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ANALYSIS OF COMMUNICATION SYSTEMS IN COAL MINES

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Dr. M. D. Aldridge
Associate Professor

USBM GRANT FINAL REPORT
Grant No. G 0101702 (MIN-39)

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DEPARTMENT OF ELECTRICAL ENGINEERING
WEST VIRGINIA UNIVERSITY
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USBM GRANT FINAL REPORT (GRANT NO. G0101702 (MIN-39))

May 1, 1973

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
WASHINGTON, D.C.

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

FOREWORD

This report was prepared by West Virginia University, Department of Electrical Engineering, Morgantown, West Virginia, under USBM Grant No. G 0101702 (MIN-39). The contract was initiated under the Coal Mine Health and Safety Research Program. It was administered under the technical direction of the Pittsburgh Mining and Safety Research Center with Mr. Howard Parkinson acting as the technical project officer. Mr. Joseph Herickes was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period June 5, 1970 to June 29, 1972. This report was submitted by the authors on May 1, 1973.

This technical report has been reviewed and approved.

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.

4. Title and Subtitle

Analysis of Communication Systems in Coal Mines

5. Report Date (date of submission)
May 1, 1973

6.

7. Author(s)
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8. Performing Organization Rept. No. WVU-ENG-EE-001

9. Performing Organization Name and Address

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10. Project/Task/Work Unit No.

11. Contract/Grant No.

G0101702 (MIN-39)

12. Sponsoring Organization Name and Address
United States Bureau of Mines
Pittsburgh Mining and Safety Research Center
4800 Forbes Avenue
Pittsburgh, Pennsylvania 15213

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

The results of a two-year research effort aimed at improving communication systems in coal mines is reported. A review of communication methods presently used in coal mines is presented. Theoretical and experimental results of a four pronged effort in the areas of (1) through-the-earth propagation, (2) paging system design, (3) improvement of wired telephone systems, and (4) carrier current systems are described. Auxiliary systems not included in the above are considered briefly. Various conclusions are drawn in light of practical constraints and the needs of the mining industry.

The study clearly demonstrated the need for mine communications to be designed on system basis. The viability of new technology for providing reliable mine communication for improving mine safety and operating efficiency is shown.

17. Key Words and Document Analysis. 17a. Descriptors

Coal Mines
Telecommunications

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement Release Unlimited	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 138
	20. Security Class (This Page UNCLASSIFIED	22. Price

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INTRODUCTION

This document reports the results of a two-year research effort aimed at improving communication systems used in coal mines. This work was conducted under a program whose original goal not only involved the development of practical and effective electronic systems for operational communications, but also for monitoring, at a central location, remote instruments at key positions in a mine. About half way through the originally proposed three year effort, the program was redirected to phase out the communication effort at the end of two years and to concentrate the program's resources on the investigation of new monitoring system concepts developed by this research. Thus, the work reported here is incomplete relative to the originally proposed program. However, the work was carried to the point of providing sufficient evidence to aid in the comparison of certain new communication concepts. For the concepts chosen for this study, the work was stopped short of hardware development and field testing.

Several reports in the form of Master's theses and a Doctoral Dissertation have resulted from this research. They each report in considerable detail the results of several individual's contributions to this program. In preparing this report, an attempt has been made to provide a complete description of the significant results but without burdening the reader with the minute details. These more detailed reports are referenced heavily for the convenience of those interested.

PRESENT COMMUNICATION METHODS

Two types of communication systems are presently used in coal mines. They are:

1. Various forms of telephone systems, and
2. Carrier current radio systems using the trolley line as the interconnection circuit.

Carrier current radio is used almost exclusively for control of rail traffic by the dispatcher. Almost all other communication uses the telephone system. Telephone lines generally extend to areas where trolley lines are not present such as the outside offices and warehouse. Therefore the telephone system provides the primary means of voice communication.

<u>Telephones</u> - Telephone systems employed in American coal mines fall into three categories.

1. <u>Paging type telephone systems</u> - these systems have individual stations which use battery powered transistor audio amplifiers to boost signal levels for normal communication. When in the page mode,

a higher powered amplifier is connected to a speaker at each station. This type of system generally has all telephones connected in parallel throughout the mine yielding a "party-line". In a few large mines, the telephone system is split into two to four areas which can be patched together when needed.

A typical schematic for this type of telephone is shown in Figure 1. A push-to-talk button in the handset activates the auxiliary amplifier. Paging is accomplished by pressing a spring loaded switch which applies DC voltage across the telephone line. This activates a relay (or electronic switch) in all other stations which applies power to the paging amplifier.

2. Crank ringer systems - for many years, the only communications in coal mines was supplied by the conventional telephone with carbon transmitter, dry cell batteries, and crank generator to supply AC ringing current. They were connected in a party line mode with coded long and short rings to identify the station being called. This type of system is still used in many coal mines. As coal mines grew larger, these systems suffered from inadequate signal level. Larger mines were forced to break the telephone system up into separate areas to maintain adequate signal-to-noise ratios.

3. Dial telephone systems - automatic dial systems are used at several American coal mines where they operate their own private automatic exchange for both inside and outside telephone service. Some systems feature the ability for key personnel, such as the mine superintendent, to override a busy signal. One system has the ability to put all or any number of phones into a party line mode. These systems are maintained completely independent of the local commercial telephone system, and no attempt is made to interconnect them.

The paging telephone system has wide spread use for two reasons. First, they permit persons and station areas to be paged by name and thus do not require the miners to learn ringing codes or telephone numbers. Secondly, use of booster amplifiers makes the system less affected by poor line splices and induced noise. It also yields a larger sound level at the receiver which is important when in the vicinity of large machinery. The primary disadvantage of paging telephone systems is that the telephone line must be used in a "party-line" arrangement. This prevents simultaneous conversations in the system and reduces its usefulness for "talking out" maintenance problems or other uses which can tie up the system for long periods of time.

Dial systems provide for many simultaneous conversations but do not possess the paging ability. Their need to use multiconductor cable discourages use of the dial system because of obvious maintenance problems when cable breaks occur from roof falls or accidents with machinery. This problem has been minimized by using the multiconductor cables only in the main haulage way where few roof falls occur and by taking conventional two-wire cable up to each section. However, this means all telephones on a section must be on a "party-line".

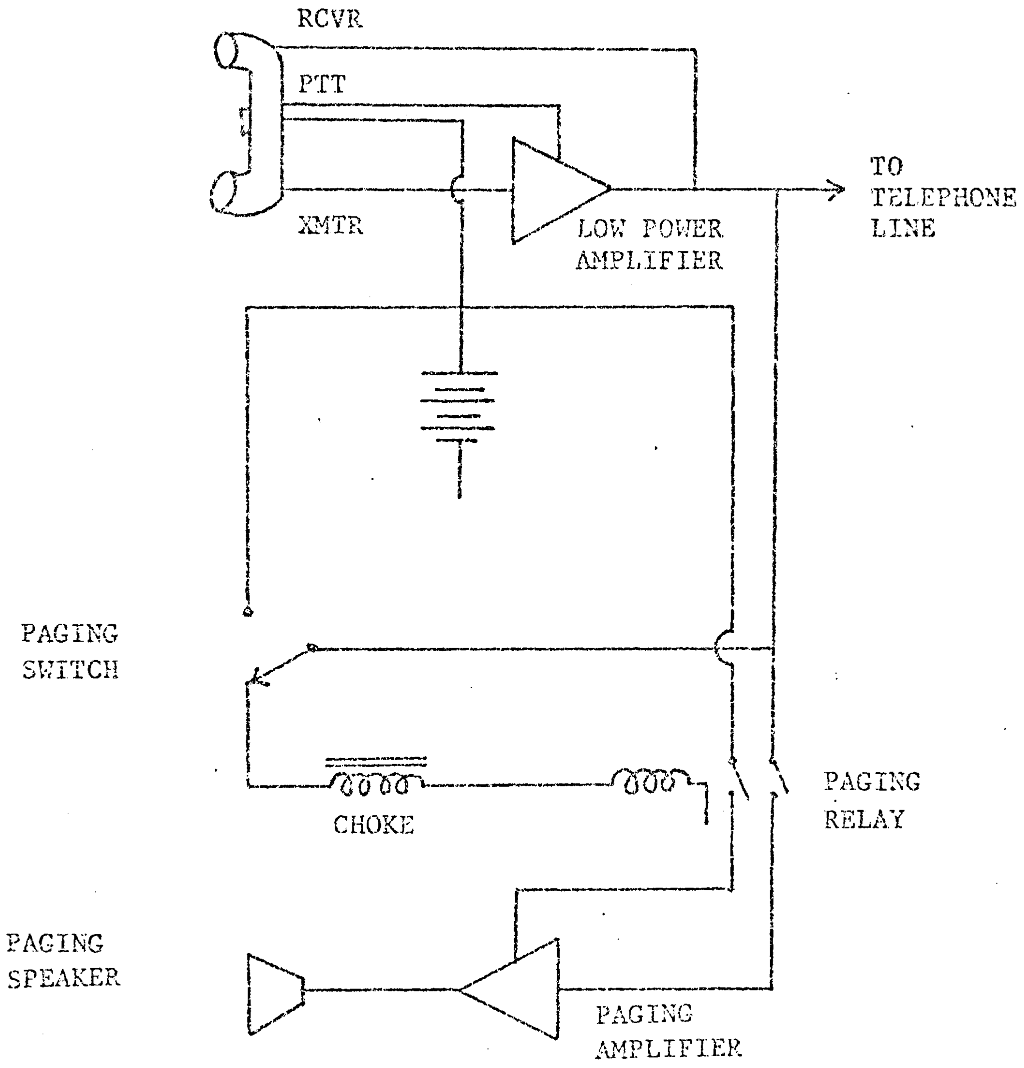


FIGURE 1

PAGING TYPE TELEPHONE

All the systems presently used in coal mines are inherently unreliable. That is, if a telephone line is broken or shorted by a roof fall, for example, all telephones beyond that point are severed from communication to the outside. If the line is shorted, communications in the entire system may be severely affected or inhibited completely. There apparently has been no attempt within the mining industry to develop a system employing alternate signal paths in the telephone system.

Carrier Phones - Carrier current communication is used almost exclusively in mines with extensive rail haulage for coordination of rail traffic. By placing carrier current communicators (called carrier phones) on moving vehicles plus units at key stationary points such as the dispatcher, dumper station, and outside . An effective mobile communication system can be achieved for distances up to 10 to 15 miles with presently available equipment. As long as haulage co-ordination is the main function of the carrier phone system, the present single channel arrangement is adequate if properly maintained. However, in mines where maintenance and management depend heavily on the carrier phone system for routine messages, it appears that a two-channel system would be desireable.

Few people are aware of the potential usefulness of the carrier phone system in an emergency if the equipment is battery powered. There is a gross lack of understanding about trolley phone systems among both engineering and management as well as the rank and file miner. Proper care and maintenance of carrier phone equipment is a common problem. These same conclusions are true for all types of electronic equipment used in and around coal mines.

Carrier current equipment possesses several operational difficulties. Foremost is the fact that a large haulage motor operating along a trolley line causes a short circuit to the carrier current signal. This effect can be minimized by utilizing the telephone wires as an alternate path for the signal to by-pass the short circuit as shown in Figure 2. Various configurations of coupling networks have been used and are available from manufacturers of carrier phone equipment. They all provide the same action of providing coupling of the carrier current signal to the telephone line from the trolley line. This solution works well when the coupling boxes are properly located and moved as the need arises, i.e. as the extremities of the trolley line circuits change.

Another problem with carrier current systems in many coal mines is the existence of "dead spots" which are caused by "destructive wave interference" in the system and can either be eliminated, or at worst, they can be "moved" to places in the system which cause the least problem. This is accomplished by properly placing coupling boxes. The proper positions for cross coupling between the trolley and telephone lines must usually be found by trial and error.

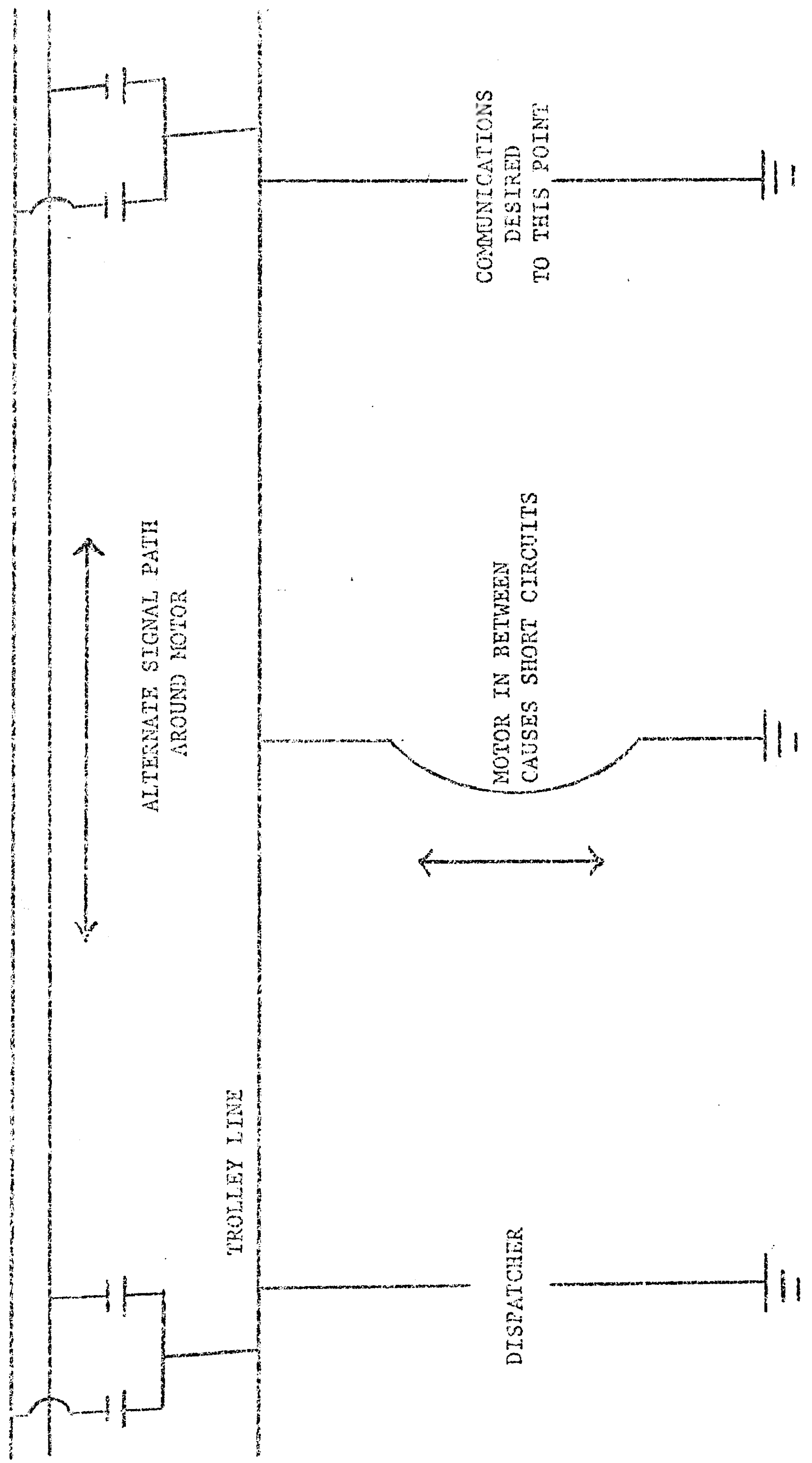


FIGURE 2

USE OF TELEPHONE LINE TO BY-PASS HAULAGE MOTOR

The manufacturers of paging telephones and carrier phones offer equipment to permit interconnection of the two systems. However, when talking from the trolley phone, the entire system operates in the page mode. This is not only annoying but it also causes the telephone batteries to discharge faster. Thus, the interconnection of the telephone and trolley phone systems is generally not employed except in special circumstances such as weekends when few people are in the mine.

Carrier current equipment is also used for control and other voice communication applications in several coal mines. The main use is for control and voice communications from cages and elevators in vertical and slope shafts. In a few mines, the technique is also employed to provide communication to the battery powered, rubber-tired vehicles. In both cases, a "messenger wire" is used in place of a trolley line and the signal is transferred to and from the vehicle via a tuned loop antenna mounted on the vehicle. The need for this type of service appears to be rather limited.

Outside Communications - Integral to the operation of an efficient mining operation is an effective communication system for activities outside the mine workings. Many mines have their own private dial exchange which may or may not be compatible to the local telephone sytem. Many mines now employ two-way VHF radio systems to provide mobile communications to the outside foreman, and maintenance crews. Very little integration of the outside and inside systems has been attempted. Those mines which use inside dial phones also utilize the same exchange for outside phones and thus achieve a fully integrated system. The general policy is to place paging telephones and trolley phones only at those outside points where someone is readily available to receive and relay the messages. Almost invariable this is the lamphouse since someone is always on duty there.

RESEARCH PROGRAM RATIONALE

As the meetings with industry progressed and the conclusions from our findings began to take shape, it became apparent that research should exist in four areas.

1. Through-the-Earth Communications - From the beginning of this program it was apparent that the feasibility of some form of direct through-the-earth communication for routine uses must be investigated. Whereas the Mine Rescue and Survival System program (Ref. 1) emphasized communication with entrapped miners between inside and outside directly through the overburden, the emphasis of this work was placed on signalling between two inside points. Some work was done on signalling from the outside to the inside for paging system applications, The unique aspect of this work was the fact that the theoretical and experimental analysis techniques were formulated in a way to be most beneficial to the communications system engineer. This also required that noise data be obtained.

2. Paging System Design - Early in this program it was obvious that the weakest link in the mine communication system is its ability to alert men during an emergency in the face area and in other areas of the mine not sufficiently close to the telephone to know when they are being called. This is not only important to individual miner safety but also to the efficient operation of a mine. In view of the limited range which is inherent in any through-the-earth system, and numerous discussions with mine personnel it was concluded that the availability of some form of wireless personal paging system would provide the best solution to this problem. Ultilizing the early findings of the through-the-earth communication studies, a unique paging receiver design was investigated. Eventually the results of the through-the-earth studies were applied to design of an optimum paging system.

3. Improvement of Wired Telephone Systems - Even with the possibility of wireless communication methods, it is evident that wired telephone systems will continue to be the primary system for routine mine communication. In view of the investment in communication equipment already in coal mines, a solution using the conversion of present equipment appeared the most viable. Thus manpower was devoted to the investigation of ways mine telephone systems can be improved.

4. Carrier Current Systems - Although the use of carrier current on trolley systems is generally adequate, additional studies were deemed necessary in two areas. First was the potential usefulness of carrier phones during emergencies by using through-the-earth radiation. This was to be covered primarily by the through-the-earth communication studies utilizing data taken in the carrier phone frequency range (100 KHz). Secondly was the study of using carrier current signalling over high voltage power cables.

Consideration was given to other aspects of the communication system but did not involve the establishment of a research effort. Such were the use of "walkie-talkie" or hand held communication devices, the use of the two-way radio outside the mine, and incorporation of the local public telephone system into the mine system.

THROUGH-THE-EARTH COMMUNICATION

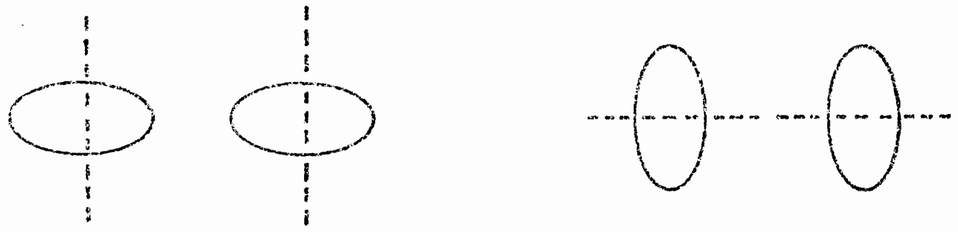
The possibility of signalling "through-the-earth" is not new to the scientific community. Theoretical analyses applicable to the problem date to Sommerfeld in 1909 (Ref. 2) and experiments were conducted as early as 1928 (Ref. 3) with communication applications in mind. Despite this early knowledge and a continuing experimental effort by the U. S. Bureau of Mines for about 20 years (Ref. 4), it was concluded that wireless communication in coal mines was not practical. However, these conclusions were based on the technology of the date and they no longer hold because of the advent of solid-state electronic devices and more sophisticated filtering and signal detection techniques.

Until recently, analytical and experimental programs involving "through-the-earth" propagation have been concerned primarily with the study of the geophysical properties of the earth and there was no attempt to conduct a systems analysis of a "through-the-earth" communication link. The work reported here was an attempt to bring together the necessary theory and experimental data to optimize the design of a practical "through-the-earth" communication system for use in an operating coal mine. The design of a paging system which evolved from this effort is described briefly.

GENERAL PROBLEM

This project was limited to the design of a communication system for use in an operating coal mine as well as having application during emergencies. It was not to be an "emergency only" communication system. With this constraint and recognizing the needs of the mining industry, the link configurations analyzed were limited to two situations: (1) between two points within a mine, and (2) between a surface transmitter and an underground receiver. Although, several different types of transmitting and receiving antennas can be used, it was decided to limit this initial endeavor to the use of tuned loop antennas for two reasons. First, when portability is desired the loop antenna is most practical, and second, the tuned loop is theoretically the best understood of the possible candidates.

Two arrangements of transmitting and receiving antennas were also analyzed as shown in Figure 3. These are described by their axial orientations, i.e. horizontal magnetic dipole (coaxial) where both loops have colinear horizontal axes, and vertical magnetic dipole (coplanar) where both loops have vertical axes and the loops are coplanar.



Vertical Magnetic
Axis

(Coplanar Loops)

Horizontal Magnetic
Axis

(Coaxial Loops)

Figure 3
Antenna Orientations Analyzed

Since the important quantity in communication systems is the available power at the output of the receiving antenna in relation to the transmitter power, the various arrangements described above were analyzed both analytically and experimentally by determining the power transfer between two loop antennas. These results are developed in detail in Reference 5 and will only be summarized here.

Since radio waves are attenuated rapidly in the earth, it appears reasonable to assume that for an inside-to-inside link in a deep mine, the transmission medium could be assumed to be of infinite extent. Moreover, although the conductivity of the earth in the vicinity of the mine may not be constant, calculations would be greatly simplified, if an average conductivity could be utilized and the medium treated as having a homogeneous conductivity. Thus the first part of the research program involved the study of power transfer between two tuned loops in an infinite homogeneous conductive medium in an attempt to determine if these assumptions would be valid and to study how system performance would depend on various parameters.

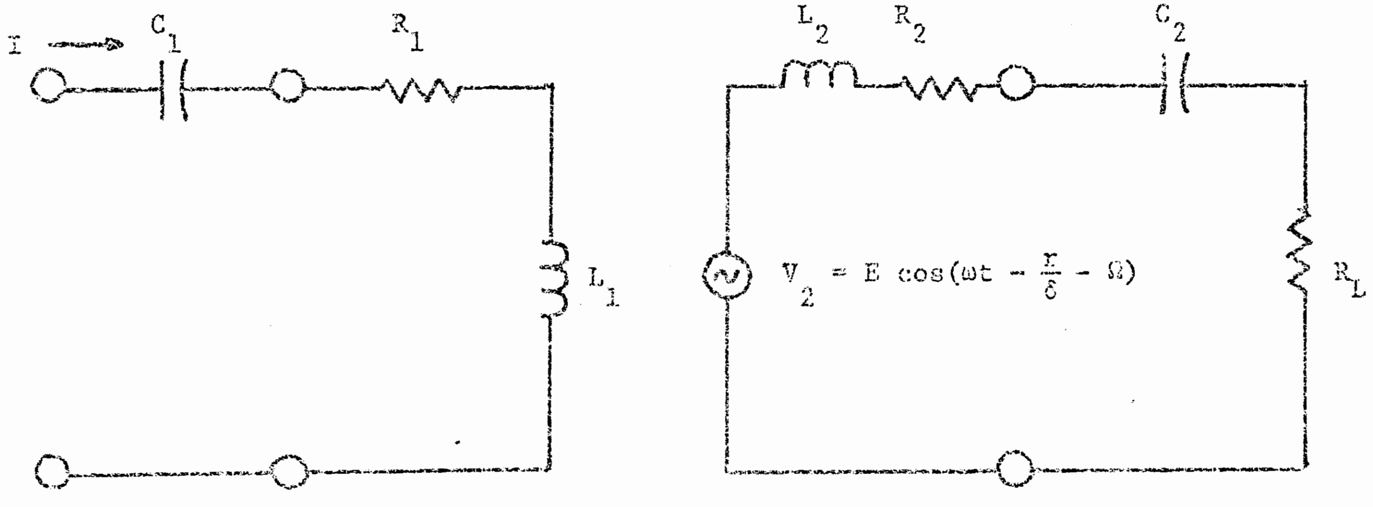
Power Transfer Between Coplanar Loops

At lower frequencies, where stray capacative reactance may be ignored, the loop antenna may be represented by an inductance in series with a resistance, as shown in Figure 4.

L_1 is the reactive component of the transmitting antenna, which is inductive at low frequencies. R_1 is the antenna resistance which includes radiation resistance plus copper losses of the loop. The input impedance may be made resistive, and equal to R_1, by correct selection of an external capacitance, C_1 , placed in series with the antenna.

The receiving antenna is represented by a voltage source, V_2, in series with a resistance, R_2 , and an inductance, L_2. Similar to the transmitting antenna these impedances represent the resistive and reactive components of the receiving antenna. In order to obtain maximum transfer of received power to the receiver, the receiver impedance must be conjagate matched to that of the antenna. The receiver is represented by a capacitance, C_2, in series with the resistive load R_L. The capacitive reactance of C_2 negates the inductive reactance of L_2, and R_L is equal to R_2. The maximum output power obtainable is:

$$P_r = \frac{[(V_2)rms]^2}{4\ R_2} \tag{1}$$



TRANSMITTING ANTENNA

RECEIVING ANTENNA

Figure 4
Antenna Low Frequency Equivalent Circuits

The transmitter source impedance will not be included in the power equations. Only the power delivered to the antenna will be considered. This exclusion will allow for a transmitter with a nonlinear output impedance to be used to drive the antenna. High transmitter efficiency may be obtained by tuning the antenna (varying C_1) to the fundamental frequency of a square wave produced by a switching type of transmitter.

The power delivered to the transmitting antenna is:

$$P_T = \frac{(I_1)_{rms}{}^2 R_1}{2} \tag{2}$$

Utilizing these equations and the relationship developed between V_2 and I_1 from known theory, reference 5 shows this yields the power transfer equation for coplanar loops:

$$\left(\frac{P_r}{P_T}\right)_{CP} = \frac{(-\omega\mu N_1\ A_1\ N_2\ A_2)^2}{64\ \pi^2\ R_1 R_2} \left[\frac{4}{\delta^4 r^2} + \frac{4}{\delta^3 r^3} + \frac{2}{\delta^2 r^4} + \frac{2}{\delta r^5} + \frac{1}{r^6}\right] e^{-\frac{2r}{\delta}} \tag{3}$$

where:

ω	signalling frequency in radian/second
A	antenna area
N	number of turns in antenna
R	total resistance of antenna
r	distance between antennas
δ	skin depth of earth at operating frequency

Although this equation gives the power transferred between two loops in a lossy medium it is not applicable without knowledge of the antenna resistance.

Radiation Resistance of a Small Loop Located in a Spherical Cavity - As mentioned previously, the reactive impedance of a small loop will appear inductive at the very low frequencies of interest. In addition to the reactive component as a result of the finite resistance to current in the loop (copper losses) plus the resistance associated with the radiated power (radiation resistance).

The copper losses of a loop antenna is determined by the size and length of the wire used in its construction. The total resistance due to copper losses becomes

$$R_c = N 2\pi a \, R_w \tag{4}$$

where

N = number of turns

a = loop radius (meters)

R_w = wire resistance in ohms per meter of length

The equation

$$R_r = \frac{\sigma(\omega\mu A N)^2}{6\pi b}\left(1 + \frac{b}{\delta}\right) e^{-\frac{2b}{\delta}} \tag{5}$$

is shown in Reference 5 to be an expression of the radiation resistance of a small loop located at the center of a spherical cavity of radius b within an infinite homogeneous lossy medium of skin depth δ. The only restriction on the equation is that the cavity radius must be small compared to a wavelength. The method used to develop this equation was to calculate the total power dissipated within the medium and equate that to radiation resistance.

The radiation resistance of a ten turn loop of one square meter area located in a 1 meter radius spherical cavity within a lossy medium is shown in Figure 5.

The total antenna resistance is the sum of R_c and R_r and equal to:

$$R = N 2\pi a \, R_w + \frac{\sigma(\omega\mu A N)^2}{6\pi b}\left(1 + \frac{b}{\delta}\right) e^{-\frac{2b}{\delta}} \tag{6}$$

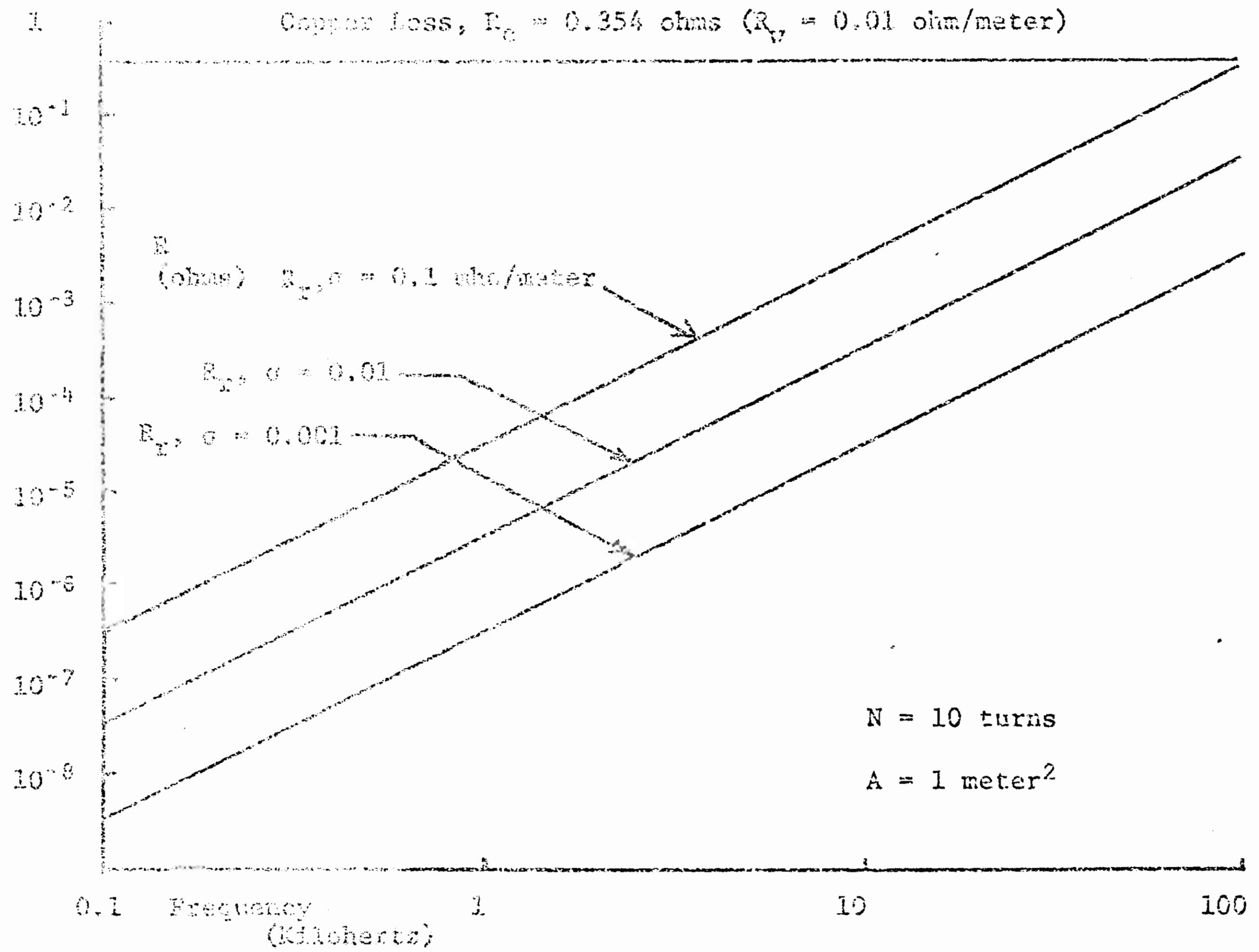


Figure 5
Radiation Resistance of a Small Loop in a Spherical Cavity

Figure 5 shows that at the lower frequencies (less than 50 to 100 Kilohertz) the copper losses are much greater than the loss due to radiation resistance. Thus it is concluded that the antenna resistance may be approximated by the copper losses.

Maximum Transfer of Power Between Coplanar Loops

This section is directed at finding the frequency at which the maximum transfer of power (minimum loss) occurs in the coupling between loops. Combining equations (3) and (6) and using the conclusion that the radiation resistance is negligible we find:

$$\left(\frac{P_r}{P_T}\right)_{CP} = \frac{f^2\mu^2\pi^2 a_1{}^3 a_2{}^3 N_1 N_2}{64\ R_{w_1} R_{w_2}} \left(\frac{4}{\delta^4 r^2} + \frac{4}{\delta^3 r^3} + \frac{2}{\delta^2 r^4} + \frac{2}{\delta r^5} + \frac{1}{r^6}\right) e^{-\frac{2r}{\delta}} \qquad (7)$$

This equation can be put into a form suitable for maximization by replacing the skin depth by its equivalent expression and grouping terms that include frequency to yield

$$\left(\frac{P_r}{P_T}\right)_{CP} = \frac{\mu^2\pi^2 a_1{}^3 a_2{}^3 N_1 N_2}{64\ R_{w_1} R_{w_2} r^6} \left[f^2(4Y^4 f^2 + 4Y^3 f^{3/2} + 2Y^2 f + 2Yf^{1/2} + 1)e^{-2Yf^{1/2}}\right] \qquad (8)$$

where

$$Y = (\pi\mu\sigma)^{1/2} r \quad .$$

Maximizing the expression within the brackets as a function of frequency will maximize the power transfer independent of the parameters not within the bracket. Substituting $x^2 = f$ and designating the expression within the brackets as g(x), the maximum power transfer occurs at

$$g'(x)\,\frac{dx}{df} = g'(x)2\sqrt{x} = 0.$$

$$g(x) = x^4(4\,Y^4x^4 + 4\,Y^3x^3 + 2\,Y^2x^2 + 2\,Yx + 1)e^{-2\,Yx} \qquad (9).$$

Taking the derivating, $\frac{d}{dx}$:

$$g'(x) = 4\,x^3[-\,2(Yx)^5 + 6(Yx)^4 + 6(Yx)^3 + 2(Yx) + 1]e^{-2\,Yx} \qquad (10).$$

Setting equation (10) to zero, real solutions occur at $x = 0, \infty$, and when:

$$-\,2(Yx)^5 + 6(Yx)^4 + 6(Yx)^3 + 2(Yx)^2 + 1 = 0 \qquad (11).$$

The solution at $x = 0$ and ∞ are readily seen to be minimums while the solution to equation (11) is the maximum power transfer. The only real solution to this equation occurs at approximately $Yx \doteq 3.86$.

By designating the frequency at which equation (11) is satisfied as f_{opt} and substituting $x^2 = f$ and $Y = (\pi\mu\sigma)^{1/2}\,r$ yields the frequency at which maximum power transfer occurs for coplanar loops as

$$f_{opt} = \frac{14.9}{\pi\mu\sigma r^2} \qquad (12).$$

Substituting $\mu = 4\pi \times 10^{-7}$ henrys/meter simplifies the expression

$$f_{opt} = \frac{3.78 \times 10^6}{\sigma \quad r^2} \qquad (13).*$$

Equation (13) shows that the optimum frequency of transmission between two coplanar loops is independent of any of the loop parameters (assuming $R_c >> R_r$) and is dependent only upon the distance between loops and conductivity. Substitution of equation (13) into the skin depth equation yields the skin depth at the optimum frequency as

$$\delta_{opt} = 0.259 \ r \qquad (14).$$

By replacing δ by δ_{opt} and f by f_{opt} in equation (7) the maximum transfer of power for coplanar antennas is found to be

$$\left[\left(\frac{P_r}{P_T}\right)_{CP}\right]_{opt} = \frac{1.81 \ a_1{}^3 a_2{}^3 N_1 N_2}{\sigma^2 R_{w_1} \ R_{w_2} \ r^{10}} \qquad (15).$$

Maximum power transfer is dependent on the inverse of range to the tenth power. Doubling the range creates an additional 30 dB loss in power compared to the normal 6 dB loss in free space. The frequency at which maximum power is obtained is given in equation (13).

