

The Bureau of Mines has conducted field studies in coal mines throughout the United States to determine the effectiveness of electromagnetic techniques in locating miners trapped underground following a mine accident. Data from these tests have been used to generate models of expected signal and noise distributions as found above these mines. These distributions have aided in placing the expected performance of a through-the-earth electromagnetic communications technique into a probabilistic framework. **Results show that at a 10% false-alarm rate, the expected probability of detecting a miner's signal from a depth of 1000 ft is 54%, at 500 ft it is 95%. These depths exceed the actual depths of 90 and 50%, respectively, of United States coal mines. Sensitivity studies have shown that at a depth of 1000 ft, the probability of detection will improve approximately 2% for each dB of increase in signal-to-noise (SNR) ratio.**

Introduction

The value of communications with miners trapped underground following a mine disaster has been recognized since the 1920's [1,2]. Tests were performed where underground reception was made of signals from the first commercial radio station, KDKA, approximately ten miles from the mine. The investigators concluded correctly that the reception of the radio signal was aided by metallic conductors located within and around the mine. Interest in through-the-earth communications to trapped miners continued to grow.

Earth conductivity measurements were made and transmission loss tests for radio frequency (RF) propagation through-the-earth were conducted. Ilsey et al. [3] performed experiments in such communications and concluded that low frequencies penetrated the earth more efficiently than higher frequencies and that much greater reception distances were obtained when metallic conductors were present. By the end of the 1920's, it was concluded that no practical system for through-the-earth radio communications was possible because of the large power requirements necessary to establish them effectively.

During the 1930's, interest in through-the-earth propagation was renewed when investigators became aware of the potential in using radio waves for geophysical exploration [4]. They found that the electric and magnetic field intensities from electromagnetic (EM) radiation from distant thunderstorms varied with local underground geology. However, little effort was placed on through-the-earth communications until the 1940's, when renewed efforts were made in South Africa and the United States.

The South Africans were concerned with establishing communications between the surface and a rescue team. Wadley [5] showed that if low frequencies were used, communications could be established through several hundred meters of earth. Later, during the 1960's, the

Electromagnetic Detection of Trapped Miners

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*A report on 94 field tests using
narrowband EM transmitters to locate
trapped miners*

South Africans developed and tested medium frequency (MF) hardware [6]. The results demonstrated that communications could be obtained over a large range, mainly due to coupling with metallic conductors; the equipment, however, proved too bulky for practical applications. These units were later modified and miniaturized, and placed in operation in a deep gold mine near Johannesburg [7].

In the United States, the Bureau of Mines maintained a modest effort to develop through-the-earth communications until after World War II, when Bureau investigators Coggleshall and Felegy [8,9] performed a series of tests at two bituminous and three anthracite mines in Pennsylvania, and at a salt mine and iron mine in New York. They also worked with MF hardware and, like the South Africans, found good success when conductors were available.

During the 1960's, the military began to realize the potential for secure through-the-earth communications. Most of the research considered electric field antennas operating at very-low frequencies (VLF) or extremely-low frequencies (ELF) [10-13]. Similar to the findings of earlier investigators, these studies showed that effective communications ranges decreased as transmission frequency and earth conductivity increased. Also, the overall effectiveness of the communications link was highly variable and required large amounts of transmitter power.

The problem of through-the-earth communications gained a new urgency as the result of a mine disaster at Farmington, WV, on November 20, 1968. A dust and gas explosion at Mountaineer Coal Co.'s Consol. No. 9 mine killed 78 miners. For some time following the disaster, the fate of the miners was unknown. The void created by the absence of emergency communications was obvious. The following year, the Bureau of Mines contracted with the National Academy of Engineering [14] to assess the technological capabilities that could be applied to improving repair techniques and miner survival following mine disasters. An important area of consideration by the Academy was post-disaster communications. The Academy recommended that the Bureau of Mines conduct research leading towards the development of equipment for the location of and communication with trapped miners through EM techniques. The Academy, drawing upon the results of the earlier studies previously discussed, concluded that the most promising avenue of investigation would be development of narrowband EM transmitters, which could be used by the trapped miner to transmit a pulsed EM signal to the surface. There, rescue team members could both detect the signal and establish its place of origin.

During the 1970's, the Bureau of Mines developed narrowband EM transmitters [15,16] and performed field tests at ninety-four different coal mines to determine the effectiveness of this technique for locating trapped miners [17,18]. This report discusses the results of these tests.

To predict the surface signal level produced from an underground transmitter, it is necessary to understand the expected loss the signal incurs when transmitted through the earth. Unfortunately, the geological structure of the overburden above coal mines differs from mine to mine. This gives rise to differing electrical conductivity structures. Therefore, for a given mine depth, it can be expected that signal transmission characteristics will vary from mine to mine. One approach for attaining information on the earth's transmission loss is through statistical analysis of through-the-earth transmission tests. A major objective of the 94-mine field test was to obtain enough data on the earth's transmission loss, as found over a large population of representative coal mines, and over a range of frequencies, to confidently characterize expected signal loss from an underground transmitter. A detailed description of equipment configurations and procedures used in the field-test program is given in [17].

To ensure success in obtaining data during the field tests, magnetic moments of the underground transmitter were used which were higher than would be expected from a transmitter to be used by a miner; this ensured that earth transmission loss data would be obtained. A strategy was then formed to predict the expected surface signal strength based upon a given magnetic moment.

It should also be mentioned that the position of the underground transmitter was determined by measuring the horizontal signal field at different locations and, by finding the null in the field, the underground location was found by triangulation. This location measurement technique had the added benefit of ensuring that the transmitted signal was actually traversing the earth medium and was not conducted along pipes, wires, or other conductors.

