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Field studies and scale modeling using cross-borehole electromagnetic diffraction probing

Goedecke, Walter B., M.S.
The University of Arizona, 1990
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FIELD STUDIES AND SCALE MODELING USING
CROSS-BOREHOLE ELECTROMAGNETIC DIFFRACTION PROBING

by
Walter Goedecke

A Thesis Submitted to the Faculty of
MINING AND GEOLOGICAL ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
With a Major in Geological Engineering
In the Graduate College
THE UNIVERSITY OF ARIZONA

1990
STATEMENT BY AUTHOR

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APPROVAL BY THESIS DIRECTOR

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Date 10/30/90
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Dedicated
to
Gus & Erika
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ABSTRACT

The scope of these studies encompasses both field site testing and scale modeling. The purpose was to better understand the complexities of electromagnetic diffraction geotomography, or the imaging of ground between boreholes using electromagnetic waves.

Two field sites and a scale model tank were investigated. One field site, the San Xavier Mine facility, is located in metamorphosed paleozoic limestone. This site proved a challenge in that the medium was fairly inhomogeneous and resulted in severe wave scattering. Inter-borehole transmission allowed only 15 MHz to penetrate for an adequate signal level. Both a parallel scan and geotomography of targets produced inconclusive results.

The Apache Leap site contained a homogeneous quartz-latite tuff, allowing penetration of 150 MHz. Parallel scans of a metal pipe target, proved that alterant geotomography, or scans performed before and after tracer injection, was a possibility for future studies.

The model tank allowed the use of horizontal dipole antennas, a coil substitute. Target effects produced strong interference patterns.
CHAPTER 1

GENERAL INTRODUCTION

The scope of these studies encompasses both field site testing and scale modeling. The purpose was to better understand the complexities of electromagnetic diffraction geotomography, or the imaging of ground between boreholes using electromagnetic waves.

This work is a continuation of the work done by Schulte (1989), in that it focuses more on the application of the setup than the equipment analysis. The techniques used for the ground-penetrating experiments were similar to what others have used, with some modifications to accommodate our setups and directed studies. The principal foundation of our studies were based upon those done at Lawrence Livermore Laboratories.

Their group has used both parallel scans and geotomography to investigate such things as medium characteristics (Lytle et al., 1974 and 1976), in-situ retorting fronts at an oil-shale facility (Daily, 1982 and 1984), and the use of alterant geotomography (Deadrick et al., 1982, Ramirez et al., 1982, Daily and Ramirez, 1984, Ramirez and Lytle, 1986, Ramirez and Daily, 1987 and 1989). The alterant geo-
tomography method compares an injected tracer to background in fractured rock by using geotomography both before and after injection.

In addition, their group has done studies on antenna characteristic determinations (Daily, 1982), and the inversion of geotomography data (Lager and Lytle, 1976, Dines and Lytle, 1979), using different approaches. Other groups have used modified straight-ray inversion algorithms that consider inversion ray-bending that normally accompanies multi-medium paths (Balanis et al., 1982).

The basic technique of determining the medium electrical characteristics came from Grubb and Wait (1971), and this technique is commonly used in all inter-borehole ground-probing projects.

Some groups such as Grubb et al. (1976) and Stolarczyk, (1988) have used vertically polarized magnetic dipoles (coils), with good results. The problem with coils is that they are generally restricted to low frequencies because of the inductive load. However, they have a horizontally polarized electric field and this interacts well with horizontal targets, and they are more compact than electric dipoles and approximate a point source better.

The antennas used for these studies are vertical electric dipoles, adjusted in length for the principle frequencies used at the three sites. Standard HF and VHF/UHF equipment was used for the setups, with some exceptions.
The signal originates on the surface and is sent down to the transmitter antenna to be received at the other antenna, then the received signal is processed on the surface. This setup is both simple and effective, without the complexity of attempting to fit the transmitter in the transmitting antenna, or processing the received signal down-hole immediately at the receiving antenna.

Studies were conducted at two field sites: the Apache Leap test site, and the San Xavier site. The Apache Leap site is in the Apache Leap tuff formation, and is located about 3 mi east of the town of Superior, Ariz. Several boreholes were drilled here for hydrogeological studies. Our studies here included the determination of the formation's electrical characteristics at both 150 and 15 MHz. Artificial targets were placed in boreholes and compared against background using the parallel scan techniques. The vertical electric dipole antenna was investigated to determine its electrical characteristics in this medium. The antenna lengths were optimized for a reasonable antenna pattern and reflection coefficient. The antenna voltage pattern as a function of vertical azimuth was plotted, and was shown to be fairly directive in the horizontal plane. The effects of electromagnetic wave propagation modes in a borehole were examined using both a ferrite-beaded cable and an unbeaded one. During inter-borehole scanning, it was noticed that the formation was heating, and subsequent tests were made on this effect.
The San Xavier facility is located about 20 mi SSW of Tucson, in overthrust metamorphosed paleozoic rock, primarily limestone. The rock-medium is fairly inhomogeneous and presented several problems to the ground penetrating radio waves. The site is on a well-developed facility that was once a silver and base metal underground mine. Several boreholes were drilled, and some straddle a mine drift that was used for target placement. The electrical properties of the medium have been examined. Some of the antenna properties were examined in great detail, such as optimum length, antenna reflection coefficients as a function of borehole depth, centered versus eccentric antennas in boreholes, and using same-diameter poles verses asymmetrical poles on the antennas. A parallel scan of the section including the mine drift was done.

Two geotomographies were done on the San Xavier site, one with a mine drift partially filled with water and an enclosed metal screen inside, and one without water or screen. Although a data error occurred during acquisition, and a direct comparison was questionable, the results did give useful information. Finally, a vertical copper pipe target was scanned in a borehole partially filled with brine.

The scale modeling was done in the Mines Building where the department is housed. The laboratory contained a stock tank that was filled with water, its conductivity variable by an acid-base balance system. The high permittivity of
water and resulting short wavelengths permitted small antennas and far-field experiments in the displacement current mode. Two types of antennas were used in the experiments, a horizontal electric dipole and a vertical electric dipole. The horizontal dipoles approximated the electric field polarization of vertically polarized coils. The vertical dipoles were similar to the antennas used at the field sites. Both antenna types were examined for voltage patterns, reflection coefficients, and transfer impedances. Parallel scans as well as geotomography were conducted on a simple copper pipe. The medium homogeneity permitted easy observation of tested characteristics.
CHAPTER 2

EQUIPMENT, SETUPS, AND TECHNIQUES

This chapter describes the pieces of equipment, configurations of equipment, and the techniques used in both data acquisition and processing for these ground penetrating radio wave experiments. Sufficient information is given to describe both the individual devices and integrated systems used so that one can both understand and build a similar system. This unit is divided into two sections: one equipment, and another on setups and techniques.

Equipment for these experiments was obtained thru some trial and error; but eventually the fully integrated system had most all the necessary components to perform the ground-penetrating studies. Similar equipment that others wishing to build a similar setup may have on hand should also work. The individual pieces of equipment are described so a comparison with other brands, makes, or styles can be made.

The setups and techniques used for these borehole projects and later for the model tank experiments were primarily to measure the two principle wave characteristics: attenuation and phase delay. From these the medium and
target characteristics such as conductivity and permittivity could be derived. Others attempting similar experiments need to do basically the same measurements; but variations on techniques do exist. For example, other types of antennas can be used, or the signal processing might be handled differently.

2.1 Equipment

2.1.1 Transmitters and Sources

2.1.1.1 Low-Power Signal Generator

For the antenna impedance measurements and the model tank transmitter, a low-power-output Hewlett Packard model 3200B VHF signal generator was used. Output power from this unit is a maximum of 200 mW for the high frequency (HF) range, 150 mW for the very high frequency (VHF) range, and 25 mW for ultra high frequency (UHF) range. Because the unit can output several bands of frequencies from 10 to 500 MHz., phase determination by swept-frequency is easily done. Although the output level is low, under one occasion circumstance it was used as a power transmitter for cross-hole transmission because of its wide frequency range.

2.1.1.2 High-Power Transmitters

A Yaesu Musen model FT-747GX 1.5 to 30 MHz. ham band transmitter was used for the HF experiments at the San Xavier site. The unit was altered to provide continuous fre-
quency output thru this range unlike its intended use for only the ham-bands. This feature permits the easy use of the swept-frequency method of total phase determination. Although the unit can output in several modulation styles, only the continuous wave mode is needed for these experiments. Output power from this unit is variable so only that level needed for an adequate transformation signal is used to avoid local heating.

For the VHF operations, a Yaesu Musen model FT-290RII 2 meter ham band transmitter was used. In general this unit operated well; but had two drawbacks: a fixed output power, and a small frequency range. Because the output is fixed at 25 Watts, formation heating occurred around the transmitting antenna at the Apache Leap site, changing the antenna impedance. Also, the limited frequency output range of 140-150 MHz. was a limitation for the swept-frequency method of phase determination, and a greater range would be more helpful.

At times a linear amplifier was used between the transmitter and the antenna to boost the signal, but for the most part amplification was done on the receiving end of the system.

2.1.2 Directional Couplers and Sampling Units

Because a sample of the transmitted signal sent to the antenna was needed for a reference, directional couplers
were placed in-line between the transmitter and the transmitting antenna. Two setup schemes were used, one for low-power-level impedance and model tank measurements, and high-power field site measurements.

Unlike the analysis done by Schulte (1989), who attempted to quantify the effects of finite coupler directivity, all directional couplers are assumed to have a large directivity so reverse wave coupling is assumed small.

2.1.2.1 Low-Power Units

For equipment measurement and calibration a Mini-Circuits model ZFCS-2-1 power splitter was used. This unit splits the signal power so each half is diverted to different ports. Power from the signal generator is applied to the source input of the splitter, and one output is input to the oscilloscope, while the other output is input to the unit under test, be it a cable or otherwise. The other end of the device under test is input to another channel of the oscilloscope, from where the gain and phase delay between the inputs can be determined. This is diagrammed and further described later under equipment calibration.

For small signal sampling in both the HF and VHF ranges, Mini-Circuit models ZFDC-20-3 and ZFDC-10-1 directional couplers sampled the forward and reflected waves respectively. A directional coupler permits low-power
sampling of a transmitted wave down a transmission line. Because the ZFDC-20-3 coupler response drops off in the UHF range, a ZFDC-10-2 coupler replaced it for the VHF/UHF model tank. Furthermore, at the higher frequencies this coupler has a high directivity.

2.1.2.2 High-Power Units

For the HF power measurements a Bird Electronic Corp. model 4266 directional coupler was used. The frequency range of this unit is 1.5 to 35 MHz. This unit permits both forward and reflected wave voltages to be monitored during transmission.

For the VHF power measurements a Bird model 4278-111-3 directional coupler was used. Its useful frequency range is 125-250 MHz. Unlike the other Bird coupler, this unit does not have a reflected wave output. Both of these Bird couplers have coupled outputs of 30 dB down from the sampled line, and the main-line insertion loss is small (<.05dB). The directivity is large enough (25dB) to assume a negligible reflected wave influence on the forward wave port.

A Bird model 4410A Thruline Wattmeter was used in some cases for amplitude only power measurements. Supplemental insertion modules permit a varied range of power sampling capabilities. This unit would free the oscilloscope by providing its own power readings.
2.1.3 Oscilloscopes

Two oscilloscopes were used for the signal processing and interpretation. The oscilloscope used for the majority of the San Xavier site investigations was a Tektronix model 2430A. This 150 MHz. scope permitted signal averaging (stacking) for up to 256 waveform sweeps, thus increasing signal-to-noise ratio up to a factor of $\sqrt{256}$. In addition, personal computer interfacing capability permitted fast data acquisition.

The newly acquired LeCroy Corp. model 9424 oscilloscope permitted higher resolution capabilities with its 350 MHz bandwidth input. It also permitted stacking of thousands of waveforms, along with expanded waveform analysis for the swept-frequency method. Communication with a personal computer should be possible; but was not used due to interfacing problems.

2.1.4 Amplifiers

The received signal levels were generally low, especially in the field. Because of this and the length of receiving antenna to receiver (oscilloscope) cable, down-hole amplifiers were needed to keep a high signal-to-noise ratio. Documented in this section are both the down-hole and surface amplifiers used.
2.1.4.1 Downhole Amplifiers

The amplifiers used to boost the receiving antenna signal are the ones that were designed and described by Schulte (1989). The only modification that I made to them are the replacement of the 10 μF tantalum DC blocking capacitors with 10 nF ceramics. The tantalum capacitors are not only polarized, necessitating the need to orient them to match the DC biases, but also inductive at higher frequencies. However, despite these components, the amplifiers have operated well even with the inductive coupling capacitors.

To help withstand the tension due to antenna and cable weight, I have also reinforced amplifiers 2, 3, and 4 by recasing them in stronger aluminum cases, and have put a stand-off inside running the entire length of the case for added strength.

The power for these amplifiers was relegated to downhole batteries once again for reasons of eliminating the possibility of RF leakage into the power inputs. We used about 12 to 14 NiCd AA batteries in two battery holders for a 14 Volts-plus source to keep above the series-pass 7812 regulator minimum voltage requirements. The battery holders were slender enough to fit inside the end of the receiving antenna's two inch diameter tubing, thus shielding them. The current drain of these 600 mA-hour batteries permitted operation for about 4 hours before
needing changing. Also, the use of small phono jacks connecting the battery pack to the amplifiers facilitated easy changing in the field.

2.1.4.2 Surface Amplifiers

At various times Mini-Circuit model ZHL-1-2W amplifiers were used to boost the received signal for the oscilloscope. These have a gain of 50 (29 dB), and the frequency range covers 5 to 500 MHz. Because the units have a relatively flat frequency response, the swept-frequency method is easily facilitated.

2.1.5 Filters

Most of the filters used for noise suppression during these experiments were the Mini-Circuits BLP series for the low-pass frequencies, and the BHP series for the high pass ones. These filters have a total drop-off of 40 dB per one octave. Placement of these filters were generally before the final surface amplifier.

For extra noise rejection, two bandpass filters were used in these experiments. For the 150 MHz experiments, one of the down-hole amplifiers has a bandpass filter in it. The other bandpass filter was used for the 15 MHz experiments at the San Xavier test site. With these exceptions, only combination high-pass and low-pass filters were used to permit some freedom in frequency selection. A wide selection of filters was useful for finding the maximum
frequency of medium penetration under certain circum-
stances. Furthermore, this variability of frequency per-
mitted the swept-frequency method to work, because no filter pole can be near the range of frequencies used for this method.

2.1.6 Antennas

The antennas used for the field sites were the same ones described by Schulte (1989). These are the so called insulated sleeve dipole antennas as described by King et al. (1981). Analysis done by them on this antenna was not to the extent as that of other studies of insulated dipoles embedded in a lossy medium. They found that the input impedance is variable by adjusting the individual pole lengths; but extensive studies concerning this were not done by us.

We would try to match the antenna length for optimum coupling to the transmission line by viewing the up-hole reflected verses forward wave voltages as sampled by the directional couplers, looking for a minimum. By inputting both the reflected and forward waves into the X and Y inputs of the oscilloscope a Lissajous ellipse pattern formed that optimally had a vertical major axis to a horizontal minor axis ratio that was large at the desired frequency. This way most of the power was being transferred to the medium. If the system frequency did not produce a desired reflection coefficient, the antenna-pole lengths
were adjusted and then tried again in the medium. The antenna lengths for each pole were always kept the same for symmetry. Once the length was set, it was never varied during the experiment.

