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Experimental studies of electromagnetic signals to enhance radio imaging method (RIM)

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EXPERIMENTAL STUDIES OF ELECTROMAGNETIC SIGNALS TO ENHANCE RADIO IMAGING METHOD (RIM)

William D. Monaghan

Thesis submitted to the College of Engineering and Mineral Resources
West Virginia University
In partial fulfillment of requirements for the degree of

**Master of Science
In
Mining Engineering**

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Keywords: Electromagnetic, Radio Imaging Method (RIM), RADAR,
Attenuation, Geologic Anomalies, Physical Model, Longwall Mining

ABSTRACT

EXPERIMENTAL STUDIES OF ELECTROMAGNETIC SIGNALS TO ENHANCE RADIO IMAGING METHOD (RIM)

William D. Monaghan

Safety and production of coal mining operations could be greatly affected by geologic anomalies such as faults, sandstone intrusions, dykes, fracture zones, sudden thinning and severe undulation of the coal seam. Since most of these geologic anomalies in coal seams effect the attenuation rate of electromagnetic signal that passes through them, the radio imaging method (RIM), using a signal in the kilohertz range, is capable of locating the zones of geologic anomalies in underground coal mines with the help of tomographic reconstruction programs. RIM technology is a promising geophysical tool for exploring the geologic anomalies ahead of modern longwall faces, which are normally wider than 1,000 ft. When multiple geologic anomalies co-exist in an area, it is very difficult for RIM technology to differentiate the contributions of each individual anomalous factor. Other problems with RIM technology are the angular spreading and moisture content is not taken into consideration of the surveyed area. To increase the accuracy of RIM technology, spatial spreading testing and a scaled physical model were employed to investigate the capabilities and limitations of RIM technology. To simulate the RIM technology, a Ground Penetration RADAR (GPR) system was modified and a higher frequency signal was used in the scaled physical model. One of the problems using the GPR was that data collected was represented in counts and formulae had to be developed in order to convert the data into volts. Laboratory testing was conducted to assure proper similarities between the actual longwall panel and the scaled physical model. These model tests were done to gain a better quantitative understanding of the propagation of EM signals in the physical model. The testing procedure and data results are presented and quantified.

DEDICATION

This Master thesis is dedicated to my great grandfather, Patrick John Monaghan (1866 - 1949) and my father Patrick David Monaghan (1934 - 2000). My father was my best friend, my greatest hero, and a great mentor. He always encouraged me to do my best and to treat others with respect. My father told me about my great grandfather's life as a coal miner. My great grandfather was a coal miner in the early 1900's in Dravosburg, PA, and placed his life in harm's way every day when he worked in the coal mines. I received my great grandfather's coal mining pick as a gift on Aug 19, 2006 at the annual Monaghan 57th family reunion held in South Park, PA. I now treasure his coal mining pick with great pride and honor.

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ABBREVIATIONS OF UNITS

dB – decibels

ft – feet

Hz – cycle/second

in – inches

m – meters

ns – nanoseconds

s – seconds

μ V – microvolts

μ W – microwatts

V – volts

W – watts

CHAPTER 1

INTRODUCTION

Electromagnetic (EM) waves can propagate via highly resistive layers in the earth. A waveguide (boundaries capable of guiding electromagnetic waves) can be formed by a coal seam bounded by conducting rock (Wait, 1976). The Radio Imaging Method (RIM), which was developed about twenty years ago, shows promise in being able to locate geologic anomalies ahead of the longwall face and is based on Wait's findings. These geologic anomalies in the coal seam may be caused by faults, sandstone intrusions, dykes, fracture zones, sudden thinning and severe undulation of coal seams and can cause difficult mining conditions, loss of production and safety issues.

RIM technology is based on the EM wave properties, velocity and attenuation in the coal seam. Geologic anomalies in the coal seam affect the velocity (electromagnetic wave propagation described by the speed of light) usually presented in meter per second (m/s) and attenuation rate (the rate of reduction of the average power with respect to distance along a transmitting path) usually presented in decibels per meter (dB/m). From these changes in the EM wave it is possible to generate tomographic imaging (similar to a medical CAT scan) of the coal seam showing the geologic anomalies within the seam.

Figure 1.1 illustrates a RIM instrumentation setup on a longwall panel. This instrumentation consists of a transmitter (Tx) antenna, which is typically positioned on the headgate side of the longwall panel, and a receiving (Rx) antenna, which is usually positioned on the tailgate side. The theory of operation for the RIM technology is that the transmitted EM wave travels along a path in the coal seam and is received by the receiver antenna. As the EM wave encounters anomalies in the coal seam the EM wave changes in velocity and magnitude.

Figure 1.1 RIM imaging instrumentation (Stolarczyk and Peng, 2003)

The objective of this research is to increase the accuracy of the RIM technology by studying the EM wave properties on a scaled physical model of a longwall panel and quantifying the data collected. When multiple geologic anomalies co-exist in an area, it is very difficult for RIM technology to differentiate the contributions of each individual anomalous factor. Other problems with RIM technology are the angular spreading and moisture content is not taken into consideration of the surveyed area.

As mentioned earlier, the RIM instrumentation uses two antennas (one transmitter and one receiver) that are physically separated. In a typical RADAR system, one antenna is used for both the transmitter and receiver. This was a problem with the GPR system, provided by the National Institute for Occupational Safety and Health (NIOSH) used in this research. The GPR system was modified using a specialized antenna break-out-box, to allow the separation of the transmitter and receiver antenna. Another one of the problems using the GPR was that data collected was represented in counts and formulae had to be developed in order to convert the data into volts.

Prior to the EM surveys on the physical model, spatial spreading tests were performed in air in order to understand the EM wave signal strength and to develop the generation of angular and center spreading equations. In the physical model, the coal seam, floor, roof strata and geologic anomalies were simulated with properly mixed materials. The physical model was tested at different times to demonstrate the effect of aging and moisture content. The physical model EM test data was post-processed in several steps to quantify the data with known physical parameters of the model. This processed data was used to generate individual EM line scans and contour maps that in turn were compared with the embedded geologic anomalies. The end results demonstrate the various attenuations for each EM signal scan. These tests provide a better understanding of the propagation and signal characteristics of the EM signals that can be used to improve RIM.

CHAPTER 2

LITERATURE REVIEW

2.1 History of EM Wave Methods

The first survey using EM wave methods was performed in 1929 to sound the depth of a glacier (Stern, 1929, 1930). This EM wave method did not become popular until the late 1950's when the United States Air Force planes RADAR were seeing through ice as they tried to land in Greenland, but the pilots misread the altitude and crashed into the ice. This started the investigation of EM waves to see into the subsurface not only for ice sounding but also for mapping of subsoil properties and water tables (Cook, 1960). In 1967, a system was proposed and then built and flown as the surface electrical properties experiments on Apollo 17 to the moon.

After 1972, an explosion of applications, publications and research started in the field of EM wave technologies for geologic surveys by Geological Survey of Canada, United States Army Cold Regions Research and Engineering Laboratory (CRREL), Ohio State University (OSU), United States Bureau of Mines (USBM), Colorado School of Mines, Stolar Horizon Inc., and others (Olhoeft, 2003). Over 300 patents have been issued around the world based on EM wave technologies to detect and map geological conditions. In addition, many institutions, including West Virginia University, are performing research to further enhance the understanding of the complex propagation mechanism of the EM signals in geological formations for underground geological mapping.

The mining industry has shown a growing interest in non-invasive technologies for detecting and mapping geological conditions for several decades. Since the Quecreek mining accident that occurred on July 24, 2002, the Pennsylvania state government established the Governor's Commission on Mine Voids and Mine Safety to investigate and document hazards regarding accurate location of voids and avoidance of other hazards associated with mining (Commonwealth of Pennsylvania, 2002). One of the Commission's recommendations was to continue research, development and refinement of the various geophysical methods and to enable these techniques to be applied separately or in conjunction with drilling to provide more positive results pertaining to the location of and definition of mine voids (PA DEP, 2002).

2.2 EM Terminology, Definitions and Examples

The common terminology and definitions associated with EM wave theory are presented in this section in order to give the reader a more comprehensive understanding of this science.

2.2.1 EM Wave Propagation

Maxwell's Equations describe the propagation of an electromagnetic field. The patterns of EM wave propagation and scattering can be used to locate and quantitatively identify changes in electrical and magnetic properties in the ground (Olhoeft, 1980). Understanding the interaction between the electric and magnetic fields and the properties of matter can provide quantitative information.

2.2.2 Electrical and Magnetic Properties of Rocks, Soils and Fluids

In the early 1960's, Watt performed experiments to examine the electrical properties of the Earth's crust (Watt et al., 1963). He found that the propagation of the EM waves through different geological material is not only frequency dependent, but also depends on the electrical properties of the rocks under investigation. Several conclusions were reached in this research. The conductivity of the water in the rock fractures affects the electrical characteristics. Pressure at the time when the rock was formed affects the electrical characteristics. Temperature and the depth of the rock affect the electrical characteristics.

The electrical and magnetic properties of rocks, soils and fluids control the speed of propagation of EM waves and their amplitudes. In most cases, the electrical properties are much more important than the magnetic properties. At RADAR frequencies, in range of 1 MHz – 1.0 GHz, electrical properties are dominantly controlled by rock or soil density, and by the chemistry, state (liquid/gas/solid), distribution (pore space connectivity) and content of water (Olhoeft, 1980; Stillman, 2006).

Electrical properties come in two basic types: one that describes energy dissipation and the other that describes energy storage (Roberts, 1988). Electrical dissipation occurs as the result of charge motion (or transport) called conduction. Electrical conductivity is the ability of a material to transport charge through the process of conduction, normalized by geometry to describe a material property. Dissipation (or energy loss) results from the conversion of electrical energy to thermal energy (Joule heating) through momentum transfer during collisions as the charges move. Electrical storage is the result of charge-storing energy when the application of an external force moves the charge from some equilibrium position and there is a restoring force trying to move the charge back. This process is called dielectric polarization (Olhoeft, 1981).

The EM properties of geological material depend on many factors. For coal measure rocks, the most important of them are the moisture content, mineral composition, orientation of planes of weakness, and crystalline structure, etc. (Parkhomenko, 1967). Boykov in 2006, performed electrical experiments on coal samples for the Sewickley coal seam and found that the moisture content of the coal sample has the greatest affect on the electrical properties: dielectric constant (Figure 2.1) and attenuation rate (Figure 2.2).

Figure 2.1 Moisture effects on the dielectric constant at different moisture levels for a coal sample from the Sewickley seam (Boykov, 2006)

Figure 2.2 Moisture effects on the attenuation rate at different moisture levels for a coal sample from the Sewickley seam (Boykov, 2006)

2.2.3 Velocity of the EM Wave

The velocity of EM wave propagation in a material is defined by the speed. The EM wave propagation in a material is always slower than the velocity of light in vacuum (or free space). The velocity is controlled by the ability of the material to store energy by pushing back against an externally applied force. In electromagnetism, this is described by dielectric permittivity and magnetic permeability polarization properties (Olhoeft, 2003). The dielectric constant affects the velocity of propagation of the EM pulse. The dielectric constant ranges from 1 for air (fastest propagation) to 81 for water (slowest propagation). In rocks and minerals, dielectric properties are primarily a function of mineralogy, porosity, water saturation, frequency, and depending on the lithology, component geometries, and electrochemical interactions (Monaghan, 2003). Some approximate dielectric constant values for rock materials are: dry coal = 4.5, dry limestone = 5.5 and wet sandstone 6.0. Table 2.1 shows some approximate dielectric constants for various materials

In low loss, nonmagnetic materials, the velocity of EM wave propagation in the material is equal to the speed of light in vacuum (c), divided by the square root of the dielectric constant (ϵ). This formula is presented as follows:

$$\nu = c / \sqrt{\epsilon} \quad (2.1)$$

Where: ν = [m/s] is the velocity of the EM wave;

$c = 3 \times 10^8$ [m/s] is the velocity of light in a vacuum.

Table 2.1 Approximate dielectric constants for various materials

Material	Dielectric Constant	Material	Dielectric Constant
Air	1	Wet Granite	6.5
Snow Firm	1.5	Travertine	8
Dry Loamy/Clayey Soils	2.5	Wet Limestone	8
Dry Clay	4	Wet Basalt	8.5
Dry Sands	4	Tills	11
Ice	4	Wet Concrete	12.5
Coal	4.5	Volcanic Ash	13
Asphalt	5	Wet Sands	15
Dry Granite	5	Wet Sandy Soils	23.5
Frozen Sand & Gravel	5	Dry Bauxite	25
Dry Concrete	5.5	Saturated Sands	25
Dry Limestone	5.5	Wet Clay	27
Dry Sand & Gravel	5.5	Peats	61.5
Potash Ore	5.5	Organic Soils	64
Dry Mineral/Sandy Soils	6	Sea Water	81
Dry Salt	6	Water	81
Frozen Soil/Permafrost	6		
Syenite Porphyry	6		
Wet Sandstone	6		

2.2.4 Wavelength of the EM Wave

The wavelength is the spatial distance traversed by one period (or cycle) of the propagating EM wave. The wavelength is the velocity of propagation in the material divided by the frequency of the propagating wave. The formula is presented as follows:

$$\lambda = \nu / f \quad (2.2)$$

Where: λ = [m] wavelength;

ν = [m/s] is the velocity of the EM wave;

f = [c/s] is the frequency.

2.2.5 Waveguides

Under the right circumstances of geometry and EM property difference, EM propagating waves may be trapped and guided along paths specified by the geometries. Stolarczyk and Fry showed that in coal-bearing formations, seams are constrained by sedimentary layers of mudstone, claystone or shale and when the electrical conductivity of the surrounding sediment layers is greater than the conductivity of a seam, a natural parallel-plate waveguide forms in the strata (Stolarczyk and Fry, 1990). The waveguide in the coal seam is well presented when there is a difference of at least one order of magnitude in the dielectric constant between the coal seam and its bounding sedimentary rocks. When the natural waveguide exist in the coal seam, the EM wave can be transmitted through the coal more easily since more energy stays in the boundary of the waveguide. Figure 2.3 shows the EM wave's flow in coal seams.

Figure 2.3 Cross section of a coal seam showing EM wave flow (Stolarczyk and Fry, 1990)

In Figure 2.3, the electric field is polarized between the mudstone and the claystone sediment layers. This means the electric field is a vector pointing in a particular direction. Generally, the magnetic field is perpendicular to the electric field, and the direction of propagation is perpendicular to both electric and magnetic field directions. There is a small electric field component (E_x) aligned in the direction of propagation. The magnetic (H_y) field component is directed into the page. The horizontal EM wave will travel in the coal seam between the Tx and Rx antennas.

2.2.6 Attenuation, Resistivity, Conductivity

The attenuation is dependent upon the resistivity/conductivity of the media through which the EM signal is propagating, as well as the frequency of the EM signal itself. The depth of penetration of the EM signal in the strata is known to be inversely proportional to the wave attenuation (Reynold, 2003). If geologic anomalies such as faults, sandstone intrusions, sudden thinning and severe undulation of the coal seam are along the EM path, the EM signal will be significantly attenuated. The formula to calculate attenuation rate is presented as follows (Boykov, 2006):

$$\alpha = 8.68\omega\sqrt{\frac{\mu_0\epsilon_0\epsilon_r}{2}\left[\sqrt{1+(\tan\delta)^2}-1\right]} \quad (2.3)$$

Where: α = [dB/100ft] attenuation;

$\omega = 2\pi f$ where f is the frequency (Hz);

$\mu_0 = 4\pi 10^{-7}$ [Henry/m] permeability of free space;

$\epsilon_0 = (1/36)\pi 10^{-9}$ [Farads/m] permittivity of free space;

ϵ_r = dielectric constant of material;

$\epsilon_r = \epsilon'$ = real part of the dielectric constant;

ϵ'' = complex part of the dielectric constant;

$\tan\delta$ = the loss tangent, which is the ratio of ϵ''/ϵ' .

The resultant attenuation losses are exhibited as temperature rises, but also may be used (as apparent attenuation) to describe energy that is lost through geometric effects. Such apparent losses are the result of geometric spreading, surface and volume scattering, waveguides and multipathing (propagating waves leave the transmit antenna and travel to the receive antenna by multiple different paths). In multipathing, the energy is not transformed to heat and is still EM, but it is following a path

that is no longer useful or observable (Olhoeft, 1993). Figure 2.4 shows an attenuation increase in a coal seam and due to energy being dissipated as heat.

The electrical resistivity (or electric resistance) is a measure of how strong the material opposes the flow of electric current. The electrical conductivity is a measure of a materials ability to conduct an electrical current. Conductivity is the reciprocal (inverse) of electrical resisitivity. The formula to calculate the resistivity of rocks is presented as follows (Boykov, 2006):

$$R = \frac{1}{2\pi\epsilon_r \tan \delta(8,854 \times 10^{-12})} \quad (2.4)$$

Where: R = [ohm-m] resistivity.

The formula to calculate the conductivity is presented as follows:

$$\sigma = 1 / R \quad (2.5)$$

Where: σ = [Seimems per meter] conductivity.

2.2.7 Phase Change

When the electromagnetic (EM) signal travels through the subsurface media it is modified relative to that which travels through the air. The receiver EM signal will differ in both phase and amplitude relative to the unmodulated field that was generated by the transmitter. The degree to which the receiving EM signal differs provides important information about the geometry, size and electrical properties of the earth material.

Figure 2.4 Attenuation increase in a coal seam

As mentioned before, various types of geologic anomalies can exist in coal seams. Figure 2.5 shows an example of some of these geologic anomalies (Stolarczyk and Fry, 1990).

Figure 2.5 Natural waveguide anomalies in coal seams

2.2.8 Scattering

Scattering results when a propagating electromagnetic wave encounters a significant change in electrical or magnetic material properties (anomaly). Scattering creates secondary waves in the seam waveguide.

2.3 Applications and Limitation of RIM Technology for Modern Longwall Mining

Stolar Horizon, Inc. has developed instrumentation, survey procedures, and they have licensed a program from an Australian company to image the geological structure in front of longwall face. The survey is conducted in the gate roads of the longwall panel usually with the transmitter (Tx) antenna in the headgate and the receiver (Rx) antenna in the tailgate. Survey marks are typically placed at 20 ft increments and are referred to as survey measurement stations. A typical RIM survey setup for a longwall panel is shown in Figure 2.5.

As the EM wave, which is generated by the Tx antenna, encounters an anomalous geologic disturbance zone in the coal seam, the EM wave propagation constants (amplitude attenuation and phase) change and energy is scattered which creates secondary waves in the coal seam waveguide. A typical EM wave showing energy scattered is shown in Figure 2.6.

Figure 2.6 Typical RIM survey setup for a longwall panel (Stolarczyk and R.C. Fry, 1989)

Figure 2.7 Energy scatter from an anomalous geologic disturbance zone

In Figure 2.8, an example of the transmitted sinusoidal radio wave at the headgate and the received sinusoidal radio wave at the tailgate are shown. The radio wave received at the tailgate is attenuated and shifted in phase by (θ) electrical degrees. When the ray pass distance is known, the attenuation rate (α) in decibels per ft can be determined. This attenuation rate can be used as the baseline for the coal seam assuming there are no geologic anomalies encountered in the ray path. When the Tx antenna and Rx antenna are moved to various measuring stations and the attenuation rate increases, it is assumed that changes are a result from geologic anomalies ahead of the longwall face.

Figure 2.8 Sinusoidal radio wave signals along a ray path (Stolarczyk and R.C. Fry, 1989)

When a tomographic survey is performed through a rectangular block of coal, the Tx antenna and the Rx antenna move alternately at the predefined measurement stations located on the opposite sides of the block. After a complete RIM survey, hundreds of transmission ray paths from the Tx antenna to the Rx antenna at various measurement stations are formed. The received signal strength and the total attenuated energy for each ray path are determined and recorded. In the data analysis phase, the surveyed block is divided into small rectangular pixels. The rate of energy attenuation within a pixel is assumed to be the same. When a EM signal penetrates through a pixel, the energy attenuated by the pixel is the product of the attenuation rate and the distance through the pixel. The total energy attenuation along a ray path is the summation of the attenuations through the pixels on the path. Sophisticated tomographic reconstruction algorithms are employed to back-calculate the attenuation rates in the pixels. By systematically changing the attenuation rates for the pixels, the calculated and measured total energy attenuations can be matched with reasonable accuracy. The resulting attenuation rates are then plotted to show the distribution of the attenuation rate within the survey block which in turn is used as the indicators of geologic anomalies.

A typical tomographic image from a short section of an actual longwall panel is shown in Figure 2.9. In this image, the hottest color (red being the highest value) represents the areas with the highest attenuation rate (lower signal strength) and the cool color (blue being the lowest value) represents the areas with the lowest attenuation rate (higher signal strength).

Figure 2.9 Example of signal attenuation rate tomogram

It should be noted that longwall panels were approximately 500 ft. wide in the earlier 1980's. While today the widest longwall panel is about 1500 ft. wide. The National Mining Association (NMA) and the U.S. Department of Energy (DOE's) Industry of the Future Mining program provided research and development funds to extend the operating range of the RIM instrumentation to greater than 3,000 feet.

Stolar Horizon, Inc. has done considerable research to develop approaches and methodologies for improving the RIM range and detection accuracy of geologic anomalies. This variety of past research indicates the importance of further understanding angular spreading, material moisture content, increasing the range, understanding the influences of multiple geologic anomalies when they co-exist in a longwall panel and increasing the accuracy of the RIM method.

