COAL MINE RESCUE AND SURVIVAL SYSTEM

VOLUME II

COMMUNICATIONS/LOCATION SUBSYSTEM

FINAL REPORT

September 1971

Prepared for

BUREAU OF MINES
U.S. Department of the Interior

Under Contract H0101262

By

WESTINGHOUSE ELECTRIC CORPORATION
Special Systems
Baltimore, Maryland

COAL MINE RESCUE AND SURVIVAL SYSTEM

VOLUME II

COMMUNICATIONS/LOCATION SUBSYSTEM

FINAL REPORT

September 1971

Prepared for

BUREAU OF MINES
U.S. Department of the Interior

Under Contract H0101262

By

WESTINGHOUSE ELECTRIC CORPORATION
Special Systems
Baltimore, Maryland

TABLE OF CONTENTS

Section	Page
1. INTRODUCTION	1
1.1 NAE Recommendations	1
1.2 The Communications System	4
1.3 Program Synopsis	6
1.4 Related Reporting	9
2. ELECTROMAGNETIC COMMUNICATIONS SYSTEM	11
2.1 Predesign Tasks	11
2.1.1 Theoretical Analysis	11
2.1.2 Natural and Cultural Noise	16
2.1.3 Field Measurements	16
2.1.4 Electromagnetic Predesign Summary	44
2.2 Design and Fabrication	45
2.2.1 Design Goals and Guidelines	45
2.2.2 Make or Buy Decisions	45
2.2.3 Description of Equipment	45
2.2.4 Performance Specifications	52
2.2.5 Breadboarding and Testing	53
2.2.6 Final Design Considerations	53
2.2.7 Design Reviews and Design Modifications	54
2.2.8 Fabrication and Assembly	57
2.3 Predemonstration Tests	60
2.3.1 Laboratory Tests	60
2.3.2 Field Tests	60
2.3.3 Design Modifications	61

Section	Page
2.4 Demonstration Tests	61
2.4.1 Site Description	61
2.4.2 Ground Conductivity	61
2.4.3 Signal and Interference Comparisons of Voice Downlink	62
2.4.4 Signal and Interference Comparisons with Beacon Uplink	62
2.4.5 Results of Voice Downlink Tests	62
2.4.6 Results of Beacon Uplink Tests	66
2.5 Performance Evaluation	66
2.5.1 Voice Downlink	66
2.5.2 Beacon Uplink	69
3. SEISMIC LOCATION/COMMUNICATIONS SYSTEM	77
3.1 Predesign Tasks	78
3.1.1 Data Base	78
3.1.2 Detection Study	78
3.1.3 Location Solutions and Error Study	84
3.1.4 Predesign Field Tests	90
3.1.5 Summary of Results	111
3.1.6 Specific Conclusions	112
3.2 Design and Fabrication	114
3.2.1 Design Goals and Guidelines	114
3.2.2 Make or Buy Decisions	114
3.2.3 Description of the Equipment	114
3.2.4 Equipment Specifications	117
3.2.5 Breadboarding and Testing	120
3.2.6 Design Tradeoffs and Design Decisions	120
3.2.7 Design Reviews and Design Modification	125
3.2.8 Fabrication and Assembly	125

Section	Page
3.3 Predemonstration Testing	126
3.3.1 Laboratory Testing	126
3.3.2 Imperial Mine, Erie, Colorado	126
3.3.3 Clyde Mine, Fredricktown, Pennsylvania	131
3.3.4 Harewood Mine, Longacre, West Virginia	135
3.4 Demonstration Tests	145
3.4.1 Phase I - Chronology	145
3.4.2 Engineering Tests	147
3.4.3 Summary of System Performance	153
3.5 Performance Evaluation	166
3.5.1 Summary of Performance	166
3.5.2 System Results	166
3.5.3 Major Problem Areas	168
4. CONCLUSIONS AND RECOMMENDATIONS	175
4.1 Electromagnetic System Conclusion Summary	175
4.1.1 Voice Downlink	175
4.1.2 Coded Beacon Uplink	177
4.1.3 General Comments	177
4.1.4 Recommendations	178
4.2 Seismic Location System Conclusion Summary	180
4.2.1 Signal Detection	180
4.2.2 Location System Performance	181
4.2.3 System Location Accuracy	181
4.2.4 General Comments	182
4.2.5 Recommendations	182
Appendix A. Communications/Location Subsystem Operating Procedures	A-1
Appendix B. Description of Computer Program Miner and Location Error Analyses	B-1

Section		Page
Appendix C.	Electric Blasting Cap Hazards and Explosive Seismic Sources	C-1
Appendix D.	Geophysical Data Base	D-1

LIST OF ILLUSTRATIONS

Figure		Page
1-1	Mine Communication/Location Subsystem	8
2.1-1	Calculation of the Magnetic Field Excited Above a Dipole in a Homogeneous Earth	13
2.1-2	Geometry of Horizontal Wire Antenna Over a Horizontally Stratified Earth. The Observer May be Located Within Any of a Maximum of Three Layers	15
2.1-3	Vertical Magnetic Field at Surface from a Buried Horizontal Loop Antenna (VMD)	17
2.1-4	Variation of Typical Atmospheric Noise Spectra with Depth	18
2.1-5	Map of Imperial Coal Mine Showing Locations of EM and Seismic Measuring Points	20
2.1-6	Comparison of Measured Magnetic Field with Theoretical Prediction for HWA (Downlink) EM Transmissions as a Function of Frequency, Imperial Mine	22
2.1-7	Downlink Field Strength Variation with Horizontal Distance Normal to Plane of HWA	23
2.1-8	Comparison of Measured Magnetic Field With Theoretical Prediction for Beacon (Uplink) System	25
2.1-9	Measured Relative Field Strength of Beacon Magnetic Field Components vs Distance, Imperial Mine	26
2.1-10	Pre-Design Field Measurement Locations	27
2.1-11	Portion of the Clyde Mine Used for EM and Seismic Experiments	28
2.1-12	Background Magnetic Field Levels in Clyde Mine in 6 Hz Bandwidth With Loop Oriented for Minimum Coupling to Power Lines	32
2.1-13	Comparison of Measured Magnetic Field with Theoretical Prediction for Beacon (Uplink) System, Clyde Mine	34
2.1-14	Maximum Beacon Field Strength vs Horizontal Separation, Clyde Mine	35

Figure		Page
2.1-15	Pre-Design Field Measurement Locations	36
2.1-16	Geometry of Horizontal Wire Antenna, Beacon Location, and Measurement Points; Cambria Slope Mine No. 33	40
2.1-17	Observed and Calculated Field Strengths From HWA at Cambria Slope Mine	41
2.1-18	Comparison of Calculated and Observed Field Strength at the Surface Over the Beacon Transmitter at Cambria Mine No. 33	42
2.1-19	Relative Beacon Field Strength (Maximum) Versus Distance On The Surface, Cambria Slope Mine No. 33	43
2.2-1	Subsurface Components of Communications/Location Subsystem	47
2.2-2	Seismic Signaller (Thumper)	48
2.2-3	Man-Pack Voice Receiver Mounted on Battery	49
2.2-4	Geophone and Preamplifier	49
2.2-5	EM System Surface Equipment	51
2.2-6	Habitat Voice Receiver Channel Frequency Response	56
2.2-7	Frequency Response Manpack Receiver S/N 001	58
2.2-8	Beacon Receiver, Measured Frequency Responses	59
2.4-1	Subsurface Signal and Noise Field Intensity Measurements (Munson Mine No. 14)	63
2.4-2	Surface Signal and Noise Field Intensity Measurements Beacon Receiving Location, Munson Mine No. 14	64
2.4-3	Area of CMRS Demonstration, U.S. Steel Mine No. 14 Munson, W. Va.	65
2.5-1	Horizontal Magnetic Field Directly Under an Infinite HWA	68
2.5-2	Horizontal Field Strength (H_x) (dB Relative to 1A/m) Directly Under an Infinite HWA	70
2.5-3	Magnetic Field Strength in a Two Layer Earth from an Infinite Horizontal Wire Antenna at the Surface	71
2.5-4	Vertical Magnetic Field Strength on Surface, Directly Over Transmitting Loop	73
2.5-5	Magnetic Field Strength Directly Over Beacon Transmitting Loop	74

Figure		Page
3.1-1	Geometry of Point Source in Unbounded Solid	81
3.1-2	Expected Spectrum Characteristics from a Hammer Blow	81
3.1-3	Overburden Characteristics at Imperial Mine	92
3.1-4	Geological Environment at Imperial Mine	93
3.1-5	Geophysical Environment: Time-Distance Plot of Refraction Data Taken at Both Ends of a Linear Spread of Geophones	94
3.1-6	Spectrum of Coherent Noise at the Imperial Site	95
3.1-7	Geophysical Environment: Frequency-Wavenumber Plot Showing Coherent Noise at the Imperial Mine	96
3.1-8	Response of 7 Geophone Hexagonal Array	97
3.1-9	Signals From a Hammer Blow on a Plate on the Mine Floor 300 Ft Under the Center Array as Recorded on the 19-Geophone Surface Arrays and the Vertical Component of the Buried Geophone. (Preliminary Work Done at Imperial Mine by Globe Universal Sciences)	100
3.1-10	Signal and Spectrum of Hammer Blow Recorded at the Surface by Globe Universal Sciences at Imperial Mine	102
3.1-11	Signals From a Hammer Blow on an Isolated Section of Rail 155 Ft From Geophone 17 and 1475 Ft From Geophone 24. (Preliminary Work Done at Imperial Mine by Globe Universal Sciences)	103
3.1-12	Signal and Spectrum of a Hammer Blow Recorded Below the Surface at the Imperial Mine	105
3.1-13	WGL Observation at Imperial Mine	106
3.1-14	Hammer Blows on Well Casing, Clyde Mine	109
3.1-15	Hammer Blows on Roof Bolt, Clyde Mine	109
3.1-16	Seismic Record of Hammer Blows on Rail at Clyde Mine, Pennsylvania	110
3.1-17	Signal from Cambria Slope Mine, Site 1	110
3.1-18	Signal from Cambria Slope Mine, Site 2a	111
3.2-1	Seismic Location System (Hardware Block Diagram)	115
3.2-2	Seismic Location System - Minor Location Computing	116
3.2-3	Rack Layout, Seismic Location System Signal Processing	118

Figure		Page
3.2-4	Frequency Response of Undamped Geophone Element	122
3.2-5	Frequency Response of Critically Damped GSC-11D Geophone in Plastic Case	123
3.3-1	Map of Imperial Coal Mine Showing Locations of Seismic Measuring Points	127
3.3-2	Signals Received at Imperial Mine - 11-25-70	128
3.3-3	Signal and Spectrum of Hammer Blow Recorded by WGL - 11-25-70	129
3.3-4	Comparison of Signal Response (Hammer Blow)	130
3.3-5	Imperial Mine Signals - Seismic Transmitter/Used for Locations 12-1-70	132
3.3-6	Locations Obtained at Imperial Mine	133
3.3-7	Clyde Mine Array and Source Locations	134
3.3-8	Clyde Mine - Seismic Waves from Refraction Survey	136
3.3-9	Interpretation of Refraction Survey - Clyde Mine	137
3.3-10	Clyde Mine, Miner Signals Used for Array Comparison 12-10-70	138
3.3-11	Clyde Mine, Miner Signals Used for Locations 12/12/70	140
3.3-12	Harewood Mine Array and Source Locations	142
3.3-13	Harewood Mine - Spectrum of Hammer Blow 12-19-70	143
3.3-14	Results from 1st Setup at Harewood Mine 12/20-70	144
3.3-15	Harewood Mine - Miner Signals Used for Locations	146
3.4-1	Geologic Cross Section No. 14 Mine Barricade Area	150
3.4-2	Signals Used for Location of Barricade Area at CMRSS Demonstration	151
3.4-3	Location Calculations Using Seismic Transmitter and Signal Averaging	152
3.4-4	Gary No. 14 Mine - Location Accuracies - Timber on Plate - Test 25	155
3.4-5	Gary No. 14 Mine Signals From Timber on Roof Test 27 - 1/20/71	156
3.4-6	Location Calculations - Test 27 - Timber on Roof	157

Figure		Page
3.4-7	Gary No. 14 Mine - Location Calculations - Test 23 - A Seismic Transmitter	158
3.4-8	Gary No. 14 Mine - Location Calculations - Test 23 - Seismic Transmitter	159
3.4-9	Gary No. 14 Mine Signals - Test 30 - from 10 lb Sledge on Floor	160
3.4-10	Gary No. 14 Mine - Location Calculations - Test 30 - 10 lb Sledge on Floor	161
3.4-11	Gary No. 14 Mine - Location Calculations - Test 24 - Rail on Plate	162
3.4-12	Gary No. 14 Mine, Signals - Test 26 - from Rail on Plate 1/20/71	163
3.4-13	Gary No. 14 Mine - Location Calculations - Test 26 - Rail on Plate	164
3.4-14	Facsimile of Oscillograph Monitor Record - Sledge Hammer on Plate	165
3.5-1	Seismic Noise Levels Encountered During Predemonstration Testing	167
3.5-2	Comparison of Noise Reduction - 1/7/19	169
3.5-3	Comparison of Signal to Noise Improvement Using Signal Summation	170
3.5-4	Location Results after Times are Adjusted for Anisotropic Earth	172

PREFACE

This final report on the Communications/Location System is one of four volumes prepared for the Bureau of Mines in compliance with Section 3.1 of Contract No. H0101262. The other volumes describe the rescue subsystem, the survival subsystem, and the program management. They describe work performed between June 1970 and March 1971 by the Westinghouse Electric Corporation and its subcontractors. The objective of this contractual effort was to develop and demonstrate a Coal Mine Rescue and Survival System, following recommendations by the National Academy of Engineering and as requested by the Bureau of Mines.

This Communications/Location report is divided into two basic subsystem areas: electromagnetic and seismic. The development programs conducted in each area are described chronologically, beginning with design strategy and ending with performance evaluation.

The surface system for initial location would consist of four subarrays deployed in a square approximately one-half mile across a diagonal. Analysis of the arrival time of the P-waves at each of the subarrays will give approximate location, after which the array size will be reduced to a 500-foot square to minimize the effects of an irregular topography, geologic structure, and other inhomogeneities. With the smaller array, knowledge of the depth of the mine at this location, and knowledge of rock velocity in this area, it should be possible to locate the signal source with ± 25 feet.

