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Ground-Penetrating Radar for Strata Control

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UNITED STATES DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot
ft/ns	foot per nanosecond
GHz	gigahertz
in	inch
kW	kilowatt
µF	microfarad
MHz	megahertz
MΩ	megohm
ns	nanosecond
Ω	ohm
pct	percent
s	second
V	volt

GROUND-PENETRATING RADAR FOR STRATA CONTROL

By Ronald H. Church,[1] William E. Webb,[2] and James R. Boyle, Jr.[1]

ABSTRACT

As part of the Bureau of Mines health and safety research program in strata control, a ground-penetrating radar (GPR) system capable of penetrating approximately 10 ft into the mine roof has been devised to identify anomalistic conditions. The GPR system consists of a transmitter with carrier frequencies of 250, 500, and 1,000 MHz, utilizing a dipole antenna, and a receiver, consisting of a dipole antenna fed into a sampler with a time base housed in a storage oscilloscope. A computer was utilized for data acquisition and data processing.

Data analysis by computer enhancement revealed recognizable return radar signatures from the middle man rock and main roof of the test site. These stratigraphic anomalies can be cataloged for recognizable features, which from the past history of the mine may have been shown to create strata control problems. Early recognition of such features could lead to immediate corrective actions and result in the saving of lives.

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INTRODUCTION

Historically, the failure of mine roof strata has been the primary cause of accidental death of miners in underground coal mines. Mine roof falls are often associated with fractures, voids, strata changes, and other defects that exist within a few yards of the surface of the roof. At present there are no reliable means of determining the structure of a mine roof other than by drilling at predetermined intervals to determine the actual geologic nature, which is a slow process and is site specific. A means to quickly, accurately, and economically survey conditions behind the immediate roof would be an invaluable aid in roof strata control. With the passage of the Coal Mine Health and Safety Act of 1969, research in strata control has expanded into the use of electronic and electromagnetic devices to detect strata types or transitions that could lead to roof failure, such as fractures, voids, strata changes, and other anomalistic conditions.

A review of GPR development has been compiled (1).[3] Much of this work has been done by or through the Bureau's research efforts. Successful deployment of a GPR system would eliminate exposing mining personnel to the hazards associated with the roof-drilling operation and would improve operation efficiency. Early recognition of the features associated with roof failure could lead to immediate corrective actions and result in the saving of lives.

TECHNICAL BACKGROUND

In recent years GPR has been used in a number of applications in the mining industry, including geological exploration (2), measurement of coal seam thicknesses (3-5), and location of abandoned mine tunnels, voids, and seam anomalies (6-7). The major problem encountered in GPR use has been the extremely high attenuation of the signal at conventional radar frequencies. Because this attenuation increases rapidly with increasing frequency, it is desirable to use the longest wavelength possible. For this reason, most GPR systems operate at between 20 and 500 MHz. Low frequencies have the disadvantage of having insufficient resolution, since the smallest detectable object is on the order of a few tenths of a wavelength.

To overcome the disadvantages of lower frequency, other variables in GPR have been manipulated by designers to achieve better performance. In order to improve resolution, several GPR systems have used a pulse consisting of a single cycle, or even half cycle, of the carrier frequency. Such monocycle pulse radars give the highest resolution consistent with a given carrier frequency. The choice of the carrier frequency itself is a tradeoff between using the lowest possible frequency to obtain the maximum range and using a high frequency for better resolution. The frequency selected therefore depends on the particular application.

Another problem with a GPR system is the design of an adequate antenna. The monocycle pulse has a very wide frequency spectrum, so a broadband antenna is required. At the low frequencies necessary for GPR use, antennas small enough to be practical tend to have extremely low antenna gains and broad beams.

Any GPR system designed for in-mine use must represent a series of compromises among desired characteristics. Higher frequencies allow better resolution and more practically sized equipment, while lower frequencies provide better penetration. For optimum performance, GPR designed for strata control in underground coal mines must be designed with these factors in mind. This report describes the design and testing of a GPR system for in-mine strata control.

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[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

GROUND-PENETRATING RADAR (GPR) SYSTEM

REQUIREMENTS

In the initial phase of research for the strata control GPR, system requirements were established for maximum performance in detecting conditions that create roof stability problems in mine roof strata. From conversations with mining operations personnel and a review of accident reports of the Mine Safety and Health Administration (MSHA), guidelines were established calling for a maximum penetration depth of approximately 10 ft into the mine roof. The choice of carrier frequency required a decision between maximum penetration and optimum resolution. Since the necessary penetration of the roof strata was limited to 10 ft, higher frequencies could be used and higher resolution could be obtained. Carrier frequencies of 250, 500, and 1,000 MHz were therefore selected as a compromise between these variables.

DESIGN

The design of a GPR system for strata control had to reconcile system requirements with practical and available technology. Mobility and reliability became determining factors since the system would be taken underground into a cramped environment. To control the system, it was decided to use a commercial computer that could easily be reprogrammed in BASIC, rather than an imbedded microprocessor. In this way the operating system could be modified as necessary. The penalty for this approach was that the resulting system was rather heavy and bulky for underground use. However, because of the nature of the research, it was decided that flexibility in the system was a necessity. The system selected consisted of four units: a transmitter, a receiver, a computer for system control and data acquisition, and a portable power supply. The overall GPR system is shown schematically in figure 1.

The transmitter consisted of an AVTECH Electrosystems Ltd. model AVD,[4] monocycle pulse generator, which produced a single-cycle pulse of approximately 4-ns width; pulsers producing 2-ns and 1-ns pulses were also available. The pulse width could be changed simply by interchanging this one component. The pulse was fed through a 50-Ω cable and a 50Ω:200Ω balun to the antenna. In order to minimize loss in the cable, the pulser was mounted in close proximity to the antenna feed. The nanosecond pulser was driven by a 600-ns, 4-V trigger pulse produced by a 555 timer. The pulse repetition frequency was continuously variable from 500 pulses per second to 10,000 pulses per second. The timer circuit also provided pulses for synchronizing the operation of the receiver sampling unit and the computer. The timer circuit is shown in figure 2.

The transmitting and receiving antennas were half-wave triangular dipoles with vertex angles of 90°. This configuration was chosen because it is the simplest geometry that seemed likely to provide adequate bandwidth in a reasonably sized antenna. Some problems were encountered with the antennas; a ringing was observed in the transmitted pulse that was not present when the pulser output was fed directly into a 50-Ω resistive load. This effect was attributed to the antenna's not being perfectly matched over the required bandwidth.

The receiver consisted of a dipole antenna that fed the reflected pulse through a balun, a matched filter, a voltage variable attenuator (Watkins Johnson WTG-1), and a low-noise preamplifier (Watkins Johnson 6203) to a sampling unit. In order to minimize transmission line losses, the balun, filter, attenuator, and amplifier were mounted in close

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[4] Reference to specific trade names or equipment does not imply endorsement by the Bureau of Mines.