The root-mean-square (rms) values of the vertical magnetic field, H_z , of all of the data taken were normalized to a transmitter magnetic moment (M) of $M = 1 \text{ amp-m}^2$. Since the surface field is directly proportional to the magnetic moment of the underground transmitter, the expected level of the surface field for a given transmitter could then be found by accounting for the actual magnetic moment used. Following this normalization, statistical studies were performed to relate the surface field strength and mine depth at each frequency tested.

Each normalized data point can be denoted as S_{ij} , where i represents the specific frequency and j represents the specific depth of test for each mine. Thus, each surface measurement S_{ij} taken can be considered as a single observation of signal strength at a predetermined frequency and overburden depth level at a particular mine.

The relationship between field strength and mine depth was found through regression analysis. This work assumes that the errors are normally distributed and the

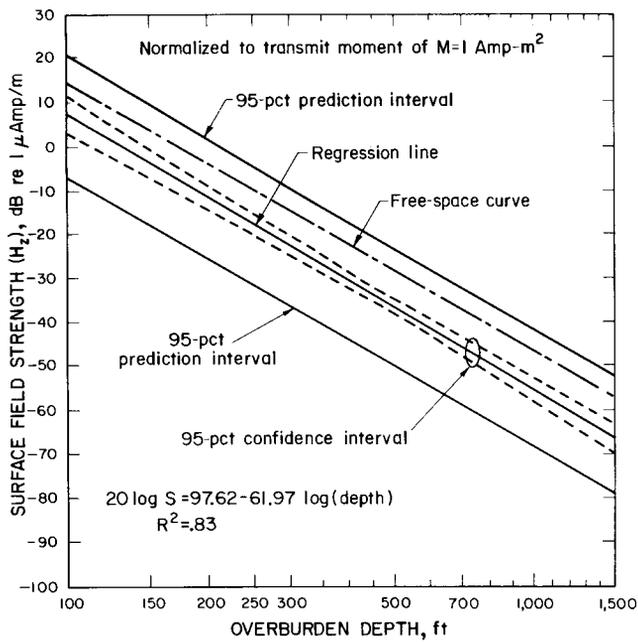


Fig. 1. Uplink regression results for 630-Hz-normalized vertical signal strength vs. depth.

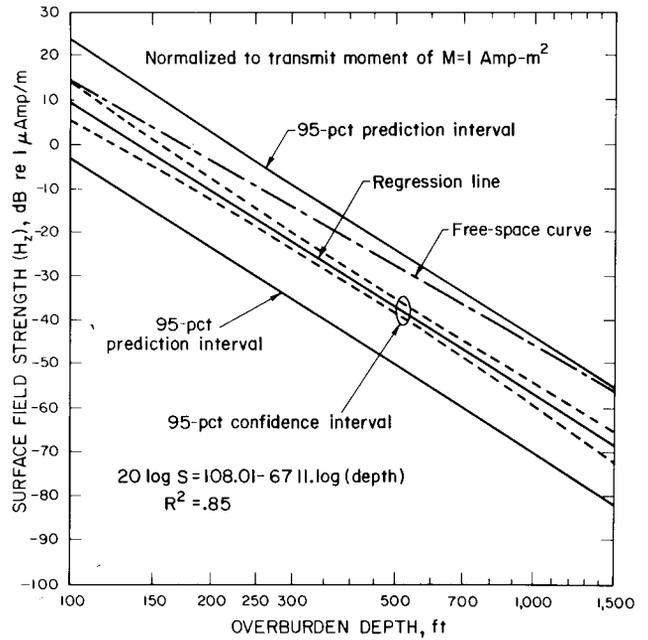


Fig. 2. Uplink regression results for 1050-Hz-normalized vertical signal strength vs. depth.

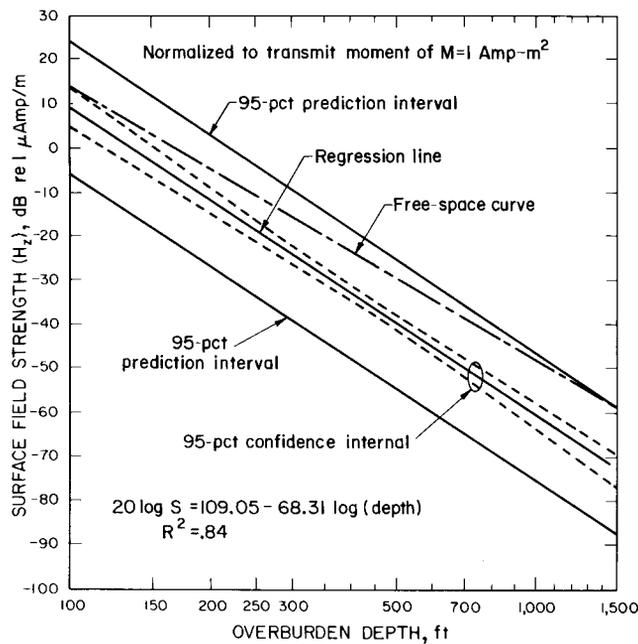


Fig. 3. Uplink regression results for 1950-Hz-normalized vertical signal strength vs. depth.

