PHYSICAL MODELING OF A PROTOTYPE SLIM-HOLE
TIME-DOMAIN DIELECTRIC LOGGING TOOL

by

Jared D. Abraham
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Golden, Colorado
Date ______________

Signed: ________________________
Jared D. Abraham

Approved: ________________________
Dr. Gary R. Olhoeft
Professor of Geophysics
Thesis Advisor

Golden, Colorado
Date ______________

________________________
Dr. Thomas L. Davis
Professor and Interim Head, Department of Geophysics
ABSTRACT

Dielectric logging tools were originally developed by the oil industry to determine oil saturation in highly resistive environments. Conventional resistivity and induction tools are insensitive to the oil/water interface with high resistivity water. Recently dielectric logging tools have found potential uses in environmental applications to estimate porosity, to distinguish between water and organic-solvents, to provide velocity information for migration of surface radar, and to provide boundary constraints for radar tomography. Oil industry tools are large for the typical 2-inch to 4-inch environmental monitoring well. A prototype slim-hole time-domain dielectric logging tool was developed at the U.S. Geological Survey by David L. Wright. This tool was engineered to use the propagation of a broadband EM pulse to determine the frequency dependent dielectric properties of the surrounding geologic medium. In an attempt to understand and characterize the tool, physical modeling experiments were conducted using a 100 gallon polyethylene barrel filled with dry silica sand, deionized water saturated silica sand, and deionized water.

Examination of the results indicated that the borehole has a strong influence on the dielectric logging tool. We have found that the travel time and amplitude are not monotonic with dielectric properties. The likely explanation of the observed effect is that wave guides are being set up within the borehole and/or the tool. Reflections and resonances internal and external to the tool produce a frequency dependent tool response. Results also indicate that physical model, used in the experiments, introduces effects into the data. These effects indicate that the typical plane wave propagation formulas are invalid for the determination of dielectric permittivity, as many of the effects in the data
are in the near field of the transmitter. However, physical modeling and field tests have
determined that the tool is sensitive to changes in the dielectric permittivity of the
surrounding geologic media, particularly to thin layers perpendicular to the borehole.

Future efforts in the development of the tool need to focus on numerical
modeling. The use of a sophisticated finite difference time-domain (FDTD) code may be
able to sort out the tool response and remove the influences of the physical model. This
thesis provides a data set from physical modeling to test such numerical modeling. Future
tool development may also be necessary to refine a design that will minimize the strong
borehole effects observed in the data.
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Chapter 1.
INTRODUCTION

1.1 Why measure electrical properties?

From the beginnings of applied geophysics, electrical properties were measured to identify and or characterize geological strata in the subsurface (Bates et al., 1982). It was discovered that ore-bearing rocks influenced electrical properties. One of the first patents for the use of electrical measurements in prospecting for minerals was issued in 1900 (Dorbin, 1951). Electrical measurements do not directly give geological data, i.e., grain size, porosity, rock type, ore-grade, % hydrocarbon, color, texture, but the measurements are related to the properties of the rocks. It was soon realized that the resistivity of rock was dependent on the fluid within the porosity and fractures. Application of electrical measurements to borehole geological problem solving was first accomplished by the Schlumberger brothers in 1927 (Schlumberger, 1996). The well logging industry was born and soon became a powerful tool in geoexploration. Spurred by the success of the Schlumberger brothers, workers began investigating the relation between electrical properties and geological materials, and the discipline of rock physics was born. As the industry matured, workers began to draw conclusions about the effects of pore fluids on the resistivity/conductivity of rocks.
Electrical magnetic properties including resistivity/conductivity, magnetic susceptibility, and dielectric permittivity are some of the properties measured in geophysics. The measurement of these properties allowed workers to start drawing conclusions about the subsurface from measurements made in a borehole or from the surface.

Imaging of the subsurface is primarily done to assist geologists and exploration managers to locate areas that may produce economical commodities. Much of geophysics is used to assist in placing boreholes that will intersect ore-bodies or penetrate hydrocarbon-containing strata. Recently, as geophysics is being more widely used in the environmental clean-up industry and geotechnical applications, the traditional types of targets have changed. In environmental and geotechnical investigation, the targets do not fit into the traditional economic products categories but rather in the area of waste or near-surface structure. But again, the measurement of electrical properties can assist in the interpretation of the subsurface. The answer to the question, “Why measure electrical properties?” is, “To identify properties of the subsurface without directly examining the geologic materials.”

1.2 Dielectric permittivity

Dielectric permittivity is a measure of the ability of a medium to polarize and store energy when an electric field is applied (Sheriff, 1994). Dielectric properties are normally measured at high frequencies. Dielectrics research began with Faraday in the
early 1800’s (Smith, 1997). Further research in dielectrics was stimulated by the work in capacitor, radar, and other microwave technologies. Dielectric permittivity is related to the material composition, water content, density, and physical arrangement (porosity, size of grains). Researchers in physical chemistry used the dielectric properties of materials to help characterize and identify substances (Cole and Cole, 1941, Debye, 1929, Böttcher, 1952). The geoscience community also started to conduct work in dielectrics and soon discovered that the properties of dielectrics could be yet another piece of useful information in solving the complex geological problem of the subsurface. Dielectrics are commonly referred to in terms of the ratio of the dielectric permittivity of the material to the dielectric permittivity of free space ($\approx 8.854 \times 10^{-12} \text{F/m}$). In older literature the ratio is commonly termed the dielectric constant ($K$); however, as will be discussed later, the ratio is seldom a constant, but is temperature, pressure, and frequency dependent. A more appropriate name for the ratio is the relative dielectric permittivity ($\varepsilon_r$), this terminology will be used throughout this work. Tabulations of the measurements of geological materials can be found in (Keller, 1987, Olhoeft, 1980) and many industrial materials can be found in the CRC Handbook of Chemistry and Physics (Lide, 1998).

Workers in the geosciences soon realized that when radar frequencies are transmitted into the ground, their attenuation and velocity are controlled predominately by dielectric permittivity and conductivity. The frequencies for which dielectric permittivity is important in electromagnetics (EM) relates to EM-wave propagation, as opposed to traditional exploration EM, which is related to the diffusion of low frequency
signals in a conductive earth (Kaufman, 1994, Grant and West, 1965). EM-propagation has the ability to detect objects and geological materials, by the direct effect of the objects material properties on the propagated wave. This transmission of EM-waves through geologic media has led to the development of ground penetrating radar (GPR). The study and application of GPR to geological problem solving is a growing and diverse field of study including: geotechnical, construction, geological, surveillance, ground water, mining, petroleum, and archaeology disciplines (Annan, 1996b, Daniels, 1989).

1.3 Dielectric logging

As most of the technological innovations in the world are stimulated by conflict or market pressures, the oil industry started to look at the dielectric properties for assistance in the identification of oil in highly resistive formations. The problem in highly resistive formations is that traditional logging tools, including resistivity and induction logs, can not differentiate highly water bearing formations from highly resistive hydrocarbons bearing formations. However, the relative dielectric permittivity of water is on the order of $\varepsilon_r \approx 80$ and most hydrocarbons are on the order of $\varepsilon_r \approx 2$. The most commonly encountered reservoir rock is sandstone. Hydrocarbons are typically found in the pore space between the sand grains, which have a relative dielectric permittivity of $\varepsilon_r \approx 4.5$. When dielectric materials are mixed, they generally yield a dielectric value between the dielectric values of the end members of the mixture. If assumptions are made on the mixing of components, models can be used that give the amount of porosity
and the volume of hydrocarbon in a rock. The determination of the volume of hydrocarbons allows oil companies to make economic decisions on reserves, field development, and production plans.

In 1949, Daev (1974) began to design and test logging tools that would respond to dielectric permittivity, from which logs of the porosity and hydrocarbon content in a formation could be calculated (Shen, 1985, Wright, and Nelson, 1993). These tools were designed specifically for the use in petroleum industry wells and typically only provide information at one frequency. Other problems result from mud cake on the borehole wall and borehole rugosity. Also, the petroleum industry tools are poorly configured to fit into the boreholes of the environmental and geotechnical industries (further discussion of the petroleum industry tools is included later).

Other work is being conducted on the measurement of dielectric properties using capacitive circuits and time-domain reflectometry (TDR) (Dean et al. 1987, Greenhouse et al. 1993). These methods also have limitations in use (further discussion on these tools is included later).

Recent regulation regarding the use of radioactive isotope source nuclear tools, (gamma-gamma and neutron porosity tools) have made it increasingly costly to use these tools in boreholes through potable aquifers. The Nuclear Regulator Commission (NRC) regulates the loss of a source. However, state-specific regulations are usually more stringent than the NRC regulations. To operate an active source tool, the operator must be licensed under the state and NRC. For each license, the specifics for the way of
handling lost sources is addressed, including: how many attempts at retrieval, type and amount of grout that is required to plug the hole, and the marking and signage requirements. In most circumstances the loss of a source initiates the closing, capping, and abandonment of the hole, but again the economic risks have begun to outweigh the benefit of the nuclear tools. The ultimate problem lies in the liable parties. Many contractors require the client to take liability for the lost source in a borehole. Other contractors take liability for the hole in case the source is lost. These specific details are worked out for each contract. The two tools that are specifically targeted include the gamma-ray density and the neutron porosity tools (Western Atlas, 1992). These tools both have performed well over the past 50 years in the geoscience disciplines. Both the gamma-density and the neutron porosity tool’s provide valuable information on porosity and density properties of the geologic materials that is of use to petroleum engineers and environmental contractors. At this point, the factor of economics enters into the equation as the petroleum industry has continued to use the nuclear tools; however, the mining, geotechnical, and environmental industries simply are not as lucrative as petroleum, and therefore can not risk severe economic consequences if a source is lost. This is where dielectric measurements could be useful in the determination of the density and porosity of a medium.

A dielectric logging tool has many other uses, including high resolution logging of dielectric layers within a formation. Many of the organic contaminants that are of interest in the environmental field have dielectric permittivities on the order of $\varepsilon_r \approx 2$. 
These products can be either light non-aqueous phase liquids (LNAPL’s) or dense non-aqueous phase liquids (DNAPL’s). In a simplified way, these can be thought of as either floating on the water table or sinking below the water table. The specific behavior of the compounds are much more complex than the above classifications, and there is much work that has been completed and is in progress on the subject (Cohen and Mercer, 1993, Pankow and Cherry, 1995). These organic compounds can displace water from a formation, as in hydrocarbons in petroleum exploration, and therefore change the bulk dielectric permittivity of the formation. Many techniques, including GPR can not resolve small layers of organics in the subsurface. The use of high-resolution dielectric logging may have the ability to resolve these thin layers.

Dielectric logging also has the potential of establishing boundary conditions that can be used in the processing of GPR data. To be able to properly migrate surface GPR data, a velocity model for the subsurface needs to be calculated. A record of the dielectric permittivity with depth can produce such a velocity model. Also, in borehole radar tomography, dielectric permittivities are helpful in determining the boundary conditions for the boreholes.

To use dielectric measurements effectively, the frequency dependence of the dielectric permittivity needs to be measured (Kutrubes, 1986, Olhoeft, 1987, Canan, 1999). A tool that is to be used in near-surface environmental and geotechnical applications needs to be able to fit in to small boreholes on the order of 2 inches. A tool
needs to be able to collect data rapidly and be easily deployed. And, as previously mentioned, the tool has to be inexpensive to operate.

1.4 **Design and testing of a dielectric tool**

Initial design and testing of a laboratory time-domain dielectric logging tool was completed by Wright and Nelson (1993). This laboratory tool was constructed from 2-inch diameter aluminum tubes. The laboratory tool used two voltage gaps, one for a transmitter and one for a receiver. These gaps were separated by a 6-inch or a 12-inch spacer constructed of 2-inch diameter aluminum tubes. A coaxial cable was connected to the transmitter and passed out the bottom of the simulated borehole, and a coaxial cable was connected to the receiver and passed out the top of the simulated borehole. A pulse generator was connected to the transmitter and a digital oscilloscope was connected to the receiver. Measurements were made by placing the tool in a sand pack that had a polyvinyl chloride (PVC) pipe mounted in the center. A measurement was made with the 6-inch spacer installed and then repeated with the 12-inch spacer. To avoid the reflections from the ends of the tool and the model, the waveform was truncated at the peak and then folded over to form a Gaussian pulse. Wright and Nelson (1993) then calculated a dielectric permittivity assuming plane wave propagation and taking a difference between the 6-inch and 12-inch spacers. Results indicated that the time-domain dielectric logging tool was a feasible tool for measuring dielectric permittivity.
Based on the results of the laboratory experiment, David L. Wright of the U.S. Geological Survey designed a prototype slim-hole time-domain dielectric logging tool. Laboratory and field testing of the tool were conducted to determine the ability of the tool to respond to frequency dependent dielectric permittivity. Further discussion of the design of the tool is found in Chapter 4.0.

1.5 Thesis goals and assumptions

To determine if the prototype USGS slim-hole time-domain dielectric logging tool responds to dielectric permittivity, it was decided to set up a full-scale laboratory physical model (no electromagnetic scaling was required). The model was filled with typical earth materials that are easily accessible and characterizable. These tests were conducted using the tool design of David L. Wright, a custom built drawworks, a digital oscilloscope, and a personal computer (PC) interface. The tool was to be configured in the same manner in which it would be deployed in the field. This differs from the tool that Wright and Nelson (1993) tested where the cables were brought out the top and bottom of the simulated borehole. As will be seen later, this necessary step of having both the cables come out the top of the tool significantly influenced the performance of the dielectric logging tool.

The materials used in the model were simple and were carefully constructed so as to attempt to construct a homogenous medium. The materials used in the physical modeling included: air (empty), dry silica sand, deionized water saturated silica sand,
deionized water, and Wyoming bentonite. The model was constructed in a polyethylene barrel, and an environmental borehole was simulated with a section of schedule 40 PVC pipe. Further discussion of the model setup can be found in Chapter 5.0.

The final step in the physical modeling was to compile a detailed empirical data set that could be used by modelers to numerically characterize the tool and possibly produce inversion methodologies. These physical model data were tabulated and complied in a digital record (Appendix G) that can be accessed by modelers in the future. With each data record, detailed information on the physical configuration of the tool and the model were recorded. Laboratory measurements were made of the materials used in the models so the appropriate dielectric properties could be input for the models. The project goals can be summarized in the following list:

1. Build a field worthy dielectric logging tool that can be easily deployed.
2. Determine if the tool can respond to changes in dielectric permittivity.
3. Conduct physical modeling of the tool.
   - borehole effects
   - thin layer detection
   - depth of investigation
4. Determine if the tool can provide frequency dependent dielectric permittivity data.
5. Supply data for numerical modeling.

Several assumptions are included in the physical modeling of the dielectric logging tool and the following discussion. These assumptions deal with the way the electromagnetic field is conceptualized, as well as simplification of the material
properties. Specific problems with assumptions will be discussed in detail in later sections, include those inherent to the FFT and the deconvolution operators.

The first and most important assumption is the magnetic permeability of all test materials are assumed to be that of free space ($\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$) and thus relative magnetic permeability is $\mu_r = 1$. Exceptions to this assumption are in the discussion in Section 2.0 concerning the influence of magnetic permeability on the wavenumber, and the steel rod used in the depth of investigation measurements and the bentonite grout tests. Laboratory tests of the materials, on a HP-8753D vector network analyzer used in the physical modeling, show that their magnetic permeability is that of free space.

In much of the discussion in Section 2.0 on the dielectric properties of soil and rocks, plane-wave assumptions are used in the derivations of the electromagnetic quantities and the descriptive equations related to the wave propagation. As will be demonstrated later, the assumption of plane-wave propagation is not valid for the dielectric logging tool. Further discussion of plane-wave assumption is found in Chapter 7.0.

Operationally the tool is assumed to always be centered in the borehole. Before the measurements, the tool and the hoist were aligned with the borehole to keep the tool centered in the borehole though the data collection. Some of the other assumptions that are found in the following sections include that the digitizing scope provides an accurate time base, and the measurements of the response of the tool is accurate to within the
calibrated standards of the manufacturer. Further discussion on measurement accuracies can be found in Chapter 6.0.
2.1. Background

The first step in physical modeling of a tool or any system involves an understanding of the physical parameters that are being used and measured. The dielectric logging tool was designed to measure the frequency dependent dielectric properties of the geologic materials around the borehole. These materials could contain soil, rock, and other substances introduced into the borehole vicinity by anthropogenic influences. The tool was designed to propagate electromagnetic waves through a medium to determine that medium's electrical properties. To gain an understanding of electromagnetic wave propagation in geologic materials and then understand the dielectric properties of the earth materials, this chapter will examine the theory of electromagnetic wave propagation, frequency dependence and dispersion, measurements of dielectric materials, and dielectric materials mixing formulations.
2.2. Theory of electromagnetic wave propagation

Maxwell's equations describe the coupling of time varying electric and magnetic fields. The electromagnetic field is influenced by the electrical and magnetic properties of the media through which waves propagate. This influence of the physical properties allows investigators to use electromagnetic wave propagation to determine the electrical properties by measuring the change in the wave propagation.

2.2.1. Maxwell's equations and electromagnetic wave propagation

In differential form, Maxwell's equations can be written as (Balanis, 1989),

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \]

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}, \tag{2.1} \]

\[ \nabla \cdot \mathbf{D} = \rho, \]

\[ \nabla \cdot \mathbf{B} = 0, \]

where:

- \( \mathbf{E} \) is the electric field vector (V/m),
- \( \mathbf{H} \) is the magnetic field vector (A/m),
- \( \mathbf{J} \) is the current density vector (A/m²),
- \( \mathbf{D} \) is the displacement current vector (C/m²),
- \( \mathbf{B} \) is the magnetic induction vector (T/m²),
- \( \rho \) is the electric charge density (C/m³), and
- \( t \) is time (s).
The relationships between \( \mathbf{E} \), \( \mathbf{H} \), \( \mathbf{J} \), \( \mathbf{D} \), and \( \mathbf{B} \) are called the constitutive equations. The first constitutive equation describes charge transport (Ohm’s Law),

\[
\mathbf{J} = \sigma \mathbf{E} ;
\]

(2.2)

where \( \sigma \) is the conductivity (S/m). Generally \( \sigma \) is a tensor (Keller, 1987),

\[
\sigma = \begin{bmatrix}
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz}
\end{bmatrix}.
\]

(2.3)

A common simplifying assumption is that the medium is isotropic and homogeneous. This produces a scalar function for the conductivity that may be complex

\[
\sigma^\prime = \sigma^\prime(\omega) - i\sigma^{\prime\prime}(\omega)
\]

(2.4)

where \( i = \sqrt{-1} \).

Further simplification is gained by letting the real part \( \sigma \) reach a stable value over a long time interval. This is referred to as the static or direct current (DC) conductivity.

