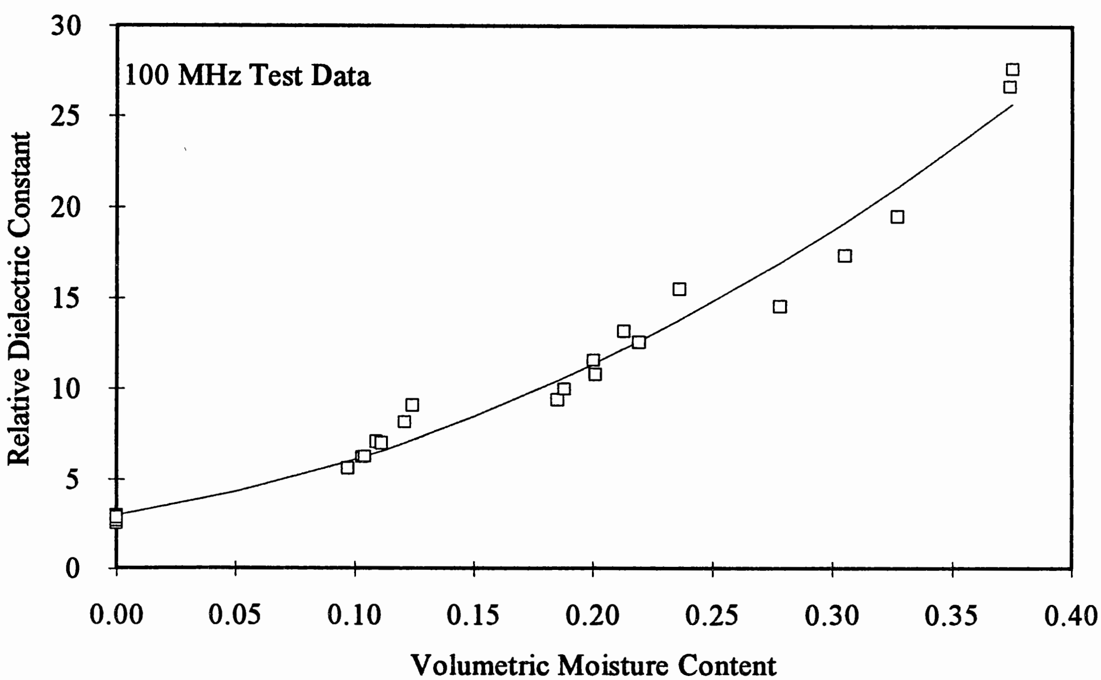

Figure 13. Relative dielectric constant for the silty loam group at 100 MHz.

The Altus soil (silty clay loam) represents a fifth "group". Since it is different from the other soils, it is used to illustrate the density dependence of the dielectric constant in Figure 14. Increased density produces a greater dielectric constant for a given moisture content. Figure 14 also shows that the dielectric constant for the soil-water mixture is not a purely linear mixing model or a mass average model. The difference in dielectric constants between lines of constant density increases with increased moisture content.

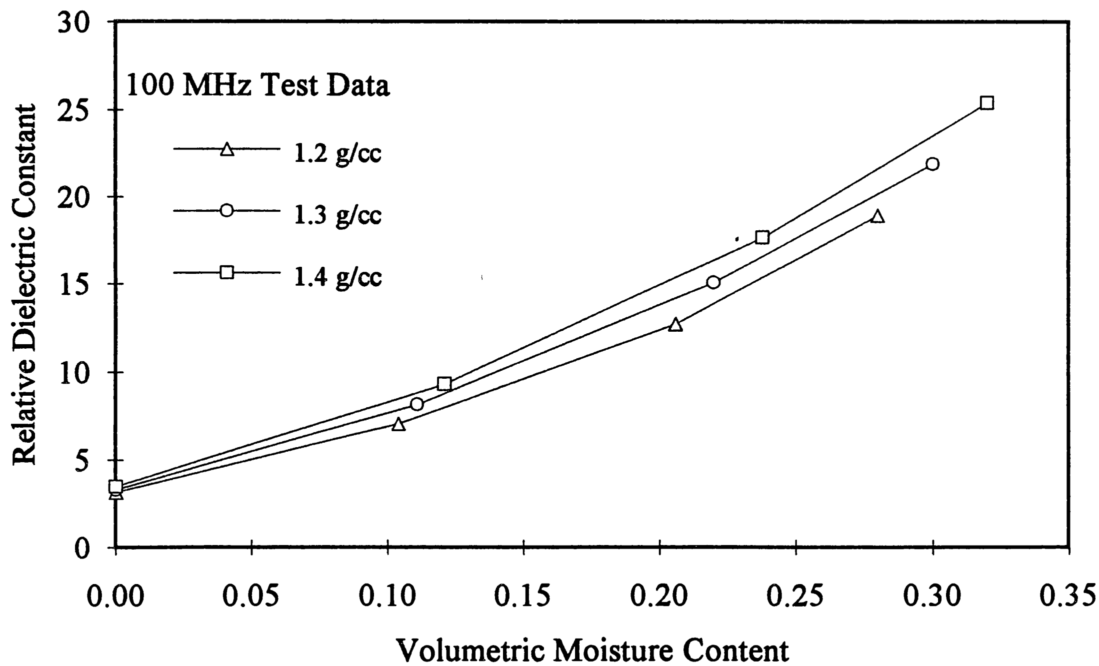

Figure 14. Density dependence of the relative dielectric constant for silty clay loam at 100 MHz.

A multiple regression of the dielectric constant with moisture content and bulk density was performed on the entire data set. It was compared to the regression that took only moisture content into consideration. Pertinent test statistics for the comparison are shown in the following table.

TABLE 5

STATISTICAL COMPARISON OF TWO REGRESSION MODELS

Parameter	Moisture Only	Moisture and Bulk Density
Adjusted r^2	0.978	0.982
Root Mean Square Error	0.99	0.890

The coefficient of determination and the root mean square error were not significantly affected by the addition of the density term. The primary reason is the variability of the dielectric constant for different soils at the same density and moisture content. This is true for the entire data set, but within a given soil type, the multiple regression should have a more significant impact on the accuracy.

Although the dielectric properties tests were performed to determine the effect that soil variables have on the dielectric properties, the laboratory tests were examined to determine the accuracy of predicting soil moisture content when using measured impedance. By estimating the accuracy of the laboratory tests, the results can be compared to the prototype sensor results to make evaluations on performance. In order to obtain a measure of the error associated with using impedance measurements to predict volumetric moisture content, the predicted moisture content was compared to the actual moisture content. This comparison is shown in Figure 15, with the solid line representing the ideal one-to-one case. The standard deviation of the error term associated with the predicted value and actual value is 0.014 volumetric moisture content, which translates into a probable error of ±0.009 volumetric moisture content. In other words, 50 percent of the time, the predicted value for moisture content will lie within plus or minus 0.9 percent volumetric moisture content of the actual value.

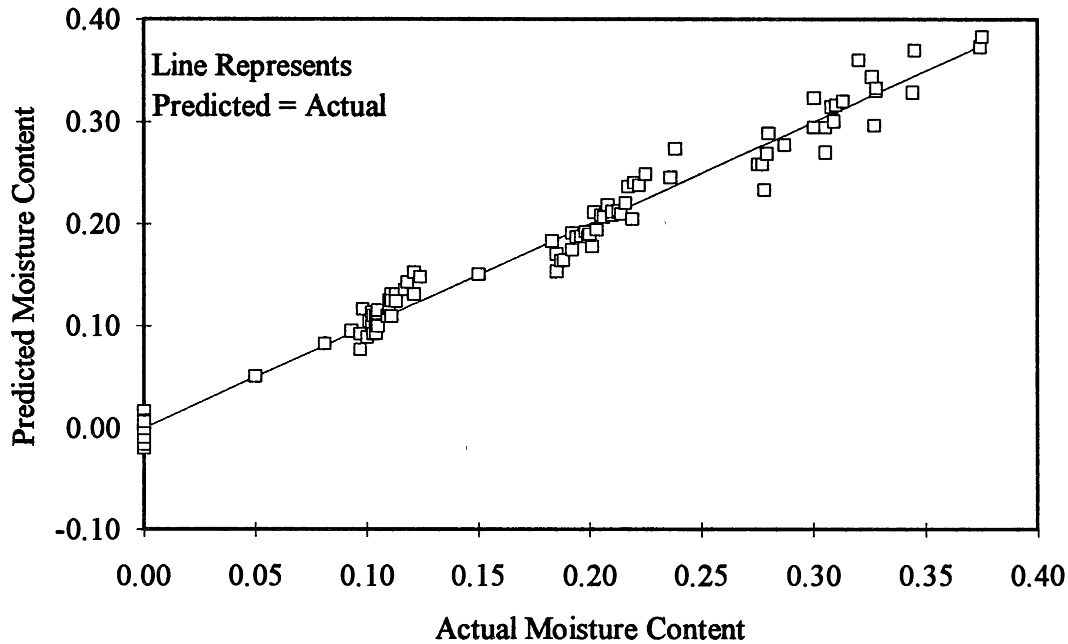

Figure 15. Comparison of predicted moisture content to actual moisture content for the laboratory tests. The measurement frequency is 100 MHz.

<u>Summary of Dielectric Property Tests</u>

The dielectric constant is a good indicator of the volumetric moisture content of soils. At low frequencies (1 MHz), the data are scattered about a regression line and very dependent on soil type and density. At higher frequencies (100 MHz), the data have less variance about a regression line, and the soil type and density have less effect on the dielectric constant. The dielectric loss factor is much smaller at the higher frequencies, which is a desirable characteristic for a capacitance type sensor. The probable error for predicting the dielectric constant from soil moisture content is 0.67 (units of relative dielectric constant), and the largest contributors to the error are the readings taken at higher moisture contents.

Within a given soil type, the error is generally reduced. The standard deviation and the probable error values showing the reduction in error are given in Table 6. A multiple regression with moisture content and density as independent variables showed that the inclusion of bulk density improves the accuracy of predicted dielectric constant, but the contribution is small.