After location, the seismic equipment can be used to communicate with the men below. The miner below ground would use a single seismometer to trigger an audio oscillator connected to an earplug speaker. These devices have been used successfully in personnel intrusion detection. Any tool can be used for hammering - a 10 lb. hammer would be preferable if available. The signaling code and instructions for using the system could be pasted inside each miner's helmet.

With this system it would be possible to determine the number of miners trapped, their physical condition, the condition of the air in their vicinity, and perhaps an estimate of their survival time to provide the rescue team guidance on priorities with which they should explore various areas of the mine.

1.2 THE COMMUNICATIONS SYSTEM

The design, fabrication, and testing of the interim communications subsystem was undertaken by the Westinghouse Georesearch Laboratory in Boulder, Colorado. The basic communications/location subsystem problems to which this group addressed their efforts were summarized in one section of the Westinghouse proposal* which is reproduced in the following paragraphs.

Communications/Location Subsystem

Communication from surface rescue operations to miners trapped in a mine is the problem considered in this discussion. The situation existing within a mine during a disaster will be briefly considered to better define the problem. Hypothetical but realistic situations will be considered to pinpoint specific difficulties. Finally, this section briefly discusses the peculiar environmental problems associated with communications in the mine.

The Mine Disaster Situation

Just prior to a mine disaster, there will likely be one or more working sections of 8 to 15 men, depending on the mine and the mining methods employed. In addition, there will be a number of work teams composed of 2 to 4 men engaged in ore hauling trips, maintenance, safety inspections, mine construction or repair, etc. All men below surface will usually be within

* Coal Mine Rescue & Survival Systems, Proposal to U. S. Bureau of Mines in Response to RFP No. H0101262, Sec. 2.5, Westinghouse Electric Corporation, April 1970.

1 or 2 miles of each other, but may be separated by 5 to 10 miles in mines using trains or other mechanized vehicles to transport crews from the portals to the working faces.

Suddenly an explosion or explosions occur at one or more of the working faces within the mine. Some of the men in the immediate vicinity of the explosions and fires may be killed immediately. Injured and uninjured men will leave the vicinity of the explosion and fires and will seek refuge in refuge chambers, or will barricade themselves in some reasonably safe section of the mine. Some men may escape to the surface or may escape to remote sections of the mine relatively unaffected by the disaster. Smaller groups of men may be trapped anywhere within the mine and may or may not have access to refuge chambers or special equipment placed in areas designated for the construction of barricades. These men will likely have no equipment or means of communication other than that which was part of their attire at the time of the disaster. Since they might be in transit from one location to another, or in various possible work locations, their location may be completely unknown by other personnel within the mine or by men on the surface.

Immediately following a disaster it is probable that power to most, if not all, sections of the mine will be disrupted, or, if not disrupted, disconnected as a safety precaution. Therefore, previously existing communications via telephone lines or carrier system cannot be depended upon.

On the surface, the mine operators, and surface personnel and rescue forces will have information relative to the work assignments of each of the men in the mine. They will know the location of rescue chambers and/or preferred barricade locations. After the explosions and/or fires, they will not know how many men have survived the explosions, nor will they know positively where the survivors have located themselves. This would be particularly true if the exact location of the explosions are not known and if alternate rescue chambers or barricade locations were available. Even less information will be available on the surface relative to the condition and probable location of the smaller work teams which were operating trains, performing maintenance, etc.

Communications for the Mine Disaster Situation

The situation described requires communication systems to indicate the presence of miners within specific rescue chambers or barricade regions of known location. In addition it would be desirable to know the number and condition of survivors at each location.

The problem of locating and communicating with the individual miner or small groups of miners whose positions are not known is more demanding. The problem might be solved by locating the source of a signal from the lost miners. It would also be solved by providing a sufficiently sophisticated communications link such that the lost miner can designate his position to personnel on the surface.

In addition to uplink communications from the miners to the surface, downlink communications for the purpose of giving instructions, describing known conditions within the mine, and requesting information from the trapped miners would be of great value in effecting extended survival and a rapid rescue. Since this communication system is for use by frightened, confused, and perhaps injured men, it is imperative that simplicity of operation and reliability of operation be uppermost of all considerations.

The Environmental Situation

The variation of geological and geophysical characteristics from one mine to another must be considered in designing a communication system capable of performing satisfactorily at all locations, since the electrical and seismic properties of the strata from the surface of the mine down to the lowest working level will affect the performance of the communication systems.

Furthermore, it will not be sufficient to design a system capable of generating and receiving "pure" or even contaminated signals. Natural and man made noise and interference will be present at all times, and perhaps present in the extreme during a disaster. Of particular significance is man made noise or interference which will probably be greater than natural noise at many locations and which may vary widely from one location to another. Establishing upper-limit noise levels as a worst-case design condition is important in solving the communications problem.

It is also necessary to consider the effect of the system upon the mine environment. We must assure the safe operation of the equipment within the mine, being particularly concerned with the detonation of explosives or explosive environments within the mine.

In summary, the communications problem associated with a coal mine disaster will require development of hardware to permit:

- Detection of presence and location of trapped miners.
- Communications from trapped miners to rescue personnel on the surface,
- Communications from rescue personnel on the surface to trapped miners below the surface,
- Surface communications for direction of rescue operations.

1.3 PROGRAM SYNOPSIS

This volume describes the design approach used, the performance objectives, the performance evaluation, and final demonstration of the equipment which was fabricated.

Two basic types of subsystems were conceived to meet the requirements. One, for communicating with trapped miners, uses electromagnetic (EM) signaling through-the-earth and the other, utilized primarily for locating trapped miners, uses seismic signals. The surface-to-subsurface downlink is capable of communicating by EM voice transmissions. A subsurface-to-surface uplink permits communications by an EM coded beacon. The seismic portion of the system is designed to locate trapped miners by sensing subsurface hammer blows using seismic geophone arrays deployed on the surface and subsequently processing these signals to improve detectability and determine source location.

Thus, two basic subsystem development and test programs are involved, each based on different technologies and concepts. Both programs were accomplished by conducting each phase in parallel during the nine-month contractual period. An approximate month-by-month synopsis for the nine month contract duration is given below.

Date	Tasks Performed
June 1970	Initial planning and development of design approach
July	Develop design concepts and test planning
August	Conduct predesign tests at Imperial Mine in Colorado, Clyde and Cambria Slope Mines in Pennsylvania
September	Define performance specifications, finalize design, and begin fabrication
October	Complete fabrication and begin performance evaluation
November	Conduct field tests at Imperial Mine, Colorado, and evaluate system performance
December	Conduct predemonstration tests at Clyde Mine, Pa., and Harewood Mine, W. Va.
January 1971	Demonstration tests, U. S. Steel #14 Mine, W. Va.
February	Performance Evaluation, Manual and Report preparation
March	Finalize reporting and deliverables

The resulting system is shown pictorially and in block diagram form in Figure 1-1. The Communications Subsystem is designed to perform several basic functions. Its primary functions include an EM voice downlink, a coded beacon uplink, and a seismic location subsystem. Secondary functions include a downlink using explosives, and a seismic uplink relay using the EM beacon. A seismic transmitter (Thumper) for use in refuge areas is also part of the total system.

Operation of the total system during a disaster assumes the availability of certain subsurface equipments such as coded beacon transmitters, voice receivers, and seismic transmitters in refuge chambers or barricade areas. Each miner would also carry a man-pack voice receiver which operates from his lamp battery. When an emergency or disaster occurs, the surface equipment would be brought to the site. Antennas would then be deployed, geophone arrays installed, and communication and location procedures established.

These subsurface equipments, however, are not available in mines at the present time. Therefore, use of the system in an emergency or disaster

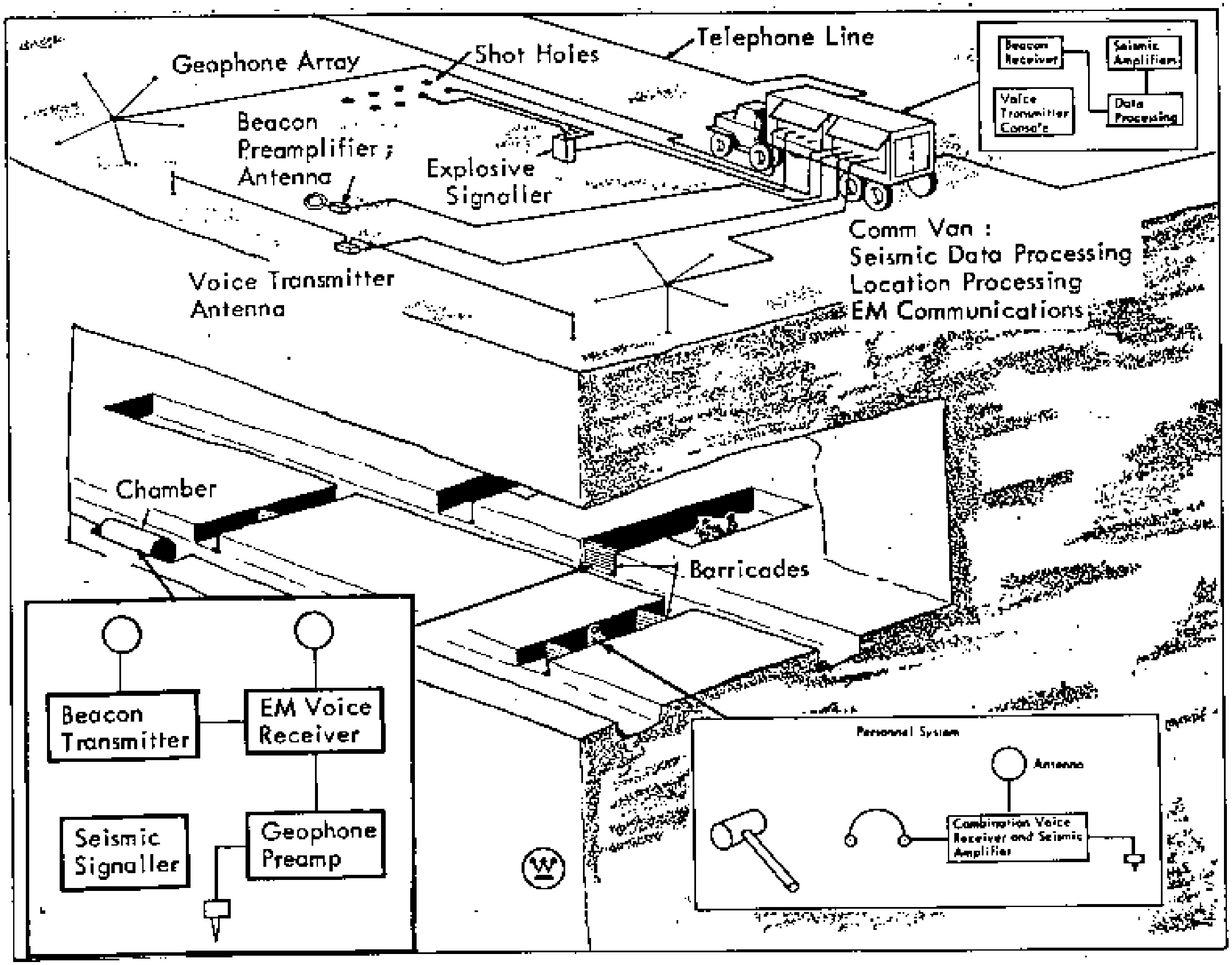


Figure 1-1. Mine Communication/Location Subsystem

situation is limited to seismic signaling. The electromagnetic voice equipment could be used by rescue personnel underground in unaffected areas of the disabled mine as an aid to coordinating a combined surface and subsurface rescue effort. Trapped miners must use available equipment such as a shoring timber or a sledgehammer to generate seismic signals. The geophone arrays deployed on the surface, and the associated electronics, detect, process, and analyze these signals to determine the presence and location of the trapped men. Multiple detonations of explosive charges can also be used on the surface to signal miners below using simple prearranged codes.

Appendix A describes the procedures for operating the Communications/ Location Subsystem. These procedures were used during the demonstration at the U.S. Steel Coal Mine #14 in Gary, West Virginia, and are representative of procedures which would be used during an actual disaster where the total system could be utilized.

1.4 RELATED REPORTING

A description of the operation and maintenance of specific hardware is covered in separate equipment manuals. These manuals include the following:

Subsurface Equipment Manual

The "Manual of Operating and Maintenance Instructions for Subsurface Communications Equipment, Coal Mine Rescue and Survival System," describes the operational and maintenance procedures on the Beacon Transmitter, the Voice Receiver, the Man-Pack Receiver, and the Seismic Transmitter (Thumper). In addition, the procedure for using the Man-Pack geophone to aid in receiving seismic signals from the surface is explained.

Surface Equipment Manual

The "Manual of Operating and Maintenance Instructions for Surface Equipment, Coal Mine Rescue and Survival System," covers the set-up and use of the Voice Transmitter (downlink) and the Beacon (uplink) surface receiver.

Seismic Location System Manual

The "Manual of Operating and Maintenance Instructions for Seismic Equipment, Coal Mine Rescue and Survival System," details the operation of the Seismic Analysis equipment, the location of the seismic geophone array system, and the network to the data processing system. Instructions are also provided for the use of explosive charges for seismic downlink signaling. Appendices include instructions for seismic refraction and surveying, and a list of pertinent manufacturers' handbooks for operation and maintenance of commercial modular units.

2. ELECTROMAGNETIC COMMUNICATIONS SYSTEM

In developing an emergency communications system for use in mine disaster rescue operations, the design efforts were directed toward meeting the requirements stated in the National Academy of Engineers Interim and Final Report on Mine Safety and Rescue, March 1970, and the U.S. Bureau of Mines request for proposal. The NAE reports identified, as a promising communications concept, a system using emergency radio beacons underground for location of and communication with trapped miners. They suggested a transmitting frequency of 500 to 1000 Hz to assure penetration even under the most adverse conditions. It was recommended that such a system could later evolve into an operational mine radio communications system with an emergency location and communications capability. The Bureau of Mines request for proposal stated that voice communications were desirable but not essential. After a detailed evaluation of the user's requirements and some preliminary theoretical calculations and experimental measurements, the Westinghouse Electric Corporation proposed and contracted to build an Electromagnetic Communications Subsystem consisting of a voice communications downlink and a coded beacon uplink. A description of the tasks performed to design, fabricate and test this Electromagnetic Communications System follows. Section 3.0 describes the separate Seismic Location System.