The second constitutive equation describes charge displacement,

\[
\mathbf{D} = \varepsilon \mathbf{E} ,
\]

(2.5)

where \( \varepsilon \) is the dielectric permittivity (F/m). As with \( \sigma \), \( \varepsilon \) is generally a tensor (Keller, 1987),

\[
\varepsilon = \begin{bmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\
\varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\
\varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz}
\end{bmatrix}.
\]

(2.6)
Applying the same assumption for conductivity, \( \varepsilon \) can be reduced to a scalar function, which is also typically complex and frequency-dependent (Olhoeft, 1987),

\[
\varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega),
\]

where \( \varepsilon' \) and \( \varepsilon'' \) are the real and imaginary parts, respectively. Further discussion of the complex behavior of dielectric permittivity will be covered in Section 2.2.3 on frequency dependent electrical properties. Typically in electromagnetics, only one electrical property is expressed as complex. Conventionally in high frequency geophysics, a complex permittivity is defined by incorporating the conductive losses into the imaginary part of the dielectric permittivity in equation (2.7). The relationship between conductivity and the imaginary part of the dielectric permittivity in the absence of any other relaxations is,

\[
\sigma(\omega) = -\varepsilon''(\omega).
\]

The third constitutive equation describes a magnetic flux,

\[
\mathbf{B} = \mu \mathbf{H},
\]

where \( \mu \) is the magnetic permeability (H/m). Magnetic permeability is generally a tensor (Keller, 1987),

\[
\mu = \begin{vmatrix}
\mu_{xx} & \mu_{xy} & \mu_{xz} \\
\mu_{yx} & \mu_{yy} & \mu_{yz} \\
\mu_{zx} & \mu_{zy} & \mu_{zz}
\end{vmatrix}.
\]
As with dielectric permittivity and conductivity, assumptions of isotropy and homogeneity allow simplification to a single function. This function can also be complex (Olhoeft and Capron, 1994);

\[ \mu^*(\omega) = \mu'(\omega) - i\mu''(\omega) \]  

(2.11)

where \( \mu' \) and \( \mu'' \) are the real and imaginary parts, respectively. For work presented here the magnetic permeability is assumed to be that of free space (\( 4\pi \times 10^{-7} \) H/m). However the discussion in Section 2.2.2 on propagation velocity, attenuation, and wavelength will include both the complex dielectric permittivity and complex magnetic permeability.

Substituting these constitutive equations into Maxwell's equations (2.1) provides the following (Balanis, 1989),

\[ \nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}, \]

\[ \nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t}, \]  

(2.12)

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon}, \]

\[ \nabla \cdot \mathbf{H} = 0. \]

In addition to the assumptions of homogeneity and isotropy, other less common classes of materials are neglected in the above equations. These include ferroelectric, ferromagnetic, magnetoelectric, pyroelectric, and piezoelectric materials (Powers, 1995).
The development of wave equations for electromagnetic propagation is omitted. Excellent discussions of the methods for the development of these equations can be found in Balanis (1989). The method is basically accomplished by applying the divergence operator $\nabla \cdot$ and the curl operator $\nabla \times$, then using vector simplification and Maxwell’s equations to arrive at the following:

$$\nabla^2 E = \mu \sigma \frac{\partial E}{\partial t} + \mu \epsilon \frac{\partial^2 E}{\partial t^2} - \nabla \cdot \rho, \quad (2.13)$$

and

$$\nabla^2 H = \mu \sigma \frac{\partial H}{\partial t} + \mu \epsilon \frac{\partial^2 H}{\partial t^2}. \quad (2.14)$$

If the medium has no point electric charges, and is thus source free, equations (2.13) and (2.14) become

$$\nabla^2 E = \mu \sigma \frac{\partial E}{\partial t} + \mu \epsilon \frac{\partial^2 E}{\partial t^2}, \quad (2.15)$$

and

$$\nabla^2 H = \mu \sigma \frac{\partial H}{\partial t} + \mu \epsilon \frac{\partial^2 H}{\partial t^2}, \quad (2.16)$$

which are the vector wave equations for the electric and magnetic fields. $E$ and $H$ may vary with time according to

$$E(t) = E e^{i\omega t} \quad \text{and} \quad H(t) = H e^{i\omega t}. \quad (2.17)$$
where \( \omega \) (\( \omega = 2\pi f \) with \( f \) in Hz) is the angular frequency. Solving for the differentials in equations (2.15) and (2.16), substituting the results into equations (2.15) and (2.16), and suppressing the time dependence, provides the following forms of the wave equations:

\[
\nabla^2 \mathbf{E} = -\omega^2 \mu \varepsilon \mathbf{E} + i\omega \mu \sigma \mathbf{E}, \quad (2.18)
\]

and

\[
\nabla^2 \mathbf{H} = -\omega^2 \mu \varepsilon \mathbf{H} + i\omega \mu \sigma \mathbf{H}. \quad (2.19)
\]

Equations (2.18) and (2.19) are commonly simplified to (Balanis, 1989)

\[
\nabla^2 \mathbf{E} = -k^2 \mathbf{E} \quad \text{or} \quad \nabla^2 \mathbf{E} = \gamma^2 \mathbf{E}, \quad (2.20)
\]

and

\[
\nabla^2 \mathbf{H} = -k^2 \mathbf{H} \quad \text{or} \quad \nabla^2 \mathbf{H} = \gamma^2 \mathbf{H}, \quad (2.21)
\]

where

\[
k^2 = \omega^2 \mu \varepsilon - i\omega \mu \sigma, \quad \text{and} \quad \gamma^2 = i\omega \mu \sigma - \omega^2 \mu \varepsilon \quad (2.22)
\]

2.2.2. Propagation velocity, attenuation, and wavelength

The parameter \( k \) is termed the wavenumber, and \( \gamma \) is termed the propagation constant. The propagation constant is related to the wavenumber according to \( \gamma = ik \). In the simple free space case, the conductivity is zero and propagation occurs without material loss, the wavenumber is
\[ k = k_0 = \frac{\omega}{c} = \frac{\omega}{c} \sqrt{\mu_0 \varepsilon_0} = \frac{\omega}{c} \]  

(2.23)

where \( \mu_0 = 4\pi \times 10^{-7} \text{(H/m)} \), the magnetic permeability of free space; \( \varepsilon_0 = 8.854 \times 10^{-12} \text{(F/m)} \) is the dielectric permittivity of free space; and \( c = 3.0 \times 10^8 \text{(m/s)} \) is the speed of light in free space (Balanis, 1989). In geophysical applications, the wave propagates not through free space but through earth materials that are typically lossy. When the lossy nature of the earth is taken into account, the solution for the wavenumber with respect to frequency becomes (Powers, 1995)

\[
k(\omega) = \frac{\omega}{c} \sqrt{\left(\mu'_r - i\mu''_r\right) \left(\varepsilon'_r - i\varepsilon''_r\right) - i \left(\mu'_r - i\mu''_r\right) \left(\sigma_{DC} / \varepsilon_0 \omega\right)}
\]

(2.24)

where \( \varepsilon_r \) is the relative dielectric permittivity, \( \mu_r \) is the relative magnetic permeability, and \( \sigma_{DC} \) is the DC conductivity. The relative dielectric permittivity and relative magnetic permeability are defined as follows:

\[
\varepsilon'_r = \frac{\varepsilon^*}{\varepsilon_0}, \quad \text{and} \quad \mu'_r = \frac{\mu^*}{\mu_0}.
\]

(2.25)

For the above lossy case, the wavenumber can be expressed in terms of real and imaginary parts

\[
k(\omega) = \beta(\omega) - i\alpha(\omega)
\]

(2.26)

where \( \beta \) and \( \alpha \) are the real and imaginary parts of the wavenumber. Note that both the real and imaginary parts are frequency dependent. This relationship can also be written in terms of the propagation constant
\[ \gamma(\omega) = \alpha(\omega) + i\beta(\omega). \quad (2.27) \]

These real and imaginary parts become very useful in the description of the field behavior: \( \beta \) is termed the phase parameter and \( \alpha \) is termed the attenuation parameter. The phase parameter \( \beta \) is expressed in units of radians per meter (rad/m), and the attenuation parameter \( \alpha \) in Nepers per meter (Np/m). It is common practice to express the attenuation in terms of decibels per meter (dB/m). This is accomplished using the relationship: amplitude change in dB = -8.686\( \alpha(\omega) \). For \( \alpha \) and \( \beta \) to be useful they need to be expressed in terms of the complex material properties \( \mu^* \) and \( \varepsilon^* \) (Powers, 1995);

\[
\alpha = \left(\frac{\omega}{c}\right)\sqrt{\frac{\sqrt{\xi^2 + \zeta^2} - \xi}{2}}, \quad (2.28)
\]

and

\[
\beta = \left(\frac{\omega}{c}\right)\sqrt{\frac{\sqrt{\xi^2 + \zeta^2} + \xi}{2}}, \quad (2.29)
\]

where:

\[
\xi = \mu^* - \mu, \quad \varepsilon^* - \varepsilon, \quad \left(\varepsilon^* + \frac{\sigma}{\omega\varepsilon_0}\right),
\]

and

\[
\zeta = \mu^* - \mu, \quad \varepsilon^* + \varepsilon, \quad \left(\varepsilon^* + \frac{\sigma}{\omega\varepsilon_0}\right). \quad (2.30)
\]
This provides a solution for an electric field for a plain wave polarized in the x direction moving in the +z direction, as follows (Balanis, 1989):

$$\mathbf{E}(z) = \mathbf{e}_x E_0 e^{-\alpha z} \cos(\omega t \pm \beta z) = \mathbf{e}_x E_0 e^{-(\alpha \pm \beta)z} = \mathbf{e}_x E_0 e^{-\gamma z},$$  \hspace{1cm} (2.31)

where \( \mathbf{e}_x \) is a unit vector in the x direction.

Another useful expression for how a material influences a wave is the wave impedance \((Z_w)\) (Balanis, 1989)

$$Z_w = \frac{E^+}{H^+} = \sqrt{\frac{\mu^*}{\varepsilon^*}} \text{ (V/A or } \Omega),$$  \hspace{1cm} (2.32)

where \( \mu^* \) is the complex magnetic permeability in (H/m) of the material and \( \varepsilon^* \) is the complex dielectric permittivity of the material in (F/m).

By using \( \alpha \) and \( \beta \) as descriptors, several important quantities in electromagnetic propagation can be expressed as follows:

wave velocity \hspace{1cm} \( v = \frac{\omega}{\beta(\omega)} \text{ (m/s)}, \hspace{1cm} (2.33) \)

wavelength \hspace{1cm} \( \lambda = \frac{2\pi}{\beta(\omega)} \text{ (m)}, \hspace{1cm} (2.34) \)

and skin depth \hspace{1cm} \( \delta = \frac{1}{\alpha(\omega)} \text{ (m)}. \hspace{1cm} (2.35) \)
The losses in propagation of an electromagnetic wave can also be expressed using the material properties and the attenuation and phase constants:

**electrical loss tangent:**
\[
\tan \delta_E = \left( \frac{\varepsilon''}{\varepsilon'} + \frac{\sigma}{\omega \varepsilon'} \right) = \cot(\theta_{JE}) , \quad (2.36)
\]

**magnetic loss tangent:**
\[
\tan \delta_M = \left( \frac{\mu''}{\mu'} \right) = \cot(\theta_{BH}) , \quad (2.37)
\]

**electromagnetic loss tangent:**
\[
\tan \delta_{EM} = \tan\left( \frac{\delta_E + \delta_M}{2} \right) = \cot(\theta_{EM}) = \frac{\alpha}{\beta} , \quad (2.38)
\]

where, \( \theta \) is the phase angle in time between the vectors of the fields for \( J \) and \( E \), \( B \) and \( H \), and \( E \) and \( M \), respectively.

It was shown above that electromagnetic wave propagation is controlled by electromagnetic material properties. The next section will discuss the frequency dependent behavior of electrical properties, specifically dielectric permittivity.

### 2.2.3. Frequency dependent electrical properties

Frequency dependent electrical properties are caused by energy loss through charged particle motion. These losses result from one or more combinations of the following mechanisms: 1) intrinsic conduction loss; 2) displacement (orientational/relaxation) loss; and 3) magnetic losses (Olhoeft and Capron, 1994). These losses lead to a complex frequency-dependent dielectric permittivity, \( \varepsilon^* \) and magnetic
permeability $\mu_r^\ast$. A brief description of the frequency dependent loss mechanisms follows (excluding magnetic losses). The tool was designed to measure dielectric permittivity assuming that the relative magnetic permeability $\mu_r$ = 1.

As described earlier by Maxwell's equations, conductivity is the ability to transport charge. In most geological materials the charge movement (current) does not occur as in a metallic wire, but through movements of ions in a solution. When an E-field is applied, any free charge is quickly accelerated to the terminal velocity, and then moves at a constant velocity until the E-field is removed. This charge motion generates heat from the scattering and transfer of momentum with the surrounding material. The motion of the charges is controlled by the electrical field. Energy is irreversibly lost through the collisions between the charged particles and the surrounding medium. The influence of conductivity is illustrated by its effect on the wave equation (2.17). As conductivity increases the diffusion term "$i\omega\mu\sigma\mathbf{E}$" becomes larger. There is usually no need to define both a complex conductivity and a complex dielectric permittivity. As will be shown later, both describe a charge moving in response to an electric field.
Displacement currents are caused by charges being separated (polarized) by an applied E-field. These charges are not able to drift freely in space and are displaced from the natural rest state by some finite distance. When an external field is applied, charges accelerate to a constant terminal velocity and then decelerate to a stop when the charge amount and displacement create an internal E-field that balances the external E-field. While in motion, the charges lose energy through interactions with the surrounding material, as in the charge conduction case. While the charges are held apart in equilibrium, energy is stored in the balancing E-field that is built up between the charges. Frequency dependence results from their finite velocity while moving and interactions
between particles and boundaries. Several mechanisms result from electrical polarization with respect to frequency, including (from high to low frequency): electronic polarization; ionic or molecular polarization; dipole or orientational polarization, and interfacial polarization (Figure 2.2) (Balanis, 1989, Olhoeft, 1987).

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>No applied field</th>
<th>Applied field</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electronic polarization</strong></td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Ionic or molecular polarization</strong></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Dipole or orientational polarization</strong></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Interfacial polarization</strong></td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Figure 2.2. Mechanisms producing electric polarization in dielectrics (modified from Balanis, 1989)
Electronic polarization is observed in all materials, and is caused by the apparent distortion of the electron cloud center of an atom relative to the center of the nucleus by an imposed E-field. One side of the atom appears to become more positive and another side to become more negative (Balanis, 1989, Olhoeft, 1985).

Molecular polarization is evident in many materials, such as halite, common salt (NaCl), that possess positive and negative ions. An external E-field distorts an entire molecule in which one part of the molecule becomes more positive than the rest and another part more negative. Ions distributed through a material will redistribute with the positive ions migrating toward the negative side of the field and the negative ions migrating toward the side of the positive field (Balanis, 1989, Olhoeft, 1985).

Dipole or orientational polarization occurs in materials that possess dipole moments. When an electric field is applied, the dipoles realign or reorient without distortion of shape to an applied E-field. These materials are commonly known as polar materials, of which water is a prime example (Balanis, 1989, Olhoeft, 1985).

Interfacial polarization occurs from charge separation and accumulation at local variations and discontinuities in a material due to the migration of charges in response to an external field (Olhoeft, 1985).

These mechanisms store electric field energy via cumulative charge displacements, and lose energy to electrochemical, mechanical, or thermal energy (Olhoeft and Capron, 1994).
The electrical energy stored during each polarization process determines the real part of the dielectric permittivity for the specific frequency, and the electrical energy lost during charge movement determines the imaginary part of the dielectric permittivity. As the time between reversals shortens due to an increase in frequency, some of the polarizations cannot occur. The different mechanisms incur specific characteristic amounts of energy loss in proportion to the amount of the charged particles and the distance moved. This leads to an overall complex dielectric permittivity and frequency dependence. A simplified graphical representation of the energy storage term ($\varepsilon'$) and the energy loss term ($\varepsilon''$) (Figure 2.3) demonstrates that maximum loss occurs at the change from one polarization mechanism to the next, as maximum charge movement occurs. The frequencies at which these transitions occur are different for different materials. The most common polarization mechanisms influencing high frequency geophysics, within the unconsolidated soil section, are orientational rotation of the water molecule and interfacial polarization at the water-solid soil particle interface (Olhoeft and Capron, 1994).
2.2.4. Cole-Cole parameters

In Section 2.2.3, it was explained that several polarization mechanisms could occur in a single medium. Each one of these has its own storage and loss characteristics, with the sum of the energy lost and storage of the system contributing to a overall dielectric permittivity.

To explain the frequency dependent dielectric permittivity of a single mechanism, a single Debye relaxation model can be used (Keller, 1987) as in:

\[
\varepsilon'(\omega) - i\varepsilon''(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau_\varepsilon},
\]  

(2.39)
where $\varepsilon_r'$ and $\varepsilon_r''$ are the real and imaginary parts of the relative dielectric permittivity, $\varepsilon_s$ is the static dielectric permittivity at zero frequency, $\varepsilon_\infty$ is the dielectric permittivity at infinite frequency, and $\tau_\varepsilon$ is the time constant of relaxation determined for a single type of polarization process. However, real earth materials, including moist sandy soil and any other combinations of loam and clay, exhibit multiple polarization mechanisms (Kutrubes, 1986, Olhoeft, 1987, Olhoeft and Capron, 1994, Canan, 1999). To better characterize the frequency dependence behavior, a more complex distribution of polarization mechanisms needs to be used. The Cole-Cole equation includes a log-normal distribution of time constants (Cole and Cole, 1941);

\[
\varepsilon_r'(\omega) - i\varepsilon_r''(\omega) = \varepsilon_s + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (i\omega\tau_\varepsilon)^{\alpha_\varepsilon}}, \tag{2.40}
\]

where $\alpha_\varepsilon$ is the time constant distribution parameter that varies between 0 and 1. As $\alpha$ goes to one, the result is a single relaxation. Plots of the log loss tangent (Equation 2.35) versus log frequency exhibit asymptotic slopes of $-\alpha$ and $\alpha$ on either side of the maximum loss (Olhoeft, 1985).

Using the Cole-Cole parameters to describe the complex behavior of earth materials allows for input directly into models (Powers, 1995). Cole-Cole parameters have been used to characterize many measured samples (Olhoeft, 1987, Olhoeft and Capron, 1994, Canan, 1999).
2.3. Measurements of dielectric materials

Measurements of dielectric materials are typically made using a vector network analyzer. The system measures S-parameters (Kutrubes, 1986, Canan, 1999) of a sample placed in a coaxial air-line over a range of frequencies. These S-parameters can be used to calculate the dielectric permittivity, magnetic permeability, and conductivity. A description of the experimental setup and data processing is found in Kutrubes (1986) and Canan (1999). From the dielectric permittivity and conductivity of the measurements, Cole-Cole parameters can be calculated for the materials. Dielectric properties of dry materials are predominately influenced by dry bulk density and are usually frequency independent. However, with the addition of a small amount of water the frequency dependence becomes much larger.

2.3.1. Dry materials

For dry materials, Olhoeft and Strangway (1975) found that the high frequency relative dielectric permittivity, $\varepsilon_\infty$, is determined by bulk density:

$$\varepsilon_\infty = 1.92^d$$  \hspace{1cm} (2.41)

Where:
- $\varepsilon_\infty$ = relative dielectric permittivity at infinite frequency
- $d$ = dry bulk density (g/cm$^3$).
This formula fails when applied to wet materials as it does not include frequency
dependence. However, in nature it is extremely difficult to find materials that do not
contain liquid water, with the exception of the moon and
extreme polar regions.

