MEASUREMENT OF SOIL MOISTURE BY ATTENUATION
OF A VERTICALLY POLARIZED RADIO WAVE

by

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Approved:

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Arlo D. Mickelsen
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ABSTRACT

Measurement of Soil Moisture by Attenuation of a Vertically Polarized Radio Wave

by

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Utah State University, 1971

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Major Professor: Dr. Glen L. Smerage
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The purpose of this thesis is to determine feasibility and to investigate some of the problems encountered in making soil moisture measurements using radio wave propagation. The procedure consists of propagating a vertically polarized wave over the earth and measuring the field strength attenuation. A brief summary of present methods of measuring soil moisture is given.

Certain aspects of radio wave propagation theory are discussed, covering such topics as the surface wave, the space wave, the skin depth, and the effect of the dielectric constant on radio wave propagation. Based on this theory, measurement parameters such as frequency, antenna separation, and antenna height were chosen for optimum performance. Using these parameters and information gained from preliminary measurements, the instrumentation was designed and is given in detail.

Measurement variables such as antenna height, reflections, temperature, and vegetation were investigated with the use of experimental data. The width of the area affecting the propagating wave was also looked at experimentally. A relationship between soil moisture and signal strength is presented from measurements taken for various values of soil moisture content.

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INTRODUCTION

There are numerous methods of determining soil moisture which measure moisture at only one point or position. Most of these measurements require a substantial amount of time to complete and can, therefore, be somewhat costly. A more desirable soil moisture measurement, in some instances, would be one that covered a relatively large area and produced immediate results. One possible method which shows promise is the use of radio waves.

In radio wave propagation the ground wave attenuation depends upon the conductivity and dielectric constant of the earth it is transversing. These two electrical properties of soil vary with soil moisture. Utilizing this fact, soil moisture could possibly be determined by measuring the relative intensity of a radio wave. The purpose of this research is to determine the feasibility of measuring soil moisture using radio wave propagation, and to investigate the variables and problems encountered in making such a measurement.

The first section of this thesis gives a brief investigation of the present methods of measuring soil moisture. A detailed description of each method is not given, but sufficient information is given to understand the principle of the method, and to know where additional information can be found.

The following section discusses theory on radio wave propagation. Topics such as the surface wave, the space wave, the skin depth, and the effect of the dielectric constant on propagation are discussed. This theory will be used as a basis for the next section on measurement parameters.
Measurement parameters are investigated with values given for frequency, antenna separation, and antenna height. These values were chosen to give optimum performance based on theory. Using these parameters, and making other considerations, the instrumentation was designed and a description of the equipment is given in enough detail that the measurements taken can be repeated.

The last two sections involve actual measurements using the equipment and parameters outlined in previous sections. The first investigates measurement variables, including antenna height, reflections, temperature, vegetation, and effective width, which is the width of the area that affects the propagating wave. The last section discusses experimental results which demonstrate a relationship between relative signal strength and soil moisture content.

The onset of winter and bad weather conditions imposed a limitation on the time available for collection of field data. As a consequence, a quantitative evaluation of the method for determining soil moisture is not complete. The information given here will hopefully determine feasibility and provide the ground work for additional research on this method.
PRESENT STATE OF THE ART OF SOIL

MOISTURE MEASUREMENT

Introduction

There are many methods of measuring soil moisture based on different physical principles. Ballard (1970) has compiled a comprehensive study of the methods of measuring moisture and has put them in the following categories: hygrometric, electrical resistivity, capacitance, nuclear, gravimetric, radiation, tensiometry, thermal conductivity, and miscellaneous. Almost all of the methods are point or small restricted area measurements and require a substantial amount of time to perform. They differ in application due to the differences in many characteristics such as, size, accuracy, reliability, speed, cost, and type of measurement. No attempt will be made to describe each method in detail, but enough information is given to know the principle of the method, its salient features, and where additional information can be found.

Hygrometric

The relationship between relative humidity of the immediate atmosphere and the moisture content of porous materials under equilibrium conditions is well known. This presents a method of measuring soil moisture if the relative humidity just above the ground can be determined. Wexler and Ruskin (1965) give a detailed study of humidity sensors or hygrometers.

Electrical resistance hygrometers operate on the principle that the electrical resistance can be varied by changes in the water content of volumetric and electrolytic processes. Some materials that are used are
salts that disassociate in the presence of water, lowering the electrical resistance between two electrodes. Another material used is aluminum oxide (Cutting, Janson and Wood, 1955) which is used as a dielectric film for a capacitor. Both the resistance and the dielectric constant of aluminum oxide change with humidity.

One electrolysis system consists of two platinum wires wound inside an insulating tube and coated with a layer of partially hydrated phosphorus pentoxide. A gas flows over the wires and water vapor is absorbed by the \( \text{P}_2\text{O}_5 \) layer. At the same time, a direct current is passed through the wires which decomposes water into gaseous \( \text{H}_2 \) and \( \text{O}_2 \). When equilibrium is reached between the water absorbed by the \( \text{P}_2\text{O}_5 \) layer and that decomposed by electrolysis, the relative humidity can be found knowing the current flow, the temperature, and the pressure.

A similar system to the one just mentioned consists of a tubular wick impregnated with a hygroscopic salt (lithium chloride). An alternating voltage is applied to two wires bifilar wound around the wick. As the lithium chloride absorbs humidity it becomes conductive and passes a current. At the same time, it generates heat proportional to the current flow which evaporates moisture from it. An equilibrium is reached where water is neither gained nor lost from the layer, and the humidity can then be determined from the temperature associated with this equilibrium.

There are two known types of dielectric hygrometers, capacitor transducers and microwave refractometers. The capacitor transducers consist of a dielectric whose dielectric constant changes with the addition of moisture. The microwave system consists of a cavity with a resonant frequency that varies with dielectric constant and therefore humidity.
Another hygrometer operates by the method of piezoelectric sorption. A quartz crystal, which has a resonant frequency dependent upon its mass, is coated with a hygroscopic material. The mass changes with the absorption of moisture and the humidity is determined from the change in resonant frequency.

Various optical methods are used for humidity sensors. One of the more popular methods (Wood, 1958) consists of an optical instrument which operates in the infrared region and monitors two selected frequencies. The ratio of the amplitudes at the two frequencies is a function of water vapor concentration.

