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GROUND PENETRATING RADAR COAL MEASUREMENTS DEMONSTRATION AT THE U.S. BUREAU OF MINES RESEARCH CENTER PITTSBURGH, PENNSYLVANIA

FINAL REPORT

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January 4, 1994

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1. Introduction

In situ and near real-time measurements of coal seam thickness have been identified by industry as a highly desirable component of robotic mining systems. With it, a continuous mining machine can be guided close to the varying boundary of the seam while the cutting operation is underway. This provides the mining operation the ability to leave behind the high-sulpher, high-particulate coal which is concentrated near the seam boundary. The result is near total recovery of high quality coal resources, an increase in mining efficiency, and opportunities for improved safety through reduction in personnel in the most hazardous coal cutting areas.

In situ, real-time coal seam measurements using the Special Technologies Laboratory (STL) ground penetrating radar (GPR) technology were shown feasible by a demonstration in a Utah coal mine on April 21, 1994. This report describes the October 18, 1994 *in situ* GPR measurements of coal seam thickness at the United States Bureau of Mines (USBM) robotic mining testing laboratory. The demonstration was funded by the U.S. Department of Energy (DOE), Office of Research and Development (NN-20), On-Site Systems Division, and performed by STL[1].

In this report, an overview of the measurements at the USBM Laboratory is given. It is followed by a description of the technical aspects of the STL frequency modulated-continuous wave (FM-CW) GPR system. Section 4 provides a detailed description of the USBM Laboratory measurements and the conditions under which they were taken. Section 5 offers conclusions and possiblities for future communications.

[1] Work supported by the U.S. Department of Energy, Nevada Operations Office, under contract DE-AC08-93NV11265

2. Measurements at the USBM laboratory facility - Overview

The presentation and demonstration of the STL GPR to the USBM were arranged by Dr. Karl F. Veith from NN-20. The point of contact at the USBM was Jeffrey H. Welsh, Program Manager for Continuous Mining Robotics Systems.

The USBM laboratory is located in a suburb of Pittsburgh, Pennsylvania and is housed in a large, hangar-like building. The rear of the building is a football-field sized enclosed structure with an open floor area. Resting on a portion of the floor within this laboratory is a slab of material called "coalcrete." Coalcrete is a man-made substance composed of standard portland cement substituting coal for the sand and using the same aggregate found in conventional concrete. The material emulates the mechanical and electrical properties of a coal seam. The laboratory with its coalcrete slab provides a site for testing and proof-of-principal demonstrations of various robotic mining systems without having to go to an underground mine. The slab of coalcrete is approximately 50 x 50 ft and is approximately 5 ft thick. One corner of the slab has a 10 ft by 20 ft section removed by a continuous mining unit. Just to the rear of this area, the continuous mining unit has cut a horizontal tunnel from the floor upward such that a 2 ft thick (see Figure 1) roof remains. The depth of the tunnel is approximately 5 ft.

Figure 1. Coalcrete overhang measurement

STL personnel participating in the tests were Michael Martinez, Duane Gardner, and Jack Guerrier. Seven to ten additional personnel from the USBM were present at various times to witness the demonstration. This group of observers included Robert L. Chufo, the technical leader of the USBM FM-CW radar effort, and Gary L. Mowrey who directs the effort in the video pulse radar domain. Carl Ganoe, who also works with the video pulse systems, directed the sequence of coalcrete tests with the goal of quickly establishing the GPR's ability to measure coal seam thickness in real time. He requested several measurements from the roof of the directed the sequence of coalcrete tests with the goal of quickly establishing the GPR's ability to measure coal seam thickness in real time. He requested several measurements from the roof of the coalcrete. These consisted of GPR measurements at the area of maximum thickness and the undercut area. The measurement of the undercut area indicated that the coalcrete was approximately 2 ft thick followed by a 3 ft air interface to the floor of the test area. The GPR system experienced no difficulty in measuring the coalcrete-to-floor distance throughout the maximum thickness areas.

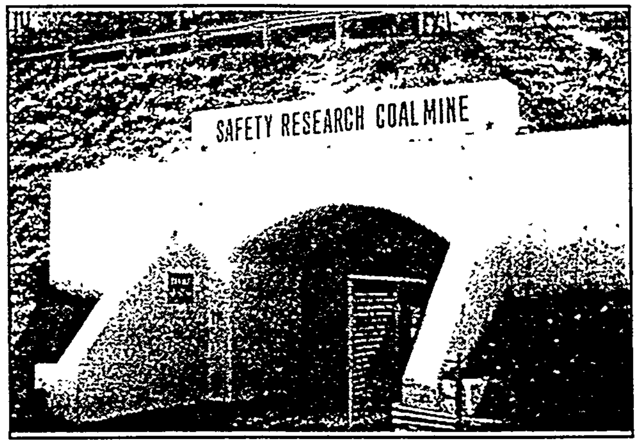


Figure 2. USBM Test mine

Upon the conclusion of the coalcrete demonstration, additional measurements and tests commenced within an actual coal mine. The coal mine is also part of the USBM laboratory (Figure 2). Inside the mine, the USBM has provided test areas within the coal seam by cutting or mining the walls to form several large caverns. The GPR measured the thickness between the coal-to-air interface as well as the thickness of the coal-to-overburden. The STL GPR performed well in most all instances. Targets less than 2 ft in range are difficult to interpret and measure because they coincide with the surface and cross talk returns. This is due to the antenna separation distance of 2 ft. One additional measurement that was not successful involved the measurement of the wall thickness in one of the cavern structures. This measurement was in excess of 14 ft where there was evidence of water dripping from the wall of the cavern. The underground measurements were observed by USBM personnel Carl Ganoe, Robert Chufo, Gary Mowrey, Jeffrey Welsh, and two visiting graduate students.