TABLE 6

EFFECT OF SOIL TYPE ON ERROR

Soil Type	Standard Deviation	Probable Error
Clay Loam	0.79	0.53
Loam	0.66	0.44
Sand	0.40	0.27
Silty Loam	1.06	0.71
Silty Clay Loam	0.79	0.53
All Types	0.99	0.67

Using relative dielectric constant to predict moisture content, the predicted value correlates well with the actual moisture content. A standard deviation from the true moisture content was calculated by using the difference between the predicted moisture content and actual moisture content. The probable error of the predicted value was estimated to be ± 0.9 percent volumetric moisture content.

CHAPTER IV

PROTOTYPE SENSOR

Introduction

This chapter contains a description of the prototype dielectric-based soil moisture sensor and the testing method used to evaluate its performance. The sensor consists of the transducer, a signal amplifier, and a frequency counter. The transducer includes a reference oscillator, a moisture dependent oscillator, a mixer, a low-pass filter, and an infrared emitter and detector that are fitted to a fiber optic cable. The signal amplifier was used to increase the output voltage from the infrared detector to the level needed by the frequency counter. With the exception of the reference oscillator, all of the parts used for construction were inexpensive and readily available.

Design

Sensor Geometry

A cylindrical geometry with two conductors around the circumference was selected. This geometry allows simple field installation. The diameter of the sensor was set at 5.1 cm to allow a core sampler to be used when making the hole for field installation.

With a parallel plate capacitor, field installation would be very difficult, and it would disturb the soil to be tested. A fork-type capacitor with two metal rods for conductors has been used successfully, but this type of sensor presents difficulties when the moisture content at a point below the soil surface is of interest. Specifically, the sensor must be installed horizontally to measure moisture content at a given depth. Another drawback to using a fork-type sensor is that the distance between the two metal rods must remain constant, a condition difficult to implement.

Figures 24 and 25 in Appendix A show schematics of the sensor construction. The body of the sensor is constructed of clear acrylic plastic. Electrodes are constructed of copper tape. The electrodes are soldered to two wires that run into the local oscillator circuit. There is also a 2-mm layer of epoxy covering the electrodes for protection from corrosion.

The original design made use of two electrical socket connectors at the top of the acrylic case. These connections were implemented so that the main circuit could be detached from the sensor body between tests for the removal and packing of soil. This idea was abandoned after preliminary tests, because the capacitance of the connection was changed each time the circuit was removed from the sensor body and replaced. Instead, the circuit was connected to the sockets and secured, and the circuit was not removed from the sensor body during the tests.

Frequency

The sensor operating frequency was chosen to be centered around 110 MHz. As shown in the dielectric properties tests, the variance about a regression line is less at higher frequencies than at lower frequencies. Also, the small loss tangent at the higher frequencies is very important for an oscillator circuit, because it is undesirable for changes in conductivity to affect the output frequency. Since the salt concentration in soils changes significantly between different locations, the effect of conductivity on oscillator frequency must be minimized. Equation 4 shows that if the loss tangent is greater than or equal to one, the loss factor is greater than the dielectric constant. Ideally, the loss tangent should approach zero so that all of the variation in the sensor impedance is caused by the dielectric constant. The maximum value for the loss tangent in the 50-MHz data was 1.5 and the maximum loss tangent for the 100-MHz data was 0.9. For the worst case at 50 MHz, the change in impedance due to soil conductivity would dominate the change in impedance due to the soil dielectric constant. The maximum loss tangent at 100 MHz is higher than would be desired, but the average value of the loss tangent for the 100 MHz soil tests was 0.45. Selection of 110 MHz as an operating frequency for the sensor assures that for the soils used in this study, soil conductivity will not play a dominating role in affecting the oscillator frequency.

Basic Circuit Elements

The sensor uses two electrodes for the soil capacitor which sets the frequency of an oscillator. The electromagnetic wave that is being transmitted into these electrodes passes through the soil dielectric medium surrounding the electrodes. Since the dielectric constant of the soil varies according to moisture content, the electrical impedance of the soil capacitor also varies with moisture content. In the oscillator circuit, this variable impedance effect is used to change the oscillator output frequency.

A mixer-oscillator circuit was used to produce the frequency data which correlate with the volumetric moisture content of the soil. A block diagram of the circuit is shown in Figure 16. The actual circuit diagram is shown in Figure 17. The soil capacitor was used in the local oscillator on the mixer circuit. A 110-MHz crystal oscillator was used as a reference. The local oscillator was tuned to a frequency about 100 kHz below that of the reference oscillator, using a variable inductor that was placed in the oscillator circuit. Soil dielectric properties change not only with moisture content and density, but also with frequency. The change in dielectric properties with frequency is called dielectric dispersion. The soil capacitor was placed in parallel with a larger capacitor to limit the

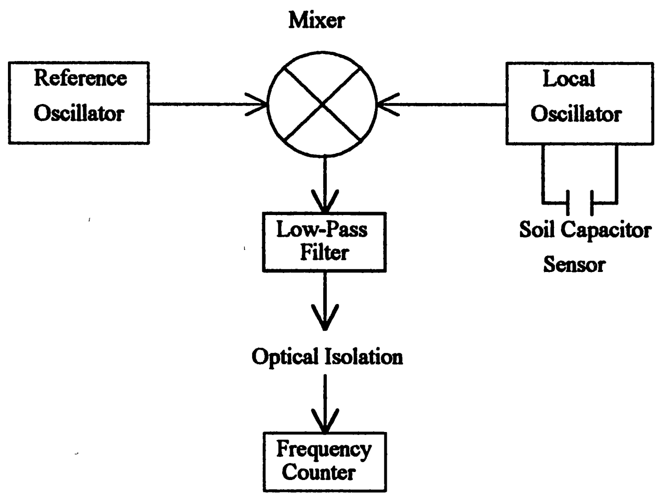

Figure 16. Block diagram of the sensor circuitry.

change in frequency due to moisture. The frequency shift due to the impedance change of the electrodes remained well below 1 MHz, and the output frequency of the sensor is not significantly effected by dielectric dispersion.

The output from a mixer can be the sum or the difference of two input frequencies, depending on the filtering applied to the output signal. The input signals in this case are the 110-MHz reference oscillator and the signal from the oscillator with the soil capacitor. In the circuit developed, the sum frequency signal is eliminated by using a low-pass filter that also serves as an impedance matching bridge. The remaining difference frequency signal from the mixer circuit is then amplified and transmitted through a fiber optic cable by an infrared emitting diode. The optical signal was then converted back to an electrical signal using an infrared detector on a prototyping board. The electrical signal on the prototyping board was then amplified and measured by a frequency counter.

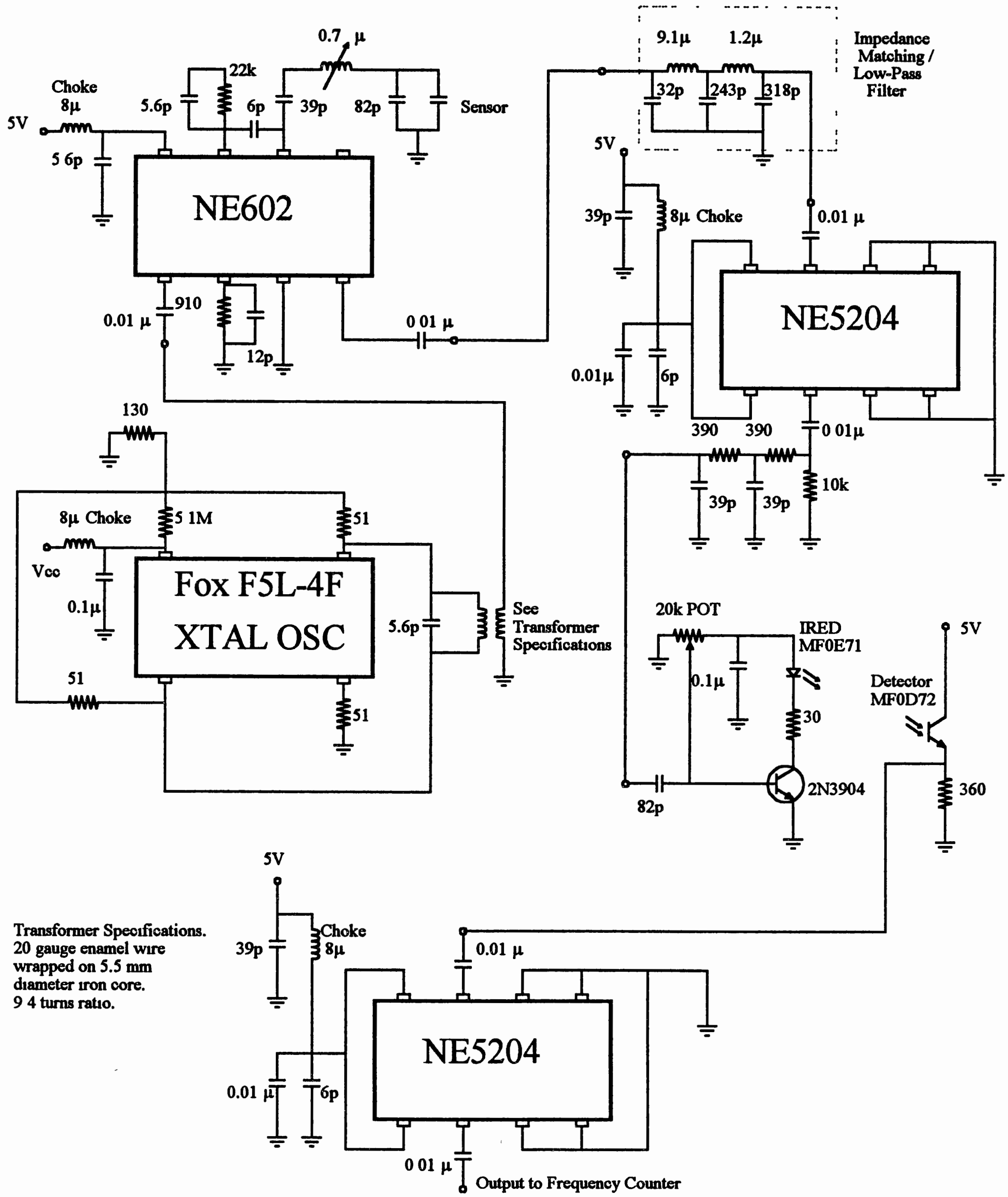

Figure 17. Diagrams for the sensor, emitter, and detector circuitry.

