Volume III

Monitoring, Locating and Communication System for Normal Mine Operation and Post-Disaster Rescue Operations

J. W. Allen
R. F. Linfield
The Westinghouse Electric Corporation
Friendship International Airport
Baltimore, Maryland

May, 1973

Final report covering the period
July, 1972 to April, 1973

Prepared for

The Bureau of Mines
Under Contract H0220073

Volume III

Monitoring, Locating and Communication System for Normal Mine Operation and Post-Disaster Rescue Operations

J. W. Allen
R. F. Linfield
The Westinghouse Electric Corporation
Friendship International Airport
Baltimore, Maryland

May, 1973

Final report covering the period
July, 1972 to April, 1973

Prepared for

The Bureau of Mines
Under Contract H0220073

Disclaimer

The views and conclusions contained in this report are those of the authors and should not be interpreted as necessarily representing the official policies of the Interior Department, Bureau of Mines, or the U. S. Government.

PREFACE

This report is the third in a series of four volumes documenting work done by the Westinghouse Electric Corporation for the Bureau of Mines under Contract H0220073 between July, 1972 and April, 1973.

The work described herein is the result of efforts to develop and test a prototype model of a quasi-hardened subsurface communication system. Conceptually, the system provides a one way digital information link interface between multiple subsurface terminals and a single surface station. Two way voice communication is also provided. The system is capable of both a direct through-the-earth mode of operation or alternate linking through existing mine telephone hardware circuits.

Vol III

MONITORING, LOCATING AND COMMUNICATIONS SYSTEM FOR NORMAL MINE OPERATING AND POST DISASTER OPERATIONS

CONTENTS

CONTENTS

1.0 INTRODUCTION

This report reviews the work performed on Task III of BuMines Contract H0220073 to develop an engineering model of a surface and subsurface communications system for normal mine operations and for post disaster rescue operations. The system concept provides for one-way transmission of digital information between a number of identifiable subsurface terminals or subcenters and a single surface station. It also provides 2-way voice communications between the subcenters and the surface station. The basic communications link is electromagnetic signaling through-the-earth, but the system is also capable of using mine phone lines as an alternate link.

Engineering models of three subcenters and one surface terminal (see Figure 1-1) have been fabricated in order to demonstrate the system's performance. The system concept, however, permits up to 20 subcenters to be incorporated if desired. Additional subcenters are also feasible for large mines if they can be deployed in the mine to operate on a noninterfering basis.

1.1 Program Objectives

The overall objective of this task is to develop a quasi-hardened, fixed location, in-mine communications subcenter that can be used in normal mine operations and be ready for use in post disaster rescue operations. Information from a large number of subcenters is to be gathered together in a single display identifying board with an intercom. The system must use the earth-rock overburden as the communications media and the design concept should consider use of existing mine phone lines and means of changing the signal path from phone line to through-the-earth or energizing both simultaneously.

Hardware design should consider the following features:

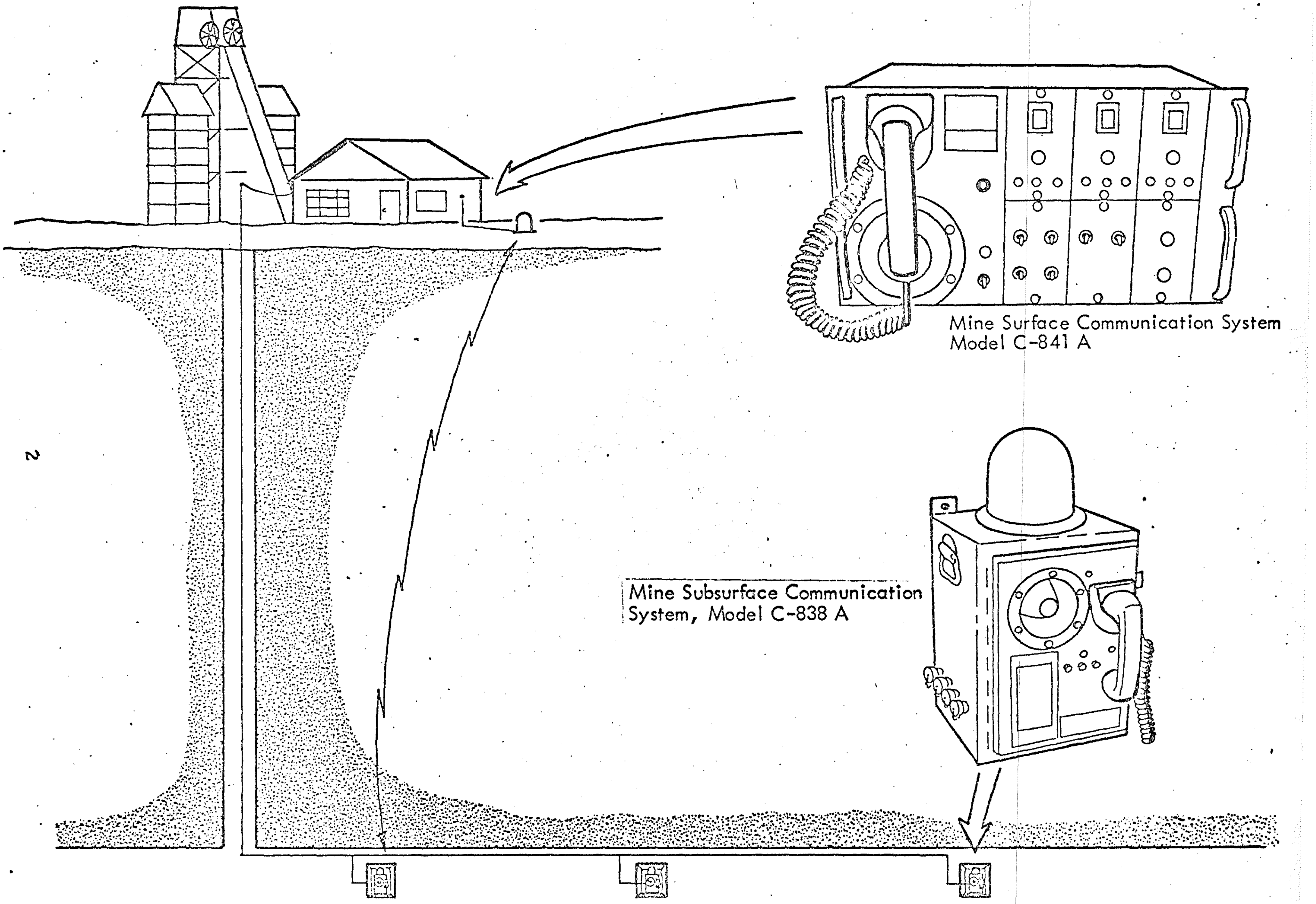


Figure 1-1 Mine Communication and Monitoring System

Subsurface Subsystem:

a. Operation from a 440 V AC float-charge battery.

b. Sensor signaling of three (3) ranges - below normal, normal, and alarm. Continuous operation.

c. Small speaker used as a microphone/speaker.

d. Basic receiver element similar to receiver developed under Contract H0101262.

e. Amplifier-transmitter similar to amplifier developed as uplink transmitter under Contract H0101262 [1].

f. Uplink-signaling similar to that utilized on uplink transmitter developed on Contract H0101262.

g. Packaging and mounting permits station to endure shock wave and flame front to a limit twice that of which a human being could endure (i.e., 10 PSI, half second pressure impulse, 2500° Kelvin).

h. Uplink voice is minimum bandwidth that permits intelligible communications.

i. Voice or uplink signaling may interrupt monitoring.

Surface Subsystem

a. Data monitored shall be accumulated and compiled at one surface communications center.

b. Problems encountered when mine is situated under a developed community/undeveloped community.

c. Alarm signal is audible and visible.

d. Alarm light identifies station reporting alarm.

e. Downlink voice transmitter similar to unit developed under Contract No. H0101262.

f. Uplink signal monitor similar to unit developed under Contract H0101262.

A demonstration system consisting of three subcenters and one surface station was to be designed, fabricated, tested, and delivered to Bruceton, Pennsylvania for demonstration at the U.S. Experimental Mine.

1.2 Approach Pursued

The work described here was performed at the Westinghouse Georesearch Laboratories in Boulder, Colorado. System concepts were based on previous experience in developing through-the-earth communication systems for mine rescue operations (Contract H0101262) and subsequent tests and evaluations of these systems (Contract H0210063).

In general these systems operate at lower frequencies ($<$ 10 kHz) because the attenuation through the earth increases with frequency. However, the background noise and interference from mine equipment becomes troublesome at the lower frequencies, particularly for wideband systems such as voice transmissions. For voice downlink systems the most important component of the noise is that generated in the mine itself. Atmospheric noise is rarely of any consequence because it attenuates as the signal propagates through the earth.

Atmospheric noise can limit the performance of narrowband data uplinks if these links are operated at frequencies between the continuous wave type of interference caused by power line harmonics.

The initial design effort was directed toward determination of the optimum signaling frequency, antenna configuration, and transmitter power requirements. These parameters are affected by the conductivity of the overburden, the transmission path length, and the noise. The worst-case path was assumed to be 1000 feet through the earth, with a conductivity of 10^{-2} mhos/meter. The noise model assumed was based on surface and subsurface measurements of noise obtained at various mines.

The frequency, antenna, power, and bandwidth selection processes also must consider certain operational aspects and deployment configurations. For example, when a large number of subcenters are to be installed in a single mine the data monitoring transmissions must be identifiable and must not interfere with each other.

Equipment designed to operate near the working face in a coal mine must also meet certain permissibility standards. This involves either the use of explosion proof packaging and connectors or limiting power levels so the unit is intrinsically safe.

Cost, size, and weight of subsurface equipment is also a factor since several units may be installed in a mine and they may be moved as the mine working face advances.

1.3 Report Synopsis

This report summarizes the work accomplished on this task.

Section II discusses the basic design criteria used to establish the overall system concept. At the completion of this phase of work a design review was held with the Bureau of Mines to finalize the total system concept and to consider potential packaging techniques. Circuitry was then developed, engineering models were fabricated and their performance verified by laboratory testing.

Section III describes the system as fabricated in terms of its five basic operating modes: 1) Two-way phone line with paging capabilities, 2) voice downlink, 3) voice uplink, 4) coded beacon uplink, and 5) condition monitoring. Block diagrams are used to indicate the various operational functions. A summary of the performance characteristics is included.

Section IV covers the installation procedures and operational aspects from a user's standpoint. The functions of the various switches, control knobs, and display lights are defined for the surface and subsurface terminals.

One surface station and three subsurface stations were delivered and installed in the U.S. Bureau of Mines experimental mine in Bruceton, Pennsylvania.

Section V describes the installation and discusses the results of the demonstration tests conducted at this mine.

Section VI gives a performance evaluation of the system.

Our conclusions and recommendations are given in Section VII. It is concluded that the system concepts and demonstration hardware developed on this program fulfill the basic objectives of the program and incorporate nearly all the design objectives specified by the Bureau of Mines. As in any development program of this type we recognize, in retrospect, several additions and modifications which could enhance system usefulness to the mine industry, not only in terms of performance, but also operation and maintenance. It is recommended that a prototype system be designed for use in a working mine. The prototype should incorporate the desirable features of the engineering model. The engineering model presently installed at the USBM Experimental Mine in Bruceton should be up-dated and used for demonstrating the system concept to the mine industry.

2.0 DESIGN CONSIDERATIONS

Electromagnetic through-the-earth systems have been fabricated previously for use during mine emergencies [1, 2]. Two basic concepts have been demonstrated: 1) a voice downlink system which transmits direct audio signals from the surface to portable manpack receivers carried by the miner and 2) a beacon uplink system capable of transmitting six interrupted CW coded messages from a fixed mine location to a surface receiver. Both systems were designed to operate in the frequency band between 500 and 3000 Hz. The voice system utilized the total bandwidth to obtain intelligible signals. The beacon system required a very narrow bandwidth (typically 50 Hz) and several beacons could be operated simultaneously using different assigned frequencies between 2 and 3 kHz.

The test and evaluation of these systems provides the basis for developing a design concept for the links required on the present program. In the following subsections we define the mine noise environment and the expected signal levels and thereby determine the frequency, power, and antenna requirements for the desired links.

2.1 The Mine Noise Environment

The performance of any communication system is ultimately limited by noise which perturbs the received signal and causes errors in digital data, reduces reliability of analog information and degrades the intelligibility of voice transmissions. This noise is an additive disturbance, either natural or man-made, whose effects can be reduced by increasing the signal power, by proper signal design, and by noise suppression circuitry.

Low frequency electromagnetic (EM) systems used for through-the-earth communications in mines must contend with three basic types of noise, thermal, atmospheric, and man-made. Thermal noise generated by resistance in the antenna and front-end circuits determines the receiver's ultimate sensitivity. Atmospheric noise is a natural occurrence caused by lightning strokes which radiate electromagnetic impulses that propagate great distances. Man-made noise is probably the worst offender in mines. It is usually caused by the mine equipment itself and can severely limit the performance of receivers operating near the working face, near trolleys, and near d.c. rectifiers used in mines.

The three types of noise, thermal, atmospheric, and man-made, all have different characteristics. The average power of thermal noise is usually fairly constant throughout the lower frequency bands, whereas atmospheric and man-made noise may vary considerably with frequency. The probability density distribution of thermal noise is typically Gaussian. Atmospheric noise on the other hand contains intermittent impulses superimposed on a Gaussian noise background. The characteristics of man-made mine noise vary considerably, but the observed spectrum usually contains several discrete frequency components which vary in amplitude. This continuous wave (CW) interference generally occurs at 60 Hz and various harmonics of 60 Hz extending to several kilohertz.

Thermal noise can limit the sensitivity of both surface and subsurface receivers unless the system designer selects a receiver antenna and front-end configuration so that acceptable signal-to-noise ratios are achieved.

The performance of narrowband systems with receivers on the surface may sometimes be limited by atmospheric noise. A considerable reduction in the effects of atmospheric noise impulses on the narrowband circuits can be achieved by clipping noise peaks in wideband circuits preceding the band limiting portions of the receiver. This clipping process, however, is ineffective against CW interference which may capture the receiver and thereby actually degrade the performance.

The 60 Hz harmonic noise effects may be reduced by judicious choice of frequency, by narrowband rejection filters, and by using sophisticated rejection circuits which reduce the harmonic content.

Figure 2-1 indicates the vertical magnetic field strength of atmospheric

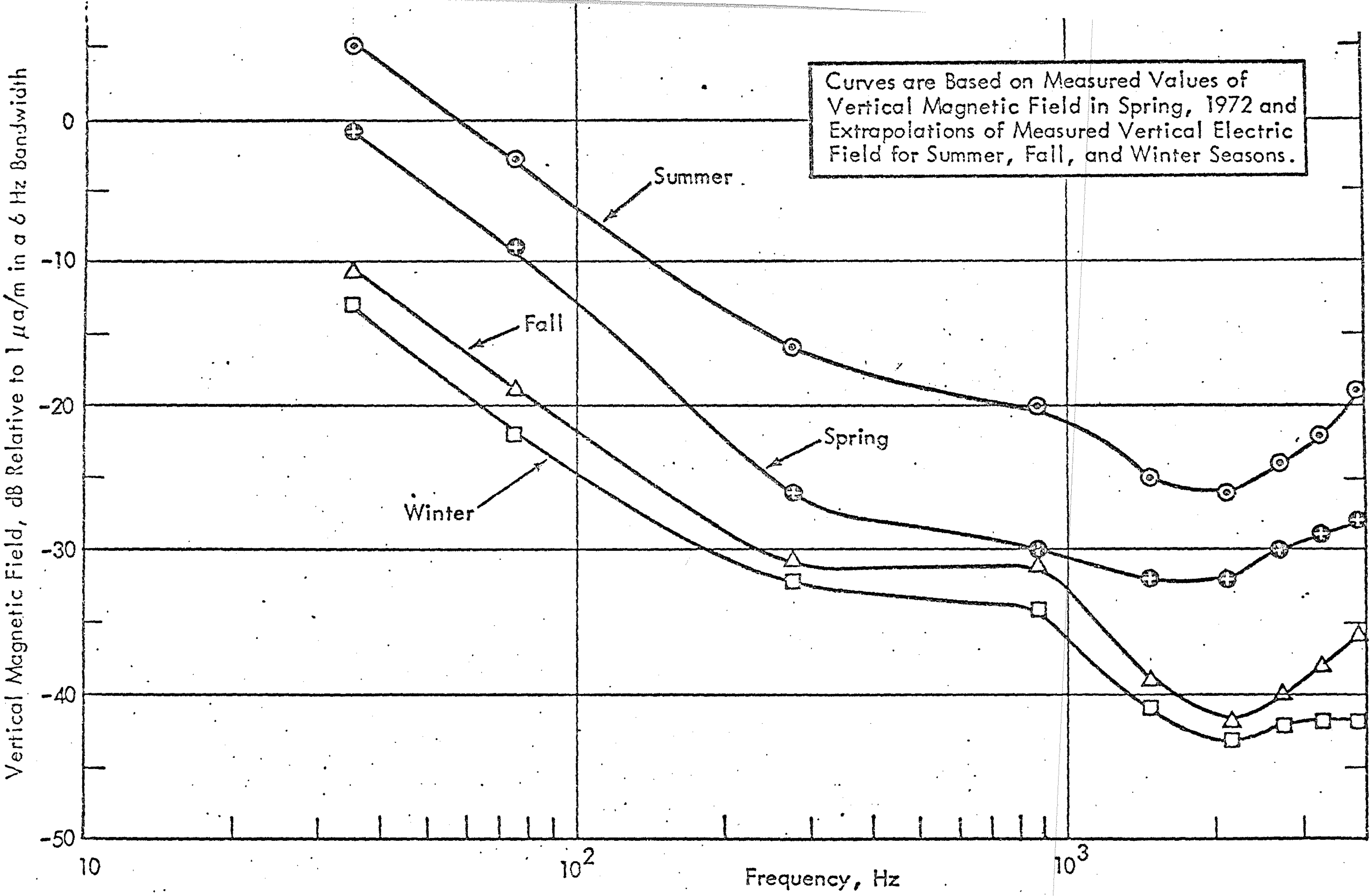


Figure 2-1 Seasonal Model for Median Levels of Vertical Magnetic Field Noise at Boulder, Colorado

noise in Boulder, Colorado in the Spring of 1972 and extrapolated curves for other seasons of the year. Figure 2-2 shows how the atmospheric noise below the surface changes with depth.

Figure 2-3 shows the surface and subsurface 60 Hz harmonic noise observed at one location, and Figure 2-4 is one example of the total noise spectra measured on the surface near the entrance to an operating mine.*

These noise spectra typify the noise environment in which electromagnetic through-the-earth systems must operate. Actually both the atmospheric noise and the man-made noise may vary considerably from the examples given, depending on location and mining equipment used. The examples shown, however, are representative of the limited amount of data available and will be used in the following section as models for signal design purposes.

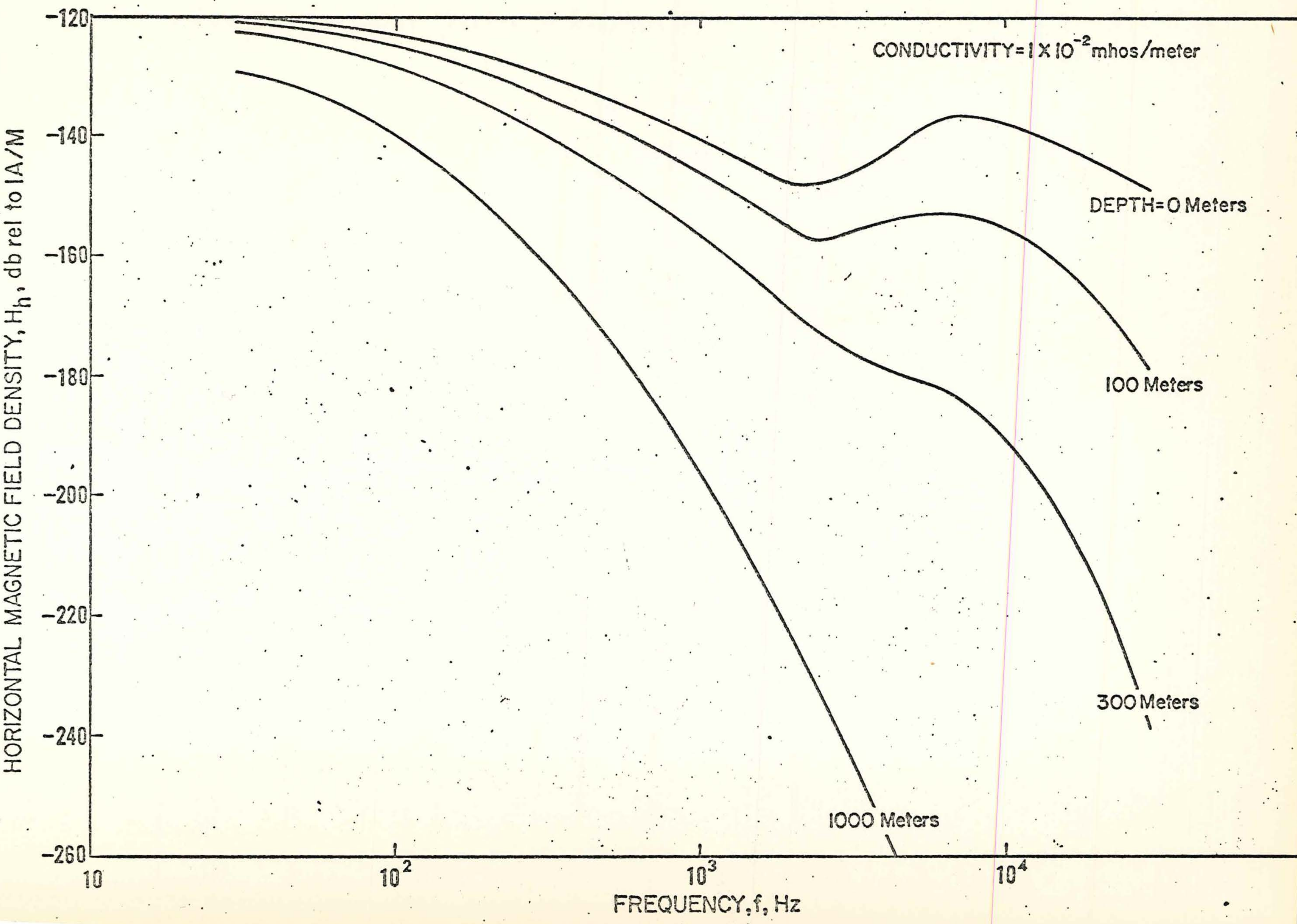
2.2 Signal Level Available

We have shown some samples of the noise environment in which EM mine communications systems must operate. The next step is to select design parameters so that the signal available at the receiver equals or exceeds that required to achieve a reliable transfer of information in a given noise environment. For EM through-the-earth systems the available signal is determined by the transmitter power, antenna configuration, path length, and conductivity of the earth. The required signal is determined by intelligibility of mine transmissions and reliability of data transmissions. It is a function of the modulation, detection, noise suppression, and signal processing techniques employed.