2.1 PREDESIGN TASKS

Fundamental to the basic system design is the development of theoretical models and the acquisition of basic data on performance characteristics. This section describes the theoretical models used for uplink and downlink communication calculations and the analysis of corroborating data obtained in Colorado and Pennsylvania coal mines.

2.1.1 Theoretical Analysis

The mathematical models used to predict EM field strengths are a simplified representation of the real earth medium. Their application proved to be very useful in the initial design phases of the EM Communication Subsystem.

Uplink Propagation

The Beacon Transmitter antenna is represented as an electrically small loop, or "magnetic dipole." The dipole is referred to as a vertical magnetic dipole (VMD) or a horizontal magnetic dipole (HMD) according to the orientation of the loop axis (the axis being perpendicular to the plane of the loop). The strength of the source is given by the dipole moment:

$M \equiv$ dipole moment = I· N· A ampere-turn-meters squared (2.1-1)

where: I = the loop current (amperes)
N = number of turns of wire in the loop
A = loop area (square meters)

The low frequency magnetic field generated by a HMD buried in a homogeneous earth has been calculated by Wait and Campbell [1953].* A graph based on their results is given in Figure 2.1-1. The ordinate on the graph is an attenuation factor, $|D|$, used to compute the amplitude of the total magnetic field, $\bar{H}$, at the earth's surface directly above the HMD. (For this configuration, there is no vertical component of H at the observation point). The abscissa represents a normalized transmitter depth: z/δ = depth/δ, where the earth "skin depth," δ, is given at low frequencies by

$$\delta \equiv \text{earth skin depth} \approx \frac{1}{(\pi \mu f \sigma)^{1/2}} \qquad (2.1\text{-}2)$$

where f is the frequency in Hertz, σ is the effective earth conductivity in mhos per meter, μ is the magnetic permeability, and δ is in meters.

The attenuation factor for the VMD configuration have been given by Sinha and Bhattacharya [1966]*. A graph of their results is given as the $|G|$ curve in Figure 2.1-1. The observer is again assumed to be directly above the source, and the total magnetic field at this point is now vertical. The graph again gives a multiplicative factor which in this case goes to unity as the influence of the earth goes to zero (i.e., as $\sigma \to \sigma_{air} \approx 0$). In Figure 2.1-1 note that the $|D|$ and $|G|$ functions converge at $z/\delta = 5$. A VMD would be more effective for shallower depths; whereas an HMD is slightly better whenever the depth is greater than five skin depths.

Both of the analyses leading to the curves in Figure 2.1-1 assumed an electrically homogeneous earth. Hence, in applying these results, one must use an appropriate average (or "effective") conductivity which best describes the real (i.e., inhomogeneous) environment. For cases in which the earth may

---

* Wait, J.R. and L.L. Campbell, The Fields of an Oscillating Magnetic Dipole Immersed in a Semi-Infinite Conducting Medium, JGR, Vol. 58, No. 2, pp. 167-178. (This analysis of Wait & Campbell actually applies to a HMD on the surface with the observer being at a variable depth. Reciprocity holds here, however, and their results may be applied directly to the reverse situation.)

** Sinha, A.K. and P.K. Bhattacharya, Vertical Magnetic Dipole Buried Inside a Homogeneous Earth, Radio Science, Vol. 1 (New Series), No. 3, pp. 379-395, March 1966.

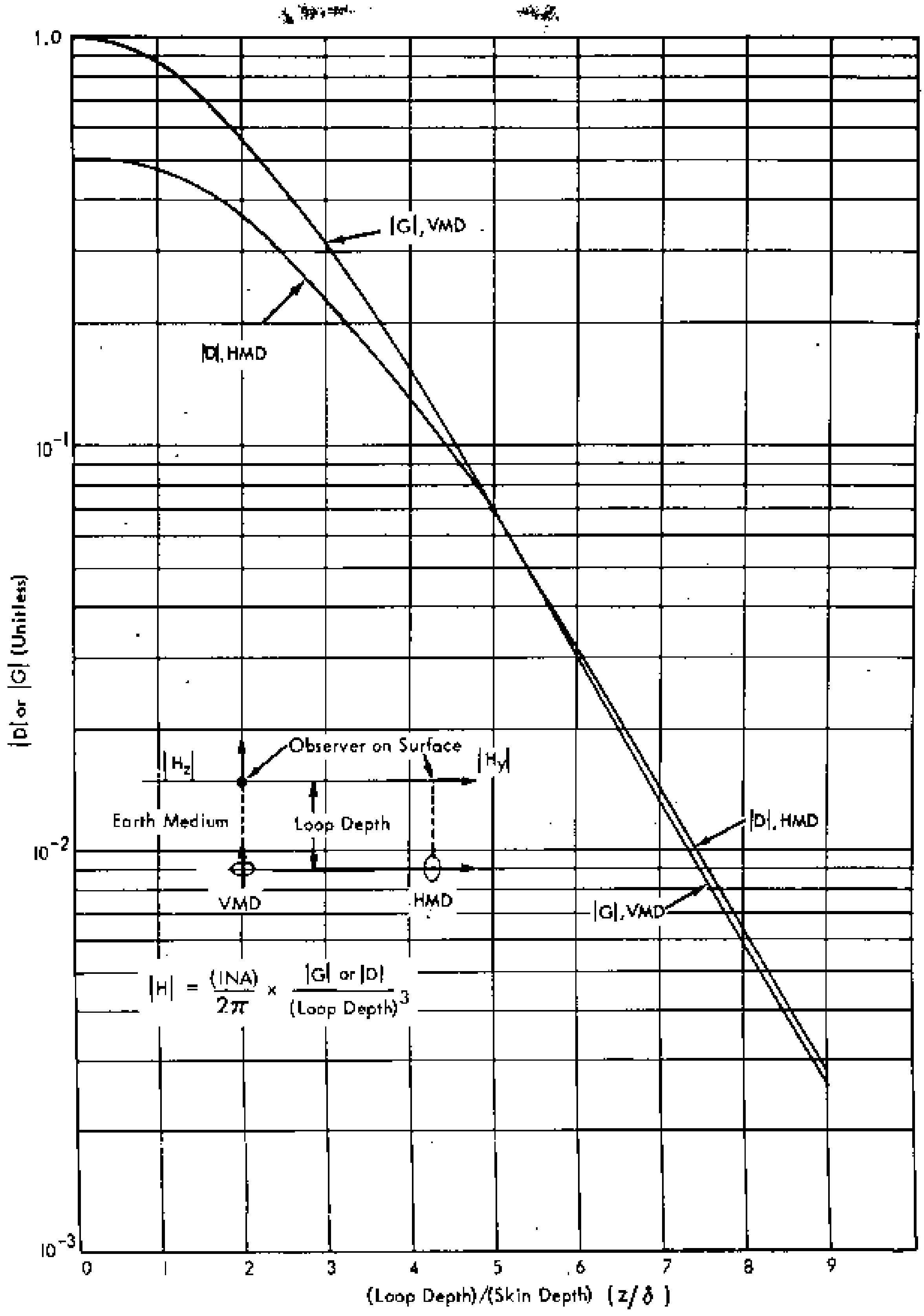


Figure 2.1-1. Calculation of the Magnetic Field Excited Above a Dipole in a Homogeneous Earth

be considered to be horizontally stratified into n homogeneous layers, an appropriate average conductivity, $\bar{\sigma}$, of the overburden material was computed as follows:

$$\bar{\sigma} = (h_1 \sigma_1 + h_2 \sigma_2 + \cdots + h_n \sigma_n) / \text{depth} \qquad (2.1\text{-}3)$$

where each layer has vertical thickness h_i meters and conductivity σ_i mhos/m, and where h_n = the antenna depth into the last layer of conductivity σ_n.

Beacon field strengths calculated from homogeneous earth models have proven to be sufficient for design considerations. Several comparisons between measured and calculated beacon field-strength data taken during the predesign field tests are given in subsequent paragraphs.

Downlink Propagation

The effects of horizontal earth stratification may be included explicitly in the calculation of the field produced by a long horizontal wire antenna if the wire may be considered effectively infinite; i.e., if the receiver depth is small compared to the distance to the nearest end of the wire. Even with this idealization, the analysis is somewhat complicated in that the electric and magnetic field components are given in terms of rather complicated integral expressions, Wait (1970).*

The geometry of the infinite line model is shown in Figure 2.1-2. Only three layers are shown, since this is the maximum number considered in the numerical work. The depth to the bottom of each layer is d_i meters. Homogeneous and two layer earth models are special cases of the three layer configuration. A computer program was written to perform electric and magnetic field strength calculations at arbitrary depth and frequency, assuming an infinite length antenna carrying one ampere of current at ground level. (We assume linearity, so that the received fields are directly proportional to antenna current.) The electric field for such a configuration is parallel to the antenna, while the magnetic field, $\bar{H}$, has both z and x directed components. Both components of the magnetic field are suitably combined in the computation to yield the total $\bar{H}$ seen by a loop oriented to receive maximum signal (H parallel to loop axis).

In predicting the field generated by an antenna of length L, where the finite length is important, only homogeneous earth models are considered. The fields at depth may then be predicted by dividing the antenna length L into a number of subsections of length $\ell \leq L$, applying the appropriate electric dipole** formulas to each subsection, and summing the results. The dipole expressions were taken from Bannister and Hart (1968).***

* Electromagnetic Waves in Stratified Media, Pergamon Press, 2nd edition, chapter 2.

** An "electric dipole" as used here means a horizontal wire antenna whose length is small compared to the range to the receiver and to an earth skin depth.

*** Quasi Static Fields of Dipole Antennas Below Earth's Surface, U.S. Navy Underwater Sound Laboratory, Report #870.

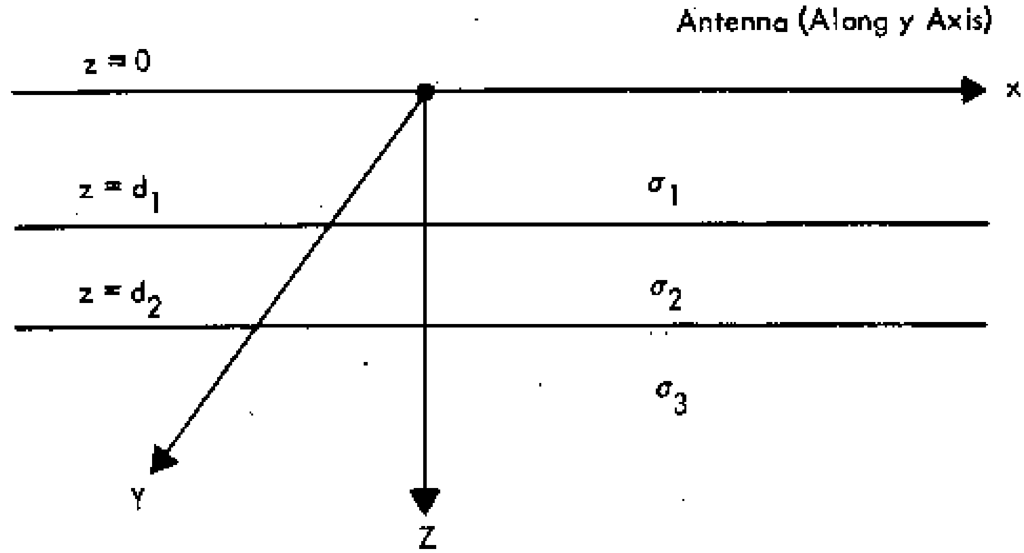


Figure 2.1-2. Geometry of Horizontal Wire Antenna Over a Horizontally Stratified Earth. The Observer May be Located Within Any of a Maximum of Three Layers

In order to reduce the complexity of the "bookkeeping" in the computer program, the receiver is assumed to be located directly below the source; i.e., the x coordinate of the receiver is zero in the finite antenna calculations. One further shortcoming of this model is that the field strengths near the grounded ends of the line cannot be calculated accurately. However, this is of little significance in the application of the results. Example horizontal wire calculations are compared with experimental data in subsequent paragraphs.

2.1.2 Natural and Cultural Noise

Low frequencies ($f < 10,000$ Hz) are required in a communications system designed to penetrate up to 1000 feet or more of earth. The background noise and interference is especially troublesome at these low frequencies and must be carefully evaluated. For the voice downlink system, the limiting component of noise is normally cultural. Cultural noise is that generated by man made devices. Natural atmospheric noise resulting from thunderstorm activity is rarely of any consequence in mines since it attenuates rapidly as it propagates through the earth. A troublesome cultural noise source in many mines is the 3-phase rectifier used to supply dc voltage to drive the mine trolleys. The steady interference from these rectifiers has a fundamental frequency of 360 Hz with significant harmonics up to several kilohertz.

For uplink beacon communications the limiting component of noise is normally either atmospheric noise generated by local and worldwide lightning activity or power line harmonic noise. Atmospheric noise passes through a pronounced minimum in the vicinity of 2.5 kHz and the magnitude of power line harmonics are substantially reduced at frequencies above 2.5 kHz. An analysis was made of the magnetic fields at the earth's surface as a function of transmitting loop depth and noise spectra for a typical earth of $\sigma = 10^{-2}$ mhos/m for several different frequencies. Results indicate that the optimum signal-to-noise ratio for a beacon system operating at a depth of 1000 feet would be obtained using a carrier frequency somewhere between 1.5 and 3.5 kHz. See Figures 2.1-3 and 2.1-4.

2.1.3 Field Measurements

Various tests in the field were made to determine key physical and environmental parameters to which the equipment would be designed. Electromagnetic and seismic measurements were obtained at three coal mines during the period July 27, 1970 to September 4, 1970. The seismic measurements are reported in Section 3.1. The following mines were visited during the time periods shown.