Antenna Impedance Determination

Fig. 2.1-1. Setup used to determine the antenna length, impedance, and reflection coefficient in the field.

Because of medium coupling, the antenna must be centered in the borehole. Studies have been done of both
eccentrically placed (Lytle, 1974) and insulated antennas (King and Smith, 1981); but here the horizontal radiation field is kept circular to avoid this variable.

The 2 inch diameter pipe and tubing of the antenna permitted the down-hole amplifier batteries to be placed within, eliminating another potential scatterer. Because the main body of the antenna is 2 inch copper pipe, and the additions are 2 inch brass tubing, one will fit into the other since pipe is specified by an inside diameter and tubing by an outside diameter.

**Electric Dipole Sleeve Antenna**

---

**Electric Equivalent**

---

*Fig. 2.1-2.* These are diagrams of the sleeve dipole: the one constructed mostly of plumbing supplies used in the field, and the electrical equivalent.

The antennas used for the model tank were much simpler. The horizontal electric dipole antennas were constructed using 50 Ohm coaxial cable. These are diagrammed and further discussed in chapter 5.
2.1.7 Coaxial Cables

Two types of cable were used, RG-8 and RG-213. These cables have characteristic impedances of 52 and 50 Ohms respectively. Losses at cable connections were about .1 to .2 dB, relatively low compared to other system losses.

To prevent borehole electromagnetic wave modes, or energy reflected back from the antenna-cable mismatch to the surface by cable sheath to borehole wall guidance, the cable had ferrite beads placed irregularly about every foot. A description of this for our system was done by Schulte (1989).

The ferrite beads were also used by Lytle et al. (1975) for their geotomography setup. They placed beads for an interval above the sleeve dipole antennas to prevent both radiation and pickup for the transmitting and receiving antenna respectively. Grubb et al. (1976) used irregularly-placed ferrite choke cores for the same coupling minimisation due to shield currents. King et al. (1981) described the use of transverse metal discs placed every quarter-wavelength to short transverse electric fields between the cable shield and medium wall, thereby reducing shield currents near the antenna. Ramirez (1990), described the need to place ferrite beads end-on-end for an interval of 1 to 2 meters above the antenna for frequencies above 40 MHz, and that this interval was frequency dependent.
2.2 Setups and Techniques

2.2.1 General Data Acquisition Setups

2.2.1.1 Antenna Impedance and Reflection Coefficient Measurements

To compute the transmitting antenna input current, both the antenna's input voltage and impedance must be known. During medium probing experiments, the oscilloscope samples the transmitted downhole power (forward wave), and from this the transmitter antenna voltage can be calculated. Because the system's impedance is 50 Ohms and the antenna's impedance varies with the surrounding medium, the mismatch will reflect power back to the transmitter. This reflected power (reverse wave) must be sampled to understand what power is reflected back up the cable from the antenna, to know what power actually remains dissipated by the antenna. This procedure is done separately with the low-power signal generator and is described here.

Because the impedance of the antenna is medium dependent, this complex quantity can change with depth in the borehole setting so an impedance log must be made. However, if the medium is homogeneous, only one impedance value need be taken.

Referring to Figure 2.1-1, a signal is sent to the antenna and both the forward and reverse waves are sampled by the directional couplers. Because the reflected signal
is not attenuated very much, only a low-power generator need be used for this operation. As stated earlier, all the transmission lines and ports are 50 Ohms characteristic impedance.

An example is presented here. Assume that the sampled forward wave is input to channel 1 of the oscilloscope and the reverse wave to channel 2, and are indicated as $[CH1]$ and $[CH2]$; the bracket indicates a complex value consisting of a rms magnitude and a phase delay, or $[CH2] = |CH2| \angle \arg(CH2)$.

A convenient unit that has proved useful here for the phase delay is transit time in ns (nanoseconds). This is because the cables and other equipment have wave-propagating transit times relatively constant with respect to frequency, and as such, even large mis-adjustments of measuring frequency do not affect the values.

If the cables connecting the directional coupler's coupled ports to the oscilloscope's input channels are the same length, the cable effects will not matter, because both the forward and reflected waves are attenuated and delayed equally, and the ratio of the two is the same. However, if they are not the same length, the difference must be taken into account.

The reflection coefficient at the input port of the reverse directional coupler is designated as $\Gamma(0)$, where the 0 indicates zero length to the antenna. The forward
voltage from this point is affected by the travel thru the
mainlines of both couplers, then there is the coupling from
the forward coupler's input to coupled port. The reverse
(or reflected) wave must travel from the reverse coupler's
input port, and be sampled by the coupled port. The cou­
pled ports will then have a ratio equal to the oscillo­
scope's inputs. Putting all this in equation form:

\[
|\Gamma(0)| = \frac{|CH2|}{|CH1|} 10^{\frac{(C_{rev}+L_{for}+L_{rev}-C_{for})}{20}} (2.2.1.1-1)
\]

where, \( C_{for} \) = forward directional coupler's coupling (dB)
\( C_{rev} \) = reverse directional coupler's coupling (dB)
\( L_{for} \) = forward directional coupler's mainline loss (dB)
\( L_{rev} \) = reverse directional coupler's mainline loss (dB)

And for the delays:

\[
\angle\Gamma(0) = \angle CH2 - \angle CH1 - \angle C_{rev} + \angle D_{for} + \angle D_{rev} - \angle C_{for} (2.2.1.1-2)
\]

where, \( \angle C_{for} \) = forward directional coupler's coupling delay (ns)
\( \angle C_{rev} \) = reverse directional coupler's coupling delay (ns)
\( \angle D_{for} \) = forward directional coupler's mainline delay (ns)
\( \angle D_{rev} \) = reverse directional coupler's mainline delay (ns)

Now that both the forward and reflected wave voltages
are known at the antenna cable input point, the reflection
coefficient can be calculated. Let the complex voltage at
this point of the cable be:
\[ V = V^* + V^- \]  \hspace{1cm} (2.2.1.1-3)

where,  

- \( V^* \) = forward voltage  
- \( V^- \) = reverse voltage

By factoring out the forward voltage:

\[ V = V^* \left( 1 + \frac{V^-}{V^*} \right) = V^*[1 + \Gamma(0)] \]  \hspace{1cm} (2.2.1.1-4)

where,  

- \( \Gamma(0) \) = reflection coefficient at \( z = 0 \)

The reflection coefficient at the antenna is:

\[ \Gamma(\text{ant}) = [(\text{cable gain})^2 \angle (-2 \cdot \text{cable delay})] \Gamma(0) \]  \hspace{1cm} (2.2.1.1-5)

This indicates that the forward wave will be attenuated and delayed by the cable traveling down to the antenna, but the reverse wave is attenuated and delayed already by the cable when sampled at the couplers. From the reflection coefficient, the antenna impedance is:

\[ Z(\text{ant}) = Z_0 \frac{1 + \Gamma(\text{ant})}{1 - \Gamma(\text{ant})} \]  \hspace{1cm} (2.2.1.1-6)

where,  

- \( Z_0 \) = system impedance = 50 Ohms

Consider the specific example using the Mini-Circuit directional couplers ZFDC-20-3 and ZFDC-10-1 for the forward and reverse wave sampling and a typical length of cable used in the field. The coupler specifications for
this example are listed below. A typical cable length used between the antenna and the couplers is 20.3 meters, with a gain of .761 and delay of 50.88 ns.

<table>
<thead>
<tr>
<th>Directional Coupler</th>
<th>Coupling (dB)</th>
<th>Coupling Delay (degrees)</th>
<th>Insertion Loss (dB)</th>
<th>Insertion Delay (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZDFC-20-3</td>
<td>10.4</td>
<td>180</td>
<td>.78</td>
<td>0</td>
</tr>
<tr>
<td>ZDFC-10-1</td>
<td>19.4</td>
<td>180</td>
<td>.18</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2-1. Directional couplers used in example.

Then, using Equation 2.2.1.1-1 and 2.2.1.1-2, the reflection coefficient magnitude and phase at \( z = 0 \) is:

\[
|\Gamma(0)| = \frac{|CH2|}{|CH1|} 10^{(10.4+180+0.78-19.4)/20} = 0.396 \frac{|CH2|}{|CH1|}
\]

\[
\angle \Gamma(0) = \angle CH2 - \angle CH1 - 180^\circ + 0^\circ + 0^\circ - 180^\circ = \angle CH2 - \angle CH1
\]

Finally, the reflection coefficient at the antenna is:

\[
\Gamma(ant) = .761^\circ \angle (-2*50.88\text{ns}) \times 0.396 \frac{[CH2]}{[CH1]} - 0.684^\circ - 101.76\text{ns} \times \frac{[CH2]}{[CH1]}
\]

Using the oscilloscope values of:

\[
\frac{[CH2]}{[CH1]} = \frac{18.9mV \angle 200.00\text{ns}}{23.0mV \angle 0\text{ns}} = 0.822^\circ \angle 200.00\text{ns}
\]

The antenna reflection coefficient then is:
\[ \Gamma(\text{ant}) = 0.684 \angle -101.76 \text{ns} \times 0.822 \angle 103.62 \text{ns} = 0.562 \angle 1.85 \text{ns} = 0.562 \angle 99.9^\circ = -0.0966 + j0.5536 \]

2.2.1.2 Inter-Antenna Transmission

This section describes the medium probing experiments, or transmission between the two antennas. Referring to the diagram, the antennas are placed either down the borehole or into the solution of the model tank. As in the antenna impedance diagram, the transmitter antenna is powered, but here by a higher power source. The directional coupler must handle more power, but only in the forward direction; the reverse power need not be known, because the antenna impedance is determined separately. The reverse power can be monitored to see if the formation is heating or changing, if the directional coupler has a reverse power port in addition to the forward one. The signal then continues on to the transmitting antenna.
Equipment Set-up for Transmitted Wave Experiments

The field radiates thru the formation and the receiving antenna intercepts this at the other hole. The field induces a voltage at the antenna and this is amplified right above the antenna by the down-hole amplifiers. The signal continues up thru the amplifiers and filters to the oscilloscope (usually Ch2). The received signal is compared to the sampled transmitted one, and the attenuation (or gain) and phase delay of both the system and medium can be obtained.
To characterize the transmitted wave, consider the expression of the vertical electric field that propagates in the far field:

\[ E_z(r) = \frac{I\gamma^2}{4\pi r} G_T f_T(\theta) \ e^{-\gamma r/\omega t} \quad (2.2.1.2-1) \]

where,

\[ I = \text{antenna current} \]
\[ \gamma = \text{complex propagation constant} \]
\[ \omega = \text{radian frequency} \]
\[ G_T = \text{antenna gain} \]
\[ f_T(\theta) = \text{transmitter pattern factor dependent on vertical azimuth} \]

This radiation pattern is a measure of the directional radiation field with respect to the vertical azimuth. For an electric dipole as the one used here, each small segment that makes up the entire dipole radiates a field that interferes collectively with all the other segments to cause preferential lobes in certain directions (Collin, 1969).

The antenna gain is the directivity with the influence of efficiency. The directivity is the field density in a direction relative to that which an isotropic source radiates. In a lossy medium the energy input to the antenna is not all radiated, some is lost to formation heating. Antenna gain is the field density in a direction relative to the antenna input power.
Because both transmitting and receiving antennas are always used as a pair, the pattern factor, gain, and other constants are lumped with the receiving antenna factors when transfer-impedances are determined.

Referring back to Figure 2.2-1, the voltage that is input to the oscilloscope, say channel 1, is the coupled forward wave potential from the forward directional coupler thru the short inter-connecting cable. This sampled voltage is a small fraction of that appearing at the output of the coupler. Expressing this complex output potential:

(2.2.1.2-2)

Directional coupler's output forward voltage = $V'(0) = 10^{(L_c + C_{\text{Short Cable Loss (dB)})}/20 \angle (-\text{Short Cable Delay (ns)} - C_{\text{delay}} + D_i)}$ [CH1]

where,

- $C$ = directional coupler's coupling (dB)
- $C_{\text{delay}}$ = directional coupler's delay (ns)
- $L_c$ = directional coupler's mainline loss (dB)
- $D_i$ = directional coupler's mainline delay (ns)

The channel 1 voltage is compensated by the short cable length to obtain the coupled forward voltage. Then the coupler output voltage is calculated from the coupled voltage, the coupler's coupling factor, and the mainline characteristics. This voltage is now the input to the cable feeding the transmitting antenna. The transmitting antenna's forward voltage is:
\[ V'(ant) = (\text{Cable Gain}) (\text{Cable Phase}) V'(0) \quad (2.2.1.2-3) \]

where, \( V'(0) \) = antenna cable input voltage at coupler's output

The total antenna voltage is now (from the previous eq.):

\[ V(ant) = V'(ant) * V'(ant) = V'(ant) [1 + \Gamma(ant)] = (2.2.1.2-4) \]

\( (\text{Cable Gain}) (\text{Cable Phase}) V'(0) [1 + \Gamma(ant)] \)

To obtain the transmitting antenna current:

\[ I(ant) = \frac{V(ant)}{Z(ant)} = (2.2.1.2-5) \]

\[ V'(ant) [1 + \Gamma(ant)] \]

\[ \frac{Z_0 [1 + \Gamma(ant)]}{Z_0 [1 - \Gamma(ant)]} \]

\( (\text{Cable Gain})(\text{Cable Phase}) V'(0) Y_0 [1 - \Gamma(ant)] \) \quad (2.2.1.2-6)

where, \( Z_0 \) = characteristic impedance of system = 50\( Z^0 \) \( \Omega \)

\( Y_0 = \frac{1}{Z_0} \) = characteristic admittance of system = 0.02\( Z^0 \) Siemans

Next, the receiver antenna voltage induced by the electric field is:

\[ V(\text{rec}) = A(R) f_\theta(\theta) E_s(ant) \quad (2.2.1.2-7) \]

where, \( A(R) \) = effective aperture of receiving antenna

\( f_\theta(\theta) \) = receiving antenna pattern factor dependent on vertical azimuth

\( E_s(ant) \) = vertical electric field at receiving antenna
The effective aperture of the antenna can be considered as an effective antenna length that induces a potential from the intercepted electric field (Collin, 1969). The pattern factor is similar to the transmitting pattern factor, it is a measure of the vertical azimuth-dependent receiving ability.

The complex receiving antenna voltage as a function of the potential measured at the oscilloscope, say channel 2, is:

\[
V(\text{rec}) = 10^{\left( \frac{\text{Factors (dB)}}{2} \right) + \left( \frac{\text{Delays (ns)}}{20} \right)} \cdot \left[ \text{Cable Delays (ns)} - \sum D_i - \sum D_i \right] \quad \text{[CH2]}
\]

(2.2.1.2-8)

Where,

- \( L_F \) = filter loss (dB)
- \( D_F \) = filter delay (ns)
- \( G_A \) = amplifier gain (dB)
- \( D_A \) = amplifier delay (ns)

This voltage is determined by compensation for all the filters, cables, and amplifiers between the antenna and the oscilloscope. The channel 2 voltage is multiplied by each component's attenuation (or divided by the component gains), and all the component delays are subtracted from the delay of the received signal. This gives the total antenna voltage.

