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THROUGH-THE-EARTH ELECTROMAGNETIC TRAPPED MINER LOCATION SYSTEMS. A REVIEW

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THIS IS AN OVERVIEW

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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CONTENTS

LIST OF UNIT OF MEASURE ABBREVIATIONS

AWG	American wire guide	MHz	megahertz
$ampm^{-1}$	ampere per meter	ms	millisecond
dB	decibel	mW	milliwatt
°C	degree Celcius	pct	percent
h	hour	s	second
Hz	hertz	SM^{-1}	siemen/meter
kHz	kilohertz	V	volt
kW	kilowatt	W	watt
m	meter	yr	year

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By Walter E. Pittman, Jr.,[1] Ronald H. Church,[2] and J. T. McLendon,[2]

*** ABSTRACT

In its role of providing technical assistance to the mining industry, the Bureau of Mines' Tuscaloosa Research Center has conducted research to develop trapped miner location systems which would aid in locating miners trapped by underground mining disasters.

Efforts to produce electromagnetic systems for the location of trapped miners underground and to communicate with them were surveyed, from the 1920's to 1981. Theoretical studies of through-the-earth electromagnetic transmissions are described as well as studies of the electrical characteristics of various rocks, minerals, and soil. Several trapped miner location systems are reviewed including the Westinghouse systems, the DEVELCO system, and an automated three-dimensional location system, and the phase difference of arrival technique. Tangential research, relevant to trapped miner location systems is described. A comprehensive bibliography covering all aspects of trapped miner, through-the-earth electromagnetic location and communications systems is appended.

*** INTRODUCTION

Mine disasters often leave survivors trapped underground. Would-be rescuers on the surface or underground who attempt to reach the victims are seriously inhibited in their work by their lack of knowledge of the actual location and condition of the victims. In order to mount an effective and timely rescue effort, rescuers need to have immediate knowledge of the precise location of any survivors and the precariousness of their situation. The nature and urgency of a rescue campaign needed in the case where the miners face a speedy death due to poisonous gas or fire is very different from the one in which the trapped miners have an adequate atmospheric environment. Some method of locating trapped survivors and communicating with them is essential. However, normal mine communications are usually disrupted by the same disaster that entrapped the miners and are not available to rescuers. Emergency systems of location and communication that can operate through the earth, either from the surface or through the rock and earth material of a cave-in is needed. Such a system must operate under many constraints. It must be reliable under adverse physical and environmental conditions in a mine; it must be inexpensive, and portable, it must be built within the "intrinsic" safety limits for mine use and it must be simple to operate. Furthermore, it must produce a signal whose source can be located with

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precision. The time constraints on rescue efforts are critical as was pointed out by K. H. Sacks in a 1977 analysis (251)[3] of 43 coal mine disasters in which miners were trapped underground. The ability to locate trapped miners and to reestablish communications quickly is necessary for successful rescue efforts.

A 1982 study (185) done by Arthur D. Little, Inc., of 29 recent mine disasters, under a Bureau of Mines contract, revealed that generally, the time to death of survivors is so short that most search operations take too long. The study delineated the narrow time window, usually a maximum of 1 to 5 h, in which postdisaster mine rescue is necessary and possible. Timely knowledge of trapped miner location is critical to quick rescue. However, because of the strict time constraints involved, only rescue systems that are already in place have a chance of being successful.

For many years research and development of such systems have been undertaken, usually with the support and guidance of the Bureau of Mines. These systems are rapidly approaching the point where they can be practically distributed in operating mines.

*** EARLY EFFORTS AT THROUGH-THE-EARTH COMMUNICATIONS

The earliest pioneers of radio were keenly interested in the possibility of using the earth for radio transmission. They were concerned with the mechanisms of radio transmission through-the-earth which was part of the initial efforts to understand the general mechanisms of radio transmission. As early as 1899, Nicola Tesla suggested the use of what are today described as extremely low frequencies (ELF) for worldwide communications using an earth medium (355). The theoretical basis of radio propagation through the solid earth was elucidated by the great theoretical physicists, Arnold Sommerfeld and Hermann Weyl. They derived reasonably accurate mathematical descriptions of the propagation of radio waves through earth by making two simplifying assumptions. These were to treat the earth as a uniform half-space and to assume that the earth had uniform electrical characteristics (264, 354).

As usual under wartime conditions, WWI spurred technological development of all sorts including through-the-earth radio. In their search for secure communications, the Allies designed and deployed on a large scale the secret T.P.S. ("telegraphie par sol") communication system. Using low frequencies (500 to 1,800 Hz) the T.P.S. system utilized ground conduction paths to provide secure communications with the front lines. The maximum reliable range of the T.P.S. system was about a kilometer and transmissions had to be in code because of the limited information carrying capability of the very low frequencies used. In the system, two stakes or ground antennas were driven into the earth 15 to 300 m apart and a battery-supplied direct current was allowed to flow between them. This current was interrupted by a code key which provided the signal and which could be detected at a distance somewhat over four times the separation distance between the antenna stakes (13).

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[3] Underlined numbers in parentheses refer to the bibliography at the end of the report.

Another technological innovation of the War was the geophone invented by French physicists to detect underground mining and tunnelling in the battle area. The geophone was designed to detect sounds of military mining operations and was essentially a sensitive microphone. The technology quickly spread to both sides and mining was effectively neutralized as a major technique of War (201).

When the United States belatedly entered the War in 1917, it seriously lagged the combatants in military technology. To overcome one area of deficiency, the Army turned to the U.S. Bureau of Mines to undertake studies of underground sound that might be applicable to offensive or defensive warfare. These tests also revealed the possibility of using military technology for peacetime purposes; specifically, the use of the geophone in mine rescue operations. After the War ended, Alan Leighton, a physicist who had worked on the Army project, devised an improved geophone and conducted a series of experiments that demonstrated the geophone's usefulness in mine rescue work (201).

Bureau of Mines' engineers quickly saw in the new technology an answer to the old problem of communicating with surviving miners trapped by a mine disaster. Although the geophone, in improved versions, has proven useful in mine rescue work to this day, its limitations are severe. It is short-ranged, can convey very little useful information and is subject to interference from many sources including mine rescue efforts. Recognizing these constraints, research interest soon turned to through-the-earth radio. During the 1920's intensive research was undertaken by Bureau of Mines' and independent scientists to develop through-the-earth radio.

Ironically, the big question was whether or not radio waves penetrated the earth at all. The presence of any metallic conductor greatly enhanced the transmission of radio waves through-the-earth. Mines usually have pipes, power cables, rails, or structural metal in shafts leading to the surface. Radio receivers situated near such metallic carriers detected much stronger signals than those further removed. Many critics in the 1920's felt that all through-the-earth radio transmission was by means of such "anomalistic conduction."

In 1922, Bureau of Mines' and Westinghouse engineers, in a mine near Pittsburgh, succeeded in detecting radio broadcasts from the first American radio station, KDKA. The signal, evidently carried by pipes and cables, was detectable for a few hundred meters into the mine. In an area further from metallic conductors it was detectable through only 15 m of overburden (59). These modest results encouraged much more research by government and independent engineers in the next few years. J. J. Jakosky, a Bureau of Mines' engineer, was probably the most important figure. Many significant discoveries were made. For the first time the frequency dependency of earth penetrating radio became clear. Roughly, the higher the frequency the shorter the distance the radio could penetrate the earth. But lower frequencies could convey less information. The role of serendipitous metallic conductors was explored and found to be crucial to successful transmission and detection. The effects of differing soil and rock types and of the presence of water were studied. Power requirements were determined and the directional characteristics of antenna configurations were studied (165-168). Field tests were made in coal mines, Western hard-rock mines and Canadian railway tunnels (89).

Despite the money, time, work and widespread publicity, no practical through-the-earth radio resulted from the efforts of the 1920's. It was still unclear, in fact, if radio waves actually penetrated the earth, to any extent, in the absence of metallic conductors (162). The latter point was finally cleared up by J. Wallace Joyce, a Bureau of Mines' geophysicist, in 1929 and 1930, when he undertook a series of carefully controlled experiments at Mammoth Cave in Kentucky. Joyce tested various shapes and sizes of loop antennas as well as the earth attenuation of radio waves at various frequencies from 500 Hz to 810 kHz, through the limestone and sandstone overburden. He also proved, conclusively, that radio waves did penetrate through rock and earth in the absence of metallic conductors. Low frequency (LF) signals gave the best results: at 500 Hz the signal was detectable at a depth of 274 m. On the other hand, Joyce obtained a maximum range of only 91 m using radio frequency waves in the 20 to 110 kHz range even at a power of 50 W. This attenuation was so great that Joyce concluded that radio waves could not penetrate the earth enough to be useful for mine rescue operations. Theoretical results that he derived from Maxwell and Sommerfeld reinforced his pessimissism (170). It was a conclusion increasingly shared by most other researchers in the field. Interest in through-the-earth radio declined after 1930 and remained at a low ebb until after WWII.