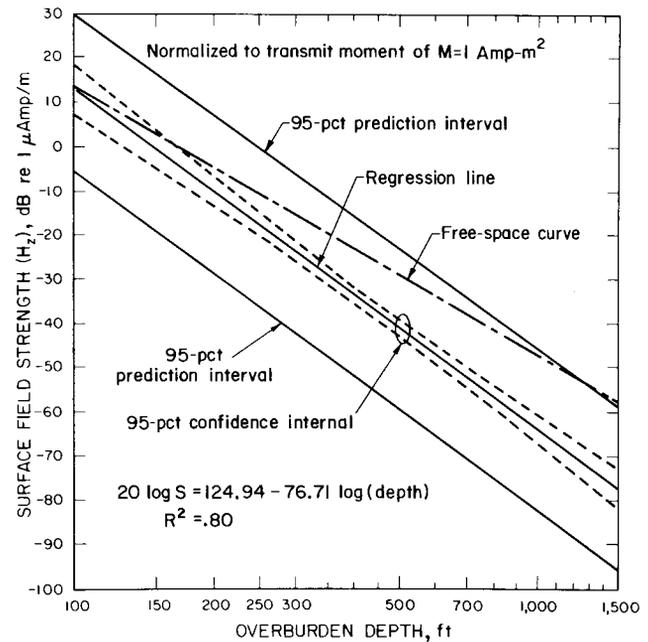


Fig. 4. Uplink regression results for 3030-Hz-normalized vertical signal strength vs. depth.

variance is equal across the independent variable. These assumptions were considered, and it was concluded that meaningful statistical inferences from the regression analysis could be made. Several linear regression models were hypothesized and tried. The model found to best fit the behavior of the data is one in which the mean value of the normalized signal strength S_{ij} is linearly related to the logarithm of overburden depth. This is shown in (1):

$$S_{ij} = \alpha_i + \beta_i \log (\text{depth}_j) + \epsilon_{ij} \quad (1)$$

Here, S_{ij} is the normalized vertical magnetic field signal strength (expressed in dB re $1 \mu\text{amp/m-rms}$ for the i th frequency and depth j for a transmitter magnetic value of the normalized signal strength S_{ij} is linearly related to the logarithm of overburden depth. This is shown in (1):

The parameters α_i and β_i were estimated from the data, where depth is in meters. The parameter ϵ_{ij}

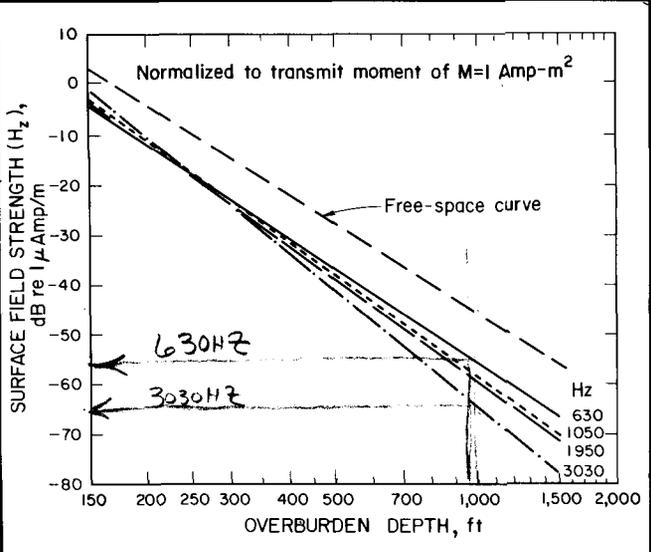


Fig. 5. Normalized overburden response curves—uplink regression results: Average surface vertical signal strength vs. overburden depth by frequency.

surface signal strengths produced by this transmitter can be predicted by computing the expected magnetic movement at each frequency and then translating each of the overburden response curves of Fig. 5 upwards by an amount equal to the values of the magnetic moment expressed in dB re 1 amp-m².

The assumed loop configuration of the GI transmitter is a square. This loop configuration was chosen because it best represents the practical implementation of the procedure that the miners will be instructed to follow. Figure 6 shows the predicted surface field strength when the GI transmitter is used. Also shown are the expected magnetic moments for each frequency.

Surface EM Noise

During the field tests at 27 of the mines tested, tape recordings were made of the vertical magnetic noise (receiver loop lying flat on earth) on the surface. These recordings were later used to obtain data on the noise at the four frequencies of interest. These data were obtained by performing a Fast-Fourier-Transform of the recorded noise.

For the purposes of signal detectability, the rms value of the vertical magnetic field noise is of interest. The statistical distribution of this noise, using the Bureau data base from 27 mines, at each frequency for a 30-Hz bandwidth is shown in Figs. 7-10. The 30-Hz bandwidth was chosen because it represents the bandwidth of a typical receiver which would be used in this application.

Surface SNR Ratio

In the previous sections, the behavior of signal and noise data obtained in this study has been characterized

represents a random variable that is normally distributed, with expected value zero and variance σ^2_{ij} , which is the same for all values of j .

The derived regression lines for each of the four frequencies are plotted in Figs. 1-4. The R^2 statistic, a measure of goodness of fit, indicates that the log-linear relationship of (1) is appropriate. Also shown in these figures are confidence and prediction intervals.

Figure 5 summarizes the normalized average overburden response as a function of depth and frequency by plotting the four regression lines and the free space curve on one graph. This figure shows that the frequency dependence of signal strength is relatively insignificant for depths less than 500 ft, and that the change across the band is only about 10 dB even at the maximum depth of 1500 ft.

These summary normalized overburden response plots, together with the confidence and prediction levels in this section, can be used to generate estimates of signal strength produced on the surface above coal mines as a function of overburden depth and operating frequency for transmitters having any prescribed magnetic moment vs. frequency characteristics in the 630- to 3030-Hz band. These results assume that, for a fixed magnetic moment, the size of the transmitting loop has no influence on the surface field. It is recognized that this assumption is not totally valid, as demonstrated by Wait [19], but it is considered that the size of loop used during the tests and the typical offsets for measuring the surface field were not severe enough to greatly influence the results.