From this information, the trans-medium impedance (ratio of received voltage to transmitted current), otherwise
known as the transfer-impedance, can be calculated. Consider the following numerical example from Figure 2.2-1. The equipment used for this is tabulated below:

<table>
<thead>
<tr>
<th>Device</th>
<th>Gain (dB)</th>
<th>Loss (dB)</th>
<th>Delay (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bird Directional Coupler:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mainline</td>
<td>0</td>
<td>0</td>
<td>1.40</td>
</tr>
<tr>
<td>Coupled</td>
<td>-29.6</td>
<td>29.6</td>
<td>-.55</td>
</tr>
<tr>
<td>150 MHz Low Pass Filter</td>
<td>-1.5</td>
<td>1.5</td>
<td>3.05</td>
</tr>
<tr>
<td>150 MHz High Pass Filter</td>
<td>-1.5</td>
<td>1.5</td>
<td>2.47</td>
</tr>
<tr>
<td>Mini-Circuits Amplifier</td>
<td>35.3</td>
<td>-35.3</td>
<td>6.11</td>
</tr>
<tr>
<td>Down-hole Amplifiers:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>28.3</td>
<td>-28.3</td>
<td>.89</td>
</tr>
<tr>
<td>#4</td>
<td>8.3</td>
<td>-8.3</td>
<td>5.28</td>
</tr>
<tr>
<td>Coupler to CH1 Cable</td>
<td>- .17</td>
<td>.17</td>
<td>10.84</td>
</tr>
<tr>
<td>Coupler to Antenna Cables</td>
<td>-9.26</td>
<td>9.26</td>
<td>318.80</td>
</tr>
<tr>
<td>Antenna to CH2 Cables</td>
<td>-7.80</td>
<td>7.80</td>
<td>61.37</td>
</tr>
</tbody>
</table>

Table 2-2. List of equipment used in numerical example.
Using Table 2-2 and Equations 2.2.1.2-5 and 6:

Directional coupler's output forward voltage =

\[ V'(0) = 10^{(0.296 + .17) \frac{dB}{20}} \angle(-10.84ns - .55ns - 1.40ns) \] [CH1] = 30.8\angle - 11.69ns [CH1]

\[ I(\text{ant}) = \frac{V(\text{ant})}{Z(\text{ant})} = \] (2.2.1.2-5)

\[ \frac{V'(\text{ant}) [1 + \Gamma(\text{ant})]}{Z_0 \frac{1 + \Gamma(\text{ant})}{1 - \Gamma(\text{ant})}} = \]

(Cable Gain)\angle(Cable Phase) \[ V'(0) \] \[ Y_0 \left[ 1 - \Gamma(\text{ant}) \right] = \] (2.2.1.2-6)

\[ 10^{-9.26 \frac{dB}{20}} \angle 318.80ns \cdot 30.8\angle - 11.69ns \cdot 0.02Si \cdot (1 + 0.0966 - j.5536) = \]

\[ .212\angle 307.11ns \cdot 1.228\angle - .496ns [\text{CH1}] \]

\[ .260\angle 306.61ns [\text{CH1}] \text{ Amps} \]

\[ V(\text{rec}) = 10^{[\text{Cable Loss} + (\Sigma \epsilon_1 + \Sigma \epsilon_2)]/20} \angle[-\text{Cable Delays} + \Sigma D_F - \Sigma D_A] \] [CH2] =

\[ 10^{(.80 + .1.50 + 35.3 + 28.3 + 8.39.28) \frac{dB}{20}} \angle(-1.37 - 3.05 - 2.47 - 6.11 - 0.89 \cdot 5.28)ns \] [CH2] =

\[ 10^{-61.10 \frac{dB}{20}} \angle -79.17ns \] [CH2] =

\[ .881 \cdot 10^{-2} \angle -79.17ns \] [CH2]

To obtain the transfer impedance of the medium, the received antenna voltage is divided by the transmitted antenna current:
2.2.1.2 Calibration of System

To remove the effects of the equipment electrical characteristics from the medium measurements, the gains (or attenuations) and the phase delays of the individual and/or combined components must be determined. Referring to Figure 2.2-2, this was generally done by inputting the signal generator into the splitter and directing one of the outputs into Ch1 of the oscilloscope. The other output went thru the unit under test, and then into Ch2 of the oscilloscope. Both the gain and delay can then be determined, and then applied for adjustments to the medium measurements.

\[
Z_{\text{transfer}} = \frac{V_{\text{received(ant)}}}{I_{\text{transmitted(ant)}}} = (2.2.1.2-7)
\]

\[
\frac{.881 \times 10^{-3} \angle -79.17 \text{ns}}{.260 \angle 306.61 \text{ns}} \frac{\text{[CH2]}}{\text{[CH1]}} \frac{V}{\text{Amps}} =
\]

\[
\frac{.00339 \angle -385.78 \text{ns}}{\text{[CH2]}} \frac{\text{[CH2]}}{\text{[CH1]}}
\]

Inserting the following typical values of both channel 1 and 2:

\[
Z_{\text{transfer}} = .00339 \angle -385.78 \text{ns} \quad \frac{63.3mV \angle 416.20 \text{ns}}{1.092A \angle 0} = 196\mu\text{Ohms} \angle 30.42 \text{ns}
\]

This is the transfer impedance encompassing both the antenna characteristics and the medium.

2.2.2 Calibration of System

To remove the effects of the equipment electrical characteristics from the medium measurements, the gains (or attenuations) and the phase delays of the individual and/or combined components must be determined. Referring to Figure 2.2-2, this was generally done by inputting the signal generator into the splitter and directing one of the outputs into Ch1 of the oscilloscope. The other output went thru the unit under test, and then into Ch2 of the oscilloscope. Both the gain and delay can then be determined, and then applied for adjustments to the medium measurements.
2.2.2.1 Swept-Frequency Technique to Determine System Phase

This is a variation of the method used by Lytle et al. (1973) in their geotomography work. To determine the total phase delay that a system of equipment and/or medium presents to a propagating wave, the frequency is varied with a resulting change of phase. With Lytle (1973), the dielectric constant is determined by:
\[ \epsilon_k = \frac{c^2}{(\omega_2 - \omega_1)^2} \frac{(\Delta \Phi)^2}{R^2} \]  
(2.2.2-1)

where,

- \( \epsilon_k \) = dielectric constant
- \( c \) = velocity of light in free space
- \( \Delta \Phi \) = change of phase
- \( \omega \) = radian frequency
- \( R \) = propagation distance

This is a solution of \( \epsilon_k \) from the difference of the following two equations:

\[ \frac{\sqrt{\epsilon_k} R \omega_2}{c} = \Phi_2 \]  
(2.2.2-2)

\[ \frac{\sqrt{\epsilon_k} R \omega_1}{c} = \Phi_1 \]  
(2.2.2-3)

This means that for a given frequency of a wave propagating thru a medium of distance \( R \), there will be a certain phase, and a change of frequency will give another value of phase. This equation will determine the relative permittivity approximately, but only if the wave travels thru just the medium. Referring back to the diagrammed system Figure 2.2-1, the wave must travel thru the following: the directional couplers, the antenna feed cable, radiate from the transmitter antenna, thru the medium, be received by the receiver antenna, up the antenna cable, the amplifiers,
and filters, and finally to Ch2 of the oscilloscope. The total phase thru this system is affected not only by the medium, but by the equipment.

The technique derived determines the total phase thru the whole system, then this phase can be adjusted to yield the antenna and medium phase delay by subtracting the equipment phase characteristics. Then from this information the electrical constants can be deduced.

Referring to the waveform diagram, Figure 2.2-3, assume the sampled transmitted wave is input to channel 1 (Ch1) of the oscilloscope, the upper trace, and the received signal is inputted to Ch2, the lower trace. For this example, assume that both the signal generator is set to the frequency under test, \( f_0 \), and the trigger is set on the peak of the marked trace, at \( t = 0 \). This peak represents the input of a train of waves into the system.
Fig. 2.2-3. These two sets of waveforms illustrate the display on the oscilloscope of a wave both entering and exiting a unit under test at two different frequencies. Note the waveform crests fixed at both $t=0$ for channel 1 and at $t=t_{\text{trans}}$ for channel 2, and the result of $t_1 > t_0$ and $u_1 < u_0$ when the frequency is increased from $f_0$ to $f_1$.

With the time-base properly set, some corresponding peak exists on the lower trace that represents the emerging wave from the system under test. This emerging wave peak is marked by the vertical line, at $t=t_{\text{trans}}$ which represents the transit time for the wave to propagate thru the system.
This time, however, is not known and is to be sought. The delay observed on the oscilloscope at only one frequency is $\Delta t + nT$, or the delay between adjacent peaks plus an unknown number of periods.

Picking an arbitrary point on the oscilloscope, say at $t = t_0$ let $u_0$ be defined as:

$$u_0 = t_{\text{trans}} - t_0 \quad (2.2.2-4)$$

This is the time from the picked point to the emerging wave peak. For simplicity this point is on a peak of the received waveform. Referring to the second diagram, the signal generator's frequency is increased to $f_1$. The position of both $t = 0$ and the peak of the first waveform does not move, but the rest of the upper wave is compressed about this trigger point. If the frequency was lowered the waveform would expand about this point. The increase of frequency causes the lower trace to compress about the emerging peak, because this represents the trigger point delayed by the system transit time under test. So the lower trace is an attenuated replica of the upper trace delayed by $t_{\text{trans}}$.

Noting the position of the picked transmitted waveform peak, let the time from $t = 0$ to this new position be $t_1$ for the higher frequency. Then the time from this point to the emerging wave on the lower trace is $u_1$, expressed as:

$$u_1 = t_{\text{trans}} - t_1 \quad (2.2.2-5)$$
With the increase of frequency, \( t_1 > t_0 \) and \( u_1 < u_0 \). From both Equations 2.2.2-4 & 5, \( t_{\text{trans}} \) can be expressed as

\[
t_{\text{trans}} = u_0 + t_0 = u_1 + t_1 \quad (2.2.2-6)
\]

The variable \( u_m \) represents the time of \( m \) periods between the picked point and the emerging wave peak on the second trace, Ch2, so:

\[
m = \frac{u_m}{T_m} = u_m f_m
\]

or,

\[
u_o f_o = u_1 f_1 \quad (2.2.2-7)
\]

where,

- \( T_m \) = period at frequency \( m \)
- \( f_m \) = frequency \( m \)

With this and equation 14, both \( u_0 \) and \( u_1 \) can be eliminated. Continuing by substitution:

\[
u_1 = u_0 \frac{f_o}{f_1} \quad (2.2.2-8)
\]

\[
u_o = \frac{t_1 - t_0}{1 - \frac{t_0}{t_1}} \quad (2.2.2-9)
\]

Then by Equations 2.2.2-6 & 2.2.2-9,

\[
t_{\text{trans}} = f_1 \frac{\Delta t}{\Delta f} + t_0 \quad (2.2.2-10)
\]

where,

- \( \Delta t = t_1 - t_0 \)
- \( \Delta f = f_1 - f_0 \)
This is the transit time from Ch1 to Ch2, or the time for a signal to go thru the system. The phase in degrees can then be calculated by multiplying this time with the test frequency and then by 360 degrees.

A visual application of this phase determination technique is to observe the oscilloscope as either the frequency increases or decreases. The waveform on Ch2 will either compress or collapse on the emerging point respectively. An oscilloscope that has a delaying sweep or waveform expansion capabilities greatly facilitates this.

Errors are introduced by the fact that the trigger point is usually not on a peak; however, it can be made just before it. The trigger must be at \( t=0 \) for the equation to work. Also, the greater the transit time thru the system (equipment + medium) with respect to the period, the greater the error in determining the transit time. This results from the large change of phase when the frequency is changed. This drawback means that the total phase of the system will be more difficult to find if the test wavelength is much less than the system length, as is often the case with high-frequency measurements in deep boreholes. Usually, as in the case of inter-antenna transmission between boreholes, only one or two total phase measurements using the swept-frequency technique needs be taken for control. Adjacent single-frequency phase measurements taken within a small increment of the wavelength are a safe way to keep track of the number of whole wavelengths.
One other difficulty using this method, either by application of the equation or by the visual technique, arises when there are filter or amplifier poles near the test frequencies. The phase shifts caused by the poles are large, and hard to predict. For our system we have a large supply of filters so that during the swept-frequency method some filters can still be used to remove noise at higher or lower frequencies than those being swept thru.

Generally, only the whole number of wavelengths thru the system (or number of periods in the transit time) need be sought during the swept-frequency method; the accurate fractional wavelength (or period) can be determined at the center frequency \( f(0) \) with all the filters re-inserted.

2.2.3 Medium Probing Configurations

2.2.3.1 Differential Method of Medium Characteristics Determination

Medium electrical characteristics are determined by the technique used by Grubb & Wait (1971). This method assumes the predominance of displacement currents over conduction currents. Referring to Figure 2.2-4, three colinear boreholes, or antenna positions are used. One position is for the transmitting antenna, and the other two are for the receiving antenna for two separate operations. All antenna positions are also colinear, but the vertical azimuthal angle need not be 90 degrees.
For the two operations, the transmitting antenna remains in the same place, which is an end location. However, the receiving antenna is repositioned for each operation, one in the middle location, and then to the other's end position. Both system gain and delay are recorded for each operation. The difference of gains and delays between the two operations are the result of the wave propagation thru extra medium, not by the equipment nor by the antennas, assuming far-field factors are in play. An expression of this is as follows:
\[
\frac{V_{\text{recv}}(r_2)/V_{\text{trans}}(r_2)}{V_{\text{recv}}(r_1)/V_{\text{trans}}(r_1)} = \frac{r_1}{r_2} e^{-(\gamma(r_2-r_1)-j\omega t)} \tag{2.2.3.1-1}
\]

where, \( r_m \) = receiver distance with respect to transmitter

\( m = 1 \) is middle

\( m = 2 \) is end

\[ V_{\text{recv}}(r_m) = \text{Receiving Voltage at } r_m \]

\[ V_{\text{trans}}(r_m) = \text{Transmitting Voltage at } r_m \]

and \( \gamma = \text{propagation constant} = \tag{2.2.3.1-2} \]

\[ \alpha + j\beta = \sqrt{j\omega \mu_0 (\sigma + j\omega \varepsilon)} \]

where, \( \omega = \text{radian frequency} \)

\( \mu_0 = \text{permeability of free space} = 4\pi \cdot 10^{-7} \text{ H/m} \)

\( \sigma = \text{medium conductivity} \)

\( \varepsilon = \text{permittivity of medium} \)

The sampled transmitting voltages are included to compensate for transmitter drift. The attenuation constant \( \alpha \), phase constant \( \beta \), and wavelength \( \lambda \), can be determined as follows:

\[ \alpha = -\frac{1}{r_2-r_1} \ln \left( \frac{r_2}{r_1} G_m \right) \tag{2.2.3.1-3} \]

where, \( G_m = \text{medium gain thru distance } r_2-r_1 = \)

\[ \left| \frac{V_{\text{recv}}(r_2)/V_{\text{trans}}(r_2)}{V_{\text{recv}}(r_1)/V_{\text{trans}}(r_1)} \right| \]
\[ \beta = \frac{t_m \omega}{r_2 - r_1} \quad (2.2.3.1-4) \]

where \( t_m \) = medium phase delay time thru distance \( r_2 - r_1 \) =

\[ [\text{Delay}_{rec}(r_2) - \text{Delay}_{trans}(r_2)] - [\text{Delay}_{rec}(r_1) - \text{Delay}_{trans}(r_1)] \]

\[ \lambda (\text{meters/cycle}) = \frac{2\pi}{\beta} \quad (2.2.3.1-5) \]

The medium attenuation can be expressed as the attenuation of a plane wave propagating thru the medium in dB as:

\[ \text{Atten. (dB/m)} = 20 \log_e \left( \frac{e^r}{r} \right) = 8.686\alpha \quad (2.2.3.1-6) \]

Once these medium-dependent wave characteristics are known, the conductivity, permittivity, and relative permittivity can be calculated:

\[ \sigma (\text{Si/m}) = \frac{2\beta \alpha}{\omega \mu_0} \quad (2.2.3.1-7) \]

\[ \epsilon = \frac{\beta^2 - \alpha^2}{\omega^2 \mu_0} \quad (2.2.3.1-8) \]

relative permittivity = \( \epsilon_r = \frac{\epsilon}{\epsilon_0} = (2.2.3.1-9) \)

\[ \frac{c^2}{\omega^2 (\beta^2 - \alpha^2)} = \frac{\beta^2 - \alpha^2}{\beta_0^2} \]

where, \( \epsilon_0 = 8.85 \cdot 10^{-12} \), the permittivity of free space

\[ c = \text{velocity of light in free space} \]

\[ \beta_0 = \text{phase constant in free space} \]
2.2.3.2 Antenna Characteristics Determination

The received antenna voltage as a function of the transmitted antenna current, assuming far-field effects, is, by combining Equations 2.2.1.2-1 and 2.2.1.2-7:

\[ V_{reco}(r) = \frac{I \gamma^2}{4\pi r} A_R f(\theta) G_T e^{-\gamma r + i\omega t} \quad (2.2.3.2-1) \]

where:
- \( I \) = transmitting antenna current
- \( \gamma \) = propagation constant
- \( A_R \) = effective aperture of receiving antenna
- \( G_T \) = directional gain of transmitting antenna
- \( f(\theta) \) = combined receiving & transmitting antenna pattern factors dependent on vertical azimuth

By using the previously described difference method to determine the medium characteristics, and with the transfer impedance known, the factor \( f(\theta) G_T A_R \) can be calculated.