Previous measurements at eight different test mines ranging in depth from 130 to 1500 feet and with effective conductivities from 4.5×10^{-3} to 1.9×10^{-1} mhos/meter showed that it is possible to predict signal field

---

* The surface noise spectra (Figure 2-4) was recorded and analyzed by the National Bureau of Standards. Frequency dependent corrections and calibrations were applied by A. D. Little, Inc. as directed by NBS.



Noise Spectra with Depth

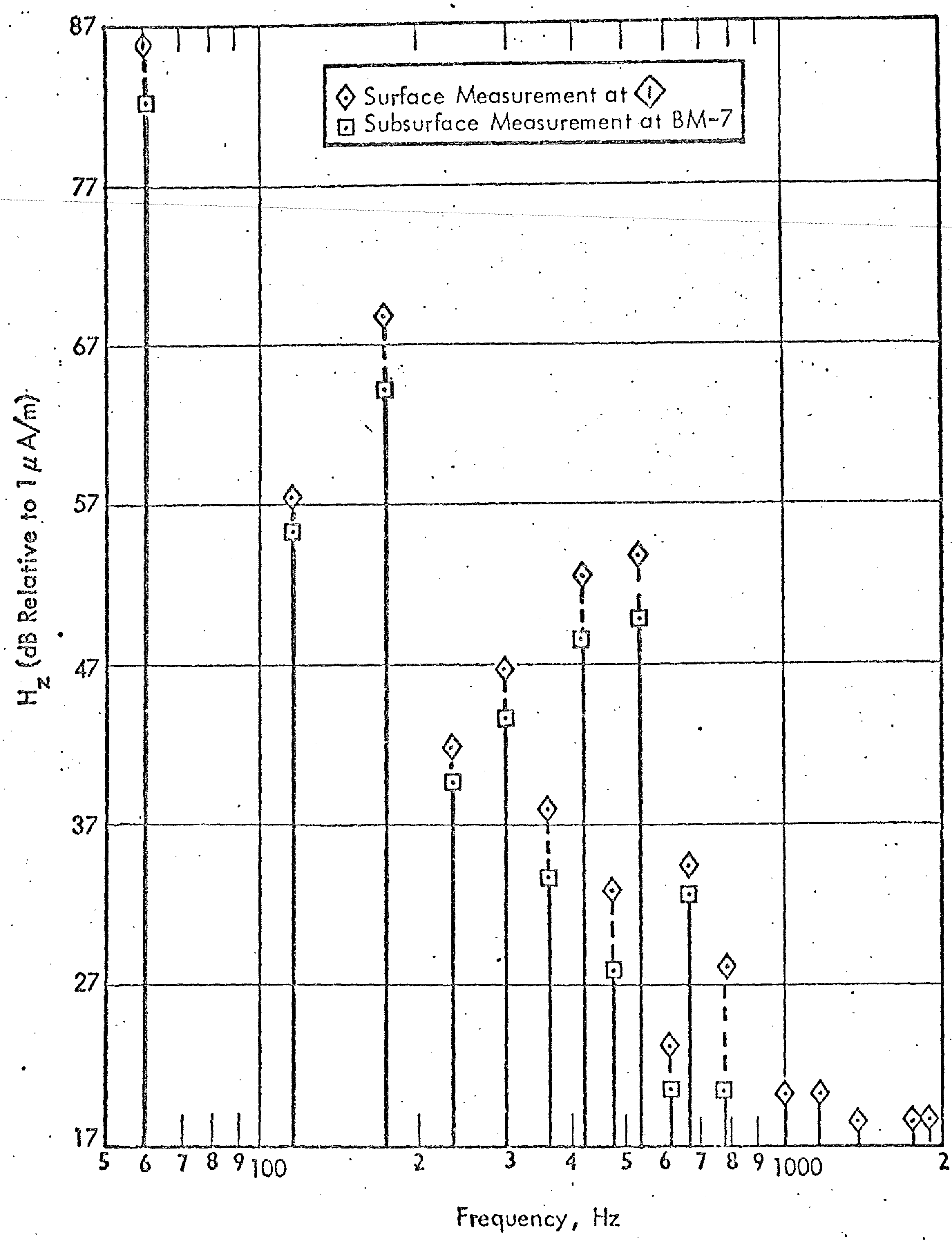


Figure 2-3 Simultaneous Surface and Subsurface EM Noise Spectra, USBM Experimental Mine Bruceton, Pa., June 1972

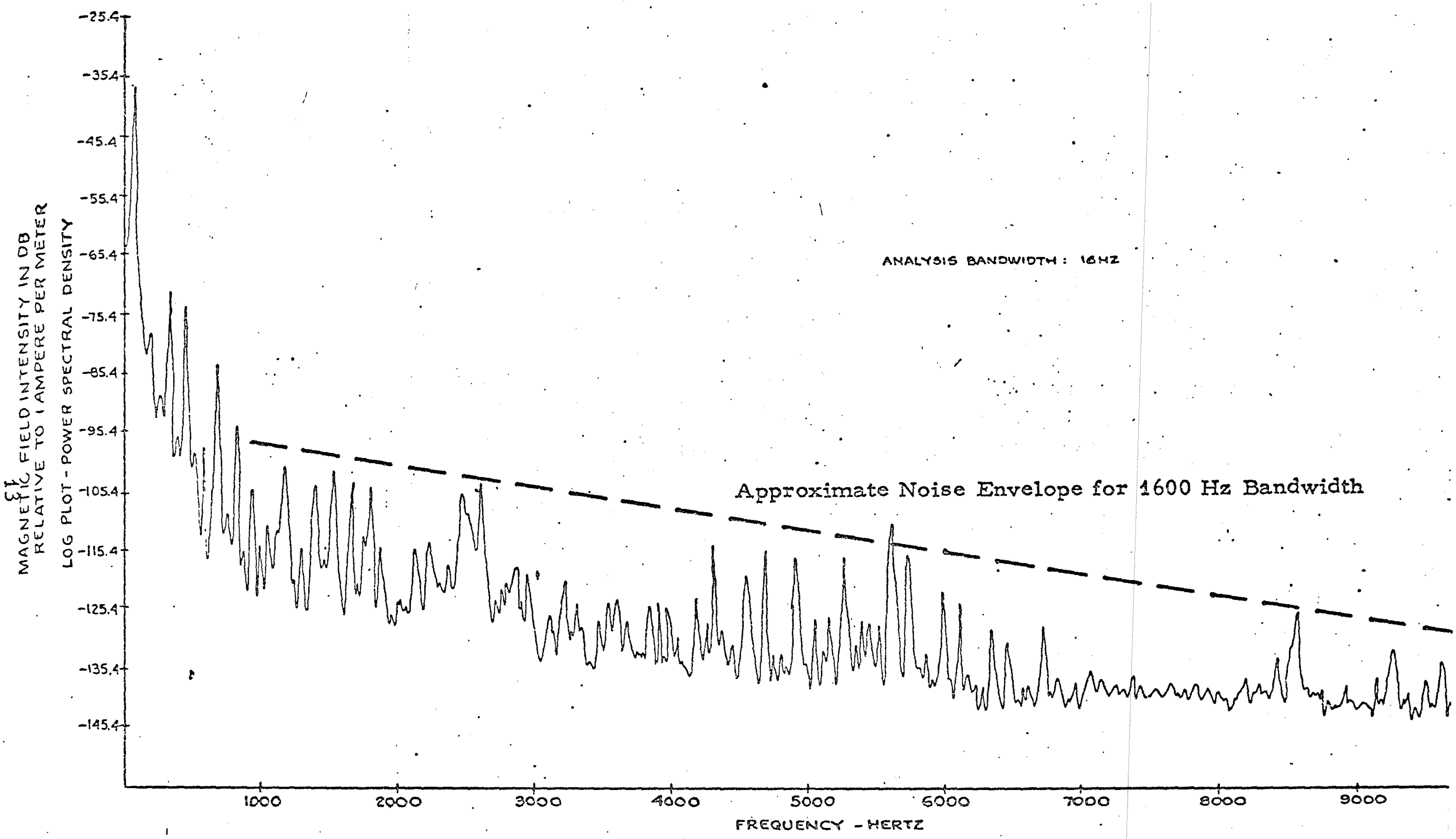


Figure 2-4 RUN (5) LOOP AXIS VERTICAL POWER LINE ~ 150 FEET AWAY (ELECTRIC ARC WELDER ~ 200 FEET) (IN BUILDING) NEAR #3 ENTRANCE TO MID CONTINENT MINE

strengths usually to within 1 or 2 dB of measured values if the earth's conductivity is known. Metallic structures near a receive antenna may enhance or degrade the signal depending on the relative locations.

The field strength prediction process varies depending upon the antenna configuration employed. Figure 2-6 shows the attenuation factor versus depth to skin depth ratio for three commonly used antenna configurations, coaxial loop, coplanar loop, and horizontal wire [1]. The skin depth, δ, is a function of frequency and a weighted average conductivity, σ, as given in Figure 2-5.

Using these figures it is possible to predict the signal fields available for given antenna configurations and path characteristics. This has been done in Figure 2-7, showing coaxial loop antennas and a mine depth of 1000 feet and conductivity of 0.01 mhos per meter. The field strength, H, is plotted as a function of frequency and parametric in INA where I is the antenna current, N the number of turns, and A the area enclosed by the loop. On the same plot the atmospheric and man-made noise levels from Figures 2-1 and 2-4 are indicated. The man-made noise model is estimated from an average curve drawn on Figure 2-4.

Figure 2-8 is a similar plot for a surface to a subsurface link where a long (compared to mine depth) horizontal wire is used for the surface antenna. The signal field intensity calculated using Figures 2-5 and 2-6 is plotted parametric in antenna current in amperes for 1000' depth and 0.01 mhos/meter conductivity. The subsurface noise spectra is that given in Figure 2-3 for subsurface noise measurements at the Experimental Mine in Bruceton, Pennsylvania.

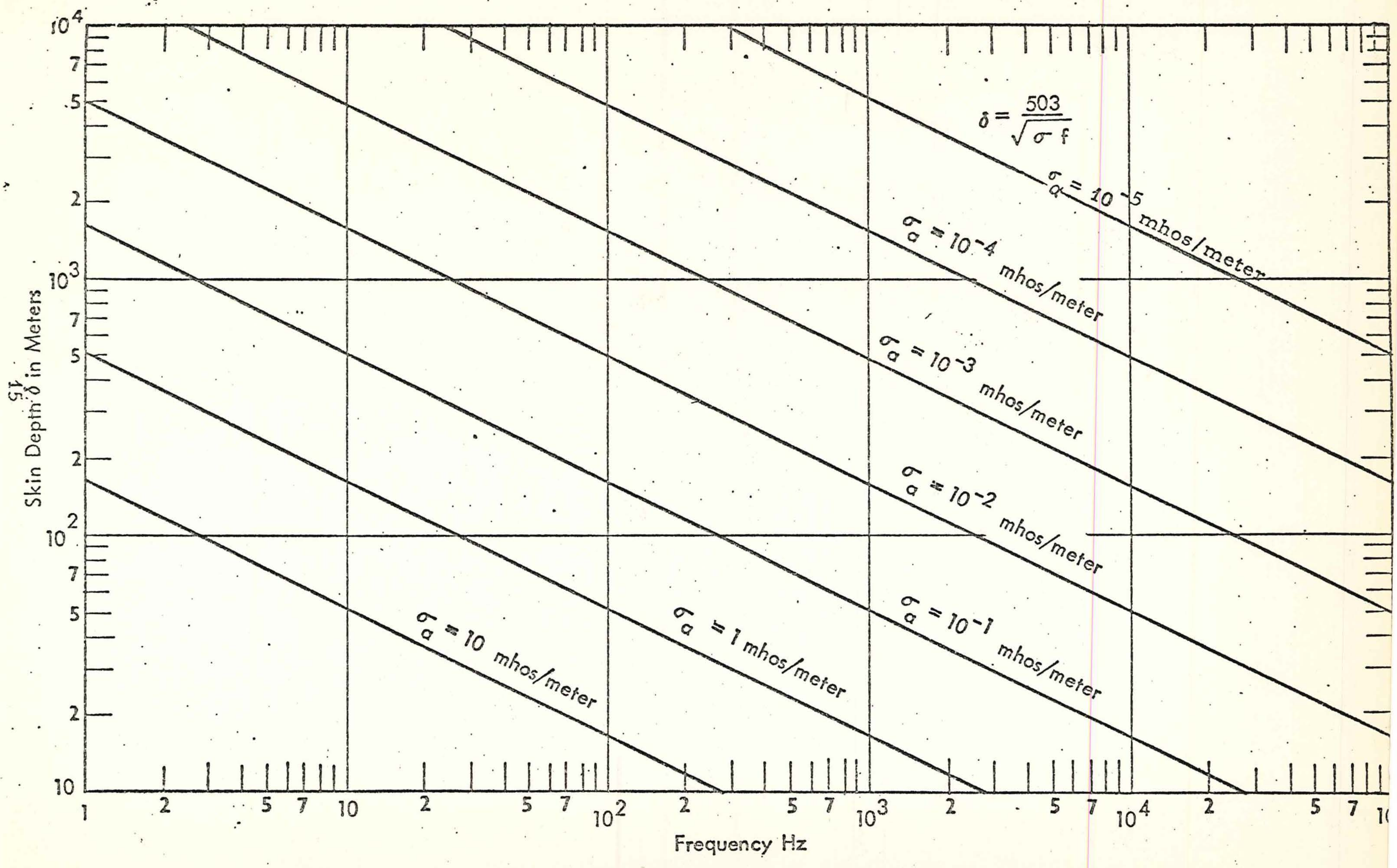


Figure 2-5 Skin Depth as a Function of Frequency and Conductivity

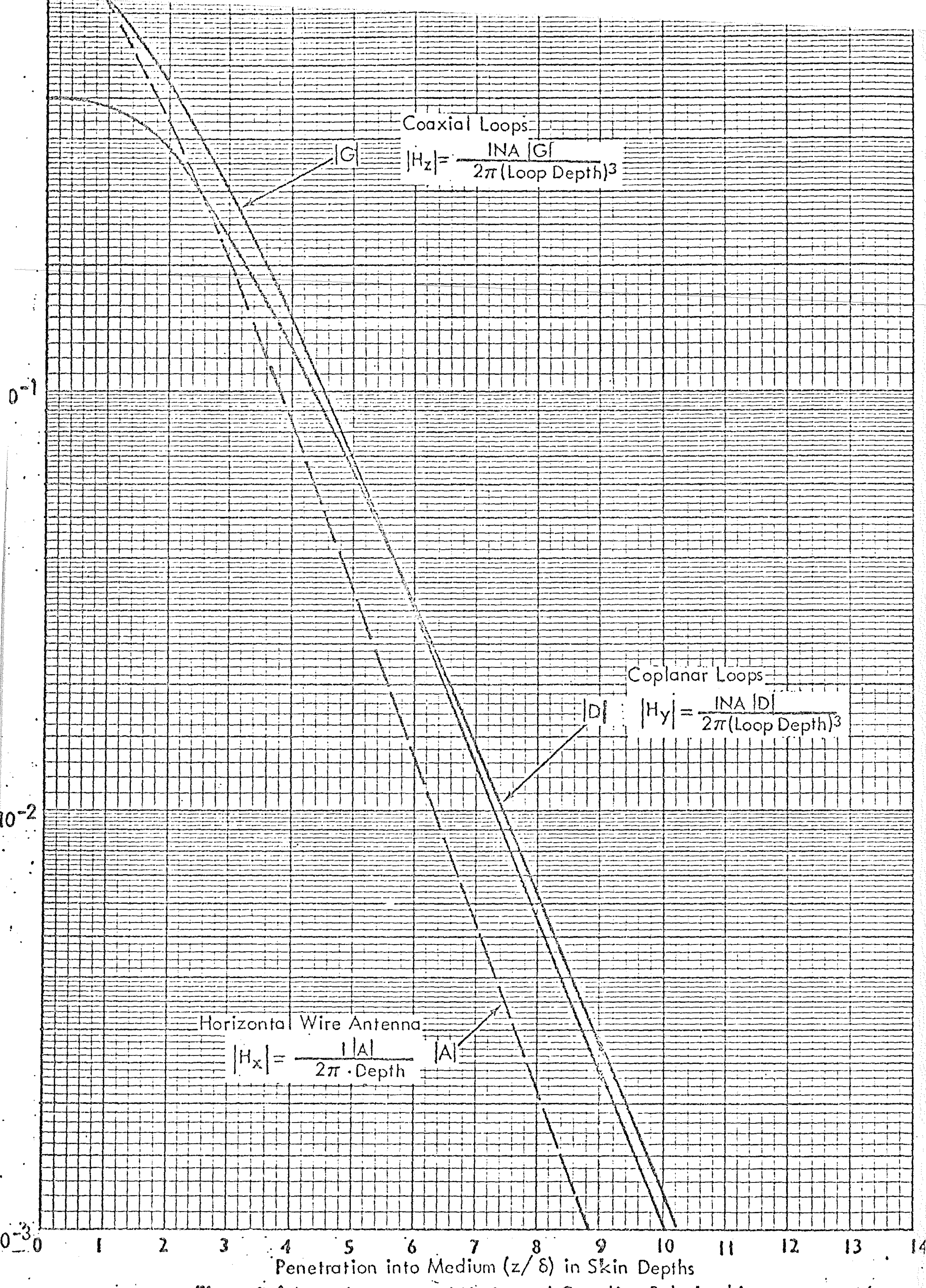


Figure 2.6 Loop Antenna and Horizontal Coupling Relationships

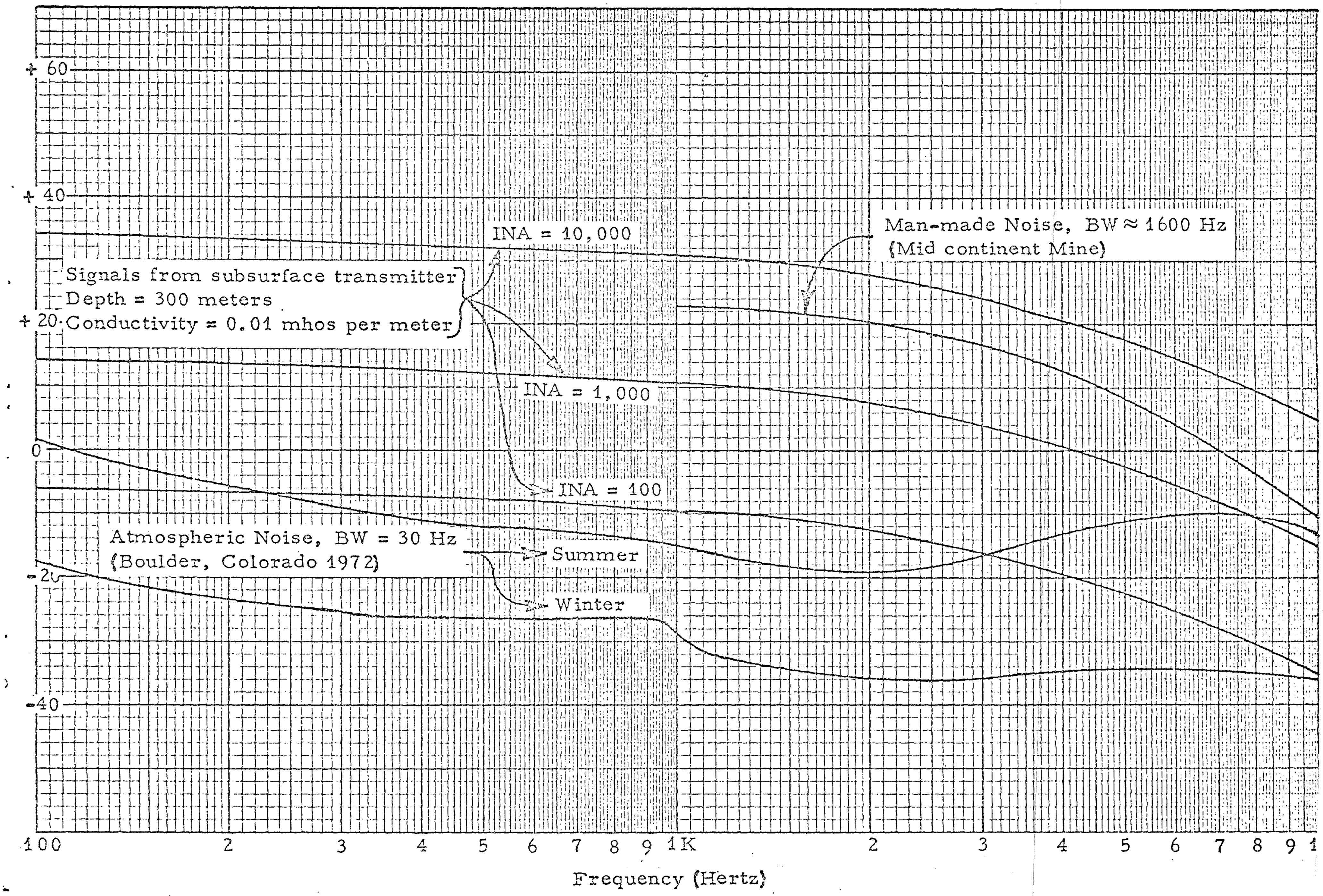


Figure 2-7. Estimated Surface Noise and Signal Strengths for Mine Communication System.