General Instrument (GI) fabricated an EM trapped miner transmitter [20]. This instrument was designed to be lightweight, worn on the belt, and capable of deploying a loop of wire 300 ft in length. The expected

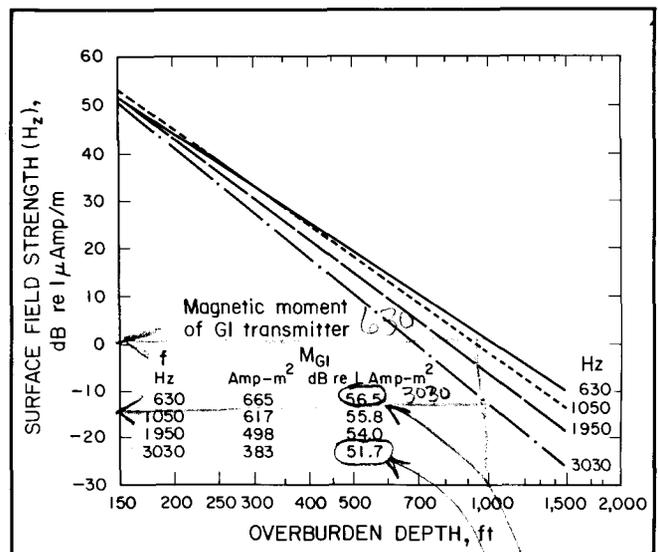


Fig. 6. Predicted uplink response curves for General Instruments transmitter: average surface vertical magnetic field signal strength vs. depth by frequency.

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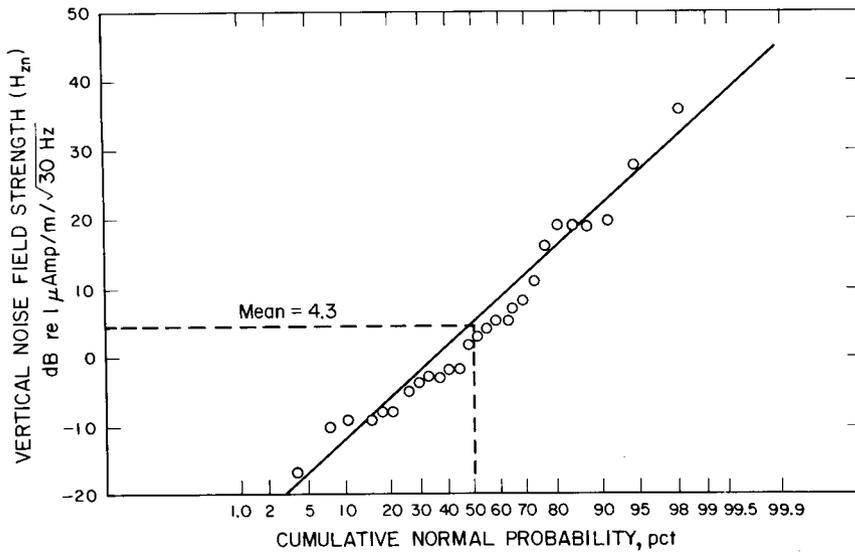


Fig. 7. Statistical distribution of rms surface noise at 630 Hz for a 30-Hz bandwidth.

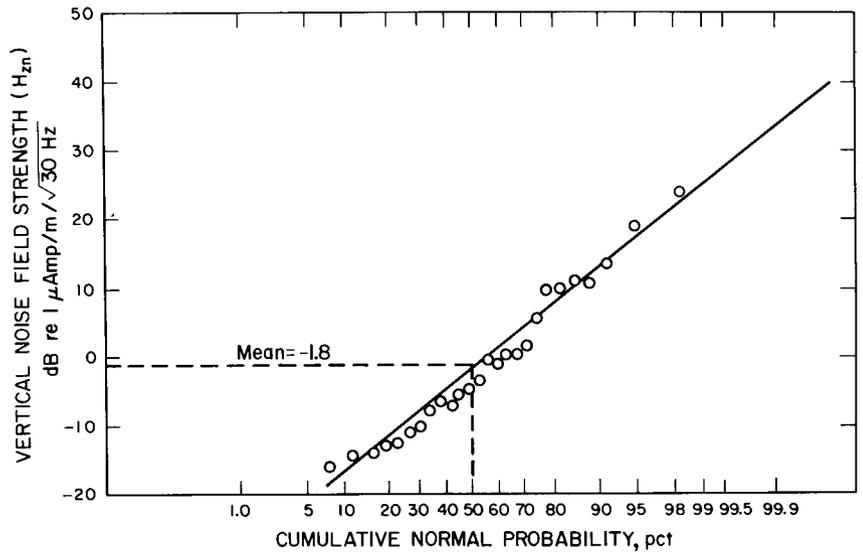


Fig. 8. Statistical distribution of rms surface noise at 1050 Hz for a 30-Hz bandwidth.

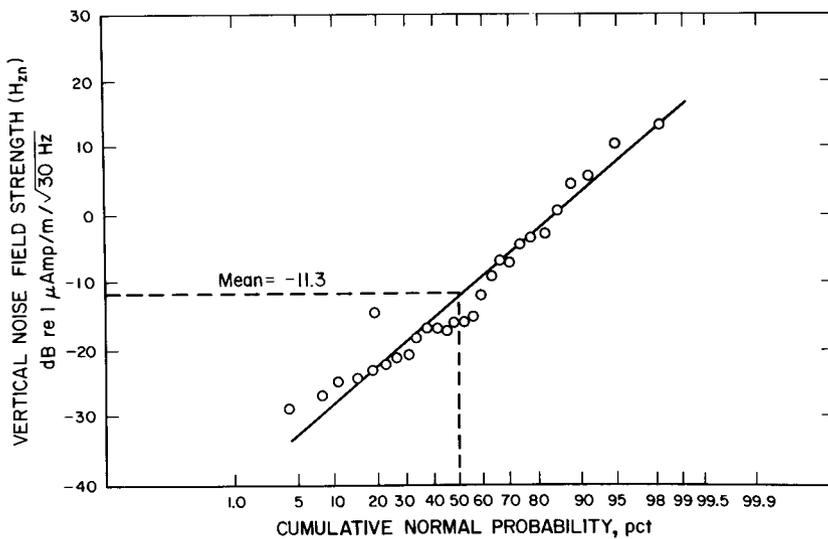


Fig. 9. Statistical distribution of rms surface noise at 1950 Hz for a 30-Hz bandwidth.