3. Stepped FM-CW GPR: System Description.

The DOE's Threat Assessment Division, Special Technologies R&D Program (DOE/STP), has sponsored the investigation into a class of advanced short range radars for intelligence and law enforcement applications. As part of this investigation, STL has developed a stepped FM-CW GPR for high resolution imaging of subsurface objects [2]. The initial application of this unit was the detection and imaging of unexploded ordnance. In recent years the target types have been expanded to hazardous waste storage containers [3, 4], pipes, and utility lines. Additionally, some field tests have been conducted where nonmetallic targets were of interest; these include the detection of dinosaur fossils and the mapping of animal burrows [5]. The FM-CW system has also been used to survey large areas of ground at the DOE Rabbit Valley Characterization site in Colorado [6]. NN-20 has also provided funding to enhance the capabilities of the GPR by integrating global positioning system (GPS) data. This positioning information will be correlated with radar information to provide improved survey maps and data presentation.

The stepped FM-CW GPR is a portable, fully self-contained unit (see Figure 3) comprised of three separate pieces: the RF/antenna assembly, the computer assembly, and a rechargeable battery box. It acquires, processes, and displays data in a real-time mode, approximately seven times per second. The system operates over the frequency range of 100 Mhz to 1 Ghz and has the capability of detecting targets to depths of 30 ft with a range resolution of 8 in. Precise systems engineering has provided the GPR with an operational dynamic range in excesss of 96 dB. The overall performance of the GPR depends on the properties of the interrogated media.

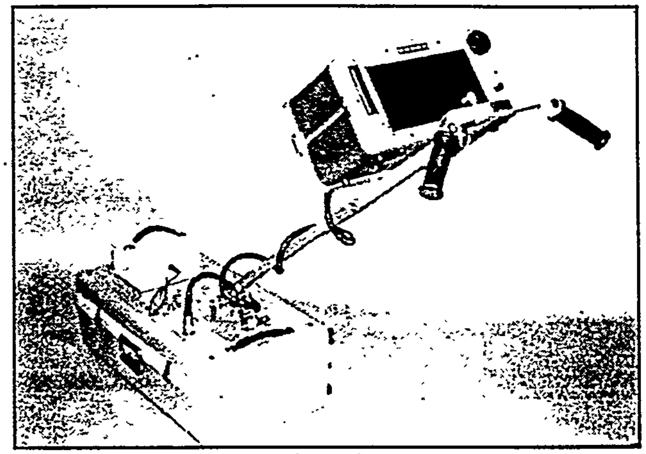


Figure 3. DOE FM-CW GPR

The RF/antenna assembly contains the microwave electronics and antennas. A phase locked loop synthesizer generates the transmitted frequency. The antennas are a dielectrically-loaded, cavity-backed design with a planar, 2-arm log spiral element and are used bistatically with opposite circular polarization. Modulation circuitry and amplifiers also are contained in this assembly.

The computer assembly is based upon the IBM-PC compatible 80486 architecture and controls the entire radar process. It initiates the RF "sweep" and data acquisition, performs a Fast Fourier Transform (FFT), and displays the data. The radar returns are shown on a liquid crystal display (LCD) which provides full functionality in direct sunlight. Data can be saved to floppy discs and hardcopies may be obtained from a standard printer.

The GPR acquires data and indicates depth profile data on two areas of the LCD (see Figure 4). A depth profile showing reflectivity and depth versus distance is displayed on the left portion of the screen. The right portion displays an amplitude histogram of the current sample depth. The closer targets and surface return appear toward the top of the vertical display while deeper targets are at the bottom. The horizontal axis of the depth profile represents lateral distance on the surface. The horizontal axis of the histogram is signal strength. The intensity of the radar return from targets in the depth profile is indicated by mapping the radar data using a variable 9-level gray scale. The minimum threshold level of the gray scale is operator adjustable so that the amount of "clutter return" shown on the display can be minimized.

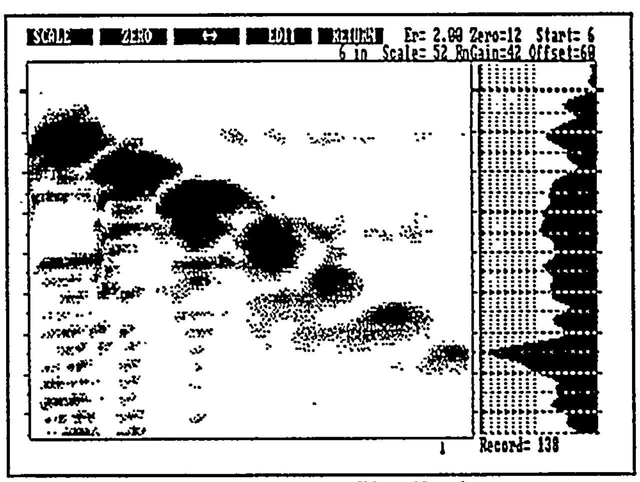


Figure 4. GPR Depth profile display

Several other display parameter adjustments can be made to the depth profiles. A uniform gain or SCALE is used to raise the general level of the return. An exponential gain or RANGE GAIN is used to compensate for the exponential loss factor of the ground. The deeper information is amplified while the shallower information is attenuated. All parameter modifications are performed only on the displayed data. The stored, raw data remain intact.