The development of through-the-earth radio for geophysical exploration continued. In 1928, Hans Lundberg, demonstrated a very successful system for locating underground metallic ore bodies based upon the transmission of audio frequency (50 to 10,000 Hz) current between two line electrodes on the surface, each 300 m long. In the next 20 yr the use of LF electromagnetic radiation for underground exploration became common, especially in oil and gas exploration (40, 156, 268). There was very little transfer of this new technology to communications, however, at least in the United States.

The first successful through-the-earth communications system was developed by South African engineers. Facing a requirement for communications with their famous crack mobile fire fighting teams ("Prototeam") in deep, hard rock, gold mines, the South Africans undertook investigations of electromagnetic propagation through rock strata. T. L. Wadley showed, in 1949, that communications through hundreds of meters of rock were possible if low radio frequencies were utilized. The South Africans achieved a useful range of 600 m at 300 kHz and a maximum range of 2,100 m (14, 283-284). With this experience, the South Africans developed a practical operating apparatus which they successfully tested in 1961. Radio communications through-the-earth proved suitable both for ordinary communications and for emergency operations. But the original equipment proved to be too bulky for practical applications. Smaller equipment was developed in the 1960's utilizing the new miniaturization technology then becoming available. The

South Africans also learned that equipment size could be reduced by lowering output power to as little as 1 W without seriously degrading detection ranges. The introduction of single-sideband modulation vastly improved performance of the equipment which operated at 903 kHz. Experimental units were so successful that over 100 were built between 1970 and 1973. They were used to provide all the communications in some mines (279).

While the equipment fulfilled expectations, the South Africans soon discovered that operator training, which must involve all levels of mine personnel, was required if the system was to succeed in actual mining operations (14). A South African company currently markets a through-the-earth radio system for in-mine use.

In the United States, the Bureau of Mines continued its efforts to develop through-the-earth communication at a reduced level until after WWII when Coggeshall and Felegy (58, 104) undertook a series of underground experiments at two bituminous coal and three anthracite mines in Pennsylvania and at a salt and an iron mine in New York. They found that the high frequency "walkie talkie" radios of the Army failed to work underground but that a LF system gave adequate communication ranges through the earth. However, they were unable to separate conductor effects from ground transmission and finally concluded that all LF transmission was due to ground conduction or man-made metallic conductors serendipitously situated for radio pathways. Tests of voice, amplitude modulated, inductively coupled, radio frequency transmissions through the earth in several mines gave promising results. Operating in the 33 to 220 kHz range, with a transmitter output below 2 W in most cases and below 3 W in every case, the Bureau of Mines' investigators established radio communication through a minimum of 320 m of overburden to a maximum of 622 m. Tests were conducted successfully through ground containing anthracite beds, ground without anthracite beds, and through ground containing mined out levels. It was found that extreme wetness, either at the level of communication or between it and the surface had no appreciable effect. Optimum frequencies for transmission efficiency were found to be a characteristic of each mine and to fall in the 33 to 188 kHz range. Conductor effects were again found to be important. Any metallic conductor running along any portion of the radio wave transmission path, greatly enhanced transmission range. At one mine, a body of magnetite was utilized as a metallic conductor in a test. The researchers also concluded that loop antennas were unsatisfactory because of their high power requirement (224). The experiments did not produce immediate concrete results.

Interest in through-the-earth communication continued, however, outside the United States. French investigators transmitted to a depth of over 400 m (110) while in Austria, Bitterlich was able to locate an underground transmitter from the surface (35).

*** BACKGROUND STUDIES OF EARTH ELECTRICAL PHENOMENA

Increasing use of electrical prospecting techniques and interest in making radio communications more effective led to basic studies of the electrical characteristics of the earth from the 1930's to the 1960's (3, 36, 56, 140, 178-179, 250, 261). Data were systematically collected on the electrical properties of rocks, minerals, and soil types and made available through technical literature such as Parkhomenko's, "Electrical Properties of Rocks" (234), and John G. Heacock's (ed.), "The Structure and Physical Properties of the Earth's Crust" (139). Progress was also made toward an understanding of the physical mechanisms by which electrical charges pass through earth materials (60, 252, 254). B. J. Meakins (217), Howell and Licastro (160) reported on the dielectric behavior of rocks while G. V. Keller (177) studied the response of various rock types to transient electromagnetic fields. The latter is the basis of many electrical techniques used in geophysical work. Earth material electrical characteristics at radio frequencies were studied by Russell E. Griffin and Robert L. Marovelli (133) of the Bureau of Mines. John C. Cook (64), working with electronics in mine environments in England reported on the "RF Properties of Bituminous Coal Samples." Long-term investigations undertaken by the Bureau of Standards for radio propagation studies, made available large quantities of data on ground conductivity in most parts of the country (182).

Military interest in the possible use of through-the-earth transmissions for hardened and secure communications caused a flurry of new research, particularly with low or very low frequencies (VLF) or ELF (17, 72, 80, 114, 124, 127, 136, 29, 103). Studies were undertaken of the radiation and reception of underground antennas and of the coupling of these antennas to the earth medium as well as the mutual coupling of the (very large) antenna elements (113, 115, 125-126, 135, 42). Numerous studies of electromagnetic noise were undertaken after it was realized that at VLF or ELF ambient noise was a major problem (45, 76, 214, 230, 245, 347). The source of some of the noise was attributed to the interaction of particles of solar origin with the earth's electric and magnetic fields. Worldwide lightning is the source of most VLF and ELF radio interference. At the low frequencies involved, attenuation is so low that lightning interference from all over the world combines to provide a background of noise. The data collected on VLF-ELF electromagnetic noise was subjected to statistical analysis and from this mathematical models were derived to describe the noise background. The VLF-ELF noise background was discovered to exhibit a generally Gaussian distribution with impulse "spikes" or high points superimposed. The latter were caused by nearby lightning (128, 215, 219, 348, 359). These computer models of LF noise allowed the prediction of the performance of electronic systems at VLF or ELF (232, 251).

Some investigators were quick to see the geophysical application of LF radio waves to underground exploration (1). Limitations in the use of radio methods were also quickly discovered. The same limitations would later be found to apply equally as well to through-the-earth signalling and location techniques using radio. It was found that penetration through the ground was best at low frequencies but because of the long wavelengths involved, the lower frequencies gave poor resolution. Interpretation of data proved difficult. Also, models based upon uniform earth electrical characteristics failed to produce representative results. Both two layer and multiple thin layer models were developed to account for radio wave data for through-the-earth transmissions (293).

It was also found, later, when actual field testing began, that electromagnetic transmission through-the-earth was a more complicated process than theory predicted. Conductivity proved to be a function of the type (or types) of rock or soil through which a signal passed as well as a function of the signal frequency. The conductivity could (and did) vary at individual mine sites; varying with depth, lateral displacement, and frequency; these variations were not necessarily uniform or predictable. Recognizing that the precise location of an underground transmitter depends upon an accurate knowledge of the local conductivity, in-mine tests were conducted. Efforts to determine conductivities at representative mine sites throughout the country have been undertaken by the Bureau of Mines and its contractors. J. Durkin (82) of the Bureau of Mines has begun a systematic survey.

*** NATIONAL ACADEMY OF ENGINEERING RECOMMENDATIONS

The problem of through-the-earth signalling and location techniques gained a new urgency as the result of a mine disaster at Farmington, W. Va., November 20, 1968. A dust and gas explosion at Mountaineer Coal Co.'s Consol No. 9 mine killed 78 miners. In the sealed mine, the fate of the trapped miners was unknown for some time. Out of this tragedy came numerous programs intended to make mining safer. At the request of the Bureau of Mines, the National Academy of Engineering put together the Committee on Mine Rescue and Survival Techniques to "conduct a study program to assess the technological capabilities that can be applied to survival and rescue techniques following mine disasters." Particularly the Committee was asked to consider new devices and technology that might be applicable to the problems of mine safety. Their recommendations led to several programs to develop through-the-earth communications and location systems (227).

Moved by the same events, Congress, on December 30, 1969, passed the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173). This Act made the health and safety of miners "the first priority and concern" of all in the industry. The Act also required the Secretaries of Interior, and Health, Education and Welfare to develop, promulgate and enforce mandatory health and safety standards. In turn, this committment led to expanded research efforts by the Bureau of Mines in the area of mine safety including items designed for postdisaster mine rescue applications. This included the development of trapped miner location and communication systems.

The Committee on Mine Rescue and Survival Techniques suggested a three-phase program to the Bureau of Mines. In the first, an emergency beacon was to be built and tested. It was to be a simple device, rugged and inexpensive, with a narrow bandwidth suitable for one-way signalling in the 500-1,000 Hz range and consisting of only a battery, a buzzer and a key. Stored in refuge chambers and work areas, the beacon would provide a method for through-the-earth location of trapped miners from the surface. In the second phase, individual, mobile transceivers were to be developed that could tie the individual miner into the regular mine communication system. The functions of the first two phases would be combined in the third; the development of an in-mine mobile communication system for individual miners that had through-the-earth capabilities for emergency use. In the third phase, the effective signal strength would have to be increased 100-fold from the beacon signal to transmit voice.