TABLE I
ESTIMATED PARAMETERS CHARACTERIZING SIGNAL AND NOISE DISTRIBUTIONS ABOVE COAL MINES

Overburden depth, ft.	630 Hz	1050 Hz	1950 Hz	3030 Hz
Estimated Mean Signal in dB re 1 $\mu\text{A}/\text{m}$ for GI Transmitter				
250	37.50	37.51	34.50	32.27
500	18.84	17.31	13.93	09.18
1000	0.19	-2.90	-6.63	-13.92
1500	-10.72	-14.71	-18.66	-27.42
Standard deviation	06.65	06.52	07.08	08.92
Estimated Mean Noise in dB re 1 $\mu\text{A}/\text{m} / \sqrt{30 \text{ Hz}}$				
All depths	04.3	-2.8	-11.3	-17.1
Standard deviation	13.5	11.5	12.5	12.5

by statistical relationships. It has been found that both the signal and noise data are log-normally distributed. To develop an understanding of detection probability, it is necessary to characterize the probability distributions of the surface rms SNR at each frequency. The basic input for the derivation of rms-SNR estimates on the surface is summarized in Table I. Mean rms signal strength and standard deviation values adjusted to pertain to the GI transmitter are given at each frequency for different mine depths. Mean rms noise strengths and their standard deviations are also given at each frequency.

The independence of signal and noise distributions, in addition to the property of normality exhibited by each distribution, permits straightforward combination of the two distributions to generate SNR probability estimates. The SNR distributions are conveniently plotted using normal probability paper and are given in Figs. 11-14 for five different overburden depths at each of the four frequencies. These four figures provide a straightforward method of estimating the probability of having

various SNR's in actual practice. The vertical axis represents the area under the normal curve from minus infinity to some SNR value R_0 and provides the probability of achieving an SNR value less than or equal to R_0 . Figure 15 gives the probability that the rms signal is at least greater than the rms noise as a function of depth.

Probability of Detection Estimate

The success of a rescue effort when using a trapped-miner transmitter rests on the ability of surface personnel to confidently detect the signal from the underground transmitter. The pulsed signals from the underground transmitters are detected by searchers carrying rescue receivers equipped with a hand-held loop antenna and headsets. The mode of detection is aural, based on the headset signals perceived by the ear. It is thus necessary to establish a relationship between the nature of the signal, SNR, and the probability of aural signal detection.

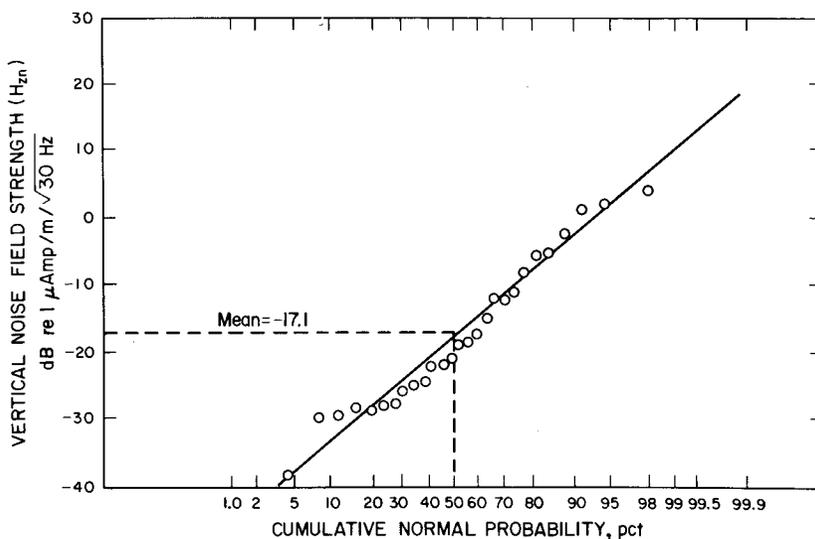


Fig. 10. Statistical distribution of rms surface noise at 3030 Hz for a 30-Hz bandwidth.

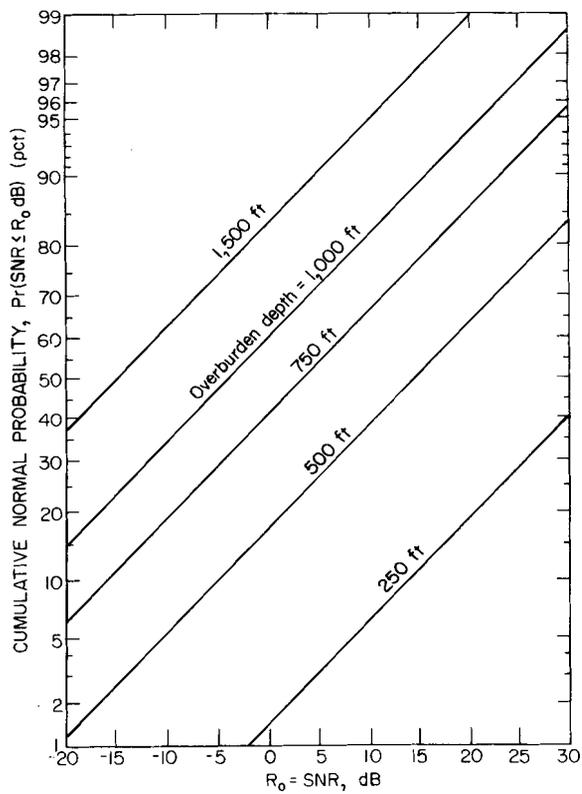


Fig. 11. Cumulative probability distribution of SNR expected above United States underground coal mines at 630 Hz.