Rearranging terms:

\[ \frac{\gamma^2}{4\pi} A_R f(\theta) G_T e^{i\omega t} = Z_{transfer} e^{i\gamma r} \quad (2.2.3.2-2) \]

where
- \( Z_{transfer} = \frac{V_{reco}}{I_{transmitted}} \)

The factor on the left has the dimensions of resistivity (Ohm-m) for a spherically diverging wave, and is what generally was plotted for the antenna pattern factor. The antenna characteristic determination assumes a homogeneous
medium and far-field approximations; if they are at least two wavelengths apart this holds well (electrical length = $4\pi = 12.6$), to within 90%. There is also a transmitting antenna current distribution; but since this is not known in the medium, the antenna input current along with the directional gain and pattern factor model the radiation well (Lytle, 1974).

2.2.3.3 Parallel Scanning to Determine Geology and Target Characteristics

A very useful and quick cross-borehole technique is to put the antennas at the same depth and move them together, so the geometry does not change. This was done many times by Lytle et al. (1976, 1979, and Davis et al., 1979). Geology can quickly be determined, and if there are three colinear boreholes the medium electrical characteristics with respect to depth are easily found (Lytle, 1976). A target can quickly be detected by plotting the ratio of received voltage to sampled transmitted voltage in the field with no further data processing.

2.2.3.4 Geotomography

The mechanics of geotomography are shown in Figure 2.2-5. There are various transmitter locations, and for each one there are a suite of receiver locations. This configuration scans the area to be imaged by many ray-paths. Both the transmitter and receiver locations are chosen to resolve the target sufficiently with the
wavelength used. The area to be imaged between the boreholes is divided into areas called patches. These patches are characterized by the receiver-transmitter paths.

The procedure for the geotomographic scans done with intent to invert using the volume current method (Howard et al., 1983, 1986) is to place the transmitter antenna at intervals in one of the boreholes, and for each transmitter antenna position move the receiver antenna in the other borehole. Both transmitted wave attenuation and phase are recorded for each position of transmitter-receiver antenna-pair.

Once this is done the data is processed normally to obtain the transfer-impedances of both the antenna-pair and medium. This is then inverted for a reconstruction of the image plane.
Fig. 2.2-5. Transmitter-to-receiver antenna raypaths for geotomography in a homogeneous ground, or with no refraction. Shown are 3 transmitter locations and 11 receiver positions.
CHAPTER 3

APACHE LEAP TEST SITE

3.1 Introduction

The Apache Leap test site is located about 3 miles east of Superior, Arizona (see Figure 3.1). This site has rocks similar to that at the proposed Yucca Mountain waste repository test site in Nevada, and it serves as a convenient field laboratory to examine jointing and test ground water flow. There are many boreholes drilled into the test site for the various studies. We are using the site to test the ground-probing system in an environment that is both homogeneous and supportive of wave propagation.

Four field trips were made to the site: the first during the summer of 1989 with Joe Schulte, Ben Sternberg, Karl Glass, and Mike Sully. Inter-borehole transmission of 150 MHz was successfully tested. For the remaining trips Dave Droge accompanied me. The second trip on the 17th and 18th of Feb., 1990, we chose an antenna length, characterized the antenna pattern, logged borehole impedance, and used the parallel scan technique to look at simple targets. The third trip made on the 3rd and 4th of March, we looked at another target and verified previous findings; but were unfortunate enough to have some equipment fail. The last
trip, made from the 1st to the 3rd of June, we examined the medium electrical characteristics at both 15 and 150 MHz, examined a larger target, investigated medium heating due to the transmitter antenna, and then looked at borehole modes.

Fig. 3.1-1. Geophysical test site on the Apache Leap tuff formation, approximately 3 mi E of the town of Superior.
Fig. 3.1-2. Looking NW over test site. The medium probing operation is on the black plastic. The light buff-colored rock is the Apache Leap tuff. The Magma Copper Company operates the shaft in the background; this penetrates thru the volcanics to the Martin and Escabrosa limestones.
Fig. 3.1-3. Antenna probing setup at test site. Boreholes V-1 and V-3 are under left and right reels, with Dave Droege holding the stranded target over borehole V-2, with the transmitter trailer directly behind. The receiving truck is to the right.
3.2 Geology

The test site is on a simple-cooled ash flow sheet of nearly 2,000 feet thick (Peterson, 1969), deposited about 20,000,000 years ago (Miocene). The ash-flow sheet is divided into five zones classified by the degree of welding: lower nonwelded, lower partly welded, densely welded, upper partly welded, and upper nonwelded. The site is on the top unit, also called the white unit.

The rock at the test site is an altered poorly-welded quartz-latite porphyry tuff in an aphanitic ground mass. It has a light gray to white color when fresh, and weathers brown to reddish gray, due to the decomposing biotite. Composition of this part of the Apache Leap unit is plagioclase feldspar, quartz, biotite, sanadine, and some oxides. The altered products are chlorite replacing biotite, and more oxides. Vapor-phase crystallization, or the deposition of cooling vapor material from lower units as they cooled, has reduced pore spaces to make the rock fairly impermeable. There are however many vertical fractures from subsequent orogenies, and perhaps from cooling.

3.3 Borehole Setups

The borehole configurations used for our test are shown in Figure 3.3, the V and Z-series. The V-series are three colinear boreholes spaced every 3 meters. The Z-series boreholes are colinear also; however they dip to the east
by 45 degrees. The horizontal spacing for these are 10 meters, and the perpendicular inter-borehole separation distance is 7.1 meters.

Apache Leap Boreholes

V-Series Boreholes

Z-Series Boreholes

Fig. 3.3. V and Z-Borehole series used at the test site.

3.4 Medium Electrical Characteristics

The electrical characteristics at both 15 and 150 MHz were determined by the co-linear three-hole difference method. Results for all the medium tests are tabulated here. Referring to Figure 2.2.3.1, the transmitting antenna is placed down an end borehole, and the receiver
antenna is placed down to the appropriate spots in the remaining two boreholes for each of the two sets of transmission readings.

15 MHz wave propagation characteristics were taken at both Z and V-series boreholes. In the Z-series, the transmitting antenna was placed down Z1 at 10 m depth, and the receiving antenna was placed at each of the depicted spots in Z2 and Z3, perpendicular to the borehole axes from the transmitting antenna. Antennas were placed deep to keep the surface reflection low, and a later calculation for the transmitting antenna depth at 9.7 m was 2.6 skin depths at 15 MHz.

Both 15 and 150 MHz tests were done on the V-series boreholes. The transmitting antenna position was in V1, and the receiving positions were in both V2 and V3.

<table>
<thead>
<tr>
<th>Date</th>
<th>Hole</th>
<th>Freq. (MHz)</th>
<th>α (1/m)</th>
<th>β (1/m)</th>
<th>Plane Wave Atten. (dB/m)</th>
<th>λ (m)</th>
<th>σ (mS/m)</th>
<th>ρ (Ωm)</th>
<th>ε₀</th>
<th>ε₀/ωε (s s/F)</th>
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<td>V</td>
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<td>8.73</td>
<td>5.85</td>
<td>.719</td>
<td>9.93</td>
<td>100.7</td>
<td>7.68</td>
<td>.155</td>
</tr>
<tr>
<td>6/1</td>
<td>Z</td>
<td>15</td>
<td>.394</td>
<td>1.12</td>
<td>3.42</td>
<td>5.60</td>
<td>7.47</td>
<td>133.9</td>
<td>11.2</td>
<td>.800</td>
</tr>
<tr>
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<td>.346</td>
<td>1.18</td>
<td>3.01</td>
<td>5.32</td>
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<td>.643</td>
</tr>
<tr>
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<td>7.72</td>
<td>129.6</td>
<td>7.69</td>
<td>.120</td>
</tr>
</tbody>
</table>

Table 3. Electrical characteristics for Apache Leap site.

Both transmitting and receiving antenna lengths for the 150 MHz medium tests were 1.14 m; however, because the directional gain and receiving aperture were so small for
the 15 MHz. tests, the lengths had to be increased to about 3 m. When the antenna lengths are large compared to the distance between them, wave divergence is no longer spherical but cylindrical (Wait, 1990). Although this antenna length was not too large for the Z-series boreholes, it was for the V-series.

Referring back to Equation 2.2.1.2-1, this equation is modified for cylindrical spreading:

\[ E_z(r) = \frac{\gamma \varepsilon}{4\pi} \frac{G_T f_T(\theta)}{r} e^{-\gamma r} e^{i\omega t} \quad (2.2.1.2-1) \]

This becomes:

\[ E_z(r) = \frac{1}{4\pi \sqrt{r}} \frac{\gamma \varepsilon}{G_T f_T(\theta)} e^{-\gamma r} e^{i\omega t} \quad (3-1) \]

The medium wavelength is not affected much by this, but the attenuation is, so:

\[ \alpha = \frac{1}{r_1 - r_2} \ln \left( \frac{r_2}{r_1} \frac{G_M}{G_M} \right) \quad (2.2.3.1-3) \]

becomes:

\[ \alpha = \frac{1}{r_1 - r_2} \ln \left( \sqrt{\frac{G_M}{r_1 r_2}} \right) \quad (3-2) \]

The cylindrical attenuation constants for both the Z and V series respectively are: .443 and .462 (plane wave attenuation constants are 3.85 and 4.01 dB/m). Because distance between antennas as compared to antenna lengths
are large, the attenuations derived from the Z boreholes for both the spherical and cylindrical values are very close. However, because of the dimensions, the V-series values are not, and hence are considered less valid.

Borehole spacing in terms of wavelength was 1.26 for 15 MHz in the Z-series, and 4.29 for 150 MHz in the V-series. Far-field approximations are good for the V-series, but marginal for the Z-series. Except for these medium measurements, all other experiments were done using 150 MHz in the V-series.

Examining other electrical characteristics, the permittivity decreases with increasing frequency. This is consistent with King (1981) and other sources; the high frequency causes hysteresis effects on polar molecular components, usually water. This is also known as high-frequency relaxation. The electrical effect of this is quadrature shift from the real component to the imaginary component of the permittivity, and thus an increase of conductivity at the expense of the permittivity.

In this medium at 150 MHz, displacement currents dominate over conduction currents with a loss tangent ($\sigma/\omega\epsilon$) of .12. Because of this, diffraction studies are work well at this frequency. For 15 MHz the loss tangent is .8, or nearly equal effects of both displacement and conduction currents.
3.5 Antenna Characteristics

The use of the system for medium probing is very dependent on the antennas, and to better understand the electrical properties of the probing antennas, the following tests were done. The field patterns surrounding the antennas are medium-dependent, and might change in another setting.

3.5.1 Determination of Length

To obtain both a reasonable transmission line to antenna match, and a predictable field pattern, the antenna length has to be optimized. To determine the length at near-resonance, the sampled reflected and forward power were monitored by the oscilloscope using the procedure described in chap. 2. Antenna lengths are easily adjusted by the telescoping tube-in-pipe design; however the overall test was time consuming and as a result the chosen lengths were used for the remaining experiments.

An optimum resonance frequency for the final length of 1.14 meters is in the range of 133 to 145 MHz. A slightly shorter than half-wavelength is used to avoid a break up of the antenna field pattern from the perpendicular plane (King, 1981, and Wait, 1986).

3.5.2 Antenna Impedance in Medium

The antenna impedance in the medium must be known to calculate the transmitting antenna feed current, and then for the trans-medium impedance (received voltage / transmitted current). The tuff was very homogeneous in that
logging the V-series boreholes resulted in a reflection coefficient standard deviation of less than 2% of the mean over 20 meters of depth for the boreholes.

From the measurements taken on 6/3/90 with a short cable between the antenna and the signal generator, the antenna reflection coefficient is $0.563 \angle 7.6^\circ \Omega$, or $0.558 - j0.074$ Ohms. The resultant impedance is $174 \angle -12.8^\circ \Omega$, or $169 - j38.4$ Ohms. This value is rather large and is almost all resistive and somewhat capacitive. The magnitude of the reflection coefficient is more accurate than the phase because of the much larger possibilities of phase errors. Even slight adjustments to frequency caused the antenna impedance to vary considerably, so a very stable signal generator is a must, or constant monitoring for frequency drift. The result of a phase error could make the impedance closer to 20 Ohms magnitude, a much more believable value. There were no other similar antenna impedance tests done there to confirm this, however.

3.5.3 Antenna Field Pattern

Medium transmission and target determination are dependent on both the transmitting and receiving antenna properties, and one of these properties is the pattern factor. For vertical electric dipoles this factor results from the electric field induced by the antenna current distribution. For a half-wavelength antenna in free-space a polar plot of the field strength resembles a lemniscate with major axis perpendicular to the antenna axis. Because of destructive
electric field interference, these directional lobes can break up perpendicular to the antenna axis if the length exceeds a half wave-length. Also, the field is more complicated in a lossy medium, and would be dependent on the depth or local medium. For this reason the length is chosen to be shorter than a half-wavelength and the pattern characterized assuming a homogeneous medium.

Figures 3.5-1 thru 3.5-3 show the transfer impedance from V1 to V2 and from V1 to V3. The transmitting antenna is at 10 meters depth in V1, and the receiving antenna is varied in depth for both V2 and V3. Signal strength magnitude and phase delay are normalized relative to the receiver at 10 meters depth in V3. Figures 3.5-1a and 3.5-1b show the magnitude and phase of the signal versus the receiver depths. Magnitudes are logarithmic to better show both V3 and V2 receiver position strengths relative to each other, and for this same reason phase delay is shown in periods. The upper four points of Figure 3.5-2b are not quite accurate, this is probably from a defective down-hole amplifier battery.

The phase curves show no phase dependent on the vertical azimuth. In fact, the curves are hyperbolic for this reason.