2.3.2. Wet materials

Wet materials behave much differently than dry materials. Pure water by itself has
its own frequency dependent behavior. As was noted earlier, the orientational
polarization of the water molecule is the cause of the dominant relaxation over the
frequencies of typical geophysical investigation. The dielectric permittivity Cole-Cole
parameters for pure water are summarized in Table 2.1 (Hasted, 1973). When water is
added to a water-wet dry material, the water begins to form a double layer on the
particles (Shaw, 1992). As the double-layer approaches or exceeds the size of the
physical particle, polarization becomes more important (Olhoeft, 1985).

<table>
<thead>
<tr>
<th>Temperature in °C</th>
<th>$\epsilon_r$</th>
<th>$\epsilon_{\infty}$</th>
<th>$\tau_\epsilon \times 10^{-9}$ sec</th>
<th>$\alpha_\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>88.3</td>
<td>4.46</td>
<td>0.0179</td>
<td>0.986</td>
</tr>
<tr>
<td>10</td>
<td>84.1</td>
<td>4.10</td>
<td>0.0126</td>
<td>0.986</td>
</tr>
<tr>
<td>20</td>
<td>80.4</td>
<td>4.23</td>
<td>0.0093</td>
<td>0.987</td>
</tr>
<tr>
<td>30</td>
<td>76.8</td>
<td>4.20</td>
<td>0.0072</td>
<td>0.988</td>
</tr>
<tr>
<td>40</td>
<td>73.2</td>
<td>4.16</td>
<td>0.0058</td>
<td>0.991</td>
</tr>
<tr>
<td>50</td>
<td>70.0</td>
<td>4.13</td>
<td>0.0048</td>
<td>0.987</td>
</tr>
<tr>
<td>60</td>
<td>66.6</td>
<td>4.21</td>
<td>0.0039</td>
<td>0.989</td>
</tr>
<tr>
<td>75</td>
<td>62.1</td>
<td>4.49</td>
<td>0.0032</td>
<td>------</td>
</tr>
</tbody>
</table>
Figure 2.4 is a plot of measurements of the dielectric permittivity of a mixture of silica sand, Na-montmorillonite, and water (Olhoeft, 1987). Note the increase in the real part of the dielectric permittivity and loss tangent with increasing clay and water. This is caused by the liquid-solid interface interaction that produces an interfacial polarization (Olhoeft, 1987). This behavior is commonly termed the clay effect.

The small highly chemically reactive clay particles cause the interfacial polarization to increase, causing a net increase in dispersion (Olhoeft, 1987). Note that the effect of clay decreases with increasing frequency. This clay effect can be linked to the electric double layer that forms on the clay particles when liquid is added. When an E-field is applied, ions in the double layer polarize. This polarized field is opposite the applied field causing the dielectric permittivity and dielectric loss to increase at low frequencies. At higher frequencies, exceeding several hundred MHz, the clay effect has less impact on the dielectric permittivity as the motion of the particles during polarization is too slow to keep up with the driving frequency of the external field. Further discussion on the clay effect can be found in Olhoeft (1987), Kutrubes (1986), and Canan (1999).
Figure 2.4. Dielectric permittivity and loss tangent as a function of frequency for different combinations of silica sand, clay, and water % by weight (modified from Olhoeft, 1987)
Table 2.2 is a summary of Cole-Cole parameters for an engineered size-fraction clay showing the effect of the addition of water (Olhoeft and Capron, 1994). The data show the addition of water causes the dielectric permittivity of a material to change significantly. It should be noted that the mineralogical clay used by Olhoeft (1987) (Figure 2.4) produces a much stronger frequency dependence then the size-fraction clay in Table 2.2.

Table 2.2 Cole-Cole parameters for a size-fraction clay from Olhoeft and Capron (1994)

<table>
<thead>
<tr>
<th>Wt. % water</th>
<th>$\varepsilon_s$</th>
<th>$\varepsilon_\infty$</th>
<th>$\tau_\varepsilon \mu$sec</th>
<th>$\alpha_\varepsilon$</th>
<th>$\rho \ \Omega$-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>3.46</td>
<td>2.65</td>
<td>0.0134</td>
<td>0.38</td>
<td>10000</td>
</tr>
<tr>
<td>15.77</td>
<td>29.43</td>
<td>8.30</td>
<td>0.0183</td>
<td>0.66</td>
<td>56.0</td>
</tr>
<tr>
<td>30.18</td>
<td>43.04</td>
<td>20.73</td>
<td>0.0089</td>
<td>0.70</td>
<td>23.5</td>
</tr>
</tbody>
</table>

To further illustrate the effect of water on the dielectric permittivity of a material, Figure 2.5 is a plot of the real part of the relative dielectric permittivity and the log(loss tangent) versus log(frequency) for a dry silica sand (40% porosity) and a saturated silica sand (40% porosity) measured on a HP-8753D vector network analyzer. The dry silica sand and the saturated silica sand in Figure 2.5 are same materials used in the physical models later described in Chapter 5.0.
Figure 2.5 Measurements of real part of the relative dielectric permittivity and log(Loss tangent) for dry silica sand (40% porosity) and distilled water saturated silica sand (40% porosity) used in the physical model.
2.3.3. Effect of porosity

Porosity is defined as the pore volume per unit gross volume (Sheriff, 1994). Porosity has a large effect on the dielectric permittivity. Porosity defines the space that a liquid or gas can fill within the rock. As demonstrated in the previous section, the addition of water can drastically change the dielectric properties of a material. The water or other fluid is found within the pore spaces of the host material. The addition of fluid in the pores may cause an increase in the total conductivity of the material if the pores are interconnected and provide a path for the currents to flow and conductive losses to occur. The fluid can have a different dielectric property than the host material and can cause an increase in the total bulk dielectric permittivity of the material, such as adding water to sandstone. Under the same argument, the addition of a substance with a lower dielectric permittivity into a material’s porosity can cause a net reduction in the bulk dielectric permittivity. The pores of the material can also influence the polarization of dielectrics that fill the pores by providing a mechanical boundary. Frequency dependence can arise from the pore distribution through interfacial polarization (Kenyon, 1984). Also if the size of the pores or grains are approximately equal to the wavelength of the electromagnetic field in the materials, scattering losses can occur within the sample, and frequency dependent effects will be exhibited (Olhoeft and Capron, 1994).
2.4. Mixing laws

The way in which conductivity of a rock is influenced by different compounds is commonly expressed in the oil industry using Archie's law (Western Atlas, 1992), assuming the rock contains no clay and has interconnecting pores. Several formulations have been used to express the way materials of different dielectric permittivities mix. Some of these formulations appear in Shen, (1985), Dukhin, (1971), and Meador and Cox, (1975). The most accepted is the Bruggeman-Hanai-Sen (BHS) formula of which Archie’s law is a limiting subset (Sen et al. 1981).

The BHS formula is based on the theory of a disordered system in solid state physics. The theory is based on a model for which the conducting paths remain interconnected with the grains spherically coated with water. In order to include the effects around each grain a self-similar model includes each grain coated with a skin made of other coated grains (Sen, et al., 1981). Sen, et al. (1981) derived the following mixture formula for a two-component system under the assumption of static fields:

\[
\frac{\varepsilon^*_{\text{m}} - \varepsilon^*_r}{\varepsilon^*_{\text{w}} - \varepsilon^*_r} \left( \frac{\varepsilon^*_{\text{w}}}{\varepsilon^*_r} \right) = \phi \tag{2.42}
\]

where,
- \(\varepsilon^*_r\) = theoretical complex dielectric permittivity of the mixture,
- \(\varepsilon^*_m\) = complex dielectric permittivity of the host medium (matrix),
- \(\varepsilon^*_w\) = complex dielectric permittivity of component mixed into the medium (water),
- \(\phi\) = porosity as a volume fraction of \(\varepsilon^*_w\) in \(\varepsilon^*_m\),
- \(c\) = depolarization factor dependent on the geometrical shape of the rock grains.
The depolarization factor $c$ is set equal to $1/3$ for spherical grains. A mixture formula may be derived for a multiple component system using equation (2.42) repeatedly. Note, however, that the formula is not symmetric. Mixing component one into component two will not provide the same result as mixing component two into component one. The theory also assumes that the mediums are noninteracting, and can not yield dielectric permittivities higher than any one of the components. Kutrubes (1986) demonstrated that the BHS formula does not hold for interacting clay mixtures. The BHS formula also can not predict any loss from scattering. Hashin-Shtrickman (H-S) bounds for the BHS indicate the range of the mixing formula based on the end members of mixing component one into component two or component two into component one (Olhoeft, 1987). Figure 2.6 is a plot of BHS formula showing the H-S bonds for a mixture of water and silica sand. The application of the BHS formula to dielectric permittivity measurements can be found in Olhoeft (1987), Kutrubes (1986), and Canan (1999).
Figure 2.6 Illustration of the BHS formula for a two component mixing of silica sand and water showing the two paths that the mixing can be calculated along for mixing silica into water and water into silica these represent the HS-bounds.
Chapter 3.

DIELECTRIC LOGGING

3.1. Borehole environment

To begin the discussion of dielectric logging techniques, a limitation needs to be imposed on the borehole environment. As stated earlier, the 2-inch slim-hole time-domain dielectric logging tool was specifically designed to operate in environmental wells cased with 2-inch i.d. plastic pipe. This borehole can be either air-filled or fresh water-filled. The tool will not operate in steel cased wells nor in a well filled with a highly conductive fluid, e.g., mud or salt water. A following section gives a more detailed discussion of the specific environments where the USGS 2-inch dielectric tool will operate.

An environmental well is much different from an oil industry well. Petroleum wells are typically logged while open, prior to being cased with steel, and are full of drilling mud. The drilling mud can be either salt based or oil based depending on the specific drilling environment, which depends on formation pressure, depth, and temperature. The wells are typically much larger in diameter than the standard 2-inch environmental well. A distinction between environmental and oil industry wells is being
made to better understand the oil industry tools. These tools are not suitable, as they are to large, for many environmental wells, thus specific tools needed to be designed for the environmental field.

The mining industry wells fall between the realms of the environmental industry and the oil industry. Some of the wells are drilled with mud and are logged with a mud-filled borehole. Typically the boreholes are left open and are air filled. These wells are almost always drilled at angles for the purpose of intersecting as much of a geologic feature as possible, and to retrieve core samples for mineralogical and petrophysical analysis.

Engineering wells are usually designed for a specific propose, e.g., to get information on the soils, depth to bedrock, location of fractures, etc. These wells are cased or left open depending on the purpose of the well. They are sometimes sealed with a bentonite grout, as are the environmental monitoring wells. They are usually smaller and not as deep as the oil industry wells.

3.2. Dielectric logging techniques

The development of dielectric logging tools was stimulated by the oil industry to investigate the pore-fluids in highly resistive formations. Later tools were designed by the chemistry and soil science disciplines to provide information on the dielectric properties of materials. As the need arose for characterization of environmental areas, tools that
provided dielectric properties of the subsurface were looked at as potentially useful. The following sections provide a description of the logging tools that have been developed to measure dielectric properties of the subsurface. The oil field tools are presented for background information on the development of the slim-hole time-domain dielectric logging tool.

### 3.2.1. Mandrel tools

Dielectric mandrel tools were developed in the former Soviet Union by Daev (1974) in 1949. This tool was called the Dielectric Inductive Logging Sonde, operating at 14.5 or 24 MHz. The sonde had two transmitter coils and one receiver coil with coil spacings of 0.8 m and 1.0 m, respectively. Another tool operated at 43 or 60 MHz and was called the Wave Dielectric Logging Sonde. It had one transmitting coil and two receiving coils separated by 1 m. Mandrel tools use coaxial loop antennas wound on a non-conducting mandrel for transmitting and receiving an electromagnetic field. These tools typically transmit a fixed frequency between 16-47 MHz (Shen, 1985). To avoid borehole and invasion effects more than one receiver is used so a relative measurement of phase and amplitude can be made (Cox and Warren, 1983). Figure 3.1 is a diagram of the Western-Atlas 47 MHz mandrel tool in a borehole (Western-Atlas, 1992). The transmitter is located at the bottom of the sonde and the transmitted signal is received uphole. The Western-Atlas system operates at 47 MHz in continuous wave mode (CW) mode. The tool is restricted to environments with conductivities less than 200 mmhos ($\rho$...
>5 ohm-m). Western-Atlas claims that the tool has a vertical resolution of 8 in. (20.3 cm) and a depth of investigation of 5 to 10 in. (12.7 to 25.4 cm) (Western-Atlas, 1992). The spacing of the transmitter and receiver is typically between 0.6 and 1.4 m. Some mandrel tools that have been developed include: Texaco (16 MHz), Gearhart (20MHz), Welex (20MHz), Texaco (20MHz), Schlumberger (25MHz), Gearhart (30MHz), and the Western-Atlas (47 MHz) (Shen, 1985). China has also developed a mandrel dielectric-logging tool that operates at 60 MHz, with one transmitting and two receiving coils (Geng et al., 1983). The coil spacing was approximately 1 m for the first coil and 1.3 m for the second coil.

These tools were designed for use in the oil industry and are typically larger than 2 -inches in diameter and operate at low frequencies. This precludes their use in many environmental wells, also these tool do not avoid the clay effect at their low frequencies of operation (Section 2.3.3).
3.2.2. Pad tools

A second type of dielectric logging tool operates by pressing a pad up against the side of the borehole. These tools operate from 200-1500 MHz in continuous wave mode (CW-mode). They typically have two transmitters and two receivers spaced from 3 to 10 inches apart. These tools utilize decentralizers that push the tool against the wall of the borehole. The tool has a relatively shallow depth of investigation, and is influenced by the mudcake and scattering from the borehole rugosity. Figure 3.2 is a diagram of the
Western-Atlas 200 MHz pad tool in a borehole (Western-Atlas, 1992). Schlumberger also has a 1.1 GHz tool called the electromagnetic propagation tool (EPT), and Halliburton developed a 1.0 GHz tool (Wright and Nelson, 1993, Shen, 1985). These tools are typically greater than 2-inches in diameter and are poorly configured to be used in environmental wells. The fact that these tools only measure one frequency, as do the mandrel tools, prevents the acquisition of frequency dependent dielectric permittivity.

Figure 3.2 Schematic of the Western-Atlas 200 MHz pad tool (modified from Western-Atlas, 1992)
3.2.3. Resonant frequency capacitance (RFC) gauges

The resonant frequency capacitance (RFC) gauge operates by lowering a capacitance sensor down a PVC access tube. A capacitor forms part of a feedback loop of a modified Clapp high-frequency transistor oscillator that operates at approximately 150 MHz (Dean, et al., 1987). Figure 3.3 is a schematic diagram of the probe and read-out unit. The RFC uses the oscillation frequency $F$ as an inverse square root function of the capacitance to be measured, $C$:

$$F = \frac{1}{2\pi \sqrt{L}} \left( \frac{1}{C} + \frac{1}{C_b} + \frac{1}{C_c} \right)^{1/2} \quad (3.1)$$

where $F$ is the frequency of oscillation, $C$ is the capacitance to be measured, $C_b$ is the total base capacitance including the emitter-base interelectrode capacitance of the oscillator transistor, and $C_c$ is the total collector capacitance. The relationship between the capacitance and the dielectric permittivity is given by

$$C = g \varepsilon \quad (3.2)$$

where $g$ is a geometrical constant, and $\varepsilon$ is the dielectric permittivity (Dean, et al., 1987).

The point of the RFC gauge is to measure the volumetric moisture content of the soil, but as discussed in Section 2.0, the relationship between water, soil, and the pore space is much more complicated than a single frequency measurement can determine. The procedure for the use of the RFC gauge is to calibrate the moisture readings to mass-
determined water percentages. It was found that the increase in conductivity and a very dry environment could have a negative effect on this probe (Waugh, et al., 1996).

Figure 3.3. Schematic diagram of the RFC gauge probe and read-out unit electronics (modified from Dean, et al., 1993)

Figure 3.4. A simplified schematic of the RFC gauge probe and read-out unit
3.2.4. Time-domain reflectometry (TDR)

Time-domain reflectometry (TDR) tools use the propagation of an electromagnetic pulse down a transmission line and look at the time of travel of the first reflection. The tools are typically constructed of a metallic probe, of various lengths (dependent on frequency), a pulse generator, sampler, electronic recorder, and readout device (O'Connor and Dowding, 1999). These tools are typically inserted directly into the material of investigation. As was examined in Section 2.0, the propagation of the electromagnetic energy is influenced by the surrounding material. By measuring the time to a reflection and knowing the length of the probe or transmission line, the dielectric permittivity of the surrounding can be calculated. TDR measurements can provide frequency dependent measurements of dielectric permittivity. The use of TDR is treated in detail in Cole (1977), Fellner-Feldegg (1972), and Topp, et al. (1980). These systems are disadvantageous as they are typically inserted directly into the medium of interest, and the soil moisture value is derived from empirical calibrations. However, TDR has shown usefulness in environmental applications (Greenhouse, et al., 1993, Brewster, et al, 1995, O'Connor and Dowding, 1999).
3.2.5. Time-domain tool

The time-domain dielectric logging tool emerged out of the use of borehole radar, as workers realized that the electrical properties of the surrounding borehole influenced the radar transmitters (Bradley and Wright, 1987, Olhoeft, 1988). The materials around the tool loaded the antennas, causing a shift in the center frequency of the transmitted pulse. A theoretical study of time-domain dielectric logging tools by Schlumberger showed that this technique could be potentially useful in determining frequency dependent dielectric properties (Anderson and Chew, 1989). Working in the time-domain would allow fast acquisition of a broadband response of the material surrounding the borehole. This would allow for more than the single frequency measurements of the larger oil field tools. The tool needed to fit into the standard 2-inch PVC that is used to case many of the environmental wells. The frequency of the pulse needed to be sufficiently high as to attempt to avoid the effects of clays at low frequencies discussed in Section 2.0. An experiment was conducted, at the USGS, to test the potential of a time-domain dielectric logging tool (Wright and Nelson, 1993). Based on the favorable results of the experiment, Wright designed a prototype slim-hole time-domain dielectric logging tool system. This tool was designed with several desired properties in mind including the physical size, frequency range, and speed of acquisition.

Table 3.1 summarizes the desired properties of a time-domain dielectric logging tool. Detailed description of the tool is found in Section 4.0.
Table 3.1 Desired properties of a slim-hole time-domain dielectric logging tool

<table>
<thead>
<tr>
<th>Desired Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical configuration</td>
</tr>
<tr>
<td>Fit in a 2” PVC cased well</td>
</tr>
<tr>
<td>Easily deployed by one person</td>
</tr>
<tr>
<td>Log to a depth of typical groundwater investigations</td>
</tr>
<tr>
<td>Have various depths of investigation into the formation (different spacings for the Tx and Rx)</td>
</tr>
<tr>
<td>Operation characteristics</td>
</tr>
<tr>
<td>Operate at frequencies above 100 MHz to avoid the clay effect</td>
</tr>
<tr>
<td>Allow rapid collection of broadband measurements</td>
</tr>
<tr>
<td>Operate in standard groundwater monitoring wells</td>
</tr>
<tr>
<td>Output</td>
</tr>
<tr>
<td>Provide frequency dependent dielectric permittivity data</td>
</tr>
<tr>
<td>Provide high-resolution dielectric data</td>
</tr>
<tr>
<td>Provide porosity and density data, to replace active source tools (neutron and gamma density logging tools)</td>
</tr>
<tr>
<td>Provide detailed stable and reproducible results to be used in monitoring cleanups</td>
</tr>
</tbody>
</table>
Chapter 4.