It was recognized that low frequencies would have to be used for sufficient earth penetration; but that presented another problem, that of a low rate of data transmission. Higher frequency signals could transmit more useful information, even voice, but were quickly attenuated in rock and dirt. Some sort of trade-off would be required. The same was true of antennas. Two antenna types, the grounded long wire and the loop, were recognized as potentially effective in mine usage at low frequencies. In the grounded long wire the signal strength was proportional to its length times the current intensity. It would usually be possible to lay out the long wire in a mine. Coupling of the antenna to the rock overburden would be no problem in damp mines but might be one in dry- or well-ventilated mines. In a loop antenna the signal strength is proportional to the area of the loop times the current intensity. Here the loop size is the limiting factor, larger loop sizes needed for lower frequencies are impractical due to bulk. Loop antennas can be located more easily and accurately than long wire (227).

*** THEORETICAL STUDIES OF THROUGH-THE-EARTH TRANSMISSION

Theoretical understanding of electrical wave propagation through the earth was advanced enough to allow rapid laboratory development of hardware systems. As early as 1952, James R. Wait, (319) whose studies, and those of his associates, underly most work on through-the-earth electromagnetic probing or signalling, derived expressions for the electric field of a small loop buried in a dissipative medium, the earth. Wait's earth was considered to have a finite conductivity and the loop was energized by a step-function current. Approximate solutions were also found for the magnetic fields. Wait also considered the case of a conducting sphere in a transient magnetic field; an example of interest for geophysicists (285). About the same time, R. H. Lien (203) derived the expressions for the electric field produced by an oscillating horizontal dipole in a dissipative medium when the radiating frequency is low. In 1970, Wait (318) derived the expression for the radiation into the earth of a line source of current on the surface when the source is an impulse function. Wait and D. A. Hill (325, 330) found expressions for the subsurface electric fields of a grounded cable on the surface carrying a time harmonic varying current under transient and steady state conditions. They also calculated the electromagnetic fields on the surface produced by a pulse excited loop buried in the earth (147, 325, 328, 330). In 1976, Wait and K. P. Spies (336) investigated the case of a small loop radiating in the earth which was considered to be stratified. They found that the ratio of the horizontal to vertical magnetic field strength at the surface was not appreciably affected by the geometry of the earth at sufficiently low frequencies. Hill and Wait determined the theoretical response of a small wire loop, buried in the earth (considered homogeneous) to a transient electromagnetic field (147). Wait and Spies derived the expressions for the impedance of a circular loop, over conducting ground to a LF signal; a case that resembled actual search coils (338). They also derived equations describing the attenuation of radio waves in the earth's crust from ELF to VLF (334). Hill (142) derived expressions for the case in which the buried radiator, a cable of finite length, was oriented at an incline to the surface. In each case it was found that radio waves induced in the earth are affected by the electrical properties of the earth so as to cause the current density within the earth to decrease with depth (293). As R. G. Geyer and G. V. Keller (122) pointed out only the frequency is within the control of the experimenter and designer. Permeability, conductivity, and the dielectric constant may also be frequency dependent, and at least partially susceptible to design parameters.

To study through-the-earth electromagnetic wave propagation, S. M. Shope developed an earth model, in 1982, incorporating a magnetic dipole buried in a three-layered earth (255). Applying appropriate limiting values, Shope was able to reduce the three-layered model to two separate two-layered models and then to a homogeneous half-space model. Shope's solutions were in the form of infinite integrals. Numerical analysis was carried out and a computer program devised to allow the estimation of the surface magnetic fields above the buried source.

Wait and his colleagues also did considerable work describing the theory of transmission of radio waves in mine tunnels and along metallic conductors such as pipes, conduits, wire ropes, etc. (315, 332). Such cases were of more use in normal mine operations than under emergency conditions and were centered in the middle frequency range. Shortly after the National Academy of Engineering recommendations were published, Wait (290) pointed out the possibility of precisely locating a trapped miner if he were able to broadcast a LF electromagnetic signal from a source loop underground. Location would be determined by comparing the magnitude of the ratios of the horizontal and vertical magnetic fields on the surface or the difference in phase between the vertical and horizontal magnetic fields at different surface positions. Wait and Hill (323) then (1972) worked out the explicit expressions describing the waveforms of transient magnetic fields produced by a step-function-excited loop buried in the earth and observed on the surface. They suggested that these waveform functions could be used to interpret signals received on the surface in a manner that might lead to the location of the source from observations at a single point on the surface. The accuracy of these methods depended greatly upon the accurate orientation of the underground transmitting loop parallel to the surface. If, as D. A. Hill (142) pointed out in 1973, the loop is not exactly horizontal then the magnetic dipole moment would have an additional horizontal component that would change both the waveform and the apparent location of the source. He derived expressions for a horizontal magnetic dipole, primarily to consider the effects of possible random antenna orientation but he also suggested that the vertical magnetic field of a horizontal loop could be used for location purposes.

The question of precisely locating an underground signal, once it was detected, was studied by Wait and C. H. Stoyer. They identified the possible errors inherent in locating an underground signal (a magnetic dipole) located in an inhomogeneous earth which varied laterally from the source to the receiver (271). T. W. H. Caffey and L. Romero in a recent study derived expressions for the location of a similar underground magnetic dipole (44).

*** ELECTROMAGNETIC NOISE STUDIES

The electromagnetic background noise environment of mines is highly complex and derives from many sources. The primary source of interference is the omnipresent 60 Hz and its harmonics. Mine machinery, lighting, transmission lines and nearby inhabited areas all contribute to the 60 Hz haze which prevents the use of many low frequencies for through-the-earth communications. Heavy DC machinery often used in mining also produces strong, LF interference when it is starting up or being switched. Natural interference is also present and highly significant at the low signal strengths involved in through-the-earth electronics. For nearly a century LF interference has been noted on telephones, radios, etc. These are variously described as "whistlers," "growlers," or a steady hiss. It is believed that the world-wide pattern of thunderstorms produces most of these noises; at these low frequencies attenuation is so low that almost the entire world can contribute. The "hiss" and other noises are believed to be caused by solar particles falling into the earth's magnetic envelope. Furthermore, in recent years, several LF and VLF radio stations, mostly military, have gone into operation, contributing further interference. The nature, distribution and magnitude of these electromagnetic noises were largely unknown quantites in 1970.

The next phase of the effort to create through-the-earth trapped miner location systems was the measurement of the electromagnetic noise field within mines and on the surface above mines. At the same time efforts were being made to produce effective communication systems for use within the mine during normal operations using wire or radio. The studies were useful for both purposes. Under Bureau of Mines' contracts several research groups began, in 1971, to systematically study electromagnetic noise in mines (4-5, 12, 26-27). The Colorado School of Mines group, which included R. J. Geyer and G. V. Keller (123), took measurements at a number of coal mines in Colorado, Illinois, and West Virginia. The data were deliberately taken above the working faces and working sections and included measurements taken near a power station. A wide frequency band (20 Hz to 10 kHz) was taken to sample, and data were collected over the full 24-h period spanning all work shifts in the mine.

The Institute for Telecommunications Sciences under the direction of J. H. Crary (69) undertook a study for the Bureau of Mines of the background electromagnetic noise, natural and manmade, in the frequency range 20 Hz to 20 kHz. The magnitude of the electromagnetic noise field as a function of frequency, above and below the surface was recorded. Studies were made of the attenuation of radio waves through the earth at frequencies from 20 Hz to 100 kHz, and tests were made of the accuracy of location of an underground signal source. Various loop antenna combinations of characteristics were tested; shielded and unshielded, horizontal and vertical orientations, varying number of turns, etc. For each location and antenna loop configuration, a frequency band that was exceptionally quiet was selected for further analysis as well as an unusually noisy frequency band. The quiet band was chosen because it gave promise of being useful for through-the-earth communications and the noisy one could provide evidence as to the source of electromagnetic noise. The noise patterns proved to be very complex and it proved impossible to separate temporary local noises from the general background except in a few isolated cases (12).

These results showed generally good agreement with an earlier National Bureau of Standards study (25). For their work, the Bureau of Standards group put together a versatile, semi-portable integrated unit which was capable of the calibration and measurement of the entire noise recording system they used. On tape, they recorded the wideband magnetic field noise waveforms over the frequency range 40 Hz to 10 KHz. This data was later subjected to computer-assisted spectral and statistical analysis in the laboratory. Tests were made at three operating coal mines in Colorado which were considered representative under every working condition; full production, shift change, etc. The Bureau of Standards group found that the magnetic field strength of the background noise varied from a low of 20 dB (relative to 1 $ampm^{-1}$ at 60 Hz) at a quiet location to a high of 138 dB at a frequency of 500 Hz near an AC power buss. At locations distant from arcing DC machinery and at frequencies between 60 Hz harmonics, noise minima of over 60 dB were found, giving promise of being suitable for through-the-earth transmission usage (12).