July 27, 1970 - August 11, 1970
Imperial Mine
Imperial Coal Company
Erie, Colorado

August 17, 1970 - August 27, 1970, and
September 3, 1970 - September 4, 1970
Clyde Mine, near Clyde shaft
Republic Steel Corporation
Fredericktown, Pennsylvania

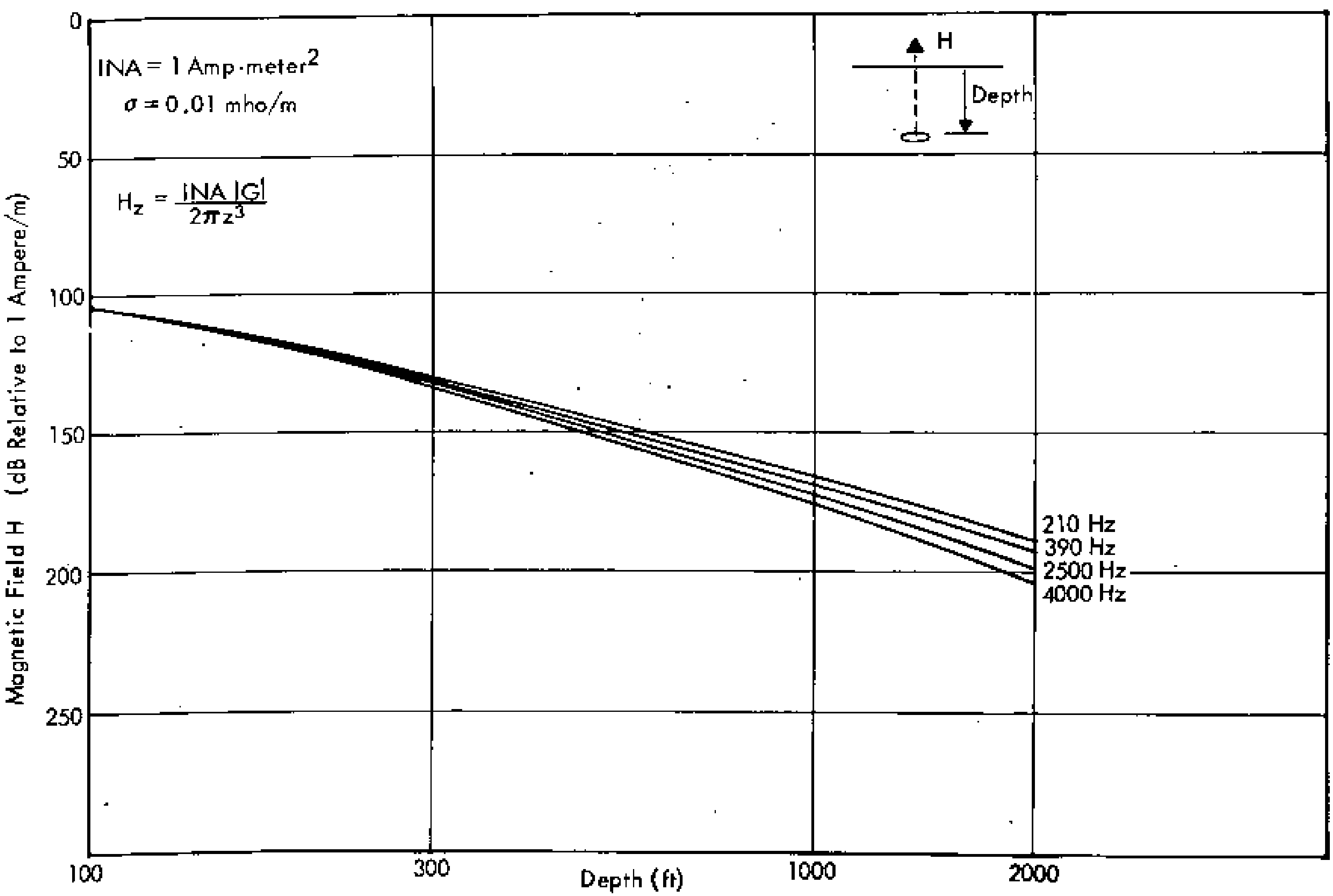


Figure 2.1-3. Vertical Magnetic Field at Surface from a Buried Horizontal Loop Antenna (VMD)

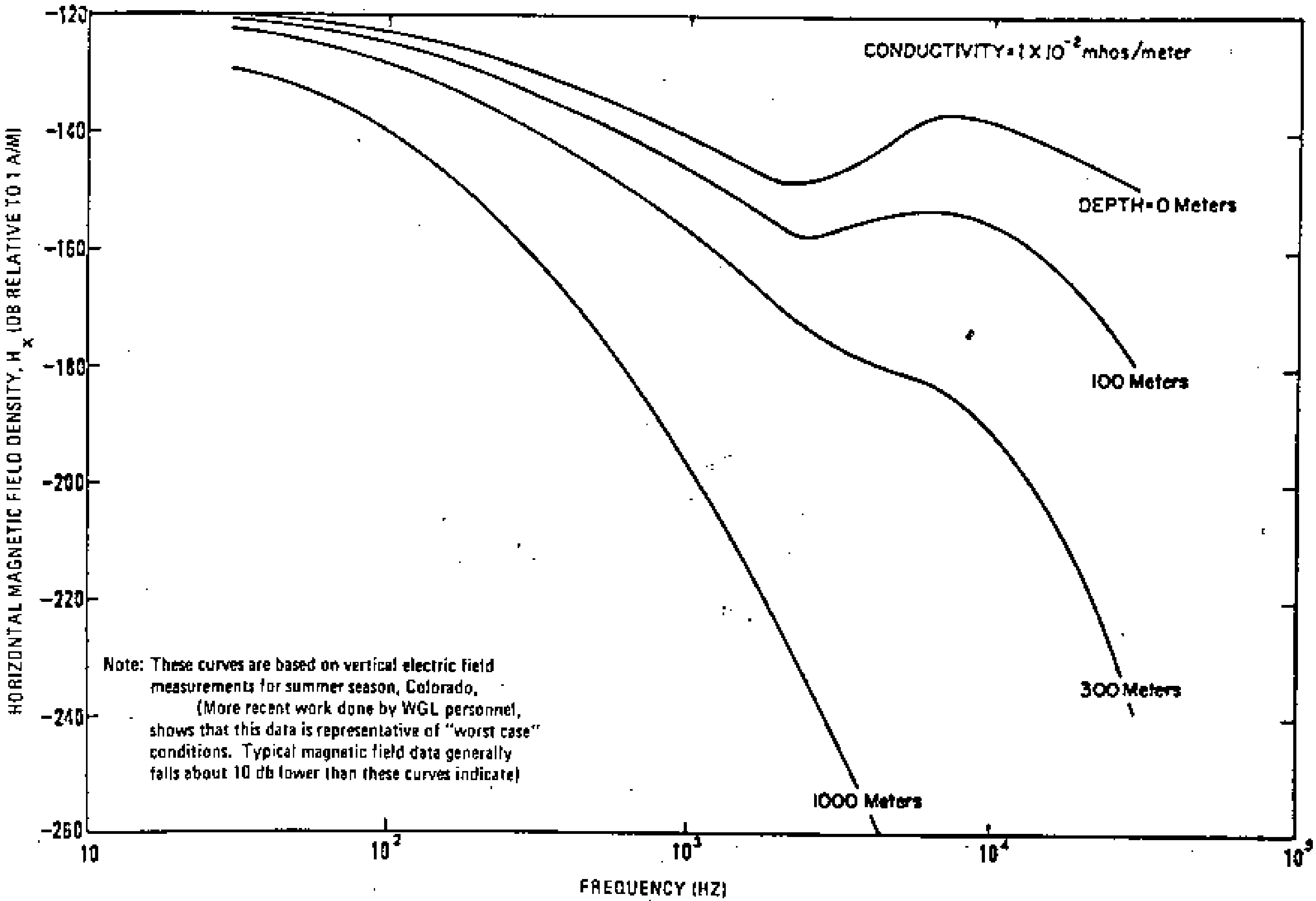


Figure 2.1-4. Variation of Typical Atmospheric Noise Spectra with Depth

August 27, 1970 - September 2, 1970
Cambria Slope Mine No. 33
Bethlehem Mines Corporation
Ebensburg, Pennsylvania

Electromagnetic data obtained at each of the three mines included a conductivity survey, measurements of the performance of the beacon uplink, voice downlink evaluations, and subsurface background noise measurements. Each mine's characteristics and measurement results are discussed in the following paragraphs.

Imperial Mine, Colorado

A map of the mine workings and the location where tests were conducted are shown in Figure 2.1-5. At the hoisting shaft, the depth to the bottom is 290 feet. This is a representative depth for most sections of this mine. Seismic tests were performed above and in the main north entries. The electromagnetic beacon was located in #1 and #2 East, just west of #2 North, and the voice transmitter antenna was located above and parallel to #1 and #2 West and #1 and #2 East. Voice downlink transmissions were made in the east-west entries and as far out in main north as possible. The overburden consists largely of sandstone with interbedded layers of shale and partly consolidated siltstone. The Laramie coal seam is approximately 11 feet thick at this location with entries bored in the bottom eight feet of coal, leaving three feet of coal on the ceiling to maintain the integrity of the shale roof.

The Imperial Mine is adjacent to the Eagle Mine, which is also owned and operated by the Imperial Mining Company, Denver, Colorado. The Imperial Mine is a much older mine with very little coal remaining; hence operations are at a relatively low level. During the time that the measurements were made, the Imperial Mine was not operating and only supervisory maintenance personnel were at the mine. This made an ideal test bed for the initial tests, since there was complete freedom for using all of the mine facilities.

The apparent conductivity of the earth was measured using galvanic conductivity methods discussed by Keller and Frischknecht (1966).* The basic method involves the measurement of earth potential between two points on the surface while current is injected into the earth between two other points. The apparent conductivity for one measurement is calculated from

$$\sigma_a = \frac{K I}{V} \qquad (2.1\text{-}4)$$

where I and V are the measured current and voltage and K is a geometric factor based on the relative geometry of the electrodes. A sounding is accomplished by measuring σ_a at successively larger electrode spacings, thus

* Keller, G. and F. Frischknecht (1966). Electrical Methods in Geophysical Prospecting, Pergamon Press.

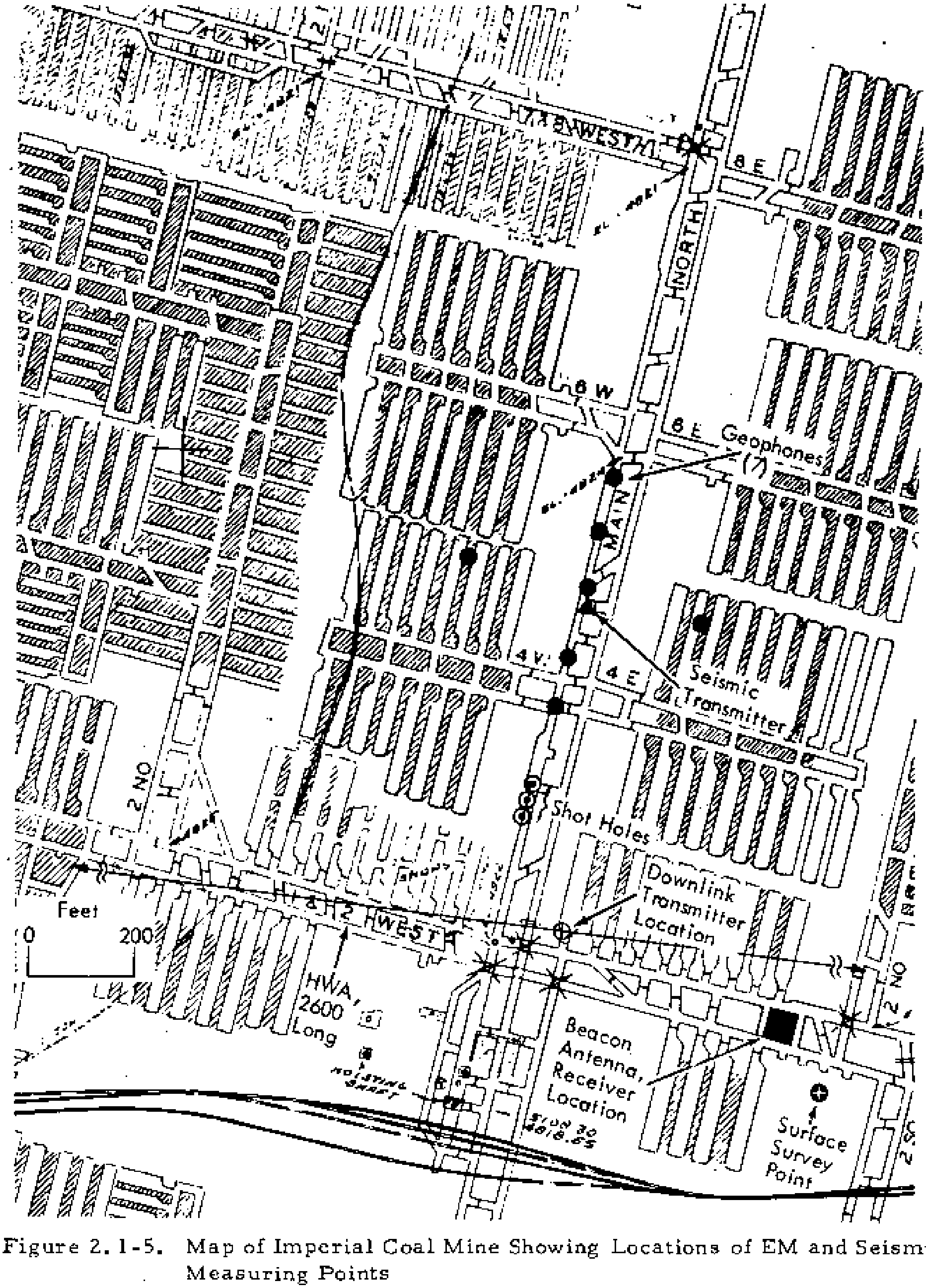


Figure 2.1-5. Map of Imperial Coal Mine Showing Locations of EM and Seismic Measuring Points

effecting a deeper current penetration. For the predesign tests, a frequency of about 20 Hz was used to approximate dc.

Two arrays of the electrodes, arranged in line, were used. In the Eltran array,* the electrodes were equispaced and current was injected into the electrode pair at one end and potential was observed between the other pair. Beyond spacings of about 50 meters, a dipole-dipole array* was used with dipole lengths held constant at 50 or 100 meters while the dipole separation was varied. Values for apparent conductivity were plotted versus electrode separation and compared with theoretical curves to obtain the equivalent layered earth situation, using the partial curve matching technique described by Keller and Frischknecht.* The average conductivity is calculated using the formula given in Section 2.1.1.

In the results shown below, σ represents the conductivity, in mhos/meter, of the layer indicated by the corresponding subscript. Similarly, h indicates the thickness of the corresponding layer.