There are many materials which vary dimensionally with humidity. Some of these materials which have been used to make hygrometers are human hair, Dacron thread (Monfore, 1963), white oak and scotch pine strips, and certain ceramic materials (Cole and Birthwistle, 1969). The relative humidity can be determined by detecting the changes in the dimensions of these materials.

The dew point hygrometer depends upon a temperature measurement and is, therefore, simple and inexpensive but has a slow response time. The temperature at which dew appears on the surface of a cooled object can be related to the partial pressure of water of the gas sample being measured.

Psychrometric instruments make very simple hygrometers. This method uses the temperature between the "wet bulb" and the "dry bulb" of temperature sensors. The relative humidity can be determined from this information with the use of the psychrometric formula (Wexler and Ruskin, 1965).
**Electrical resistivity**

The resistance of soil varies with the amount of moisture it contains. Soil moisture measurements are, therefore, possible with a simple resistance measurement. Two of the problems encountered in resistance measurements are electrode contact resistance and changes in resistance due to the presence of ionized salts.

Two types of measurements are made, sample resistivity and sensor resistivity. Sample resistivity measurements are made with the electrodes in direct contact with the soil sample (Bouyoucos and Mick, 1948). The sensor resistivity measurement involves a sensor that must first reach moisture equilibrium with the sample and then the resistance of the sensor is measured.

**Capacitance**

The capacitance of soil varies with moisture due to the fact that the dielectric constant for most soils is about 2.6 and for water is about 80. Errors in this type of measurement result from variations in the dielectric constant due to non-water components, particle size, packing density, and ionized salts.

As with resistance measurements, there are two general methods. The capacitance of a soil sample or the capacitance of a sensor, which must reach moisture equilibrium with the soil, can be measured.

A comprehensive treatment of the capacitance method is given by Wexler (1965).

**Nuclear**

The method of neutron scattering for determining soil moisture is based on the principle of measuring the slowing of neutrons emitted into
the soil from a fast-neutron source (Smith et al., 1968). Fast neutrons are changed to slow neutrons upon collision with atoms of low atomic weight, such as hydrogen. Hydrogen is the principal element of low atomic weight in soil and its presence is due largely to water content. The number of slow neutrons detected, after emission of fast neutrons, is therefore, proportional to the amount of water surrounding the fast neutron source. This method is a volumetric measurement. Some measurement interferences that exist are sensitivity to the total sample density, sensitivity to sample composition, sensitivity to surface roughness, and sensitivity to sample homogeneity. The research and literature, on this method and ways to minimize measurement interferences, is almost limitless and no attempt will be made to describe them here.

A second nuclear method uses gamma ray transmission which varies with changes in soil moisture. This method was used to measure moisture within a half inch layer of soil by Smith, Taylor, and Smith (1967).

**Gravimetric**

The gravimetric method of measuring soil moisture involves five steps: (1) collecting a soil sample, (2) weighing it, (3) removing the moisture, (4) weighing the dry sample or the removed water, and (5) calculating the moisture content. This is the most direct method of soil moisture measurement and is often used for calibration in other methods. Applications of this technique are given by Wexler (1965), Monfore (1970), and Geary (1956).

Thermal extraction is probably the more popular method of removing moisture from the sample. This method involves techniques such as oven
drying, freeze drying, distillation, heating in oil, dissicant weight gain, and alcohol burning (Geary, 1956).

Another method of removing moisture involves chemical extraction. Three principal categories are alcohol, calcium carbide (hydride) (Geary, 1956), and Karl Fischer reagent (Roth, 1966).

Two other methods of removing moisture are mechanical extraction and immersion. Samples with a high water content can be mechanically pressed to remove water (Geary, 1956). The immersion method uses procedures for determining specific gravity and was first worked on in 1936.

Radiation

Radiation techniques involve mechanical and electromagnetic waves and how they are affected by changes in soil moisture.

Mechanical radiation involves ultrasonics in the high frequency range and the penetrometer in the low frequency range. The effect of moisture on ultrasonic energy propagation was studied experimentally by Mack and Brach (1966). The penetrometer is based on the principle that the resistance to penetration or deformation will vary with soil moisture (Geary, 1956).

Electromagnetic radiation methods can be divided into four categories, radio wave, microwave, nuclear magnetic resonance, and infrared. Both radio wave and microwave energy is absorbed by moisture and measurements are made using this principle. The difference between the two lies in the frequency range and, therefore, the type of equipment used. Radio frequency measurements have been made using probe-type electrodes (Roth, 1966) and by an airplane airflight technique (Geleynst and Barringer, 1965) where a radio wave is reflected from the ground.
The nuclear magnetic resonance technique involves placing a sample in both a fixed and a varying magnetic field simultaneously. At specified frequencies there is an increased absorption of energy of the varying magnetic field due to nuclear magnetic resonance. Water molecules in a material can be measured by looking at the hydrogen nuclei spectra (Geary, 1956).

Another method is based on infrared reflection which is proportional to the moisture content of the exposed solid. This is primarily a surface measurement and is not accurate if the moisture is not homogeneous.

**Tensiometry**

A tensiometer is a device for measuring the capillary tension produced by water held in soil (Richards and Gardner, 1936). Two types of instruments have been used, the porous cup tensiometer and the permeable membrane tensiometer. Instead of capillary flow through a porous ceramic wall, the permeable membrane uses osmosis for its flow mechanism. The measured capillary tension can be related to soil moisture.

**Thermal conductivity**

Changes in thermal conductivity are proportional to changes in moisture content of porous materials. This principle may be applied by measuring the rise in temperature of the material at a known distance from the heat source, or by measuring the temperature rise of the heating element due to the change in heat dissipation rate. An easy technique for making the above measurement has been developed using a thermistor as a combination heating element and temperature indicator (Bloodworth and Page, 1957).
Miscellaneous

The volumetric expansion of water is very large upon evaporation. If a sample is enclosed in a small volume and the temperature is raised to evaporate the water it contains, the pressure of the container will rise and the moisture content of the sample can be related to this pressure (Geary, 1956).