A West Virginia University group under the direction of M. D. Aldridge and W. W. Cannon (9) undertook, for the Bureau of Mines, studies to measure electromagnetic noise from 2 kHz to 200 kHz in operating mines. The West Virginia University group was primarily interested in developing a wireless paging system for use in mines and in improving mine telephone communication. Data were taken from eight coal mines in the West Virginia-Pittsburgh area at 20 frequency steps between 2 kHz and 200 kHz. The West Virginia University group measured the horizontal and vertical field components of the electromangetic noise near DC and AC equipment and transmission lines. The conducted noise on trolley and telephone lines was also measured. Some attention was given to through-the-earth transmissions and from the experimental results and theoretical calculations an optimum system was proposed. This system transmitted 10 W at 870 Hz from a 100 turn, 15 AWG wire antenna, 1 m in radius and was picked up by a 29 turn 0.4 m radius antenna. A range of 600 m should be realized but to increase the range to 750 m would require 100 W; to increase it to 1,200 m would require 10 kW (12).

As part of its ongoing work in subsurface location and communications the Westinghouse Georesearch Laboratory collected some data on electromagnetic noise in the frequency range 20 Hz to 5 kHz. The data was collected at four coal mines that were either closed down or only partly operational in order to simulate the quiet conditions of a postdisaster period. A portable minicomputer originally designed for seismic signal processing allowed real-time analysis of noise at the mine site. The Westinghouse group also collected, on a long-term basis, background electromagnetic noise produced by atmospheric sources and human activity at Boulder, Colorado.

Review of these studies done by Bureau of Mines' contractors in electromagnetic noise were conducted by Arthur D. Little, Inc., (12) and the Institute for Telecommunication Sciences (6). Both studies were found deficient to a greater or lesser degree and the reviewers recommended a further program of research to correct the deficiencies and to provide coverage of frequencies not studied in the earlier work.

Following these guidelines a National Bureau of Standards research group undertook the systematic study of the electromangetic noise environment of representative mines, six coal and two hardrock, to compile a "comprehensive library" of electromagnetic noise data. Data were recorded under a wide variety of combinations of mining conditions, equipment, and power supplies. It was found that for mines deeper than 300 m, and an average conductivity of 10^{-2} SM^{-1}, low frequencies (100-500 Hz) would have to be used to achieve adequate penetration. For depths approaching 3,000 m even lower frequencies were necessary. But these very low frequencies can transmit little useful information and 60 Hz interference becomes serious. Shallower depths or more conductive ground (approximately 10^{-1} SM^{-1}) could allow the use of frequencies up to 5 kHz or even higher (184). Signal power requirements for various depths, noise levels, and conductivities were calculated and the signal to noise ratios were predicted for various conditions (192). The noise data recorded in the mines were random and required statistical analysis to be meaningful.

Motohisa Kanda (172) showed that five statistical measures had meaning in the analysis of electromagnetic noise in mines. The Allan Variance Analysis was used to determine how much data was needed. The Interpulse Spacing Distributions gave the probability distributions for the spacing of successive pulses in the received noise. These distributions are functions of the noise amplitude level. The Pulse Duration Distribution gave the probability distribution for pulse widths which are measured in terms of the percentage of pulses exceeding an arbitrary width in a given time period. The Average Crossing Rate gave the average number of times the noise amplitude level "crosses" an arbitrary level. The Amplitude Probability Distribution provided the fraction of a given time period that the electromagnetic noise envelope exceeded various arbitrary levels. This is the most common and useful measure of noise for the design of electronic communication systems.

E. C. Field, Jr. and M. Lewinstein (105) produced an "Amplitude-Probability Model for VLF/ELF Atmospheric Noise." They found that the amplitude-probability distributions could be represented in terms of two parameters. One of these characterized the "impulsivity" of noise from local noise sources. The other represented the ratio of energy in the impulsive-noise component to the energy in the background-noise component. Both of these can be measured at the receiver. Each of these concepts had potential applicability to trapped miner location systems because the very low signal strengths received on the surface were highly sensitive to background noise interference.

A Colorado School of Mines group (122) proposed in 1974 the possibility of using a system based upon the detection of a buried, passive loop excited from the surface as a means of trapped miner location. The loop could either be worn by or deployed by the miner. However, calculations showed that the ambient electromagnetic noise levels on the surface of most operating mines exceeded the fields radiated by a buried passive loop. The group suggested that a passive loop system be used only as a backup to an actively powered transmitter for trapped miner location.

*** WESTINGHOUSE - BUREAU OF MINES SYSTEM

FIRST PHASE DEVELOPMENT AND TESTING

Sponsored by a Bureau of Mines' contract and based upon the National Academy of Engineering's recommendations, the Special Systems Division of Westinghouse undertook the development and testing of an electromagnetic communications/location system in 1970-1971 (101). Utilizing off-the-shelf technology as far as possible, the Westinghouse group developed a low power (4 W) beacon transmitter for mine refuge chambers with simple, keyed, signalling capabilities that could also be located from the surface. A powerful (1 amp) voice transmitter, using a long horizontal wire antenna laid on the surface, was built for downlink transmissions. A manpack voice receiver, with very low battery power drain was designed to be attached to the miner's cap light battery pack. Using this equipment, Westinghouse engineers tested the concept of through-the-earth communications at five coal mines in Colorado, Pennsylvania, and West Virginia at depths of 88 to 259 m.

Preliminary work included determining the effective local earth conductivity at each site as well as measurement of the background noise, natural and man-made, in operating and in closed down mines. Voice transmission tests at various depths, and at various horizontal surface offset distances were made at frequencies from 300 to 3,000 Hz. The beacon uplink transmitter was operated at 1,375 or 2,750 Hz. Reliable uplink communications were established through a distance of 457 m, but only simple coded signals were possible. Downlink "intelligible voice communications" proved possible in every case to an underground mine shaft through a slant range of 443 m but not to one 867-m distant. Very high quality communications were established through a 311-m slant range. Depending upon local earth condictivity these results indicate a maximum usable depth for the Westinghouse equipment of 488 m using the manpack unit and 975 m using a heavier, high power, refuge or "Habitat" receiver. Little field degradation was found when the signal from the beacon uplink transmitter was detected on the surface at points distant from the spot directly above the transmitter. The equipment functioned properly even under adverse (below 0° F) weather conditions. The tests proved the possibility of through-the-earth location and communications systems using (then) current technology. About 90 pct of the coal mines in the United States were within the range of the Westinghouse equipment. There were some unresolved problems. The tests had shown the need for extensive earth conductivity studies in the areas of coal mines as well as a need to survey the electromagnetic background noise environment at various frequencies of interest around and within coal mines. It also appears that conductor effects were ignored in the early Westinghouse tests (353).

SECOND PHASE DEVELOPMENT AND TESTING

In the second phase, Westinghouse engineers working under Bureau of Mines contracts, developed and tested a prototype through-the-earth location and communication system in 1972 and 1973 (101, 204, 236). The location system was based upon the detection, at the surface, of the null (minimum signal) of the horizontal magnetic field produced by a buried transmitter. Electromagnetic pulse as well as continuous wave, half wave, and full wave transmitters were tested. Numerous limitations had to be placed upon the underground electromagnetic transmitter design parameters. Fewer were required for the surface units where size, weight, simplicity of operation, intrinsic safety, and power consumption were less critical factors.

The system used the miner's 4-V cap lamp battery pack as a power source and therefore the power drain was a critical factor. The design attempted to achieve the greatest transmission efficiency (power drain for a given signal strength) as well as the maximum possible transmitting moment (INA - where I = current, N = number of turns of a loop antenna, A = area of the loop) to weight ratio. The aim was to build a transmitter capable of producing a 10 dB signal to atmospheric noise ratio at the surface. The continuous wave transmitters proved to be much more efficient. It gave a 10 dB enhancement of signal strength which, for example, would allow a four-fold reduction in antenna weight for the same battery drain. Full wave continuous wave was safer too. Because the DC component delivered to the antenna was lower, there was less danger that the antenna lead power level could exceed intrinsically safe levels.

The transmitter itself was miniaturized by using a printed circuit with a tuning fork oscillator and four switching transistors to obtain full wave signal to a resonated loop antenna. A 200 ms tone burst was broadcast every 2 s for a duty cycle of about 9 pct. In a test, a fully charged battery pack gave over 57 h of transmission. The transmitter was also tested for durability under extreme temperature conditions (-20° C to + 60° C) and for frequency stability (drift >2 Hz at 2,010 Hz).