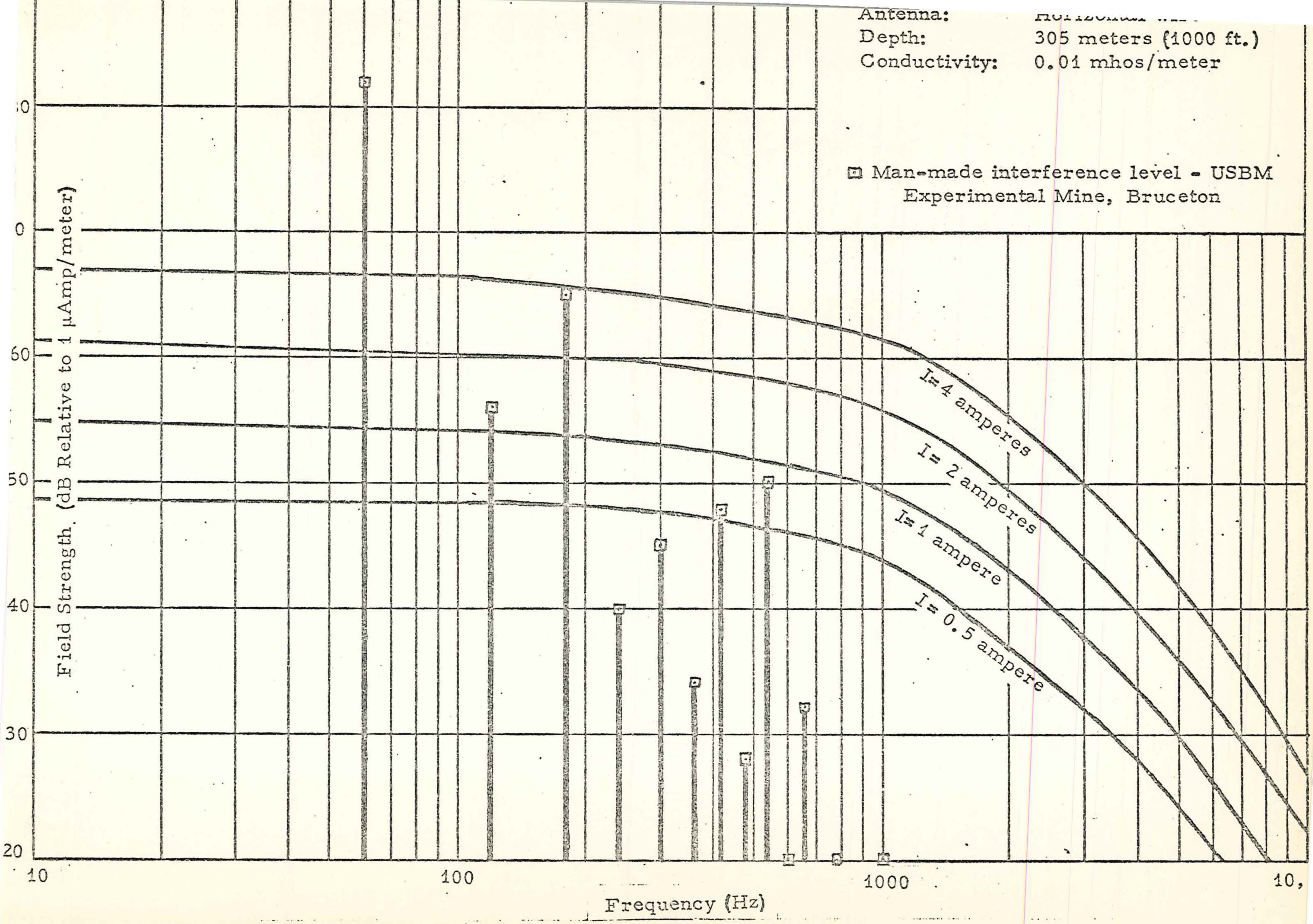


Figure 2-8. Signal and Noise for Mine Subsurface Communication System

2.3 Signal-to-Noise Ratio Required for Voice Systems

A basic limitation on the intelligibility of voice transmission systems is the ratio of signal-to-noise power available at the receiver. Since noise power is proportional to bandwidth, the reception bandwidth must be minimized. For direct audio systems the baseband, B_a, is the transmission and reception bandwidth. The ratio S/N_a, where S is the signal power and N_a the noise power in the base bandwidth B_a, is a factor against which the intelligibility of a voice communication link can be judged. The required S/N_a is the minimum signal-to-noise ratio out of receiver which gives acceptable intelligibility. The S/N_a available at the receiver output must equal or exceed the S/N_a required in order for the link to be usable.

Voice signals occupy a spectrum between 50 and 7500 Hz, however most of the information content occurs at the lower frequencies between 200 and 3000 Hz. Reducing the bandwidth reduces the noise, but ultimately distorts the signal to the point where intelligibility is lost. Conventional voice channels operating with a 2.5 kHz bandwidth in a Gaussian noise environment require that the signal power be about 16 times the noise power, i.e., $S/N_a \approx 12$ dB. Measurements on a direct audio system in one type of mine noise [2] indicate that intelligible reception can be achieved using a band between 600 and 2000 Hz. These tests indicated that the intelligibility falls off sharply for S/N_a between 0 and - 10 dB.

It is useful to show the input power requirements in different types of systems which will produce the required S/N_a. For comparison purposes it is assumed that the noise is Gaussian and N_o is the noise power spectral density in the RF bandwidth. B_a is the base bandwidth of the voice modulation signal. In the following paragraphs values are obtained for the received input power required (P_r), assuming $S/N_a = 16$.

Direct Audio

In this system no carrier modulation is required, the signal power equals the received power and the transmission bandwidth equals the signal bandwidth.

$$S/N_a = \frac{P_r}{N_o B_a} .$$

Therefore,

$$P_r = 16\, N_o B_a .$$

<u>Amplitude Modulated-Double Sideband with Envelope Detector*</u>

Here part of the received power includes an unmodulated carrier. The total received power is given by

$$P_r = P_c + 2\left(\frac{m^2}{2}\right) P_c = \left(1 + \frac{m^2}{2}\right) P_c$$

where m is the modulation index and P_c is the received unmodulated carrier power.

For a base bandwidth of B_a the rf bandwidth B_{rf} is $2B_a$, and

$$S/N_{B_a} = \frac{m^2 P_r}{2\left(1 + \frac{m^2}{2}\right) B_a N_o} .$$

By clipping the peaks of the modulating signal at the transmitter the average power can be increased for a peak output limited amplifier. It has been shown that speech can be clipped to one quarter of its amplitude with little effect on intelligibility. A value of average m = 0.5 (peak to average ratio

* The basic derivatives given here and on other systems which follow are obtained from References [3] and [4].

of 6 dB) should still permit acceptable voice communication. Using this value of m = 0.5 and $S/N_a = 16$, then

$$P_r = 144\ N_o B_a$$

for the AM-DSB system.

Amplitude Modulation - Double Sideband - Suppressed Carrier with Coherent Detection

In this system all the received power is signal power contained in two sidebands and these side bands add coherently upon detection, so that the detected output signal power is twice the input signal power. The noise output, however, is the same as the input noise and $B_{rf} = 2B_a$. The output signal-to-noise ratio is

$$S/N_a = \frac{P_r}{N_o B_a} ,$$

and using the previous values for S/N_a

$$P_r = 16\ N_o B_a \quad .$$

Amplitude Modulation - Single Sideband with Coherent Detection

Here we get the same result as above except it should be noted that $B_{rf} = B_a$ since all the received power is contained in one sideband. Although the output noise is half that obtained above the sidebands no longer overlap and the output signal power is 3 dB less. Therefore again,

$$P_r = 16\ N_o B_a \quad .$$

Frequency Modulation

For FM modulation it can be shown that

$$S/N_a = \frac{3}{2} m^2_f \frac{P_r}{N_o B_a} ,$$

The FM modulation index $m_f = \dfrac{f_d}{B_a}$.

For $S/N_a = 16$, as before, this gives for wideband FM ($m_f = 10$),

$$P_r = \frac{16 \times 2}{3 \times 100} N_o B_a \approx 0.1 N_o B_a$$

and for narrowband FM ($m_f = 0.5$),

$$P_r = \frac{16 \times 2}{3 \times 0.25} N_o B_a \approx 43 N_o B_a .$$

These results are summarized in Table 2-1.

TABLE 2-1

System	Received Power Required	Bandwidth Requirements
AM - Direct Audio	$16 N_o B_a$	B_a
AM - DSB	$144 N_o B_a$	$2 B_a$ ($m = 0.5$)
AM - DSB - SC	$16 N_o B_a$	$2 B_a$
AM - SSB	$16 N_o B_a$	B_a
WBFM	$0.1 N_o B_a$	$2 m_f B_a$ ($m_f = 10$)
NBFM	$43 N_o B_a$	$2 B_a$ ($m = 0.5$)

It must be noted that the results shown assume that the required output $S/N_a = 16$ and the noise environment is Gaussian with a constant noise spectral density, N_o. In other types of noise the results may be quite different because the S/N_a required is different and because some modulation/ demodulation schemes are more susceptible to certain types of noise. As noted previously, laboratory tests on voice intelligibility showed $S/N_a = 1$ where N_a was mine noise containing in-band harmonics of 60 Hz. There is very little data on the performance of the other types of systems in non-Gaussian noise.

Wideband FM systems which appear to be optimum on the basis of receive power requirements are not, however, compatible with other requirements for through-the-earth mine communications systems. The ≈ 60 kHz bandwidth required for a WBFM system with $m_f = 10$ and $B_a = 3000$ is totally incompatible with the frequency dispersion normally encountered in through-the-earth transmission.

The three AM systems, direct audio, DSB-SC, and SSB, are all 9 dB better than the AM-DSB system because no power is wasted in the carrier. The SSB and DSB-SC systems require a local oscillator operating at the carrier frequency for product detection. The oscillator stability required is a function of the type of signal transmitted. For voice transmissions, a 20 Hz maximum frequency error is tolerable [4] and independent oscillators with this frequency stability may be used in the modulator and demodulator. The requirement for a stable oscillator in the receiver adds to the cost and complexity of the system.

AM-Direct Audio and AM-SSB both appear to be optimum for through-the-earth systems, in terms of received power and bandwidth requirements. Both systems require linear power amplification, however, and are susceptible to impulse type noise. The AM-Direct Audio is the simplest to implement, requiring only bandlimited audio amplifiers for both transmitters and receivers.

It is, however, the system most susceptible to man-made noise and interference which is most prevalent at the lower audio frequencies.

The AM-SSB systems can be made to operate above the frequencies where man-made noise and interference are most prevalent; however, these systems require more complex equipment for signal generation and detection than either the AM-Direct Audio system or the FM systems.

Narrowband FM systems require more received power than the WBFM, AM-SSB, and AM-Direct Audio systems. Classically the bandwidth required for NBFM systems is $2\ B_a$; however, laboratory experiments have shown that intelligible voice transmissions can be effected for bandwidths as narrow as 500 Hz using a NBFM system operating at 5 kHz with $m_f = 0.5$. Narrowband FM systems, like AM-SSB systems, can be made to operate above the frequencies where man-made noise and interference is greatest, but still below the frequencies where frequency dispersion and through-the-earth signal attenuation are excessive.

FM systems, both wideband and narrowband, can be simply implemented through the use of a variety of integrated circuits which are now available for both transmitters and receivers. One characteristic of FM systems that is outstanding for mine communication uplinks is that they can employ efficient Class S (switching mode) power amplifiers to drive the transmitting antenna. This can be particularly important during emergencies when the mine power is off and the available battery power is limited. AM systems require linear or nearly linear amplifiers which are generally less efficient. The average power obtained from AM systems is reduced if peak power is limited by permissibility requirements, although clipping the voice signal prior to the modulation process removes some of this restriction.

2.4 Signal-to-Noise Required for Digital Data Systems

There are numerous methods for transmitting digital data consisting of binary bits of information. The designer usually selects a carrier frequency, coding format, and a modulation and demodulation scheme which minimizes the energy per information bit, E, required to transmit data at an acceptable error rate in a given noise environment, N. The ratio E/N is related to S/N by:

$$E/N = S/NR$$

where R is the data rate in bits per second.

Figure 2-9 shows the E/N required for some binary modulation/ demodulation systems operating in Gaussian noise and bandwidth limited channels. Here N_o is the noise power spectral density as measured in a 1 Hz bandwidth. These curves are different when the systems are operated in non-Gaussian noise. In typical atmospheric noise, performance is degraded at the lower error probabilities unless noise suppression circuits are used. When atmospheric noise is clipped in bandwidths which are wide compared to the signaling bandwidth, the E/N required may even be several dB less than that required in Gaussian noise. Wideband clipping is not useful when in-band interference is present which may capture the receiver.

On the mine surface where the digital data receiver is located, the principal source of error causing noise is expected to be 60 Hz harmonic interference and atmospheric noise. Since the data rates are low, a narrow-band system operating between the harmonic interference is feasible. The system is therefore expected to be limited primarily by atmospheric noise. As the bandwidth is reduced the atmospheric noise distribution approaches a Gaussian distribution and the curves shown in Figure 2-9 apply.

The coherent systems shown in Figure 2-9 require added sophistication in the receiver to achieve the improved performance. The non-coherent FSK system was therefore selected, since it appeared that the

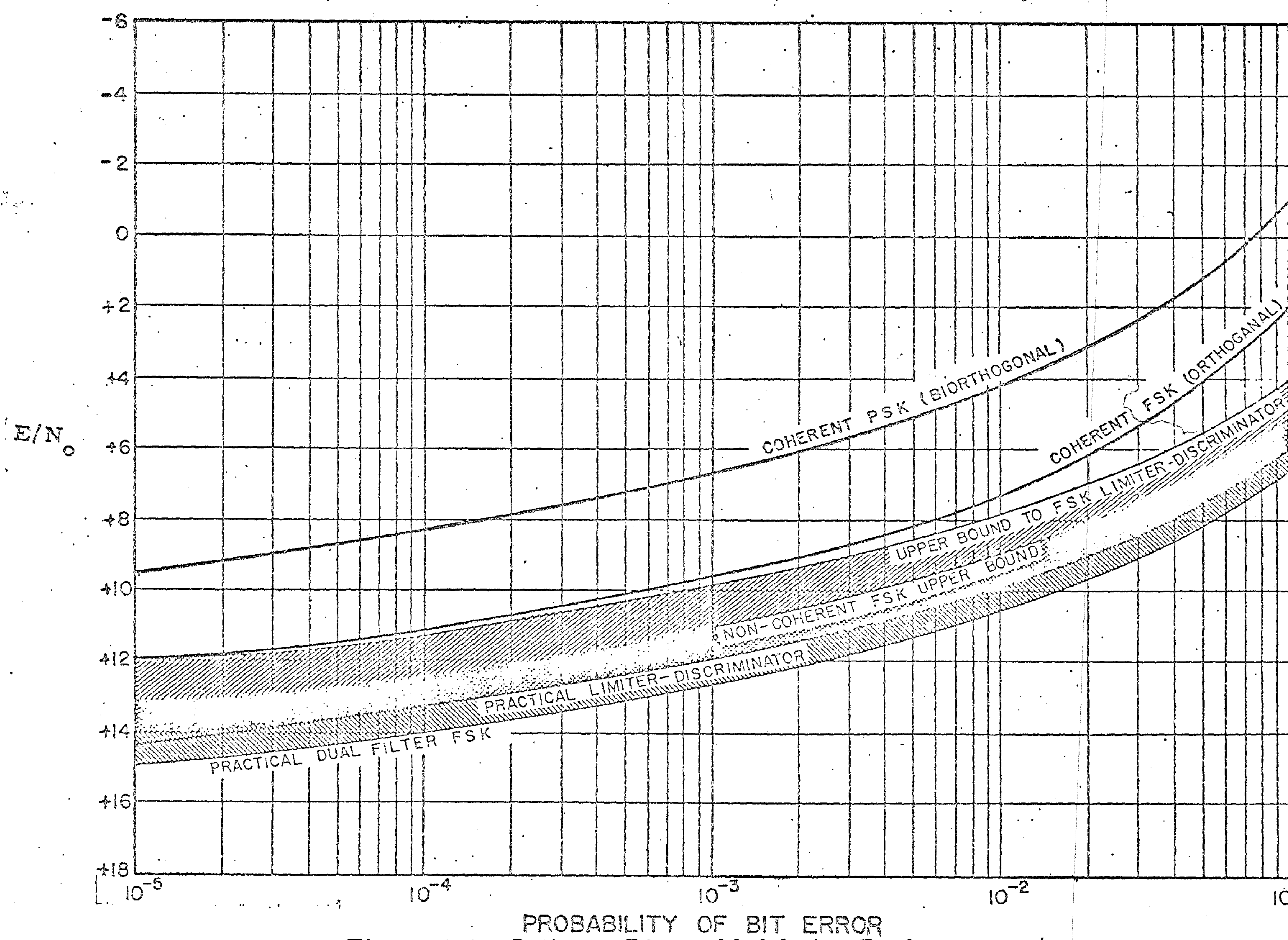


Figure 2-9 Optimum Binary Modulation Performance

transmitter power required for the voice uplink would be more than adequate for a low data rate digital link.

The E/N_o required for this system is 13 dB for bit error ratio of 1 in 10,000, which is assumed acceptable. The required S/N_o depends on the system's data rate which was selected to be 5 bits/second (see Section 2.5) as follows:

$$S/N_o \text{ (dB)} = E/N_o \text{ (dB)} + 10 \log R$$

$$= 13 + 7 = 20 \text{ dB}.$$

The received signal required is a function of noise level which depends on the selection of operating frequency. This is discussed in the following section.

2.5 Selected Design Concept

After considering all the various trade-offs two basic design concepts were selected for the voice links of the system; a direct audio downlink and a narrowband FM uplink. The direct audio downlink utilizes the frequency band from about 600 to 3000 Hz. The FM uplink operates on carrier frequency of 7 kHz.

The voice band separation permitted simultaneous operation of both voice systems and left a band of frequencies between the two voice bands which could be used for digital coded messages and condition monitoring. Since low data rates are required for the digital data each substation can transmit data in a narrow band and each can be on a different frequency to permit automatic station identification and simultaneous operation on a noninterference basis.

2.5.1 Voice Downlink

The voice downlink transmitter is government furnished equipment developed and delivered to the Bureau of Mines on Contract H0101262. The unit contains two independent power amplifiers and antenna matching channels. Output power is typically 200 watts per channel and the impedance matching is variable in binary steps between 4 and 128 ohms. Detailed characteristics are given in Reference [5].

2.5.2 Voice Uplink

The 7 kHz narrowband FM modulation was selected for the voice uplink primarily because of the efficiency obtainable with Class S power amplifiers and tuned loop antennas. The narrow bandwidth required, together with a frequency well above the most prevalent man-made noise and interference should minimize the most severe limitation on voice system performance.

The performance of the voice uplink will depend upon the noise environment at the surface receiver. Since the noise may vary considerably from mine to mine and performance of the various systems has not been measured in non-Gaussian noise, it is difficult to determine the required transmitter power and antenna moment to use. The received power required can be estimated, however, by assuming that the S/N_a required for the NBFM system is the same as measured for the direct audio system, i.e., 0 dB. At the receiver the bandwidth may be limited to about 1600 Hz so that the received power, P_r required for a modulation index of 0.5 and for $S/N_a = 1$ is given by:

$$P_r = \frac{2}{3\,(0.25)} N_{1600} \approx 2.7\, N_{1600}$$

$$P_r\,(\mathrm{dB}) = 4.3 + 10 \log N_{1600} .$$

One example for surface mine noise was given in Figure 2-4. The dashed line approximation of the noise envelope in a 1600 Hz bandwidth gives a value of N_{1600} = + 4 dB relative to 1 μA meter at the center of the frequency band used for the voice uplink (6 kHz). Therefore:

$$P_r\,(\text{dB}) = 4.3 + 4 = 8.3 \text{ dB relative to } 1\ \mu\text{amp/meter.}$$

It is seen from Figure 2-7 that this would require an antenna moment, INA, of about 5,000 ampere turn meters^2 for mine depths of 1000 feet and 10^{-2} mhos/meter conductivity if the mine noise is as shown in Figure 2-4.