The relationship in equation (13) can also be useful in determining the effective conductivity of the earth in the vicinity of the antennas by measuring the power transfer between two underground coplanar loops, observing the peak value and calculating the conductivity from equation (13).

Figures 6, 7, and 8 are power transfer curves derived from equation (7) for standard antennas defined by: $a_1 = a_2 = 1$ meter, $N_1 = N_2 = 1$, and $R_{w_1} = R_{w_2} = 0.01$ ohm/meter (15 gauge copper wire).

Figure 9 is a graph of the maximum power transfer versus range at the optimum frequency at each range. Figure 10 plots the optimum frequency versus range.

The equations in this section are adequate for use in analyzing the transmission parameters for a communication system in which the transmitter or transmitters are located generally at equal depths and have loop antennas oriented as vertical magnetic dipoles.

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*During the preparation of this report it was discovered that the solution to equation (11) is more accurately given by Yx = 3.85 which yields the numerator in equation (13) more correctly as 3.75×10^6. However 3.78×10^6 is used throughout this report.

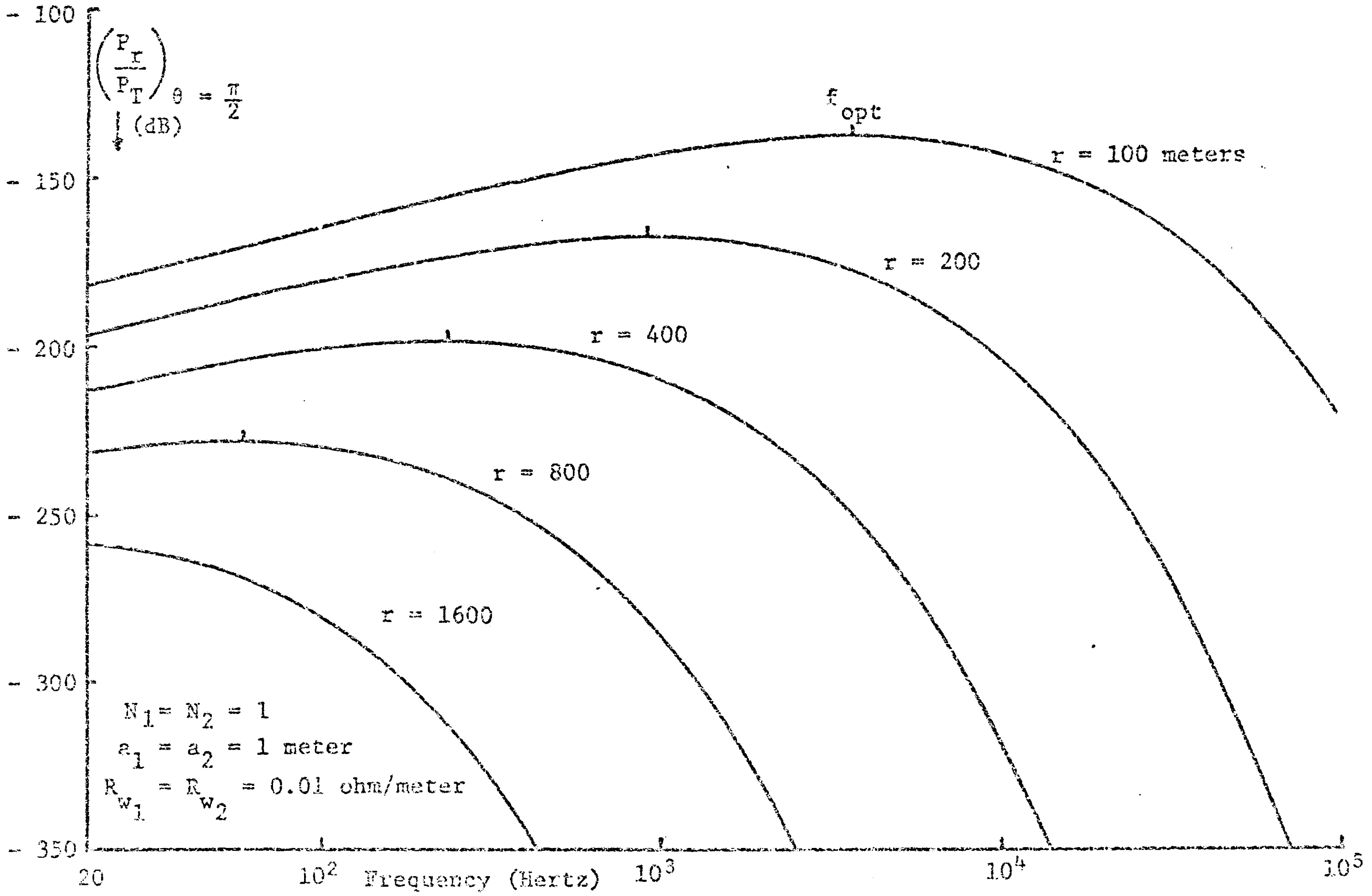


Figure 6
Power Transfer, σ = 0.1 mho/meter

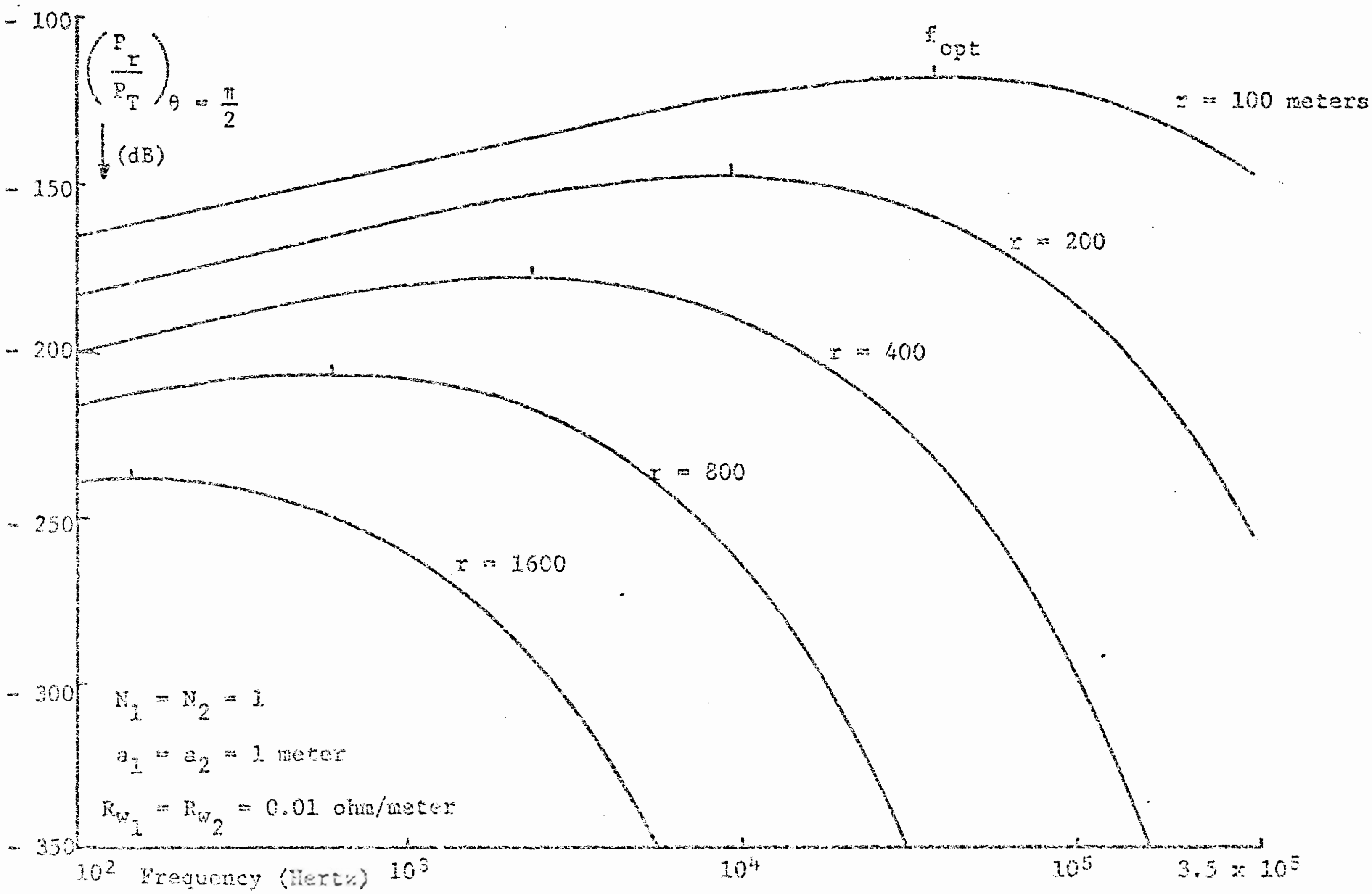


Figure 7
Power Transfer, $\sigma = 0.01$ mho/meter

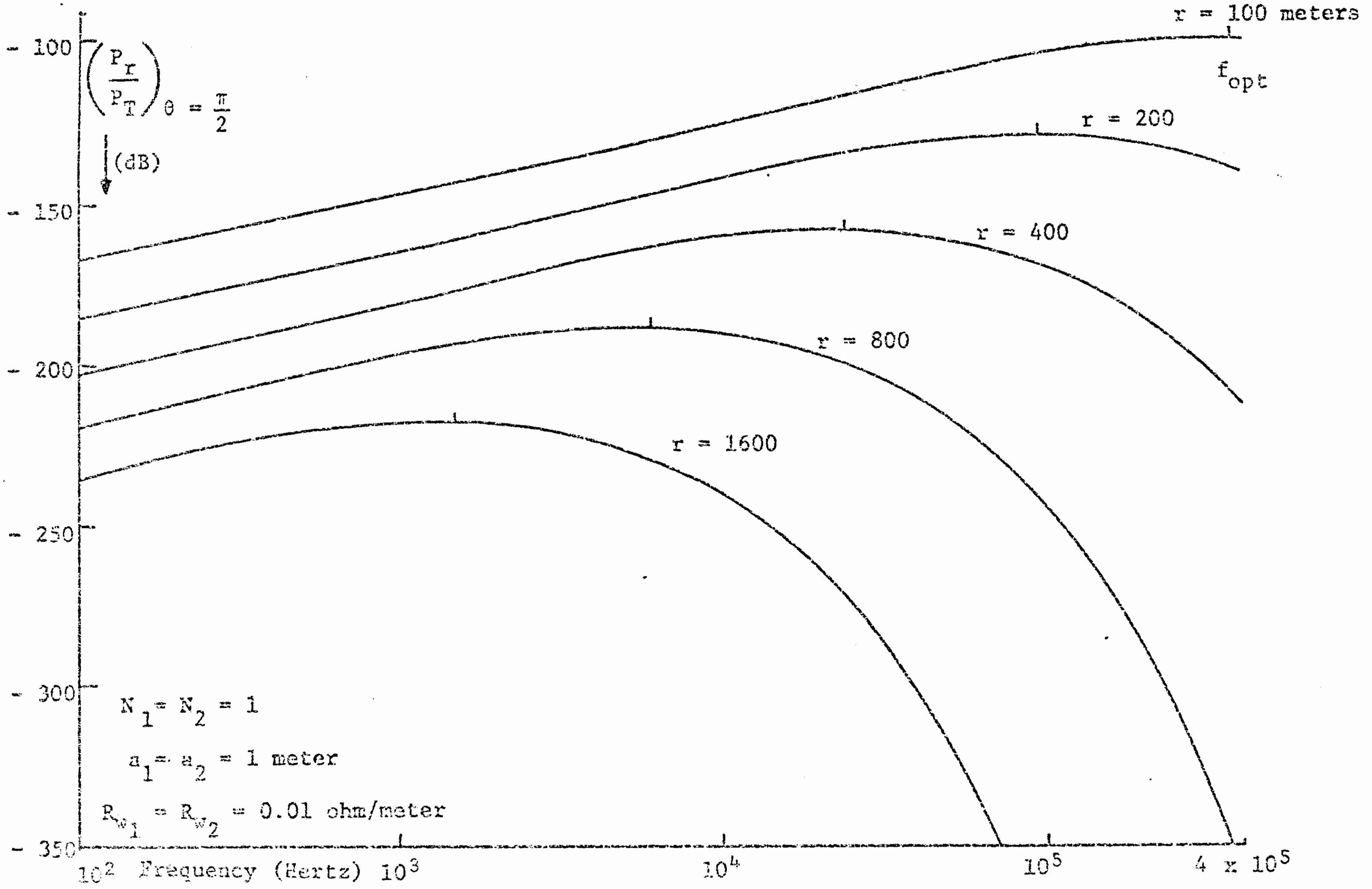


Figure 8
Power Transfer, $\sigma = 0.001$ mho/meter

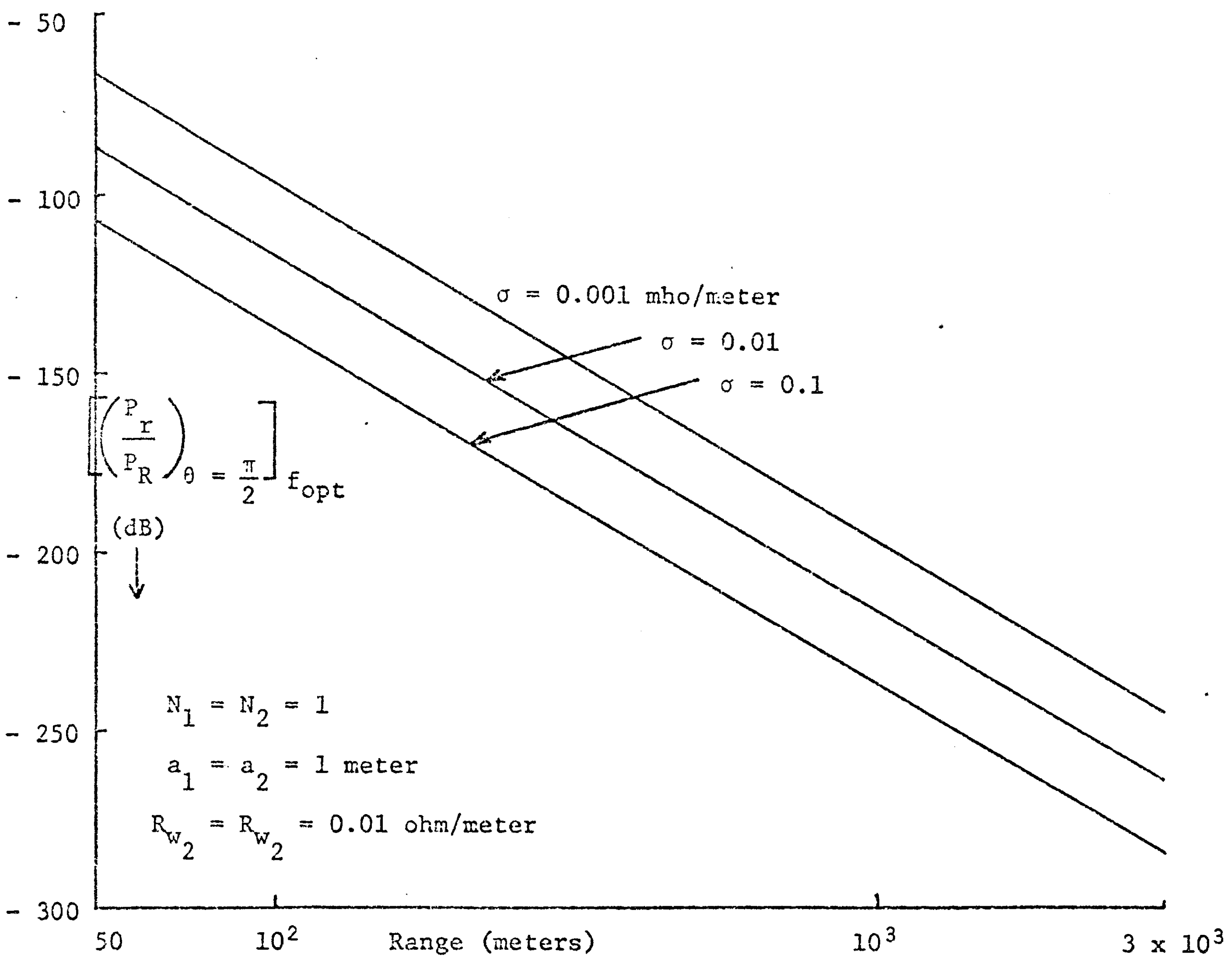


Figure 9
Maximum Transfer of Power Between Coplanar Loops

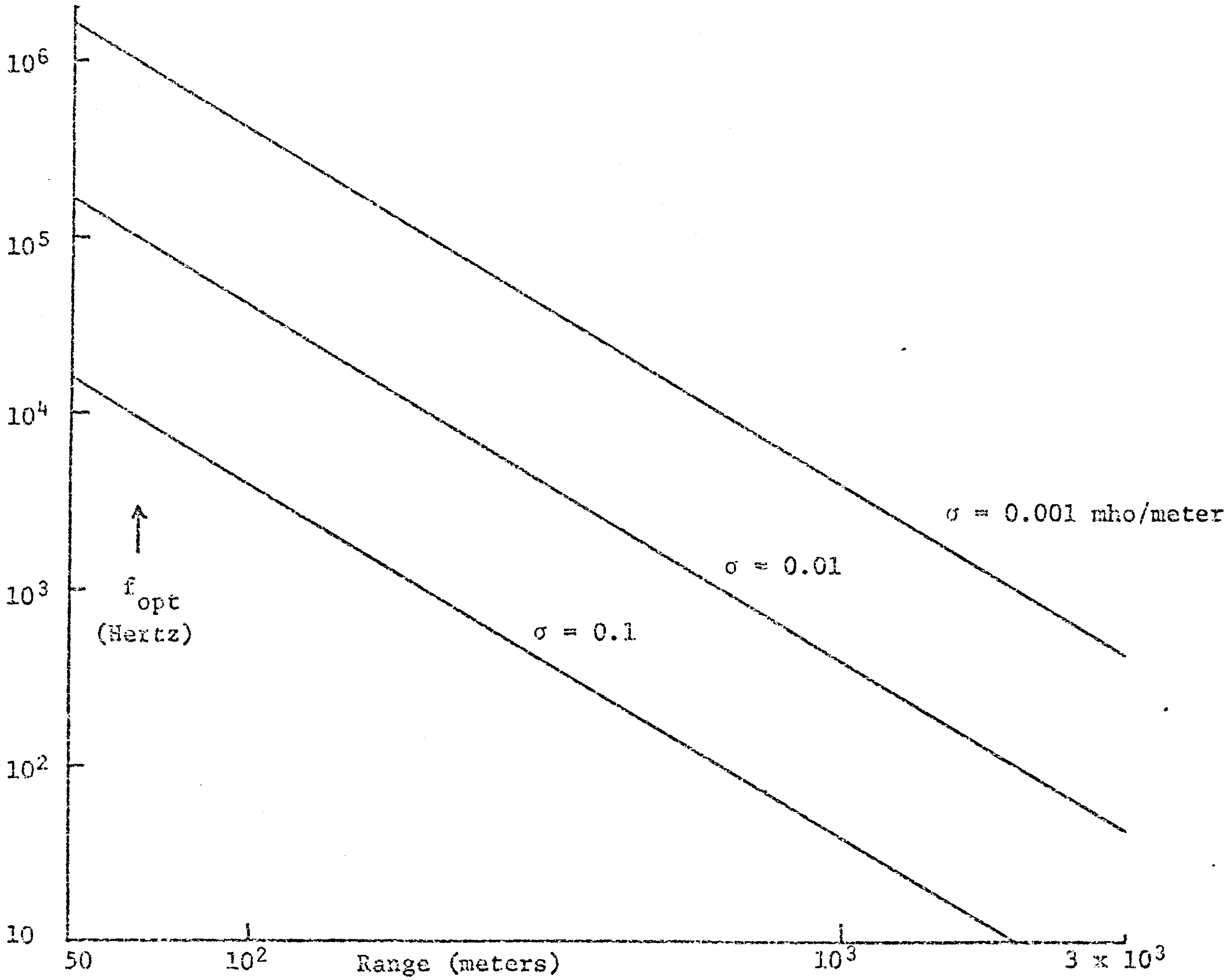


Figure 10
f_{opt} Versus Range, Coplanar Loops

Power Transfer Between Coaxial Loops

Beginning with the equivalent circuit used in the previous development for coplanar loops as shown in Figure 4, one can derive the relationship between V_2 and I_1 from known theory for coaxial loops. Reference 5 gives the details of this development and shows that the ratio of power received to the power transmitted is

$$\left(\frac{P_r}{P_T}\right)_{CA} = \frac{f^2\mu^2\pi^2 a_1^3 a_2^3 N_1 N_2}{16\, R_{w_1}\, R_{w_2}} \left(\frac{2}{\delta^2 r^4} + \frac{2}{\delta r^5} + \frac{1}{r^6}\right) e^{-\frac{2r}{\delta}} \qquad (16)$$

where it is again assumed that the radiation resistance is insignificant as compared to copper losses in the antennas as discussed in a previous section.

Equation (16) can be analyzed in the same manner as equation (8) to yield the following coaxial loop optimum frequency properties:

$$(f_{opt})_{CA} = \frac{2.03 \times 10^6}{\sigma\, r^2} \qquad (17)$$

$$(\delta_{opt})_{CA} = 0.353\, r \qquad (18)$$

$$\left[\left(\frac{P_r}{P_T}\right)_{CA}\right]_{opt} = \frac{.345\, a_1^3 a_2^3 N_1 N_2}{\sigma^2\, R_{w_1}\, R_{w_2}\, r^{10}} \qquad (19).$$

A comparison of the properties of coplanar and coaxial loops is shown in Figure 11 and Table I. From these it is seen that when operating at the optimum frequency for each antenna orientation, the coplanar orientation shows a 7.2 dB advantage over the coaxial orientation and the optimum frequency for the coplanar orientation is higher. Since noise usually decreases with increasing frequency, the coplanar orientation holds a double advantage over the coaxial orientation when operating in the vicinity of their optimum frequencies. Coplanar loops possess the advantage of producing an omni-directional pattern in the plane of the antenna. Due to all these properties a practical system will be assumed to be designed with coplanar loops.

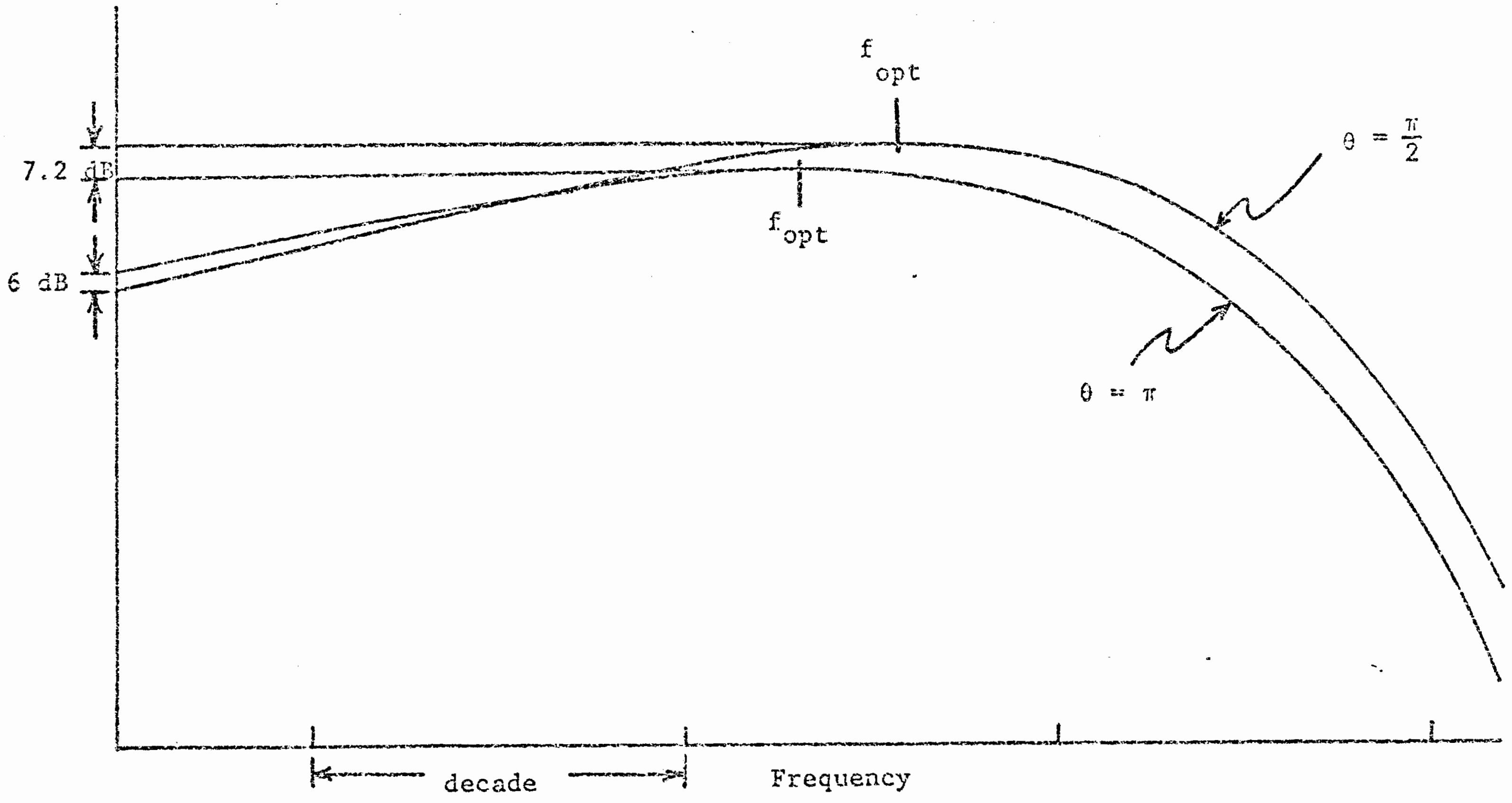


Figure 11
Comparison of Power Transfer for CP [illegible] and CA Orientations

TABLE I

Comparison of Loop Orientations

$$(f_{opt})_{CP} = 1.86\ (f_{opt})_{CA}$$

$$\left(\frac{P_r}{P_T}\right)_{CA} = \left(\frac{P_r}{P_T}\right)_{CP} + 6\ \text{dB where } r << \delta$$

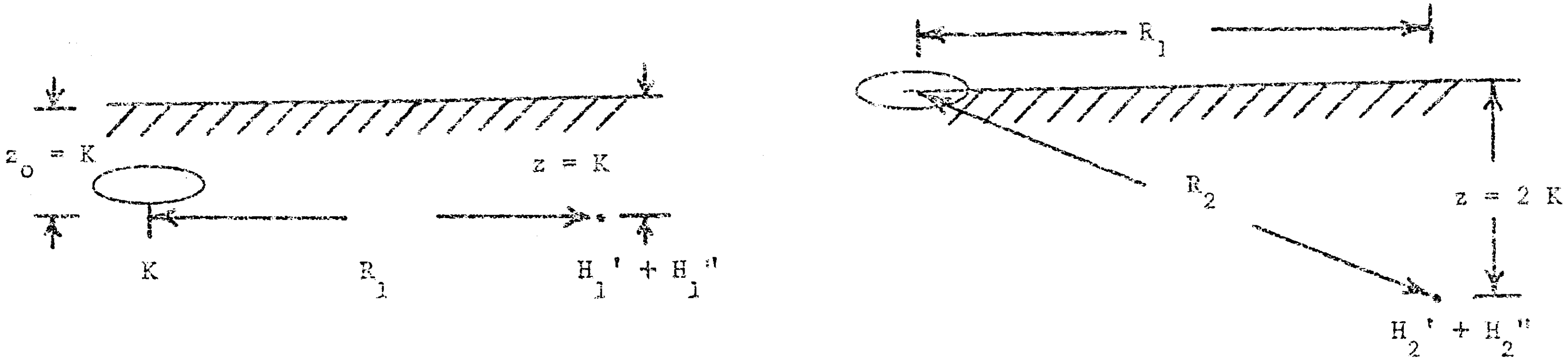
$$\left[\left(\frac{P_r}{P_T}\right)_{CP}\right]_{opt} - \left[\left(\frac{P_r}{P_T}\right)_{CA}\right]_{opt} = 7.2\ \text{dB}$$

Power Transfer Between Loops in a Half-Space

Communication between two points inside a mine will be in a half-space lossy medium rather than the space of infinite extent as assumed in the preceding sections. Although it appears reasonable that in a deep mine the infinite medium assumption would be accurate, it is important to understand the extent to which this assumption is acceptable. This may be particularly important for propagation behavior for shallow mine applications.

In order to solve this problem, Layman adapted a procedure developed by Wait (Ref. 6) for analyzing the field radiated from a loop above a conducting half-space. Wait's procedure decomposed the total wave into two parts -- the primary wave or that wave which would be radiated in the absence of the conducting half-space; and the secondary wave which resulted from reflections from the half-space boundary.

In Reference 5 Layman adapts this procedure by considering the situation shown in Figure 12, wherein the field within the conductive medium is decomposed into the primary and secondary components. He presents a complete derivation which shows that the magnetic Hertz potential inside the homogeneous, conductive half-space is given by



where: $H_1'' = H_2''$

Figure 12

Secondary Field Dependance Upon $z + z_o$

$$\Pi_{m1} = \frac{NIA}{4\pi}\left[\frac{e^{-\gamma_1 R}}{R} + \int_0^\infty \left(\frac{(\mu^2 + \gamma^2)^{1/2} - (\mu^2 + \gamma_o^2)^{1/2}}{(\mu^2 + \gamma_1{}^2)^{1/2} + (\mu^2 + \gamma_o{}^2)^{1/2}}\right.\right. \tag{20}$$

$$\left.\left.\exp[(\mu^2 + \gamma_1{}^2)^{1/2}(z + z_o)]J_o(\rho u)\ \frac{u}{(\mu^2 + r_1{}^2)^{1/2}}\ du\right)\right]$$

where $R = [(z - z_o)^2 + \rho^2]^{1/2}$

I = current in transmitting antenna

A = area of transmitting antenna

N = number of turns in transmitting antenna

γ_1 = propagation constant of wave in conductive medium

γ_o = propagation constant of wave in free space

z_o = depth of transmitting antenna

z = depth of observation point

ρ = distance between transmitting loop axis and observation point

The first term in equation (20) describes the primary field while the remaining term describes the secondary. In order to study the significance of the secondary field, equation (20) is normalized by setting the NIA/4π term equal to unity. Maxwell's equations are then used to find the resulting magnetic field intensity which has only a z component due to the cylinderical symmetry. The primary field yields

$$H_z' = 2\left[\left(\frac{\gamma_1}{R^2} + \frac{1}{R^3}\right)\cos^2\theta - \left(\frac{\gamma_1{}^2}{R} + \frac{\gamma_1}{R^2} + \frac{1}{R^3}\right)\sin^2\theta\right] e^{-\gamma_1 R} \tag{21}$$

where

$$\theta = \text{arc}\cos\left(\frac{z - z_o}{R}\right)$$

$$H_z'' = \int_0^\infty \left(\frac{(u^2 + \gamma_1{}^2)^{1/2} - (u^2 + \gamma_o{}^2)^{1/2}}{(u^2 + \gamma_1{}^2)^{1/2} + (u^2 + \gamma_o{}^2)^{1/2}} \exp[u^2 + \gamma_1{}^2)^{1/2}(z + z_o)] \right.$$

$$\left. J_o(\rho u) \frac{u^3}{(u^2 + \gamma_1{}^2)^{1/2}} \right) du \qquad (22)$$

Based on these two equations the power transfer between two loops buried at various depths in a homogeneous conductive half-space was calculated using digital programming to perform the integration in equation (22). These results are shown in Figures 13 - 15 for different conductivities for both the complete field at various depths and also for the primary field only. As expected, as the antennas are placed deeper in the medium, the primary field approximation becomes more accurate. However, it is also shown that in the vicinity of the optimum operating frequency, as determined by the primary field approximation, the primary field is essentially equal to the exact solution even for very shallow depths. The large errors occur for frequencies much higher than f_{opt} where analysis of the equations show propagation is taking place via free space along the boundary. These analyses show that when antenna separation is less than approximately four times the depth, the primary field approximation is excellent. Even with larger separations the approximation is still good when operating at frequencies in the vicinity of f_{opt} and below.

The interesting point raised by this analysis is the possibility of an operating frequency more optimum than that found from the primary field approximation. This possibility is vividly demonstrated in Figure 15 in a low conductivity situation. Caution should be exercised in interrupting these results at the higher frequencies because of the assumptions made early in the analysis which neglects radiation resistance and assumes that $\sigma >> \omega\varepsilon$. However, it appears reasonable that in some shallow mine situations where communication distances much greater than mine depth may cause the optimum operating frequency to be much larger than would otherwise be anticipated because of the outside propagation path.