Recognizing that lower frequences gave superior through-the-earth penetration, the Westinghouse transmitter was designed to utilize the frequency range 300 Hz to 3,000 Hz. Because of man-made noise, the frequency domain below 1,000 Hz was not actually used. Instead, the transmitters were designed to operate at one preset frequency each in the 1,000 Hz to 3,000 Hz range. In actual field tests at three mines, signals broadcast at frequencies near 1,000 Hz (1,050 Hz) were more severely affected by man-made noise than those between 2,000 and 3,030 Hz (2,010, 2,070, 3,030 Hz) and the maximum signal to noise ratio was obtained in this higher frequency range.

Antenna design proved troublesome because of weight and intrinsic safety considerations. The main determinant of antenna performance was the question of intrinsic safety because it imposed limits on the output power. Weight was another major factor. Westinghouse attempted to maximize the antenna moment (INA) to weight ratio. But the output power is a function of the size and length (the weight) of the antenna and is itself limited to permissible values to be intrinsically safe. No perfect combination was possible; several were investigated. The best proved to be a horizontal loop antenna deployed in the mine. Westinghouse designers envisioned loop antennas semi-permanently mounted around coal pillars where they would be available to a trapped miner in case of a disaster. A portable, deployable long wire antenna was also designed. It was housed in a molded plastic package that also contained the transmitting unit. The container which was to be worn by the miner on his belt was built to be rugged enough to withstand the severe mine environments.

Westinghouse designed two variations, fixed and variable frequency, of the surface receivers. The fixed frequency receiver came to be preferred because of its relative simplicity of operation, relatively low cost and portability. Its sensitivity was far better than its design requirements (0.1 ampm^{-1}) and its batteries were sufficient for 40 h of continuous operation. The antenna or receiving loop was a small (0.45 m diameter) multi-turn, hand held loop. An approximate underground location was first achieved on the surface by measuring the strength of the underground signal. The strongest signal would be detected on the surface above the source of the underground transmission. After roughly determining this point on the surface it was located precisely by rotating by hand the receiving loop to the position of minimum signal. This is normally done from at least two separate directions and the intersection of the two (or more) planes, defined by the receiving loop orientation, in the null position directly above the buried transmitter.

Tests were performed by the Westinghouse group at three Eastern coal mines and one Western hard-rock mine. Conductivities at the coal mines were of the order of 1.1×10^{-2} SM^{-1} and the maximum depth for a successful test was 300 m. The Western hard-rock mine had an average conductivity of 3.4×10^{-3} SM^{-1}. Tests at this mine proved the capability of the system to pinpoint a transmitter location through 119 m of overburden to an accuracy of 5 m. Severe weather conditions and steep hillsides above the test mines added difficulties and realism to the tests. At each mine, ground conductivities were determined and the electromagnetic noise in the frequency range of interest was recorded.

The tests consisted of surface location exercises in which the position of a buried transmitter was determined from the position of the surface null and compared to that obtained by land survey. Field intensity measurements of the transmitted signal were made at varying radial distances from the surface point directly above the buried transmitter as far as the signal could be detected. A test was also made to determine if the location of one underground transmitter could be determined in the presence of another one, nearby, also broadcasting. The signals were easily separable and identifiable. The effects of sloping surface ground above the transmitter were also found to be insignificant in affecting location accuracies. An experiment was designed to test the effect of tilting the underground antenna from its normal horizontal orientation as could readily occur in a mine disaster. The antenna (at a depth of 116 m) was laid upon a pile of rubble at approximately a 20° inclination.

This shifted the apparent surface null position by 13 m, which could be a significant distance in mine rescue operations. Anomalous results were also obtained when metallic conductors (metal pipes, power cables, a fence line) were in the path of the through-the-earth transmissions.

Attempts to detect the signal from a moving helicopter gave poor results. No signals could be detected from within either a reciprocating or a jet engine aircraft. However, when an antenna loop was hung 11 m beneath the jet powered helicopter it proved possible to detect the transmitter signal at an altitude of 38 to 76 m and at a position 30 m from the surface location. This opens the possibility of using helicopters for a rapid area survey to locate trapped miners whose position is unknown.

These Westinghouse tests proved the practicability of the designs. Some questions remained. Exactly what were the optimum frequencies? Could a two-way communication system be designed? What could be done about the anomalous propagation effects of metallic conductors? Antenna design was an area open to further development. Finally, some method of location that was more precise and more predictable than homing on the null signal point was highly desirable. Could one be designed and built?

FREQUENCY-SHIFT KEYING (FSK) BEACON SIGNALLER

A related project was simultaneously undertaken by another group of Westinghouse engineers (10). The objective was to develop a durable, fixed location and communications system which would have through-the-earth capability and be available for normal use as well as for postdisaster mine rescue operations. It was to be connected to the mine phone system, to be capable of simultaneous through-the-earth and phone line transmission and to have paging capability. The system was also to be able to integrate a number and variety of underground sensors. All of this (up to 20 underground stations) was to come to a single surface station where the data were to be displayed, with visible and audible alarms and where centralized mine communications came under the control of one center for both normal and emergency use.

Each underground station could be connected to the mine phone system but each was also capable of through-the-earth voice transmissions to the surface (uplink) using a voltage controlled oscillator to generate frequency modulated (FM) carrier frequency of 7 kHz. Under normal conditions the subsurface FSK beacon dignaler broadcasts coded signals from a variety of sensors. These operate on 1 of 20 assigned frequencies between 3,390 and 4,530 Hz. There is an emergency feature whereby an operator may manually depress one of six push buttons on the FSK Beacon generating automatically one of six emergency signals (Yes, No, Don't know, Repeat, Wait and Morse Code Follows). There is a separate Morse code button. There is also an emergency feature that, when turned on, produces a continuous wave signal for 20 s then cuts off for 20 s as long as the switch is on. This allows identification (it broadcasts at the local subsurface station frequency) and location from the surface. The FSK beacon utilizes the same antennas, surface and subsurface as the voice uplink.

The surface station contains receiving equipment for the voice uplink and display consoles for the subsurface condition monitoring system. It also has a voice downlink transmitter which uses a direct audio system at 200 W. Special subsurface receivers were designed for this system. All underground equipment was hardened to approximately twice the instantaneous shock and temperature levels that a human can be expected to survive but it was not tested. The system itself was tested, satisfactorily, in January 1973 at the Bureau of Mines, Bruceton, Pa., experimental mine (10). The Westinghouse designed equipment was also tested (95) in a very deep (915 m and 1,311 m) hard-rock metal mine (Galena Mine in Idaho). The system, designed primarily for coal mines, proved to be useful in the deeper metal mine. Location accuracies were 46 m for the long wire antenna, 150 m for the horizontal loop and 140 m for the vertical loop at 915 m depth. An important anomalous effect was produced on transmissions by the deep mine shaft which was lined with various metallic conductors. Signals passing near the shaft utilized this route with a resulting enhancement of signal strength by a full 30 dB.

*** ANOMALOUS EFFECTS

Field tests of through-the-earth transmissions conducted by a Colorado School of Mines research group at several mines with various combinations of antennas and frequencies often resulted in anamolous data because of the presence of underground conductors (108). Sometimes these serendipitous conductors enhanced transmissions greatly but the scattering effects could also hinder efforts at precise location of the source of a transmission.

The problem was an old one. Anomalous conduction effects had been found as early as the 1920's. B. A. Austin (14) pointed out that the South Africans with 20 to 30 yr experience in underground radio had found that when metallic conductors (pipes, rails, power lines, etc.) were present, anomalous effects were the rule rather than the exception. Transmissions in the presence of metallic conductors were sometimes enhanced as much as 10-fold. The existence of conductors also enhanced transmission along intermittent or broken or buried conductors. Austin also pointed out that mine tunnels had a wave guide effect on electromagnetic transmissions which could be very significant and which were utilized by the South Africans (14).

Other investigators, particularly James R. Wait (291, 326) and D. A. Hill (142, 144) had already begun theoretical investigations of the problems created by the presence of buried conductors, particularly as they related to the problem of precisely locating an underground transmission source. In a series of studies Wait and Hill derived mathematical solutions to describe the effects of buried conductors of various shapes, sizes, and inclinations upon electromagnetic fields in the earth as well as for transmission along such conductors. They concluded that detection and location from the surface of a trapped mine equipped with a special transmitter was feasible within certain limits and that the experimental data being amassed was in good agreement with theoretical predictions.

Raymond D. Watts (352) of the U.S. Geological Survey used the Fast Fourier Transform (FFT) to compute the electromagnetic fields scattered by a long straight conductor (pipe, cable, rails, etc.) within the earth. Watts considered the currents induced in the buried conductors by a plane wave electromagnetic source field. The induced currents give rise to secondary radiated fields from which the position and depth of the conductor can be determined. Watts also derived a method for determining the effect of more than one buried conductor and their possible interaction.