Difference frequency was used instead of the absolute frequency to allow the optical isolator device to operate below 10 MHz. In addition, the change in frequency from 100 kHz to 300 kHz is much easier to measure than a change in frequency from 100.1 MHz to 100.3 MHz. The optical isolator was used to remove the effects of parasitic capacitance on the sensor circuitry. With the frequency counter connected directly to the output of the mixer, the output frequency varied dramatically when the probe was touched or moved. The same problem arose with the wires supplying the source voltage to the circuit. This problem was solved by using 9-volt batteries and a voltage regulator, both mounted on the circuit enclosure, to supply power.

Long-term stability of the circuit was a problem. A daily drift of about 4 kHz was observed. Weekly drift was about 20 kHz. The output frequency of the sensor in air was recorded before soil was added in the testing stage. This technique allowed a frequency shift to be calculated by subtracting the frequency reading with soil from the frequency reading with air.

Several variables affect the stability of the circuit, but the most prevalent is probably temperature. Humidity may also have some effect on the sensor stability. The room temperature was held nearly constant during all testing to minimize the error due to temperature variation, but relative humidity was not recorded.

Sensor Test

Equipment

A schematic of the test equipment is shown in Figure 18. The sensor was mounted on a clear acrylic disk which had concentric grooves to hold the soil retaining ring. The cylinder used to retain the soil is 15 cm in diameter, 9-cm long, and was constructed of PVC pipe. The sensor support disk was placed on a clear acrylic support base.

A circuit prototyping board was used to implement supporting circuitry. The infrared detector that converts the optical signal from the sensor to an electrical signal was placed on the proto-board. The amplifier between the detector and the frequency counter was also placed on the proto-board.

A Fluke 7261A frequency counter was used to measure the output frequency of the circuit. Measurements were read from the display and recorded by hand.

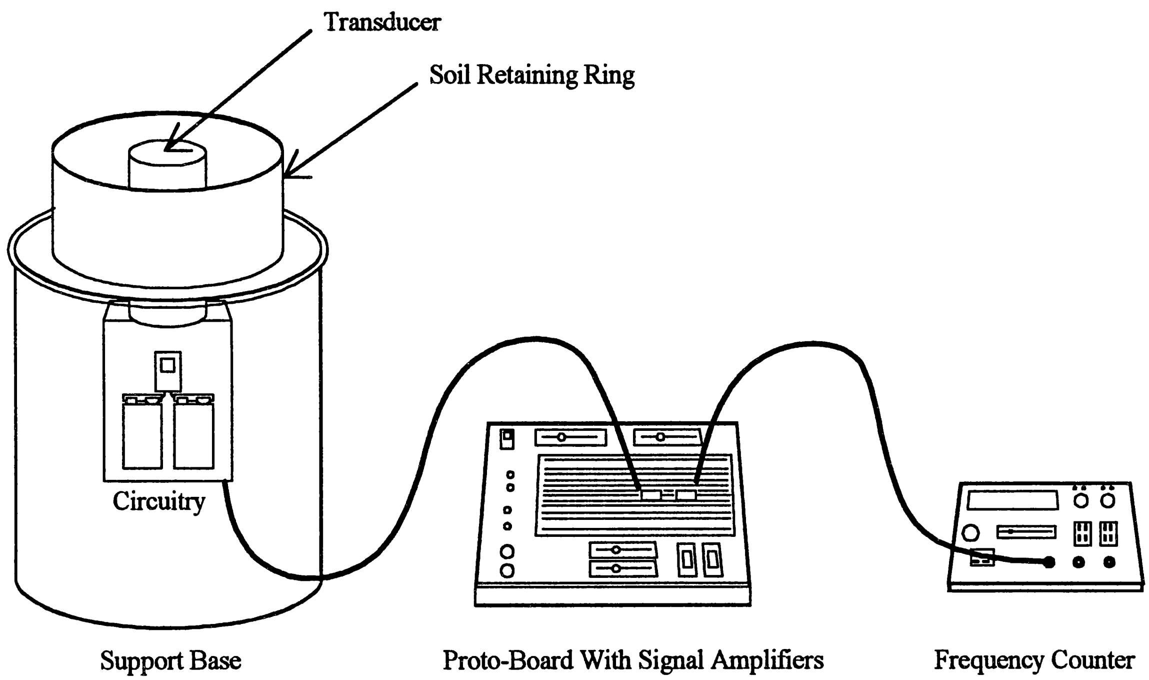

Figure 18. Schematic of the equipment used for the sensor test.

Procedure

Three soils from the original ten were used to test the performance of the sensor. The soils that were selected provide a wide range of texture. The soil types used - a loamy sand, a clay loam, and a loam - were from Fort Cobb, Stillwater, and Tipton, respectively. The soils were prepared using the same method developed for the dielectric properties tests, except the larger samples were stored in 2-liter sealed jars to provide the soil volume needed for the sensor test.

In order to determine the mass of soil needed for the sensor tests, the volume of the region between the sensor and the soil retaining ring was determined. The mass of soil needed for a specific density was then calculated by using Equation 16. The frequency of the sensor with air in the sample volume was recorded, and then half of the desired mass of soil was placed in the sample volume. The soil was packed to a volume slightly greater than half of the sample volume. The other half of the soil was added and packed into the sample volume until the surface of the soil was even with the top of the sensor body. The sensor frequency was recorded, and the soil was removed for oven-drying and actual moisture content determination.

Properties of the soils tested were set to the same values as in the dielectric properties tests. The original plan was to test the sensor using three densities, four moisture contents, and three repetitions. Because of the large area of the region between the sensor and the soil retaining ring and the force required to compress the soil, it was not possible to pack the soil to its highest density. As a result, only two densities were observed for each soil type. Another difficulty arose with the very moist soils. After the first test, the wet soil was clumped together and could not be broken into a fine mixture. The soil "clods" may have caused small air gaps on the electrodes, which may have affected the output frequency of the sensor and caused larger variations at high moisture content.

Results and Discussion

Results of the sensor test are similar to those of the coaxial cell tests. The response of the sensor is shown in Figure 19. The quadratic equation to predict the sensor response is

$$F = 16.7 + 143.1\theta + 386.2\theta^2 \qquad r^2 = 0.96 \qquad (22)$$

where

F = frequency and
θ = volumetric moisture content.

Frequency is the output frequency of the sensor in soil subtracted from the output frequency of the sensor in air.

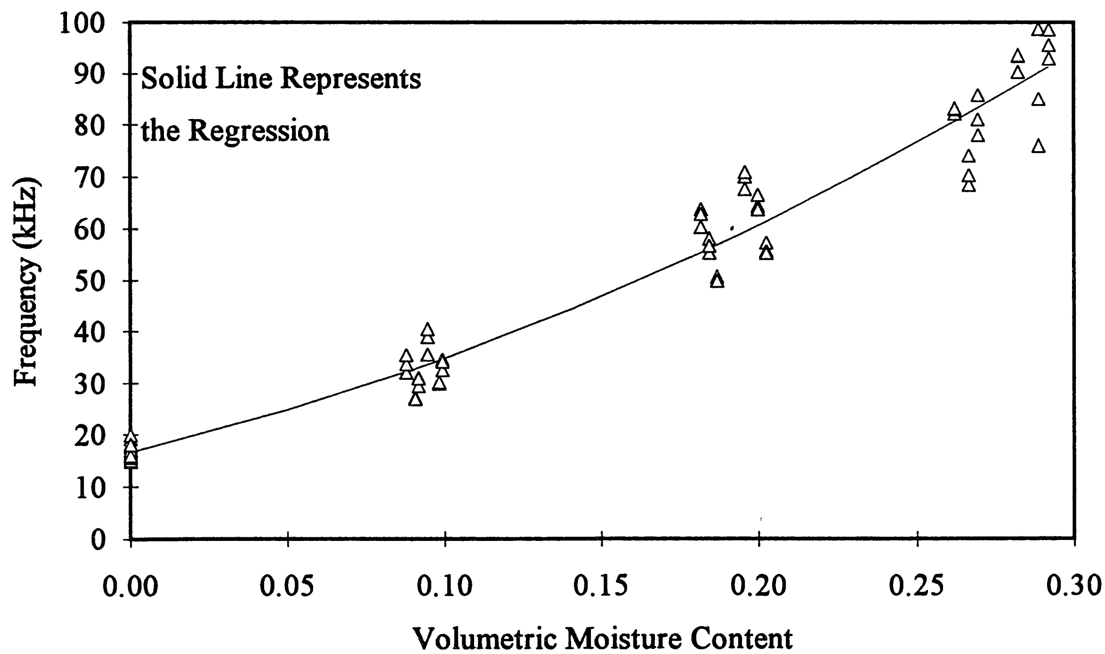

Figure 19. Regression curve and sensor response for all soils and densities tested.

The difference in the response of the sensor compared to the dielectric properties data is that the deviations at all moisture contents are more pronounced. The deviations can be partially explained by the inconsistency involved with packing the sample volume with soil.

The primary goal of the sensor test was to determine how effectively the sensor can be used to estimate soil moisture content. A regression was performed on the data with frequency as the independent variable, and the following equation results.

$$\theta = -0.0997 + 6.69 \cdot 10^{-3}\, F - 2.75 \cdot 10^{-5}\, F^2 \qquad (23)$$

where

θ = volumetric moisture content and

F = difference of soil-filled frequency and air-filled frequency.

Using Equation 23, the estimated moisture content can be plotted as a function of actual moisture content. If the predicted moisture content is the same as the actual moisture content, the result should be a straight line with a slope of one. Figure 20 shows the response of the sensor with all soils. The error of the sensor was calculated by subtracting the predicted value from the actual value for all data points. Simple statistics were then performed on the error terms and are listed in the following table.