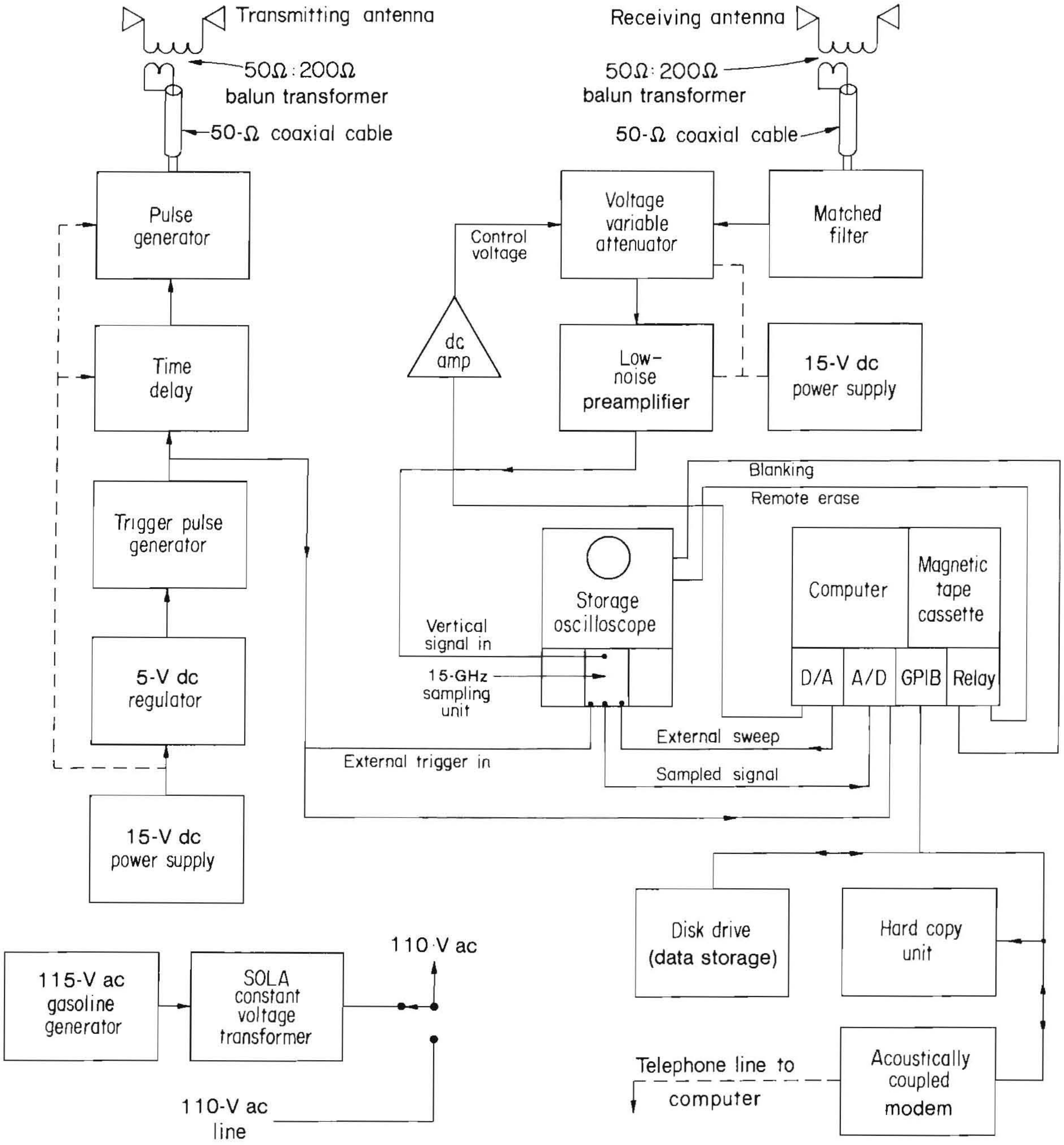

FIGURE 1. - Schematic detailing GPR system.

proximity to the receiving antenna. The pulse sampling unit was a Tektronix 7S-11 sampler and 7T-11 time base in a 7834 storage oscilloscope mainframe. The sampling unit had an S-4 sampling head with 15-GHz bandwidth.

The computer for system control and data acquisition was a Tektronix 4052 graphics computer, with a 4907 disk drive, a 4631 hard copy unit, and an acoustically coupled modem. The computer had a CRT display and magnetic tape cassette. Read-only memory (ROM) packs provided 2 digital-to-analog (D/A) channels, 16 A/D channels, and 16 relay closures. Additional ROM packs provided extended mathematical capabilities such as fast Fourier transform (FFT) and numerical integration firmware. The power supply for preliminary field testing was a 5-kW

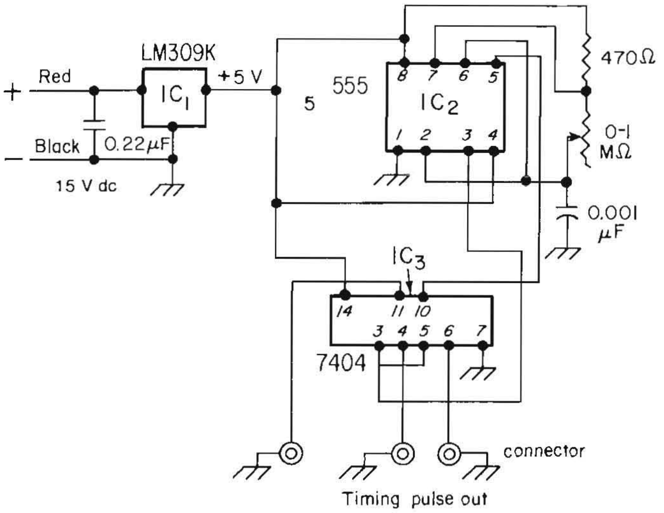

FIGURE 2. - Schematic of pulse timer circuit.

gasoline-powered ac generator with a SOLA constant voltage transformer. It was mounted in a utility trailer, which was also used to transport the antennas and the components mounted on them. The sampling unit and computer were mounted in a console in the back of a vehicle.

OPERATION

The system, as designed, provided a portable GPR unit suitable for underground testing. The operation of the GPR was automatically controlled by the computer. A timer generated a trigger pulse that activated the nanosecond pulse generator. A synchronization pulse was applied to the sampling unit to initiate sampling. The delay between the arrival of the synchronization pulse and the time at which sampling occurred was controlled by a voltage (external sweep) that was provided by the computer. Thus, after each pulse, the sampling unit produced as an output a voltage proportional to the magnitude of one particular point on the received waveform. This value was digitalized and fed into the computer through an A/D channel. The computer then stepped the external sweep signal (and therefore the time delay) to a new value, and another point in the waveform was sampled. This process was continued until the entire waveform had been sampled point by point. In actuality, the sampling point was not changed after each pulse but the same point was sampled on a number of successive pulses. These values were averaged to eliminate noise. The number of pulses averaged was under program control and could be varied from the computer console. Usually 25 to 100 pulses were sampled and averaged at each point, and 256 points were taken per scan. About 100 s was required to reconstruct the complete waveform.

When the entire received waveform had been sampled, the smoothed data were recorded on either magnetic tape or disk. The smoothed waveform was also displayed on the graphic system's CRT to provide the operator with "quick-look" data allowing monitoring of the system operation. A hard copy unit allowed the operator to make a permanent record of the display if desired.