C. H. Stoyer (270) analyzed the case in which the buried conductor presented two long dimensions to the surface such as in the case of a buried mass of conducting metallic ore or a trapped miner with a loop antenna. The loop is realized as a vertical magnetic dipole if the surface is far enough away. A conductor (ore body, pipe, rail, cable, etc.) in its path will have its field on the surface distorted. Stoyer used a finite-difference method to predict the surface magnetic fields in terms of the magnetic field polarization ellipse parameter. The error involved in locating the source of the transmission is "quite small." But R. J. Greenfield (132) pointed out that small errors could have substantial effects particularly in the case where there were large lateral changes in ground conductivity along a transmission path. An anomalous effect of vertically varying conductivity could be useful in both normal and emergency mine communications as R. L. Lagace and A. G. Emslie pointed out. A coal seam, of relatively low conductivity, bounded by more highly conductive rock can serve as a mode of transmission for medium frequency radio waves. While the signal attenuates rapidly in coal, if there is a metallic conductor nearby, the signal will be coupled to it. It then follows a low attenuation mode guided by the metallic conductor which is the same effect noticed earlier by other investigations.

Investigation of three types of anomalies became part of a later study by T.S. Cory (67) undertaken for the Bureau of Mines primarily to gather data for the development of middle frequency for mine face area communications. Cory found that wireless communications in the absence of nearby metallic conductors was equivalent to lateral through-the-earth communication. The transmission efficiency was enhanced by nearby conductors. Ranges of 600 m were regularly obtained if metallic conductors were located near the signal source or receiver. In their absence, the reliable ranges were reduced to 100 to 300 m. If both transmitter and receiver were close to metallic conductors (the same entry, for example, as a mine trolley) then ranges of several kilometers become possible. Cory found that the optimum frequency (in the middle frequency range) for conductor-free transmission was 520 kHz and for conductor-assisted transmissions 700 to 1,000 kHz.

In a related study a group from West Virginia University, C. A. Balanis and others, (15-16) studied the conductivity of coal as a function of frequency in the microwave range. Wait (303) pointed out that theoretically a coal seam can be visualized as a resistive layer bounded by conductive rock. If the source is a vertical electric dipole then the dominant mode of propagation has relatively low attenuation. The possibility then was clearly open, of using the coal seam itself as a medium of transmission of radio frequency signals.

The effect of adjacent conductors on the propagation of radio waves in a coal seam was treated theoretically by D. C. Chang and J. R. Wait in 1980 (51). They found, as had been discovered in actual mines, that attenuation was lower in the presence of metallic conductors and derived mathematical approximations for low and medium frequencies.

Practical use of serendipitously situated conductors is also beginning. ARF Products, Inc., has developed (1981) a voice communication system for within mine use (102). The ARF system uses low and medium frequencies which are coupled into adjacent conductors such as mine wiring, pipes, cables, and rails. Commercial systems are expected to be available from ARF in the future.

*** FIELD TESTING AND HARDWARE EVOLUTION

Some actual field tests seemed to give promising results. D. Kalvels of Westinghouse (171) under a contract for the Bureau of Mines tested an earlier developed trapped miner location device in over 36 mines at depths ranging from 60 to 430 m at the frequencies, 630, 1,050, 1,950, and 3,030 Hz. Voice signals were successfully transmitted through 213 m of rock. The research program measured the transmission loss of signals through the overburden and a data base of this information was compiled. As predicted, the transmission loss increased with the length of the overburden path and with the frequency. The study also found that uplink transmission loss characteristics could not be extrapolated from downlink values probably because of the difference in the types of antennas used on the surface and within a mine.

Another Westinghouse group (A. J. Farstad) (99) attempted to apply the through-the-earth communications system developed for the Bureau of Mines to metal and nonmetal mines. In these mines the depths are usually much greater and to achieve coverage of 90 pct of the mines a through-the-earth capability of 900 m was needed. There is also extreme variability in the conductivity of the rock strata of these non-coal mines. In particular, metal and salt mines are likely to have much higher than normal conductivities. Furthermore, the underground geology and topography are likely to be much more complex and less predictable. Penetration of the earth can be achieved using VLF (10 Hz) and very long (long compared to the overburden) wire receiving antennas on the surface. Direction finding, Farstad suggested, could be done by deploying a grid of long wire antennas on the surface.

Other tests and analyses were made of the Bureau of Mines' system. In 1974, Collins Radio investigators (144) determined that through-the-earth systems were impractical. They required too much power to penetrate the earth. The large power supplies also may not be intrinsically safe. The needed antenna size is too large to be practical in any portable form and too large to be readily deployed. The "prime" use, said the Collins Radio group, was one-way paging of individual miners from the surface where large fixed transmitters and antennas could be used. They suggested that a loop antenna (20.3 cm diameter) could be wound in the miner's hard hat and they also suggested the systematic use of anomalous conduction by metallic conductors such as rails, pipes, etc. Another suggestion called for the creation of an emergency mine communication system designed exactly like the normal mine communications and located in the same places for familiarity under the stress of a mine emergency.

Concurrent with the Westinghouse studies, a research group from the Colorado School of Mines was conducting similar studies for the Bureau of Mines (122). At a variety of mine test sites the effective earth conductivity was measured for various depths and locations. The electromagnetic noise environment was recorded and analyzed both within the mines and on the surface. A pulse transmitter was also developed and tested for downlink communication through the earth, using a step current which excited a long wire (223 m) antenna. Underground, the transient signal was picked up on a long wire antenna at a depth of 23 m. While the pulse system gave advantages in signal compression, the ambient electromagnetic noise levels were a problem. Field tests were made of the transmission through the earth of LF signals (20 Hz to 20 kHz) by vertical axis loops and horizontal wire antenna and the results compared with theoretical predictions.

Hardware development also continued. Collins Radio engineers under a Bureau of Mines' contract (62-63) built 50 miniature waveform generators. These were designed to drive a LF loop antenna and to be a part of the electromagnetic trapped miner location system. The miniature (3.6 by 0.9 by 8.8 cm) waveform generators were securely encased ("potted"), could operate under water, and were capable of being produced economically on a large scale. They were designed for a single preset frequency each in the range 1,050 to 3,030 Hz and had a 10-pct duty cycle; that is, they generated signals of 100-ms duration about 10 pct of the time and were off the rest (58).

R. L. Lagace and others of Arthur D. Little (187-188) did substantial work before 1978 in the development of antennas for in-mine use, both for through-the-earth communications and for normal use in mining operations. The problem of antenna development was complicated by the fact that at the frequencies of most interest (VLF to MF) the wavelengths are extremely long while the antennas, for practical reasons, must be physically small. Trade-offs among the various constraints were necessary to achieve the maximum possible transmission efficiency.

Other trapped miner transmitters and transceivers were developed and tested by General Instrument Corporation under a Bureau of Mines' contract from 1978 to 1981. Breadboard units and prototypes were built and tested and finally 95 transmitters and 12 transcievers were produced. The frequencies of the units were 630, 1,050, 1,950 or 3,030-Hz. Some of the units were built with aluminum wire instead of copper to save weight and several were built integrally as part of the miner's cap and battery pack. Representative units were tested environmentally. An improved version was developed by General Instrument Corporation (48) for the Bureau of Mines and subjected to extensive testing. This trapped miner electromagnetic signalling and detection system was based upon the belt-worn miniature transmitter, which, in an emergency, would be attached to the cap lamp battery for power. The transmitter would drive a loop antenna which consisted of 91 m of #18 copper wire, normally carried on the belt, and deployed in an emergency around a coal pillar or in a passageway. The Collins Radio-General Instrument Corporation system was field tested by the Bureau of Mines (J. Durkin) and Westinghouse (R. F. Kehrman, A. J. Farstad, and D. Kalvels) under a Bureau research contract.

The Bureau of Mines' researchers (82, 189) tested the system in coal mines throughout the United States and used the data to develop models of the signal and noise distributions that would be found on the surface above coal mines throughout the country. These signal and noise distributions were then used to estimate the probable performance of through-the-earth electromagnetic communications. The expected probability of detecting a miner's signal from a depth of 305 m is 54 pct; this depth exceeds 90 pct of all American coal mines. The expected probability of detecting a signal from 153 m is 95 pct; this is deeper than 50 pct of American coal mines. Improvements in the signal to noise ratio (SNR) greatly enhances the probability of detection. For every 3-dB improvement in the SNR, the probability of detection increases 6 to 8 pct. The Westinghouse researchers (176) generally obtained better results which presented a more optimistic view of the "reliability and effectiveness" of the system tested. Successful communications were established in 91 of the 93 Eastern and Western coal mines, where tests were conducted through overburden thicknesses ranging from 21 to 472 m. The frequencies used were 630, 1,050, 1,950, and 3,030 Hz. The conclusion was drawn that the communications system would work in practically all mine environments. The Westinghouse resarchers were not so sanguine about the trapped miner location system whose reliability and accuracy depended upon the ambient electromagnetic noise, the depth involved and the possible presence of metallic conductors which might distort the signal. The strength of the through-the-earth signals reported by the Westinghouse scientists proved to be higher than those of the Bureau of Mines; running 10 to 20 dB higher at the higher (1,950 and 3,030 Hz) frequencies. An independent evaluation of the conflicting data was made by workers at Arthur D. Little, Inc., from 1978 to 1980 (190). They concluded that the Bureau of Mines measurements had been more accurate due to a systematic bias introduced by Westinghouse equipment or procedures and that the expected probability of detection derived by Bureau scientists was realistic.