TABLE 7

STATISTICS FOR THE SENSOR ERROR
IN ALL SOILS

Parameter	Value
Standard Deviation	0.018 cc/cc
Probable Error	±0.012 cc/cc

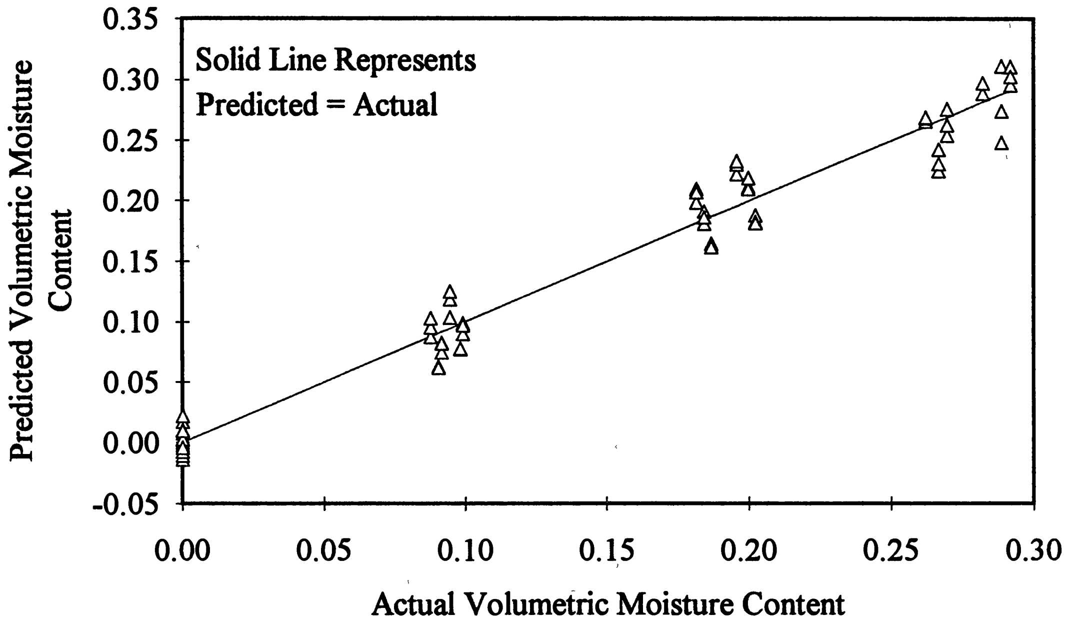

Figure 20. Comparison of predicted volumetric moisture content to the actual volumetric moisture content.

The probable error indicates that for 50 percent of the measurements made, the predicted moisture value from the sensor should be within plus or minus 1.2 percent volumetric moisture content of the actual value. The general case is that the accuracy of the predicted moisture content can be increased when soil type is known. The statistics are given for the individual soils in Table 8. Figures 21 through 23 show the prediction accuracy for the individual soils.

TABLE 8

STATISTICS FOR THE SENSOR ERROR IN SPECIFIC SOIL TYPES

Soil Type	Standard Deviation (cc/cc)	Probable Error (cc/cc)
Loamy Sand	0.009	±0.006
Clay Loam	0.013	±0.008
Loam	0.020	±0.013

The loamy sand and clay loam soils have less deviation about their regression lines, but the loam soil actually has a larger standard deviation than the combined data set. The larger standard deviation is probably due to the non-uniformity of the soil density during the second and third repetitions. Before the first repetition, the soil was loose, and no clods were present. Due to packing in the first repetition, the moist soil was compacted into clods. After the first test, the clods were broken up in an effort to restore the soil to its previous texture, but the initial state of the soil could not be completely reproduced at high moisture content. The soil clods may have caused an air gap on the sensor electrodes, or the clods may have caused a region of high density around the electrodes. Either of these conditions would affect the sensor output frequency.

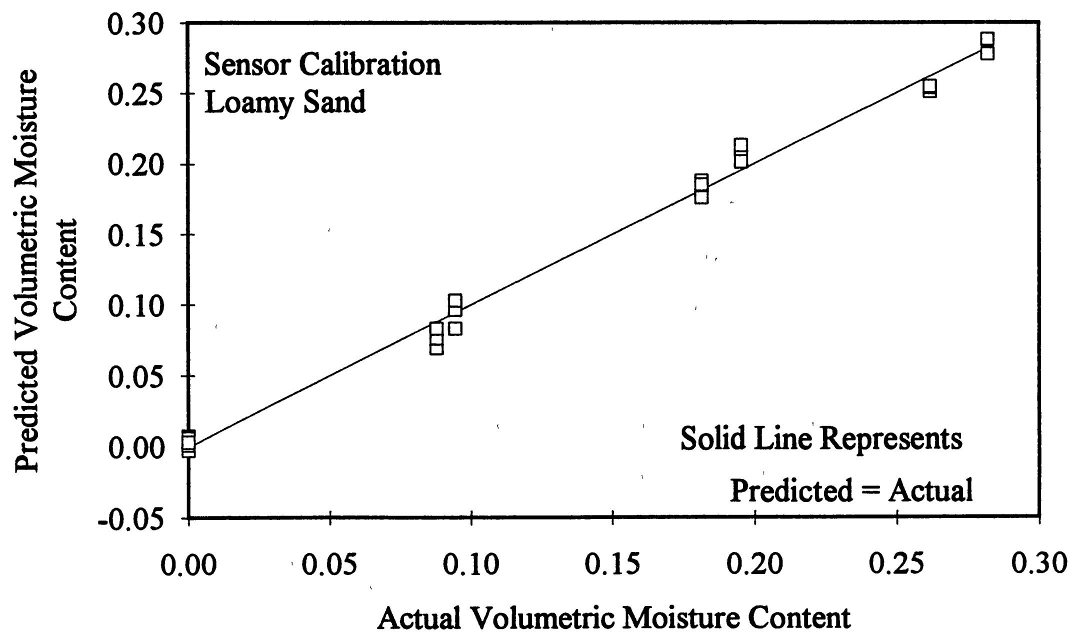

Figure 21. Comparison of predicted to actual volumetric moisture content for loamy sand.

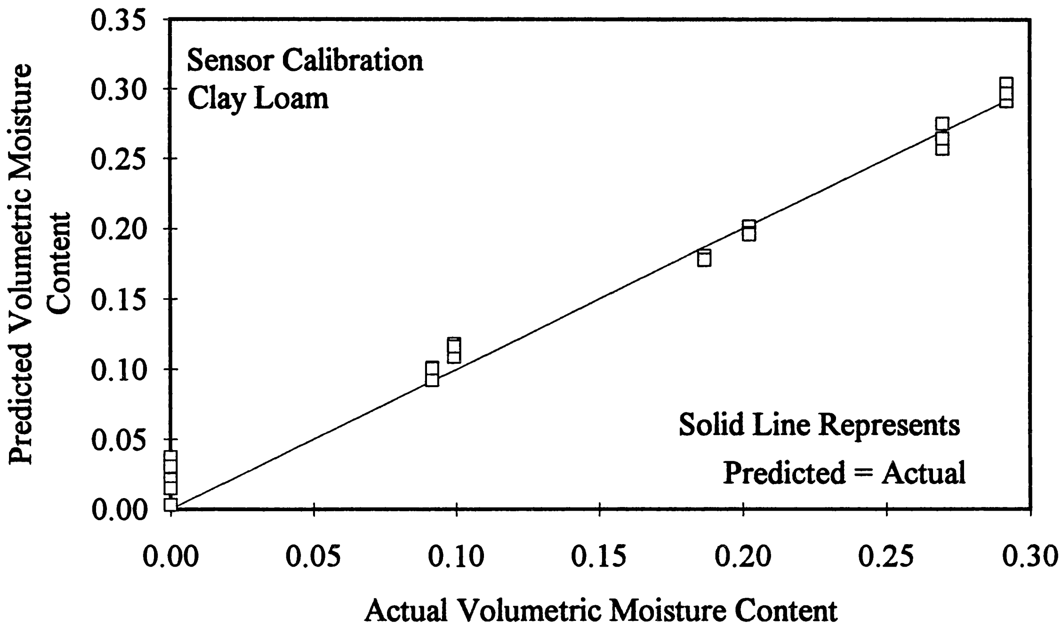

Figure 22. Comparison of predicted to actual volumetric moisture content for clay loam soil.

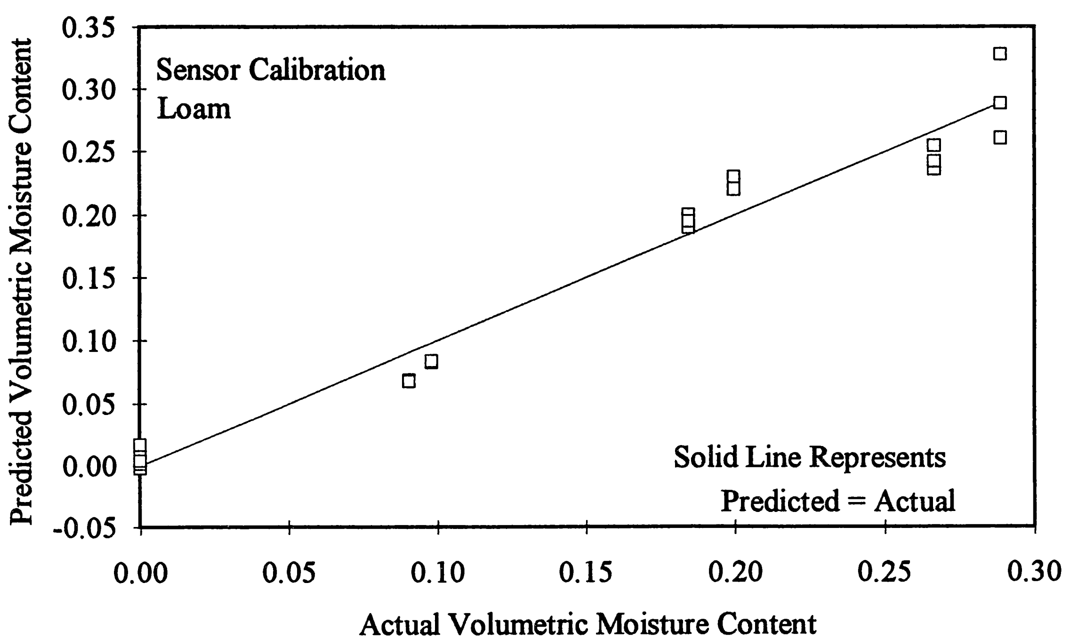

Figure 23. Comparison of predicted to actual volumetric moisture content for loam soil.

A final analysis was made to determine the error associated with using a single regression to estimate moisture content in different soil types. The regression curve that was produced from all of the sensor data was used in each soil type, and the resulting error was calculated.

