Westinghouse Research Laboratories

EM LOCATION SYSTEM PROTOTYPE AND COMMUNICATION STATION MODIFICATION

FINAL REPORT

July 1973

Submitted to:

Bureau of Mines
Department of Interior
under Contract H0232049

Georesearch Laboratory
Boulder, Colorado

LOCATION SYSTEM PROTOTYPE
AND
COMMUNICATION STATION MODIFICATION

Part I	LOCATION SYSTEM PROTOTYPE DEVELOPMENT AND TEST
Part II	COMMUNICATION STATION MODIFICATION AND DEMONSTRATION AT BRUCETON EXPERIMENTAL MINE
Part III	ARMCO #9 LOCATION SYSTEM DEMONSTRATION

Prepared by

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Boulder, Colorado 80303

DISCLAIMER NOTICE

For the

U. S. BUREAU OF MINES
DEPARTMENT OF THE INTERIOR
USBM Contract H0232049

PART I

LOCATION SYSTEM PROTOTYPE DEVELOPMENT AND TEST

A. J. Farstad, C. Fisher, and R. F. Linfield

CONTENTS

SUBJECT INVENTIONS REPORT

The following Subject Invention was disclosed on Contract H0232049.

Westinghouse Disclosure No. 73-240

"Differential Technique for Locating Electromagnetic Signal Sources."

Date of Disclosure: May 8, 1973

FOREWORD

This final report was prepared by Westinghouse Georesearch Laboratory, 8401 Baseline Road, Boulder, Colorado 80303, under USBM Contract No. H0232049. 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. H. E. Parkinson acting as the technical project officer. Mr. G. Honold 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 April 1973 to July 1973. This report was submitted by the authors on 20 July 1973.

This technical report has been reviewed and approved.

ABSTRACT

A prototype EM Location System was fabricated and tested at the Geneva Mine near Dragerton, Utah. This system consisted of six manpack transmitters and six manpack receivers covering the frequency band from 900 Hz to 2900 Hz as well as a six channel receiver designed for use in a helicopter. Tests showed that EM signals from lightweight (3/4 lb) transmitters could be detected both on the surface and from a helicopter through as much as 1650 ft of relatively high conductivity (2×10^{-2} mhos/m) overburden. Furthermore, the resulting field strength profiles could be used to determine source location to within 150 ft of the actual surveyed location in the mine.

Modifications were made to a Monitoring, Locating and Communications System being tested at the Bruceton Mine, Pittsburgh, Pennsylvania. These modifications have improved the performance and quality of the paging and voice telephony mode of the system. Subsurface receiver modifications have improved reception of voice downlink signals.

PREFACE

This final report covers the work performed for the U.S. Bureau of Mines on Contract H0232049 between April and July 1973.

The report is divided into three parts and covers in detail all work accomplished on Tasks I, II, and III under the contract.

Task I involves the development and test of an electromagnetic location system prototype. Based on design concepts developed previously on Contract H0220073, six each single frequency manpack transmitters and receivers were fabricated, along with one airborne six-frequency detection receiver. Subsequently one of these units was demonstrated at the Armco #9 coal mine near Charleston, West Virginia, and all were field tested at the U.S. Steel Corporation's Geneva Coal Mine near Dragerton, Utah. Part I of this report describes the systems fabricated and the results of the field tests. Conclusions and recommendations are included with the report.

Task II involves modifications and additional tests on the Monitoring, Locating and Communications System which was initially developed on Contract H0220073. Part II of this report covers the modifications made to the system and the results obtained after reinstalling the equipment in the USBM Experimental Mine near Bruceton, Pennsylvania.

Task III resulted from a contract modification to furnish the engineer services and equipment necessary to conduct an EM location system demonstration at a West Virginia coal mine for the Bureau of Mines. The demonstration was performed in conjunction with other mine emergency operations equipment, including the Seismic Location System, the EM Communications equipment, and support equipment normally located at the Charleston Staging Facility in West Virginia for emergency use. Part III of this report summarizes the EM location activities performed at this demonstration.

1.0 INTRODUCTION

A prototype electromagnetic location system consisting of 6 miniature transmitters, 6 miniature receivers and one multichannel receiver was developed by Westinghouse Georesearch Laboratory and is described in this section of the report. The equipment was designed to operate in a deep coal mine of relatively high overburden conductivity. One mine having these characteristics is the Geneva Coal Mine operated by U. S. Steel Company near Dragerton, Utah. Since Westinghouse personnel had previously conducted similar tests at this mine (September 1971) and the pertinent parameters such as overburden depth and ground conductivity were well known, it was decided to return to this mine and conduct field performance tests of the newly developed equipment. Because of significant overburden depth and high conductivity, it was felt that if the equipment performed satisfactorily at the Geneva Mine it could also perform satisfactorily at most coal mines in this country.

The field tests consisted basically of the detection of magnetic field intensities produced by the miniature EM manpack transmitters deployed in the mine and the utilization of the measured field strength patterns to estimate the location of the transmitters. Both surface measurements and airborne (helicopter) measurements were conducted. Prediction of field strength at a variety of frequencies and overburden depths were made prior to the development of the equipment to insure that the transmitters would have sufficient transmitting moment to penetrate the deep, conductive overburdens and that the receivers would have sufficient sensitivity and selectivity to detect the fields produced on the surface as well as above the surface. Comparisons between predicted and measured field strengths are given in this report along with comparison of location determined by electromagnetic methods and conventional land surveying. Representative tape recordings were made from each of the receiver outputs and were photographed on playback in the laboratory.

2.0 PERFORMANCE PREDICTIONS

In this section we discuss the basic concept of the EM Location System, the limitations on transmitted signals, and indicate the detectable depth of different system configurations in terms of the antenna moment, conductivity, and the noise environment expected at the Geneva Coal Mine test site.

2.1 EM Location Concepts

It has been demonstrated theoretically and experimentally that miners equipped with a radio transmitter and loop antenna which generates a vertical magnetic dipole moment can be located by measuring the electromagnetic fields on the surface [1], [8]. Directly above the source there is a single null in the total horizontal magnetic field and this null provides the location criteria. Location accuracy depends on the depth of null which is a function of signal level and the background noise. Accuracy also depends on the axis orientation of the buried source and the slope of the terrain on the surface, as well as the presence of any structure in the area.

The system designer can select operating frequencies and transmitter power, and detection schemes to optimize the signal-to-noise ratio at the receiver and thereby increase detection range and location accuracy. Source axis tilt is under the control of the transmitter operator. Terrain slope corrections can be developed, and when applied, could reduce terrain produced location errors.

Figure 2-1 shows the equivalent circuit of the full-wave transmitter developed for location purposes. The symbols represent the following:

E_b = Battery voltage

R_b = Internal resistance of battery

R_s = Internal resistance of switch

R_a = Loss resistance in antenna circuit

L_a = Antenna inductance

C_a = Antenna tuning capacitor

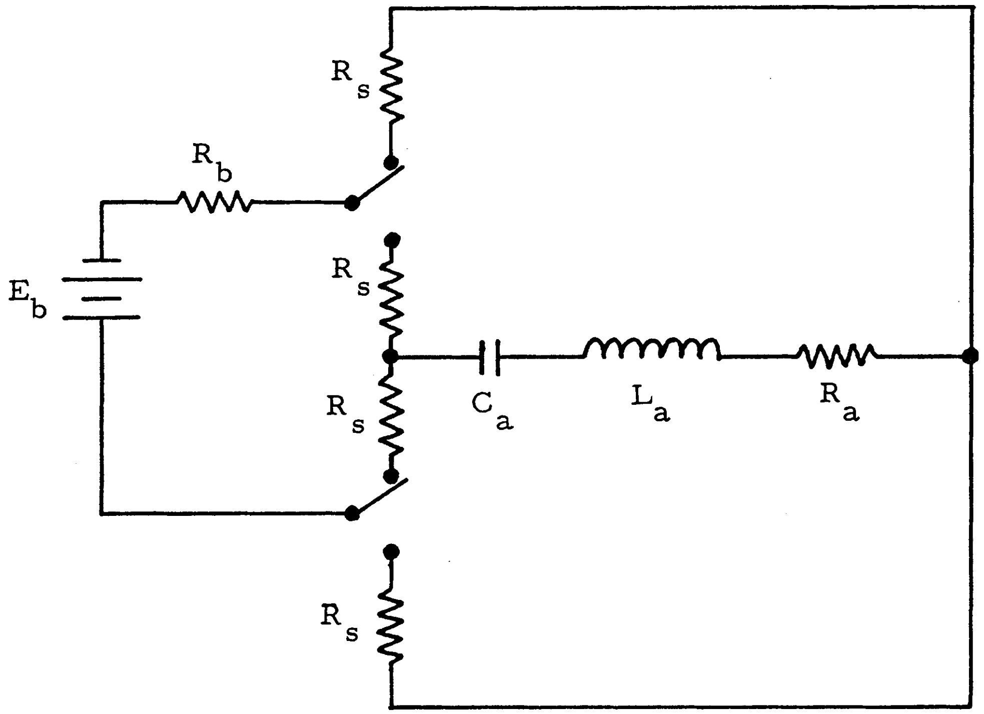


Figure 2-1. Equivalent Circuit of Location Transmitter used at Geneva.

Solid state devices are used for the switches and these are operated on an intermittent duty cycle using a continuous waveform generating circuit whose frequency is controlled by a stable oscillator. When the loop antenna inductance is resonated to the operating frequency, the current waveform in the antenna circuit is sinusoidal with an rms amplitude given by equation (1), (see Reference [1]).

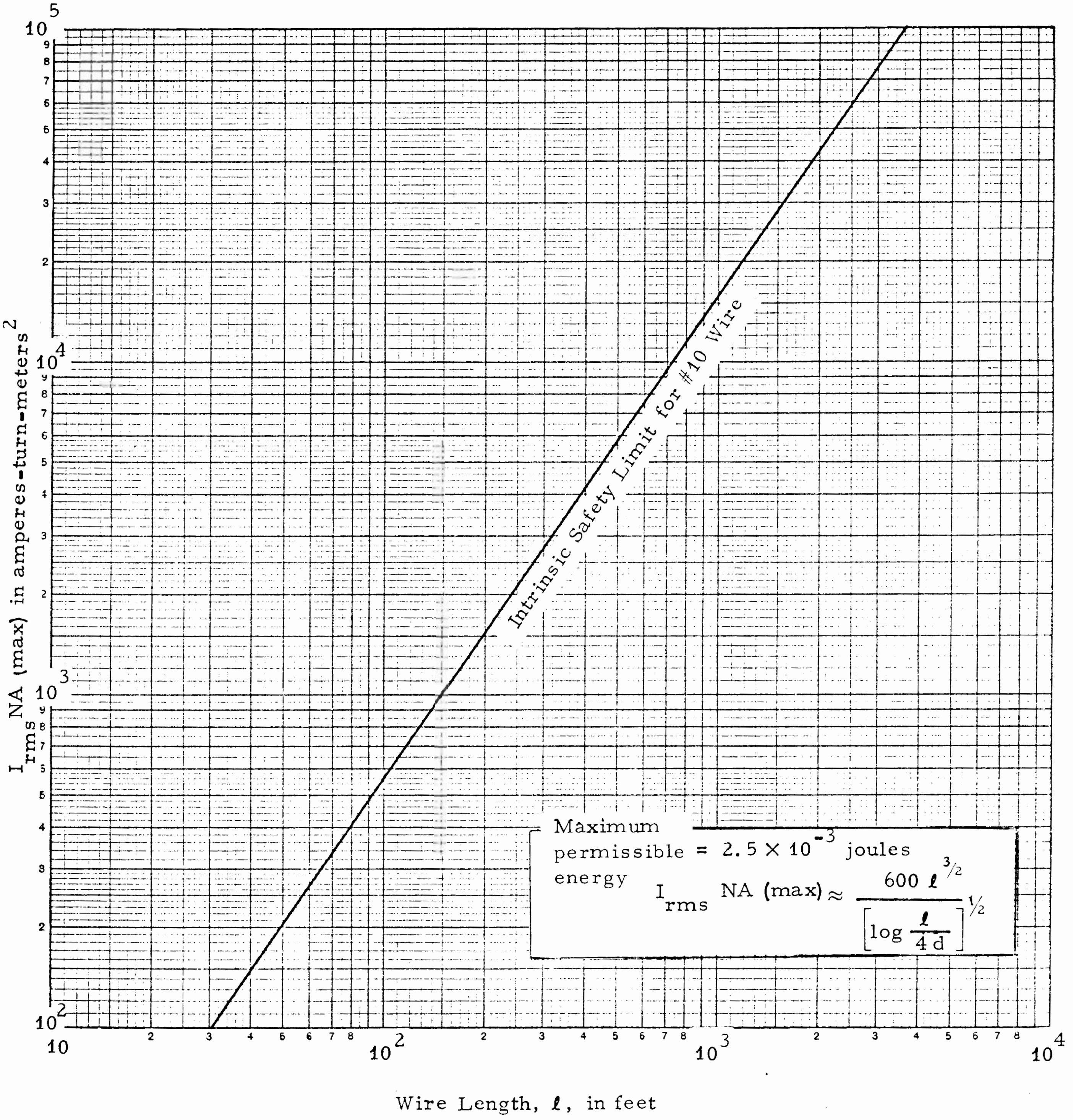
$$I_{rms} = \frac{0.9\ E}{R_b + 2R_s + R_a} \quad . \tag{1}$$

The antenna moment is given by INA, where I is the rms current, N the number of turns, and A the area enclosed by the loop. Usually this moment is expressed in the international system of units, i.e., ampere-turn-meters^2.

Figure 2-2 shows the maximum intrinsically safe antenna moment which can be achieved as a function of the length of #10 wire used to form a square loop antenna.

The coal pillars at the Geneva test mine in Utah were found from mine maps to be typically 500' (152.4 m) in circumference and usually shaped in the form of a parallogram 80 × 170 feet with the acute angle of approximately 45 degrees. The antenna moment with this antenna configuration varied between 1800 and 2600 ampere-turn-meters^2 depending on whether #12 or a #9 AWG wire was used. These antenna moment estimates are based on measurements made near the WGL laboratory using a similar antenna configuration laid out on the surface. In the mine the antenna moments could be different because of the different losses in the surrounding coal. Antenna currents were not measured in the mine because permissible current measuring equipment was not available.

Figure 2-2. Maximum Intrinsically Safe Antenna Moment Achievable with a Given Length of Wire for Resonated Square Loop Antenna.



2.2 Field Strength Predictions and Measurements

Given the antenna moment and the conductivity of the overburden, it is possible to predict the vertical electromagnetic field component, H_z, over the transmitting dipole as a function of depth. For a coaxially oriented receiver antenna, H_z is given by equation (2). (See Reference [2]).

$$H_z = \frac{|G|}{2\pi z^3} \tag{2}$$

where z is the depth and $|G|$ is an attenuation factor which is a function of the skin depth and varies with frequency and conductivity of the overburden.

Figure 2-3 shows how H_z varies with frequency and conductivity for a fixed antenna moment and a depth of 500 meters (1640 feet). An estimate of the expected summertime atmospheric noise in a 6 Hz bandwidth is shown on the same curve. A comparison of the signal strength and the noise indicates that at a depth of 500 meters the optimum signal-to-noise ratio occurs at lower frequencies as the earth conductivity increases.

The effective conductivity of the earth at 460 meters over the Geneva Mine had been measured earlier, using an Eltran array on the surface, and found to be 2.7×10^{-2} mhos/meter. This was based on a two layer interpretation of the conductivity profile. Given this value of conductivity and the transmission frequency, the expected signal strength can be calculated for various depths. The results, obtained by computer, are shown in Figures 2-4 through 2-9 for the six different transmitter frequencies used at Geneva and assuming a constant conductivity of 2.7×10^{-2} mhos/meter for all depths.

A comparison of the measured field strengths and these predictions was made, and in general, the measured fields were higher than expected. This indicates that either the in-mine antenna moment was greater than measured

Figure 2-3. Field Strength vs. Frequency&Parametric in Conductivity. (Depth = 500 meters, INA = 1000 ampere turn meters^2.

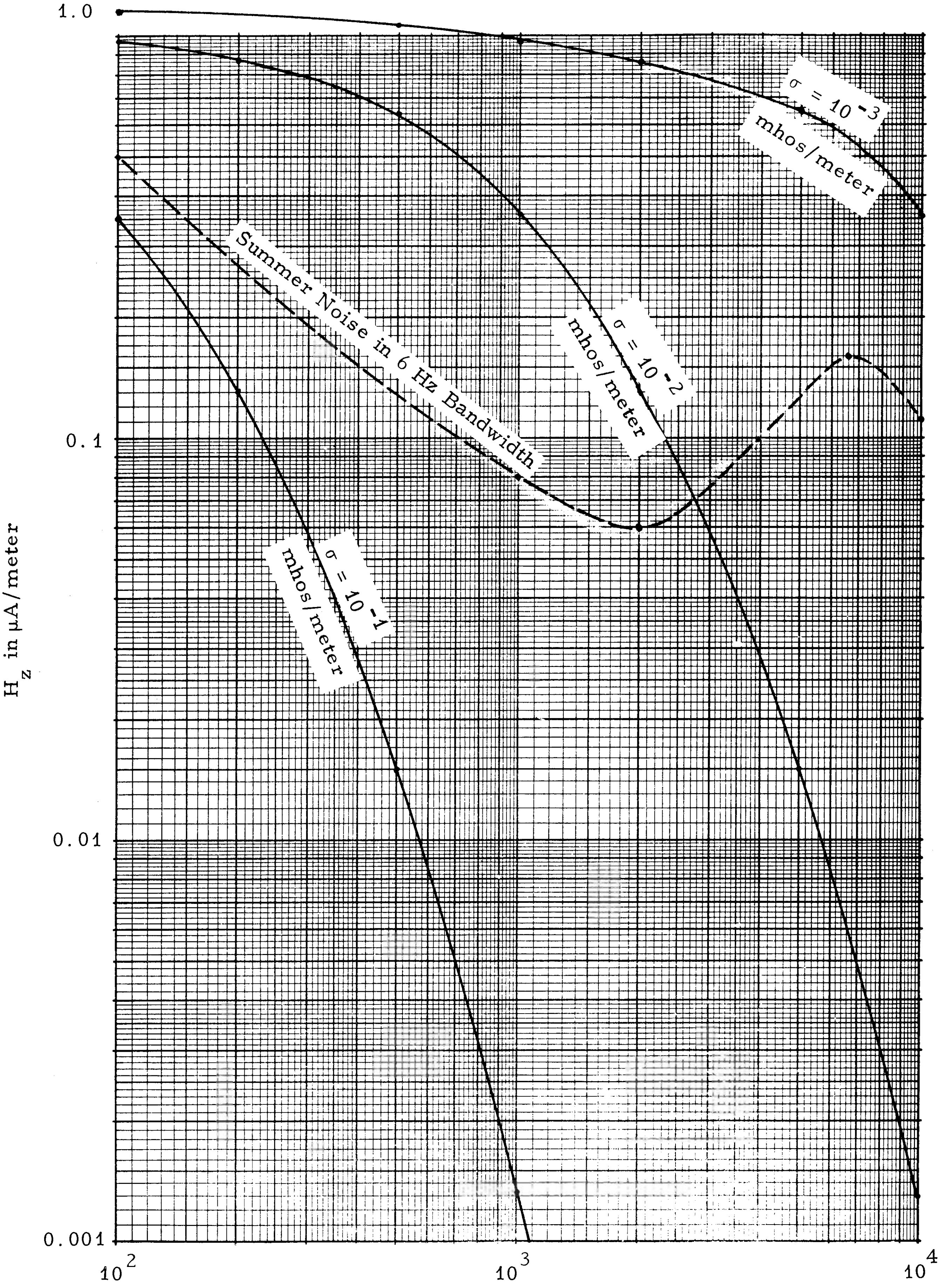


Figure 2-4. Vertical EM Field Predictions at Geneva for 922.5 Hz.

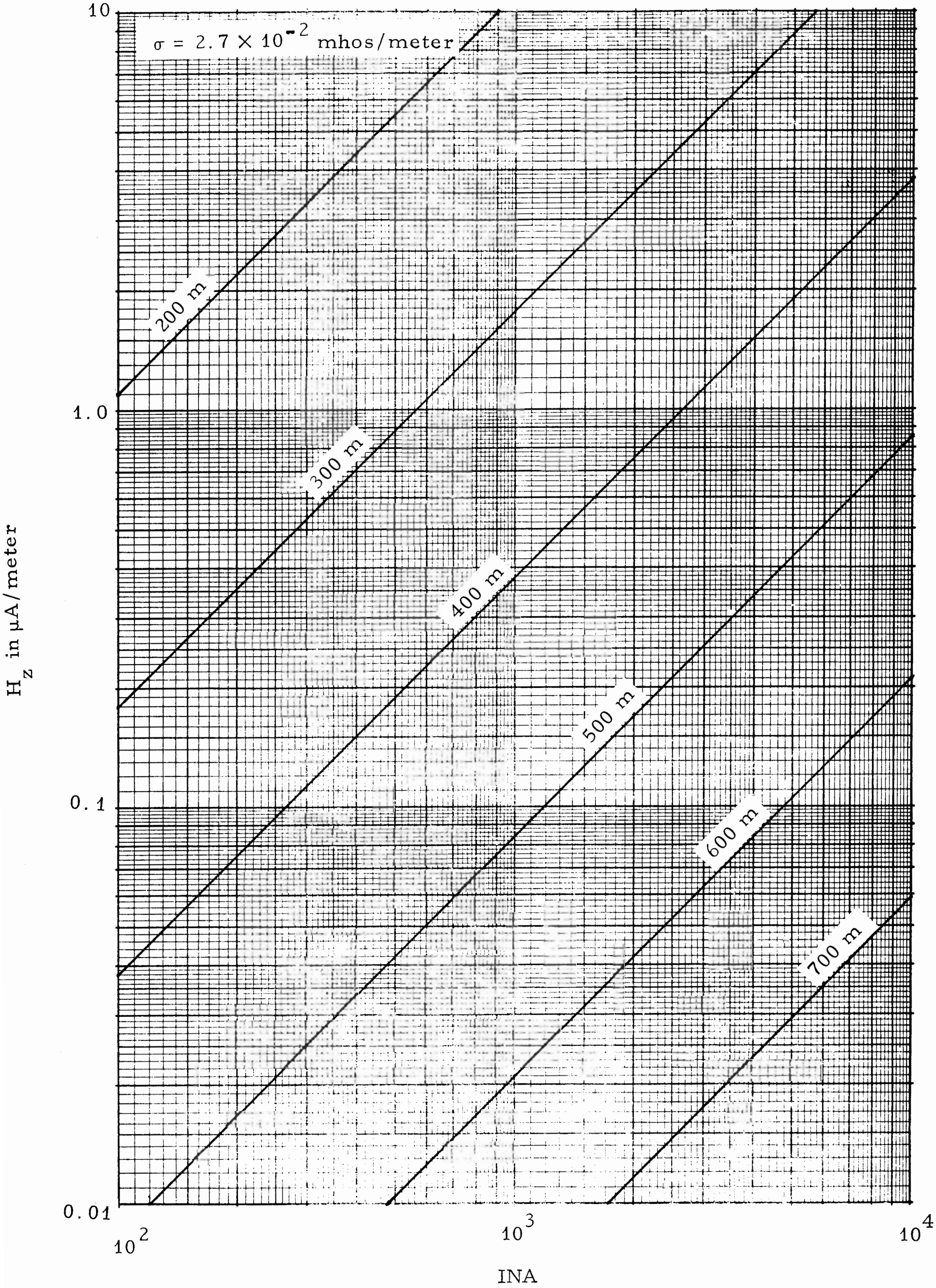


Figure 2-5. Vertical EM Field Predictions At Geneva for 982.5 Hz.

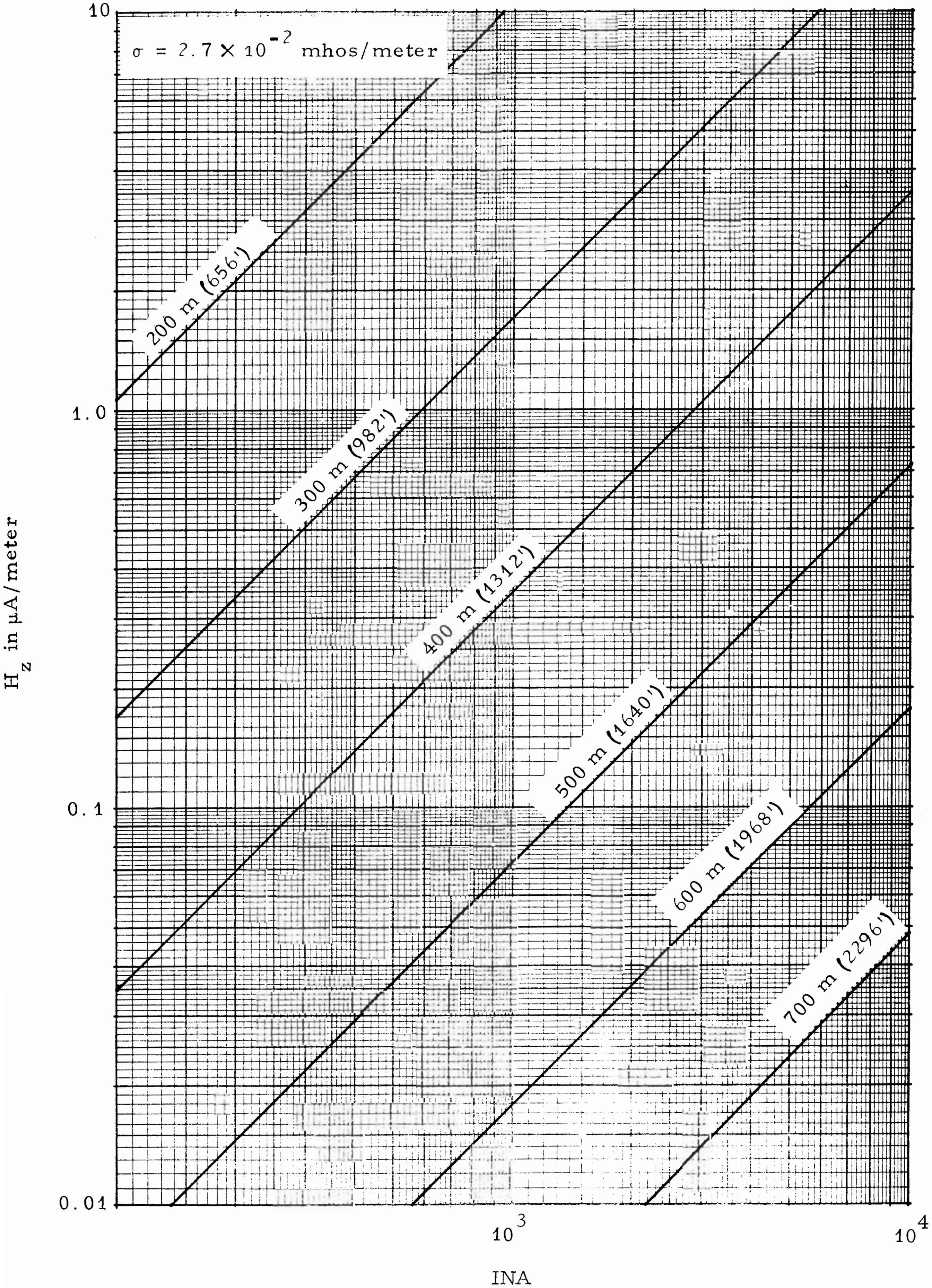


Figure 2-6. Vertical EM Field Predictions at Geneva for 1700 Hz.

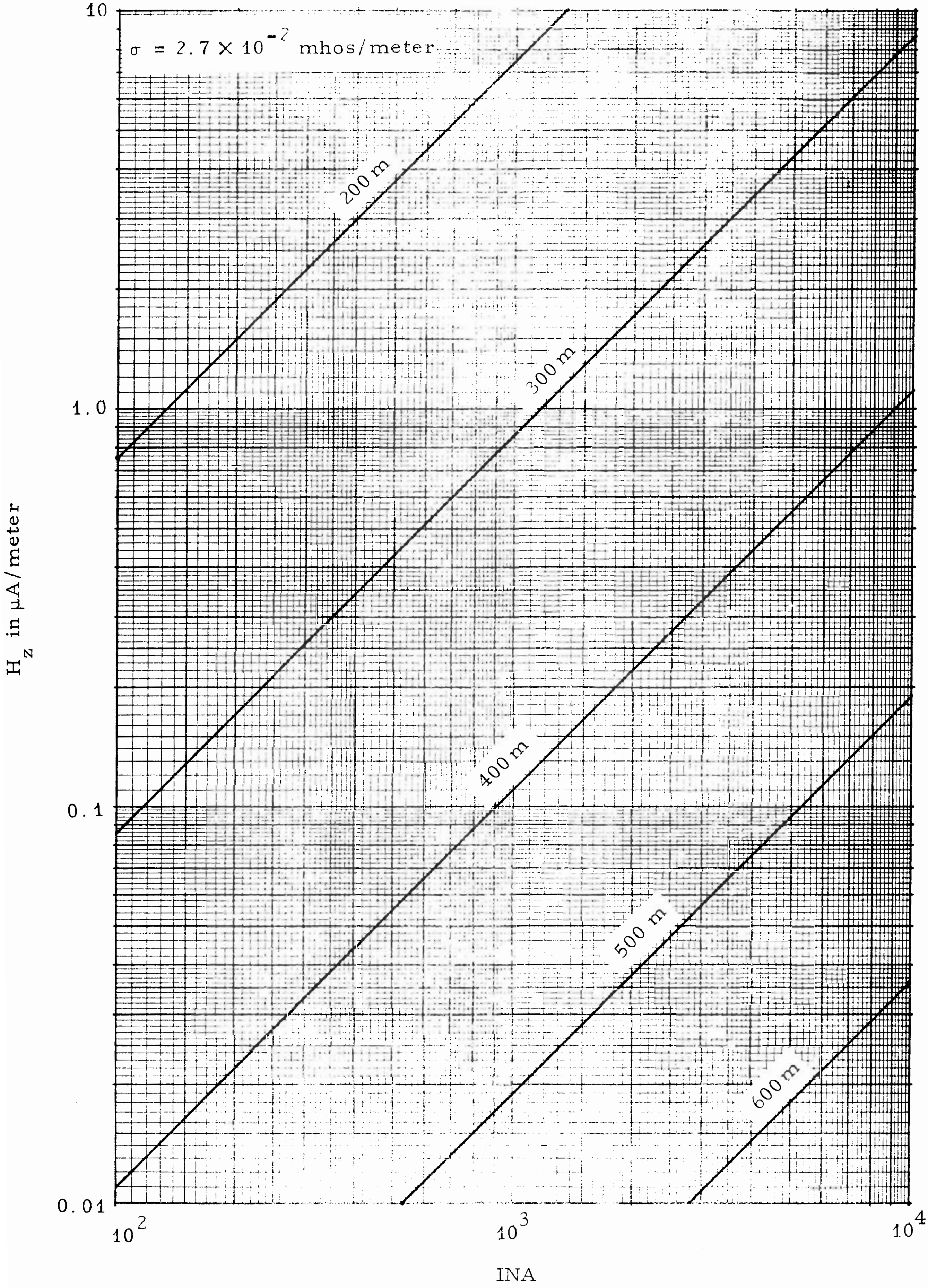


Figure 2-7. Vertical EM Field Predictions at Geneva for 1900 Hz.

