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Ground Penetrating Radar

A Review of Its Application in the Mining Industry

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	lb/in^2	pound per square inch
cm	centimeter	m	meter
dB	decibel	MHz	megahertz
dB/ft	decibel per foot	mi/h	mile per hour
°F	degree Fahrenheit	mm	millimeter
ft	feet	m/s	meter per second
GHz	gigahertz	MW	megawatt
Hz	hertz	ns	nanosecond
in	inch	pct	percent
kHz	kilohertz	V	volt
km	kilometer	W	watt
kW	kilowatt		

GROUND PENETRATING RADAR

A Review of Its Application in the Mining Industry

By W. E. Pittman, Jr.,[1] R. H. Church,[2] W. E. Webb,[3]
and J. T. McLendon[2]

ABSTRACT

The Bureau of Mines, as part of its Health and Safety Technology Program, is conducting research on the use of ground penetrating radar (GPR) for mine hazard detection. GPR offers a possibility of mapping immediate below-surface geologic conditions, including faulting and other anomalies, thereby exposing potential safety hazards to miners. This report summarizes a literature review of the current status of GPR research in and outside the Bureau.

INTRODUCTION

The presence of unsuspected geologic anomalies in coal-bearing strata poses a threat to the safety of coal miners during mining. Clay veins can create structural weaknesses and cause the collapse of mine openings. Uncharted well casings, sand channels, sulfur balls, "horsebacks," "kettlebottoms," and mine voids are known to be hazardous features. While coal mining will remain a dangerous industry, it is obvious that advance knowledge of what lies around the mine opening and ahead of the coal face could save many lives and also improve the efficiency of coal production. Many techniques have been proposed for premining investigation and some have proved valuable. GPR is one of those holding promise of becoming an important method of detecting near-face hazards.

As part of its continuing effort to advance mine safety technology, the Bureau of Mines has been conducting research on various types of GPR's, for use from the surface, from the underground working face, or from a borehole. This report reviews the historical progress of GPR's and the current status of research to apply them in the mining industry.

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ORIGINS OF GPR CONCEPTS

GPR probably owes most of its beginnings to military research. In particular, the U.S. Army has maintained a long term interest in GPR as a rapid means of detecting land mines and subsurface tunnels. In 1956, Cook separately proposed and demonstrated the use of an airborne radar to measure the thickness of floating sea ice (33-34).[4] He recognized that there were two interfaces (air-ice, ice-seawater), each of which would give clear radar returns. The thickness of the ice could be determined from the different times of arrival at the receiver of the two echoes and knowledge of the electromagnetic wave's transit speed in ice. Frequencies between 75 and 200 MHz were used to achieve penetration of the ice, using a single cycle or "pulse" of the radiofrequency (RF) carrier for good distance resolution of the two echoes. This has been the primary concept adopted for use in most GPR's.

However, several variations of the single or short pulse radar systems have been proposed and tested for use in GPR. Most of the successful ones have been of the short pulse type (fig. 1). In GPR work, compared with standard radar use, the distances involved are very short. Hence, the times of travel of an electromagnetic radar pulse and its reflection from a target are correspondingly short. To avoid interference between outgoing pulses and the returning reflected pulses, it is necessary to keep the pulses extremely short. The problem is complicated by the fact that certain frequencies can achieve better depth penetration, and these optimum frequencies vary according to the nature and type of the soil or rock.

The most common type of short pulse GPR uses a short pulse of known waveform whose return signal is received in the time domain and can provide information about the target from its amplitude, time delay, phase, polarization, and propagation direction. The return signals are normally displayed and recorded as amplitude with respect to delay time. The frequencies used are usually in the 30-MHz to 2-GHz range (8, 23).

Another form of GPR is the video pulse radar. It transmits a very short pulse with a bandwidth that is very wide. This video pulse output spectrum spreads from essentially direct current to beyond 3 GHz. The signal scattered by the target can then be sampled over a very broad frequency range, and information about the target can be derived from each sample. The extremely short pulse also allows for "time isolation"; the transmitted pulse magnitude can fall to a very small value before the reflected pulse returns. This avoids signal interference (23, 25).

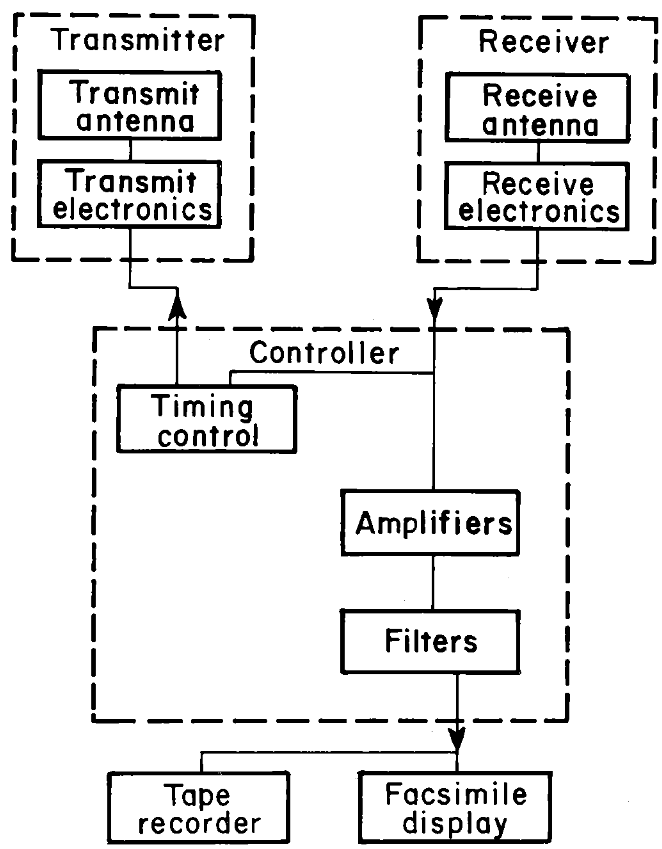

FIGURE 1. - Block diagram of a simple short pulse radar system.

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[4] Underlined numbers in parentheses refer to items in the bibliography at the end of this report.

Synthetic pulse radar (fig. 2) transmits a single frequency at a time. The returning signal is measured for its amplitude and phase, and the transmitter frequency is then stepped up to the next value, and so on. From the return data, a pulse can be reconstructed by taking the inverse Fourier transform of the received signal (146).

A frequency modulated-continuous wave (FM-CW) GPR system sweeps through a band of frequencies that it transmits and then compares the instantaneous output frequency with the frequency of the signal reflected from the target. The difference in frequencies is a function of the distance to the target and the dielectric constant (or constants) of the material in the wave path (8, 46-49).