TABLE 9

ERROR FOR SPECIFIC SOIL TYPES USING
A SINGLE REGRESSION EQUATION

Soil Type	Standard Deviation (cc/cc)	Probable Error (cc/cc)
Loamy Sand	0.015	±0.010
Clay Loam	0.013	±0.009
Loam	0.020	±0.013

Although the results from the preliminary test look very good, some error may have been introduced by daily variations in the circuit. The variation in circuit output due to inconsistent packing of the soil is an important issue for testing of the sensor. In a field situation, the sensor will be subjected to the same "sample" at all times, which should decrease the variability due to density. Assuming good initial contact can be made between the soil and the sensor, the primary variation over time should only be moisture content and temperature. The density should remain nearly constant over time, and the variation due to density changes should be small. Although there may be cases where the soil under observation is being compacted while the sensor is in place, the only foreseeable cause for a change in density at the sensor location is natural settling of the soil. It would be difficult to compact the soil around the sensor mechanically without destroying the sensor.

CHAPTER V

SUMMARY

The objective of this research was to develop a real-time sensor to estimate the volumetric moisture content of soils. In order to realize this objective, two major tasks were required. First, ten different soils were tested to understand the variables influencing soil dielectric properties. The tests were designed to show how the dielectric properties of soil are influenced by moisture content, soil type, soil bulk density, and frequency. The resulting properties were then used to determine the accuracy and limitations in the use of a dielectric approach to estimate soil moisture content. The second task of developing a working prototype sensor was accomplished by choosing an appropriate electrode geometry, designing the measurement circuit, and testing the sensor. The results of the sensor calibration were then analyzed to determine the effectiveness of the sensor.

The most effective frequency in the 1 to 100 MHz range is near 100 MHz, because much of the soil type and density dependence is removed. The relatively small dielectric loss at 100 MHz also makes it a suitable frequency for a capacitance-type moisture sensor. For a given soil type and density, dielectric properties are good indicators of soil moisture content. Soil type has a noticeable effect on the dielectric constant for a soil at a given frequency and moisture content. An increase in density causes an increase in dielectric constant, but the addition of density in a multiple regression does not significantly decrease the error. Also, clay soils have a higher dielectric constant than sandy soils for a given bulk density.

When using an impedance meter to evaluate the dielectric properties of moist soils, the moisture content can be estimated with a probable error of ± 0.9 percent volumetric moisture content, independent of soil type. The sensor developed in this study is comparable in performance with a probable error of ± 1.2 percent volumetric moisture content, also independent of soil type. In general, the accuracy of the sensor can be increased if the soil type is known.

CHAPTER VI

RECOMMENDATIONS

For the prototype sensor, there are many possibilities for enhancement. Probably the most important test needed to make the sensor field-capable is to determine the effect that temperature has on the circuitry and on the dielectric constant of the soil surrounding the sensor. If the temperature calibration is to be useful for other sensors of similar design, the electrode dimensions, circuit components, and circuit assembly method may need to be standardized. Otherwise, multiple sensors may require individual calibration. There is also the possibility that even with standard elements, each sensor may need to be individually calibrated because of large variability in stray capacitance.

Improvements must be made to the stability of the circuit. The use of temperature-stable capacitors or temperature-compensated capacitors in oscillator circuits should reduce some of the temperature dependence. The integrated circuit components that generate heat, such as voltage regulators and amplifiers, should be isolated from the oscillator and the components that set the oscillator frequency. If humidity affects the sensor stability, the entire circuit may be encapsulated in a material that is impervious to water. It may also be helpful to choose a thermally insulating material to encapsulate the circuit to prevent heat transfer between circuit components.

The loss factor may affect the sensor output frequency in soils with high saline concentrations. One suggestion for dealing with the change in resistance in the sensor is to place a resistive circuit element in line with the capacitive sensor to minimize the change in frequency due to change in soil conductivity. The added resistance should buffer the impact that soil conductivity has on the output frequency.

Although many refinements can be made to the actual circuit to improve its ability to measure moisture content, a microprocessor could also be added to the sensor to improve accuracy. This would be most useful for a sensor that remains in a single location. The microprocessor could keep track of the conditions that had been encountered and reference information in a calibration database to estimate the type of soil in which the sensor is located. For a sensor that must be portable, separate calibration curves could be stored in a memory device, and the user could give the sensor a soil type estimate for the area of interest.

REFERENCES

Ansoult, M., L.W. De Backer, and M. Declercq. 1984. Statistical relationship between apparent dielectric constant and water content in porous media. Soil Science Society of America Journal, 48:47-50.

Babb, A.T.S. 1951. A radio-frequency electronic moisture meter. Analyst. 76(1).

Birchak, J.R., C.G. Gardner, J.E. Hipp, and J.M. Victor. 1974. High dielectric constant microwave probes for sensing soil moisture. Proceedings of the IEEE. 62(1):93-98.

Buckley, F. and A.A. Maryott. 1958. Tables of dielectric dispersion data for pure liquids and dilute solutions. National Bureau of Standards Circular 589.

Campbell, J.E. 1988. Dielectric properties of moist soils at rf and microwave frequencies. PhD Thesis, Dartmouth College.

Cheng, D.K. 1983. Field and Wave Electromagnetics. Addison-Wesley Publishing Company. Reading, Mass.

Cherniak, G. Ya. 1964. Dielectric Methods for Investigating Moist Soils. Israel Program for Scientific Translations Ltd., Jerusalem, Israel. (Available from the U.S. Department of Commerce, Clearinghouse for Federal Scientific and Technical Information, Springfield, VA 22151)

Dean, T.J., J.P. Bell, and A.J.B. Baty. 1987. Soil moisture measurement by an improved capacitance technique, part I. sensor design and performance. Journal of Hydrology, 93:79-90.

Doeblin, E.O. 1990. Measurement Systems: Application and Design. McGraw-Hill Publishing Company. New York, NY.

Grantz, D.A., M.H. Perry, and F.C Meinzer. 1990. Using time domain reflectometry to measure soil water in Hawaiian sugarcane. Agronomy Journal, 82:144-146.

Herkelrath, W.N., S.P. Hamburg, and F. Murphy. 1991. Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. Water Resources Research, 27(5):857-864.

Hillel, D. 1982. Introduction to Soil Physics. Academic Press, Inc. San Diego, CA.

Hipp, J.E. 1974. Soil electromagnetic parameters as functions of frequency, soil density, and soil moisture. Proceedings of the IEEE, 62(1):98-103.

Jorgenson, J.L., A.R. Edison, S.O. Nelson, and L.E. Stetson. 1970. A bridge method for dielectric measurements of grain and seed in the 50 to 250 MHz range. Transactions of the ASAE, 13(1):18-20, 24.

Kraft, C. 1987. Constitutive parameter measurements of fluids and soil between 500 kHz and 5 MHz using a transmission line technique. Journal of Geophysical Research, 92(B10):10,650-10,656.

Nelson, S.O. 1983. Density dependence of the dielectric properties of particulate materials. Transactions of the ASAE, 26(6):1823-1825, 1829.

Richards, K.A. 1990. Soil permittivity determination using a fringe field capacitor. PhD Dissertation, University of Nebraska.

Selig, E.T. and S. Mansukhani. 1975. Relationship of soil moisture to the dielectric property. Journal of Geotechnical Engineering Division, pp. 775-770.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content by measurements in coaxial transmission lines. Water Resources Research, 16(3):574-582.

Van Wesenbeeck, I.J., and R.G. Kachanoski. 1988. Spatial and temporal distribution of soil water in the tilled layer under a corn crop. Soil Science Society of America Journal, 52:363-368.

Von Hippel, A.R. 1961. Dielectric Materials and Applications. Cambridge Mass.: M.I.T. Press.

APPENDICES

APPENDIX A

SENSOR CONSTRUCTION DIAGRAMS

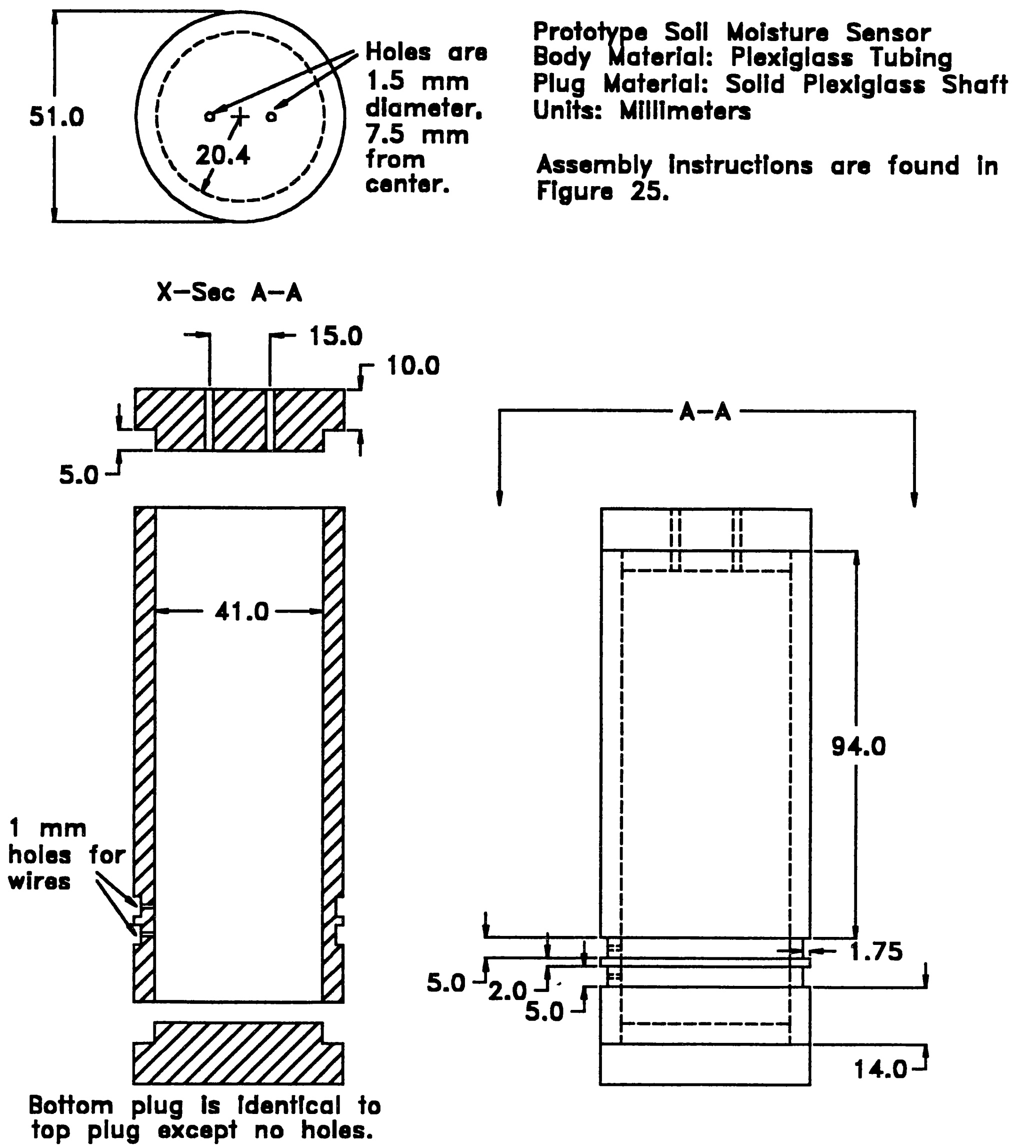

Figure 24. Design schematics for the sensor body.