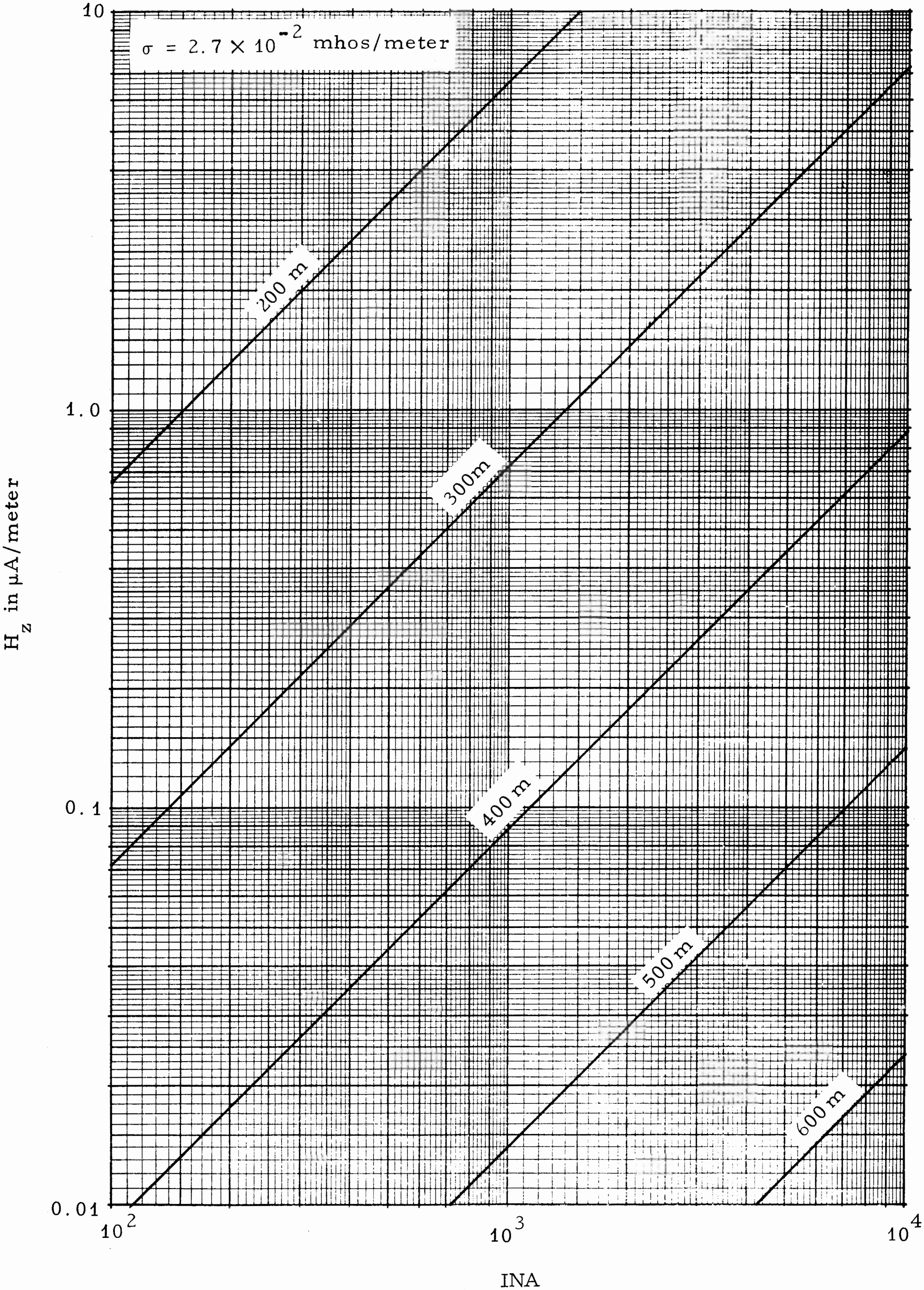


Figure 2-8. Vertical EM Field Predictions at Geneva for 2300 Hz.

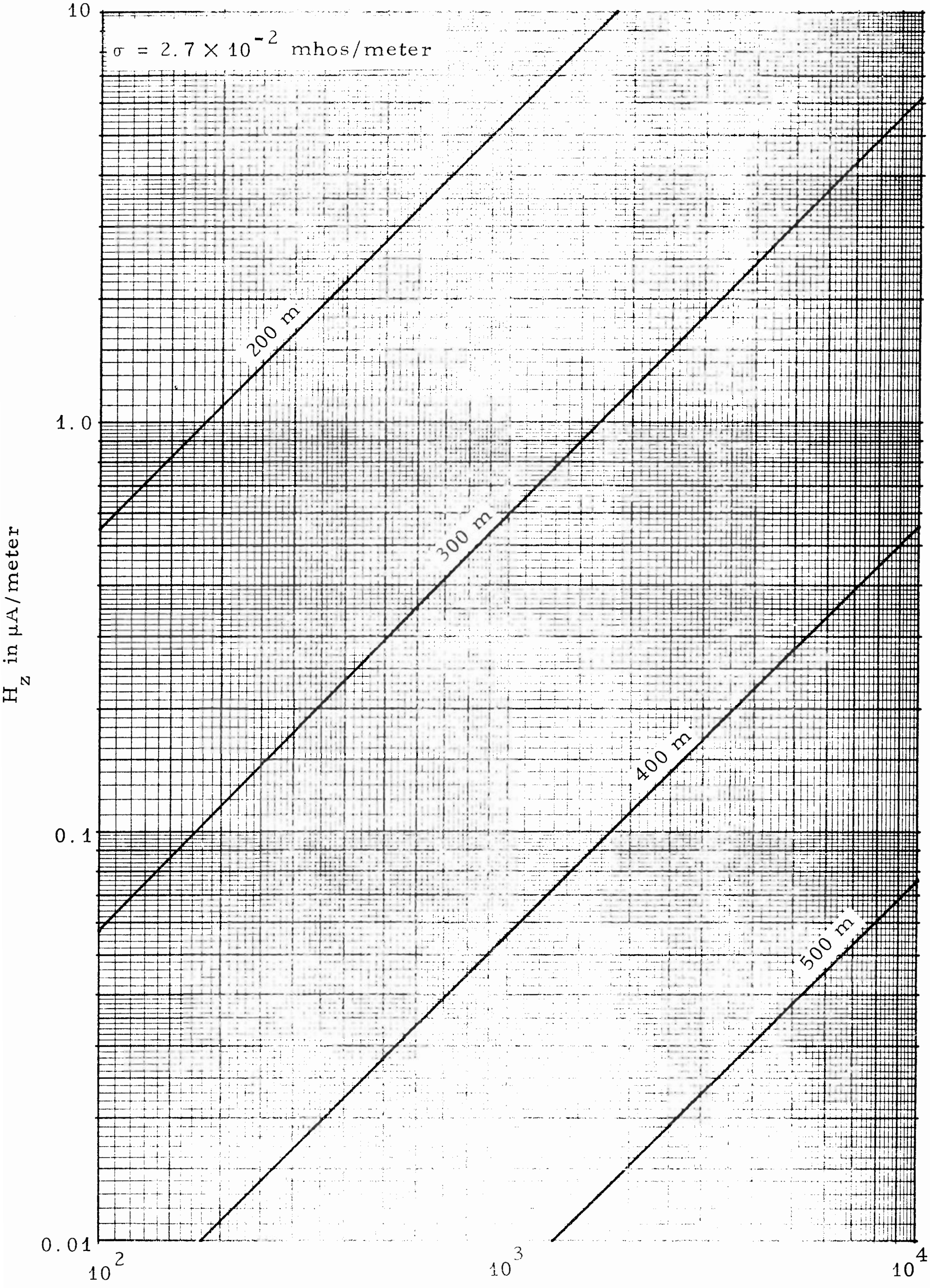


Figure 2-9. Vertical EM Field Predictions at Geneva for 2500 Hz.

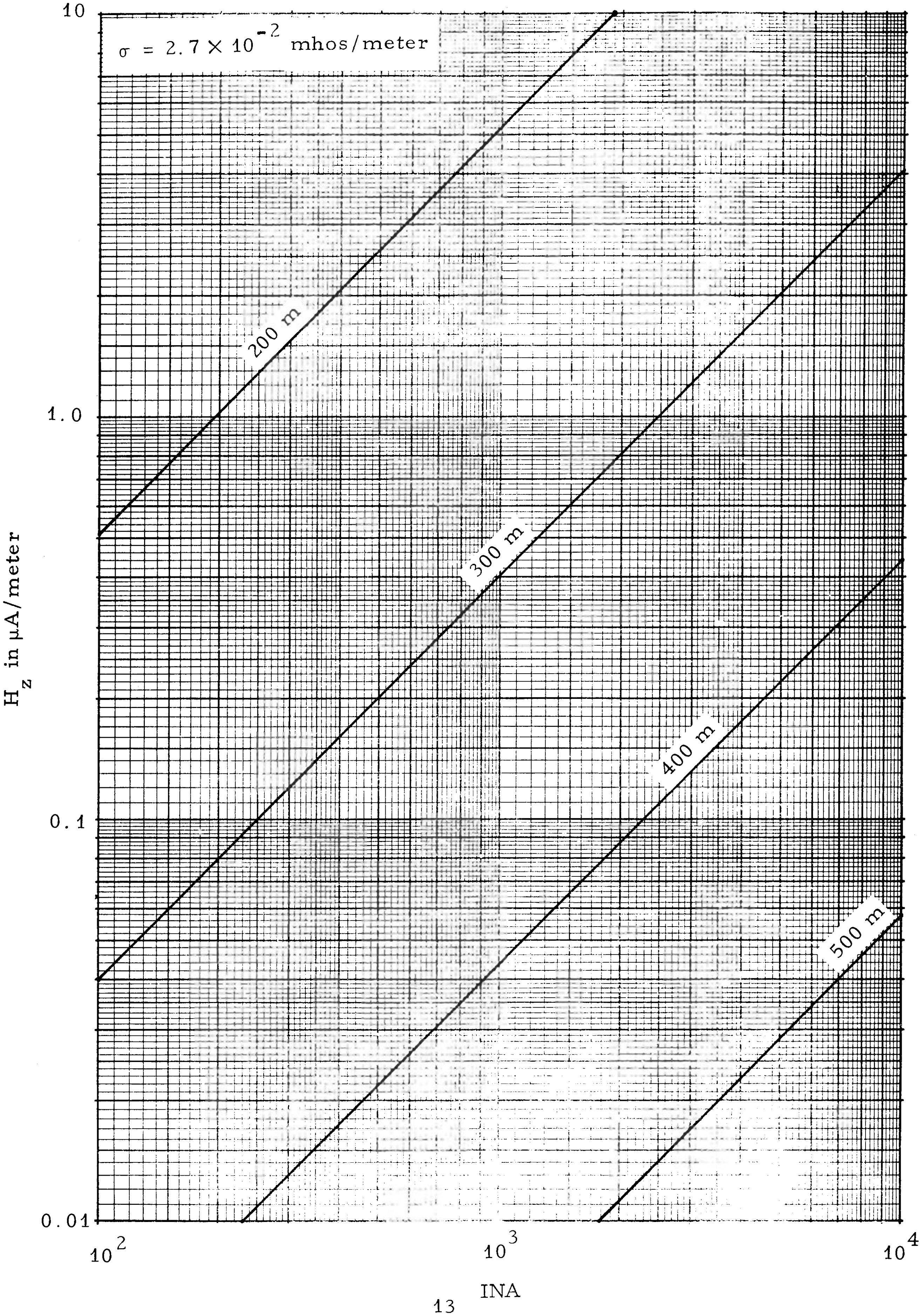
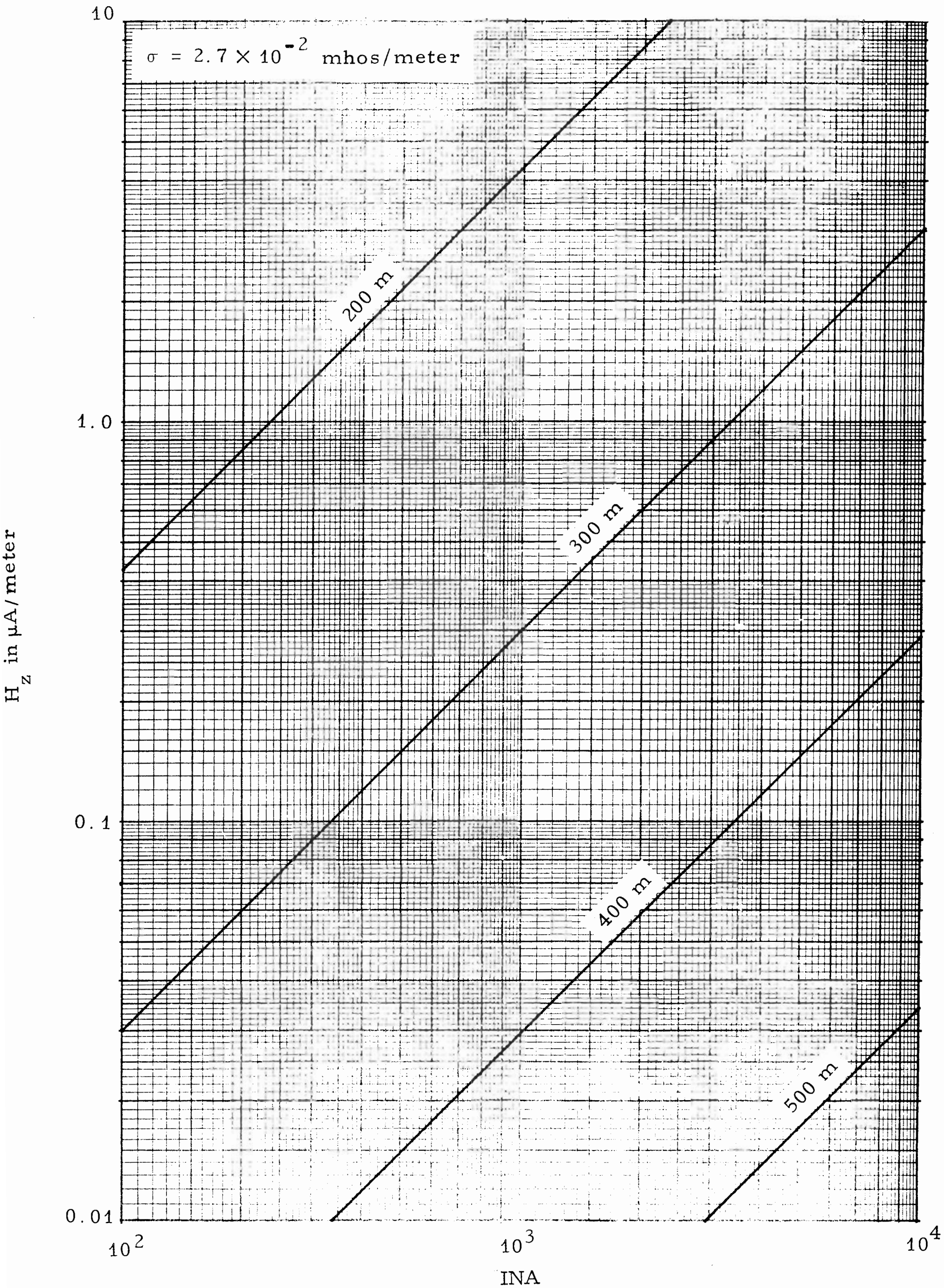


Figure 2-10. Vertical EM Field Predictions at Geneva for 2900 Hz.



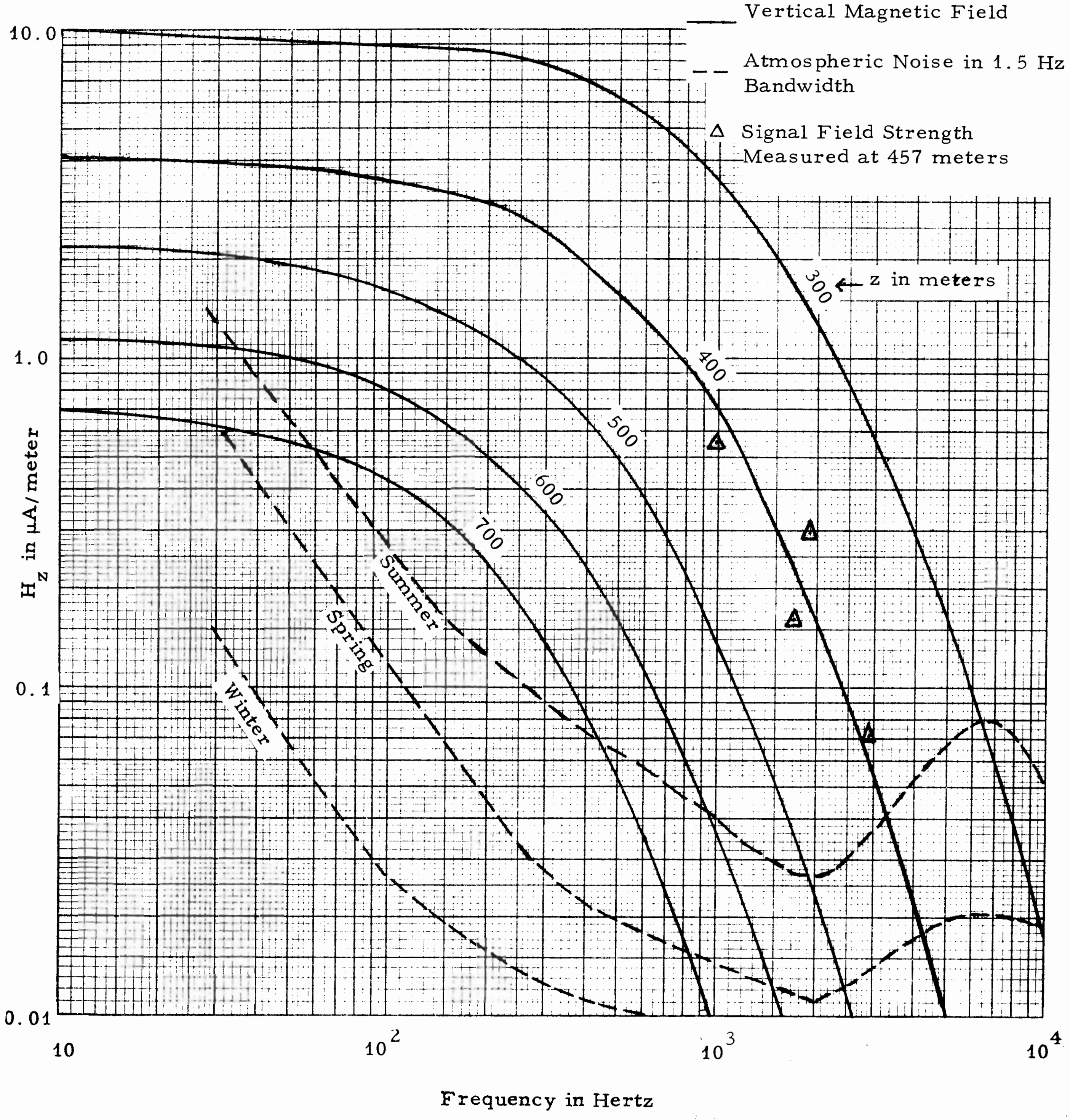
on the surface or that the actual conductivity was less than originally assumed. The conductivity profile was later reexamined and a three-layer interpretation performed to obtain effective conductivities as a function of depth. Measured and predicted values of field strength are given in Section 4.2 using these revised conductivity estimates.

Predictions of the vertical magnetic field, H_z, as a function of frequency for a fixed antenna moment can be obtained from Figures 2-4 through 2-10. This was done for the antenna moment expected for Geneva tests ($INA \approx 2000$ ampere-turn-meters^2) and for an effective overburden conductivity of 2.7×10^{-2} mhos/meter. Results are shown in Figure 2-11 with depth as the parameter.

Also Figure 2-11 shows the expected atmospheric noise in a 1.5 Hz bandwidth for the spring, summer, and winter seasons. These noise curves are based on measured values of the median levels of the vertical magnetic noise fields from 35 Hz to 3875 Hz. These measurements were obtained by WGL at Boulder, Colorado in the Spring of 1972 [3] and extrapolated for the summer and winter seasons. The standard deviation of the measured data for a one month period (March, 1972) was 10 dB at 1000 Hz. This deviation accounts for diurnal variations of the noise and for day to day variations during the month. The ratio of the rms to average value of the noise, V_d, was also measured for shorter periods. V_d varied depending upon frequency and time of day, but was usually less than 2 dB when measured in a 6 Hz bandwidth. Thus the atmospheric noise envelope has almost a Rayleigh distribution at the frequencies and bandwidths used for the Geneva tests.

By comparing the available signal fields with the expected noise fields in Figure 2-11 it is apparent that the maximum signal-to-noise ratio is quite broad and occurs at decreasing frequency with increasing depth. At 300 meters the maximum signal-to-noise ratio is obtained around

Figure 2-11. Signal and Atmospheric Noise Field Estimates for Geneva Mine. ($\sigma = 2.7 \times 10^{-3}$ mhos/meter INA = 2000 amp-turn-meters^2.)



1000 Hz, and at 500 meters it is obtained around 200 Hz. However, man-made noise, which contains spectral lines at the harmonics of 60 Hz, increases substantially at the lower frequencies and leads to the selection of the higher operating frequencies. The 6 transmitter frequencies used for the Geneva tests fell between 900 Hz and 3000 Hz.

Data obtained at Geneva tend to verify the noise model shown since field strength measurements as low as 0.03 μA/meter were measurable at 1900 Hz.

Field strength measurements obtained for four different frequencies at a depth of 457 meters (1500 feet) are also shown on Figure 2-11. The decreasing signal level as a function of frequency follows the predicted value, although the results indicate that the initial conductivity interpretation (2.7×10^{-2} mhos/meter) is high.

3.0 INSTRUMENTATION DEVELOPMENT

3.1 Transmitter

Much of the development of the transmitter used in the Geneva field tests was accomplished on BuMines Contract H0220073. Out of this work evolved a transmitting system prototype utilizing a full wave transformerless switching amplifier as shown in the schematic of Figure 3-1. This transmitter is designed specifically to get maximum switched AC current from a low voltage DC source (4 volt cap lamp battery)into a low impedance series tuned loop antenna (heavy wire wrapped around a mine pillar). The output transistors used were complementary MJ 4032 and MJ 4035 (Motorola PNP and NPN low saturation voltage devices). Laboratory performance tests of this transmitter powered by a 4 volt miners cap lamp battery to drive a 0.4 Ω resistive load indicated an equivalent switch resistance of 0.2 ohms per transistor.

The transmitter derives its oscillation frequency from a tuning fork oscillator and its tone pulse repetition rate from an RC integrated circuit oscillator. All of the integrated circuits used in this transmitter are complementary MOS (CMOS) and a bank of 2N4400/4402 transistors is used to interface the CMOS outputs to the power transistors. A three way manual power switch is provided so the operator may either key the transmitter to send coded messages to the surface or turn it on and leave it run on a 10% duty cycle interrupted tone sequence. The Geneva tests were performed using the interrupted tone sequence switch position with the transmitter unattended. Figure 3-2 is a photograph of the transmitter chassis and leather carrying case. This transmitter was tested at the BuMines approval and Testing Laboratory in Pittsburgh, Pennsylvania and has been rated permissible for use in gassy mines. A complete list of transmitter specifications is shown in Table 3-1.

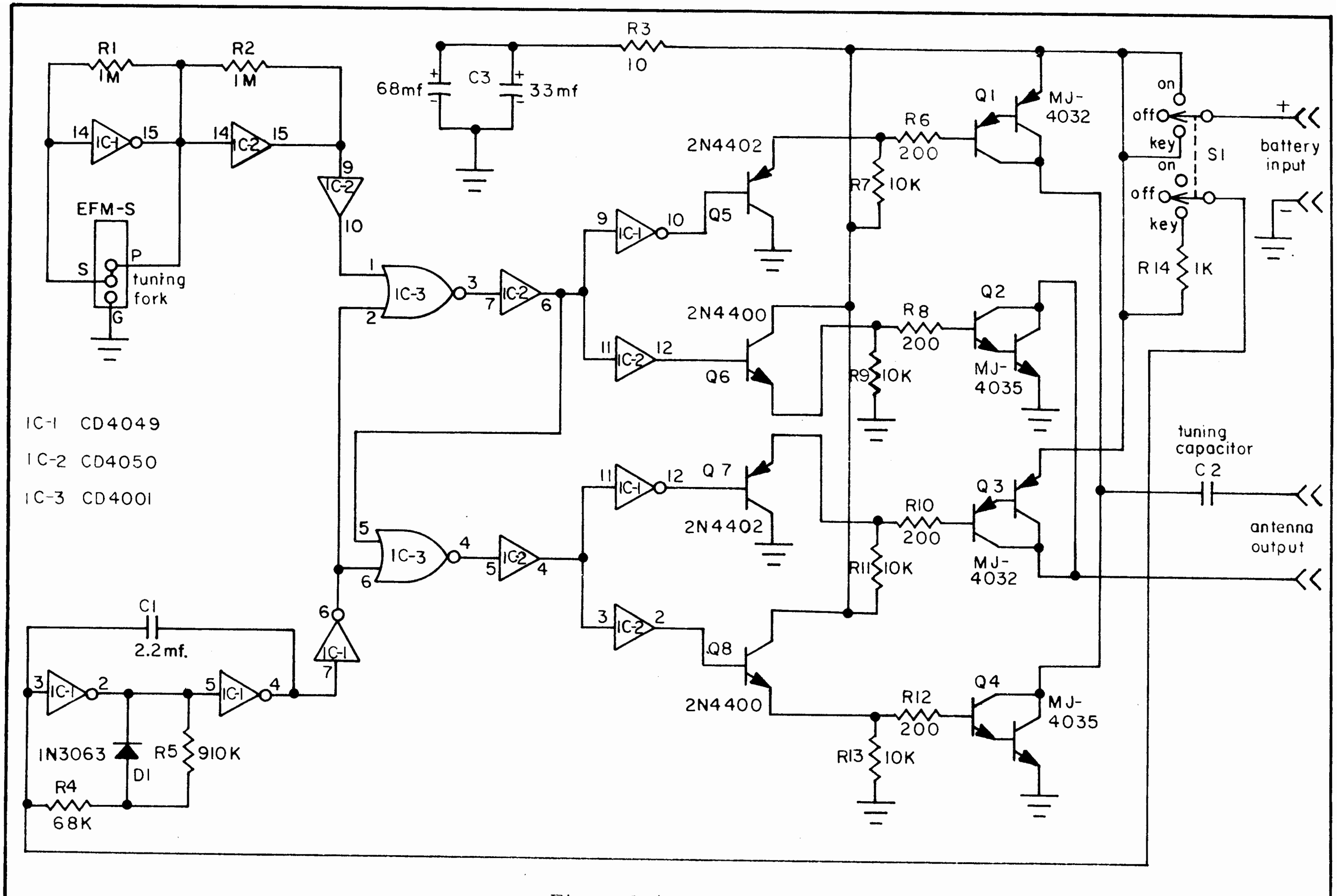


Figure 3-1

WESTINGHOUSE GEORESEARCH LABORATORY
8401 BASELINE ROAD
BOULDER, COLORADO 80303

TITLE EM FULL-WAVE MANPACK LOCATION TRANSMITTER
MODEL C848A

DRAWING NUMBER 73-MIN-848-50

DRAWN BY C. Fishup.