Outside to Inside Transmission

The results of the preceding station sheds some light on the problem of placing the transmitting antenna outside the mine rather than inside. Consider a comparison of the two situations shown in Figure 16. It is evident that the primary wave will always have a longer range for the surface antenna case, and thus one would expect poorer results. However, the secondary wave due to outside propaga-

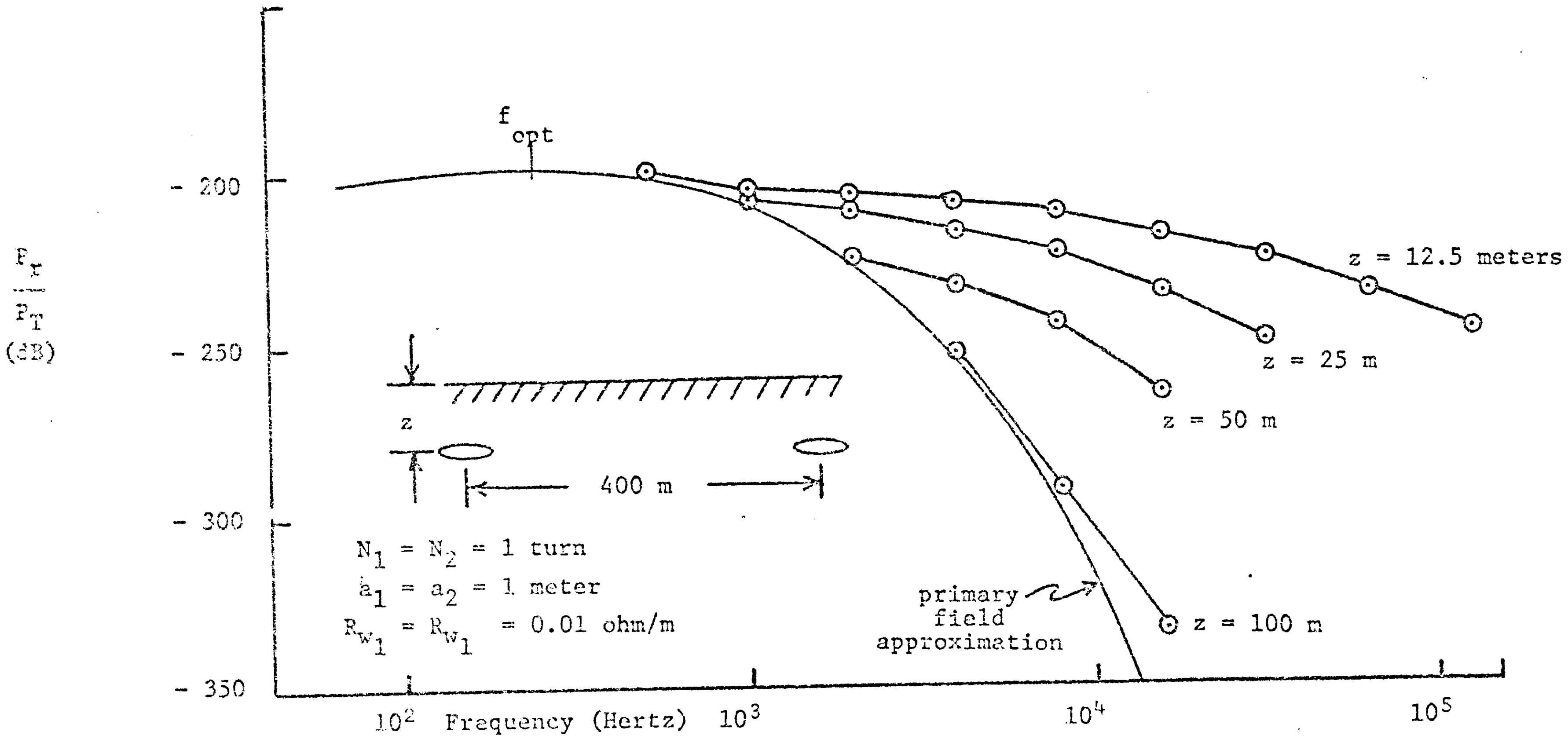


Figure 13
Power Transfer Between Loops in a Lossy Half-Space, $\sigma = 0.1$ mho/meter

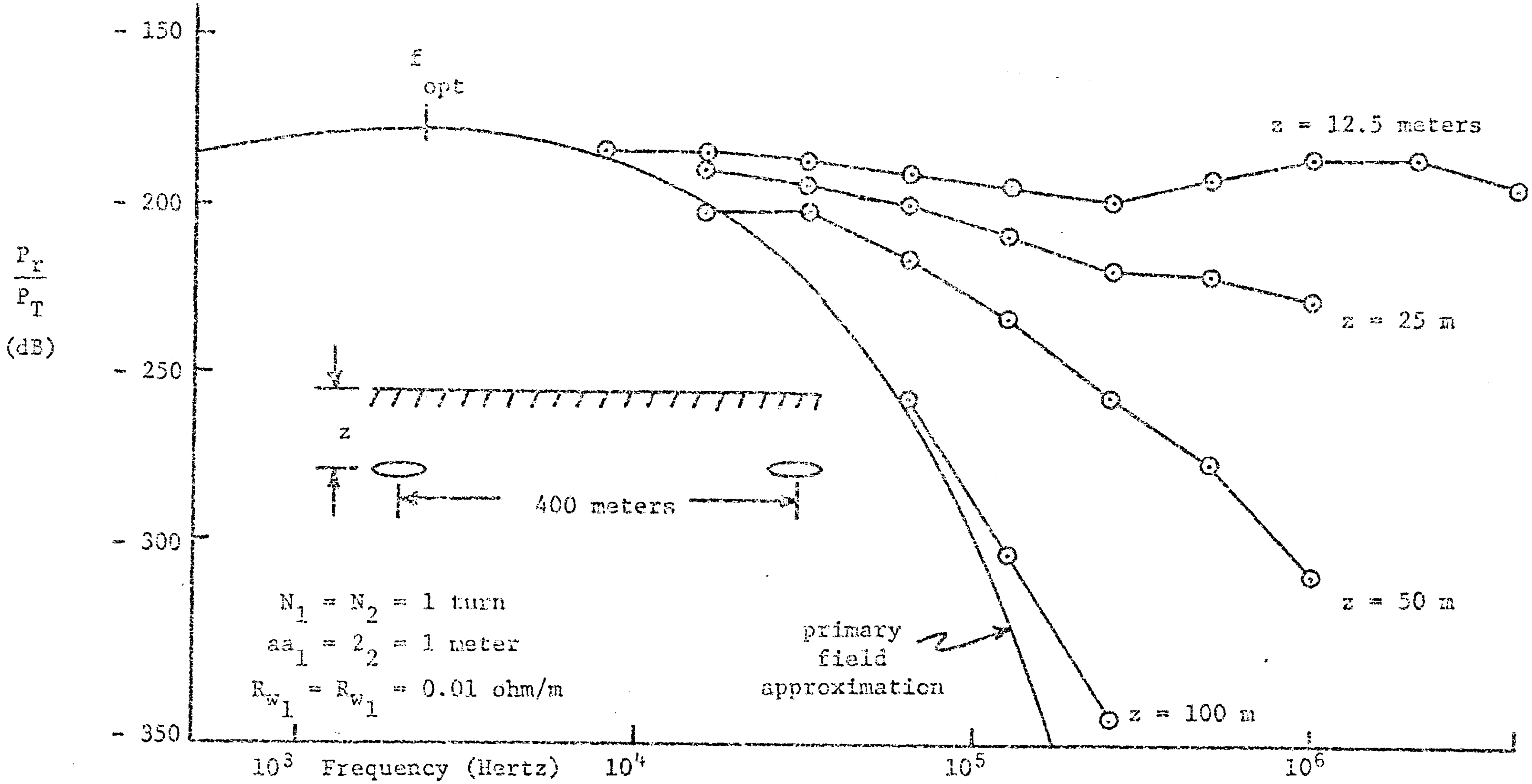


Figure 14
Power Transfer Between Loops in a Lossy Half-Space, σ = 0.01 mho/meter

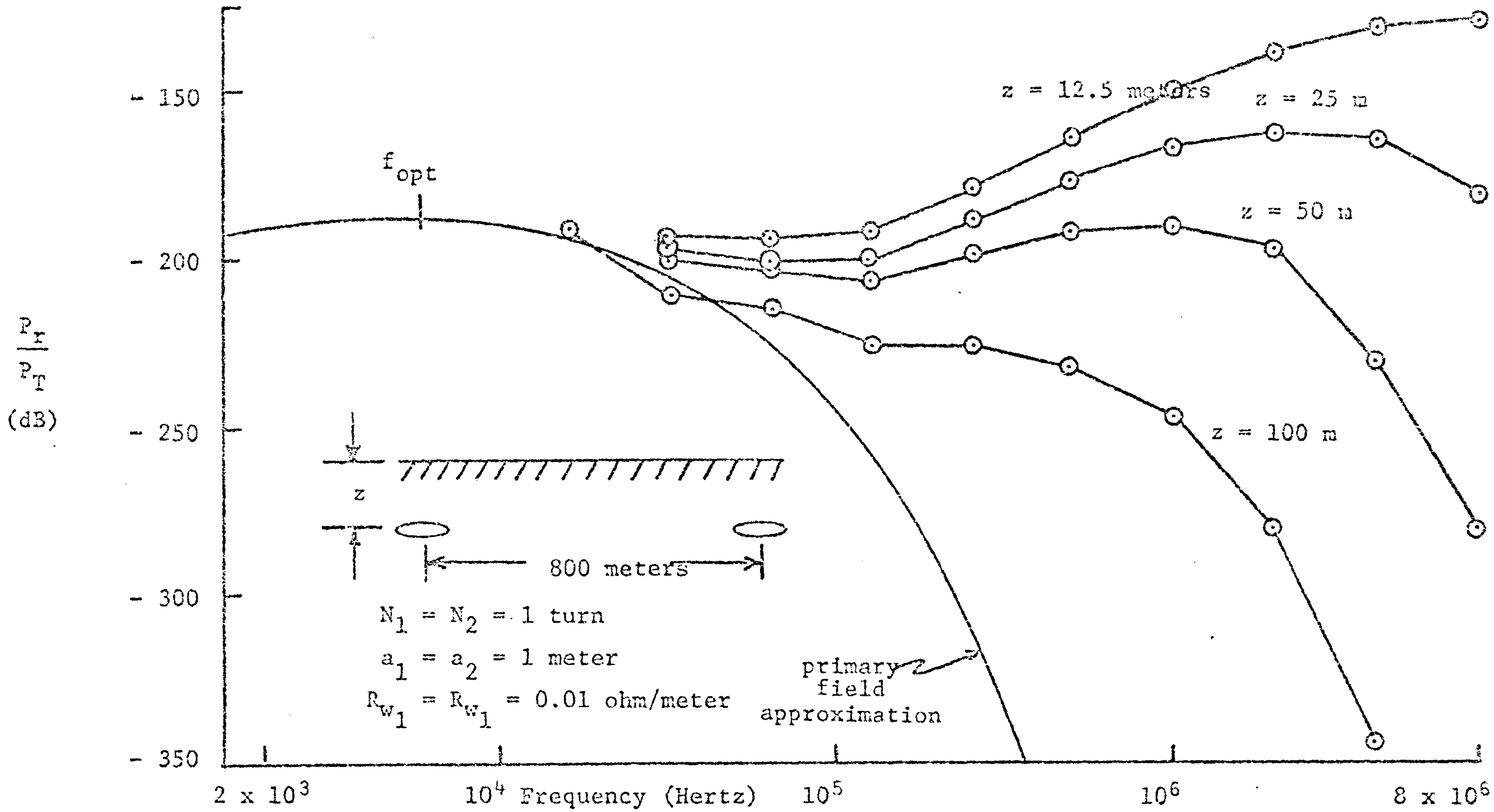


Figure 15
Power Transfer Between Loops in a Lossy Half-Space, $\sigma = 0.001$ mho/meter

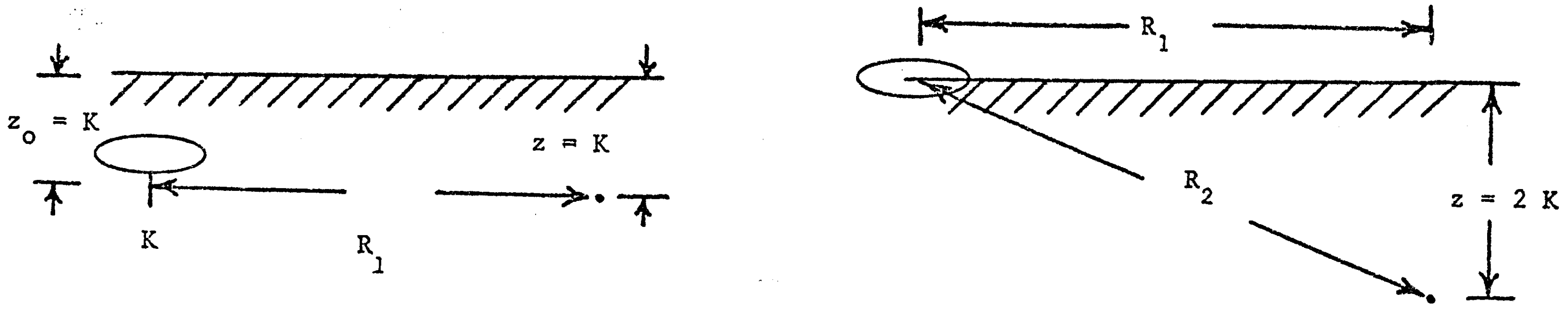


Figure 16
Surface vs Inside Transmitting Antennas

tion may suffer less attention since it is launched outside the mine. Thus as the desired radial range is made larger and R_1 and R_2 become nearly equal, it should not be surprising to find superior signal strengths arising from the outside transmitting antenna because of the larger secondary wave.

From the data of the preceding section, the secondary wave was found to provide significant contributions only when the desired radial range was larger than about four times the mine depth. Therefore an outside transmitting antenna would probably provide larger field strengths than an inside antenna only in the cases of very shallow mines or in areas of extremely low earth conductivity. Of course other factors would enter into the choice of transmitting location. One practical problem is the fact that the earth consists of layers which may have widely varying conductivities. A band of high conductivity in a mine overburden might prevent outside to inside transmission whereas the earth in the vicinity of the coal seam may be rather low in conductivity and thus permit inside to inside communication.

Even if one can assume the earth is homogeneous, the use of an outside transmitting antenna might offer some signal strength advantages only if the mine depth and earth conductivity were such that practical communication ranges were on the order of three to four times the mine depth. The above statement is made on the assumption that the inside and outside antennas and transmitters are effectively the same. If one permits the possibility of a larger antenna and transmitter outside, the outside transmitting system becomes attractive for a wider range of conditions.

Comparison of Experimental and Theoretical Data

In order to determine the actual transmission characteristics of the earth near coal seams, experiments were conducted in several coal mines in West Virginia and Pennsylvania. By comparing data acquired from these measurements and that obtained from the theoretical analysis, it was hoped to determine the extent to which the homogeneous approximation is legitimate, the earth's conductivity in the vicinity of coal seams, and how variations in the earth's structure affect low frequency transmission over short distances.

A block diagram of the test equipment used is given in Figure 17.

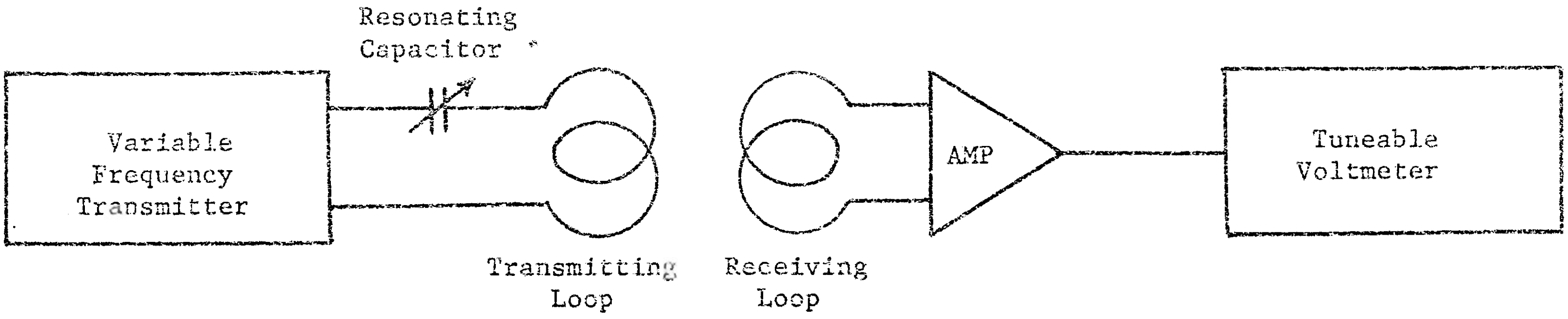


Figure 17

Block Diagram of Test Equipment

A brief description of the test equipment follows:

Transmitter - variable frequency, crystal controlled, switching type, maximum power output of 10 watts.

Resonating Capacitance - capacitor bank, variable from 1000 pico farads to 10 micro-farads.

Transmitting Loop - 30 turn, loose wound, (1 turn per inch) 1 square meter area, 3 ohms d.c. resistance (Rw = 0.028 ohm/meter), L = 22 millihenrys.

Receiving Loop - 50 turn, (close wound) 1.3 square meter area, 20 ohms d.c. resistance (Rw = 0.1 ohm/meter).

Amplifier - 40 dB gain, 13 megohm input impedance, 8 ohms output impedance.

Voltmeter - Philco Frequency Selective Voltmeter, Model 127 C, 300 Hz Bandwidth.

The transmitter delivered a square wave to the resonating capacitor and the transmitting loop. This circuit was tuned to the fundamental frequency of the square wave where it exhibited an impedance of 3 ohms resistive. The power dissipated by the harmonics contained in the square wave was insiginficant considering their amplitude and the input impedance of the resonating capacitor in series with the loop at those frequencies. The open circuit voltage of the receiving antenna was measured and the available power calculated.

The entire test setup was calibrated by the Standard Field Method (Reference 7) except that both transmitting and receiving loops were calibrated simultaneously.

Surface conductivity measurements were made according to a method described by Williams and Benning (Reference 8) using two loop antennas at the surface.

Table II lists the name and location of the mines that were tested, the measured surface conductivities and the conductivities obtained by observing the measured data for f_{opt} and applying equation (12).

Table II
Measured Conductivities at Mining Locations

Test No.	Mine	Location	Mine Depth (meter)	Conductivities Sur. (mho/m)	Conductivities Mine (mho/m)
1	Upshur	Adrian, W. Va.	68	0.88×10^{-3}	1.55×10^{-2}
2	U.S. Steel, No. 50	Pineville, W. Va.	40	Note a	1.46×10^{-2}
3	U.S. Steel, No. 50	Pineville, W. Va.	40	Note a	1.09×10^{-2}
4	Badger No. 14	Phillipi, W. Va.	135	2.5×10^{-2}	0.49×10^{-2}
5	Badger No. 14	Phillipi, W. Va.	135	2.5×10^{-2}	Note b
6	U.S. Bur. of Mines	Bluefield, Penn.	18	1.4×10^{-2}	6.6×10^{-2}
7	U.S. Bur. of Mines	Bluefield, Penn.	18-27	1.4×10^{-2}	2.9×10^{-2}
8	Federal No. 2	Miracle Run, W. Va.	255	0.76×10^{-2}	Note c
9	Loveridge	Fairview, W. Va.		1.1×10^{-2}	Note c
10	Loveridge	Fairview, W. Va.		4.4×10^{-2}	Note c, d

Note a: Surface conductivity measurements were not made
Note b: Unable to calculate (see text)
Note c: Surface conductivity measurements only
Note d: Surface conductivity measurements were on a coal/shale bed

Figure 18 shows a comparison of the calculated power transfer between standard loops at 2 KHz and those measured at the mines given in Table II. This curve was obtained by evaluating equation (7).

Figures 19 through 25 contain the measured power transfer points made at the mines outlined in Table II. The solid line is the infinite homogeneous power transfer approximation. Each curve is offset by the value as shown in Figure 18 to allow for correction of system calibration errors. The conductivities within the mine were calculated by making use of the range, f_{opt}, and equation (12). These calculated conductivities are shown in Table II along with the conductivities measured at the surface.

One great irregularity appears in the data contained in Figure 23 taken at the Badger No. 14 mine. The peak power transfer point, f_{opt}, did not occur within the range of frequencies that measurements were made. A second factor, as seen in Figure 18, is that the power transfer at 2 KHz is 22 dB greater than calculated. One possible explanation for this condition could be that coupling occurred from the transmitting antenna to a metal object such as the rails or power lines which carried the signal along its length and retransmitted it near the receiving antenna. However, there is evidence there may be some special characteristic of the overburden as will be discussed later.

With the exception of the data presented in Figure 23, all other sets of data agree in general with the infinite homogeneous medium approximation curve shown on each graph. This data supports the hypothesis that the infinite homogeneous medium case is a good approximate model for the analysis of electromagnetic communication in most mines. The data points, in general, fall near the predicted curve on the graphs. Some isolated data points are off the curve a significant amount. Many factors could contribute to errors in the operation of the test equipment and in making the measurement readings. Although care was taken to determine the range, some latitude for error was present. Signal coupling onto wiring within the mines could have some effect, particularly at the higher frequencies, but care was taken in all cases to stay at least 100 feet away from wiring, pipes, etc.

The conductivity data presented in Table II indicate that conductivity measured at the surface using the two loop method may not be an accurate indication of the effective conductivity experienced within the mine.

The experimental data presented thus far are only for the case of communication between two points inside a mine. Some data were also taken by transmitting from outside to inside the mine. These data are tabulated in Appendix A along with the data used to establish the curves already presented. It should be noted that the outside to inside data behaved similarily to that expected for an infinite homo-