For demonstration purposes at the USBM experimental mine at Bruceton, Pennsylvania, lower antenna moments can be used.

The antenna selected consisted of a twelve turn loop whose circumference is 44 meters or 144 feet. When deployed around a square pillar in the mine and driven with an average current of 1 ampere, the antenna moment is about 1450 ampere turn meters^2. Using #16 wire, the AC resistance of this antenna at 7 kHz is approximately 15 ohms, so the transmitter's average output power, I^2R, is 15 watts.

In order to achieve the INA of 10,000, which may be necessary in deeper mines, the current in this same antenna would have to be increased to approximately 7 amperes and the transmitter power to 735 watts. Such a configuration is not intrinsically safe, although an explosion-proof antenna system could probably be designed using cable approved for mine use.

2.5.3 Digital Data Uplink

The digital data uplink was designed to use the same transmitting power amplifier and antenna as the voice uplink. The code format consists of 6 bit comma-free code words which are repeated 16 times during each transmission. Up to 14 different code words are available although only nine are used in the demonstration system: 6 for manually selected responses by an operator and 3 for condition monitoring. Each code selected is transmitted 16 times in 19.2 seconds using frequency shift-keying on the carrier. Thus the data rate, R, is 5 bits/sec and the keying rate, f_r, is 2.5 Hz. The binary key stream shifts the carrier frequency ± 10 Hz so the modulation index is m = 4.

The bandwidth for this system is given by [3]:

$$\therefore b = 3\, m f_r = 30 \text{ Hz.}$$

The signal-to-noise required in this bandwidth is from Section 2.4:

$$S/N_b = S/N_o \text{ (dB)} - 10 \log b \approx 20 - 15 = 5 \text{ dB.}$$

Since several units may be operated simultaneously, 20 separate frequency channels were selected to lie between the 60 Hz harmonics in the band from 3000 to 5000 Hz between the two voice band channels.

Figure 2-7 shows the atmospheric noise level in the center of this band (4 kHz) to be -13 dB in a 30 Hz bandwidth. Thus, the received signal level required for a 10^{-4} probability of error is 7 dB (since S/N_b = 20 dB from Section 2.4) relative to 1 μ amp/meter. Figure 2-7 shows that this signal level can be obtained at 1000 foot depth and 10^{-2} mhos/meter conductivity with an antenna moment of 2240 ampere-turn meters^2. The current required in the 12 turn square loops, 11 meters on a side, is

$$I = \frac{2240}{NA} = \frac{2240}{12 \times 121} = 1.5 \text{ amperes.}$$

The AC resistance of the antenna at 4 kHz is about 10 ohms, so the transmitter output power required is

$$I^2 R = (1.5)^2 (10) \approx 22.5 \text{ watts.}$$

This can be compared with the 735 watts required for the NBFM voice uplink for the same mine depth and conductivity. This factor of more than 30 difference in the required transmitter power amplifiers is due to the difference in noise, bandwidth, and performance of the two systems. This difference also indicates a potential advantage of including the coded digital response feature in the system. At any given mine, the output power must be capable of providing normal through-the-earth voice communications and using the AC power source in the mine. Under emergency conditions, when mine power is lost and the system must operate from internal batteries, the output power could be reduced by using only the coded responses. This power reduction permits more practical battery capacities to be used.

In order to demonstrate the design concept at Bruceton, both the digital and voice uplink utilize the same power amplifier. Therefore, smaller antenna configurations can be used for transmitting only digital data.

The demonstration unit is not designed to be intrinsically safe. The Class S power amplifier should be adequate for shallow, low conductivity mines; however, quantitative specifications have not been established because the power required depends on the noise existent at each mine.

In deeper, higher conductivity mines, and in high noise environments, the same basic system could be used, but with the addition of a separate high powered transmitter amplifier. In coal mines, this amplifier and the antenna would not be intrinsically safe, so explosion-proof packaging and cable would be required.

The following section describes the basic system's operating modes and overall capabilities of the system.

3.0 SYSTEM DESCRIPTION

Figure 3-1 and Figure 3-2 show simplified block diagrams of the surface and subsurface stations. The complete system is capable of several modes of operation, and it is convenient to discuss each mode separately. The operating modes include:

1. Two-way voice via phone line with paging capability.
2. Voice downlink using direct audio through-the-earth signals.
3. Voice uplink using NBFM through-the-earth signals.
4. Coded Beacon uplink using coded FSK signals.
5. Automatic condition monitoring uplink from a subsurface sensor.

Each operating mode is described in the following subsections.

3.1 Two-way Phone Link

This is an optional feature incorporated into the system which permits coupling the surface and subsurface stations to existing phone lines in the mine when available. In this operating mode, the system can be used as a mine telephone and loudspeaker paging system. A handset and paging switch and paging relay is provided at both terminals. When the paging switch and handset press-to-talk switch are depressed, voice transmissions are repeated over the loudspeakers at all other stations connected to the phone line.

It may not always be practical or feasible to connect a substation to a phone line. The unit can still be used for voice and data transmissions through the earth. The use of the phone line provides redundancy and is useful to check out the overall system operation from the surface.

One advantage to interconnecting the subsurface station to a phone line is that other conventional mine telephone and voice paging systems such as those manufactured by Mine Safety and Appliances Company in Pittsburgh, Pennsylvania can be used with the system. Depressing the page switch on

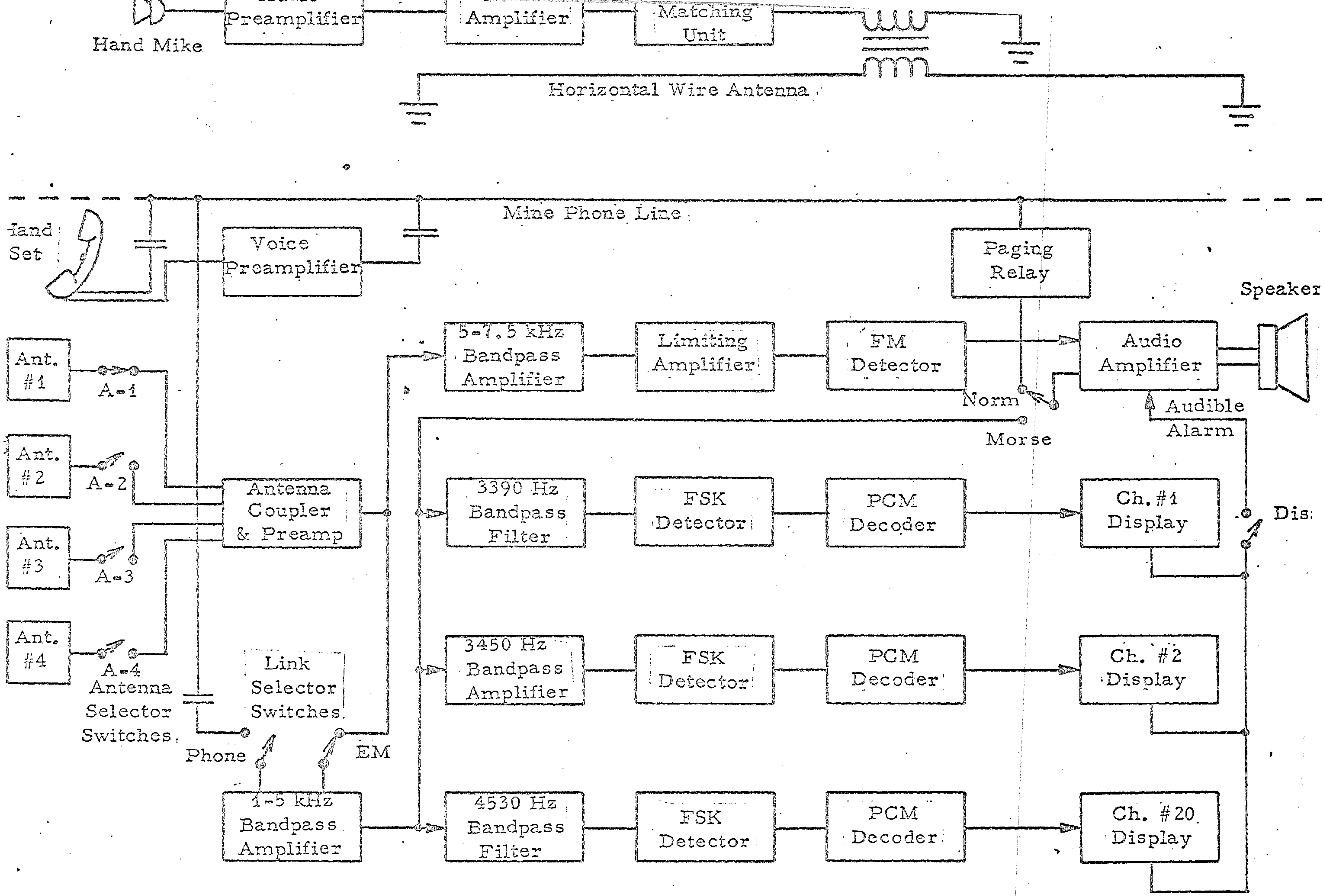


Figure 3-1, Surface Communication Station

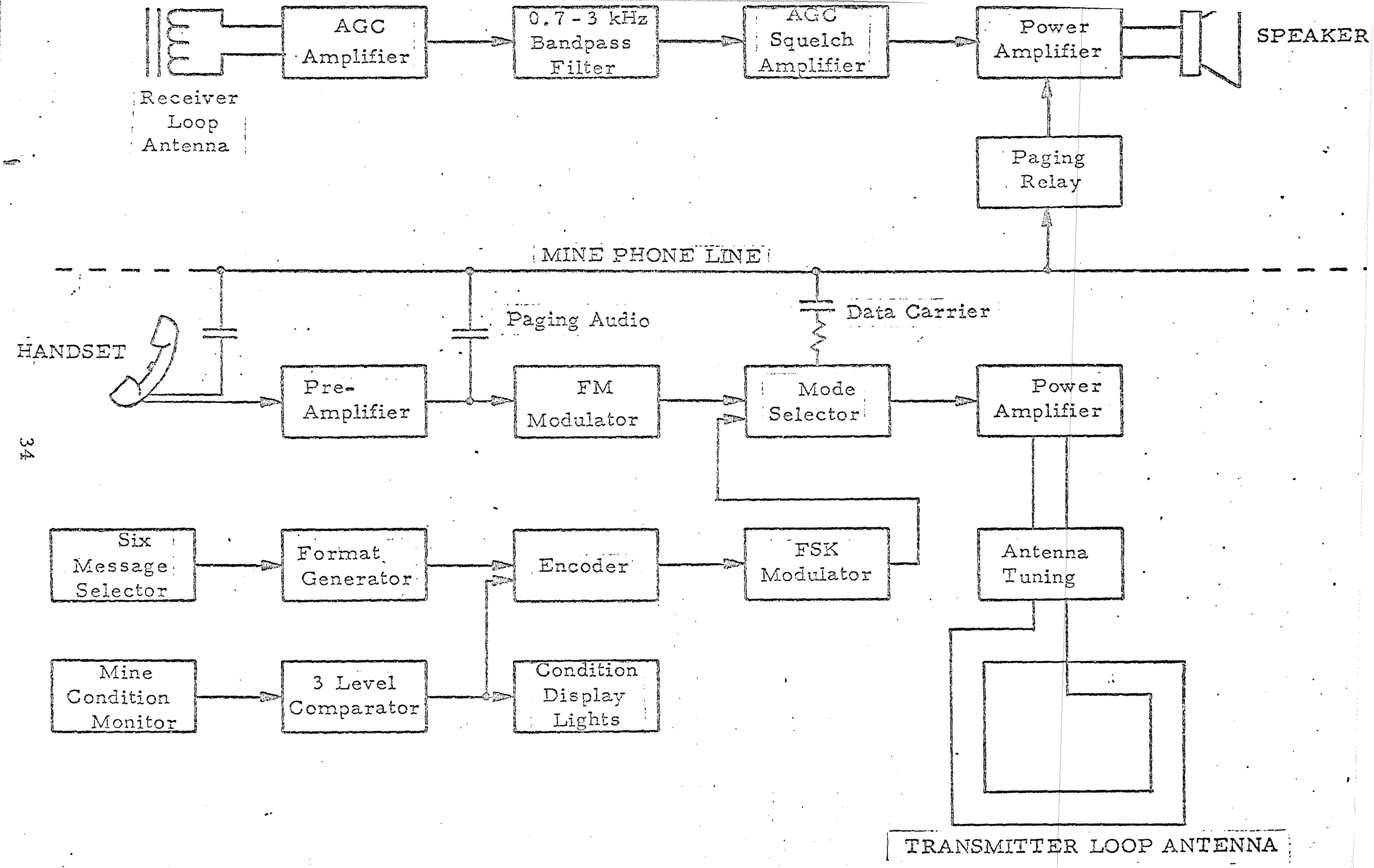


Figure 3-2. Subsurface Communications Station

a conventional pager which is connected by phone line to the subsurface station applies power to the circuitry and permits the pager's voice signals to be transmitted through the earth from the remote subsurface unit.

When the station terminals are connected by phone line, the output of the subsurface stations' FSK modulation is coupled to the line and therefore it is possible to receive both the coded beacon responses and condition monitoring data via phone line as well as through the earth. A switch is provided at the surface station for selecting the desired link.

3.2 Voice Downlink

The voice downlink transmission system is described in detail in Reference [5]. This is government furnished equipment delivered on a previous contract. Basically the unit consists of a microphone, preamplifier, audio power amplifier, antenna coupler and horizontal wire antenna. The transmitter antenna is deployed on the surface over the mine workings. It consists of a long wire terminated in the ground at the far end and driven by direct audio signals from the audio power amplifier. The wire may be several thousand feet long to provide coverage over a large area to several subsurface stations or to portable manpack receivers carried by a miner.

A special receiver has been designed for use in the subsurface station. This receiver includes a small ferrite core loop antenna mounted externally on the top of the substation case and covered by a fiberglass dome. The dome is removable so that the antenna may be rotated to maximize the signal-to-noise ratio at each installation.

The downlink receiver contains two automatic gain control amplifiers separated by band limiting filters. This dual AGC concept prevents noise interference from limiting receiver performance and permits the user to set the audio output to a constant level. A squelch circuit is also used to eliminate audible noise when no signal is present.

3.3 Voice Uplink

The subsurface station includes handset microphone and preamplifier whose output is connected to the phone line (when used) and to a voltage controlled oscillator (VCO) to generate the narrowband FM signals using a carrier frequency of 7 kHz. The output of this VCO is connected to the class S power amplifier through a switch mode selector only when the press-to-talk on the handset switch is depressed. Thus voice transmissions will interrupt any data transmissions which might be occurring at the same time.

On the surface it is necessary to deploy and couple to the receiver one or more antennas. Two high and two low impedance inputs are provided on the back of the unit for this purpose. A single turn loop antenna (low impedance) or grounded horizontal wire antenna (high impedance) or a ferrite core loop antenna can be used.

Antenna outputs can be connected separately or together and their outputs are summed in the antenna coupler. Switches are provided on the front panel to select the desired antenna combination. When substations in the mine are not too far apart, a single large (few thousand feet) loop antenna may be deployed on the surface over these stations. Otherwise, separate antennas are used to cover desired areas.

3.4 Condition Monitoring Uplink

This is the normal operating mode of the system. Coded FSK signals corresponding to one of three adjustable levels of input signals from a single sensor are transmitted automatically every 10.2 minutes or whenever the level changes to another condition. Any sensor can be used whose output can be coded corresponding to one of three levels. These three levels have been designated NORMAL, CAUTION, AND ALARM. A reversing switch permits the upper level (highest output voltage) to be either a normal or alarm condition depending on the sensor used. Green, yellow, and red lights are provided on the front panel of the subsurface station to indicate sensor level condition in the mine.

The condition code is used to frequency shift the assigned data carrier frequency in the same manner as the beacon uplink response code. Upon reception, the FSK signals are filtered into separate channels corresponding to the substation's assigned carrier frequency. After detection and decoding a green, yellow, and red light provide visual indication at the surface of the sensor level for each station. An audible tone is also generated by the loudspeaker when an alarm condition is received.

The six-bit code word corresponding to one of three condition levels is transmitted 16 times in 19.2 seconds every 10.2 minutes or whenever a condition threshold level changes. At the receiver, this signal is filtered, decoded, and the binary key stream compared with similar codes stored in the PCM decoder register. Each time the incoming key stream matches the register code a pulse is generated. When four such pulses out of a possible six are received during a transmission interval, the status light corresponding to that received code is illuminated. If the condition in one channel (one subsurface station) is NORMAL, a green light comes on and remains on until conditions change. When the condition is CAUTION, the yellow light for that channel is turned on. Under ALARM conditions, the red light is turned on and an audible tone is heard in the loudspeaker.

A blue light on each channel display comes on whenever a normal data update period is missed. This light goes off automatically if the data is updated during a subsequent transmission period. Missed updates can occur if noise perturbs the signal so that four code words are not received during one 19.2 second transmission interval or if the transmitter becomes inoperative because of a malfunction.

3.5 Coded Beacon Uplink

This is an emergency feature of the system which permits the operator to transmit coded responses by manually depressing a push button at the subsurface station corresponding to the response desired. Six responses are available. These are, YES, NO, DON'T KNOW, REPEAT, WAIT, and MORSE CODE FOLLOWS. A separate CODE KEY button is provided for sending the Morse code when desired. This button activates the carrier only when depressed.

When one of the coded response buttons is depressed, a comma-free, 6 bit binary code is generated and repeated for the period of time the button is depressed. This code stream is used to frequency shift key a carrier for subsequent transmissio Upon reception, the FSK signal is detected and decoded and visually indicated with a rear projection display which lights up the word corresponding to the button depressed.

Each subsurface station is assigned a specific carrier frequency for this data transmission to permit station identification and simultaneous operation on a noninterference basis. The assigned frequencies are selected to fall between the 60 Hz harmonic noise frequencies in a band between 3390 to 4530 Hz. The 20 available channels are shown in Table 3-1. Only three of these have been implemented for demonstration purposes. These are channels 1, 2, and 20. The surface FSK receiver uses the same antenna or antennas used for voice reception. The FSK signals received are amplified and filtered into respective channels for identification and display purposes. The FSK signal is detected and decoded in the same manner as the condition monitor codes described in the previous section.

The unit also includes a switch which, when in the ON position, permits the transmission of an intermittent continuous wave at that station's carrier frequency. The signal is on for approximately 20 seconds and off for 20 seconds and can be used for location and identification, test, and as a backup

TABLE 3-1

DATA UPLINK FREQUENCIES

Channel No.	Assigned Frequency
1	3390 *
2	3450 *
3	3510
4	3570
5	3630
6	3690
7	3750
8	3810
9	3870
10	3930
11	3990
12	4050
13	4110
14	4170
15	4230
16	4290
17	4350
18	4410
19	4470
20	4530 *

* Channels used for the three engineering models constructed to demonstrate system in USBM experimental mine in Bruceton, Pa.

emergency beacon. The surface station's loudspeaker emits an intermittent audible tone at the station's carrier frequency in this mode of operation.

3.6 Summary of System Characteristics

SURFACE STATION

General:

Mounting:	19" Relay Rack
Size:	19" wide × 10½" high × 16" deep
Weight:	42½ pounds
Power:	120 v, 60 Hz, ½ amp.

Voice Downlink Transmitter (GFE):

Input:	Hand Microphone
Output:	Two independent power amplifiers and antenna matching units
Power Output:	200 watts per channel
Antenna Impedance Matching:	4 to 128 ohms in binary steps
Frequency Response:	300 - 3000 Hz (3 dB)
Power Required:	115/230 volts, 60 Hz @ 800 watts
Transmitter Antenna:	Long horizontal wire with ground termination. Deployed over coverage area.

Receiver Antenna Coupler and Preamplifier:

Antenna Inputs:	2 high impedance, 2 low impedance. Independently switchable.
Gain:	40 dB, High Z in, 80 dB Lo Z in
Frequency Response:	3 - 50 kHz
AGC Threshold:	1 mv, High Z in, 15 μv, Lo Z in
AGC'd Output Level:	100 - 150 mv

Receiving Antennas:

Small Ferrite Core Loop
or Large Single Turn Loop
or two of each depending on coverage desired

FM Voice Receiver:

Sensitivity:	20 μA/m with ferrite core loop
Required S/N:	
Noise Quieting Threshold:	40 μv (10 dB quieting)
Gain:	43 dB to Limiter Input
Frequency Response:	5-7 kHz
Output:	½ watt Speaker and Handset
AGC Threshold:	4 mv

Beacon Amplifier:

Sensitivity:	10 μA/meter with ferrite core loop
Required S/N_o:	26 dB for $P_c = 10^{-1}$
Frequency Response:	1 - 5 kHz
Output:	700 mv
AGC Threshold:	700 μv
Gain:	60 dB

Channel Display Unit:

Beacon Display:	Rear Projection Readout for each response
Condition Display:	Green: normal, yellow: caution, Red: alarm, blue: no condition update received.