Each of these GPR systems has advantages and disadvantages. Each system also involves the use of digital circuitry to analyze the returning signal from the target. Workable models of each system have been developed and tested as described later in the text.

ELECTROMAGNETIC TRANSMISSION THROUGH THE EARTH

Studies on the transmission of electromagnetic waves through the earth date back to the 1920's. These were undertaken for geophysical research and to develop through-the-earth mine communications, and many of the studies were done by the Bureau of Mines (72-74, 76, 123). By the 1960's, theoretical models of electromagnetic wave propagation in the earth had been developed, owing largely to the work of James R. Wait and others.

In a series of seminal studies (129-137), Wait analyzed the theoretical response of the uniform earth to various forms of electromagnetic excitation and derived mathematical solutions to describe it. He, along with F. C.

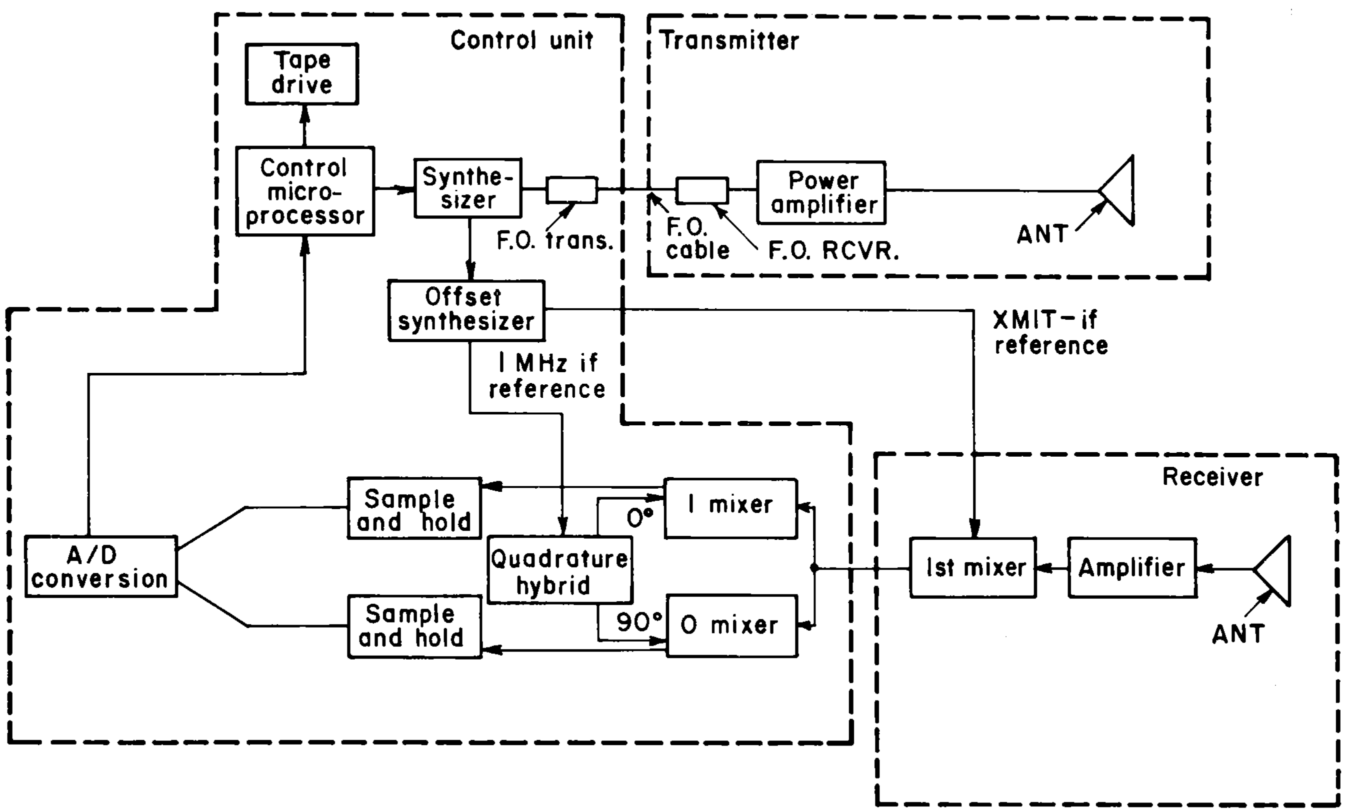

FIGURE 2. - Block diagram of a synthetic pulse radar system.

Frischknecht and others, later extended the analyses to a two (or more) layered earth (59, 127-128, 137). These cases utilized detectable interfaces within the earth. Investigators in the 1950's and 1960's also studied cases involving varying frequencies, as well as transmissions from loops, dipoles, and infinitely long wires in various locations and orientations (13-16, 60, 62, 125-126). Much of this theoretical work, which underlies most through-the-earth electromagnetic radiation studies, would later prove to have only limited applicability to GPR (27, 61, 64, 67, 80, 111-113). The frequencies studied were so much lower than those used in actual GPR that different electronic phenomena predominated.

A coal seam presented a special case. Wait pointed out that electromagnetic waves could propagate laterally in resistive layers (138). A coal seam can be considered a resistive slab bound by conductive rock. In such a model, the dominant mode of transmission of electromagnetic energy has low attenuation, a result that many observers had already noted empirically.

Not all RF energy penetrated deeply into the earth. Clough (29) pointed out that an electromagnetic wave impinging upon the earth at the critical angle given by Snell's law will be refracted and will give rise to lateral waves. These will usually be of low amplitude and lost in other signals, but they could predominate in some modes. This might be particularly true of GPR in contact with the ground surface or a coal face. The physical basis of electromagnetic surface waves was studied by Lytle, Miller, and Lager (89), who described the physical phenomena that occurred and derived the mathematics relating them.

A method of determining the distance to a buried target was described by Clay, Greischor, and Kan (28) in 1974. Using matched filter detection, a technique already common in other electronic applications, the investigators were able to determine the distance to conducting layers in the earth. In this method, a set of filters are constructed to match the waveforms of signals that have traveled to different depths within the earth and have been reflected.

ELECTRICAL CHARACTERISTICS OF EARTH AND ROCK

Concurrently, there was much research being done to determine the basic electrical characteristics of soil and rock. The mechanisms by which solids propagate electromagnetic energy were discussed at length by Von Hippel (124) and Meakins (90). Collett and Katsube also reviewed electrical characteristics of rock (conductivity and permittivity, or alternately, loss tangent), how they are determined, and the measuring systems and techniques used to determine these characteristics in the frequency range 10^2 to 10^8 Hz (30). Ward and Fraser (142) also described the conduction of electricity in rocks. Methods of measuring rock electrical characteristics were reported by Yatsyshin, Zhuk, Salamatov, and Yakovitskaya (147) and Lytle (85), who included a good overview of the subject as well, and Khalafalla and Viner (78), who described methods of dielectrometry applicable to the 10^6- to 10^9-Hz range.