DATE 6/28/73

CHECKED BY

APPROVED BY agf

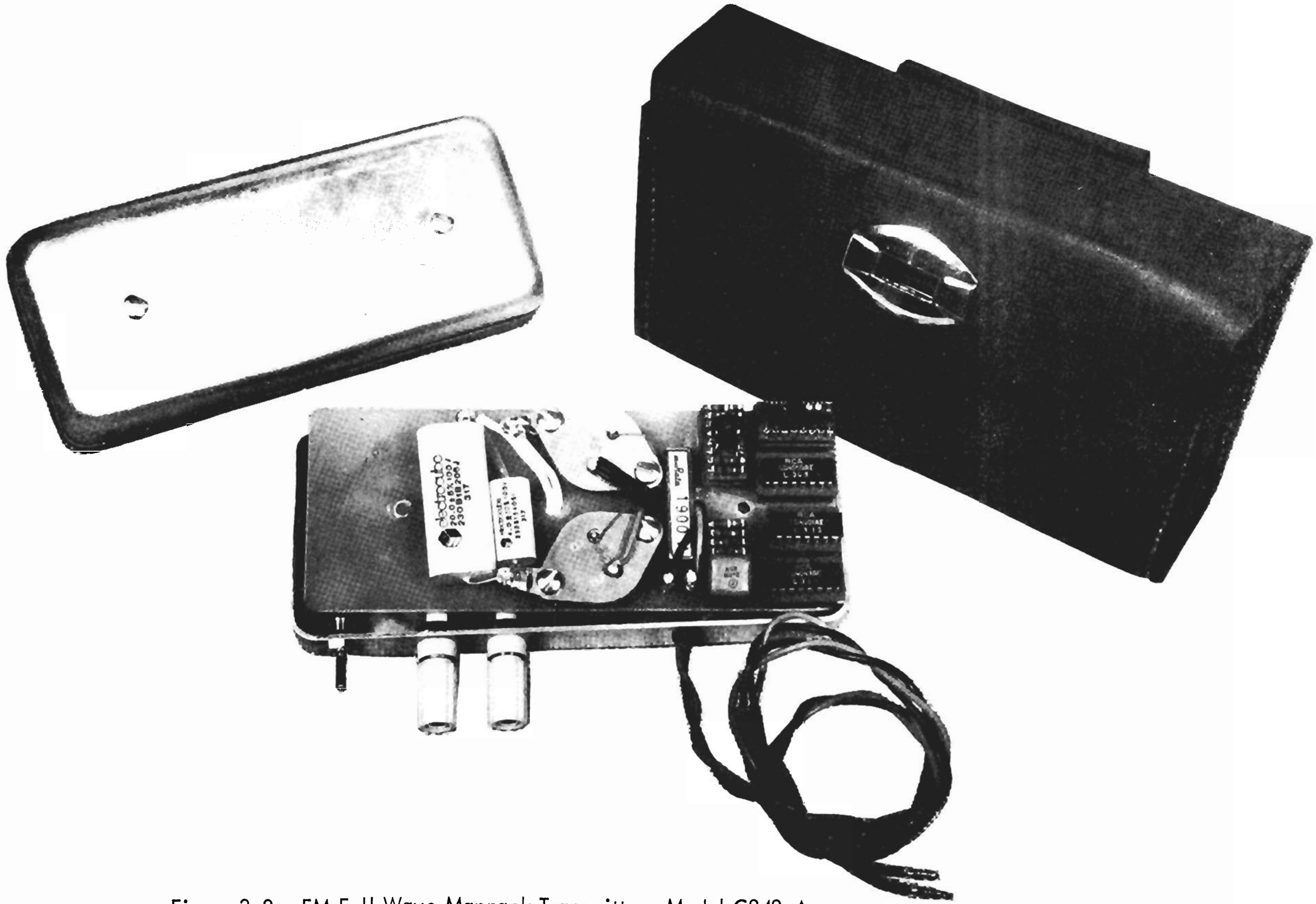


Figure 3-2. EM Full Wave Manpack Transmitter, Model C848-A.

TABLE 3-1

Specifications for Westinghouse Manpack Transmitter, Model C848A

Power Source:	4 volt miner's lamp battery furnished with each unit.
Transmitter Type:	Full Wave - Switching Mode. Intrinsically safe with specified antenna.
Operating Frequency: (1 of the following):	922.5, 982.5, 1700, 1900, 2500, or 2900 Hz.
Frequency Accuracy:	± 2 Hz.
Frequency Stability:	$2 \times 10^{-5} / {}^{\circ}F$ max.
Signal Output Format:	Interrupted continuous square wave into resistive load.
Duty Cycle:	On 0.2 seconds ± 10% Off 2.0 seconds ± 10%
Temperature Range:	0-120° F
External Connections:	Battery and antenna connections.
Minimum Output:	8 amperes peak-to-peak into 0.4 ohm resistive load at 70° F.
Controls:	Single on-off switch.
Operating Life:	Approximately 30 hours, using fully charged battery at 70° F.
Transmitter Package:	Less than 50 cubic inches with suitable belt attachments, battery and antenna excluded.
Transmitter Weight:	Less than 2 lbs. excluding battery and antenna.
Antenna Furnished:	500 feet of #12 AWG insulated copper wire. 0.8 ohms, ≈ 300 μhenries as single turn loop, and resonated to operating frequency with suitable capacitor.

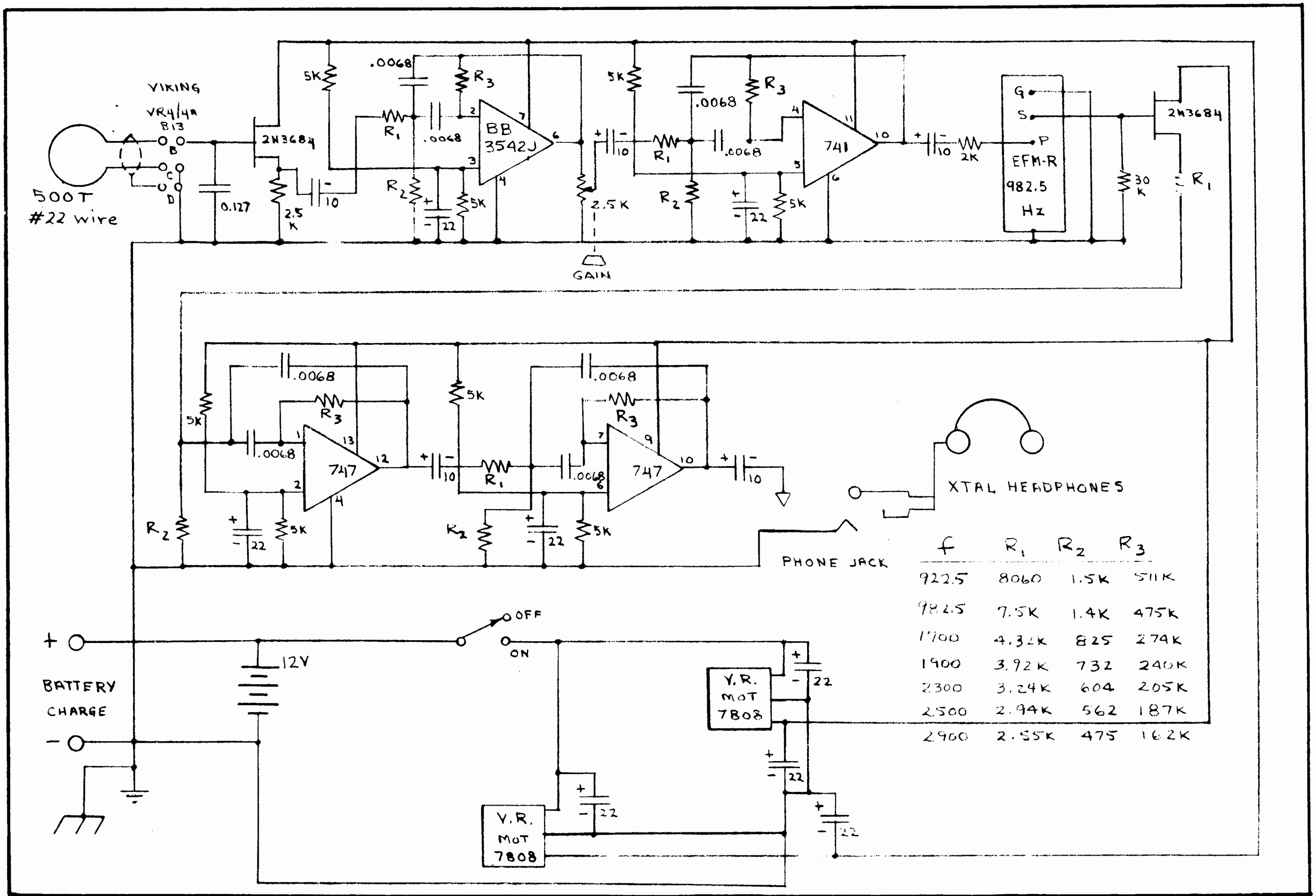
3.2 Receiver

Two different types of receivers were developed on this contract: (1) a portable single channel receiver utilizing an air core loop antenna tuned to one particular frequency and (2) a multichannel receiver utilizing a broadband loop antenna and preamp combination to receive up to six frequencies simultaneously. Six of the portable receivers were fabricated, each one tuned to a different frequency while one multichannel receiver capable of receiving six frequencies simultaneously was built for use in the helicopter search mode. Each of these receivers was tested and evaluated at the Geneva Mine in June 1973. Technical descriptions of each receiver and results of their field evaluation are given in the following sections.

3.2.1 Westinghouse Manpack Locator Model C842A

The Westinghouse Manpack Locator Model C842A is designed for single frequency detection and source location for an underground transmitter transmitting that particular frequency. A schematic diagram of this receiver is shown in Figure 3-3 and a photograph is shown in Figure 3-4. The receiver chassis weighs about 2 lbs and attaches to the operation belt. The received signal is detected on a set of headphones; source locations are determined by evaluating the surface magnetic field pattern of the transmitted signal. When good signal to noise ratios are present the source location can easily be determined by the measured null in the total horizontal field.

The receiver has six independently tuned stages counting the loop antenna tuning. In addition to the parallel resonated loop, the receiver employs four RC bandpass amplifiers, each with a Q of 10 and one sharply tuned tuning fork filter with a Q of roughly 500.



f	R1	R2	R3
922.5	8060	1.5K	511K
982.5	7.5K	1.4K	475K
1700	4.32K	825	274K
1900	3.92K	732	240K
2300	3.24K	604	205K
2500	2.94K	562	187K
2900	2.55K	475	162K

WESTINGHOUSE GEORESEARCH LABORATORY
8401 BASELINE ROAD
BOULDER, COLORADO 80303

TITLE RECEIVER, MANPACK LOCATOR, C842-A

DRAWING NUMBER 73-UND-846-51

Figure 3-3

DRAWN BY

DATE Apr 3, 1973

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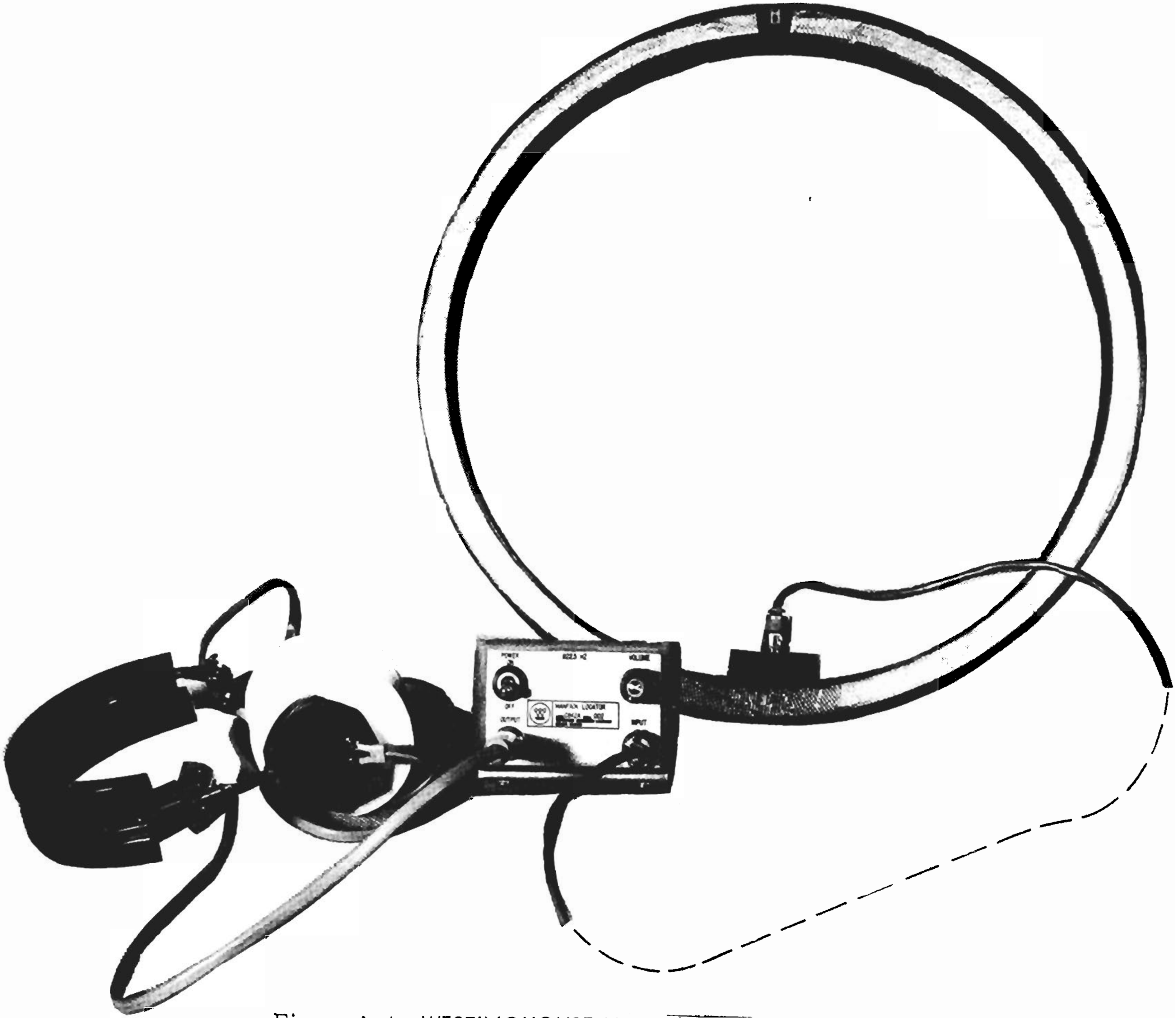

Figure 3-4 WESTINGHOUSE Manpack Locator, Model C842A

The tuned frequencies of operation range from 922.5 Hz to 2900 Hz, with 3 dB bandwidths ranging from 2 Hz to 5 Hz. A typical response curve obtained from one of these receivers (2900 Hz) is shown in Figures 3-5a & b. With this receiver, out of band interference ± 300 Hz away from center frequency is attenuated approximately 70 dB. This receiver was originally specified as having a sensitivity of 0.1 μA/meter; however, the Geneva tests showed it capable of receiving signals as low as 0.03 μA/m. A complete list of specifications for the manpack locator is given in Table 3-2.

3.2.2 Westinghouse Multichannel Receiver Model C849A

A schematic of the Multichannel Receiver C849A which was used in the helicopter test is shown in Figure 3-6. An active loop antenna circuit with a step-up transformer and a preamp gain of 20 dB was used with this receiver as shown in the schematic of Figure 3-7. This antenna preamp combination was designed to pass the signals in the operating band from roughly 1 kHz to 6 kHz with constant gain as shown in the response curve of Figure 3-8. The response is given as a transducer transfer function in terms of output voltage per amper/meter applied field strength. Figure 3-9 shows a photograph of the multichannel receiver and its associated loop antenna and built in preamp. Detailed specifications for the receiver are given in Table 3-3.

An 8-channel event recorder is included in a separate chassis to monitor the sequence of recorded impulses from the receiver and thus determine which of the channels are responding to signals in a periodic fashion. Antilogarithmic amplifiers, ac coupled to the recorder inputs, are used to extract the signal impulses from the background noise. A schematic for the recorder interface circuits is shown in Figure 3-10.

TABLE 3-2

Specifications for Westinghouse Manpack Locator Model C842A

Antenna:	Air core loop, 15-inch diameter, ≈ 500 turns #22 enameled copper wire, with electrostatic shield.
Antenna Q:	Approximately 30.
Receiver Gain: (max.)	Approximately 100 dB.
Receiver Bandwidth:	3 Hz ± 2 Hz.
Frequency Accuracy:	Within ± 2 Hz of specified frequency.
Frequency Stability:	$2 \times 10^{-5} / ^\circ F$
Normal Full Scale Sensitivity:	1 μA/meter field provides approximately 1 volt into head phones.
Minimum Detectable Signal:	0.1 μA/meter*.
Temperature Range:	0° F to 120° F
Power Source:	Two 6-volt, 1 amp-hour rechargeable batteries (nominal time between charges - 20 hours.)
Total Weight: (Antenna, receiver and earphones)	Less than 10 pounds.
Receiver Case:	Approximately 5 × 4 × 2 inches with suitable belt attachments.

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* This receiver has exceeded this specification in practice. Successful measurements as low as .03 μAmp/m were obtained.

TABLE 3-2 (cont'd.)

Specifications for Westinghouse Manpack Locator Model C842A (Continued)

Operator Controls:	On-off switch and gain adjustment on receiver; antenna hand held and manually oriented for optimum signal detectability and for null location.
Frequencies:	Each receiver is capable of receiving one of the six following frequencies: 922.5, 982.5, 1700, 1900, 2500, or 2900 Hz.

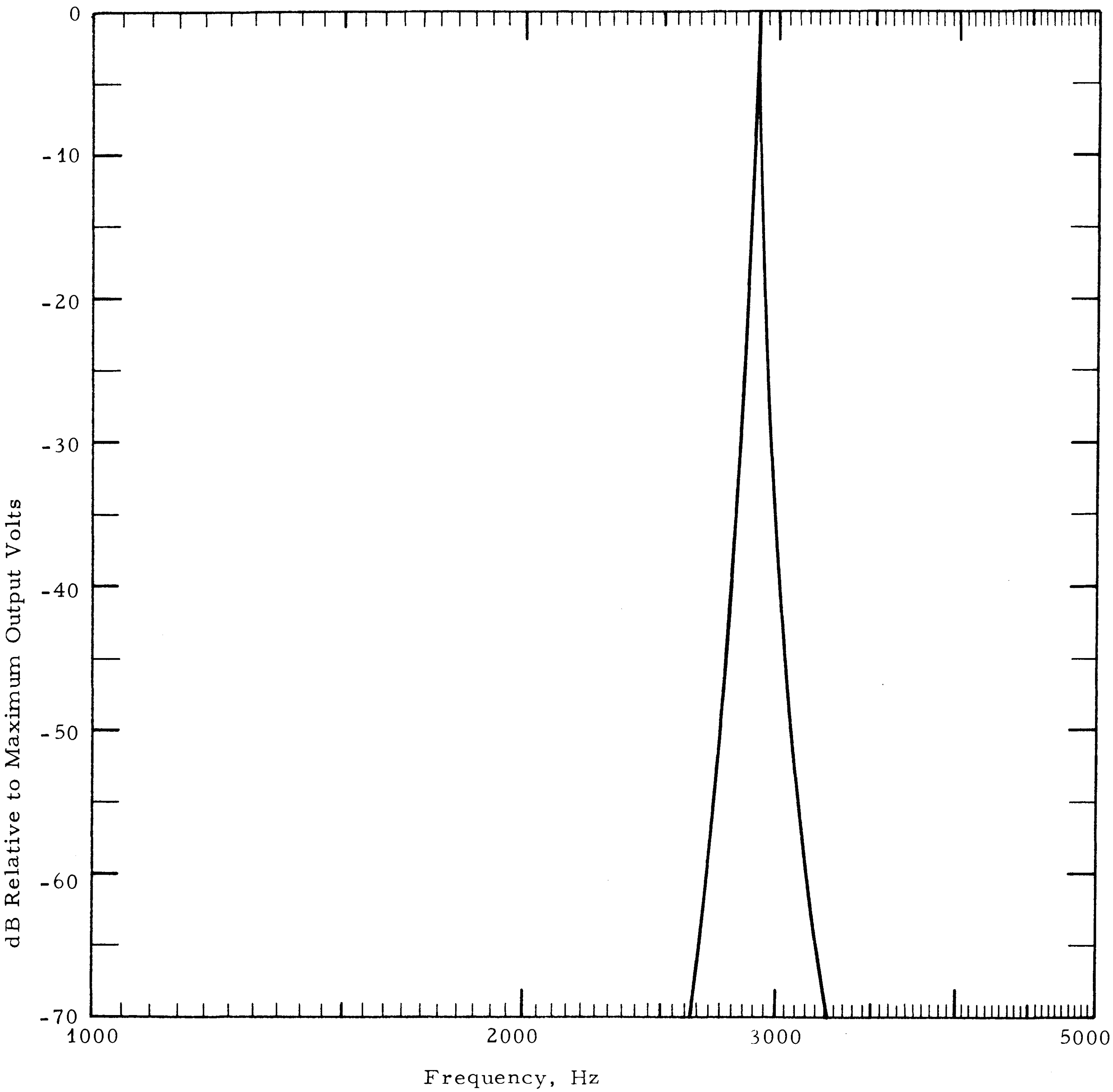


Figure 3-5a Frequency Response of Manpack Locator Model C842A

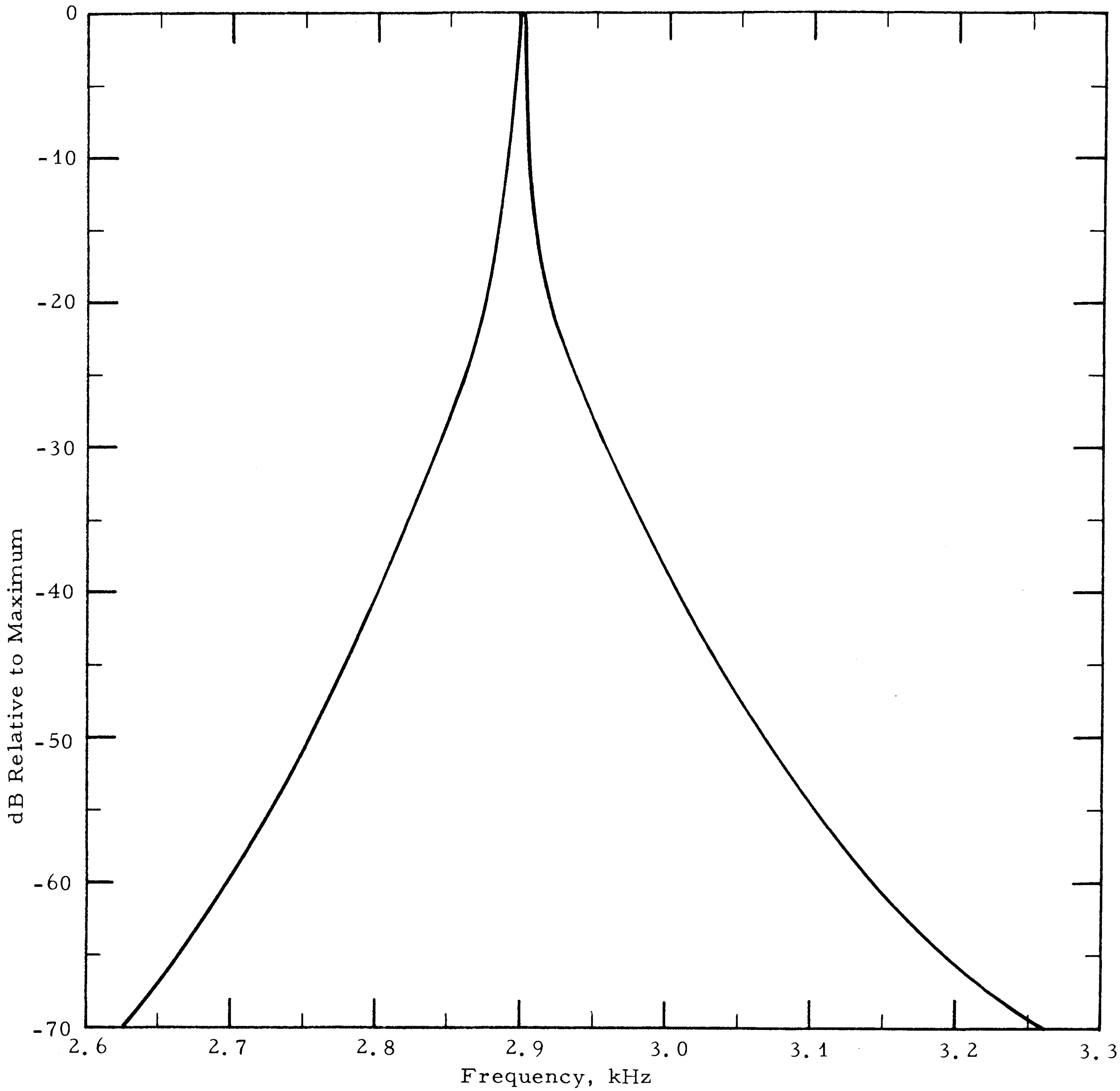
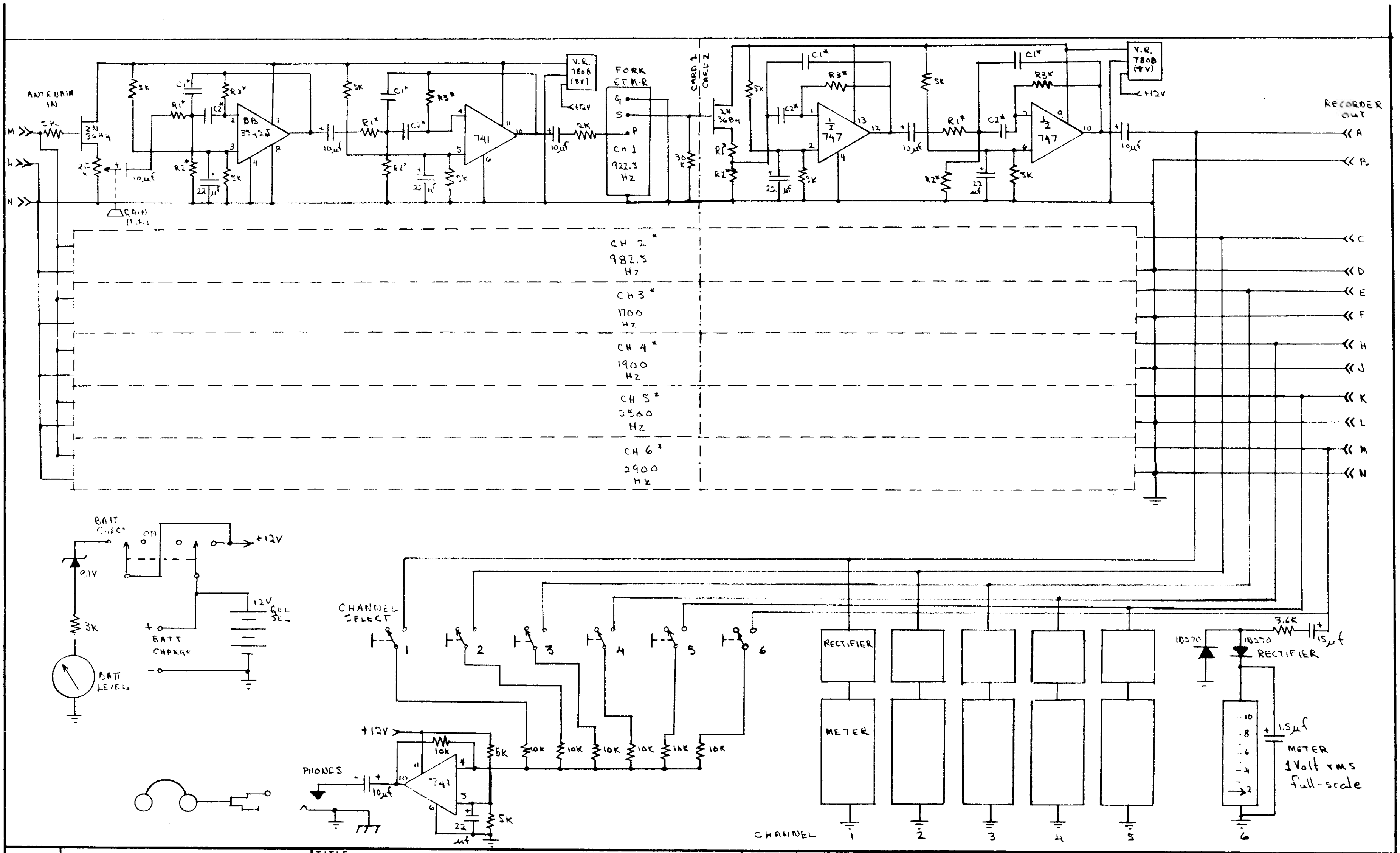


Figure 3-5b Frequency Response of Manpack Locator Model C842A

TABLE 3-3

Specifications for Westinghouse Multichannel Receiver Model C849A

Operating Frequency (all of the following):	922.5, 982.5, 1700, 1900, 2500, and 2900 Hz.
Frequency Accuracy:	± 2.0 Hz.
Frequency Stability:	$2 \times 10^{-5} / ^\circ F$
Temperature Range:	0° to 120° F
Minimum Detectable Signal:	0.1 μA/m
Bandwidth:	3 Hz ± 2 Hz at 70° F.
Output:	Crystal Earphones with jack selectable to any one or all of the six channels.
Panel Controls:	Channel Selector, individual channel gain adjust, on-off switch.
Panel Display:	Miniature Edgewide Meters for each channel.
Package Size:	Less than 240 cu. inches.
Antenna Configuration:	Air Core Loop (640 turns) with built-in wideband preamplifier at the end of a 35 ft. tethering cable.
Weight:	Less than 20 lbs. with batteries, but excluding antenna.



WESTINGHOUSE GEORESEARCH LABORATORY
8401 BASELINE ROAD
BOULDER, COLORADO 80303

TITLE
EM MULTI-CHANNEL LOCATION RECEIVER, C849A

DRAWING NUMBER
73-MIN-849-50

DRAWN BY

CHECKED BY

DATE
June 6, 1973

APPROVED BY

* RECEIVER CIRCUITRY IS THE SAME FOR ALL CHANNELS EXCEPT FOR THE VALUES OF R1, R2 AND R3. SEE ATTACHED SHEET FOR R1, R2, R3 VALUES.
C1 AND C2 ARE 0.0068µf ±5%.