CHAPTER 3

OBJECTIVE OF THE RESEARCH

The overall objective of this research is to increase the accuracy of the RIM technology by studying the EM wave properties on a scaled physical model of a longwall panel and quantifying the data collected. The properties of interest are the EM signal attenuation rates caused from interfaces between the roof, seam, floor and targets (simulated geologic anomalies). The interfaces are those that cause a significant reduction (attenuation) in the EM signal received at the Rx antenna. There are many factors that effect the EM ray path between the Tx and Rx antennas and often it is difficult to understand the changes of the received signal strength and waveform at the Rx antenna. Simply identifying a received signal at an Rx antenna measuring station does not necessarily provide sufficient information about the ray path. It is of the utmost importance to know: the geometry of the surveyed area, the positions and contact points of the Tx and Rx antennas, the center and angular spreading of the Tx EM signal, and the electrical characteristics of the coal measure rocks to accurately image the area surveyed. Therefore this research focus is on identifying the effects of the roof, seam, floor and targets (geologic anomalies) on the EM signal in a scaled physical model. This research, which used a scaled model, can be used to: further define the characteristics of EM signals during an actual longwall panel RIM survey, provide insight in the design and development for software programs used for post processing the raw EM signal data, and provide insight in the design and development for software programs used for tomographic reconstruction.

CHAPTER 4

METHODOLOGY OF THE RESEARCH

This research was conducted to increase the accuracy of the RIM technology. An off-the-shelf Geophysical Survey System, Inc. (GSSI) SIR® (Subsurface Interface RADAR) II GPR system was modified to allow the separation between the Tx and Rx antenna. This separation was necessary since the GPR system work on the principle of reflective electromagnetic methodology. The Tx and Rx antennas are housed in one box that are separated by a precise distance. As mentioned before, the RIM system works on the principle of penetrative electromagnetic methodology and it uses two antennas located on the opposite sides of the investigated object.

The first stage of this research was to determine the signal strength reduction as spatial spreading. In spatial spreading the signal energy level is reduced as it travels through air space. In the next stage, EM surveys were conducted at various times and under different conditions on a scaled physical model. Methods were then developed to process the collected data. This was done by analyzing the contributions of the spatial spreading, analyzing the contributions of the geologic anomalies in the model, determining the attenuation rate of the each received signal, and contour mapping reconstruction of the model.

4.1 Instrumentation Terminology and Definitions

The common terminology and definitions associated with the instrumentation used in this research are presented in this section in order to give the reader a more comprehensive understanding of this science.

4.1.1 Range

The range parameter is a time value and tells the Geophysical Survey System how long to record a received signal after the systems sends out a transmit pulse. The range can be set. Any portion of the transmitted pulse that can reach the Rx antenna within the set range can be recorded or displayed. For a given antenna frequency, there is always a maximum depth that the signal can penetrate. There is a maximum range for any given situation beyond which you will get no received signal.

4.1.2 Gain

The signal received at the Rx antenna is very low amplitude and must be amplified by the system for viewing in its display screen and subsequent interpretation. Adjusting the gain factor in the Geophysical Survey System does this. The amount of amplification applied depends on the material

attenuation rate between the Tx and Rx. The amount of amplification generally increases when the distance between the Tx and Rx is increased. The gain factor is expressed in the units of dB.

4.1.3 Scan

A scan is the data that is recorded or displayed for a single received signal within the set range.

4.1.4 Samples/Scan

The numbers of data points taken per scan.

4.1.5 Bits/Sample

Bits/Sample is the resolution of the data taken at a data point. Typically bits/sample can be set to 8 or 16. The resolution of the data is determined by the 2 to the power of bits/sample. For example 8 bit data would have a resolution of 2^8 or 256 and 16 bit data would have a resolution of 2^{16} or 65536.

4.1.6 Scans/Second

Scan/Second is the number of scans taken in one second.

4.2 Instrumentation

The tests were conducted using a modified GSSI SIR[®] II model number DC-2 control unit, two 900 MHz antennas (Figure 4.1), with a specialized antenna breakout box built by GSSI. Figure 4.2 shows a close-up view of the antenna breakout box. A higher frequency (shorter wavelength) EM signal was used in the physical model testing versus a lower frequency (in the kilohertz range) which is used in an actual Stolar Horizon, Inc. RIM system. This was necessary due to the small size of the physical model to ensure the “similarity” between the actual longwall panel and the scaled model.

The control unit generates an electromagnetic pulse that is transmitted by the Tx antenna and is received by the Rx antenna. The power output of the 900 MHz Tx antenna is -24 dB and the transmitted energy of the pulse is radiated in a conical pattern (Figure 4.3). The received signal provides information on the attenuation characteristics (signal strength) associated with the material and the travel time.

Figure 4.1 GSSI SIR II GPR system with antenna breakout box

Figure 4.2 Close-up of antenna breakout box

Figure 4.3 Tx antenna radiated energy pattern

The limitations of the system depend on two electrical properties of the geological materials under investigation: dielectric constant and electrical conductivity. The dielectric constant affects the velocity of propagating EM pulse as indicated by Eq. 2.1. The dielectric constant ranges from 1 for air (fastest propagation) to 81 for water (slowest propagation). As mentioned before, the electrical conductivity (measure of a material's ability to conduct electric current, Eq. 2.5) controls the depth of pulse penetration. The lower the conductivity of the material, the deeper the pulse can penetrate. The depth of penetration of the EM pulse also depends on the antenna frequency. Higher frequency antennas have a shallow penetration and lower frequency antennas have deeper penetration.

4.3 Spatial Spreading

The signal strength measured at the Rx antenna will depend on the relative position of that antenna with respect to the Tx antenna. It is therefore necessary to define the Rx antenna position and signal strength in relationship to the XYZ Cartesian coordinate system (Figure 4.4) to develop equations. The emitting point of the Tx antenna is located at the origin and points to the X-axis of the coordinated system. It should be noted that the signal received at a point (xyz) from the transmitter is weaker then that at the emitting point. The difference in signal strength is due to two parts: the signal spatial spreading and the attenuation by media on the path. In order to obtain the total attenuation between points, the reduced signal strength at point (xyz) due to spatial spreading should be know first.

Figure 4.4 Three dimensional Cartesian coordinate system

In the development of the equations to represent the spatial spreading of EM signal in air an antenna grid array was utilized as shown in Figure 4.5. Data for signal strength reduction as spatial spreading were obtained in July, August, and December of 2005 and again in February of 2007.

Figure 4.5 Antenna grid array

The Tx and Rx antennas were placed in the horizontal/side lying position (Figure 4.6). The Tx antenna was stationary while the Rx antenna was moved at the grid points. A data set was obtained on Line 1 – Line 4, A - G to generate the data for the Y-axis. The complete data set consisted of 28 data points. Then, the Tx and Rx antennas were rotated by 90 degrees to the vertical/upright position and another data set was obtained for the Z-axis (Figure 4.7). The X-axis data was obtained from the center points or D (0°). The Rx antenna locations are provided in Table 4.1.

Table 4.1 Rx positions in antenna grid array

Line	Distance ft	Distance from Emitting Point						
		A (-45) ft	B (-30) ft	C (-15) ft	D (0) ft	E (15) ft	F (30) ft	G (45) ft
1	2	2.83	2.31	2.07	2	2.07	2.31	2.83
2	3	4.24	3.46	3.11	3	3.11	3.46	4.24
3	5	7.07	5.77	5.18	5	5.18	5.77	7.07
4	10	14.14	11.55	10.35	10	10.35	11.55	14.14

Figure 4.6 Antennas horizontal position (Y-axis)

Figure 4.7 Antennas vertical position (Z-axis)

4.4 Physical Model

In the scale model (Figure 4.8), the coal seam, floor, roof strata, and geologic anomalies are simulated with mixed sand, cement, gypsum, coal powder, and iron powder. Different ratios of sand, gypsum, and cement were used to build the floor and roof strata. A mixture of coal powder and gypsum were used to simulate the coal seam. Due to the relatively small size of the physical model, a high-frequency 900 MHz EM signal had to be used in the model testing to ensure the “similarities” between the actual longwall panels and the scaled model. Using this frequency allowed approximately 2 EM waves to travel through the model when the Tx and Rx antennas were positioned for reconnaissance surveys, as shown in Figure 4.9. EM reconnaissance surveys (Tx and Rx antennas are aligned without vertical or horizontal offset) were conducted in February 2006, April 2006, February 2007, and April 2007. Data points were obtained every 2-inch. on 5 different lines: L1 Floor, L2 Coal Seam, L3 Coal Seam/Roof, L4 Roof, L5 Objects as shown in Figure 4.10. The actual physical model is shown in Figure 4.11.

Figure 4.8 Scaled physical model dimensions

Figure 4.9 EM reconnaissance survey setup

Figure 4.10 Scaled physical model reconnaissance survey lines

Figure 4.11 Scaled physical model

CHAPTER 5

DATA COLLECTION AND CONVERSION

The first step of this research was to determine the spatial spreading of the EM signal (reduction of energy level as it travels through air space). In the next stage, EM reconnaissance surveys were conducted at various times and under different conditions on a scaled physical model.

The data collected from the spatial spreading tests and physical model tests were recorded on the modified GPR instrumentation. A series of tests were conducted, generally 28 data points for the spatial spreading testing, and 155 data points for the reconnaissance physical model testing.

The data was prepared for analysis initially by downloading the raw data from the modified GPR instrumentation to a computer. In order to facilitate the handling and analysis of the data, several programs were utilized. These programs included: the GSSI data transfer utility, GSSI RADAR Data Analyzer (RADAN), GSSI RADAN to ASCII conversion, Microsoft Excel, CurveExpert and Golden Software Surfer.

The data was collected in terms of signal amplitude (counts) and time (samples). A typical waveform consists of 512 samples. A sample is a memory location, which stores five integers. The first two samples contain the header information about the signal waveform. This information includes: time, date, range, gains points and, resolution. The remaining 510 samples contain the signal amplitudes for the complete waveform. The time per sample can be determined by taking the range, which is set in the instrumentation, divided by 510. The formula is presented as follows:

$$\text{Time per sample} = \text{range}/510 \quad (5.1)$$

As an example:

$$\text{range} = 15 \text{ ns};$$

$$\text{time per sample} = 29.41 \text{ ps.}$$

5.1 Data Conversion

A number of data analysis techniques were used to convert the raw data into ASCII format and then into voltages, taking into consideration the relationship between the gain factors in dB, scaling factors for volts, and the scaling factor for counts. To generate the spatial spreading equations, the CurveExpert program was used. For the reconstruction of the attenuation signal strength distribution contour maps, the Surfer program was used.

5.1.1 Conversion of Raw Data into ASCII

The raw data generated in the GSSI instrumentation is in a proprietary format file (*.DZT). In order to further post process the raw data, the DZT files were converted to ASCII (American Standard Code for Information) using a RADAN to ASCII conversion utility program. As mention earlier, each scan has a total of 512 memory locations and the first two memory locations contain the header information which is not needed for the final data analysis. The resolution of each memory location is 65,536 absolute counts. The counts can range from +32768 to -32768. An example of single scan data converted to ASCII then imported into a Microsoft Excel spreadsheet is shown in Figure 5.1.

Figure 5.1 Single scan converted to ASCII

5.1.2 Conversion of Counts into Volts

As mentioned earlier, the raw data signal strength from the collected data is represented in counts with an absolute maximum count of 65,536. Typically signal strength is expressed in units of power (W), voltage (V), or decibels (dB). In order to make the data more understandable the absolute signal strength was converted into volts. This conversion was accomplished by using following basic equations (UNSW, 2007):

$$dB = 10 \log \left(\frac{P_2}{P_1} \right) \quad (5.2)$$

$$dB = 20 \log \left(\frac{v_2}{v_1} \right) \quad (5.3)$$

Where:

P_1, P_2 - the reference and actual power, μW ;

v_1, v_2 - the reference and actual voltage, μV .

The 900 MHz Tx antenna used in the tests emits a maximum signal strength of 4 μW or 63 μV . Since 1 mW is equivalent to 0 dB, the maximum signal strength emitted for the Tx antenna is -24 dB. The data collected in the tests used different gain factors in order to make the signal scan waveforms more easily visible on the instrumentation control panel display. The data obtained in the various tests using different gain factors had to be scaled to a level of 0 dB. If the signal strength is expressed in volts, the relationship between the scaling factors for volts is S_v . The relationship between the voltage scaling factor and the gain factor are shown in the following equations:

By using equation 5.3, and substituting in the 900 MHz maximum signal strength, the scaling factor for volts S_v , can be derived

$$dB = 20 \log \left(\frac{v_2}{v_1} \right)$$

$$-24 + G = 20 \log \left(\frac{63 S_v}{1000} \right)$$

$$(-24 + G) / 20 = \log\left(\frac{63S_v}{1000}\right)$$

$$10^{(-24+G)/20} = \left(\frac{63S_v}{1000}\right)$$

$$63S_v = 1000 \times 10^{(-24+G)/20}$$

$$S_v = (15.8730) \times 10^{(-24+G)/20} \quad (5.4)$$

Where:

S_v - scaled factor for volts;

G - Gain (dB).

If the uncorrected signal strength is in counts, the scaling factor for count S_c is determined by the following equation:

$$S_c = \frac{2^{16}}{63} \times S_v \quad (5.5)$$

Where:

S_c - scaled factor for counts;

S_v - scaled factor for voltage.

The relationship between volts (uV), and S_c (scaled counts) is determined by the following equation:

$$V = counts / S_c \quad (5.6)$$

Where:

V – Voltage (μV).

5.1.3 Signal Discrimination

A typical EM waveform converted into ASCII and then plotted in Excel is shown in Figure 5.2. The Y-axis represents the signal strength maximum and minimum in counts and the X-axis represent

samples. As mentioned earlier, the waveform consists of 510 samples on the X-axis and each sample can be converted to a time as indicated by Eq. 5.1.

This research was focused on the analysis of the first received maximum and minimum amplitudes. A recommended area for future research is to understand the signal characteristics after the first received maximum and minimum amplitudes. It should be noted that with multiple reflections in the waveform, signal discrimination techniques have been developed that consider the velocity of the EM waveform. The logic used is as follows:

1. Determine the relaxation pulse.
2. Determine the first maximum and minimum counts after the relaxation pulse.
3. Take the absolute value of the maximum and minimum counts.
4. Convert the absolute value of counts into user-friendly units of volts.
5. Use the relaxation pulse to determine the first arrival time.

Figure 5.2 Typical converted EM waveform

The scaling factors (S_v , S_c) for a range of gain factors (0 to 40 dB) are shown in Table 5.1.

Table 5.1 Gain factors (G), voltage scaling factors (S_v) and counts scaling factors (S_c)

Gain Factor G(dB)	Scaling Factor Applied to μV		Scaling Factor Applied to Counts	
	S_v	$1/S_v$	S_c	$1/S_c$
0	1.0015	0.9985	1041.83	0.0009598
1	1.1237	0.8899	1168.96	0.0008555
2	1.2608	0.7931	1311.59	0.0007624
3	1.4147	0.7069	1471.63	0.0006795
4	1.5873	0.6300	1651.20	0.0006056
5	1.7810	0.5615	1852.67	0.0005398
6	1.9983	0.5004	2078.73	0.0004811
7	2.2421	0.4460	2332.38	0.0004287
8	2.5157	0.3975	2616.97	0.0003821
9	2.8227	0.3543	2936.29	0.0003406
10	3.1671	0.3157	3294.57	0.0003035
11	3.5535	0.2814	3696.57	0.0002705
12	3.9871	0.2508	4147.62	0.0002411
13	4.4736	0.2235	4653.70	0.0002149
14	5.0195	0.1992	5221.54	0.0001915
15	5.6320	0.1776	5858.67	0.0001707
16	6.3192	0.1582	6573.53	0.0001521
17	7.0902	0.1410	7375.63	0.0001356
18	7.9554	0.1257	8275.59	0.0001208
19	8.9261	0.1120	9285.36	0.0001077
20	10.0152	0.0998	10418.35	0.0000960
21	11.2372	0.0890	11689.58	0.0000855
22	12.6084	0.0793	13115.92	0.0000762
23	14.1468	0.0707	14716.31	0.0000680
24	15.8730	0.0630	16511.97	0.0000606
25	17.8098	0.0561	18526.73	0.0000540
26	19.9829	0.0500	20787.34	0.0000481
27	22.4212	0.0446	23323.77	0.0000429
28	25.1570	0.0398	26169.71	0.0000382
29	28.2267	0.0354	29362.89	0.0000341
30	31.6708	0.0316	32945.71	0.0000304
31	35.5353	0.0281	36965.69	0.0000271
32	39.8712	0.0251	41476.19	0.0000241
33	44.7362	0.0224	46537.05	0.0000215
34	50.1949	0.0199	52215.43	0.0000192
35	56.3196	0.0178	58586.67	0.0000171
36	63.1916	0.0158	65735.33	0.0000152
37	70.9022	0.0141	73756.25	0.0000136
38	79.5535	0.0126	82755.87	0.0000121
39	89.2605	0.0112	92853.62	0.0000108
40	100.1520	0.0100	104183.47	0.0000096

CHAPTER 6

DATA ANALYSIS

As mentioned earlier, the overall goal of this research is to increase the accuracy of the RIM technology by studying the EM wave properties on a scaled physical model of a longwall panel and quantifying the data collected. This was accomplished by performing spatial spreading testing in air and EM reconnaissance surveys on a scaled physical model. After analyzing the data from the spatial spreading testing, an understanding was gained on the signal strength reduction in the X, Y and Z directions and an equation was developed. This was needed since simply identifying a received signal at an Rx antenna in an EM survey does not necessarily provide all sufficient information about the signal.

In a scaled physical model the geometry of the area being surveyed, locations of the geologic anomalies, thickness of the roof and coal seam, and the contact points of the Tx and Rx antennas were all known. These parameters are important since they were needed in the data analysis of the EM surveys performed on the scaled physical model. Surveys on the physical model were performed at different times to gain an understanding of how the moisture content effects the EM signal characteristics. It was possible to determine the attenuation rate of the EM signal in the scaled physical model. The total attenuation rate is determined by taking the difference between the signal strength measured in air and the measured signal strength in the physical model. Figure 6.1 shows the voltage differences caused by media at three different points (V1, V2, and V3) in a model. $V(a)$ is the measured strength (volts) in air and $V(m)$ is the measured signal strength (volts) in the model. The following equation shows how to determine the actual voltage drop due to the model at different points.

$$V_i = V(a) - Vm_i \quad (6.1)$$

Where:

V_i = actual voltage of model at point i;

$V(a)$ = air voltage;

Vm_i = measured voltage of the model at point i.

The voltage attenuation rate at point i can be determined by dividing the actual voltage of the model by the distance between the Tx and Rx antennas. This is shown in the following equation.

$$\text{Attenuation Rate} = V_i/L \quad (6.2)$$

Where: L = distance.

Equations are needed to determine the center and angular spreading

Figure 6.1 Example of measured signal strengths in the physical model

6.1 Signal Strength Reduction as Spatial Spreading Data Analysis

As mentioned earlier, the transmitted energy of the pulse for the Tx antenna is radiated in a conical pattern as shown in Figure 6.2. As the energy travels through space, it spreads and the signal strength is reduced. Spatial spreading testing was performed in air to generate an equation that can be used to determine this signal strength reduction in the XYZ coordinate plane. Additional data on spatial spreading is located in Appendix A.

Figure 6.2 Example of signal strength reduction and spreading in air

6.1.1 Equation Developed

The follow equation was developed to determine the signal strength $V(a)$ at a given point (xyz) . The Tx antenna is at the origin of the XYZ coordinate system and the Rx antenna is located at some point in the XYZ coordinate plane (Figure 4.4).

$$V(a) = Vc(x) * f(\phi y) * f(\phi z) \quad (6.3)$$

The derivation for each part of this equation as a function of the antennas orientation is presented below.

6.1.2 Signal Strength Reduction Development for the Equation in the X Direction

Finding the maximum signal strength at point D, lines 1 – 4 for several data sets, was the method used for the development of the X part of the equation. Figure 6.3 shows point D for lines 1 – 4.

Figure 6.3 Center spreading points used to determine the X equation

Data from four different spatial spreading tests were used in the development of the X-axis equation. The data is shown in Table 6.1. Data values were then plotted in CurveExpert as shown in Figure 6.4. The equation developed for the X-axis is as follows.

$$Vc(x) = 1/(a + bx^c) \quad (6.4)$$

Where:

$$a = -0.090073;$$

$$b = 0.1454967;$$

$$c = 0.5395678.$$

With the development of this equation, the center spreading signal strength in air at a fixed distance can be determined.

Table 6.1 X equation development

Line	Point	Distance ft	Volts uV
1	D	2.00	8.40
1	D	2.00	8.10
1	D	2.00	8.20
1	D	2.00	8.60
2	D	3.00	5.30
2	D	3.00	5.20
2	D	3.00	5.60
2	D	3.00	5.50
3	D	5.00	4.30
3	D	5.00	4.50
3	D	5.00	4.40
3	D	5.00	4.50
4	D	10.00	2.14
4	D	10.00	2.10
4	D	10.00	2.30
4	D	10.00	2.10

Figure 6.4 Curve fitting for X equation development

6.1.3 Signal Strength Reduction Development for the Equation in the Y Direction

From the spatial spreading tests, the Tx and Rx antenna were positioned as shown in Figure 4.6. The data was collected from lines 1 – 4, points A – G, as shown in Figure 6.3. The following data was obtained and is shown in Table 6.2.