DESIGN OF THE USGS SLIM-HOLE TIME-DOMAIN DIELECTRIC LOGGING TOOL

4.1 Background

The slim-hole time-domain dielectric logging tool system designed by David L. Wright at the USGS consists of a sonde (tool), a 120-foot long bundle (36.58 m) of three low-loss coaxial cables, a drawworks containing the transmitting pulser, a drawworks motor controller, a Tektronix digital oscilloscope, and a PC (Figure 4.1).

Figure 4.1. Cartoon schematic of the USGS prototype slim-hole time-domain dielectric logging tool
4.2 Sonde design with voltage gaps

The USGS slim-hole time-domain dielectric logging tool system was designed to transmit a high frequency, sub-nanosecond rise-time pulse into the media surrounding a borehole. After propagation along the borehole, the pulse is received, sent uphole, and recorded. The pulse is generated at the drawworks and is propagated down the 120 feet (36.58 m) of low-loss coaxial cable that is connected to a transmitter (Tx) voltage gap. A second coaxial cable is also connected to the Tx that measures the voltage applied at the Tx for recording uphole. The third coaxial cable is connected to a receiver (Rx) voltage gap where the transmitted pulse is recorded after it has propagated along the tool and through the geologic and borehole media. The voltage gap was chosen because it is difficult to drive a current loop at frequencies above 100 MHz. The impedance of current loop antennas increases with frequency and it becomes increasingly difficult to drive the loop at such high frequencies. A circular plate voltage gap is equivalent to a magnetic current loop tightly wrapped around a mandrel. It can be shown that the relationship for the voltage to the magnetic current is

\[ V = \frac{I_m}{2}, \]  

where \( V \) is the voltage across the gap, while \( I_m \) is the equivalent magnetic current (Anderson and Chew, 1989). The pulse propagates down the tool and through the geologic and borehole media and is received at a receiver (Rx) voltage gap.
The sonde is constructed of three sections of 1.625-inch (4.191 cm) outside diameter aluminum tubing separated by Tx and Rx gaps. The ends of the gaps are capped with brass plates that are separated by thin disks of Lucite. SMA bulkhead connectors are attached to one side of the gap and the feed-through is connected to the other side (Figure 4.2). The tool is covered by a 1.75-inch (4.445 cm) outer diameter fiberglass tube, which isolates the tool from water and other fluids. This tube is capped at the bottom with a rounded brass end cap and at the top with a brass head cap that is attached to the cable head. The center section of aluminum tubing, the Tx-Rx spacer, is interchangeable. The spacer between the Tx and the Rx can be changed to one of three different configurations, 3-, 6-, and 12-inches (7.62, 15.24, 30.48 cm). These options were designed to provide variable depth of investigation (Figure 4.3).

As a voltage differential is applied across the Tx gap, an electric field is generated between and beyond the plates that are connected to the aluminum tube. The monitor line senses the changing voltage. The electric field spreads into the surrounding media which influences the current that flows down the aluminum tube. The current induces a time-varying voltage at the Rx gap. This voltage is recorded up-hole. Holes drilled in both the Rx and the Tx voltage gaps allow the receiver cable to pass up to the cable head. Sixty-four ferrite beads\(^1\) surround the coaxial receiver cable spaced evenly over 67 cm of the 100 cm long cable to suppress electromagnetic leakage from the Tx to the Rx gaps.

\(^1\) Dexter Magnetic Materials ETA-4K5Q-2Vo/3 linear ferrite beads
along the Rx coaxial line. This is required because the coaxial lines are unbalanced, and it is possible for leakage currents to circulate on the outside conductor uncanceled by currents on the inner conductor. Appendix A contains drawings of the tool in the 3-, 6-, and 12-inch configurations.

Figure 4.2. Generalized schematic drawing of the Tx and Rx voltage gaps (not to scale)
Figure 4.3. Assembly drawing of the 2-inch USGS dielectric logging tool (not to scale)
4.3 Custom built drawworks

A custom drawworks was constructed to hold the cable, hoist the tool up and down the hole, and hold the pulse generator (Figure 4.4). The drawworks is approximately 28"x18"x17" (71.12 x 45.72 x 43.18 cm) in size, weighs 45 lbs., and can be moved by one person. The pulse generator and the batteries that power the pulse generator are mounted within the drum, which serves as a cable spool. The pulse generator is a Power Spectra PGS 401 that is driven repetitively at 20 kHz. The battery pack is composed of 10 D-cell alkali disposable batteries that will run the transmitter for a minimum of 24 hours. At both ends of the drawworks, rotary joints pass the signal out to the digital oscilloscope. At one side of the hub, the monitor line passes out and at the other the Rx line passes out. The drawworks is powered by a 1/12 H.P. Dayton electric motor.

A custom built winch controller controls the motor on the drawworks. The winch controller is linked to a PC through a computer serial (RS-232) port (Figure 4.5). The winch controller controls the speed and direction of the drawworks, and displays the depth. The depth information is generated by an optical encoder mounted on the sheave. As the logging cable passes over the sheave, the calibrated encoder sends pulses to the winch controller that in turn counts the pulses and displays the depth. This depth information is displayed on the front of the motor controller by a light-emitting diode read-out. The encoded depth signal is then passed to the PC through the computer serial (RS-232) port. Movement of the winch can be controlled either using manual controls on
the front of the winch controller or by the serial port from the PC. Custom software was
written to control the winch and read the depth information from the winch controller.

Figure 4.4 Photograph of custom built drawworks
4.4 Fast digital oscilloscope

Data transmitted from the Tx gap through the monitor line and data from the Rx gap were digitized using a Tektronix TDS820 sampling oscilloscope. This scope digitizes the signal at a sample equivalent time interval of 10 ps. The TDS820 has two input channels with a bandwidth of 6 GHz, 50 Ω input impedance, and a maximum input voltage of 6 V. The data were recorded for 25 ns at a sample interval of 10 ps providing 2500 samples per channel. The records were averaged 16 times each. The Tx monitor
line provided the trigger for the oscilloscope. The oscilloscope trigger level was set at
100 mV. The input signal is attenuated 16 dB on the Tx monitor line and 6 dB on the Rx
line. The attenuators were required to keep the input voltage below the 6.0 V limit to
avoid damaging the front end of the oscilloscope. The oscilloscope was controlled
through a PC using an IEEE-488 (GPIB) interface connection. The software included the
Tektronix scope controlling routines and libraries (Tektronix, 1993).
Figure 4.6 System setup diagram for dielectric logging tool
4.5 In-house software development for data acquisition and processing

Custom software was developed to run on a PC under MS-DOS®. The program controlled the motor controller, oscilloscope, display of data, and the recording of data. The program was compiled using a 16-bit ANSI-C DOS compiler calling Borland Graphic Interface (BGI) and Tektronix oscilloscope controlling routines and libraries (Borland, 1996, Tektronix, 1993). The listing of the code can be found in Appendix B. To run the program, an IEEE-488 GPIB board needs to be installed on the system as well as the file "EGAVGA.BGI", needed to utilize the display graphics. The program allows the user to input information on the well, site, media being logged, and the configuration of the tool. This information is stored in data file headers to be accessed later. A complete description of the data format is found in Appendix D.

4.6 System specifications

To assist in the understanding of the prototype slim-hole time-domain dielectric logging tool, Table 4.1 summarizes the as-built specifications.
Table 4.1 Specifications for the USGS prototype slim-hole time-domain dielectric logging tool

<table>
<thead>
<tr>
<th>Physical Specifications</th>
<th>As-built specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawworks size</td>
<td>28”x18”x17” (71.12 x 45.72 x 43.18 cm)</td>
</tr>
<tr>
<td>Cable length</td>
<td>120’ (36.58 m)</td>
</tr>
<tr>
<td>Tool diameter</td>
<td>1.75” (4.45 cm) (except for cable head = 1.85”)</td>
</tr>
<tr>
<td>Tool length with cable head</td>
<td>4.84 ’ (1.48 m)</td>
</tr>
<tr>
<td>Spacer sizes</td>
<td>3”, 6”, and 12” (7.62, 15.24, and 30.48 cm)</td>
</tr>
<tr>
<td>Size of electronics box</td>
<td>22”x27”x19” (55.88 x 68.58 x 48.26 cm)</td>
</tr>
<tr>
<td>Weight</td>
<td>Drawworks 45 lb., electronics box 40 lb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transmitter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-domain pulse (at pulser)</td>
<td>Power Spectra PGS401, 400 V peak output, 230 ps risetime, 1.3 ns pulse width at 50%</td>
</tr>
<tr>
<td>Tx rep. rate</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Power source</td>
<td>10 D-cell alkali batteries, or 12 NiCd rechargeable D-cell batteries (last for 24 hours)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drawworks</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Dayton 4Z7226A, 90 V DC 1/12 H.P gearmotor</td>
</tr>
<tr>
<td>Motor controller</td>
<td>Dayton 6A191 DC motor controller</td>
</tr>
<tr>
<td>PC interface</td>
<td>RS-232</td>
</tr>
<tr>
<td>Depth encoder</td>
<td>BEI model H25 incremental optical encoder</td>
</tr>
<tr>
<td>Power source</td>
<td>60 Hz, 120 V, AC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Digitizer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Digitizer scope</td>
<td>Tektronix TDS 820, 2 channel., ± 6 V max 50Ω input, 100 GHz sample frequency, 6 GHz bandwidth</td>
</tr>
<tr>
<td>PC interface</td>
<td>IEEE GPIB 488</td>
</tr>
<tr>
<td>Power source</td>
<td>60 Hz, 120 V, AC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Computer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>IBM compatible PC</td>
</tr>
<tr>
<td>Operating system</td>
<td>MS DOS 6.0 or higher</td>
</tr>
<tr>
<td>Monitor</td>
<td>VGA</td>
</tr>
<tr>
<td>Cards</td>
<td>IEEE GPIB 488</td>
</tr>
<tr>
<td>Power source</td>
<td>60 Hz, 120 V, AC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Application restrictions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. logging depth</td>
<td>= 100’ = 30 m</td>
</tr>
<tr>
<td>Battery life</td>
<td>&gt; 24 hours</td>
</tr>
<tr>
<td>Position accuracy (at encoder)</td>
<td>± 0.04” ± 1 mm</td>
</tr>
<tr>
<td>Borehole size</td>
<td>&gt; 2” I.D. &gt; 5.0 cm</td>
</tr>
<tr>
<td>Borehole casing</td>
<td>PVC, or open hole</td>
</tr>
<tr>
<td>Borehole fluid</td>
<td>Air, or fresh water</td>
</tr>
<tr>
<td>Grout</td>
<td>No grout</td>
</tr>
<tr>
<td>Tool position</td>
<td>Centered</td>
</tr>
</tbody>
</table>
Chapter 5.

EXPERIMENTAL SETUP AND PROCEDURES

5.1. Physical models

Laboratory scale models offer a valuable alternative approach for investigating geophysical techniques. However, these physical models have limitations related to the impossibility of perfectly recreating all the relevant parameters. Duplicating the intricacy of the real world is an impossible task. The major benefit of a laboratory model is that all the parameters in the model can be controlled. In much of the electromagnetic physical modeling conducted at a laboratory scale, frequency scaling is required to match the scaling of the model (Frischknecht, 1988). Scaling is not required for the dielectric logging tool. The dielectric logging tool was modeled at full scale, as it would be operated in the field. The experiment was conducted to check and calibrate the response of the system and to provide controlled data sets for numerical modeling. A description of the following will be included in this chapter: physical model setup, data collection procedures, data format, modeled materials, thin layer detection tests, depth of investigation tests, bentonite grout tests, network analyzer results, and basic system measurements. Also a detailed description of the data processing will be included.
5.1.1. Model setup

The physical model was set up using a 100-gallon polyethylene barrel that contained the test materials. A 2-inch Schedule 40 PVC pipe was mounted in the center of the barrel to simulate a borehole. The barrel rested on a steel cart to allow the barrel to be moved around the lab. Attached to the barrel and the steel cart is an aluminum hoist that holds the sheave, which lowers the tool down into the model. An optical encoder, mounted to the sheave, is connected to the drawworks motor controller. Figure 5.1 is a photograph of the physical model setup in the laboratory.

The physical models are constructed by filling the barrel with the test medium and collecting data as the tool moves through the PVC pipe. For some models, the PVC pipe is filled with water to simulate a water filled borehole. Measurements of the model are taken before the data are collected, including the depth of the modeled material and the relative position of the tool to the top of the PVC pipe. For all measurements, the model was in the same position relative to the surrounding equipment. Figure 5.2 is a schematic representation of the size and configuration of the test barrel. For all of the measurements, a relative depth at 0.0 was taken from the top of the PVC pipe relative to the top of the brass end cap on the bottom of the tool (Figure 4.3). 25 ns of data were recorded at a time equivalent sample interval of 10 ps and stacked 16 times. The tool was operated in a stop-start mode with a measurement taken every 10 mm along the PVC pipe. After the 16 averages were completed, the tool was lowered to the next depth level,
10 mm below the previous one and the next record was collected. The effective logging rate was 0.6 mm/sec with a single measurement taking approximately 16.5 seconds.

Figure 5.1 Photograph of dielectric physical model setup in the USGS laboratory
Figure 5.2 Schematic representation of the size and configuration of the physical model (test barrel)
5.1.2. Data collection procedure

Data collection procedures were standardized and followed for all the measurements in an attempt to eliminate any chance of experimental bias caused by procedural changes. The tool was referenced to the same position for all measurements. The reference point was the top of the PVC pipe and the top of the brass end cap on the bottom of the tool (Figure 5.3 and Figure 4.3). The data collection program DIE2.EXE (Appendix B) was then executed. The program guides the user through a series of questions on the position of the tool, direction of logging, logging mode, stack numbers, file to store the data, and the configuration of the logging environment in which the tool is running. Initially the tool is in the air with the Rx gap 406.4 mm above the 0.0 point at the top of the PVC pipe. The tool then logs down from the 0.0 point at the top of the PVC to 1400-1470 mm, where the tool is stopped by the program.

The tool is not moved when measurements are made without the borehole. For those measurements the tool is buried in the center of the barrel and the measurements are taken. Figure 5.4 is a flow chart diagramming the data collection procedure. Further information on the file format, data organization, and data tables can be found in Appendices D and E, respectively.
Figure 5.3 Cartoon showing the location of the 0.0 reference point relative to the 2-inch PVC and the brass end cap
5.1.3. Data format

The format of the data files collected under this experiment include the following basic configuration: 320 byte header, 2500 16 bit unsigned integers for each of the Rx data points with respect to time, another 320 byte header, and 2500 16 bit unsigned
integers for each of the Tx monitor line data points with respect to time. The header contains information on the data file, including: description of the data, type of test material, size of borehole, position of tool (centered or eccentric), length of spacer, run number, depth value, record number, record length, digitization rate, amplitude scale, number of stacks, and the trigger source. A descriptive file naming convention was used to catalogue all of the files that were taken with the dielectric logging tool. Further information on the headers, the data file formats, and the description of the file naming convention can be found in Appendix D

5.1.4. Modeled materials

Four materials make up the basis for the physical modeling: 1) air, 2) dry silica sand, 3) saturated silica sand (a mixture of approximately 60% silica sand and deionized water by volume), and 4) deionized water. These materials were selected to provide a range of relatively common dielectric values (Section 2.6). The silica sand was selected because of the relatively small frequency dependence in dry and wet state. However, dry and wet sand models provide a contrasting dielectric permittivity, as shown earlier in Section 2.3. A large effort was made to construct the silica sand models to the same bulk density and porosity values for all the modeling. The volume of the sand was kept constant throughout the experiments so as to not introduce effects by changing the porosity of the models. Air models, although unrealistic in natural environments, provide
a good base line, and are simply the empty model. The water model was constructed by filling the barrel with deionized water.

These models were tested with 3-, 6-, and 12-inch spacers installed in the tool. Three borehole configurations were also tested including: air filled borehole, water filled borehole, and no borehole. The no borehole model is as unrealistic as the air model mentioned earlier, however, it provides a base line to examine the way in which the borehole and the tool each separately influence the measurements.

Other models tested included attempts to measure thin layers of materials, depth of penetration measurements, and bentonite grouted borehole measurements. These will be discussed in more detail later in Sections 5.1.5 through 5.1.7.

A listing of all models run in this experiment can be found in Appendix E. Appendix E contains the file names of the data collected, as well as: attenuator settings, spacer used, date of the collection of the data, type of material modeled, and comments on the specific data set. By using the information in Appendix D, the listings in Appendix E, and the information in the headers, all experimental information and data can be retrieved from the files on the accompanying CD-ROM.

5.1.5. Thin layer detection

Two experiments were run to determine the dielectric logging tool’s ability to detect thin layers that perpendicularly cut across the borehole. The thin layer detection experiments included: 1) placing the sheets of Plexiglas in dry or saturated silica sand,
and 2) placing one layer of Plexiglas in the model and separating the second sheet by spacers that form an air gap between the Plexiglas sheets.

Plexiglas was solid with a dielectric permittivity of $\approx 3$ (Lide, 1998) and is relatively frequency independent. Plexiglas was chosen to simulate a layer of DNAPL with approximately the same dielectric properties, $\varepsilon_r = 2.3$ (Greenhouse et al., 1993).

Two 3/8-inch thick sheets and one ½-inch thick sheet of Plexiglas were cut to snugly fit around the borehole and within the barrel, forming donut shaped sheets. These three Plexiglas sheets were then submerged halfway into a model of dry sand with an air filled borehole. Data were collected by logging past the layers using the dielectric logging tool.

Next the two 3/8 inch sheets of Plexiglas were separated by a gap of 3/8 of an inch. The gap contained air and was sealed off to prevent sand from filling the gap when the model was filled with dry sand. This provided a 3/8 inch thick air layer in the dry silica sand model. Data were again collected with the model in this configuration. The next experiment included placing the three Plexiglas layers into a saturated silica sand model.

In Section 6.4, discussions of the results of the thin layer detection data are presented.
Figure 5.5  Cartoon of the setup used for the thin layer detection tests
5.1.6. Depth of investigation

One of the questions always asked is, "How far can the tool see into the formation?" The answer is related to the material in the borehole (drilling mud, water, or air), the material immediately around the borehole (grout and the rugosity of the borehole), the distance between the Tx and Rx, the frequency of the transmitted pulse, the length of recording time, and the electromagnetic properties of the material that the borehole is drilled into (dielectric permittivity, magnetic permeability, and conductivity).

To empirically determine the effective depth of investigation, several measurements were taken by placing a 5/8 inch diameter aluminum or steel rod 39 inches long parallel to the borehole at different distances, and recording the influence this had on the data compared to the background response without the rod placed in the model. This is the same procedure that was used in the experiments of Gilmore, et al. (1987).

Several models were run with the 3-, 6-, and 12-inch spacers in the tool. A list of the models run can be found in Appendix E. In Section 6.5, the results of these measurements are discussed.
Figure 5.6 Cartoon of the setup used for the depth of investigation tests
5.1.7. Bentonite grout

Many environmental wells are grouted in place due to environmental regulatory requirements. This typically involves drilling a 4 to 6 inch well and placing 2-inch PVC casing in the hole. The remainder of the annulus between the PVC and formation is filled with bentonite slurry or a combination of Portland cement and bentonite. This is done to prevent vertical hydraulic contact between contaminated and uncontaminated portions of the aquifers at various depths. To simulate this in the physical model, a 6-inch PVC pipe was centered around the 2-inch PVC that is mounted in the center of the barrel. The annulus between the two PVC pipes was filled with bentonite slurry. The remaining space in the barrel was filled with saturated silica sand. Measurements of the model were then completed using the dielectric logging tool using the 3-, 6-, and 12-inch spacers. A steel rod was then placed up against the outside of the of the 6-inch PVC and measurements were repeated as described in Section 5.1.6. Results of these experiments will be discussed in Section 6.6.