There are many other valuable published reports (6, 41, 66, 79, 103, 118, 122). They vary as to the type of soil or rock studied, frequencies used, method of measurement, whether the measurements were in situ or in the laboratory, and other factors. Watt, Mathews, and Maxwell published an early study of Earth crust electrical characteristics (144), while Griffin and Marovelli determined the dielectric constants and attenuation factors for six basic rock types in the frequency range 20 to 100 MHz (63). Hoekstra and Delaney (70) studied the dielectric constants of soils at ultrahigh frequency (UHF) and microwave frequency ranges. Saint-Amant and Strangway also reported on the dielectric constants of various rocks and soils (110) in a detailed investigation of powdered and solid dry rocks in the frequency range 50 kHz to 2 MHz. They found that both the dielectric constant and the loss tangent increase with increasing frequency and increasing temperature. At high enough frequency (over 1 MHz), the loss tangent approaches a constant value. A valuable study by Hipp (68) related electromagnetic propagation parameters to functions of frequency, soil density, and soil moisture. The last has particular applicability to coal. In a related study, Campbell and Ulrichs (21) pointed out the geologic implications that might be derived from the electrical characteristics of lunar rocks.

ELECTRONIC CHARACTERISTICS OF COAL

Other studies have a more direct bearing upon GPR (2, 4, 50). Cook, in 1970, reported his investigations of bituminous coal, in which he tried to determine the transparency of coal to very high frequency (VHF) radiation (32). Two fresh bituminous coal samples were tested at 1, 5, 25, and 100 MHz in a measuring circuit utilizing a capacitance test cell and an RF bridge. In situ tests were also carried out. He found that at 60-dB signal attenuation he could obtain a 50-m penetration with a 100-MHz signal and a 1- to 10-km penetration distance with a 1-MHz signal. The presence of clay or pyrite veins in the signal path strongly affected the penetration and prevented duplication of these results. Cook then undertook the systematic study of a representative range of rocks (38 kinds) to determine their transparency to radar frequency electromagnetic energy (35). Using short, broadband pulses at 1, 5, 25, and 100 MHz, he measured the transmission penetration with a circuit using an RF impedance bridge and a parallel-plate capacitance test cell. He found that low-loss propagation was possible in certain granites, limestones, coals, and dry concrete, and that (then) existing VHF mining radar could explore effectively for distances of up to several hundreds of feet. Shorter but still useful distances were possible for other coals, gypsums, oil shales, dry sandstone, high-grade tar sands, and schists. For most shales, clays, and fine-grained soils, probing distances were generally restricted to less than 10 ft. Significantly, RF losses increased by as much as a factor of 12 when the samples were wetted. The controlling factor determining rock transparency to radar evidently was the uncombined moisture content of the rock.

Balanis, Jeffrey, and Yoon (5) measured the microwave transmission characteristics of coal samples. Using two coal samples, one fine and one granular, each at two "typical" moisture levels (10 and 15 pct), they measured the transmission of 8.2- to 12.4-GHz waves through the samples. Two different waveguide techniques were used in the tests, to measure a sample with finite length as well as to simulate a sample of infinite length. Later, Balanis, Shephard, Ting, and Kardosh (7) reported on the anisotropic properties of coal in the radar frequency ranges, by using a two-path interferometer at 9 GHz. They measured the dielectric constant and conductivity of coal as a function of the direction of propagation of the transient signal and as a function of the polarization of the electromagnetic wave in the coal. Using four Eastern bituminous coals and one Eastern anthracite coal, they also studied the effects of certain other physical properties upon high frequency electromagnetic conduction. These included the rank of the coal, the pyrite concentration and distribution, the mineral content, and the moisture content. Anthracites have higher conductivities by a factor of 10, and higher permittivities by a factor of 2 to 3, than do bituminous coals. The investigators also found that high frequency electromagnetic anisotropy correlated quite well with optical anisotropy.

APPLICATIONS OF GPR

RADAR MEASUREMENTS OF ICE AND SNOW THICKNESS

While basic work on earth dielectrics and conductivity continued, there was also further research (101) into the practical applications of GPR. An earlier proposal of Cook had been the use of airborne VHF pulse radar for the measurement of ground ice and snow (33). The idea soon became reality in Antarctica, where intensive multinational explorations were in progress. Airborne VHF pulse radar in various vehicles proved an invaluable tool in profiling the snow and ice masses of the continent (52-53, 55, 106). The methods were quickly applied elsewhere. Luchinonov (84) reported on the use in the Soviet Union of airborne radar to delineate mountain glaciers. In Canada, airborne radar was used to measure the depths of ice and snow (99, 102). Campbell and Orange (20) reported on the use of pulse radar for the continuous profiling of sea and fresh water ice thickness in Arctic regions. GPR was also shown (88) to be useful in permafrost as it penetrated deeply enough to be meaningful.

Annan (3) reported in 1976 on the use of a wideband (150 MHz), short pulse radar with a 110-MHz frequency, 50-W output, and a 50-kHz repetition rate for underground surveying in the Arctic. The long wavelengths of the radar limited the resolution to features near the surface. Higher frequencies were suggested for future use. Despite its inadequacies, GPR in general proved its utility as an underground surveying method, particularly if used in conjunction with drilling. Wide-angle reflection and refraction sounding techniques (WARR), used in seismic sounding, were suggested for use in layered areas. Reliable sounding from 3 to 30 m should then to be possible with GPR in permafrost. In a related experiment, Bertram, Campbell, and Sandler (11) reported using short pulse radar to locate large masses of underground ice.

Harrison and a British group (65) used a pulse-modulated radar at 35 MHz from a U.S. Navy aircraft to penetrate glacial ice and allow the creation of a graphical reconstruction of the underlying terrain. The radar succeeded in delineating the various interfaces between ice and rock, ice and air, brine and ice, brine and air, and so on. The radar signal returns were recorded on 35-mm film for later analysis, which proved difficult because of the complicated ray paths of the radar signals and echoes. The relatively long wavelengths used did not give great resolution, but the system provided a valuable tool for subglacial exploration through maximum ice depths of 1 to 3,000 m.