1. Rx position and angle with respect to the Tx as shown in Figure 6.3.
2. Memory locations, counts, and arrival times.
3. Absolute magnitude of the memory counts.
4. Velocity of wave.
5. Air volts, derived from the gain and scaling factor as shown in Table 5.1.
6. Normalized magnitudes that are used for equation development.

Data values were then plotted in CurveExpert as shown in Figure 6.5.

Table 6.2 Spatial spreading testing Tx and Rx in the horizontal position (Y)

Tx=90 Rx=90, File # 1010-1037, Range 20(ns), Gain 15 (dB), Sv=5.6320, Sc=5858.7, Offset -1.67(ns), February 5, 2007														
Rx Point	Distance, ft	Angle, deg	Memory	Max	time	Memory	Min	time	Ave. time	Abs	First Arrival	Velocity	Air Volts	Normalized
	receiver		Location	Count	ns	Location	Count	ns	ns		ns	ft/ns	(uV)	
L1-A	2.83	-45	50	10624	1.96	36	-8832	1.41	1.69	19456	2.63	1.08	3.3209	0.40
L1-B	2.31	-30	38	18304	1.49	24	-14464	0.94	1.22	32768	2.16	1.07	5.5930	0.68
L1-C	2.07	-15	35	24448	1.37	21	-18816	0.82	1.10	43264	2.04	1.01	7.3846	0.90
L1-D	2.00	0	33	26496	1.29	19	-21632	0.74	1.02	48128	1.96	1.02	8.2148	1.00
L1-E	2.07	15	31	24496	1.22	18	-20864	0.71	0.96	45360	1.89	1.10	7.7423	0.94
L1-F	2.31	30	39	18048	1.53	25	-15488	0.98	1.25	33536	2.20	1.05	5.7241	0.70
L1-G	2.83	45	52	12416	2.04	37	-9600	1.45	1.74	22016	2.71	1.04	3.7578	0.46
L2-A	4.24	-45	81	7296	3.18	66	-4992	2.59	2.88	12288	3.85	1.10	2.0974	0.38
L2-B	3.46	-30	60	13184	2.35	46	-10368	1.80	2.08	23552	3.02	1.14	4.0200	0.72
L2-C	3.11	-15	54	16560	2.12	41	-12800	1.61	1.86	29360	2.79	1.12	5.0114	0.90
L2-D	3.00	0	52	18560	2.04	38	-14208	1.49	1.76	32768	2.71	1.11	5.5930	1.00
L2-E	3.11	15	58	16384	2.27	43	-13056	1.69	1.98	29440	2.94	1.06	5.0250	0.90
L2-F	3.46	30	62	13184	2.43	48	-10880	1.88	2.16	24064	3.10	1.12	4.1074	0.73
L2-G	4.24	45	82	9600	3.21	68	-6528	2.67	2.94	16128	3.88	1.09	2.7528	0.49
L3-A	7.07	-45	160	5760	6.27	145	-4224	5.68	5.98	9984	6.94	1.02	1.7041	0.35
L3-B	5.77	-30	126	10368	4.94	112	-8064	4.39	4.66	18432	5.61	1.03	3.1461	0.65
L3-C	5.18	-15	109	14848	4.27	96	-11520	3.76	4.02	26368	4.94	1.05	4.5007	0.94
L3-D	5.00	0	109	16000	4.27	96	-12160	3.76	4.02	28160	4.94	1.01	4.8065	1.00
L3-E	5.18	15	110	15104	4.31	96	-11520	3.76	4.04	26624	4.98	1.04	4.5444	0.95
L3-F	5.77	30	122	10136	4.78	109	-9344	4.27	4.53	19480	5.45	1.06	3.3250	0.69
L3-G	7.07	45	158	7040	6.19	143	-5760	5.61	5.90	12800	6.86	1.03	2.1848	0.45
L4-A	14.14	-45	342	2688	13.41	330	-2176	12.94	13.17	4864	14.08	1.00	0.8302	0.31
L4-B	11.55	-30	284	5760	11.13	269	-3968	10.54	10.84	9728	11.80	0.98	1.6604	0.62
L4-C	10.35	-15	246	7808	9.64	232	-5504	9.09	9.37	13312	10.31	1.00	2.2722	0.85
L4-D	10.00	0	239	9088	9.37	224	-6528	8.78	9.07	15616	10.04	1.00	2.6654	1.00
L4-E	10.35	15	246	8320	9.64	232	-6016	9.09	9.37	14336	10.31	1.00	2.4470	0.92
L4-F	11.55	30	285	6016	11.17	271	-4224	10.62	10.90	10240	11.84	0.98	1.7478	0.66
L4-G	14.14	45	346	3456	13.56	332	-2176	13.01	13.29	5632	14.23	0.99	0.9613	0.36

Figure 6.5 Curve fitting for Y equation development

The equation developed for the Y-axis is as follows.

$$f(\phi_y) = ae^{\frac{-\phi_y^2}{2c^2}} \quad (6.5)$$

Where:

$$a = 1.008668;$$

$$c = 33.37539.$$

6.1.4 Measured Radiation Distribution in the Y Direction

The measured radiation distributions for the Y direction are shown in Figure 6.6. In this figure, the hotter color (red) represent higher signal strengths and the cooler color (blue) represent lower signal strengths. The numerical values in the contour mapping are volts that were derived from the absolute magnitude counts.

Figure 6.6 Measured radiation distribution in the Y direction

6.1.5 Signal Strength Reduction Development for the Equation in the Z Direction

From the spatial spreading tests, the Tx and Rx antenna were repositioned as shown in Figure 4.7. The data was collected from lines 1 – 4, points A – G, as shown in Figure 6.3. The testing procedure was identical to the testing performed in the Y direction with the exception of the Tx and Rx antennas being rotated by 90 deg. The testing data and results are shown in Table 6.4. Data values were then plotted in CurveExpert as shown in Figure 6.7.

Table 6.3 Spatial spreading testing Tx and Rx in the vertical position (Z)

Tx=60 Rx=60, File # 1038-1065, Range 20(ns), Gain 15 (dB), Sv=5.6320, Sc=5858.7, Offset -2.67(ns), February 5, 2007													
Rx Point	Distance, ft	Angle, deg	Memory	Max	time	Memory	Min	time	Ave. time	Abs	First Arrival	Velocity	Air Volts
receiver			Location	Count	ns	Location	Count	ns	ns		ns	ft/ns	(uV)
L1-A	2.83	-45	42	12928	1.65	28	-9600	1.10	1.37	22528	2.63	1.08	3.8452
L1-B	2.31	-30	31	21632	1.22	18	-16000	0.71	0.96	37632	2.24	1.03	6.4233
L1-C	2.07	-15	28	27776	1.10	15	-18816	0.59	0.84	46592	2.12	0.98	7.9526
L1-D	2.00	0	26	31104	1.02	12	-19328	0.47	0.74	50432	2.00	1.00	8.6081
L1-E	2.07	15	30	27216	1.18	15	-17792	0.59	0.88	45008	2.12	0.98	7.6823
L1-F	2.31	30	39	19000	1.53	25	-14672	0.98	1.25	33672	2.51	0.92	5.7474
L1-G	2.83	45	54	11904	2.12	39	-9344	1.53	1.82	21248	3.06	0.93	3.6267
L2-A	4.24	-45	77	9344	3.02	64	-6528	2.51	2.76	15872	4.04	1.05	2.7091
L2-B	3.46	-30	58	14208	2.27	43	-11392	1.69	1.98	25600	3.22	1.08	4.3696
L2-C	3.11	-15	51	17536	2.00	38	-12928	1.49	1.74	30464	3.02	1.03	5.1998
L2-D	3.00	0	51	17536	2.00	37	-14464	1.45	1.72	32000	2.98	1.01	5.4620
L2-E	3.11	15	56	16488	2.20	42	-12416	1.65	1.92	28904	3.18	0.98	4.9335
L2-F	3.46	30	66	12160	2.59	52	-9856	2.04	2.31	22016	3.57	0.97	3.7578
L2-G	4.24	45	84	8448	3.29	69	-6912	2.70	3.00	15360	4.23	1.00	2.6217
L3-A	7.07	-45	151	7040	5.92	137	-5504	5.37	5.64	12544	6.90	1.02	2.1411
L3-B	5.77	-30	119	10880	4.66	105	-8320	4.12	4.39	19200	5.65	1.02	3.2772
L3-C	5.18	-15	104	13952	4.08	92	-9856	3.61	3.84	23808	5.14	1.01	4.0637
L3-D	5.00	0	105	14976	4.12	92	-10624	3.61	3.86	25600	5.14	0.97	4.3696
L3-E	5.18	15	108	13720	4.23	95	-10136	3.72	3.98	23856	5.25	0.99	4.0719
L3-F	5.77	30	125	10112	4.90	113	-9088	4.43	4.66	19200	5.96	0.97	3.2772
L3-G	7.07	45	161	6784	6.31	147	-6016	5.76	6.04	12800	7.29	0.97	2.1848
L4-A	14.14	-45	340	3968	13.33	357	-3712	13.99	13.66	7680	14.86	0.95	1.3109
L4-B	11.55	-30	278	5760	10.90	297	-4992	11.64	11.27	10752	12.43	0.93	1.8352
L4-C	10.35	-15	243	7040	9.53	227	-6016	8.90	9.21	13056	10.43	0.99	2.2285
L4-D	10.00	0	238	7296	9.33	223	-6528	8.74	9.04	13824	10.27	0.97	2.3596
L4-E	10.35	15	248	6528	9.72	233	-6016	9.13	9.43	12544	10.66	0.97	2.1411
L4-F	11.55	30	284	6528	11.13	301	-5248	11.80	11.47	11776	12.66	0.91	2.0100
L4-G	14.14	45	348	4736	13.64	363	-3712	14.23	13.94	8448	15.17	0.93	1.4420

The equation developed for the Z-axis is as follows.

$$f(\phi_z) = ae^{\frac{-\phi_z^2}{2c^2}} \quad (6.6)$$

Where:

$$a = 1.000621;$$

$$c = 38.69559.$$

Figure 6.7 Curve fitting for Z equation development

6.1.6 Measured Radiation Distribution in the Z Direction

The measured radiation distributions for the Z direction are shown in Figure 6.8. It is noted that the signal strengths are slightly higher when the antennas are in the vertical positions. As mentioned before, numerical values in the contour mapping are volts that were derived from the absolute magnitude counts.

Figure 6.8 Measured radiation distributions in the Z direction

6.2 Scaled Physical Model Data Analysis

Reconnaissance EM surveys were performed on the scaled physical model at various times and under different conditions to understand how the roof, objects, coal seam and floor effect the received signal characteristics. Two examples of the EM reconnaissance surveys and data analysis are presented in this chapter. Additional data on the reconnaissance surveys are located in Appendix B. The first set of data presented is a series of surveys from a dry model. The second set of data presented is from the same model where the moisture content was approximately 7% by weight. The data are plotted in contour forms, and in individual line scans from the dry and wet model (a short summary is provided at the end of each paragraph), which are compared to the known geometry and geologic anomalies. The data presented are quantified as they are compared to the know geometry and physical properties of the model.

6.2.1 Procedure to Determine the Voltage Attenuation Rate in the Scaled Physical Model

The following procedure was used to determine the voltage attenuation rate of a single EM scan in the physical model. An example of this procedure is shown in Figure 6.9.

1. Determine the air volts $V(a)$ by using Eqs. 6.3, 6.4, 6.5 and 6.6.
2. Determine the maximum and minimum counts of the EM model scan after the relaxation pulse as shown in Figure 5.2.
3. Determine the absolute count from the maximum and minimum count.
4. Determine the model voltage (V_m) by taking the absolute count divided by the scaling count factor Eq. 5.6.
5. Determine the voltage attenuation (V_i) caused by the media Eq. 6.1.
6. Determine the voltage attenuation rate Eq. 6.2.

Figure 6.9 Example of determining signal attenuation rate in the scaled physical model

6.2.2 Reconnaissance Survey Scaled Physical Model

In a reconnaissance survey, the Tx and Rx antenna are positioned with no offset angle in the Y or Z direction. The antennas are in line and in this testing separated by 22.5 inches, which is the width of the physical model as shown in Figure 4.8. The surveys were performed every 2 inches on 5 different lines as shown in Figure 4.10. The total number of data points generated is 155 (31 points per line) in the reconnaissance survey of the physical model.

6.2.3 Distribution of EM Signal Attenuation of the Dry and Wet Physical Model

After the reconnaissance data from the dry and wet model was analyzed, Surfer software was used to generate contour images of the EM attenuation distributions. Figure 6.10 and Figure 6.11 show examples of the contour plots of the attenuation rates. The unit for this attenuation rate is uV/ft. The unit of voltage was used since there is not a wide range of values in the data sets.

Figure 6.10 Total signal strength attenuation distribution in dry physical model

Figure 6.11 Total signal strength attenuation distribution in wet physical model

In Figures 6.10 and 6.11, in general the attenuation rate increases as the coal seam becomes thinner. The embedded objects in the model (metal box, air void (empty box), and wood box) as shown in Figure 4.8, are identified by the changes in the contour lines at the approximate locations in both the wet and dry models. In the wet model the overall attenuation rate increases compared to the dry model. In addition there are less contour lines in the wet model compared to that of the dry model. This reduction in contour lines is caused by the semi-homogeneous moisture distribution in the model. In the case of the wet model, there are fewer changes in the attenuation rate throughout the model. In general, in the wet physical model the attenuation rate is lower on the top (roof) and higher on the bottom (floor). This indicates drying of the model from the top to the bottom.

6.2.4 Reconnaissance Survey of the Dry Physical Model

To better understand the EM signal characteristics, line scans were compared to the known geologic anomalies in the model. As mentioned earlier, 31 data points were obtained on every line. The higher voltage signals represent lower attenuation rates while the lower voltage signals represent higher attenuation rates. The voltage attenuation rate as determined by equation 6.2, ranged between 0.72 uV/ft to 4.22 uV/ft in the dry model.

It should be noted that in rare cases the manufacture of the instrumentation has observed model voltage signal higher than the air voltage signal while performing similar type of tests. These tests were performed on very dry fire bricks (composed of hard clay material and metal fines) used in high temperature kiln ovens. In these cases the attenuation would appear negative which is not possible. It

was believed that the media material (hard clay and metal fines) focused the EM signal on the Rx antenna (GSSI, 2006).

As mentioned earlier the characteristics of interest are the EM signal attenuation rates caused from interfaces between the roof, seam, floor and objects (simulated geologic anomalies). The interfaces are those, which cause a significant reduction (attenuation) in the EM signal received at the Rx antenna. Attenuation rates for each line: L5 Objects, L4 Roof, L3 Coal Seam/Roof, L2 Coal Seam, L1 Floor and air voltage as determined by Eq. 6.3 are shown in the figures below. It is important to show the air voltage in these figures since the actual line attenuation is determined by subtracting the measured model voltage from the air voltage as determined by Eq. 6.1 As mention earlier, Eq. 6.2 determines the attenuation rate. In addition, each data table for these lines is presented.

In Figure 6.12, the edge effect of the model is shown at approximately 6 inches at the beginning and end for both line 5 (L5 Objects) and line 4 (L4 Roof). The edge effect is caused by the physical geometry of the model and the wooden frame and metal lag bolts used to support the model as shown in Figure 4.11. Near the edge of the model the EM signal may find a multipath. As shown by L5, the first object (metal box) caused a voltage attenuation increase starting at approximately 7 inches and continuing until 14 inches. The second object (empty box) caused a voltage attenuation increase starting at approximately 28 inches and continuing until approximately 36 inches. It was expected to see a voltage attenuation decrease at the location of the empty box; however, the voltage attenuation increase may have been caused by moisture trapped inside the empty box. The third object (wood box) voltage attenuation rate changes are not as pronounced as the metal box and the empty box. A small voltage attenuation rate increase is observed at approximately 54 to approximately 57 inches then a larger voltage attenuation rate decrease is observed at approximately 57 inches.

Figure 6.12 Dry model objects and roof lines

Table 6.4 Reconnaissance survey dry physical model line 5 objects

April 22, 2007 Dry Model, Line 5 Objects, File # 1017 - 1019, X = 22.5 (in), Y= 19.625 (in), Range 15 (ns), Gain 15 (dB), Sc=5858.7, Va = 8.759 (uV), Vm = model Volts													
Z (in)	Max	Max	Max	Min	Min	Min	Abs	First	Velocity	Vm	Va -Vm	Attenuation	
	Count	Sample	Time (ns)	Count	Sample	Time (ns)		Arrival (ns)	ft/ns	uV	uV	uV/ft	db/ft
2	6619	197	5.79	-8213	215	6.32	14832	3.29	1.76	2.53	6.23	3.32	5.75
4	16819	201	5.91	-8018	184	5.41	24837	3.41	1.82	4.24	4.52	2.41	3.36
6	21310	206	6.06	-13602	189	5.56	34912	3.56	1.90	5.96	2.80	1.49	1.78
8	17074	212	6.23	-11454	193	5.68	28528	3.73	1.99	4.87	3.89	2.07	2.72
10	9670	212	6.23	-7314	193	5.68	16984	3.73	1.99	2.90	5.86	3.13	5.12
12	9663	210	6.18	-7301	191	5.62	16964	3.68	1.96	2.90	5.86	3.13	5.13
14	11269	209	6.15	-8796	190	5.59	20065	3.65	1.94	3.42	5.33	2.84	4.35
16	12820	209	6.15	-10299	190	5.59	23119	3.65	1.94	3.95	4.81	2.57	3.69
18	17794	209	6.15	-12772	190	5.59	30566	3.65	1.94	5.22	3.54	1.89	2.40
20	20690	209	6.15	-15365	191	5.62	36055	3.65	1.94	6.15	2.60	1.39	1.64
22	18489	210	6.18	-15365	190	5.59	33854	3.68	1.96	5.78	2.98	1.59	1.93
24	17478	210	6.18	-13162	190	5.59	30640	3.68	1.96	5.23	3.53	1.88	2.39
26	20346	209	6.15	-14332	191	5.62	34678	3.65	1.94	5.92	2.84	1.51	1.82
28	18526	206	6.06	-13289	189	5.56	31815	3.56	1.90	5.43	3.33	1.78	2.21
30	13740	204	6.00	-9346	186	5.47	23086	3.50	1.87	3.94	4.82	2.57	3.70
32	11112	201	5.91	-7976	182	5.35	19088	3.41	1.82	3.26	5.50	2.93	4.58
34	9993	202	5.94	-7117	182	5.35	17110	3.44	1.84	2.92	5.84	3.11	5.09
36	9948	206	6.06	-6991	187	5.50	16939	3.56	1.90	2.89	5.87	3.13	5.13
38	15379	210	6.18	-9572	193	5.68	24951	3.68	1.96	4.26	4.50	2.40	3.34
40	15438	212	6.23	-10287	194	5.71	25725	3.73	1.99	4.39	4.37	2.33	3.20
42	12244	213	6.26	-9475	192	5.65	21719	3.76	2.01	3.71	5.05	2.69	3.98
44	11813	210	6.18	-10075	191	5.62	21888	3.68	1.96	3.74	5.02	2.68	3.95
46	14992	209	6.15	-11768	191	5.62	26760	3.65	1.94	4.57	4.19	2.24	3.02
48	14942	210	6.18	-11773	191	5.62	26715	3.68	1.96	4.56	4.20	2.24	3.02
50	13884	212	6.23	-10022	193	5.68	23906	3.73	1.99	4.08	4.68	2.50	3.54
52	15540	212	6.23	-11368	193	5.68	26908	3.73	1.99	4.59	4.17	2.22	2.99
54	16872	210	6.18	-12098	191	5.62	28970	3.68	1.96	4.94	3.81	2.03	2.65
56	13705	210	6.18	-11265	190	5.59	24970	3.68	1.96	4.26	4.50	2.40	3.34
58	23501	209	6.15	-14715	190	5.59	38216	3.65	1.94	6.52	2.24	1.19	1.37
60	32767	202	5.94	-16632	190	5.59	49399	3.44	1.84	8.43	0.33	0.17	0.18
62	26342	202	5.94	-13155	185	5.44	39497	3.44	1.84	6.74	2.02	1.08	1.21

In Figure 6.13, the edge effect of the model is shown at approximately 6 inches at the beginning and at the end for both lines 4 (L4 Roof) and line 3 (L3 Coal Seam/Roof). As shown by L4, the area below the first object (metal box) causes a voltage attenuation decrease at approximately 5 inches and continues until approximately 13 inches. This attenuation may be caused from the EM signal finding a multipath. The area below the second object (empty box) causes a voltage attenuation increase starting at approximately 28 inches and continuing until 40 inches on L4. The area below the third object (wood box) causes a voltage increase starting at approximately 50 inches and continuing until 57 inches. It appears that the wood box target is more aligned with L4 than L5 since this voltage attenuation increase is appearing on L4 and the voltage attenuation increase was not obvious on L5.