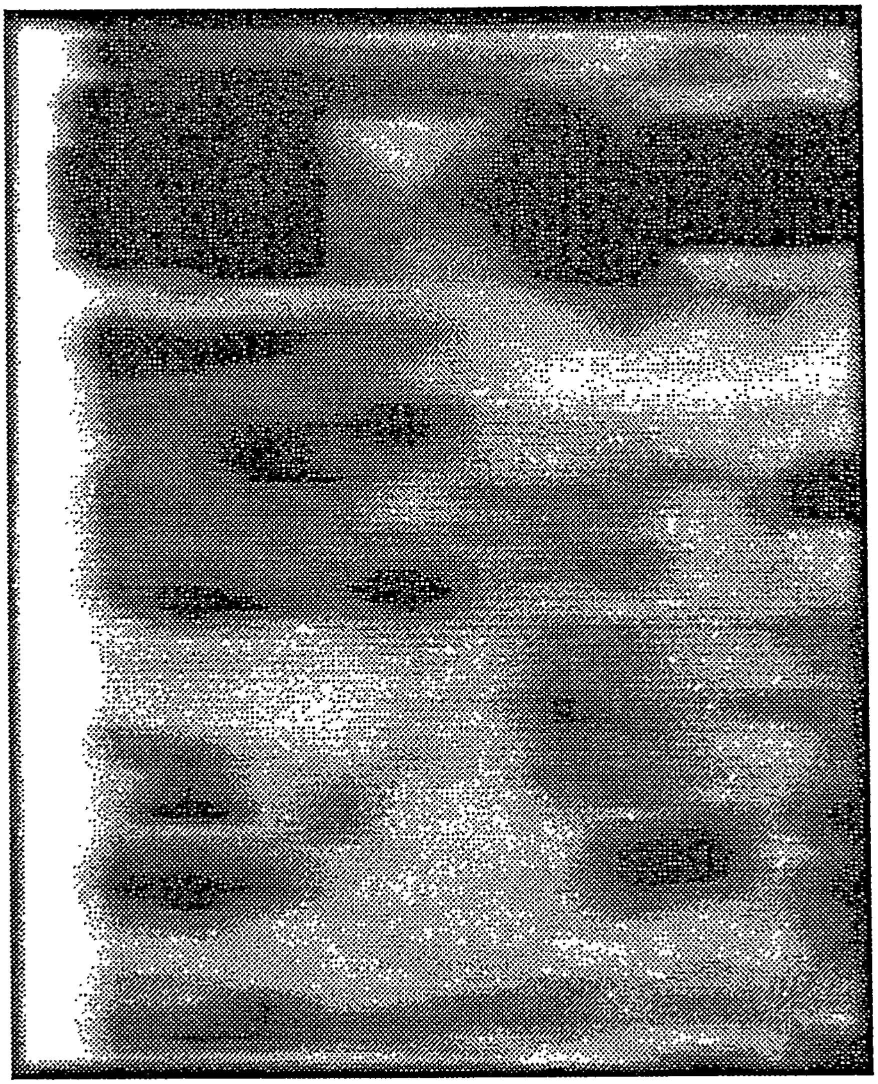
The display also has a ruler to allow an operator to approximate the range measurements of targets. Since the propagation velocity is determined by the dielectric constant of the interrogated media, the ruler can be adjusted based upon known or estimated media properties. This ruler is not designed to be 100% accurate, but to provide a useful estimation of depth.

An example depth profile for some buried metallic targets is shown in Figure 4. A GPR test pit in Santa Barbara, California contains standard test targets consisting of seven square metal plates (12 x 12 in) placed in a staircase fashion from 1 to 7 ft deep and aligned parallel to the surface. The soil composition is entirely sand. As Figure 4 shows, seven distinct target returns, evenly spaced horizontally and vertically, are clearly identified. Note the large peak in the histogram on the right that corresponds to the metal plate 7 ft deep.

The GPR data can be presented in an alternate format where adjacent depth profiles of a surveyed area are combined to create a reflectivity map (see Figure 5). A reflectivity map is an X-ray like picture showing the lateral location and strength of targets, but without depth information. This is useful in analyzing large areas. When a section of interest is encountered, the individual depth profiles can be examined for greater details.

Producing a reflectivity map requires the relative position information be acquired simultaneously with depth profile data. One method used to acquire relative position information, is to mount a measuring wheel on the rear of the GPR RF/antenna assembly. The wheel rotation information is provided by an optical encoder that interfaces to the radar control system which is programmed to collect data at a specific distance interval. Since the exact location of each individual radar reflection data point is known, it can be processed to create a reflectivity map.

A more detailed description of the STL GPR and a discussion of stepped FM-CW radar can be found in reference 2.



Intensity Map capability provides an "X-Ray-like" surface view of a 30 x 40 ft surveyed area.

Figure 5. Intensity map of GPR data

4. Stepped FM-CW GPR: Detail demonstration results

The DOE GPR was demonstrated at two locations at the USBM. The first GPR measurements were taken in the coalcrete indoor test facility building #152. This location offered an opportunity to verify that the system was operating correctly and to complete initial calibration measurements. The dielectric value of coalcrete matches that of coal (E_r = 4.0). Because coalcrete is easily molded to fit any form, this location offered many thicknesses of the substance to measure. The DOE GPR indicated that the thickness of a shelf of coal over a void, shown in Figure 1, was about 24 in, in good agreement with physical measurements. The GPR also measured maximum coalcrete thickness, which again agreed with physical data.