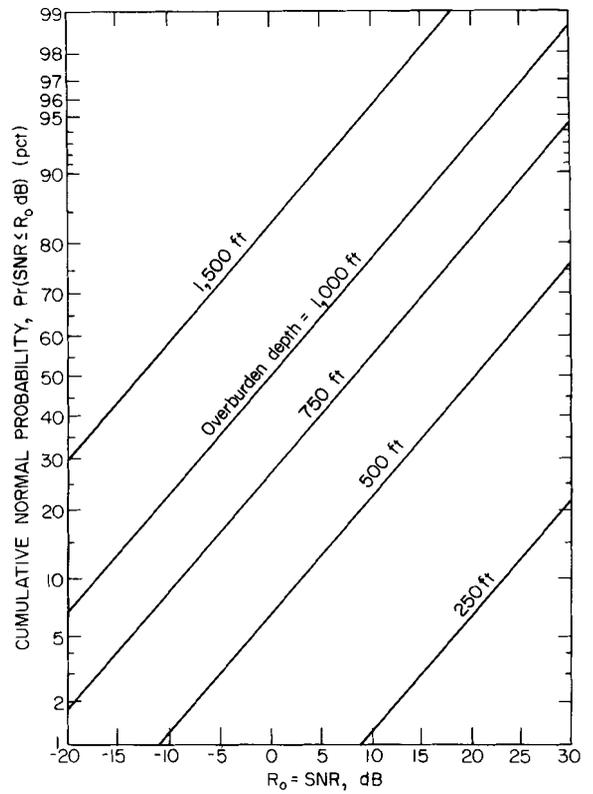


Fig. 12. Cumulative probability distribution of SNR expected above United States underground coal mines at 1050 Hz.

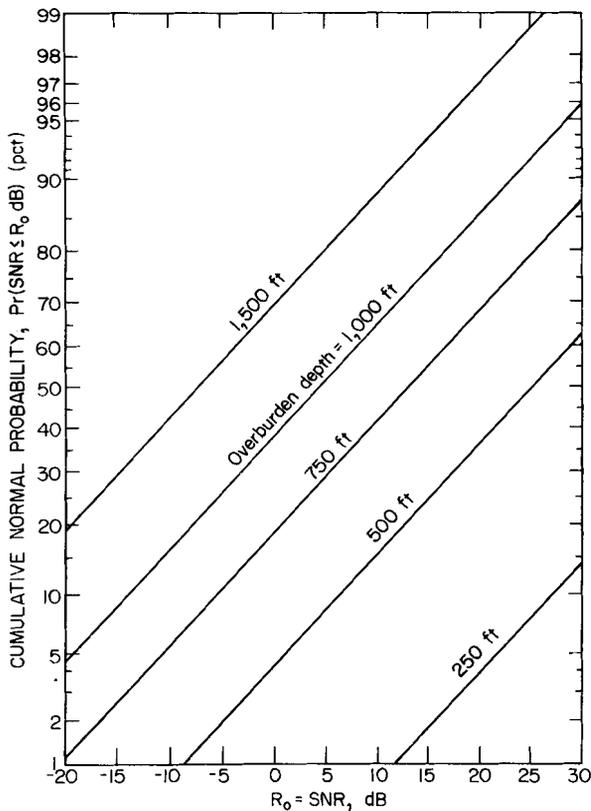


Fig. 13. Cumulative probability distribution of SNR expected above United States underground coal mines at 1950 Hz.

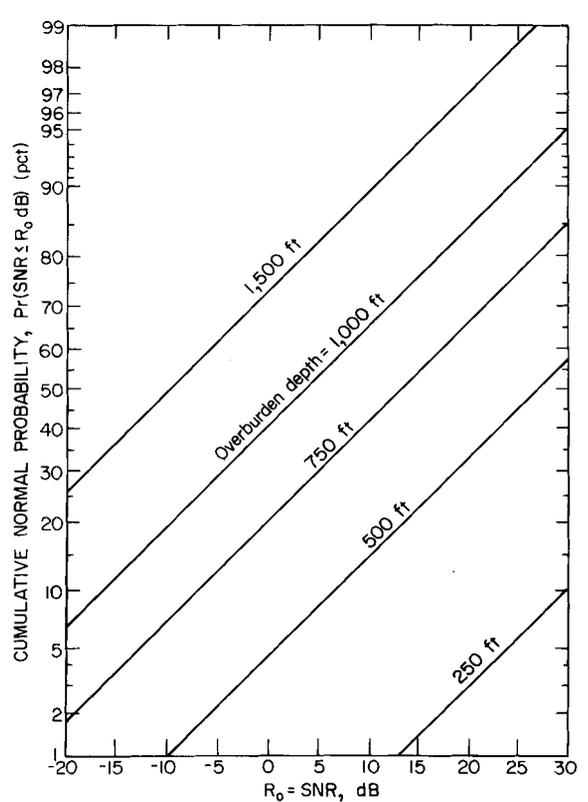


Fig. 14. Cumulative probability distribution of SNR expected above United States underground coal mines at 3030 Hz.