Figure 6.13 Dry model roof and coal seam/roof lines

Table 6.5 Reconnaissance survey dry physical model line 4 roof

April 22, 2007 Dry Model, Line 4 in Roof, # 10141016 X = 22.5 (in), Y= 16.125 (in), Range 15 (ns)													
Gain 15 (dB), Sc=5858.7, Va = 8.759 (uV), Vm = model Volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
2	8040	206	6.06	-4666	186	5.47	12706	3.56	1.90	2.17	6.59	3.51	6.47
4	18081	213	6.26	-10793	194	5.71	28874	3.76	2.01	4.93	3.83	2.04	2.66
6	31546	219	6.44	-10793	198	5.82	42339	3.94	2.10	7.23	1.53	0.82	0.89
8	32668	225	6.62	-10793	204	6.00	43461	4.12	2.20	7.42	1.34	0.72	0.77
10	22895	226	6.65	-18672	204	6.00	41567	4.15	2.21	7.09	1.66	0.89	0.98
12	19954	226	6.65	-16722	205	6.03	36676	4.15	2.21	6.26	2.50	1.33	1.56
14	17590	226	6.65	-14929	204	6.00	32519	4.15	2.21	5.55	3.21	1.71	2.11
16	17688	226	6.65	-14848	204	6.00	32536	4.15	2.21	5.55	3.21	1.71	2.11
18	18423	226	6.65	-15222	204	6.00	33645	4.15	2.21	5.74	3.02	1.61	1.96
20	17767	226	6.65	-14327	204	6.00	32094	4.15	2.21	5.48	3.28	1.75	2.17
22	16782	226	6.65	-13239	204	6.00	30021	4.15	2.21	5.12	3.63	1.94	2.48
24	16149	225	6.62	-13438	204	6.00	29587	4.12	2.20	5.05	3.71	1.98	2.55
26	16581	224	6.59	-14758	204	6.00	31339	4.09	2.18	5.35	3.41	1.82	2.28
28	15134	223	6.56	-12793	202	5.94	27927	4.06	2.16	4.77	3.99	2.13	2.82
30	11249	223	6.56	-8719	202	5.94	19968	4.06	2.16	3.41	5.35	2.85	4.37
32	7105	223	6.56	-5629	201	5.91	12734	4.06	2.16	2.17	6.59	3.51	6.46
34	6997	226	6.65	-5314	203	5.97	12311	4.15	2.21	2.10	6.66	3.55	6.61
36	9102	227	6.68	-7696	204	6.00	16798	4.18	2.23	2.87	5.89	3.14	5.17
38	12594	227	6.68	-11483	206	6.06	24077	4.18	2.23	4.11	4.65	2.48	3.51
40	16381	228	6.71	-14492	208	6.12	30873	4.21	2.24	5.27	3.49	1.86	2.35
42	16600	230	6.76	-15559	210	6.18	32159	4.26	2.27	5.49	3.27	1.74	2.16
44	14072	230	6.76	-13645	210	6.18	27717	4.26	2.27	4.73	4.03	2.15	2.85
46	13955	229	6.73	-13150	210	6.18	27105	4.23	2.26	4.63	4.13	2.20	2.96
48	14758	230	6.76	-14101	210	6.18	28859	4.26	2.27	4.93	3.83	2.04	2.67
50	17197	231	6.79	-15884	211	6.21	33081	4.29	2.29	5.65	3.11	1.66	2.03
52	15034	230	6.76	-13362	210	6.18	28396	4.26	2.27	4.85	3.91	2.09	2.74
54	12764	227	6.68	-11484	205	6.03	24248	4.18	2.23	4.14	4.62	2.46	3.47
56	12230	225	6.62	-11501	202	5.94	23731	4.12	2.20	4.05	4.71	2.51	3.57
58	15340	218	6.41	-12020	196	5.76	27360	3.91	2.09	4.67	4.09	2.18	2.91
60	10946	212	6.23	-7535	191	5.62	18481	3.73	1.99	3.15	5.60	2.99	4.73
62	5819	211	6.21	-5389	235	6.91	11208	3.71	1.98	1.91	6.85	3.65	7.05

In Figure 6.14, the edge effect of the model is shown at approximately 6 inches at the beginning and end for line 3 (L3 Coal Seam/Roof) and line 2 (L2 Coal Seam). As shown by L3, the voltage attenuation rate remains fairly constant until about 24 inches. The voltage attenuation rate then increases slightly between 24 inches – 35 inches and again between 38 inches – 47 inches. This increase may be caused by slightly higher moisture content in this area.

Figure 6.14 Dry model coal seam/roof and coal seam lines

Table 6.6 Reconnaissance survey dry physical model line 3 coal seam/roof

April 22, 2007 Dry Model, Line 3 in Coal Seam Roof # 1011-1013, X = 22.5 (in), Y= 12.625 (in), Range 15 (ns), Gain 15 (dB), Sc=5858.7, Va = 8.759 (uV), Vm = model Volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
												uV/ft	db/ft
2	12963	207	6.09	-8174	189	5.56	21137	3.59	1.91	3.61	5.15	2.75	4.11
4	22421	213	6.26	-16168	194	5.71	38589	3.76	2.01	6.59	2.17	1.16	1.32
6	23799	219	6.44	-17304	199	5.85	41103	3.94	2.10	7.02	1.74	0.93	1.03
8	18246	225	6.62	-15732	204	6.00	33978	4.12	2.20	5.80	2.96	1.58	1.91
10	16937	225	6.62	-14606	205	6.03	31543	4.12	2.20	5.38	3.38	1.80	2.25
12	18512	227	6.68	-14743	207	6.09	33255	4.18	2.23	5.68	3.08	1.64	2.01
14	18901	228	6.71	-15300	210	6.18	34201	4.21	2.24	5.84	2.92	1.56	1.88
16	19345	230	6.76	-16130	211	6.21	35475	4.26	2.27	6.06	2.70	1.44	1.71
18	20162	231	6.79	-17063	211	6.21	37225	4.29	2.29	6.35	2.41	1.28	1.49
20	19466	231	6.79	-16696	211	6.21	36162	4.29	2.29	6.17	2.59	1.38	1.62
22	18886	232	6.82	-16413	212	6.23	35299	4.32	2.31	6.03	2.73	1.46	1.73
24	19723	233	6.85	-16022	212	6.23	35745	4.35	2.32	6.10	2.66	1.42	1.68
26	16993	235	6.91	-13314	213	6.26	30307	4.41	2.35	5.17	3.59	1.91	2.44
28	14407	234	6.88	-12082	213	6.26	26489	4.38	2.34	4.52	4.24	2.26	3.06
30	14136	234	6.88	-11667	213	6.26	25803	4.38	2.34	4.40	4.35	2.32	3.18
32	15529	235	6.91	-12086	214	6.29	27615	4.41	2.35	4.71	4.05	2.16	2.87
34	17257	236	6.94	-13411	216	6.35	30668	4.44	2.37	5.23	3.52	1.88	2.38
36	19496	236	6.94	-14362	216	6.35	33858	4.44	2.37	5.78	2.98	1.59	1.93
38	19934	237	6.97	-15222	218	6.41	35156	4.47	2.38	6.00	2.76	1.47	1.75
40	16366	236	6.94	-13402	216	6.35	29768	4.44	2.37	5.08	3.68	1.96	2.52
42	15956	238	7.00	-12790	218	6.41	28746	4.50	2.40	4.91	3.85	2.05	2.68
44	18938	240	7.06	-14264	219	6.44	33202	4.56	2.43	5.67	3.09	1.65	2.02
46	15480	223	6.56	-11722	243	7.15	27202	4.06	2.16	4.64	4.12	2.20	2.94
48	19714	241	7.09	-13999	219	6.44	33713	4.59	2.45	5.75	3.00	1.60	1.95
50	19289	240	7.06	-14755	219	6.44	34044	4.56	2.43	5.81	2.95	1.57	1.90
52	18602	239	7.03	-14073	219	6.44	32675	4.53	2.42	5.58	3.18	1.70	2.09
54	16959	237	6.97	-13160	217	6.38	30119	4.47	2.38	5.14	3.62	1.93	2.47
56	19115	234	6.88	-14201	213	6.26	33316	4.38	2.34	5.69	3.07	1.64	2.00
58	21638	228	6.71	-13241	209	6.15	34879	4.21	2.24	5.95	2.81	1.50	1.79
60	15480	223	6.56	-8100	204	6.00	23580	4.06	2.16	4.02	4.73	2.52	3.60
62	7808	218	6.41	-3156	199	5.85	10964	3.91	2.09	1.87	6.89	3.67	7.15

In Figure 6.15, the edge effect of the model is shown at approximately 6 inches at the beginning and end for line 2 (L2 Coal Seam) and line 1 (L1 floor). As shown by L2, the voltage attenuation rate is lower from approximately 2 inches up to approximately 24 inches. This is the area where the coal seam height is 5 inches and it was expected to see a lower voltage attenuation rate. At approximately 24 inches, the coal seam height decreases to 3 inches and the voltage attenuation rate increases slightly and remains constant until the end of the model with the exception of the edge effect. At approximately 44 inches the coal seam height decreases to 2 inches and there is not a noticeable change in the voltage attenuation rate. This change may not have been detected due to instrumentation limitations. As shown by L1, the voltage attenuation rate is fairly constant with the exception of the edge effects.

Figure 6.15 Dry model coal seam and floor lines

Table 6.7 Reconnaissance survey dry physical model line 2 coal seam

April 22, 2007 Dry Model, Line 2 in the Coal Seam File # 1008-1010, X = 22.5 (in), Y= 9.625 (in), Range 15 (ns), Gain 15 (dB), Sc=5858.7, Va = 8.759 (uV), Vm = model Volts													
Z (in)	Max	Max	Max	Min	Min	Min	Abs	First	Velocity	Vm	Va -Vm	Attenuation	
	Count	Sample	Time (ns)	Count	Sample	Time (ns)		Arrival (ns)	ft/ns	uV	uV	uV/ft	db/ft
2	3496	196	5.76	-2562	160	4.71	6058	3.26	1.74	1.03	7.72	4.12	9.90
4	6422	203	5.97	-4894	172	5.06	11316	3.47	1.85	1.93	6.83	3.64	7.00
6	8246	207	6.09	-7313	180	5.29	15559	3.59	1.91	2.66	6.10	3.26	5.53
8	7770	213	6.26	-6662	186	5.47	14432	3.76	2.01	2.46	6.30	3.36	5.88
10	6412	218	6.41	-5361	189	5.56	11773	3.91	2.09	2.01	6.75	3.60	6.82
12	6296	218	6.41	-4842	189	5.56	11138	3.91	2.09	1.90	6.86	3.66	7.08
14	6462	218	6.41	-5392	193	5.68	11854	3.91	2.09	2.02	6.74	3.59	6.79
16	6992	218	6.41	-6011	194	5.71	13003	3.91	2.09	2.22	6.54	3.49	6.36
18	5991	219	6.44	-4966	195	5.73	10957	3.94	2.10	1.87	6.89	3.67	7.15
20	5283	226	6.65	-4027	194	5.71	9310	4.15	2.21	1.59	7.17	3.82	7.91
22	6740	227	6.68	-3723	196	5.76	10463	4.18	2.23	1.79	6.97	3.72	7.37
24	8919	227	6.68	-3409	207	6.09	12328	4.18	2.23	2.10	6.65	3.55	6.61
26	8842	228	6.71	-3308	210	6.18	12150	4.21	2.24	2.07	6.69	3.57	6.67
28	7526	228	6.71	-2756	207	6.09	10282	4.21	2.24	1.75	7.00	3.74	7.45
30	5867	228	6.71	-2549	200	5.88	8416	4.21	2.24	1.44	7.32	3.91	8.37
32	4536	232	6.82	-2489	197	5.79	7025	4.32	2.31	1.20	7.56	4.03	9.21
34	4103	234	6.88	-2499	194	5.71	6602	4.38	2.34	1.13	7.63	4.07	9.50
36	3895	233	6.85	-2612	193	5.68	6507	4.35	2.32	1.11	7.65	4.08	9.57
38	2956	234	6.88	-3168	189	5.56	6124	4.38	2.34	1.05	7.71	4.11	9.85
40	2788	235	6.91	-3736	189	5.56	6524	4.41	2.35	1.11	7.65	4.08	9.55
42	3333	235	6.91	-3679	188	5.53	7012	4.41	2.35	1.20	7.56	4.03	9.22
44	4007	236	6.94	-3405	189	5.56	7412	4.44	2.37	1.27	7.49	4.00	8.96
46	4831	237	6.97	-3403	189	5.56	8234	4.47	2.38	1.41	7.35	3.92	8.48
48	5087	238	7.00	-3403	190	5.59	8490	4.50	2.40	1.45	7.31	3.90	8.33
50	4868	238	7.00	-3403	190	5.59	8271	4.50	2.40	1.41	7.35	3.92	8.46
52	4223	235	6.91	-3766	189	5.56	7989	4.41	2.35	1.36	7.40	3.94	8.62
54	4934	234	6.88	-3904	190	5.59	8838	4.38	2.34	1.51	7.25	3.87	8.15
56	5769	227	6.68	-5785	188	5.53	11554	4.18	2.23	1.97	6.79	3.62	6.91
58	6221	218	6.41	-6867	181	5.32	13088	3.91	2.09	2.23	6.53	3.48	6.33
60	5154	213	6.26	-5062	176	5.18	10216	3.76	2.01	1.74	7.02	3.74	7.48
62	3252	204	6.00	-1720	-177	-5.21	4972	3.50	1.87	0.85	7.91	4.22	10.81

Table 6.8 Reconnaissance survey dry physical model line 1 floor

April 22, 2007 Dry Model, Line 1 in the Floor, File # 1005-1007, X = 22.5 (in), Y= 5.125 (in), Range 15 (ns), Gain 15 (dB), Sc=5858.7, Va = 8.759 (uV), Vm = model Volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
												uV/ft	db/ft
2	12727	180	5.29	-9839	156	4.59	22566	3.59	1.92	3.85	4.91	2.62	3.81
4	19096	188	5.53	-13913	165	4.85	33009	3.83	2.04	5.63	3.12	1.67	2.04
6	25564	195	5.73	-15681	175	5.15	41245	4.03	2.15	7.04	1.72	0.92	1.01
8	21325	200	5.88	-12571	179	5.26	33896	4.18	2.23	5.79	2.97	1.59	1.92
10	14422	203	5.97	-9332	179	5.26	23754	4.27	2.28	4.05	4.70	2.51	3.57
12	12630	203	5.97	-8817	176	5.18	21447	4.27	2.28	3.66	5.10	2.72	4.04
14	12613	204	6.00	-8174	180	5.29	20787	4.30	2.29	3.55	5.21	2.78	4.19
16	12379	204	6.00	-9135	179	5.26	21514	4.30	2.29	3.67	5.09	2.71	4.03
18	10516	205	6.03	-8760	179	5.26	19276	4.33	2.31	3.29	5.47	2.92	4.54
20	10561	205	6.03	-8701	179	5.26	19262	4.33	2.31	3.29	5.47	2.92	4.54
22	9956	206	6.06	-8010	178	5.23	17966	4.36	2.32	3.07	5.69	3.04	4.86
24	9987	206	6.06	-7443	179	5.26	17430	4.36	2.32	2.98	5.78	3.08	5.00
26	10835	205	6.03	-7921	179	5.26	18756	4.33	2.31	3.20	5.56	2.96	4.66
28	10503	205	6.03	-7813	179	5.26	18316	4.33	2.31	3.13	5.63	3.00	4.77
30	10623	205	6.03	-7681	179	5.26	18304	4.33	2.31	3.12	5.63	3.01	4.78
32	10819	206	6.06	-7405	181	5.32	18224	4.36	2.32	3.11	5.65	3.01	4.80
34	10008	207	6.09	-6872	181	5.32	16880	4.39	2.34	2.88	5.88	3.13	5.15
36	9571	207	6.09	-7266	179	5.26	16837	4.39	2.34	2.87	5.89	3.14	5.16
38	9368	207	6.09	-7434	179	5.26	16802	4.39	2.34	2.87	5.89	3.14	5.17
40	9061	208	6.12	-7541	180	5.29	16602	4.42	2.36	2.83	5.93	3.16	5.23
42	9157	209	6.15	-7963	180	5.29	17120	4.45	2.37	2.92	5.84	3.11	5.09
44	9093	210	6.18	-8900	181	5.32	17993	4.48	2.39	3.07	5.69	3.03	4.85
46	9703	210	6.18	-8711	182	5.35	18414	4.48	2.39	3.14	5.62	3.00	4.75
48	10426	209	6.15	-8891	183	5.38	19317	4.45	2.37	3.30	5.46	2.91	4.53
50	11126	209	6.15	-9008	184	5.41	20134	4.45	2.37	3.44	5.32	2.84	4.33
52	11126	207	6.09	-9532	184	5.41	20658	4.39	2.34	3.53	5.23	2.79	4.22
54	11951	206	6.06	-10842	182	5.35	22793	4.36	2.32	3.89	4.87	2.60	3.76
56	18178	204	6.00	-14379	181	5.32	32557	4.30	2.29	5.56	3.20	1.71	2.11
58	21288	197	5.79	-16347	177	5.21	37635	4.09	2.18	6.42	2.34	1.25	1.44
60	15402	193	5.68	-10084	-174	-5.12	25486	3.98	2.12	4.35	4.41	2.35	3.24
62	7761	189	5.56	-2039	-174	-5.12	9800	3.86	2.06	1.67	7.09	3.78	7.67

6.2.5 Reconnaissance Survey Wet Physical Model

In order to study the effects of moisture, approximately 20 gallons of water was sprayed on the top and around the model. The model dried for 10 days prior to testing. In general, voltage attenuation rates of the wet model were higher than the voltage attenuation rate of the dry model. Voltage attenuation rates of the wet model ranged between 2.60 uV/ft to 4.53 uV/ft and as mentioned earlier the voltage attenuation rate of the dry model ranged between 0.72 uV/ft to 4.22 uV/ft. In general, the wet model was driest at the top and wettest on the bottom. The water percolated from the top to the bottom. Figure 6.16 shows the wet model with the survey lines (L1-L5).

From the data analysis it appears that the moisture did not distribute evenly through out the model. Cracks in the model appeared to provide channels for the water and allowed quicker drying around these areas. Wax paper was used between the roof, coal seam, and floor during construction that possibly formed a water barrier. Figure 6.17 shows the wax paper and one of the cracks between the 5 and 3-inch coal seam.

Figure 6.16 Image of wet physical model with survey lines (L1-L5)

Figure 6.17 Image of wax paper and crack in wet physical model

In Figure 6.18, the edge effect of the model is shown at approximately 4 inches at the beginning for line 5 (L5 Objects); however no edge effect is apparent at the end of L5. The voltage attenuation rate of L5 decreases slightly at the end of the line. As shown in Figure 6.16, the model appears to have a dry area from approximately 44 inches to the end of the model above L5. This voltage attenuation rate decrease at the end of L5 is possibly due to this drier area. For line 4 (L4 Roof) the edge effect of the model is shown at approximately 6 inches at the beginning and at approximately 4 inches at the end. As shown by L5, the first object (metal box) caused a voltage attenuation increase starting at approximately 5 inches and continuing until approximately 16 inches. The second object (empty box) caused a voltage attenuation increase starting at approximately 28 inches and continuing until 36 inches. Water may be trapped in this area that could cause this attenuation increase. The third object (wood box) voltage attenuation rate changes are not as pronounced as the metal box and the empty box. A small voltage attenuation increase is observed at approximately 54 inches then a larger voltage attenuation rate decrease is observed at approximately 57 inches. The voltage attenuation rate trend of the wet model follows a similar trend of the dry model for L5.