Phone Link:

Input/Output:	Handset connected to 2 wire phone lines
Paging Switch:	Controls paging relays for voice paging via loudspeaker at remote station

SUBSURFACE STATION

General:

Mounting:	Tabs with 7/16" holes, 9½"apart
Size:	12" wide X 22" high X 12" deep (excl. handset)
Weight:	57 lbs. (excluding antenna & charger)

Battery Charger:

Input:	440 volt AC, 60 Hz, 1 ϕ
Output:	12 volt DC @ 2 amps
Battery Capacity:	20 ampere hours @ 12 volt. Rechargeable

Phone Link:

Input/Output:	Connect to existing 2 wire system
Paging:	Switch applies 12 volts to line and paging relays for voice paging

FM Voice Modulator:

Carrier Frequency:	7 kHz
Modulation Index:	$\approx$ 0.5 at 1 kHz
Frequency Deviation:	$\approx \pm$ 500 Hz

FSK Beacon Signaler:

Frequency:	Ch. 1 = 3390 Hz, Ch. 2 = 3450 Hz, Ch. 20 = 4530 Hz
Normal Input:	6 Push button Selectable Response (Yes, No, Don't know, Repeat, Wait, and Morse code follows)
Code Input:	Morse Code Button
Location/Identification Mode:	Switch permits continuous channel frequency transmissions for 20 seconds on and 20 seconds off

FSK Condition Monitor:

Frequency:	Same as Beacon Signaler
Input:	0-5 volts
Threshold:	Two selectable between 0-5 volts for increasing or decreasing sensor outputs
Coding:	6 bit binary, comma-free
Transmission Rate:	5 bits/sec
Transmission Period:	16 code words in 19.2 seconds
Transmission Interval	10.2 minutes

Power Amplifier:

Output Power:	30 watts, into 15 to 30 Ω resistive load
Frequency:	1 - 10 kHz

Transmitter Antenna:

Type:	12 turn loop, #16 wire. Length varies depending on installation. Typically 150 feet, 50 lbs.
Tuning:	2 variable capacitors selected by relay; one tuned for channel frequency and the other tuned for 7 kHz (FM voice channel)

Direct Audio Voice Receiver:

Antenna:	Adjustable Ferrite Core Loop
Sensitivity:	20 µA/m
Gain:	90 dB
Required S/N_o:	+ 6 dB
Output:	½ watt, Speaker and Handset
Controls:	Volume and Squelch

Phone Link: Same as Surface Station

4.0 SYSTEM INSTALLATION AND OPERATION

The following subsections describe the installation wiring, operating, and control functions of the surface station and each subsurface terminal.

4.1 Surface Station Installation

The surface station is packaged for rack mounting in a standard 19" relay rack. Figure 4-1 is a photograph showing the front face of the surface station. The basic unit requires 10.5 inches of rack space. Modular construction is used for each subsystem. The basic unit contains the power supply, control panel with speaker and handset. Plug-in modules include the antenna coupler, beacon amplifier, voice receiver, and individual channel display units. The basic unit contains space for 3 channel display modules. Additional display modules operating in conjunction with additional subsurface stations can be added. Five more modules would require an additional 5¼ inches of rack space. The existing power supply is capable of powering five additional modules. If still more channel displays are added, a separate power supply is required.

Power to the surface station is obtained from any 115 volt, 60 Hz receptacle using a plug-in type power cord. The basic unit using 3 display channels requires 50 watts of power. Three fuzes are located on the back of the control module, one for AC input line (½ slo-blow), one for the 12 volt DC supply (2 amp), and one for phone line reversed polarity (2 amp).

The station is normally installed at the desired location on the surface near or in the same rack as the voice downlink transmitter. This transmitter contains a preamplifier (Model C809-A), a power amplifier (Model C810-A) and antenna matching unit (Model C811-A), and a horizontal wire antenna deployed over the desired coverage area in the mine. This transmitter subsystem provides through-the-earth direct audio voice signals to the subsurface stations.* No interconnections are required between the

* The voice downlink subsystem is GFE equipment. Installation and operation details are given in Reference [5] .

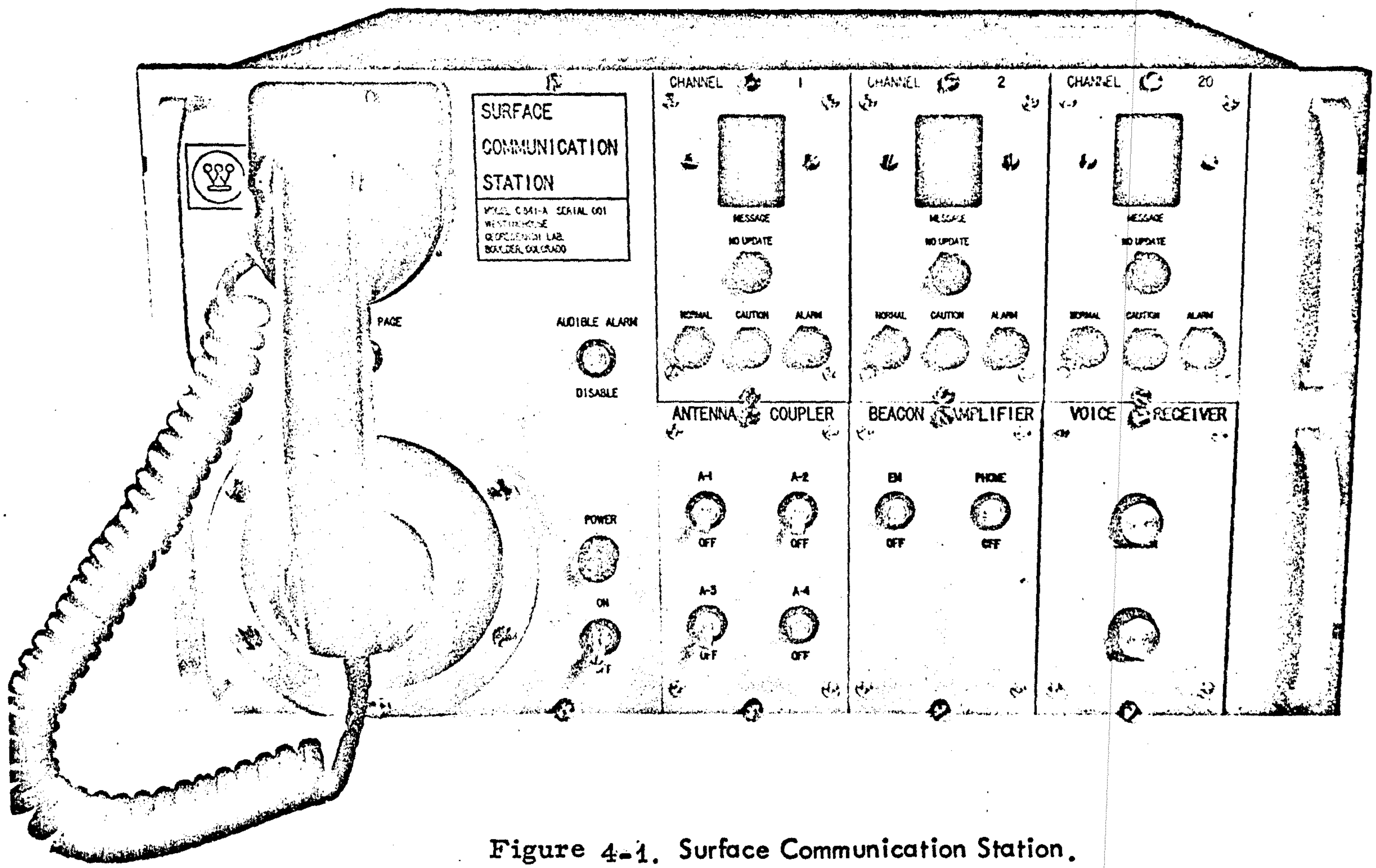


Figure 4-1. Surface Communication Station.

surface station and the downlink transmitter; however, it is necessary to have both systems co-located for 2-way voice communications.

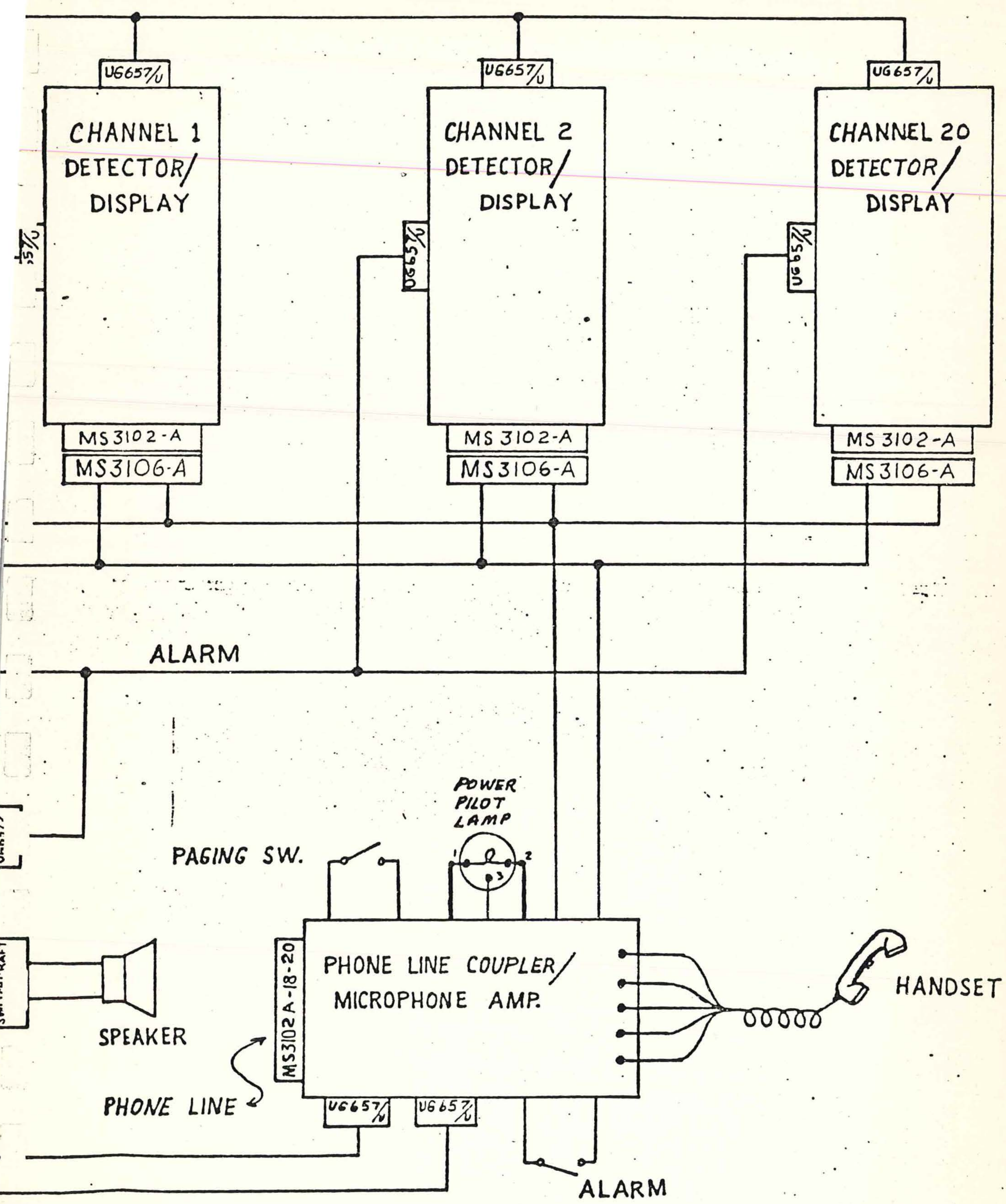
The surface station is capable of receiving through-the-earth signals from subsurface stations which may be widely separated by using separate receive antennas. Two small ferrite loop antennas in weather-proof cases are furnished with the basic unit. These are designed for sensing signals from individual subsurface stations. Connections between these antennas and the basic unit are made using RG-58 coaxial cable with BNC connectors to the back of the antenna coupler module. Cable lengths should not exceed approximately 100 feet. Two twin lead coaxial receptacles are also provided on the rear panel. Each may be used for connecting to a large single wire loop antenna deployed on the surface over a larger area of mine workings, where several substations are located. These loops may be a few thousand feet in length.

The surface station can be hardwired to other stations and operated as a conventional mine paging system if desired. Connections to the line are made to the back of the control panel using the plug and receptacle provided.

No other external connections to the unit are necessary. Interconnections between function modules are made on the back of each module. Power plugs are available from the back of the control panel and these must be connected to the power receptacle on each module. Signal connections between modules are made using the coaxial cables furnished with the unit. Figure 4-2 indicates the interconnections required and the types of plugs and receptacles used.

4.2 Surface Station Control Functions

The front panels of each subsystem module contain the various switches, control knobs, and indicators required for operating the surface station. The function of these controls are described below for each module.


UG657/U
CHANNEL 1
DETECTOR/
DISPLAY
MS3102-A
MS3106-A
UG657/U
CHANNEL 2
DETECTOR/
DISPLAY
UG657/U
MS 3102-A
MS3106-A
UG657/U
CHANNEL 20
DETECTOR/
DISPLAY
UG657/U
MS 3102-A
MS3106-A
ALARM
POWER
PILOT
LAMP
PAGING SW.
PHONE LINE COUPLER/
MICROPHONE AMP.
MS3102A-18-20
HANDSET
SPEAKER
PHONE LINE
UG657/U
UG657/U
ALARM

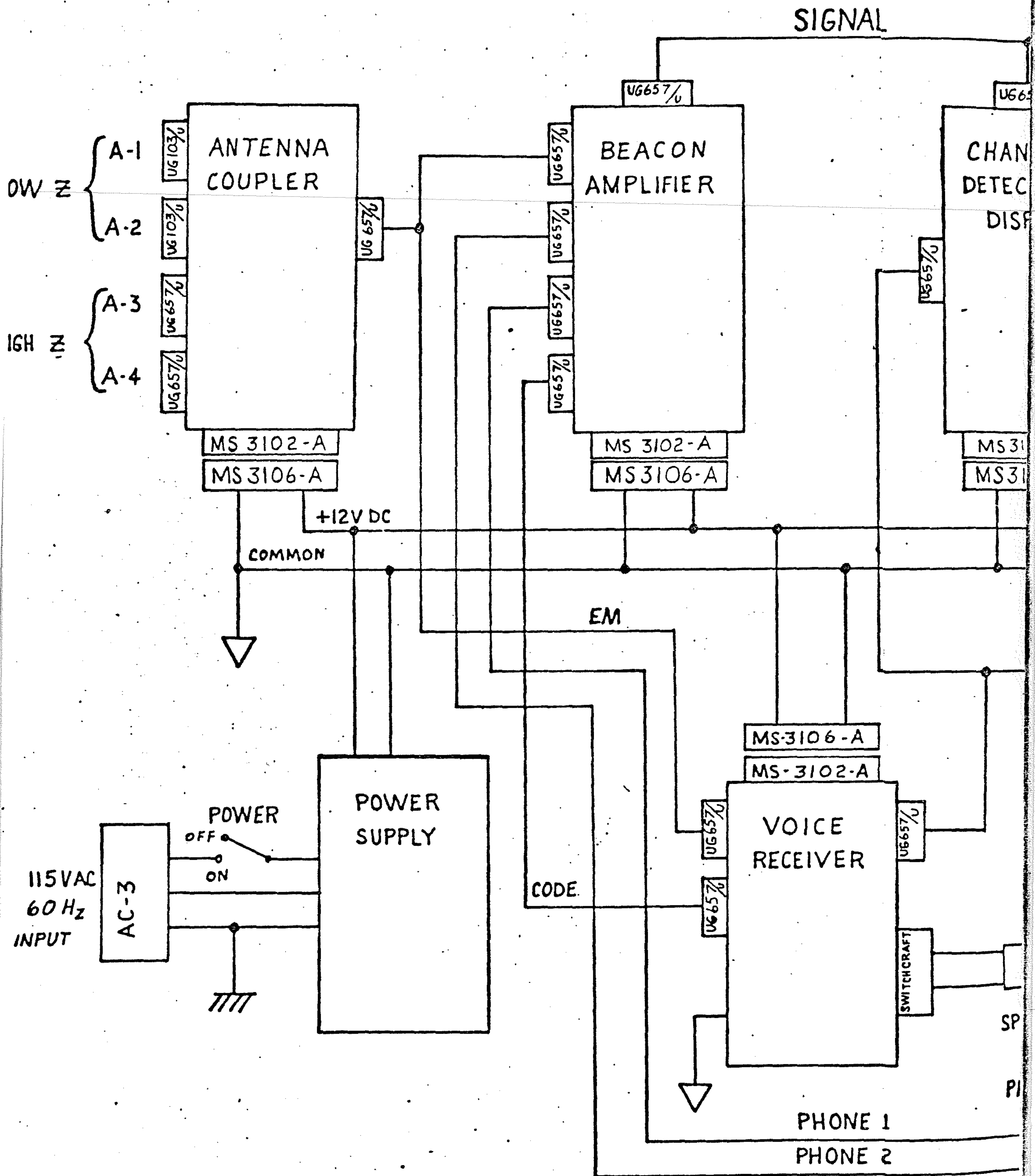


Figure 4-2. Surface Communication Station Interconnections.

Control Panel:

Power Switch: This switch in the ON position provides power to all the modules in the unit. A panel light above the switch indicates when power is applied.

Switch-to-Page: This is a spring return switch. When held in the depressed position the paging relays at other paging stations connected to the same phone line are activated. The station operator can then transmit voice to other station loudspeakers by depressing the push-to-talk switch on the handset and speaking into the microphone. Upon receiving a page the two station operators can converse over the phone line using handsets just as a conventional mine pager.

Audible Alarm Disable: This switch permits the operator to disable the audible alarm emitted from the loudspeaker. In normal position the alarm is automatically activated when the subsurface condition monitor transmits an alarm condition.

Voice Receiver Module:

Volume Control: This knob adjusts the output level of the loudspeaker.

Squelch Control: This knob is normally set just below the noise threshold heard in the loudspeaker. When through-the-earth voice signals are transmitted from a subsurface station the signal level overrides the squelch and permits signals to be heard.

Antenna Coupler Module:

A-1, A-2, A-3, A-4: These four switches control the inputs from the antenna receptacles on the back. When all switches are in the ON position the outputs from each antenna are summed and amplified to the common output.

Beacon Amplifier Module:

EM: This switch connects the input of the beacon amplifier to the output of the antenna coupler for through-the-earth reception of beacon and condition monitor signals.

Phone: This switch connects the input of the beacon amplifier to the phone line for hardwire reception of beacon and condition monitor signals.

Morse Code/Normal: This switch connects the output of the beacon amplifier to the audio amplifier in the voice receiver so Morse code signals transmitted by the subsurface station are audible. It can also be used to audibly monitor other beacon signals and condition monitor transmission periods.

Channel Display Module:

Message Display: This is a lighted presentation of the word responses corresponding to the beacon response buttons in the subsurface station. When a response has been selected, coded, and transmitted, the decoded word appears on this display for as long as that button is depressed, by an operator (usually about 10 seconds).

No Update Light: This is a blue indicator light which comes on automatically whenever condition monitor signals have not been received for a period longer than 12 minutes. The light automatically goes off when up date signals are received.

Normal, Caution, Alarm Lights: These green, yellow, and red lights indicate the condition monitor status as determined by these condition levels which are preset at the subsurface station. Condition data is transmitted for approximately 20 seconds every 10 minutes or whenever this condition changes to another level. The light corresponding to the condition transmitted remains on between transmission intervals. When the ALARM light is on, an audible tone is heard in the loudspeaker unless disabled by the switch on the control panel.

4.3 Subsurface Station Installation

Each subsurface station includes a transmitter and receiver (T/R) station, a power converter unit and a transmitting antenna with tuning box. The T/R station (Figure 4-3) is packaged in a steel enclosure (National Electrical Manufacturers Association standard size 12) with a hinged door for access to the internal battery and the electronics module. Two screws hold clamps on the door which is closed for normal operations. The door may be opened for battery replacement and routine maintenance and certain adjustments required for initial installation. The power switch is also located behind this door. A separate panel in the door can be removed for access to the beacon response buttons.

The basic dimensions of the TR enclosure are 12" wide, 16 inches high, and 12 inches deep. An adjustable ferrite core loop antenna for reception of voice downlink transmissions is mounted on top of the unit. This antenna is covered by a removable fiberglass cap which is 7" high and 8" in diameter. This cap may be removed by loosening three screws in order to adjust the antenna for best reception during the initial installation.

External connections to the unit are accomplished using the four receptacles on the side of the enclosure. These receptacles are, reading from front to back, 1) Sensor (Condition Monitor) Input, 2) Phone Line, 3) Transmitter Antenna, and 4) Battery Charger.

The T/R enclosure is designed for wall mounting in the mine at any convenient height for the operator. Handles on the side are provided for transporting the unit. Two tabs with 7/16" holes spaced 9½ inches apart are welded to the top-rear for mounting purposes. A notch may be cut in the mine wall so the entire package can be recessed to protect it from damage.