*** RESEARCH IN COMMUNICATION TECHNIQUES

Work has also been done under Bureau of Mines sponsorship to improve the detectability of through-the-earth signals. Enhancement in detection can mean greater depths through which a system may operate as well as greater reliability.

Voice bandwidth compression techniques were applied in 1975 to mine wireless communications by R. H. Spencer and W. G. Bender (265) with disappointing results. Narrower bandwidths would allow less electromagnetic noise interference with the received signal. But it required a higher SNR for intelligibility and therefore more transmitted signal power. Sophisticated techniques to overcome this problem are expensive. In a related study, Penn State investigators in 1977 (218) evaluated the Bureau of Mines-developed downlink through-the-earth communications system by testing the intelligibility of human speech broadcast through the system. They used a modified rhyme test in which tapes recorded with standardized word patterns recorded at known, calibrated levels were broadcast and the received signals evaluated for intelligibility. Computer simulations were used rather than actual in-mine tests. These simulations indicated that the system would be of dubious reliability at a depth of over 300 m even at optimum frequency.

A group of researchers at the University of Michigan's Cooley Laboratory developed in 1979 and 1980 an automated emergency mine communication system under a Bureau of Mines contract (248). The system utilizes a unique (repeating pseudonoise) signal and a sensitive detection system that includes matched filter detectors. This is coupled with sophisticated signal processing techniques including the use of a new decision-variable algorithm to estimate (and allow elimination of) the noise between the signal peaks. The new system proved capable of operating, in the laboratory, with an input SNR of -34 dB. The system developed by the Bureau of Mines required an input SNR of +6 dB. The difference is 40 dB. It was also determined by the investigators from earlier Bureau of Mines propagation studies that the received signal power for through-the-earth transmissions decreases to the tenth power of distance. Hence, a 40-dB improvement in needed input strength would mean an increase in range by a factor of 2.5. The greatest improvement comes from the fact that the Bureau of Mines system uses the human ear as a detector, while this prototype uses an automated system. The new technique, however, was a laboratory evaluation and demonstration which did not undergo actual field tests.

*** IN-MINE COMMUNICATION SYSTEMS

Dual purpose in-mine communication systems have been suggested and their use investigated by the Bureau of Mines (53). Such a system would function as a normal in-mine working communication system and as an emergency system in a postdisaster scenario. These systems usually operate at higher frequencies than the trapped-miner through-the-earth systems and they often deliberately utilize the anomalous conduction paths provided by metallic conductors along the line of propagation.

Recognizing the need for a broader range of in-mine communications, Nelson and Johnson Engineering in 1981 proposed a more comprehensive system (102). Among the functions that a complete mine communication system could perform are monitoring (for example, methane, rock bursts, flooding, carbon monoxide), point to point, postdisaster and point to mining face communications (or communications with remote sections). A computer controlled system was designed which was connected to a network of underground terminals located at strategic points. These terminals routinely emit radio frequency pulses to interrogate the miniature transponders worn by miners or attached to equipment or vehicles. The transponders would be constantly powered by float charged equipment batteries or by the miners 4-V cap lamp battery. The transponders would respond to the interrogation with a uniquely programmed coded signal so that the underground radio frequency terminal can identify the individual transponders. The underground terminals are then interrogated by the main computer on the surface which keeps a running account of underground conditions and personnel. There was a favorable reaction to the proposal from most of the nine mine operators contacted, particularly from the larger operations, and the Mine Health and Safety Administration (MHSA), but there was some opposition expressed due to the cost and complexity of the proposed system.

Propagation studies under a Bureau of Mines' contract were undertaken in several low (91 to 122 cm) coal mines at medium frequencies (98 to 4,050 kHz) by a Collins Radio communications switching system team in late 1977 and 1978 (66). The primary work was the measurement of the magnetic field strength which was taken so that it characterized the radio transmission properties of each of the five mines and four coal seams tested in Pennsylvania, West Virginia, and Kentucky. The magnetic field strength measurements were taken as a function of range and frequency. Tests were conducted both in "quasi-conductor free mine areas" and in proximity to metallic conductors. The tests were run under conditions of negligible ambient electromagnetic noise from mine operations because the mines were not operating. Maximum communication ranges were calculated from the magnetic field strength versus range and frequency data under assumption of low ambient electromagnetic noise (set-noise-limited) and the levels of noise (median mine noise) expected during normal mine operations. The communication ranges for the set-noise-limited example varied from 180 to 260 m in the frequency range 200 to 300 kHz; the ranges varied from 115 to 140 m between 400 and 800 kHz.

*** TANGENTIAL RESEARCH

Research in areas tangential to through-the-earth communications often proved valuable to investigators. A group from Stanford Research Institute (77), in an effort to determine if there were hidden chambers in the Egyptian pyramids, and for other archeological uses, developed a high frequency (16 to 50 MHz) electromagnetic sounder. This was tested in a California dolomite mine before being used in Egypt. Using the Wawona Tunnel at Yosemite National Park, R. J. Lytle and D. L. Lager (209) studied the transmission of high frequency (3 to 50 MHz) radio waves through 300 m of hard rock and determined the bulk conductivity of the rock (2 to 5 x 10^{-4} SM^{-1}). T. W. H. Caffey (43) devised a miniature telemetry link capable of receiving data from sensors buried up to 50 m below the surface. He also built a control link capable of turning the telemetry transmitter on or off from the surface. A matched filter detection system designed by University of Wisconsin engineers (57) to correct distortions in through-the-earth electromagnetic transient signals used in geophysical work offered the possibility of being useful for the precise location of trapped miners.

There was other work in areas common to both electromagnetic geophysical methods and through-the-earth communications and location. N. Harthill (137) reported on time domain electromagnetic sounding and

T. Lee (200) on the "Estimation of Depth to Conductors by Use of Electromagnetic Transients," both of which had dual applicability. D. F. Moore and E. A. Quincy (221) wrote on the statistical (Bayes) classification of subsurface electromagnetic responses while Ling to Szeto devised a minicomputer program for analyzing time-difference-of-arrival data.

Another area was the use of supersensitive receiving equipment on the surface. One, which grew out of antisubmarine warfare research, was the cyrogenic SQUID (superconducting quantum interference device) magnetometer. J. E. Zimmerman and W. H. Campbell (362) developed several varieties of SQUID in semi-portable forms. Field tests and standardization tests showed the system to be "reliable, accurate, portable, and simple to operate in geophysical operations. Directional measurements of natural magnetic field fluctuations as small as 0.0001 gamma with periods from 0.5 seconds to several hours" were obtained. Liquid helium, used to cool the SQUID to superconducting ranges, presented problems of storing and handling. Zimmerman and Campbell concluded that present (1975) and nearly achieved technology will allow the storage, within SQUID devices of liquid helium for a period of weeks or months; and thus make it a practical geophysical tool of extreme sensitivity. Because of its sensitivity it held particular interest for through-the-earth location efforts particularly in the case of great depths, or if passive devices were to be used underground to signal the trapped miner's presence.

Military interest in LF communications had application to mine through-the-earth location and communication systems. Research for the U.S. Navy's Seafarer Project SANGUINE, included the design of a noise processor for the SANGUINE receiver. Basing their design on extensive world-wide recordings of ELF (3 to 300 Hz) atmospheric noise, J. E. Evans and Andrew S. Griffiths (87) in 1974 suggested using nonlinear processing to suppress the effect of large, random noise "spikes" in the ELF range as well as "notch" or narrow band filters at the frequencies of man-made interference. A computer simulation of the noise processor gave an enhanced performance of 15 to 20 dB over a linear receiver in high level noise periods.

*** CURRENT RESEARCH

Presently, research is progressing into separate areas for through-the-earth location and communication systems. Much of it is based upon past research and earlier recommendations for future research. Each of the methods suggested utilizes a microcomputer as an essential element.

DEVELCO SYSTEM

DEVELCO engineers (249) in 1979 began the development of a location system for trapped miners in deep mines that would give accurate location results through 1,000 m of overburden. The DEVELCO group recognized that the previously developed loop antenna was nearly of optimum design because of the weight, cost and intrinsic safety factors that limited its size. Improvement could possibly come through better beacon design including the use of a high efficiency transmitter, of larger diameter wire for the loop antenna, lighter metal (aluminum, for example) for the antenna, and the development of better and lighter batteries (lithium). The system proposed by DEVELCO included taking vector magnetic field measurements of the surface magnetic field produced by the underground transmitter at three or more surface locations. Then using iterative techniques the data can be solved for the transmitter location. DEVELCO would use a microcomputer with necessary peripherals for this. Accurate location measurements require "static, precise field sensors in a carefully surveyed array," which can be either permanent or semi-portable. The key problem, according to DEVELCO engineers, is that of detecting very small signals in the presence of high noise levels and getting enough information from those signals for accurate location measurements. It can be done, DEVELCO says, by using sophisticated communication techniques including noise processing, coherent detection methods and special modulation.