Measurements were next taken in the test coal mine. Data were first collected at a site in the mine known as F Butt 18 Room (Figure 6). Here the location offered an opportunity to determine if the GPR system could measure coal thicknesses of 2 ft 6 in, and 6 ft 3 in. Data were collected from both thicknesses and are shown in Figure 6. The 0-ft position on the screen was not easily identified because of the very lossy coal. As such, an approximation of zero range was assigned along with an E_r value (other than 4.0) which yielded an approximate 2-ft target depth. This scale value was used for all subsequent tests. The 2 ft 6 in slot, which contained "fines," can be clearly observed in the data file of Figure 6. The additional data display represents the 6-ft 3-in slot real distance at about the 6-ft scale marker. The 6 ft 3 in target is visible, but the scale value has about 5% error.

Data were also collected from an 8 in long channel void that was cut at a 60° angle such that the beginning of the channel was 2 ft 9 in from the coal wall, and the end of the channel was 7 ft from the coal side wall (see Figure 7). The accuracy of the system was adequate at the narrow depth of the of the channel. However the coal was found to be too lossy to accurately determine the channel/coal interface as the thickness approached the 7 ft range. One of the additional reasons for the error in measurement relates to the antennae plane of the GPR being positioned 30° to the channel. This forces the radar interrogation/return signals to be proportionally changed. By calculation it may be shown that a target located at 7 ft on a 60° cut should indicate a 5 ft 11 in apparent depth.