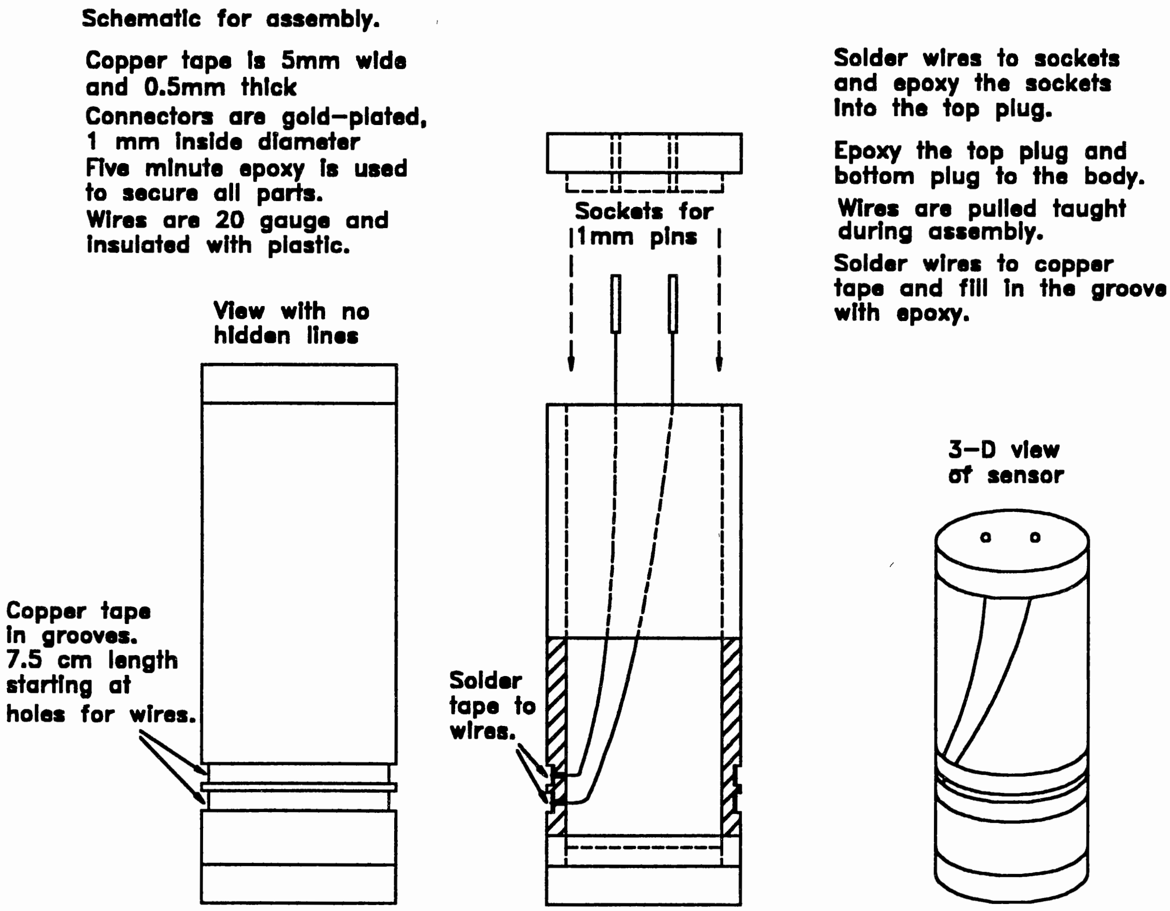

Figure 25. Construction schematics for the sensor unit.

APPENDIX B

SOIL TYPE AND DIELECTRIC PROPERTIES DATA

Appendix B contains the particle size distribution data and the dielectric properties data that were collected during this study. Table 10 contains the particle size distribution of each soil used in this study. The particle sizes are given as the percent of particles finer than a specified diameter. Listed in Table 11 are the soil type, moisture content, bulk density, and the dielectric properties for 1 MHz, 10 MHz, 50 MHz, and 100 MHz.

TABLE 10

PARTICLE SIZE DISTRIBUTION OF SOILS

Location	Percent of Particles Finer than the Specified Diameter (%)	Diameter (mm)
Altus	26.7	0.001
Altus	31.6	0.002
Altus	40.2	0.005
Altus	43.0	0.007
Altus	44.5	0.009
Altus	46.6	0.012
Altus	49.5	0.015
Altus	55.9	0.022
Altus	58.8	0.026
Altus	67.4	0.030
Altus	90.1	0.075
Altus	96.8	0.150
Altus	97.9	0.300
Altus	98.4	0.600
Altus	99.0	2.000
Chickasha	19.3	0.001
Chickasha	21.3	0.003
Chickasha	23.2	0.004
Chickasha	27.1	0.011
Chickasha	29.0	0.013
Chickasha	32.9	0.014
Chickasha	35.8	0.019
Chickasha	41.6	0.026
Chickasha	50.3	0.031
Chickasha	88.5	0.075
Chickasha	99.2	0.150
Chickasha	99.8	0.300
Chickasha	100.0	0.600
Chickasha	100.0	2.000

TABLE 10 (Continued)

Location	Percent of Particles Finer than the Specified Diameter (%)	Diameter (mm)
Fort Cobb	7.5	0.001
Fort Cobb	8.2	0.003
Fort Cobb	8.9	0.004
Fort Cobb	9.7	0.013
Fort Cobb	10.4	0.021
Fort Cobb	10.4	0.029
Fort Cobb	11.9	0.040
Fort Cobb	17.3	0.075
Fort Cobb	90.2	0.150
Fort Cobb	99.5	0.300
Fort Cobb	100.0	0.600
Fort Cobb	100.0	2.000
Goodwell	12.2	0.001
Goodwell	15.9	0.002
Goodwell	21.2	0.004
Goodwell	23.0	0.006
Goodwell	26.5	0.010
Goodwell	27.4	0.012
Goodwell	28.3	0.013
Goodwell	30.0	0.016
Goodwell	31.8	0.019
Goodwell	35.3	0.025
Goodwell	47.7	0.034
Goodwell	63.7	0.075
Goodwell	78.3	0.150
Goodwell	92.6	0.300
Goodwell	98.7	0.600
Goodwell	99.9	2.000

TABLE 10 (Continued)

Location	Percent of Particles Finer than the Specified Diameter (%)	Diameter (mm)
Haskell	12.4	0.001
Haskell	14.7	0.003
Haskell	15.4	0.005
Haskell	19.3	0.009
Haskell	20.8	0.012
Haskell	23.2	0.014
Haskell	27.0	0.017
Haskell	33.2	0.023
Haskell	35.5	0.026
Haskell	44.8	0.030
Haskell	93.0	0.075
Haskell	98.3	0.150
Haskell	99.7	0.300
Haskell	100.0	0.600
Haskell	100.0	2.000
Lahoma	27.7	0.001
Lahoma	28.8	0.002
Lahoma	31.5	0.006
Lahoma	32.4	0.007
Lahoma	34.2	0.008
Lahoma	35.1	0.009
Lahoma	37.8	0.013
Lahoma	42.3	0.016
Lahoma	49.6	0.029
Lahoma	61.3	0.034
Lahoma	86.4	0.075
Lahoma	92.3	0.150
Lahoma	98.4	0.300
Lahoma	99.8	0.600
Lahoma	100.0	2.000

TABLE 10 (Continued)

Location	Percent of Particles Finer than the Specified Diameter (%)	Diameter (mm)
Mangum	4.3	0.001
Mangum	4.3	0.003
Mangum	4.3	0.009
Mangum	4.3	0.014
Mangum	4.8	0.026
Mangum	5.6	0.030
Mangum	7.8	0.059
Mangum	11.2	0.081
Mangum	22.5	0.150
Mangum	68.3	0.300
Mangum	98.6	0.600
Mangum	100.0	2.000
Perkins	14.6	0.004
Perkins	15.1	0.008
Perkins	16.1	0.009
Perkins	18.1	0.011
Perkins	20.1	0.014
Perkins	22.1	0.019
Perkins	24.1	0.022
Perkins	30.0	0.030
Perkins	40.2	0.042
Perkins	70.3	0.075
Perkins	83.4	0.150
Perkins	96.5	0.300
Perkins	100.0	0.600
Perkins	100.0	2.000

TABLE 10 (Continued)

Location	Percent of Particles Finer than the Specified Diameter (%)	Diameter (mm)
Stillwater	27.6	0.001
Stillwater	30.3	0.005
Stillwater	32.1	0.007
Stillwater	33.9	0.010
Stillwater	34.8	0.011
Stillwater	36.6	0.014
Stillwater	38.3	0.015
Stillwater	41.0	0.021
Stillwater	44.6	0.024
Stillwater	51.7	0.031
Stillwater	75.2	0.075
Stillwater	93.3	0.150
Stillwater	99.3	0.300
Stillwater	99.9	0.600
Stillwater	100.0	2.000
Tipton	15.9	0.001
Tipton	16.8	0.002
Tipton	16.8	0.003
Tipton	17.7	0.005
Tipton	18.6	0.007
Tipton	19.5	0.009
Tipton	22.1	0.014
Tipton	23.9	0.018
Tipton	25.6	0.021
Tipton	28.3	0.024
Tipton	37.1	0.034
Tipton	72.6	0.075
Tipton	90.4	0.150
Tipton	97.9	0.300
Tipton	100.0	0.600
Tipton	100.0	2.000