On the frozen Great Lakes, Cooper, Muller, and Schertler (40) experimented with the use of a GPR mounted on an all-terrain vehicle for rapid profiling of the lake ice depth. Earlier experiments from a C-47 aircraft at a 2,300-m altitude and a 75-m/s groundspeed had given inconclusive results because of the inherent difficulties in locating the aircraft's position accurately enough to make the later calibration measurements by surface auger meaningful. They could not determine how close to reality the observed thicknesses (10 to 92 cm) actually were.

Experiments with a Coast Guard helicopter showed similar disadvantages. The airborne radar did not react to ice thicknesses of less than 10 cm, and any surface melt water over 1 mm thick blocked the radar. Hoping to overcome these problems, a short pulse, 2.86-GHz radar with 20-W peak power was mounted on an all-terrain vehicle to be used on the frozen lake surface.

Extensive laboratory measurements of the dielectric constant of lake ice were made under various conditions before the actual tests were made on the lake. As the vehicle-borne radar proceeded across the lake ice, work teams bored auger holes for verification measurements. The results showed a maximum depth overestimate by radar of 9.8 pct, a maximum underestimate of 6.6 pct, and an average error of 0.1 pct. Upon analysis, it appeared that most of the inaccuracy was due to error in auger depth measurements and the rest to nonuniform dielectric constants or the resolution of radar at the wavelength used.

RADAR MEASUREMENTS OF SALT DOMES

GPR's have also been used in salt domes where the much lower RF attenuation of salt has allowed its use over much greater penetration ranges. Several researchers associated with Texas A. & M. University (69, 116, 122) did early work in this area. One group (71) utilized borehole radar, made small enough and rugged enough to be used in an oil well under 10,000-lb/in^2 pressure and at 250° F. The 250-MHz pulse radar with a 400-Hz pulse-repetition rate and a 10-kW peak power was lowered into the borehole. Attenuation through salt ranged from 1.2 to 2.8 dB per 100 ft, which gave penetration ranges through rock and salt of up to 8,208 ft. Internal reflecting surfaces within the salt body produced anomalous reflections that were difficult to interpret. Despite this and other difficulties of interpretation created by an insufficient data base, the technique was considered a viable tool for geophysical exploration. Another group (115) made extensive tests of a 440-MHz radar in the Cote Blanche Salt Dome. It was used within the mine to outline the salt body and to detect discontinuities within the salt. The roof of the salt dome was also outlined. Penetration ranges of up to 2,040 ft were achieved at low power, and 3,177-ft ranges were achieved at high power.

ARCHEOLOGICAL AND GEOTECHNICAL APPLICATIONS

GPR has been used in archeology as an exploration tool by a group (43) seeking a means of detecting hidden chambers within the Great Pyramids of Egypt. The "sounder" operated in the frequency range 16 to 50 MHz, with a pulse 1-1/2 cycles in length and a peak power of 0.2 MW. It was tested in a Western dolomite mine where empty chambers 100 to 130 ft from the transmitter produced good radar echoes. Lytle and Lager (86) used a 3- to 50-MHz transmitter at the Wowona tunnel in Yosemite National Park for tests from within the tunnel to the surface, through 300 m of solid granite. They measured the in situ bulk conductivity of the rock as well as the relative dielectric constant as a function of frequency.

Geophysical Survey System, Inc., engineers (99), have put together a small portable array of GPR's designed for near-surface location of various targets. The signal is a wideband (120 MHz) pulse with a repetition rate of 50 kHz. The antenna is a small wheeled carriage that can be towed or pulled by hand up to 2-3 mi/h. The radar receiver's output is by means of a graphic recorder, a continuous strip chart that provides profiles of the underground target. The set is easily portable even in an experimental form. It has low power requirements (12 V, 1.5 A) and uses the same antenna for transmission and reception. The system uses a time-domain sampling technique, which reduces the signal frequency to audio ranges where it can be conveniently recorded on the strip chart. The unit has been successfully tested for the detection of pipes buried up to 13 ft below the surface, for use in the presence of multiple targets, to detect underground wires, and to profile lake and delta deposits.

Another imaginative use of GPR came from New Mexico where National Bureau of Standards (NBS) investigators, working with the National Park Service (91), used a FM-CW radar to find the structural weaknesses of an ancient Spanish mission undergoing restoration. The technique holds much promise for archeological work, particularly since the radar returns give an accurate representation of the water distribution in the sample area.

GPR was also suggested (10) as a basic tool for geotechnical site assessment in conjunction with traditional survey methods. Radar was suggested as a cheap and effective method to fill in between expensive exploratory boreholes. It also could be used in hydrological and soil studies, and analyses of hazardous material disposal sites. However, GPR appears to be extremely "site specific" in its ability to penetrate the earth because of the differences in soil and the presence or absence of water. The U.S. Air Force (12) has also shown interest in GPR for use in rapid evaluation of airfield pavements for damage under combat conditions.

SUBHIGHWAY MEASUREMENTS

There is a growing awareness of the potential for subsurface testing offered by GPR. It is obvious GPR is a viable new tool for geologists and engineers (106). Highways continue to be a fruitful area for the application of the new technology. A persistent problem for highway builders is the instability of sloping ground, caused by subsurface geologic anomalies. Exploratory drilling is expensive and frequently gives incomplete data. Working with the Federal Highway Administration (FHWA) and the U.S. Geological Survey (USGS), NBS developed four microwave probing systems (120). From them, the FM-CW system was chosen for highways investigation because of its suitable resolution at ranges of interest. It had adequate penetration, could be built with commercially available components, and had previously been successful in a subsurface survey. The FM-CW system was built and subjected to 5 weeks of testing in the Pike National Forest in Colorado. Boreholes and borehole TV cameras were used to determine the details of underground geology at the test site and to verify the results of the radar tests. The FM-CW radar successfully located a series of fractures in granite at depths between 5.96 and 6.86 m.

Moore, Echard, and Neill (98) reported the use of a short pulse radar (approximately 1 ns) to detect the presence of voids under concrete slabs on an interstate highway. Experiments were done on test blocks and on a highway. The varying radar responses seemed to delineate a true picture of the underslab voids, but it was impossible to verify them. When the group attempted to drill into the voids for verification, the cooling water used in the drills rushed through the newly opened holes into the voids, carrying with it dirt and concrete, disturbing the voids. Also, the effect of the differences in dielectric constant of the concrete and earth was poorly understood and was not compensated for properly. The technique works, but a large body of experimental data will have to be built up for it to reach full potential.