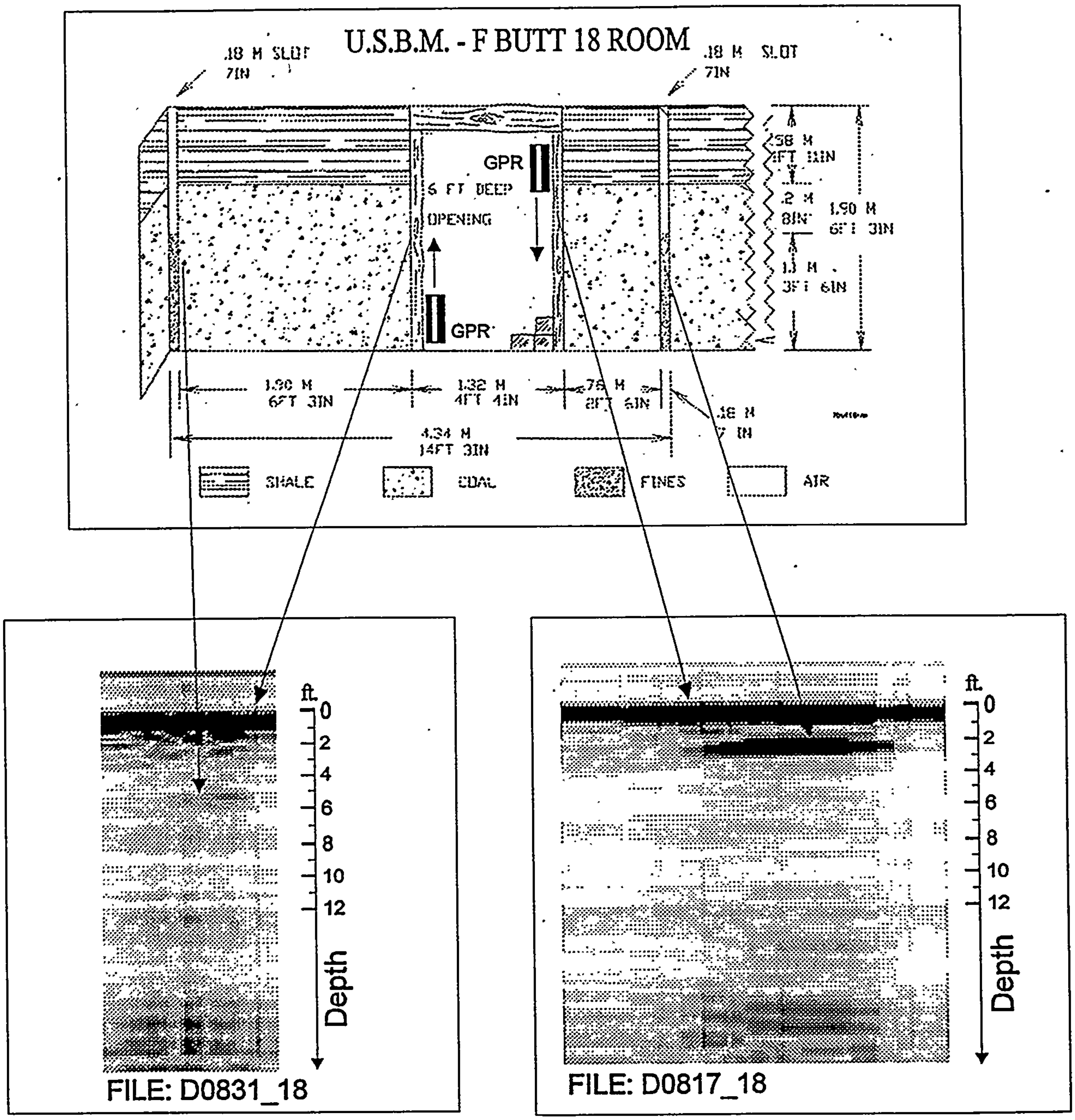


Figure 6. F Butt 18 Room

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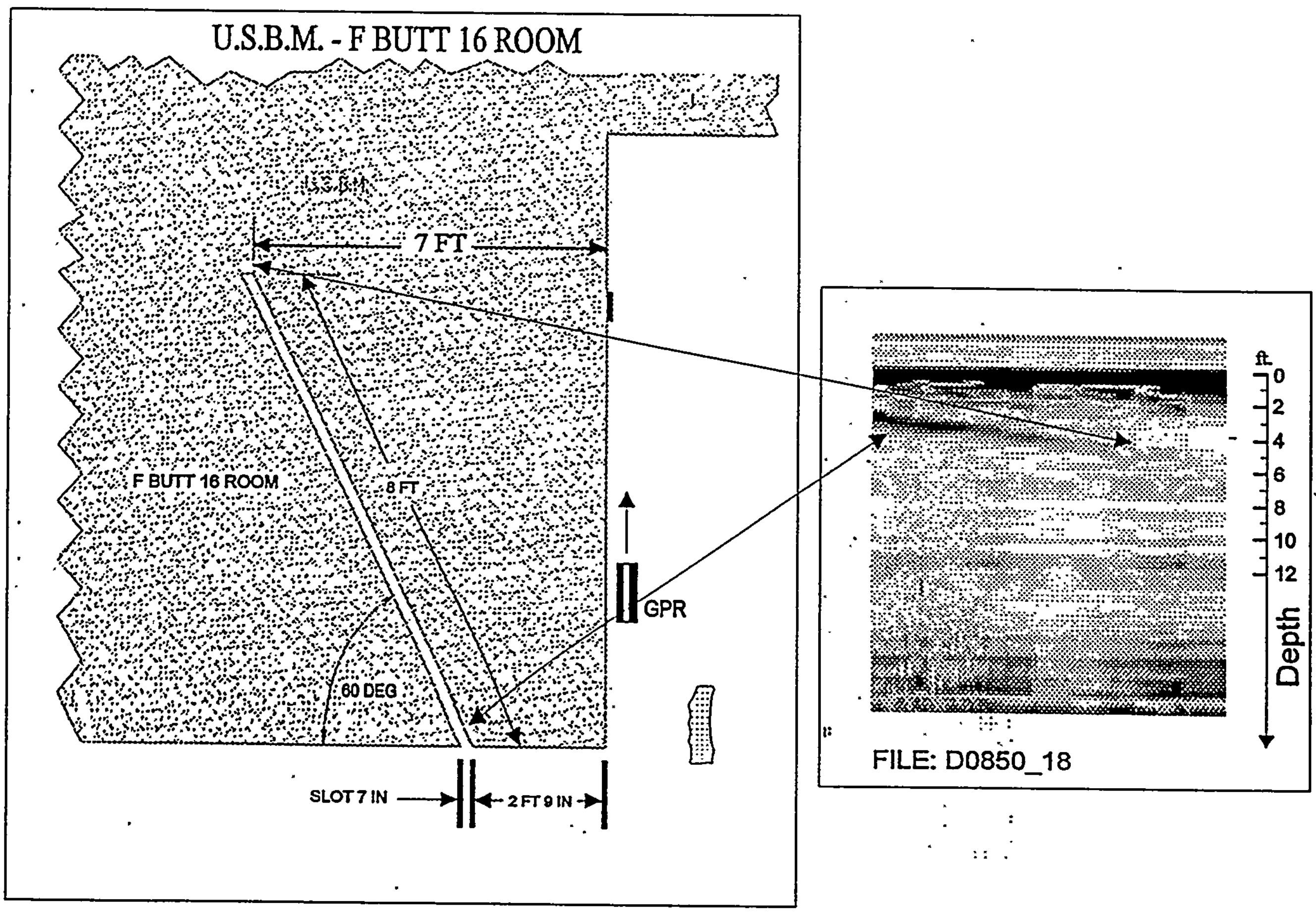