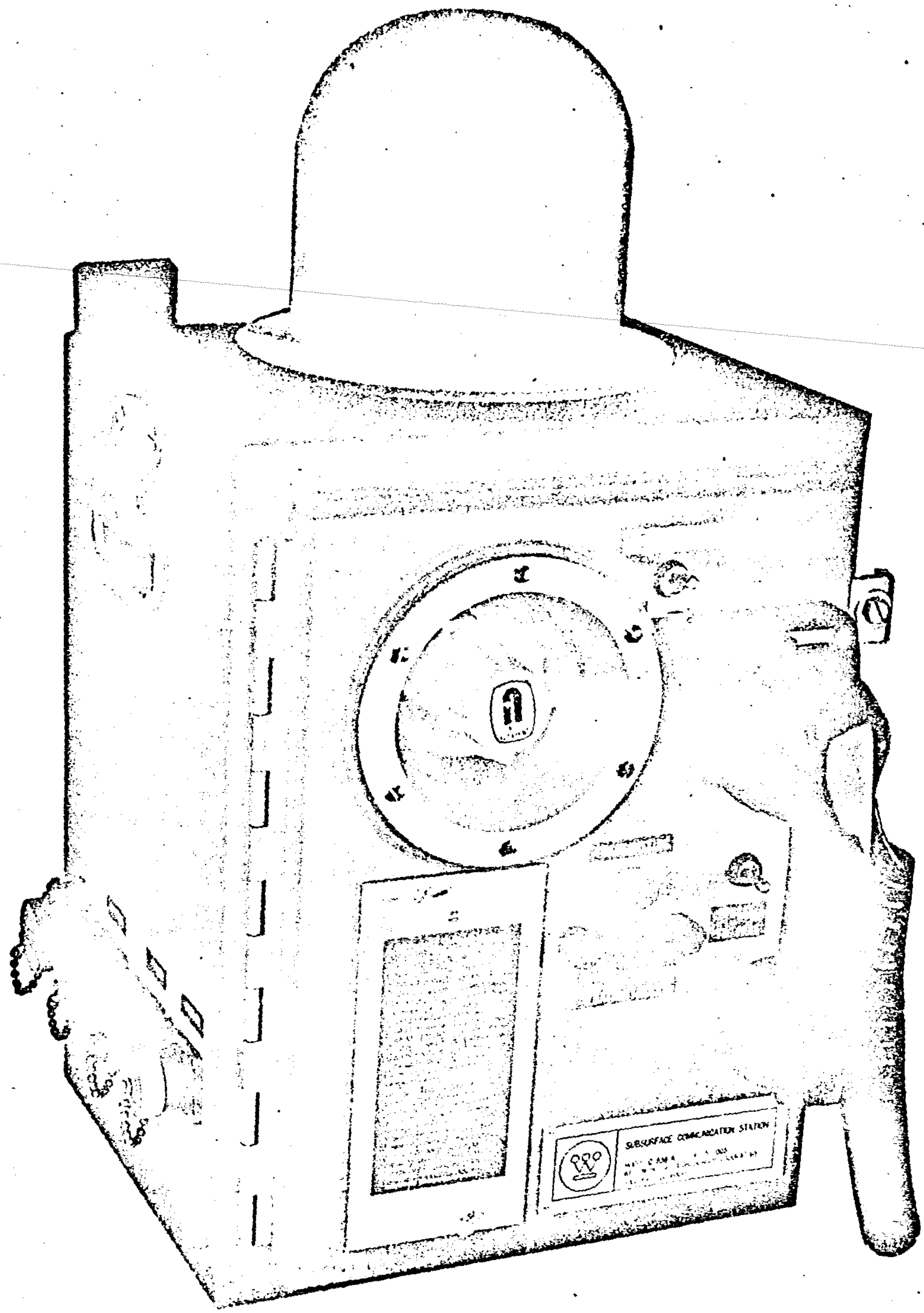


Figure 4-3. Subsurface Transmitter-Receiver Station.

This notch should be approximately 18" wide, 30" high, and 15 inches deep to allow access to the receptacles on the side and for adjusting the receive antenna on the top.

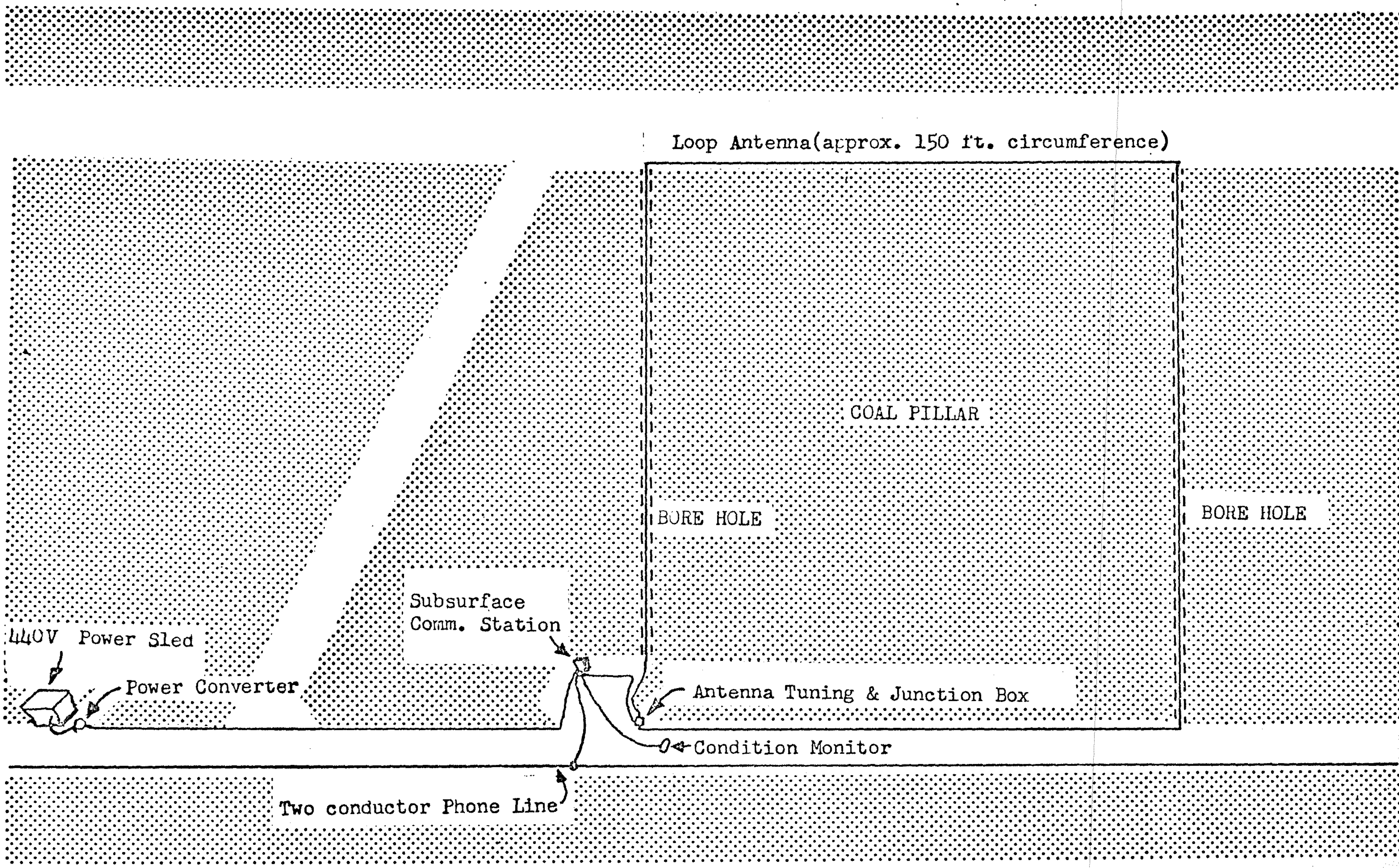
The unit is designed to be powered from a 440 volt power sled in the mine. An explosion proof power converter unit is located near and connected to the 440 volt, 60 Hz, single phase power source on the sled.

The + 12 volt DC output of this converter unit is connected to the T/R station using a three conductor cable capable of carrying 2 amperes of current. This cable is typically one to two hundred feet long. Separating the T/R station from the power sled is desirable to reduce the pickup of electromagnetic noise generated at the sled. The 12 volt DC from the converter unit is used to maintain charge on an internal battery which can furnish power to the unit for a finite period when the external power is lost.

The transmitter's antenna system should be located near the T/R station. A 30' cable is provided for connecting the station to the antenna tuning box. The transmitting antenna itself is a 12 turn loop connected to two receptacles on opposite sides of the tuning box. The length of antenna may vary for each installation depending upon the mine depth, overburden characteristics and available area in the mine. The antenna loop should be deployed horizontally either on the floor or hung from the roof. It should enclose as large an area as possible. A typical coal mine installation would use an antenna which is 100 to 200 feet long and deployed around a pillar of coal in the mine using available entries, or if necessary, horizontal boreholes through portions of the coal seam.

Connections to a phone system and to the condition monitor are made using 2-wire cables and plugging into the receptacles provided on the side of the transmit-receive station. Figure 4-4 shows the interconnections required for a complete subsurface station installation.

After the installation and interconnections are complete, certain



NOTE: This drawing is not to scale

Figure 4-4 Typical Subsurface Station Installation adjustments are required before the system is operational. These are shown in the photograph of Figure 4-5 and are described below.

Power Switch: This is a screwdriver operated switch located behind the door, which is turned on after the installation is completed.

Receive Antenna Adjustment: This adjustment should be made under normal mine operating conditions with the complete system operating. The antenna cap is removed and the antenna rotated and tilted for best reception of signals from the surface voice down-link transmitter by nulling on nearby noise sources.

Transmit Antenna Tuning: The antenna tuning unit contains two variable capacitance boxes marked Voice and Data. Each is adjusted for maximum current in the antenna at the proper carrier frequency, using the intensity of the transmitting light on the station door as an indicator. The voice capacitor box is adjusted for maximum light intensity by depressing the push-to-talk switch on the handset. The data capacitance box is adjusted for maximum light intensity by depressing the code key button located behind the removable panel in the door.

Condition Monitor Adjustments: These adjustments are located behind the door. Any condition monitor can be used whose output is an analog voltage which varies between 0 and +5 volts. Two potentiometers marked LO and HI must be adjusted with a screwdriver to selected three desired status conditions of the monitor's output level. A screwdriver switch also permits the selection of either the highest or lowest condition to be an alarm condition.

Voice Receiver Adjustments: A volume control and squelch control are located behind the door. The volume control adjusts the loudspeaker amplitude to a convenient level. The squelch control is normally set just below the noise threshold.

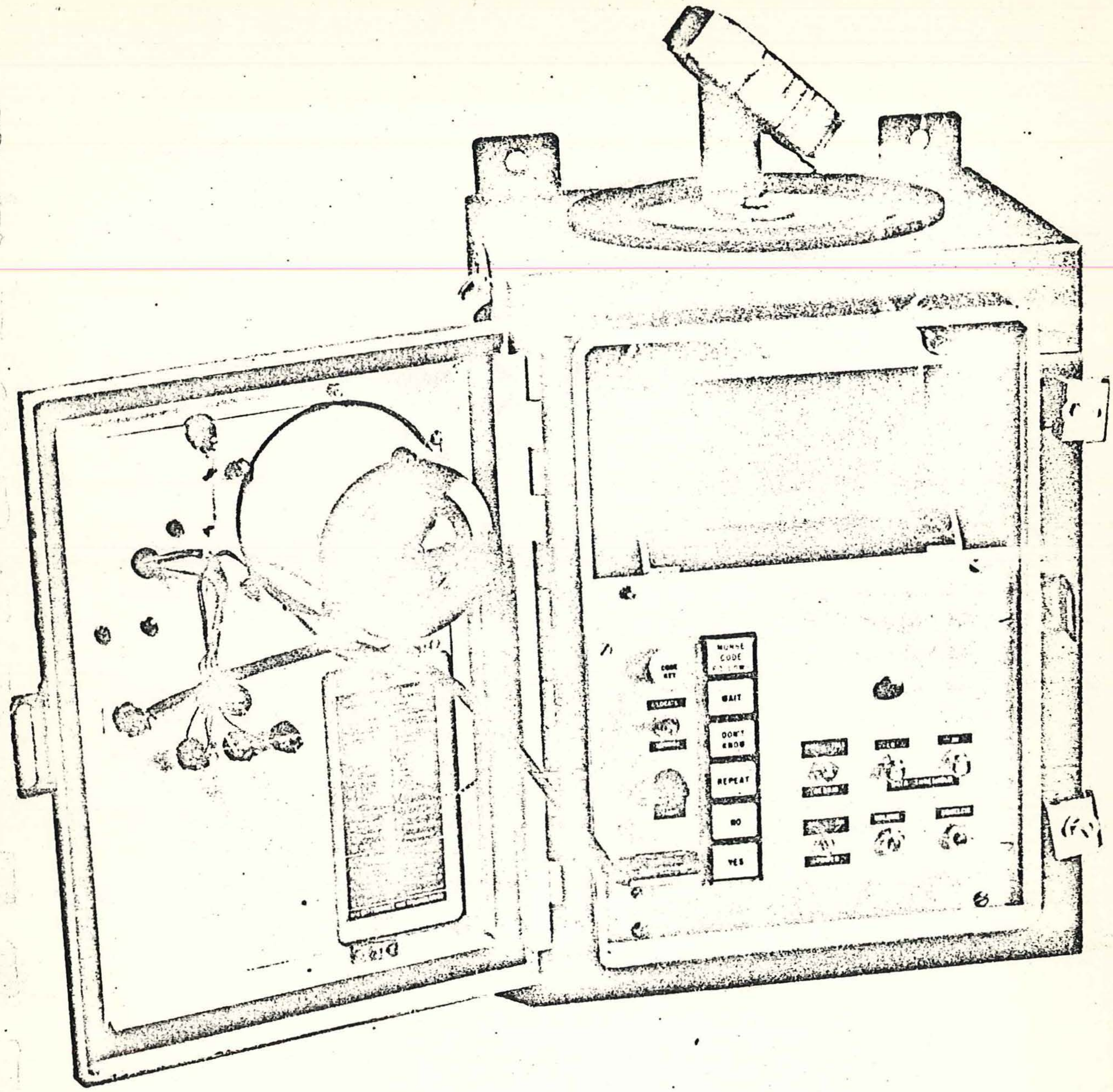


Figure 4-5. Subsurface Transmitter-Receiver Station Controls and Adjustments.

4.4 Subsurface Station Control Functions

After the installation and initial adjustments are made the subsurface station operates in various modes. The operational modes and the control functions involved are described below.

Condition Monitor Transmission: This is the normal operating mode and is accomplished automatically by the unit after the initial adjustments have been made. Green, yellow, and red lights on the door of the T/R station indicate the normal, caution and alarm conditions. The transmitting light comes on whenever the condition status code is transmitted to the surface. This automatically occurs every 10 minutes or whenever the status level changes. An audible alarm is sounded when an alarm condition exists. This can be turned off with the ALARM-DISABLE switch on the door. Condition data is always transmitted simultaneously through the earth and via phone line on each station's channel frequency carrier.

Phone Paging: This mode of operation permits station operation as a conventional mine paging system using two wire phone lines and when the paging switch is depressed the station operator can transmit voice to other station loudspeakers by depressing the push-to-talk switch on the handset and speaking into the microphone. Upon receiving a page, the two station operators can converse over the phone line in the conventional manner.

Voice Uplink Transmissions:

FM voice signals are transmitted through the earth from the subsurface station whenever the push-to-talk switch on the handset is depressed Remote paging stations can also transmit FM signals from the same station using the remote station paging switch. These voice transmissions take precedence over the other operating modes of the station. The transmitting light comes on whenever the handset switch is depressed and this indicates carrier current is flowing in the transmitting antenna.

Voice Downlink Reception:

Reception of through the earth signals from the surface voice transmitter are audible from the loudspeaker and involve no control by the operator.

Beacon Uplink Transmissions:

This is an emergency operating mode for the station. Instructions for use of the beacon transmissions are printed on the small panel on the door of the unit. This panel is removed by rotating two thumb screws to gain access to the beacon response buttons and code key. The standard Morse code is printed on the back of the panel.

5.0 USBM EXPERIMENTAL MINE DEMONSTRATION

After completing the design, fabrication, and laboratory checkout the communications system was delivered to the USBM in January, 1973 for installation in the experimental mine at Bruceton, Pennsylvania. The mine is developed in a 5 to 5½ foot seam of Pittsburgh coal with a clay floor underlain by limestone. Above the coal bed there is a foot and a half of soft shale, which is pulled down as the coal is removed. Above this shale there are 1½ feet of shaly coal, which makes a strong roof. The overburden above is shale. The main portal is at an elevation of 1000 feet and the overburden at the crest of the hill southwest of the portal is about 130 feet.

Previous tests at this mine [Reference 2, Appendix III-D] included a conductivity survey over portions of the mine where the depth to the workings was approximately 50 feet. The effective conductivity was measured to be 1.9×10^{-2} mhos/meter.

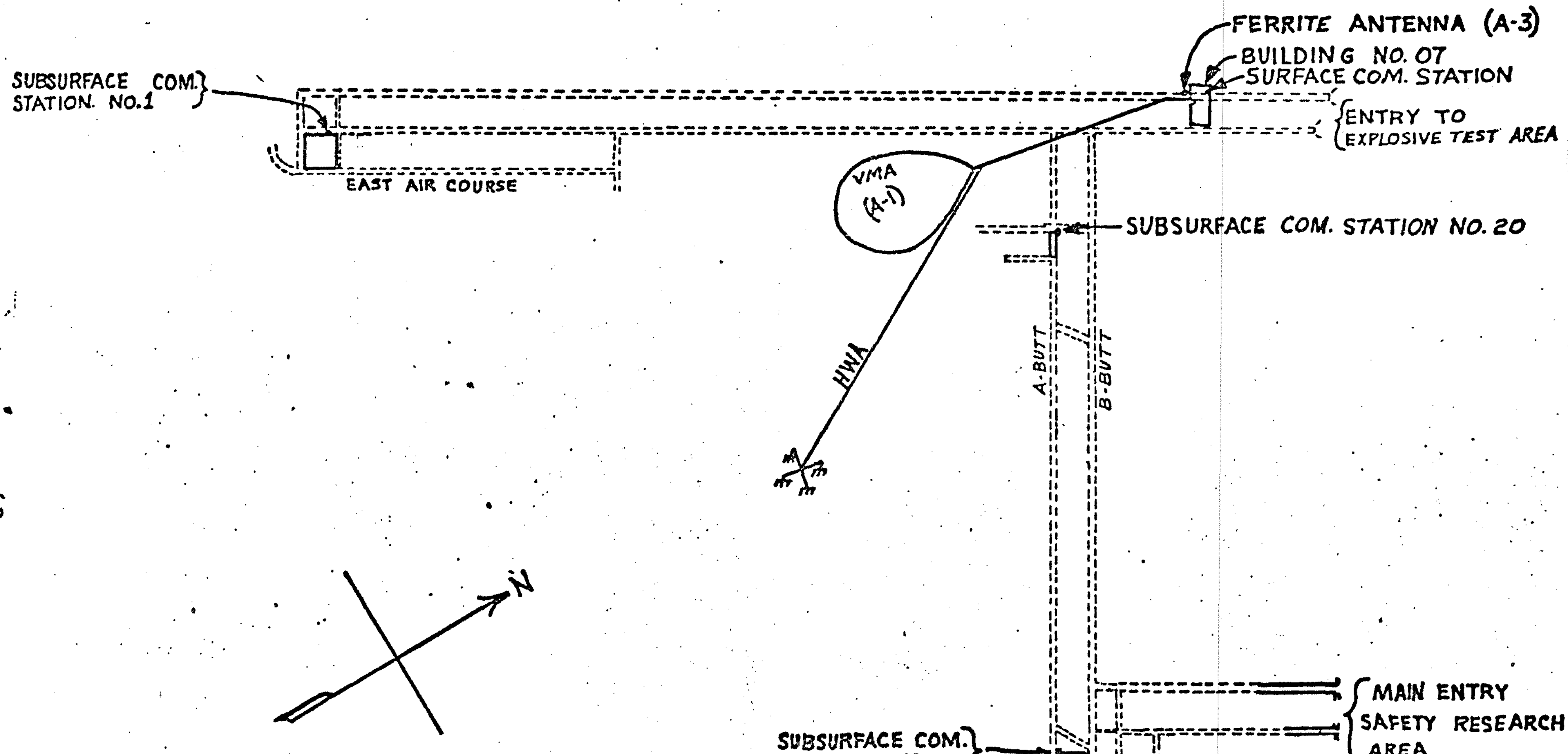
5.1 Installation of System at USBM Experimental Mine

The system was installed in the USBM Experimental Mine at sites selected and prepared by USBM. Figure 5-1 is a plan view of the installation showing the relative positions of the surface and subsurface stations, and their respective antenna deployment configurations.

Surface Station

The surface station was installed in building 0-7 which is centrally located in the area to be covered by the system. Building 0-7 also houses the central control and monitoring equipment for another mine environment monitoring system which has several stations scattered throughout the mine.

The building has metal sides and roof and a raised computer room type floor with metal sheathing on the undersides of the floor panels. This construction provides some degree of shielding from EM fields and permits



Station	Loop Area	Distance to Surf. Ant. A-3
1	120 m^2	1090 ft.
2	120 m^2	880 ft.
20	13 m^2	240 ft.

Figure 5-1. Communication and Monitoring System Installation Plant at USBM Experimental Mine, Bruceton, Pa.

easy installation and modification of cabling to external locations.

The modular chassis of the surface unit was mounted in a relay rack furnished by USBM, together with the government furnished direct audio, voice downlink transmitter. Blank panels were installed in the spare panel space which could permit future expansion of the monitoring and communication system or inclusion of other equipments.

Cables were pulled under the floor and through a conduit to a junction box outside the building for deployment to the external antennas and to the phone line connecting to the subsurface stations in the mine.

Two receiving antennas were deployed; one a large single turn loop vertical magnetic antenna (VMA) and the other a small ferrite core loop with adjustable axes. The VMA consisted of a single #16 AWG insulated conductor deployed in a roughly egg shape of approximately 200 feet diameter as shown in Figure 5-1.