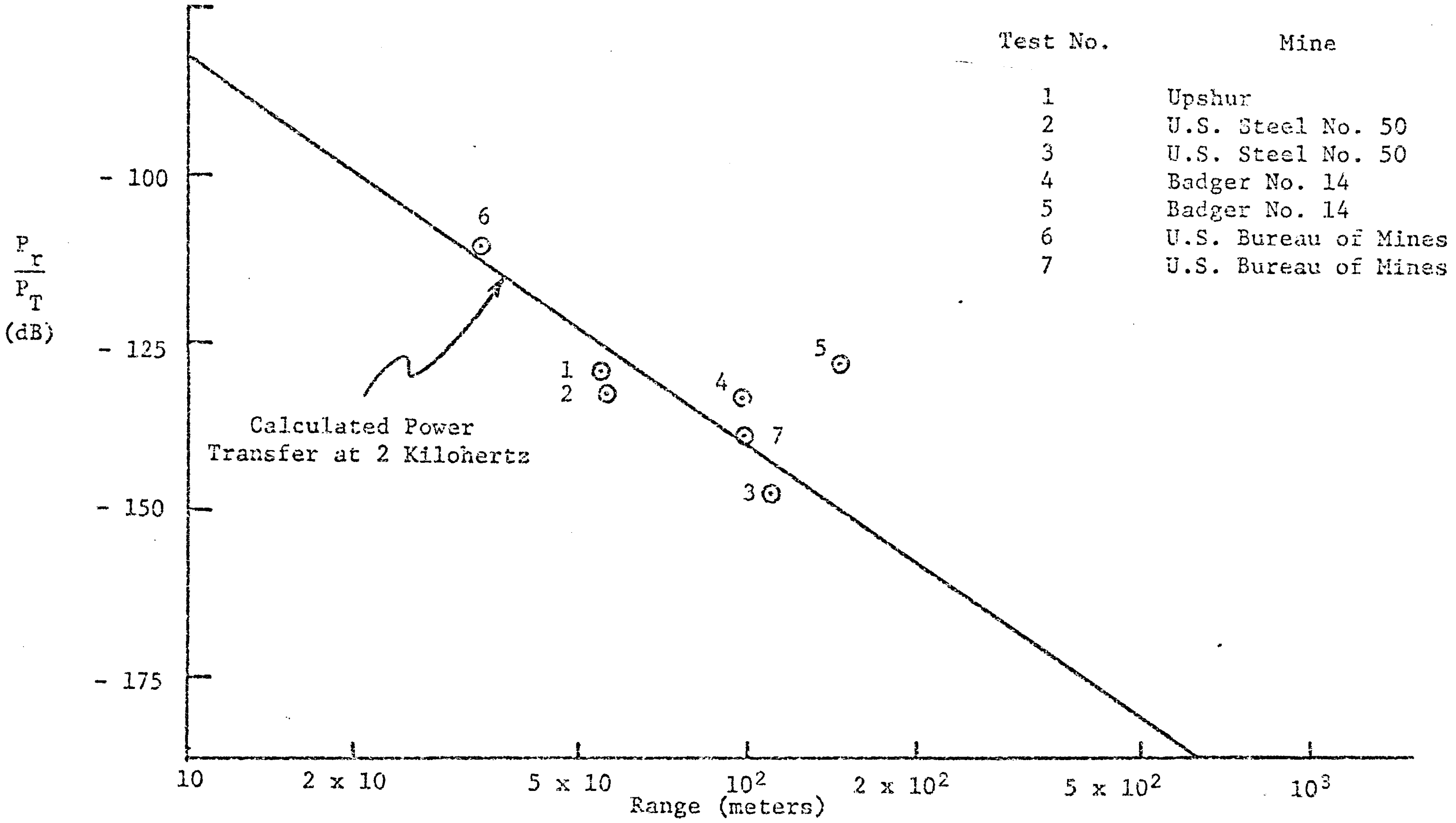


Figure 18
Comparison of Calculated to Measured Power Transfer at 2 Kilohertz

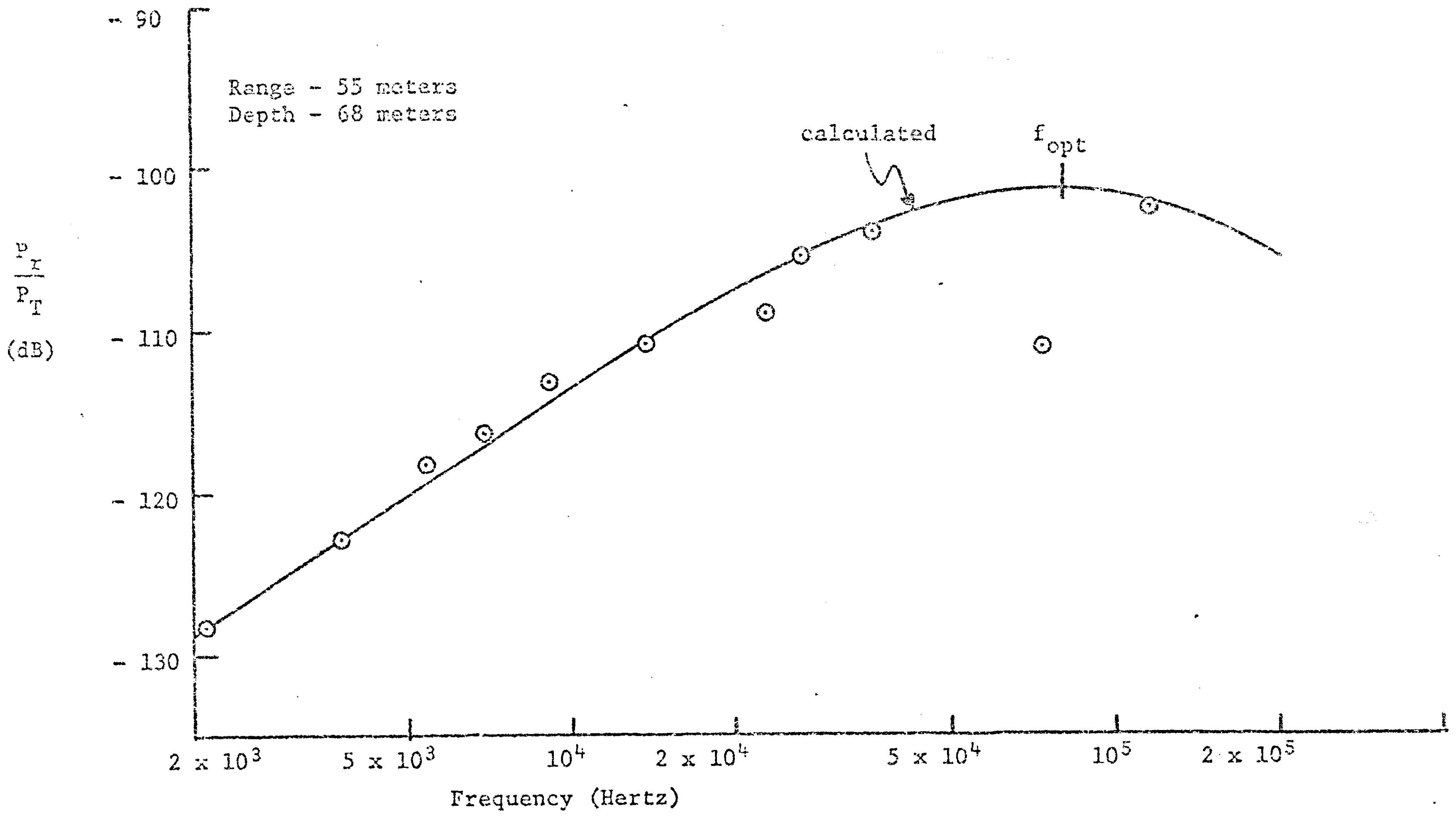


Figure 19
Measured Power Transfer, Test No. 1, Upshur Mine

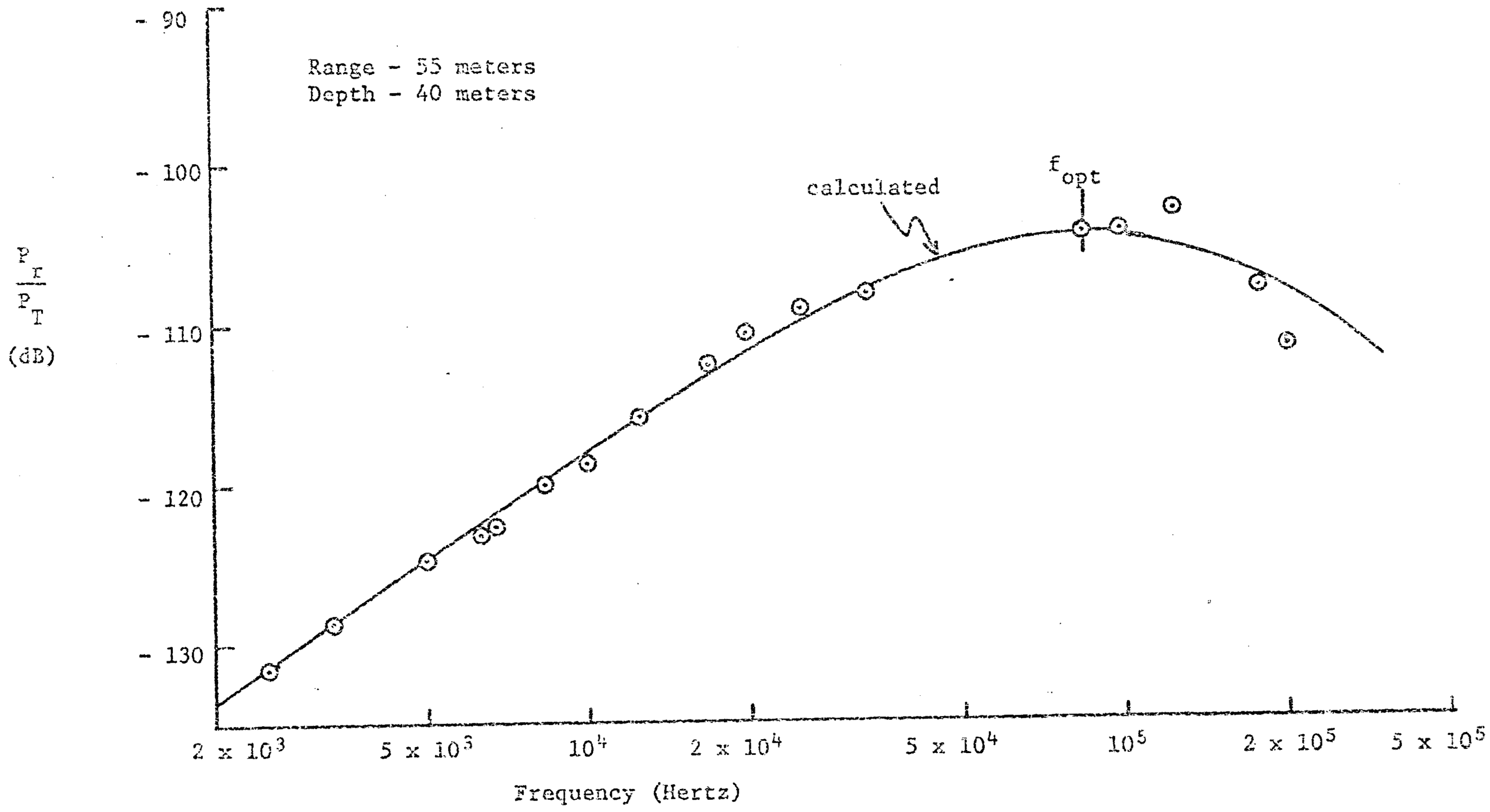


Figure 20
Measured Power Transfer, Test No. 2, U.S. Steel No. 50

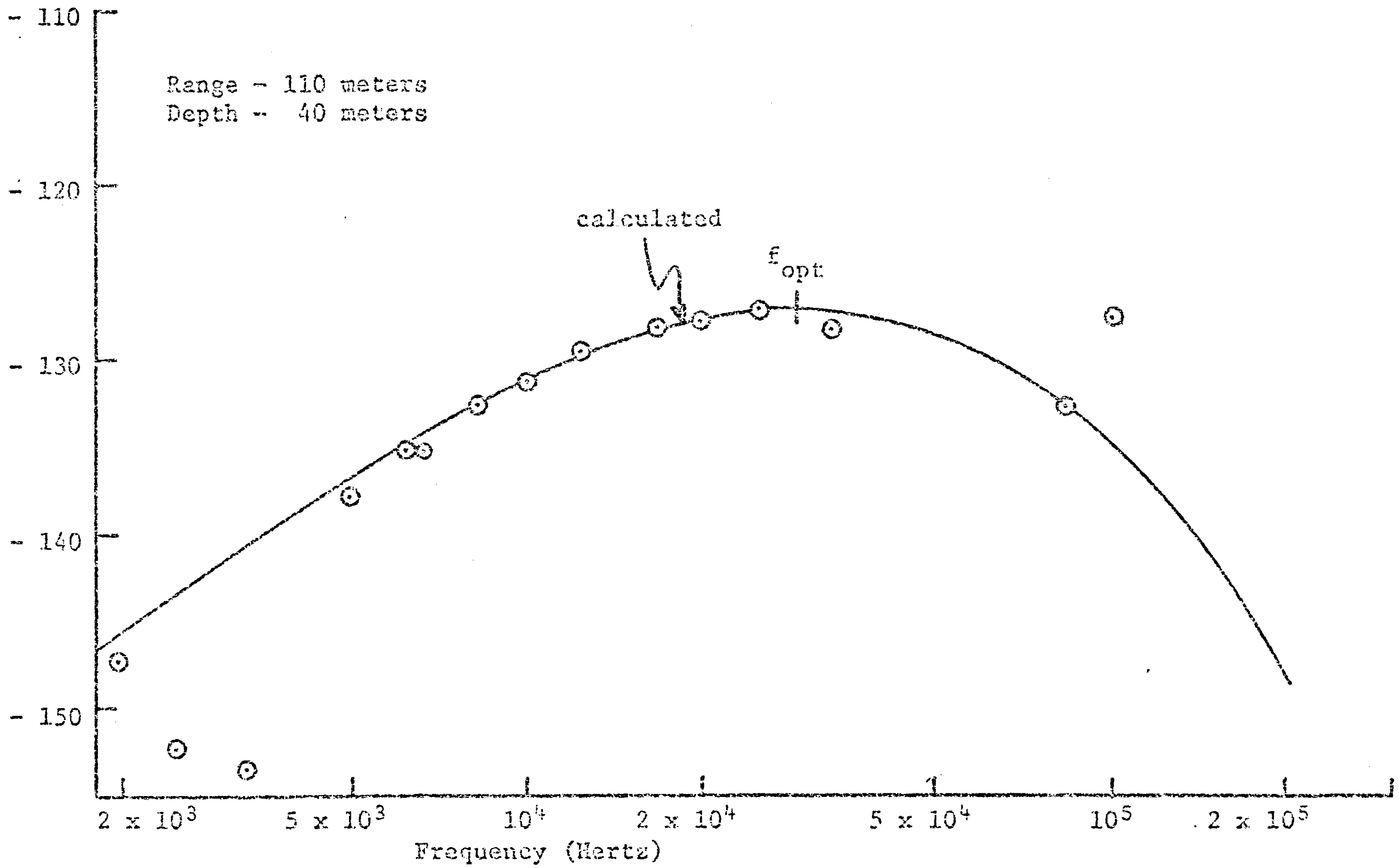


Figure 21
Measured Power Transfer, Test No. 3, U. S. Steal No. 50

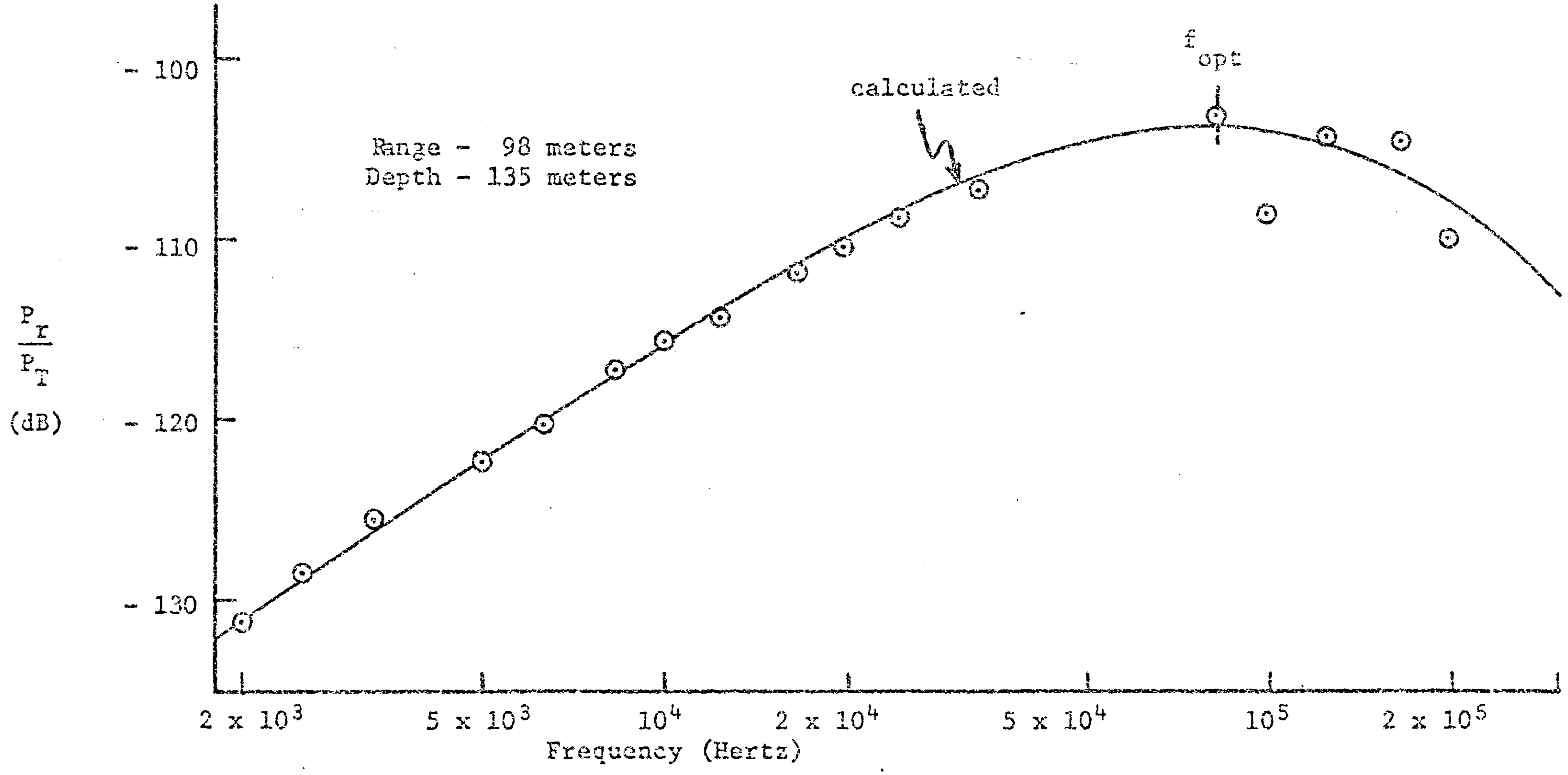


Figure 22
Measured Power Transfer, Test No. 4, Badger No. 14

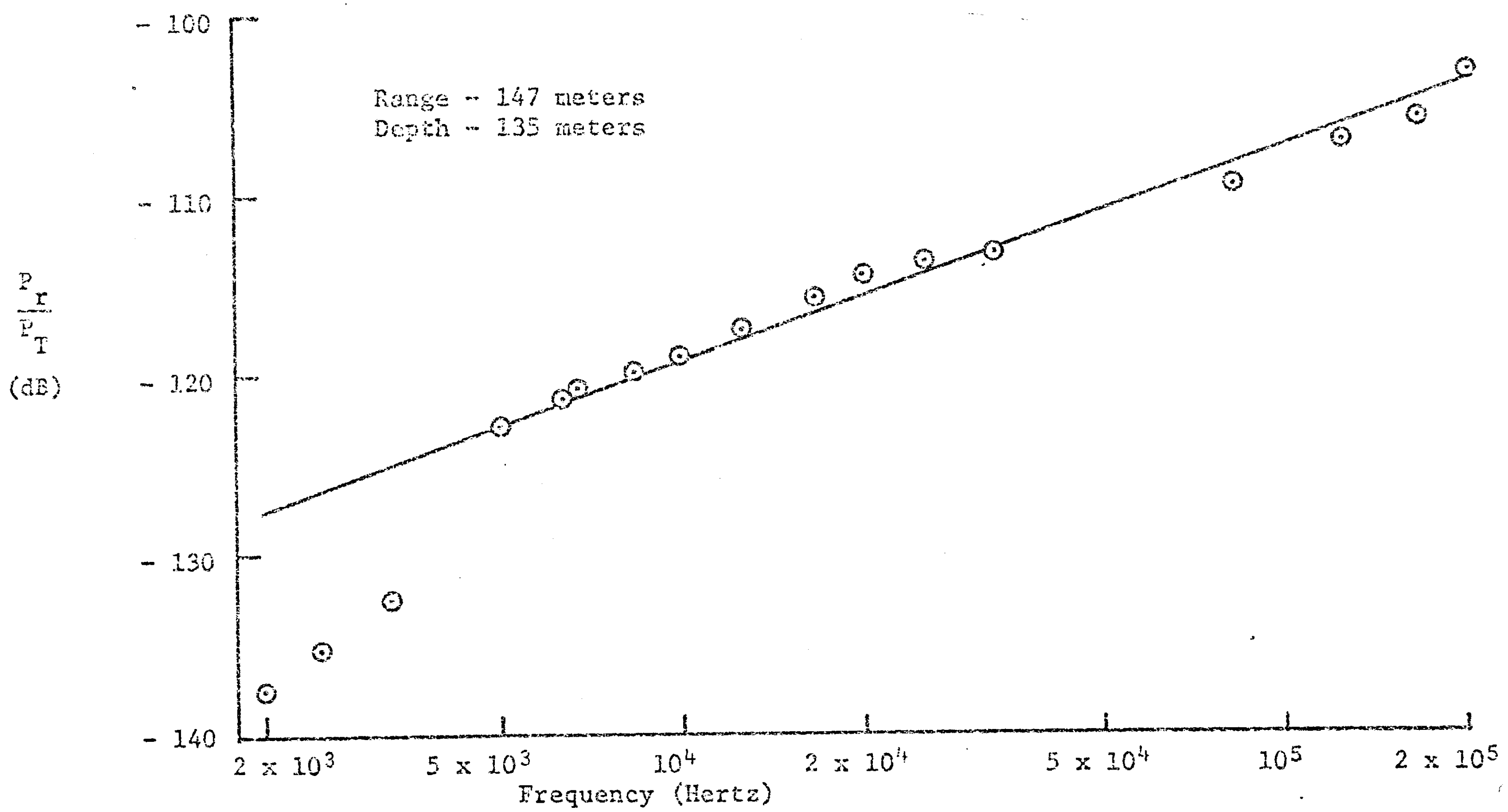


Figure 23
Measured Power Transfer, Test No. 5, Badger No. 14

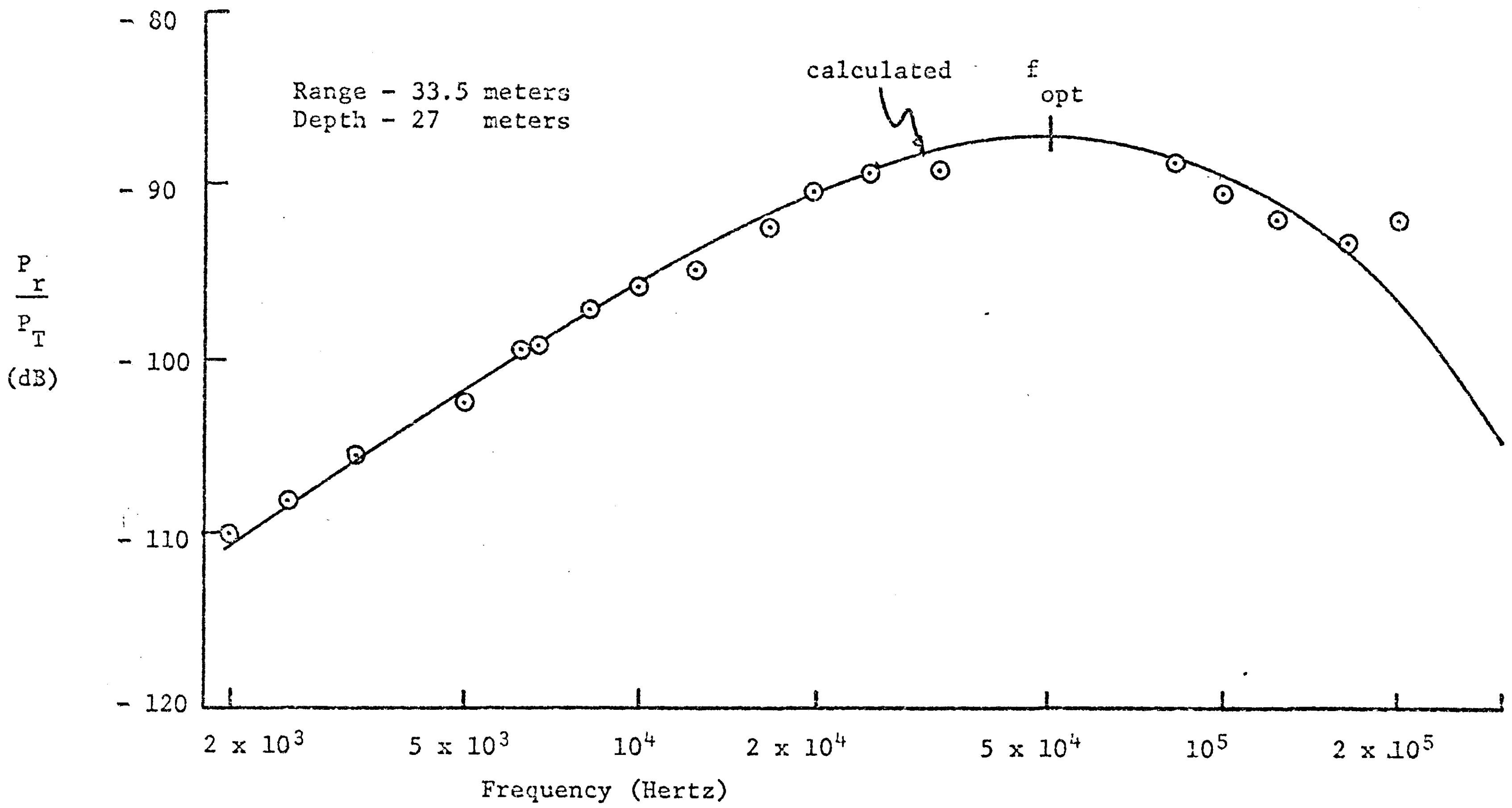


Figure 24
Measured Power Transfer, Test No. 6, U. S. Bureau of Mines

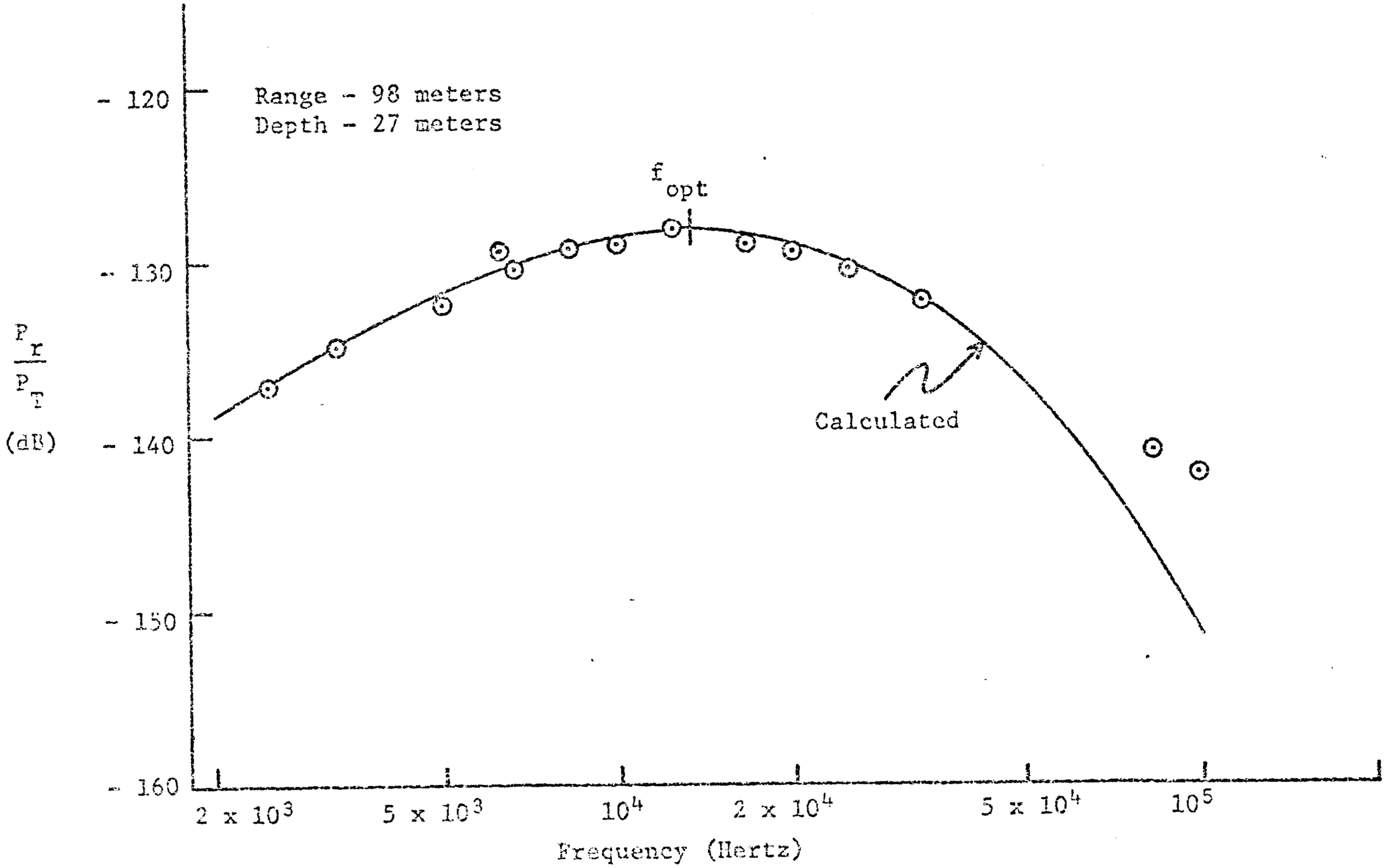


Figure 25
Measured Power Transfer, Test No. 7, U.S. Bureau of Mines

geneous medium in that an optimum frequency existed. However, the use of Equation 12 tended to yield unusually large conductivities. Unfortunately sufficient time was not available to fully analyze the outside to inside data relative to the theory developed herein.

The outside to inside tests did yield some interesting results which should be documented. Of the mines where experiments were attempted, the mine whose roof was dripping with water (U. S. Steel, No. 50), yielded some of the best data. On the other hand, the mine which was completely dry with no drainage from the roof (Badger No. 14) absolutely no signal could be received over a distance no greater than those which were successful at other mines. Note that Badger No. 14 also yielded unusual data for the inside to inside experiments.

Noise Measurements

The successful operation of communication systems depend on the existence of an adequate ratio of signal to noise level at the receiver. Thus, knowledge of the earth's transmission characteristics alone is not sufficient to determine the feasibility of through-the-earth communication application. The magnitude of noise which must be tolerated at the receiver must also be known. Since the noise generated by the first amplifying stages in a receiver may be made very small by proper design, the noise emitted by electrical circuits or from other sources outside the receiver becomes the noise which must be overcome by the signal.

Since coal mines contain many electrical circuits of various forms it is to be expected that noise will exist inside an operating mine. Since the objective of this work was to study the feasibility of through-the-earth communication for normal operation applications, measurement of noise in operating coal mines was conducted. An attempt was made to take data in a variety of situations with the objective of determining the order of magnitude of noise as a function of frequency. No attempt was made to determine the exact cause of source of the noise measured.

Data were taken with the receiver arrangement shown in Figure 17 and described in that section. The tunable voltmeter had a bandwidth of 300 Hz. The antenna used was found to possess a self-resonance in the vicinity of 50 KHz. A gain correction factor was determined by calibrating the 50 turn loop against a one turn loop of similar dimensions. Attempts were made to correct all data according to this calibration information, but in some cases this yielded erratic data points which were neglected.

Data were taken with the receiving loop axis vertical and horizontal and in the vicinity of various types of electrical wiring and machinery at the following types of locations:

Near AC and DC power centers

Near HV and LV AC power cables

Near DC trolley lines

Places isolated from electrical cables and equipment

Outside the mine

The following general conclusions were reached from these tests:

1. In general, the worst noise generator in an operating mine is the DC trolley line system. The trolley line acting with the grounded rail return acts as a large transmitting loop antenna. The current fed into this radiating system is rich in harmonics of 360 Hz on up to the 15 to 20 KHz region. On main line haulage circuits, current surges are common which drastically increase the noise. This type of "rectifier noise" can be detected anywhere in and around a mine which uses track haulage. The tests indicate that the magnitude of the noise decreases as the distance from the trolley line increases.

2. Noise radiated by HV shielded AC cables attenuates rapidly to a very low level within about 10 to 15 feet (i.e. 10 dB in the first foot, 5 dB in the second foot). Mines using all AC and DC cables (i.e. no trolley lines) were found to exhibit no measurable noise over most of the spectrum in the next entry adjacent power carrying cables. Noise from unshielded Low Voltage cables was about 10 dB higher than for the High Voltage cables.

3. The orientation of the receiving loop can have a large affect on received noise. With the plane of the loop horizontal, the noise was 10 to 15 dB larger than when vertical. This was true in mines with trolley lines and mines with only power cables. However, in an AC mine away from power circuits, there was little difference in noise with loop orientation.

Figures 26 and 27 show plots of the maximum and minimum measurements made at each frequency from all the tests taken inside operating coal mines. The noise data is also presented in tabular

COMPOSITE NOISE DATA - HIGHEST AND LOWEST READINGS

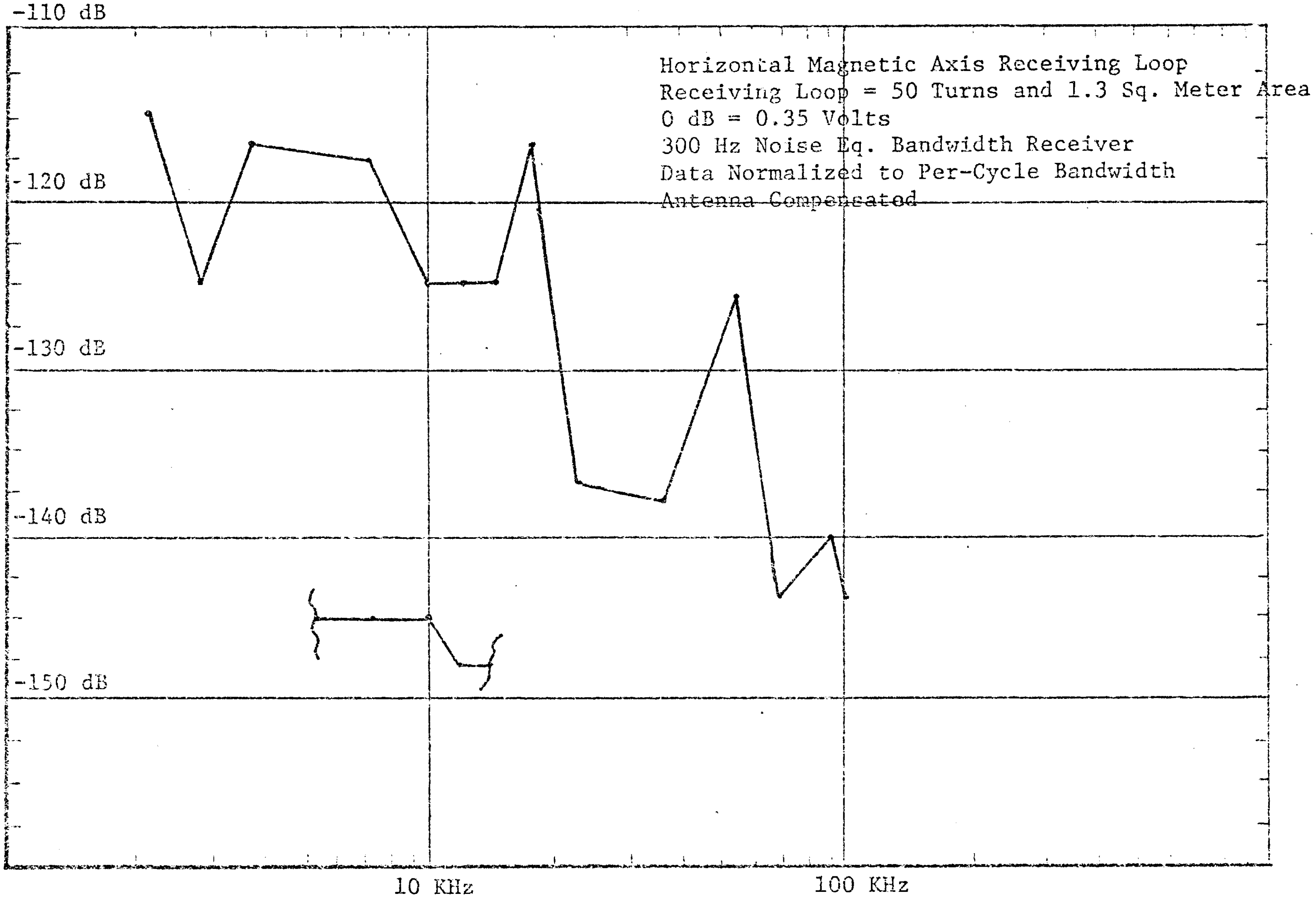


Figure 26

COMPOSITE NOISE DATA - HIGHEST AND LOWEST READINGS

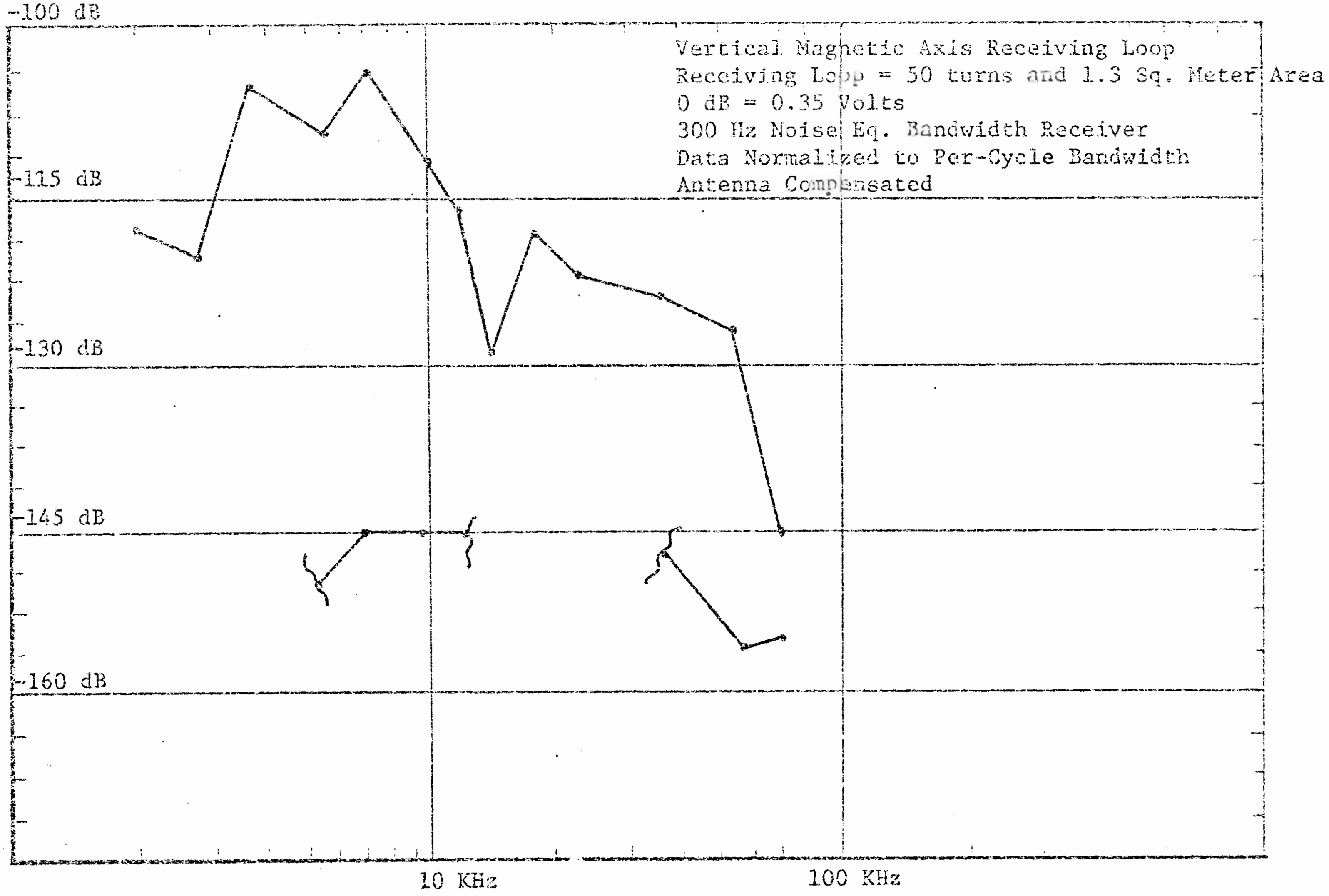


Figure 27

form in Appendix B for several test sites. The data taken within a few inches or feet of the cables and power center may not be accurate since a large loop was being employed. Thus in areas where the electric field is not constant over the loop, voltage due to the electric field may have been induced.

System Optimization

With the establishment of the earth's transmission characteristics and typical noise spectra to be encountered in mines, sufficient information is available to proceed with the investigation of the optimum operating frequency for a through-the-earth communication system. Since it is apparent from the data presented in the previous sections that the optimum frequency will depend on several factors which can be determined only by the application involved, the purpose of this section is to discuss those parameters which must be determined and the procedure which can be used to find the optimum frequency. In a succeeding section on the paging system design this procedure will be applied to an example situation.

Receiving Antenna Design -- it is well known that low frequency amplifiers can be built with noise figures less than 10 dB using designs that can be mass produced. Thus it is assumed that although amplifier noise may be present its effect can be made insignificant if the receiving antenna is designed with sufficient effective area. That is, due to the existence of noise fields from mining machinery and natural sources it is possible to make the noise voltage appearing at the antenna terminals much larger than the amplifier noise. Once this situation has been achieved, any further increase in receiver antenna gain will be of no advantage since the induced voltage due to signal and that due to noise would increase at the same rate yielding no further increase in the signal to noise ratio.

The receiving antenna design then would be determined by the minimum amount of external noise to be experienced at the frequency of operation and the receiver noise figure. A good rule of thumb might be to require the receiving antenna effective area and number of turns to be that required to yield the induced noise voltage to be ten times the amplifier noise voltage referred to the input.

Receiver Bandwidth -- as in the design of any communication receiver its bandwidth must be sufficiently wide to pass the information but yet be as narrow as possible to minimize the input noise. This optimization of receiver bandwidth depends on the type of modulation used. It should be pointed out that most classical forms of filter optimization in the literature are built around a "white" gaussian input noise whereas in coal mining applications this assumption would be very incorrect. In particular the existence of 60 Hz harmonics in the spectral region below 25 KHz can be very significant and be the dominate system noise to be combated. Thus the optimization procedure may not be of the classical form.

Threshold Level -- assuming the receiver must be capable of operating in a noise only environment (i.e. no received signal present) without producing erroneous outputs, some form of threshold or squelch circuit must be used. For example, in a signalling system a maximum allowable false alarm rate will be specified which would establish the required threshold level depending on the magnitude and statistical characteristics of the noise at the receiver output. The important point is that the threshold level must be set on the basis of the noise environment without consideration of the signal level to be present.

Received Signal Level -- the desired probability of detection can now be used in conjunction with the threshold level to establish the required signal level. That is, the received signal must be sufficiently larger than the threshold level to produce the required probability of detection for the noise statistics involved. This level can be referred to the receiver input to determine the signal level required at the receiving antenna output for successful system operation.

Frequency Optimization -- the design parameters that remain to be chosen are the transmitter power, the transmitting antenna design, operating frequency, and the maximum possible range between the transmitter and receiver. Although these can be traded off it is assumed here that since range is severely limited, the transmitter power and antenna gain design have been chosen as large as practical. In this case, the problem is reduced to determining system operating frequency that will yield the maximum possible range and still permit reception of an adequate signal level. The following iterative procedure can be used:

1. Arbitrarily select an operating frequency.
2. Assuming this frequency is optimum and using design parameters already established, solve equation (15) for range.
3. From the known conductivity and the range found in step 2, use equation (13) to find f_{opt}.
4. Compare f_{opt} found in step 3 to that used in step 2. If not equal, choose a new frequency and repeat steps 2 and 3. Continue until equality is established.
5. Select the exact final frequency based on practical considerations.
6. If the final frequency is near the optimum frequency, equation (15) can be used to yield the approximate maximum range that can be expected in the optimized system.

Since the resulting maximum range may not be large enough to cover an entire mine, the use of antenna arrays and phase synchronized transmitters may have to be utilized. Work on this idea was terminated before an adequate study of this problem could be undertaken. Some preliminary results are presented in reference 5.

The use of this optimization procedure in example situations had led to the following conclusions:

1. Even with an optimized system using a small (relative to one wavelength) transmitting loop more than one transmitting antenna will be required to completely cover most coal mines.

2. The use of other transmitting antenna configurations such as grounded rods should be studied for systems where the transmitter is located outside the mine.

3. Signalling systems designed to operate in a designated area of the mine, such as one section, are practical with radial ranges in excess of 400 to 500 feet using transmitting loops.

PERSONAL PAGING SYSTEM DESIGN

The usefulness of personal paging receivers in various business and industrial situations has been proven through many different applications over the past few years. Various designs using VLF, VHF, and UHF frequencies have been employed depending on the practicular operating environment. Very low frequencies have been used in and around metal buildings to take advantage of the properties of magnetic induction.

The coal mine application is similar in many ways to other industrial uses in and around metal buildings. That is, the presence of the earth attenuates the propagation of the electromagnetic field. However, as was shown in the preceding section of this report it is possible to achieve ranges of several hundred feed between two antennas placed underground if the operating frequency is properly chosen. In view of the potential application of the personal paging concept to extend the calling range of the telephone system into important areas such as the mining section, it was decided to study one way a personal paging system might be designed in order to achieve the maximum possible range and to operate in the noise environment normally encountered in and around operating mining machinery.

It should be pointed out here that this approach is not necessarily considered to be optimum for all mine applications. It is hoped the knowledge and experience reported here will add to the overall program of research where other approaches may have been attempted.

Two factors motivated the study of the autocorrelation detector for this application. First, due to the severe attenuation of signals by the earth it was desired to utilize a detector which could achieve extreme sensitivities. Secondly, due to the presence of large amplitude harmonics of 60 Hz in many operating mines a detector must be used which can attenuate or cancel their effect when operating at low frequencies. Since longer ranges have been shown to require a lower operating frequency for optimum results, it is expected that most practical applications would require operating frequencies in the region where 60 Hz harmonics can be severe.

This section summarizes the results of a study which is reported in considerable detail in references 9 and 10. The theory of operation, circuit design consideration, and results of laboratory testing of prototype circuits are summarized herein.

Summary of the Pertinent Aspects of Autocorrelation -- in binary communications, which can be used in a paging system, the receiver is required only to make a decision as to whether or not a signal is present in its particular channel. Since it is the presence and not the shape of the signal that is to be detected, receivers can merely rely on the differences in strengths between the signal and the noise to make this decision. To enhance this decision-making process conventional receivers use filtering techniques to improve the signal-to-noise ratio. The minimum detectable signal (MDS) is then governed primarily by the economics and practicability of obtaining a very narrow noise bandwidth.

Detection using autocorrelation techniques, however, relies on the differences between the statistics of signal and noise to aid its decision-making process. Signal-to-noise ratio improvements which are possible with autocorrelation lower the MDS to levels otherwise impractical to implement using conventional filtering techniques.

The autocorrelation function (ACF) of the signal plus noise input to a paging receiver in a typical mine environment may be represented as:

$$R_{s+n}(\tau) = R_s(\tau) + R_r(\tau) + R_h(\tau) \tag{23}$$

where

$R_{s+n}(\tau)$ = ACF of composite signal plus noise input

$R_s(\tau)$ = ACF of signal

$R_r(\tau)$ = ACF of random noise

$R_h(\tau)$ = ACF of the interferring 60 Hz harmonics

The second and third terms on the right hand side are undesired and constitute the noise to be combated. The $R_s(\tau)$ and $R_h(\tau)$ terms both originate from periodic sources and thus are likewise periodic while the $R_r(\tau)$ term is caused by the random noise. Signal-to-noise enhancement in this new domain may be realized by:

1. Choosing τ to be near an integral multiple of the signal period to increase the effect of $R_s(\tau)$ while
2. Choosing τ large enough so that the $R_r(\tau)$ terms is quite small while
3. Choosing τ such that $R_h(\tau)$ is negligible.

It will be seen in this report that these three options can be simultaneously realized.

Auto-Correlation Detector Design -- Figure 28 shows a block diagram of one approach to realizing an autocorrelation type detector. A crystal controlled oscillator and countdown chain provide a time base consisting of two complementary outputs spaced τ seconds apart. These outputs are followed by one-shots which generate 0.5 μsec sample command pulses for the analog gates. The input signal (a sinusoid) which may be contaminated with noise is preconditioned by a bandpass pre-filter and applied simultaneously to both analog gates. The input is then sampled alternately by each gate with a timing difference of τ seconds. The sampled input from each gate is "held" by the hold amplifier until the next sample arrives 2τ seconds later. The output from the hold amplifier then changes quickly to its new sampled value. The outputs from both hold amplifiers are applied to the two inputs of an analog multiplier which continuously forms the product of the two sampled values. The multplier is followed by an integrator which continually time averages the output.

If the input consists of only noise and if τ is chosen long enough so that successively sampled noise values are independent, then the products coming from the multiplier are as equally likely to occur positive as they are negative, and the average value is zero. The noise is truly uncorrelated only for τ approaching infinity and so a small mean or dc component will be obtained from the integrator even without a signal input. Furthermore, since the averaging period is not infinite the integrator output also contains a variance term with a noise-only input which must too be considered.

If a sinusoidal signal of proper frequency is applied to the input, the outputs from the multiplier will all be of like sign and the output from the integrator will continually build up. The time constant of the integrator is easily varied to give it sufficient "memory" to look at an input for several seconds duration.

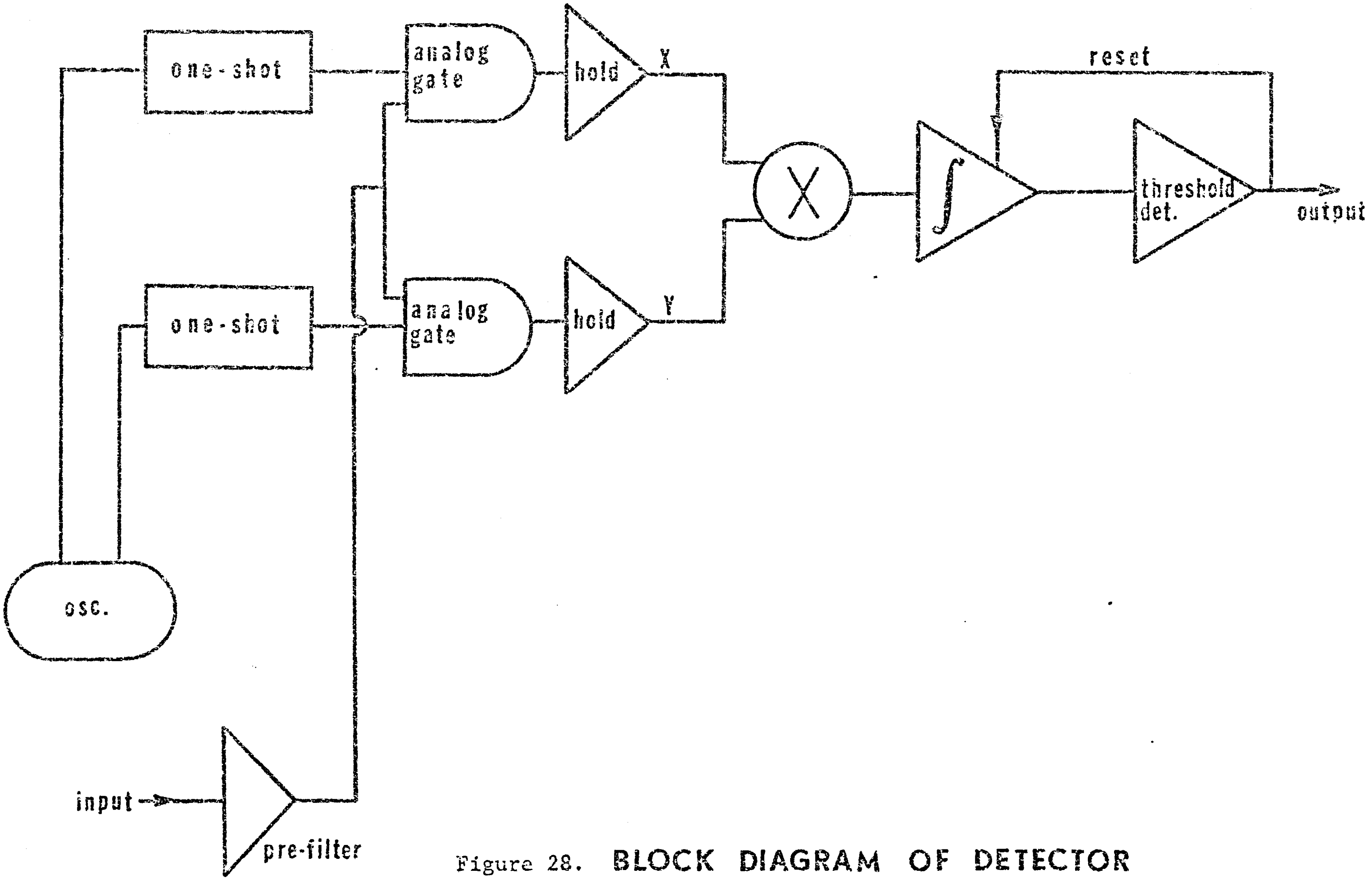


Figure 28. **BLOCK DIAGRAM OF DETECTOR**

The integrator is followed by a threshold detector which continually monitors the averaged output. If, at any time, the integrator output builds up to a pre-specified value a comparator will change state and reset the integrator. After an adjustable length of time the reset is removed and the integrator is once again able to build up (hopefully, only from an input signal). The reset-hold feature is necessary in order to keep the integrator from responding more than once to the same signal pulse in cases of high input signal-to-noise ratios.

As illustrated in Figure 29, one channel of the receiver samples the incoming signal plus noise at time x_1 and holds the sampled value until several cycles of signal later at x_2 when the next sample is obtained. The sampled value obtained from the second channel at y_1 is then multiplied with x_1 and the product entered into the integrator. The sampled value y_1 is similarly held until the first. The number of products averaged is dependent on the time constant of the integrator and the rate at which the products are being received. The approximate mathematical operation performed by the detector is then an estimation of the autocorrelation function for a particular τ and is expressed as

$$\overline{R}(\tau_o) = \frac{1}{N} [x_1 y_1 + x_2 y_1 + x_2 y_2 + \cdots + x_n y_{n-1} + x_n x_n]$$

where N is the number of products averaged.