Figure 7. F Butt 16 Room

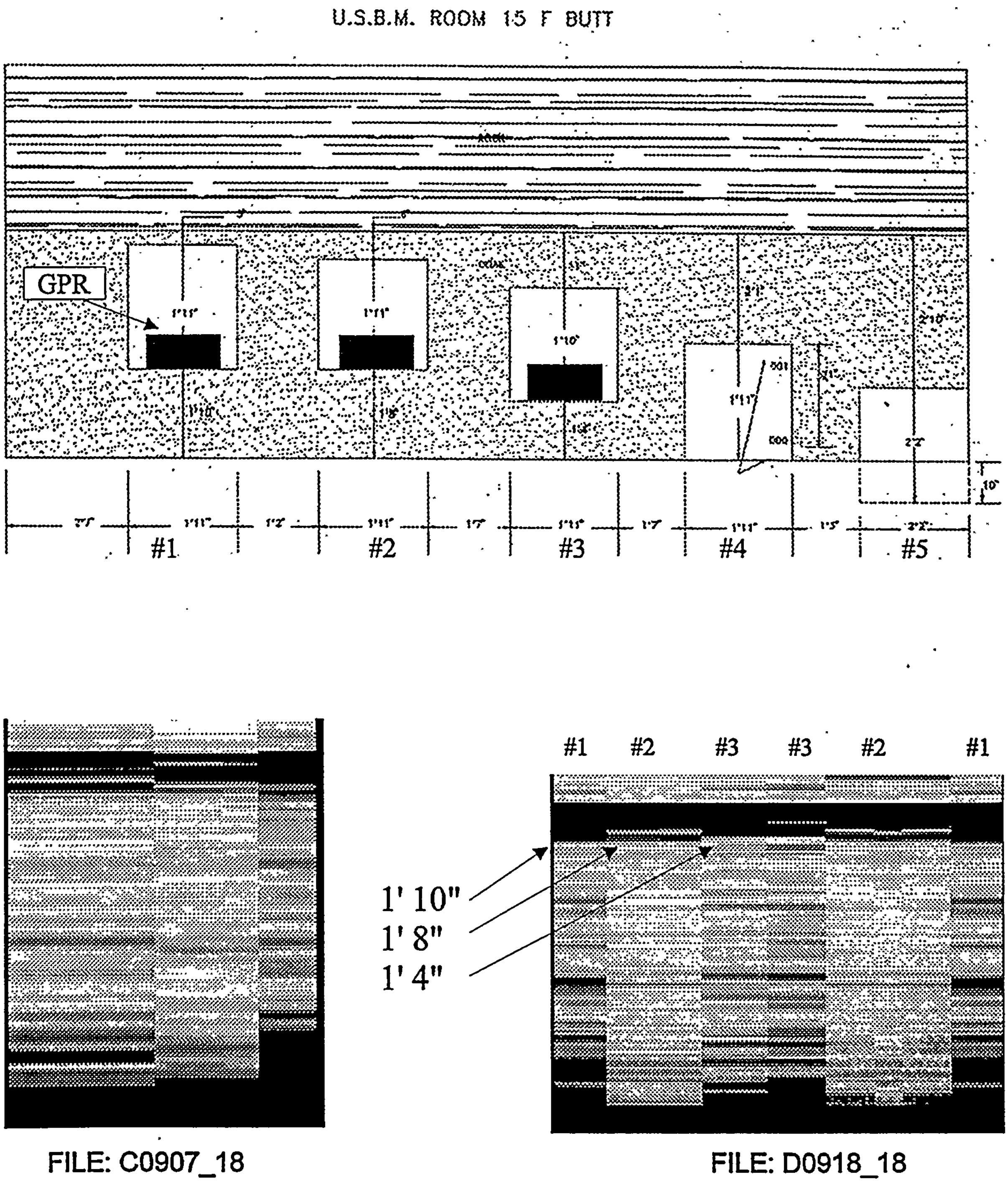

Figure 8. GPR looking down , Room 15 F Butt

Room 15 F Butt offered an opportunity to measure various coal thicknesses (Figures 8, 9 & 10). The data files shown in Figure 8 contain two composite data sets. File D0918-18 is a composite data set taken from different alcoves which are at different heights above the floor of the mine. Changes in depth were detected for each alcove but an absolute depth could not be