$\sigma_1 = 3.4 \times 10^{-1}$ mho/m	$h_1 = 2.4$ meters
$\sigma_2 = 1.46 \times 10^{-1}$	$h_2 = 15$
$\sigma_3 = 3.06 \times 10^{-1}$	$h_3 = 7$
$\sigma_4 = 8.56 \times 10^{-2}$	

This was later reduced to an equivalent 3 layer structure so that field calculations could be made using the 3 layer analysis computer program. (Figures 2.1-6, 2.1-7.) The average conductivity of the surface in the vicinity of the main North entry was found to be 1.2×10^{-1} mho/meter by using Equation 2.1-3. These conductivity measurements were used to calculate the theoretical performance of the Electromagnetic Communications System.

A horizontal wire antenna for voice transmission was installed at the surface over the entry marked #1 West and #1 East at a depth of about 290 feet. The antenna was one mile long and was fed near the center with ground terminations at each end. The average antenna current was .5 amperes. The total magnetic field strength from the antenna was measured directly under the antenna, 200 feet down the #2 East entry. Figure 2.1-6 compares measured and theoretical field strength as a function of frequency. The curve is normalized for one ampere of transmitting current. Figure 2.1-7 shows the variation of the received field strength at a frequency of 1000 Hz for various horizontal separation distances ranging from one meter from the antenna to about 550 meters from the antenna. These measurements were taken in the main North entry. The field strength did not vary as a function of antenna length

---

* Ibid.

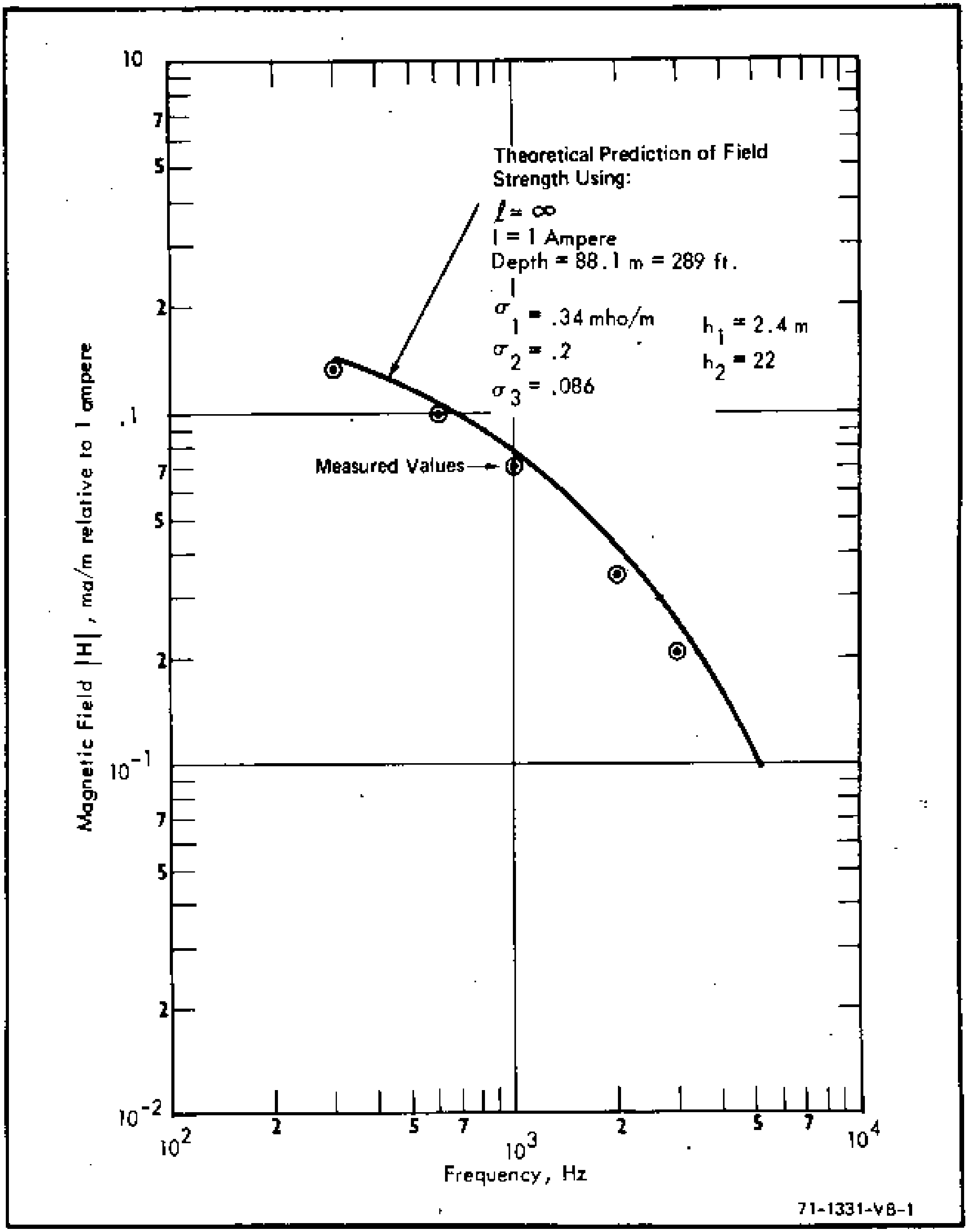


Figure 2.1-6. Comparison of Measured Magnetic Field with Theoretical Prediction for HWA (Downlink) EM Transmissions as a Function of Frequency, Imperial Mine

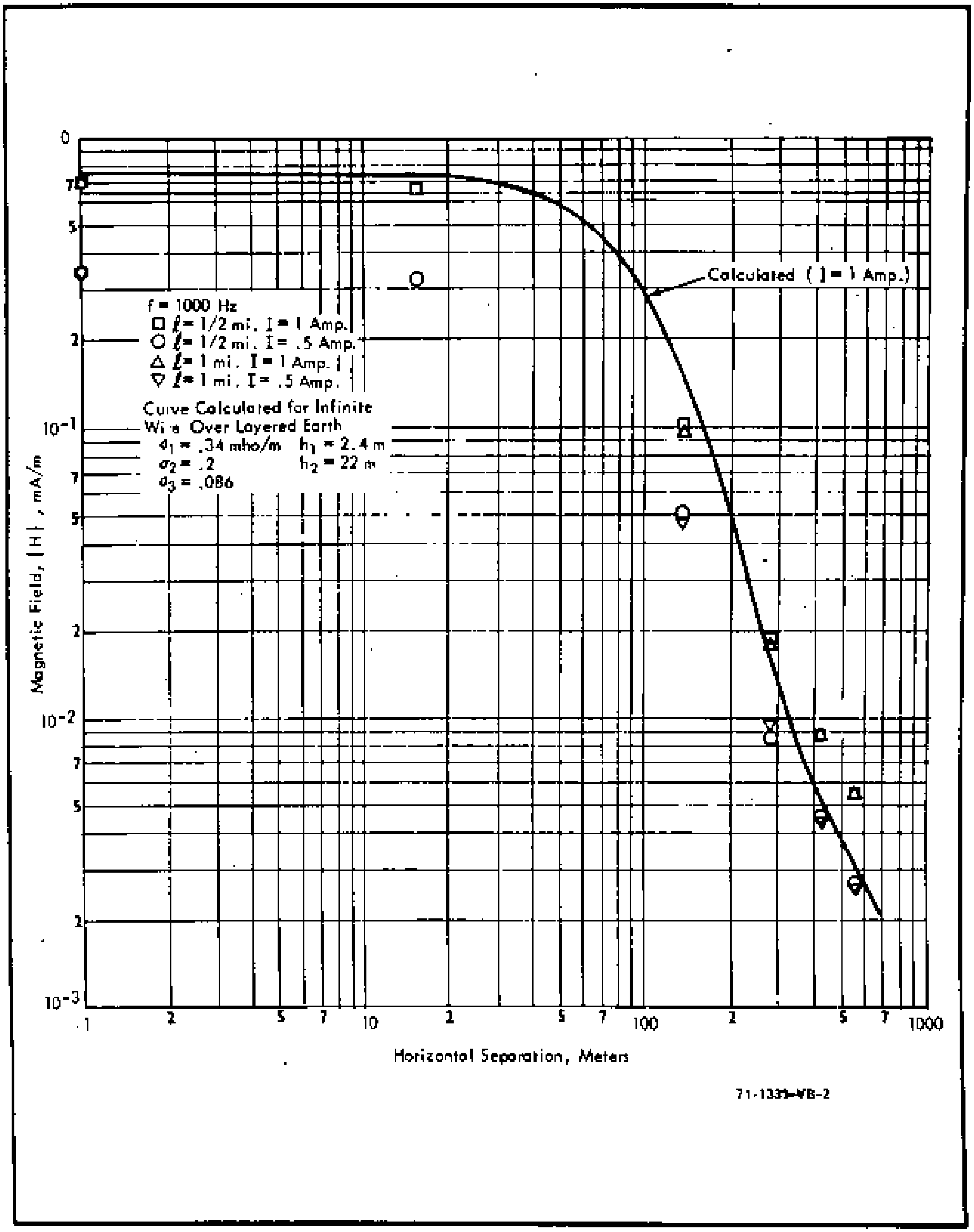


Figure 2.1-7. Downlink Field Strength Variation with Horizontal Distance Normal to Plane of HWA

for lengths of one-half mile or one mile, and was directly proportional to the transmitting current.

The beacon transmitter antenna was installed at the point shown on the map in entries #1 and #2 East. Six turns of wire were wound around a coal pillar which had the dimensions of about 14 × 43 feet. The test transmitter consisted of a signal generator driving a McIntosh audio amplifier with decade capacitor boxes for tuning the antenna. It was possible to obtain two amperes of antenna current for frequencies between 275 Hz and 5500 Hz and about one ampere for frequencies up to 10 kHz. Figure 2.1-8 shows absolute values for the measured vertical magnetic field at the surface above the beacon location as a function of frequency. Agreement with theoretical values is excellent. Figure 2.1-9 shows the variation of field strength with distance. The curves for both frequencies were normalized to show relative performance. (Reference values were: at 2750 Hz, I = 2 amp, H_z = .022 mA/m; at 275 Hz, I = .6 amp, H_z = .11 mA/m.) Normally, H_x component would not be present; however in this case, a lack of precision in the physical geometry is likely to have caused the resulting x component of magnetic field.

Since bandwidth is a critical design parameter for receivers, tests were made to determine the maximum allowable bandwidth in which the received field was relatively uncontaminated by noise. Results indicated that this bandwidth was approximately 100 Hz for frequencies below 1 kHz and 1000 Hz for frequencies from 1 kHz to 5 kHz. The major factor in the determination of maximum allowable bandwidth at this location was the presence of strong power line harmonic interference at the lower frequencies.

Clyde Mine, Pennsylvania

At the Clyde Mine, electromagnetic measurements were made between August 18 and August 26, 1970, and seismic measurements were made on September 3-4, 1970. The Clyde Mine is located south of Pittsburgh, with its #1 portal at Fredericktown on the Monongahela River. The mine extends approximately ten miles to the southwest of Fredericktown to the Clyde shaft area where the measurements were made. Figure 2.1-10 illustrates the major areas of the Clyde Mine.

Figure 2.1-11 shows the portion of the Clyde Mine which was used for the electromagnetic and seismic experiments. Several requirements dictated this choice. First, it was necessary to find an area in the mine which had 115 volt ac power available with which to power test equipment for the beacon transmitter. Secondly, it was necessary to find an area which had a relatively thick overburden. This set of conditions was met at Power Bore Hole #9. The location for the horizontal wire antenna (HWA) was selected to be one-third mile long on the top of a ridge along a road which crossed the main entries (overburden was 800 feet). The choice of the seismic site was dictated by the need for 115 volt ac power on the surface and a bore hole having a telephone connection directly to the mine. These conditions were satisfied at Power Bore Hole #14. Table 2.1-1 is a drill log record for #14 Bore Hole, and is typical for the area.

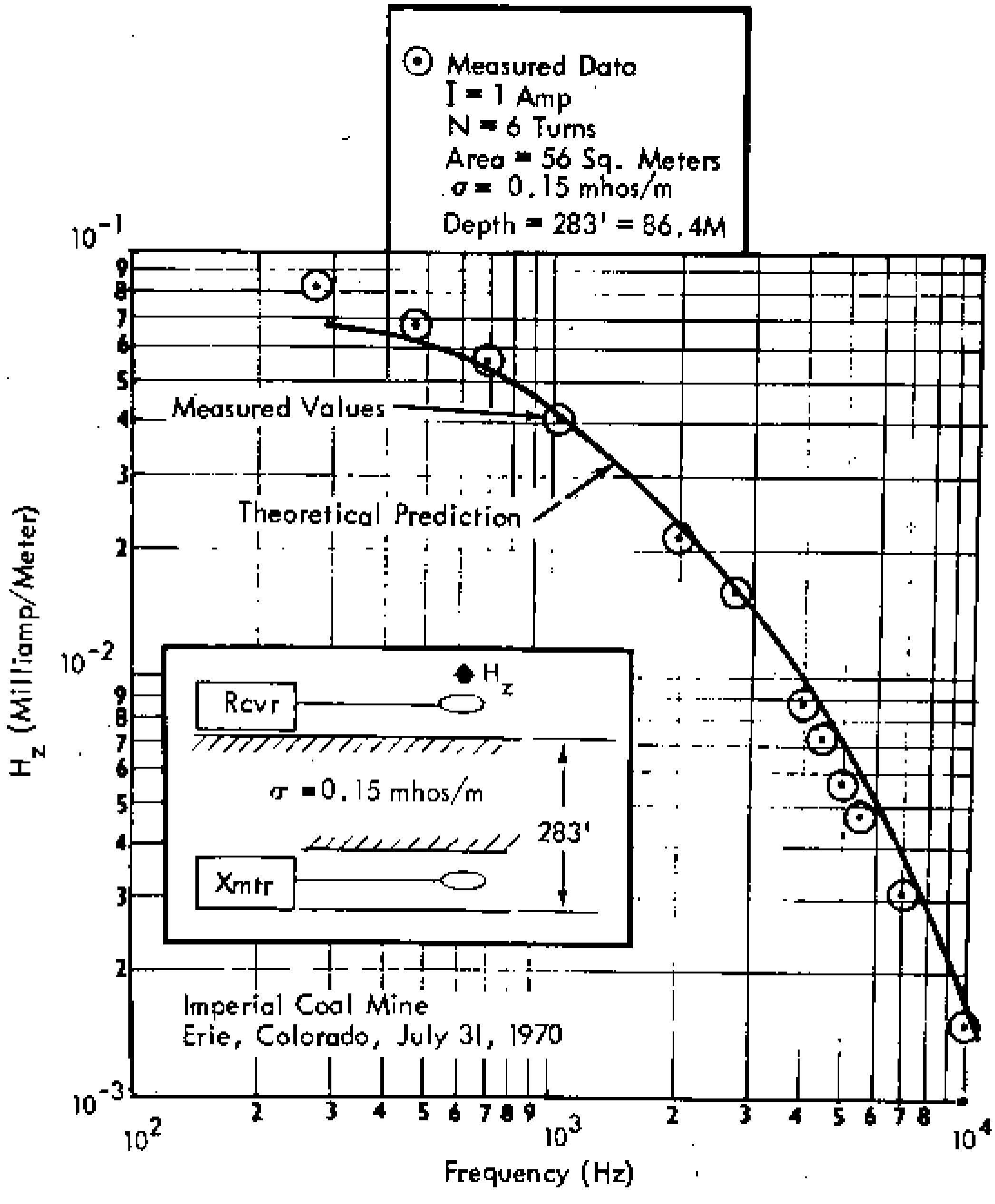


Figure 2.1-8. Comparison of Measured Magnetic Field With Theoretical Prediction for Beacon (Uplink) System