Actually, equation (24) is the arithmetic mean of samples of the function

$$s(t, \tau_o) = [S(t) + N(t)] \times [S(t - \tau_o) + N(t - \tau_o)] \qquad (25)$$

where

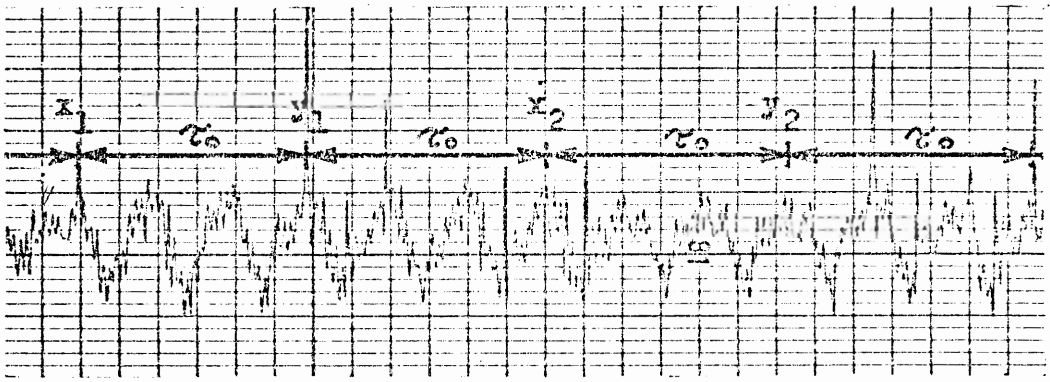
S(t) represents the input signal as a function of time

N(t) represents the input noise as a function of time

τ_o is the time delay between samples.

The presence of 60 Hz harmonics is ignored for the moment. The transmitted signal can be represented by

$$S(t) = E_m \sin (\omega_1 t + \theta) \qquad (26)$$



Note: sampling rate not to scale.

Figure 29
Illustration of the Sampling Procedure

with a normalized input signal power of

$$S_{in} = \frac{E_m{}^2}{2}$$

The noise is assumed to be white Gaussian noise (WGN) with a zero mean and a variance or normalized average power of

$$N_{in} = \overline{N^2(t)} \qquad (27)$$

where the bar indicates a time average.

Since the actual or true value of the ACF for an aperiodic signal is obtained only with an infinite sample size, the actual operation must be examined to note the effects of a finite sample size. Letting ψ be the sample mean as a randcm variable which is the measured value of the autocorrelation function at $\tau = \tau_0$; Mayhugh shows in reference 9 that its variance is

$$\sigma_\psi{}^2 = \frac{1}{N}\left[\frac{S^2_{in}}{2} + N^2_{in} + 2S_{in}\,N_{in}\right] \qquad (28).$$

If the input had only the desired signal present, the autocorrelation function would be

$$R_s(\tau) = S_{in} \cos\,(\omega_1\tau_0) \qquad (29).$$

Assuming that $\omega_1\tau_0$ will not be an exact multiple of $\pi/2$ and a sufficiently large number of samples are taken over the complete cosine wave cycle, the variance of the correlator output becomes

$$S_o = \frac{S^2_{in}}{2} \qquad (30).$$

The effective detector output signal to noise ratio is the ratio of equations (30) and (28) yielding

$$\left(\frac{S}{N}\right)_o = \frac{N}{1 + \frac{1}{2\left(\frac{S}{N}\right)_{in}^2} + \frac{4}{\left(\frac{S}{N}\right)_{in}}} \tag{31}$$

which describes the relationship between the output and input signal to noise ratios as a function of the number of autocorrelation function samples. Equation (31) is plotted in Figure 30 which shows the large increase in signal to noise ratio which can be obtained via autocorrelation.

Optimization of Pre-Filter Bandwidth and Sampling Data -- The necessity of bandpass filtering in the early stages of the receiver means that a bandlimited noise spectrum will be applied to the correlator instead of the usually and conveniently assumed white input. As this "pre-filter" bandwidth is decreased, the signal to noise ratio applied to the correlator increases. One might suppose that better performance would be obtained from the correlator with a more and more narrow pre-filter bandwidth. However, as adjacent samples become correlated with the decreasing bandwidth, the signal to noise ratio improvement due to sample averaging decreases. Therefore, as the pre-filter bandwidth is decreased two opposing effects occur - one which improves and one which degrades detector performance. Thus for a given detector integration time, there may exist an optimum choice of pre-filter bandwidth and sampling rate. The purpose of this section is to study this problem to show that an optimum choice of these quantities exists and to determine their approximate optimum values.

The problem to be analyzed is depicted in Figure 31. It is desired to find the pre-filter bandwidth and sampling rate of the correlator which yields the most signal to noise improvement for the pre-filter and correlator combination. The relationship between the input and output signal to noise ratio for the correlator is given in Equation (31). The following equation describes the pre-filter action

$$\left(\frac{S}{N}\right)_{in} = \frac{S_{in}}{\eta B} \tag{32}$$

where

η noise density input to the pre-filter (watts/Hz)

B noise equivalent bandwidth of the pre-filter

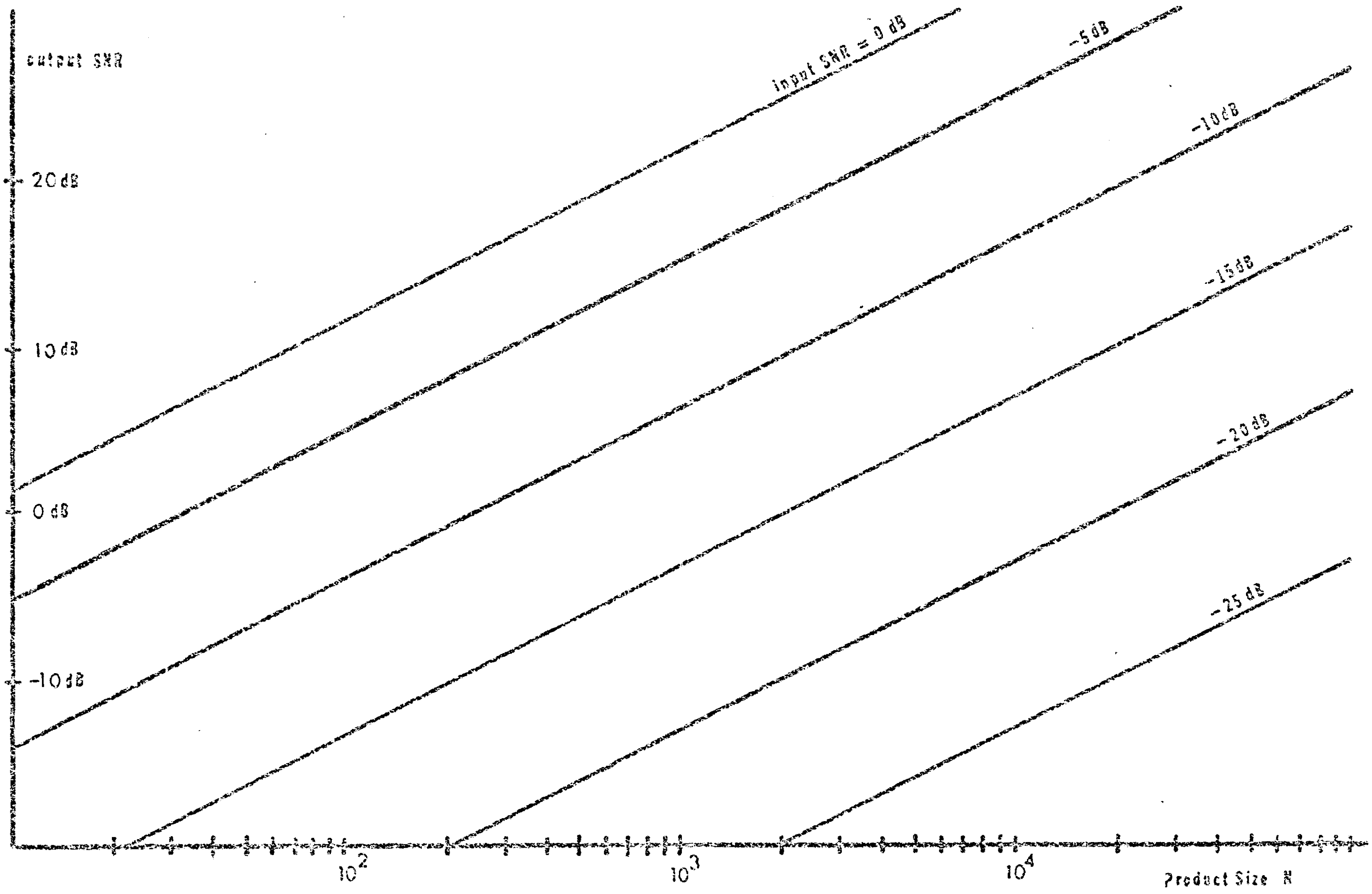


Figure 30. AUTOCORRELATOR GAIN

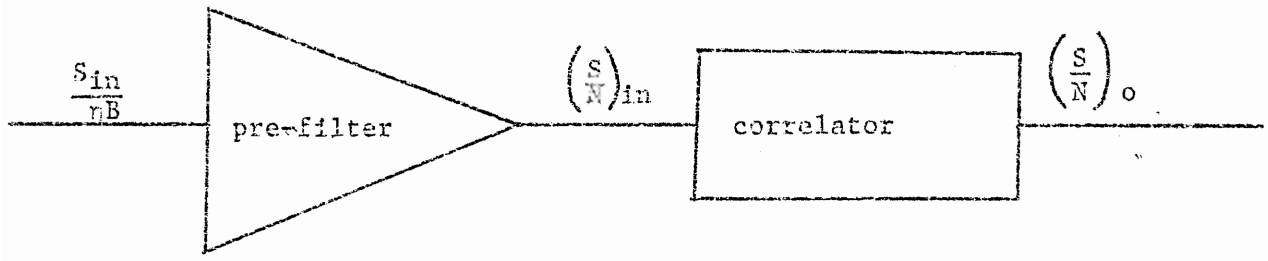


Figure 31. Optimizing Pre-Filter Bandwidth and Product Size

One method of studying the optimization problem is to set a desired output signal to noise ratio and search for the optimum arrangement of the remaining variables. Thus, let S_o/N_o = 10 dB for the present analysis.

Another factor which must be considered is the relationship between independence of noise samples and the bandwidth B of the pre-filter. It is well known that if the following relationship holds

$$B \simeq \frac{1}{\tau_o} \tag{33}$$

adjacent noise samples will be approximately independent.

Combining equations (31), (32), and (33) and solving for S_{in}/η yields the result

$$\frac{S_{in}}{\eta} = \frac{\frac{N}{T}}{(-1+\sqrt{0.5 + .05N})} \tag{34}$$

where T is the total length of the integration period and is equal to $N\tau_o$. Equation (34) is plotted in Figure 32 as a function of N and T. The minimum clearly shows that a sample size exists where the least S_{in}/η ratio is required to produce the desired output SNR of 10 dB. Fortunately for the range of T investigated the optimum N is relatively constant near 55.

It will be convenient in system calculations to know the noise equivalent bandwidth of the pre-filter and correlator combination. This can be easily found since

$$\frac{S_{in}}{\eta B_N} = \frac{S_o}{N_o} \tag{35}$$

where B_N is the noise equivalent bandwidth desired. Since S_o/N_o = 10 for Figure 32, B_N can be found from the relation

$$B_N = \frac{1}{10}\left(\frac{S_{in}}{\eta}\right) \tag{36}$$

and is graphed in Figure 33.

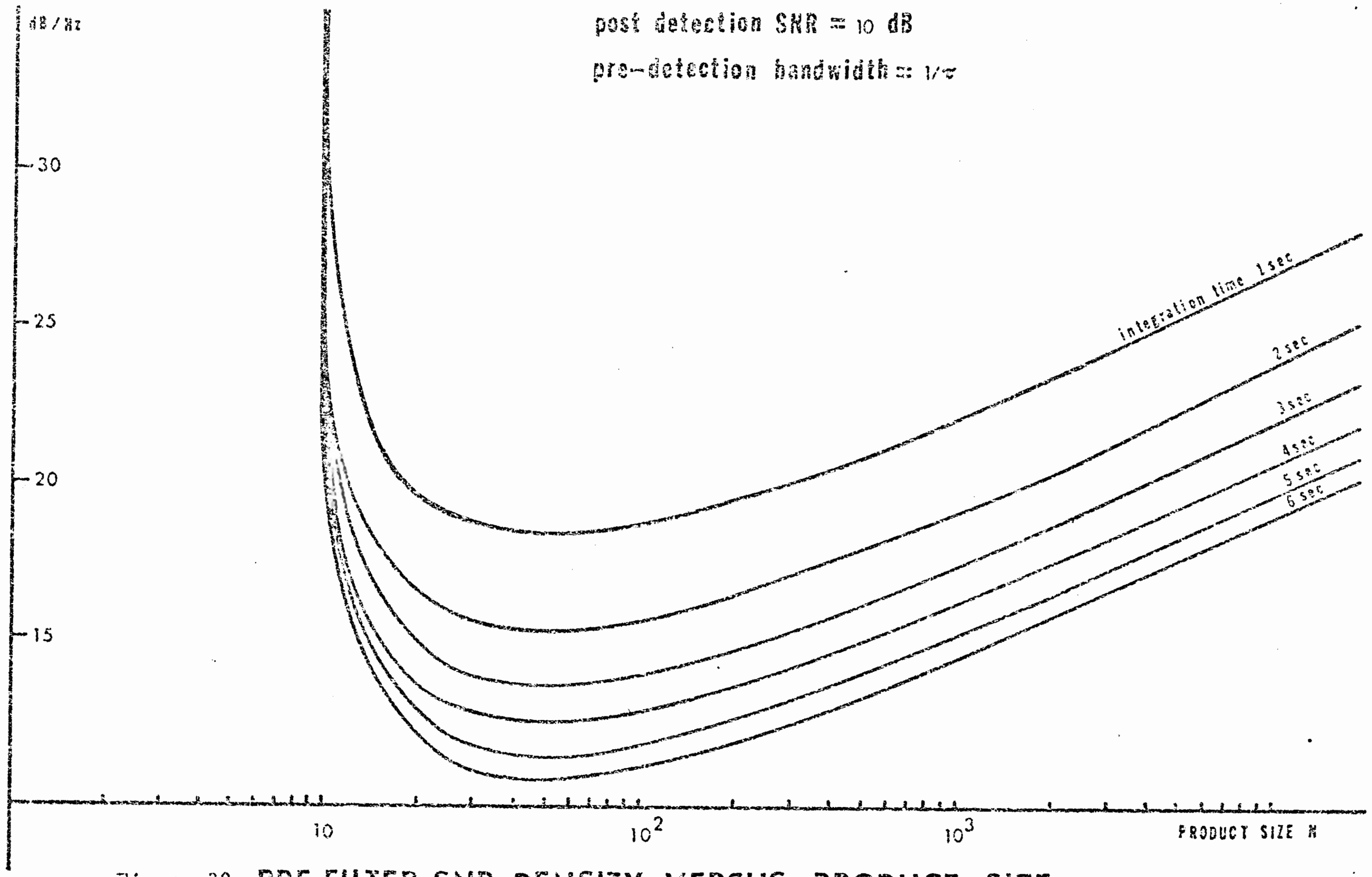


Figure 32. **PRE-FILTER SNR DENSITY VERSUS PRODUCT SIZE**

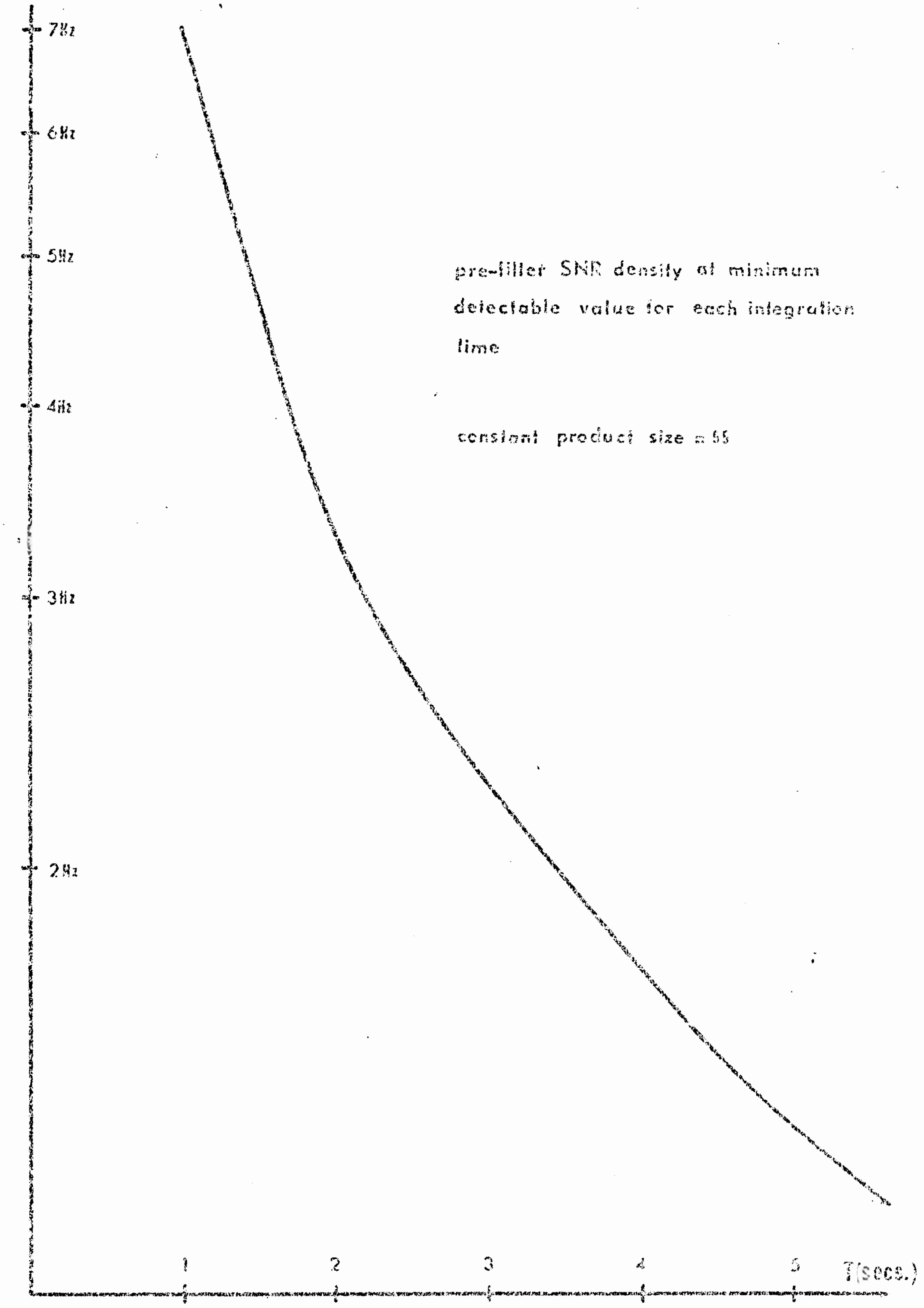


Figure 33. DETECTOR NOISE BANDWIDTH vs INTEGRATION TIME

Selection of Sampling Period and Signalling Frequency -- at the beginning of this section on the paging system design, the basic thesis of utilizing autocorrelation was set forth. It was assumed that if a sampling rate could be established which would simultaneously yield (1) zero correlation of samples of 60 Hz harmonics, (2) zero correlation of random noise samples, and (3) large positive or negative correlation of signal samples, then a detector could be built which would permit the signalling frequency to exist at very low frequencies in between harmonics of 60 Hz. The problem of selecting a sampling period and a signalling frequency to achieve these ends are discussed in this section. A summary of the more pertinent results presented in reference 9 is given here.

Obviously a sampling period can be found to yield zero correlation for any one 60 Hz harmonic. For example, the n-th harmonic has the autocorrelation function

$$R_h(\tau) = S_n \cos(2\pi\ n\ 60\tau) \tag{37}$$

where S_n is the average power. If τ is chosen such that

$$\tau = \frac{M}{240\ n} \qquad M = 1, 3, 5, \cdots \tag{38}$$

then $R_h(\tau)$ will be zero. The problem arises in the desired rejection of two adjacent harmonics of 60 Hz. What if it is also desired to reject the (n + 1)th harmonic simultaneously with the n-th harmonic. Thus in addition to equation (38) it follows that

$$\tau = \frac{N}{240\ (n+1)} \qquad N = 1, 3, 5, \cdots \tag{39}$$

must also be true and since τ must be the same for both cases

$$\frac{M}{n} = \frac{N}{n+1} \tag{40}$$

Since N must be larger than M and both must be odd, then

$$N = M + k \tag{41}$$

where k must be even and positive. Substituting equation (41) into (40) yields

$$M = nk \tag{42}$$

which must be true if the autocorrelation function for both the n-th and (n + 1)th harmonics are to be zero. However, (42) can never be true since M must be odd while k must be even. Thus it is not possible to make both harmonics correlate to zero simultaneously.

This result is not too discouraging since the strongest harmonics are multiples of 180 Hz due to the use of three phase AC power to operate mine rectifiers. Also, by choosing the operating frequency sufficiently high that the nearest harmonic has a large n, the correlator output for the (n + 1)th harmonic will still be small and can be made of opposite sign to that expected from the signal. Coupling these two properties with the fact that the pre-filter can be designed to offer some attenuation to nearby 60 Hz harmonics, it can be concluded that the combination of correlation and filtering can be used to reject strong harmonics of 60 Hz while providing long averaging times for extremely sensitive detection.

The fact that the sampling period can be chosen to minimize the non-zero correlation harmonic can be seen in Figure 34. First it must be noted that since both harmonics are multiples of 60 Hz, the two autocorrelation functions will peak simultaneously every 1/60 seconds. This means that the least separation between the zero points will exist one quarter cycle on either side of the simultaneous peaking points. Therefore if one chooses

$$\tau = \frac{m}{60} - \frac{1}{120\ n} \tag{43}$$

where m is any positive integer then the n-th harmonic will correlate to zero while the (n + 1) or (n - 1) harmonic will exhibit the least possible correlation. Since it will normally be desirable to sample as rapidly as possible, commensurate with the pre-filter bandwidth, m will usually be one. This means the sampling rate will require a pre-filter bandwidth on the order of 60 Hz which is in line with the optimum sample size of N = 55 when a one second integration time is used.

Using the early results of the through-the-earth communication studies, it appeared that an optimum operating frequency might lie some-

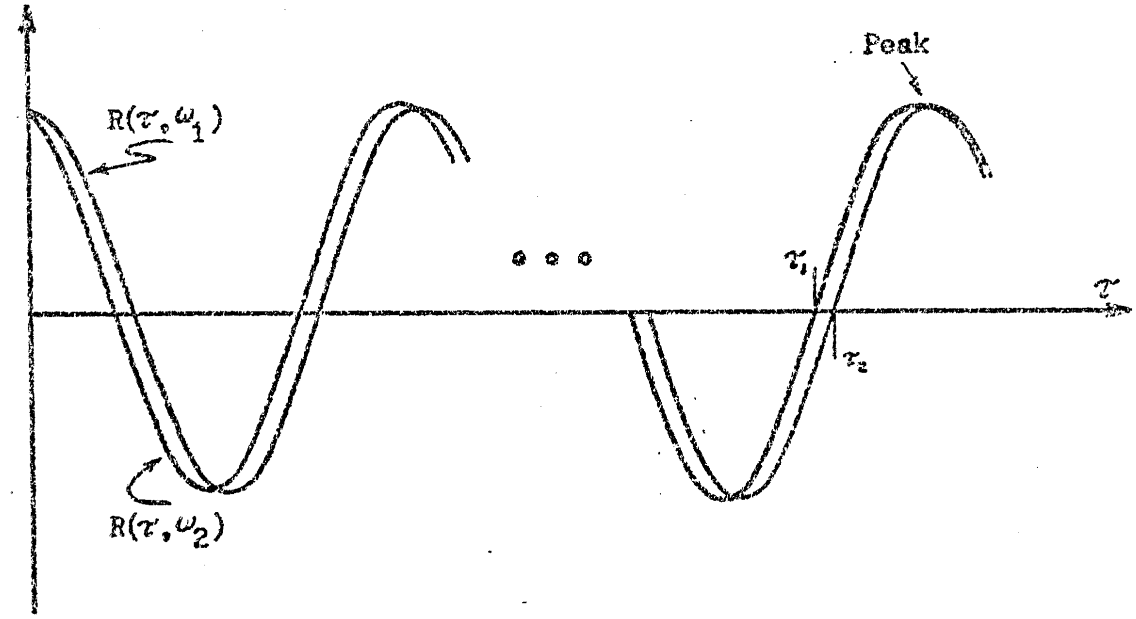


Figure 34
Appropriate Nulling of Troublesome Harmonic

where between 2 and 3 KHz. Thus in order to proceed with the design and testing of this detection concept it was decided to pick an operating frequency between the 47th and 48th harmonic of 60 Hz, i.e. between 2820 and 2880 Hz. The 2820 frequency was chosen to yield zero correlation. It would have been better in practice to have chosen the 2880 frequency since it is a multiple of 180 Hz. Utilizing equation (43) where m is one and n is 47 yields

$$\tau_0 = 0.165780142 \text{ sec.} \tag{44}$$

which is a sampling rate of

$$f_0 = 1/\tau_0 = 60.32085556 \text{ Hz} \tag{45}$$

Utilizing this value of τ_0 in equation (37) for the two harmonics yields

$$\begin{aligned} R_h(\tau_0) &= 0 \qquad \text{for } n = 47 \\ R_h(\tau_0) &= -.035 \text{ for } n = 48 \end{aligned} \tag{46}$$

thus producing the desired result.

Using the sampling period given in equation (44) one can easily show that only one frequency between the 47th and 48th 60 Hz harmonics will yield a maximum positive correlation which is

$$f_1 = 2835.080200 \text{ Hz} \tag{47}$$

Substitution of (44) and (47) into equation (29) will yield a correlation of S_{in}. However, this frequency is not suitable to be used as the signalling frequency with the above sampling period. Since the correlator uses only samples of the incoming signal, and in this case would be taken exactly every 47 cycles of f_1, the possibility exists that the first sample could be near the zero crossing of the incoming signal. In this case the correlator output would be zero even if no noise were present. There are several ways that can be devised to circumvent this problem. The one used here is to choose the signalling frequency slightly different than f_1 given in equation (47) such that two adjacent samples of the signal are nearly but not exactly equal. Because of the slight frequency difference sample pairs will be taken over the entire cycle of the signal sine wave. This operation is in agreement with the use of equation (30) in earlier derivations. Reference (9) discussed this problem in more depth and concludes that a frequency difference which yields a phase difference between adjacent samples of ten degrees over one cycle of the signalling frequency should be adequate. Arbitrarily choosing a frequency slightly less than f_1 given in equation (47) yields the desired signalling frequency

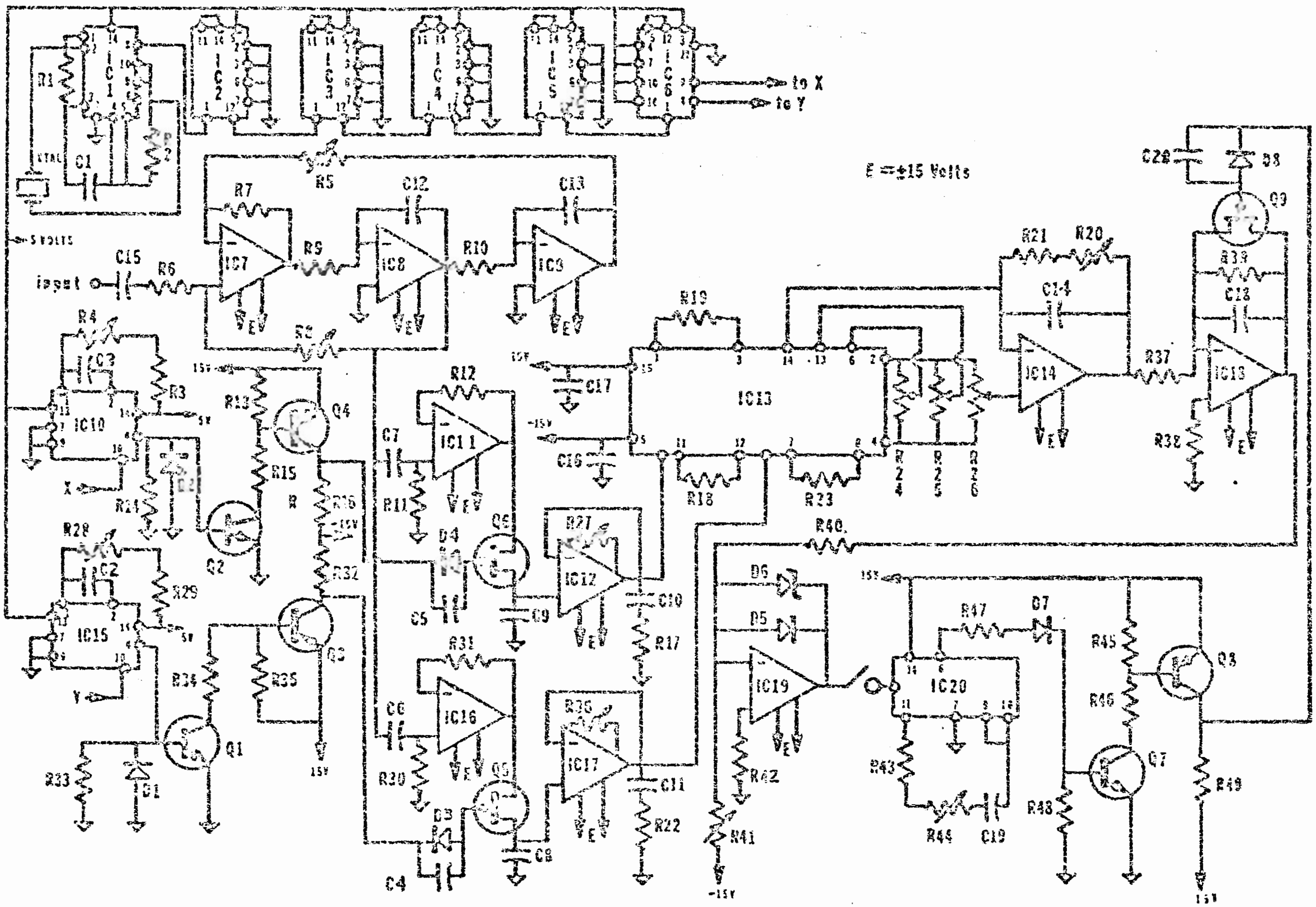
$$f_c = 2833.404632 \text{ Hz} \qquad (48)$$

The success of this approach obviously depends on the sampling frequency and signalling frequency closely maintaining their desired values. To analyze this problem assume the two frequencies can be maintained within ± .005% of the designed value. Assuming worst case situations where the two frequencies are at opposite extremes it can easily be shown the signal correlation term (i.e. output signal power) varies less than 2.5% of its maximum value. Thus it is seen frequency drift will have very little effect if crystal controlled sources are used.

<u>Circuit Design</u> -- a prototype circuit was designed and the schematic diagram is shown in Figure 35 followed by a complete parts list in Table III. This circuit was used in all tests described in subsequent sections. The sub-circuits are of conventional design except for the analog multiplier. The particular device employed is the key to the autocorrelation technique being suitable for actual use. Thus the discussion of circuit design presented here concerns the analog multiplier.

The multiplication operation was the most difficult to implement. One common approach to the multiplication process is to A/D the input initially and perform the multiplication digitally. The analog approach was chosen because it is less complex and inexpensive. However, it was soon learned that the accuracy of most analog multiplication techniques falls far short of their digital counterpart.

Multiplier accuracy is usually defined by the manufacturer as a per cent of full scale value. Nearly all of the present multipliers (hybrid, monolithic, or discrete) have a linearity of approximately ± 1% full scale. This means that if the maximum output product is 10 volts, then the maximum error for all products is ± 0.1 volt. The answer obtained is then .09V ± .1V, and the error is large.



SCHEMATIC DIAGRAM OF PROTOTYPE

Figure 35

TABLE III PROTOTYPE COMPONENT IDENTIFICATION

C1	.01 uf
C2	.002 uf
C3	.002 uf
C4	39 pf
C5	39 pf
C6	2 uf
C7	2 uf
C8	.001 uf
C9	.001 uf
C10	12 pf
C11	12 pf
C12	.0015 uf
C13	.0015 uf
C14	10 pf
C15	47 uf
C16	.1 uf
C17	.1 uf
C18	1 uf
C19	250 uf
D1	IN914
D2	IN914
D3	IN914
D4	IN914
D5	IN914
D6	IN754
D7	IN914
D8	IN914
IC1	SN7400
IC2	SN7490
IC3	SN7490
IC4	SN7490
IC5	SN7490
IC6	SN7473
IC7	SN72741
IC8	SN72741
IC9	SN72741
IC10	N8162A
IC11	SN72741
IC12	uA740
IC13	MC1594
IC14	MC1741
IC15	N8162A
IC16	SN72741
IC17	uA740
IC18	SN72741
IC19	SN72741
IC20	SN74721
Q1	2N3013
Q2	2N3013
Q3	Hep 52
Q4	Hep 52
Q5	2N4856A
Q6	2N4856A
Q7	2N3013
Q8	Hep 52
Q9	2N4856A
R1	470
R2	470
R3	820
R4	10K pot
R5	100K pot
R6	20K
R7	20K
R8	3.5 Meg pot
R9	20K

R10	20K
R11	10K 1%
R12	10K 1%
R13	200
R14	4.7K
R15	820
R16	330
R17	510
R18	10K
R19	16.2K 1%
R20	50K pot
R21	22K
R22	510
R23	20K
R24	20K pot
R25	20K pot
R26	50K pot
R27	10K pot
R28	10K pot
R29	1K
R30	10K
R31	10K
R32	330
R33	4.7K
R34	820
R35	200
R36	10K pot
R37	1 Meg
R38	1 Meg
R39	3.9 Meg
R40	2.2K
R41	100K pot
R42	2.2K
R43	4.7K
R44	20K pot
R45	200
R46	820
R47	4.7K
R48	4.7K
R49	330

All resistors ¼ watt 10% unless otherwise specified. Resistance values are in ohms.

Bypass IC7, IC9, IC11, IC12, and IC14 with .01 uf in parallel with 1 uf.

Our first attempt at a multiplication scheme was to use the Motorola MC1595 monolithic four quandrant multiplier. This relatively inexpensive IC is specified with a linearity of ± 1% of full scale, an adjustable scale factor, and "excellent" temperature stability. Three samples were tested and found to be unacceptable for this particular application for the following reasons:

1. Although tests showed that linearity was near that specified, the zero reference was not stable and varied as much as a few tenths of a volt over a several minute period.[1]

2. The input impedance to the circuit is so high (35 Meg-ohms) that the output was particularly sensitive to stray capacitance as well as stray RF fields. (In fact, with a six inch lead connected to the X-Y terminals, a local radio station was received quite well). This would require that particular care would have to be paid to shielding and layout.

3. Alignment and adjustment of offsets were particularly difficult and time consuming. Four controls are used to align the device, and they are so interactive that at least three iterations in the trimming procedures are required.

4. The scale factor and therefore the output is directly dependent on the supply voltage. Tight voltage regulation would be required in the final receiver.

It was decided that since all variable transconductance multipliers such as the MC1595 have a common inherent linearity problem that it might be wiser to investigate a discrete "quarter-square" method with diode shaping networks. Two versions were constructed using three operational amplifiers and two one-quadrant squaring circuits. Two of the op amps perform the summing and the diodes perform the absolute value operation. The squaring modules consisted of diode shaping networks that contained six biased IN914 diodes. The circuit is inexpensive, relatively easy to align (compared to the MC1595), and linearities on the order of .4% were obtained. This approach was used temporarily in an early version of the prototype and performed quite well. It may be an attractive alternate in the final receiver since diode arrays on monolithic chips are available whose characteristics track with temperature.

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[1] This instability may have been peculiar only to the particular IC's tested and not generally indicative of the MC1595. Neil Wellenstein, a Motorola instrumentation application engineer in Phoenix, Arizona, advised that he had not previously noted such instability.