A colorimeter may also be used to measure soil moisture. This instrument utilizes the reaction between cobalt chloride and moisture which produces a measurable color change proportional to moisture content. This method may be considered a gravimetric method since the weight of the sample being measured must be known.
RADIO WAVE THEORY

Surface wave

Near the surface of the earth a radio wave is composed of two components, a surface wave and a space wave. The surface wave propagates with its lower edge in contact with the ground and can, therefore, only be vertically polarized since any horizontal electric field is short-circuited by the earth.

Power from the surface wave is dissipated in the earth's crust depending upon the characteristics of the soil over which the wave is propagating. Charges are induced in the earth due to the vertically polarized electric field of the surface wave. These charges induce a current flow through the earth which behaves like a leaky capacitor and can be represented by a resistance shunted by a capacitance (Terman, 1955). Therefore, the electrical characteristics of the earth can be expressed by a conductivity $\sigma$ and a dielectric constant $\varepsilon$. Power is dissipated by the induced current flowing through the earth's resistance. This power loss accounts for the attenuation of the surface wave as it propagates.

Mathematical expressions describing the nature of the surface wave, first given by Somerfield, are discussed by Norton (1936). For an earth assumed flat, the surface wave field strength can be expressed by

$$\text{Field Strength} = A \frac{E_0}{d}$$

(1)
in which

\[ E_0 = \text{field strength of wave at the surface of the earth at a unit distance from the transmitting antenna, neglecting earth's losses} \]

\[ d = \text{distance from transmitting antenna} \]

\[ A = \text{attenuation factor due to ground losses} \]

The factor A is expressed by the curves in Figure 1. The numerical distance \( P \) for a vertically polarized wave is found by the relations

\[ P = \frac{\pi d}{x \lambda} \cos \theta \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2) \]

\[ \tan \theta = \frac{\varepsilon_r + 1}{x} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3) \]

in which

\[ x = 1.80 \times 10^{12} \sigma/f \]

\[ \frac{d}{\lambda} = \text{distance in wavelengths} \]

\[ \sigma = \text{ground conductivity in mhos per cm} \]

\[ f = \text{frequency in hertz} \]

\[ \varepsilon_r = \text{dielectric constant of the ground referred to air as unity} \]

For \( \theta \leq 90^\circ \), the curves in Figure 1 can be expressed approximately by the relation (Terman, 1943)

\[ A = \frac{2 + 0.3p}{2 + p + 0.6 \ p^2} - \sqrt{\frac{p}{2}} - \varepsilon_r \frac{5p}{8} \sin \theta \ldots \ldots (4) \]

The factor A is shown by Equations (2), (3), and (4) to be dependent upon the conductivity and dielectric constant of the earth, the frequency, and the distance from the transmitting antenna.
Figure 1. Attenuation factor (A) versus numerical distance (p).
Space wave

The space wave is the second component of the radio wave of interest and is the vector sum of two separate waves. One is a direct wave between the transmitting and receiving antennas, and the other is a wave reflected by the surface of the earth before reaching the receiving antenna.

According to Terman (1955), if the heights of the transmitting and receiving antennas are small compared with the distance between the antennas, causing the angle of incidence of the reflected wave to be small, the two waves will be equal in amplitude but will differ in phase. This is due to the fact that the reflected wave will travel essentially the same distance as the direct wave giving it the same magnitude, but will undergo a phase shift due to the reflection. Under these conditions, the field strength of the space wave can be expressed by

\[ \text{Field strength} = \frac{2 E_0}{d} \sin \frac{2 \pi h_{rs}}{\lambda d} \]  

(5)
in which

- \( E_0 \) = strength of the direct wave at unit distance
- \( d \) = distance between transmitting and receiving antennas
- \( \lambda \) = wavelength
- \( h_s, h_r \) = height of transmitting and receiving antennas

Examination of Equation (5) shows that the field strength of the space wave will be very small and possibly negligible, compared to the surface wave, when the antenna heights are very small in relation to the distance between the antennas.

Skin depth

Current flow in a conductor at radio frequencies is distributed so that most of the current flows near the surface of the conductor. This
is due to the fact that the inductance, and therefore, the impedance, is less near the surface than it is deeper in the conductor where more magnetic flux lines are linked with current flow (Terman, 1955).

With the surface of the conductor at the \( Y = 0 \) plane, the current distribution in the \( Y \) direction will be given by (Jordan, 1950).

\[
i = i_0 e^{-\gamma Y}
\]

(6)

in which \( i_0 = \) current density at the surface

\[
\gamma = \sqrt{j \omega \mu (\sigma + j \omega \varepsilon)}
\]

Since we are interested in the attenuation of current with depth we will only use the real part of \( \gamma \), which is called the attenuation constant \( \alpha \), are rewrite Equation (6) as

\[
i = i_0 e^{-\alpha Y}
\]

(7)

The skin depth is the depth at which the current density is \( 1/e \) or 37 percent of the surface current density \( i_0 \). This occurs at a depth of \( 1/\alpha \) as can be seen from Equation (7). From Jordan (1950) the attenuation factor can be expressed by

\[
\alpha = \sqrt{\frac{\mu \varepsilon}{2}} \left( \sqrt{1 + \frac{\sigma^2}{\omega^2 \varepsilon^2}} - 1 \right)
\]

(8)

Using Equation (8) the skin depth can be calculated for any frequency and soil conditions. For good earth, with conductivity \( \sigma = 10^{-4} \) mhos per cm and relative dielectric constant \( \varepsilon_r = 15 \), and poor earth, with \( \sigma = 2 \times 10^{-5} \) mhos per cm and \( \varepsilon_r = 5 \), as defined by Terman (1943)
the skin depths are plotted as a function of frequency in Figure 2. As can be seen from the curves, the skin depth becomes independent of frequency above 30 MHz. From this analysis, it appears that the skin depth in soil would be difficult to control by varying the frequency of the propagating wave.

For the above calculations using Equation (8), the permeability $\mu$ was set at the value for free space giving a relative permeability of unity for all soil conditions. The relative permeability may change from unity for different soils, but will have a negligible change for increases in moisture in the same soil. This is evident knowing that the relative permeability for water is $1.9 \times 10^{-6}$ (Terman, 1950).