5.2. Network analyzer measurements

Samples of the dry silica sand, deionized saturated silica sand, and bentonite slurry used in the physical model were measured on a HP-8753D vector network analyzer. The measurements yield values of the real and imaginary part of the dielectric permittivity as well as the real and imaginary part of the magnetic permeability with respect to frequency within the frequency range of 30 kHz to 3 GHz. Note the magnetic
property results were neglected in the physical modeling experiment as, these laboratory measurements indicated that the relative magnetic permeabilities were close to $\mu_r = 1$ ($\mu_r < 1.002$). The samples were measured in 3 cm long GR-900 sample holders. An effort was made to preserve the porosity ($\approx 40\%$ by volume Table 5.1) of the model when loading the sample holders. Procedures followed in the measurements of the materials and processing of the data can be found in Canan (1999).

Figure 5.7 gives the results of the dry silica sand, deionized water saturated silica sand, and bentonite slurry measured in the 3 cm GR-900 sample holder. Note the very low frequency dependence of the dry silica sand and the deionized water saturated silica sand compared with the bentonite slurry.

The deionized water that was used in the model was not measured in the vector network analyzer. The relative real part of the dielectric permittivity was assumed to be $\varepsilon_r = 80$ (Hasted, 1973), and the conductivity of the deionized water was measured at 1.0 $\mu$S/cm ($\rho = 10000 \Omega$m) on a conductivity meter. Table 5.1 gives the weight and percent water for each sample used in the determination of bulk density and porosity.

Table 5.1 Density, percent water, and porosity for each of the samples measured on the network analyzer

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample density (g/cm$^3$)</th>
<th>Grain density (g/cm$^3$)</th>
<th>% water by (weight)</th>
<th>Porosity by (volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry silica sand</td>
<td>1.48</td>
<td>2.65</td>
<td>0 %</td>
<td>44 %</td>
</tr>
<tr>
<td>Deionized water saturated silica sand</td>
<td>1.48 (g/cm$^3$)</td>
<td>2.65 (g/cm$^3$)$^1$</td>
<td>22 %</td>
<td>44 %</td>
</tr>
<tr>
<td>Bentonite slurry</td>
<td>0.92</td>
<td>2.53</td>
<td>77 %</td>
<td>64 %</td>
</tr>
</tbody>
</table>

$^1$ Kutrubes (1986), $^2$ Grim (1968)
Figure 5.7 Dielectric permittivity measurements of dry silica sand, deionized water saturated silica sand, and bentonite slurry measured in the 3 cm GR-900 sample holder on a HP-8753D vector network analyzer.
5.3. Basic dielectric logging tool system measurements

Several basic system measurements were completed to measure the system’s timing and the influence of the various components of the tool. These included measuring the time delay in the length of the Rx and monitor lines, measuring the influence of the Rx line that passes through the Rx and Tx ring voltage gaps, and the laboratory radio frequency (RF) environmental noise.

5.3.1. Cable length

The digital oscilloscope is triggered by the signal on the monitor line attached at the driving point of the Tx. The signal propagates up to the oscilloscope and sets time zero. The Rx line is nominally the same length as the monitor line; however, they do not have to be necessarily the same electrical length. To test that the lines were the same electrical length, the model was set up and the Tx to Rx first arrival was recorded. The lines were then physically interchanged, and again the first arrival was recorded. When the lines were reversed it was determined that the Rx line introduced a 560 ps delay in the first arrival time. All time measurements of the Rx line were corrected for the 560 ps delay. This time shift was assumed to be constant throughout the measurements of the dielectric logging tool.

The cable length also has another effect on the transmitted waveform. As the transmitted pulse travels down the cable it is attenuated and the rise-time is degraded.
These effects lead to a frequency dependent cable behavior. To test this effect, the pulser output was recorded using only a short length of cable connected directly to the scope. The measurement was then repeated with the Tx line (the line that is connected normally to the pulser and the Tx voltage gap) in the loop. Then the measurements were repeated a third time with the Tx monitor line (the line that is normally connected to the scope and the Tx voltage gap) connected to the Tx line. The results of the measurements are presented in Figure 5.8. Caution needs to be used in looking at these measurements as the Tx voltage gap was not in the loop, thus the effects in Figure 5.8 are only from the cable. To remove the effects of the cable from the measurements the Tx signal will be deconvolved out of the Rx data (Section 5.4.3)

![Figure 5.8](image.png)  
*Figure 5.8 Plot of the influence of the logging cable on the Tx pulse*
5.3.2. Influence of the internal coaxial cable

As stated earlier in Section 4.0, a coaxial cable had to be passed up from and through the Rx voltage gap through the spacer and through the Tx voltage gap. Electromagnetic leakage does occur along this coaxial cable even though it is loaded with ferrite beads. To test the influence of the coaxial cable within the tool, the tool was disassembled to allow the Rx line to be passed out the bottom of the tool. The tool was then suspended horizontally between two nonconductive supports and securely attached to prevent movement. Next, measurements were made with the 3-, 6-, and 12-inch spacers with the Rx line passing out the bottom of the tool. The coaxial cable was then replaced in its normal configuration and the measurements were repeated. Figures 5.8 through 5.11 are the measurements of the influence of the internal coaxial cable on the 3-, 6-, and 12-inch configurations of the tool. These measurements indicate some energy coupling to the Rx-line. The 3-inch spacer configuration is influenced the most by the leakage, while the 12-inch spacer is least influenced by the leakage.
Figure 5.9 Tx and Rx response with and without the internal coaxial cable for the 3-inch spacer

Figure 5.10 Tx and Rx response with and without the internal coaxial cable for the 6-inch spacer
5.3.3. Environmental RF and oscilloscope noise measurements

Measurements of the system without the Tx turned on were conducted to provide a basis for the radio frequency environmental noise in the dielectric tool and the laboratory. The tool was positioned above the model, hanging from the sheave in the same manner that it would be operating in data acquisition. The model, the computer, and the other electronics were all in the same position to emulate a normal data collection run, with the exception of the transmitter being turned off. As the data records are triggered from the Tx-monitor line, the trigger on the scope was reduced to 0.0 mV to allow it to free-run. The data were not stacked for this set of measurements. Figure 5.11 Tx and Rx response with and without the internal coaxial cable for the 12-inch spacer.
5.12a shows the time-domain results of the Tx-monitor and Rx-line measurements. In order to assess the noise spectrum, the time-domain measurements were transformed to the frequency-domain using an FFT (RSI, 1998b). From the results of the transformation, the power spectra of the environmental noise were plotted in relative to 1 mW (dBm) (Figure 5.12b). To compare the environmental noise recorded while the transmitter was turned off, a measurement of the transmitted and the received power spectrum for a 3-inch spacer measured in free space was also plotted in dBm (Figure 5.12b). The environmental noise is 40 dB down from the Rx signal, indicating that the environmental noise is below the measured Rx signal. The plot also shows that the Rx is also approximately 45 dB down from the Tx signal.
Figure 5.12 Measurement of environmental and oscilloscope noise with trigger level set to 0.0 mV a) time-domain response of the Rx and Tx, b) power spectra for the system noise and the power spectra from the measurement of the 3-inch spacer in free space.
5.3.4. Free space measurements

To assess the tool’s response in free space, an experiment was conducted that isolated the tool from the model. Figure 5.13 is a schematic representation of the tool suspended in a large room. In this configuration the bottom of the tool was suspended 12 feet from the floor. The floor was the closest object to the tool that could cause a reflection. This distance off the floor was chosen to avoid any reflections in the 25 ns long recording window for the dielectric tool. In this configuration, the driving point of the tool was approximately 13.5 feet from the floor. Assuming a wave velocity equal to the speed of light \( c = 3.0 \times 10^8 \text{ m/s} \), the wave would have a two-way travel time of approximately 26 ns before it would encounter the Rx voltage gap point 13.3 feet off the floor (when the 3-inch spacer was installed). The nearest wall was 18 feet away from the tool. The tool was positioned in this manner to avoid reflections from the floor, the sheave, and surrounding walls. Measurements of the 3-, 6-, and 12-inch spacers were collected as if the tool were in the model. The only exception was that the tool was not moved during the measurements. After each spacer was changed, the tool was hoisted back up to the original position with the bottom of the tool 12 feet off the floor and the measurements repeated.
5.4. Data processing

Originally the data from the dielectric logging tool was to be processed in the same manner that the data was proceed in Wright and Nelson (1993). This involved truncating the waveform at the peak and folding the waveform over to produce a Gaussian pulse. This was originally done to avoid problems from the reflections from the ends of the tool and the boundaries in the physical model. This process was not implemented with the data in this thesis. From the measurements of the depth of investigation tests (Section 5.1.6 and 6.5) it was determined that the influence of the formation was past the peak in the Rx signal. Also no good way of truncating the data
before the 25 ns end of the record was found. Thus, the complete 25 ns long waveform was used in the data processing.

Data processing included: windowing of the time-domain data (to dampen the reflections from the edges of the model), smoothing the end of the time series to zero (to avoid truncation errors), transforming the data into the frequency domain, deconvolving of the Tx from the Rx to remove the system-dependent transmitted pulse, and deconvolving system response of the empty model from the system response of the filled model. Data records were selected from the center of the modeled runs at 64 cm Rx position (100.4 cm from referenced zero), as this was the position that provided the least amount of influence from the reflections from the edges of the model. Figure 5.14 is a 2-D image representation of the amplitude of the Rx data mapped into a 8-bit gray scale with 104.0 cm position marked. From Figure 5.12 it can be noted that this location is where the influence of the top of the sand and the bottom of the model is at a minimum.

The data were processed using a program written in IDL 5.2 (RSI, 1998). IDL is an integrated development environment that allows the user to call many predefined routines and display the results in a graphical user interface (GUI) environment. Code used to create this data processing can be found in Appendix C. Figure 5.15 is a flow chart diagramming the processing of the dielectric logging tool's data.
Figure 5.14 Image of 2-D dielectric tool data showing the measurement point where the waveform data were selected for data processing, and also showing the reflections from the edges of the model.
Figure 5.15 Flow chart of the processing of the dielectric logging tool's data
5.4.1. Windowing of the time-domain data

Windowing of the time domain data was conducted for two reasons. First to reduce reflections from the edges of the model, and to smooth the ends of the records to minimize truncation effects when the data are padded with zeros and transformed to the frequency domain. The window used was an asymmetrical Hanning window (RSI, Inc., 1998) with the center of the window placed on the time zero and with the end rolling off to zero at 25 ns. This window was selected to preserve the initial (high frequency) part of the waveform. This windowing was applied to all of the data. Figure 5.16 are the results from windowing a selected data set.

![Figure 5.16 Example of applying the windowing used for data processing](image)
5.4.2. Transforming to the frequency domain

The transformation of the data was completed by utilizing the FFT function supplied with IDL 5.2 (RSI, Inc., 1998). The windowed time series was padded with zeros out to 32,768 points (equivalent to extending the time series out to 327.68 ns) to provide a smooth result in the frequency domain. While zero padding helps resolve the discrete fourier transform (DFT) at more frequencies, inherent problems with spectral resolution and spectral leakage still occur because of the finite length of the time series (Karl, 1989). Selected results of the frequency domain transformation of the Tx and Rx data for the free-space measurement with the 3-inch spacer installed are provided in Figure 5.17. The phase wraparound in Figure 5.5a was left to emphasize that effect of the phase at high frequencies rather than unwrapping the phase and showing the plot on a much smaller scale. The transformation was checked for accuracy by transforming the measurements back to the time-domain and also by transforming a known sine wave to the frequency-domain.
5.4.3. Deconvolving the transmitted waveform from the receiver response

As the tool is lowered into a model that contains a material with a dielectric permittivity other than that of free space, the Tx is impedance loaded. This loading of the Tx at the driving point causes the transmitted pulse to change. The net capacitance of the voltage gap increases, causing an increase in rise-time and an amplitude decrease. This increase in rise time changes the spectral content of the Tx pulse. This change in the transmitted pulse for different materials leads to the need to remove the effects of the transmitter from the measurements. Figure 5.18 illustrates the change in the transmitted pulse for an air filled borehole with the 3-inch spacer in air, dry sand, wet sand, and deionized water.
Figure 5.18 Transmitted pulse for an air filled borehole with the 3-inch spacer in air, dry sand, wet sand, and deionized water
The removal of the transmitted waveform from the recorded receiver signal was accomplished in the frequency domain. A simple frequency domain DFT exact inverse deconvolution was implemented, including all the inherent assumptions (Karl, 1989). These assumptions include: linearity, that the series is causal, no aliasing of the signal, the time series was infinitely long, the FFT properly preserved the frequency content, proper convolution of two discrete series, and low noise. The system is treated as convolution of a periodic stimulus and a system transfer function that produces an output that is the product of the convolution (Figure 5.19).

Deconvolution involved using the transformed frequency domain Tx \((T)\) signal and the transformed Rx \((R)\) signal. The system transfer \((S)\) was calculated by multiplying the inverse operator of the Tx signal \((T^{-1})\) and Rx signal \((R)\) in the frequency-domain. To avoid the instabilities in the system function \((S)\) at very small values of the Tx-signal, 0.01% (peak) white noise was added to the inverse \((T^{-1})\). This addition of white noise is not without consequences. With the addition of white noise a perfect impulse response can no longer be achieved. The trade off is between accuracy and stability (Karl, 1989, and Yimaz, 1987). The deconvolution is expressed in equation 5.1.

![Figure 5.19 Illustration of the convolution of a periodic stimulus and a linear system](image-url)
where $S$ is the transfer function, $R$ is the received signal, $T$ is the transmitted signal, and $\alpha$ is the white-noise.

The deconvolution operator was tested to be certain that the results were dependable. The test consisted of feeding the deconvolution operator a signal that contains two sine waves. By using one of the sine waves as the transmitted signal the other sine wave was resolved in the system transfer function. Note no white-noise was used in the assessment of the deconvolution operator. Figure 5.20 is a selected result of the deconvolution of the Tx out of the Rx signal. A discussion of the results can be found in Section 6.2.
Figure 5.20 Transfer function calculated by deconvolving the Tx waveform out of the Rx waveform for the 3-inch spacer in an air filled borehole compared to the amplitude and phase of the Tx and Rx waveforms
5.4.4. Deconvolving the empty model out of the measurements

For all of the borehole configurations, measurements of the tool’s response in an air filled (empty model) was recorded. The empty model data was to be used in attempting to deconvolve the model response out of the data of the models filled with materials. Data were recorded using the 3-, 6-, and 12-inch spacers for the air filled and water filled borehole. These data were windowed and the Tx was deconvolved out as in the case of a filled model. The empty model data were deconvolved out of filled models for the same spacer and borehole configuration, (i.e., deconvolve a empty model, air filled borehole, 6-inch spacer) with a dry sand filled model, (air filled borehole, 6-inch spacer) (Figure 5.15).

The deconvolution operator that was used to deconvolve out the empty models was the same style deconvolution operator used to deconvolve out the Tx from the receiver (Section 5.4.3). Again 0.01% peak value of white-noise was added to the inverse operator. An example of the deconvolution of the system response of the empty model out of the system response of the filled model is presented in Figure 5.21. Discussion of the results of deconvolution can be found in Section 6.3
Figure 5.21 Transfer function calculated by deconvolving an empty physical model out of a dry silica sand filled physical model with the 6-inch spacer installed and an air filled borehole compared to the transfer function calculated by deconvolving the Tx waveform out of the Rx waveform for the empty physical model and the dry silica sand filled physical model.
Chapter 6.

EXPERIMENTAL RESULTS

6.1. Time-domain data

The time-domain data were analyzed including all of the tool and physical model configurations. These included the 3-, 6-, and 12-inch spacers in air (empty), dry silica sand, deionized water saturated silica sand, and deionized water, with no borehole, an air filled borehole, and a deionized water filled borehole.

As observed earlier the Tx responds to the materials surrounding the tool. This is due to the impedance loading of the Tx ring voltage gap by the surrounding materials. Results of removing the system effects of the transmitter will be discussed in Section (6.2).

One of the first attributes that can be examined in the time-domain data is the propagation time from the Tx to the Rx. Travel times were calculated by subtracting the time at which the transmitted pulse reached 50% of maximum from the time that the receiver reached 50% of maximum. The times at the 50% peak values were chosen, because of the relative insensitivity and difficulty of determining the time related to the peak voltage. Looking at the value of 50% maximum peak value allows for a better
determination of time value as the signal is changing rapidly compared with the small changes over the peak. As stated earlier in Section (2.2), the propagation of electromagnetic waves is controlled by the electrical properties of the medium. The velocity of the EM-wave can be calculated from the travel time and the distance between the Tx and the Rx. Assuming the velocity of the EM-wave is equal to that of a plane wave high frequency approximation,

\[ v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \]  

(6.1)

where \( v \) = velocity (m/s), \( c \) = speed of light in free space (m/s), and \( \varepsilon_r \) = relative dielectric permittivity. The velocity of a EM-wave should vary as the inverse of the square root of the dielectric permittivity. Figure 6.1 is the velocity of the EM-wave calculated from the travel time for the 12-inch spacer in air, dry silica sand, saturated silica sand, and deionized water for no borehole, an air filled borehole, and water filled borehole. These velocities do not fall along a straight line and clearly show a different slope than the plane-wave velocities. There may be several explanations for this, including the fact that the Rx is in the near field of the Tx throughout the frequency range of the tool. More important, when examining the results of the air filled borehole, there is virtually no change in the velocities for the saturated silica sand and the deionized water. These results seem to indicate that the EM-wave is propagating down the borehole similar to a guided wave.
Figure 6.1 Velocity of an electromagnetic wave plotted versus \((1/\sqrt{\varepsilon_r})\) for a plane wave, no borehole, air filled borehole, and water filled borehole.
In examining the travel times for the free space measurements (Section 5.3.4), the travel time for the spacers showed a rough correlation in the travel times to the velocity of a plane wave in free space. The propagation time was systematically off by 0.230 ns. These travel times were calculated by examining the first break of the Rx. This error could be caused by the assumption that the electrical length of the spacer is equal to the physical length, or errors in correcting the propagation time of the Rx line calculated from tests explained in Section 5.3.1. When the same procedure was applied to the measurements without a borehole, the first arrivals did not correlate with the dielectric permittivity of the model material. The result that the plane wave assumptions do not apply to the dielectric tool should be no surprise, as the Rx is well within the near field of the transmitter for the frequency range of the measurements. Within the near field zone the waves do not propagate as plane waves and contain inhomogenous (evanescent) waves (Kirkendall, 1998). This region is roughly defined as the region within 1 wavelength of the source (Sheriff, 1994). Thus, the plane wave assumptions do not hold, as was also indicated from laboratory measurements of Wright and Nelson (1993).