Figures 3.5-3a and b show the antenna voltage pattern versus the vertical azimuth, zero degrees being perpendicular to the antennas. Figure 3.5-3a is of the magnitude
curves in Figure 3.5-1a, and is logarithmic. Figure 3.5-3b is linear and shows the pattern of the V1 to V3 antenna pair. These clearly show the angular range of effectiveness of these antennas. Assuming something is to be imaged in the middle borehole V2, geotomographic scans are limited to 30° receiver depth ranges relative to the transmitter.
Fig. 3.5-la and b. First set of acquired antenna magnitude and phase voltage patterns. The transmitter antenna position is fixed in V-1 at 10 m and the receiver is roving in V-2 and V-3.
Figs. 3.5-2a and b. Second acquired set of antenna voltage patterns, with similar antenna configurations as the first set. The peak magnitude of V-2 is distorted due to amplifier saturation.
Polar Plot of Vert. Dipole Ants.

Log Relative Mag.

Polar Plot of Ant. Radiation Pattern

Figs. 3.5-3a and b. Polar plots of the first and second sets of antenna voltage magnitudes. Note the directivity in the horizontal direction, at 0 degrees.
3.6 Parallel Scans

3.6.1 Targets

To detect simple targets in the field, the aforementioned parallel scan technique was used. The transmitting and receiving antennas were placed at 10 meters depth in both V1 and V3 boreholes respectively, and borehole V2 is for the target. Simple target tests were conducted to see what effect some targets would have on the cross-borehole transmission. By moving the target in and out of the transmission path with no movement of the antennas, both the geology and geometry effects are held constant.

The first tests were conducted on 2/17 & 2/18/90. The target consisted of a simple extension cord extending the length of 30 meters depth to the surface. This had no effect on either transmission amplitude or phase. Next, a couple of 2 in antenna pieces were put together configured as an electric dipole antenna, about 1 meter long. A 50 Ohm resistor connected the two pole elements for an energy absorbing element. This target again had no discernable effect.

On suggestion (Sternberg, 1990) we next clamped several thick (4 gauge) copper strands to the pipe for conduction to the borehole wall. This target did have an effect on transmission, so the target was placed at every meter from the surface to 19 meters depth, and resulting amplitude and phase recorded, as shown on Figures 3.6-2a and b. These
plots show the trans-medium amplitude and phase normalized to background with no target. Note that the amplitude decreases about 10% when the target is at 10 meters, directly in the transmission path. Also, at this depth the phase delay increases by about 10 to 20 degrees. Multiple readings were taken to check for repeatability. Finally, the 50 Ohm dissipative resistor was removed; but no effects on either amplitude nor phase were noticed.

The next two targets were examined on 3/4/90. One was a brass-shimmed 2 inch dia. 1.04 meter-long copper pipe (see diagram) placed at 10 meters in borehole V2. The target was similar to the previously mentioned one except that the clamped shims keep the target better centered. The other one was a 3.5 inch dia. brass-shimmed PVC pipe filled with concentrated copper sulfate solution. The shims were connected to internal brass screens perpendicular to the length of the pipe. Because of this the solution had good electrical contact to the borehole wall.
Shimmmed Target

![Diagram of a target with labels: 3\' Cu Pipe, 5' Length, Cross-Bolt for Rope Attachment, Brass or Stainless Steel Shims Bowed for Wall Contact, Hose Clamps, 3' to 2' Reducer Brazed On.]

Fig. 3.6-1. Large constructed borehole target. The metal shims space the target in the middle of the borehole and help with conduction.

Target to background effects were compared by taking readings at every 1 m depth with target, then with no target. Because of this the antennas were never moved for each reading. While this is not a true parallel scan of a section with and then without a target, this method avoids possible changes in the connector reflection coefficients due to movement.

Figs. 3.6-2a and b show transmission amplitude and phase effects due to the copper pipe at 1 m increments from 2 to 20 m depth. The plots are normalized to background 10 meter depth transmission. Notice that there is no transmission difference when the antennas are at 10 m, but the gain increases at both 1 m above and below, and the phase
delay decreases. At these depths constructive interference occurs, with a 10% increase of amplitude and a 4 degree decrease of phase shift.

The copper sulfate solution pipe had no effect on the inter-borehole transmission, so a plot was not done for this target.

The next target test was done on 6/3/90, with a shimmed 3 in dia. 1.5 m length copper pipe. Placement of this target was at 15 m depth in V2. The same method of antenna placement and then readings taken with and then without target was done. Here, the target pipe filled up most of the 4 inch dia. borehole.

Figures 3.6-3a and b show the amplitude and phase effects of this target. There is a slightly broader depth range effect here; however the phase does not reflect a noticeable change. Also, the effect is destructive interference.
Figs. 3.6-2a & b. Relative magnitude and phase plots of the transmission from borehole V-1 to V-2, with the effects of the target at 10 m depth in V-2. Note that the greatest change is at 10 m.
Figs. 3.6-3a & b. Relative magnitude and phase plots of a parallel scan with the transmitter and receiver antennas in V-1 and V-3 respectively. On each plot are the inter-borehole transmissions of both background and of the target, positioned in V-2 at 10 m depth. Note the slight change at target depth.
Figs. 3.6-4a & b. Parallel scan of the larger target. On each plot are the inter-borehole transmissions of both background and of the target, positioned in V-2 at 10 m depth. Note the somewhat greater effect of the larger diameter.
3.6.2 Geology

Referring to the borehole logs, Figures 3.6-5 and 3.6-6, the resistivity logs show a gradual increase in resistivity from surface to 10 m depth of 100 Ohm meters in V1 and 70 in V3, then an abrupt drop to 40 Ohm meters at 14 m in V1 and 12 m in V3. The sonic logs show an increase of transit time for this depth also. From this point the resistivity increases to 60 Ohm meters and then varies less dramatically.

The fracture log sheet, Figure 3.6-7, shows a large fracture at 15.8 m (51 ft) in V1, and another large fracture is reported at 12.2 m (40.2 ft) in V3. Both these fractures are very close to the respective high-conductivity zone, and no doubt represent a large joint running thru all the V-series boreholes. Indeed, borehole V2 has a reported large fracture at 11.6 m (38 ft), a depth about half-way between the other two depths. This fracture probably has an abnormally high water content compared to the unbroken areas.

The steady increase of resistivity from the surface to 10 m is probably a result of both decreasing pore volume water, and decreasing alteration with depth. Petterson (1969) describes the replacement of biotite by chlorite and other oxidants most prominent in the upper white unit, where the boreholes are located. Also, welding is less in
this upper unit and consequently the material is more permeable. Thornburg (1990) also concluded this based on conductivities of laboratory samples.

The data from the inter-borehole transmission supports these findings. Wave propagation is dependent on medium conductivity, if the medium is lossy, the transmission of radio waves is less. Referring to Figures 3.6-3 and 3.6-4, the background geology effects are very noticeable. The amplitude plots are very similar to the resistivity logs. The transfer impedance high at 10 to 11 m matches the resistivity highs on the logs. The low due to the fracture shows up at 14 to 15 m on Figures 3.6-3a and 3.6-4a.

Phase change over the 20 meter interval is also large, from 0 degrees at 10 m to a delay of 270 degrees (3/4 period) at 17 m. The decreasing phase delay from the surface to 8 m depth, then leveling from 8 to 11 m, is probably due to the water content. Increasing water content will cause molecular polarization effects increasing the permittivity. Because wavelength and wave velocity are inversely proportional to the square of the permittivity, there is an increased phase delay between the boreholes. Low pore water saturated zones would then have both a high resistivity and low permittivity.
Below 15 m on the phase plots the phase increases although the amplitudes remain low. This is probably due to the increased water content with little argillization. This zone would decrease wavelength, but not attenuate waves as much because this medium is not as lossy.
Fig. 3.6-5. Sonic and resistivity log for V-1. Note the general increase of resistivity from the surface to 10 m depth, then the abrupt decrease near the fracture. Also, there is an increase of transit time near the fracture.
Fig. 3.6-6. Sonic and resistivity logs for V-3. Again, note the same increase of resistivity to 10 m depth, then the abrupt decrease near the fracture, and the increased sonic time.

The weather was warm with lows of 60 degrees F in the early morning and highs in the low 90's. The sky was clear and no precipitation.

**Borehole V-1** drilled 6/89, depth-100 ft, diameter-4 inches approx 5 ft of casing, verticle

- 52.0 ft BTC irregular steeply dipping fracture
- 34.3 high angle large fracture

**Borehole V-2** drilled 6/89, depth-100 ft, diameter-4 inches approx 5 ft of casing, verticle

- 78.0-77.0 ft BTC many small fractures
- 38.0 high angle large fracture
- 38.0 high angle fracture
- 31.0-29.6 high angle fracture
- 27.0 high angle fracture
- 25.0 high angle fracture

**Borehole V-3** drilled 6/89, depth-100 ft, diameter-4 inches approx 5 ft of casing, verticle

- 66.4 ft BTC fracture
- 59.7 hairline fracture
- 51.0 fracture (measured dip)
- 44.0 fracture
- 43.0 fracture
- 42.0 fracture
- 40.2 large fracture (approx 1.75 inch apperture)

**Borehole W-1** drilled 6/89, depth-50 ft, diameter-4 inches approx 5 ft of casing, 45 angle to SE

- 37.0 ft BTC fracture (measured dip)
- 34.0
- 19.0

**Borehole W-2** drilled 6/89, depth-102 ft, diameter-4 inches approx 5 ft of casing, 45 angle to SE

- this hole was caked with drilling mud and therefore the video is very poor.
- 92.6 ft BTC unknown
- 80.0
- 72.0
- 58.7 hole intersects with V-2
- 59.2 fracture
- 43.0
- 42.0
- 37.7

Fig. 3.6-7. Listing of the borehole fractures for V-Series.
3.7 Miscellaneous

3.7.1 Formation Heating

During a medium characteristic test on 6/2/90, it was noticed that the inter-antenna transmission amplitude was steadily increasing with time. This effect would diminish when transmission was ceased for several minutes, but would then increase when transmission was re-started. Furthermore, this effect would localize at a depth and not be noticed immediately at another when the antenna was moved, ruling out equipment drift.

The calculated antenna power was 10 W, and the antenna reflection coefficient was .56, so the power dissipated by the antenna came to 3.1 W. This value is for the start of the experiment. Because the directional coupler had only the forward-wave port, antenna power dissipation with respect to time was not monitored; however the effect was examined by observing the inter-borehole transmission verses time.

Figure 3.7-1 shows the results, and the curve resembles that of a heating curve. At first there is an increase then as time goes on a leveling. What probably happens is the water content of the rock surrounding the transmitting antenna is drying out. During the various tests the antennas would have moisture on them after being in the boreholes for a while. The antenna to cable reflection coefficient is no doubt changing to allow more radiated
power, or possibly the near-field losses are decreasing when the water is being driven out. King et al. (1981) described a similar situation of the use of an insulated antenna similar to the type here for heating living tissue. There also heat-generation is due to near-field effects in a lossy medium.

Fig. 3.7-1. Effects of transmission vs. time between V-1 and V-3. The effect diminished after time when the transmission was halted.

3.7.2 Borehole Modes

The last test done on 6/3/90 was to examine the possibility of borehole electromagnetic modes that propagate up and down the borehole. A device was made to examine these
using the construction advised by Pierce (1990). Referring to Figure 3.7-2, a cylindrical PVC pipe is surrounding the cable under test. Another cable is attached to the cylinder wall and the end is stripped back about 1 inch exposing the center conductor. This conductor is pointing to the center, and is parallel with the E-field of the transverse electromagnetic mode (TEM), because it is assumed that this is the dominant mode. The other end of this cable went to the oscilloscope for monitoring signals. The electric field is calculated by assuming homogeneity across the probe and multiplying the oscilloscope voltage by the probe length.

Tests were conducted with beaded cable and unbeaded. The electric field intensity was approximately twice as strong for unbeaded cable compared to beaded cable over an interval of about 1 to 2 meters above the antenna. A similar more quantitative study by King (1981) revealed that transmission line shield currents would continue up the borehole. He used metal discs to suppress these currents, one every 90 degrees of wavelength.

Above this interval the electric field was small (about 0.2 V/m) for both cases. The strongest electric field was about 1.2 V/m; this being the case of the unbeaded cable near the antenna.

Some idea of the wavelength of the borehole modes was sought, and with this in mind the electric field was moni-
stored with this tester as it was moved up and down the cable. There were minimums and maximums, but because of constant jarring of the beads against the probe no precise measurements could be taken.

**Borehole Mode Sensor**

Fig. 3.7-2. Constructed unit for detecting the axial electric field surrounding the transmission line in the borehole.
3.8 Conclusions

The system operated well at this site, however there were constraints. Amplitude measurements were much easier than phase, because use of the swept frequency method requires total system phase determination. It can be very easy to be off several wavelengths due to equipment connections, filter poles, etc.

We had to shorten the standard cables in order to obtain good phase measurements, and even then the frequency range of the high power Yaesu transmitter was not enough to use the method; the signal generator had to be used. For a medium test between Boreholes V1 and V3, a total phase measurement took four hours.

The borehole electromagnetic-mode test would indicate that ferrite beads are not necessary the whole length of the cable. Further tests on this are needed to quantify results for antenna radiation requirements and up-over-and-down cross-talk tolerances between boreholes.

Errors on amplitude are about 1 dB. or 12 %. Phase errors can commonly be as high as 10°, and vary with connections greatly; connecting and disconnecting a UHF connector can change the phase by 10 degrees at 150 MHz. Keeping the equipment and antennas relatively stable during the experiments helps considerably.
Vertical copper pipe targets can be detected using the parallel scans as shown, but only compared to background, and, as mentioned, with stable equipment. To detect injected saline plumes, their diameter relative to their skin depth should be comparable to those targets examined here (Wait, 1990).

Geotomography can be attempted here, but again only with and without target, because the geologic effects are much greater than the targets studied here. Also, geotomography requires much more movement of equipment than simple parallel scanning, so errors will be larger.
CHAPTER 4

SAN XAVIER TEST SITE

4.1 Introduction

The San Xavier site is located 22 mi S of Tucson on Mission Rd, and is a former lead, zinc, copper, and silver mine. There are several boreholes for various studies, and access to the underground mine. The geology is a mixture of metamorphosed limestone and hornfels facies rock. Nearby igneous plutons have caused contact metamorphism with mineral-rich solutions implanting ores in the altered limestone (Sternberg et al., 1988).

The main thrust of using this site was to develop the cross-borehole ground probing system and then ultimately both detect a tunnel between two boreholes and map seeping effluent placed therein over time.

4.2 Borehole Setups

Three principal boreholes were used for these experiments: H4, H12, and H13 (see Figure 4.2-1). These boreholes were drilled co-linear with the expectation of using the difference method, described in chapter 2, and in addition boreholes H4 and H12 straddle a mine drift at 135 feet (41.1 m from H4 top) below the surface, to examine the effect of targets placed therein. These boreholes are
fairly vertical with the following exceptions (at 50 m): H4 trends .4 m SSE, H12 trends 1.0 m S, and H13 trends .4 m SW. The trends are very nearly linear from the surface.

The test facility includes a 100 ft. cemented channel inside the drift to hold water. This can be flooded from the surface holding-tank for the purpose of adding an extra attenuating factor to the inter-borehole propagating waves.

Fig. 4.2-1. Plan map of the 150 ft depth mine drift, with borehole locations at the San Xavier Mine. Note the cemented segment between the east and west dams (Sternberg et al., 1988).
Fig. 4.2-2. Geologic map of the 150 ft depth mine drift (Sternberg et al., 1988).
Fig. 4.2-3 (Top). Ground-probing truck and trailer setup positioned between boreholes H4 and H12 at San Xavier site.