Figure 3-6. EM Multi-Channel Location Receiver, Air Recon, C849A

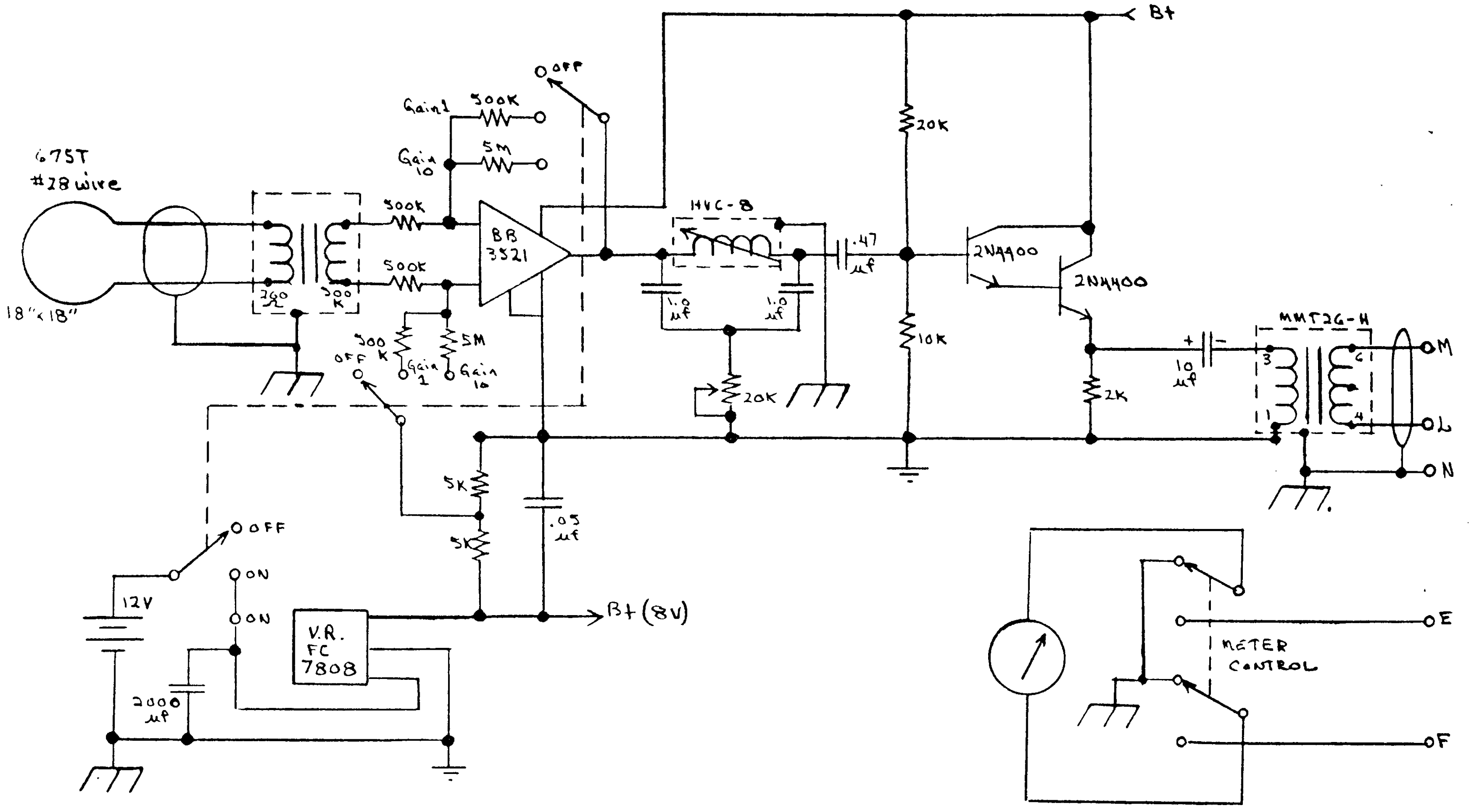


Figure 3-7

WESTINGHOUSE GEORESEARCH LABORATORY 8401 BASELINE ROAD BOULDER, COLORADO 80303	TITLE Helicopter Loop and Preamplifier, Miner Location DRAWING NUMBER	DRAWN BY GDM.	DATE May 7, 1973	
		CHECKED BY H.D.G.A.	APPROVED BY	

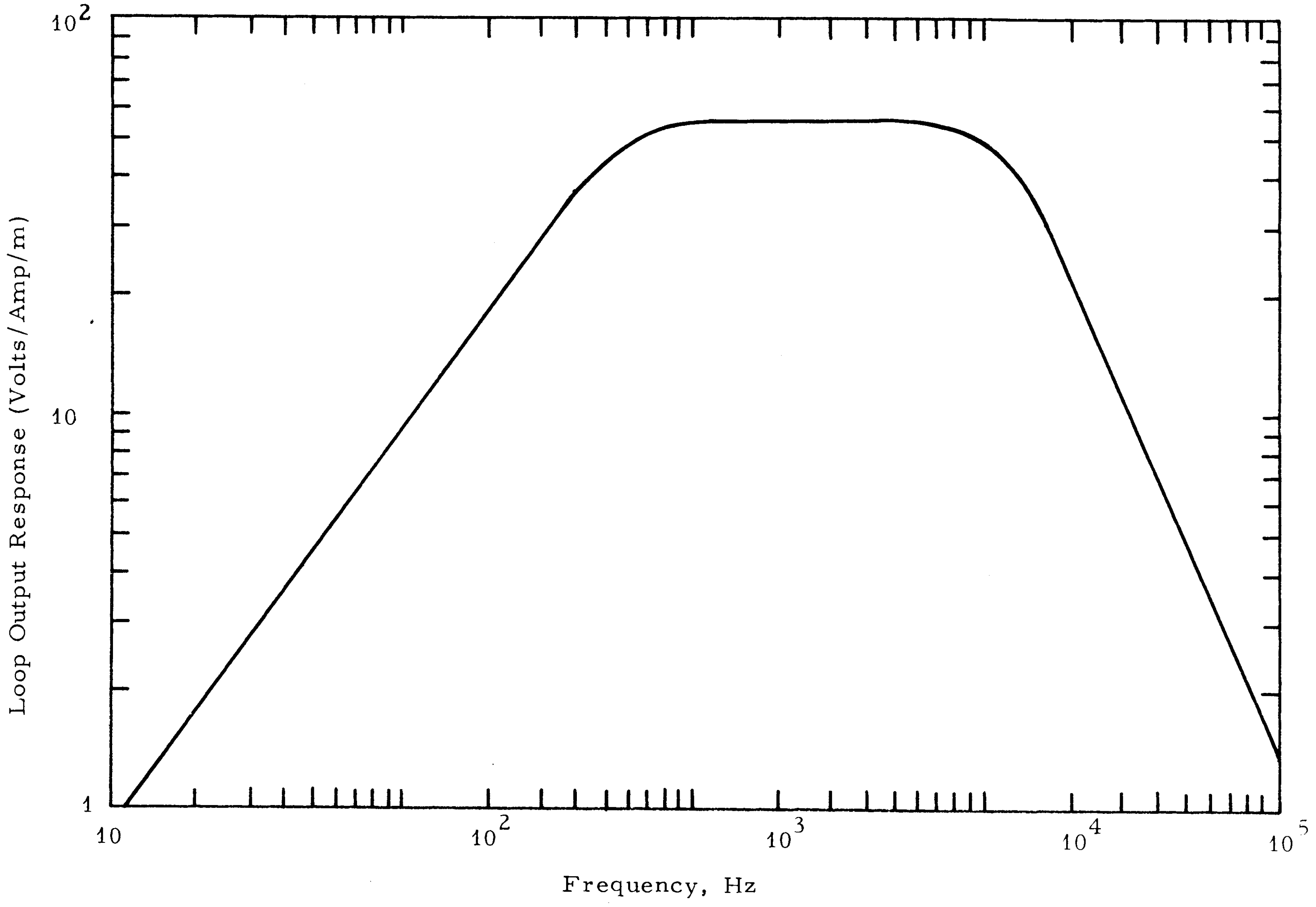


Figure 3-8 Calibration of Airborne Loop and Preamp

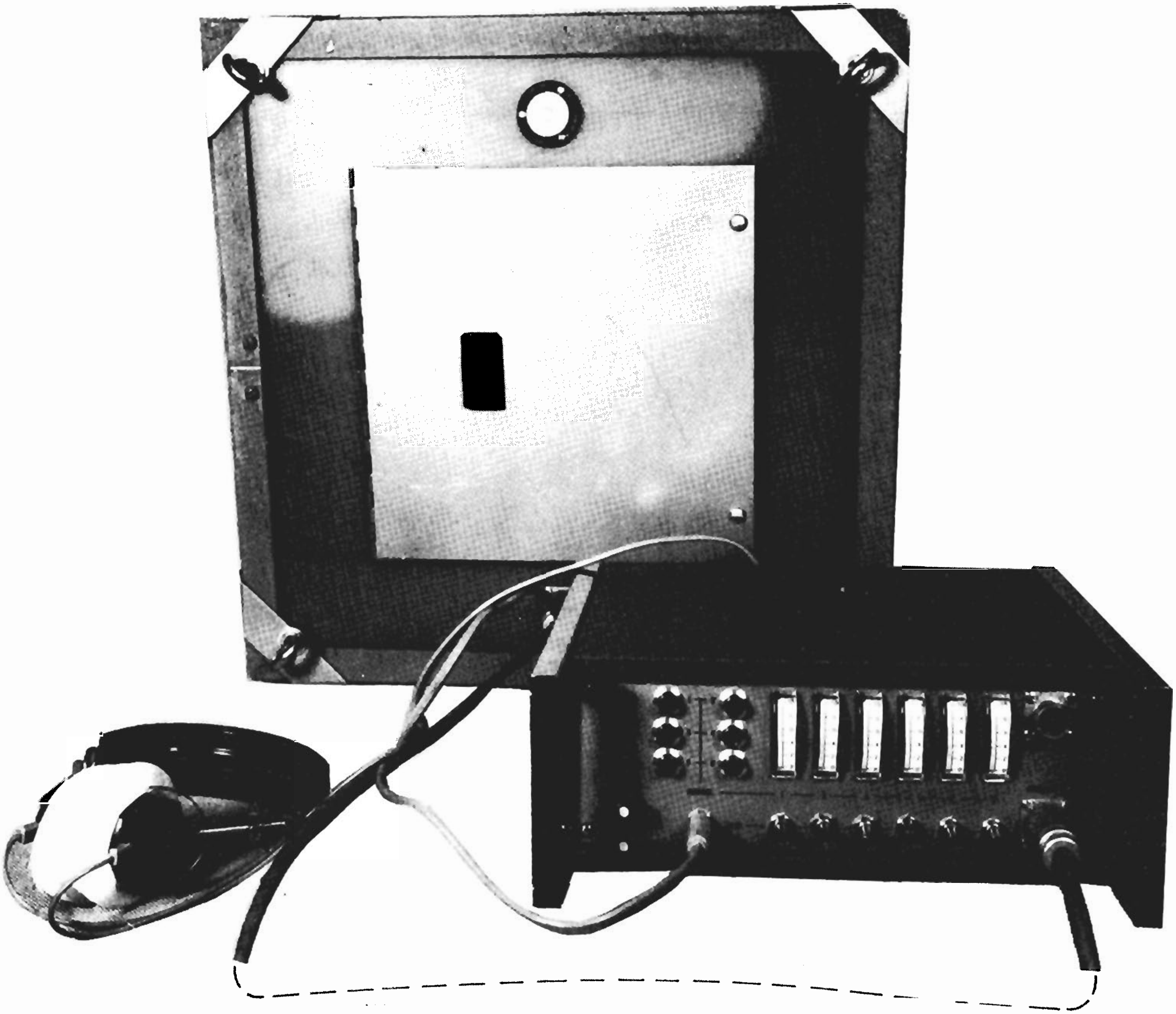
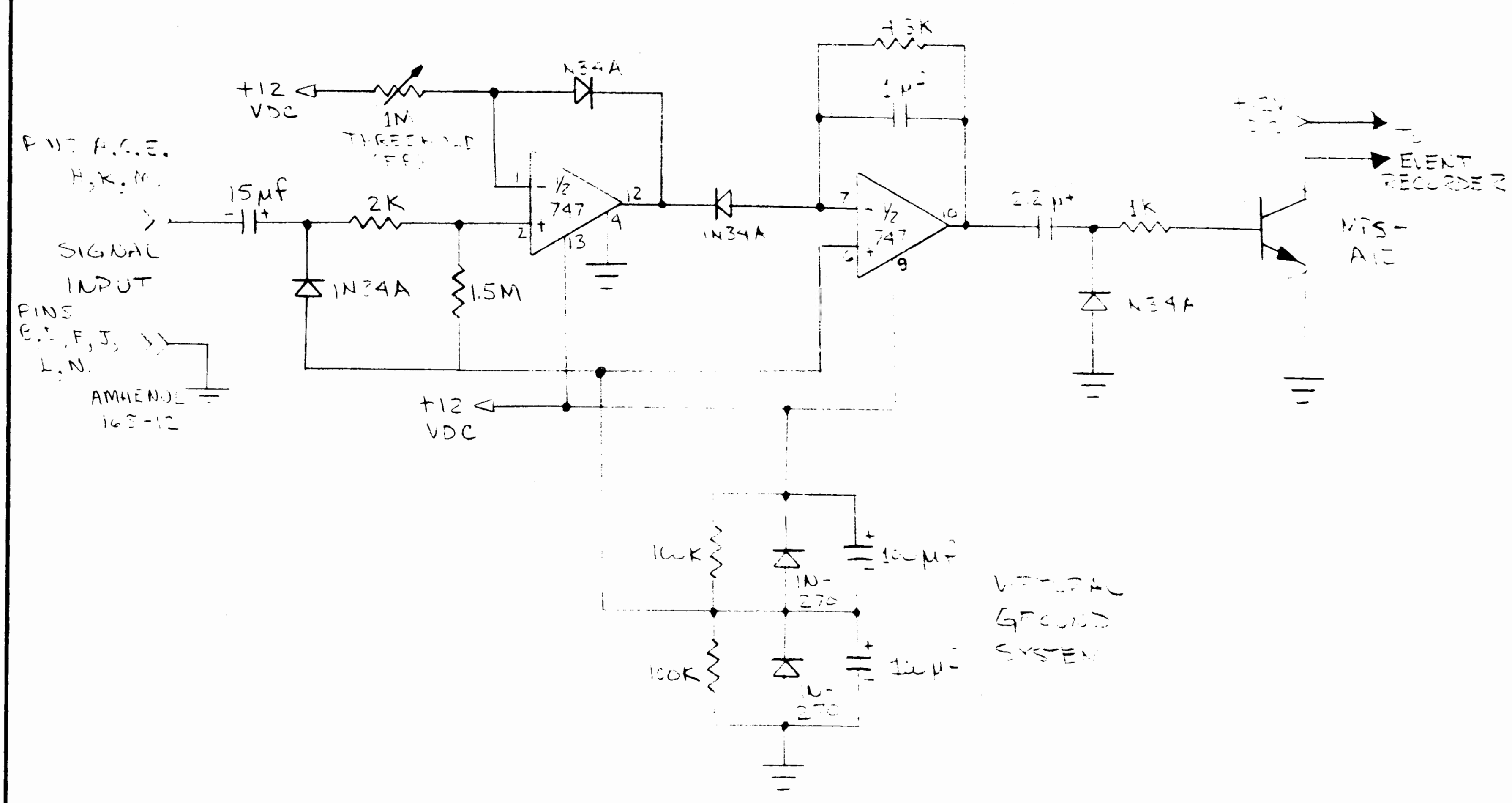


Figure 3-9 WESTINGHOUSE Multichannel Receiver, Model C849A



WESTINGHOUSE GEORESEARCH LABORATORY
8401 **BASELINE ROAD**
BOULDER, COLORADO 80303

TITLE RECORDER INTERFACE CIRCUIT

DRAWING NUMBER Figure 3-10

DRAWN BY [illegible]

DATE 7/10/73

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APPROVED BY

4.0 PERFORMANCE TESTING

4.1 Laboratory Tests

Laboratory tests included measurements of frequency accuracy and stability for both transmitters and receivers. The expected weak signals in the field necessitated systems with extremely narrow bandwidths and high gain. In order to maintain proper frequency alignment of transmitters and receivers over a wide range of environmental conditions, it was necessary to obtain the utmost stability from both transmitter and receiver circuits. The results of the frequency accuracy tests showed that all of the transmitters were within 1 Hz of their specified frequency at room temperature and typically varied less than 1 Hz away from this value over a temperature range of 0° F to 120° F. The receivers were all within 2.9 Hz of their specified frequencies, and were temperature stable to within 1 Hz deviation over the temperature range from 0° to 120° F. The resulting misalignment between transmitter and receiver was never greater than 3 Hz and proved to be more than adequate for receiving the fields at the Geneva Mine. For more stringent applications it may be desirable to include in the receiver a variable trimmer control to precisely align each receiver before going in the field.

Preliminary performance measurements were made in a field adjacent to the Georesearch Laboratory to insure that the receivers were all operating satisfactorily and that the transmitted signals could be detected at least 1500 ft. away from the source using a moment comparable to that anticipated for the actual mine tests. Each receiver was calibrated for total gain in the full scale position. The results of the receiver calibrations are given in Table 4-1. These receiver gains were used to reduce the field data from output volts to equivalent μAmps/m of field strength.

TABLE 4-1

Gain Calibration of Manpack Receivers

Frequency (Hz)	Ser. No.	Current (Amps)	d	H_z (μA/m)	V_{out}	Gain V/Amp/m
922.5	002	.2	10 m	1.06	1.38	1.3×10^6
982.5	003	.2	10 m	1.06	1.38	1.3×10^6
1700	004	.02	10 m	.106	.75	7.1×10^6
1900	005	.02	10 m	.106	.39	3.67×10^6
2500	006	.05	10 m	.265	1.2	4.5×10^6
2500	007	.05	10 m	.265	1.2	4.5×10^6
2900	008	.02	10 m	.106	.85	8.0×10^6

4.2 Field Tests

The Geneva Coal Mine, operated by U. S. Steel Corp. near Dragerton, Utah was chosen for the test mine because of its high conductivity and deep overburden. The combination of these two characteristics make this mine an ideal test bed for determining performance limitations of the system.

4.2.1 Description of Field Site

The Geneva Mine is located at the north edge of Emery County, in east-central Utah, about eight miles southwest of Dragerton, Utah. The mine is developed in the extensive Book Cliffs coal field, in which bituminous coal occurs in the Mesaverde group of Upper Cretaceous Age. The Book Cliffs are a prominent physiographic feature in central and eastern Utah, and extend into western Colorado. In the local area of this report, the cliffs form a southwest-facing escarpment with about 2000 feet of topographic relief. The rocks at the base of the escarpment are Mancos shale, an even-bedded marine shale which erodes faster than the relatively more resistant rocks of the overlying Mesaverde group and the younger (Tertiary) rocks overlying the Mesaverde. The coal occurs in the Blackhawk formation, the basal unit of the Mesaverde. The Blackhawk is divided in this locality into a basal marine sandstone, and overlying mixed marine and continental units which contain the coal seams. The continental sandstones in the Blackhawk and the overlying Price River formation (upper part of Mesaverde group) are discontinuous channel sands characteristic of fluviatile deposits [4, 5]. The major coal seams are the Upper and Lower Sunnyside seams. The unit being mined at the Geneva Mine is the Lower Sunnyside seam, which has a thickness at this location of about 14 feet [6].

The portal of the Geneva Mine is at an elevation of 6400 feet in Horse Canyon. The tests performed by the Westinghouse Georesearch Laboratory were conducted within an area of about 5000 feet by 7000 feet, mostly in S½-3-T16S-R14E (see Figure 4-1)*. The workings extend to the east and southeast under a portion of the Book Cliffs known locally as Lila Point. The relatively flat portion of Lila Point has a surface elevation of 7500 feet. The mine workings slope downward to the north and east at about 500 feet per mile, following the regional dip of the Blackhawk formation. The strike of the beds is about N21° W, according to the U. S. Steel mine maps. The terrain is extremely rugged with sharp mountain peaks, shear cliffs and deep canyons. A typical terrain profile is given in Figure 4-2 showing the unexaggerated elevation change with horizontal distance for a straight line cross section proceeding 21° NE from the exhaust fan in Lila Canyon. The average slope of this profile is about 30°.

The overburden depth where this terrain profile intersects the road is about 1100 feet. In general the overburden depths for the transmitter-receiver locations used in the Geneva Mine tests varied from 1100 ft. to 1650 ft.

Extensive ground conductivity surveys were run over this mine during the previous visit by Westinghouse personnel and were not repeated during these tests. The conductivity sounding used to obtain the initial average conductivity estimate of 2.7×10^{-2} mhos/m is shown in Figure 4-3. A layer interpretation was made on the conductivity sounding which shows the high conductivity material to be near the surface with a much lower conductivity material down at the mine level. This is to be expected since coal seams generally exhibit low conductivity. The effective horizontal layer interpretation indicates a surface layer about 7 meters thick with a conductivity of 1.1×10^{-1} mhos/m, an underlying layer approximately 150 meters thick with a conductivity of 3.5×10^{-2} mhos/m and a basement layer having a conductivity of approximately 7×10^{-3} mhos/m. In terms of average overburden conductivity, for the shallow overburdens of 1100 ft., the average conductivity is about 2.1×10^{-2} mhos/m and for the deeper overburden of 1650 ft., the average conductivity is approximately 1.7×10^{-2} mhos/m.

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* Transmitters were installed at locations (A_1, A_2, B_1, B_2, C_1, D_1) with antennas deployed around the coal pillars shown in black on Figure 4-1.

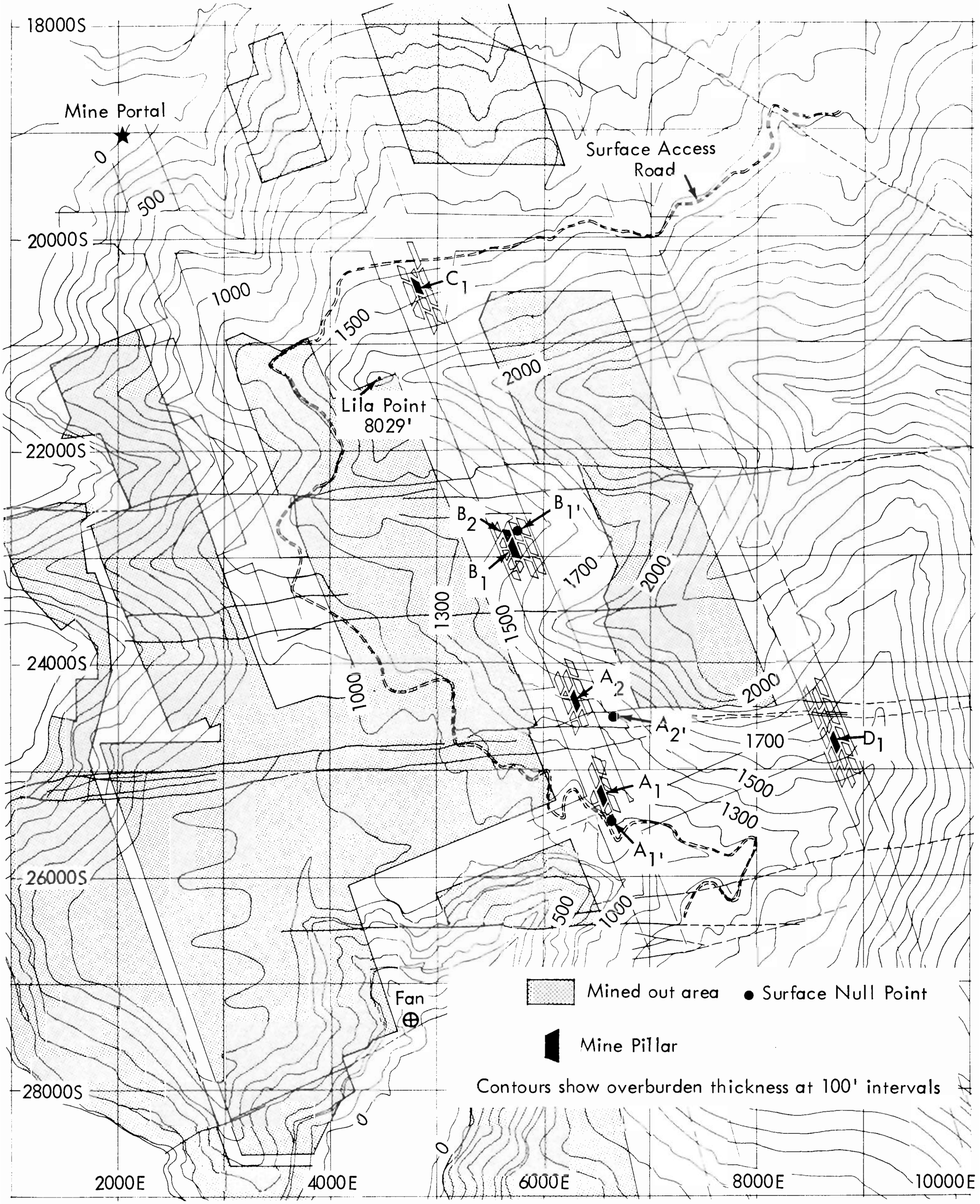


Figure 4-1. Map of Geneva Mine Transmitting Locations

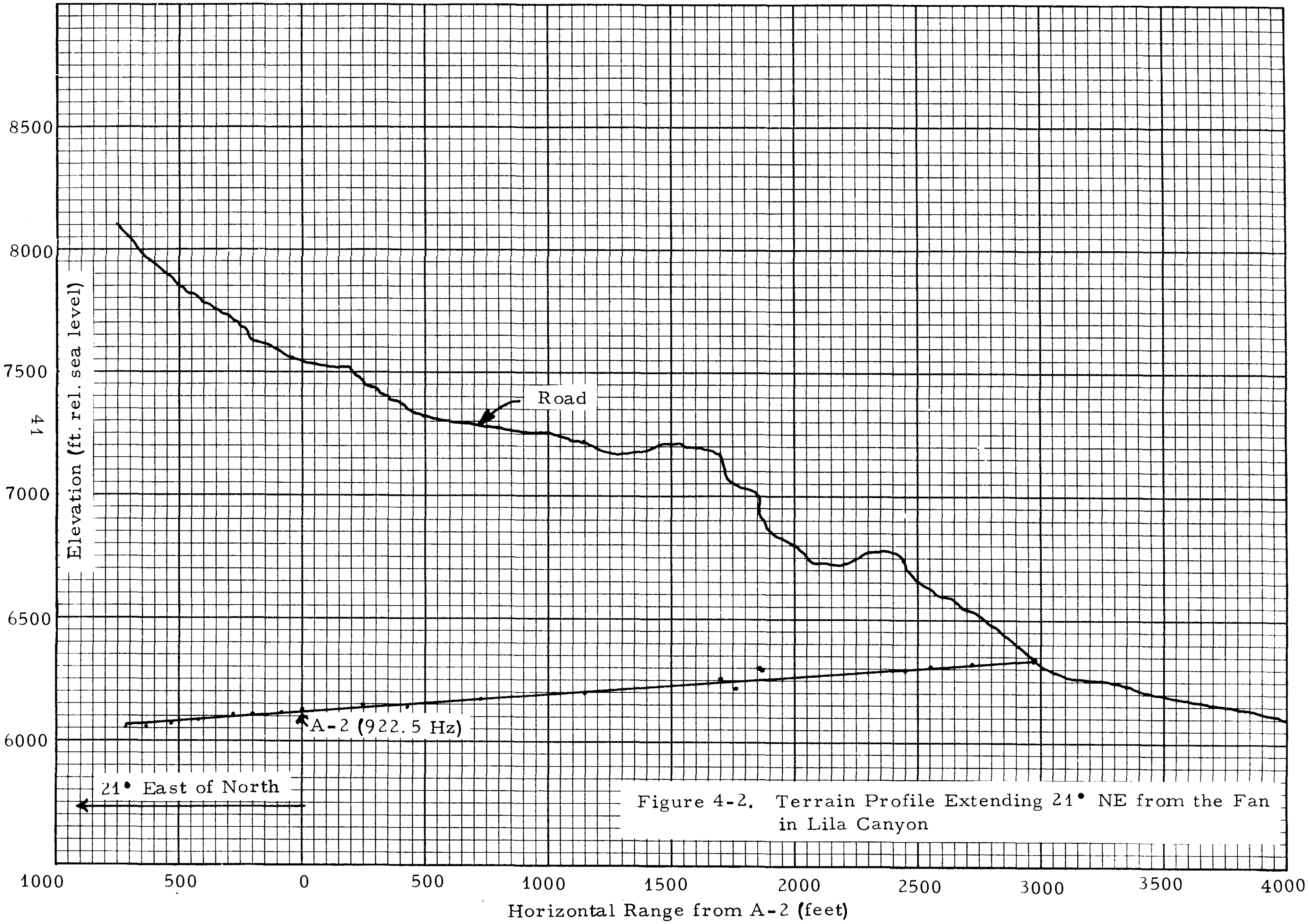


Figure 4-2. Terrain Profile Extending 21° NE from the Fan in Lila Canyon

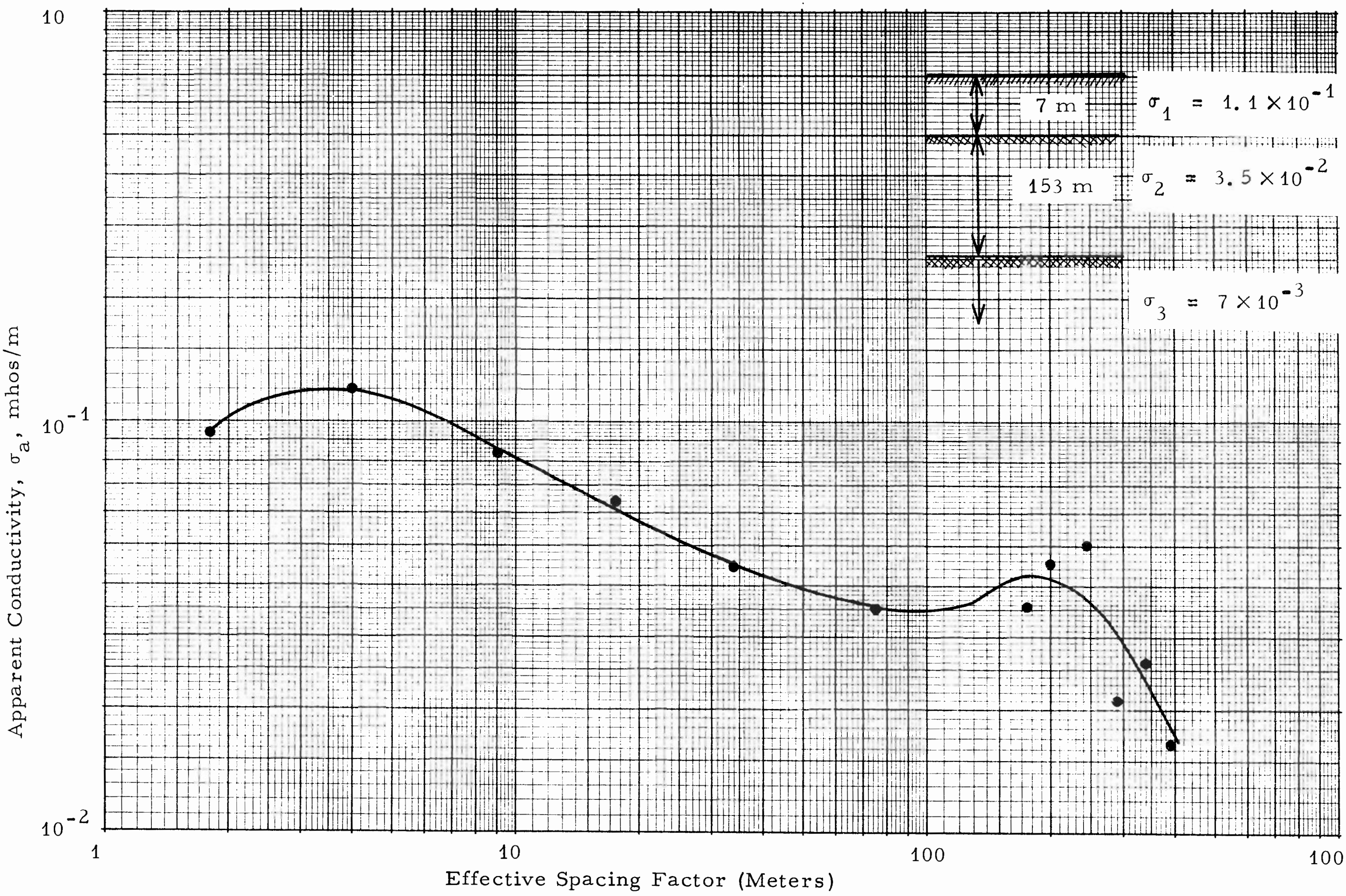


Figure 4-3 Conductivity Sounding, Geneva Mine

4.2.2 Surface Tests

The surface tests conducted at the Geneva Mine included: (1) magnetic field profile measurements using manpack locator with portable oscilloscope (Tektronix 211), (2) magnetic tape recordings of manpack locator and multichannel receiver outputs for laboratory signal analysis and (3) EM location determination by null technique and comparison with surveyed location. The trapped miner location problem consists of two phases: (1) detection of airborne and surface signals from the underground transmitters, and (2) analysis of the resulting field patterns to determine most likely location of source. The results of the Geneva Mine tests were encouraging from the standpoint of detection range and capability; however the null locations were not as accurate as those obtained previously in shallower mines.