**Effect of dielectric constant on radio wave propagation**

According to Josephson and Blomquist (1958) the dielectric constant of soil is determined mainly by the moisture content and is relatively independent of the type of soil. If this is true, soil moisture measurements could best be made for a dielectric earth where conductivity, which is dependent upon other soil properties besides moisture, would have a negligible effect upon surface wave attenuation.

Jordan (1950) considers a material a good dielectric when $\sigma/\omega \varepsilon \ll 1$. This is true for most soils for frequencies above 100 MHz. Terman (1955) defines the numerical distance $P$, which can be used in Equation (4) to find the surface wave attenuation factor $A$, for a dielectric earth by

$$P = \frac{\pi d}{c} \frac{f}{\varepsilon + 1}$$

(9)
Figure 2. Calculated skin depth versus frequency for good earth and poor earth.
in which

\[ d = \text{distance from transmitting antenna} \]

\[ c = \text{velocity of light} \]

\[ f = \text{frequency} \]

\[ \varepsilon_r = \text{dielectric constant of the ground referred to air as unity} \]

\( P \) in Equation (9) is dependent upon \( \varepsilon_r \) and no other soil properties making the surface wave attenuation almost entirely dependent upon the dielectric constant and, therefore, soil moisture.

Josephson and Blomquist (1958) give an approximate relation for \( \varepsilon_r \) as a function of soil water content to be used for VHF field strength calculations. With dry earth having a relative dielectric constant of 2.5 and the relative dielectric constant for wet earth being proportional to the percentage water content, \( w \) percent, the relation is

\[ \varepsilon_r = .78w + 2.5 \]  

(10)

Note that for pure water, or \( w = 100 \) percent, \( \varepsilon_r = 80.5 \) which is close to the value given for water, \( \varepsilon_r = 80 \).

An idea of how surface wave signal strength varies with changes in soil moisture can be obtained from Equations (4), (9) and (10). For a water content of 10 percent \( \varepsilon_r = 10.3 \) and for an increase of 10 percent, or \( w = 20 \) percent, \( \varepsilon_r = 18.1 \). Using a frequency of 170 MHz and a separation of 17 wavelengths, the surface wave attenuation factor \( A \) is .16 for \( \varepsilon_r = 10.3 \) and .29 for \( \varepsilon_r = 18.1 \). This gives a signal strength increase of 81 percent for a soil moisture increase of 10 percent.
MEASUREMENT PARAMETERS

Frequency

Considering the wide range of frequencies over which radio wave propagation is feasible, the possibility of an optimum frequency for radio wave measurement of soil moisture was investigated.

There are several factors affected by frequency that must be considered. One is the separation between transmitting and receiving antennas. If very low frequencies are used the separation may have to be in the order of miles just to eliminate the effects of the near or induction field. On the other extreme, frequencies in the microwave region might necessitate a separation so small that the intent of an integrated measurement of soil moisture over a reasonable area would be defeated. Antenna size is another factor dependent upon frequency as an antenna small enough to be portable would be desirable. Other considerations are the commercial equipment readily available and the ratio of field strengths of signals propagated over poor and good earth which is a function of frequency and must also be investigated in choosing an optimum frequency.

The field strength as a function of frequency was determined theoretically. Parameters for good and poor earth were taken from Terman (1943), with conductivity \( \sigma = 10^{-4} \) mhos per cm and relative dielectric constant \( \varepsilon_r = 15 \) for good earth and \( \sigma = 2 \times 10^{-5} \) mhos per cm and \( \varepsilon_r = 5 \) for poor earth. Using Equation (1) the field strength ratio would be expressed by

\[
\text{Field Strength Ratio} = \frac{A_1 \frac{E_0}{d}}{A_2 \frac{E_0}{d}}
\]
This relation is correct if the space wave is negligible compared to the surface wave leaving the surface wave as the only component. Since the reference field strength $E_0$ and the antenna separation $d$ are the same for both poor and good earth, Equation (11) reduces to

$$\text{Field Strength Ratio} = \frac{A_1}{A_2} \ldots \ldots \ldots (12)$$

in which

$$A_1 = \text{attenuation factor over good earth}$$
$$A_2 = \text{attenuation factor over poor earth}$$

$A_1$ and $A_2$ can be calculated, for a given frequency and the appropriate $\sigma$ and $\varepsilon$, using Equations (2), (3), and (4).

Examination of Figure 1 shows that the attenuation factor $A$ differs only slightly from unity for $P < 1.0$. The losses in the earth then will have little effect upon the surface wave. For the factor $A$ to vary for different soil conditions, the relation $P > 1.0$ must be satisfied.

Table 1 lists the values of the numerical distance $P$ and the phase constant $b$ for various frequencies, for two soil conditions, and at three different antenna separations, 10, 34.6, and 80 wavelengths. Examination of Table 1 shows that $P$ and $b$ approach constant values at frequencies above 30 MHz.

Figure 3 is a plot of the ratio of field strengths for good and poor earth versus frequency for the three antenna separations mentioned above. The peaks seen at the low frequency end are due to the changes in slope of the curves in Figure 1 for various values of $b$ in the region $1.0 \leq p \leq 10$.

---

1A separation of 34.6 wavelengths corresponds to 200 feet at 170 MHz where many preliminary measurements were made.
Table 1. Calculated values of phase angle, numerical distance, and attenuation factor at different frequencies and distances for both good and poor earth.

<table>
<thead>
<tr>
<th>Distance = 20 wavelengths</th>
<th>Frequency (MHz)</th>
<th>Good Earth</th>
<th>Poor Earth</th>
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<td></td>
<td></td>
<td>b(degrees)</td>
<td>p</td>
</tr>
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<td>1</td>
<td>5.1</td>
<td>0.35</td>
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<tr>
<td></td>
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<td>23.9</td>
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</tr>
<tr>
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<td>3.88</td>
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<td>3.90</td>
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<th>Poor Earth</th>
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<td></td>
<td>b(degrees)</td>
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</tr>
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<td>69.5</td>
<td>6.34</td>
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<td></td>
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<td>6.74</td>
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<th>Frequency (MHz)</th>
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<th>Poor Earth</th>
</tr>
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</tr>
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<td>200</td>
<td>86.8</td>
<td>15.59</td>
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</tbody>
</table>
Figure 3. Calculated ratio of field strengths for good and poor earth ($A_1/A_2$) versus frequency ($f$) for three distances, 20, 34.6, and 80 wavelengths.
For frequencies above 30 MHz, the field strength ratio stays nearly a constant value.