Figure 6.18 Wet model objects and roof lines

Table 6.9 Reconnaissance survey wet physical model line 5 objects

February 16, 2007 Wet Model, Line 5 in Objects, File # 1030, X = 22.5 (in), Y= 19.625 (in), Range 15 (ns), Gain 20 (dB), Sc=10418.35, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
												uV/ft	dB
2	11517	215	6.32	-10832	234	6.88	22349.0	3.82	2.04	2.15	6.61	3.53	6.52
4	21220	218	6.41	-16425	245	7.21	37645.0	3.91	2.09	3.61	5.15	2.74	4.10
6	16215	227	6.68	-11568	209	6.15	27783.0	4.18	2.23	2.67	6.09	3.25	5.51
8	15359	227	6.68	-11653	249	7.32	27012.0	4.18	2.23	2.59	6.17	3.29	5.64
10	15733	226	6.65	-10835	247	7.26	26568.0	4.15	2.21	2.55	6.21	3.31	5.72
12	15837	226	6.65	-11420	204	6.00	27257.0	4.15	2.21	2.62	6.14	3.28	5.60
14	15317	225	6.62	-11544	204	6.00	26861.0	4.12	2.20	2.58	6.18	3.30	5.67
16	15506	225	6.62	-11519	204	6.00	27025.0	4.12	2.20	2.59	6.17	3.29	5.64
18	19137	225	6.62	-14074	242	7.12	33211.0	4.12	2.20	3.19	5.57	2.97	4.68
20	20819	225	6.62	-15645	242	7.12	36464.0	4.12	2.20	3.50	5.26	2.80	4.25
22	17936	224	6.59	-13608	203	5.97	31544.0	4.09	2.18	3.03	5.73	3.06	4.92
24	18409	219	6.44	-14100	242	7.12	32509.0	3.94	2.10	3.12	5.64	3.01	4.78
26	21951	219	6.44	-15768	241	7.09	37719.0	3.94	2.10	3.62	5.14	2.74	4.09
28	22130	218	6.41	-15226	238	7.00	37356.0	3.91	2.09	3.59	5.17	2.76	4.14
30	15932	217	6.38	-12945	234	6.88	28877.0	3.88	2.07	2.77	5.99	3.19	5.33
32	11070	215	6.32	-9688	234	6.88	20758.0	3.82	2.04	1.99	6.77	3.61	6.86
34	11108	215	6.32	-9702	234	6.88	20810.0	3.82	2.04	2.00	6.76	3.61	6.85
36	21677	218	6.41	-15637	237	6.97	37314.0	3.91	2.09	3.58	5.18	2.76	4.14
38	21551	218	6.41	-15626	238	7.00	37177.0	3.91	2.09	3.57	5.19	2.77	4.16
40	20338	219	6.44	-14827	240	7.06	35165.0	3.94	2.10	3.38	5.38	2.87	4.42
42	16104	219	6.44	-11284	241	7.09	27388.0	3.94	2.10	2.63	6.13	3.27	5.58
44	14897	218	6.41	-10033	201	5.91	24930.0	3.91	2.09	2.39	6.37	3.40	6.01
46	17058	219	6.44	-11161	202	5.94	28219.0	3.94	2.10	2.71	6.05	3.23	5.44
48	15434	219	6.44	-10531	241	7.09	25965.0	3.94	2.10	2.49	6.27	3.34	5.82
50	15528	219	6.44	-10542	241	7.09	26070.0	3.94	2.10	2.50	6.26	3.34	5.80
52	16857	219	6.44	-12273	241	7.09	29130.0	3.94	2.10	2.80	5.96	3.18	5.29
54	17437	218	6.41	-13809	241	7.09	31246.0	3.91	2.09	3.00	5.76	3.07	4.96
56	13770	218	6.41	-9057	201	5.91	22827.0	3.91	2.09	2.19	6.57	3.50	6.42
58	15035	226	6.65	-13020	242	7.12	28055.0	4.15	2.21	2.69	6.07	3.24	5.46
60	29878	226	6.65	-32768	242	7.12	29813.0	4.15	2.21	2.86	5.90	3.15	5.18
62	19653	223	6.56	-20819	241	7.09	40472.0	4.06	2.16	3.88	4.87	2.60	3.77

In Figure 6.19, line 4 (L4 Roof) the edge effect of the model is shown at approximately 6 inches at the beginning and at approximately 4 inches at the end. As shown by L4, the area below the first object (metal box) causes a slight voltage attenuation increase at approximately 8 inches and continues until approximately 15 inches. The area below the second object (empty box) causes a voltage attenuation increase starting at approximately 28 inches and continuing until approximately 35 inches. The area below the third object (wood box) causes a voltage increase starting at approximately 50 inches and continuing until 57 inches. Line 3 (Coal Seam/Roof) shows no edge effect. The voltage attenuation rate remains fairly constant through out the complete line scan.

Figure 6.19 Wet model roof and coal seam/roof lines

Table 6.10 Reconnaissance survey wet physical model line 4 roof

Febuary 16, 2007 Wet Model, Line 4 in Roof, File # 1031, X = 22.5 (in), Y= 16.125 (in), Range 15 (ns), Gain 20 (dB), Sc=10418.35, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
												uV/ft	dB
2	4758	226	6.65	-3503	249	7.32	8261.0	4.15	2.21	0.79	7.97	4.25	11.13
4	9997	241	7.09	-7614	216	6.35	17611.0	4.59	2.45	1.69	7.07	3.77	7.62
6	10073	241	7.09	-7638	217	6.38	17711.0	4.59	2.45	1.70	7.06	3.76	7.59
8	7715	241	7.09	-7108	218	6.41	14823.0	4.59	2.45	1.42	7.34	3.91	8.42
10	7542	241	7.09	-6812	218	6.41	14354.0	4.59	2.45	1.38	7.38	3.94	8.57
12	7132	241	7.09	-5988	218	6.41	13120.0	4.59	2.45	1.26	7.50	4.00	8.98
14	5773	241	7.09	-5188	215	6.32	10961.0	4.59	2.45	1.05	7.71	4.11	9.82
16	5120	241	7.09	-4960	215	6.32	10080.0	4.59	2.45	0.97	7.79	4.16	10.21
18	6455	239	7.03	-5905	215	6.32	12360.0	4.53	2.42	1.19	7.57	4.04	9.26
20	7364	235	6.91	-6002	214	6.29	13366.0	4.41	2.35	1.28	7.48	3.99	8.90
22	6361	238	7.00	-5334	213	6.26	11695.0	4.50	2.40	1.12	7.64	4.07	9.52
24	8222	234	6.88	-6682	212	6.23	14904.0	4.38	2.34	1.43	7.33	3.91	8.39
26	8494	233	6.85	-7295	210	6.18	15789.0	4.35	2.32	1.52	7.24	3.86	8.13
28	7111	233	6.85	-6421	256	7.53	13532.0	4.35	2.32	1.30	7.46	3.98	8.84
30	4977	233	6.85	-5180	256	7.53	10157.0	4.35	2.32	0.97	7.78	4.15	10.17
32	4207	233	6.85	-3826	255	7.50	8033.0	4.35	2.32	0.77	7.99	4.26	11.26
34	4767	234	6.88	-4857	256	7.53	9624.0	4.38	2.34	0.92	7.84	4.18	10.42
36	5566	234	6.88	-5687	256	7.53	11253.0	4.38	2.34	1.08	7.68	4.10	9.70
38	7918	233	6.85	-5893	210	6.18	13811.0	4.35	2.32	1.33	7.43	3.96	8.75
40	9366	213	6.26	-7596	213	6.26	16962.0	3.76	2.01	1.63	7.13	3.80	7.79
42	8779	235	6.91	-7858	215	6.32	16637.0	4.41	2.35	1.60	7.16	3.82	7.88
44	8048	238	7.00	-7302	217	6.38	15350.0	4.50	2.40	1.47	7.29	3.89	8.26
46	8491	239	7.03	-7843	218	6.41	16334.0	4.53	2.42	1.57	7.19	3.84	7.97
48	8303	240	7.06	-7644	218	6.41	15947.0	4.56	2.43	1.53	7.23	3.86	8.08
50	7444	240	7.06	-6843	218	6.41	14287.0	4.56	2.43	1.37	7.39	3.94	8.59
52	6441	240	7.06	-4922	216	6.35	11363.0	4.56	2.43	1.09	7.67	4.09	9.65
54	5080	238	7.00	-4034	213	6.26	9114.0	4.50	2.40	0.87	7.88	4.20	10.67
56	3972	234	6.88	-5057	211	6.21	9029.0	4.38	2.34	0.87	7.89	4.21	10.72
58	8207	234	6.88	-7626	211	6.21	15833.0	4.38	2.34	1.52	7.24	3.86	8.11
60	8386	233	6.85	-7570	257	7.56	15956.0	4.35	2.32	1.53	7.23	3.85	8.08
62	3524	233	6.85	-5495	257	7.56	9019.0	4.35	2.32	0.87	7.89	4.21	10.72

Table 6.11 Reconnaissance survey wet physical model line 3 coal seam/roof

February 16, 2007 Wet Model, Line 3 in Coal Seam Roof, File # 1033, X = 22.5 (in), Y= 12.625 (in), Range 15 (ns), Gain 20 (dB), Sc=10418.35, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max	Max	Max	Min	Min	Min	Abs	First	Velocity	Vm	Va -Vm	Attenuation	
	Count	Sample	Time (ns)	Count	Sample	Time (ns)		Arrival (ns)	ft/ns	uV	uV	uV/ft	dB
2	2721	264	7.76	-2551	294	8.65	5272.0	5.26	2.81	0.51	8.25	4.40	13.21
4	4545	264	7.76	-4677	302	8.88	9222.0	5.26	2.81	0.89	7.87	4.20	10.62
6	5028	272	8.00	-4642	241	7.09	9670.0	5.50	2.93	0.93	7.83	4.18	10.40
8	3682	277	8.15	-4480	241	7.09	8162.0	5.65	3.01	0.78	7.98	4.25	11.18
10	3415	272	8.00	-4432	241	7.09	7847.0	5.50	2.93	0.75	8.01	4.27	11.37
12	4255	279	8.21	-4403	242	7.12	8658.0	5.71	3.04	0.83	7.93	4.23	10.91
14	4539	279	8.21	-4565	310	9.12	9104.0	5.71	3.04	0.87	7.89	4.21	10.68
16	4440	279	8.21	-4312	242	7.12	8752.0	5.71	3.04	0.84	7.92	4.22	10.86
18	4826	278	8.18	-4402	248	7.29	9228.0	5.68	3.03	0.89	7.87	4.20	10.61
20	5240	272	8.00	-4437	242	7.12	9677.0	5.50	2.93	0.93	7.83	4.18	10.39
22	4220	272	8.00	-3790	309	9.09	8010.0	5.50	2.93	0.77	7.99	4.26	11.27
24	3623	279	8.21	-3201	310	9.12	6824.0	5.71	3.04	0.66	8.10	4.32	12.01
26	3067	279	8.21	-2614	303	8.91	5681.0	5.71	3.04	0.55	8.21	4.38	12.86
28	2728	279	8.21	-2269	303	8.91	4997.0	5.71	3.04	0.48	8.28	4.42	13.46
30	2704	279	8.21	-2000	310	9.12	4704.0	5.71	3.04	0.45	8.31	4.43	13.74
32	2722	279	8.21	-2019	310	9.12	4741.0	5.71	3.04	0.46	8.30	4.43	13.70
34	2594	279	8.21	-2028	249	7.32	4622.0	5.71	3.04	0.44	8.32	4.43	13.82
36	2927	279	8.21	-2147	249	7.32	5074.0	5.71	3.04	0.49	8.27	4.41	13.39
38	3583	279	8.21	-2341	249	7.32	5924.0	5.71	3.04	0.57	8.19	4.37	12.67
40	3710	278	8.18	-2562	249	7.32	6272.0	5.68	3.03	0.60	8.16	4.35	12.40
42	3122	275	8.09	-2788	249	7.32	5910.0	5.59	2.98	0.57	8.19	4.37	12.68
44	2155	275	8.09	-2437	249	7.32	4592.0	5.59	2.98	0.44	8.32	4.44	13.85
46	1314	295	8.68	-2112	248	7.29	3426.0	6.18	3.29	0.33	8.43	4.50	15.20
48	1801	265	7.79	-2508	246	7.23	4309.0	5.29	2.82	0.41	8.35	4.45	14.14
50	1782	265	7.79	-2499	247	7.26	4281.0	5.29	2.82	0.41	8.35	4.45	14.17
52	2288	265	7.79	-2619	248	7.29	4907.0	5.29	2.82	0.47	8.29	4.42	13.54
54	1671	271	7.97	-1895	249	7.32	3566.0	5.47	2.92	0.34	8.42	4.49	15.02
56	1648	310	9.12	-1195	335	9.85	2843.0	6.62	3.53	0.27	8.49	4.53	16.07
58	1645	310	9.12	-1203	336	9.88	2848.0	6.62	3.53	0.27	8.49	4.53	16.06
60	1701	303	8.91	-1938	326	9.59	3639.0	6.41	3.42	0.35	8.41	4.49	14.93
62	1275	295	8.68	-1734	318	9.35	3009.0	6.18	3.29	0.29	8.47	4.52	15.81

In Figure 6.20, line 2 (Coal Seam) shows no edge effect. As shown by L2, the voltage attenuation rate is lower from approximately 2 inches up to approximately 22 inches. This is the area where the coal seam height is 5 inches and it was expected to see lower voltage attenuation rate. At approximately 24 inches as mentioned before the coal seam height decreases to 3 inches and the voltage attenuation rate increases slightly and remains fairly constant until approximately 46 inches. As mentioned before, the voltage attenuation rate was expected to increase along this section of L2 due to the thinner coal seam. The voltage attenuation then decreases slightly from approximately 46 inches till approximately 56 inches. It was expected to see a slight voltage attenuation increase starting at 46 inches and continuing to the end of L2. The voltage attenuation decrease may have been caused by a drier media, in this case the 2-inch coal seam, was drier. From approximately 56 inches to approximately 62 inches the attenuation rate increases slightly.

Figure 6.20 Wet model coal and floor

Table 6.12 Reconnaissance survey wet physical model line 2 coal seam

February 16, 2007 Wet Model, Line 2 in Coal Seam, File # 1035, X = 22.5 (in), Y= 9.625 (in), Range 15 (ns), Gain 20 (dB), Sc=10418.35, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max	Max	Max	Min	Min	Min	Abs	First	Velocity	Vm	Va -Vm	Attenuation	
	Count	Sample	Time (ns)	Count	Sample	Time (ns)		Arrival (ns)	ft/ns	uV	uV	uV/ft	dB
2	2199	277	8.15	-1859	301	8.85	4058.0	5.65	3.01	0.39	8.37	4.46	14.42
4	3716	279	8.21	-2942	303	8.91	6658.0	5.71	3.04	0.64	8.12	4.33	12.13
6	2780	279	8.21	-1775	302	8.88	4555.0	5.71	3.04	0.44	8.32	4.44	13.89
8	3438	279	8.21	-1957	303	8.91	5395.0	5.71	3.04	0.52	8.24	4.40	13.10
10	3836	279	8.21	-2274	303	8.91	6110.0	5.71	3.04	0.59	8.17	4.36	12.52
12	4312	280	8.23	-2462	308	9.06	6774.0	5.73	3.06	0.65	8.11	4.32	12.05
14	4897	280	8.23	-2824	310	9.12	7721.0	5.73	3.06	0.74	8.02	4.28	11.44
16	4452	280	8.23	-2809	310	9.12	7261.0	5.73	3.06	0.70	8.06	4.30	11.73
18	5519	279	8.21	-3439	303	8.91	8958.0	5.71	3.04	0.86	7.90	4.21	10.75
20	6324	279	8.21	-3937	302	8.88	10261.0	5.71	3.04	0.98	7.77	4.15	10.12
22	5761	280	8.23	-3893	306	9.00	9654.0	5.73	3.06	0.93	7.83	4.18	10.41
24	4324	280	8.23	-2928	304	8.94	7252.0	5.73	3.06	0.70	8.06	4.30	11.73
26	3632	279	8.21	-2140	303	8.91	5772.0	5.71	3.04	0.55	8.20	4.38	12.79
28	3204	279	8.21	-2170	303	8.91	5374.0	5.71	3.04	0.52	8.24	4.40	13.12
30	2887	279	8.21	-1641	257	7.56	4528.0	5.71	3.04	0.43	8.32	4.44	13.91
32	2487	280	8.23	-1369	260	7.65	3856.0	5.73	3.06	0.37	8.39	4.47	14.66
34	2200	279	8.21	-2961	302	8.88	5161.0	5.71	3.04	0.50	8.26	4.41	13.31
36	3709	277	8.15	-2939	303	8.91	6648.0	5.65	3.01	0.64	8.12	4.33	12.13
38	2780	279	8.21	-1775	303	8.91	4555.0	5.71	3.04	0.44	8.32	4.44	13.89
40	3447	279	8.21	-1957	302	8.88	5404.0	5.71	3.04	0.52	8.24	4.39	13.09
42	3837	279	8.21	-2279	303	8.91	6116.0	5.71	3.04	0.59	8.17	4.36	12.52
44	4299	279	8.21	-2477	308	9.06	6776.0	5.71	3.04	0.65	8.11	4.32	12.05
46	4442	280	8.23	-2783	310	9.12	7225.0	5.73	3.06	0.69	8.07	4.30	11.75
48	4422	280	8.23	-2794	310	9.12	7216.0	5.73	3.06	0.69	8.07	4.30	11.75
50	5519	279	8.21	-3439	303	8.91	8958.0	5.71	3.04	0.86	7.90	4.21	10.75
52	6324	279	8.21	-3877	304	8.94	10201.0	5.71	3.04	0.98	7.78	4.15	10.15
54	5761	280	8.23	-3893	304	8.94	9654.0	5.73	3.06	0.93	7.83	4.18	10.41
56	4324	280	8.23	-2928	307	9.03	7252.0	5.73	3.06	0.70	8.06	4.30	11.73
58	3632	280	8.23	-2140	303	8.91	5772.0	5.73	3.06	0.55	8.20	4.38	12.79
60	3204	279	8.21	-2170	257	7.56	5374.0	5.71	3.04	0.52	8.24	4.40	13.12
62	2887	279	8.21	-1641	257	7.56	4528.0	5.71	3.04	0.43	8.32	4.44	13.91

Table 6.13 Reconnaissance survey wet physical model line 1 floor

February 16, 2007 Wet Model, Line 1 Floor, File # 1040, X = 22.5 (in), Y= 5.125 (in), Range 15 (ns), Gain 20 (dB), Sc=10418.35, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
												uV/ft	db/ft
2	6818	188	5.53	-8734	166	4.88	15552.0	3.03	1.62	1.49	7.27	3.88	8.20
4	6889	196	5.76	-12873	178	5.23	19762.0	3.26	1.74	1.90	6.86	3.66	7.09
6	4832	233	6.85	-7390	186	5.47	12222.0	4.35	2.32	1.17	7.59	4.05	9.31
8	2937	238	7.00	-4827	188	5.53	7764.0	4.50	2.40	0.75	8.01	4.27	11.42
10	2005	215	6.32	-4276	193	5.68	6281.0	3.82	2.04	0.60	8.16	4.35	12.40
12	2049	218	6.41	-4149	196	5.76	6198.0	3.91	2.09	0.59	8.16	4.35	12.46
14	2161	255	7.50	-3985	196	5.76	6146.0	5.00	2.67	0.59	8.17	4.36	12.50
16	2015	254	7.47	-3812	201	5.91	5827.0	4.97	2.65	0.56	8.20	4.37	12.74
18	2106	223	6.56	-4323	202	5.94	6429.0	4.06	2.16	0.62	8.14	4.34	12.29
20	2105	223	6.56	-4361	202	5.94	6466.0	4.06	2.16	0.62	8.14	4.34	12.26
22	2473	220	6.47	-4478	201	5.91	6951.0	3.97	2.12	0.67	8.09	4.32	11.93
24	2086	218	6.41	-4044	195	5.73	6130.0	3.91	2.09	0.59	8.17	4.36	12.51
26	2098	216	6.35	-4056	195	5.73	6154.0	3.85	2.05	0.59	8.17	4.36	12.49
28	2098	216	6.35	-4053	195	5.73	6151.0	3.85	2.05	0.59	8.17	4.36	12.49
30	1945	214	6.29	-3482	192	5.65	5427.0	3.79	2.02	0.52	8.24	4.39	13.07
32	2294	211	6.21	-3957	189	5.56	6251.0	3.71	1.98	0.60	8.16	4.35	12.42
34	2723	211	6.21	-4449	192	5.65	7172.0	3.71	1.98	0.69	8.07	4.30	11.78
36	2331	212	6.23	-3853	192	5.65	6184.0	3.73	1.99	0.59	8.17	4.35	12.47
38	1681	216	6.35	-3133	195	5.73	4814.0	3.85	2.05	0.46	8.30	4.43	13.63
40	1342	257	7.56	-2775	196	5.76	4117.0	5.06	2.70	0.40	8.36	4.46	14.35
42	1871	232	6.82	-3069	211	6.21	4940.0	4.32	2.31	0.47	8.28	4.42	13.51
44	1859	232	6.82	-3070	211	6.21	4929.0	4.32	2.31	0.47	8.29	4.42	13.52
46	1849	233	6.85	-2961	212	6.23	4810.0	4.35	2.32	0.46	8.30	4.43	13.63
48	1612	234	6.88	-2478	211	6.21	4090.0	4.38	2.34	0.39	8.37	4.46	14.38
50	1795	233	6.85	-2675	211	6.21	4470.0	4.35	2.32	0.43	8.33	4.44	13.97
52	2555	234	6.88	-2736	211	6.21	5291.0	4.38	2.34	0.51	8.25	4.40	13.19
54	3376	233	6.85	-2988	210	6.18	6364.0	4.35	2.32	0.61	8.15	4.35	12.34
56	2914	236	6.94	-2671	211	6.21	5585.0	4.44	2.37	0.54	8.22	4.39	12.94
58	8726	233	6.85	-6312	255	7.50	15038.0	4.35	2.32	1.44	7.32	3.90	8.35
60	8540	226	6.65	-5510	249	7.32	14050.0	4.15	2.21	1.35	7.41	3.95	8.67
62	4376	219	6.44	-3758	242	7.12	8134.0	3.94	2.10	0.78	7.98	4.26	11.20

CHAPTER 7

CONCLUSIONS

The Radio Imaging Method (RIM), which uses electromagnetic wave propagation, was developed about twenty years ago and shows promise in being able to identify geologic anomalies ahead of the longwall face. In coal seams, geologic anomalies can cause difficult mining conditions, unsafe working conditions, and loss of production. These geologic anomalies may be caused from sandstone intrusion, faults, dykes, fracture zones, gas well pipelines, sudden thinning and severe undulation of coal seams. Geologic anomalies affect the EM signal attenuation rate (the rate of reduction of the EM signal strength) and phase angle (θ) with respect to distance along a transmitting path. From the attenuation rate changes it is possible to generate mapped images such as contour maps and tomographic imaging. It is then possible to see the geologic anomalies within the coal seam prior to mining.