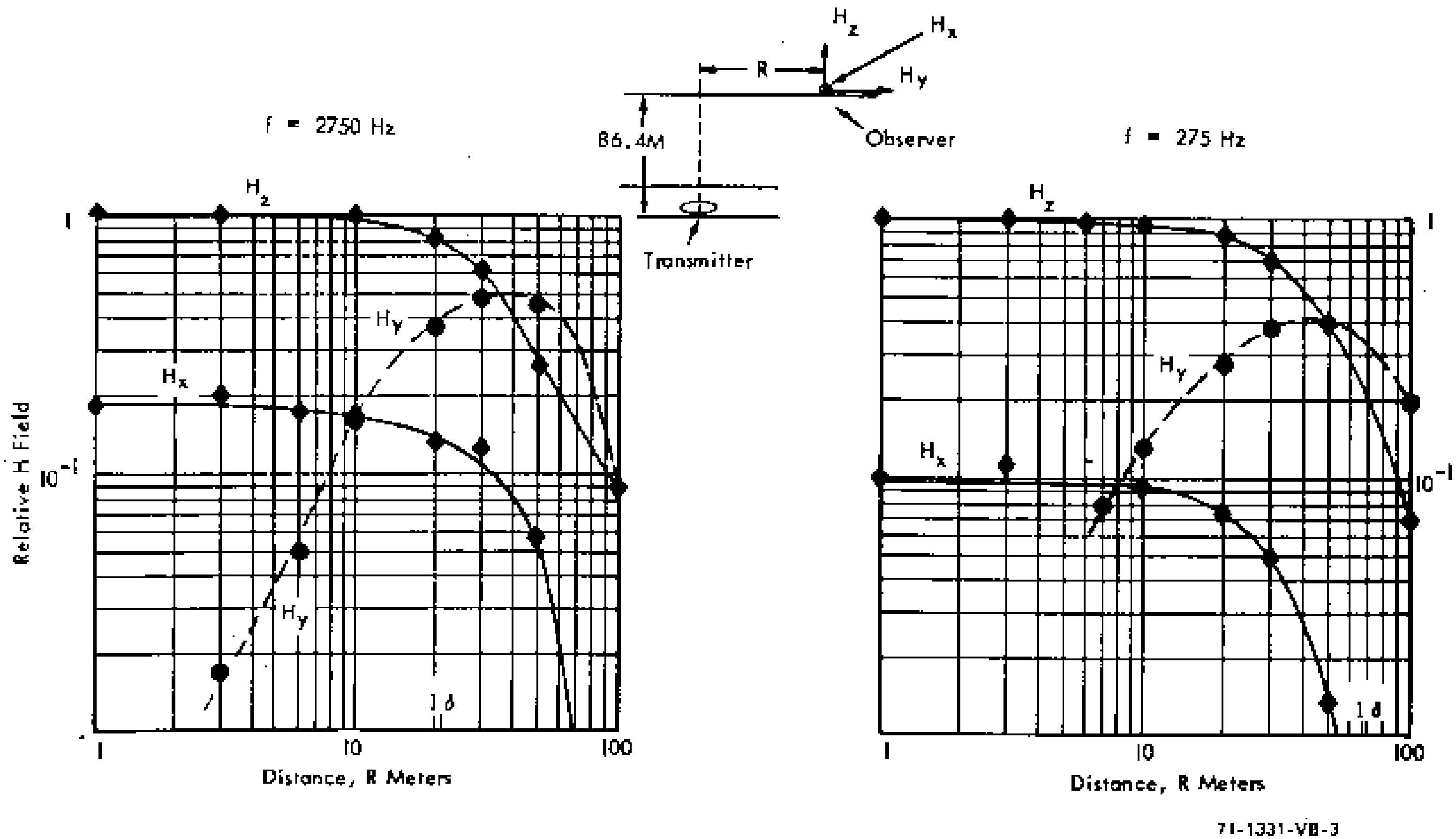


Figure 2.1-9. Measured Relative Field Strength of Beacon Magnetic Field Components vs Distance, Imperial Mine (See test for reference values)

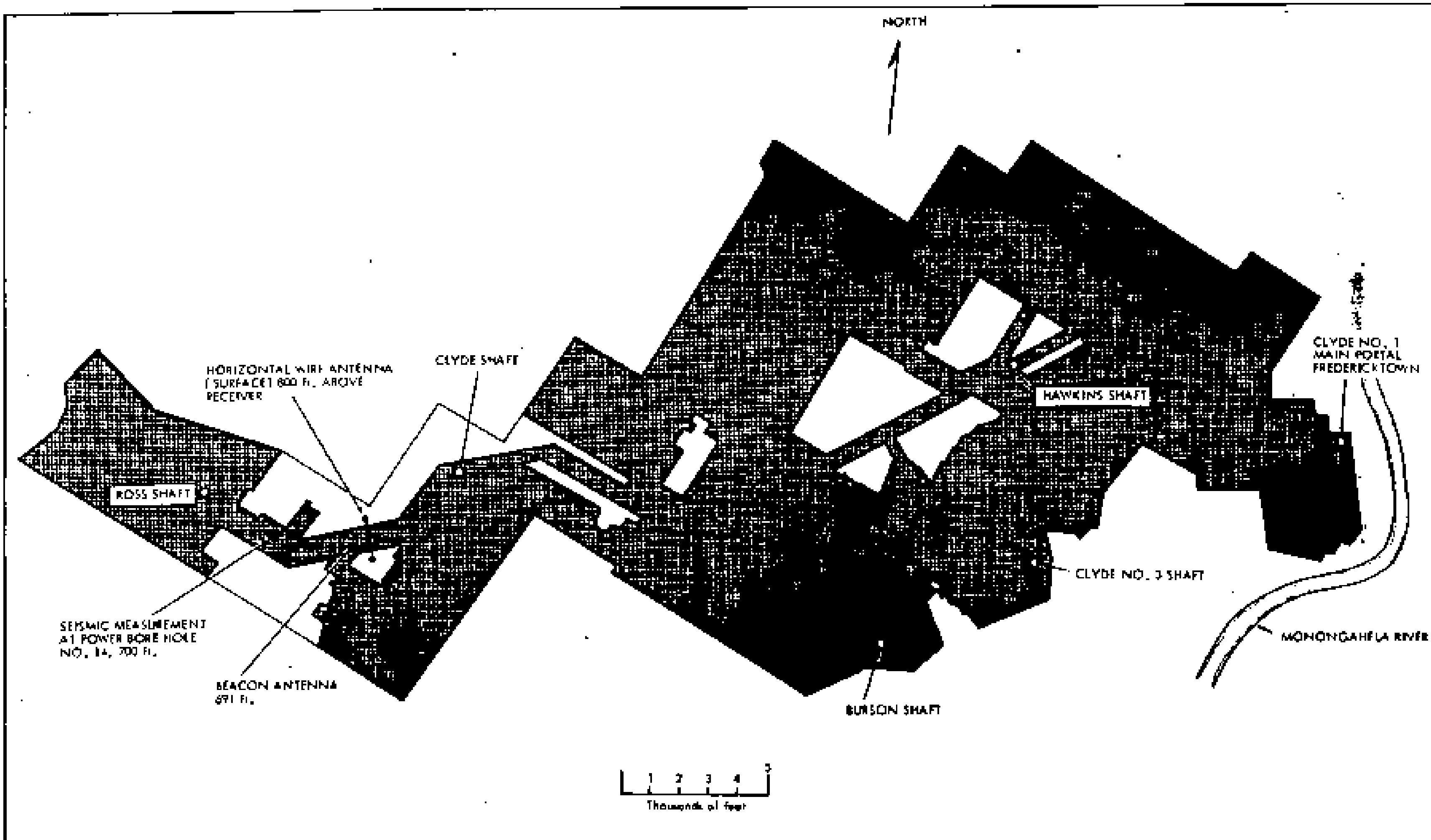


Figure 2.1-10. Pre-Design Field Measurement Locations

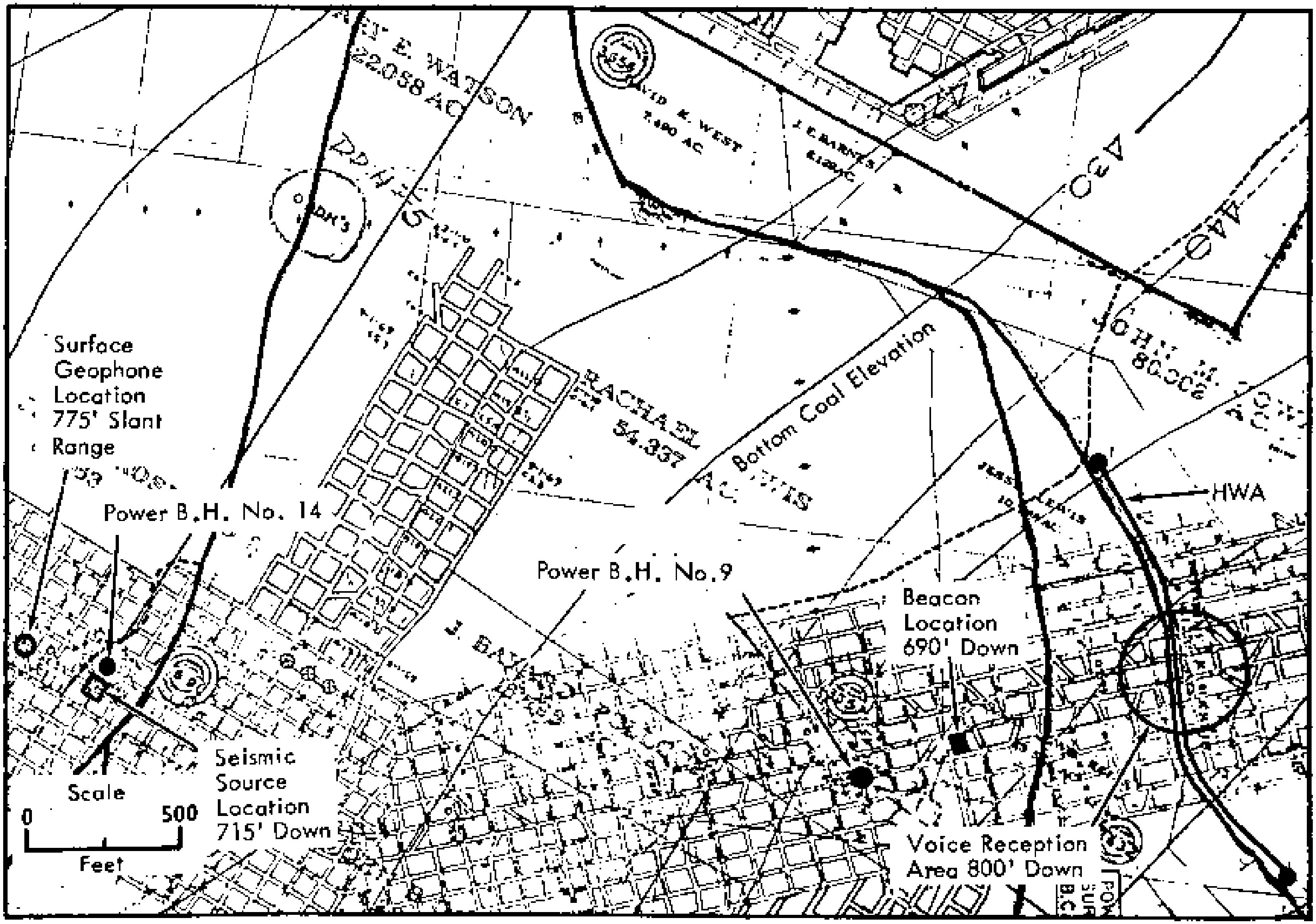
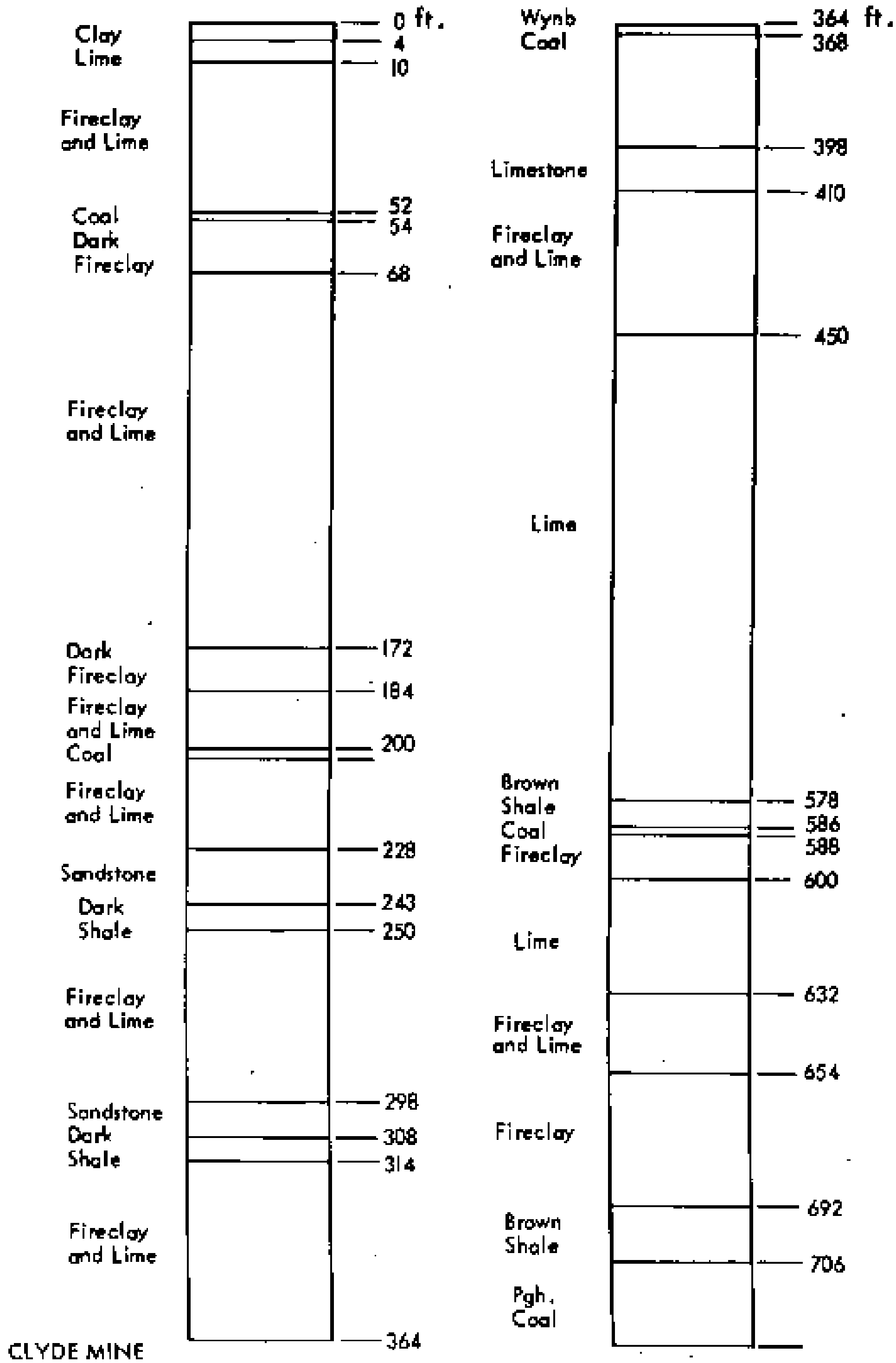