The time-domain data provides information on the reflections from the ends of the tool and the edges of the physical model, as the measurements are with respect to time and the reflections are dependent on distance from the source. First the reflections from the tool parts can be examined by looking at the measurements of the time-domain response of the tool in the free space measurements (Section 5.3.4). Figure 6.2 is a plot of the raw Rx response of the tool with the 12-inch spacer installed. To assist in
identification of potential reflections, the position in the time-series that the reflections from parts of the tool would occur are plotted and labeled. The arrival time of the reflections were calculated by assuming that the EM-wave propagates at the speed of light in free space, the zero time of the scope is absolute, and that the electrical length of the parts of the tool are equal to the physical length. Figure 6.2 shows that there is a good correlation between the inflection of the Rx signal and the arrivals of the reflections from the top of the cable head and the bottom of the tool. These reflections from the tool could constructively and destructively add at the Rx causing waveform distortions.

Figure 6.2 Arrival times of reflections from parts of the tool plotted on the raw Rx data from the free space measurements of the tool with the 12-inch spacer installed.
Reflections from the edges of the physical model are also apparent in the data as was noted in Section (5.4). These reflections are from the top and bottom of the model, the bottom of the borehole, and from the sheave. The reflections can be observed in Figure 6.3 which is a plot of the amplitude of the raw Rx time-domain data collected mapped into an 8-bit gray scale image, for the 3-inch spacer in a air filled (empty) model. The black lines plotted on Figure 6.3 represent the position of the reflections if the waves were traveling at the speed of light ($c$) in free space. The three lines that are plotted on Figure 6.3 are for reflections from the sheave, bottom of the cart and the floor (see Figure 5.2 for model setup). The reflections in the data do not line up exactly with the plotted free-space reflection positions. This would seem to indicate that the velocity in the air-filled model is not that of free space. The slopes of the reflections in the data indicate a velocity that is slightly less than free space. This is not unreasonable as the cable is clad in polyurethane, the tool is covered with a fiberglass sheath, and the tool is lowered into a PVC pipe, which have relative frequency independent dielectric permittivity over the frequency range of the tool around $\varepsilon_r \approx 2$ (Lide, 1998). These materials would cause a reduction of the velocity of the EM-waves traveling along the materials, producing a velocity intermediate between the velocities in the materials (cable cladding, fiberglass, and PVC pipe) and free-space (Balanis, 1989). With increasing dielectric permittivity of the test material, changing time dependence in the arrival times of the reflections can be observed.
Figure 6.3 Raw Rx amplitude data mapped into an 8-bit gray scale image for the 3-inch spacer in an empty model. Black lines indicated reflections at the velocity of light in free space (see text)
Figure 6.4 is a plot of the amplitude of the time domain data collected mapped into an 8-bit gray scale image, for the 3-inch spacer in a deionized water saturated silica sand filled model with an air filled borehole. As in Figure 6.3, the position of the free space reflections are plotted as dark black lines. Note that additional reflections are observable from the top of the sand in the physical model. These reflections again show that the waves are propagating at a velocity lower than that of free-space. The dashed black line is the position of the reflection from the top of the sand assuming a plane wave traveling in a medium with a relative dielectric permittivity of $\varepsilon_r \approx 18$ (the saturated silica sand measured dielectric permittivity was $\varepsilon_r \approx 18$). The result indicates that the reflections do not travel at the speed of the sand (assuming a plane-wave). Again the velocity of propagation is between that of the air and the saturated sand. While the plots of the idealized velocities on Figure 6.3 and Figure 6.4 can provide an insight into the behavior of the model, there are several assumptions built in that may be violated, including: the EM-waves are behaving like plane-waves, the material is continuous, and the waves will travel at the velocity of the medium surrounding the tool. This is not the case for the physical model geometry. Some of the propagation paths may allow plane wave propagation; however, this is clearly not the case for many of the propagation paths as demonstrated in the above discussion of the arrival times. Furthermore the finite size of the physical model is such that the tool is not fully immersed in the model for all of the measurements. The reflection from the sheave is in a ray path that would encompass air, PVC, and the sand. All of these materials will influence the time dependence of the
reflections. The effect of the borehole may also be influencing the position of the reflections and severely influencing the propagation of the EM-waves. A closer examination of individual time series from the data sets provides the evidence that the EM-wave is influenced by the borehole. Further discussion of the reflections from the physical size of the model will be discussed in the Section 6.2 and Chapter 7.0.
Figure 6.4 Raw Rx amplitude data mapped into an 8-bit gray scale for the 3-inch spacer in a saturated sand filled model with an air filled borehole. The solid black lines indicate the position of reflections at the velocity of light and the dashed line indicates the position of the reflection from the top of the sand at the velocity of the saturated sand.
The effect of the borehole is expressed in the amplitude and position of the primary pulse in the raw Rx data (Figure 6.5). Figure 6.5 is a plot of the raw Tx and Rx data for a 6-inch spacer in an air filled borehole in air, dry silica sand, deionized water saturated silica sand, and deionized water. The amplitude of the primary pulse shows an increase with respect to dielectric permittivity of the model material. Also the travel time to the 50% max amplitude from the water filled model is shorter than the travel times in saturated silica sand, dry silica sand, and air. A similar borehole effect can also be seen in the 3- and 12-inch spacers in the air filled borehole. The borehole effect would seem to be caused by the presence of a guided wave within the air-filled borehole annulus. The data show that as the dielectric permittivity of the model material increases so does the amplitude of the Rx signal. This is counterintuitive, as the effect of the higher dielectric permittivity materials like the deionized water would be to slow the pulse and for attenuation to occur from the electrical losses. Also, the transmitter loading with increasing permittivity shows a decrease in the pulse amplitude, while the received amplitude is increasing. Such an increase is expected if the tool and the borehole are guiding the waves as the increased permittivity will confine more energy in the wave guide.
Figure 6.5 Raw time-domain data for the tool in an air filled borehole with the 6-inch spacer installed for air, dry sand, wet sand, and deionized water.
The influence of the borehole can also be observed when the annulus is filled with water (Figure 6.6). The travel times are in the correct order with regard to dielectric permittivity. However, the amplitude of the Rx signal shows an increase from air to saturated sand, then a decrease for the deionized water case. Again there is a possible waveguide or surface wave effect that is causing the energy of the EM-wave to propagate down the fiberglass sheath or down the PVC. Further discussion of the borehole effect will be included in Chapter 7.
Figure 6.6  Results of raw time-domain data for the 6-inch spacer in a water filled borehole.
6.2. Deconvolving the Tx waveform out of the Rx waveform

As explained earlier in Section (5.4.3), the Tx was deconvolved out of the Rx in the frequency-domain to remove the variations of the transmitted pulse with the loading from the material surrounding the borehole and from cable effects. The results of the deconvolution were examined by plotting the magnitude and phase of the transfer function against LOG(frequency) (Hz). The plot interval was chosen from 3.2 MHz to 1.0 GHz. This decision was based on the power spectrum of the measurements and the bandwidth of the measurement.

Reflections from the model were pointed out in Section 6.1, and the evidence of their impact on the time series was obvious. The next question is, "What is the influence of the model on the frequency domain data that has the Tx deconvolved out of the Rx producing the system transfer function?" To address this question, the complete log of the physical model (data from when the tool was in the air to when the tool was at the bottom of the model) was transformed to the frequency-domain as explained in Section (5.4.2). The Tx waveform was then deconvolved out of the Rx waveform as explained in Section (5.4.3). The magnitude of the transfer function was then plotted with respect to the position of the Rx versus LOG(frequency) (Hz). Figure 6.7 through Figure 6.10 are plots of the amplitude of the transfer function resulting from deconvolution of the Tx from the Rx for the 3-inch spacer in an air filled borehole with an air (empty), dry silica sand, deionized water saturated silica sand, and deionized water filled models.
Figure 6.7 Deconvolution of the Tx out of the Rx for the air (empty) model 3-inch spacer air filled borehole (see text)
Figure 6.8 Deconvolution of the Tx out of the Rx for the dry silica sand model 3-inch spacer air filled borehole (see text)
Figure 6.9 Deconvolution of the Tx out of the Rx for the saturated silica sand model 3-inch spacer air filled borehole (see text)
Figure 6.10  Deconvolution of the Tx out of the Rx for the water model 3-inch spacer air filled borehole (see text)
These plots show that the reflections from the model are influencing the frequency-domain results. Over the range from approximately $10^{8.2}$ to $10^{9.0}$ Hz the model is introducing effects. The results also indicate that the dielectric permittivity of the models is influencing the frequency-domain results. However, the reflections from the model are influencing the frequency-domain results in such a manner that the frequency-domain data may not be directly examined for frequency dependent dielectric permittivity.

To confirm that the model is introducing high frequency effects, field data were analyzed to determine if the high frequency effects seen in the physical model data were present. A data set was collected at the Department of Energy, Savannah River Site (SRS), Aiken, SC. The data were collected in an air filled 2-inch PVC cased borehole that was pushed in using a cone penetrometer (the PVC casing was not grouted). The borehole penetrated several alternating layers of sand and clay located above the water table. Data were collected using the 12-inch spacer, logging in a continuous mode and stored on a mass-storage device (Wright et al., 1998). The time-domain data were transformed to the frequency-domain, and then the Tx waveform was deconvolved out of the Rx waveform using the procedures outlined in Section (5.4). Figure 6.11 is a plot of the amplitude of the transfer function with respect to Rx position and LOG(frequency). These data do not exhibit the high frequency effects in the amplitude of the transfer function as do the data in the model. All of these data do exhibit a peak in the magnitude of the transfer function between $10^{7.5}$ and $10^{8.5}$ Hz. This test confirms the result that the
laboratory physical model is introducing perturbations on the frequency response of the tool. Further discussion of the effect of the model and possible solutions can be found in Chapter 7.

Figure 6.11 Plot of the magnitude of the transfer function from the deconvolution of the Tx from the Rx for the SRS data
The peak in the magnitude of the transfer function located between $10^{7.5}$ and $10^{8.5}$ Hz can be analyzed in more detail by looking at single waveforms from the Rx position in the physical model of 63 cm. This peak in the magnitude of the transfer function is dependent on material in the model, spacer used, and borehole configuration. One of the first potential sources of this strong response in the frequency domain investigated was that the model was supporting a resonant mode based on the geometry of the model and the material of the model. This was discounted as the cause of the peak for the following reasons: 1) the free-space measurements contained the peak, 2) field data that were collected over 100 feet below the surface contained the peak, and 3) simple cylindrical resonators were numerically modeled to simulate the geometry and configuration of the test barrel and did not indicate a peak in the frequency range over which these effects were noted. These points indicated that a tool response and not the model was the cause of the peak observed in the data. Figure 6.12 is a plot of the results of the deconvolution of the Tx waveform out of the Rx waveform for the three spacers in free-space. These data show that the dominant peak at approximately $10^{8.1}$ Hz shifts slightly with the spacer length. This shift may very well be related to the experimental error in reconnecting the cables and reassembling the tool between measurements. There are three other peaks in the magnitude of the transfer function of the free-space measurements that do not change with the configuration of the spacers. These peaks are located at $10^{8.35}$, $10^{8.59}$, and $10^{8.86}$ Hz. In an attempt to explain these magnitude peaks in the frequency-domain, the half-wavelength that would correspond to the observed peak was calculated, and compared to
the physical dimensions of the tool to try to identify any potential resonators using a plane-wave assumption that

\[ 0.5 \nu = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \quad \text{(6.2)} \]

where,

\( \lambda \) = wavelength (m)

\( c \) = speed of light 299792500 (m/s)

\( f \) = frequency (Hz)

\( \varepsilon_r \) = real part of the relative dielectric permittivity.

The half-wavelengths for the above frequencies are summarized in table 6.1.

Table 6.1 Calculation of the half-wavelength based on the peaks of the magnitude of the free space measurements

<table>
<thead>
<tr>
<th>LOG(Frequency) (Hz)</th>
<th>8.10</th>
<th>8.35</th>
<th>8.59</th>
<th>8.86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-wavelength (m)</td>
<td>1.19 m</td>
<td>0.67 m</td>
<td>0.39 m</td>
<td>0.21 m</td>
</tr>
</tbody>
</table>

The calculated values in Table 6.1 do not match any of the tool dimensions assuming that the geometry would support a half-wavelength. Apparently a more complicated tool response occurs that causes the peaks at the observed frequencies.
Figure 6.12 The free space measurements for the 3-, 6-, and 12-inch spacers. The Tx waveform has been deconvolved out or the Rx waveform. The arrows indicate the positions of peaks in the magnitude of the transfer function.
The first assumption used in an attempt to identify the resonances that produced the peaks in the magnitude of the frequency-domain, was that they occurred only on the external surfaces of the tool. To test this assumption, the tool with the 3-inch spacer installed was filled with dry silica sand (with a relative dielectric permittivity of $\varepsilon'_r = 2.5$). The tool was then resuspended in the same configuration as the free space measurements were taken (Section 5.3.4). The measurements were then repeated as described in Section (5.3.4). These data were then converted to the frequency-domain using the same procedure as all the other data, and then the Tx waveform was deconvolved out of the Rx waveform in the same manner used in all the other data. Figure 6.13 is the comparison of the transfer function calculated from deconvolving the Tx waveform out of the Rx waveform for the tool filled with air with the 3-inch spacer installed and the tool filled with dry silica sand also with the 3-inch spacer installed. Results of this experiment indicated that the sand inside the tool changed the frequency response of the tool. Notably the peak at $10^{8.1}$ Hz has shifted down to $10^{8.06}$ Hz. Also the second peak at $10^{8.33}$ Hz (air filled tool) has increased in magnitude and has shifted down to $10^{8.23}$ Hz. These data indicate that the tool is supporting a resonance internal to the tool.
Figure 6.13 Tx waveform deconvolved out of the Rx waveform for free space results from the 3-inch spacer with the tool filled with air and dry silica sand.
The tool response is further complicated by the fact that the tool does show a response to the different materials external to the tool which shifting the location of the peak between $10^{7.5}$ and $10^{8.1}$ Hz. Figure 6.14 is a plot of the transfer function of the 3-inch spacer in an air filled borehole with the model filled with air (empty), dry silica sand, saturated silica sand, and deionized water. The data show an increase though not monotonic in the magnitude of the peak as well as a decrease in the frequency with an increase in the dielectric permittivity of the material in the physical model. Note that the data at the higher frequencies above $10^{8.5}$ are probably caused by the influences of the reflections from the boundaries inherent in the model.
Figure 6.14  Tx waveform deconvolved out of the Rx waveform for the 3-inch spacer in an air filled borehole.
6.3. Deconvolving the empty model out of a filled model

As described in Section (5.4.4) the air filled (empty) model was deconvolved out of the filled model for the same borehole configuration. However, with the reflections in Section 6.1 and Section 6.2 bring into question the legitimacy of the deconvolution of the empty model out of the filled model. From the examination of the magnitude of the transfer function for the complete log of the physical model, it is clear that the physical model introduces frequency perturbations that are dependent on the material surrounding the tool.

Figure 6.15 is a plot of the transfer function calculated by deconvolving the transfer function of the empty model out of the filled models for a 3-inch spacer in an air filled borehole. The results from the deconvolution of the empty model out of the filled models are similar to the results of the deconvolution of the Tx out of the Rx. With increasing dielectric permittivity, the frequency of the peak, observable between $10^{7.5}$ and $10^{8.1}$ Hz, shifts down and the amplitude increases. Again there are some higher frequency effects that are strongly influenced by the reflections from the boundaries of the physical model. Similar trends are observed in the 6-inch spacer in an air filled borehole (Figure 6.16) and the 12-inch spacer in an air filled borehole (Figure 6.17). The 12-inch spacer shows that the wet sand and the water filled models are producing almost the same magnitude response for the peak that is observable between $10^{7.5}$ and $10^{8.1}$ Hz. The phase shows a difference between the water and the wet sand. A potential cause for
the similar magnitude response in the wet sand and the water could be wave guiding.
However, the results of deconvolving the empty model out of the filled model need to be
looked at with great skepticism, as the effects of the reflections from the tool as presented
in Section 6.1 and the reflections from the model (Section 6.1 and Section 6.2) can cause
the waveform to change from the constructive and destructive addition of the reflections.
In Chapter 7.0, a further discussion of these reflections and the tool influence will be
presented.
Figure 6.15 Results of deconvolving the empty model out of the filled models of the 3-inch spacer in an air filled borehole.
Figure 6.16 Results of deconvolving the empty model out of the filled models of the 6-inch spacer in an air filled borehole.
Figure 6.17 Results of deconvolving the empty model out of the filled models of the 12-inch spacer in an air filled borehole.
6.4. Thin layer detection

As described in Section 5.15, two experiments were completed to determine the tool’s sensitivity to thin layers that perpendicularly cut across the borehole. The first test consisted of submerging a 1.25 inch Plexiglas sheet into the dry silica sand model with an air filled borehole. The dielectric logging tool did not respond to the layer with any of the spacers installed (Figure 6.18). Figure 6.18 shows two different ways of looking at the data for a 6-inch spacer in an air filled borehole: plots of the positions of 10%, 50%, 90%, maximum amplitude of the time-domain Rx response, and the amplitude of the Rx response mapped into a 256-color table image. The colors are completely arbitrary and only serve to visually enhance differences in the amplitude. The result that the Plexiglas is not detectable is not completely unexpected as the real part of the dielectric permittivity of the dry silica sand is $\varepsilon_r \approx 2.5$ (Section 5.2) and the real part of the dielectric permittivity of Plexiglas is $\varepsilon_r \approx 3.0$ (Lide, 1998). The contrast between the dielectric properties of the medium and the layer were not large enough to allow the dielectric logging tool to sense the layer.
Figure 6.18 Plot of the tool response using the 6-inch spacer in the model of the 1.25 inch Plexiglas sheet in a dry sand filled model (see text)
To be sure that the tool was actually responding to the medium and the layer in the dry sand, an air gap of 3/8 inch was constructed between two sheets of 3/8 inch Plexiglas. As described in Section 5.1.5, the air gap was sealed off to prevent sand from sifting in, and the physical model was refilled. The dielectric logging tool was again run down past the layer. The results of the 3-inch spacer indicated that the tool was responding to the layer. The response is subtle but there is a discernible response (Figure 6.19). However, these results are so subtle that in a field deployment of the tool, the response would surely be lost in the geological and borehole noise. In the laboratory, with the known location of the air gap, the anomaly can be picked out, but would probably not be identifiable in field data.
Figure 6.19 Plot of the tool response using the 3-inch spacer in the model of the 3/8 inch air gap between two 3/8 inch Plexiglas sheet in a dry sand model (see text)
The final test was to submerge a 1.25-inch Plexiglas sheet into a physical model filled with deionized water saturated silica sand. The model was constructed with an air filled borehole, and the 3-, 6-, and 12-inch spacers were used in the data collection. Deionized water saturated silica sand has a relative dielectric permittivity of \( \varepsilon_r \approx 18 \) (Section 5.2) and as stated above the Plexiglas has a relative dielectric permittivity of \( \varepsilon_r \approx 3 \). This is a much larger contrast than the air versus the dry silica sand used in the experiment explained above. The results of the thin layer detection tests indicate that the 3-, 6-, and 12-inch spacers all detected the Plexiglas layer in the saturated sand (Figure 6.20 to 6.22).