The overall objective of this research was to increase the accuracy of the RIM technology by studying the EM wave properties on a scaled physical model of a longwall panel and quantifying the data collected. The properties of interest were the EM signal attenuation rates caused from interfaces between the roof, seam, floor and objects. This object was accomplished by modifying an off-the-shelf GPR system, performing spatial spreading testing in air, and performing EM reconnaissance testing on a scaled physical model under different moisture conditions, and using signal discrimination.

The GPR system was modified to allow the separation between the Tx and Rx antennas. This separation was necessary since the GPR system works on the reflective principle and uses one antenna that houses both the Tx and Rx antennas. The RIM system works on the penetrative principle with two antennas separated by a distance.

The signal strength measured at the Rx antenna will depend on the relative position of that antenna with respect to the Tx antenna. It should be noted that the signal received at a point (xyz) from the transmitter is weaker than that at the emitting point. The difference in signal strength is due to two parts: the signal spatial spreading and the attenuation by media on the path. After analyzing the data from the spatial spreading testing in air, an understanding was gained on the voltage attenuation rate in the X, Y, and Z directions in air and an equation was developed.

In the scaled physical model, the geometry of the area being survey was known, locations of geologic anomalies and objects (small metal box, small empty box and solid wood box) were known, the thickness of the roof, coal seam and floor were known, and the contact points of the transmitting and receiving antenna were known. Different ratios of sand, gypsum, and cement were used to build the floor and roof strata. A mixture of coal powder gypsum and iron powder was used to simulate the coal seam. Due to the small size of the physical model, a high-frequency 900 MHz EM signal was used in the model

testing to ensure the “similarity” between the actual longwall panels and the scaled model. EM reconnaissance surveys of the physical model were performed at different times to gain an understanding of how the moisture content and aging affect the voltage attenuation rate. Signal discrimination techniques were used to obtain the information needed from the EM waveform. Voltage attenuation rates of the EM waveforms in the scaled physical model were determined by taking the difference of the signal strength measured in air and the signal strength measured in the physical model then divided by the distance along the transmitting path. The data is presented in waveforms, graphs, radiation distribution maps, flow chart, data tables, contour images, and individual line scans from both the dry and wet model. These individual line scans are compared to the known geometry and geologic anomalies of the scaled physical model.

From the individual line scans on the physical modeling testing, the drier model roof, coal seam, floor and objects, were easier to identify than in the wet model. The wet model roof, coal seam, floor and objects were identifiable; however, one must know the condition of the physical composition and understand how the moisture traveled through the model. As quantified by the comparisons of data collected from the dry and wet physical model, moisture content plays a significant role in EM waveforms. In an actual RIM survey, knowing the surrounding geological conditions will help improve the data analysis in the post processing and reconstruction phases. Moisture is a problem and careful post processing of the data must be done.

This research can be used to further: define the characteristics of the attenuation rate during an actual longwall panel RIM survey, provide insight on the spatial spreading of the EM signal, provide insight on how moisture content effect the EM signal, provide insight in the design and development for software programs used for post processing, and provide insight in the design and development for software programs used for tomographic reconstruction. The testing procedures and data results are presented and quantified.

CHAPTER 8

RECOMMENDATIONS FOR FUTURE RESEARCH

It is recommended to increase the size of future physical models taking into consideration the wavelength of the EM system. For example, if using a 900 MHz system, one wavelength as determined by Eq. 2.2, is approximately 13.0 inches (using an EM velocity of 3×10^8 m/s). The minimum width of physical model is recommended to be 2 wavelengths. As seen from these experiments, start scanning at least one wavelength from the edge of the physical model to avoid the edge affects. Another suggestion is to remove the forms that are used during the construction of the physical model. The geologic anomalies should be a minimum of $\frac{1}{4}$ wavelength, since this is typically the minimum detectable size. If using a 900 MHz system, it is recommended that the minimum size of the embedded object be a 3.5-inch cube. Placement of the geologic anomalies inside the model should be one wavelength from the outer boundaries of the physical model.

A better method of surveying future physical models is needed. One suggestion, use a device similar to a computer controlled Raster scanner. In an actual longwall EM survey, a robotic device that positions the antenna in the exact locations using laser-surveying techniques is suggested. In addition, it is suggested to set up the survey marking stations every 5 feet in an actual longwall EM survey to increase the resolution of the area survey and to perform 2 EM surveys of the same area for comparison purposes.

It is recommended to develop better software processing methods for data analysis. For example, software processing to handle large quantities of data and software processing for single scan data. Software processing for signal discrimination will be needed to identify the maximum and minimum signal strength of the first reflected pulse. Software processing should be used for signal discrimination to identify first relaxation pulse to determine the first arrival time. Software processing to convert digital data counts into the user-friendly units such as of volts will be needed. The author also suggests software processing to determine the attenuation rate, taking into consideration the spatial spreading formulae developed, and software processing for tomographic reconstruction.

The moisture content of the material significantly affects the attenuation rate of the EM waveform and signal strength. This study showed that additional research is needed to fully understand the effect of moisture on the EM signal characteristics. One suggestion is to place a scaled physical model in a controlled environmental chamber where the moisture content can be precisely controlled. It is also recommended to determine a non-invasive method to measure the moisture content within the model.

A few suggested future scaled physical model designs are: a model with a rock parting, a model with a fault, and a model with a seam undulation.

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APPENDIX A: RESULTS FROM SIGNAL STRENGTH REDUCTION AS SPATIAL SPREADING STUDIES

The first signal strength reduction as spatial spreading testing was performed near the fitness center at West Virginia University in July of 2005. Figure A-1 shows the test arrangement. The persons in this figure are William D. Monaghan (author of this Thesis), Jun Lu, Ph.D. graduate student and Yi Luo, Ph.D. Associate Professor Department of Mining Engineering. Additional testing was performed in August 2005, December 2005 and February 2007. Figure A-2 show the antenna grid array used in these tests.

Figure A-1. Initial spatial spreading testing at WVU, July 2005

Spatial Spreading Testing

Figure A-2 Antenna grid array

Figure A-3 Spatial spreading air attenuation test 001 – antennas Y position – July 2005

Figure A-4 Spatial spreading air attenuation test 001 – first arrival – antennas Y position – July 2005

Figure A-5 Spatial spreading air attenuation test 002 – antennas Y position – July 2005

Figure A-6 Spatial spreading air attenuation test 002 – first arrival – antennas Y position – July 2005

Figure A-7 Spatial spreading air attenuation test 003 – antennas Z position – Aug. 2005

Figure A-8 Spatial spreading air attenuation test 003 – first arrival – antennas Z position – Aug. 2005

Table A-1 Test 001 spatial spreading air attenuation testing antennas in Y position July 2005

Tx=90 Rx=90, Range 20(ns), Gain 15 (dB), Sv=5.6320, Sc=5858.7															
File #	Rx Point	Distance, ft	Angle, deg	Memory	Max	time	Memory	Min	time	Ave. time	First Inflection	Abs	Velocity	Air Volts	Normalized
		receiver		Location	Count	ns	Location	Count	ns	ns	Arrival (ns)		ft/ns	(uV)	
531	L1-A	2.83	-45	91	14464	3.57	105	-18304	4.12	3.84	2.57	32768	1.10	5.5930	0.569
529	L1-B	2.31	-30	81	24192	3.18	96	-29056	3.76	3.47	2.18	53248	1.06	9.0887	0.924
527	L1-C	2.07	-15	79	27264	3.10	93	-28000	3.65	3.37	2.10	55264	0.99	9.4328	0.959
525	L1-D	2.00	0	78	26496	3.06	92	-31128	3.61	3.33	2.06	57624	0.97	9.8356	1.000
523	L1-E	2.07	15	81	24192	3.18	94	-28800	3.68	3.43	2.18	52992	0.95	9.0450	0.920
521	L1-F	2.31	30	85	20352	3.33	100	-17024	3.92	3.63	2.33	37376	0.99	6.3796	0.649
519	L1-G	2.83	45	100	9600	3.92	115	-12672	4.51	4.21	2.92	22272	0.97	3.8015	0.387
504	L2-A	4.24	-45	118	10368	4.63	134	-12672	5.25	4.94	3.63	23040	1.17	3.9326	0.523
506	L2-B	3.46	-30	103	17792	4.04	118	-21376	4.63	4.33	3.04	39168	1.14	6.6854	0.890
508	L2-C	3.11	-15	98	19584	3.84	113	-24192	4.43	4.14	2.84	43776	1.09	7.4720	0.994
510	L2-D	3.00	0	102	19584	4.00	116	-24448	4.55	4.27	3.00	44032	1.00	7.5157	1.000
513	L2-E	3.11	15	106	16000	4.16	121	-19840	4.74	4.45	3.16	35840	0.99	6.1174	0.814
515	L2-F	3.46	30	131	15744	5.14	115	-12416	4.51	4.82	4.14	28160	0.84	4.8065	0.640
517	L2-G	4.24	45	127	10112	4.98	143	-7296	5.61	5.29	3.98	17408	1.07	2.9713	0.395
502	L3-A	7.07	-45	199	5248	7.80	213	-6016	8.35	8.08	6.80	11264	1.04	1.9226	0.415
500	L3-B	5.77	-30	161	12416	6.31	176	-10112	6.90	6.61	5.31	22528	1.09	3.8452	0.830
498	L3-C	5.18	-15	156	14720	6.12	171	-11904	6.70	6.41	5.12	26624	1.01	4.5444	0.981
496	L3-D	5.00	0	155	12160	6.08	170	-14976	6.66	6.37	5.08	27136	0.99	4.6317	1.000
494	L3-E	5.18	15	163	9856	6.39	179	-12672	7.02	6.70	5.39	22528	0.96	3.8452	0.830
492	L3-F	5.77	30	179	7296	7.02	195	-9600	7.64	7.33	6.02	16896	0.96	2.8839	0.623
490	L3-G	7.07	45	216	3968	8.47	231	-5248	9.06	8.76	7.47	9216	0.95	1.5730	0.340
475	L4-A	14.14	-45	406	2688	15.92	390	-1920	15.29	15.60	14.92	4608	0.95	0.7865	0.367
478	L4-B	11.55	-30	302	4224	11.84	317	-5248	12.43	12.13	10.84	9472	1.07	1.6167	0.755
480	L4-C	10.35	-15	288	5504	11.29	302	-6784	11.84	11.56	10.29	12288	1.01	2.0974	0.980
482	L4-D	10.00	0	286	5504	11.21	300	-7040	11.76	11.49	10.21	12544	0.98	2.1411	1.000
484	L4-E	10.35	15	298	4992	11.68	311	-6272	12.19	11.94	10.68	11264	0.97	1.9226	0.898
486	L4-F	11.55	30	324	3456	12.70	339	-4736	13.29	12.99	11.70	8192	0.99	1.3983	0.653
488	L4-G	14.14	45	398	1920	15.60	413	-2688	16.19	15.90	14.60	4608	0.97	0.7865	0.367

Table A-2 Test 002 spatial spreading air attenuation testing antennas in Y position July 2005

Tx=60 Rx=60, Range 20(ns), Gain 15 (dB), Sv=5.6320, Sc=5858.7															
File #	Rx Point	Distance, ft	Angle, deg	Memory	Max	time	Memory	Min	time	Ave. time	First Inflection	Abs	Velocity	Air Volts	Normalized
		receiver		Location	Count	ns	Location	Count	ns	ns	Arrival (ns)		ft/ns	(uV)	
534	L1-A	2.83	-45	103	10368	4.04	118	-12928	4.63	2.83	2.83	23296	1.00	4.0	0.47
536	L1-D	2.00	0	82	21888	3.21	97	-27264	3.80	2.01	2.00	49152	1.00	8.4	1.00
538	L1-G	2.83	45	97	13440	3.80	112	-17024	4.39	2.60	2.59	30464	1.09	5.2	0.62
544	L1-A	4.24	-45	132	7552	5.17	148	-10112	5.80	3.99	3.96	17664	1.07	3.0	0.57
542	L1-D	3.00	0	102	13888	4.00	117	-17264	4.59	2.79	2.79	31152	1.08	5.3	1.00
540	L1-G	4.24	45	125	8832	4.90	140	-11392	5.49	3.69	3.69	20224	1.15	3.5	0.65
546	L1-A	7.07	-45	211	4992	8.27	226	-6528	8.86	7.07	7.06	11520	1.00	2.0	0.46
548	L1-D	5.00	0	158	11136	6.19	173	-13952	6.78	4.99	4.98	25088	1.00	4.3	1.00
550	L1-G	7.07	45	207	5760	8.11	222	-7296	8.70	6.91	6.90	13056	1.02	2.2	0.52
556	L1-A	14.14	-45	430	2432	16.86	411	-2944	16.11	14.98	15.65	5376	0.90	0.9	0.45
554	L1-D	10.00	0	287	5248	11.25	302	-6784	11.84	10.04	10.04	12032	1.00	2.1	1.00
552	L1-G	14.14	45	389	2688	15.25	405	-3712	15.88	14.06	14.04	6400	1.01	1.1	0.53

Table A-3 Test 003 spatial spreading air attenuation testing antennas-Z position Aug. 2005

Tx=60 Rx=60, Range 20(ns), Gain 15 (dB), Sv=5.6320, Sc=5858.7															
File #	Rx Point	Distance, ft	Angle, deg	Memory	Max	time	Memory	Min	time	Ave. time	First Inflection	Abs	Velocity	Air Volts	Normalized
		receiver		Location	Count	ns	Location	Count	ns	ns	Arrival (ns)		ft/ns	(uV)	
652	L1-A	2.83	-45	110	14464	4.31	106	-9856	4.16	4.23	2.99	24320	0.95	4.2	0.51
651	L1-D	2.00	0	98	26240	3.84	84	-21120	3.29	3.57	2.12	47360	0.94	8.1	1.00
650	L1-G	2.83	45	119	16048	4.66	104	10160	4.08	4.37	2.91	26208	0.97	4.5	0.55
649	L2-A	3.00	0	120	17216	4.70	105	-13120	4.12	4.41	2.95	30336	1.02	5.2	1.00
646	L3-A	7.07	-45	206	6528	8.08	191	-4992	7.49	7.78	6.32	11520	0.47	2.0	0.43
647	L3-B	5.00	0	169	14208	6.62	155	-12416	6.08	6.35	4.91	26624	1.02	4.5	1.00
648	L3-C	7.07	45	213	6912	8.35	198	-5632	7.76	8.06	6.59	12544	1.07	2.1	0.47
644	L4-A	14.14	-45	408	2944	15.99	394	-2432	15.44	15.72	14.27	5376	0.99	0.9	0.40
643	L4-D	10.00	0	299	7552	11.72	284	-6016	11.13	11.43	9.96	13568	1.00	2.3	1.00
645	L1-G	14.14	45	414	2688	16.23	399	-2176	15.64	15.93	14.47	4864	0.98	0.8	0.36

Figure A-9 Spatial spreading air attenuation test 004 – antenna in Y position – Dec. 2005

Figure A-10 Spatial spreading air attenuation test 004 – first arrival time – antenna in Y position – Dec. 2005

Figure A-11 Spatial spreading air attenuation test 004 – antenna in Z position – Dec. 2005

Figure A-12 Spatial spreading air attenuation test 004 – first arrival time – antenna in Z position – Dec. 2005

Table A-4 Test 004 spatial spreading air attenuation testing antennas in Y position Dec. 2005

Tx=90 Rx=90, Range 20(ns), Gain 25 (dB), Sv=10.0152, Sc=10418.3, Offset=-1.94(ns), Dec 17, 2005														
File	Rx Point	Distance, ft	Angle, deg	Memory	Max	time	Memory	Min	time	Ave. time	Abs	First Arrival	Velocity	Air Volts
		receiver		Location	Count	ns	Location	Count	ns	ns		ns	ft/ns	(uV)
739	L1-A	2.83	-45	50	12794	1.96	63	-17627	2.47	2.21	30421	2.90	0.98	2.9200
741	L1-B	2.31	-30	47	30825	1.84	33	-25050	1.29	1.57	55875	2.23	1.03	5.3632
743	L1-C	2.07	-15	40	32767	1.57	28	-27715	1.10	1.33	60482	2.04	1.02	5.8054
745	L1-D	2.00	0	39	32767	1.53	27	-29206	1.06	1.29	61973	2.00	1.00	5.9485
747	L1-E	2.07	15	40	32767	1.57	27	-27143	1.06	1.31	59910	2.00	1.04	5.7505
749	L1-F	2.31	30	47	30408	1.84	34	-23672	1.33	1.59	54080	2.27	1.02	5.1909
751	L1-G	2.83	45	56	17465	2.20	42	-13023	1.65	1.92	30488	2.59	1.09	2.9264
724	L2-A	4.24	-45	89	15175	3.49	103	-10667	4.04	3.76	25842	4.98	0.85	2.4804
726	L2-B	3.46	-30	71	24015	2.78	57	-17178	2.23	2.51	41193	3.17	1.09	3.9539
728	L2-C	3.11	-15	60	28071	2.35	47	-21062	1.84	2.10	49133	2.78	1.12	4.7160
730	L2-D	3.00	0	64	28807	2.51	51	-20738	2.00	2.25	49545	2.94	1.02	4.7556
732	L2-E	3.11	15	66	26497	2.59	53	-19408	2.08	2.33	45905	3.02	1.03	4.4062
734	L2-F	3.46	30	71	21543	2.78	57	-16079	2.23	2.51	37622	3.17	1.09	3.6111
736	L2-G	4.24	45	88	14592	3.45	103	-10151	4.04	3.74	24743	4.98	0.85	2.3750
710	L3-A	7.07	-45	160	13094	6.27	147	-2503	5.76	6.02	15597	6.70	1.05	1.4971
712	L3-B	5.77	-30	120	13531	4.70	133	-17471	5.21	4.96	31002	6.15	0.94	2.9757
714	L3-C	5.18	-15	113	23928	4.43	100	-18008	3.92	4.17	41936	4.86	1.07	4.0252
716	L3-D	5.00	0	113	24358	4.43	99	-18381	3.88	4.16	42739	4.82	1.04	4.1023
718	L3-E	5.18	15	116	22273	4.55	103	-17272	4.04	4.29	39545	4.98	1.04	3.7957
720	L3-F	5.77	30	129	17610	5.06	116	-13912	4.55	4.80	31522	5.49	1.05	3.0256
722	L3-G	7.07	45	177	9675	6.94	163	-7079	6.39	6.66	16754	7.33	0.96	1.6081
696	L4-A	14.14	-45	370	3875	14.50	355	-5345	13.92	14.21	9220	14.86	0.95	0.8850
698	L4-B	11.55	-30	277	6073	10.86	291	-8888	11.41	11.13	14961	12.35	0.94	1.4360
700	L4-C	10.35	-15	242	8250	9.49	257	-11866	10.07	9.78	20116	11.01	0.94	1.9308
702	L4-D	10.00	0	232	8764	9.09	246	-13257	9.64	9.37	22021	10.58	0.94	2.1137
704	L4-E	10.35	15	252	11293	9.88	238	-8437	9.33	9.60	19730	10.27	1.01	1.8938
706	L4-F	11.55	30	283	8021	11.09	269	-5874	10.54	10.82	13895	11.48	1.01	1.3337
708	L4-G	14.14	45	347	4352	13.60	365	-3343	14.31	13.96	7695	15.25	0.93	0.7386

Table A-5 Test 004 spatial spreading air attenuation testing antennas in Z position Dec. 2005

Tx=60 Rx=60, Range 20(ns), Gain 20 (dB), Sv=5.6320, Sc=5858.7, Offset=-1.94(ns), Dec 17, 2005														
File	Rx Point	Distance, ft	Angle, deg	Memory	Max	time	Memory	Min	time	Ave. time	Abs	First Arrival	Velocity	Air Volts
		receiver		Location	Count	ns	Location	Count	ns	ns		ns	ft/ns	(uV)
740	L1-A	2.83	-45	43	16018	1.69	57	-21302	2.23	1.96	37320	2.63	1.08	3.5822
742	L1-B	2.31	-30	34	23135	1.33	48	-29091	1.88	1.61	52226	2.27	1.02	5.0129
744	L1-C	2.07	-15	29	26794	1.14	41	-32768	1.61	1.37	59562	2.08	1.00	5.7171
746	L1-D	2.00	0	27	27852	1.06	39	-32768	1.53	1.29	60620	2.00	1.00	5.8186
748	L1-E	2.07	15	26	27331	1.02	38	-32768	1.49	1.25	60099	1.96	1.06	5.7686
750	L1-F	2.31	30	33	22030	1.29	47	-28765	1.84	1.57	50795	2.23	1.03	4.8756
752	L1-G	2.83	45	44	14730	1.72	59	-19254	2.31	2.02	33984	2.66	1.06	3.2620
725	L2-A	4.24	-45	75	11808	2.94	90	-18021	3.53	3.23	29829	3.88	1.09	2.8631
727	L2-B	3.46	-30	57	16366	2.23	71	-22624	2.78	2.51	38990	3.17	1.09	3.7425
729	L2-C	3.11	-15	49	20481	1.92	63	-27368	2.47	2.20	47849	2.86	1.09	4.5928
731	L2-D	3.00	0	47	21391	1.84	61	-28009	2.39	2.12	49400	2.78	1.08	4.7417
733	L2-E	3.11	15	51	19667	2.00	65	-26693	2.55	2.27	46360	2.94	1.06	4.4499
735	L2-F	3.46	30	56	16341	2.20	70	-21908	2.74	2.47	38249	3.14	1.10	3.6713
737	L2-G	4.24	45	76	9847	2.98	91	-15315	3.57	3.27	25162	3.92	1.08	2.4152
711	L3-A	7.07	-45	145	10212	5.68	159	-13558	6.23	5.96	23770	6.62	1.07	2.2816
713	L3-B	5.77	-30	116	14503	4.55	130	-19285	5.10	4.82	33788	5.49	1.05	3.2431
715	L3-C	5.18	-15	99	17891	3.88	112	-23334	4.39	4.14	41225	4.82	1.07	3.9570
717	L3-D	5.00	0	98	18666	3.84	111	-24363	4.35	4.10	43029	4.78	1.05	4.1301
719	L3-E	5.18	15	104	17672	4.08	117	-23298	4.59	4.33	40970	5.02	1.03	3.9325
721	L3-F	5.77	30	117	12607	4.59	130	-16733	5.10	4.84	29340	5.53	1.04	2.8162
723	L3-G	7.07	45	156	7105	6.12	181	-9592	7.10	6.61	16697	7.06	1.00	1.6027
697	L4-A	14.14	-45	333	4372	13.05	346	-5684	13.56	13.31	10056	13.99	1.01	0.9652
699	L4-B	11.55	-30	273	6928	10.70	286	-8872	11.21	10.96	15800	11.64	0.99	1.5166
701	L4-C	10.35	-15	239	8836	9.37	253	-11069	9.92	9.64	19905	10.31	1.00	1.9106
703	L4-D	10.00	0	229	8914	8.98	224	-12264	8.78	8.88	21178	9.92	1.01	2.0328
705	L4-E	10.35	15	238	8569	9.33	252	-10957	9.88	9.60	19526	10.27	1.01	1.8742
707	L4-F	11.55	30	270	5616	10.58	283	-7757	11.09	10.84	13373	11.52	1.00	1.2836
709	L4-G	14.14	45	335	3401	13.13	348	-4593	13.64	13.39	7994	14.07	1.00	0.7673

Examples of test results for EM waveforms in the spatial spreading studies are shown in the Figures below.