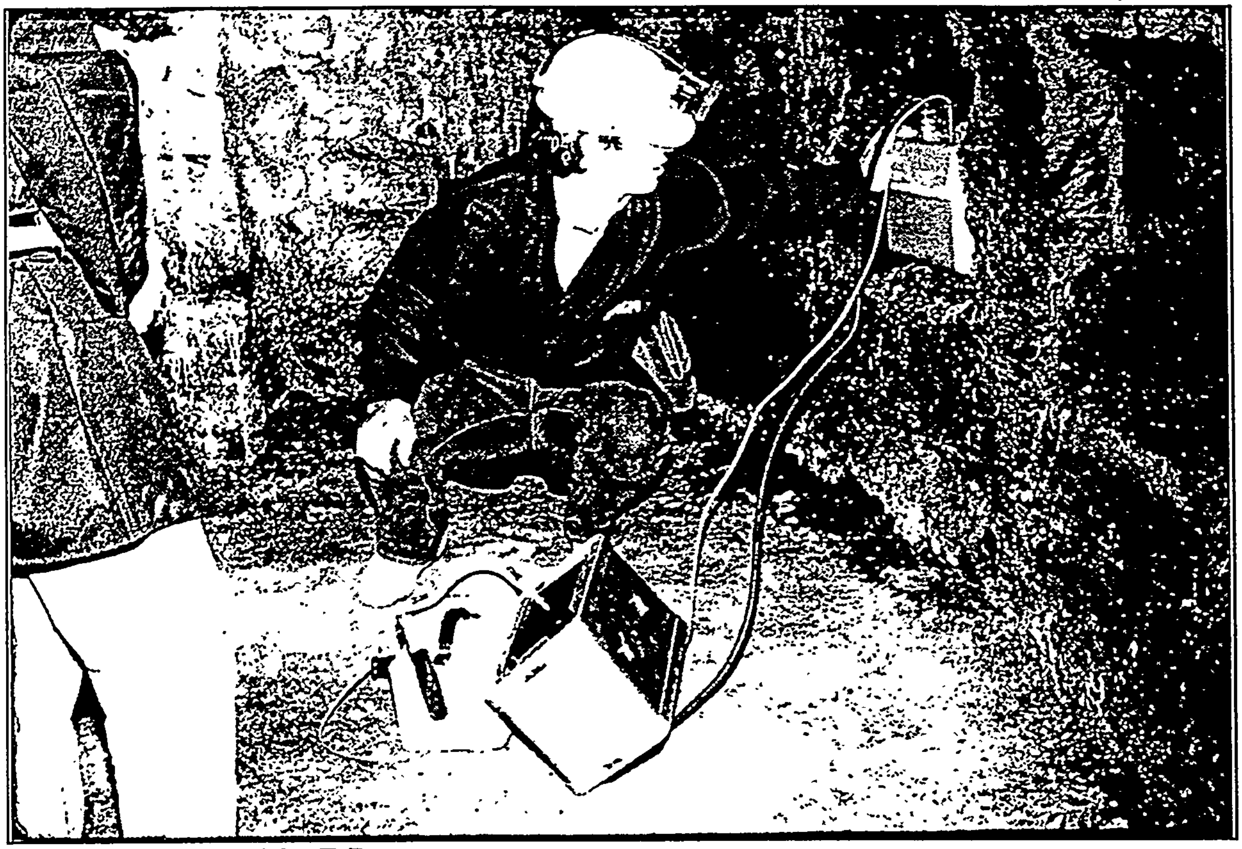

Figure 9. Room 15 - F Butt

obtained. The alcoves were too shallow to accommodate the physical length of the GPR. Therefore the radar returns were confused because part of the GPR extended beyond the hole in the face of the coal seam and viewed the mine floor through the air (see Figure 10). The result was an erratic data set.

Figure 10. GPR Room 15, F Butt

The data file shown in Figure 11, are collected from a slant cut of coal which begins at 8 ft 3 in from the mine floor and slopes to zero 15 ft away. The mine floor was not detected during this test. This could be due to the high loss factor of this coal, the lack of a dielectric contrast with the material of the floor, or poor coupling caused by the narrow width of the slant cut, which could not accomodate the full GPR antenna size.

Data shown in Figure 12, was collected in room 17 F Butt of the mine. Here the antenna was placed on the side of a 4 ft 1 in thick column of coal. The interface on the opposite side of the column of coal was easily detected.

5. Conclusions

The FM-CW Ground Penetrating Radar that has been developed by the DOE Special Technologies Laboratory demonstrated an ability to detect the dielectric contrast of coal seam interfaces during the majority of the field trials performed at the USBM Pittsburgh mine research center. The results of these tests suggest that the DOE GPR technology could prove to be a viable technology even though the system has not been optimized for this type of application. STL technical capabilities and extensive experience in the development of robust field systems may be extended to augment and support the real time detection of coal seam interfaces that would be required by automated coal extraction equipment.

STL would be pleased to offer technical research and development support to the efforts of the USBM and encourages further dialogue to better ascertain support and technology transfer areas.

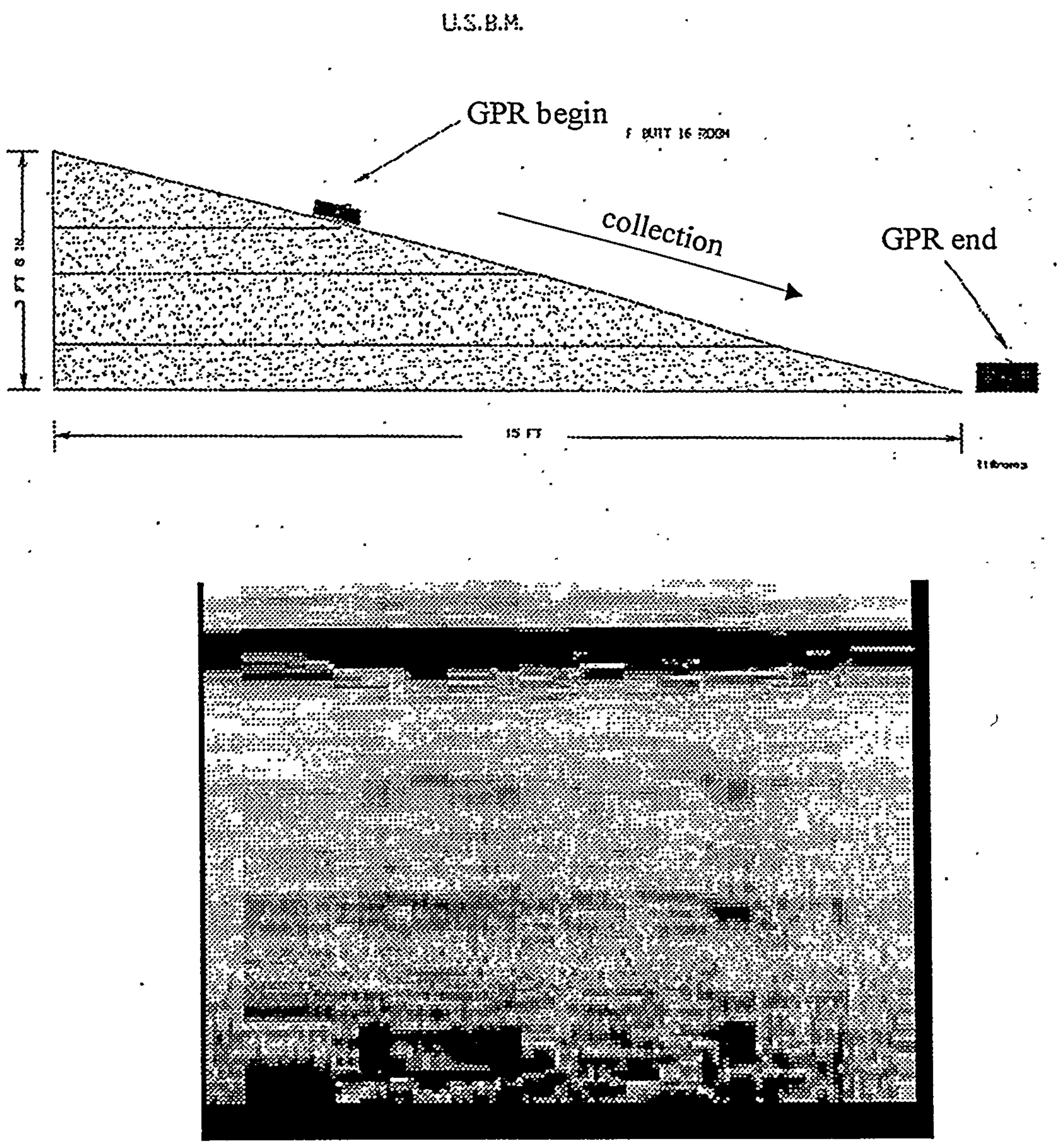

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Figure 11. Data collection on slant cut of lossy coal