PHASE DIFFERENCE OF ARRIVAL TECHNIQUES

A research group at the U. S. Bureau of Mines' Tuscaloosa Research Center developed a through-the-earth location system based upon phase difference of arrival techniques. Operating with continuous wave radio signals, whose phase differences can be accurately measured even when the signal is weak, location is automatically determined by a microcomputer which is an integral part of the system. The system is based on multiplexed transmission frequencies, an array of surface receivers to measure the phase differences of the transmitted signal and a microcomputer for real time location calculations. In the first phase, computer modeling of the propagation of electromagnetic fields through-the-earth was undertaken. Equations were derived, based on phase difference of arrival techniques, to enable the location of a trapped miner, assuming uniform conduction of the overburden and a point source transmitter. Sufficient field testing was not conducted prior to the project's termination.

AUTOMATED THREE-DIMENSIONAL LOCATION SYSTEM

Another suggested method of locating trapped miners gives promise of a high degree of accuracy in location position. A system developed by F. H. Raab and associates (242) used a three-axis magnetic-dipole source and a three-axis magnetic sensor to determine the position and orientation of the three-axis magnetic dipole source. The magnetic source generates a LF or quasi-static dipole field exciting the three-axis magnetic sensors which give sufficient information to allow the determination of both the position and orientation of the sensors relative to the source. This signal is amplified and fed into a computer where it is used to update previous coordinate measurements of the position and orientation of the three-axis magnetic dipole source. Raab's group recognized that the presence of nearby metallic conductors could seriously affect the accuracy and reliability of their system but their calculations indicated that the problem was of manageable proportions.

Another new automated trapped miner location system was developed by Polhemus Navigation Sciences in 1978 and 1979 under a Bureau of Mines contract (243-244). It was based upon the phase quadrature technique and involved the retransmission of an ELF signal by an underground transceiver. In this system, three transportable three axis magnetic-dipole transmitters are deployed on the surface. The three transmitters receive timing and control signals from a centrally located van-mounted control system through a very high frquency (VHF)/FM radio link. Each transmitting antenna contains three mutually orthogonal wire loop elements which when properly excited produce a quasi-static magnetic field whose phase depends upon the position and orientation of the signal. The ELF (13 Hz for typical coal mine depths) downlink signal is received by the subsurface receiver and used to modulate the uplink carrier with the received downlink signal. The subsurface receiver/transmitter is similar to the beacon transmitter previously developed for the Bureau of Mines by Westinghouse. It operates in the ultra low frequency range (600 Hz to 3 kHz) for typical coal mine depths. On the surface, the uplink receiver uses a three-axis antenna to receive the signal and extensive digital signal processing based on a small computer to integrate data, estimate the subsurface position and control the system operation through the VHF/FM ratio net. Having demonstrated the feasibility of their system, Raab, Hansen, and their collaborators, plan to build and test breadboard models and then field test the system.

ADAPTIVE NOISE CANCELLATION

LF radio signals, especially in the ELF-VLF region, can penetrate the earth much more readily than those of higher frequency. However, in the ELF-VLF region atmospheric noise becomes a major problem. Most of the noise comes from thunderstorms around the world. Because of the extremely low attenuation of ELF-VLF radio waves, even far away thunderstorms make a contribution to the background radio noise. Nearby thunderstorms have a stronger effect. The background electromagnetic noise at ELF and VLF is distributed according to a Gaussian distribution with sharp impulses, caused by nearby thunderstorms, superimposed on this background. Signal processing must therefore contend with both the steady background and the impulsive noise.

By the 1970's much basic research had been done in the ELF-VLF range (see above) particularly in regard to the U.S. Navy's Seafarer Project SANGUINE and by geophysicists (163, 273). The geophysicists were interested in using the low radio frequency ranges for subsurface exploration and, in fact, the Adaptive Noise Cancellation (ANC) system is based on magnetotelluric techniques used in geophysical exploration. In the magnetotelluric method typically a remote receiver and antenna are used to provide a reference signal to be used for noise cancellation in signal processing. Because these wavelengths are extremely long the background noise waveforms are essentially the same at considerable distances of separation between the reference receiver and the actual receiver (107, 116-117, 273). The coincidental noise signals, representing the background electromagnetic noise can be made to cancel, using computer assisted signal processing. This leaves the desired signal, greatly enhanced.

However, because the background electromagnetic noise contains impulsive elements a simple integration (cancellation) of the signal and reference signal will not produce an adequate signal-to-noise ratio over an appreciable time period. Instead, ANC techniques have been developed and applied.

ANC techniques are based upon the use of a distant reference receiver to provide a reference signal that is essentially free of the desired signal but comprised almost exlusively of background noise. This is used in a sort of feed back mode to cancel that portion of the signal that is due to background noise. The signal comparison is carried out dynamically by a computer. The result is, usually, a vastly increased gain in the signal strength of the desired signal (28, 73, 75, 118, 129-130, 220, 240, 246, 357).

Green Mountain Radio Research Company (F. H. Raab and associates) under a Bureau of Mines' contract undertook to apply ANC techniques to the through-the-earth communication and location problem (239). The first phase of the study, now complete, involved developing a computer model for the multicomponent (Gaussian plus impulsive) ELF electromagnetic noise and the development of the computer software needed for noise correlation-cancellation and the review of ANC algorithms.

Raab and his associates recognized that the ELF needed to penetrate the earth imposed special conditions and afforded special opportunities. It meant, for example, that the field produced at the surface by a buried transmitter was essentially a pure quasi-static magnetic dipole field and that the associated electric field was negligible. A local electric field antenna then would receive no signal but only propagating noise. Thus it could be used as a reference source of correlated noise for ANC (241). Conversely, the amplitude of the magnetic field falls off very rapidly with distance (signal loss of 60 dB for a distance change of 1 to 10 km), so that a remote magnetic field sensor can provide an essentially signal-free source of correlated noise to use in ANC. The researchers predicted that noise reductions in the order of 20 to 30 dB are possible by ANC techniques (239). Hill and Wait also derived related theoretical noise and propagation models (154).

*** NATIONAL RESEARCH COUNCIL EVALUATION

Ten years after the original 1970 National Academy of Engineering report ("Mine Rescue and Survival") an evaluation of the progress made was undertaken by the National Research Council. The Council consists of representatives from the National Academy of Engineering, the National Academy of Science and the Institute of Medicine. In surveying the effectiveness of the work done by the Bureau of Mines and its contractors in postdisaster survival research, the Council report was generally very favorable.

While the postdisaster work of the Bureau of Mines made up only a small part of its research budget (5.5 pct) during the 1970's, its work had "clearly shown the practicality of communicating with and locating trapped miners." There had been "significant" advances in theoretical, analytical, and experimental aspects and in design of hardware for postdisaster use. In general, the Council concluded that the Bureau of Mines' research effort "has more than met the recommendations of the 1970 NAE report."

The Research Council report found some problem areas. There was a lag between the research and development process and implementation in industry. Hardware and techniques developed by research are not being usefully applied in the mining industry. There is a "lack of a clear policy or methodology for the transition from basic research to applied research, development, demonstration, testing, and ultimately, implementation." The Council added that it was unclear how much of this transition was considered to be a responsibility of the Bureau of Mines.

The Research Council also suggested that, in the future, more emphasis be placed on exploratory or basic research and less on equipment development and demonstration. It also said that insufficient research attention had been paid to the problem of communications between trapped miners and underground rescue teams. Finally, the Research Council recognized that the development of inexpensive digital circuits and dense packaging techniques in the 1970's has made possible the use of specialized microcomputers in through-the-earth systems. The Council suggested that these systems can be adapted, on short notice, to conditions in individual mines. They could provide sophisticated signal processing techniques to minimize ambient noise and to compensate for peculiar local conditions that affect radio transmission and reception (228).

*** SUMMARY

Trapped miner, through-the-earth location and communication systems have been under development for many years. Researchers have succeeded in deriving theoretical models which describe the transmission of electromagnetic energy through the earth accurately. The mechanisms of the ambient background noise have been investigated and a large body of data has been accumulated describing the noise under actual mine conditions. There also has been a large amount of research done to accumulate a large body of knowledge on the variable earth electrical characteristics such as conductivity. Prototypes of location systems have been built and tested successfully and from these tests a second generation of trapped-miner location systems is evolving.

Current research seems to be approaching the successful development of a workable system which is small, low powered, inexpensive to produce, intrinsically safe, rugged and reliable, and which has vastly superior earth penetrating capabilities. Much more sensitive receiving equipment and integrated minicomputers have made the requirements for underground equipment much less stringent. Coupling trapped miner location systems to small computers makes possible rapid and accurate location computations and is a vigorous field of research at present.

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