Figure A-14 Air attenuation test 005 – EM waveform – location 2 ft. point D – Feb. 2007

Figure A-15 Air attenuation test 005 – EM waveform – location 3 ft. point D – Feb. 2007

Figure A-16 Air attenuation test 005 – EM waveform – location 5 ft. point D -- Feb. 2007

Figure A-17 Air attenuation test 005 – EM waveform – location 10 ft. point D – Feb. 2007

Example of test results for lines (L1-2 ft., L2 – 3 ft., L3 – 5 ft., L4 – 10 ft.) for the EM waveforms in the spatial spreading studies are shown below.

740-point A, 742-point B, 744-point C, 746-point D, 748-point E, 750-point F, 752-point G,

Figure A-18 Spatial spreading air attenuation test 003 – L1 – 2 ft. – antennas in Y position – Dec. 2005

725-point A, 727-point B, 729-point C, 731-point D, 733-point E, 735-point F, 737-point G,

Figure A-19 Spatial spreading air attenuation test 003 – L2 – 3 ft. – antennas in Y position – Dec. 2005

711-point A, 713-point B, 715-point C, 717-point D, 719-point E, 721-point F, 723-point G,

Figure A-20 Spatial spreading air attenuation test 003 – L3 – 5 ft. – antennas in Y position – Dec. 2005

697-point A, 699-point B, 701-point C, 703-point D, 705-point E, 707-point F, 709-point G,

Figure A-21 Spatial spreading air attenuation test 003 – L 4 – 10 ft. – antennas in Y position – Dec. 2005

APPENDIX B: RESULTS FROM EM RECONNAISSANCE STUDIES

The graphs contained in this appendix show additional EM reconnaissance testing data on the scaled physical model at different times.

It should be noted that in the reconnaissance survey tests performed on the dry physical model in February 2007, the voltage signals in the model were higher than air voltage signal at the same distance. The author of this Thesis spoke to the manufacture of the instrumentation about these higher voltage signals. The manufacture has also observed higher voltages in a media while performing similar tests on very dry firebrick used in kiln ovens. The results of the tests performed in February 2007 are shown below.

Figure B-1 Total signal attenuation distribution in dry physical model – Feb. 2007

Reconnaissance Tests Results from February 2007

Table B-1 Reconnaissance survey test 003 – dry physical model – line 1 floor – Feb. 2007

February 11, 2007 Dry Model, Line 1 in the Floor, File # 1007, X = 22.5 (in), Y = 5.125 (in), Range 15 (ns), Gain 4 (dB), Sv=1.5873,Sc=1651.2, Va = 8.759 (uV), Vm = model volts														
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation uV/ft db/ft		
2	14622	219	6.44	-12169	243	7.15	26791	3.94	2.10	16.23	-7.47	-3.98	-2.86	
4	14478	219	6.44	-12184	243	7.15	26662	3.94	2.10	16.15	-7.39	-3.94	-2.83	
6	28255	225	6.62	-20352	248	7.29	48607	4.12	2.20	29.44	-20.68	-11.03	-5.62	
8	32551	229	6.73	-17263	252	7.41	49814	4.23	2.26	30.17	-21.41	-11.42	-5.73	
10	26033	230	6.76	-20909	255	7.50	46942	4.26	2.27	28.43	-19.67	-10.49	-5.45	
12	21286	229	6.73	-14826	253	7.44	36112	4.23	2.26	21.87	-13.11	-6.99	-4.24	
14	21352	229	6.73	-17103	254	7.47	38455	4.23	2.26	23.29	-14.53	-7.75	-4.53	
16	21411	229	6.73	-17018	254	7.47	38429	4.23	2.26	23.27	-14.51	-7.74	-4.53	
18	19747	229	6.73	-16630	254	7.47	36377	4.23	2.26	22.03	-13.27	-7.08	-4.27	
20	20110	230	6.76	-16583	254	7.47	36693	4.26	2.27	22.22	-13.46	-7.18	-4.31	
22	20538	230	6.76	-16559	255	7.50	37097	4.26	2.27	22.47	-13.71	-7.31	-4.36	
24	20723	230	6.76	-16680	255	7.50	37403	4.26	2.27	22.65	-13.89	-7.41	-4.40	
26	22203	231	6.79	-16678	254	7.47	38881	4.29	2.29	23.55	-14.79	-7.89	-4.58	
28	22721	231	6.79	-16757	254	7.47	39478	4.29	2.29	23.91	-15.15	-8.08	-4.65	
30	19887	230	6.76	-13395	254	7.47	33282	4.26	2.27	20.16	-11.40	-6.08	-3.86	
32	19133	230	6.76	-13230	255	7.50	32363	4.26	2.27	19.60	-10.84	-5.78	-3.73	
34	19516	231	6.79	-13775	255	7.50	33291	4.29	2.29	20.16	-11.40	-6.08	-3.86	
36	18988	230	6.76	-12931	255	7.50	31919	4.26	2.27	19.33	-10.57	-5.64	-3.67	
38	18986	230	6.76	-13043	255	7.50	32029	4.26	2.27	19.40	-10.64	-5.67	-3.68	
40	18523	231	6.79	-13560	255	7.50	32083	4.29	2.29	19.43	-10.67	-5.69	-3.69	
42	20551	231	6.79	-16124	256	7.53	36675	4.29	2.29	22.21	-13.45	-7.17	-4.31	
44	21936	232	6.82	-16711	256	7.53	38647	4.32	2.31	23.41	-14.65	-7.81	-4.55	
46	21795	232	6.82	-16737	256	7.53	38532	4.32	2.31	23.34	-14.58	-7.77	-4.54	
48	23056	233	6.85	-16421	256	7.53	39477	4.35	2.32	23.91	-15.15	-8.08	-4.65	
50	24804	233	6.85	-17482	257	7.56	42286	4.35	2.32	25.61	-16.85	-8.99	-4.97	
52	24682	233	6.85	-17589	257	7.56	42271	4.35	2.32	25.60	-16.84	-8.98	-4.97	
54	25003	233	6.85	-17180	255	7.50	42183	4.35	2.32	25.55	-16.79	-8.95	-4.96	
56	26268	231	6.79	-19711	255	7.50	45979	4.29	2.29	27.85	-19.09	-10.18	-5.36	
58	26500	232	6.82	-19520	256	7.53	46020	4.32	2.31	27.87	-19.11	-10.19	-5.36	
60	23535	224	6.59	-18352	247	7.26	41887	4.09	2.18	25.37	-16.61	-8.86	-4.93	
62	23784	224	6.59	-18613	247	7.26	42397	4.09	2.18	25.68	-16.92	-9.02	-4.98

Figure B-2 Dry physical model coal seam and floor lines – Feb. 2007

Table B-2 Reconnaissance survey test 003 – dry physical model – line 2 – -coal seam – Feb. 2007

February 11, 2007 Dry Model, Line 2 in Coal Seam, File # 1010, X = 22.5 (in), Y= 9.625 (in), Range 15 (ns), Gain 4 (dB), Sv=1.5873, Sc=1651.2, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
												uV/ft	db/ft
2	12270	214	6.29	-6959	196	5.76	19229.0	3.79	2.02	11.65	-2.89	-1.54	-1.32
4	18629	219	6.44	-11616	202	5.94	30245.0	3.94	2.10	18.32	-9.56	-5.10	-3.42
6	15984	222	6.53	-9591	205	6.03	25575.0	4.03	2.15	15.49	-6.73	-3.59	-2.64
8	9584	221	6.50	-6738	199	5.85	16322.0	4.00	2.13	9.88	-1.13	-0.60	-0.56
10	9568	221	6.50	-6660	199	5.85	16228.0	4.00	2.13	9.83	-1.07	-0.57	-0.53
12	10026	219	6.44	-6855	199	5.85	16881.0	3.94	2.10	10.22	-1.46	-0.78	-0.72
14	10545	219	6.44	-6920	199	5.85	17465.0	3.94	2.10	10.58	-1.82	-0.97	-0.87
16	9319	219	6.44	-6448	198	5.82	15767.0	3.94	2.10	9.55	-0.79	-0.42	-0.40
18	8652	220	6.47	-6311	198	5.82	14963.0	3.97	2.12	9.06	-0.30	-0.16	-0.16
20	8520	220	6.47	-5932	198	5.82	14452.0	3.97	2.12	8.75	0.01	0.00	0.00
22	10527	221	6.50	-6781	202	5.94	17308.0	4.00	2.13	10.48	-1.72	-0.92	-0.83
24	12397	222	6.53	-8018	205	6.03	20415.0	4.03	2.15	12.36	-3.60	-1.92	-1.60
26	13250	223	6.56	-8562	205	6.03	21812.0	4.06	2.16	13.21	-4.45	-2.37	-1.90
28	12418	223	6.56	-8101	206	6.06	20519.0	4.06	2.16	12.43	-3.67	-1.96	-1.62
30	12399	223	6.56	-8123	206	6.06	20522.0	4.06	2.16	12.43	-3.67	-1.96	-1.62
32	11407	224	6.59	-7603	205	6.03	19010.0	4.09	2.18	11.51	-2.75	-1.47	-1.27
34	11528	224	6.59	-7532	206	6.06	19060.0	4.09	2.18	11.54	-2.78	-1.48	-1.28
36	11703	224	6.59	-7677	206	6.06	19380.0	4.09	2.18	11.74	-2.98	-1.59	-1.36
38	11443	223	6.56	-7557	204	6.00	19000.0	4.06	2.16	11.51	-2.75	-1.47	-1.26
40	9683	223	6.56	-6616	204	6.00	16299.0	4.06	2.16	9.87	-1.11	-0.59	-0.55
42	9525	223	6.56	-6514	204	6.00	16039.0	4.06	2.16	9.71	-0.95	-0.51	-0.48
44	11183	225	6.62	-7481	206	6.06	18664.0	4.12	2.20	11.30	-2.54	-1.36	-1.18
46	11280	225	6.62	-7486	207	6.09	18766.0	4.12	2.20	11.37	-2.61	-1.39	-1.21
48	13599	227	6.68	-8818	208	6.12	22417.0	4.18	2.23	13.58	-4.82	-2.57	-2.03
50	13599	227	6.68	-8818	208	6.12	22417.0	4.18	2.23	13.58	-4.82	-2.57	-2.03
52	13907	229	6.73	-8801	210	6.18	22708.0	4.23	2.26	13.75	-4.99	-2.66	-2.09
54	14913	228	6.71	-9350	210	6.18	24263.0	4.21	2.24	14.69	-5.94	-3.17	-2.40
56	14847	228	6.71	-9412	210	6.18	24259.0	4.21	2.24	14.69	-5.93	-3.16	-2.40
58	17109	228	6.71	-10111	210	6.18	27220.0	4.21	2.24	16.48	-7.73	-4.12	-2.93
60	21892	225	6.62	-14193	207	6.09	36085.0	4.12	2.20	21.85	-13.09	-6.98	-4.24
62	18737	222	6.53	-11470	205	6.03	30207.0	4.03	2.15	18.29	-9.53	-5.09	-3.41

Figure B-3 Dry physical model coal seam and coal seam/roof lines – Feb. 2007

Table B-3 Reconnaissance survey test 003 – dry physical model – line 3 – coal seam roof – Feb. 2007

February 11, 2007 Dry Model, Line 3 in Coal Seam Roof, File # 1011, X = 22.5 (in), Y = 12.625 (in), Range 15 (ns), Gain 4 (dB), Sv=1.5873, Sc=1651.2, Va = 8..759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation uV/ft	db/ft
2	14273	215	6.32	-8574	236	6.94	22847.0	3.82	2.04	13.84	-5.08	-2.71	-2.12
4	24016	220	6.47	-15109	202	5.94	39125.0	3.97	2.12	23.69	-14.94	-7.97	-4.61
6	23480	224	6.59	-14278	206	6.06	37758.0	4.09	2.18	22.87	-14.11	-7.52	-4.45
8	14462	224	6.59	-9003	205	6.03	23465.0	4.09	2.18	14.21	-5.45	-2.91	-2.24
10	15884	222	6.53	-9528	204	6.00	25412.0	4.03	2.15	15.39	-6.63	-3.54	-2.61
12	15961	223	6.56	-9714	204	6.00	25675.0	4.06	2.16	15.55	-6.79	-3.62	-2.66
14	15651	222	6.53	-9448	205	6.03	25099.0	4.03	2.15	15.20	-6.44	-3.44	-2.55
16	14309	221	6.50	-8592	203	5.97	22901.0	4.00	2.13	13.87	-5.11	-2.73	-2.13
18	14138	221	6.50	-8670	202	5.94	22808.0	4.00	2.13	13.81	-5.05	-2.70	-2.11
20	14066	221	6.50	-8667	202	5.94	22733.0	4.00	2.13	13.77	-5.01	-2.67	-2.09
22	15850	221	6.50	-9768	205	6.03	25618.0	4.00	2.13	15.51	-6.76	-3.60	-2.65
24	17461	223	6.56	-11200	206	6.06	28661.0	4.06	2.16	17.36	-8.60	-4.59	-3.17
26	18023	223	6.56	-11497	206	6.06	29520.0	4.06	2.16	17.88	-9.12	-4.86	-3.31
28	18034	223	6.56	-11595	206	6.06	29629.0	4.06	2.16	17.94	-9.18	-4.90	-3.32
30	16857	223	6.56	-10800	206	6.06	27657.0	4.06	2.16	16.75	-7.99	-4.26	-3.00
32	16970	223	6.56	-10810	206	6.06	27780.0	4.06	2.16	16.82	-8.07	-4.30	-3.02
34	18110	224	6.59	-11726	207	6.09	29836.0	4.09	2.18	18.07	-9.31	-4.97	-3.35
36	20678	225	6.62	-12844	207	6.09	33522.0	4.12	2.20	20.30	-11.54	-6.16	-3.89
38	18034	224	6.59	-11868	207	6.09	29902.0	4.09	2.18	18.11	-9.35	-4.99	-3.36
40	16559	224	6.59	-10755	207	6.09	27314.0	4.09	2.18	16.54	-7.78	-4.15	-2.95
42	16373	224	6.59	-10566	207	6.09	26939.0	4.09	2.18	16.31	-7.56	-4.03	-2.88
44	17408	225	6.62	-11201	207	6.09	28609.0	4.12	2.20	17.33	-8.57	-4.57	-3.16
46	17785	226	6.65	-10962	208	6.12	28747.0	4.15	2.21	17.41	-8.65	-4.61	-3.18
48	18014	226	6.65	-10925	208	6.12	28939.0	4.15	2.21	17.53	-8.77	-4.68	-3.21
50	17100	226	6.65	-10626	208	6.12	27726.0	4.15	2.21	16.79	-8.03	-4.28	-3.01
52	15043	226	6.65	-10039	207	6.09	25082.0	4.15	2.21	15.19	-6.43	-3.43	-2.55
54	18258	227	6.68	-11453	250	7.35	29711.0	4.18	2.23	17.99	-9.23	-4.93	-3.34
56	18402	228	6.71	-11287	250	7.35	29689.0	4.21	2.24	17.98	-9.22	-4.92	-3.33
58	25006	225	6.62	-15463	208	6.12	40469.0	4.12	2.20	24.51	-15.75	-8.40	-4.77
60	22516	222	6.53	-13501	205	6.03	36017.0	4.03	2.15	21.81	-13.05	-6.96	-4.23
62	9229	217	6.38	-6665	239	7.03	15894.0	3.88	2.07	9.63	-0.87	-0.46	-0.44

Figure B-4 Dry physical model coal seam/roof and roof lines – Feb. 2007

Table B-4 Reconnaissance survey test 003 – dry physical model – line 4 – roof – Feb. 2007

February 11, 2007 Dry Model, Line 4 in Roof, File # 1012, X = 22.5 (in), Y= 16 (in), Range 15 (ns), Gain 4 (dB), Sv=1.5873, Sc=1651.2, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation	
												uV/ft	db/ft
2	18251	218	6.41	-13911	242	7.12	32162.0	3.91	2.09	19.48	-10.72	-5.72	-3.70
4	30061	223	6.56	-20318	246	7.23	50379.0	4.06	2.16	30.51	-21.75	-11.60	-5.78
6	31407	227	6.68	-21084	250	7.35	52491.0	4.18	2.23	31.79	-23.03	-12.28	-5.97
8	19321	227	6.68	-14266	253	7.44	33587.0	4.18	2.23	20.34	-11.58	-6.18	-3.90
10	19308	227	6.68	-14334	253	7.44	33642.0	4.18	2.23	20.37	-11.62	-6.19	-3.91
12	21314	225	6.62	-14627	248	7.29	35941.0	4.12	2.20	21.77	-13.01	-6.94	-4.22
14	19084	225	6.62	-12216	249	7.32	31300.0	4.12	2.20	18.96	-10.20	-5.44	-3.58
16	19279	225	6.62	-12317	249	7.32	31596.0	4.12	2.20	19.14	-10.38	-5.53	-3.62
18	20677	224	6.59	-13028	207	6.09	33705.0	4.09	2.18	20.41	-11.65	-6.22	-3.92
20	20299	224	6.59	-12869	247	7.26	33168.0	4.09	2.18	20.09	-11.33	-6.04	-3.84
22	20741	224	6.59	-13413	248	7.29	34154.0	4.09	2.18	20.68	-11.93	-6.36	-3.98
24	19840	225	6.62	-13395	248	7.29	33235.0	4.12	2.20	20.13	-11.37	-6.06	-3.85
26	19549	224	6.59	-12935	248	7.29	32484.0	4.09	2.18	19.67	-10.91	-5.82	-3.75
28	19603	224	6.59	-12722	248	7.29	32325.0	4.09	2.18	19.58	-10.82	-5.77	-3.73
30	18263	224	6.59	-11644	247	7.26	29907.0	4.09	2.18	18.11	-9.35	-4.99	-3.37
32	16893	223	6.56	-10845	246	7.23	27738.0	4.06	2.16	16.80	-8.04	-4.29	-3.02
34	16720	223	6.56	-10454	246	7.23	27174.0	4.06	2.16	16.46	-7.70	-4.11	-2.92
36	19056	224	6.59	-11984	247	7.26	31040.0	4.09	2.18	18.80	-10.04	-5.35	-3.54
38	19944	224	6.59	-12462	207	6.09	32406.0	4.09	2.18	19.63	-10.87	-5.80	-3.74
40	21115	225	6.62	-13051	206	6.06	34166.0	4.12	2.20	20.69	-11.93	-6.36	-3.98
42	20905	225	6.62	-12949	207	6.09	33854.0	4.12	2.20	20.50	-11.74	-6.26	-3.94
44	18918	225	6.62	-12179	207	6.09	31097.0	4.12	2.20	18.83	-10.07	-5.37	-3.55
46	18973	225	6.62	-12162	207	6.09	31135.0	4.12	2.20	18.86	-10.10	-5.39	-3.55
48	19211	225	6.62	-12017	206	6.06	31228.0	4.12	2.20	18.91	-10.15	-5.42	-3.57
50	17480	225	6.62	-11059	206	6.06	28539.0	4.12	2.20	17.28	-8.52	-4.55	-3.15
52	18163	225	6.62	-11815	206	6.06	29978.0	4.12	2.20	18.16	-9.40	-5.01	-3.38
54	15689	223	6.56	-10687	206	6.06	26376.0	4.06	2.16	15.97	-7.21	-3.85	-2.78
56	17985	226	6.65	-13031	251	7.38	31016.0	4.15	2.21	18.78	-10.02	-5.35	-3.53
58	25556	224	6.59	-16691	248	7.29	42247.0	4.09	2.18	25.59	-16.83	-8.97	-4.97
60	25995	224	6.59	-16558	248	7.29	42553.0	4.09	2.18	25.77	-17.01	-9.07	-5.00
62	10248	216	6.35	-8720	240	7.06	18968.0	3.85	2.05	11.49	-2.73	-1.46	-1.26