A frequency of 170.225 MHz was chosen for the operating frequency for several reasons. It occurred in a region that gave a good field strength ratio as shown in Figure 3. Antennas for this frequency are of a reasonable size to be portable. Equipment was readily available for this frequency and the antenna separation was practical as will be shown in the next section.

**Antenna separation**

The separation between the transmitting and receiving antennas has a definite effect upon the attenuation factor \( A \) and, therefore, must be chosen carefully in measuring soil moisture. As the separation becomes smaller, the field strength becomes larger which is a desired condition in order to simplify instrumentation. A desired separation would be one that would give a maximum ratio of field strengths measured over good and poor earth but would be as small as possible in order to maximize the signal strength.

The effect of separation on the field strength ratio was investigated theoretically. The field strength ratio is given by Equation (12) and the attenuation factors \( A_1 \) and \( A_2 \) are calculated using Equations (2), (3), and (4) and the appropriate values for \( \sigma \) and \( \varepsilon \). It is apparent from Equation (2) that the numerical distance \( P \) is proportional to the separation in wavelengths and, therefore, the separation essentially determines the position on the curves in Figure 1 which show the relationship between \( A \) and \( P \).
The curves in Figure 4 show the relationship between the field strength ratio $A_1/A_2$ and the separation in wavelengths for three different frequencies, 30, 100, and 170 MHz. From the curves, it is evident that a good field strength ratio is sustained for separations greater than about 15 wavelengths.

A separation of 100 feet or 17.3 wavelengths at 170 MHz was chosen for the soil moisture measurements. This is about the smallest separation that will still give a field strength ratio near the maximum value attainable.

**Antenna height**

The heights of the receiving and transmitting antennas above the ground determine which component of the propagating wave is dominant in producing a given signal at the receiver. According to Terman (1955), with vertically polarized waves and earth having good conductivity, the surface wave ceases to dominate and the space wave becomes more important when the antennas are one or two wavelengths above ground. Since near the ground the space wave is independent of earth characteristics, it is desirable to have the surface wave dominate.

The effect of antenna height was investigated with the use of Equation (5) which gives the theoretical field strength of the space wave. In order to compare the two wave components, an expression for the space wave attenuation factor was derived from Equation (5) which could be compared with the surface wave attenuation factor given by Equation (4). The relation is

$$As = 2 \sin \left( \frac{2 \pi h \sin \theta}{\lambda d} \right)$$

(13)
Figure 4. Calculated ratio of field strengths for good and poor earth ($A_1/A_2$) versus distance ($d/\lambda$) for three frequencies, 30, 100, and 170 MHz.
since both the reference field $E_0$ and the separation $d$ are common to both wave components.

At 170 MHz and a separation of 100 feet, the surface wave attenuation factor, which is independent of antenna height, for good earth is .244 and for poor earth is .079. The space wave attenuation factor for various antenna heights is given in Table 2 below.

**Table 2. Calculated space wave attenuation factor for various antenna heights.**

<table>
<thead>
<tr>
<th>Height (wavelengths)</th>
<th>Attenuation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1/8</td>
<td>.0114</td>
</tr>
<tr>
<td>1/4</td>
<td>.0454</td>
</tr>
<tr>
<td>1</td>
<td>.726</td>
</tr>
</tbody>
</table>

Examination of these figures indicates that the height of the antennas should be in the order of 1/8 wavelength or less for the surface wave to dominate for both poor and good earth.
INSTRUMENTATION

General configuration

Soil moisture measurements were made using the instrumentation shown in Figure 5. A wattmeter was inserted between the transmitter and the transmitting antenna in order to monitor the power delivered to the antenna. The field strength at the receiving antenna was monitored with an RF millivoltmeter which measured RF voltage on the transmission line which was terminated in its own characteristic impedance. A filter was inserted in the transmission line to limit the bandwidth and, therefore, eliminate undesired signals.

Transmitter

The transmitter consisted of the RF section of a Motorola 132-174 MHz "Handie Talkie" Motorola No. 63E8103LA32-D. A variable voltage, battery power supply was used to power the transmitter. The output power was controlled by varying the supply voltage.

The wattmeter used to monitor the power delivered to the transmitting antenna was a Bird Electronic Corporation Thruline wattmeter Model 43.

Antennas

Identical ground plane antennas were used for both transmitting and receiving. The ground plane was chosen because it consists of an artificial ground which is separate from earth ground. This makes it possible to vary the antenna height and to eliminate the effects of local ground conditions on the antenna.
Figure 5. Instrumentation block diagram.
The antennas were constructed of sheet metal cones with quarter wave vertical whips extending from the top. Cones were used for three reasons, to make the antennas rigid and, therefore, more portable, to make the characteristic impedance of the antennas near 50 ohms (A.R.R.L., 1968), and to produce maximum radiation in the horizontal plane (Kraus, 1950). Ninety degree cones were used with 18 inch skirts, which is slightly longer than a quarter wave at 170 MHz. The vertical whips were 16.25 inches long, which tuned the antennas at the desired frequency of 170 MHz.

**Field strength indicator**

The field strength present at the receiving antenna was measured using a Hewlett Packard RF millivoltmeter Model 411A. The meter was powered from a 12 volt car battery and a Heathkit power converter Model MP-10. The RF voltage was measured across a 50 ohm carbon resistor used to terminate the RG-58 A/U coaxial transmission line leading from the receiving antenna.

The filter inserted in the transmission line just before the 50 ohm termination is a parallel LC section resonant at 170.2 MHz. A more elaborate filter could have been used, but this simple filter seemed to be adequate.
MEASUREMENT VARIABLES

Antenna height

Antenna height has a notable effect upon field strength and, therefore, becomes an important factor in making soil moisture measurements. According to theory, there are two reasons for changes in field strength with changes in antenna height. One reason is demonstrated with the use of Equation (5) which shows how the field strength of the space wave varies as the heights of the transmitting and receiving antennas are changed. The space wave becomes a more prominent component of the propagating radio wave as the antenna heights are increased. A second reason involves changes in antenna loading with changes in height. For a given input voltage the antenna current will vary due to reflections from the ground (A.R.R.L., 1968). The amplitude and phase of the reflected wave depends upon the distance between the antenna and ground, as well as earth characteristics, causing the antenna current and, therefore, characteristic impedance to vary with antenna height. The loading and efficiency of the antenna will change as the characteristic impedance changes.