For underground testing, magnetic tape was used for data storage. This allowed the hard copy unit and disk drive to be removed from the system, thereby reducing the amount of equipment that had to be transported underground.

During in-mine operations, because of the high attenuation through rock, the signal reflected from deep within the rock would be much weaker than signals reflected near the surface. Therefore, it was desirable to increase the sensitivity of the receiver as penetration increased. This was accomplished under computer control by decreasing the front end attenuation between sample points. An algorithm was constructed to provide the proper change in attenuation, taking into account the exponential dependence of attenuation on distance and the nonlinear relation between the variable attenuator and its central voltage.

TESTING PROCEDURE

A series of tests was initiated for each phase of development of the prototype GPR unit. These tests consisted of (1) laboratory measurement of signal propagation in air, (2) field measurement of signal propagation through soil, and (3) underground measurement of signal propagation through mine roof strata.

PROPAGATION IN AIR

Signal propagation tests in air were conducted in the laboratory to determine optimum system operation. In a series of tests, antennas were placed at 1-ft intervals and were oriented at different polarities for each test. Afterwards, data stored on tape were analyzed and instrumentation adjustments made to improve the system performance. Analysis of the data revealed clear signal pulse readings with little signal attenuation when antennas were directed parallel to each other.

Figure 3 shows the radar scan in air. For this test the antennas were pointed toward each other, separated 5 ft, and had parallel polarization. Secondary reflections were noted in the scan. This was attributed to the nondirectional wave path of the antenna with reflections. With antennas misaligned (vertical to horizontal), lower signal-to-noise ratios were observed in the scans. Polarity of antennas clearly affected the signal pulse and attenuation: parallel polarization provided the optimum performance in air.

PROPAGATION IN SOIL

Initial field testing in soil was conducted at a site in Jefferson County, AL, to determine the propagation characteristics of the radar unit through the earth. The GPR unit was transported to a location where a tank was buried

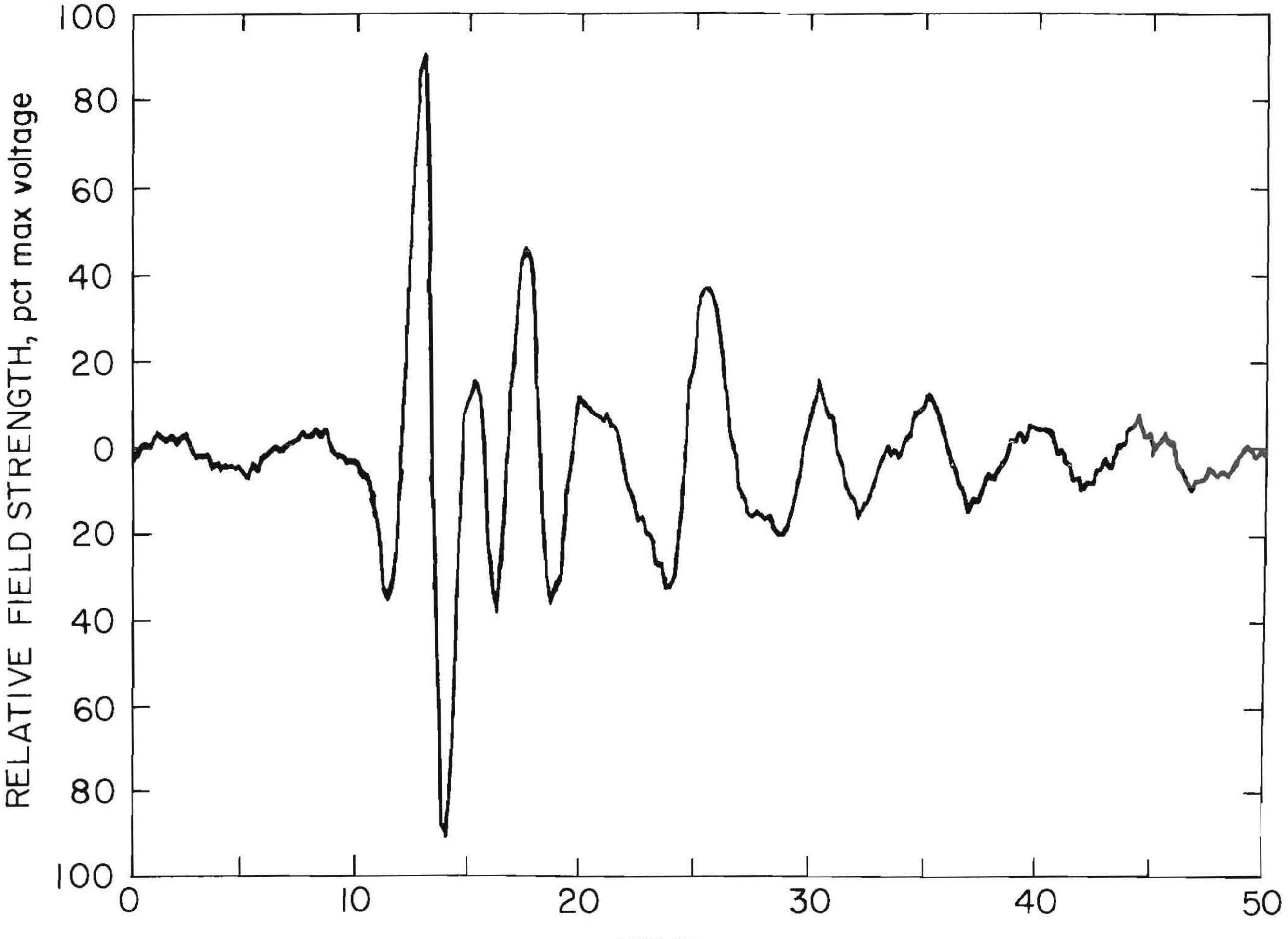

FIGURE 3. - GPR test in air.

approximately 3 ft underground. There were approximately 6 in of asphalt overlying the clay soil. Unconsolidated material consisting of rock and clay comprised the overburden.

Figure 4 shows typical results of the soil radar scan. The antennas were located on the ground surface and had parallel polarization. Propagation velocities through the clay soil were approximately 0.5 ft/ns. The pulse began at approximately 9 ns, and the reflected signal from the tank was received at 22 ns.

In figure 4 the radar signatures correlated closely with anticipated reflections expected from a large buried metallic object located 3 ft below the surface.

PROPAGATION IN UNDERGROUND MINE ROOF

Field testing of the GPR at an underground mine was conducted at Jim Walter Resources Inc. No. 5 Mine, located in Tuscaloosa County, AL. Figure 5 shows the radar control console housing the computer, storage oscilloscope, pulsers, receivers, timing units, and power supplies. A magnetic tape controlled the system and directed unit operation. Power was supplied by a 110-V ac outlet from an underground sectional power transformer. Figure 6 illustrates typical antenna installations against the mine roof. Parallel polarization of antennas again gave the highest signal-to-noise ratios.