TABLE 11

DIELECTRIC PROPERTIES OF VARIOUS SOILS

			1 MHz		10 MHz		50 MHz		100 MHz	
Location	θ	ρ_b	ε'	$\tan(\delta)$	ε'	$\tan(\delta)$	ε'	$\tan(\delta)$	ε'	$\tan(\delta)$
Altus	0.000	1.20	3.66	0.075	3.35	0.078	3.14	0.083	3.13	0.091
Altus	0.000	1.30	3.75	0.062	3.48	0.065	3.29	0.072	3.30	0.082
Altus	0.000	1.40	4.09	0.079	3.75	0.080	3.51	0.114	3.48	0.144
Altus	0.100	1.19	17.00	7.828	11.42	1.431	8.02	0.685	7.08	0.545
Altus	0.111	1.29	20.31	10.233	13.25	1.836	9.28	0.810	8.16	0.609
Altus	0.121	1.39	22.83	14.092	15.08	2.397	10.65	0.970	9.31	0.702
Altus	0.206	1.18	32.35	19.851	18.66	3.700	14.11	1.249	12.73	0.837
Altus	0.220	1.28	38.36	23.541	22.00	4.386	16.62	1.440	15.08	0.940
Altus	0.238	1.37	46.45	24.467	25.85	4.690	19.56	1.501	17.69	0.950
Altus	0.282	1.19	48.13	20.625	26.69	3.978	20.79	1.277	18.93	0.838
Altus	0.305	1.29	55.93	22.157	31.15	4.255	24.14	1.361	21.92	0.872
Altus	0.324	1.40	66.93	22.896	35.52	4.634	27.62	1.467	25.42	0.916
Chickasha	0.000	1.10	3.18	0.097	2.86	0.079	2.69	0.076	2.70	0.080
Chickasha	0.000	1.20	3.45	0.096	3.11	0.079	2.93	0.075	2.95	0.076
Chickasha	0.000	1.30	3.60	0.105	3.20	0.084	3.00	0.080	3.01	0.082
Chickasha	0.104	1.09	15.35	9.415	9.58	1.772	6.89	0.724	6.30	0.512
Chickasha	0.109	1.19	17.40	11.537	10.56	2.154	7.76	0.816	7.09	0.560
Chickasha	0.121	1.29	20.47	13.684	12.10	2.580	8.94	0.931	8.15	0.628
Chickasha	0.124	1.40	23.73	15.361	13.57	2.965	9.96	1.052	9.07	0.693
Chickasha	0.188	1.09	21.70	13.876	13.52	2.448	10.61	0.823	10.00	0.538
Chickasha	0.200	1.20	26.03	15.945	15.73	2.863	12.43	0.920	11.58	0.588
Chickasha	0.213	1.30	31.25	16.844	18.01	3.157	14.21	0.995	13.17	0.614
Chickasha	0.236	1.40	36.21	17.948	20.91	3.351	16.62	1.042	15.51	0.643
Chickasha	0.374	1.44	53.82	18.588	34.46	3.110	28.76	0.917	26.71	0.553
Chickasha	0.375	1.51	57.71	17.914	35.66	3.101	29.69	0.921	27.67	0.551
Ft. Cobb	0.000	1.30	2.96	0.062	2.78	0.051	2.70	0.051	2.72	0.057
Ft. Cobb	0.000	1.40	3.15	0.069	2.97	0.052	2.86	0.052	2.89	0.058
Ft. Cobb	0.000	1.50	3.35	0.063	3.14	0.053	3.03	0.055	3.06	0.058
Ft. Cobb	0.081	1.31	9.87	9.126	7.18	1.429	5.98	0.468	5.85	0.307
Ft. Cobb	0.103	1.39	11.67	9.190	8.56	1.413	7.27	0.450	7.09	0.294
Ft. Cobb	0.110	1.50	12.67	10.138	9.43	1.517	8.07	0.472	7.82	0.307
Ft. Cobb	0.185	1.30	15.67	7.729	11.93	1.147	10.59	0.355	10.38	0.227
Ft. Cobb	0.196	1.40	17.37	8.307	13.38	1.199	11.84	0.369	11.48	0.234

TABLE 11 (Continued)

Location	θ	ρ_b	1 MHz ε'	1 MHz tan(δ)	10 MHz ε'	10 MHz tan(δ)	50 MHz ε'	50 MHz tan(δ)	100 MHz ε'	100 MHz tan(δ)
Ft. Cobb	0.210	1.50	19.43	8.995	15.09	1.266	13.37	0.388	12.85	0.243
Ft. Cobb	0.275	1.47	30.86	9.679	18.17	1.252	16.73	0.361	16.47	0.222
Ft. Cobb	0.305	1.30	21.94	9.639	21.73	1.254	19.98	0.362	19.38	0.220
Ft. Cobb	0.344	1.40	26.40	10.636	25.48	1.371	23.57	0.387	22.39	0.232
Goodwell	0.000	1.20	3.00	0.055	2.86	0.050	2.78	0.050	2.80	0.060
Goodwell	0.000	1.30	3.26	0.058	3.09	0.047	2.98	0.056	3.01	0.063
Goodwell	0.000	1.40	3.55	0.058	3.33	0.054	3.20	0.059	3.22	0.064
Goodwell	0.093	1.20	15.69	13.619	9.55	2.487	7.09	0.911	6.41	0.631
Goodwell	0.102	1.30	17.41	17.697	10.59	3.163	7.98	1.077	7.26	0.723
Goodwell	0.113	1.39	21.07	19.230	11.85	3.685	8.91	1.226	8.14	0.801
Goodwell	0.183	1.20	25.99	24.126	14.84	4.471	11.85	1.333	11.15	0.818
Goodwell	0.202	1.29	30.90	26.219	17.18	4.972	13.74	1.460	13.02	0.881
Goodwell	0.217	1.40	36.54	26.469	19.56	5.209	15.62	1.507	14.80	0.878
Goodwell	0.310	1.37	43.68	31.221	25.88	5.509	22.02	1.466	21.32	0.822
Goodwell	0.313	1.38	43.83	32.552	25.94	5.759	22.04	1.550	21.62	0.877
Goodwell	0.345	1.56	51.12	35.615	32.27	5.907	27.05	1.587	26.30	0.863
Haskell	0.000	1.10	2.79	0.068	2.62	0.057	2.53	0.057	2.55	0.063
Haskell	0.000	1.20	2.99	0.058	2.80	0.057	2.69	0.057	2.70	0.065
Haskell	0.000	1.30	3.22	0.062	2.98	0.061	2.86	0.061	2.87	0.066
Haskell	0.097	1.09	12.22	10.515	8.28	1.808	6.07	0.705	5.62	0.479
Haskell	0.103	1.19	14.68	11.825	9.27	2.126	6.78	0.795	6.26	0.525
Haskell	0.111	1.29	16.77	13.218	10.29	2.404	7.62	0.867	7.04	0.567
Haskell	0.185	1.10	18.99	19.520	12.49	3.183	9.91	0.965	9.39	0.567
Haskell	0.201	1.20	22.14	21.574	14.04	3.619	11.32	1.063	10.80	0.618
Haskell	0.219	1.29	25.13	24.252	16.00	4.036	13.06	1.151	12.59	0.661
Haskell	0.278	1.10	24.28	24.383	17.16	3.631	14.78	0.977	14.58	0.548
Haskell	0.305	1.20	29.80	26.379	20.37	4.052	17.57	1.072	17.39	0.597
Haskell	0.327	1.29	33.44	26.883	22.90	4.118	19.94	1.083	19.57	0.604
Lahoma	0.000	1.10	2.84	0.050	2.70	0.045	2.62	0.052	2.66	0.063
Lahoma	0.000	1.20	2.94	0.046	2.83	0.041	2.76	0.047	2.79	0.055
Lahoma	0.000	1.30	3.21	0.046	3.06	0.045	2.97	0.050	2.99	0.059
Lahoma	0.100	1.09	14.31	8.122	9.28	1.527	6.71	0.654	6.13	0.479
Lahoma	0.109	1.19	15.99	11.278	10.60	1.948	7.76	0.774	7.06	0.551
Lahoma	0.113	1.29	18.63	12.294	11.77	2.207	8.59	0.855	7.76	0.604
Lahoma	0.188	1.09	22.55	15.457	13.79	2.756	10.84	0.897	10.01	0.583
Lahoma	0.203	1.19	26.83	16.708	16.16	3.000	12.81	0.959	11.86	0.618
Lahoma	0.216	1.29	31.84	18.227	18.52	3.369	14.73	1.062	13.65	0.683

TABLE 11 (Continued)