MICROWAVE MEASUREMENTS OF COAL SEAMS

Delineation of coal seams (thickness, shape, and orientation) using microwave radar was a subject of several investigations. A theoretical basis for the new technology was derived by Wait (139). Under a Bureau of Mines contract, NBS (47) used a microwave (0.5 to 4.0 GHz) radar to measure coal seam thickness in two coal mines. The technique worked to measure coal thicknesses from 10 to 40 cm, but some anomalies in the coal seams confused the results. However, the researchers recognized that detection of these anomalies might be the most valuable characteristic of microwave sensing. They also found that the dielectric constant was a function of the water content.

NBS subsequently developed a FM-CW radar system operating in the 1 to 2 GHz range (48-49). It was tested in the laboratory and in three coal mines to measure coal seam thickness up to 55 cm. The technique was suggested for possible use in controlling the operation of automated mining machinery at the coal face.

GPR SYSTEMS

VIDEO PULSE RADAR APPLIED TO GPR

Video pulse radar techniques have been applied to GPR. A video pulse radar uses broadband signaling but with the waveforms consisting of multiple frequencies (from near direct current to megahertz or gigahertz), instead of broadcasting many cycles of one frequency, as does a traditional radar. This multifrequency wave will be perturbed by any change in underground electrical characteristics such as different soil or rock types that have differing dielectric constants, or interfaces such as cavities, joints, or faults. The transmitter sweeps through the frequencies, and the reflected electromagnetic wave is picked up by the receiver to give a voltage-versus-time output. The waveforms can be processed for both time and frequency domains. This is done experimentally by a digital computer, but in actual operating units a built-in logic circuitry would do it. Using a video pulse radar, Moffatt (94) easily detected a tunnel through 20 ft of limestone, as well as some previously unsuspected steel supports. An effort to detect faulting in a quarry produced ambiguous results, however. The complex fracturing of the rock made it difficult to relate the electronic information to physical reality.

A study by Burrell and Peters (17) pointed out that using the "Low Frequency Window" (LFW), a frequency range in which the attenuation of RF waves is relatively low (below 100 kHz), penetration ranges of several kilometers were possible. One problem was the need to decouple the powerful transmitted signal from the weak reflected wave, which it could mask. So that the return signal could be observed, it was necessary for the output signal to fall to zero very rapidly. This was accomplished by including a high frequency portion of the pulse and by developing orthogonal antennas to electronically separate the output and input signals.

Video pulse radar was used by Cook in a series of experiments (37) for the British National Coal Board. The British needed to detect unmapped, abandoned mineworkings in advance of the mining face, because abandoned galleries, if penetrated unexpectedly, could release floods of mud or water under high pressure. Cook and his associates reported much work in the laboratory and tests in mines. They reported the relative radar transparency of various minerals and antenna design parameters in an actual mine test. Good results were obtained with a radar operating at 100 MHz with one-way propagation ranges from 6 to 56 ft and reflections through 28 ft of coal. These results were obtained despite having to use an inadequate antenna designed for the open air. Attenuation was from 1 to 1.6 dB/ft of coal, and particularly good reflections were obtained from any target that was wet or contained water. Long wavelengths gave poor target resolution, but there was far less loss of energy by scattering if the impinging wave had a wavelength greater than either the thickness of the layer of coal, shale, or limestone, or the individual rock crystal size. The radar successfully detected mine openings through 30 to 60 ft of rock in narrow, cluttered, dirty, wet underground workings, and was unaffected by the presence of steel paneling or beams nearby. The outlook for deep electromagnetic probing in soft ground such as sand, earth, or mud was not so favorable. Even at low frequencies, 50 to 70 ft seemed to be the ultimate range. The radar signals, Cook reported, were easy to interpret about half the time. Image interpretation was still in its infancy in underground radar, and there were many unexpected and unexplained results. There were spurious echoes on some occasions and no reflections on others. More work, it was suggested, needed to be done in mines under known conditions. The most important factor was the absorption of rock; less important were the choice of principal frequencies, the transmitter's electronic efficiency ("performance figure"), or the antenna's directivity. GPR, Cook said, offers great potential for exploring large volumes of rock at low cost in advance of mining. Other tests (96), of a road tunnel (with steel supports) in limestone, a fault in a dolomite quarry, and a coal mine tunnel, seemed to bear out Cook's prediction.

SHORT PULSE GPR

Researchers at ENSCO, Inc., now XADAR Corp., developed a short pulse GPR, which was tested in coal mines in 1977 and 1978 (39, 51, 57). The portable set consisted of a transmitter, a receiver, and a controller. The transmitter emits a short, high frequency (30- to 600-MHz) pulse that is coupled to the ground through the antenna. The transmitted pulse is shaped like a single cycle of a sine wave. The pulse is radiated from the antenna into the earth in a broad pattern. Whenever the radar pulse encounters a medium with different electrical properties, a portion of the electromagnetic energy is reflected back to the receiver. The change in electrical properties coincides with changes in the nature of the medium, such as a fault or clay vein passing from the coal seam into shale or rock. By measuring the time of passage of the radar wave and its reflection, and by knowing the velocity of the wave, the distance to the anomaly can be determined. However, in coal and rock, unlike air, the speed of propagation is not a constant and must be separately determined for each site. It is normally in the range of 0.2 to 0.5 times the speed of light. Using this type of GPR, ENSCO researchers were able to propagate (one way) a signal 100 ft in a coal seam, using signals in the 40- to 500-MHz range. Voids were detectable using the GPR at 50 ft, in the frequency range of 10 to 160 MHz. An uncased borehole was detected over 25 ft away.

BOREHOLE RADAR

Radar was also applied (119, 145) to borehole survey. Under a Bureau contract, Southwest Research Institute (117) developed a borehole radar. The entire package was required to be less than 4 in. in diameter and 1 m long, which required a special antenna design to fit the cylindrical shape. Representative models of what the various geologic anomalies in mines would look like on a radar return had to be developed. A short pulse, high-power radar, with a 15- to 30-m range surrounding the borehole, was developed using a sampling oscilloscope and signal averaging technique. The data were digitized and fed into a computer for clutter rejection. An experimental system was built and tested in single- and cross-borehole operations. There were problems of data interpretation and with penetration range. Distant targets were dim because of medium attenuation and normal geometric dispersion, while near targets reflected very strongly. A time-varying gain amplifier was used to overcome this. The system proved more suitable for hard rock than for sedimentary rock, and there were problems of spurious signals from electric cables and other components.