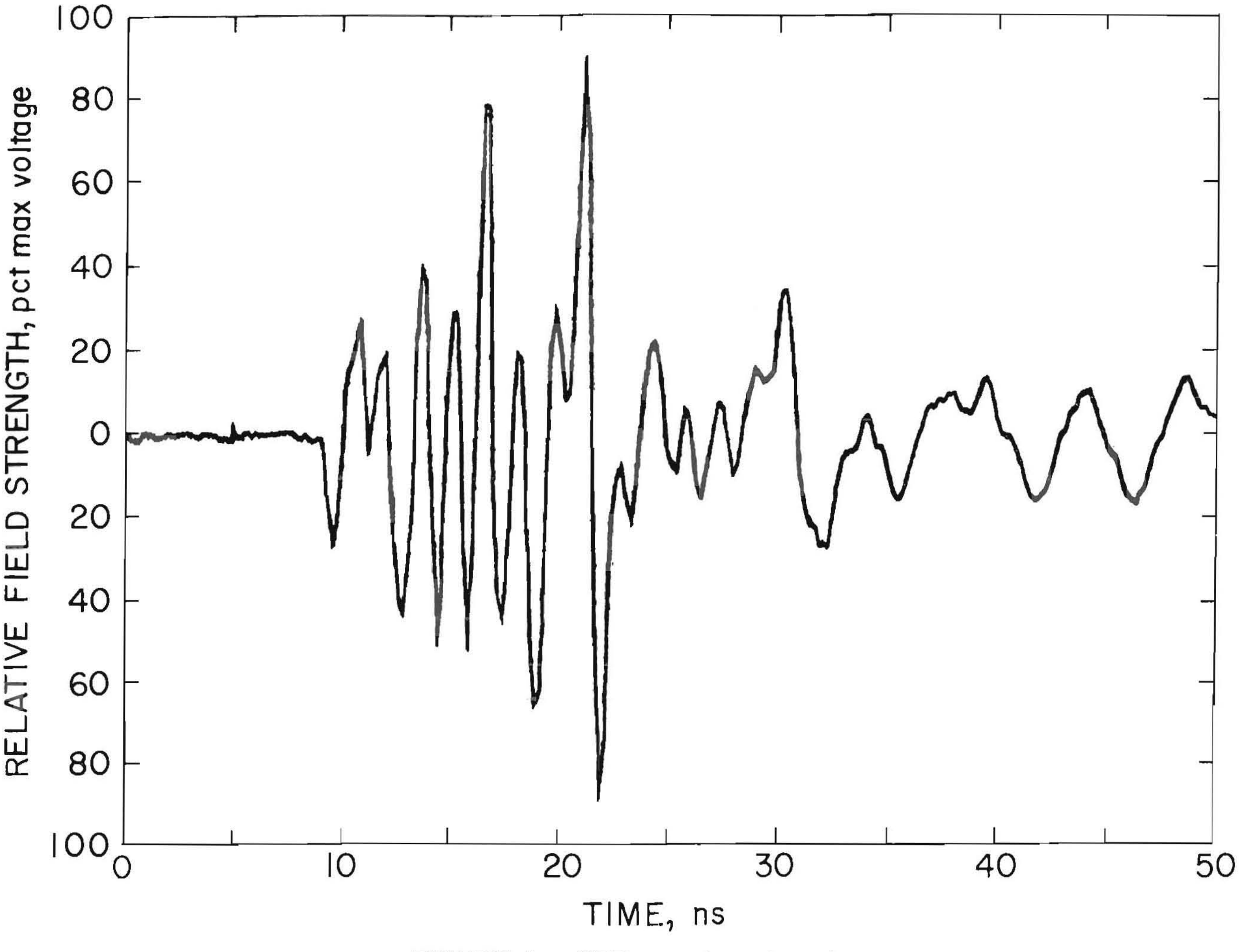

FIGURE 4. - GPR test through soil.

FIGURE 5. - GPR-operating control console.

FIGURE 6. - Antenna installation against mine roof.

Radar scans were taken in an entry near the face of the section between crosscuts and on 7-ft centers right and left, respectively, of the center line of the heading. A total of 46 radar scans were performed at 14 sites at various antenna polarizations. Figure 7 details a typical radar scan taken during the test with parallel antenna polarization.

As noted on the scan, the initial pulse (first contact of mine roof) occurred at around 7 ns. Because of direct roof coupling, this reflection would be small. The 12-ns, 17-ns, and 22-ns pulses seemed to indicate changes in homogeneity of the strata. This proved to be the case from ground-truthing[5] studies taken in the area. The pulse following (33 ns) appeared to be a secondary reflection similar to the 12-ns and 17-ns pulses. Because of this heterogeneity (small layering of rock and coal), interpretation of the coal seam and mine roof locations was left entirely to computer analysis. Overall system operation appeared adequate. The only system modifications made were for antenna support and mobility. For further testing, an antenna support stand was constructed, which allowed the antennas to be moved across a support bar for improved scanning accuracy.