Location	θ	ρ_b	1 MHz ε'	1 MHz tan(δ)	10 MHz ε'	10 MHz tan(δ)	50 MHz ε'	50 MHz tan(δ)	100 MHz ε'	100 MHz tan(δ)
Lahoma	0.277	1.10	35.11	17.063	20.90	3.078	17.29	0.974	16.47	0.656
Lahoma	0.300	1.20	41.69	18.145	24.74	3.281	20.42	1.027	19.39	0.674
Lahoma	0.328	1.29	48.86	17.323	29.22	3.120	23.95	0.982	22.60	0.637
Mangum	0.000	1.40	2.99	0.055	2.84	0.044	2.77	0.047	2.82	0.052
Mangum	0.000	1.50	3.17	0.053	3.00	0.048	2.92	0.045	2.95	0.055
Mangum	0.000	1.60	3.35	0.054	3.19	0.046	3.10	0.046	3.13	0.056
Mangum	0.098	1.60	11.08	6.420	8.49	0.977	7.43	0.321	7.40	0.216
Mangum	0.105	1.38	10.18	5.860	7.67	0.932	6.66	0.311	6.62	0.210
Mangum	0.105	1.49	10.82	5.995	8.22	0.933	7.21	0.310	7.21	0.210
Mangum	0.192	1.39	15.04	5.724	11.93	0.833	10.78	0.261	10.63	0.167
Mangum	0.198	1.50	16.51	6.081	13.35	0.859	12.02	0.269	11.74	0.172
Mangum	0.210	1.60	18.03	6.248	15.07	0.848	13.51	0.269	13.06	0.170
Perkins	0.000	1.20	2.72	0.042	2.63	0.036	2.59	0.040	2.63	0.051
Perkins	0.000	1.30	2.95	0.043	2.83	0.037	2.76	0.044	2.80	0.055
Perkins	0.000	1.40	3.15	0.044	3.03	0.045	2.95	0.044	2.99	0.054
Perkins	0.000	1.47	3.42	0.051	3.25	0.046	3.15	0.048	3.18	0.058
Perkins	0.097	1.20	12.54	14.124	8.44	2.315	6.50	0.818	6.26	0.551
Perkins	0.104	1.30	15.43	15.196	9.43	2.729	7.17	0.920	6.67	0.590
Perkins	0.110	1.40	16.89	17.777	10.34	3.135	7.97	1.010	7.44	0.634
Perkins	0.187	1.20	18.73	22.128	12.49	3.506	10.35	1.002	9.96	0.588
Perkins	0.199	1.30	21.52	23.977	14.19	3.835	11.77	1.080	11.41	0.625
Perkins	0.214	1.40	24.70	25.221	15.93	4.111	13.29	1.138	12.92	0.648
Stillwater	0.000	1.20	2.99	0.055	2.85	0.047	2.77	0.050	2.81	0.062
Stillwater	0.000	1.30	3.50	0.077	3.21	0.062	3.06	0.067	3.08	0.073
Stillwater	0.000	1.40	3.62	0.070	3.35	0.060	3.20	0.062	3.22	0.070
Stillwater	0.101	1.19	15.72	10.257	10.67	1.755	7.65	0.749	6.81	0.556
Stillwater	0.111	1.29	19.04	12.033	12.21	2.139	8.79	0.859	7.80	0.622
Stillwater	0.118	1.39	21.56	14.507	13.84	2.521	9.97	0.968	8.79	0.681
Stillwater	0.192	1.19	29.20	15.735	16.77	2.992	12.79	1.037	11.68	0.702
Stillwater	0.208	1.29	33.75	17.607	19.51	3.298	14.91	1.112	13.54	0.739
Stillwater	0.225	1.39	42.12	17.629	22.82	3.516	17.34	1.188	15.70	0.789
Stillwater	0.287	1.19	39.16	13.906	24.75	2.422	19.45	0.888	17.99	0.634
Stillwater	0.308	1.29	39.09	16.856	24.09	3.050	22.51	1.192	21.15	0.864
Stillwater	0.326	1.40	57.11	15.379	33.55	2.852	26.05	1.007	23.82	0.693
Tipton	0.000	1.20	3.05	0.061	2.87	0.056	2.76	0.062	2.79	0.073
Tipton	0.000	1.30	3.36	0.066	3.13	0.060	2.98	0.068	3.00	0.078

TABLE 11 (Continued)

Location	θ	ρ_b	1 MHz ε'	1 MHz tan(δ)	10 MHz ε'	10 MHz tan(δ)	50 MHz ε'	50 MHz tan(δ)	100 MHz ε'	100 MHz tan(δ)
Tipton	0.000	1.40	3.64	0.072	3.36	0.066	3.18	0.071	3.18	0.078
Tipton	0.102	1.19	14.91	14.010	9.21	2.488	7.15	0.850	6.62	0.573
Tipton	0.105	1.29	16.78	16.088	10.28	2.859	7.96	0.945	7.35	0.627
Tipton	0.117	1.39	19.67	17.389	11.66	3.169	9.09	1.022	8.37	0.665
Tipton	0.194	1.19	24.87	17.311	14.94	3.093	12.17	0.949	11.43	0.605
Tipton	0.205	1.29	27.83	18.022	16.65	3.225	13.64	0.982	12.81	0.623
Tipton	0.222	1.39	33.65	18.624	19.26	3.482	15.78	1.049	14.89	0.661
Tipton	0.279	1.20	34.41	11.722	22.63	1.976	18.18	0.713	17.28	0.496
Tipton	0.309	1.29	39.07	12.522	25.87	2.076	21.04	0.722	19.92	0.487
Tipton	0.328	1.39	46.89	12.084	30.49	2.057	24.31	0.738	22.83	0.502

APPENDIX C

DIELECTRIC PROPERTY EXAMPLE CALCULATIONS FOR HEPTANOL AT 1 MHZ

Appendix C contains a step-by-step calculation example for the procedures used to determine the dielectric properties. The values have been included as a method of checking the equations. There are several results that are very dependent on the precision of previous calculations. If these methods are implemented on a computer, it is recommended that double precision variables be used. The numerical results below that are given with very high precision are used in the precision-sensitive equations. As a starting point, the constant variables are defined.

$\mu_o = 1.256637e\text{-}6$ H/m	permeability of free space
$\varepsilon_o = 8.84194e\text{-}12$ F/m	permittivity of free space
$L_s = 0.064$ m	sample length
$L_{adj} = 0.01$ m	adjustable length to fine-tune the model
$Z_o = (51.4, -1.17)\ \Omega$	characteristic impedance
$C_{gap} = 0.4e\text{-}12$ F	capacitance between lid and center conductor
f = 1000000 Hz	frequency
$\omega = 2000000\pi$ rad/s	radian frequency
$\beta_{air} = \omega\sqrt{\mu_o\varepsilon_o}$	phase constant for air
a = 23.3 mm	inner conductor diameter
b = 54.4 mm	outer conductor diameter

An intial calculation that must be made is the electrical length of the cell, probe, and connector. This was done by using Equation 10 from the thesis. The termination was assumed an open circuit, and the material in the cell was air. The BNC connector and the cable from the impedance meter will add to the electrical length. Calculations for the electrical length, given the impedance of the air-filled cell, are as follows.

Z_{air} = 9950<-90.1 = (-17.37, -9950) (polar to rectangular)

$$L_{elect} = \text{real}\left\{\frac{1}{\beta}\cot^{-1}\left(\frac{j\cdot Z_{air}}{Z_o}\right)\right\} \quad \text{(From Equation 10)}$$

$$= \text{real}\left\{\frac{1}{0.020944}\cot^{-1}\left(\frac{(0,1)\cdot(-17.37,-9950)}{(51.4,-1.17)}\right)\right\}$$

L_{elect} = 0.2467 m

The next step is to find the impedance of the upper portion of the cell (heptanol), given the measured impedance of the heptanol-filled cell. The following illustrates how this is accomplished.

Calculate the combined electrical length of the lower part of the cell, the BNC connector, and the probe cable.

$L_{lower} = L_{elect} - L_s - L_{adj}$

$= 0.2467 - 0.064 - 0.01$

L_{lower} = 0.1727 m

Given the measured impedance, find the impedance of the heptanol portion of the cell.

$$Z_{meas} = 2630{<}{-89.5} = (22.95,-2629.9) \qquad \text{(Impedance with heptanol)}$$

$$Z_{upper\ ideal} = \frac{Z_o\left(Z_{meas} - j\cdot Z_o\cdot\tan(\beta_{air}\cdot L_{lower})\right)}{Z_o - j\cdot Z_{meas}\cdot\tan(\beta_{air}\cdot L_{lower})} \qquad \text{(Derived from Equation 11)}$$

$$Z_{upper\ ideal} = (51.19846954455, -3226.2590651375)$$

To obtain the actual impedance of the heptanol portion of the cell, the impedance due to the capacitance between the lid and the center conductor, Z_{gap}, must be accouted for.

$$Z_{gap} = \left(0, \frac{-1}{C_{gap}\cdot\omega}\right)$$

$$Z_{gap} = (0, -397887.35767785)$$

$$Z_{upper\ actual} = \frac{Z_{upper\ ideal}\cdot Z_{gap}}{Z_{upper\ ideal} + Z_{gap}}$$

$$Z_{upper\ actual} = (50.3782, -3200.3159)$$

The propagation constant can be found, given the impedance (open circuit termination) of the upper portion of the cell. An iterative method was used to find the propagation constant. Rather than showing the iterations, the equation that had to be solved is given, and the reader may verify the solution by putting the values into the equation.

Equation to be solved in order to find the complex propagation constant, γ:

$$\frac{1}{\gamma \cdot \tanh(\gamma \cdot L_s)} = \frac{Z_{\text{upper actual}} \cdot 2\pi}{j \cdot \omega \cdot \mu \cdot \ln\left(\frac{b}{a}\right)}$$

For 1 MHz, the complex propagation constant is

$$\gamma = \alpha + j\beta = (0.00056022947, 0.071182995)$$

From this value, all of the dielectric properties can be found as follows.

$$\alpha = \text{real}(\gamma) = 5.6023 \times 10^{-4}$$

$$\beta = \text{imag}(\gamma) = 0.07118$$

$$\kappa' = \frac{\alpha^2 - \beta^2}{-\omega^2 \cdot \mu_o \cdot \varepsilon_o} = 11.55$$

$$\sigma = \frac{2 \cdot \alpha \cdot \beta}{\omega \cdot \mu_o} = 1.0101 \times 10^{-5}$$

$$\kappa'' = \frac{\sigma}{\omega \cdot \varepsilon_o} = 0.182$$

$$\tan(\delta) = \frac{\kappa''}{\kappa'} = 0.0157$$

VITA

Gregory J. Arnold

Candidate for the Degree of

Master of Science

Thesis: THE DESIGN OF A DIELECTRIC BASED SOIL MOISTURE SENSOR

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Guymon, Oklahoma, May 3, 1968, the son of Tom and Vickie Arnold.

Education: Graduated from Hooker High School, Hooker, Oklahoma, in May, 1986; received Bachelor of Science Degree in Agricultural Engineering from Oklahoma State University in December, 1990; completed requirements for the Master of Science degree at Oklahoma State University in December, 1992.

Professional Experience: Graduate Research Assistant, Department of Agricultural Engineering, Oklahoma State University, January, 1991 to December, 1992; Computer Laboratory Teaching Assistant, College of Agriculture, Oklahoma State University, August, 1989 to December, 1989; Professor's Assistant, Department of Agricultural Engineering, Oklahoma State University, August, 1988 to May, 1989; Member of the American Society of Agricultural Engineers; Member of the National Society of Professional Engineers; Member of Alpha Epsilon; Passed Engineer-in-Training exam, December, 1990.