Magnetic Field Profiles

Figures 4-4 and 4-5 show orthogonal field profiles of vertical and horizontal magnetic field strengths measured about the estimated horizontal field null point for a 2500 Hz transmitter installed at A-1. It is immediately apparent in these figures that the horizontal field null is much deeper in the NW-SE line (Figure 4-4) than it is in the NE-SW line (Figure 4-5). This is partly attributed to the fact that the transmitting antennas were deployed around large quadrilateral pillars of dimensions roughly 70 feet by 180 feet. The deeper null in the horizontal field was observed for that profile (NW-SE) cutting across the smaller dimension of the rectangle. The average hill slope of this location was 22° in the NE/SW direction. The uncorrected null point at this location was about 200 feet downhill from the true location. This was a larger offset than was experienced at the shallower and lower conductivity mines previously visited in the east. Part of this can be attributed to the fact that conductivity anomalies have a much greater influence on the EM field readings at Geneva than at the eastern coal mines because the propagation path in terms of skin depth is much greater. Figure 4-6 shows skin depth penetrations of from 5 to 8 at Geneva while most of the

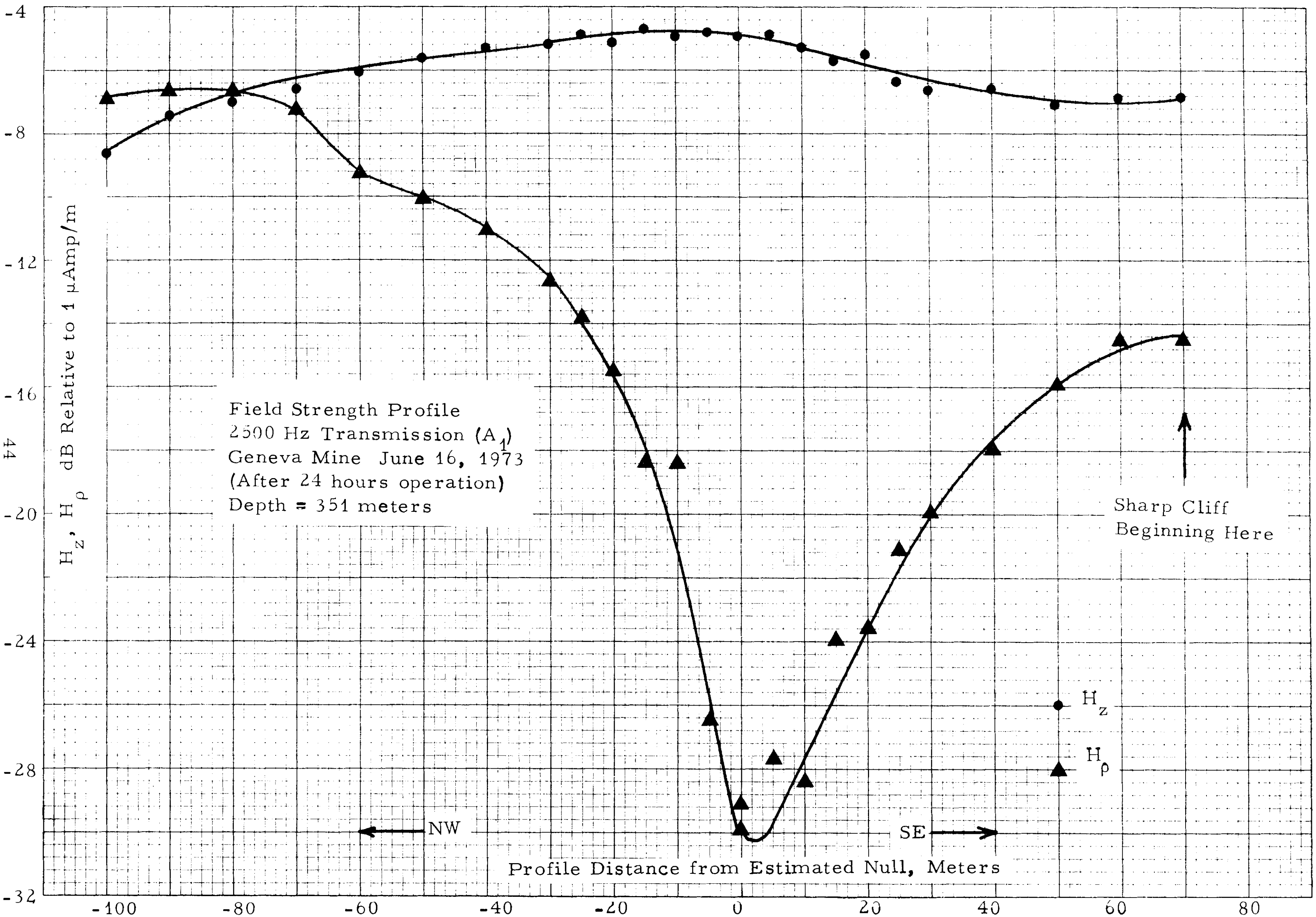
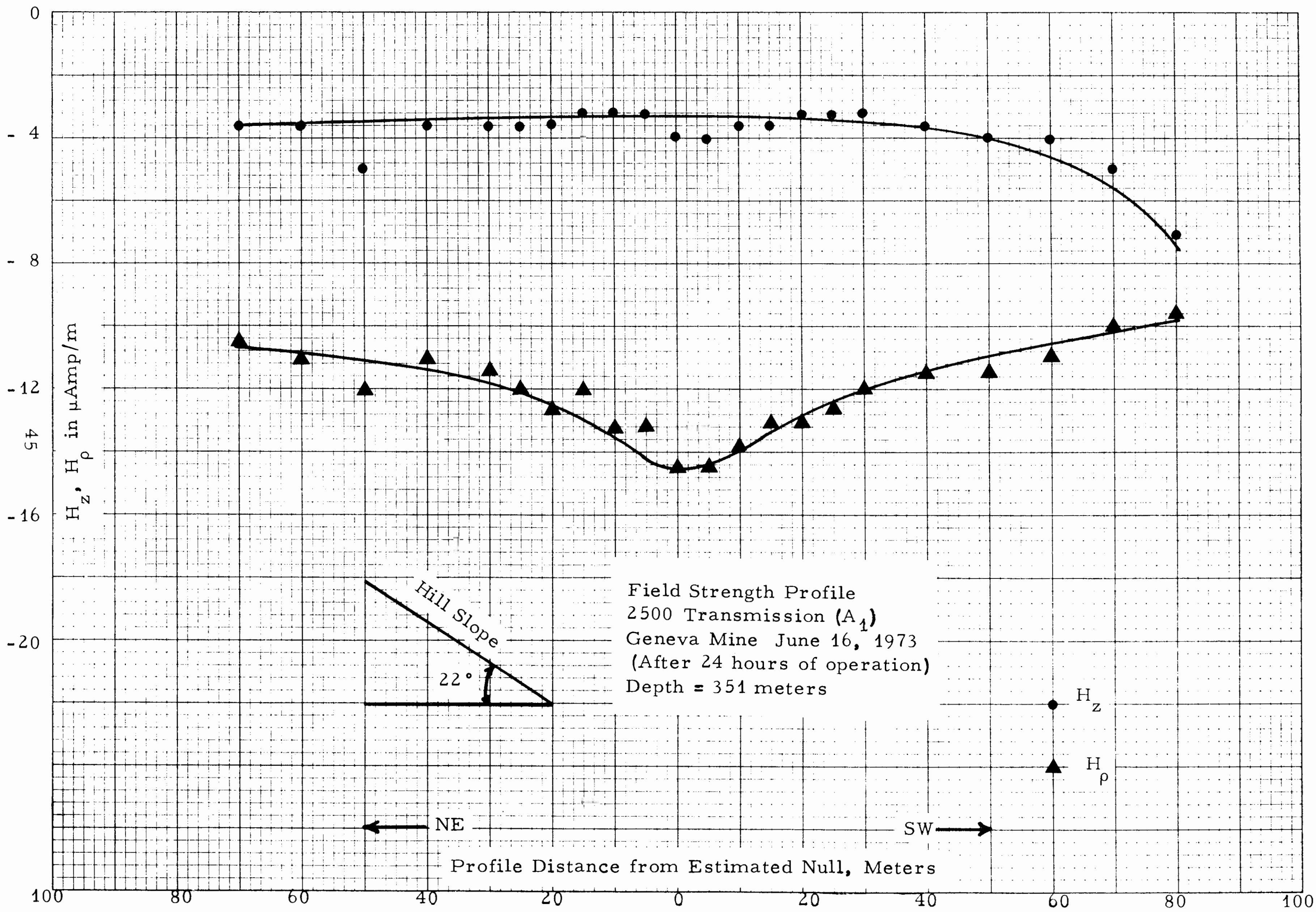


Figure 4-4 Magnetic Field Profile of 2500 Hz Transmission at A_1 (NW-SE)



Field Strength Profile
2500 Transmission (A_1)
Geneva Mine June 16, 1973
(After 24 hours of operation)
Depth = 351 meters

Figure 4-5 Magnetic Field Profile of 2500 Hz Transmission at A_1 (NE-SW)

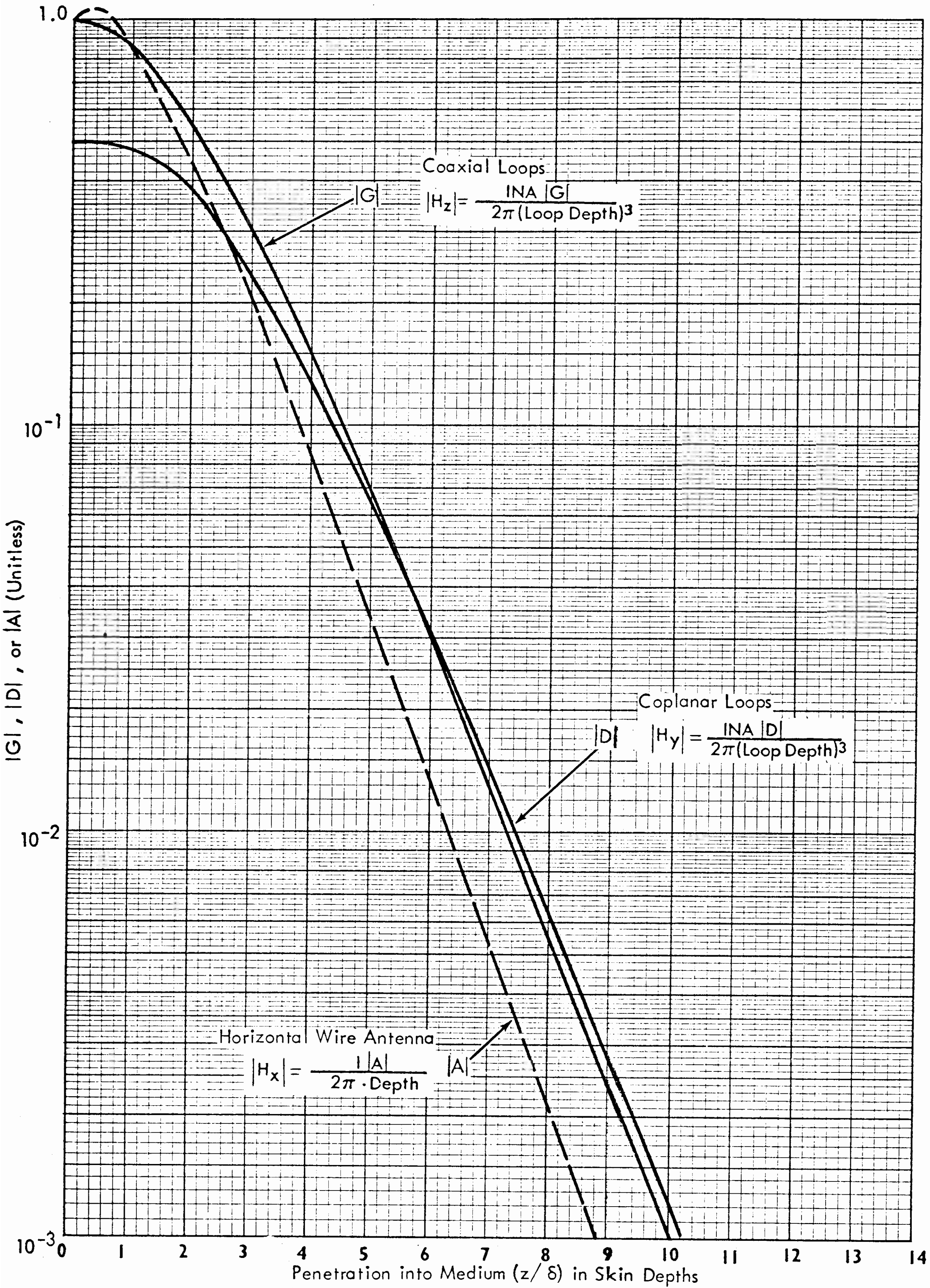


Figure 4-6 Loop Antenna and Horizontal Coupling Relationships

eastern mines had equivalent overburden depths of less than 1 skin depth.

Figures 4-7 and 4-8 show the corresponding field profiles obtained at the same location, except the 2500 Hz transmitter was replaced by a 982.5 Hz transmitter. Again the deep null is observed in the NW/SE direction consistent with transecting the short dimension of the source antenna. The measured field strength at 982.5 Hz is 4 to 5 dB higher than at 2500 Hz as expected. The location determined by the 982.5 Hz transmission was about 25 meters closer to the actual location than the 2500 Hz as slope correction theory indicates.

Figures 4-9 and 4-10 show field profiles obtained at 1900 Hz at location B_1 with an overburden depth of 1500 ft (457 meters). Calculated profiles, shown as dashed lines on these figures, compare favorably with the measured data for the horizontal field (H_ρ) in Figure 4-9, and are generally low by 5 to 8 dB for the other field components. Most of these discrepancies, however, can be attributed to the unsuitability of the continuous uniform hill slope model for the irregular terrain of the Geneva Mine. The data obtained for the horizontal field in the vicinity of the null point is contaminated by background noise since the signal levels were relatively weak for this overburden depth. These measurements did show that the receiver was capable of detecting signals well below the specified sensitivity of 0.1 μA/m (-20 dB rel to 1 μA/m).

Extended field profiles out to a distance of 550 meters in the southwest direction were also made at B_1 for frequencies of 1900 Hz and 982.5 Hz. (See Figures 4-11 and 4-12). It is interesting to note the similarity of the shape of these profiles and in particular the vertical field (H_z) nulls occurring for both frequencies at a distance of 200 meters. According to Wait [7], a null in H_z is to be expected. In the limiting case, under static field conditions, this null should be quite pronounced and should occur at a horizontal distance of 1.4 mine depths away from the source location. However, at progressively higher frequencies, this null should become less pronounced and its distance from the source location also decreases. Based on Wait's curves, for the present conditions the null should occur at a distance of 274 meters for f = 982.5 Hz and 229 meters for f = 1900 Hz. However his curves also indicate that

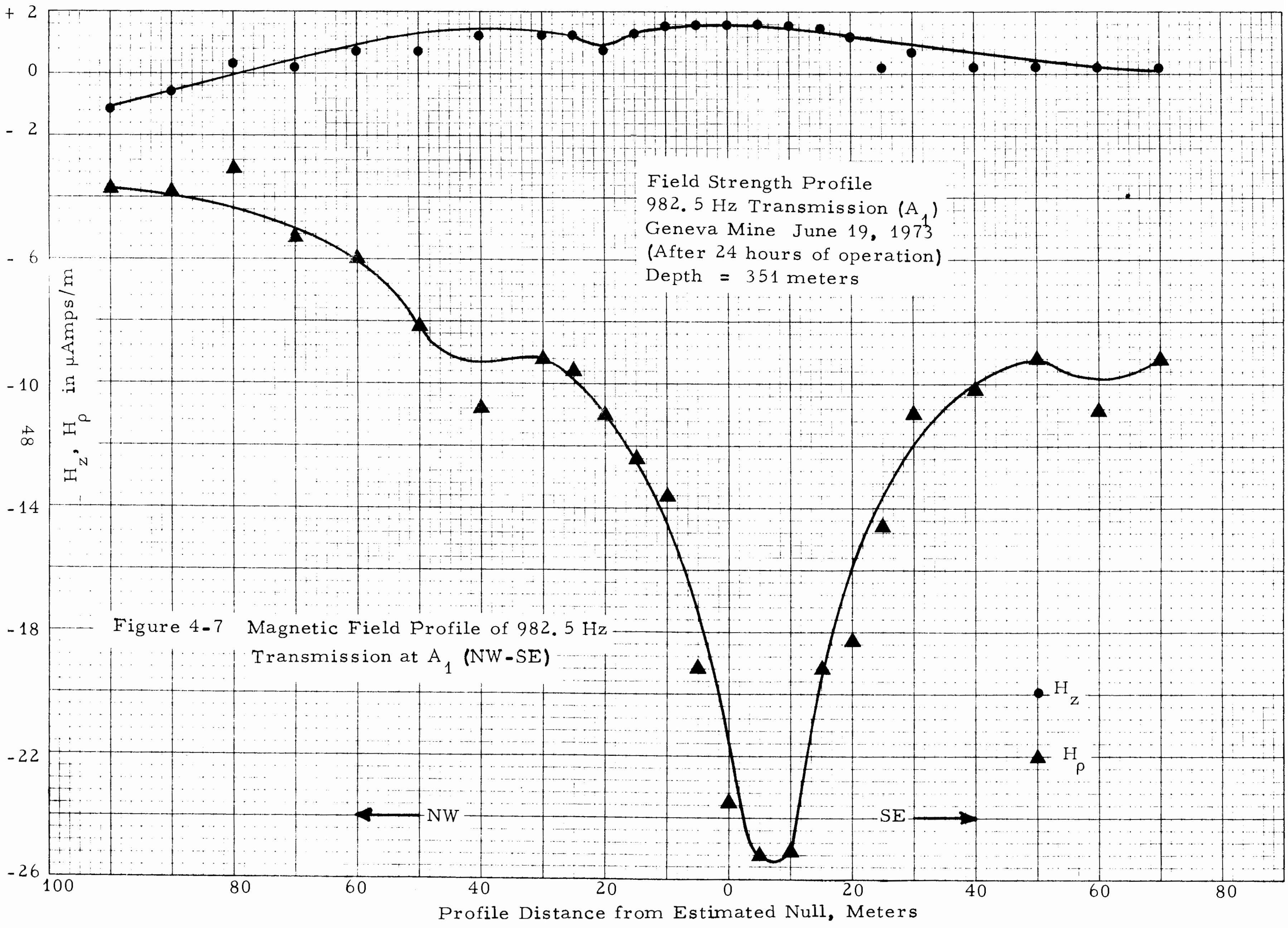
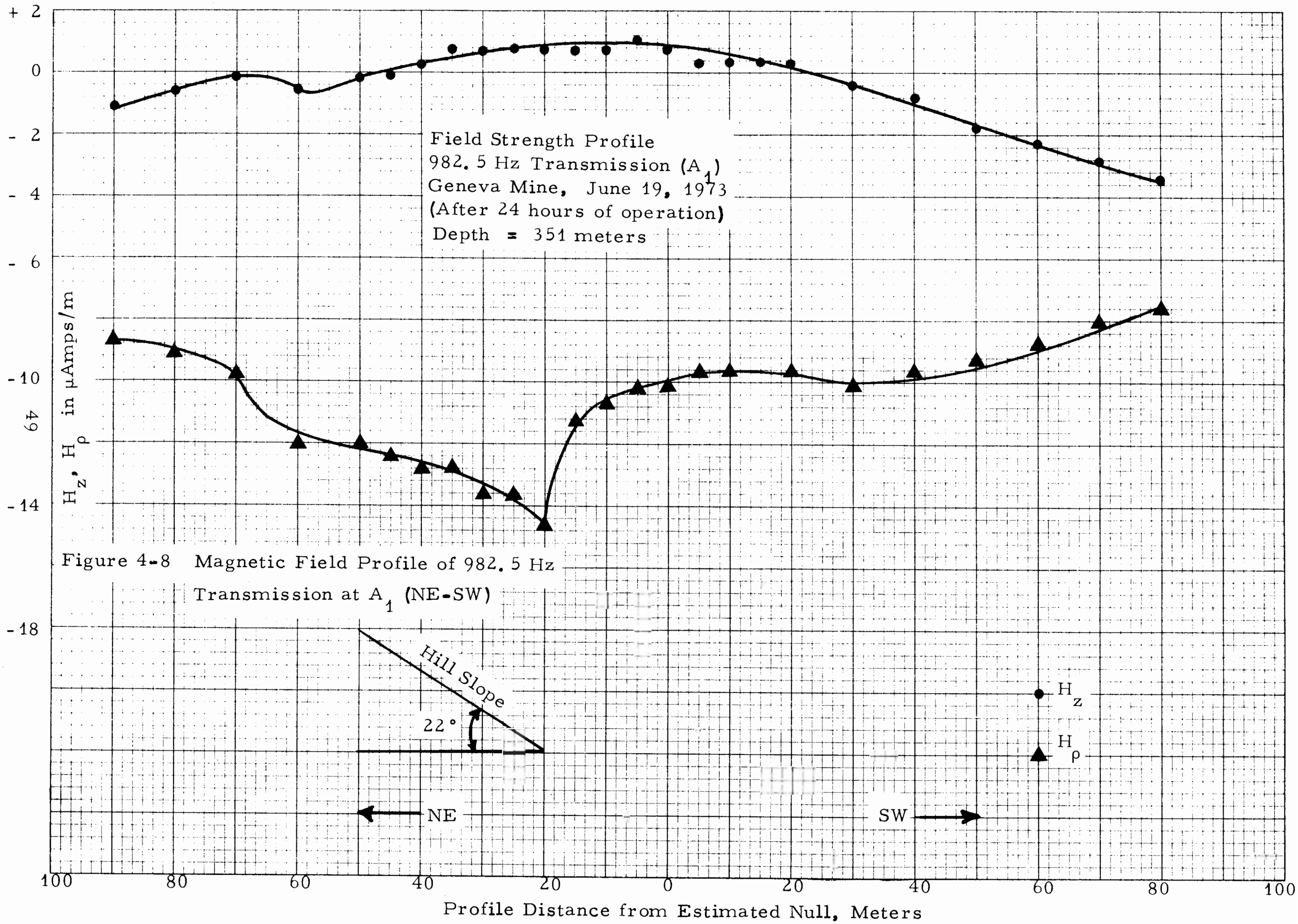


Figure 4-7 Magnetic Field Profile of 982.5 Hz Transmission at A_1 (NW-SE)



Field Strength Profile
982.5 Hz Transmission (A_1)
Geneva Mine, June 19, 1973
(After 24 hours of operation)
Depth = 351 meters

Figure 4-8 Magnetic Field Profile of 982.5 Hz Transmission at A_1 (NE-SW)

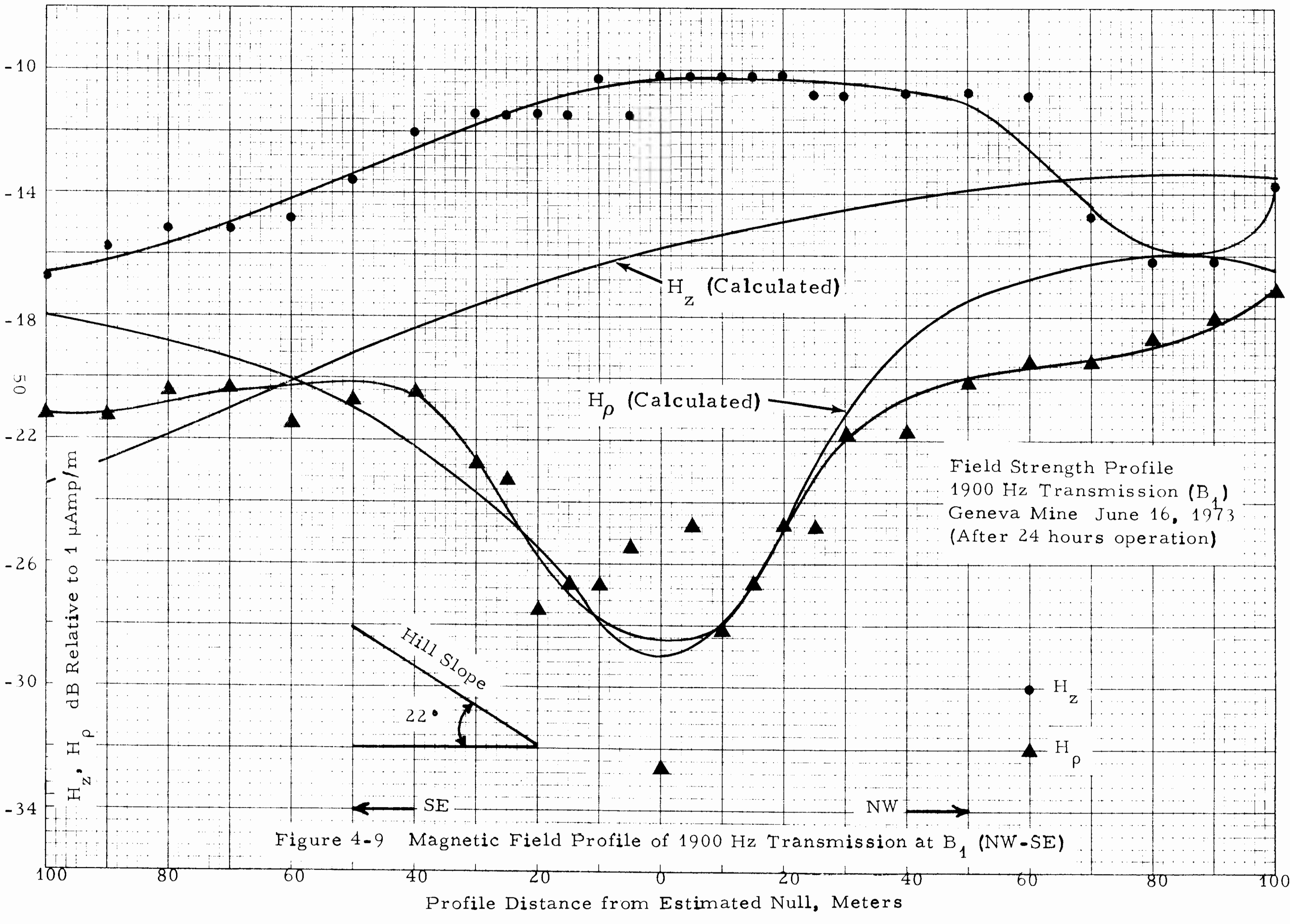


Figure 4-9 Magnetic Field Profile of 1900 Hz Transmission at B_1 (NW-SE)

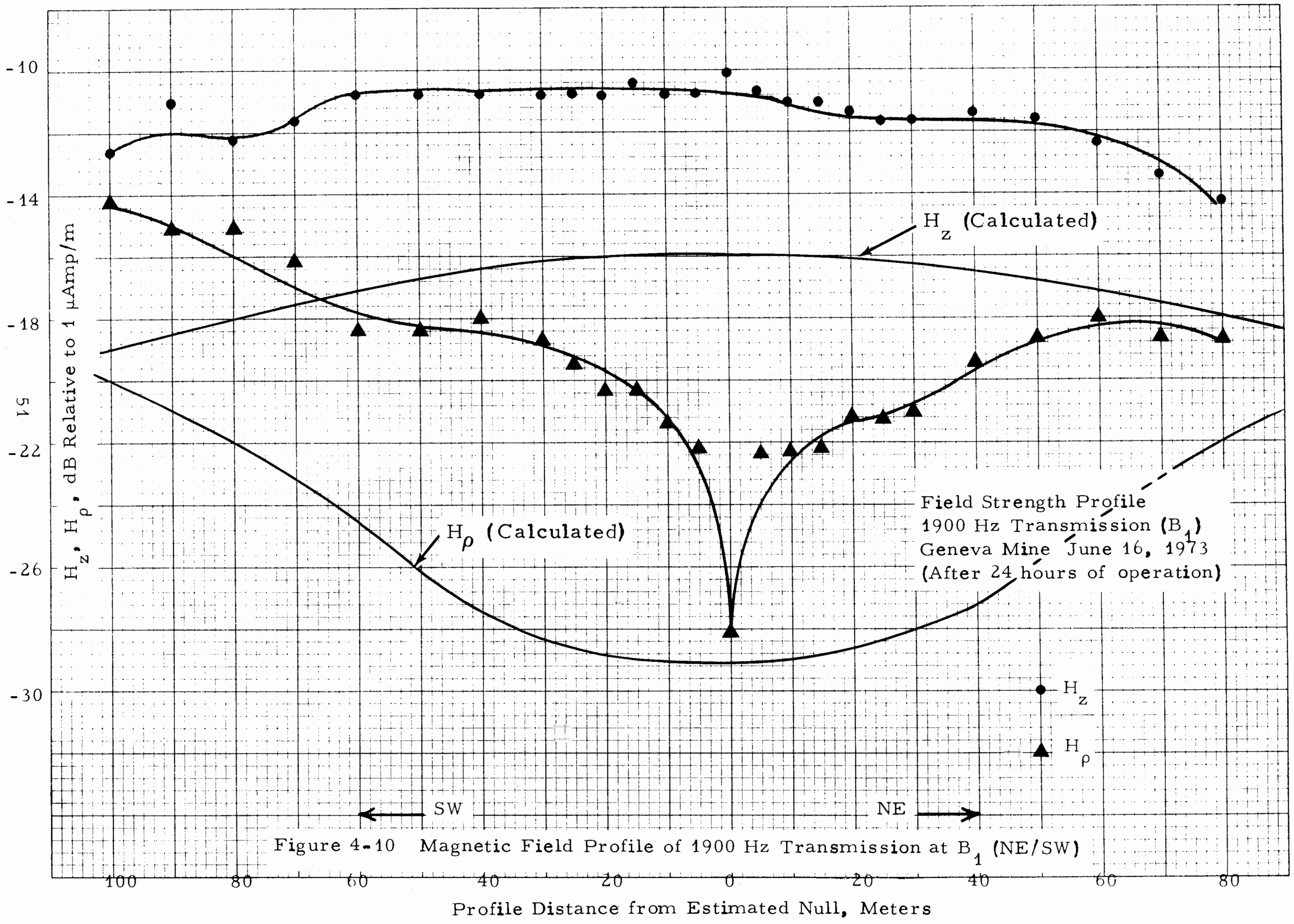


Figure 4-10 Magnetic Field Profile of 1900 Hz Transmission at B_1 (NE/SW)