It was then discovered that Motorola had available a new experimental product, the MC1594, which was hoped to overcome the many difficulties encountered with its forerunner. The MC1594 is an improved variable transconductance multiplier with internal level-shift circuitry and an internal voltage regulator which biases the entire IC to make it essentially independent of supply variations. Scale factor, input offset, and output offset are easily adjusted with four potentiometers. This version boasts a typical linearity of ± .5% in addition to being comparable in price with the MC1595. Figure 36 is a connection diagram for the multiplier as it was used in the detector prototype.

Test Results -- the purpose of this section is to report the results obtained from laboratory tests on the prototype. Three specifications are of particular significance: 1) the availability of the detector to reject 60 Hz harmonics, 2) the sensitivity obtained, and 3) linearity of the output as a function of signal input.

Figures 37 and 38 are plots of the correlator transfer characteristic as a function of signal frequency for integration times of 1 second and 6 seconds, respectively. Here the frequencies of key interest are 2.820 KHz and 2.880 KHz, the two troublesome to Hz harmonics. As can be seen from both plots there is negligible output from each. These plots were obtained with the input applied after the pre-filter which, in the completed detector, offers even more attenuation of the adjacent harmonics.

The photographs of Figure 39 illustrate two examples of the output from the sample-hold circuits. The top photograph shows the sampled output with an applied sine wave at the design center frequency. The output is, of course, a replica of the input reconstructed at a much lower frequency while still retaining a zero mean. The bottom photograph was taken with a noise-only input. Inspection shows this output to be random with a zero mean also.

Figure 40 shows photographs of test results illustrating the detection capability of the completed detector. Photo (a) shows both the signal and noise, for comparison, that is applied to the pre-filter input during the 2 second signal pulse. Here, the rms value of the input noise is about 14 times that of the signal. Photo (b) shows the output from the pre-filter during the signal pulse. The measured SNR from the pre-filter into the correlator during the signal pulse is 1.9 dB. Photo (c) shows the integrator output for the 2 second input pulse (reset disabled).

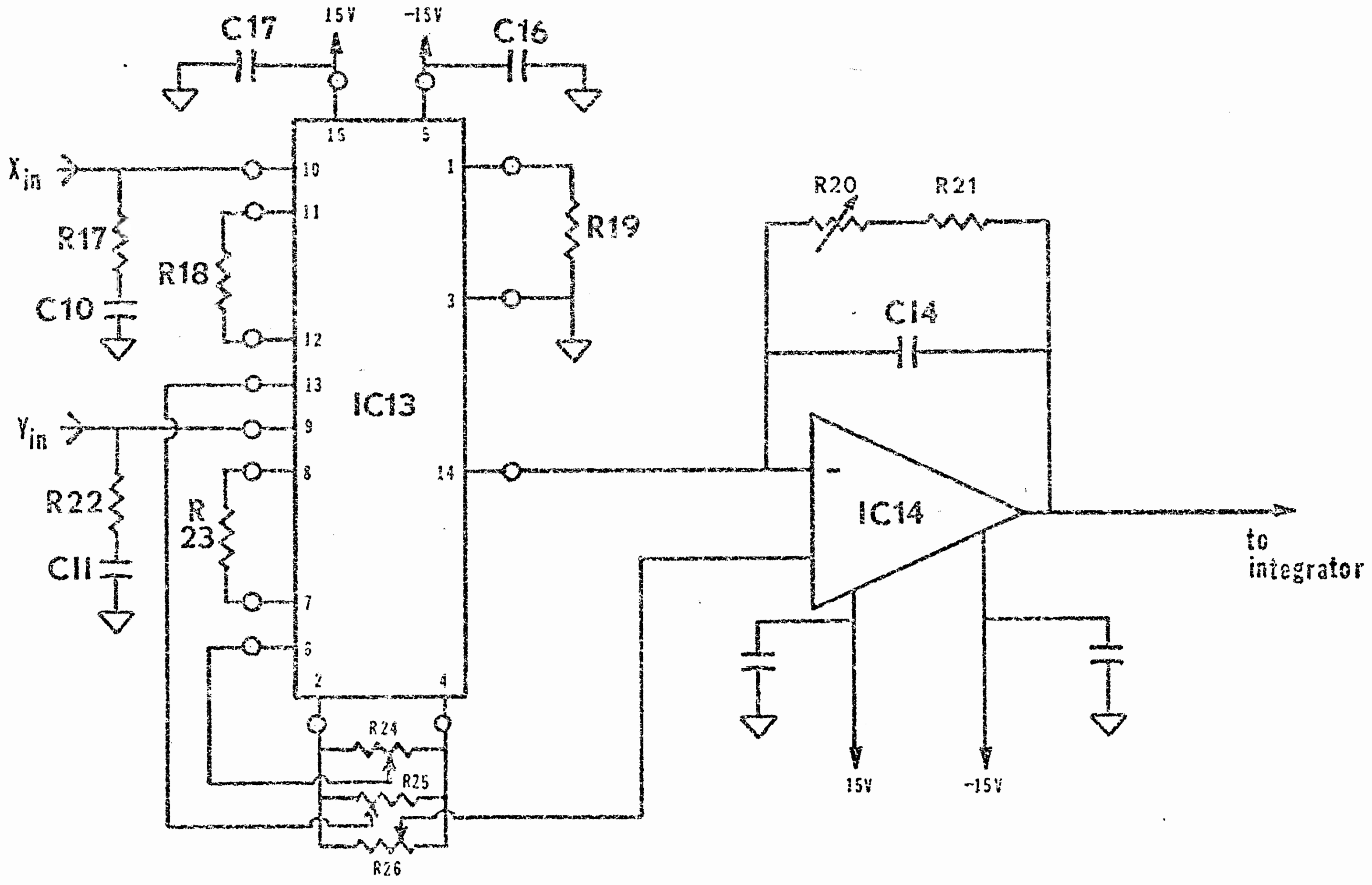


Figure 36. **ANALOG MULTIPLIER**

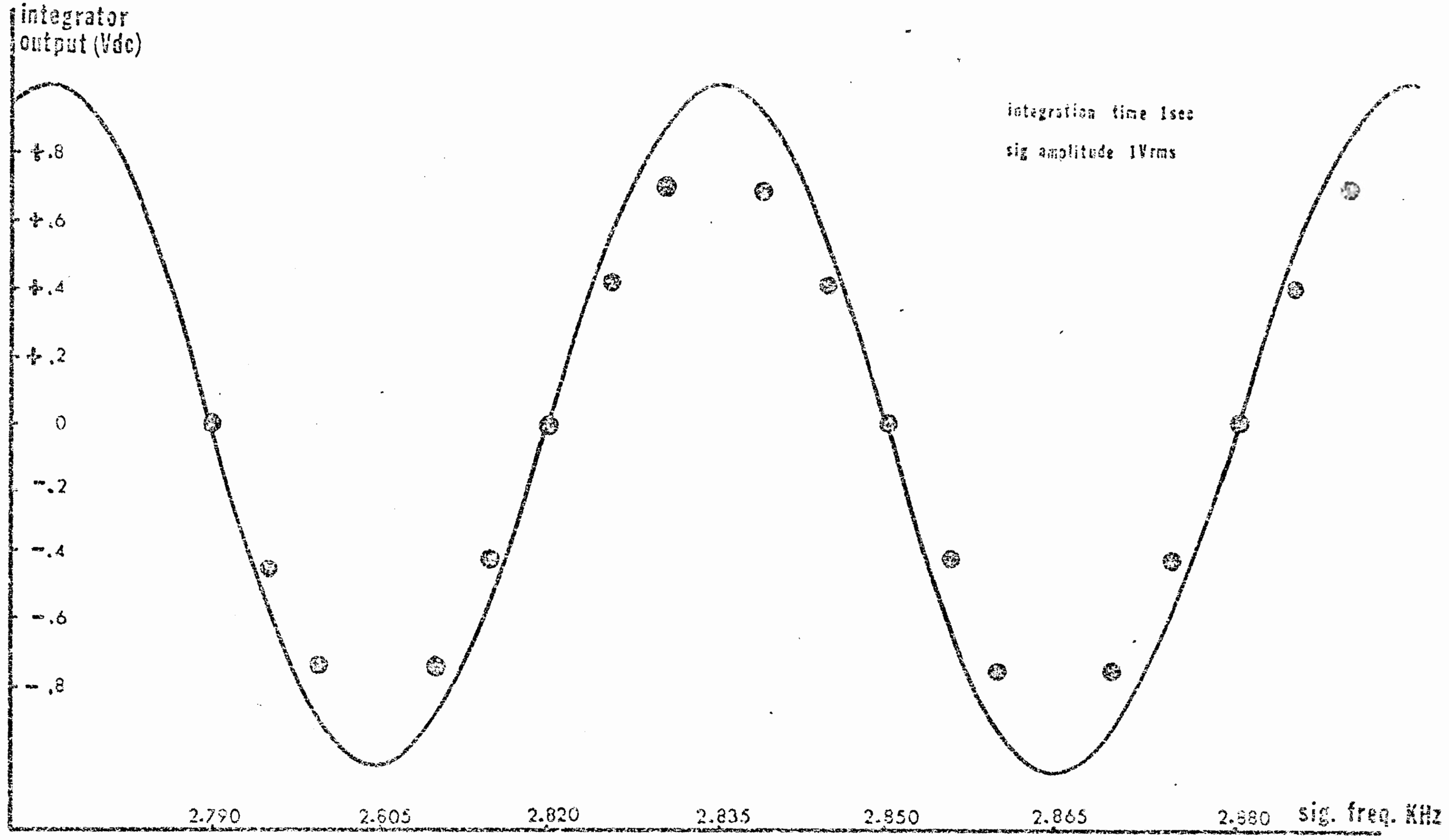


Figure 37. CORRELATOR TRANSFER CHARACTERISTIC

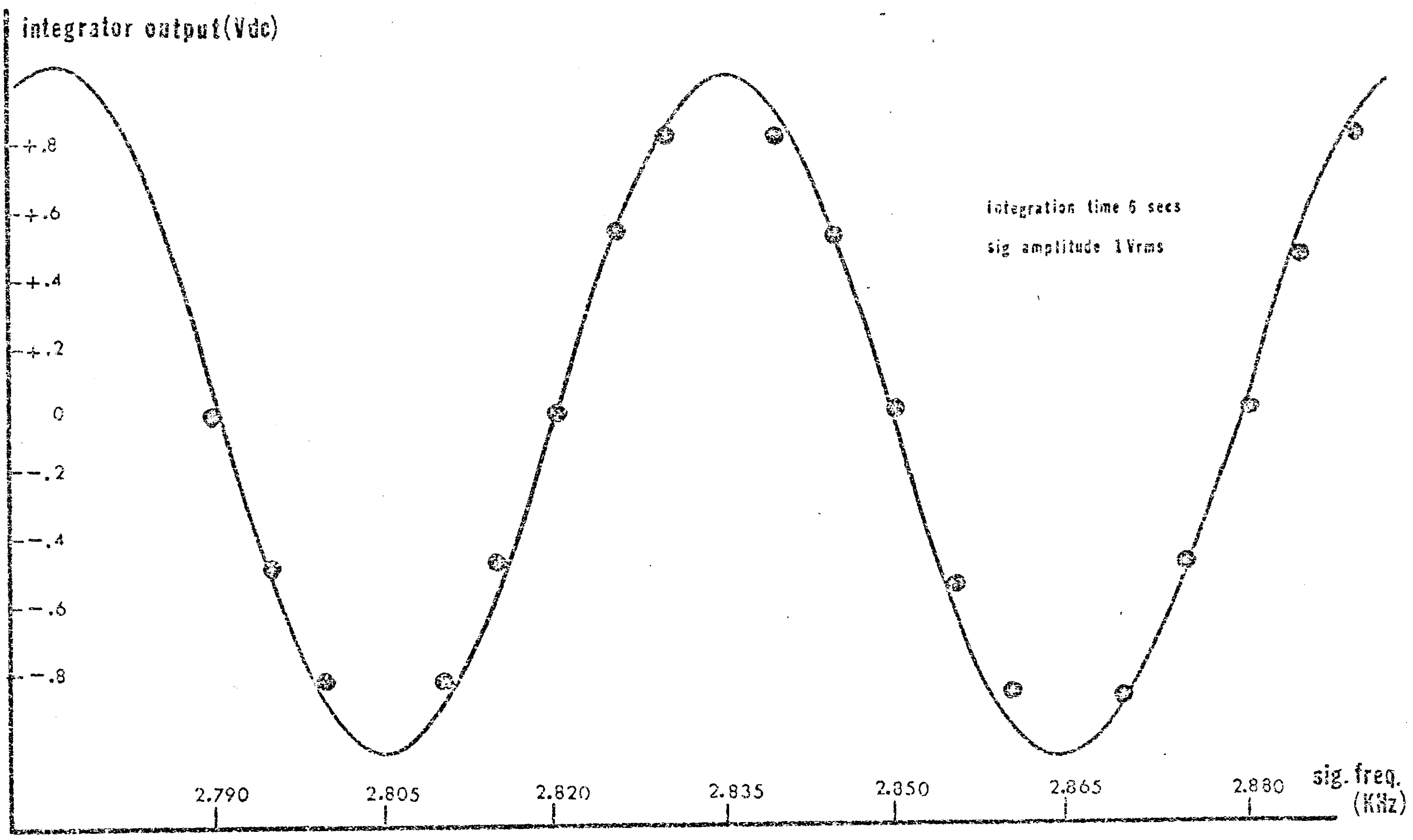
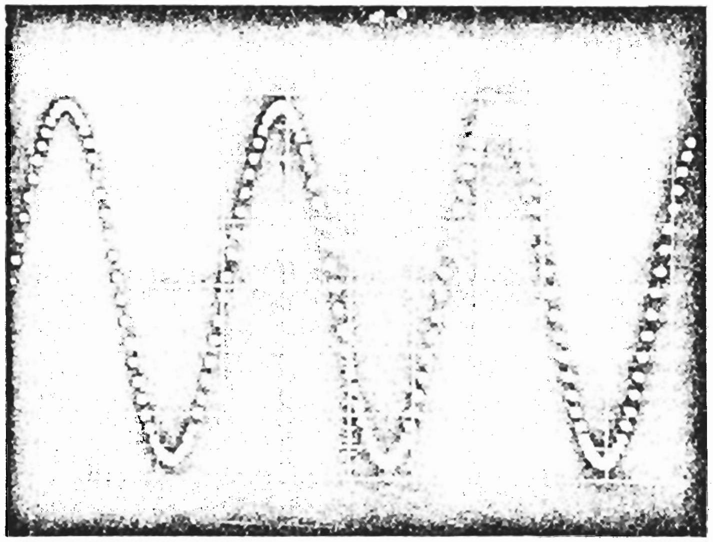
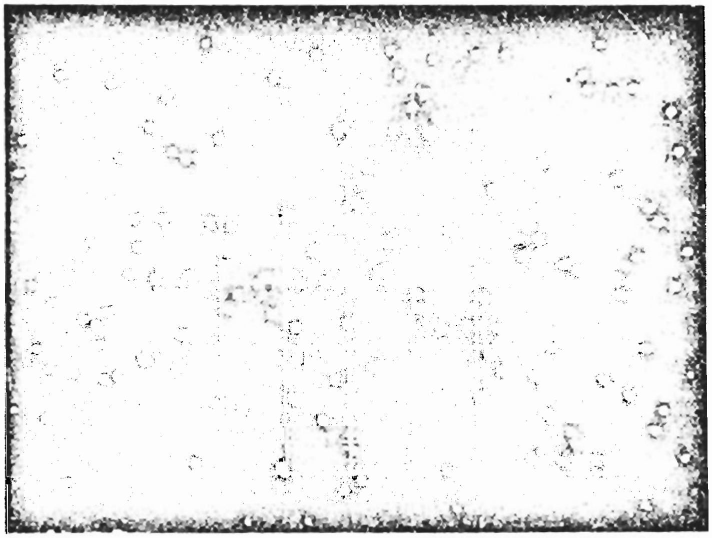


Figure 38. **CORRELATOR TRANSFER CHARACTERISTIC**

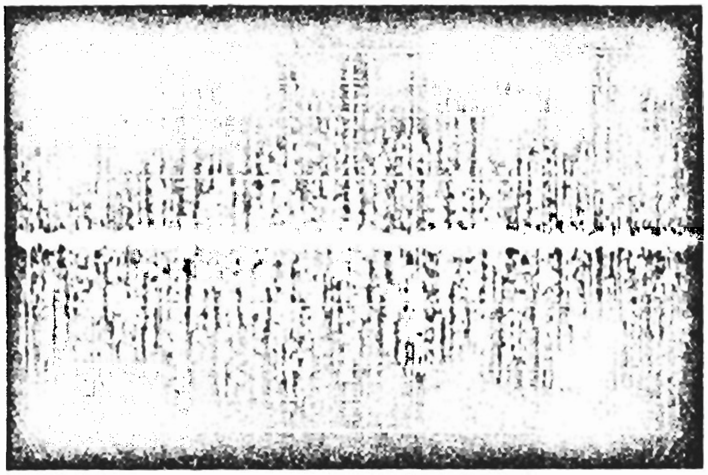


a. Output of X-Hold amplifier with a 2.833 KHz, 1 volt rms sinusoid at input to correlator
Vert. = .5V/cm.
Horiz. = .5sec/cm.

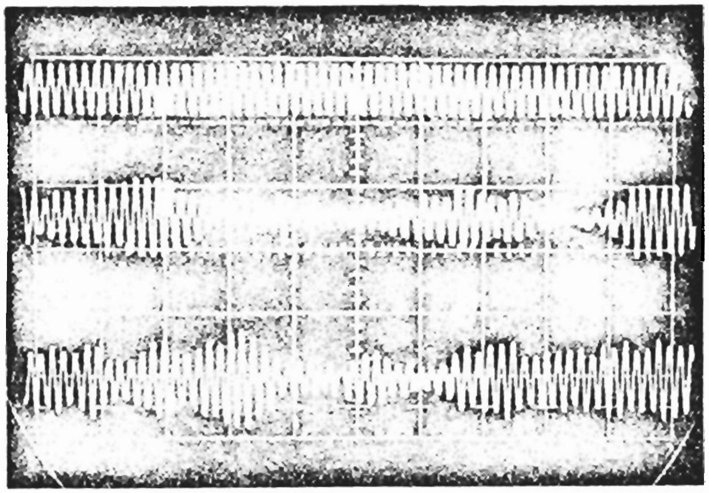


b. Output of X-Hold amplifier with 1 volt rms noise from a 20 KHz source at input to correlator.
Vert. = .5V/cm.
Horiz. = .5sec/cm.

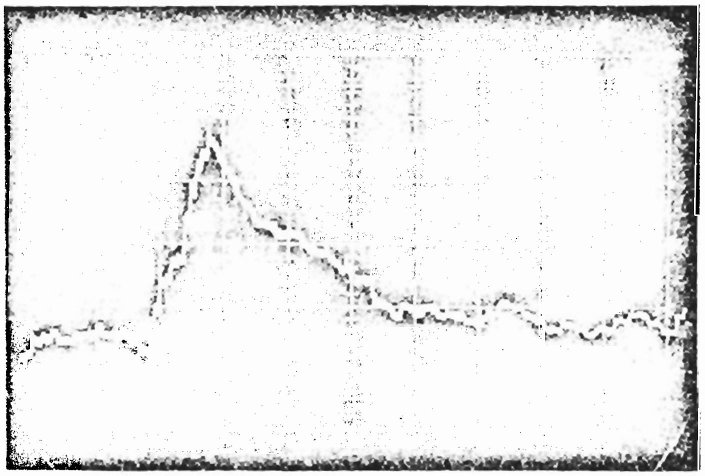
Figure 39 Sample-Hold Outputs



a. Input to pre-filter
Top: 2.833 KHz signal
at .0128 V rms
Bot: .18 V rms noise
at 20 KHz BW
Vert. = .2V/cm.
Horiz. = 1msec/cm.



b. Output from 60 Hz pre-filter
Top: signal
Mid: noise
Bot: Signal + noise
Vert. = 4V/cm.
Horiz. = 2msec/cm.



c. Output from correlator with 1 sec integrator for a 2 sec input pulse
Vert. = .5V/cm.
Horiz. = 2sec/cm.

Figure 40 Detector Test Results with Reset Disabled

Figure 41 shows the detector output amplitude as a function of signal input amplitude into the pre-filter. As can be seen from this plot the output is essentially a linear function of the input for amplitudes ranging from 0.8 V_{rms} to 11.5 dB. The non-linearity at the lower end of the curve is due to low-level distortion in the pre-filter and could be reduced with an improved design. The upper bound could be extended by reducing the multiplier scale factor K as already discussed.

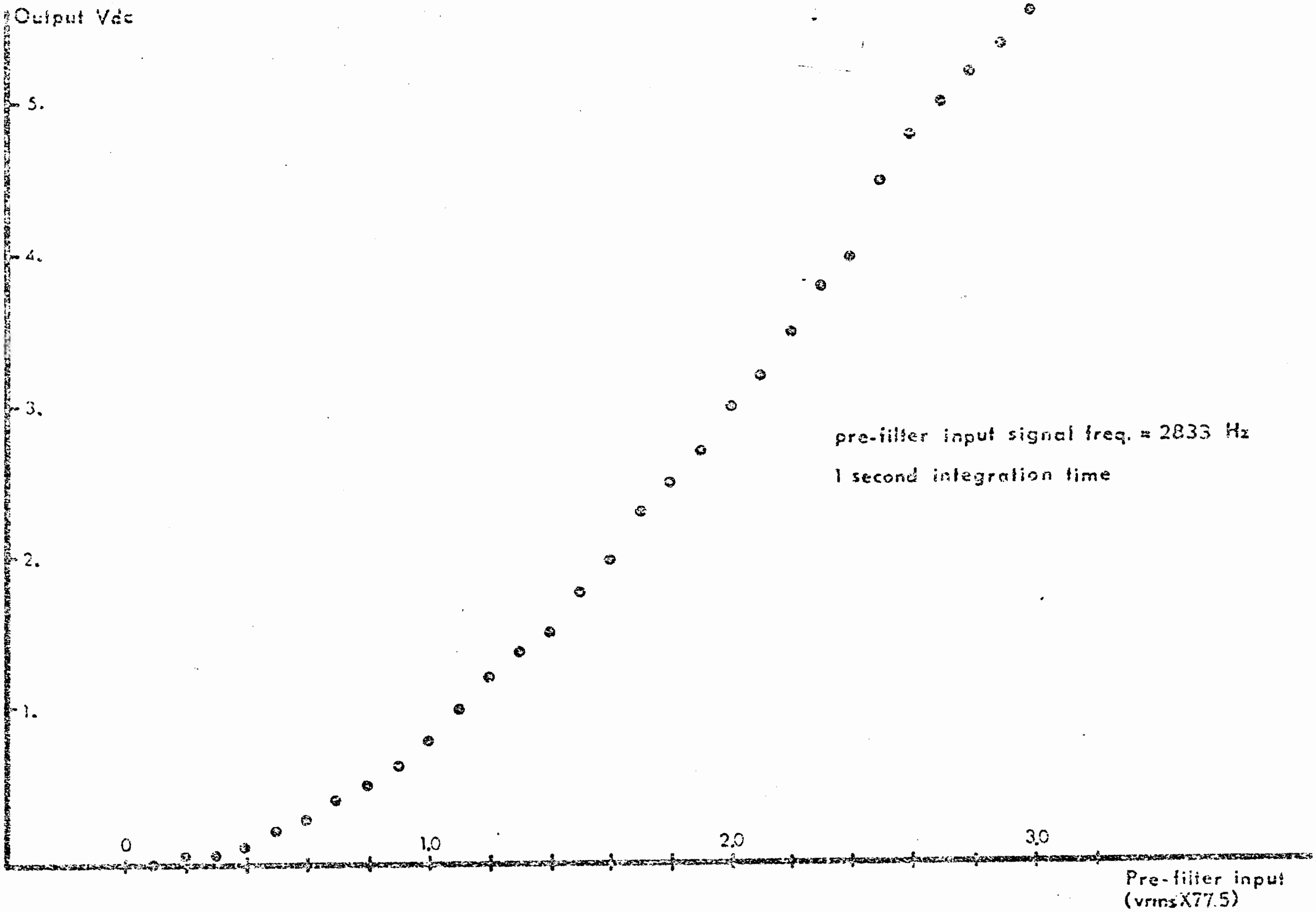
Figure 42 is a photograph of the complete breadboarded prototype.

Coding System Design -- since the autocorrelation detector output indicates the presence or absence of an input signal by virtue of the integrator's output relative to a pre-set threshold, some form of coding must be employed to selectively call different receivers. Codes involving changes in amplitude, frequency, or duration of the code pulse were ruled out by virtue of the type of detector being used. Since the detector output is binary when one threshold is used, two types of codes were studied. They were pulse position coding and binary coding. The system requirements established for the coding scheme were:

1. The ability to selectively signal any one of forty-nine receivers.
2. Maximum calling cycle time of seventeen seconds.
3. Low false call rate.
4. Emergency page facility.

After careful study of possible binary and pulse position codes that could be used, it was determined that a pulse position coding technique would be more practical to implement. Thus, the particular pulse position code chosen is described here. A more detailed description is presented in reference 10.

The pulse position code consists of three pulses -- each one second long. The spacing between the pulses can be varied from one to seven seconds in increments of one second. The longest and shortest codewords are shown in Figure 43. The code address refers to the spacing between the end of a code pulse and the beginning of the succeeding pulse. The address of the longest codeword is thus 7,7 and the address of the shortest is 1,1. For each of the seven time slots between the first and second pulses there are seven time slots between the second and third pulses, thus allowing forty-nine possible code words within the seventeen seconds calling time.



pre-filter input signal freq. = 2833 Hz
1 second integration time

DETECTOR INPUT-OUTPUT VOLTAGE TRANSFER CHARACTERISTIC

Figure 41

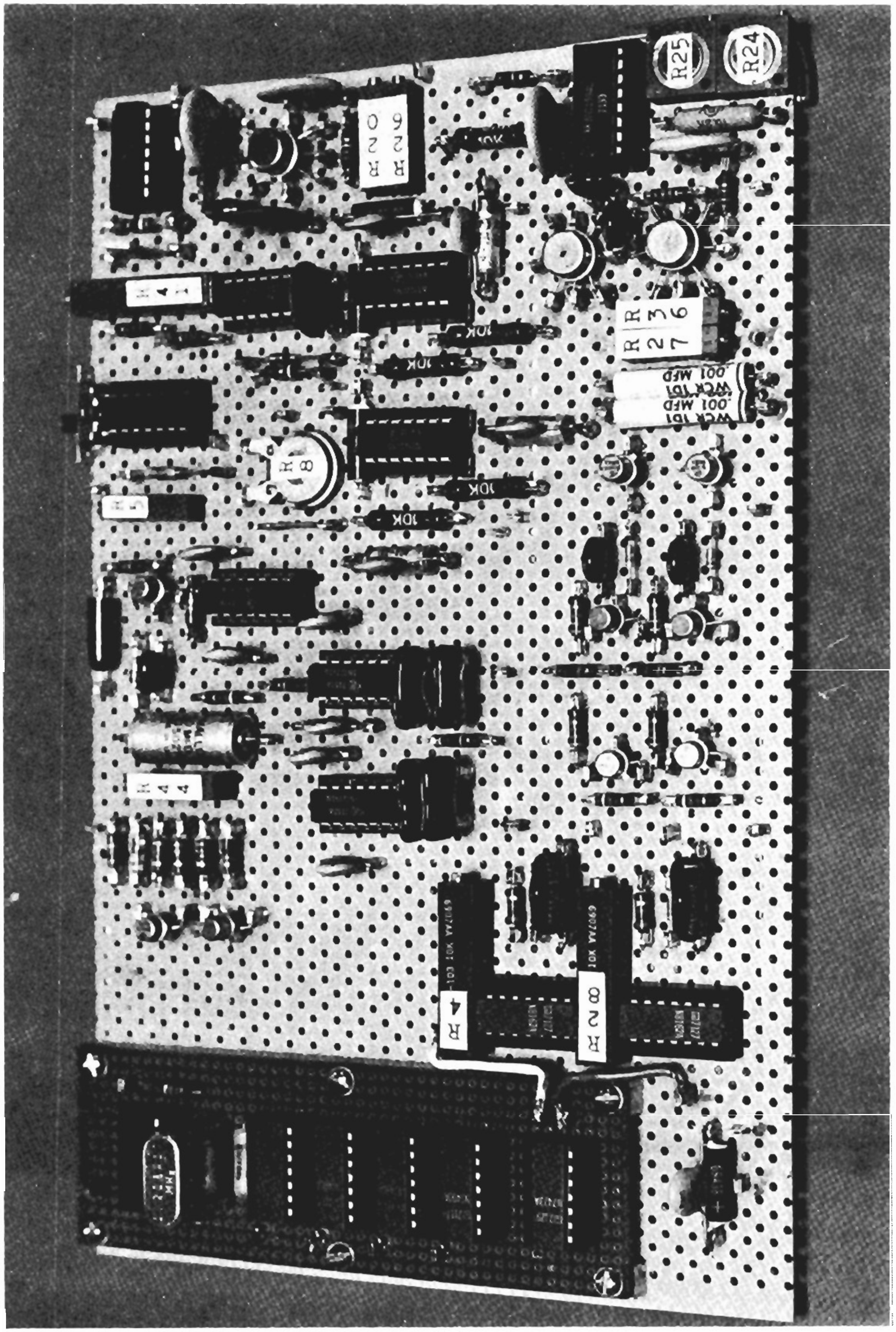


Figure 42
Assembled Prototype

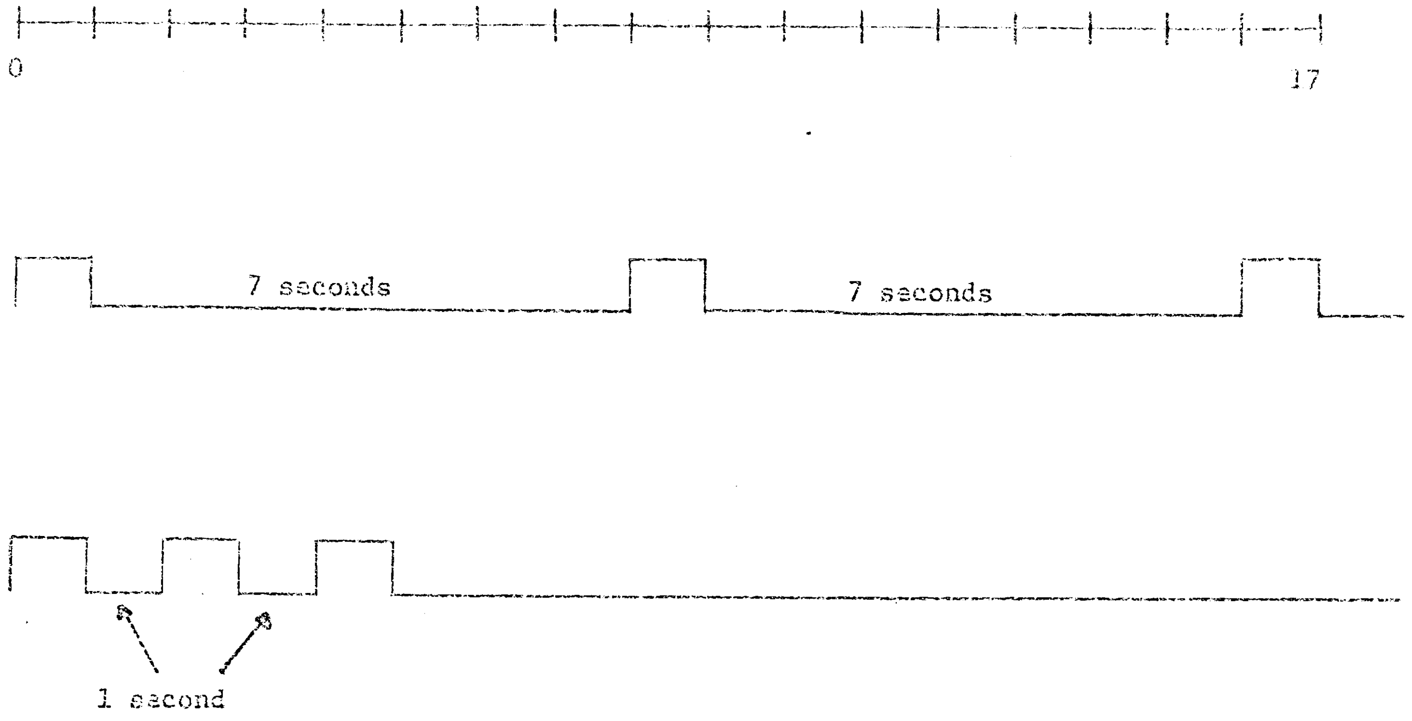


Figure 43

Maximum and Minimum Length Codes

The code pulses can be generated by digital circuitry with a master clock oscillator to generate the time base. The desired spacing between the pulses can be obtained by counting the clock pulses and generating the code pulse at the correct time.

The decoder for this code is relatively simple and has the advantage of not requiring the presence of a clock signal in the receiver. The decoding action is initiated in each of the receivers by the first pulse from the detector. Each decoder opens a window around the expected time of arrival of the second pulse of its codeword. If the second pulse arrives while this window is open, a second window is opened. The arrival of the third pulse in this window triggers the alarm. This entire sequence occurs for only one of the decoders. The action proceeds as far as opening the second window in six of the unaddressed decoders since for each time slot there are seven receivers with a pulse in this slot. The first window only will be opened in the remaining forty-two decoders. The decoding circuitry will return to the quiescent state in a time determined by the address of the decoder. (The maximum time required is seven seconds).

The code is repeated automatically until the called party answers the telephone. The operator then cancels the call manually. For this reason the encoder provides an eight second delay between the end of the last pulse of one code word and the beginning of the repeated code word. This prevents the first pulse of the repeated code word from being interpreted as a continuation of the previous code word by another receiver and thus causing a false call.

The emergency page feature is implemented by merely bypassing the encoder and transmitting the carrier continuously. An explanation of this alarm will be presented after a description of the detector.

The principal advantage of this coding system is that the decoder does not require a clock oscillator to provide the timing.

<u>Prototype System</u> -- hardware was breadboarded to demonstrate and test the pulse position coding scheme. Figure 44 shows a block diagram of the encoder and Figure 45 provides the schematic diagram of the delay register employed. Operation of the encoder is straight-forward with the delay registers providing the proper timing pulses to gate the correct pulses to the output. Switches S_1 - S_7 establishes the delay for the second pulse while S_8 - S_{14} is for the third pulse delay.

The decoder was constructed according to the schematic shown in Figure 46 and the components listed in Table IV. The decoder operation is easily understood by waveforms shown in Figure 47 which shows the sequence of events for detecting the porper code. The encoder-decoder was tested in the laboratory and found to operate as designed.