Fig. 4.2-4 (Bottom). West end of the cemented mine drift, at 150 ft level, with metal screen and water.
Fig. 4.2-5. Joe Shulte and myself lowering the vertical electric dipole antenna down borehole H4. Shown is half of the total dipole length.
4.3 Medium Electrical Characteristics

Referring to the 150 ft level (Figure 4.3.2), the metamorphosed limestone, both marble and hornfels facies, presented a very difficult material to propagate waves thru. Tabulated in Table 4 are the electrical characteristics of the medium at 15 MHz.

<table>
<thead>
<tr>
<th>Freq. (MHz)</th>
<th>α (1/m)</th>
<th>β (1/m)</th>
<th>Plane Wave Atten. (dB/m)</th>
<th>λ (m)</th>
<th>σ (mS/m)</th>
<th>ρ (Ωm)</th>
<th>εr</th>
<th>( \frac{σ}{ωε} ) (Ss/F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>.76</td>
<td>1.16</td>
<td>6.7</td>
<td>5.4</td>
<td>15</td>
<td>67</td>
<td>7.9</td>
<td>2.28</td>
</tr>
</tbody>
</table>

Table 4. Formation electrical characteristics at San Xavier test site.

On 6/11/90, the co-linear three-hole method was attempted in boreholes H4, H12, and H13, at a depth of 55 m. With the severe attenuation between H4 and H13, a proper phase determination was not possible. However, the calculated attenuation between these came to 6.7 dB/m. Trying a non-colinear three-hole method using H15 to replace H13 (see Figure 4.2-1), produced an unrealistically high relative permittivity value of 72. This no doubt is from the medium inhomogeneity.

Medium phase change between a fixed transmitting antenna in one borehole and a moving receiving antenna in
the other borehole was determined from data gathered during the geotomography experiments, described in section 3.5. The resulting calculated wavelength at 15 MHz is 5.4 meters. This makes the dielectric constant about 7.9, a reasonable value. The HF dielectric constant values for both limestone and marble reported by Lytle (1973), 7.3 - 12, and 8.2 - 9 respectively.

With the presence of sub-surface moisture and mineralization, the conductivity is a reasonable value. The log for H4 shows a DC resistivity of 30 to 60 Ohm meters, close to the tabulated value. The electrical characteristics are very localized, and the values reported here are only at 50 meters depth between H4 and H12. Regional inhomogeneity causes large deviations that were not investigated here.

4.4 Antenna Characteristics

4.4.1 Determination of Length

The construction of the antennas used here is the same as previously described in chapter 2. A length was chosen to be slightly shorter than a half-wavelength, and yet not reflect too much energy back up the transmission feed line.

The final length chosen was 6.4 m, which is very long compared to the inter-borehole distance. Shorter lengths had both too much of an antenna reflection coefficient and insufficient receiving aperture for a transmitted signal between the boreholes.
4.4.2 Antenna Impedance in Medium

Figures 4.4.a and b show the antenna reflection coefficients in boreholes H4 and H12. Considering the fact that the antennas are 6.4 m in length and the values have a large variance for an antenna depth movement of only .5 m, the medium inhomogeneity must be great. The curves do not cross-correlate between boreholes well either, but this is to be expected because there are no strata here.

Because of the inhomogeneity and lossy nature of the medium, and because of both the antenna length the wavelength compared to the inter-borehole distance, an antenna pattern determination was not attempted.
Figs. 4.4.a and b. Antenna reflection coefficient magnitude and phase vs. depth for boreholes H4 and H12.
4.5 Cross-Borehole Transmission Tests

At first, various attempts were made to propagate 150 MHz thru the rock, all in vain. Propagation of only about 1 to 2 meters between a borehole and a drift was accomplished, but this was insufficient for our project. Lower frequencies were then investigated, such as 30 MHz, and then 20 MHz, but the results were insufficient signal penetration; only 15 MHz could penetrate at the power levels we needed over the 9 m distance between H4 and H12. Even though 15 MHz would have a very long wavelength compared to our targets, we proceeded nevertheless.

4.5.1 Target Determinations

On both the 19th and 26th of April, 1989, parallel scans between H4 and H12 were done. Scans were done both with two long wire meshes formed into two circular two foot diameter cylinders in the tunnel, and a scan without. The results are shown on Figure 4.5-1. The tunnel depth is marked, and the x-coordinate is the cross-borehole attenuation.

There appears to be no effect of the mesh on the transmission. The system errors produce greater differences than seen between the curves. This target has too small of an effective cross-sectional diameter to have an effect on vertically polarized electric fields at the wavelengths used.
Another larger target investigated was the flooded cemented canal located between H4 and H12 in the drift (see Figure 4.2-1). This target consisted of the flooded canal with the wire mesh thru the length of it to help increase conductivity. The water source for this is the tank on the hill above the facility, and is gravity fed to the level thru pipes and fire hose. The water level in the canal came to approximately 75 cm as monitored on the west end.

An oversight here was not using the parallel scan technique to look at the effect of the target compared to background, but a geotomography was attempted. Five
transmitting antenna positions were selected in both H4 and H12, with 2.5 m separations. The interval range this would be at the same depth as that of the tunnel. Receiver positions were every .5 m in the opposite borehole, and the interval range was enough to sufficiently scan the target assuming straight ray paths, and then some. Two geotomographies were done, one of the dry tunnel on the 14th of Oct., 1989, and then one of the filled tunnel on the 21st and 22nd of 1989.

Figures 4.5-2 and 4.5-3 show the results of the wet tunnel transmission. Plotted are the ratio of receiver antenna voltage to transmitter antenna current, or transfer impedance, versus receiver depth. Note that there are five curves per plot, representing the five transmitter positions. For each transmitter position there are two curves, one is magnitude and the other is phase delay, in periods of 66.67 nanoseconds, the period of 15 MHz. A data acquisition error occurred during the dry tunnel geotomography and the data that were taken are incomplete. This incomplete data was reconstructed by Dave Droege and this set was compared with the data that was properly acquired. The reconstruction and system error was larger than the difference between the filled and unfilled canal curves, so no hard and fast conclusions could be drawn between these two sets.
Considering the wavelength in the medium, the lack of a concentrated antenna source (its length), and the geological inhomogeneity, follow-up tests were not conducted using this target again.
Figs. 4.5-2a and b. Geotomography data curves with 5 borehole-transmitting positions in H4, roving receiver in H12. Note the greater transmissions at depths of 33, 43, 46, and 57 m.
Figs. 4.5-3a and b. Similar curves except with transmitter and receiver in H12 and H4 respectively. Again, note the preferential transmission zones at 33 and 42 m.
The next important test conducted at the site on 1/27/90 was the effect of a vertical 1 inch diameter copper pipe, 25 ft long, placed in borehole H12, between H4 and H13. The transmitter antenna was placed in H4 at 50 m depth, and the receiving antenna in H13 at the same depth, this is because the transmission between these two boreholes is very weak above this level. The target was placed in and out of the transmission path between H4 and H13, with uncertain differences.

Next, the middle borehole was flooded with a saline solution (NaCl) and the same comparison made. The result was a 33% increase of transmission when the pipe was inserted. This indicated some constructive re-radiation of the field by the pipe. I believe the pipe had an effect on transmission, even though the increase was 120µV on the receiving channel of the oscilloscope, i.e., small compared to the background transmission.

Further attempts to perform a geotomography were unsuccessful because of antenna and cable movements, and probably changing water level in the borehole.

4.5.2 Geology

Figs. 4.5-2 and 4.5-3 do however show facets of the medium geology. Note on Figure 4.5-1 the decreased attenuation zones at 32, 43, and 54 meters depth. Figure 4.5-2a show increased transmission at 32-33 m for the 36.5 m
transmitter position curve, and at 42-45 m for the remaining transmitter position curves. Also, there is some transmission at 57 m for the 46.7 m transmitter curve. Remember that the antennas are 6.4 m in length, and cover a large zone in the boreholes. Figure 4.5-3a shows the same increased transmission at 32 - 34 and 42 - 43, except that the transmitter positions overlap the resistive non-lossy zones differently.

Figures 4.5-2b and 4.5-3b show the phase delay between transmitter and receiver antennas. The least delays are at about 33, 42, and 57 m. Note that if the medium were homogeneous the phase hyperbolas would center on the appropriate transmitter depth positions, every 2.5 m as coded on the bottom of the plots. As it is however, the hyperbolas center on the two transmissive zones, with some effect of the third one at 57 m.

Apparently the long antennas need not be centered on these zones to have a noticeable effect. In fact both the transmitter and receiver antenna need not be on the zone at all, as the curves show. This would indicate a considerable amount of refraction in the medium, and perhaps a possibility of some guided waves.

These plots, especially the phase hyperbolas, do concentrate at 41 - 43 m depth, near the tunnel depth of 41.5 m. It is hard to say that the tunnel is having any type of
effect, considering the influence of the geology. A possibility, is that although the drift is only about 1.5 to 1.8 m in diameter, the effective tunnel diameter might be within the wavelength's resolving ability. Rock fracturing from blasting the drift and subsequent drying from open-air movement might have influenced the rock's electrical properties to produce an effective diameter greater than the open drift. Further studies might be done to study this. Perhaps the effect of screen nailed to the walls in the scanned zone might provide a enough contrast instead of the flooded tunnel method to compare against background.

Comparing these results to the borehole logs in Figure 4.5-4, the resistivity log does show some increased resistivity at 30 - 33 m, 40 - 45 m, and at 57 m depth. The sonic log shows decreased transit times for these zones as well. Other non-transmissive zones might be unconsolidated rock due to jointing, fracturing, or depositional features. There is much mineralization due to the contact metamorphism, and weak zones could not only be more inhomogeneous from structural features, but also cavitated from solutions and heavy mineralization. The result would be radio wave scattering from these zones.
Figs. 4.5-4a and b. Resistivity logs of boreholes H4 and H12. Note some of the similarities where the resistivity is high to the transmissions of Figures 4.5-2 and 4.5-3.
4.6 Conclusions

The original goal of using this site to develop the inter-borehole probing system was set upon with many benefits and breakthroughs by both Joe Schulte and myself, and an understanding of both the kinds of targets and background medium this system can be used in. However, the original goals of detecting the tunnel, either wet or dry, and the detection of ground water effluent at this site were not successfully accomplished.

The equipment and technique facets of the studies have evolved to the system previously described with only small changes possible unless large scale revamping is desired, such as using fiber-optic transmission between the receiving antenna and the surface, and/or implacing the transmitter into the transmitting antenna, thus both reducing the chance of any borehole modes and to aid in keeping track of the inter-antenna phase.

The site presented the most problems; the inhomogeneous and lossy ground made this method questionable. The frequency of the system had to lowered enough to permit medium penetration, but then the resolving power of the long (5.4 m) wavelengths would not permit a target of less than half that in diameter to be well-defined (Lytle et al., 1979). As stated in the previous sub-section, the tunnel might have an effective diameter large enough to influence cross-borehole transmission.
Also, because the vertical dipole antennas used were very long for directional gain and aperture, the approximation by a point source is nearly meaningless, besides being difficult to position and adding tremendous weight to the coaxial cables. A system using coils with a vertical magnetic field would not only have a more spatially concentrated source, but be the same polarization as the target used here (Hill, 1990). This would eliminate the need to use a short wavelength. However, a coil antenna would probably need a matching network to match to the transmission line.

The experiments at this site have shown that as much understanding of the medium, targets, and available system is a must before attempting a complicated geotomography. Some modeling can be done, and no doubt with problems avoided later. When on-site testing commences, it is always advisable to do a parallel scan of both the background and then with a target, keeping the configuration geometry constant with the result of a quick conclusion for further planning.
CHAPTER 5

MODEL TANK EXPERIMENTS

5.1 Introduction

This next phase of experiments centers on an experimental model tank setup on campus. The purpose is to better understand the nature of the antennas and target effects, all in a homogeneous medium. The medium is a dilute aqueous solution that can be altered for the experiments. Because of this and by using a simple radio-frequency signal generator, both the wavelength and the medium skin depth can be adjusted.

Some aspects of the model tank setup were simplified compared to that of the field test sites. First, is the antenna to medium contact; here the bare antennas were directly immersed into the solution. In the field the antennas were centered in the boreholes with no rock contact. Also, because of direct immersion of the antennas and cable into the solution with no "boreholes", no ferrite beads were used around the coaxial cable. Shield-to-medium electromagnetic modes as might exist in a borehole were assumed to be small.

Two types of antenna were used in this environment: the standard vertical electric dipole as used in the field, and
a horizontal electric dipole, consisting of two poles driven by a perpendicular coaxial feed-line. While practicality prohibits the horizontal dipole to be used in the field due to its length and orientation, this antenna approximately models a vertically oriented coil in that its electric field is polarized the same. Also, this antenna permits the testing of an untried inversion algorithm that assumes a transverse electric field source to the image plane.

5.2 Setup

Referring to Figures 5.2-1 and 5.2-2, the scale model tank setup consists of a fiber-glass and polyester mat stock tank, the standard antenna probing equipment, and the aqueous solution medium. Because of the aqueous medium and its high permittivity, the antennas and the inter-antenna distances are small compared to that in the field, and most experiments can be done within a the range of a few decimeters.
Fig. 5.2-1. Model tank setup. The equipment is almost the same as that used in the field, except low power signals are transmitted.
Improved Jig for Holding Antennas

Fig. 5.2-2. Enlarged diagram of the jig used to position the antennas.
Fig. 5.2-3. Photograph of model tank setup. The two outer shafts are the slider assemblies that position the antennas, as diagrammed in Fig. 5.2-2, and the held center shaft is fixed to the copper pipe target.
5.2.1 Holding Tank

The model tank is a seven foot diameter by seven foot high fiber-glass and polyester mat formed stock tank commonly available for agricultural uses. A 4 in lip on the tank top serves to add hoop-strength. A base of gravel in a 4 by 4 inch wood form attached to the floor was constructed because the floor had a tilt for drainage. The gravel's surface however is level and has a 3/8 in plywood board on top to keep the tub's base free of angular rocks. The tank was filled by a garden hose over the top, and a 2 inch ball valve fitting on the bottom serve to drain the unit.

5.2.2 Equipment Configuration

Referring to the model tank diagram, Figure 5.2-1, the equipment setup is nearly the same as the field site set-ups. Because comparatively low power is needed, the HP 3200B radio-frequency signal generator supplies the 300 MHz frequency used for operation. Also, shorter equipment to antenna cables permits easier swept-frequency phase measurements than were possible in the field. Because the medium is a dilute aqueous solution, the permittivity is much higher than rock, and hence the wavelengths are much shorter, along with the antennas.

Because of the need to keep antennas motionless and in fixed positions, a jig was devised to replace the absence of the borehole (see Figure 5.2-2). A graduated board on
top of the tank serves to hold vices as the horizontal placement control. The vices hold 3/8 in dia. fiber-glass and polyester rods that are fastened to rock weights laying on the bottom. The rock blocks have drilled holes thru them for the rod placement and are wider at the bottom for a fastened hose clamp to prevent the rod from pulling out.

The antenna and cable are taped to an 18 in plastic pipe that encircles the rod, this pipe can then move up and down on the rod with practically no lateral movement. A second set of higher vices hold the cable and serves to fix the antenna depth. A graduated thin 1/4 in rod is taped to the cable and serves to measure the depth below the water surface.

5.2.3 Antenna Construction

As depicted below in Figure 5.2-3, both configurations of antennas used for these experiments are very simple. The antenna ends are sealed with silicone seal to prevent seepage of water into the cable layers when used in the model tank.