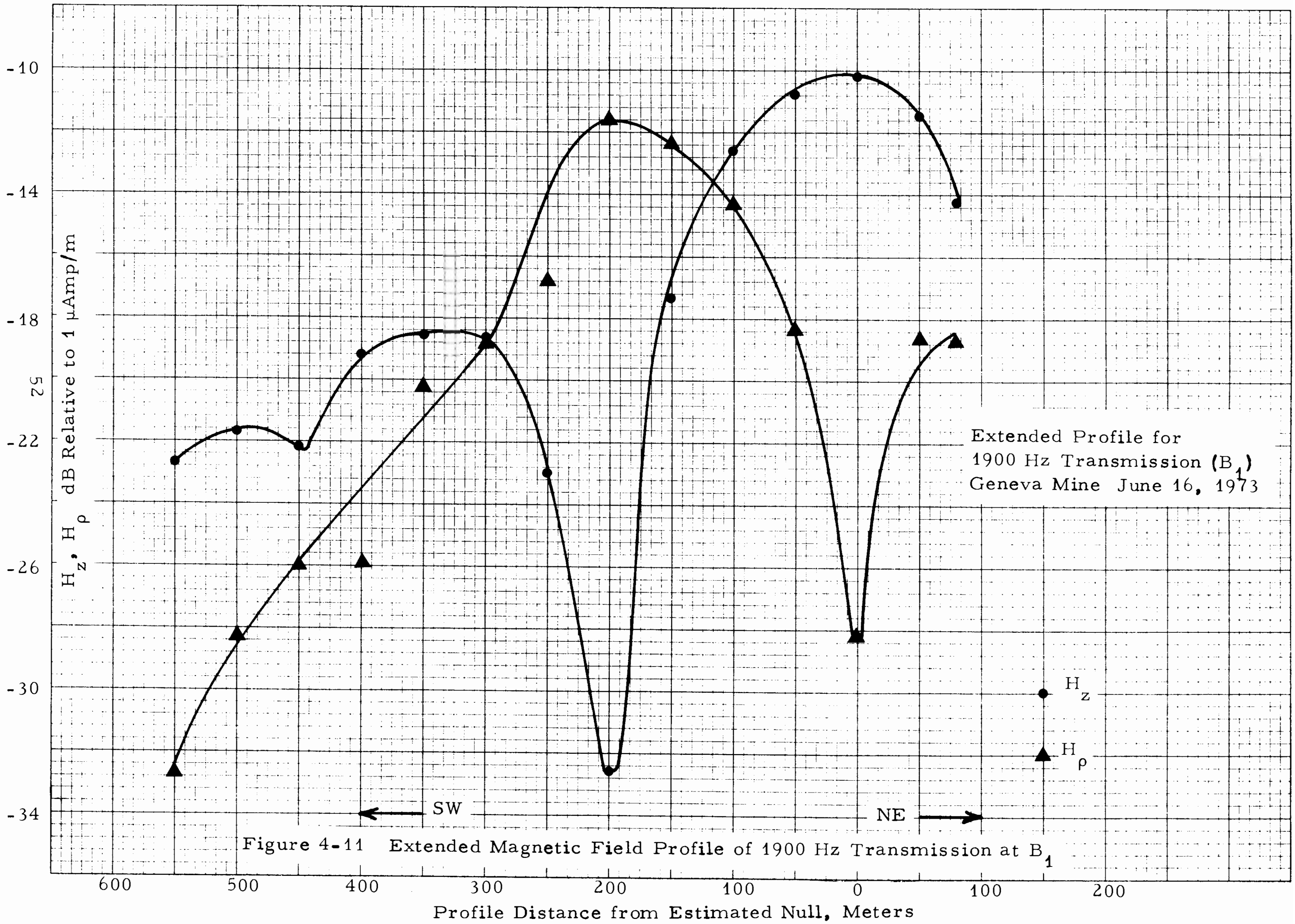


Figure 4-11 Extended Magnetic Field Profile of 1900 Hz Transmission at B_1

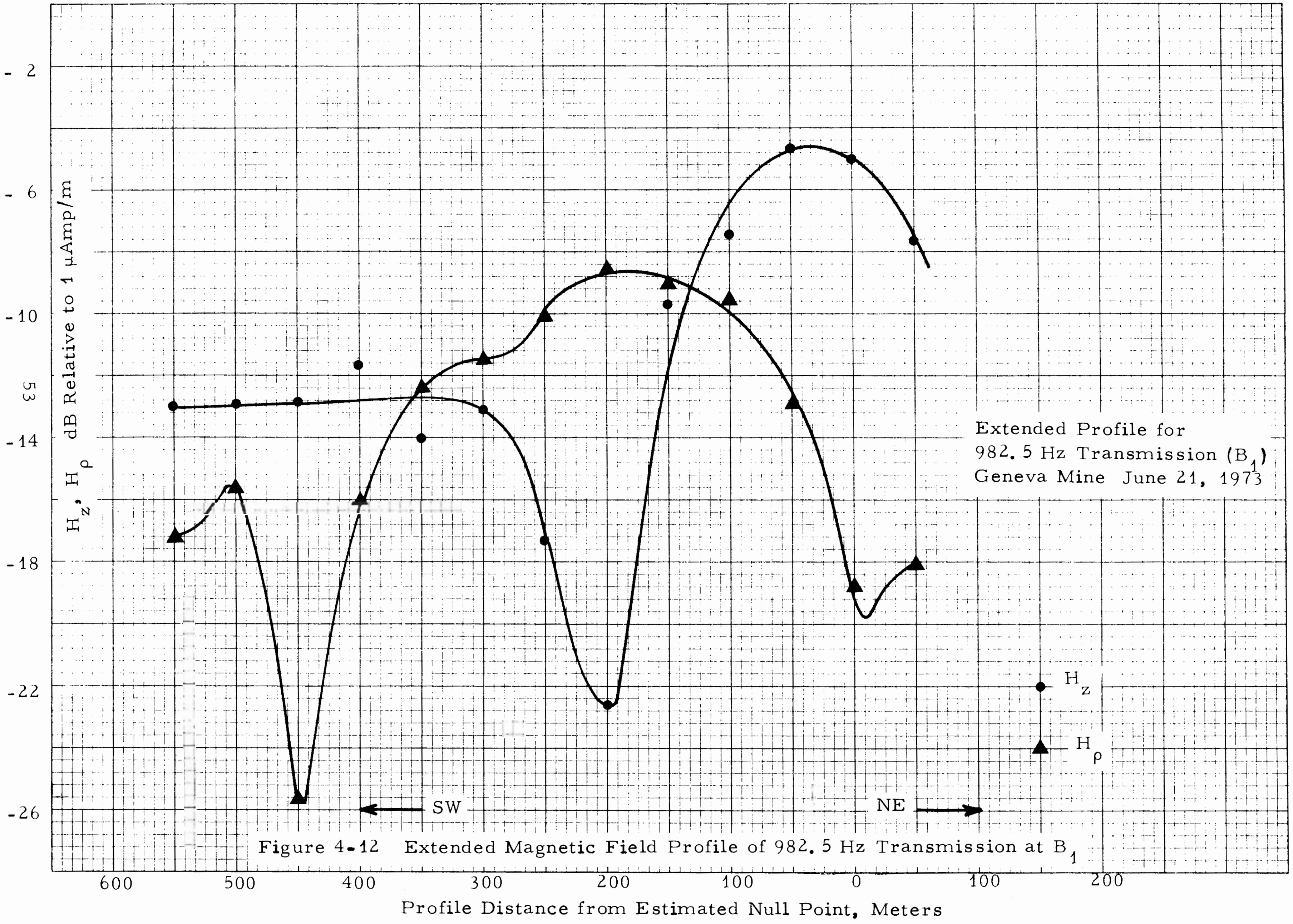


Figure 4-12 Extended Magnetic Field Profile of 982.5 Hz Transmission at B_1

the nulls should be almost indistinguishable for these frequencies and overburden conditions. This does not agree with our observations in that the measured nulls were very well defined. Note also that in Figure 4-12 there is a secondary null in the horizontal field at a location of 450 meters from the source. This coupled with a corresponding secondary peak in the vertical field could result in determining a false location at this point. Further investigations should be made to better define the field profile behavior at greater distances from the source and under rough terrain conditions.

Location Accuracy

The locations determined from magnetic field profiles at the Geneva Mine were not as accurate as those obtained earlier at shallower and less conductive eastern coal mines. Part of the increased offsets observed can be attributed to a general increase in scale brought on by a larger antenna dimension and an increased overburden depth over any used in previous mine tests. Also, the increased conductivity of this mine overburden produced a situation where the field strength became much more sensitive to local conductivity anomalies than had been experienced at eastern mines. The resulting location accuracies determined from the Geneva Mine tests are shown in Table 4-2. For signals that were easily detectable, the locations were accurate to within three hundred feet. At locations C_1 and D_1 where the signals were somewhat marginal, the locations were difficult to determine because of poor signal to noise ratios. No location was obtained at C_1 even though signals at frequencies as high as 1700 Hz could be detected there. At D_1 an attempt was made to determine its location even though the signal was marginal; this location proved to be 700 feet off the surveyed point. Hill slope corrections were not applied but would have brought the locations closer since all of the offsets were down hill from the surveyed points. Since the transmitting antennas were wound around pillars of dimensions 70 ft. × 180 ft., the location accuracies obtained were mostly within 1 pillar length away from the actual transmitter locations and as such do provide useful information from a mine rescue standpoint.

TABLE 4-2

Location Accuracy

Map Designation	Frequency	Hill Slope	Uncorrected Location Error
A_1	2500 Hz	22°	200 ft.
A_1	982.5 Hz	22°	130 ft.
A_2	922.5 Hz	30°	350 ft.
B_1	1900 Hz	22°	130 ft.
B_1	982.5 Hz	22°	130 ft.
B_2	2900 Hz	22°	130 ft.
C_1	1700 Hz	22°	No location
D_1	1900 Hz	27°	700 ft.

Field Strength Comparisons

Table 4-3 shows the comparison between computed and measured field strength for the surface fields measured above the Geneva Mine. The average conductivities used in the computations are based on the three layer conductivity interpretation described in Section 4. 1. These conductivities vary from 1.68×10^{-2} mhos/m to 2.1×10^{-2} mhos/m depending on the total overburden depth. The resulting field strength computations were obtained using the following expression:

$$H_z = \frac{INA\,|G|}{2\pi z^3}$$

and the attenuation curve given in Figure 4-6. The maximum difference between measured field strength and computed field strength occurred at location C_1 where the measured value was 6. 8 dB less than the computed value.

As mentioned before, local variations in conductivity can play an important part in distorting field patterns and lowering (or raising) field strengths. It is likely that the conductivity at the C_1 location was somewhat higher than the value used in the computation. For the most part the agreement between predicted and measured field strengths is quite good, and illustrates again the suitability of the theoretical model used in the computations.

4. 2. 3 Helicopter Tests

On two of the days of testing at the Geneva Mine a Bell Jet Ranger 206B helicopter was leased to determine the performance characteristics of the multichannel receiver in helicopter reconnaissance operations. Based on the results of previous tests at the Robena Mine in January 1973 [8], the antenna/ preamp package was lowered beneath the helicopter by about 35 feet to minimize the effect of electrical noise from the engines. The results of the helicopter

TABLE 4-3

Measured and Computed Field Strengths, Geneva Mine

Location	Depth (Ft.)	Frequency (Hz)	H_z (measured) (dB relative to 1 μAmp/m)	H_z (computed) (dB relative to 1 μAmp/m)	dB difference (dB)
A_1	1150	982.5	1.6	1.1	+ .5
		1900	- 4.3	- 2.8	- 1.5
		2500	- 4.9	- 7.2	+ 2.3
A_2	1400	922.5	- 9.06	- 5.9	- 3.26
B_1	1500	982.5	- 4.8	- 9.1	+ 4.3
		1700	-15.9	-13.6	- 2.3
		1900	-10.3	-15.7	+ 5.4
		2900	-23.0	-24.0	+ 1.0
C_1	1450	2500	-26	-19.2	+ 6.8
D_1	1650	1900	-22	-19.2	+ 2.8

tests were mostly qualitative but did show the utility of using a helicopter for quick scans over the mine area to determine the presence or absence of transmitting signals in the mine and their approximate location. At the shallowest overburden location (A_1) of 1150 ft., the horizontal detection range observed with the multichannel receiver at an altitude of 100 ft. was about 4000 ft. Detection of signals was also made at overburden depths up to 1500 ft. but the horizontal detection range was limited to about 1000 ft. for the deeper overburden locations. The signal was also detectable above the A_1 location at helicopter altitudes as high as 700 ft. Photographs of the receiver output for these tests are shown in Section 4. 2. 4.

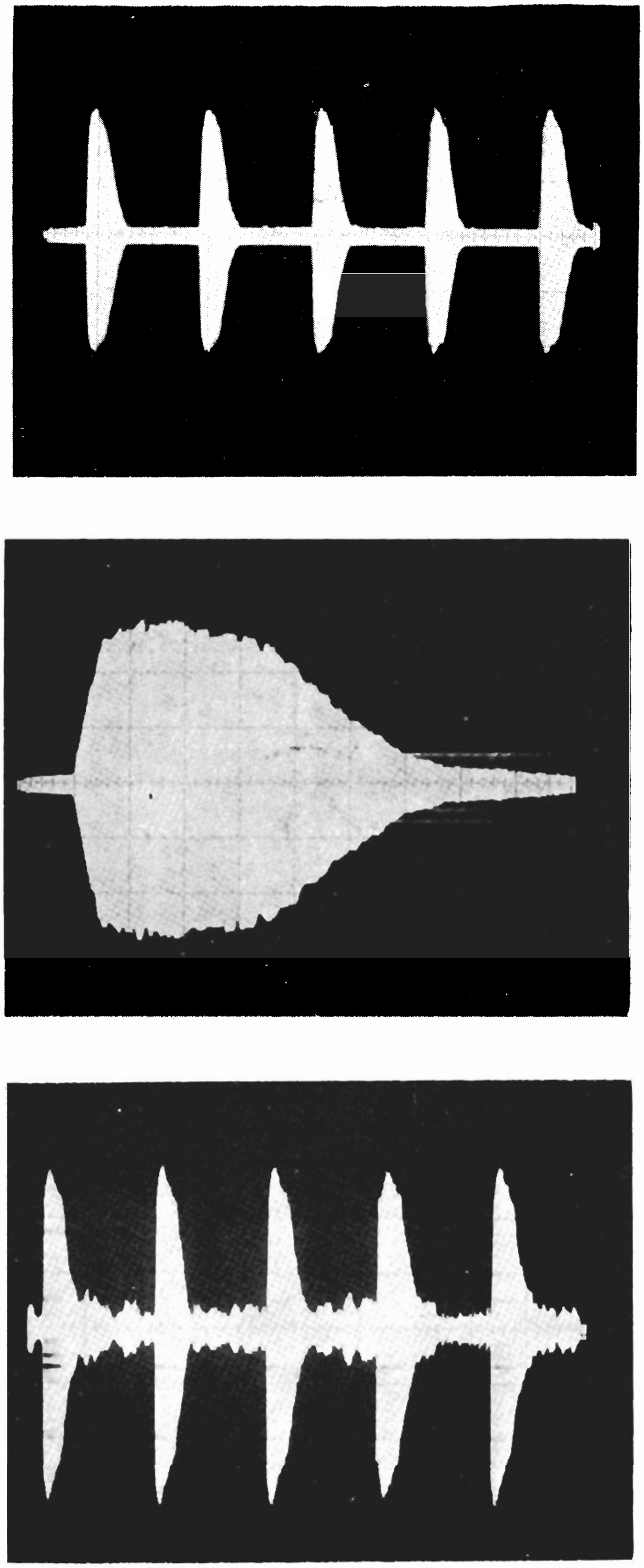
One problem area which soon became apparent in these tests was the electrostatic potential difference developed between the antenna shield (lying on the ground but cabled to the receiver chassis in the helicopter) and the helicopter frame. This potential difference caused electrical shock to the operator at times when the helicopter was in the air while the loop was on the ground. To remedy this problem the receiver chassis was firmly grounded to the helicopter chassis.

4. 2. 4 Signal and Noise Recordings

Uplink signals were recorded at the outputs of both the manpack locator and the multichannel receivers at several receiving locations on magnetic tape using a Wollensak Model 4300 cassette tape recorder. These signals were later played back onto a storage oscilloscope and were photographed as shown in Figures 4-13 through 4-19.

Figure 4-13 shows signals received at the A_1 location, 1150 ft. above the 2500 Hz transmitter. The signal to noise ratio is higher for the manpack locator than it is for the multichannel receiver; rough signal to noise estimates obtained for the two receivers from these photographs are:

Manpack Locator - 24 dB
Multichannel Receiver - 14 dB



Manpack Locator
Output

$H_z = 0.57\ \mu A/m$

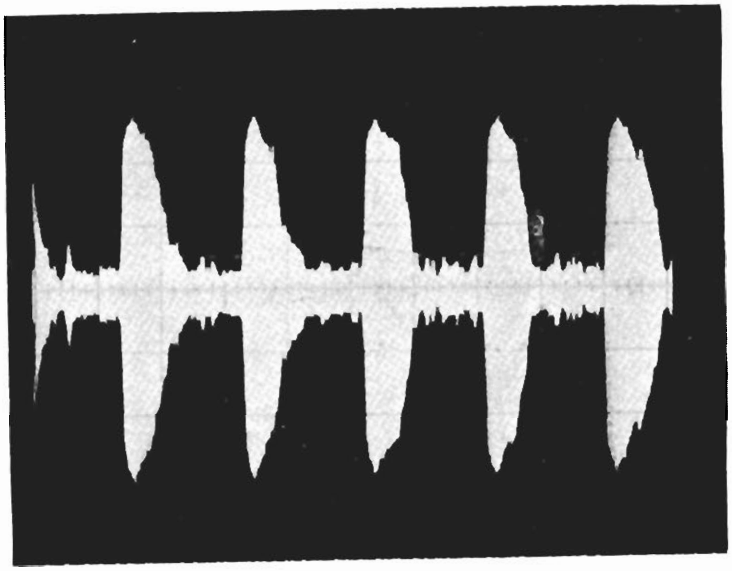
Manpack Locator
Output (Expanded)

$H_z = 0.57\ \mu A/m$

Multichannel
Receiver
Output

$H_z = 0.57\ \mu A/m$

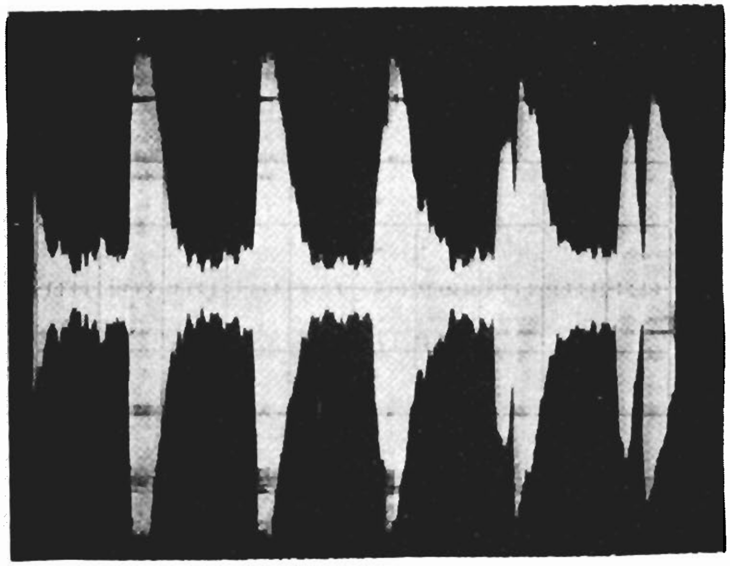
Figure 4-13. Received Surface Signals from 2500 Hz Transmitter, 1150 feet Underground



$H_z = 0.305\ \mu A/m$

Multichannel Receiver Output

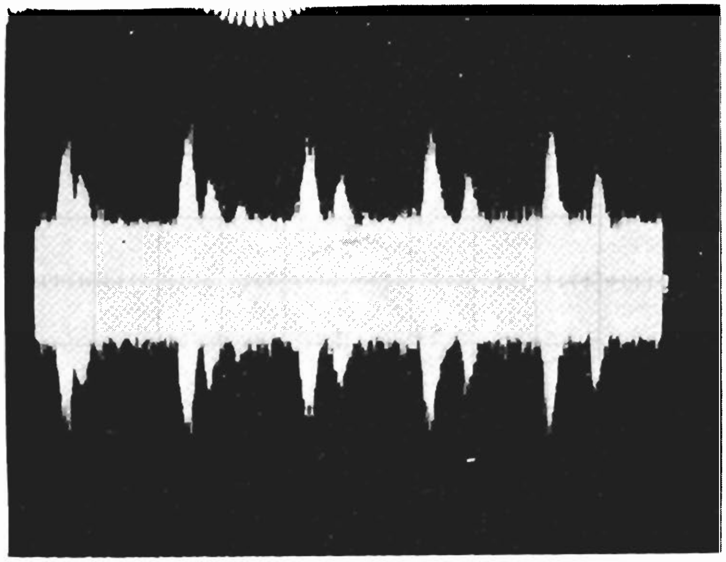
Figure 4-14 Received Surface Signal from 1900 Hz Transmitter, 1500 feet Underground



H_z = 0.193 μA/m at 1900 Hz

H_z = 0.314 μA/m at 2500 Hz

a) Surface Location (A_1)

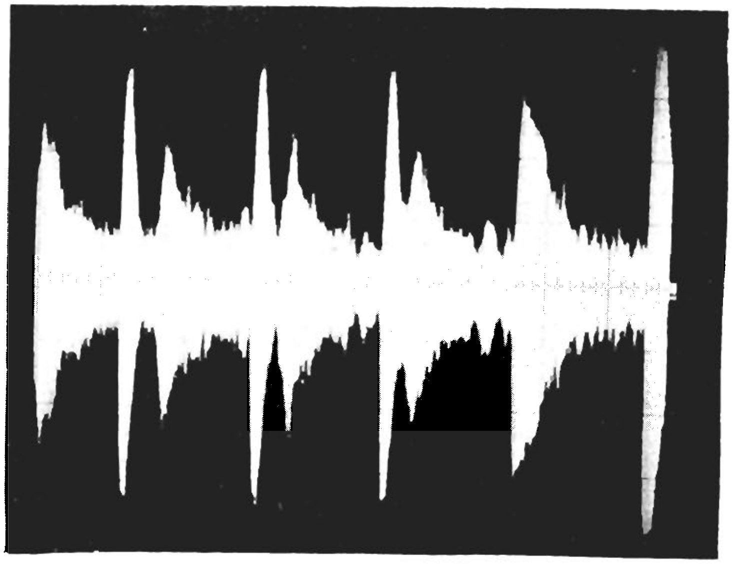


H_z = 0.27 μA/m at 1900 Hz

H_z = 0.102 μA/m at 2500 Hz

b) Mine Portal

Figure 4-15 Received Signal on Multichannel Receiver



H_z = 1.2 μA/m at f = 982.5 Hz

H_z = 0.08 μA/m at f = 1700 Hz

H_z = 0.08 μA/m at f = 1900 Hz

H_z = 0.05 μA/m at f = 2500 Hz

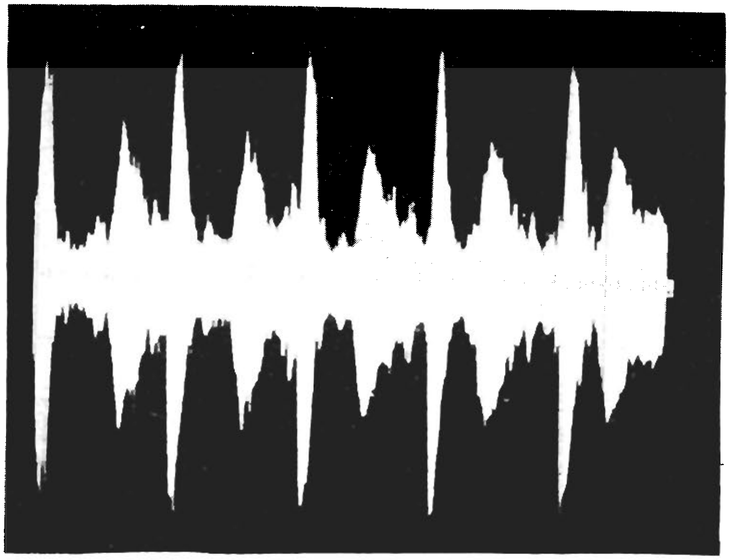
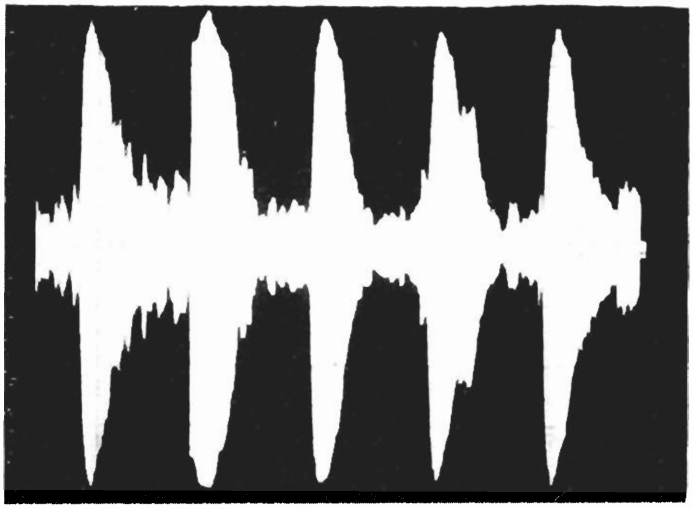
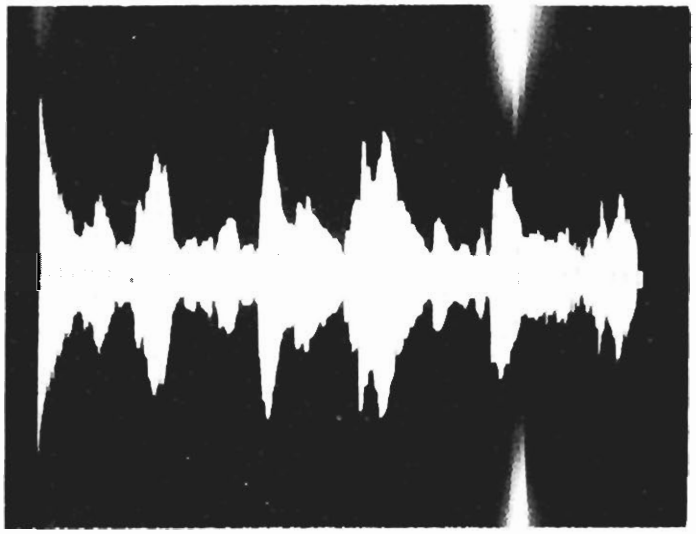


Figure 4-16 Combined Surface Signals from 4 Underground Transmitters Measured at Location A_1 with Multichannel Receiver



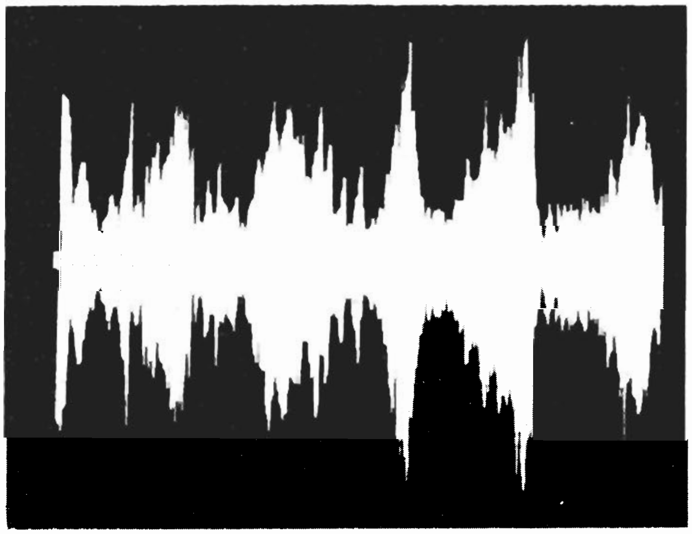
Hovering at
Altitude of
100 ft.