The ferrite core antenna consisted of 2000 turns #28 AWG enameled copper wire wound on a 1" X 1" X 4" ferrite core and mounted on a gimbel to permit 360 degree orientation adjustment. The whole assembly was housed in a small (approximately 7" high X 5" diameter) protective fiber-glass housing. This antenna was deployed just outside building 0-7.

A single horizontal wire antenna (HWA) was deployed for the voice downlink transmitter. It was deployed as shown on the sketch of Figure 5-1, and had a total length of 650 feet. The downlink transmitter produced a sinusoidal test current of 2 amperes when properly matched to the HWA with the 32 ohm output tap.

Subsurface Stations

In this report, the subsurface stations will be designated by the number corresponding to the channel number assignment for their individual data uplink frequencies as listed previously in Table 3-1.

Station Number 1 (data frequency 3390 Hz) was mounted on the rib at the far end of the East entry of the explosive testing area, opposite the dehumidifier room in the East Air Course. The antenna was deployed in a rectangular shape around a pillar as shown in Figure 5-1, and enclosed approximately 120 square meters. The antenna tuning unit and junction box was mounted on the rib directly beneath the T/R unit. The power converter was connected to a 440 volt receptacle just a few feet from the T/R unit.

No sensor installation was made at Station #1, although a cable approximately 60 feet long was fabricated to connect the T/R unit to the anemometer provided by USBM.

The phone line coupling circuit was connected to the system audio line which consisted of the white and green conductors of a 4 conductor cable. The white conductor was selected to be the positive (+) side of the line. This polarity was observed throughout the system phone circuit.

Station #2 was mounted on the rib in a power transformer station in the safety research area of the mine designated as the Number 17 Room. The transmitting antenna was deployed around a rectangular portion of a pillar which enclosed approximately 120 square meters. Two sides of the loop were formed by boreholes through the coal between two parallel entries. Approximately 30 feet of excess loop cable was folded double and stuffed into an unused borehole to keep it out of the way. The antenna tuning unit and junction box was mounted on the rib about 6 feet from the T/R unit.

The power converter was connected to a 440 volt power source about 150 feet from the T/R unit. An air velocity sensor was mounted in the entry a few feet from the station and connected to the sensor input of the T/R unit. The phone line connection was made to a tee in the audio cable about 50 feet from the station.

Station #20 was mounted on a 24 inch thick concrete bulkhead separating the safety research area from the explosive testing area near the north end of the A-butt. The transmitting antenna was attached to overhead conduit hangars near the mine roof and deployed in a long, narrow rectangle enclosing approximately 13 square meters. The low impedance of this small antenna required use of the lowest impedance tap on the transmitter output transformer. The antenna tuning and junction box was hung from electrical conduits on the opposite side of the entry from the T/R unit.

An air velocity sensor was mounted to a conduit hangar in the roof of A-butt near the slant to B-butt. Approximately 150 feet of cable were required to connect the anemometer to the T/R unit sensor input. The power converter was located near the closest 440 V., 60 Hz power source which was approximately 150 feet away in the slant from A-butt to B-butt. The phone line connection was made to the nearest tee in the audio cable which was located just a few feet from the station.

5.2 System Checkout

Checkout of the system was conducted between the surface station and one subsurface station at a time.

During the checkout of the system several problems were encountered and corrected. These are listed below:

1) Paging mode voice transmissions were distorted apparently by the presence of 7 kHz voice uplink carrier on phone line with voice. A modification was made to subsurface units to prevent coupling of 7 kHz voice uplink carrier to phone line. Now, only 3 kHz data carrier and direct audio voice downlink are transmitted through-the-earth.

2) The air velocity sensors lost their output when mounted on metal conduit and connected to inputs of subsurface stations. Problem was determined to be a short circuit through metal case of velocity sensor to grounded conduit. Use of insulated mounting for sensors corrected the problem.

3) Paging via phone line was distorted from stations #2 and #20 and could not be established from #1. Investigation revealed open circuit between #1 and rest of phone line, a short between conductors in section of

audio line in explosive test entry, and a short to ground on the green conductor near the mine office end. The problems in the section in the explosive test entry were corrected, and the green conductor was broken at the first tee in the Safety Research entry. (The section between this tee and the mine office remains shorted to ground and should be investigated.

4) The large loop receiving antenna at the surface station became inoperable. Investigation revealed the wire was cut in 5 different places and a section had been removed by electrical contractor personnel working in the area. The breaks were spliced and the performance of the antenna was tested. The large loop produced a much higher level of power line related noise than the ferrite core loop located just outside building 0-7. The ferrite core loop also provided much better reception of signals from all 3 subsurface stations than did the large air core loop.

Several other problem areas became apparent during system checkout which were not corrected because they involved either major circuit modification or changes in system design concepts. These are listed below:

(1) High EM noise level keeps subsurface receiver Squelch open at all times, causing bothersome noise output from speaker unless volume is reduced excessively. This could be corrected by modification of the Squelch circuit to provide a wider range of threshold settings or by reduction of overall receiver gain or a combination of both.

(2) Data carrier oscillators are somewhat temperature sensitive and require "in situ" frequency adjustment. This problem could be eliminated by the use of tuning forks or crystal stabilized oscillators.

(3) The single ended phone line coupling technique employed in the system is susceptible to common mode voltages that may be coupled to the phone line from other sources or induced by electromagnetic fields. While this is not apparently causing any problems now, it could in the future if conditions change. A balanced transformer coupling method could be

incorporated to reduce the probabilities of such problems.

(4) The present system implementation permits the antenna junction box (which contains the antenna tuning capacitors) to be located up to 30 feet from the subsurface station. This arrangement requires two people for tuning the antennas - one to operate the transmitter and the other to adjust the tuning capacitors. A testing mode control switch in the transmitter, and a remote tuning indicator in the antenna J-box would permit tuning by only one person. Additional test functions could be added to simplify system checkout.

(5) Some of the integrated circuits have had an unusually high failure rate, particularly the 4009 Hex inverter circuits. The manufacturer has recently introduced a replacement circuit which he claims is more rugged and reliable than the 4009. Replacement of all IC's with a history of several failures should greatly improve system reliability.

(6) Use of the Paging Switch at the surface station for checking the subsurface units by the "Loop Back" technique presently actuates all subsurface stations simultaneously. The simultaneous transmissions interfere with each other (unless the surface antenna configuration permits area selective reception) and do not provide an adequate test of the system. A selective calling and control system could be incorporated to permit remote actuation and polling of a single station at a time. Until such a system is incorporated, only the subsurface station at the furthest end of the phone line should be actuated for "Loop Back" testing. Removal of a single diode in a subsurface transmitter will prevent it from being remotely actuated by application of an external paging voltage. (It will still operate the same under local control and in all other modes.)

The final status of the system at the time WGL personnel returned to Boulder was as follows:

1) Data uplink was functioning properly for all stations for both the phone line and through-the-earth, electromagnetic propagation (EM) using the ferrite receiving antenna (A-3) outside building 0-7.

2) EM voice uplink from stations #1 and #2 not operable with the present surface receiving antenna configuration. EM voice uplink from station #20 operable but with poor voice signal quality.

3) Telephone communications between all subsurface stations and surface station acceptable with good voice signal quality.

4) Loudspeaking telephone (Paging) communications acceptable from surface-to-subsurface stations, but weak and distorted from subsurface-to-surface station.

5) EM voice downlink signal strength and voice quality acceptable at all stations; however squelch threshold range is not adequate to block EM noise in the absence of signal.

6.0 PERFORMANCE EVALUATION

The performance of a communication system can be evaluated by measuring its performance characteristics under a known set of conditions, then comparing it to theoretical standards for these same conditions. Section 2 of this report has previously defined the theoretical signal-to-noise ratio requirements of the system. This section calculates theoretical signal strengths for the installed system configuration, describes the results of laboratory and field performance tests, and relates the results obtained to the theoretical values.

6.1 Theoretical Signal Strengths

Theoretical values of signal strengths for the installed system configuration can be calculated using measured values of antenna current, antenna geometry, thickness of overburden between source and receiving antennas and conductivity of the overburden.

Uplink

Antenna currents of the subsurface transmitters were determined for both the voice and data modes by measurement of the voltage drop across the 2 ohm series resistor which normally drives the TRANSMITTING indicator lamp.

Antenna current moments were calculated using the product of the measured current times 12 turns, times the area in square meters estimated from the loop geometry. The measured currents, calculated moments, and path lengths are tabulated in Table 6-1.

TABLE 6-1

Uplink Signal Strength Parameters

tion	Mode	Freq., f (kHz)	Ant. Current, I (Amps.)	Area (sq.m)	Ant. Moment, INA (Amp turns meters^2)	Path Length, Z (meters)
	Voice	7.0	0.58	120	830	332
	Data	3.39	0.75	120	940	332
2	Voice	7.0	0.90	120	1296	268
	Data	3.45	1.2	120	1728	268
20	Voice	7.0	1.1	13	172	74
	Data	4.53	1.5	13	234	74

For all three subsurface stations, the lateral distance from the center of the transmitting antenna to the surface receiving antenna is much greater than the vertical depth. In effect then, the transmitting and receiving loops are more nearly coplanar than coaxial and the coupling relationships defined by curve $|D|$ in Figure 2-6 are used in the calculation of expected field strengths at the surface receiving antenna.

Using the transmitting frequency (f) and the average conductivity of the path (σ_a), the skin depth (δ) is:

$$\delta = \frac{503.3}{\sqrt{\sigma_a f}}$$

The average conductivity of the overburden at the Bruceton test site had previously been measured [2] and found to be 0.02 mhos per meter.

The ratio of the path length (Z) to the skin depth (δ) determines the coupling parameter $|D|$ from Figure 2-6 which is then used to determine the electromagnetic field strength (H_y) from the equation:

$$|H_y| = \frac{INA\,|D|}{2\pi (Z)^3}$$

Expected field strengths at the location of the surface ferrite antenna, A-3, were calculated for all three subsurface stations at both data and voice carrier frequencies. These are tabulated in Table 6-2 and are also plotted in Figure 6-1 together with expected levels of atmospheric and man-made noise.

TABLE 6-2

Expected Uplink Signal Strengths

Station	Mode	Freq., f (kHz)	Skin Depth, δ (meters)	Z/δ	|D|	Signal Strength, |Hy| µA/meter	dB re 1 µA/meter
#1	Data	3.39	61.1	5.4	0.048	0.196	-14.2
	Voice	7.0	42.5	7.8	0.0075	0.027	-31.3
#2	Data	3.45	60.6	4.4	0.11	1.57	3.9
	Voice	7.0	42.5	6.3	0.024	0.26	-11.8
#20	Data	4.53	52.9	1.38	0.74	43.3	32.7
	Voice	7.0	42.5	1.72	0.62	70.3	36.9

Section 2.5 calculated the required S/N for the data uplink to be 7 dB for Gaussian noise. The receiving system was designed to operate in a 30 Hertz bandwidth centered between the harmonics of the power line frequencies to reduce the susceptibility to man-made noise and interference. The noise components which should limit performance of the data uplink are the antenna and first amplifier thermal noise and atmospheric noise. In the narrow bandwidth employed, these would both appear very nearly Gaussian.

Figure 6-1 shows the required 7 dB S/N should be attainable in the winter time for all three subsurface stations using the ferrite receiving antenna located just outside building 0-7. Proper operation of the data uplink for all three subsurface stations was obtained during the checkout in January, 1973. The expected signal strength from station #1 would be marginal,

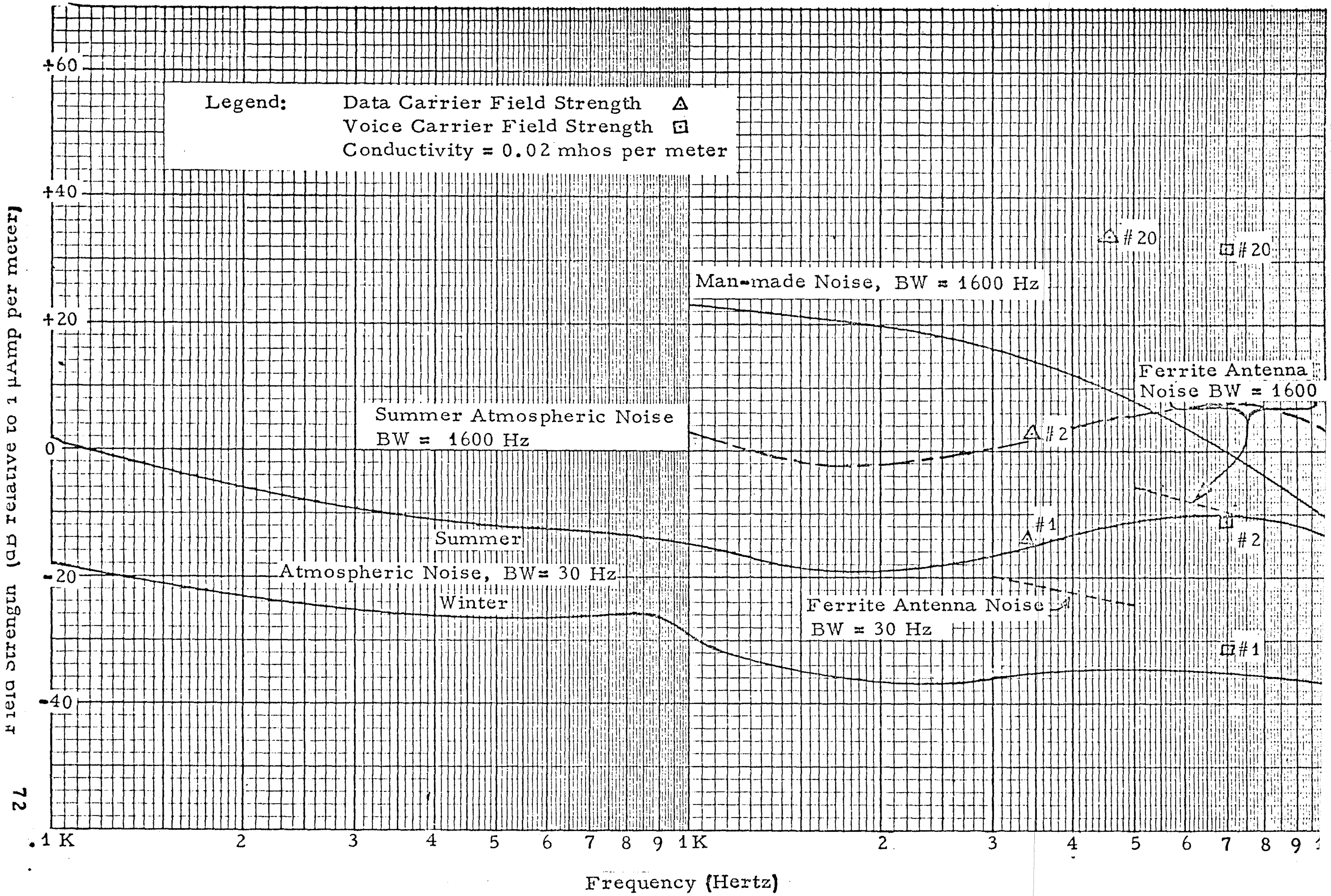


Figure 6-1. Predicted Uplink Signal and Noise Strengths

however, for summer atmospheric noise conditions, so a better receiving antenna configuration is indicated.

The voice uplink, which requires a much wider bandwidth, would normally have its performance limited by either man-made noise or atmospheric noise. Figure 6-1 shows that only station #20 should provide the required 12.5 dB S/N (as calculated in Section 2.5) with the present receiving antenna deployment. Tests made during the system checkout confirmed that through-the-earth voice uplink signals could only be received from station #20. Additional receiving antennas could be deployed to reduce the path lengths from stations #1 and #2 and provide signal strengths of about the same magnitude as that from station #20.

Downlink

Downlink signal strengths were calculated using the coupling parameter $|A|$ in Figure 2-6 for a long horizontal wire antenna as determined by the ratio of path length (Z) to skin depth (δ) at a frequency of 1.9 kHz. (The center of the downlink direct audio band of 762-3000 Hz.) For the conductivity 0.02 mhos per meter, the skin depth is 81.6 meters at 1.9 kHz.

The signal strength $|H_x|$ was calculated for an antenna current of 0.5 Ampere (which was determined experimentally for a typical voice message) using the equation:

$$|H_x| = \frac{I|A|}{2\pi Z}$$

Expected downlink signal strengths for all three subsurface stations are tabulated in Table 6-3 and are plotted in Figure 6-2, together with expected levels of man-made, subsurface EM noise and thermal noise from the receiving antenna.

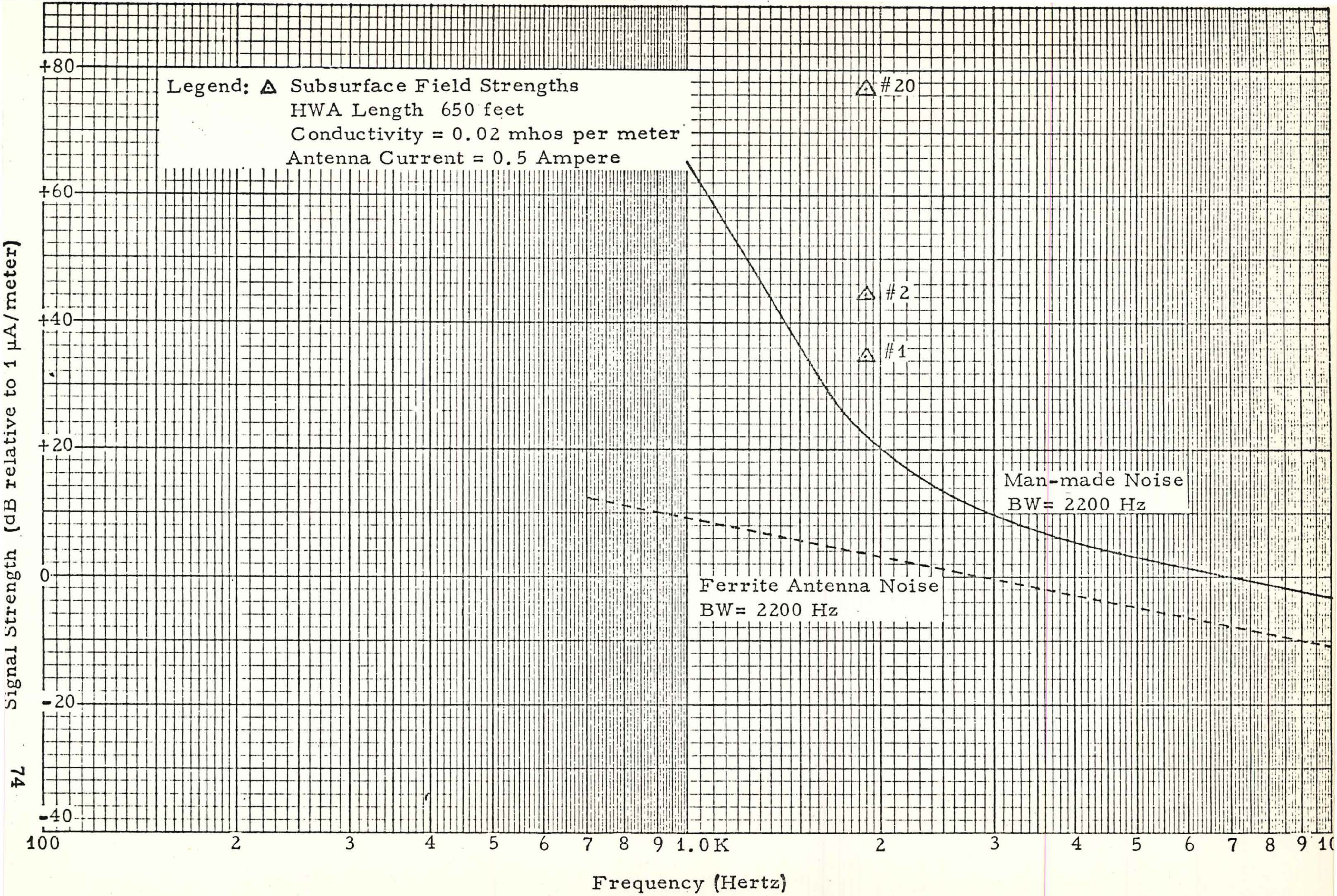


Figure 6-2. Predicted Downlink Signal and Noise Strengths

TABLE 6-3

Expected Downlink Signal Strengths

Station	Path Length, Z (meters)	Z/δ	|A|	Signal Strength μA/meter	dB re 1 μA/meter
#1	262	3.2	0.17	51.6	34.3
#2	183	2.24	0.37	161	44.1
#20	12	0.15	1.1	7300	77.3

The S/N > 0 dB required for the direct audio transmission technique (see Section 2.3) was easily achieved for all three subsurface stations. Voice transmission tests during the system checkout confirmed adequate S/N for intelligible voice downlink transmission.

6.2 Laboratory Tests

Performance of the system in the presence of Gaussian noise was measured in the laboratory for comparison with the performance predicted by the theory in Section 2.

Data/Beacon Uplink

The performance of the Data/Beacon uplink was measured, using the test set-up shown in Figure 6-3. A sample of the signal from the subsurface transmitter was coupled from the 2 ohm series resistor in the antenna circuit into an attenuator and then into a resistive summing network.

Gaussian noise from a Quan-Tech Model 420 noise generator was also coupled into the resistive summing network which had identical transfer characteristics for both input ports.

A Hewlett-Packard Model 3400-A RMS voltmeter was used to measure the signal level (S) into the summing network for calculation of signal-to-noise ratios and into the dummy antenna for determining equivalent field strengths.