Figure 2.1-11. Portion of the Clyde Mine Used for EM and Seismic Experiments

TABLE 2.1-1

GEOLOGIC SECTION AT CLYDE MINE FROM BORE HOLE LOG



Two conductivity soundings were made in the Clyde shaft area. One was made in the vicinity of the voice downlink and beacon uplink experiments while the other was made along a stream bed on the road to the Clyde shaft. The second measurement was severely affected by lateral contrasts and could not be interpreted. The results of the first measurement, however, were interpreted and are shown below.

$\sigma_1 = 6 \times 10^{-2}$ mhos/m $\qquad$ $h_1 = 2.6$ meters

$\sigma_2 = 1.06 \times 10^{-2}$ $\qquad$ $h_2 = 77$

$\sigma_3 = 4.8 \times 10^{-2}$

These data and interpretations were used to make theoretical calculations.

The background magnetic fields were measured at a location directly under the center of the HWA line. The fields were measured with an 800 turn loop and a Hewlett Packard HP-302A wave analyzer. The antenna was oriented in a horizontal plane parallel to the earth's surface. This orientation also provided minimum coupling to power and trolley wires in the mine. The mine was operating on a normal schedule. Spot measurements were made between 40 Hz and 6 kHz at all frequencies which showed significant peaks. The general background level between recorded frequencies was also noted. The results of this survey are shown in Table 2.1-2. The coupler for the loop antenna had a 40 dB notch at 60 Hz, and the field strength reported at 60 Hz is that which would exist if the notch were not present. Observe the significant field strength at 360 Hz and its harmonics, which are due to components from the 3-phase rectification. Harmonics on the ac supply lines to the rectifiers were found to have a larger magnitude than those on the dc output lines to the trolleys.

Attempts to record the field strength from the HWA transmitting system were unsuccessful because the signals could not be detected at any frequency with the high background field existing. Voice transmissions could be understood only by orienting the antenna to minimize interference picked up from the ambient fields. Figure 2.1-12 shows calculations of the expected field strength from the horizontal wire antenna system carrying one ampere superimposed on the background noise at a depth of 800 ft. The difference between the infinite line and a finite line is not expected to be significant for this depth.

The Beacon Transmitter was installed in a cross cut about 300 feet from Power Bore Hole #9. The antenna consisted of a 12 conductor cable with the conductors connected in a series to form a continuous loop having an input impedance of 4 ohms resistance and 5.5 millihenries inductance. The cable was 100 feet long and was laid out in the form of a loop in the cross cut. The Beacon Transmitter consisted of a signal generator feeding a McIntosh

TABLE 2.1-2

BACKGROUND MAGNETIC FIELDS IN CLYDE MINE UNDER VOICE TRANSMITTING ANTENNA*

Frequency, Hz	H, ma/m	Frequency, Hz	H, ma/m
40	.12-.32	1940	.13-.53
60	2	2180	.67-3.36
90	.03-.1	2300	.38-1.35
120	.3-.4	2390	.14-.27
160	.05-.09	2540	.35-.7
180	.04-.09	Occasional frequencies with	
240	.08-.16	H ≤ .07	
300	.01-.02	2660	.14-.21
330	.01-.04	2720	.07
360	37.6	2750	≤ .04
400	.07-.14	2790	.21-.35
			(2.1 peaks)
440	.07-.14	2840	.07-.36
480	.34-1.36	2910	.14-.28
520	.2-.38	2960	.07-.7
550	.14-.27	3030	.22-.74
600	.67-1	3090	.15-.44
660	.13 with spikes	3150	.22-.37
720	6.67	3210	.08-.8
840	.27-.4	3340	.08-.24
900	.07-.2	3350	.08-.38
970	.13-.4	3390	.23-1.1
1030	.07-.13	3450	.23-.69
1090	3.3-4	3540	.08-.31
General background	.07	3580	.08-.5
1150	.07	3760	.16-.8
1200	.27-.4	3810	.08-.48
1330	.27-.47	3950	.04-7.8
1450	.67-1.33	4050	.17-.42
1570	.27-.67	4K-4.6K	.1
1690	.13-.53	4.6K-5K	.1 with .2 peaks
1810	.33-.6	5K-6K	.1 with .4 peaks
1880	.13-.53		

* Measurement bandwidth is 6 Hz and loop was oriented for minimum coupling to mine power lines.

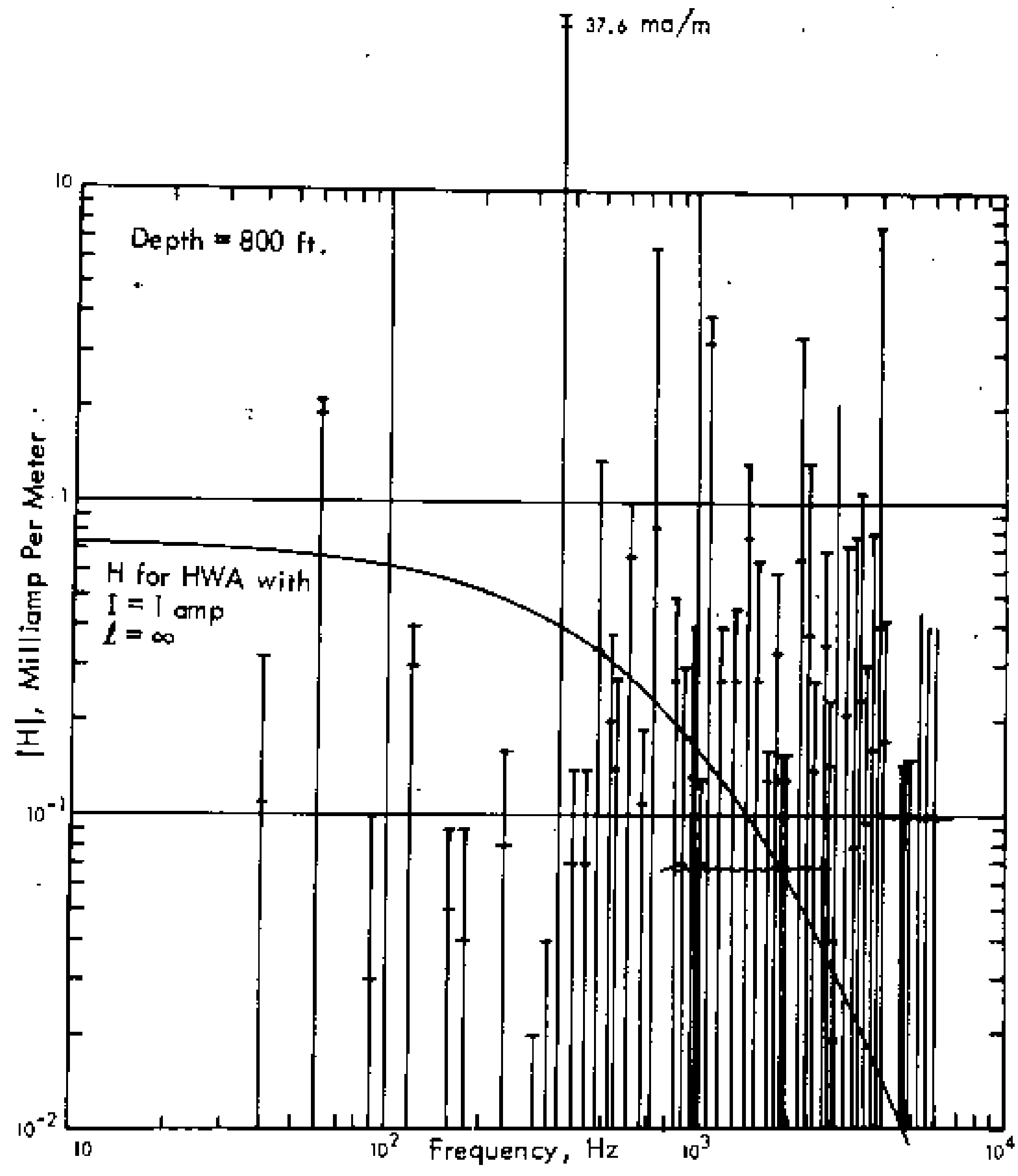


Figure 2.1-12. Background Magnetic Field Levels in Clyde Mine in 6 Hz Bandwidth With Loop Oriented for Minimum Coupling to Power Lines.

amplifier, which supplied from 0.5 to 3 amperes to the loop. The current was observed as the voltage across a one-ohm resistor and the output was monitored with a Tektronix 321 oscilloscope to ensure a clean sinusoidal wave form. There was 691 feet of overburden at the beacon location with an average conductivity of 3.44×10^{-2} mhos per meter. The average conductivity was calculated by adding the weighted conductance of each of the layers and dividing by the total thickness. Figure 2.1-13 shows a comparison of the measured magnetic field at the surface with a theoretical prediction for the beacon transmissions. Figure 2.1-14 shows the variation of the maximum field strength with horizontal separation for beacon transmissions to the surface. This curve is normalized relative to the field directly over the beacon. The scatter in the data is partly attributed to weak signal strength, the ambient noise, and inhomogeneities in the earth including a gas pipe which crossed the sounding radial at a distance of 447 meters.

A measurement of signal and noise received in various bandwidths was also made using the Quan Tech wave analyzer and an 800 turn loop. The loop was oriented to receive vertical magnetic field over the beacon location at a frequency of 1,298 Hz. It was found that with bandwidths greater than 100 Hz the noise increased substantially due to the non-Gaussian character of the noise spectral characteristics.

Cambria Slope Mine, Pennsylvania

This mine is located in Ebensburg, Pennsylvania, approximately 100 miles east of Pittsburgh on U.S. Route 22. It is the newest of several mines in the vicinity operated by the Bethlehem Mines Corporation. The workings in the 54 inch Lower Kittanning seam are not yet very extensive; however, the mining methods are quite modern. Mining is done principally by the long wall method, but continuous miners are used to drive entries for developing long wall operations. Figure 2.1-15 shows a general mine map with the locations for the electromagnetic and seismic tests.

A conductivity sounding was made along the road where the horizontal wire antenna was located. The interpretation from that sounding is shown below.

$$\sigma_1 = 4.1 \times 10^{-2} \text{ mho/m} \qquad h_1 = 4.1 \text{ meters}$$
$$\sigma_2 = 4.6 \times 10^{-3}$$

For dipole spacings up to 50 meters, the soundings were typical of those made over a simple layered earth; however, at larger spacings of 100, 200, and 300 meters, the curve of apparent conductivity versus spacings was irregular. The cause of these perturbations was not determined; however, it is probable that they represent an anomalous conductivity zone. These interpretations were used in the calculation of theoretical performance predictions.

The background magnetic noise was measured on two separate occasions in the vicinity of the beacon antenna. On August 29, the mine was not operating and provided an ideal opportunity to make background noise measurements with voltage on the power conductors, but carrying minimum currents.