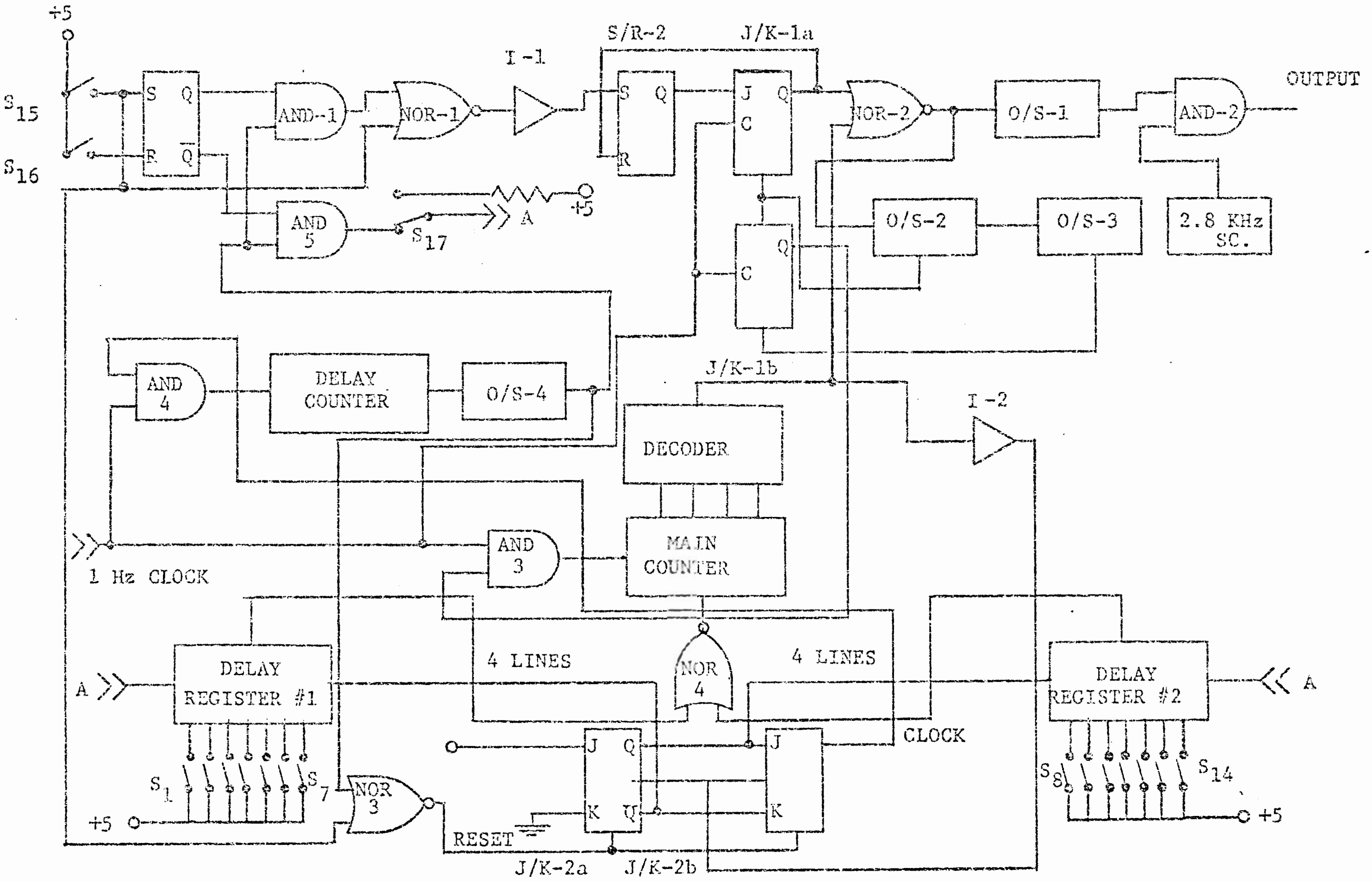
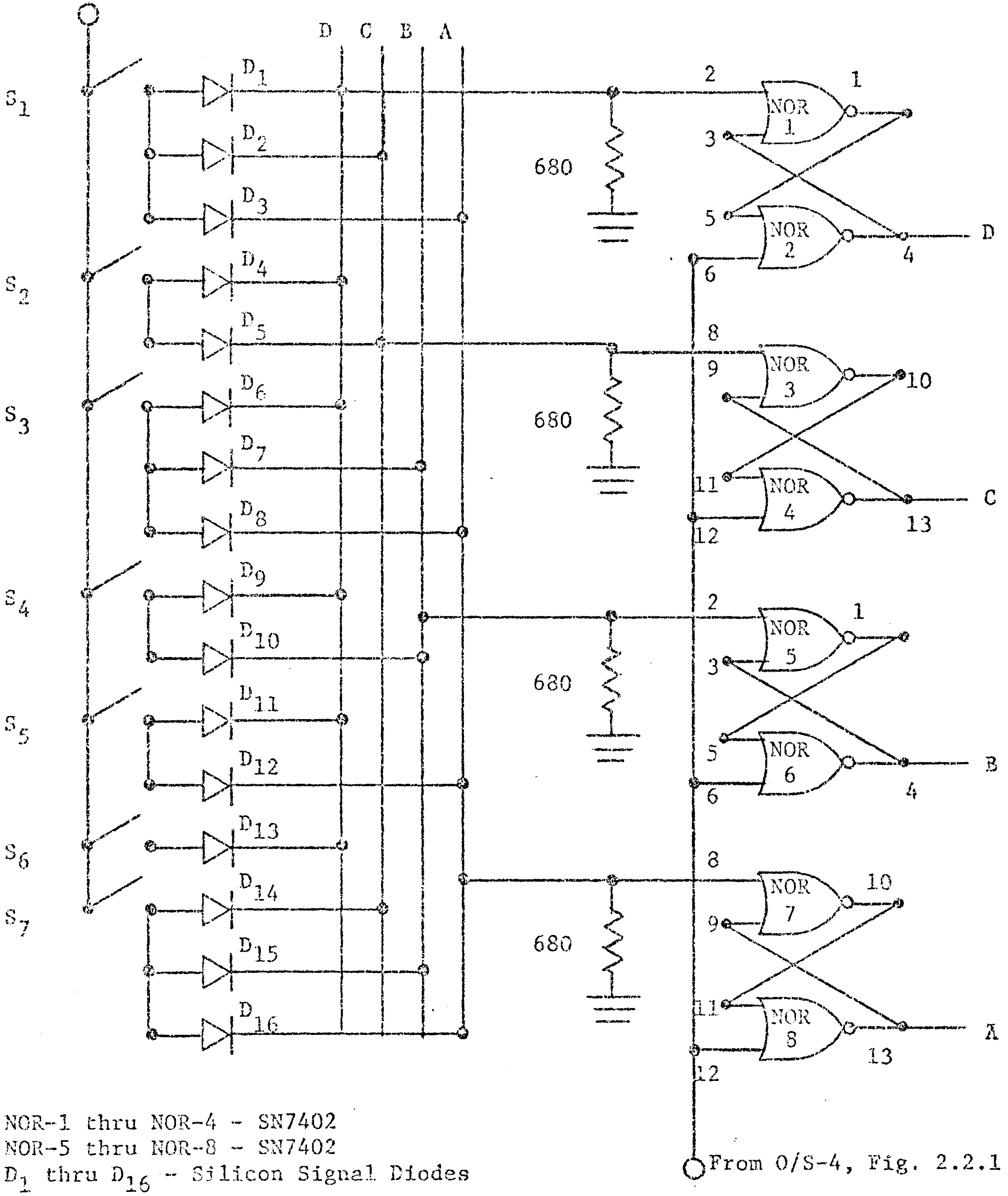


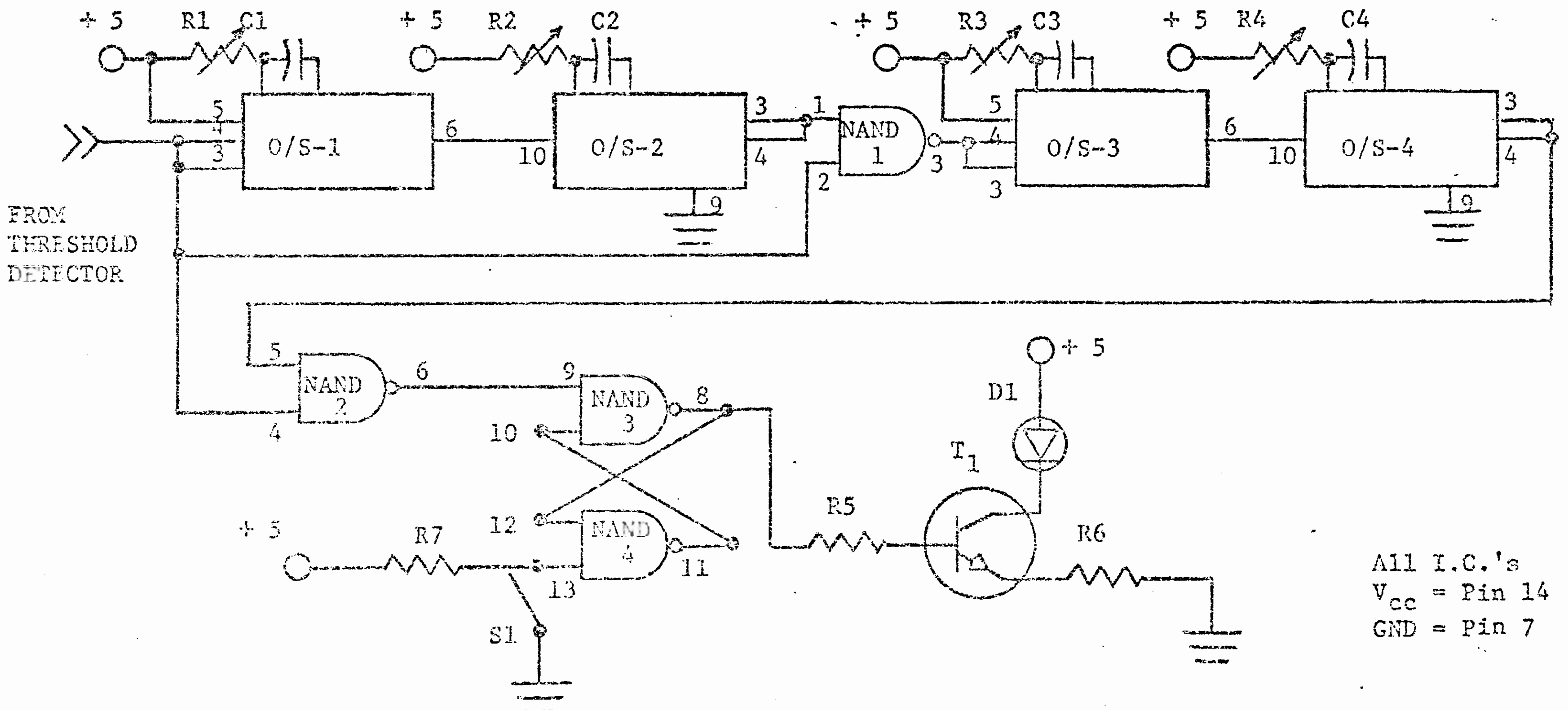
Figure 44. Encoder Block Diagram



NOR-1 thru NOR-4 - SN7402
NOR-5 thru NOR-8 - SN7402
D_1 thru D_{16} - Silicon Signal Diodes

V_{cc} = Pin 14
G_{nd} = Pin 7

Figure 45. Delay Register Schematic



Circuit Details Are Found
in Table 2.3.1

Figure 46. Decoder Schematic

DIAGRAM IDENTIFICATION	COMPONENT VALUE OR NUMBER
O/S-1	SN74121
O/S-2	8280
O/S-3	SN74121
O/S-4	8280
NAND-1 thru NAND-4	SN7400
T_1	2N3704
D_1	Light-Emitting Diode
R_1, R_3	50K, 10 turn Pot.
R_2, R_4	10K, 10 turn Pot.
R_5	1.5K, 1/2w.
R_6	82, 1/2w.
R_7	4.7K, 1/2w.
C_1, C_2, C_3, C_4	250 uf., 25V

Table IV. Decoder Component Identification

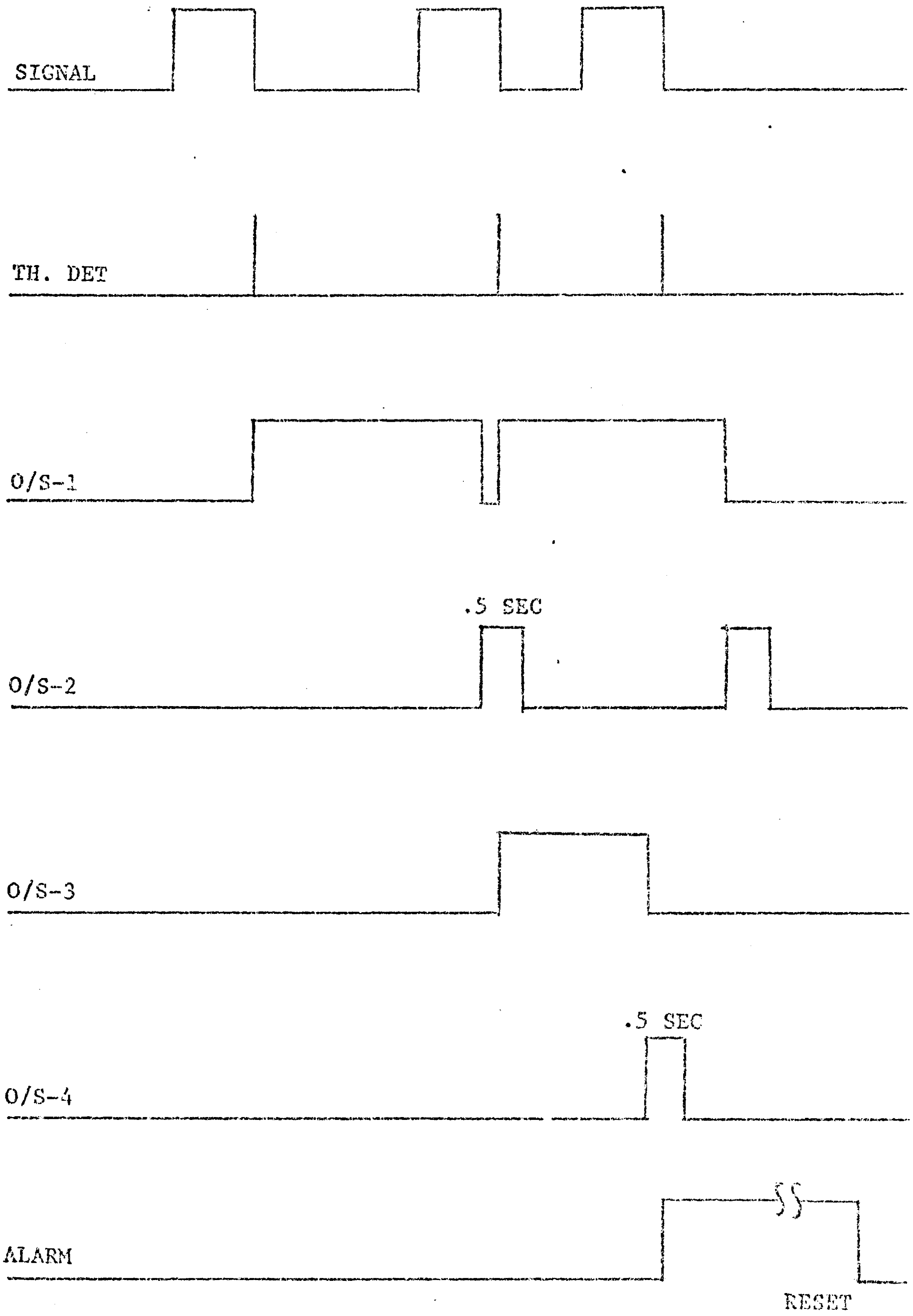


FIGURE 47 DECODER WAVEFORMS

Typical System Design -- in order to study the feasibility of implementing a paging system and to demonstrate the optimization procedure described earlier, this section presents the results of the first design attempt using the knowledge gained from this research project.

A set of hypothetical system requirements were established based on what our experience showed might be required in an actual operating mine situation.

System Definitions -- this system may consist of multiple transmitters located within the mine. The transmitters are to be sychronized in frequency and controlled from the mine's dispatch office. It is estimated that this system will be used thirty times daily and that an average of twenty men will carry a receiver during a period of eighty hours per week.

The false message rate is to be less than one per one thousand messages sent. The missed message rate is to be less than one missed message per one thousand messages.

Mine parameters -- the desired range of coverage is outlined in Figure 48. The minimum depth of the mine is 375 feet. The conductivity was measured inside the mine and was found to be fairly consistant at 1.2 x 10^{-2} mhos/meter. The darkened areas are locations at which coal will be removed during the next few years. The paging system must be designed such that no modifications will be required during this period.

The noise spectrum was measured at various locations within the mine. The maximum values of the z component of the magnetic field is plotted in Figure 49. The 60 Hertz harmonic noise is omitted.

Transmitter -- the transmitters will each transmit ten watts. The transmitting antennas loops consist of one hundred turns of 15 gauge copper wire (R_W = 0.01 ohms/meter), having a radius of one meter.

Receiver -- the receivers are to have an effective noise bandwidth of three Hertz,* a noise figure less than 8 dB, and antenna mismatch losses, bias circuit losses, etc. of less than 6 dB. The receiver loop antenna will have an effective radius of 0.4 meters.

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*This bandwidth is about one-half that actually achieved for a one second pulse width. Thus this design exercise gives a slightly large operating range.

Note:
1. distances measured in meters
2. unless specified all angles are right angle

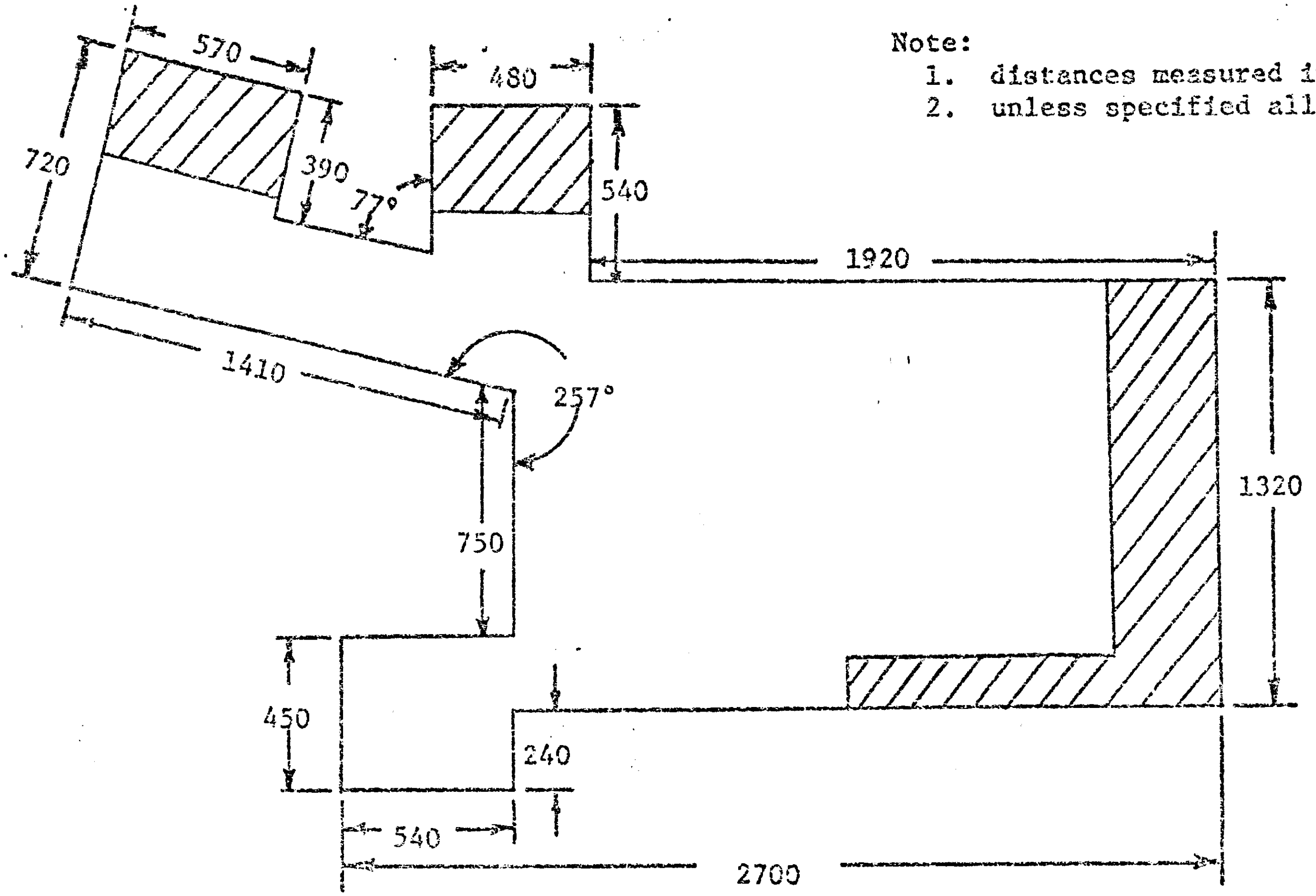

Figure 48
Sample Mine Outline

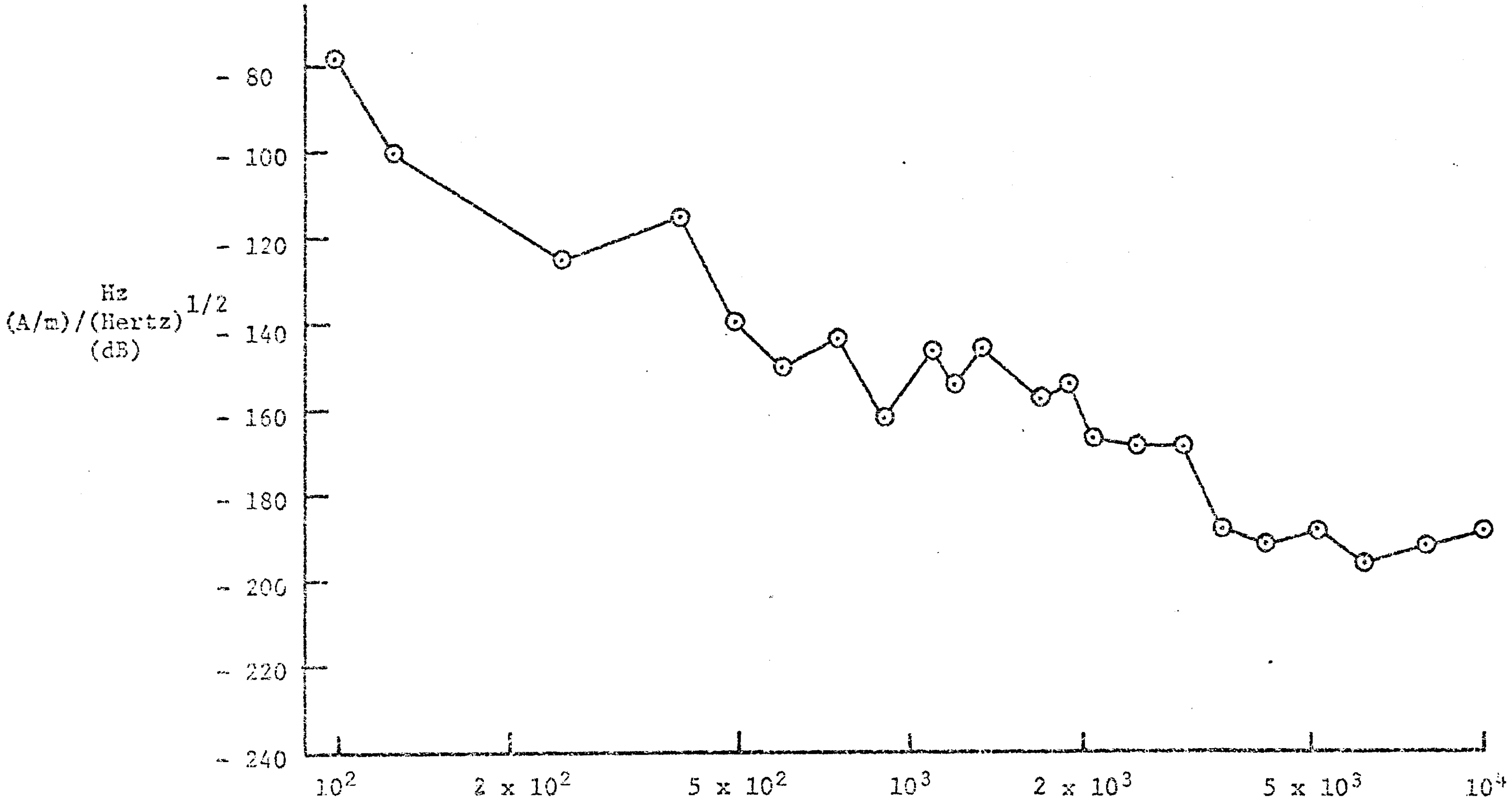

Figure 49
Sample Magnetic Field Noise Spectrum

Required Detector Parameters -- as pointed out earlier the threshold is set on a false alarm rate basis. Each false alarm, however, does not constitute a false message. An example would be a single false alarm occuring during a time in which no message had been sent for a time period of 15 seconds before and after its occurrence. A receiver would not decode this single occurrence as a message.

There are two basic types of false message. Type I may be described as a false message occuring as a result of three false alarms occuring in a single receiver each in a particular time slot so as to be decoded as a message.

A Type 2 false message is aided by the normal transmission of address signals. An example of this type would be a receiver receiving the three signals of an address other than its own pulse having a false alarm occur, providing a combination in which it decodes as its own address.

Layman shows in Reference 5 that in order to meet the false alarm requirements requires an average time between single pulse false alarms of 337 seconds due to Type I alarms while 9.500 seconds is required to meet the Type 2 alarms. The latter requirement obviously dominates and it is further shown this translates to a single pulse false alarm (at correlator threshold output) probability of no greater than 0.33×10^{-4} which requires the threshold level to be set 13.1 dB larger than the noise level.

The minimum acceptable signal is determined on the basis of the desired probability of detection as discussed earlier. Each message consists of three pulses. The probability of a missed message is three times the probability of missing a single pulse (assuming the probability of missing any two or all three is negligible). For the requirement set forth, Layman shows in Reference 5 that the minimum acceptable signal to noise ratio is 15 dB.

System Optimization -- using the data given and derived in this section, the optimization procedure presented in the section on through-the-earth communication can be applied.

Starting with an assumed frequency of 2100 Hz and continuing with four interations the resulting data is presented in Table V. These data show that the optimum frequency occurs between 800 and 900 Hz. Thus the chosen operating frequency is 870 Hz which is midway between two 60 Hz harmonics where the maximum range is approximately 600 meters. Using this range one can use an array of seven antennas to achieve coverage of the entire coal mine as shown in Figure 50.

From the graph of mine noise and the assumed receiver noise properties Layman shows the receiving antenna would require 29 turns with an area of 0.4 square meter -- or 11.6 square meter-turns.

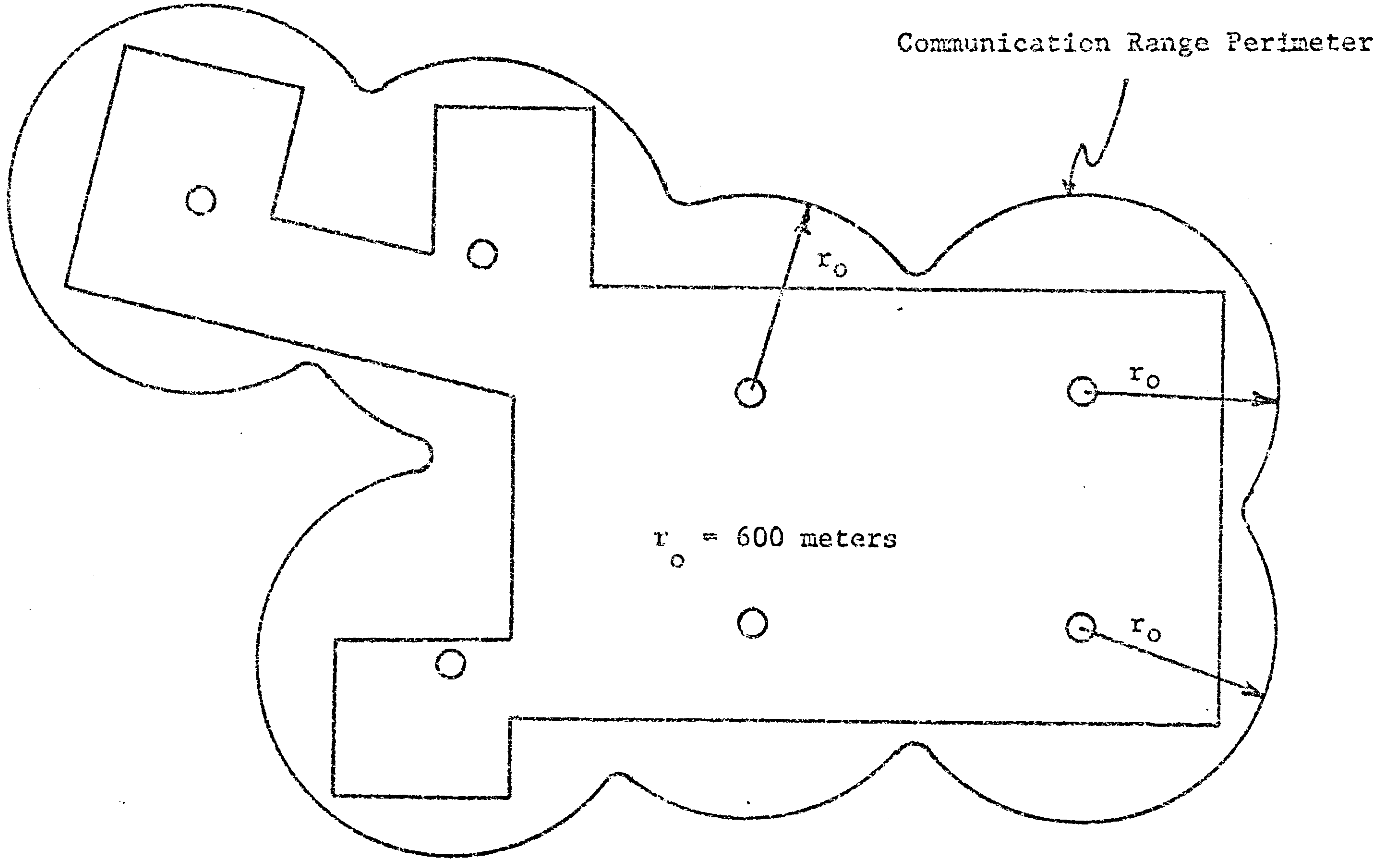

Figure 50
Antenna Placement Within the Mine

	Frequency (kilohertz)	H_{noise} [dBW/(Hz)$^{1/2}$]	Range (meters)	f_{opt} (kilohertz)
1st Selection	2.1	-167	600	0.874
1st Iteration	1.7	-159	520	1.17
2nd Iteration	1.2	-157	533	1.10
3rd Iteration	0.9	-161	620	0.82
4th Iteration	0.6	-150	520	1.17

Table V
Example Selection of Operating Frequency

Comments -- the design approach presented here should not be viewed as the only one which can yield a practical system. Other antenna arrangements should be studied, in particular the excitation of earth currents by grounded probes. These should be studied in a way their performance can be compared to loop antennas on both a theoretical and experimental basis. On the basis of theory and experiments of this project there seems to be no question but what through-the-earth signalling can be used over a limited range of several hundred feet or more. However, much more study needs to be devoted to the subject to determine the best design for such a system where both operational and emergency operation are required. Because of the potential usefulness during emergencies, technology should be pushed to its limit to obtain maximum range of direct through-the-earth operation.

THE TELEPHONE SYSTEM

Although new communication methods, such as through-the-earth signalling, are needed in the coal mining system, it appears that the backbone of the normal operating communication system should continue to be the hard wired telephone system. Not only does the hard wired approach appear to offer the best balance between economy and reliability (when properly installed), but the telephone wiring can be used for numerous other applications such as monitoring by frequency division multiplexing techniques.

After careful consideration of the communication needs in coal mines, the following items have been established as the main characteristics desired in an underground telephone system:

1. Multiple Paths to Outside -- the objective here is to prevent all telephones in-by a line break or short from becoming useless. Two possible paths appear adequate.

2. Audible Emergency Signalling -- the telephone system provides the main means of alerting miners during emergencies. The telephones should include means to emit distinct audible signals for emergency signalling. Initiation of these signals should probably be controlled from a central outside point such as a monitoring system control room.

3. Emergency Override -- provisions must be included to permit any conversation to be overridden with emergency communication.

4. Selective Area Page -- as coal mines grow larger it is apparent that the entire telephone system paging mode need not be activated each time a call is initiated. When individuals are being called in the general area of their location is usually known. This characteristic would possess the advantage of paging but reduce the paging activity at each telephone.

5. Simultaneous Conversation Capability -- although the ultimate for this characteristic would be a private line for each telephone, this is not necessary to produce the desired effect. In general, each section does not produce

much communication activity. Haulage and maintenance activities dominate telephone use. Since these activities tend to originate on the basis of mine "areas" it appears that providing different areas of the mine with a separate telephone circuit could meet the simultaneous conversation need and maintain circuit simplicity.

6. Manual or Automatic Connection Between Subsystems -- not only must provisions be made for connecting telephones within the telephone system, but also for connecting the telephone system into the other communication systems used at mine.

7. Two-wire Transmission Line -- although not a mandatory requirement, two-wire transmission lines are much easier to install and maintain than multi-conductor types and thus should be used as much as practical in the telephone system.

8. Remote Signalling -- the design of the telephone equipment and circuits should be compatible with frequency division multiplexed equipment so frequencies above 3,000 Hz can be used for signalling applications.

Relative to the present telephone system design, radical changes will be required to effect the desired reliability, selective area page, and simultaneous conversation capabilities. The system must be battery powered at least to the extent necessary to permit adequate operation during situations when inside power is turned off (fan failure for example). A minimum of electronics should be used in the signal path consistent with high system reliability.

Although several different configurations can be used to achieve the desired system properties, one configuration was chosen by this project because it can use existing paging telephones with a reasonable amount of modification. The desirability of selective area paging and simultaneous conversation capability along with the maximum possible use of two-wire transmission line makes the use of a zoning or sectionalization of the mine telephone system attractive. By locating zones or sections on the basis of power borehole and fan shaft positions, each telephone zone or section can be designed to have at least two independent paths of communication to the outside -- one by a cable routed inside the mine, and one by a cable routed outside via a borehole or fan shaft. The feasibility of this appraoch was investigated by considering a large mine with 16 operating sections. A schematic of the mine layout indicating the location of all telephones and boreholes is shown in Figure 51. Using the indicated

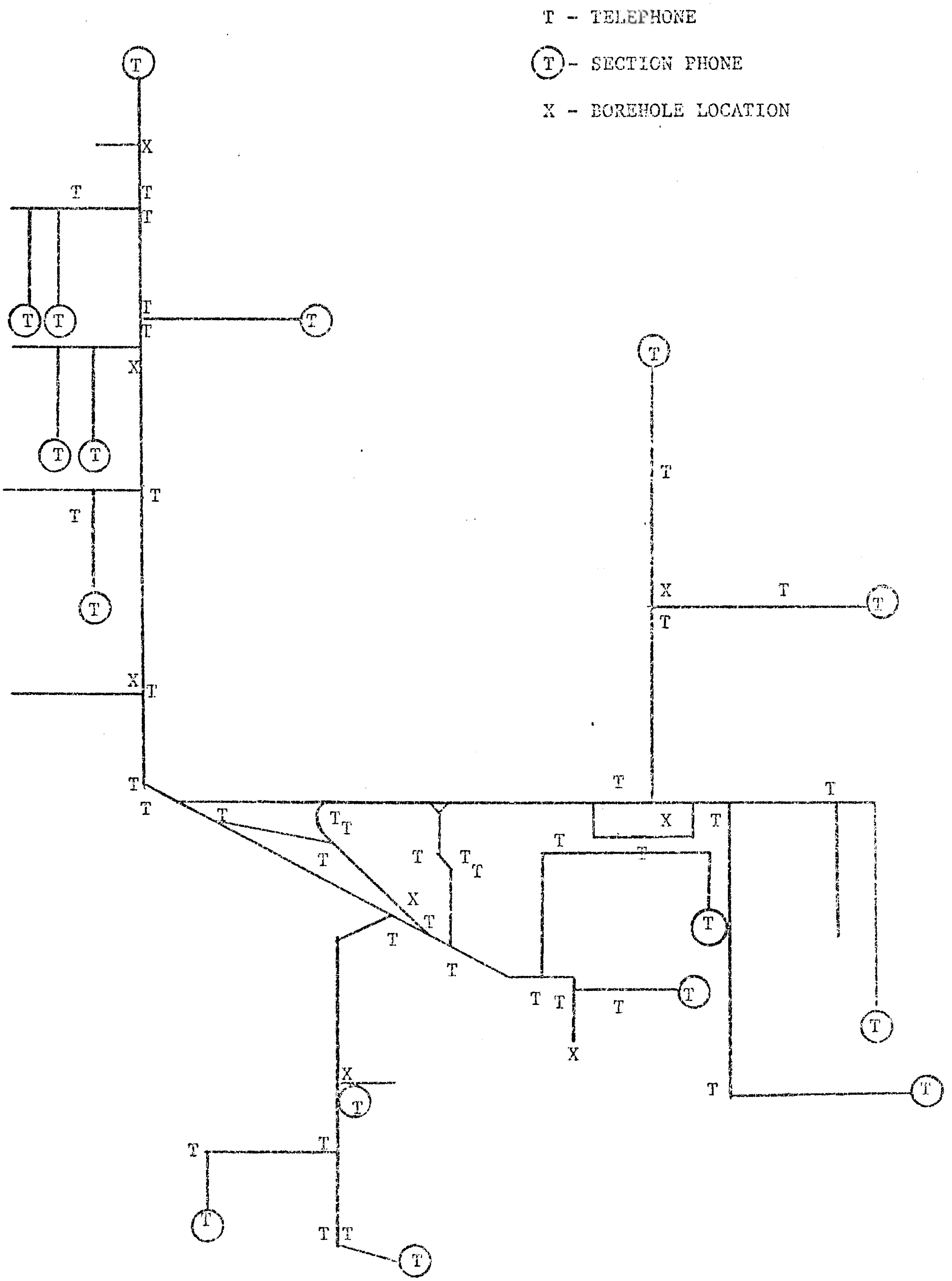

FIGURE 51 Typical Telephone System Layout

boreholes, the mine was sectioned into eight zones as shown in Figure 52. This yielded the distribution of telephones as shown in Table VI. This gives an average of about six phones per area with a maximum of three mining sections in any one area.