In a later phase of work, a borehole directional radar probe was developed by Southwest Research Institute (116) and subjected to demonstration testing in 1982. The radar was a video pulse radar. Each pulse had a time duration of 12 ns and a useful frequency spectrum of 30 to 300 MHz with a 1-kW peak power output. The probe (16.7 ft in length) was designed to fit within a 4-in borehole. The unit comprised the borehole probe and the surface control unit connected by ordinary armored four-conductor wire line cable. The borehole probe transmitter utilized a unique rotating directional antenna. Earlier units tested with single antennas for transmitting and receiving had proven unsatisfactory. The new antenna scanned in eight angular steps (45° apart) according to the command of the surface control unit. The actual orientation was determined by a built-in fluxgate north-seeker circuit for vertical drill holes or a pendulum vertical reference for horizontal holes and was reported to the surface unit. The receiver antenna was a short, omnidirectional monopole. A time-domain sampler developed a low frequency replica of the reflected signal from the receiver output by repeated sampling and enhancement by signal averaging. This replica was typically in the audiofrequency range (3 to 30 Hz or 300 to 3,000 Hz) and could be transmitted by the standard geophysical armored four-conductor wire line cable.

The unit was field-tested in York Canyon Mine near Raton, N. Mex. This mine was chosen for the tests because of ease of access and for its favorable electromagnetic propagation characteristics, and because it had a well-documented geologic anomaly to serve as a target. The anomaly was a 7-ft coal seam displaced 50 ft by a complex fault that had stopped mining development and had been encountered at points 700 ft apart. In the actual tests, the returns appeared to be omnidirectional, presumably because of the poor directional response of the antenna system. The fault was identified by one borehole probe as a target reflection from 22 ft away. Another borehole probe, 20 ft from the fault, failed to get a clear response from the fault.

As part of their work in developing cross-borehole methods (23, 25) for use in detection of mining hazards for the Bureau of Mines, Lawrence Livermore National Laboratory (LLNL) undertook experiments at the Gold Hill Mine test site near Boulder, Colo., in 1980. The tests involved using a high frequency electromagnetic (HFEM) system to locate a tunnel 49.5 m below the surface between two boreholes 10 m apart. A transmitter, broadcasting at a constant frequency and amplitude at frequencies between 45 and 70 MHz, was lowered down one borehole. The receiver was lowered down the other. Two experimental scenarios were used; in the first, the transmitter and receiver were lowered at a constant rate so that they were at the same or "common depth" at all times. In the second, the transmitter and receiver were lowered with a constant difference between their depths, which was maintained to provide "offset views" for better definition of the target. Common-depth tests were run at 45, 50, 55, 60, 65, and 70 MHz and offset-view tests at 45, 50, and 55 MHz. Data were plotted as signal strength versus depth, with the tunnel location indicated by signal minima. The tunnel was accurately located; it lay between test boreholes only 10 m apart. The size of the tunnel was not so accurately determined; it was measured as having a height of 1.7 m when it actually was 2.8 m high.

Lawrence Livermore Laboratory also developed and tested a high frequency (microwave), cross-borehole electromagnetic system (81) designed to detect water- or air-filled underground cavities. At Manatee Springs, Fla., tests were run on known water-filled caverns using microwave propagation (5 to 105 MHz) between two boreholes, one containing the transmitting antenna and the other the receiving. In this test, the test signal frequency was varied from 5 to 105 MHz and the depth from 30 to 38 m to encompass the area where the cavern was expected to be located. At Medford Caves, an air-filled cavern was mapped by using a single-frequency scan (100 MHz) and varying the depth from 25 to 70 m. The tests indicated that air- or water-filled cavities have characteristic electronic signatures but are difficult to identify if the cavity is irregularly shaped or if the matrix is extensively fractured. A medium of high conductivity creates problems also, by making it difficult to propagate a signal of sufficient strength.

SYNTHETIC PULSE RADAR

Under Bureau contract, XADAR Corp. (formerly ENSCO) is investigating a synthetic pulse radar for coal mine use (51). Short pulse systems have many disadvantages: the need to separate the transmitted and reflected signal, sampling techniques that use only part of the transmitted energy, and complicated antenna design. A synthetic pulse radar system is designed to overcome noise problems, to give a higher signal-to-noise ratio, and to increase penetration using lower energy. The latter is necessary for permissibility for use in underground coal mines. The synthetic pulse radar transmits a single frequency at a time. The amplitude and phase of the received signal are measured, and the frequency is then stepped to the next value. If the proper frequencies are transmitted and received, then a pulse can be reconstructed by taking the inverse Fourier transform of the received data. The system does require more signal and data processing and more sophisticated equipment. In the initial test, a breadboard unit was built and tested. It was designed for operation within a transmission frequency range of 20 to 160 MHz with a minimum spacing of 100 kHz. This should give a maximum time "window" of 10,000 ns or a reflection range of approximately 2,500 ft in coal, much greater than needed. In the breadboard tests, many problems with internal interference were encountered, and finally fiber optics had to be used to isolate some system elements. There were also problems with ghost signals. Nevertheless, it was shown that a prototype system having an effective penetration range of 200 ft could be developed.

From the experience gained from the breadboard unit, a prototype synthetic pulse GPR was built (146). It was completed in June 1982 and then tested. There were many changes from the original breadboard unit. The system used a heterodyne receiver, which uses two mixers. This allowed the detection circuits to operate at the lower intermediate frequency (IF) of 1 MHz, which eliminated many problems associated with the higher frequency circuits. The signal sent to the control unit from the receiver was at the intermediate frequency. Despite equipment difficulties that prevented accomplishment of all the experimental objectives, the unit was successfully tested in Eastern and Western coal mines. It was found that the synthetic pulse GPR could penetrate greater distances (approximately 2 times farther) than short pulse GPR. Reflection depths of 40 ft were achieved in the Deseret Mine, Utah, and the background noise was found to be 60 dB lower than the main signal arrival. It was estimated, based upon these results, that reflection ranges of 180 to 200 ft are possible. Because of equipment difficulties, the antenna tuning feature planned for the unit was not built and the display unit was not finished in time for the mine tests. More work on this equipment is planned.

STRATA CONTROL RADAR

The Bureau is also investigating a GPR for the identification of roof conditions in underground coal mines that might lead to roof falls. Most roof falls in coal mines are associated with geologic anomalies within a few meters of the immediate mine roof. Therefore, the primary interest of researchers is in very small, but hazardous rock features within a very narrow band of rock above or behind the surface of mine openings. This means that higher frequencies are required than for most GPR systems, in order to resolve the tiny anomalies, for example, cracks. Although attenuation is much greater for higher frequencies, the area of interest is of such shallow depth that the increased attenuation is an acceptable trade-off for better resolution.