Transmitter Depth = 1150 feet



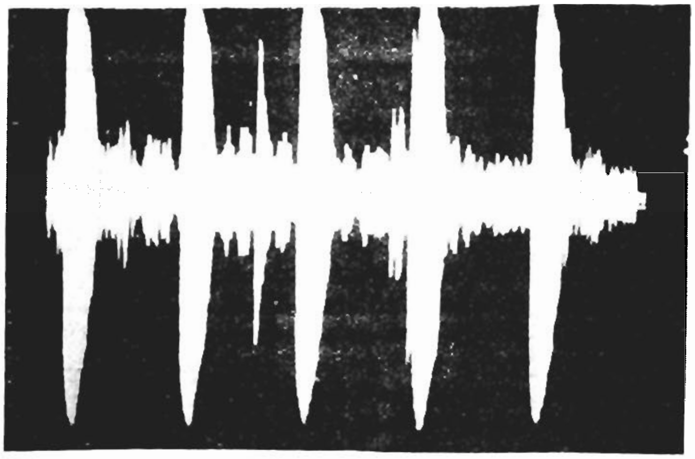
Rising to
Altitude of
700 ft.

Transmitter Depth ≈ 1150 feet

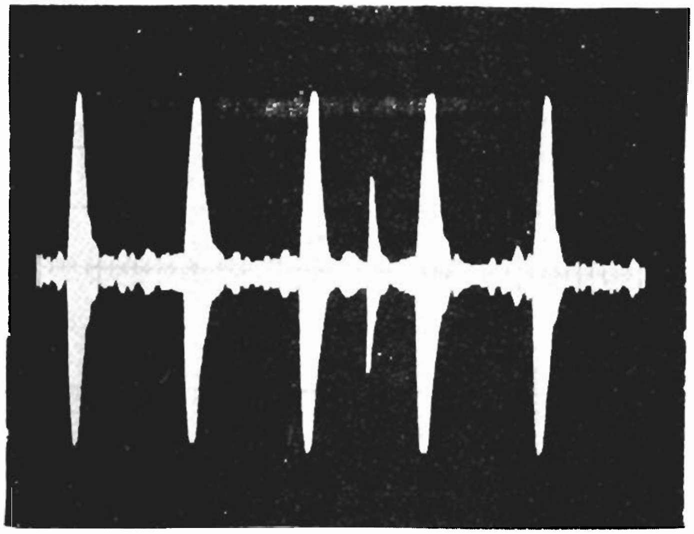


Flying over A_1
Location at
Speed of 20 mph
and altitude of 300
feet.

Figure 4-17 Received Signals from Multichannel Receiver in Flight (f = 982.5 Hz)



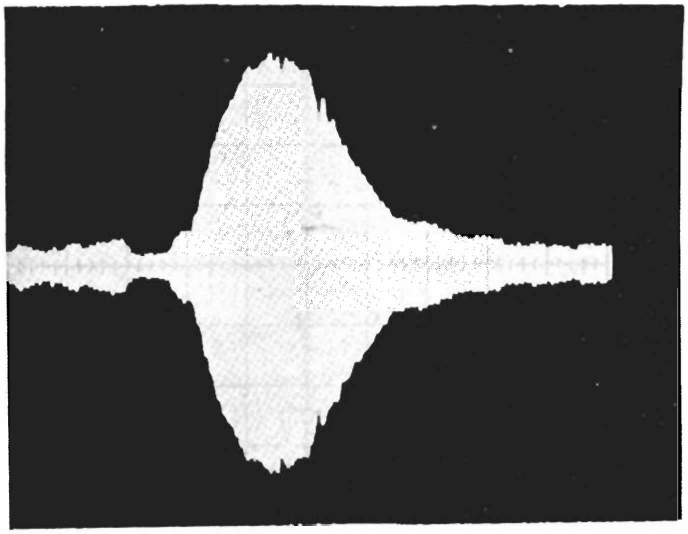
f = 922.5 Hz
d = 1400 feet
Alt. = 100 feet



f = 1900 Hz
d = 1150 feet
Alt. = 100 feet

f = 982.5 Hz
+ 2900 Hz
d = 1500 feet
Alt. = 100 feet

Figure 4-18 Received Signals from Multichannel Receiver in Flight



f = 1900 Hz

d = 1150 feet

Alt. = 100 feet

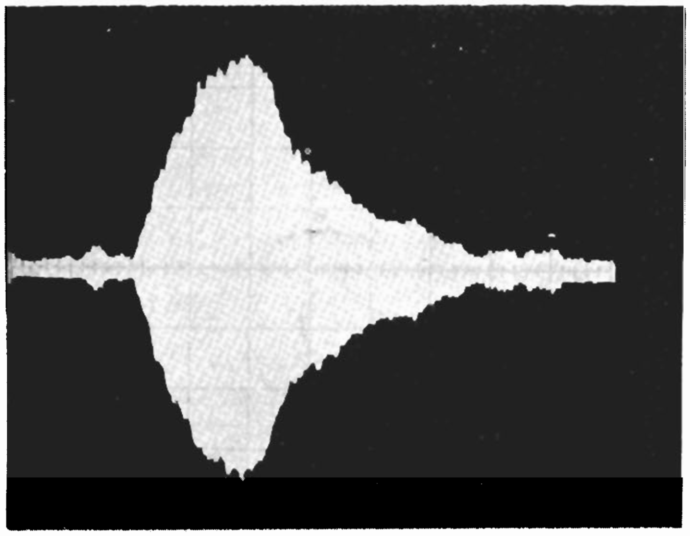


Figure 4-19 Expanded Signal Pulses from Multichannel Receiver in Flight

Signals of the above quality are not difficult to detect either audibly or with a visual output such as a meter or an oscilloscope. The received signal of the multichannel receiver is shown in Figure 4-14 at location B_1, 1500 ft. above the 1900 Hz transmitter. Here the estimated signal to noise ratio is also about 14 dB.

Figure 4-15 shows the combined signals from two transmitters (1900 Hz and 2500 Hz) received on the multichannel receiver both at the surface location, A_1 and at the mine portal. It is apparent that signal to noise ratio is degraded at the mine portal; however the very fact that signals are even detectable at the mine portal is quite encouraging since in this case the horizontal distances represented are 5500 ft. and 7500 ft. from the 2500 Hz and 1900 Hz transmitters respectively. In order to receive the signals at the mine portal, care had to be taken with the orientation of the receiving loop to null out the major sources of mine interference. It is apparent that signal enhancement due to coupling in the rails and or cables leading out to the mine portal is taking place. Otherwise, the signals would have been completely lost in the noise. The estimated signal to noise ratio for these conditions are 16.5 dB at the surface location A_1 and 6 dB at the mine portal. Being able to detect these signals at the mine portal could play an important part in preliminary mine rescue efforts to determine whether any transmitters are transmitting and possibly to aid in communications with trapped miners throughout the mine. Also, the long propagation ranges observed for these transmissions would make this system concept ideally suited to a mine paging application in an operating mine.

Figure 4-16 shows composite signals from 4 underground transmitters measured at location A_1 with the multichannel receiver. In this figure it is apparent that the background noise increases with the number of channels being added to the composite output. The signals were also measured at this location using the calibrated manpack locators and the equivalent field strengths are shown on the figure for the different transmitting frequencies.

Figures 4-17, 18 and 19 show received signals from the multichannel receiver output while it was being used in a simulated helicopter reconnaissance flight. In Figure 4-17, it is apparent that signal to noise ratios improve considerably when the helicopter is allowed to hover or fly slowly over the area. Some of the noise obtained is likely due to vibrations of the loop antenna, tethered 35 feet below the helicopter, interacting with the earth's magnetic field. However, even at speeds up to 20 mph, the signals were distinctly audible and the periodic pulse repetition rates were distinguishable. Also, the helicopter could increase its altitude to about 700 feet above the A_1 location before the signal became difficult to detect. This represents a total transmitter to receiver separation of 1850 feet at this location. For these tests, the helicopter's generator was turned off as soon as it became airborne. This was necessary because the generator interference was of an intolerable level for detection of these extremely weak fields.

Figures 4-18 and 4-19 show signals received from the helicopter in flight during the second day of helicopter tests after the transmitters had been relocated. Figure 4-18 shows the received signals as the helicopter flew past each of 4 different transmitters operating from depths from 1150 feet to 1500 feet. With the exception of an occasional uncorrelated noise burst as shown in the photographs, the signals were clearly distinguishable and would not have been difficult to detect with the present equipment in an actual emergency. However, there were two locations where the signals were not detectable by the helicopter in flight. These were C_1 and D_1 representing overburden depths of 1500 feet and 1650 feet respectively. These signals were detectable earlier using the portable manpack locators and helicopter receiver on the surface. However, different transmitter frequencies were being used at these locations at that time and it is not known whether they would have been detected on the helicopter receiver in flight since the helicopter was not available at the time. In general, it can be stated that the lower frequency transmitters had the greater probability of success at the Geneva Mine due to (1) their increased signal propagation characteristics through the deep conductive overburdens, and (2) the virtual absence of man-made noise on the surface above the Geneva Mine.

5.0 DIFFERENTIAL LOCATION RECEIVER

One subtask performed under Task I on this contract was to conduct a laboratory investigation of differential techniques for improving signal detectability and null resolution. If the laboratory test results were favorable then the concept should be tested in the field. The following paragraphs describe the differential concept, system design, and test results.

5.1 System Concept

The differential receiver concept involves measuring the gradient of the horizontal field over the region of the null of the absolute field. This is accomplished by using two loops for receiving antennas. These loops are mounted in a coaxial configuration separated by a distance, Δx, which is typically 6 to 10 feet. For small loops the spacing reduces the mutual inductance so that they may be tuned with a single capacitor. Resonating the loops in this manner increases the receiver's noise figure.

When both loops are connected in series with the turns series aiding, the receiver responds to a distant source just as a single loop and can therefore be used to measure horizontal (H_ρ) or vertical (H_z) components of the fields from that source.

When the terminals of one loop are reversed and the two loops are connected in series bucking, then the signals sensed by each loop are subtracted. In this configuration and with the loop planes perpendicular to the plane of the transmitting loop, then the profile observed over a buried source is the gradient $\frac{\Delta H_\rho}{\Delta x}$. In the region of null of a nearby signal source the gradient is a maximum. External noise from distance sources is minimized by the subtraction of the nearly equal fields sensed by each loop. Two important factors to consider when designing such a system are: 1) to make the antennas identical in order to increase noise cancellation and 2) to achieve a low receiver noise figure to permit detection of small signal gradients.

5.2 System Implementation

A breadboard of the differential sensing system was constructed and tested in the laboratory. Two 15-inch air core loops consisting of 500 turns of #22 AWG wire were installed in a coaxial configuration. Each loop inductance was about 200 millihenries and the two loops in series aiding or bucking were resonated to 1900 Hz with a 0.015 μ fd capacitor. Bandwidth measurements indicated an antenna system Q of approximately 45. A schematic diagram of this antenna system and the receiver block diagram are shown in Figure 1-1. The receiver bandwidth was determined by a 1900 Hz tuning fork. Overall system bandwidth was 4 Hz at the 3 dB points.

A magnetic dipole source was simulated in the laboratory using a small ferrite core loop (approximately 1 inch in diameter) excited with a 1900 Hz signal generator. Tests were conducted by moving this source perpendicular to the planes of the receiver loops. Profiles were measured for the H_ρ component (series aiding) and the field gradient (series bucking). Results are shown in Figure 1-2 which indicates that the system is capable of measuring the field gradient. A 10 dB reduction in the noise was also observed when the loops were connected in series bucking. The amount of noise concellation was not as great as expected. This was attributed to an imperfect loop orientation and because nearby man-made noise sources were not equally coupled to both loops.

Subsequently a new antenna system and receiver were fabricated for field use. Two identical ferrite core loops using 2000 turns of #26 AWG wire were constructed and mounted in each end of a 6 foot long, 2 inch diameter, plastic tube with an external electrostatic shield. A battery operated receiver with low noise front-end, gain control, and antenna tuning and reversing switch was designed and packaged in a portable case.

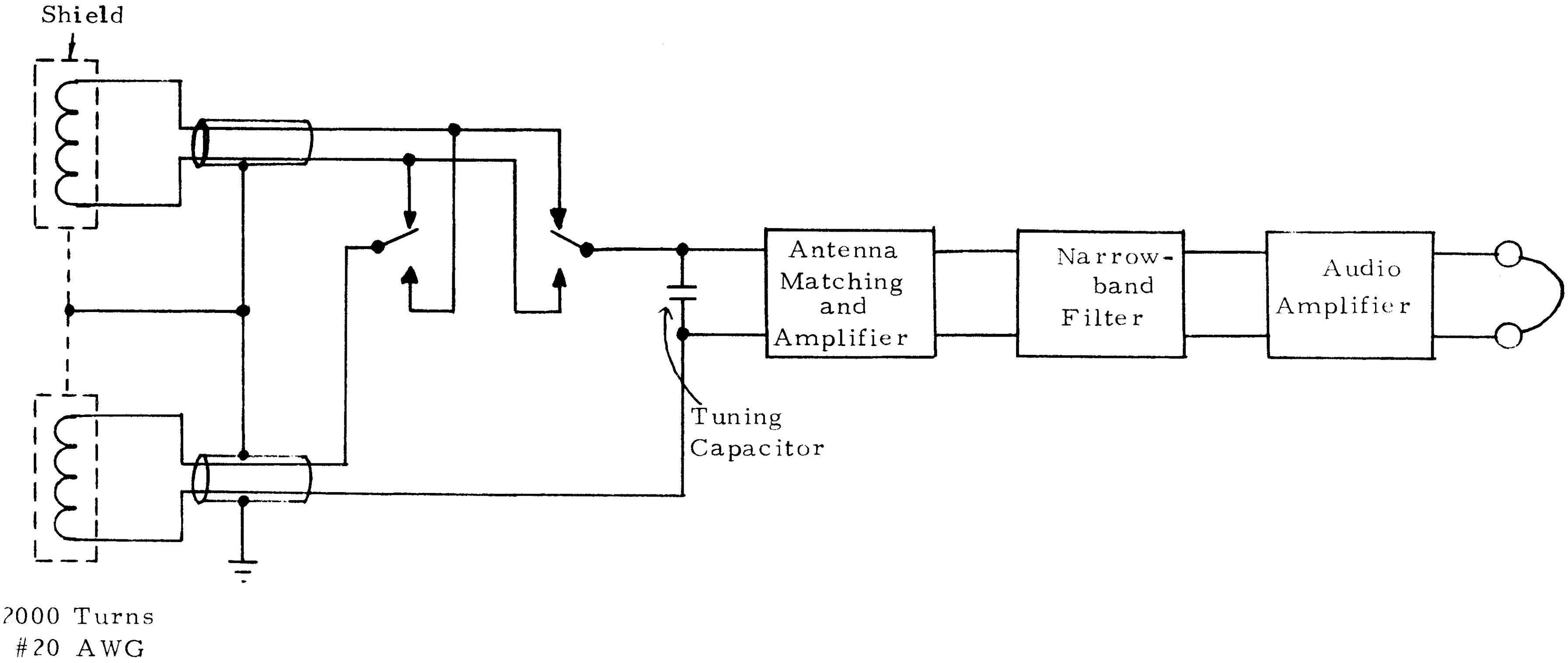


Figure 5-1. Differential Receiver Diagram.

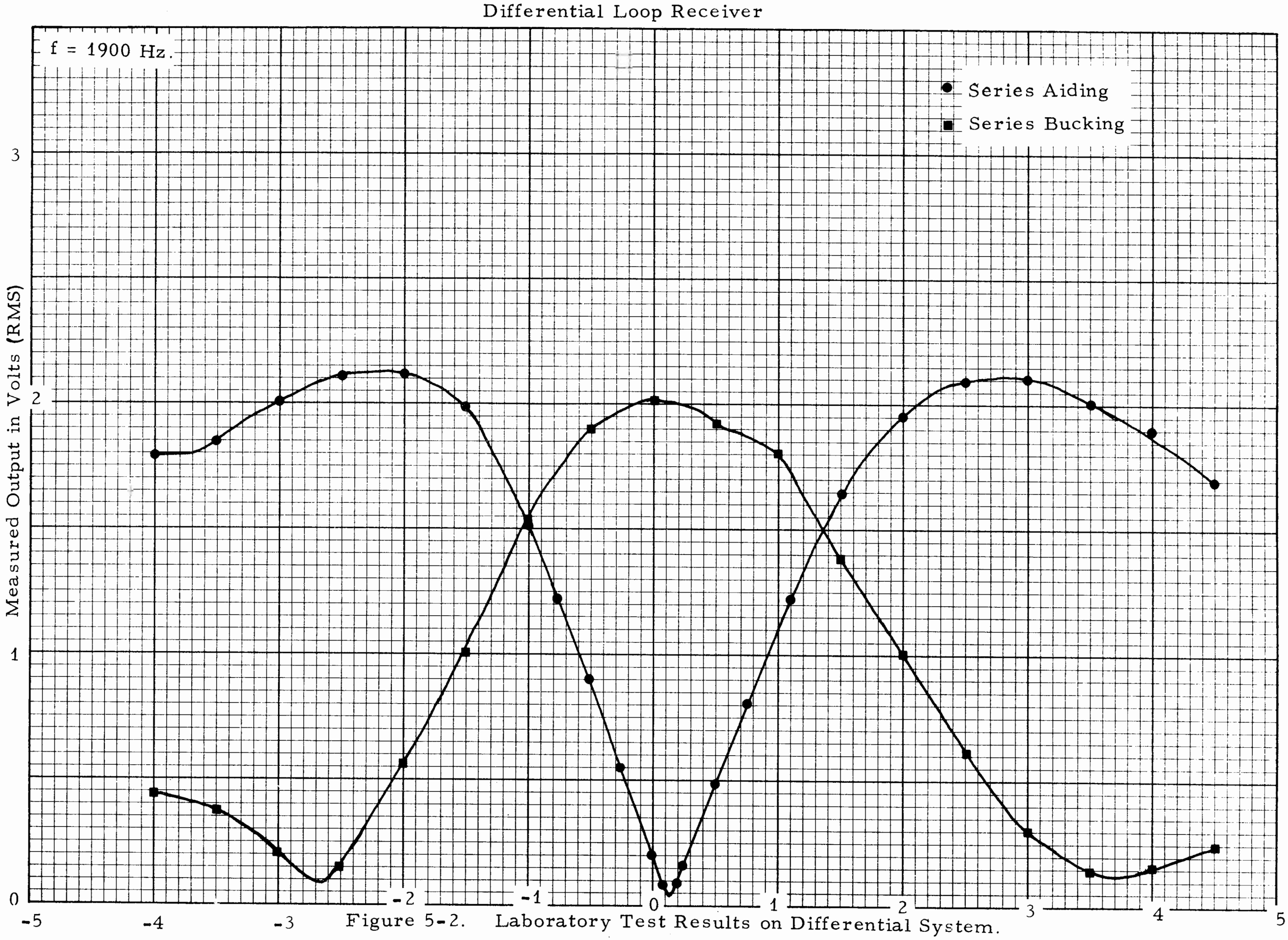


Figure 5-2. Laboratory Test Results on Differential System.

The 3 dB bandwidth of this receiver was measured to be 3 Hz, and the maximum sensitivity was less than 0.1 μA/meter. Tests were conducted near the laboratory using a 1900 Hz full-wave transmitter and an 8 foot square loop transmitting antenna consisting of 10 turns of #16 AWG in a vertical configuration. The transmitter antenna moment achieved with this setup was 96 ampere-turn-meters^2. This produced a field strength of about 10 μA/meter at a distance of 100 meters. Measurements were made using the differential receiver with the antennas connected both aiding and bucking. It was apparent that the field gradient signal peaked near the null. As expected, the observed gradient was considerably less than the H_z component observed with the antennas aiding and coaxially oriented with the transmitting antenna. It was not possible to obtain a noticeable degree of noise reduction when measuring this field gradient because the receiver was front-end noise limited. The front-end noise circuitry was revised and filtering added to the output stages to improve the noise figure. These revisions improved the receiver sensitivity to about 0.01 μA/meter. Subsequent measurements, however, indicated that only the peaks of the atmospheric noise were exceeding this reduced front-end noise level.

The differential system was then taken to the Geneva test site where field tests were already in progress. At Geneva the differential receiver was operated using the 1900 Hz transmitter installed at Location A-1 in the mine at a depth of 1150 feet. The vertical magnetic field strength was measured and found to be 0.6 μA/meter. The differential receiver's performance was similar to the manpack receiver's performance with the antennas connected in series aiding. The null location, however, was not well defined and the field gradient was, therefore, not measurable. Again, the atmospheric noise at 1900 Hz in the 3 Hz bandwith was below observable limits of the receiver. No signal-to-noise improvement was obtainable because the field gradient was not great enough to measure.

Many of the potential advantages of the differential concept could not be demonstrated at Geneva. It was apparent that a much greater antenna spacing would be required to measure field gradients. This would decrease the operational capabilities of the system. Also, a major improvement in the receiver noise figure requires further development work and probably more sophistication in the receiver's front-end and in the antenna system.

Further tests should be made with the existing receiver, but at shallower mines and where external noise levels limit performance. The basic concept could then be evaluated and the decision made at that time whether further development is warranted.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the Geneva Mine experiments show the feasibility of detecting uplink signals, both surface and airborne, from intrinsically safe manpack transmitters in a mine with overburden depths up to 1650 feet and overburden conductivities as high as 2.1×10^{-2} mhos/m. Location information obtained from the magnetic field pattern behavior was not as accurate as anticipated but did nevertheless provide useful data on the general location of the transmitters. For the most part, the locations determined by the electromagnetic method were within one or two mine pillars (150-300 feet) from the actual transmitting location. Location discrepancies occurring at this mine are attributed to (1) terrain irregularities and (2) local conductivity changes which strongly affect the field behavior when overburden conductivities and overburden thicknesses are high.

Optimum operating frequencies for a mine such as Geneva tend to be lower than the optimum frequency for shallower less conductive eastern mines. Based on the results of these tests, and performance predictions given in Section 2, the optimum frequency range for uplink signals at Geneva would probably fall between 500 and 1000 Hz.

The equipment developed for this project performed according to specifications in all cases, and the manpack locator Model C842A exceeded specifications in its capability of receiving signals down to as low as 0.03 μA/m. The multichannel receiver designed for use in the helicopter is also suitable for use on the surface and provides the added flexibility of monitoring more than one frequency simultaneously. In marginal signal situations, a visual indicator such as a meter or an oscilloscope is required on the receiver to give added discrimination needed for a proper null determination. It is recommended that on future manpack receivers, a metering device be added to the receiver to cover such situations.

Also, in view of the extremely low background noise observed at Geneva, it is recommended that more work be done on the receiver antenna and front end to lower its first circuit noise level and thus be able to take full advantage of extremely quiet electromagnetic conditions when they do occur.

The horizontal detection range of the signals transmitted from the Geneva Mine varied from about 1000 feet to over 4000 feet depending on overburden depth. Furthermore, detection ranges of 8500 feet were obtained with the receiver located near the mine portal and the transmitters located throughout the mine. This latter phenomenon exists because of the electromagnetic coupling between the transmitter and receiver via the mine rails and cables. Computations of uplink field strengths were generally in good agreement with measured values, once again demonstrating the validity of the theoretical model used in the computations.

The feasibility of multichannel reception from a helicopter was established using the 6 channel receiver built for that purpose. The signals received in the helicopter were sufficiently clean also for obtaining chart records, had a dc chart recorder been available for these tests.

To summarize the present system's capability, we can say that in overburden conductivities of 2×10^{-2} or less, the system has a horizontal detection range of at least 4000 ft at a depth of 1000 ft and at least 2500 ft at a depth of 1500 ft. Location accuracies are generally within 10% of the overburden depth. The transmitter weighs 0.75 pounds and will operate for a period of 72 hours on a fully charged 4 volt cap lamp battery driving a 500 ft long antenna of #12 wire.

It is recommended that more tests be conducted in deep metal mines where intrinsic safety limitations do not exist to determine whether increased overburden depths and higher conductivities can be compensated for by increased transmitting moments within practical limitations in the mine. Also many metal mines do not have the conventional room and pillar entries of most coal mines and tests should be conducted to determine the feasibility of using other antenna configurations such as long wire antennas for location purposes in these mines.

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PART II

COMMUNICATION SYSTEM MODIFICATION AND DEMONSTRATION AT BRUCETON EXPERIMENTAL MINE

By

J. W. Allen

CONTENTS

1.0 INTRODUCTION

An engineering model of a Monitoring, Locating and Communication System was developed on USBM Contract H0220073 and installed in the USBM experimental mine at Bruceton, Pennsylvania to demonstrate the feasibility of a system concept. This engineering model, which consisted of three subsurface stations and one surface station, included multiple function capabilities and a variety of features for evaluation. Not all of the characteristics incorporated in the engineering model would be necessary or even desirable in a system designed for a working mine.

Like most engineering models of developmental systems, some problems became apparent when the system was installed and tested in the USBM Experimental Mine at Bruceton. In order to satisfy USBM performance requirements, some modifications in design concepts and hardware implementation were deemed necessary. Task II of Contract H0232049 provided for the modification of the hardware, reinstallation and test at Bruceton, and demonstration of system operation to USBM personnel.

2.0 SYSTEM MODIFICATIONS

Subtask 1 of the contract called for specific system modifications and additions. These were determined to be necessary or desirable as a result of the tests performed during the tests at Bruceton on the previous contract. They are listed below:

a) Fabricate one (1) Test/Control Fixture for use with subsurface electronics modules.

b) Replace type CD4009AE and type CD4010AE integrated circuits with types CD4049AE and CD4050AE, respectively.

c) Install additional regulators and filters in subsurface units to eliminate feedback and noise on voice uplinks.

d) Modify power distribution in subsurface transmitters and eliminate resistive divider logic level shifters.

e) Add test jacks, test function switches, and guide rails in subsurface units to facilitate maintenance.

f) Engrave and fill nomenclature on panels of subsurface electronics modules.

g) Modify phone coupling circuits to incorporate coupling transformers and balanced shielded line to all stations.

h) Modify audible alarm circuits to permit volume control of alarm signals.

i) Extend range of SQUELCH control in all voice receivers.

j) Incorporate preamplifiers in surface ferrite antennas.

k) Modify subsurface transmitter antenna tuning unit to facilitate tuning in the mine and to improve antenna matching at the voice uplink carrier frequency.

l) Incorporate sensor excitation supply in the subsurface units.

m) Perform laboratory tests to define the performance characteristics of the modified system and deliver a set of updated drawings.

The above listed modifications, together with others deemed necessary as a result of system tests, were incorporated in the system and are discussed in more detail in the following paragraphs.

2.1 Test/Control Fixture for Subsurface Stations

A Test/Control Fixture was designed and fabricated to facilitate testing and adjustment of the electronics modules from the subsurface stations. This fixture permits testing of the subsurface station circuits in the laboratory without removing the cabinet, battery, sensor, antenna and associated cables from the mine. It includes basically the same battery, speaker, indicator lights, switches, and internal connectors normally provided by the subsurface station cabinet. In addition, it provides dummy antenna loads for the subsurface transmitter, test jacks for signal inputs and outputs, and a simulated sensor output voltage supplied from a 10-turn potentiometer.

A separate dummy receiving antenna can be connected to the RECEIVER TEST input of the Test/Control Fixture to permit testing of the EM direct audio voice downlink receiver.

Although no handset is provided on the Test/Control Fixture, a MIC AMPLIFIER input jack, an EARPHONE AUDIO output jack, and phone line terminals permit testing of the paging and voice telephony circuits.

2.2 Subsurface Station Modifications

The majority of the modifications to the system were made on the subsurface stations. Two modifications, which were purely mechanical, were made to enhance the appearance of the units and to facilitate testing and maintenance. They were the engraving and filling of nomenclature on the panels and the incorporation of guide rails for the electronics modules. The guide rails made removal and insertion of the electronics modules much easier with less chance of damaging components on the circuit boards.

A three position Test Switch was installed between the DATA/REPLY shift register and the DATA/REPLY Voltage Controlled Oscillator (VCO) to facilitate measurement and adjustment of VCO frequency. In the MINUS position it couples a logic ZERO level into the VCO which then generates the lower shift frequency. In this position, Trimmer R-3 can be adjusted to set the lower shift. In the PLUS position it feeds a logic ONE level into the VCO, which then generates the upper shift frequency. In this position, R-2 can be adjusted to set the correct upper shift frequency. In the center or NORMAL position, it couples the shift register output into the VCO, which then generates a frequency shift-keyed (FSK) signal corresponding to the selected DATA or REPLY code.

All type CD4009AE and type CD4010AE integrated circuits were replaced with types CD4049AE and 4050AE, respectively. According to the manufacturer (RCA) these types are more rugged and reliable than the previously used types which had exhibited a high rate of unexplained failures.

The power distribution in the subsurface transmitters was modified by the addition of filters, transistor switches and voltage regulators. Twelve volts DC from the battery was supplied directly to the transmitter output power transistors and driver transistors. Filtered 12 volts was supplied to the regulator inputs through a lowpass filter consisting of a 15 millihenry inductor and a 22 μf capacitor. A Fairchild type F-7808, three terminal regulator provided regulated 8 volts for the logic, while two Fairchild type F-7806, 6-volt regulators supplied the DATA/REPLY VCO and the FM VOICE VCO. A transistor switch in series with the input to each 6-volt regulator turned the power on and off as required by the transmission mode selected.

A lowpass filter consisting of a 10 Hy inductor and a 22 μf capacitor were installed on the inside of the cabinet door to filter the bias voltage for the handset carbon microphone. The use of the regulated 8-volt logic supply permitted elimination of the resistive divider logic level shifters formerly used in the transmitters.

The phone coupling circuit was redesigned to incorporate a coupling transformer and a balanced line for paging and voice telephony. DATA/REPLY and FM VOICE carriers were coupled onto the 2-wire phone line as a common mode voltage to ground. This approach greatly reduces interaction between the voice signals and the carrier signals.

A lowpass filter was incorporated between the phone line coupler and the voice uplink VCO to eliminate oscillations caused by feedback at the 7 kHz voice carrier frequency.

The electromechanical paging relay was replaced by a solid state circuit comprised of a full-wave rectifier, lowpass filter, threshold detector, logic level converter and bilateral analog switch. This circuit, which is activated by a paging voltage of either polarity in the range of 5-30 volts, activates the loudspeaker amplifier for paging and the 7 kHz FM transmitter for through-the-earth voice uplink.

The single pole PRESS TO PAGE switch which previously connected one side of the phone line to circuit common (ground) was replaced with a double pole switch which simultaneously connects one side of the phone line to circuit common and the other side to the plus 12 volt supply through an isolation inductor.