There is strong experimental evidence that both the strength of the space wave and the antenna efficiency change significantly with antenna height when the antennas are close to the ground. To demonstrate the effect of antenna height, three models were constructed for three different conditions: (1) space wave changes with height but antenna efficiency does not, (2) space wave is constant but antenna efficiency changes with height, (3) both space wave and antenna efficiency change with height.
Field strengths were calculated for dry earth and wet earth and at two antenna heights, on the ground (0) and a quarter wavelength (λ/4) above the ground. The surface wave attenuation factor was assumed constant for changes in antenna height but changed with earth conditions. The space wave attenuation factor was set at 0 when the antennas were on the ground and was assumed independent of earth conditions. The values given for the attenuation factors are only relative and not actual. The models are based on the following equation and values

\[
\text{Field Strength} = \frac{2 \text{Eo}}{d} (\text{Ag} + \text{As})
\]

in which

- \( \text{Ag} \) = surface wave attenuation factor
- \( \text{As} \) = space wave attenuation factor
- \( \frac{2 \text{Eo}}{d} \) = antenna output neglecting losses

<table>
<thead>
<tr>
<th>Dry Earth</th>
<th>Wet Earth</th>
</tr>
</thead>
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<tr>
<td>( \text{Ag} ) = .25 ( @ 0 )</td>
<td>( \text{Ag} ) = .5 ( @ 0 )</td>
</tr>
<tr>
<td>( \text{Ag} ) = .25 ( @ \lambda/4 )</td>
<td>( \text{Ag} ) = .5 ( @ \lambda/4 )</td>
</tr>
<tr>
<td>( \text{As} ) = 0 ( @ 0 )</td>
<td>( \text{As} ) = 0 ( @ 0 )</td>
</tr>
<tr>
<td>( \text{As} ) = .25 ( @ \lambda/4 )</td>
<td>( \text{As} ) = .25 ( @ \lambda/4 )</td>
</tr>
</tbody>
</table>

The results are shown as the ratio and difference between wet and dry earth for both antenna heights in each model.

Model No. 1

Conditions: As changes with height but antenna efficiency does not change with height so that \( 2 \text{Eo/d} = 100 \text{ mv} \) @ 0 and \( \lambda/4 \)

<table>
<thead>
<tr>
<th>Dry Earth</th>
<th>Wet Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ 0 F.S. = 100 (.25 + 0) = 25 mv</td>
<td></td>
</tr>
<tr>
<td>@ \lambda/4 F.S. = 100 (.25 + .25) = 50 mv</td>
<td></td>
</tr>
</tbody>
</table>
Wet Earth

@ 0 F.S. = 100 (.5 + 0) = 50 mv
@ λ/4 F.S. = 100 (.5 + .25) = 75 mv

Results

@ λ/4 Ratio of wet earth
   dry earth = \frac{75 \text{ mv}}{50 \text{ mv}} = 1.5

difference = 25 mv

@ 0 Ratio of wet earth
   dry earth = \frac{50 \text{ mv}}{25 \text{ mv}} = 2.0

difference = 25 mv

Model No. 2

Conditions: As = 0 at all times but antenna efficiency changes with height so that

@ 0 \frac{2 \text{ Eo}}{d} = 100 \text{ mv}

@ λ/4 \frac{2 \text{ Eo}}{d} = 200 \text{ mv}

Dry Earth

@ 0 F.S. = 100 (.25 + 0) = 25 mv
@ λ/4 F.S. = 200 (.25 + 0) = 50 mv

Wet Earth

@ 0 F.S. = 100 (.5 + 0) = 50 mv
@ λ/4 F.S. = 200 (.5 + 0) = 100 mv

Results

@ λ/4 ratio = \frac{100 \text{ mv}}{50 \text{ mv}} = 2.0

difference = 50 mv

@ 0 ratio = \frac{50 \text{ mv}}{25 \text{ mv}} = 2.0

difference = 25 mv
Model No. 3

Conditions: both As and antenna efficiency change with antenna heights in that

\[
\frac{2 \ E_0}{d} = 100 \ \text{at } 0
\]

\[
\frac{2 \ E_0}{d} = 200 \ \text{at } \lambda/4
\]

**Dry Earth**

@ 0 F.S. = 100 \((.25 + 0)\) = 25 mv

@ \lambda/4 F.S. = 200 \((.25 + .25)\) = 100 mv

**Wet Earth**

@ 0 F.S. = 100 \((.5 + 0)\) = 50 mv

@ \lambda/4 F.S. = 200 \((.5 + .25)\) = 150 mv

**Results**

@ \lambda/4 ratio \(= \frac{150 \text{ mv}}{100 \text{ mv}} = 1.5\)

difference = 50 mv

@ 0 ratio \(= \frac{50 \text{ mv}}{25 \text{ mv}} = 2.0\)

difference = 25 mv

Experimentally it was found that consistently the ratio of field strengths over wet and dry earth decreased with antenna elevation while the difference between the field strengths increased with elevation. These results coincide with the third model where the antenna efficiency and the space wave vary with changes in antenna height.

To show the effect of antenna height on characteristic impedance the following experiment was performed. One of the ground plane antennas was suspended so that its height above ground could be varied and the characteristic impedance was measured with a Boonton Radio Company Rx meter.
type 250 A at 170.2 MHz. The antenna height was measured from the bottom of the cone to the ground. The results are listed in Table 3.

Table 3. Measured antenna impedance for different antenna heights near the ground.