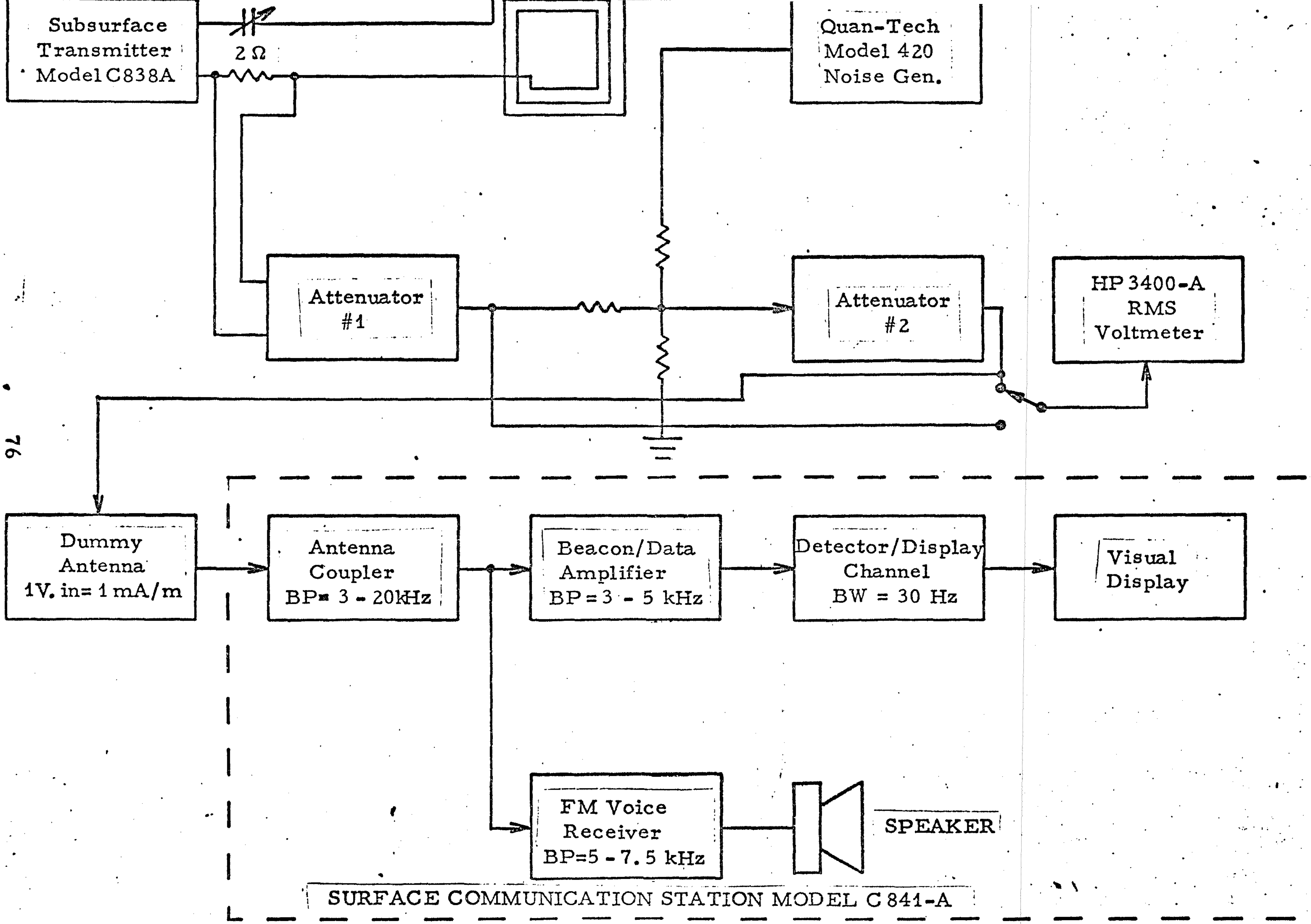


Figure 6-3. Test Set-up. Uplink Performance Tests.

The noise spectral density (N_o) was read directly in $\mu V/\sqrt{Hz}$ from the meter on the noise generator.

The lowest S/N_o for which the receiver would respond properly to changed data status signals was determined experimentally to be 20. ($S = 20$ mV, $N_o = 1$ mV/$\sqrt{Hz}$.) The equivalent signal-energy-to-noise-density ratio, E/N_o is:

$$\frac{E}{N_o} = \frac{S}{N_o}(T)$$

where: T = Duration of signal bit = 0.2 sec

$$\frac{E}{N_o} = 20(0.2) = 4 \quad \text{or} \quad 12 \text{ dB.}$$

In the coded beacon reply mode, an $\frac{S}{N_o} = 20$ produced a bit error rate of ≈ 0.02. This corresponds to a word error rate of 0.1 (because 1 error in any of the 5 bits of a data word produces a word error) which was determined by visual observation of the readout.

Figure 2-9 shows that a practical limiter-discriminator should perform with a bit error probability of 0.02 for $\frac{E}{N_o} = 9.6$ dB. The curves of Figure 2-9 assume an optimized system, where the receiver bandwidth is matched to the data rate. Since the receiver bandwidth in our system could not be made narrow enough to match the data rate (BW $\approx$ 30 Hz, R = 5 Hz) the additional noise reduces the performance slightly from the ideal system. The approximate 2 dB performance improvement which could be realized through optimization of the channel filters would not be worth the added cost and complexity required.

The data monitor display circuit in the receiver incorporates additional logic to minimize the probability of false data status indications because of noise. This circuitry requires that at least 20 bits of a block of 30 be received in the proper order to produce the correct data status indication. Gaussian noise into the detector (limiter-discriminator) produces a random stream of ones and zeros to be fed through the pattern recognition circuitry of the data status message decoder. The probability that any one of these bits would match one in one of the desired patterns is 0.5. The probability that 20 of these random bits from a group of 30 would match a preselected pattern of 20 is then

$$P_f = 30\ (0.5)^{20} = 2.9 + 10^{-5} .$$

At the bit rate of 5 bits per second, this would average 1 error every 9.7 hours, and since the data status is normally updated every 10 minutes, the probability of displaying a false data status is very small.

FM Voice Uplink

The same basic test set-up shown in Figure 6-3 was used to test the performance of the FM Voice Uplink. A tape recorded voice message was used to modulate the FM voice carrier in the subsurface transmitter. The S/N_o required to produce intelligible voice signals was measured to be 400 ($S = 4$ mV, $N_o = 0.01$ mV/$\sqrt{Hz}$).

This corresponds to S/N_a in the receiver bandwidth ($B \approx 2500$ Hz) of

$$\frac{S}{N_a} = \frac{400}{\sqrt{2500}} = 8 \qquad \text{or } 18 \text{ dB.}$$

This result is consistent with the theoretical input $\frac{S}{N_a}$ requirement of 16.3 dB for a narrowband FM system as described in the theoretical analysis of Section 2.3.

Direct Audio Voice Downlink

The performance of the direct audio voice downlink was measured, using the test set-up shown in Figure 6-4. The output of a tape recorder with a recorded voice message was filtered to a 500 - 3000 Hertz bandwidth for use as a test signal. This signal was attenuated and coupled into a dummy antenna which simulated the ferrite core receiving loop.

A Hewlett-Packard 3400A, RMS Voltmeter was used to measure the signal amplitude for determination of equivalent field strength.

The smallest equivalent field strength for which intelligible voice signals could be received was determined to be 2 μA per meter (or + 6 dB re 1 μA/m). Figure 6-2 shows the thermal noise in a 2200 Hertz bandwidth calculated for the ferrite receiving antenna. This thermal noise level is 4 dB re 1 μA/m at 1.9 kHz in the center of the receiver bandpass. Thus, intelligible voice signals could be received for $\frac{S}{N} \approx 2$ dB. Since this is a very subjective test whose results would vary greatly with the individual listener, the results cannot be considered to be in disagreement with the theoretical requirements listed in Section 2.3.

6.3 Performance Margin Tests

A communication system user usually wants to know what performance margin his system has. This will allow him to estimate the effects of changing environments and system configurations. A typical method of determining system performance margin is by comparing measured signal strengths and noise characteristics with measured receiver sensitivities and signal-to-noise requirements. While this method probably gives the best overall picture of system performance, it requires special instrumentation, which may not be available at many locations.

Another method of determining system performance margin is to determine the factors by which the transmitter antenna currents may be reduced until system operation just becomes marginal. This method infers that both

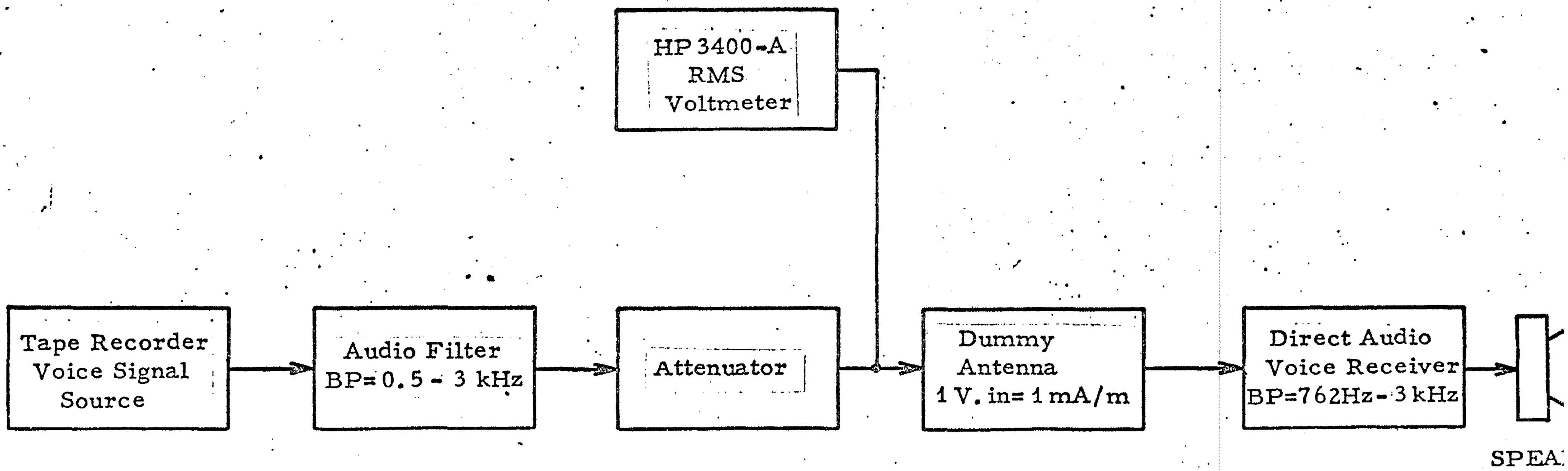


Figure 6-4. Test Set-up, Downlink Performance Test

terminals of the system are operating within their specified performance limits and that external noise conditions are typical at the time the test is performed.

This latter method was used at the Bruceton Mine to determine the operating margin for the data and voice uplinks for stations #2 and #20. Time was not available to perform this test for Station #1; however, its normal antenna currents were measured (see Table 5-1) and can be used to estimate its performance margin theoretically.

It had previously been determined by observing the beacon monitor amplifier output with an oscilloscope, that the ferrite core antenna just outside Building 0-7 provided excellent data carrier signals from all three stations. This antenna was used for the performance margin tests. The telephone line was disconnected during the test to assure that the signals were being received through only the EM link.

A variable resistance was connected in series with the transmitter antenna to reduce the antenna current. For each new value of resistance, the data monitor status was changed and the subsurface transmitter was actuated. The data status lights were observed at the surface unit to see that they changed to indicate the new status.

Using this technique, the antenna current for Station #2 was reduced to less than 48 milliamperes before the system failed to respond properly to a changed data status. This is a 28 dB reduction from the normal antenna current of 1.2 amperes for that station.

The antenna current at Station #20 was reduced to less than 6 milliamperes before the system failed to properly indicate a changed data status. This is a reduction of 48 dB from the normal antenna current of 1.4 amperes for that station.

With the present receiving antenna configuration at the surface station, FM voice uplink signals from Stations #1 and #2 are too weak to be usable. FM voice uplink signals from Station #20 were somewhat noisy and distorted, but were strong enough for a performance margin test. Again a variable resistor was inserted in series with the antenna to reduce transmitter antenna current. For each new resistance value, a short voice message was transmitted to the surface where it was evaluated.

For moderate series resistance (32-64 ohms) the quality of the transmission was improved because the series resistance widened the transmitter antenna bandwidth. For greater resistances the signal-to-noise ratio decreased until the threshold of intelligibility was reached at about 61 milliamperes of antenna current. This corresponds to a 25 dB reduction from the normal current of 1.1 amperes for this station.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The best measure of whether a communications system fulfills the objectives for which it was designed is its performance in day-to-day use. Deficiencies in concept, design, or implementation usually become apparent with age and exposure to a variety of users. Until such a history can be accumulated for a particular system, one must use other standards to evaluate its overall utility.

A review of the program objectives and the degree to which they have been achieved will aid in the evaluation of the system which was developed on this program.

7.1 Conclusions

The overall objective was to develop a quasi-hardened, fixed location, in-mine communications subcenter that can be used in normal mine operations and be ready for use in post disaster rescue operations. Information from a large number of subcenters was to be gathered together in a single display identifying board with intercom. The system was to use the earth-rock overburden as the communications media and the design concept was to consider the use of existing mine phone lines and means of changing the signal path from phone line to through-the-earth or energizing both simultaneously.

This overall objective has been met in the design concept developed and in the demonstration hardware fabricated.

Specific features which were to be considered in the hardware design (in the same order as they are tabulated in Section 1.1) will now be listed with appropriate comments.

Subsurface System

a) Operation from a 440 volt float-charge battery has been accomplished.

b) Sensor signaling of three ranges -- normal, below normal, and alarm has been accomplished and will accommodate either increasing or decreasing sensor outputs. Continuous operation has been interpreted to mean continuous monitoring. Status update is performed at 10 minute intervals or upon change of data status.

c) Small speaker used as a microphone/speaker was not implemented. A loudspeaker was used for paging and through-the-earth voice link, and a separate telephone type handset was used as a microphone and for communication on the phone line. This arrangement was judged to give better overall performance than a single small speaker.

d) The basic receiver element was not similar to the receiver developed under contract H0101262. The previously developed receiver was not readily adaptable to the requirements of the system concept adopted.

e) The transmitter-amplifier employed the same basic amplifier circuits and antenna as developed on contract H0101262. The modulator was changed to accommodate the PCM/FSK coding method used.

f) Uplink-signaling was not similar to the on-off coding used on the uplink transmitter of contract H0101262. The PCM/FSK coding employed for this system offers better performance as well as circuit and parts standardization for the subsurface transmitters and surface receiver data channels.

g) Packaging and mounting to permit station to endure shock wave and flame front to a limit twice that of which a human being could endure (i.e., 10 psi, half second pressure impulse, 2500° Kelvin) has not been tested and is difficult to evaluate. Packaging is in rugged steel case with provision for mounting by two 3/8" steel bolts and exposed components are generally small and rugged.

h) Uplink voice using minimum bandwidth that permits intelligible communications is a rather subjective specification. Past experience has shown that bandwidths as narrow as 500 Hz may provide intelligible messages for a trained listener, but that other listeners require much wider bandwidths. This system utilizes a receiver bandwidth of $\approx$ 2500 Hz and a transmitting antenna bandwidth which is somewhat dependent on losses for each individual antenna configuration, but is ≈ 1 kHz at the -3 dB points. This combination produces an acceptable compromise between voice fidelity and susceptibility to EM interference.

i) Uplink beacon mode signaling overrides data monitoring, and voice uplink overrides both data and beacon signaling.

Surface Subsystem

a) Data monitored is accumulated and compiled (displayed) at a central communications center. The system concept employed accommodates up to 20 individual subsurface stations with a single surface station. Additional subsurface stations can be accommodated by additional surface stations at the same central location if space diversity (physical separation) of the systems is employed.

b) Problems encountered when mine is situated under a developed community/undeveloped community would relate primarily to the deployment of surface station antennas and the greater amount of man-made noise to be encountered in a developed community. Deployment of antennas in a developed community would have to be considered on an individual mine requirement basis. It is very likely that for a mine underlying a developed community that through-the-earth transmission links would only be employed in a post-disaster situation if the normal phone-line links became disabled.

For a system required to operate in a developed community where man-made noise is very high, special noise reduction techniques such as the use of synchronous, power line harmonic filters, can be employed at the surface receivers.

c) The alarm signal is visible and audible, both at the surface station and at the subsurface stations. The audible alarm can be disabled by a front panel switch at each station.

d) At the surface station, individual channel display lights indicate the status of each subsurface data monitor and identify the station reporting an alarm.

e) The downlink transmitter used is GFE, identical to the unit developed under contract H0101262.

f) The uplink signal monitor is entirely different from the unit developed under contract H0101262 which was not adaptable to the concept employed for this system. Physical size alone would make a multistation system employing such a receiver very impractical.

The system concepts and demonstration hardware developed on this program fulfill the basic objectives of the program and incorporate nearly all of the design considerations requested by USBM. As in any development program, we find in retrospect that we would probably do things differently if we were starting over with the knowledge and experience we have gained.

Some of the features incorporated in the present system have proven to be quite desirable and would be retained, others which are unneeded or not as desirable would be eliminated, and some totally new features conceived during this program would be added.

7.2 Recommendations

Development of a system optimized to meet the requirements of a variety of working mines is a logical consequence of the work performed on this program. Such a program should be undertaken using the knowledge and experience gained on this program.

System concepts should be reviewed and updated in view of experience with the present system, system hardware implementation should be revised to incorporate the features necessary and desirable for use in working mines, and finally, prototype hardware should be designed, fabricated, and thoroughly tested in a working mine environment.

The present system hardware can continue to be used by USBM to demonstrate the system concepts developed on this program and to accumulate a use history which can aid in future evaluations of mine communications and monitoring system concepts.

Present System

The present hardware, which was developed on this program to demonstrate the feasibility of certain system concepts, requires some additional work to optimize its performance. It is recommended that the following steps be taken to assure that the hardware, now installed at Bruceton, adequately demonstrates the capabilities requested by USBM in the program objectives:

1) Replace certain integrated circuits which have had several unexplainable failures with new more rugged, direct replacement units now available from the manufacturer.

2) Improve the phone line link by the addition of balanced coupling transformers and a twisted shielded line to all stations.

3) Perform minor circuit modifications to voice link receivers which will improve the squelch characteristics and permit less critical receiving antenna orientation.

4) Incorporate preamplifiers in the surface station ferrite receiving antennas and redeploy in a configuration optimized for through-the-earth reception of the FM voice uplink.

5) Incorporate circuit modifications in subsurface stations which will increase operational reliability and will facilitate maintenance and checkout. These would include the addition of internal test points and controls, a remote tuning indicator in the antenna tuning box, and a sensor excitation supply for the air velocity sensors presently used with the system.

Future Systems

Even though the in-mine experience with the present system has been quite limited, it has provided valuable insight for development of future mine communication and monitoring systems. Some recommended guidelines to follow when designing equipment for such systems are listed below:

1) Use modular construction concepts with subsystem modules organized according to circuit function. Maximize the number of modules which can be used interchangeably in a number of

different stations, and minimize the number of modules or components which are unique to individual stations. This concept can greatly facilitate maintenance and troubleshooting through the use of module replacement and substitution.

2) Minimize the number of separate functions a given piece of equipment is to perform and design it to optimize its primary function. Use the modular function concept to provide independent operational capabilities within the same basic package. For example, the data monitor and beacon message functions which utilize narrowband PCM/FSK transmissions in the 3-5 kHz range should be completely independent of the voice links which utilize direct audio in the range 700-3000 Hz and FM audio in the 5-8 kHz range.

   It should be possible to remove the modules for one or more functions at a given station without disabling or impairing the effectiveness of the other functions.

3) Use strong, lightweight, corrosion resistant packaging material, such as fiberglass, with size and shape of packages designed for easy transport, convenient mounting and blast resistance.

4) Incorporate self-test circuits or integral test function generators, together with easily accessible adjustments and test points wherever practical.

5) Design the underground transmitter amplifiers to provide greater antenna matching flexibility while still maintaining intrinsically safe operation. This would permit optimization of the through-the-earth uplink at a variety of mines by the use of tuned moderate size multiturn loops, tuned or untuned large area single turn loops, or long wires terminated in roof bolts or ground stakes.

6) Incorporate a selective call-up system to provide remote actuation of individual subsurface transmitters from the central monitor station at the surface, to permit polling of data status at a specific time and for verification of system operation.

   This concept could be extended to permit subsurface transmitters to also provide EM paging signals for selective actuation of several individual portable receivers within the section served by the station.

8.0 REFERENCES

1. "Coal Mine Rescue and Survival System, Final Report Vol. II, Communications/Location Subsystem," September 1971. Prepared for Bureau of Mines under Contract H0101262 by Westinghouse Electric Corporation.

2. "Mine Emergency Operations Program, Summary Report Vol. I, Data Collection and Field Testing," June 1972. Prepared for the Bureau of Mines under Contract H0210063 by Westinghouse Electric Corporation.

3. An Introduction to the Principles of Communication Theory, John C. Hancock, McGraw Hill, 1961.

4. Modulation, Noise and Spectral Analysis, Philip F. Porter, McGraw Hill, 1965.

5. "Manual of Operating and Maintenance Instructions for Surface Equipment, Coal Mine Rescue and Survival System, Second Edition," Westinghouse Georesearch Laboratory for Bureau of Mines on Contract H0101262.