In the examination of the results in Figure 6.20, several items can be observed that demonstrate the response of the tool to the layer. One of these items is the elongated response of the layer that is related to the space between the Tx and the Rx. On the figure, the length of the spacer is graphically indicated. Note that the anomaly is related to the thickness of the layer and the spacer length. Anomalies are also observable with the 6- and 12-inch spacers installed (Figure 6.21 and Figure 6.22). The plots with the 6- and 12-inch spacers installed also show a similar relationship between the spacer length and the size of the anomaly. There is a reduction in the amplitude and a decrease in the travel time right at the point that Tx and the Rx pass by the Plexiglas layer.
Figure 6.20  Plot of the tool response using the 3-inch spacer in the model of the 1.25 inch Plexiglas sheet in a saturated sand model (see text)
Figure 6.21 Plot of the tool response using the 6-inch spacer in the model of the 1.25 inch Plexiglas sheet in a saturated sand model (see text)
Figure 6.22  Plot of the tool response using the 12-inch spacer in the model of the 1.25 inch Plexiglas sheet in a saturated sand model (see text)
Field data have also indicated that the dielectric logging tool can detect thin layers. The data collected at the SRS site (Section 6.2) were collected in an environment that contained alternating layers of sand and clay. Figure 6.23 is a plot of the travel times for the 10%, 50%, 90%, and maximum amplitude for the Rx pulse calculated from the SRS data. These data clearly show that the tool is responding to thin layers within the formation. When these data were compared to borehole radar data collected at the same site there was a strong correlation between the dielectric logging tool data and the radar data (Wright et al., 1998). Results of the thin layer detection tests indicate that the tool can respond to layers as thin as 1.25 inches.
Figure 6.23  Plot of the travel times for the 10%, 50%, 90%, and maximum amplitude of the Rx pulse from SRS.
6.5. Depth of investigation tests

As explained in Section 5.1.6, several tests were conducted to attempt to characterize the effective depth of investigation of the dielectric logging tool. These tests were conducted to identify the maximum depth that the Tx pulse travels in the model during the recorded time-series. These data were analyzed by first collecting a background measurement in the model with no rod. Next a rod was inserted, without moving the tool, at increasing distances from the edge of the borehole. For each rod position, data were collected without moving the tool from the background position. For each of the configurations, (i.e., 3-inch spacer in a water filled borehole, and a water filled model), the data collected while the rod was inserted were subtracted from the background measurement. These data were then plotted in the time-domain. The results show a time dependence in the reflections related to the different rod positions.

Figure 6.24 is a plot of the results of the depth of investigation measurements for a 3-inch spacer in a water filled borehole in a water filled model. The top portion of Figure 6.24 shows the Rx data plotting over each other, and the bottom portion of the figure shows the results of subtracting the data collected with the rod inserted from the background measurement. The reflections can easily be observed in the difference portion of the plot and show a reduction in the amplitude of the reflection and an time dependence of the peak of the reflection. Figure 6.25 is a plot of the results of the depth of investigation measurements for a 12-inch spacer in a water filled borehole in a water
filled model. Again, the top portion of Figure 6.25 shows the Rx data plotted over each other, and the bottom portion of the figure shows the results of subtracting the data collected with the rod inserted from the background measurement. The 12-inch spacer data in Figure 6.25 also display a decrease in the amplitude of the reflections with distance from the borehole as well as a time dependence in the reflections. These reflections were analyzed to identify if the propagating wave traveled at a velocity that would be equal to the velocity of a plane-wave in a dielectric medium with a dielectric permittivity of $\varepsilon_r \approx 80$. First the arrival time of the reflections was picked at the peak of the reflections, and the ray path was calculated by determining the straight line from the Tx to the rod and back to the Rx. These results were calculated for the data in Figure 6.24 and Figure 6.25, and plotted on a graph of travel time versus ray path (Figure 6.26). Also plotted in Figure 6.26 is the travel time versus the distance for a plane wave traveling in water with a dielectric permittivity of $\varepsilon_r \approx 80$. Figure 6.26 shows that the reflections demonstrate a rough correlation with the travel time of a plane wave when the ray path is over 0.2 m long for the 3-inch spacer and 0.4 m long for the 12-inch spacer.
Figure 6.24 Depth of investigation test with a 3-inch spacer in a water filled borehole in a water filled model.
Figure 6.25  Depth of investigation test with a 12-inch spacer in a water filled borehole in a water filled model.
The next step was to test whether the variation in the amplitude of the time-domain data was related to attenuation of the EM-wave in the water from dielectric and spreading losses. The results of this test did not correlate with the attenuation of a plane wave traveling in water. This may again signify that the effects of the dielectric tool are in the near field, violating the assumptions of plane waves. These results do, however, indicate that the tool is influenced by changes in the model 25 cm from the edge of the bore within the 25 ns data collection time window. The question that was not answered by this experiment was, "At what distance can the dielectric logging tool detect dielectric changes from the borehole?" Further analysis on the effectiveness of the dielectric logging tool will be discussed in Chapter 7.
Figure 6.26  Plot of the interpreted travel time versus ray path for the 3- and 12-inch depth of investigation measurements in the deionized water filled model and borehole
6.6. Bentonite grout tests

Tests were completed to determine the sensitivity of the dielectric logging tool to the model when bentonite grout surrounds the borehole (Section 5.1.7). These tests were conducted in a manner similar to the depth of investigation measurements described in Section 5.1.6 and Section 6.5. A 6-inch PVC pipe was centered on the 2-inch PVC pipe that is mounted in the test barrel. The annulus between the 6 and 2-inch PVC pipes was then filled with a bentonite slurry. The bentonite slurry has frequency dependent dielectric permittivity (Section 5.2) and a resistivity equal to approximately 2 \( \Omega \text{m} \). The model was then filled with deionized water saturated silica sand. Measurements were then taken with the tool in one position in the center of the model. Then a steel rod was placed next to the outer edge of the 6-inch PVC and the measurement was repeated. The steel was then moved to 6 inches from the edge of the 6-inch PVC and then to 12 inches from the edge of the 6-inch PVC and measurements were repeated for each of the rod positions.

Figure 6.27 is a plot of the results of the test, and is plotted in the same manner as Figure 6.23 and Figure 6.24. These results indicate that the dielectric logging tool is detecting the presence of the steel rod. However, the amplitude of the reflections is an order of magnitude less then the reflections from the aluminum rod in water. These results show that the bentonite grout greatly decreases the ability of the tool to sense any material outside of the grout. Field measurements taken at Arnold Air Force Base, Tennessee in a
grouted well showed no variation with depth. The borehole at Arnold Air Force Base cut through a highly fractured region of Paleocene limestone saturated with water that would have had a substantially different dielectric permittivity from that of the surrounding formation. These field results indicated that the tool was not able to detect any differences in the surrounding formation when run in a grouted ground water well.

Figure 6.27 Bentonite grout test showing the Rx amplitude and the difference from background with a 5/8-inch diameter steel rod inserted at various distances from the outer edge of the 6-inch PVC pipe
Examination of the travel time of the pulse in the bentonite models shows that the wave reaches the Rx before the pulse for the deionized water, deionized water saturated silica sand, dry silica sand, and air filled models in an air filled borehole configuration. This observation may again point to a waveguide effect that is being introduced by the borehole.

6.7. Errors in the dielectric logging tools measurements and data analysis

The error in the dielectric logging tool measurements can be categorized into four areas: 1) measurement errors from the scope (timing, amplitude, dynamic range, band width); 2) errors from reassembly of the tool (the tool has to be disassembled each time the spacer between the Tx and Rx is changed); 3) error from inaccurately measuring the position of the model and tool (encoder errors, errors from filling the model); and 4) errors introduced from numerical manipulation of the data. These errors may occur singly or may be cumulative.

Errors from the scope may include: timing errors, amplitude errors (from the A/D), errors from exceeding the dynamic range of the system, and errors in measuring outside the bandwidth of the scope. Timing errors in the scope are assumed to be negligible. This is based on a comparative measurement of the, 12-inch spacer in a deionized water saturated model with an air filled borehole taken on 6-26-97 and 3-31-98 (Figure 6.28). These data were taken at different times after several months, in which the tool had been taken apart many times to change the spacer and the model had been
changed several times from different configurations. The measurements of the two records compare very well. The difference of the two measurements is plotted as a thin black line on the same plot. In light of the excellent reproducibility of the measurements in Figure (6.28), the calibration and warranted characteristics of the Tektronix TDS-820 scope can be referenced for the level of accuracy in the scope. According to Tektronix (1993) the scope has a random noise threshold of $\leq 600 \mu \text{V}$ with an accuracy (DC gain) of $\pm 0.7\%$, and a impedance of $50\Omega \pm 0.5\Omega$. 
Figure 6.28  Plot of two data sets taken on 6-26-97 and 3-31-98 using a 12-inch spacer in a deionized water saturated sand with an air filled borehole
Errors in the amplitude of the signal can be examined by looking at the dynamic range of the A/D within the scope. Tektronix quotes a level of 14 bit resolution which gives the A/D an 84 dB dynamic range. The bandwidth of the scope is 6 GHz which is more than sufficient to cover the frequency range of the dielectric logging tool. To help minimize errors from the scope, the scope was allowed to warm-up for at least an hour before collecting data.

Reassembly of the tool is another possible source of errors in the measurements. The dielectric logging tool needs to be disassembled each time the spacer between the Tx and Rx is changed. This procedure includes: the detachment of the tool from the cable head, removal of the fiberglass tube, disassembly of the aluminum tubes from the voltage gaps, removal of the spacer, then the replacement of the new spacer, and reassembly. This process could introduce errors in the tool by changing the impedance or geometry. Reassembly was carried out with great care, keeping all the parts clean and free from defects. The evidence that the reassembly is introducing minimal errors is illustrated by the repeatability of the measurements in Figure 6.28.

Another source of errors could be the measurement of the position of the model relative to the tool. The biggest problem could be the positioning of the tool with the sheave that is tied to the optical encoder. Laboratory tests indicated that the accuracy of the encoder operating in the laboratory is within 0.01% in 100 ft. We require accuracies on the order of 1 cm in 2 m. The results have been checked, and the accuracy of the tool
position is well within the 1 cm range for all of the laboratory measurements. The position of the model was constant throughout the measurements as the length of the PVC pipe was not changed and the tool was referenced to that point for all of the measurements (Section 5.1). After every measurement, the tool was repositioned to the reference point before the next measurement was begun. There were changes with the position of the sand in the barrel for some of the earlier measurements of 0.5 inches. These changes in the position of the top of the sand and water level in the models were recorded in the header of the data file containing the measurements.

There also could be errors introduced from numerical manipulation of the data. These errors were discussed in Section (5.4.2) for the errors introduced by transforming to the frequency-domain, and Section (5.4.3) for errors in the deconvolution.

Unfortunately, many of the errors in the transformation of the data to the frequency-domain and the subsequent deconvolution are caused by the violation of the assumptions in the FFT. These problems are not limited to this tool, but are encountered throughout geophysics. More advanced deconvolution and windowing procedures may help to reduce the spectral leakage, but short of recording for a longer time interval, many of these effects could only be improved by making measurements directly in the frequency-domain. Further suggestions on the future instrumentation and analysis will be included in Chapter 7.
Chapter 7.

DISCUSSION OF RESULTS AND CONCLUSIONS

7.1 Tool Response

The internal tool response was observed to be much more important than initially assumed. The free space measurements made when the tool was suspended in a large room were useful in identifying the tool responses. Observations included effects external and internal to the tool. These effects have been identified as potentially being caused by reflections from the parts of the tool and resonances set up within the tool. The reflections from the ends of the tool are contained within the waveform. As the reflections are received at the receiver gap, they constructively and destructively add to produce a composite waveform. These changes in the waveform influence the spectral content of the measurement.

To add complications to the tool response, there is an observable effect from the Rx-line running up through the ring voltage gap of the Tx. Measurements made with and without the Rx-line installed indicated that there is a wave traveling up the Rx-line. The problem with the tests for the effects of the Rx-line is that the tool was disassembled to allow the Rx-line to pass out the bottom. This involved removing the brass end cap from the tool. This may have drastically influenced the way in which the tool was
resonating and the position of the reflections. Another complication in the Rx-line tests was that the cable head was not attached to the tool. This was done again to allow for the Rx-line to be looped out through the bottom of the tool. These complications start to erode the usefulness of the Rx-line tests. The results however, indicated that the Rx-line cable, internal to the tool, has an influence on the received signal, but to do a thorough examination of the wire’s effect is impossible with the tool in the current configuration. Figure 7.1 is an idealized schematic of the reflections in the dielectric logging tool.

Possible solutions include changing the configuration of the tool, or modeling the tool with a sophisticated finite difference time-domain (FDTD) that can accurately model the reflections and resonances in the tool. By knowing the position of the reflections, they could be removed from the original data, thus possibly allowing analysis of the tool. Another test of the tool’s resonances could include the use of a vector network analyzer. The network analyzer could be swept over a range of frequencies in an attempt to identify the frequencies at which the effects are observed.
Figure 7.1  Idealized schematic of the reflections internal and external to the dielectric logging tool
7.2 Influence of the model on the measurements

The time-domain and frequency-domain results also indicate the finite size of the physical model is appearing in the data. The effects from the model are due to the finite size of the physical model and the consequent reflections from the model's boundaries. The time-domain data of Figure 6.3 and Figure 6.4 showed the effect of the reflections in the data. Again these reflections can constructively and destructively add to produce effects that will influence the spectral content of the waveform. These spectral effects appear in the plots of the complete log of the physical model, with the Tx waveform deconvolved out of the Rx waveform, in Figures 6.7 through Figure 6.10. As discussed in Chapter 6.0, the physical model appears to be causing high frequency effects in the data, as these effects show spatial dependence as the tool is lowered into the physical model. Further evidence that the model is influencing the measurements is that the features seen in the laboratory data are missing from the data collected at the SRS site (Figure 6.11). The SRS data was taken were the tool was isolated from external reflectors (geological structure could still cause reflections) such as the sheave, floor, bottom of the cart, and the top of the model. The SRS data do not show the same high frequency features as the laboratory data (Chapter 6.0). Figure 7.2 is an idealized schematic of the reflections in the physical model.
Figure 7.2  Idealized schematic representation of the reflections in the physical model
Can these reflections be removed from the data? Theoretically, they could be removed from the data; however, this would necessitate accurate velocity and geometry models for the propagation of the waves back to their sources. On top of the complexity of developing velocity and geometry models for the reflections, many of the reflections are in the near field of the Tx. This complicates the way in which the propagation of a wave is influenced by the coupling of the Tx and Rx to the surrounding material. The physical model may be introducing evanescent waves (Smith, 1997). These processes need to be clearly understood before the effects of the physical model can be removed from the data. One way to remove the effects of the physical model would be to build a physical model that is large enough to avoid reflections from the boundaries. This new physical model would need to be room size so as to be certain that the reflections from the walls would not reach the Rx during the recorded time interval. However, the costs associated with building a sufficiently large model may be a limiting factor in the experiment. Another potential solution may be to test the tool in well logging characterization pads or in formations that are relatively homogenous and well characterized. As in the other cases, a sophisticated FDTD model may be useful in determining the effect of the reflections on the time-series. These effects then could be removed from the data and the waveform analyzed.
7.3 Influence of the borehole on the measurements

Results indicate that the borehole has a large effect on the dielectric logging tool. This effect is strongest in the air-filled borehole measurements. The travel times and the amplitude of the primary pulse are not monotonic with increasing dielectric permittivity. In fact, the results show that the travel time decreases for increasing dielectric permittivity and the amplitude increases for increasing dielectric permittivity. These results indicate that the borehole is acting like a waveguide and channeling the energy down the borehole. Figure 7.3 is an idealized representation of a guided wave in the borehole annulus of the physical model. As the contrast between the air-filled annulus and the materials in the model increase, the amplitude of the primary pulse increases. The model may acting like a dielectric insulating cladding around the tool, holding the energy closer to the tool as the dielectric permittivity of the outer material increases (Balanis, 1989).
Figure 7.3  Idealized representation of the guided wave in the borehole annulus
Other borehole configurations measured included tests without a borehole, and a
deonized water filled borehole. The effects of the water filled borehole also showed
non-monotonic results. In this case, the insulating cladding may be the PVC of the
borehole. The results do not show what one would expect if the wave were traveling
through a homogeneous medium. Results from the experiments without a borehole
indicate that the relative position of the arrivals of the primary pulses are in the right
order. The amplitude of the pulses increase from water to wet sand, but then decreases
for deionized water. This behavior, when the tool is directly embedded in the material,
would indicate yet another tool response from the fiberglass tube that covers the tool.

Figure 7.4 through 7.6 are plots of the three different spacers in the three different
borehole configurations for the saturated silica sand model. As was seen before, it would
seem that the effect of the tool couldn't be separated from the model. The thickness of
the annulus and the fiberglass tube are very small compared to the wavelength of the
transmitted pulse. This may indicate that a surface wave is established along the tool and
borehole. Simple waveguide and resonator numerical models were generated for the tool
and the borehole. These were simple models that are based on the shape and size of the
physical model, borehole, and tool. These were calculated based on analytical
formulations found in Balanis (1989) chapter 9.0. Calculations were made to determine
the cutoff frequency of the resonators and waveguides. Analytical model matched the
spectral behavior observed in the dielectric logging tool's data. To identify and to
appropriately understand the behavior of the tool in a borehole, detailed numerical
modeling is needed. Possibly with the use of a detailed FDTD model, the position of the waves and the physical cause of their formation could be understood. One useful characteristic of the FDTD model is the ability to produce snapshots of the EM-waves in time. This can be very useful in the determination of the position and their relative strength of the different modes that are excited by the tool.
Figure 7.4 Raw time-domain data for the 12-inch spacer in a saturated silica sand model with no-borehole, air filled borehole and water filled borehole
Figure 7.5 Raw time-domain data for the 6-inch spacer in a saturated silica sand model with no-borehole, air filled borehole and water filled borehole.
Figure 7.6 Time-domain data for the 3-inch spacer in a saturated silica sand model with no-borehole, air filled borehole and water filled borehole
7.4 Waveguides, resonators, and surface waves

The data collected in the physical model have demonstrated that there are complicated modes of propagation, including wave guides, resonators, and surface waves. These effects are having an impact on the measurements of the system and the response of the tool in the physical model. These effects are the cause of the non-monotonic behavior noted in the travel times of the primary pulse in the time-domain data. The resonances of the tool, which are seen throughout the frequency-domain data, have a strong impact on all the measurements. The data also indicate that a possible surface wave is established on the fiberglass tube covering the tool. This is based on the behavior of the tool when it is emerged directly into the model without a borehole.

Waveguides have specific traits that can be examined, including cutoff frequencies. These are the frequencies at which the waveguide will no longer transmit a wave without strong attenuation. The frequency that the waveguide will function is related to the physical size of the waveguide and the electrical properties of the material from which it is made (Balanis, 1989). Sheriff (1994) defines a waveguide as, "an arrangement which constrains wave travel to within a unit by repeated reflection at the boundaries." The wave propagates down a waveguide by reflecting off the sides thus bounding the energy within the waveguide. This selective propagation of a wave provides the cutoff associated with the waveguide and a Q-factor describing the quality of the waveguide to propagate a single frequency. The literature is full of examples of waveguides that are commonly used in many electronic applications (Collin, 1991,
Balanis, 1989). For a specific configuration of a waveguide, several specific TM and TE modes can exist. Related to the dielectric logging tool, the tool itself is a waveguide, guiding the wave from the Tx down to the Rx. The problem that is observed in the data is the way in which the borehole affects the measurements. The borehole is guiding the energy of the transmitted pulse down the borehole and not allowing the majority of the energy to propagate outside the borehole. Evidence for this is the decreasing travel time with respect to increasing dielectric permittivity and the increasing amplitude with respect to increasing dielectric permittivity. To attempt to identify what was causing the apparent waveguide in the borehole, simple numerical models were constructed to simulate the borehole. Cutoff frequencies were calculated for the waveguides. These cutoff frequencies were far above the frequencies that the tool operates, and there were no matches to the observations in the data.