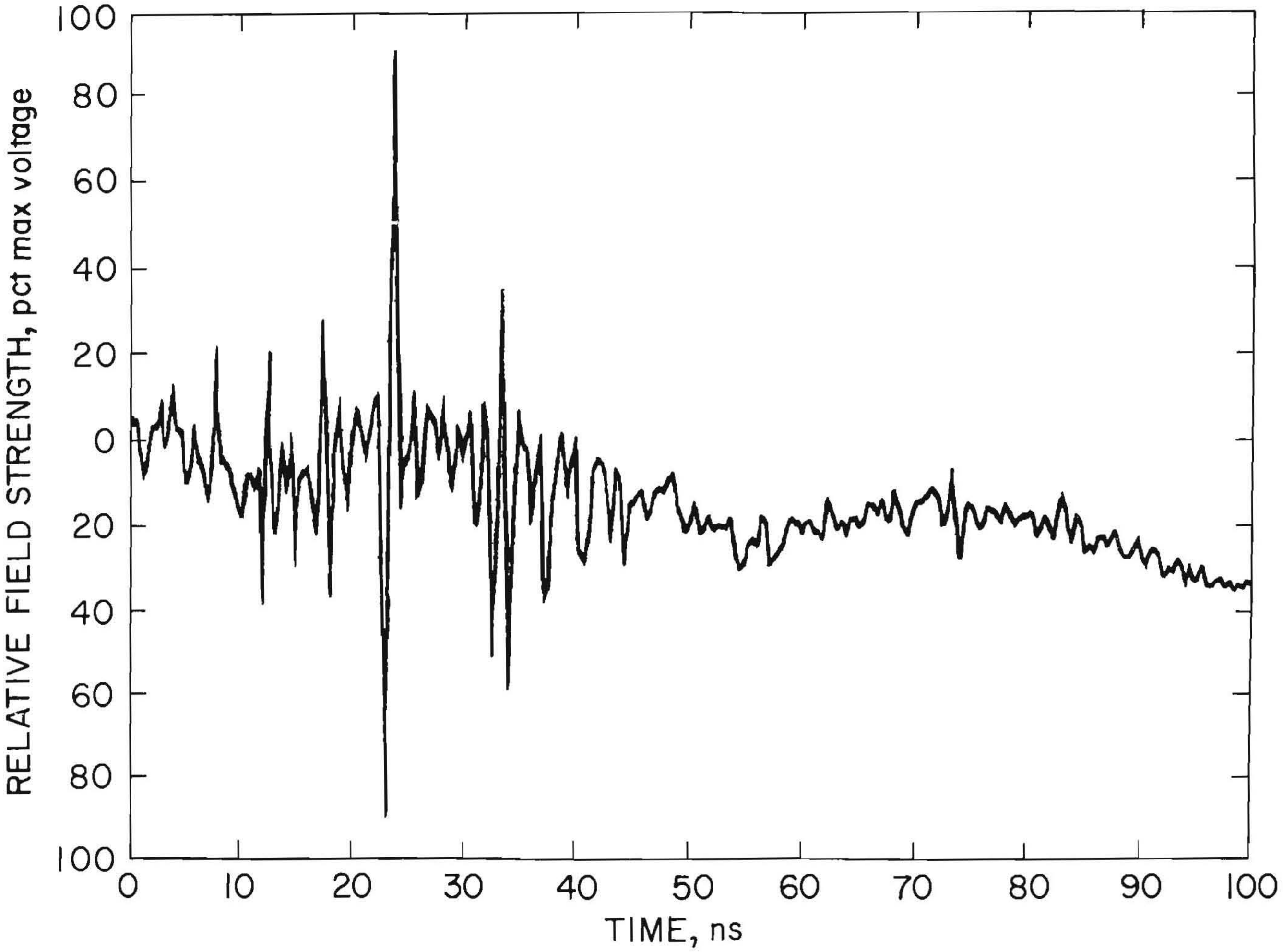

FIGURE 7. - Radar scan taken during first underground field test.

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[5] "Ground-truthing" refers to visual inspection of the mine roof, utilizing a borescope placed inside a borehole in the roof.

GROUND TRUTHING

To determine the accuracy of radar scans in mine roof stratigraphy, it was necessary to ground-truth the mine roof. To accomplish this, a series of holes was drilled in and beyond the first underground test area to catalog the roof strata for future research. These holes were drilled on 7-ft centers approximately in the center of the heading and 5 ft to the left and right of the center line. A borescope was used to survey each hole, and the data were recorded in a lithographic log of the area.

Results of the survey detailed an immediate roof ranging in thickness from 3 to 4 ft and comprised of a sandy shale material; an upper coal seam overlying this immediate roof, ranging from 2 to 4 ft in thickness; and the main roof, approximately 7 ft into the strata. These were the general classifications of materials found in each hole; however, individual holes showed signs of hairline cracks, coal streaks, rash, and other discontinuities, which varied considerably from hole to hole.

STRATIGRAPHIC VERIFICATION OF GPR

Two additional underground tests were conducted to determine system accuracy in identifying unknown anomalistic conditions in the mine roof. From the lithographic catalog plotted against the GPR patterns, it was determined that certain peak patterns of the scan represented the rock-coal-rock interfaces encountered in ground truthing. These underground tests were designed to provide a comparison of the GPR image and the ground truth. They consisted of laying out an antenna pattern against the mine roof perpendicular to the entry heading. Figure 8 shows the modified antenna supports, which allowed for accurate antenna placements against the mine roof and mobility for scanning on 6-in intervals.

During the first verification test, difficulty was encountered in synchronizing on the initial pulse. With the system not under computer control, the initial pulse can normally be seen on the CRT of the oscilloscope. During the test this could not be achieved, so the pulse could only be synchronized during the scan. This also was not successful because the signal would drift occasionally as if the pulse were lost, which proved to be the case. It was later discovered that the coaxial lead connections were shorting the scan, causing loss of reception, while the computer searched for a signal it could not find.

The second verification test setup was similar to the first, except that it was in a mine area that had not been ground-truthed. This test consisted of 16 scans on approximately 6-in centers where direct roof coupling of the antenna was possible. The scan was conducted at 5- and 10-ns divisions. The data collected were analyzed visually, underground. They predicted the rock-coal-rock boundaries from the lithographic signatures derived from previous ground truthing and GPR reconciliation. Ground-truthing studies were then made of the test area to verify these results.

DATA ANALYSIS

The data from the underground tests were subjected to posttest mathematical analysis. Computer programs were written to read and process the radar signatures. First the signatures were digitally fitted by convolution with the transmitted pulse. This is equivalent to detection with a matched filter. The convolution was carried out on the Tektronix 4052 computer using the Tektronix-supplied FFT routine. The filtered signature was then processed to select the peaks in the signals and record the return times. These times were used to determine the distances to the strata interfaces, as described below.

The Jim Walter Resources Inc. No. 5 Mine consists of two coal seams. The

FIGURE 8. - Modified antenna support stand.

lower Blue Creek Seam, which is being mined, ranges from about 6 to 8 ft in thickness. The upper Mary Lee Seam is 1 to 3 ft in thickness and is separated from the Blue Creek Seam by a 3- to 4-ft middle man of shale. At the interface between the middle man and upper seam there is typically a layer of rash consisting of carbonaceous material that is a mixture of rock and coal. The rash ranges from 1 to 12 in, although in places it may be missing entirely. This rash material created problems in interpreting the radar signatures. Radar signatures from the No. 5 Mine roof showed two strong returns. These were interpreted as being reflections from the interfaces between the middle man and upper seam and between the upper seam and main roof.

In order to calculate the thickness of the middle man and upper coal seam, an idealized roof geometry has been assumed, where both strata are assumed to be planes parallel to the mine roof. Furthermore, it is assumed that the principal reflection from each interface is due to a small region where the directions of propagation of the incident and reflected waves make equal angles to the normal reflecting surface. The roof model is shown in figure 9.

The transmitting antenna is located at T and the receiver at R; T and R are separated by a distance (a) equal to 2.6 ft. The first pulse propagates from T to A where it is reflected to R. The second pulse travels along the path TCBDR; h_1 and h_2 are the thicknesses of the middle man and upper seam, respectively; and ℓ_1,