Figure B-5 Dry physical model coal seam and roof lines – Feb. 2007

Table B-5 Reconnaissance survey test 003 – dry physical model – line 5 – objects – Feb. 2007

February 11, 2007 Dry Model, Line 5 Objects, File # 1013, X = 22.5 (in), Y= 19.56 (in), Range 15 (ns), Gain 4 (dB), Sv=1.5873,Sc=1651.2, Va = 8.759 (uV), Vm = model volts														
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation uV/ft db/ft		
2	22140	214	6.29	-14832	236	6.94	36972.0	3.79	2.02	22.39	-13.63	-7.27	-4.35	
4	31056	219	6.44	-19875	201	5.91	50931.0	3.94	2.10	30.84	-22.09	-11.78	-5.83	
6	20360	221	6.50	-13317	245	7.21	33677.0	4.00	2.13	20.40	-11.64	-6.21	-3.92	
8	20142	221	6.50	-13197	245	7.21	33339.0	4.00	2.13	20.19	-11.43	-6.10	-3.87	
10	22924	220	6.47	-14305	202	5.94	37229.0	3.97	2.12	22.55	-13.79	-7.35	-4.38	
12	22886	220	6.47	-14383	202	5.94	37269.0	3.97	2.12	22.57	-13.81	-7.37	-4.38	
14	21796	220	6.47	-14764	242	7.12	36560.0	3.97	2.12	22.14	-13.38	-7.14	-4.30	
16	19021	219	6.44	-12020	201	5.91	31041.0	3.94	2.10	18.80	-10.04	-5.35	-3.54	
18	20004	219	6.44	-13025	201	5.91	33029.0	3.94	2.10	20.00	-11.24	-6.00	-3.83	
20	20339	218	6.41	-13309	201	5.91	33648.0	3.91	2.09	20.38	-11.62	-6.20	-3.91	
22	20779	218	6.41	-13439	201	5.91	34218.0	3.91	2.09	20.72	-11.96	-6.38	-3.99	
24	21683	219	6.44	-13919	201	5.91	35602.0	3.94	2.10	21.56	-12.80	-6.83	-4.17	
26	22104	218	6.41	-14119	201	5.91	36223.0	3.91	2.09	21.94	-13.18	-7.03	-4.25	
28	20427	216	6.35	-13363	199	5.85	33790.0	3.85	2.05	20.46	-11.70	-6.24	-3.93	
30	20697	216	6.35	-13549	199	5.85	34246.0	3.85	2.05	20.74	-11.98	-6.39	-3.99	
32	18706	216	6.35	-11867	199	5.85	30573.0	3.85	2.05	18.52	-9.76	-5.20	-3.47	
34	16474	216	6.35	-10577	199	5.85	27051.0	3.85	2.05	16.38	-7.62	-4.07	-2.90	
36	19319	217	6.38	-12224	200	5.88	31543.0	3.88	2.07	19.10	-10.34	-5.52	-3.61	
38	20948	218	6.41	-13636	201	5.91	34584.0	3.91	2.09	20.94	-12.19	-6.50	-4.04	
40	21191	218	6.41	-13484	240	7.06	34675.0	3.91	2.09	21.00	-12.24	-6.53	-4.05	
42	22332	218	6.41	-14100	201	5.91	36432.0	3.91	2.09	22.06	-13.30	-7.10	-4.28	
44	21002	218	6.41	-13264	201	5.91	34266.0	3.91	2.09	20.75	-11.99	-6.40	-4.00	
46	20301	217	6.38	-13391	200	5.88	33692.0	3.88	2.07	20.40	-11.65	-6.21	-3.92	
48	20167	217	6.38	-13327	200	5.88	33494.0	3.88	2.07	20.28	-11.53	-6.15	-3.89	
50	21828	219	6.44	-13618	201	5.91	35446.0	3.94	2.10	21.47	-12.71	-6.78	-4.15	
52	21993	218	6.41	-13924	201	5.91	35917.0	3.91	2.09	21.75	-12.99	-6.93	-4.21	
54	22244	218	6.41	-14024	201	5.91	36268.0	3.91	2.09	21.96	-13.21	-7.04	-4.26	
56	20001	217	6.38	-13400	201	5.91	33401.0	3.88	2.07	20.23	-11.47	-6.12	-3.88	
58	19519	220	6.47	-13591	244	7.18	33110.0	3.97	2.12	20.05	-11.29	-6.02	-3.84	
60	30912	217	6.38	-19893	200	5.88	50805.0	3.88	2.07	30.77	-22.01	-11.74	-5.82	
62	19600	213	6.26	-14611	235	6.91	34211.0	3.76	2.01	20.72	-11.96	-6.38	-3.99	

Reconnaissance Tests Results from April 2006

Figure B-6 Reconnaissance test 002 – floor, coal seam and objects – Apr. 2006

Table B-6 Reconnaissance survey test 002 – physical model – floor – Apr. 2006

April 2006, Model, in the Floor, X = 22.5 (in), Y= 4.25 (in), Range 15 (ns) Gain 22 (dB), Sc=13115.92, Va = 8.759 (uV), Vm = model volts							
Z (in)	Max	Min	Abs	Vm	Va -Vm	Attenuation	
	Count	Count		uV	uV	uV/ft	dB/ft
2	9651	-11734	21385	1.63	7.13	3.80	7.79
4	15525	-19362	34887	2.66	6.10	3.25	5.52
6	21061	-23859	44920	3.42	5.33	2.84	4.35
8	15831	-20802	36633	2.79	5.97	3.18	5.29
10	11455	-16422	27877	2.13	6.63	3.54	6.56
12	11107	-14987	26094	1.99	6.77	3.61	6.87
14	11571	-15577	27148	2.07	6.69	3.57	6.68
16	12727	-16793	29520	2.25	6.51	3.47	6.29
18	12518	-16196	28714	2.19	6.57	3.50	6.42
20	11394	-14933	26327	2.01	6.75	3.60	6.83
22	11395	-15220	26615	2.03	6.73	3.59	6.77
24	11884	-16241	28125	2.14	6.61	3.53	6.52
26	11813	-16372	28185	2.15	6.61	3.53	6.51
28	11457	-16089	27546	2.10	6.66	3.55	6.62
30	10577	-15321	25898	1.97	6.78	3.62	6.90
32	10921	-14883	25804	1.97	6.79	3.62	6.92
34	11102	-15454	26556	2.02	6.73	3.59	6.78
36	11400	-15611	27011	2.06	6.70	3.57	6.71
38	10787	-14595	25382	1.94	6.82	3.64	6.99
40	11768	-15401	27169	2.07	6.69	3.57	6.68
42	12016	-16039	28055	2.14	6.62	3.53	6.53
44	11837	-15975	27812	2.12	6.64	3.54	6.57
46	11402	-15601	27003	2.06	6.70	3.57	6.71
48	11861	-16895	28756	2.19	6.57	3.50	6.42
50	11523	-16525	28048	2.14	6.62	3.53	6.53
52	11851	-16900	28751	2.19	6.57	3.50	6.42
54	11851	-16834	28685	2.19	6.57	3.51	6.43
56	12091	-17062	29153	2.22	6.54	3.49	6.35
58	18433	-21761	40194	3.06	5.69	3.04	4.86
60	17755	-19785	37540	2.86	5.90	3.14	5.18
62	12119	-11377	23496	1.79	6.97	3.72	7.35

Table B-7 Reconnaissance survey test 002 – physical model – coal seam – Apr. 2006

April 2006, Model, Line in the Coal Seam, X = 22.5 (in), Y= 11.5 (in), Range 15 (ns), Gain 22 (dB), Sc=13115.92, Va = 8.759 (uV), Vm = model volts							
Z (in)	Max	Min	Abs	Vm	Va -Vm	Attenuation	
	Count	Count		uV	uV	uV/ft	dB/ft
2	10086	-16567	26653	2.03	6.73	3.59	6.77
4	13535	-21573	35108	2.68	6.08	3.24	5.49
6	14733	-21798	36531	2.79	5.97	3.19	5.31
8	13166	-18540	31706	2.42	6.34	3.38	5.96
10	12992	-19943	32935	2.51	6.25	3.33	5.79
12	13796	-20564	34360	2.62	6.14	3.27	5.59
14	14532	-20547	35079	2.67	6.08	3.25	5.50
16	12328	-18031	30359	2.31	6.44	3.44	6.16
18	11179	-17070	28249	2.15	6.61	3.52	6.50
20	11704	-16758	28462	2.17	6.59	3.51	6.46
22	13164	-18288	31452	2.40	6.36	3.39	6.00
24	14547	-21954	36501	2.78	5.98	3.19	5.31
26	14831	-23260	38091	2.90	5.85	3.12	5.11
28	14870	-22859	37729	2.88	5.88	3.14	5.16
30	14620	-21942	36562	2.79	5.97	3.18	5.30
32	14384	-21166	35550	2.71	6.05	3.23	5.43
34	14946	-20715	35661	2.72	6.04	3.22	5.42
36	13540	-19400	32940	2.51	6.25	3.33	5.79
38	14335	-19031	33366	2.54	6.22	3.31	5.73
40	13355	-16057	29412	2.24	6.52	3.48	6.31
42	11334	-14200	25534	1.95	6.81	3.63	6.97
44	11097	-14326	25423	1.94	6.82	3.64	6.99
46	13241	-18043	31284	2.39	6.37	3.40	6.03
48	14423	-20366	34789	2.65	6.11	3.26	5.53
50	14029	-19709	33738	2.57	6.19	3.30	5.68
52	14853	-20363	35216	2.68	6.07	3.24	5.48
54	14748	-20690	35438	2.70	6.06	3.23	5.45
56	15352	-20298	35650	2.72	6.04	3.22	5.42
58	17577	-23260	40837	3.11	5.65	3.01	4.79
60	12299	-21653	33952	2.59	6.17	3.29	5.65
62	7456	-13111	20567	1.57	7.19	3.84	7.97

Table B-8 Reconnaissance survey test 002 – physical model – objects – Apr. 2006

April 2006, Model, Line in the Objects, X = 22.5 (in), Y= 21 (in), Range 15 (ns) Gain 22 (dB), Sc=13115.92, Va = 8.759 (uV), Vm = model volts							
Z (in)	Max	Min	Abs	Vm	Va -Vm	Attenuation	
	Count	Count		uV	uV	uV/ft	dB/ft
2	17364	-21333	38697	2.95	5.81	3.10	5.04
4	18027	-24809	42836	3.27	5.49	2.93	4.57
6	11449	-14491	25940	1.98	6.78	3.62	6.89
8	9022	-7732	16754	1.28	7.48	3.99	8.92
10	9412	-9745	19157	1.46	7.30	3.89	8.30
12	9220	-10653	19873	1.52	7.24	3.86	8.13
14	9198	-11328	20526	1.56	7.19	3.84	7.98
16	8940	-11603	20543	1.57	7.19	3.84	7.97
18	10570	-13336	23906	1.82	6.94	3.70	7.27
20	10640	-14210	24850	1.89	6.86	3.66	7.09
22	9617	-12710	22327	1.70	7.06	3.76	7.59
24	9937	-13796	23733	1.81	6.95	3.71	7.31
26	11376	-15879	27255	2.08	6.68	3.56	6.66
28	12234	-16235	28469	2.17	6.59	3.51	6.46
30	13261	-16189	29450	2.25	6.51	3.47	6.31
32	14109	-15412	29521	2.25	6.51	3.47	6.29
34	13942	-15162	29104	2.22	6.54	3.49	6.36
36	12907	-14520	27427	2.09	6.67	3.56	6.64
38	11159	-13653	24812	1.89	6.87	3.66	7.10
40	10521	-12179	22700	1.73	7.03	3.75	7.51
42	9962	-11263	21225	1.62	7.14	3.81	7.82
44	10000	-10547	20547	1.57	7.19	3.84	7.97
46	12679	-14445	27124	2.07	6.69	3.57	6.69
48	13214	-15694	28908	2.20	6.55	3.50	6.39
50	13925	-17349	31274	2.38	6.37	3.40	6.03
52	13857	-17573	31430	2.40	6.36	3.39	6.00
54	13840	-17215	31055	2.37	6.39	3.41	6.06
56	12646	-14063	26709	2.04	6.72	3.59	6.76
58	14083	-19509	33592	2.56	6.20	3.31	5.70
60	23728	-32768	56496	4.31	4.45	2.37	3.29
62	19615	-27265	46880	3.57	5.18	2.77	4.15

Reconnaissance Tests Results from February 2006

Figure B-7 Reconnaissance test 001 floor, coal seam, objects, and roof – Feb. 2006

Table B-9 Reconnaissance survey test 001 – physical model –floor – Feb. 2006

February 7, 2006 Line 1 in the Floor, File # 830, X = 22.5 (in), Y= 4.25 (in), Range 6 (ns), Gain 25 (dB), Sc=18526.73, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation uV/ft db/ft	
6	14852	306	3.60	-29393	362	4.26	44245	4.26	2.27	2.4	6.4	3.40	6.02
12	9691	304	3.58	-17019	364	4.28	26710	4.28	2.28	1.4	7.3	3.90	8.36
18	9172	305	3.59	-17639	364	4.28	26811	4.28	2.28	1.4	7.3	3.90	8.34
24	10713	318	3.74	-19583	365	4.29	30296	4.29	2.29	1.6	7.1	3.80	7.77
30	11537	305	3.59	-19101	360	4.24	30638	4.24	2.26	1.7	7.1	3.79	7.72
36	9770	304	3.58	-17778	363	4.27	27548	4.27	2.28	1.5	7.3	3.88	8.22
42	9499	321	3.78	-17088	371	4.37	26587	4.37	2.33	1.4	7.3	3.91	8.38
48	11812	322	3.79	-18225	372	4.38	30037	4.38	2.34	1.6	7.1	3.81	7.81
54	16037	302	3.55	-25339	360	4.24	41376	4.24	2.26	2.2	6.5	3.48	6.33

Table B-10 Reconnaissance survey test 001 – physical model – coal seam – Feb. 2006

February 7, 2006 Line 2 in Coal Seam, File # 831, X = 22.5 (in), Y= 11.5 (in), Range 6 (ns), Gain 25 (dB), Sc=18526.73, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation uV/ft db/ft	
6	21375	305	3.59	-29588	361	4.25	50963	3.59	1.91	2.8	6.0	3.20	5.37
12	21886	303	3.57	-30097	360	4.24	51983	3.57	1.90	2.8	6.0	3.18	5.27
18	17176	303	3.57	-23998	357	4.2	41174	3.57	1.90	2.2	6.5	3.49	6.35
24	22242	306	3.60	-32768	358	4.21	55010	3.60	1.92	3.0	5.8	3.09	5.01
30	21969	305	3.59	-28963	357	4.2	50932	3.59	1.91	2.7	6.0	3.21	5.37
36	21989	302	3.55	-27280	350	4.12	49269	3.55	1.89	2.7	6.1	3.25	5.52
42	18604	302	3.55	-22413	353	4.15	41017	3.55	1.89	2.2	6.5	3.49	6.37
48	19700	305	3.59	-27229	361	4.25	46929	3.59	1.91	2.5	6.2	3.32	5.75
54	25020	304	3.58	-31164	354	4.16	56184	3.58	1.91	3.0	5.7	3.05	4.91

Table B-11 Reconnaissance survey test 001 – physical model – roof – Feb. 2006

February 7, 2006 Line 3 in Roof, File # 835, X = 22.5 (in), Y= 16 (in), Range 6 (ns), Gain 25 (dB), Sc=18526.73, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation uV/ft db/ft	
6	29994	290.7	3.42	-32768	346	4.07	62762	3.42	1.82	3.4	5.4	2.86	4.40
12	24780	287.3	3.38	-31235	339	3.99	56015	3.38	1.80	3.0	5.7	3.06	4.93
18	27992	287.3	3.38	-32768	333	3.92	60760	3.38	1.80	3.3	5.5	2.92	4.55
24	30497	285.6	3.36	-32768	339	3.99	63265	3.36	1.79	3.4	5.3	2.85	4.36
30	23920	283.05	3.33	-31841	326	3.84	55761	3.33	1.78	3.0	5.7	3.07	4.95
36	28052	287.3	3.38	-32768	340	4.00	60820	3.38	1.80	3.3	5.5	2.92	4.55
42	26188	288.15	3.39	-32768	339	3.99	58956	3.39	1.81	3.2	5.6	2.97	4.69
48	28979	285.6	3.36	-32768	338	3.98	61747	3.36	1.79	3.3	5.4	2.89	4.48
54	30566	285.6	3.36	-32768	339	3.99	63334	3.36	1.79	3.4	5.3	2.85	4.36

Table B-12 Reconnaissance survey test 001 – physical model – objects – Feb. 2006

February 6, 2006 Line 4 in Objects, File # 836, X = 22.5 (in), Y= 21 (in), Range 6 (ns), Gain 25 (dB), Sc=18526.73, Va = 8.759 (uV), Vm = model volts													
Z (in)	Max Count	Max Sample	Max Time (ns)	Min Count	Min Sample	Min Time (ns)	Abs	First Arrival (ns)	Velocity ft/ns	Vm uV	Va -Vm uV	Attenuation uV/ft db/ft	
6	10222	228	2.68	-11484	283	3.33	21706	2.68	1.43	1.2	7.6	4.05	9.32
12	10643	226	2.66	-13166	281	3.31	23809	2.66	1.42	1.3	7.5	3.99	8.89
18	9091	225	2.65	-12931	284	3.34	22022	2.65	1.41	1.2	7.6	4.04	9.25
24	10350	225	2.65	-13406	285	3.35	23756	2.65	1.41	1.3	7.5	3.99	8.90
30	16838	225	2.65	-21873	266	3.13	38711	2.65	1.41	2.1	6.7	3.56	6.64
36	13385	227	2.67	-14349	279	3.28	27734	2.67	1.42	1.5	7.3	3.87	8.18
42	13055	229	2.69	-14024	281	3.31	27079	2.69	1.43	1.5	7.3	3.89	8.29
48	12304	231	2.72	-15794	286	3.36	28098	2.72	1.45	1.5	7.2	3.86	8.12
54	14913	230	2.71	-20868	288	3.39	35781	2.71	1.45	1.9	6.8	3.64	7.00

APPENDIX C: EXAMPLE OF CONTROL UNIT SETUP PARAMETERS

A modified SIR-2 ground penetrating radar built by Geophysical Survey Systems, Inc was used in these studies. The SIR-2 a lightweight, portable, general-purpose radar system and is available as an intrinsically safe unit. Prior to an EM surveys, the control unit requires setup parameters. An example of the set-up parameters is shown in the Table C-1 below.

Table C-1 Example of set parameters for the EM control unit

Parameter	900-MHz Antenna
Data collection mode	Continuous
Range, ns	15
Samples per scan	512
Resolution, bits	16
Gain Points	20, 20, 20, 20
Vertical high pass filter, MHz	100
Vertical low pass filter, MHz	1800
Scans per second	32
Horizontal Smoothing, scans	4
Transmit Rate, KHz	32

APPENDIX D: ANTENNAS

The antennas used in this study were 900 MHz. The Figures below show additional antennas.

Figure C-1 300 – (antenna size 27 in by 31 in), 200 – (antenna size 24 in by 24 in) and 400 – (antenna size 12 in by 12 in) MHz antennas

Figure C-2 100-MHz antenna (as configured antenna size 33 in by 44 in).

Figure C-3 80-MHz antenna

CURRICULUM VITAE

William D. Monaghan was born on December 16, 1961, in McKeesport, Pennsylvania, USA. He is the son of Patrick David Monaghan and Grace Antionette Monaghan and has a brother Patrick James Monaghan. He obtained a Bachelor of Science in Electrical Engineering in 1984 from The Pennsylvania State University

After graduation, he worked from 1984 – 1987, at Westinghouse Defense and Electronic Center, in Baltimore, Maryland. His primary duties included: design, debug and integration of sophisticated electromagnetic equipment.

In 1987, he transferred to Westinghouse Transportation System Inc. Pittsburgh, Pennsylvania. From the 1987 – 1990, he served as an Electronic Design Engineer designing analog/digital control printed circuit boards, automatic test equipment and customer training. He received his first patent, “On-line Processor Based Diagnostic System” while working for Westinghouse Transportation System Inc.

In 1990, he accepted a position as Research Electrical Engineer with the U.S. Bureau of Mines (USBM) in Pittsburgh, Pennsylvania, at the Pittsburgh Research Laboratory. In 1996, he transferred to the National Institute for Occupational Safety and Health (NIOSH). His primary research duties include: fire prevention, ground penetrating radar, teleoperated control systems, proximity detection systems, and infrared detection. He received his second patent, “A Method and Apparatus for Monitoring Coal Rib Thickness on a Highwall Mining Operation” while working for the USBM.