The audible alarm circuit was modified from the old configuration which employed the audio power amplifier as a feedback oscillator to the new configuration which employs a separate alarm oscillator (an NE 555 Timer) and permits volume control of the alarm signals. The front panel VOLUME control now controls volume of both alarm signals and EM voice downlink signals. An internal trimmer sets the volume of voice paging signals.

A sensor excitation circuit was added which supplies a regulated 8 volts to the Abirko "Flowmaster" Air Velocity Sensors. A fuse holder was installed in the side of the subsurface station cabinet near the sensor input connector. The fuse was connected in the sensor excitation circuit to protect the voltage regulator if the sensor chassis should get shorted to the station circuit ground. (The plus side of the sensor supply is connected to the sensor chassis and requires insulation from the station circuit ground.)

The sensor threshold circuits were referenced to the plus 8-volt supply and the RISE/FALL switch rewired to accommodate the sensor output voltage which decreases (changes from plus 8 volts toward ground) as the air velocity into the sensor increases.

The 2-conductor phone plug provided on the Abirko anemometer for a remote meter was changed to a 3-conductor to provide sensor excitation input as well as the output to the subsurface station sensor input. A bypass capacitor was added in the anemometer circuit to prevent EM signals radiated by the subsurface station transmitter from affecting the sensor readings.

The transmitter antenna coupling and tuning circuit were modified to facilitate tuning in the mine and to improve antenna matching at the voice uplink carrier frequency. The four-conductor cable between the station cabinet and the antenna tuning unit was replaced with a six-conductor cable. One of the added wires was used to connect a second tap on the output transformer to the VOICE mode antenna tuning capacitor. The other was connected to a remote tuning indicator light mounted in the tuning box.

The subsurface voice downlink receiver squelch circuit was modified to provide a wider range of squelch control. A three-position gain control switch was added to provide reductions of 20 and 40 dB in receiver gain for use in strong signal locations such as the Bruceton mine.

A number 12 AWG conductor was added in parallel to the printed circuit ground strip on the receiver PC card to improve receiver stability and reduce the tendency to oscillate. In addition, certain ceramic coupling and bypass capacitors which were determined to be microphonic, were replaced with Mylar film capacitors.

In addition to the modifications listed above, several components were changed or replaced to provide more stable or reliable operation. As an example, some electrolytic coupling and filter capacitors were replaced with monolythic capacitors to reduce effects of leakage currents.

The DATA/REPLY VCO's were retuned to provide a ± 15 Hz frequency shift about their center frequencies to allow a wider variation in environmental temperature before oscillator frequency drift becomes a problem.

2.3 Surface Station Modifications

The receiving antenna configuration of the surface station was extensively modified to provide better overall performance and greater operational flexibility. Preamplifier units were fabricated for three ferrite core receiving antennas. The antennas were mounted on the lids of the preamplifier boxes and covered by protective fibreglass domes similar to the ones used to house the downlink receiving antennas in the subsurface stations.

The preamplifiers incorporated a FET input circuit, a 1 kHz high-pass filter, a voltage amplifier, an output emitter follower, and a balanced line matching transformer. A balanced RG-22/U cable connected each preamplifier to a lightning protection unit located near the input to the surface receiver. The same cables provided power for the preamplifiers from a source in the surface receiver. The preamps are capable of driving cables of at least 4000 foot length.

The lightning protection unit contains magnetic gap type surge arrestors, series bifilar inductors and 50 watt zener diodes to limit voltage transients appearing at the receiver input terminals. In addition, fifty watt zener diodes are used from each line to ground in the preamp units to provide protection for the preamp circuits.

The antenna coupler module in the surface receiver was modified by the addition of three balanced input transofrmers to match the preamplifiers. The fourth channel (A-4) in the antenna coupler was left unmodified to accommodate high impedance loops or as a convenient input for test signals, etc. A fuse was installed in the antenna coupler module and connected in the circuit which supplies 12 volts to the preamplifiers.

The alarm circuit was modified to permit control of the alarm signal volume by the front panel VOLUME control. A 1 kHz tone burst is derived from the clock circuitry in each decoder/display module and connected through a diode "OR" circuit to the audio amplifier circuit in the surface station.

All type CD4009AE integrated circuits were replaced with type CD 4049AE to improve reliability. This change necessitated a reduction in value of the biasing resistor in the 1 kHz clock oscillator to maintain the proper frequency.

To reduce the false reply probability, a type CD4017AE, decoded decade counter was added to the output of each reply pattern decoder and wired to require a total of 4 out of a possible 6 input pulses before it activated the reply indicator. The reply driver time constant was tailored to be approximately 5 seconds. These modifications seemed to completely eliminate the problem of ambiguous replies (2 or more showing simultaneously) that was previously observed.

The FM voice uplink receiver squelch circuit was modified to provide a wider range of squelch threshold control.

The phone coupling circuit was modified to incorporate a coupling transformer and balanced 2-wire phone line for paging and voice telephony. A solid state paging circuit, similar to the one used in the subsurface stations, replaced the electromechanical paging relay. As in the subsurface stations, the single pole paging switch was replaced with a double pole unit which simultaneously connects circuit common to one side of the phone line and +12 volts to the other side.

2.4 Laboratory Tests

After incorporation of the modifications described previously, the system was tested in the laboratory. Gain, frequency response, and maximum signal capability of the surface ferrite antenna preaplifier were measured. Capacitors and resistors were installed to simulate 4000 feet of cable between the preamp and the surface station and the resultant loss measured. Since the loss was less than 1 dB, the preamplifiers could probably be located up to 2 or 3 miles from the surface station and still provide satisfactory operation.

Operational tests of the modified anemometers and sensor input circuits were conducted. These tests revealed need for a bypass capacitor in the anemometer to eliminate the effects of EM signals radiated by the subsurface station transmitter.

The new solid state paging circuit which replaces the electromechanical paging relay was tested to verify that it would operate properly with paging voltages of either polarity ranging from 5 to 50 volts.

The subsurface station voice downlink receivers were functionally tested by inducing EM voice signals into their receiving antennas. The output of a tape recorder was connected to a small ferrite loop antenna which acted as the EM signal source. The receiving antenna orientation was varied, together with the amount of coupling to the EM signal source to provide a wide range of signal amplitudes and signal-to-noise ratios for testing operation of the receiver gain and squelch controls.

The three subsurface stations and the surface station were set up at different locations within the laboratory building and interconnected with a 2-wire cable. Functional tests were conducted to verify proper operation of voice paging; voice telephony; FM voice transmission and detection; reply message transmission, detection and display; and data sensor status transmission, detection and display.

No actual EM transmission tests were performed since the antennas remained in their original Bruceton installations; however, the transmitters were tested using the dummy loads in the Test/Control fixture.

3.0 BRUCETON TESTS AND DEMONSTRATION

Before reinstalling subsurface station equipment in the mine at Bruceton, the subsurface stations were set up at different buildings on the surface and connected to the surface station in Building 07 by a common twisted pair cable. The distance between stations was approximately 70 to 100 feet.

Functional tests of the voice paging, voice telephony, Reply messages, and Sensor status monitoring were performed by WGL and USBM personnel. The Data/Reply VCO in Station 2 was found to be unstable during these tests. The integrated circuit (CD4007AE) was replaced and the oscillator frequency observed. Stability appeared to be greatly improved.

3.1 Surface Receiving Antenna Deployment

The three surface ferrite core receiving antennas and their associated preamplifiers were deployed as nearly above the three subsurface stations as possible. Roads, buildings, property lines, and a limited amount of RG-22/U Twinax available (2000 feet) determined the choice of locations.

Figure 3-1 is a plan view showing the location of the subsurface stations, the surface station, and the receiving antenna locations. Antenna A-1 was located at the edge of the fire break along the boundary fence near the large water storage tank (Structure 0-66) on the hill. It was approximately 540 feet from the point directly above Station No. 2. To place the antenna closer to the desired location would require going outside the USBM property fence.

Antenna A-2 was located near the edge of the road just below Building No. 41. It was approximately 400 feet from the point on the surface above Station No. 2. If additional Twinax cable were available,

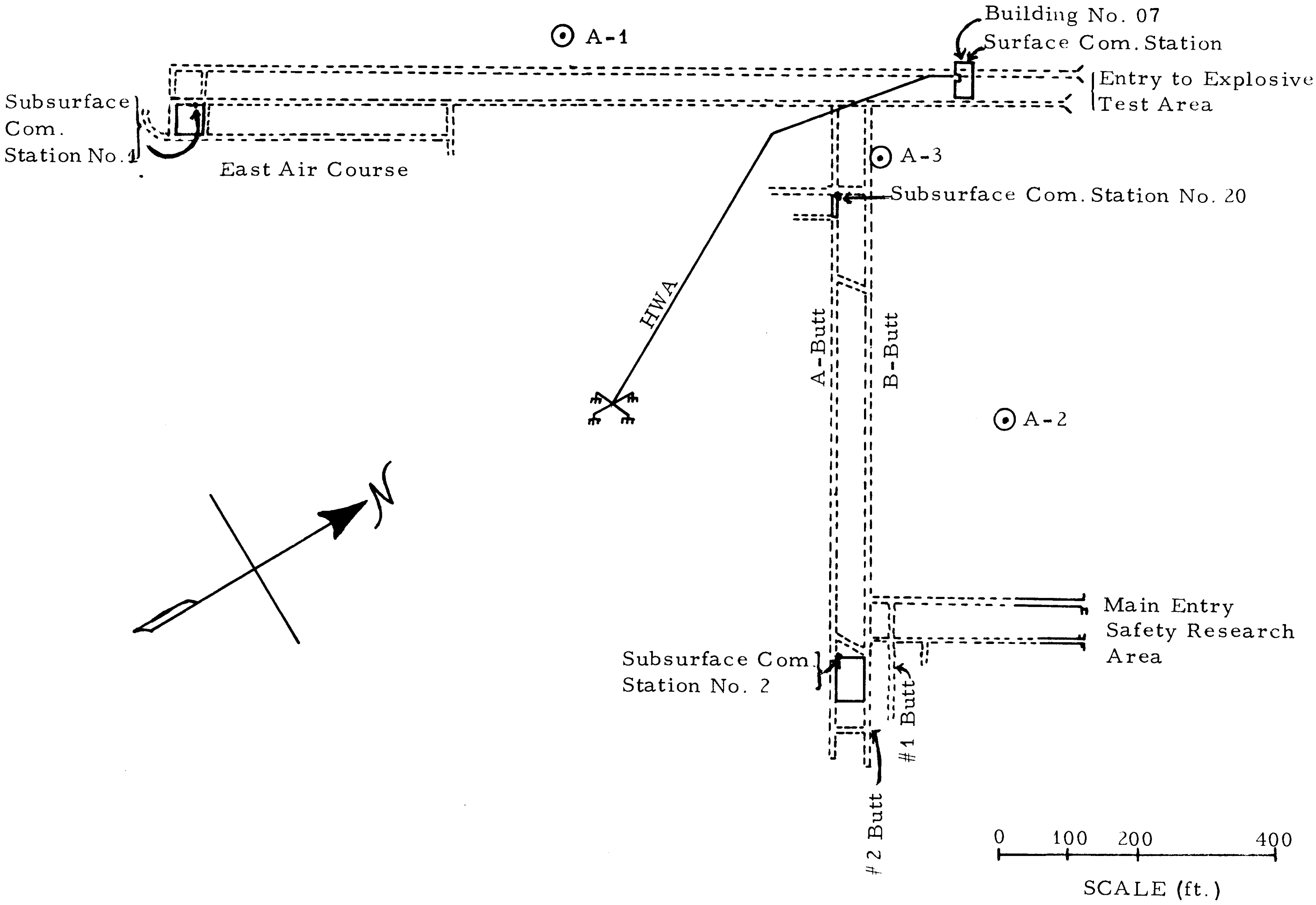

Figure 3-1. Communication and Monitoring System Installation Plan at USBM Experimental Mine, Bruceton, Pa.

A-2 could be placed directly above Station No. 2.

Antenna A-3 was located approximately 100 feet from the point above Station No. 20. Buildings and roads prevented any closer placement to the desired location.

The lightning protection network was installed in the large metal JIC box on the concrete bulkhead outside Building 07. It was earth grounded through a heavy copper wire to a copperweld rod driven into the ground directly below it.

Observation with an oscilloscope of the amplified signals from the three preamplifiers revealed that A-1 was quite free from 60 Hz synchronous noise, A-2 had a high level of 60 Hz synchronous noise, and A-3 had a moderate level. Antenna A-2 was oriented to minimize the line synchronous noise; however, the level was still objectionable.

3.2 Installation and Checkout of Subsurface Stations

All three subsurface stations were reinstalled at their original locations (see Figure 3-1) and connected to their antennas, chargers, and phone line. Air velocity sensors were installed at Stations #1 and #20. No sensor was available for Station #2 so it was set up to give a NORMAL indication with no sensor connected.

During the system checkout several problems were encountered and repaired. The most severe problem encountered was chatter of the antenna tuning relay when the transmitter was properly tuned in the DATA/REPLY mode. This was determined to be caused by EM coupling from the transmitter antenna into the phone line where it was rectified by the steering diode bridge and activated the paging circuit. Activation of the paging circuit caused the transmitter to switch to the VOICE mode and the antenna relay to close. As soon as the antenna relay transferred to the voice position, the EM feedback loop was broken, the unit switched back to the DATA/REPLY mode and the cycle began again.

The problem was solved by installation of a lowpass filter at the input to the steering diodes from each side of the phone line to ground.

No antenna current indication could be obtained for Station #20 in the VOICE uplink mode. The problem was finally traced to a piece of dirt lodged between the armature and the coil of the antenna tuning relay. Removal of the dirt cured the problem and the station operated normally.

During checkout of Station #2, the DATA/REPLY VCO had to be retuned because it was low in frequency by about 10 Hz. Further monitoring indicated it was still drifting and behaving in an erratic manner. After demonstration of system operation, it was removed from the mine and returned to WGL in Boulder for further testing and repair.

3.3 Demonstration of System to USBM

After completion of system checkout, WGL personnel demonstrated system operation to Mr. Bob Bradburn of USBM, who had been designated by the T. P. O. as his representative.

Voice paging, voice telephony, data status monitoring, and coded reply messages were received at the surface station via phone line from each subsurface station. The phone line was then disconnected and 2-way EM communications were demonstrated. Mr. Bradburn asked questions via the direct audio voice downlink, and coded reply message responses were received from the subsurface stations.

The FM voice uplink was also demonstrated. Voice quality and signal-to-noise ratio were acceptable from Station No. 1 using Antenna A-1 (the closest one), which was about 540 feet away. Signal-to-noise ratio was not adequate from Station No. 1 using the other two surface receiving antennas.

FM voice uplink signals from Station No. 2 were very marginal because of the high level of 60 Hz synchronous noise at surface antenna location A-2.

FM voice uplink from Station No. 20 was acceptable after repair of the antenna tuning relay (previously discussed); however the signal-to-noise ratio was not adequate for high quality voice communication.

After completing the demonstration at the surface station, Mr. Bradburn went into the mine for demonstration of the subsurface stations. Three-way paging and voice telephony were conducted between the surface station and two subsurface stations. Again, two-way through-the-earth EM communications were demonstrated with Mr. Bradburn operating the subsurface station.

4.0 CONCLUSIONS, RECOMMENDATIONS, AND FUTURE APPLICATIONS

The time allotted for the reinstallation of the system and demonstration to USBM did not permit extensive in-situ testing of the modified system. The conclusions presented herein are based, therefore, on a limited number of experiences with the system, rather than statistically meaningful figures and data.

4.1 Conclusions

The modifications incorporated in the system have improved the performance and quality of the paging and voice telephony operational mode of the system. The modifications to the subsurface voice receivers have reduced the objectionable noise output and have improved reception of downlink voice signals.

The addition of guide rails and test switches have improved the maintainability of the subsurface stations. The Test/Control Fixture provides a useful tool for setup and testing of the subsurface station electronics modules outside the mine. Addition of regulators, filters, and transistor switches in the subsurface transmitters, together with replacement of the CD4009AE and CD4010AE integrated circuits should improve the reliability and performance of the system.

Addition of the CD4017AE counter in the Reply message decoders should greatly reduce the probability of false or ambiguous replies. The clarity of the reply certainly justifies the additional delay (approximately 5-10 seconds) before the message is displayed.

The addition of preamplifiers to the surface receiving antennas permits better selection of a suitable location for them. The limitations imposed by surface developments such as buildings, roads, power lines, parking lots and fences, together with a limited amount of Twinax cable on hand, did not permit sufficient optimization of the signal-to-noise ratio for good quality voice uplink signals. Previous theoretical studies [1] have shown that the limitations imposed by permissibility requirements and high surface noise environments would restrict the usefulness of such systems to mines with very shallow overburdens and/or very low conductivity.

One system problem presently remains unresolved, the instability of the subsurface station DATA/REPLY VCO's. The present VCO uses a type CD4007AE COS MOS integrated circuit in a voltage controlled multivibrator developed by RCA. With a regulated voltage source and components selected to minimize temperature effects, the circuit exhibits excellent short term stability and acceptable temperature stability. The drift during warmup, however, and unexplained frequency changes when the unit has been turned off for a period of time, make it unsuitable for long term unattended operation. WGL is presently investigating other circuits suitable for this application under an in-house funded research program.

4.2 Recommendations

It is recommended that USBM personnel exercise the present system on a regular basis (say, weekly) to accumulate performance statistics and a record of operational characteristics. Performance of each of the various operational modes should be tested and the results recorded. System maintenance should also be recorded in detail, since component failures or the need for frequent adjustments would indicate the need for a design change in future systems.

The use of a system concept which employs independent, modular subsystems is recommended for future systems. This concept permits tailoring the system to the requirements of a particular mine or installation, facilitates maintenance, and provides flexibility for future expansion or modification.

4.3 Future Applications

The overall objective of this task was to develop a quasi-hardened, fixed location, in-mine communications subcenter for use in normal mine operations and for post disaster rescue operations. Information from a large number of subcenters was to be gathered together on a single display at the central station. The earth overburden is used as a 2-way communication medium, but the signal path can be changed to use existing mine phone lines or to use both links simultaneously.

This task has now been completed including the design, fabrication, installation, and demonstration of an engineering model of the system using three subcenters. It is useful, in retrospect, to re-evaluate the basic system concepts based on the results achieved, to discuss problem areas, and to consider potential applications in operating mines.

1. The basic concept of transmitting digital data and beacon codes through the earth to a central collection point from multiple stations is entirely feasible, using different frequency allocations in the 3-5 kHz band. The signaling depth is limited by conductivity of the earth, the noise environment, and the antenna moment. Therefore, the optimum system should utilize a transmitter power amplifier and antenna system designed to maximize antenna moment and still remain intrinsically safe. It may be desirable to increase the number of condition monitors available per station. This could be accomplished either by reducing the number of beacon replies or by increasing the code word length.

2. The use of the two-wayvoice link via phone line is useful since it permits an interface to the system from remote conventional mine pagers, provides a redundant link to the surface, and is a convenient means to check out both the phone line and through-the-earth links from a single point on the surface.

3. The performance of the NBFM voice uplink through the earth using 7 kHz carrier was marginal. This is attributed in part to the bandwidth limitation of the antenna system, but mostly to the high noise environment existent over the Bruceton mine. Acceptable operation of this link through 1000 feet of overburden with conductivities of 10^{-2} mhos/meter,

using an intrinsically safe transmitting system is questionable unless the surface noise environment is extremely low. The NBFM link can be used on the phone line and by using different carrier frequencies provides additional 2-way voice communications on separate channels using a single phone line.

4. The direct audio voice downlink function is useful in emergencies, since subcenters equipped with direct audio receivers and beacon code transmitters provide two-way links to the surface. For daily operations this link may be impractical because the surface transmitter requires deployment of an antenna over the desired coverage area. This may be impractical for large mines; however limited coverage can be provided over certain areas using mobile equipment deployed only for an emergency. Such a system has added merit when individual miners are also equipped with manpack voice receivers.

5. It is also possible to incorporate a call-alert feature in the system whereby the phone line is used to activate the subcenter transmitter and by selective addressing codes alert miners equipped with portable receivers. This function was not included in the present system but could be incorporated in future systems to enhance their usefulness.

Based on our experience with the present system and the above analysis, it is possible to define second generation prototype equipment which could be fabricated and demonstrated in an operating mine.

The surface center would provide basic functions and incorporate features as follows.

- 2-way simplex voice communications via phone line to any one or all subcenters using direct audio or on any one of six separate channels using narrowband frequency modulation (NBFM).

- Selective calling via phone line and subcenter EM transmissions to any one of 30 addressable call-alert receivers plus one common all-call address.

- Receiver system for sensing and displaying the through-the-earth transmissions from each subcenter for automatic monitoring of in-mine condition sensor and for manually generated code responses.
- Handset for normal voice communications and loudspeaker for paging and audible alarm.
- Indicator lights to display three (3) levels of condition sensor data from 3 sensors at each subcenter.
- Display lights to indicate reception of any one of three beacon codes from each subcenter.
- A means of indicating which of the six (6) NBFM channels are in use on the phone line.
- A method of calling any one of 30 addressable call-alert receivers located within detectable range of a subcenter which automatically retransmit such signals using a through-the-earth mode.
- A means for generating a distinguishable all-call signal which, when retransmitted by all subcenters, can be received by every call-alert receiver within detection range of the subcenters.

Each in-mine subcenter should be designed on the basis of intrinsic safety and would provide:

- 2-way voice communications via phone line to any other station using direct audio or on any one of six channels using NBFM.
- Full-wave type transmitter and loop antenna capable of transmitting 1) automatic condition data from a single sensor, 2) coded beacon responses, 3) call-alert signals to portable receivers.
- A direct audio voice receiver and antenna system capable of receiving voice signals and call alert signals which are transmitted through the earth from the surface.

- Operation from a 12-volt battery which is continuously trickle-charged from the 440 volt AC power sled.
- Automatic condition monitoring of 3 sensors at approximately 10 minute intervals using three adjustable sensor ranges to indicate normal, caution, and alarm conditions.
- A means to interface voice signals received on any voice channel to the 470 MHz transmission system in the mine.
- A full-wave class S transmitter and resonated loop antenna system capable of retransmitting through-the-earth the call-alert signals received from the surface center, the three coded beacon responses and the automatic condition monitor data.
- A means of indicating which of the six (6) NBFM channels are in use.
- A handset for originating and receiving voice transmissions via the phone line.
- A direct audio voice receiver and loudspeaker for receiving through-the-earth voice transmissions.

The portable call-alert receivers would provide both visual and aural means to indicate reception of a preselected address code and be capable of distinguishing between normal call-alert signals and an all-call signal.

This prototype system should be fabricated using solid state circuitry whenever feasible and should utilize modular construction techniques so that certain basic functions can be easily expanded or omitted without affecting performance of remaining functions. Most of the basic subsystems required for this prototype system have already been developed and demonstrated. Areas where further work is necessary include:

- The design of a stable frequency generator for FSK data transmissions.
- Development of an address code for the call-alert system and the portable receivers.
- Breadboarding and testing the multichannel NBFM voice system for use on phone line and develop method indicating channel usage.
- Developing methods which may be either hardwire or radio for relaying data from surface antenna locations to central station.
- Interfacing voice signals between subcenter voice channel and 470 MHz transmission system in mine.

5.0 REFERENCES

[1] "Monitoring, Locating and Communication System for Normal Mine Operating and for Post-Disaster Rescue Operations," J. W. Allen and R. F. Linfield. Submitted to USBM on Contract H0220073, 1 April 1973.

PART III

ARMCO #9 LOCATION SYSTEM DEMONSTRATION

By
R. F. Linfield

CONTENTS

1.0 INTRODUCTION

A test and demonstration of the EM location system was conducted on June 2 and 3, 1973 for the Bureau of Mines at the Armco #9 coal mine near Bandytown, West Virginia. This effort was conducted as a supplemental agreement to the contract to cover the cost of equipment checkout and for engineering services required at the mine.

Two different types of transmitters were furnished; 1) a portable half-wave transmitter mounted in the top of a miner's cap-lamp battery and using a 90' loop antenna enclosed in a reel, and 2) a full-wave belt type transmitter using a vertical magnetic dipole (VMD) antenna consisting of 500 feet of #12 AWG wire. Operating frequencies were 2900 Hz and 2500 Hz. Spare transmitter units of each type were furnished to insure a successful demonstration. Three manpack location receivers were also supplied, along with one helmet type receiver which could be used to demonstrate the call-alert concept.

A three-man team consisting of 1 engineer and two technicians departed from Boulder on June 1, 1973 to check out the system in the mine on Saturday, June and then to demonstrate its performance to approximately 40 visitors on Sunday, June 3.

The test results obtained were only qualitative but are presented here because the operational experience gain at this exercise could have useful implications at future real emergencies.

2.0 TEST CONDITIONS AND RESULTS OBTAINED

The Armco #9 Mine is located near Bandytown, West Virginia about one and a half hours' drive from Charleston. The mine portal is on a ledge at about 1600 feet elevation. Seismic and EM equipment vans were located on this ledge near the portal. A 15' coal seam (of which 7' is mined) is exposed at the bottom of a 200' cliff cut into the mountainside. Access to the area over the mine could be gained via four-wheel drive vehicle or on foot. Working depth for the demonstration exercise was 350' to 400'. Distance from the portal to the in-mine preselected location was approximately 1300 feet. The surface over the mine was covered with heavy vegetation (trees and bushes) which, along with the steep slopes, made it extremely difficult to traverse. Since the primary objective of this task was to demonstrate the EM location system capabilities, no quantitative performance data was taken, nor is the conductivity of the overburden known. Test and demonstration results are, however, useful from an emergency operations standpoint.

The WGL team arrived on site at 10:00 am on Saturday. One 2900 Hz full-wave transmitter was operational within 10 minutes after two men arrived at the preselected in-mine location. This installation time includes the deployment of the 500' of #12 wire by two men. This loop antenna was wrapped around three pillars of coal in a single turn rectangular configuration approximately 50 by 200 feet. The 2500 Hz half-wave transmitter was set up by one man in less than five minutes, including the deployment of the 90' reel antenna, into a circular configuration within an entry cross-cut. This separation between the centers of the two loop antennas was 50 feet, as scaled from the mine map.

The antenna moments of the full-wave transmitter at 2900 Hz was about 20 times that of the half-wave system, at 2500 Hz., i.e., 1800 as compared to 90 ampere-turn-meters^2.

After installing the antennas and leaving the mine, the location receivers were operated outside and near the portal, 1400 feet away from the transmitters. The full-wave transmitter 2900 Hz was immediately detectable and a null line determined immediately by rotating the receiver loop in the vertical plane. The half-wave transmitter at 2500 Hz was not detectable outside the portal at the 1400 foot range.

The location receivers were subsequently transported to the hilltop over the mine workings via a 4-wheel drive vehicle. Two surface locations over each transmitter were then determined within about 20 minutes, beginning about 400 feet away at the point where the vehicle was parked. It has since been estimated that the surface location over the 2900 Hz transmitter could have been determined beginning at the portal and walking the null line (with deviations around the cliff) in approximately one hour. Most of this time would be spent climbing the steep slope and making a path through the thick underbrush.

It turned out that the null location of the half-wave transmitter with the smaller antenna was easier to determine even though the signal amplitude was about 20 dB less than that obtained with the full-wave system. This is attributed to the smaller antenna generating a dipole moment which appeared as a point source, of the dimensions of the full-wave transmitting antenna approached the mine depth and appeared as a much larger source.

The three team members independently located the half-wave transmitter, and these location points were all within five feet of each other. This location was paced off and was found to be about 15 feet downslope from the surveyed location. This error could be the result of a 30° slope of surface terrain.

The null locations obtained on the full-wave transmitter by team members varied an estimated 20 feet with points on a line along the long axis of the subsurface transmitting antenna. The average location obtained was about 50' away from the other location and in the right direction.

Upon leaving the surface area, periodic stops were made along the road to obtain a qualitative measure of detection range.

The half-wave transmitter (2500 Hz) was detectable an estimated 1000' from the null location. The full-wave transmitter was detectable up to about 3500 feet.

A helmet receiver operating at 2900 Hz was used to demonstrate the call-alert concept whereby a location type transmitter can be used to alert miners. Signal reception was obtained in the mine from the full-wave transmitter. Outside the portal the unit was inoperative. The existence of other cables and conductors in the entry traversed probably contributed to the range achieved with this unit.

During the actual demonstration on Sunday, June 3, one member of the WGL team was stationed inside the mine to describe and demonstrate the transmitter operation to the groups of visitors. Another team member was stationed on the hill and remotely demonstrated the null location process via a special TV link to the communications van and TV monitors near the portal. The third team member set up spare transmitters and receivers near the portal so visitors could see the location equipment and hear the transmitted signals.

The EM location system's transmitters caused considerable interference with other EM systems being demonstrated and therefore could only be operated intermittently during the demonstration.

3.0 CONCLUSIONS AND RECOMMENDATIONS

Although the objective of this task was primarily to demonstrate the EM location system capabilities to the Bureau of Mines, the experience gained on this exercise could be applied to future emergency operations. Since no quantitative data was obtained, only generalized conclusions can be given concerning the system's performance.

The Armco #9 mine is typical of many such mines in West Virginia. At such mines the heavy vegetation and steep terrain could seriously increase the time required for surface searches of trapped miners, particularly in the larger mines where a considerable area must be covered. The use of airborne receivers in helicopters could reduce this search time if adequate signals and detection capabilities can be achieved and if weather is suitable for flying. Accurate surveying over this type of mine could be extremely difficult because of the terrain and vegetation. Locations obtained in a real emergency usually must be related to the mine map, using tie points to determine drilling points for life support and rescue. This could be time consuming because of the scarcity of the points from the mine workings to the surface. As more experience is gained with the EM location system, its accuracy may be refined using slope corrections. The system itself could then be used as a simple means for locating the points on the surface which could later be used to establish locations relative to the mine map during an emergency. The system also could be used to determine surface boundaries of mine workings.

When the EM location system is operated in conjunction with other EM communication systems, the interference caused by one system on the other must be considered. The EM location transmitter does interfere with direct audio voice reception in manpack receivers, although the 10% duty cycle allows reception between signal pulses. A miner equipped with both an EM location transmitter and a voice receiver could of course communicate with the surface by shutting off his transmitter to receive voice messages.