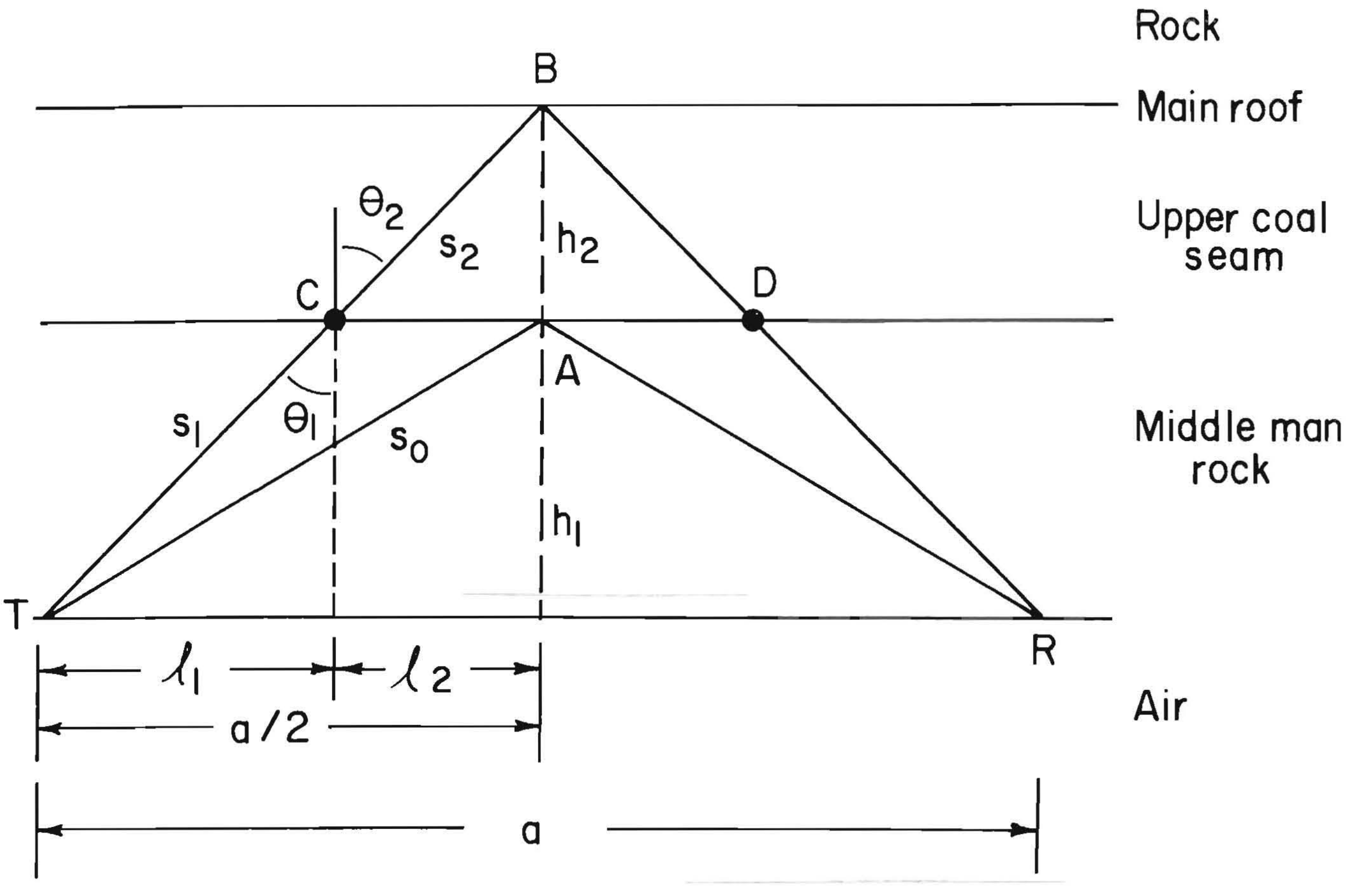

FIGURE 9. - Roof model of GPR propagation characteristics.

ℓ_2, s_1 and s_2 are as shown in the figure. Let V_1 and V_2 be the speed of propagation in rock and coal, respectively, and T_1 and T_2 be the propagation times of the first and second peaks.

Also,
$$n_1 = \frac{c}{V_1}, \tag{1}$$

and
$$n_2 = \frac{c}{V_2}, \tag{2}$$

where n_1 and n_2 are the indexes of refraction of the media and c is the speed of light in air.

From the figure,
$$T_1 = 2\,\frac{s_o}{V_1}$$
$$= 2\,s_o\,\frac{n_1}{c}; \tag{3}$$
$$s_o = \sqrt{\left(\frac{a}{2}\right)^2 + h_1{}^2}. \tag{4}$$

Hence,
$$h_1 = \left\{\left(\frac{T_1 c}{2n_1}\right)^2 - \left(\frac{a}{2}\right)^2\right\}^{1/2}. \tag{5}$$

For the second pulse,
$$n_1 \sin\Theta_1 = n_2 \sin\Theta_2 \text{ (Snell law)}, \tag{6}$$
$$\ell_1 + \ell_2 = \frac{a}{2}, \tag{7}$$
$$\sin\Theta_1 = \frac{\ell_1}{s_1}, \tag{8}$$
$$\sin\Theta_2 = \frac{\ell_2}{s_2}, \tag{9}$$
$$s_1{}^2 = \ell_1{}^2 + h_1{}^2, \tag{10}$$
$$s_2{}^2 = \ell_2{}^2 + h_2{}^2, \tag{11}$$

and $$T_2 = 2\left(\frac{n_1 s_1}{c} + \frac{n_2 s_2}{c}\right). \quad (12)$$

By combining equations 6 through 12 so as to eliminate Θ_1, Θ_2, s_1, s_2, h_2, and ℓ_2, the following equation is obtained:

$$A\ell_1^4 + B\ell_1^3 + C\ell_1^2 + D\ell_1 + E = 0, \quad (13)$$

where $$\eta = n_2^2 - n_1^2, \quad (14)$$

$$\alpha = \frac{n_2^2 a}{2}, \quad (15)$$

$$A = \eta^2, \quad (16)$$

$$B = 2\alpha\eta, \quad (17)$$

$$C = \eta^2 h_1^2 + \alpha^2 - \eta_1^2 \beta_2^2, \quad (18)$$

$$D = Bh_1^2, \quad (19)$$

$$E = \alpha^2 h_1^2, \quad (20)$$

and $$\beta_2 = \frac{T_2 c}{2}. \quad (21)$$

Furthermore, it can be shown that

$$h_2^2 = \left(\frac{n_2 \ell_2}{n_1 \ell_1}\right)^2 \left(h_1^2 + \ell_1^2\right) - \ell_2^2, \quad (22)$$

where $$\ell_2 = \frac{a}{2} - \ell_1. \quad (23)$$

Now h_1 can be found from equation 5. Equation 13 is then solved numerically for ℓ_1 and the results are substituted into equation 22 to obtain h_2.

These calculations form the basis for interpretation of the radar signatures obtained during field testing. A computer program was developed to calculate the immediate roof-coal seam interface and the coal seam-main roof interface from the points picked during a computer scan of the raw data.

In order to apply this method, it is necessary to know V_1 and V_2--the speeds of propagation in rock and coal. No data were available for the specific rock and coal in the test mine. Therefore, it was assumed that V_1 (rock) = 0.433 c_o and V_2 (coal) = 0.684 c_o, where c_o is the speed of light in air. These values are typical of those reported in the literature (8). However, the actual speeds of propagation at the test site could vary from the assumed values.

The computer was programmed to scan the radar signal and select the points corresponding to the reflections from the lower face of the coal seam and the main roof. The polarity of the signal (+ or -) corresponds to the placement of the antenna.

Figure 10 shows both the stratigraphic structure of the mine roof, as determined from ground truthing, and the computer search for signal peaks, as represented by X's and O's. The "X" corresponds to the main roof-coal seam interface, and the "O" corresponds to the coal seam-immediate roof interface. Note points *A* and *B* on figure 10. These correspond to signal peaks (X and O), as determined by the computer, for the radar scan taken at the 6.5-ft reference location. Figure 11 is the graphic representation of the GPR signal; points *A* and *B* lie close to the immediate roof and main roof, as shown in figure 10.