<table>
<thead>
<tr>
<th>Antenna Height (Inches)</th>
<th>Rp (ohms)</th>
<th>Cp (pf)</th>
<th>Z ohms</th>
</tr>
</thead>
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<td>0</td>
<td>55.5</td>
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<td>49.6</td>
</tr>
<tr>
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<td>55</td>
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</tr>
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<td>-6.3</td>
<td>51.2</td>
</tr>
<tr>
<td>9</td>
<td>53</td>
<td>-5.3</td>
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</tr>
<tr>
<td>13</td>
<td>51</td>
<td>-4.9</td>
<td>49.3</td>
</tr>
<tr>
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</tr>
<tr>
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<td>-5.2</td>
<td>47.3</td>
</tr>
<tr>
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<td>48</td>
<td>-5.5</td>
<td>46.2</td>
</tr>
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<td>26</td>
<td>48</td>
<td>-5.9</td>
<td>45.9</td>
</tr>
<tr>
<td>28</td>
<td>48</td>
<td>-6.1</td>
<td>45.8</td>
</tr>
</tbody>
</table>

Rp is the parallel resistance component of the impedance while Cp is the relative parallel capacitance with the negative sign indicating it represents an inductive reactance. As can be seen, the antenna parallel resistance becomes independent of antenna height above about 19 inches while the impedance steadily decreases with height.

Experimentally, the height of the antenna was found to be very critical in making repeatable measurements. Raising the antenna from ground level to a height of 5 feet would increase the signal strength by a factor as high as six. Raising the antenna from ground level to a quarter wavelength high would usually double the signal strength. In making repeatable measurements, small variations in height were shown to be very critical when a 1 inch change in antenna height consistently caused almost an 8 to 10 percent change in field strength.

In making soil moisture measurements, antenna height as a measurement variable becomes very important. Both the space wave and the antenna
efficiency are affected by changes in antenna height and even small variations in antenna height can be a source of considerable error.

Reflections

Any time radio wave measurements are made in the VHF region there is the possibility of reflections being a source of error. Even with the transmitter and field strength indicator located 30 feet from the antennas, the change in position of the operator from sitting to standing caused slight variations in the signal strength. A person walking around the transmitting antenna caused a 10 to 20 percent change in signal strength reading. As a general rule, people or objects at least 50 feet from the antennas caused only slight variations in signal strength and the effect of objects 100 feet or more away could not be detected.

Reflections can be a source of error and the surroundings at a measurement site must be noted and care must be taken that they do not change in the vicinity of the antennas if repeatable results are expected.

Temperature

According to Josephson and Blomquist (1958) temperature will have no direct effect upon VHF propagation. The only other possible source of error would be changes in the instrumentation with temperature. To check this possibility readings were taken with the equipment at 75°F and then again after it had been cooled to 22°F. No change in the readings was obtained for this temperature change. The coaxial cable used for the transmission lines was checked the same way and although there was a slight change detected it was much less than one percent for the above temperature differential. The above results indicate that temperature is not a
measurement variable and can be neglected in our soil moisture measurements.

Vegetation

The effect of vegetation on surface wave propagation can by no means be neglected. The effect is very prominent and creates a problem that must be solved if this method of soil moisture measurement is to be successful.

Since soil with vegetation will differ from soil without vegetation, measurements were conducted in fields which were in the process of being harvested. This made vegetation the only variable, eliminating the possibility of soil characteristics affecting the results. In a 5 foot stand of corn a signal generated by one watt of input to the transmitting antenna was not detectable at the receiving antenna. The separation between the antennas was 200 feet. The antennas were next left at permanent locations parallel with the corn and the corn was then harvested away from the antennas two rows at a time. The signal strength increased for each pass of the harvester, staying at a constant value once the corn was 15 feet or greater from a path extending between the antennas. Measurements were also made in an alfalfa field that was half cut and half standing. The signal strength in the standing portion, which was 15 inches high, was half of the signal strength in the cut portion.

Vegetation is a measurement variable that has as great an effect, and sometimes greater, as the principal variable of concern, that of soil moisture. In fact the field strength sensitivity to vegetation cover was so remarkable that this technique may have application for measuring incremental vegetative growth.
Effective width

In making integrated soil moisture measurements a question of the area encompassed by the measurement arises. One dimension of the area is always known and that is the distance between the transmitting and receiving antennas. The width of the area is not as simply defined as it could vary with moisture content and soil characteristics, and also soil moisture in line with the antennas will have more of an effect on the signal strength than soil moisture on the outskirts of the area.

To get an idea of the effective width, the following experiment was designed. An area between the transmitting and receiving antennas was sprinkled heavily with water and time was allowed for the water to seep into the ground. The area was 100 feet by 24 feet with the antennas separated by the length and centered on the width. The antennas were moved 24 feet each side of the center line joining them with signal strength readings taken every 2 feet. The results are given graphically by the curves in Figure 6. One curve is a plot of signal strength as a function of antenna distance from the center line, and the other curve shows the moisture boundary. The moisture content of the area may not be even and the boundaries are probably not as sharp as shown in the figure as the sprinkling was uneven at times due to wind. As can be seen from the curves the signal strength levels off at about 12 or 14 feet either side of the center line. This experiment by no means gives an exact figure for effective width but gives a general idea of the area involved for this type of soil moisture measurement.
Figure 6. Effective width shown as a curve of measured field strength versus distance with respect to a wet area.
EXPERIMENTAL EFFECTS OF SOIL MOISTURE

Method of procedure

The equipment used in making the measurements is described in detail in the previous section on instrumentation. The frequency chosen was 170 MHz, the antenna height used was 8 inches or about 1/8 wavelength, and the separation between transmitting and receiving antennas was set at 100 feet or 17.3 wavelengths. The reasons for choosing these values are given in the previous section on measurement parameters. The equipment and parameters mentioned above were used for all of the measurements taken for this research.

Some of the data was obtained in taking preliminary measurements. These measurements were taken at many different locations and, therefore, involve different types of soil and also required that the antennas and equipment be reset for each measurement. Care was taken to avoid errors due to reflections and to avoid changes in antenna height which can also be a source of great error. Measurements were also repeated in locations after a heavy rainstorm and as the soil dried out.

Two sets of data were taken with the antennas left at permanent locations. The soil moisture was varied by sprinkling a set area of 100 feet by 24 feet with known amounts of water. Data taken in this way eliminated the possibility of error due to relocating the antennas.