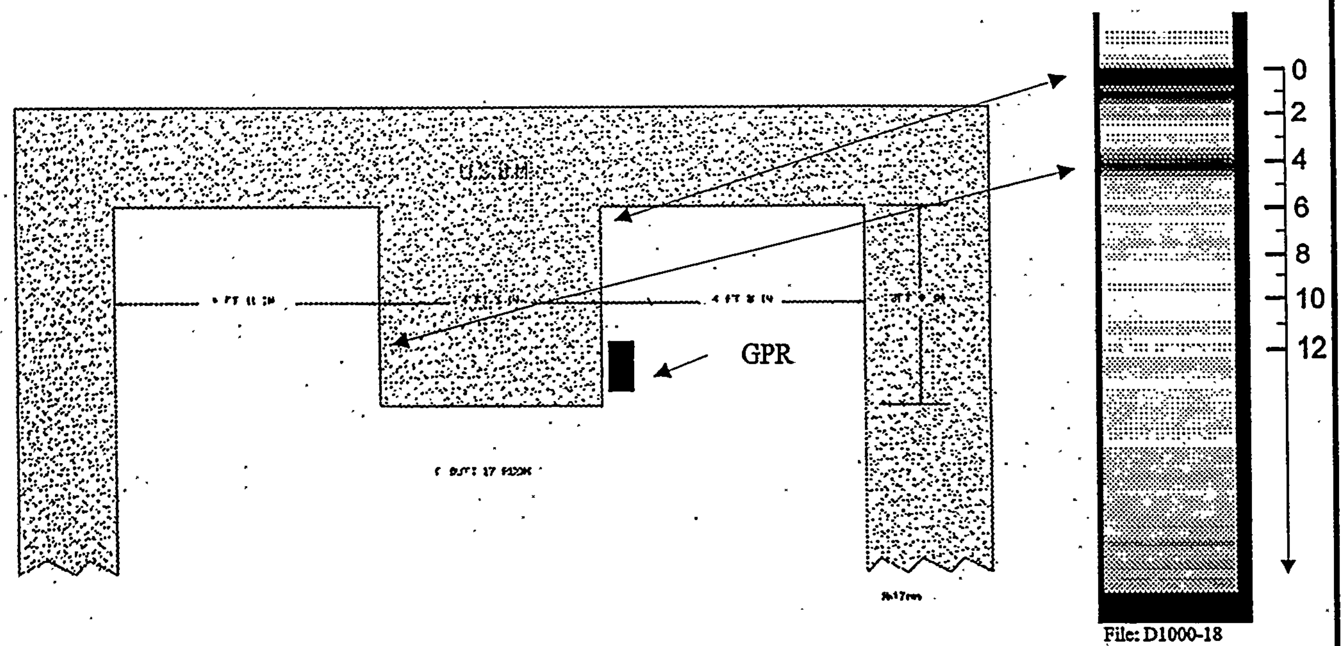

Figure 12. GPR, Data collection
from side of coal column, Room 17 F Butt

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GLOSSARY

bistatic: the use of two antennas where one is for transmitting, the other for receiving; as opposed to monostatic where the same antenna transmits and receives.

chirped: as in a "chirped" radar, a transmission of an electromagnetic wave where the frequency starts at one end of a fixed bandwidth and finishes at the other end in a specified time; a method used in FM pulse compression radar systems.

conductivity: the ability to conduct electricity, the reciprocal of resistivity.

continuous wave (CW): an uninterrupted repetition of an electromagnetic wave.

dielectric constant (E_r): the real part of the complex permittivity.

dynamic range: the ratio of the largest receivable signal to the noise level, usually expressed in decibels (dB).

FM-CW: frequency modulated-continuous wave

frequency modulation (FM): the process of impressing intelligence onto a carrier wave by coherently changing the number of cycles per second .

permittivity: the ratiometric ability of a capacitor, formed using dielectric material, to store electrical energy versus the same capacitor using vacuum as the dielectric.

pulse compression: a technique of using a long, modulated pulse to obtain the resolution of a short pulse, but with the energy of a long pulse.

pulse repetition frequency (PRF): the rate at which waveform of some pulse length is transmitted; reciprocal of the pulse period.

range resolution: the minimum distance that a radar can resolve two closely spaced targets, usually defined by the half power or -3dB point of a return.

reflectivity map: an X-ray like image (plan view) of the ground where the range (radar return) information is integrated.

STL: the United States Department of Energy's Special Technologies Laboratory, Santa Barbara, California.

unambiguous range: the furthest distance that a radar can detect a target without aliasing occurring. Aliasing is the unavoidable result of sampling the data. In effect, the higher frequencies (further target ranges) are folded back onto the lower frequencies (closer target ranges), making absolute distance indeterminate.