The frequency domain data clearly show a large resonance peak around 100 MHz throughout the data (Chapter 6.0). This peak is a tool response, as the tool displays the same behavior when the tool is in the free space configuration (Section 5.3.4). At first inspection one would think that the tool is resonating at a frequency related to a geometrical length of the tool. To examine the potential of the resonator, several numerical models were constructed to simulate the tool. These models were based on cylindrical resonators with solutions from Balanis (1989) and Collin (1991). As with the waveguides, specific TE and TM modes will be excited in a waveguide that are controlled by the geometric size and electrical properties of the media that make up the
resonator. These models were based on the sizes of the tool and its parts. Again the results indicated cutoff frequencies far above the 100 MHz resonance observed in the tool.

Next the lengths of the tool were compared to half-wavelength antennas. The reasoning was that the tool might be acting like an antenna resonating at 100 MHz, and there are shifts in the peak of the resonance dependent on the material in the model. However, the results were that the tool could not be directly compared with an antenna, as no length within the tool corresponded to the lengths required to produce the observed resonances. A complication to the resonance effect is that the tool was not completely embedded in the materials of the physical mode because of the finite size of the physical model.

Another area to examine is the effect of surface waveguides. The data from the tool did display some characteristics that may be attributed to a surface wave. Surface waveguides are a class of waveguides that have the ability to support a mode that is intimately bound to the surface and propagate tangent to the surface (Collin, 1991). The field is bound to the surface of the waveguide, but is related to the size of the structure and decays exponentially axially from the surface. As with the waveguides and resonators discussed above, only specific modes will be supported based on the electrical properties of the waveguide and the geometrical size of the waveguide. To fully understand and characterize these effects, an FDTD numerical model needs to be examined to attempt to identify the source of these effects.
7.5 Requirements to model the dielectric logging tool

Before selecting a numerical model, specific needs must be addressed when numerically modeling the data presented within this thesis. First, the numerical model needs to be detailed enough to accurately represent all the parts of the tool. The model would include the aluminum tubes, brass end cap, cable head, fiberglass tube, coaxial cables inside the tool, the voltage gaps, and the holes in the voltage gaps. The numerical model would also need to include details of the physical model including: the PVC pipe, the air filled annulus, the test barrel, level of material in the test barrel, the logging cable, the cart that supports the model, and the sheave. All of the above items have been shown to influence the data. A first step would be to model the tool in a free space arrangement as described in Section 5.3.4. If the situation is successfully duplicated, much could be gained by an examination of the tool response. As pointed out above, the reflections of the tool influence the measurements. If the numerical model performs satisfactorily in the case of the free space measurements, the next step would be to numerically model the air filled (empty) physical model. The results would be very useful, as the data has clearly shown that the physical model influences the measurements. The addition of the fluid filled borehole, and the sand and water filled physical model will help to define the response of the tool, but only after reflections of the model and the cause of the resonances are clearly identified. This is not a simple task to accomplish, as the model has to include dispersion and near field solutions. Before a
complete undertaking of the numerical modeling, a possible redesign of the tool may be more appropriate.

7.6 Applications of the tool

Currently the tool has a very limited area of deployment. The tool was specifically designed to fit into a 2-inch PVC cased (or open) borehole. The borehole needs to be ungrouted. This is based on the field and laboratory measurements (Chapter 6.0). At first thought, this is a very restrictive environment; however, many boreholes exist where the borehole has been installed by direct-push technologies (Wright et al., 1998). These boreholes are in the near-surface and are not grouted. Their installation involves driving a cone shaped tool forward of a PVC pipe. The soil is pushed to the side as the tool is pushed in to the formation. These types of boreholes are limited to areas that contain relatively unconsolidated sediments.

Currently the tool is only capable of determining relative changes in the dielectric permittivity of a surrounding formation. No frequency dependent data on the dielectric permittivity can currently be calculated. This leaves the tool in a position of being a high-resolution anomaly detector. The tool responds clearly to different dielectric permittivities in the laboratory and the field (Chapter 6.0) (Wright et al., 1989).

The slim-hole time-domain dielectric logging tool has promise in the environmental and geotechnical fields. However, before the tool can provide frequency dependent dielectric permittivities, the tool response and complex behavior in a borehole need to be determined and removed from the effects of the geologic medium. The ability
of the tool to detect thin layers has many possibilities for assisting in the solution to complex geological problems. Currently the tool can detect thin layers (down to 1.25 inches), but the ability of the tool to clearly define the dielectric permittivities of the layers is beyond its current capability.

7.7 Future design suggestions

Several designs may be useful to examine in the future. Some of these include separating the Tx and Rx ring voltage gaps (not connecting the Tx and the Rx with a aluminum tube), moving to a different antenna (bi-cone for example), or going to small coaxial loops. With regard to the reflection, the use of an EM absorbing material (ECCOSORB) (Peden and Brew, 1995) to dampen the EM-waves from the ends of the tool and possibly between the Tx and the Rx may be advantageous.

As was noted, the Rx-line traveling through the Tx and Rx ring voltage gaps is allowing some energy to leak along the coaxial cable. One way of correcting this would be to transpose the Tx and the Rx (move the Tx to the bottom) and install a pulser in the tool. This would not be without consequences, as there would need to be a power source in the bottom of the tool. Moving the pulser down to the Tx ring voltage gap would also allow a faster rise time and thus a high frequency to be transmitted into the formation. This would also free up one coaxial line in the cable bundle (currently used to pulse the Tx gap) allowing for the use of multiple Rx spacings that could be used to calculate relative amplitude and phase for the measurements.
Whatever future tool designs are used, the designer needs to investigate the use of frequency-domain measurements to obtain dielectric permittivity measurements. The potential benefits of the use of frequency-domain measurements are in the location of resonances within the tool and the avoidance of these resonances. The use of frequency domain measurements is not without consequences, as changing from the time-domain to the frequency-domain will cause the measurement time to increase.

Again the use of a FDTD model may be of help in redesigning the tool. By modeling different tool geometries and designs, the tool may be optimized for the 2-inch borehole. However, empirical testing of the tool design will be the proof of any new design.

7.8 Future physical modeling suggestions

This study has provided a great deal of information related to the physical modeling of a dielectric logging tool. The physical model that was used in this study turned out to be small compared to the size of the tool. The physical model introduced reflections from the sides and from the boundaries at the top and the bottom of the model. In future physical modeling, a larger physical model needs to be used on the scale of approximately 13 x 13 x 13 feet (as we record for 25 ns, thus the reflection traveling at the speed of light $c$ in free space would not have time to reflect and return in the recorded time window). The inside of the tank (barrel) needs to be coated with an EM absorbing material like ECCOSORB. This would help to limit the reflections from the outside and
the boundaries of the model. In the case of the physical models presented in this thesis, the tool was not completely immersed within the medium of the physical model at one time. This was initially done as the tool was assumed to be influenced only by the immediate surroundings. When the data were analyzed, it was determined that the tool was strongly influenced by the edges of the physical model and the borehole. The size of the model would need to be large enough so that a reflection can not make it back to the tool during the measurement time window.

7.9 Thesis goals revisited

In Chapter 1.0 several thesis goals were outlined. These goals included the following:

1. Build a field worthy dielectric logging tool that can be easily deployed (completed by David L. Wright at the USGS).
2. Determine if the tool can respond to changes in dielectric permittivity.
3. Conduct physical modeling of the tool.
   - test borehole effects
   - thin layer detection
   - depth of investigation
4. Determine if the tool can provide frequency dependent dielectric permittivity.
5. Supply data for numerical modeling.

Thesis goal one, to build a field worthy dielectric logging tool, was completed with the construction of the USGS prototype slim-hole time-domain dielectric-logging tool designed by David L. Wright of the USGS. Much of the construction of the tool was completed by the time the author began working on the dielectric logging tool project.
Project goal number two was to determine if the tool can respond to changes in dielectric permittivity and project goal number three, conduct physical modeling of the tool were conducted at the same time. These project goals were completed by the acquisition of physical model data over a two-year period of time. Measurements were taken of the tool with the 3-, 6-, and 12-inch spacer installed, in models of air, dry silica sand, deionized saturated silica sand, and deionized water. Several borehole configurations were measured to determine the effect of the borehole on the measurements, including: no borehole, air filled borehole, deionized water filled borehole, and bentonite grouted borehole. Measurements were made of the tool’s response to thin layers that perpendicularly cut the borehole. These measurements were analyzed in both time and frequency domains to determine if the tool was responding to the medium in the model. Results indicated that the tool was responding to the materials in the model, the geometry of the model, and the construction details of the internal parts of the tool.

Project goal number four was to determine if the tool can provide frequency dependent dielectric permittivity. This project goal was not achievable without further detailed numerical modeling of the data. While results indicated that the tool was responding to the dielectric properties of the models, many other influences were affecting the measurements of the dielectric logging tool. These included the finite size of the physical model, the tool response, and the borehole effects. Altogether these contributed reflections, waveguides, resonators, and surface waves influenced the measurements in such a way that, without removing these strong influences, no
meaningful relationship between the measured response and the dielectric permittivity could be drawn.

Project goal number five was to supply data for numerical modeling. Appendix E is a listing of all the data collected in this research. The attached CD-ROM (Appendix G) containing this information can be accessed by using the data format as outlined in Appendix D. The completion of project goal number five may allow for the completion of project goal number four.

In conclusion, the data presented in this thesis has shown that the USGS slim-hole time-domain dielectric logging tool can respond to dielectric changes in the subsurface. However, the calibration of the tool is not simple and needs to be examined by numerical means to determine if the tool can accurately determine frequency dependent dielectric permittivity. Future work is warranted on this tool or other tools that measure the dielectric properties of the subsurface. The positive result that the tool can distinguish, with high resolution, thin layers of dielectrically contrasting materials can be used in many disciplines.
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APPENDIX A

TOOL CONSTRUCTION DRAWINGS

The following drawings are intended to help the reader and to provide information for any models incorporating the data included in this thesis. All the drawings are labeled in centimeters and are not to scale. This was done to provide a simple illustration showing the dimensions for the tool. These drawings are not intended to be used as mechanical drawings that a machinist would use to build the tool.
Figure A-1  Drawing of the 2-inch dielectric tool with the 12-inch spacer installed. All dimensions in cm (not to scale)
Figure A-2  Drawing of the 2-inch dielectric tool with the 6-inch spacer installed. All dimensions in cm (not to scale)
Figure A-3  Drawing of the 2-inch dielectric tool with the 3-inch spacer installed. All dimensions in cm (not to scale)
APPENDIX B

DATA COLLECTION PROGRAM

The code for the data collection program can be found on the attached CD-ROM under the directory “\programs\collect”. The code is ANSI C compiled under Borland 5.0. Note the file EGAVGA.BGI needs to be in the directory from which the program is running, and the object file MCIB.OBJ need to be used when using the Tektronix 820 scope. Files in the directory “\App_B” on the CD_ROM include the following:

- DIE2.C
- DIE2.EXE
- EGAVGA.BGI
- MCIB.OBJ

System requirements are the following:

- MS DOS 5.0 or higher
- 486 66 MHz processor or better
- 4 MB RAM or better
- VGA monitor with 8-bit color or better
- IEEE-488 (GPIB) interface card (National Instruments NI-488.2 with MS-DOS/Windows Handerler for the AT-GPIB version 1.5)
APPENDIX C

DATA DISPLAY AND PROCESSING PROGRAM (IDL 5.2)

The code for the data display and processing program can be found on the attached CD-ROM under the directory “\programs\IDL\”. The code is written in Research Systems Incorporated (Research Systems, 4990 Pearl East Circle, Boulder, CO 80301, (303)-786-9900, www.rsinc.com) Integrated Development Laboratory (IDL) language version 5.2. The file name for the program is DIE2.PRO. To run the program you need to have a licensed version of IDL. IDL 5.2 runs on the following platforms:

<table>
<thead>
<tr>
<th>Platform</th>
<th>Vendor</th>
<th>Hardware</th>
<th>Operating System</th>
<th>Supported versions</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMS</td>
<td>Compaq</td>
<td>Alpha</td>
<td>VMS</td>
<td>7.1</td>
</tr>
<tr>
<td>Unix</td>
<td>Compaq</td>
<td>Alpha</td>
<td>Digital Unix</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>HP</td>
<td>PA-RISC</td>
<td>HP-UX</td>
<td>10.20</td>
</tr>
<tr>
<td></td>
<td>IBM</td>
<td>RS/6000</td>
<td>AIX</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intel x86</td>
<td>Linux</td>
<td>2.0 (^1)</td>
</tr>
<tr>
<td></td>
<td>SGI</td>
<td>Mips</td>
<td>Irix</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>SUN</td>
<td>SPARC, Ultra 1/2</td>
<td>Solaris 2</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>SUN</td>
<td>Intel x86</td>
<td>Solaris 2</td>
<td>2.6</td>
</tr>
<tr>
<td>Windows</td>
<td>Microsoft</td>
<td>Intel x86</td>
<td>Windows 95, 98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Microsoft</td>
<td>Intel x86</td>
<td>Windows NT</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Microsoft</td>
<td>Alpha</td>
<td>Windows NT</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Macintosh</td>
<td>Apple</td>
<td>PowerPC</td>
<td>MacOS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.1</td>
</tr>
</tbody>
</table>

\(^1\) Redhat 5.1

Note the operating system version number listed above is the minimum supported version. IDL will run on operating system versions later then the version listed above.
APPENDIX D
FILE FORMAT AND DATA ORGANIZATION

2" DIELECTRIC LOGGING TOOL HEADER INFORMATION

The header is composed of 320 bytes of binary data. In a text editor the header would be displayed with the following format:

Line 1: description of data
Line 2: type of test medium
Line 3: size of borehole (in), position of tool (centered or eccentric), and spacer length (in)
Line 4: run number, depth value (mm), and record number
Line 5: record length, digitization rate (sample/sec), and amplitude scale (V/div)
Line 6: number of averages on channel 1, and trigger source and level of channel 2

EXAMPLE HEADER:

air only model 0 at top of 2" pvc and top of end cap
air
Simulated Borehole diameter 2 inches  Centered  3 inches
Run number 01  Depth: 0  Rec# 1
Record Length=2500  10 ps/point   200 mv/div
nave=16  CH:1  Trigsource=CH:  Triglevel=+100mv

air only model 0 at top of 2" pvc and top of end cap
(Description of data)
air
(Type of test medium)
Simulated Borehole diameter 2 inches  Centered  3 inches
(Size of borehole)(tool position)(size of spacer)
Run number 01  Depth: 0  Rec# 1
(run number)(Depth)(record number)
Record Length=2500 10 ps/point 200 mv/div
(record length)(digitization rate)(vertical scale)
 nave=16  CH:1  Trigsource=CH:2  Triglevel=+100mv
(number of averages)(trigger source)(trigger level)

The header is written before each record in the data file. For one reading there is a header for the transmitter monitor channel and the receiver channel

*Note for the versions of the data collection program noted in appendix E Table E-1 to E-15*

For die2f.c and die2m.c the header is organized as noted above

For die2ja.c (no depth) there is no depth record. However, the record number can be translated to depth by multiplying the record number by 10 mm. This version of the data collection program also doesn't contain information on the size of spacer. The overall header length and the record length are the same.

For die2ja.c (depth) the depth information is contained in the file; however, the size of the spacer is not in the header.
2” DIELECTRIC LOGGING TOOL FILE NAMING CONVENTION

File Name: eleven entries that make up six fields
   _ (1), _ (2), _ (3), _ (4), _ (5) . _ (6)

(1) Test Medium Type:
  Wet Sand:   WS
  Dry Sand:   DS
  Water Model: WM
  Air Model:  AM

(2) Borehole size in inches:
  No Borehole:  0
  2 inches:    2
  3 inches:    3
  4 inches:    4
  6 inches:    6

(3) Layer or other object introduced into model:
  No Layer:   NL
  Plexiglas Sheet: PS
  Steel Rod:   SR
  Aluminum Rod: AR
  Air Layer:   AL
  Bentonite Layer: BL

(4) Borehole fluid:
  No fluid:   N
  Air:        A
  Water:      W
  Bentonite:  B
  Cement:     C

(5) Run Number:
  Run # 1   01
  Run # 23  23

(6) File extension:
  *.DAT

Example:  WS2NLA23.DAT
  Wet Sand, 2-inch borehole, no layer, air filled borehole, run #23
APPENDIX E

DATA TABLES

Included on the attached CD-ROM, under the directory and file

“:\thesis\word\app_E.doc ” the following data tables can also be found in the PDF file

“:\thesis\pdf\app_E/pdf.” These data tables represent the laboratory notes recorded at the
time the data was collocated and contain notes on each data run.

Table E-1  Dry sand data
Table E-2  Dry sand with Plexiglas data
Table E-3  Dry sand with 4” PVC air filled annulus-air filled 2” data
Table E-4  Dry sand with 3” PVC air filled annulus-air filled 2” data
Table E-5  Wet sand data
Table E-6  Wet sand with Plexiglas
Table E-7  Wet sand with 6” PVC water filled annulus-air filled 2” data
Table E-8  Wet sand with 4” PVC water filled annulus-air filled 2” data
Table E-9  Wet sand with 3” PVC water filled annulus-air filled 2” data
Table E-10 Wet sand with bentonite grout
Table E-11 Air filled (empty) model data
Table E-12 Free space data
Table E-13 Water filled model data
Table E-14 Iron layer data
Table E-15 Depth of investigation measurements data
APPENDIX F

HP-8753D Vector Network Analyzer Data

Data from the HP-8753D vector network analyzer is formatted as in Canan (1999). The files can be found on the CD-ROM as outlined in Appendix G. The files are located in the directory "\data\network\". The files can be viewed using the program "EM_MODEL.EXE" also include the directory "\programs\network\". A list of the network analyzer data files for materials used in the physical models the follow.

<table>
<thead>
<tr>
<th>Material:</th>
<th>File name:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite Slurry</td>
<td>&quot;bentonit.dat&quot;</td>
</tr>
<tr>
<td>Dry silica sand</td>
<td>&quot;dry_sand.dat&quot;</td>
</tr>
<tr>
<td>D.I. saturated silica sand</td>
<td>&quot;wet_sand.dat&quot;</td>
</tr>
</tbody>
</table>
APPENDIX G

CD_ROM DIRECTORY STRUCTURE

\thesis
  \word
  \pdf

\programs
  \collect
  \idl
  \network

\data
  \air
  \depth
  \ds
  \ds3
  \ds4
  \dpsps
  \free
  \iron
  \network
  \water
  \ws
  \ws3
  \ws4
  \ws6
  \wsbent
  \wsps

1 All *.doc files are Microsoft Office 97 Word version SR-2
2 All *.pdf files are Adobe Acrobat version 4.0
3 The IDL source code is for Version 5.2