To determine the soil moisture content for each field strength measurement, soil samples were taken at three different levels, 0 to 1 foot, 1 foot to 2 feet, and 2 feet to 3 feet. The samples were weighed and then oven dried at 105°C for 2 to 3 hours. After weighing again,
the moisture weight could then be calculated and expressed as a percentage of the dry weight.

Even on a piece of ground subjected to the same rainfall or sprinkling, the moisture content at various points in close proximity varied significantly. This necessitated that several samples be taken and the average moisture content be used to represent the area under measurement.

Results

Measurements could be repeated with good accuracy. Readings were taken in a large, open dry field with the antennas moved to various locations keeping the same antenna separation and height. Variations in signal strength were no greater than 1 or 2 percent. Changing the antenna separation by 1 or 2 feet or tipping the vertical whip to one side by a few degrees caused only slight variations in signal strength readings. Antenna height was the only position change found to be critical. In general, good repeatability was obtained in the preliminary measurements.

All the preliminary measurements showed increases in signal strength with increases in soil moisture. After a heavy rainstorm, which left 1.67 inches of precipitation, signal strength readings were found to be about twice the readings taken in the same locations before the rain. Readings taken daily after the storm showed that the signal strength decreased as the soil moisture decreased. In one location a moisture change from 6.75 percent to 10.6 percent produced a signal strength change from 6.4 millivolts to 14.0 millivolts.1 All of the preliminary readings

1These particular readings were taken with the wrong transmission line termination on the receiving antenna and, therefore, must not be compared to later data.
were similar to those just mentioned showing substantial increases in signal strength for increases in soil moisture and vice versa.

Figure 7 shows the results of measurements taken with the antennas positioned permanently and the moisture changed by sprinkling. The newly sprinkled water was allowed to set over night before a signal strength reading was taken. The curve is plotted with three points showing signal strength as a function of moisture in the top foot of soil. The circled data point was a fourth measurement taken two days after the previous measurement without any additional sprinkling. The position of this data point is unexplained but could have been due to a measurement error or change in moisture content with depth. Three data points are not nearly enough for an accurate curve, but are all that could be obtained under the circumstances. The curve in Figure 7 may be inadequate, but does show an encouraging relationship between signal strength and soil moisture.

A similar experiment to the one mentioned above was conducted but this time a known amount of water was sprinkled on a known area. Each sprinkling consisted of 135 gallons of water covering an area of 2,400 square feet giving a water increase of .09 inch per sprinkling. Signal strength readings were taken within an hour after each sprinkling and the experiment was completed within an eight hour period. Because of the time involved, the moisture never penetrated more than two or three inches into the ground. The results of this experiment are shown in Figure 8 where signal strength is plotted as a function of moisture increase.
Figure 7. Measured signal strength versus soil moisture in top foot of soil.
Figure 8. Measured signal strength versus water added to soil.
CONCLUSIONS

These conclusions will cover two areas, first a discussion of the accomplishments and results of the research, and second a discussion of some of the problems and questions that still exist on soil moisture measurement using radio wave propagation.

Measurement parameters such as frequency, antenna separation, and antenna height were chosen based on theory. Any frequency above 30 MHz was found to be optimum and a frequency of 170 MHz was chosen for convenience because of the equipment available and the size of antenna needed for that frequency. The optimum antenna separation was found to be about 20 wavelengths. A separation of 100 feet, or 17.3 wavelengths at 170 MHz, was used for all measurements. An antenna height was desired which would make the space wave negligible compared to the surface wave. This condition occurred at a height of 1/8 wavelength. The effect of the ground on antenna loading was also considered. It was found experimentally that the antenna impedance decreased with antenna height.

Several variables, other than moisture, that could have an effect on the propagating wave were investigated. Antenna height was found to be very critical. Caution had to be exercised when antennas were relocated if repeatable results were desired. Reflections were a source of error if objects were allowed to move within 50 feet of the antennas. One hundred feet was considered a good distance for metal objects. Temperature had an insignificant effect on the equipment and theoretically did not affect the propagating medium. Temperature, therefore, was not considered a variable. Vegetation was found to have as great an effect on the signal
strength, and sometimes greater, as soil moisture. For this reason, vegetation was usually eliminated for experimental measurements. The width of the area which affected the signal strength of the propagating wave was found experimentally to extend from 10 to 15 feet on either side of the center line joining the two antennas which were separated by 100 feet.

Experimental measurements comparing soil moisture with signal strength gave promising results. In almost all measurements an increase in soil moisture content gave a substantial increase in signal strength. After a heavy rainstorm, which left 1.67 inches of precipitation, signal strengths at all measurement sites had approximately doubled. Good correlations were obtained between signal strength and newly applied moisture. A problem may be encountered when the applied moisture is given substantial time to penetrate deeper into the ground, as indicated by the stray data point in Figure 7.

Some problems and questions on soil moisture measurement by attenuated radio waves have arisen which are beyond the scope of this thesis, due to the limited amount of time available for obtaining data. Three of these problems involve skin depth, vegetation, and changing soils. As the characteristics of the soil change, the skin depth also changes. This could create measurement problems in soils that have inhomogeneous or layered moisture content. The fact that soil near the surface has a greater effect on the propagating wave than deeper soil may also present a problem with inhomogeneous moisture content. Another problem is encountered with vegetation and its relation to signal strength. Vegetation has a dominant effect on the propagating wave, and enough is not
known to separate its effects from those of soil moisture. The effects of different soils with the same moisture content on signal strength measurements needs investigation. Above 30 MHz the dielectric constant is the dominant soil characteristic affecting radio wave attenuation and the dielectric constant may depend more on soil moisture than other soil properties. If these assumptions are correct, attenuation may not be a function of soil type.

From this preliminary research it appears that radio wave measurement of soil moisture may be feasible using the technique developed, but problems such as those mentioned above must be solved before it can become an established method of measurement. Further work is presently contemplated which should help answer the questions that still remain. They are considered to be beyond the scope of this thesis, however.
SELECTED BIBLIOGRAPHY


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Professional Experience: 1971, research engineer for Utah Water Research Laboratory, Utah State University; 1969-70, field engineer for Bonneville International Corporation; 1967-68, research technician for Electrodynanmic Laboratories, Utah State University.