Figure 12 depicts the stratigraphic structure of the mine roof at the second underground verification test site. GPR signal peaks are indicated by X's and O's. Figure 13 shows the graphic representation of the GPR; the correlation of points *A* and *B* is shown on figure 12.

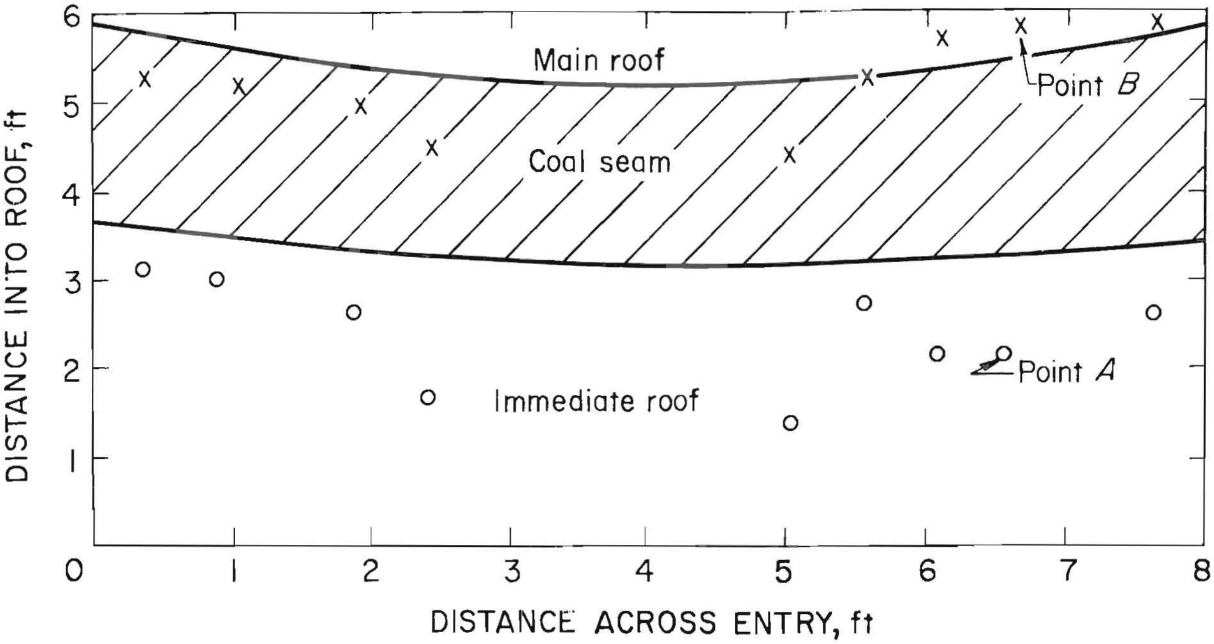

FIGURE 10. - Stratigraphic representation of borehole log and GPR data points (X's and O's) for verification test 1.

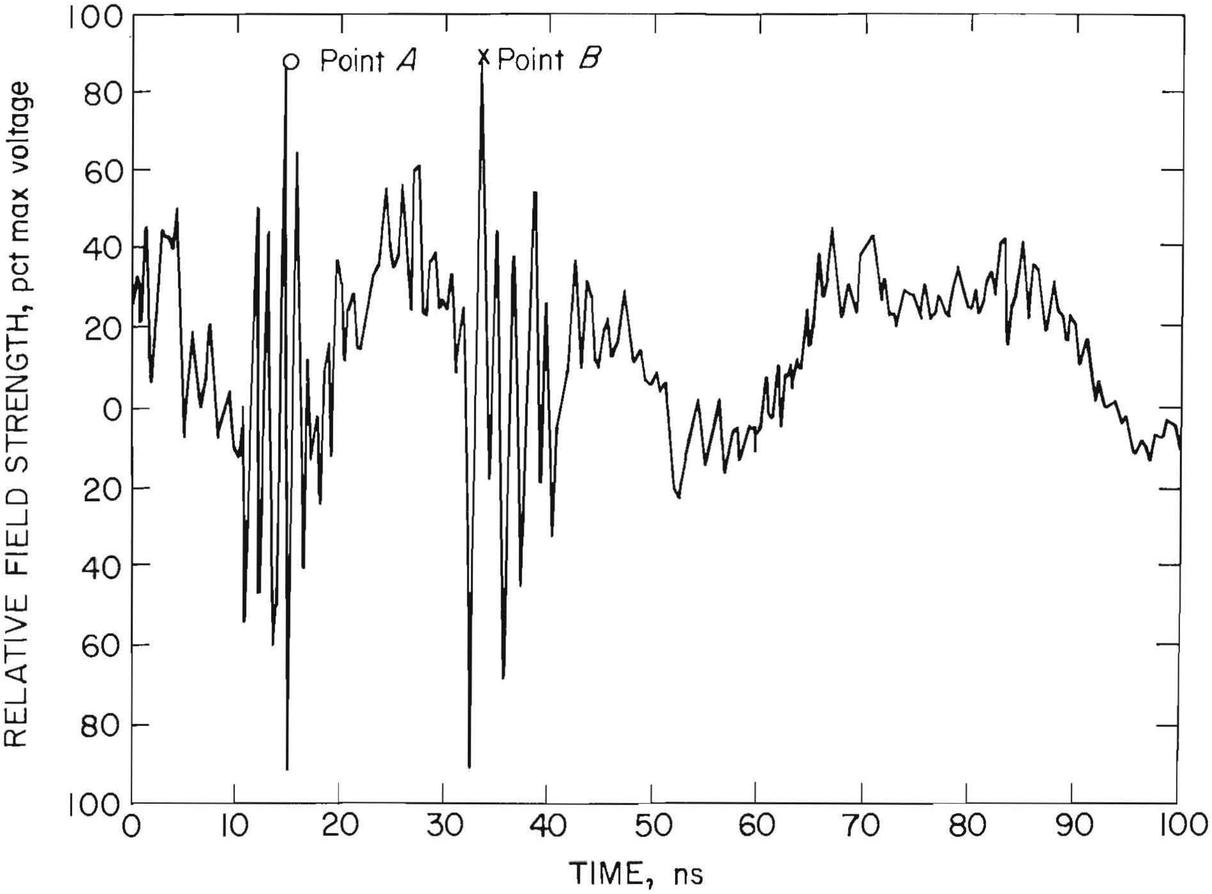

FIGURE 11. - Radar scan of underground verification test 1, depicting points that fall on figure 10 (6.5 ft from the reference).