The antennas used to generate the horizontally polarized electric field are a set of stripped back coaxial cables, with the center conductor bent perpendicular to the main cable body, and another solid copper wire (about 14 gauge) wrapped around the outer shield with an end pointing the opposite direction to that of the center conductor.
The vertical electric dipole antennas are constructed similarly to the ones used in the borehole experiments, except on a smaller scale. A brass tube placed on the outer insulation serves as the coaxial shield-feed element, and the coaxial center conductor is the other pole; both poles are the same length.

Diagram of Model Tank Antennas

Fig. 5.2-3. The two model tank antennas: the horizontal and vertical electric dipole antennas. They are simple modified coaxial cable-ends.

5.2.4 Model Tank Solution

The water solution serves two purposes: to compress the waves enough to present a scaled-down version of an actual field site, and to attenuate the waves enough to keep the sides, bottom, and surface reflections small. Because the permittivity of water is generally an order of magnitude
greater than that of most rocks, the same frequency electromagnetic waves can be scaled to a third the length. Furthermore, frequencies higher than that in the field can be employed, decreasing wavelength even more. The medium's skin depth is adjusted by adding ionic compounds such as salt to a specified concentration, yielding the necessary conductivity needed to achieve this (Frischknecht, 1971, 1989).

To choose a modelling scheme for this tank, I desired to have an attenuation per wavelength similar to that found in the field. In this way, the same conditions encountered in the field can be looked at in a controlled environment, such as wavelength resolving ability, and penetration in the medium. For these experiments, displacement currents were desired over conduction currents, so conductivities were kept low. Because of this, the wavelength is almost entirely controlled by the characteristic permittivity of the water, which is 78.3 of that in free space at 25 degrees Celsius (Olhoeft, 1981).

To model the same attenuation per wavelength as might be found in a geologic situation, consider the wave propagation's distance dependent term, $e^{-ax}$. Substituting the wavelength for the distance term $z$, the product is made constant for both the field example and model case:
where, \( \alpha_f \) = field attenuation to be modeled
\( \lambda_f \) = field wavelength to be modeled
\( \alpha_m \) = modeled attenuation
\( \lambda_m \) = modeled wavelength

Expressing this in terms of the conductivity, permittivity, and permeability:

\[
\alpha \lambda = 2\pi \frac{\alpha}{\beta} = 2\pi \frac{\sqrt{\frac{\omega \mu}{2}} \left[ \sqrt{\sigma^2 + (\omega \epsilon)^2} - \omega \epsilon \right]}{\sqrt{\frac{\omega \mu}{2}} \left[ \sqrt{\sigma^2 + (\omega \epsilon)^2} + \omega \epsilon \right]} \quad (5-2)
\]

where, \( \omega \) = radian frequency
\( \sigma \) = conductivity
\( \epsilon \) = permittivity
\( \mu \) = permeability

Simplifying, and then factoring:

\[
2\pi \frac{\sqrt{\frac{\omega \mu}{2}} \left[ \sqrt{\sigma^2 + (\omega \epsilon)^2} - \omega \epsilon \right]}{\sqrt{\frac{\omega \mu}{2}} \left[ \sqrt{\sigma^2 + (\omega \epsilon)^2} + \omega \epsilon \right]} = \quad (5-3)
\]

\[
2\pi \frac{\sqrt{\frac{\sigma}{\omega \epsilon} \left[ \sqrt{\left(\frac{\sigma}{\omega \epsilon}\right)^2 + 1} - 1 \right]}}{\sqrt{\frac{\sigma}{\omega \epsilon} \left[ \sqrt{\left(\frac{\sigma}{\omega \epsilon}\right)^2 + 1} + 1 \right]}}
\]

where, \( \frac{\sigma}{\omega \epsilon} \) is also known as the loss tangent
This implies that to model the same attenuation per wavelength as that found in the field, the model medium's loss tangent $\eta/(\omega\varepsilon)$ must be made the same as that of the field situation to be modeled.

Common practice for increasing the conductivity of these modeling aqueous solutions in the past have used salts such as sodium chloride. This is fine if one decides upon a concentration to achieve a specific conductivity, and not have to later lower the salinity if the solution is over concentrated. However, for large modeling tanks such as this one, the need to change the conductivity often has prompted the use of an ion-changeable system using an acid as the principle source of ions. This works well for low concentration solutions.

Because conductivity in an aqueous solution is proportional to ion-carrier mobility, an ion readily influenced by an electric field is desirable. On Table 5 are ions and their mobilities expressed as the ratio of ion velocities / electric field (after Keller, 1971). Note that the mobility of a hydronium (hydrogen) ion is nearly 7 times that of a sodium ion, and relative ion mobility of equal molar solutions of hydrogen chloride to that of sodium chloride is 3.4. Taking into account the weight of the compounds, the ion mobility per mass ratio is 5.4. This means that a 1 gallon (3.79 liter) 12 molar solution of hydrochloric acid is commonly available for $2 or $3, and provides 45.5 moles of HCl, whereas to achieve the same conductivity
using sodium chloride, one needs nearly 20 pounds. Furthermore, dispersing the hydrochloric acid is very easy, one needs only to pour it into the tank. However, the NaCl salt must be dissolved, and for this many pounds of large crystals, this can be difficult.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁺</td>
<td>36.2</td>
</tr>
<tr>
<td>OH⁻</td>
<td>20.5</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>8.3</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>7.9</td>
</tr>
<tr>
<td>K⁺</td>
<td>7.6</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>7.4</td>
</tr>
<tr>
<td>Na⁺</td>
<td>5.2</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>4.6</td>
</tr>
<tr>
<td>Li⁺</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 5. Ion mobilities for common ions (Keller, 1971).

One other important feature of using an acid, the solution conductivity can be decreased by exchanging hydronium ions for ones that have a lesser mobility. One has no alternative using a neutral salt except to dilute by draining part of the tank and refilling it with fresh water. On
the other hand, using an acid such as hydrochloric acid, one can "neutralize" a portion with a base, such as potassium hydroxide. What actually happens is that hydronium cations are being replaced with less mobile potassium cations, with the total molar concentration of the remaining chloride anions unchanged. This is useful especially with a large tank that is difficult to drain and fill (about 2 hours), such as our 2,000 gallon capacity tank.

A drawback of using this type of system for a higher concentration to achieve a large medium conductivity is that electropositive metals such as copper will slowly corrode when left in solution too long. However, for these experiments operating in the diffraction regime with low conductivities, this worked well.

Referring to Figure 5.2-4, the loss tangent vs. frequency plot (after Olhoeft, 1981), the desired modeling conductivity is achieved by computing the loss tangent ($\frac{\sigma}{(\omega\epsilon)}$) at the desired frequency, then plotting the log of this with the frequency. The resulting matched or interpolated curve represents the resistivity at 0 Hz, or DC. The concentration of salt needed is then computed by using a chart such as from Keller (1971) describing the resistivities of sodium chloride solutions vs. concentrations. The molar quantity can then be adjusted for other salts (or acids, bases) by using Table 5 or something similar on ion mobilities.
Once the proper amount of ionic compound is added, the standard three antenna technique can be used to determine the actual conductivity and permittivity at the operating frequency. Further adjustments then can be made to the solution to fine-tune the conductivity.

5.3 Cable Cross-Coupling

To examine the possibility of cross-coupling between the cables used to both transmit and receive antenna sig-
nals, a simple test of sending a signal down a matched terminated cable next to a receiving cable also terminated was conducted. The two transmission line cables were terminated in matching 50 Ohm loads, and placed close to each other, for approximately a 2 meter interval in length.

Results showed that the cross-coupled signal was less than 90 dB, or equivalently, a 1 Volt signal across the resistive load on the transmitting cable would only produce a 23 micro-Volt potential across the transmitting cable load. This is much smaller than the signal levels used for these experiments.

5.4 Antenna Characteristics

The effect of a saline solution on the bare antennas was investigated by King and Smith (1981). The principal effect was that the fields propagating from the feed point to the ends of the antenna would attenuate, causing a decreased current flow compared to that of an antenna in a lossless medium. Because the radiation pattern is dependent on the antenna current distribution, the resulting end antenna currents in the lossy medium will be smaller than that of a free-space current distribution. In a saline solution a slightly longer than half-wavelength antenna will probably not have as great of lobe-breakup as one in a lossless medium.
Because the solution was made relatively weak for these experiments, the skin depth was large with respect to the antenna lengths, and hence the currents in the antenna would not pinch out towards the ends more than that in a lossless medium.

The antennas designed for the model tank experiments are five centimeters long. This length is just short of the 11.3 cm half-wavelength of a 300 MHz wave in water of high permittivity. The idea was to prevent the breakup of non-perpendicular radiation lobes that occur from partial cancellation of the fields resulting from an electrically long antenna (Wait, 1986).

The radiation patterns of both types of antennas were examined. Because the horizontal electric dipole antennas would be used in the transverse electric mode, perpendicular to the vertical image plane, the horizontal voltage pattern was not measured quantitatively. Both receiving and transmitting antennas were tested qualitatively by placing them in the tank about 30 cm apart at the same depth, and both rotated about the vertical axis with the trans-medium voltage ratio monitored. The maximum was when both antennas were parallel with each other, as expected.

On the other hand, the voltage pattern of the vertical antenna with respect to the vertical azimuth would not be circular as with the horizontally polarized antennas, but probably resembling a lemniscate if built short enough.
The antenna voltage pattern was determined by placing the transmitting antenna in a fixed position and then by placing the receiving antenna in various positions to cover the desired range of vertical azimuth with respect to the transmitting antenna. The receiver voltage normalized by the transmitting antenna's input current was measured at each of the positions, giving a vertical azimuth-dependent transfer impedance with the dimensions of Ohms. Then, the medium effects were taken out. These are the attenuation and phase delay of the propagating waves thru the medium, plus the effects of spherical spreading with the assumption that the antenna length is small with respect to the propagating distance.

The results are shown on Figures 5.4-1 and 5.4-2. Figures 5.4-1a and 5.4-2a are of the transfer impedance magnitude and Figures 5.4-1b and 5.4-2b are of the phase delay. Figures 5.4-2a and 5.4-2b are polar plot versions of 5.4-1a and 5.4-1b. Even though the length of the antenna poles came to 5 cm, less than the half-wavelength, the pattern did break up into non-perpendicular radiation lobes, unlike the horizontal dipoles.
Figs. 5.4-1a and b. Magnitude and phase delay with respect to vertical azimuth for the vertical electric dipole antenna-pair used in the experiments. Note the preferential radiation directions.
Figs. 5.4-2a and b. Polar plots of the magnitude and phase delay for the vertical electric dipole antenna-pair.
Figures 5.4-1 and 5.4-2 show that the radiation pattern forms a four-leaved rose curve of maximum radiation directions other than the perpendicular, unlike the circular one using the horizontal electric dipoles. Figs. 5.4-1a and 5.4-2b show a preferential radiation direction of 40 degrees from the horizontal. Surface effects prevent complete symmetry about the target depth on all plots.

This effect might be due to the radiation of the coaxial cable feeding the antenna. The antenna to transmission mismatch causes energy to be radiated back up the transmission line on the shield. These electromagnetic modes would be similar to the borehole modes, in that the fields are between the shield and the medium (Pierce, 1990). King et al. (1981) describes a center driven dipole in a borehole using perpendicular metal disks as chokes. The model described by King shows currents distributed beyond the antenna end up the cable until the metal choke section.

We have used ferrite beads in the field, but for the model tank experiments nothing was used. Here, the cable is directly immersed into the medium with no air insulation between. No doubt, in the model tank the cable feeding the antenna does act as a radiator providing partial cancellation of fields and thus preventing a main perpendicular radiation lobe. This was not a problem with the horizontal
dipoles, probably because the feed cable was perpendicular to the antenna, and did not contribute to the field pattern.

5.5 Target Effects

A simple target consisting of a meter long 2" diameter M-schedule copper pipe was placed with its main axis perpendicular to the image plain (see model tank setup). The target effects were first examined by the parallel scan, using a fixed geometry for quick results, and then the fixed transmitter with roving receiver setup, for a target radiation pattern determination.

5.5.1 Parallel Scans

On 7/8/90, the model tank's conductivity was increased to decrease the reflective effects of the tank sides enough to decrease the skin depth to about 25 cm. This would put the sides about two skin depths away from the antennas. One gallon of 37% (12 molar) hydrochloric acid was added to the tank bringing the conductivity to .196 Siemans/meter. Relative permittivity was measured as 76.6, making the wavelength 11.4 cm, and the skin depth 23.8 cm. The loss tangent came to .153, indicating a dominance of displacement currents over conduction currents.

The first target test on 7/10/90 in the model tank employed the horizontal dipole antennas to produce a parallel scan of the 2 inch diameter copper pipe. Figures 5.5-1a and b show the effects of the pipe positioned 80 cm
beneath the water surface, and midway horizontally between the antennas. The horizontal spacing between the transmitting and receiving antennas was 60 cm. The antennas were moved simultaneously from 40 to 120 cm in intervals of 2.5 cm. Diffraction is clearly evident, with distinctive maxima and minima.

To model the effects of these diffraction patterns synthetic data were created (Figures 5.5-2a & b). These are the plots of the two-path sum and phase of the following equation:

\[
\text{Total RCVR Voltage} = \text{Direct Ray} + \text{Refl. Ray} = \quad (5-4)
\]
\[
e^{-z_1}\sin(-\beta R_1)/R_1 + e^{-z_2}\sin(-\beta R_2)/R_2
\]

where,
\[
R_1 = \text{Direct Ray Distance}
\]
\[
R_2 = \text{Reflected Ray Distance}
\]
These equations represent a wave originating at the transmitting antenna and then going both directly to the receiving antenna and also reflecting off the target. Attenuation is effected by both the medium and also by spherical divergence, as modeled by the equation. The equation is a very simplified model to the test condition and does not take into account the back-scattering due to the pipe or induced fields in the medium, so the center part of the curve near 80 cm depth is the most inaccurate. These plots do show the relative maximums and minimums due to constructive and destructive interference respectively, and the phase plots show zero phase change when either a maximum or minimum occurs on the amplitude, as expected.
Figs. 5.5-la and b. Parallel scans of the 2 in Cu Pipe at 80 cm depth, using horizontal electric dipoles. Note the interference waveforms.
Figs. 5.5-2a and b. Synthetic data used to model the interference waveforms of the parallel scans.
After some experiments such as previously described, it was desired to increased signal penetration, so on 8/15/90, the tank's conductivity was lowered. About 150 grams of sodium hydroxide and 750 g potassium hydroxide were added to bring the conductivity down to .153 S/m, and the skin depth increased to 30 cm.

Figures 5.5-3a and b show the parallel scan of the same pipe using vertical electric dipoles. The target is at the same physical depth as with the horizontal dipole scan, except the plot's abscissa is of target depth below the antenna-positioning vices.

Fig. 5.5-3b shows a large phase effect, two whole periods of shift from background to target. Several runs were done to confirm this. The maximum phase change transition takes place at the 40 degree inclinations, at 155 and 105 cm depth. The parallel scans using the vertical electric dipoles do show a more pronounced effect compared to the horizontal dipoles, even though the polarization for the former is the same as the target's.