Primarily utilizing off-the-shelf components, a short pulse GPR was put together in 1981, for tests and evaluation in the laboratory and mines. The transmitter of this radar emits a single pulse of 4-ns duration and 400-V amplitude at 100 or 250 MHz. Both transmitter and receiver utilize triangular dipole antennas. The receiver consists of a voltage variable attenuator, a high-gain preamplifier, and a sampling unit. It is controlled by a small computer that performs several functions. The computer provides an external signal to the sampling unit to set the sampling gate on a particular point of the received pulse. It converts the sampling unit output to digital form and averages the signal from a number of pulses to remove noise. It then steps the sampling gate to the next point on the pulse and repeats the process. When a full pulse has been sampled, the computer stores the data on a magnetic tape. In addition, it supplies an exponentially variable voltage to the voltage variable attenuator to adjust the receiver system sensitivity to compensate for the signal attenuation through the rock. At the completion of a run, the small computer can be connected to a large computer and the data transferred to a disk file for later analysis.

Several surface and three underground tests of the strata control GPR were made in 1982 and 1983 in mines near Tuscaloosa, Ala. Figures 3 and 4 show the computer control console and antenna installations underground. Radar signatures were correlated with rock stratigraphies. In tests, three rock strata were identified; the middleman rock 2 to 3 ft thick, the overlying coal seam 3 to 6 ft thick, and the main roof. These were correlated with ground-truthing test holes, drilled and borescoped in the mine roof. The data are currently being computer-enhanced so that they can be displayed in a two-dimensional graphic representation that reveals stratigraphic conditions and any anomalies encountered in the radar scan.

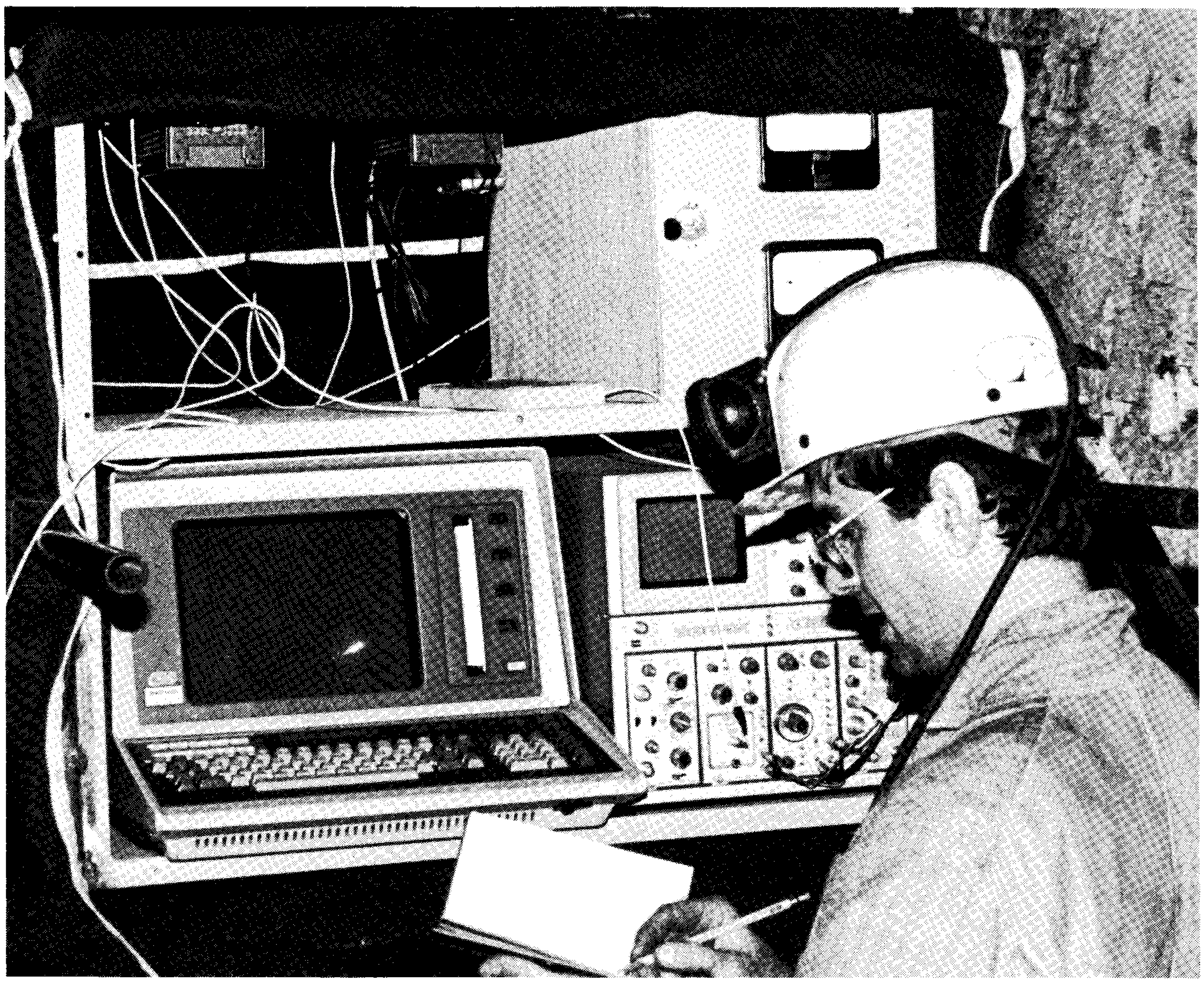

FIGURE 3. - Radar control console of GPR used during underground testing.