In order to see how the telephone sections would be interconnected, consider the simplified four area system shown in Figure 53. Within each area, the paging telephones would operate normally (see earlier section on present communication systems). That is, all phones in each area would operate on a party line basis, and the page mode would be established via direct current. When contact with a phone outside the local area is desired, an additional button or buttons would be provided to effect the desired signalling. Connection to the area being called would be made at an outside central exchange.

TABLE VI

Sectionalization of Phone System

	NUMBER OF PHONES			
AREA	MAIN-LINE HAULAGE	COAL TRANSFER	MINING SECTIONS	TOTAL
1	2	1	3	6
2	1	2	3	6
3	4	1	1	6
4	2	2	3	7
5	6	4	0	10
6	2	1	1	4
7	4	2	3	9
8	1	2	2	5
INSIDE TOTAL	22	15	16	53
OUTSIDE TOTAL				2
			TOTAL	55

The system is made more reliable by having two different signal paths available between each area and the central exchange, i.e. the outside line and the inside line. Consider the situation when the outside line from area No. 1 is borken. The inside line may be normally idle or used for telephones needed along the main

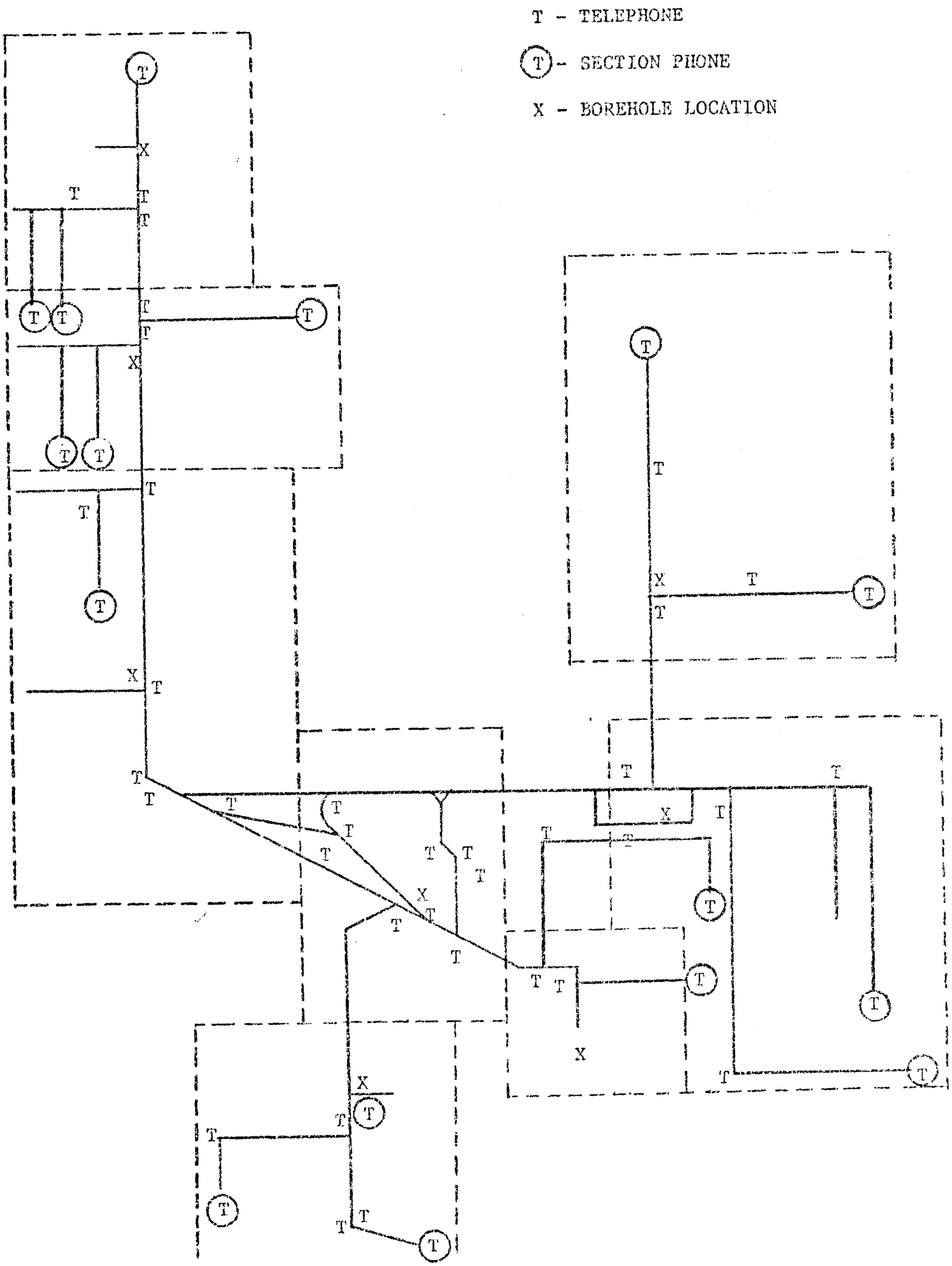

FIGURE 52 Sectionalization of Telephone System

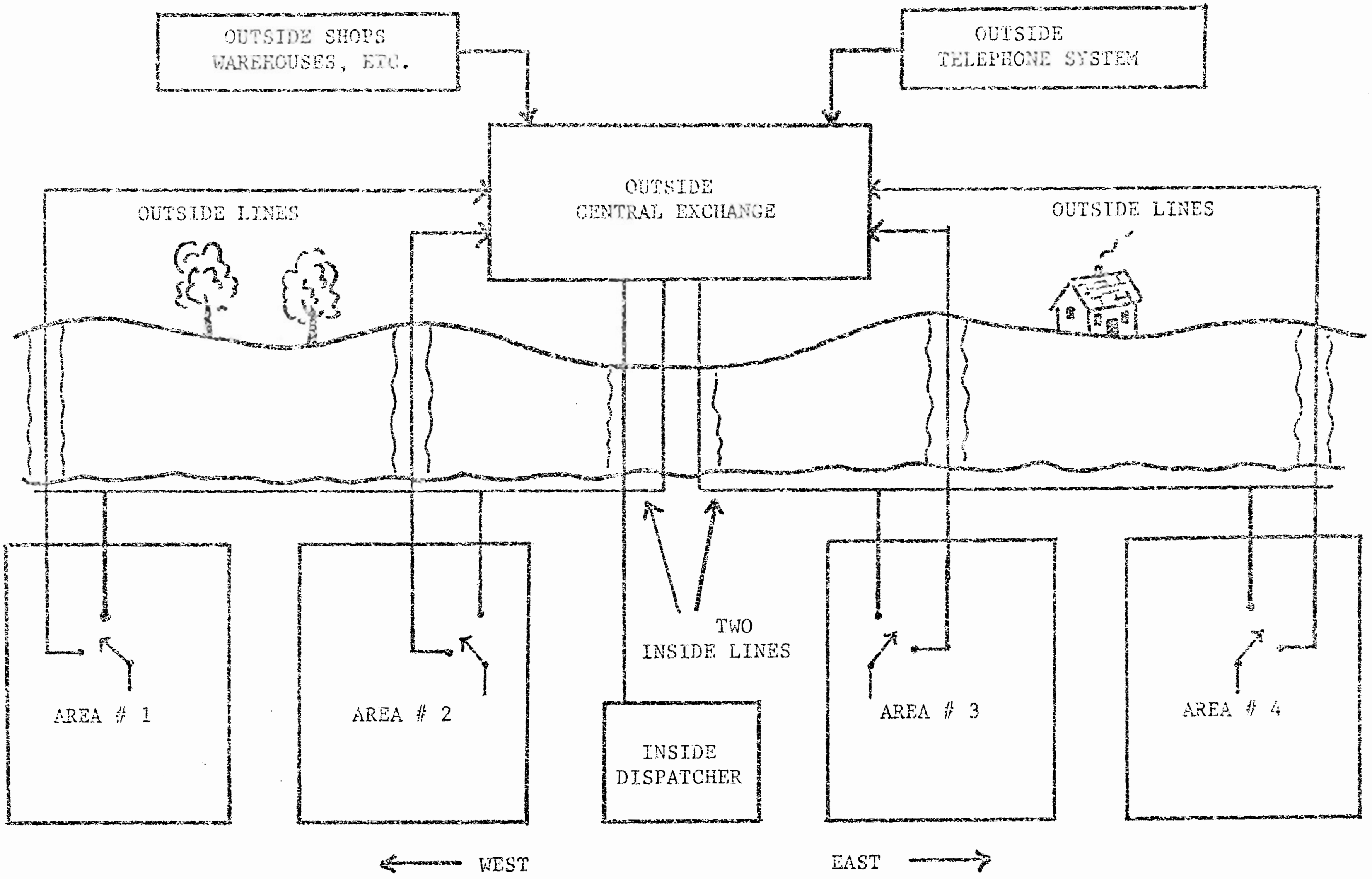

FIGURE 53

GENERAL TELEPHONE SYSTEM LAYOUT

haulage way. If a continuous test signal is sent over the outside circuit, the broken line is immediately detected, and a signal would be activated over the inside circuit to connect area No. 1 to the inside line. Area No. 1 circuits at the central exchange would also be connected to the inside lines and the exchange operator notified of the line break. Despite the line break the system could operate almost normally until the outside line is repaired.

If both outside lines for areas No. 1 and No. 2 were broken at the same time, the system would switch both areas cnto the inside line. The system would operate in this mode until the first outside line is repaired.

The system described here has the major advantage of providing redundant paths from each area and simultaneous conversation capability without the need of in-line electronics (other than that at each telephone). That is, a direct hard-wired connection exists between all telephones and the central exchange. This yields a more reliable and economic system than possible with other methods which require electronic processing between the telephones and central exchange.

The outside central exchange can take on many different forms with various degrees of complexity. Discussed here are the two extremes -- the manually operated and the automatically operated.

Manual Exchange -- The central exchange can be designed to require a human operator to effect the switching between the telephone areas. The simplest arrangement would utilize the paging telephones as now used with no alterations. When a caller desires to talk between telephone areas, he would page the central exchange operator by paging in the normal manner. A light could be activated by the paging signal to identify the calling circuit. The operator would answer and throw a switch to establish the connection between sections. One obvious difficulty with this arrangement is that the central exchange operator hears all paging in the sections. In a large mine this could be confusing to the exchange operator. This problem could be alleviated by providing each phone with a special button for calling central exchange. The button would activate a tone or tone pair to signal the central exchange operator which circuit required service. By using the tone no other telephones in that area would be activated to page. Similarily the central exchange operator would not be bothered when calls within a section takes place.

A problem with both of the above arrangements is that the operator must monitor a connection between two sections until the conversation is completed so that the two circuits can be disconnected. If the central exchange operator is to be used for other jobs, the monitoring activity could occupy a large portion of his time. The problem may be cured by employing a voice operated relay at the central exchange which would automatically open the connection when voice signals on the two lines cease for some set time period (ten seconds for example). This would be a relatively inexpensive addition and would release the operator for other duties.

Automatic Exchange -- In this arrangement the need for a human operator at the central exchange is eliminated and the switching between sections takes place automatically by signals sent from the calling telephone. A device capable of sending 16 unique "Touch-Tone" signals over the normal audio line is avilable at a price of less than $40.00 and could be added to each paging type telephone. For example, if the caller wants section No. 6 he would push button No. 6 which would cause him to be connected to that section. He could proceed to page for the person or station in that area in the normal manner. When the conversation is over, the connection between the two areas would be automatically disconnected after a time delay of several seconds. A special button could be provided for calling all sections simultaneously in case of emergencies.

Various designs for the automatic exchange are possible. In all designs considered, the biggest problem encountered was the automatic disconnect between areas. The voice operated relay method discussed above may not prove practical in an operating system. The time delay for cutoff may have to be so long for normal use, that when a caller is waiting for a busy area, he may not wait sufficiently long for the previous connection to open. The present paging telephone circuit prohibits the use of DC current as in conventional dial telephones to supply this information. Because of this problem, a recommended central exchange design was not established by this project. It is apparent that distinct advantages exist in using existing paging telephones at coal mines, but it is equally apparent that circuit additions and modifications will be required to make them compatible to the type of service described here. This problem should be considered further.

No Exchange -- For relatively small mines where telephone activity is not large enough to merit need for simultaneous telephone conversations within the mine, the concept of zoning or sectionalization can still be utilized to yield a more reliable telephone system. For example, some coal mines have only one, two, or three operating sections which may be far removed from one another or may use very long underground haulageways. In these cases alternate outside telephone lines can still be utilized but with the entire system still tied together in a party line mode. Electronics to continually monitor the alternate paths should be used and provisions made to switch circuits in case of a line break. Thus the increased system reliability is achieved without the added cost of the central exchange or modification to the paging telephones.

<u>In-Between Systems</u> -- One can visualize many variations of the above system designs. They were chosen to demonstrate the variation in possibilities one has in designing a more reliable system. The three examples show that no one system can be expected to answer all possible situations. The zoning or sectionalization to achieve higher system reliability is the major point for safety. The choice of exchange should be traded off against the potential increase of mine operating efficiency.

CARRIER CURRENT SYSTEMS

Work conducted in this area included testing currently available carrier phones (1971), use of standard carrier phones for emergency through-the-earth communication, study of ways to alleviate present carrier system problems, and use of carrier current signalling on power cables.

In 1971 there were three manufacturers of carrier phone equipment in the United States which served the coal mining market. They were Mine Safety Appliances Company, Femco, Inc., and Marshall Elevator Company. New carrier phones were supplied to us by each manufacturer for testing and evaluation in our laboratory. The purpose of the tests was not to determine which was the "best equipment," but rather to identify ways in which carrier phone communication can be improved in coal mines.

A complete series of identical tests were performed on the units as received from the manufacturers. Prior to the tests no adjustments were made on the carrier phones. From a study of the schematic diagrams provided and the results of the tests, the following conclusions were drawn:

1. All units were of similar design, i.e. narrowband frequency modulated in the 100 KHz frequency band, utilizing about 15 watts of transmitter output power into a 25 ohm load and tuned frequnecy (TRF) receivers.

2. Transmitters and receivers were not accurately tuned to the channel frequency when received from the factory. Receiver bandpass was not well tuned for maximum signal-to-noise ratio (3 to 5 KHz off channel frequency).

3. Squelch behavior was vastly different. Two manufacturers achieve the desired characteristic of opening on the basis of signal-to-noise ratio over some region of noise input. One manufacturer's equipment had poor squelch behavior.

4. Minimum input signal required for proper reception (i.e. full limiter action) ranged from 1.3 to 14 millivolts and thus presented an order of magnitude difference in receiver sensitivity between the different brands.

5. Only one brand had good audio bandwidth characteristics for suppressing high frequency noise.

6. One brand showed very poor short and long term transmitter frequency drift. One brand showed exceptionally good frequency stability.

7. Only two units were designed for operation on a 12 volt storage battery. The other unit would require extensive redesign for efficient battery operation.

8. Widely different methods of construction are employed with differing degrees of ruggedness and ease of repair.

There has been no attempt by the manufacturers to emphasize the potential usefulness of carrier current equipment in case of emergencies such as entrapment. That is, design features have not been employed which would make trolley phones useful through-the-earth communicators even if power is cut off and all telephone and trolley lines have been severed. Indeed, the early work of the United States Bureau of Mines on carrier current techniques recognized that through-the-earth communication might be possible with carrier current equipment in the event of isolating rock falls. In present designs, the low receiver sensitivity generally prevents this possibility. For normal trolley line operation low sensitivity is desired because of the high noise levels present. With high sensitivity and large noise levels, undesirable effects normally occur. However, in emergency situations when inside mine power has been removed, the maximum receiver sensitivity is needed due to highly attenuated signals.

If adequate sensitivity and battery operation were employed, through-the-earth operation could be achieved by three possible methods:

1. System left in place and hooked to trolley line remaining after emergency. Trolley line acts as antenna.

2. A stored pre-tuned loop antenna could be deployed. Our through-the-earth experiments indicated ranges of at least 500 feet might be achievable by this method (inside to inside).

3. Earth currents could be established via conductive rods on roof bolts.

Audio tones for signalling could be easily achieved by adding additional electronics. This method offers the most range but would be most difficult to deploy and would require the most extensive modifications of the basic electronic design.

As already discussed in an earlier section of this report several problems arise with the use of carrier phone systems in the shorting effect caused by a trolley haulage motor and the existence of "dead zones" due to standing waves on the trolley line. A third problem is the fact that if a roof fall or haulage accident severs the trolley line, all carrier phone communications in-by the accident will be disrupted.

The first two problems have been effectively controlled in most situations by using devices to couple the signal onto the telephone lines as depicted in Figure 2. By proper positioning of the coupling devices both of the first two problems can be combated. Unfortunately, the position of dead spots can be controlled only by "cut and try" methods. As the trolley lines are lengthened and shortened, the optimum position of couplers will vary.

One method of controlling all three problems mentioned above would be to use satellite remote controlled carrier phone stations at critical positions in the trolley system. Control and voice signals could be frequency multiplexed over the telephone lines. When a signal is to be received at the dispatcher's office, circuits would automatically choose the receiver with the strongest received signal. Communications would be carried on by this satellite station. When the dispatcher initiates the call, he would choose the satellite station nearest the position of the station being called.

Other ideas that have been discussed include the use of RF chokes in motor power supply lines to alleviate the "short circuit" problem. The possibility of using inductive coupling to the telephone line exclusive of the trolley line has been considered as a method to deal with the same problem.

Despite the problems with carrier phones mentioned here, it appears that the low frequency carrier current method is still the best choice for communication with moving trolley vehicles.

As part of the research effort, the potential use of carrier current signalling on power cables was also investigated. This work was undertaken for several reasons. The possibility of extending carrier phone services to the section power center and even to the face area could require the signals to be transported on the power cables. As the system studies progressed it became evident that there was little need for this type of application. The major need for carrier current on power cables appears to be for situations where the use of a conventional telephone line would not be economical and an alternate signal path would add to system reliability. For example, it would be desireable to bring telephone circuits outside the mine at different places to offer alternate circuit paths in case of a telephone line fault. It may be more economical to use carrier current over an existing borehole cable than to replace the cable with one containing the needed communication circuits or to install a new borehole. Another alternative to this particular problem may be the use of through-the-earth signalling.

Although the original intent was to conduct a complete investigation of carrier current transmission on power cables, difficulties were encountered in obtaining the needed equipment for coupling to high voltage circuits. With the early termination of this effort, as explained in the Introduction, this work was limited to the study of impedances and attenuation rates exhibited by power cables in the low frequency range.

Both analytical and experimental studies were accomplished and compared. A mathematical model was developed which yielded via digital computer solution the expected attenuation per unit length and the complex characteristic impedance as a function of frequency. Good agreement was obtained between the predicted and measured values of characteristic impedance. Difficulty was encountered in measuring attenuation because the cable samples available were too short to exhibit measurable amounts of attenuation.

The following conclusions were drawn from this study. The characteristic impedance and attenuation of power cables at carrier current frequencies can be predicted with good accuracy by analytical methods using the known cable dimensions. For the same cable size, the characteristic impedance of a high voltage rated cable is more than that of a lower voltage rated cable. The attenuation per unit length of a cable depends on both cable size and voltage rating. The higher the voltage rating, the less will be the attenuation for the same cable size and for the same voltage rating, larger size cables will have lower attenuation values.

The detailed results including graphs of impedance and attenuation for typical cables used in coal mines are presented in Reference 11.

In the work discussed above, the carrier signal is placed on one high voltage phase relative to ground. An alternate method may be useable in some applications. The ground check wire is insulated relative to ground in the cable and must be connected at the load end so as to permit flow of the 60 Hz gorund check current. A radio frequency choke can be used at the load end to permit flow of the ground check current, but also exhibit a high impedance at the carrier current frequency. Thus the carrier current can flow through the ground check wire and the ground wire without interferring with the ground check system. Although this arrangement may exhibit more attenuation per unit length than the conventional approach, it may prove better due to using a cheaper and simpler coupling system and being less noisy.

AUXILIARY SYSTEMS

The complete mine communication system will usually involve needs not serviceable by the major systems discussed in the other sections of this report. Although the design details for systems to meet these needs were not a part of this program, the incorporation of "auxiliary systems" into the total system in order to meet special needs was considered. Each of these systems is discussed briefly in this section.

"Walkie-talkie" Systems -- this type of system uses two-way voice communication devices that can be carried in a miner's pocket or hand. Depending on the application, communication may be between two portable units or between a portable unit and a fixed location unit. Three different types of propagation mechanisms can be employed to couple signal power between the transmitter and receiver. Each is discussed below.

(a) Through-the-earth -- this is the propagation method using electromagnetic waves which penetrate the earth and inherently requires the use of very low frequencies as discussed in a previous section of this report. Several problems exist with this propagation method for use with hand held communicators. Most obvious is the limitations imposed on the antenna. However, through the use of ferrite materials the effective area-turn product of physically small antennas can be significantly increased. This works extremely well for receiving where signal levels are low. For transmitting, the saturation properties of ferrite materials limit the magnetic field strengths that can be produced.

Another inherent problem in the use of through-the-earth propagation for voice applications is that to achieve optimimum operation for ranges of several hundred feet normally requires operating frequencies in the audio range. The use of direct transmission of audio is limited by the presence of severe noise from harmonics of the power frequencies. The use of conventional modulation techniques demands the use of higher, and thus, sub-optimum frequencies.

Despite these limitations this method of propagation has the unique advantage of propagating directly through-the-earth and would be useful in emergency situations where all other propagation techniques would not be available. Devices for such use have been developed for use in African gold mines (Ref. 12). If carrier phones were modified to permit through-the-earth communication during emergencies as discussed in the previous section of this report, portable devices for communicating with such carrier phones would be necessary.

"Leaky" Transmission Line -- this method of propagation requires a transmission line to facilitate the propagation of signals between the transmitter and receiver although no physical connection to the transmission line is necessary for the transmitter or receiver. The "leaky" transmission line may be a balanced twin lead, coaxial cable with a loosely woven shield, or a well shielded coaxial cable with slots placed in the shield. It appears the best method is the use of radiating slots introduced only as often as required to maintain communications. By the reciprocity principle it follows that a transmission line that can radiate can also receive signals. Systems of this type used thus far are of two configurations. In a Belgium and British developed system the coaxial line acts as a passive transmission medium for a simplex channel (Ref. 13, 14). Another system developed by Motorola Communications, Inc., uses active repeaters connected to the transmission line (Ref. 15).

"Wave guide" Propagation -- by using signals with wavelengths on the order of the mine entry dimension, a waveguiding effect can occur permitting direct transmission of radio waves. Work in this area is presently underway by U. S. Bureau of Mines Contractors. Preliminary experiments indicates UHF frequencies may provide useful ranges of several hundred feet in open airways.

<u>Usefulness</u> -- our studies indicated that hand held communicators or "walkie-talkies" will be useful only in certain areas of the mine. Situations identified where such devices could be used are as follows:

1. Along conveyor belts -- mines that use primarily belt haulage could use two-way communication to roving belt patrolmen and maintenance men. However, it may be that low frequency paging to the miner combined with the telephone system may prove more economical with little sacrifice of system capability.

2. haulage terminals -- many track haulage terminals require communication between a motorman and a miner walking nearby. Hand held communicators would be ideal for this application.

3. face area -- communication between workman in the face area (continuous, conventional, or longwall) would be very valuable. Experiments should be planned to determine to what extent this need exists. Experience on long walls are indicating a definite need.

In each of the above situations it is apparent the hand-held communicators are to provide two-way communication between two people in a given area and the need for connecting these sub-systems into the mine-wide communication system is very limited. Thus, these types of sub-systems should normally operate independent of the mine telephone system. However, provisions should be made for the interconnection to be established especially for the case of emergencies. This could be accomplished by including a button on each hand held communicator which would activate a tone to establish connection to central control. Similar provisions could be made to permit central control to connect into each local sub-system.

Outside Radio -- coal mines require the use of men who work outside the mine for such activities as surveying, power system maintenance, fan maintenance, etc. As a mine grows larger these crews become more dispersed and difficult to communicate with. Many mining companies have found that two-way radio can provide significant improvement in the utilization of outside manpower. By installing radio equipment in all outside vehicles and providing hand held communicators to crews on foot, communications with outside personnel can be established at any time.

Outside Telephone -- most coal mines maintain an outside telephone system independent of the inside system. The outside systems have many different forms. They can be categorized into three types.

(a) Independent Private Exchange -- this type of system is maintained totally independent of the inside system or the local commercial system. Usually no provisions are made to interconnect the two systems. In some cases, this system and the inside system are interconnected and served by the same exchange or operator.

(b) Private Business Exchange (PBX) -- this is a small private exchange supplied by the local commercial telephone company and provides direct connection to local public telephone lines. Usually no provisions are made for interconnecting the inside telephone system into the PBX. In some cases a dial telephone connected to the PBX system is placed at the dispatchers office underground. A very few mines use the P BX arrangement for both the inside and outside systems.

(c) Business Phones -- many mines, especially the smaller ones, utilize some form of business phone service provided by the local telephone company. This is popular where only a few offices have to be served and a private business exchange would not be required.

In general there has been very little attempt to integrate the outside telephone system with the inside system. Apparently this has been because the two systems are usually vastly different electrically and it is not clear to many that an interconnection of the two systems is possible. At many recently developed mines where the value of interconnecting the inside and outside system was recognized, it was decided to use a dial system throughout the mine complex.

CONCLUSIONS

Although this program stopped short of its original goal, several important conclusions of a general nature were made.

The original hypothesis of this program was that the mine communication problem needed to be tackled on a system basis. The experience gained by this project has clearly shown the validity of this hypothesis. Moreover, it is increasingly evident that as mine communication systems require upgrading the redesign of the whole system should be undertaken on a truly system basis with due consideration to newly developing technology.

Difficulty was encountered in accurately evaluating the communication needs of the mining industry for two reasons. First each mine is unique and thus usually has its own special operating characteristics which affect the communication requirements. Secondly, because the miners and the mine management are so accustomed to the presently used communication methods it is impossible to evaluate the worth of new possibilities without trying them in operating coal mines.

This study led to several conclusions about specific needs in mine system design. The most obvious is the general need for improvement of communication system reliability. Ways to achieve this are presented herein. There is an important need to be able to alert or page miners throughout the entire mine. A first step in this direction would be to establish such capability in the vicinity of each working face.

Telephone systems in large mines become overloaded at certain times during a shift. Thus there is a need for increased telephone system capacity. There are a variety of ways this can be accomplished, some of which are discussed in this report.

All mine communication systems consist of several distinct sub-systems. Provisions should be made to permit manual or automatic interconnection between the subsystems when required.

The mine communication system is obviously going to be required to handle more than voice communication as new electronic monitoring and control systems are integrated into the mining system. Thus alterations to existing systems and the design of systems for new mines should consider these future requirements. This is especially important in the choice of a telephone line and its installation.

Obviously the work presented in this report is incomplete and effort should continue, in some form, in each of the areas discussed.

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APPENDIX A

Measured power transfer between two standard loops are given in the following tables. The test equipment setup is described in Figure 17. The data ia normalized for standard loop antennas, defined by: radius - 1 meter, single turn, and copper resistance of the wire equal to 0.01 ohm/meter. All measurements were made with the axis of the two loops parallel.

The measurements are in dB, and being the ratio of powers, are equal to:

$$\left(\frac{P_r}{P_t}\right)_{dB} = 10 \log_{10}\left(\frac{P_r}{P_t}\right)$$

Location: Upshur Mine, Adrian, W. Va.
Date: 6-15-71

Antenna Orientation:	HMD, $\theta = \pi/2$	VMD, $\theta = \pi$	HMD, $\theta = \pi/2$
Overburden:	70 meters	70 meters	40 meters
Range:	70 meters	70 meters	40 meters
Surface-to-Mine or Mine-to-Mine:	S-M	S-M	S-M
Frequency (kilohertz)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)
2.1	139.7	136.4	130.7
2.8	138.6	134.4	129.0
3.7	136.1	133.4	126.9
5.4	135.0	131.1	130.6
6.9		131.5	
7.4	132.8	129.9	121.2
9.1	131.6	128.8	119.7
11.6	130.7	128.4	118.6
13.8	129.7	128.4	116.7
18.3	130.1	128.2	116.6
22.6	131.7	128.4	115.8
26.5	135.1	131.3	124.7
36	135.8	138.8	127.5
73.5	149.1	139.1	114.4
89.3	150.8	146.8	120.7
116		150.8	123.7
134			127.7

Location: U. S. Steel No. 50, Pineville, W. Va.
Date: 6-29-71

Antenna Orientation:	HMD, $\theta = \pi$	HMD, $\theta = \pi/2$	HMD, $\theta = \pi$	HMD, $\theta = \pi/2$	VMD, $\theta = .65\pi$
Overburden:	40 meters	40 meters	40 meters	40 meters	39 meters
Range:	52 meters	52 meters	111 meters	111 meters	85 meters
Surface-to-Mine or Mine-to Mine:	M-M	M-M	M-M	M-M	S-M
Frequency (kilohertz)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)
2.0		134.7	147.2	150.1	153.6
2.5	127.7	132.6	147.1	152.0	147.3
3.3	124.7	130.6	144.6	149.4	143.8
5.0	122.0	126.5	140.1	143.6	138.9
6.3	118.7	124.3	138.0	141.7	136.0
6.7	118.1	123.3	137.8	140.7	136.0
8.3	117.2	135.1	135.3	139.6	133.7
10.0	117.1	132.9	133.9	135.8	131.2
12.5	126.9	118.5	136.3	133.3	128.7
16.7	112.0	113.3	135.1	129.7	125.9
20	111.4	111.7	133.7	127.7	123.6
25	111.4	110.8	132.1	126.7	123.3
33	109.9	107.2	131.4	126.5	121.3
83	111.9	105.9	139.7	129.3	117.8
100	99.3	106.3		132.3	120.0
125	116.6	106.1		135.1	132.3
167		109.3			130.7

Location: Badger No. 14, Phillipi, W. Va.
Date: 7-20-71

Antenna Orientation:	HMD, $\theta = \pi$	HMD, $\theta = \pi/2$
Overburden:		
Range:	148 meters	148 meters
Surface-to-Mine or Mine-to-Mine:	M-M	M-M

Frequency (kilohertz)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)
2.0		146.7
2.5	144.7	145.1
3.3	143.2	142.1
5.0	139.4	136.4
6.3	137.3	133.4
6.7	136.7	
8.3	134.7	129.8
10.0	133.0	127.3
12.5	130.4	124.5
16.7		120.5
20	125.2	123.1
25	123.8	116.8
33	121.0	112.8
83	115.1	104.6
100	116.3	104.9
125	115.7	100.1
167	120.8	94.8
200	128.3	100.3

Location: U. S. Bureau of Mines, Bluefield, Pa.
Date: 9-30-71

Antenna Orientation:	HMD, $\theta = \pi/2$	HMD, $\theta = \pi/2$	VMD, $\theta = \pi$	HMD, $\theta = \pi/2$
Overburdau:	27 meters	27 meters	25 meters	25 meters
Range:	34 meters	99 meters	25 meters	25 meters
Surface-to-Mine or Mine-to-Mine:	M-M	M-M	S-M	S-M
Frequency (kilohertz)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)
2.0	110.3			
2.5	108.5	133.0	99.2	103.4
3.3	106.3	129.2	96.7	101.2
5.0	102.5	124.7	93.3	98.0
6.3	100.2	122.5	92.0	95.8
6.7	99.9	121.9	91.3	95.4
8.3	97.7	119.3	89.7	94.3
10.0	96.3	116.9	88.8	92.4
12.5	94.2	114.5	87.4	91.1
16.7	91.4	110.9	86.1	89.7
20	91.2	110.3	85.2	88.6
25	89.2	109.4	86.5	88.5
33	85.9	107.5	87.0	88.2
83	85.3	112.5	95.8	96.3
100	86.8	114.8	99.3	99.3
125	85.0	115.1	100.5	101.5
167	83.0	115.6	104.5	105.1
200	89.0	125.6	108.5	108.5

Continued on next page

Location: U. S. Bureau of Mines, Bluefield, Pa.
Date: 9-30-71

Antenna Orientation:	VMD, $\theta = \pi$	HMD, $\theta = \pi/2$
Overburden:	20 meters	20 meters
Range:	20 meters	20 meters
Surface-to-Mine or Mine-to-Mine:	S-M	S-M

Frequency (Kilohertz)	$\frac{P_r}{P_t}$ (-dB)	$\frac{P_r}{P_t}$ (-dB)
2.0		
2.5	94.1	99.9
3.3	92.0	96.9
5.0	87.7	93.3
6.3	86.9	91.3
6.7	86.4	91.2
8.3	84.8	89.2
10.0	83.7	87.2
12.5	81.5	85.8
16.7	79.3	83.6
20	77.9	82.4
25	77.6	80.9
33	75.9	78.8
83	78.6	81.1
100	83.3	83.8
125	82.4	84.4
167	88.6	88.8
200	94.8	97.5

APPENDIX B

Noise Measurements

The data presented here was measured using the receiver test setup described in Figure 18.

The magnitude of H is found from the equation

$$H = \frac{V}{N \omega\mu A}$$

where:

V = open circuit receiver antenna voltage

N = number of turns in antenna loop

A = antenna loop area

Location: Upshur Mine, Adrian, W. Va.
Date: 6-15-71

Antenna Orientation:	VMD	HMD	VMD	HMD	VMD	HMD
Overburden:	70 meters	70 meters	40 meters	40 meters		
Note:	1	1	2	2	3	3
Frequency (kilohertz)	H (dB)	H (dB)	H (dB)	H (dB)	H (dB)	H (dB)
2.0	-100	-110	-116	-117	-103	-110
2.5	-105	-119	-122	-122	-112	-122
3.3	-108	-124	-124	-124	-118	-124
5.0	-114	-123			-128	-128
6.3	-115	-135				
6.7	-117	-136			-131	-126
8.3	-118	-122			-132	-127
10.0	-118	-124				-134
12.5	-121	-131			-131	-136
20	-123	-136			-140	-140
25	-123.5	-134.5			-140.5	-138.5
33	-118.5	-131.5			-141.5	-144.5

Notes:
1. 2 crosscuts from trolley line, Station 7 + 72
2. Station 9 + 52
3. Outside of mine

Location: Federal No: 2, Miracle Run, W. Va.
Date: 6-22-71

Antenna Orientation:	HMD	VMD
Overburden:	255 meters	255 meters

Frequency (kilohertz)	H (dB)	H (dB)
2.1	-115	-104
2.8	-113	-101
3.7	-118	-108
5.4	-112	-110
7.1	-112	-115
9.9	-124	-129
11.6	-119	-130
13.8	-118	-137
18.3	-129	-139
22.6	-138	-141
26.5	-142	-142
36	-145	-145

Location: Badger No. 14 Mine, Phillipi, W. Va.
Date: 7-20-71

Antenna Orientation:	VMD	HMD	VMD	HMD
Overburden:				
Note:	1	1	2	2
Frequency (kilohertz)	H (dB)	H (dB)	H (dB)	H (dB)
2.1	-93	-110	-110	-115
2.8	-103	-115	-113	-123
3.7	-108	-123	-115	-125
5.4	-112	-126	-124	-129
7.1	-115	-124	-124	
9.9	-124	-134	-129	-134
11.6	-130	-130	-135	
13.8	-127	-137		
18.3	-124	-139		
22.6	-141	-141		
26.5	-144	-142		
36.0	-145	-145		

Notes: 1. Near New Mains, trolley power on.

2. Near New Mains, trolley power off.

Location: U. S. Bureau of Mines, Bluefield, Pa.
Date: 9-30-71

Antenna Orientation:	VMD	VMD	HMD	VMD
Note	1	2	3	3
Frequency (kilohertz)	H (dB)	H (dB)	H (dB)	H (dB)
2.1	-108	-110	-101	-102
2.8	-111	-114	-105	-111
3.7	-112	-109	-101	-112
5.4		-122	-109	-122
7.1	-115	-118	-109	-122
9.9		-130	-117	-127
11.6	-127	-133	-117	-130
13.8		-135	-120	-133
18.3		-139	-122	-134
22.6	-139	-145	-124	-139
26.5	-135	-143	-120	-137
36	-134	-148	-133	-143

1. Road 10
2. Between 6 and 7
3. Road 13

All measurements were made at depths of 18-27 meters

(Continued)

Antenna Orientation:	HMD	VMD	HMD
Note:	4	5	5
Frequency (kilohertz)	H (dB)	H (dB)	H (dB)
2.1	-87	-113	-113
2.8	-99	-115	-113
3.7	-103	-118	-111
5.4	-107	-127	-118
7.1	-108	-124	-124
9.9	-112	-127	-124
11.6	-113	-128	-118
13.8	-113	-129	-125
18.3	-118	-127	-130
22.6	-121	-135	-134
26.5	-122	-135	-132
36	-124	-140	-143

4. One crosscut from Road 13
5. Near operating cutting machine