Lytle et al (1979) showed that the parallel scans done of tunnels show two amplitude lows indicating the tunnel roof and floor, and furthermore the minimums tend to merge when the tunnel is of circular cross-section. Both vertical and horizontal scan plots done here tend to confirm this also.
Figs. 5.5-3a and b. Parallel scans of the 2 in Cu Pipe at 130 cm depth, using vertical electric dipoles. Note the intensified interference waveforms at 155 and 100 cm. Many experiments were made to confirm curve shapes.
5.5.2 Target Patterns

For continued progress toward geotomography reconstructions, an understanding of the target radiation pattern was needed. The method used here to find the secondary radiation pattern is similar to a typical geotomography scan where the transmitting antenna is fixed and the receiving antenna is roving.

On 8/17/90, experiments were done to gather data for a target voltage pattern using horizontal electric dipole antennas. The medium skin depth was 30 cm. The configuration was the same as used for the parallel scan previously discussed; except the receiving antenna is roving. For these experiments, the receiving antenna is moved thru the range of 90 to 200 cm depth, 30 cm away horizontally from the target and 60 cm away in-line from the transmitting antenna. Both transmitting antenna and the target are 140 cm below the vice.
Figures 5.5-4a and b depict the amplitude and phase delay of the transfer impedance due to the total wave potential from both the receiver and from target scattering. Again, note the minimum from 138 to 150 cm depth; but the minimum is thru a larger range than that of the parallel scan. This is due to the larger occultation from the target as a result of a stationary transmitting antenna. Similar results were obtained as reported by Lytle et al (1979) in that the minimums are further spread apart with respect to receiver depths using a fixed transmitter and roving receiver as compared to simultaneously moving antennas.

Figure 5.5-4b, the phase delay plot, shows the typical phase hyperbola except with a center distortion due to the target; an increase of about 35 degrees.
Figs. 5.5-4a and b. Magnitude and phase of a fixed transmitter and roving receiver-pair, the setup used for a geotomography. The target is at 140 cm depth; note the decreased transmission here.
Figs. 5.5-5a and b. Target scattered potential magnitude and phase delay, with respect to vertical azimuth, using horizontal dipole antennas.
Figs. 5.5-6a and b. Polar plots of the magnitude and phase delay for the target's scattered potential.
To obtain the target voltage pattern, data are taken of the roving receiver as shown on Figures 5.5-4a and b, then similar data are taken without the target at the same receiver locations. The receiving antenna voltages are normalized by the transmitting antenna input currents giving a transfer impedance with the dimensions of Ohms, as before, then the primary potentials are subtracted from the total potentials to yield the secondary potentials, all normalized by the respective transmitting antenna currents.

These transfer impedance values are then adjusted to originate at the target by taking the medium effects out, and to assume spherical spreading. These potentials normalized by the transmitting antenna input currents are then considered as scattered by the target only. The procedure is outlined by the following equations:

\[
\text{Scattered Transfer Impedance } (R_1) = \text{Total Transfer Impedance } (R_1) - \text{Primary Transfer Impedance } (R_1) = \frac{\text{RCVR Potential (with target, at } R_1) - \text{RCVR Potential (without target, at } R_1)}{\text{XMTR Current}}
\]

where, \( R_1 = \text{RCVR to Target Distance} \)
This scattered transfer impedance is then adjusted to the target:

\[ Z_{\text{transfer}}^{\text{scattered}}(R_0) = Z_{\text{transfer}}^{\text{scattered}}(R_1) \cdot R_1 e^{i\alpha} e^{i\beta R_1} \]  \hspace{1cm} (5-6)

where, \( Z_{\text{transfer}}^{\text{scattered}}(R_n) \) = Scattered Transfer Impedance at \( R_n \)

\( R_0 \) = Position at Target

All these equations are reasonably valid here with far-field assumptions. The term on the left has the dimensions of Ohm-m, and can be considered as a transfer impedivity; but is never the less termed as an impedance. The adjusting of the scattered potential by spherical divergence is not quite valid because of a long non-spherical target; however, consistency was maintained nevertheless, and at these distances the factors \( R \) and \( \sqrt{R} \) are approximately the same.

Figures 5.5-5 and 5.5-6 are results of the target transfer impedances using the horizontal electric dipole antennas. Figures 5.5-5a and b show the magnitude and phase of the target's transfer impedance pattern with respect to the vertical azimuth, 0 degrees is horizontal. Figures 5.5-6a and b are polar plot versions of the same. Note the amplitude lobe at -20 to +10 degrees; this plus the phase delay of 0.3 periods over this interval interferes with the primary pattern potential to produce the total potential-low and phase-delay high at 145 cm depth on Figures 5.5-4a and b respectively.
The other target pattern potential high lobes at 35 and -60 degrees constructively interfere with the transmitting antenna pattern to produce the total potential highs on Figure 5.5-4a at 115 and 175 cm depth. The graph is not quite symmetrical due to the slight dissimilarity of depth between the target and the transmitting antenna; the target is one half to one centimeter deeper.

Figures 5.5-7 thru 5.5-9 reveal the target effects using the vertical electric dipoles. Figures 5.5-7a and b show the transfer impedance amplitude and phase delay of the roving receiving antenna with respect to the fixed transmitting antenna. As with the horizontal electric dipole Figures 5.5-4a and b, these transfer impedances take into account both the antenna pair and the medium. Note the intensifying interference effects as the antenna is moved closer to the surface.

On Figure 5.5-7a, the maximums are further separated than those of Figure 5.5-4a. This is because of the preferential radiation directions of the vertical electric antennas, 40 degrees from the horizontal (see Figures 5.4-1a and 5.4-2a). The phase curve on Figure 5.5-7b is hyperbolic just as with Figure 5.5-4b, but the sides slope less.
The target's amplitude as shown on Figures 5.5-8a and b, reveal three lobes, one at 0 degrees, and the other two both at 50 degrees above and below the horizontal, with the lower one more intense. The asymmetrical nature between these lobes is probably due to the air-water interface, as shown on Figure 5.5-7a. The phase plot shows a fairly constant phase delay from -30 to +30 degrees, and then decreasing phase delay above and below this vertical azimuthal range.
Figs. 5.5-7a and b. Magnitude and phase of a fixed transmitter and roving receiver-pair; except using vertical electric dipoles. The target is at 130 cm depth, and again, note the decreased transmission here. The interference effects are from surface reflections.
Figs. 5.5–8a and b. Target scattered potential magnitude and phase delay, with respect to vertical azimuth, using the vertical dipole antennas.
Figs. 5.5–9a and b. Polar plots of the magnitude and phase delay for the target's scattered potential.
5.6 Conclusions

The scale model tank has simplified the antenna probing experiments greatly compared to those taken in the field. Having a homogeneous background has helped better understand the antenna fields and the target interactions. Although these are simplified scale models, the model tank configuration has helped isolate the various effects so each could be studied independently.

The vertical dipole antenna had some radiation from the coaxial shield feeding it, unlike the horizontal antenna. This same effect was described by King (1981), in that electromagnetic modes exist between the cable shield and the medium, in this case the solution. This could be fixed by perhaps choking the cable with beads or coiling the end near the antenna to at least re-orient the cable away from the vertical. Another way might be to strip back the cable insulation for an interval above the outer antenna tube so the solution is directly touching the shield. This would short any transverse electric fields between the solution and the shield, and hence prevent electromagnetic modes that propagate from the antenna back up between the solution and the outer conductive shield.

The 2 inch diameter pipe used as a target did have a strong effect on both the horizontal and vertical dipole antenna configurations. Because the target orientation was transverse to the image plane and hence the same electric
field polarization as the horizontal dipole antennas, a smaller diameter pipe could have been detected. The vertical electric dipole antenna configuration had no difficulty seeing the target either, even though the diameter (5 cm) was slightly less than the 5.8 cm half-wavelength used in the experiment. Lytle et al. (1979) stated that the lower limit resolving ability of the probing wave was half the wavelength. Here, the high contrast of the target against the background was enough to extend this limit. This high contrast does represent an idealized situation, but the results can be compared to some real-world situations, by scaling.
CHAPTER 6

GENERAL CONCLUSIONS AND SUGGESTIONS FOR FURTHER IMPROVEMENTS AND STUDY

The equipment and setups used for the experiments done in these studies were sufficient for general data accuracy. Medium attenuation and simple phase measurements could easily be measured once the equipment was configured for the particular experiment, and the more complex swept-frequency phase determination, although also more difficult to take, was usually seldom required. Because attenuation of a wave propagating thru a material is a monotonically increasing continuous function with respect to distance traveled, the measurement of this quantity lends itself much less to errors than the wave-phase delay.

However, the errors for phase measurements increase with the increasing number of either wavelengths in the system path, or wave periods in the wave travel-time. There are two ways this number can be large: from a high frequency, or by long cable lengths. The use of 15 MHz at the San Xavier Mine permitted longer cable lengths, but the use of 150 MHz with these long lengths did not permit the swept-frequency technique to be used at the Apache Leap site; shorter lengths had to be used. To show this, consider the following example.
Referring back to Equation 2.2.2-2:
\[ \frac{\sqrt{\varepsilon_r}}{c} R \omega_2 \approx \Phi_2 \]  
(2.2.2-2)

Modifying, then dividing by \(2\pi\)
\[ \Phi = \frac{\sqrt{\varepsilon_r}}{c} l \omega \]  
(6-1)

and,
\[ T = \frac{\sqrt{\varepsilon_r}}{c} l f = \text{velocity} \cdot l f \]

where,
- \(T\) = period
- \(l\) = length of cable
- \(f\) = frequency

And then taking the differential:
\[ \delta T = \text{velocity} l \delta f \]  
(6-2)

For a cable wave velocity of 200 Mm/s and length of 75 m, and a maladjustment of 2 MHz at 150 MHz, the phase error is \(3/4\) period, a very significant amount.

Although the frequency for the model tank experiments was high, 300 MHz, no significant problem arose because the cable lengths were short.

The employment of the parallel scan to determine the effect of a target was very useful. No geotomography should be attempted without a preliminary parallel scan first. With the constant antenna geometry, quick on-site
evaluations can be made with virtually no processing. If the parallel scan shows no target effect over that of the background, a subsequent geotomography would be unfounded.

The medium of investigation ultimately determines the frequency of use. An upper limit of frequency is determined by the medium wave-attenuation. Because of the need to resolve a target with a short enough wavelength, there is a restriction on the lower frequency limit. Hence, these two wave factors, the attenuation and the resolving power, are often at odds with each other in certain mediums. One such site was the San Xavier Mine; the medium scattering was such that a short enough vertically polarized electric wave could not discern tunnel targets unambiguously. Referring to Table 6, the wavelength at the San Xavier site is 5.4 m, and the diameter of the tunnel is no more than 2 m. Targets placed inside the tunnel would not be seen due to wavelength resolution (Lytle et al., 1979), unless the effective diameter of the tunnel was larger, as discussed earlier in chapter 4. When the two factors leave no overlap of useful frequency for a particular site, it is time to use another probing method.

A summary of the test site electrical characteristics are listed in Table 6. As can be seen from the table, the loss tangent was less than unity as displacement currents dominating over conduction currents, with the exception of
San Xavier. At this site, wave propagation was difficult, and very long antennas had to be used for cross-borehole reception.

<table>
<thead>
<tr>
<th>Location</th>
<th>Freq. (MHz)</th>
<th>α  (1/m)</th>
<th>β  (1/m)</th>
<th>Plane Wave Attenu. (dB/m)</th>
<th>λ  (m)</th>
<th>σ  (S/m)</th>
<th>ρ  (n/m)</th>
<th>ε′</th>
<th>ε″</th>
<th>$\frac{ε″}{ωε}$ (S s/F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Xavier</td>
<td>15</td>
<td>.76</td>
<td>1.16</td>
<td>6.7</td>
<td>5.4</td>
<td>.015</td>
<td>67</td>
<td>7.9</td>
<td>2.28</td>
<td></td>
</tr>
<tr>
<td>Apache Leap</td>
<td>15</td>
<td>.394</td>
<td>1.12</td>
<td>3.42</td>
<td>5.60</td>
<td>.00747</td>
<td>133.9</td>
<td>11.2</td>
<td>.800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>.523</td>
<td>8.73</td>
<td>4.54</td>
<td>.720</td>
<td>.00772</td>
<td>129.6</td>
<td>7.69</td>
<td>.120</td>
<td></td>
</tr>
<tr>
<td>Model Tank</td>
<td>300</td>
<td>4.20</td>
<td>55.1</td>
<td>36.5</td>
<td>.114</td>
<td>.196</td>
<td>5.10</td>
<td>76.6</td>
<td>.153</td>
<td></td>
</tr>
<tr>
<td>(7/8/90)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Tank</td>
<td>300</td>
<td>3.35</td>
<td>54.2</td>
<td>29.1</td>
<td>.116</td>
<td>.153</td>
<td>6.53</td>
<td>74.1</td>
<td>.124</td>
<td></td>
</tr>
<tr>
<td>(8/15/90)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Summary of different medium electrical characteristics.

At Apache Leap, however, the loss tangent was low enough for diffraction to pervade. Because the penetrating wavelength (72 cm) was short enough, and the medium is much more homogeneous compared to that at the San Xavier site, targets were easier to see.

The model tank medium and operating frequency yielded an attenuation per wavelength, or loss tangent (see section 5.2.4), that was very close to that of Apache Leap. Studies in the model tank used only direct immersion of the antennas in the medium, unlike that at Apache Leap where the boreholes insulated the antennas from the medium.
Also, no type of antenna to transmission line isolation was used in the model tank, such as the ferrite beads used in the field. This difference in the model tank might explain the electrically long length with resulting splitting of radiation lobes from the antenna (see section 5.4).

Some preliminary theoretical studies should be done before a site is investigated using geotomography. There are some references of electrical characteristics of rocks that include the conductivity, permittivity, and permeability that one can use to compute the wave attenuation and phase effects, such as Parkhomenko (1967), Lytle (1973), and Poley et al. (1978).

The cited resistivity for limestone (20-40 k Ohm-m, Parkhomenko, 1967) is much higher than that observed at the San Xavier site, about 67 Ohm-m, and hence, very misleading. The borehole logs (Figures 4.5-4a & b) for the San Xavier site do have resistivities of 50-60 Ohm-m at 50 m (165 ft) depth, very close to the cross-borehole tested values. In a case such as this, simple borehole logs could guide further studies, or other surface probing methods such as a resistivity or CSAMT survey.

Stolarczyk (1988) uses both an antenna with encapsulated transmitter, and fiber-optics at the receiving antenna to transfer the signal pre-processed so that both phase and attenuation errors are kept to a minimum. However, the investment in these equipment additions would be
The use of coils for antennas could be undertaken for a horizontally polarized electric field source. This would be more useful for detecting long horizontal objects, such as tunnels. Also, the source is more concentrated than electric dipole antennas, especially at lower frequencies. A future study site for this would be the San Xavier site.

A drawback of using coils, however, is that they have to be matched to the transmission line. The load is almost pure inductive at higher frequencies and coils are generally used at lower frequencies (King and Smith, 1981).

Theoretical models of plane wave scattering by a cylindrical object have been examined by Wait (1955), and by Lytle (1979), and studies such as these can be useful for ideas to approach tunnel detection problems.

A future use of this system might be the investigation of rock fracturing at the Apache Leap site using alterant geotomography. The site is currently being used for hydrogeological studies for permeability of volcanic tuff, as a precursor for nuclear waste storage studies done at a similar site. An array of boreholes are being drilled for the inclusion of a packer that will contain an electrical contrasting salt for fracture tracing, similar to the ones done by Ramirez and Daily (1987).
Effluent studies might be done at the San Xavier site using the cemented canal to hold a seeping saline solution for the purposes of ground water flow. Vertical coils would have to be used for sufficient target scattering of the horizontally polarized electric field.
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