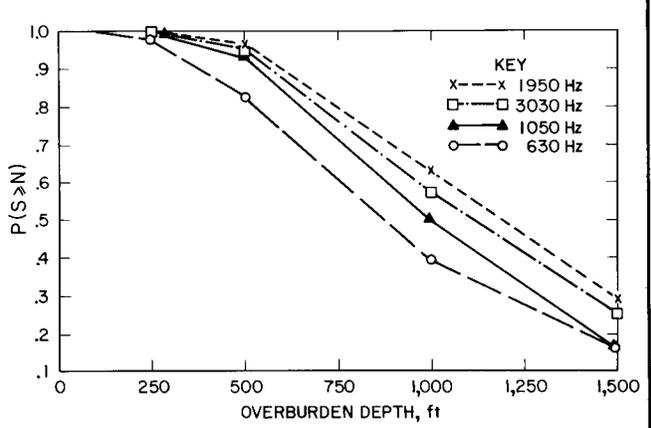


Fig. 15. Probability that mean rms signal is greater than or equal to rms noise for the General Instruments transmitter.

The GI transmitters have a fixed pulse duration of 100 ms and a repetition rate of once per second. The present receiver mixes the received signal with an internal oscillator to a higher frequency for purposes of narrowband filtering, and then remixes the filtered signal to present a listening signal of 978 Hz to the operator.

In the work by Ristenbatt [21], tests were performed to verify the signal detectability performance of the present system. Tests were made using nine observers and the actual transmitter and receiver. The signal from the transmitter was mixed with wideband white noise and entered into the receiver at input SNR's of 0, 3, and 6 dB. The acoustic output of the receiver was then connected to a headset worn by the observer. Each observer was exposed to a series of 100 trials at each input SNR. Each trial lasted for 15 s. After each 15-s test, the observer was asked to note each test during which a signal might have been presented on a four-point rating scale; for example:

- 0—Confident, signal absent;
- 1—Less confident, signal absent;
- 2—Less confident, signal present;
- 3—Confident, signal present.

These data were then used to determine the expected probability of detection (P_D) and probability of false alarm (P_{FA}) at the different SNR's. This testing provides the receiver operating characteristics (ROC) for the present receiver, and the results are shown in Fig. 16. The shaded area around SNR's of 0 and 6 dB shows the variability in the data obtained. The variability around the SNR = 3 dB curve is similar to that of the 0-dB curve but is not shown in the interest of retaining clarity in the figure. Therefore, for a particular input SNR and preassigned P_{FA} , it is possible to determine the expected P_D of the observer.

The practical effect of false alarms is increased delay due to added search time. Hence, false alarms are important not only for comparing different receivers but also for understanding the practical impact a receiver

may operate in a search-and-find mission. A reasonable operating point for the false alarms of this system would be $P_{FA} = 0.10$. For this P_{FA} , Fig. 16 can be used to obtain the expected P_D for the observer at different SNR's.

It is now possible to calculate the probability of detecting the trapped miner's signal based upon the ROC of the receiver. The probability of detection curve in Fig. 16 actually represents a conditional probability; that is, the likelihood that detection will occur given the presence of a fixed rms SNR. As a consequence, the chance of detecting a signal transmitted through the earth can be calculated according to

$$P(D \text{ and } R_k) = P(R_k) \times P(D|R_k) \quad (2)$$

where $P(D \text{ and } R_k)$ represents the probability of achieving an SNR of size R_k and also detecting the signal in the noise. $P(R_k)$ is the probability of the occurrence of an SNR of size R_k , and $P(D|R_k)$ is the conditional probability of detecting a signal given an SNR of size R_k .

Figure 16 gives $P(D|R_k)$, and Figs. 11-14 show the SNR probability distributions. The latter figures show that these probabilities depend on frequency and depth. Using additional subscripts to account for these parameters, the probability of achieving an SNR of size R_k and detecting the signal transmitted from a depth j at frequency i is

$$P_{ijk}(D \text{ and } R_k) = P_{ij}(R_k) \times P(D|R_k) \quad (3)$$

However, the primary result is the expected probability of detecting a signal transmitted at a specified depth and

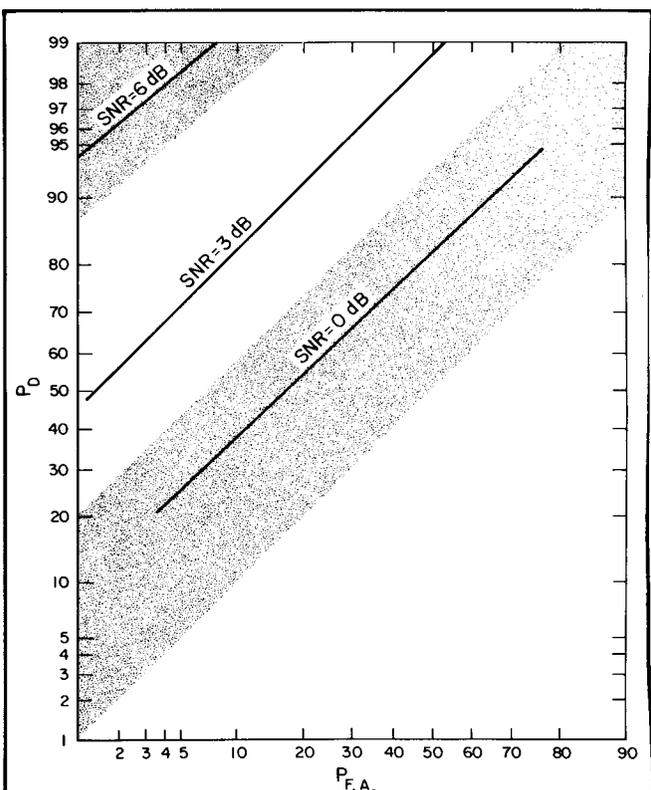


Fig. 16. Receiver operating characteristic curve for trapped-miner receiver.