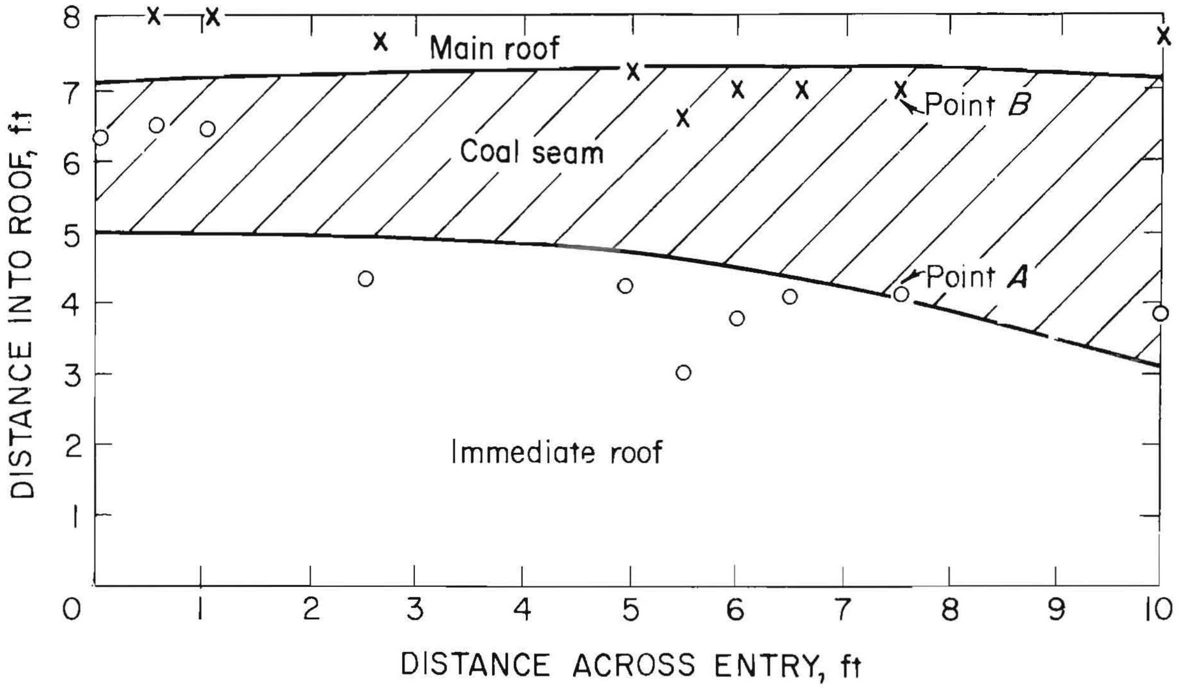

FIGURE 12. - Stratigraphic representation of borehole log and GPR data points (X's and O's) for verification test 2.

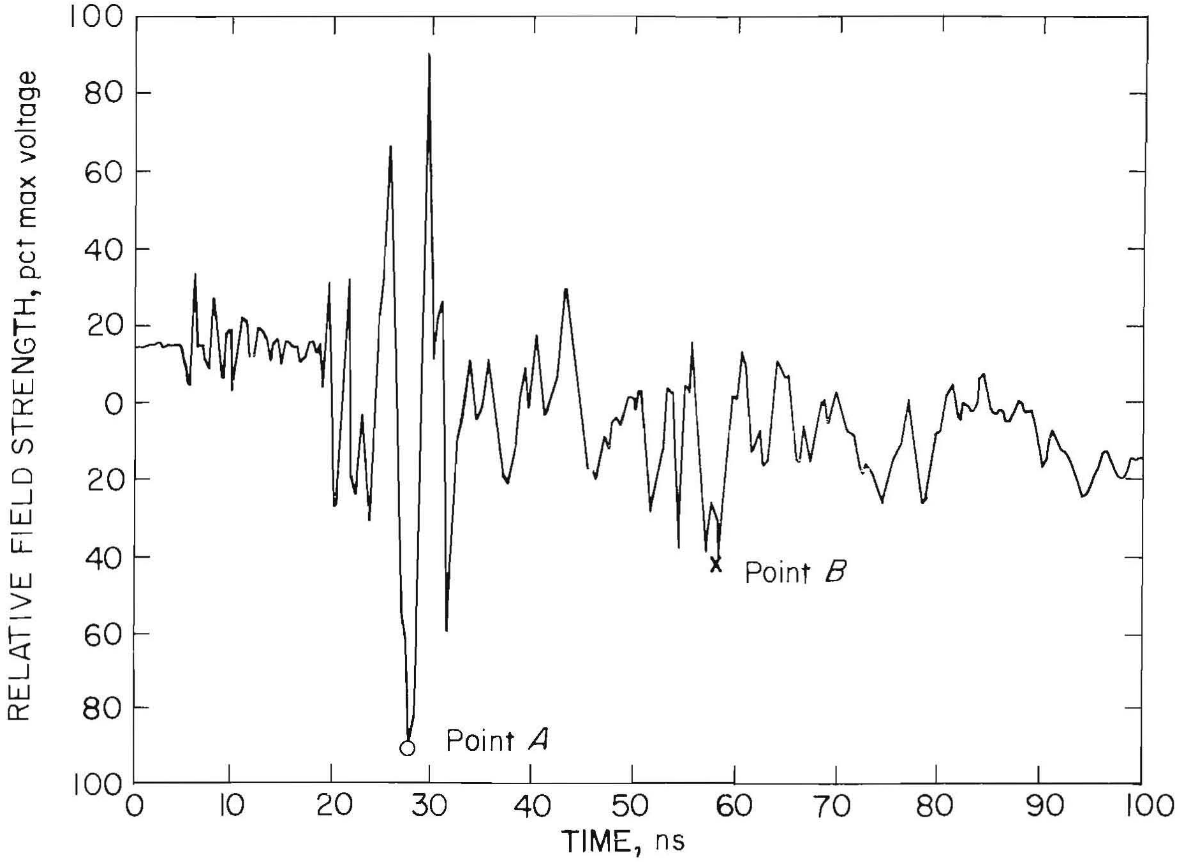

FIGURE 13. - Radar scan of underground verification test 2, depicting points that fall on figure 12 (7.5 ft from the reference).

CONCLUSIONS

The Bureau of Mines strata control GPR proved successful in laboratory tests and in its initial deployment underground. Test data indicated that a GPR system can be adapted to underground mine strata control practices by being used to map large-scale mine roof features. The system is capable of penetrating 8 to 10 ft of mine roof material while accurately portraying mine roof conditions. Analysis of the data has shown a correlation between the return signal and the geologic changes in the mine roof. Such features as middle man rock, upper coal seam, and the main roof were identifiable from the return radar signals. As can be seen in figures 10, 11, 12, and 13, a correlation exists between the plotted data points of the computer-enhanced filtered signatures, which selected the signal peaks, and the borescope data.

An exact knowledge of the dielectric properties of the strata should shift the points closer to the ground-truthing curve. Rash material, encountered in the fringe zones of the major strata changes, created interpretational problems. This rash material ranged from nothing to approximately 1 ft thick. Difficulty was encountered in trying to enhance radar images where this material existed. In view of the generally successful operation of the strata control GPR, experimental work in these unresolved problem areas is expected to produce significant results.

Future research should include optimizing frequency and resolution characteristics for determining of micro features. Image-enhanced radar signature data is an area of continuing research, and more work in this area should yield dividends. The system hardware should be redesigned to miniaturize it using an integral microprocessor containing all system functions where possible. The permissibility requirements of MSHA must be considered for any system designed to be used underground. Incorporation of the GPR into mining equipment (e.g., a roof bolter), as system deployment is presently envisioned will require MSHA approval. Redesign of the antenna would also help in system deployment. Data output should be simplified, ideally in the form of an interpretative digital printout for use of personnel not technically trained.

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