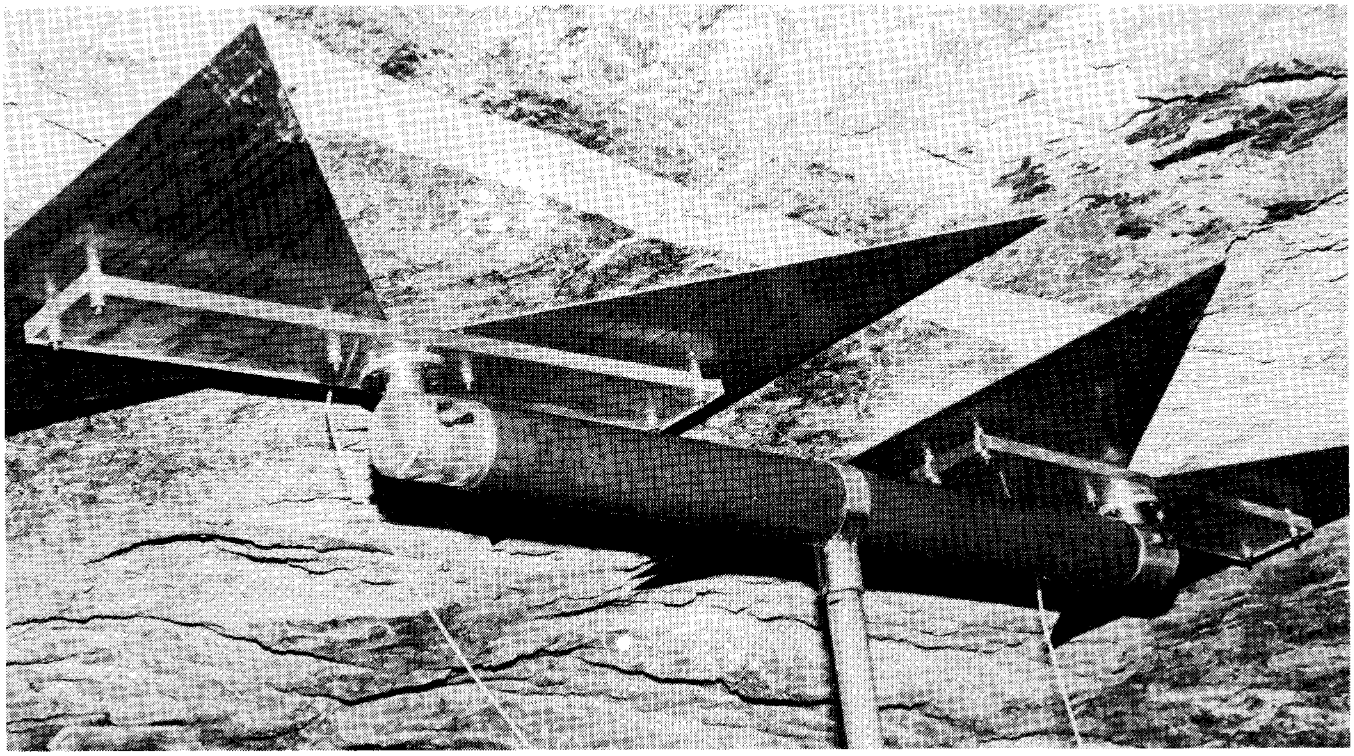

FIGURE 4. - Antenna deployment against mine roof.

GPR ANTENNAS

A group from the Electromagnetics Division of NBS evaluated antennas suitable for GPR for the Bureau of Mines (8). After a literature review had narrowed the possible choices, several antenna types were tested, most of which were horn-type antennas. Eventually one was selected as being the best compromise among competing requirements, for example, small physical size needed in mine work and some superior electronic characteristics of larger antennas. Transverse electromagnetic (TEM) horns appeared to be the most promising, so most of the tests were run on modifications of this basic type. Eventually three antennas were built, which were TEM horns, labeled NBS-TG. They were small (49 cm long, 50 cm high, 21.5 cm wide), metal TEM horns with variable width and variable flare angle. The NBS group also put together two GPR systems, a pulse radar time-domain system and a FM-CW system. Only initial evaluations of these two systems were undertaken.

INTERPRETATION OF GPR DATA

The question then becomes not whether radar can penetrate the ground and be used to map ahead of mining, but increasingly one of analysis (9, 22, 82, 95, 97, 105) of radar returns to determine the nature of the target. For example, an ambitious study (23) was made by investigators at Ohio State whose purpose was to develop a simple, automatic, "single look," real-time method of identifying subsurface targets. A commercially available radar was used. It was a video pulse radar (direct current to more than 3 GHz) with a very short pulse that allowed for "time isolation" or a radar "dead zone" between the transmitted and reflected signals. Separate orthogonal dipole antennas for transmission and reception aided signal separation. The orthogonal antenna was insensitive to layering within the earth. The receiver used a sampling oscilloscope that reduced signal noise by averaging a large number of waveforms rather than by using filters. A signal processor was used for clutter and noise reduction, and another unit for target characterization and identification. A general purpose digital computer was used for characterization and identification of the targets as well as for controlling the sampling oscilloscope.

In the experiment, five targets of differing shapes and materials (plastic landmine, brass cylinder, aluminum sphere, copper sheet, and woodboard) were buried at known positions and depths in a small yard at Ohio State University. Radar reflection images of each target were obtained. The result was a processed time-domain waveform. These waveforms exhibited a transient behavior (a superimposed signal upon the basic return waveform) in the time region late in the signal pulse, where only the natural response of the target had any effect. On analysis, the Fast Fourier Transforms (FFT) of these waveforms showed strong peaks indicative of resonance behavior. These proved unchanging with variations in antenna location or orientation. It was concluded from this that "the complex natural resonances of the target are excitation invariant."

Thus, the individual targets produced "complex natural resonances," depending upon their shape and constituent material, which could be used as the basis for target characterization and identification. The signal level of these several natural resonances varied greatly, creating a problem of dynamic range, and varying ground conditions introduced even more complications. The value of the complex natural resonances of the targets was calculated from experimental data by using Prony's method, a two-century-old system for the mathematical treatment of waveforms. These calculated waveforms were then compared to the actual waveforms of the buried objects by the computer.

The researchers at Ohio State continued to improve their process for using radar in identifying buried objects (25). A redesigned antenna was a step forward. The new antenna resonated at the middle of the range of the band of complex resonances of the target. This provided a better match between the resonant frequency of the radar system and the frequency band spanned by the target resonances and allowed improved target identification.

Interpreting the signal return reflected back from a buried target is a difficult process. For targets in air, analytical methods modeled on physical optics are used to image the targets. The situation is more complex for buried targets, but target imaging is similarly based on the backscattered field (24, 148). Investigators at Ohio State working under an Army contract found that, for below-the-surface target imaging, the most important part of the signal is the early return (high frequency) part of the backscattered field. The backscattered field is attenuated by the ground, and this attenuation determines the signal strength and, therefore, the depth of penetration. The backscattered field contains several complex functions of the reflected radar pulse and is very difficult to interpret. The problem of the interpretation of reflected subsurface radar signals remains one that will undoubtedly require extensive attention in the future.

CONCLUSIONS

It has long been known that electromagnetic waves can penetrate earth and rock. Various GPR's in portable, low-powered forms have been used successfully to locate subsurface objects and voids in military operations, highway construction, and archeological work at short ranges. This same technology could be used to detect hidden geologic anomalies in mine roof, ribs, or faces, which might pose a safety hazard to miners. Bureau of Mines research efforts have been directed toward investigating various types of GPR systems capable of detecting such hidden hazards, ahead of and during mining. The electromagnetic radar systems that may have significance for exploration and mine safety include microwave radar, borehole radar, short pulse radar, synthetic pulse radar, and strata control radar. More research is needed to perfect the systems that have been initiated, especially in the area of data analysis.

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