a known frequency summed over all possible R_k 's. This is given as

$$P_{ij}(D) = \sum_{R_k} P_{ijk}. \quad (4)$$

Using this formulation, Fig. 17 shows the expected probability of signal detection as a function of depth for the different frequencies. From Fig. 17, it can be seen that 1950 Hz is the frequency most likely to be detected. For this frequency, the expected probability of detecting a miner's signal from a depth of 1000 ft is 54%, and from 500 ft is 95%. These depths exceed the actual depths of 90 and 50%, respectively, of United States coal mines.

Performance Improvement

It is informative to observe the amount of increase in probability of signal detection for increases in SNR of the trapped-miner signal on the surface of the mine. Insight is provided by way of Fig. 18, where the detection probabilities are shown for each frequency at a depth of 1000 ft as the SNR is improved. To obtain a detection probability of 90% at 1000 ft, an SNR improvement of approximately 18 dB would be needed for the 1950-Hz case. A rough estimate shows that, for all frequencies, the probability of detection increases approximately 2% at 1000 ft for every dB improvement in SNR.

Various areas of investigation may lead to improved performance. The obvious first choice is to increase the strength of the signal source. However, inherent constraints due to intrinsic safety considerations would limit any gain by this technique to only a few dB. Correlation techniques could be used, employing an array of receiving antennas to improve detectability. This is the objective of a current project [22]. Incoherent integration of the present signal has been suggested by Ristenbatt [23] and is the technique proposed by General Instrument Corp. [24] in an adaptation to the present receiver.

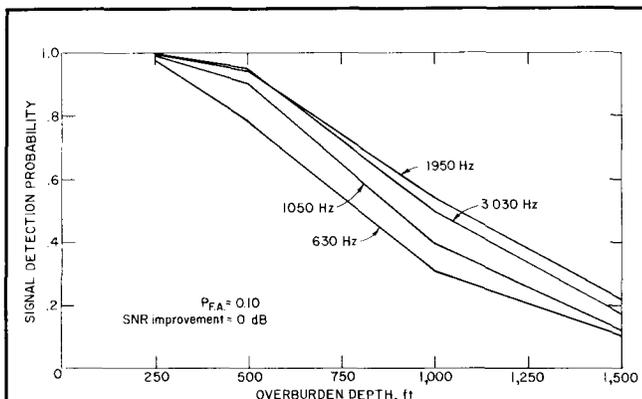


Fig. 17. Predicted probability of signal detection vs. overburden depth by frequency for the GI transmitter as found by the ROC method.

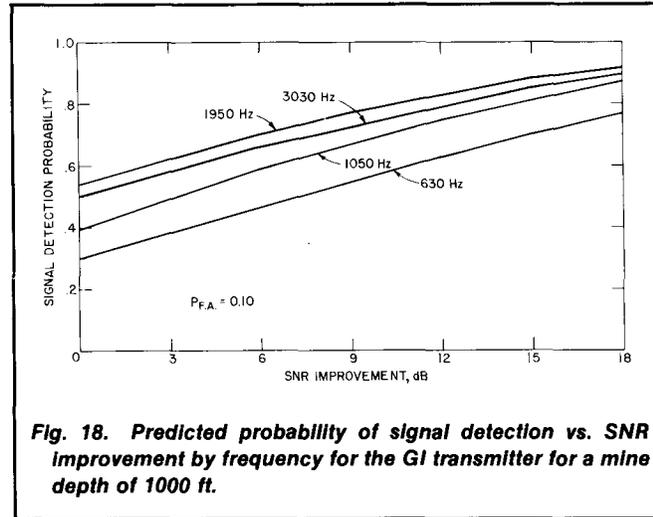


Fig. 18. Predicted probability of signal detection vs. SNR improvement by frequency for the GI transmitter for a mine depth of 1000 ft.

Noise cancellation through correlation techniques, involving the noise at the receiving antenna and a distant antenna outside the signal's range, is an area for future study.

The parameters of the signal that affect an observer's ability to detect a pulsed continuous wave signal in noise could be studied to improve detectability. However, these studies must also be conscious of the efficient use of the power of the transmitter battery and of schemes used in search procedures.

Possibly the most promising venture to improve signal detectability is a project under investigation by Develco [25]. Here, the underground transmitter is similar to the one discussed in this report, though the signal is not pulsed, but is transmitted continuously. The surface receiver uses a microcomputer which coherently integrates the transmitted signal. The principal idea is to exchange time for signal detectability. The receiver continually monitors the signal, and if it exists and is within the detectable range of the receiver, it will eventually be detected. This system was originally designed to detect signals transmitted from a depth of 3000 ft and should be able to easily detect signals at a depth of 1000 ft in a few minutes of operation. Location is performed by vector calculation of the signal at a number of receiving-antenna locations.

Summary

This paper has discussed the results of an extensive field-testing program to evaluate the performance of the EM trapped-miner transmitter. Analysis of the data obtained has provided a probabilistic framework from which signal detection can be predicted. It was found that for a 10% false alarm rate the probability of detection at 1000 and 500 ft is 54 and 95%, respectively. This information is vital for the future formulation and promulgation of new regulations written for the use of the EM system. Studies are underway to improve the detection capability by providing signal-processing capability to the receiver.

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