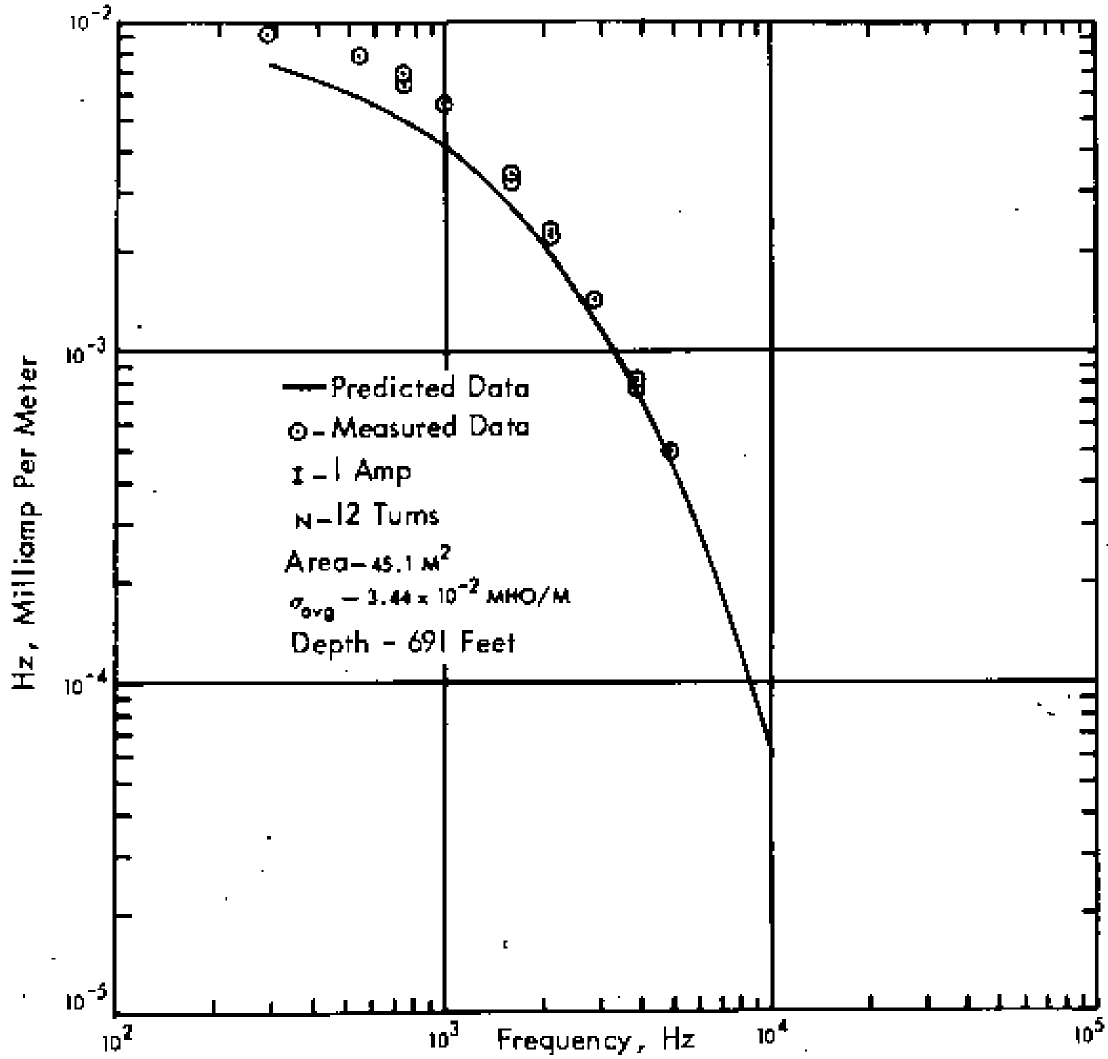


Figure 2.1-13. Comparison of Measured Magnetic Field with Theoretical Prediction for Beacon (Uplink) System, Clyde Mine

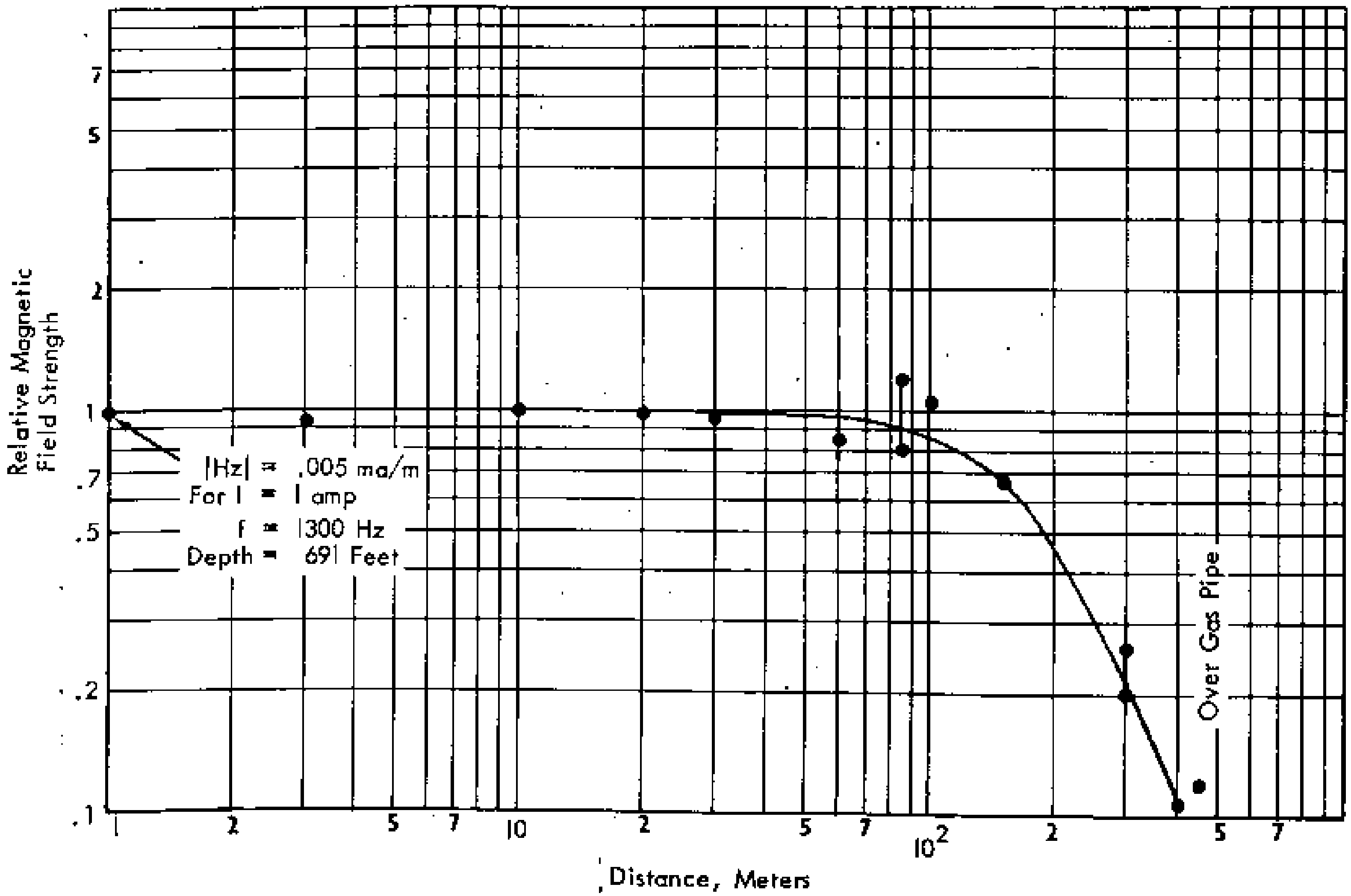


Figure 2.1-14. Maximum Beacon Field Strength vs Horizontal Separation, Clyde Mine

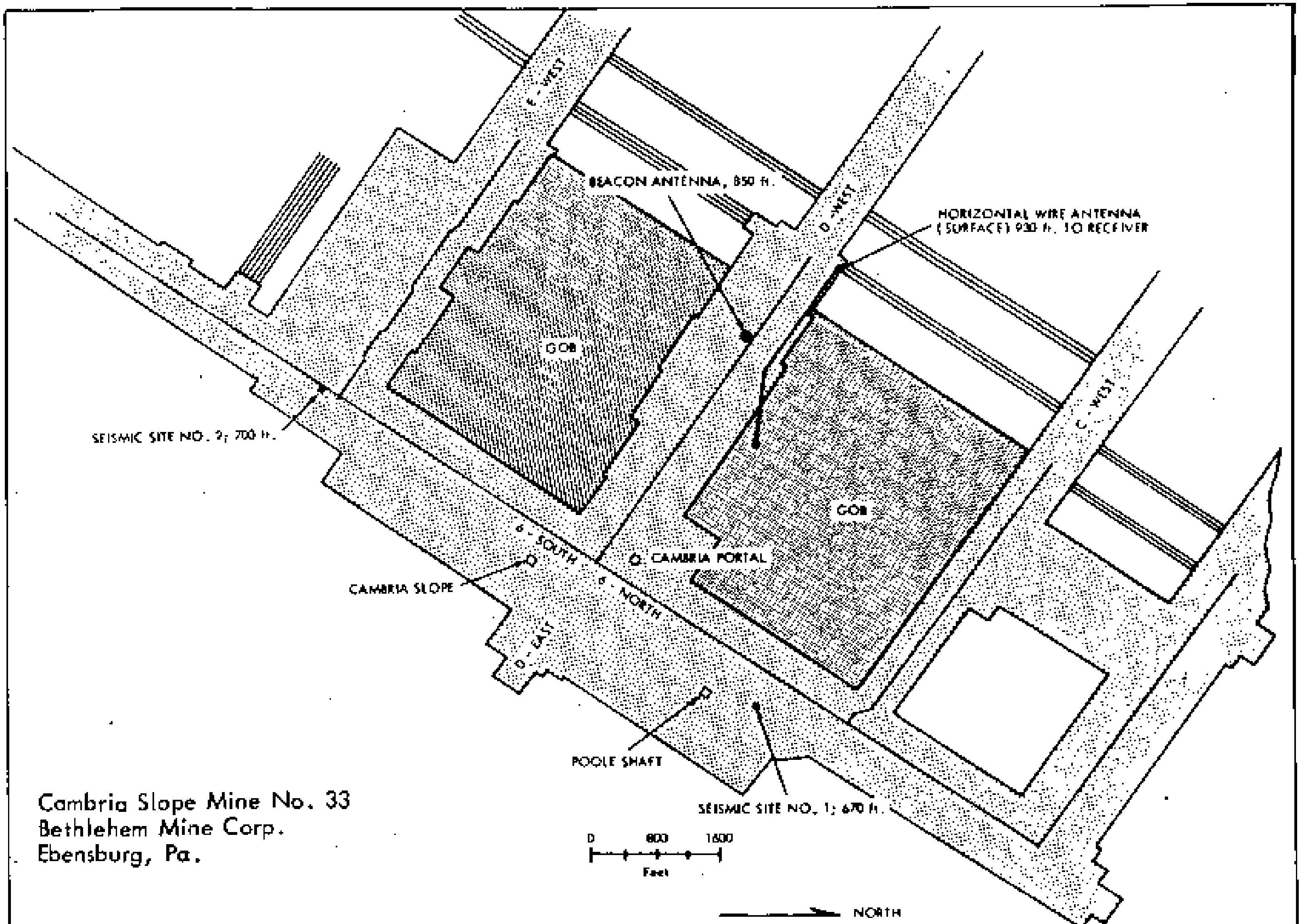


Figure 2.1-15. Pre-Design Field Measurement Locations

This data is shown in Table 2.1-3. The following table, Table 2.1-4, shows magnetic field measurements made on September 1, 1970, when the mine was operating normally. It will be noted that the recorded field strengths are significantly higher.

The beacon and horizontal wire antennas were located over one of the deepest parts of the mine (850 ft) where 115 volt ac power was also available underground. Figure 2.1-16 shows the pertinent features of these locations. This figure also shows measurement locations at which field strengths from the horizontal wire antenna were measured along the trolley line and the D-west entry. Figure 2.1-17 shows the observed and calculated field strengths from a horizontal wire antenna. The calculations, based on an infinite line, considered two conductivity cases as shown in the figure. The two conductivity cases are based on two possible interpretations of the conductivity sounding data. The variation of field strength with frequency, as observed at the beacon location, behaves similarly to the theoretical calculations except that they are about 8 dB lower than predicted. At locations A, B, and C, along the main entry, field strengths of 1.37, 2.36, and 1.7 milliamps per meter were observed. These field strengths were significantly higher (up to 13 dB) than predicted. Satisfactory field strength measurements at stations D, E, and F were not obtained because of a loose cable in the preamp battery supply. This was later corrected; however, time did not permit returning to the sites to repeat the measurements. The reason for the discrepancy between the measured values and the calculated values is not known. The theoretical difference between the infinite wire calculation and a finite wire calculation is 2 to 3 dB and could not account for the observed difference. Conductivity variations may not have sufficient effect. One possible explanation is that there may be large inhomogeneities in the ground which are distorting the fields. This may also account for the higher field strengths observed at stations A, B, and C, which were further away from the center of the moment of the antenna. Recordings of the downlink voice signals were made at several locations in the vicinity of the beacon antenna. For intelligible voice reception, it was usually necessary to orient the receiving antenna to minimize noise and interference pickup.

The beacon characteristics were the same as those at the Clyde Mine and the depth at the beacon location was 850 feet. Figure 2.1-18 shows a comparison of the calculated and observed field strengths at the surface over the Beacon Transmitter. The mathematical model would only allow for homogenous earth, therefore an average conductivity was calculated as before. Again, the disagreement between observed and calculated fields is probably due to unknown inhomogeneities in the earth. Figure 2.1-19 shows the relative beacon field strength as a function of distance away from the center point on the surface. The maximum field strength is relatively constant over a radius of 40 or 50 meters. Signals measured at the maximum slant range of approximately 1,390 feet had an absolute field strength of 5.7×10^{-4} milliamps per meter.

TABLE 2.1-3

BACKGROUND MAGNETIC FIELDS IN CAMBRIA SLOPE MINE NO. 33 NEAR BEACON ANTENNA* (MINE NOT OPERATING)

Frequency, Hz	H, ma/m	Frequency, Hz	H, ma/m
30	.012	1920	.007
60	2	2170	.017
120	.67	2520	.01
150	.05	3250	.015
180	.2	3260	.016
240	.23	3980	.017
300	.22	4340	.017
360	1.8	General background	.0003
420	.1	4700	.013
480	.03	5790	.01
510	.01	General background	.0002
540	.05	6520	.011
580	.01-.013	6880	.013
600	.017	Background to 10K Hz	.0001
660	.04		
690	.007		
720	.13		
840-930	.007		
960	.02		
1010	.007		
1080	.086		
1140-1240	.007-.01		
1440	.007-.05		
1800	.026		

* Measurement bandwidth is 6 Hz and loop plane was oriented to measure the radial H vector from trolley wire 20 feet away.

TABLE 2.1-4

BACKGROUND MAGNETIC FIELDS IN CAMBRIA SLOPE MINE NO. 33 NEAR BEACON ANTENNA*
(MINE OPERATING)

Frequency, Hz	H, ma/m
40	2.68
60	10-30
90	1.37-3.42
120	1.1
160 background	.46-.56
180	.44-.88
240	1.17
300	1.1
360	10.6-28.4
varies with trolley opr.	
420	.69
460	.51
480	.34-1
500	.068
540	.27
600	.4
660	.4-.67
730	.67-2
780	.2
800-950	.013
960	.2-.67
1000	.13-.67

Frequency, Hz	H, ma/m
1090	.53
1450	1
1200-1400	≤ .33
1810	.27
2K Hz background	.0067
2180	.2
2750	.00V-.021
2920	.07
3200	.007
3000-5000	.008
5090	.02

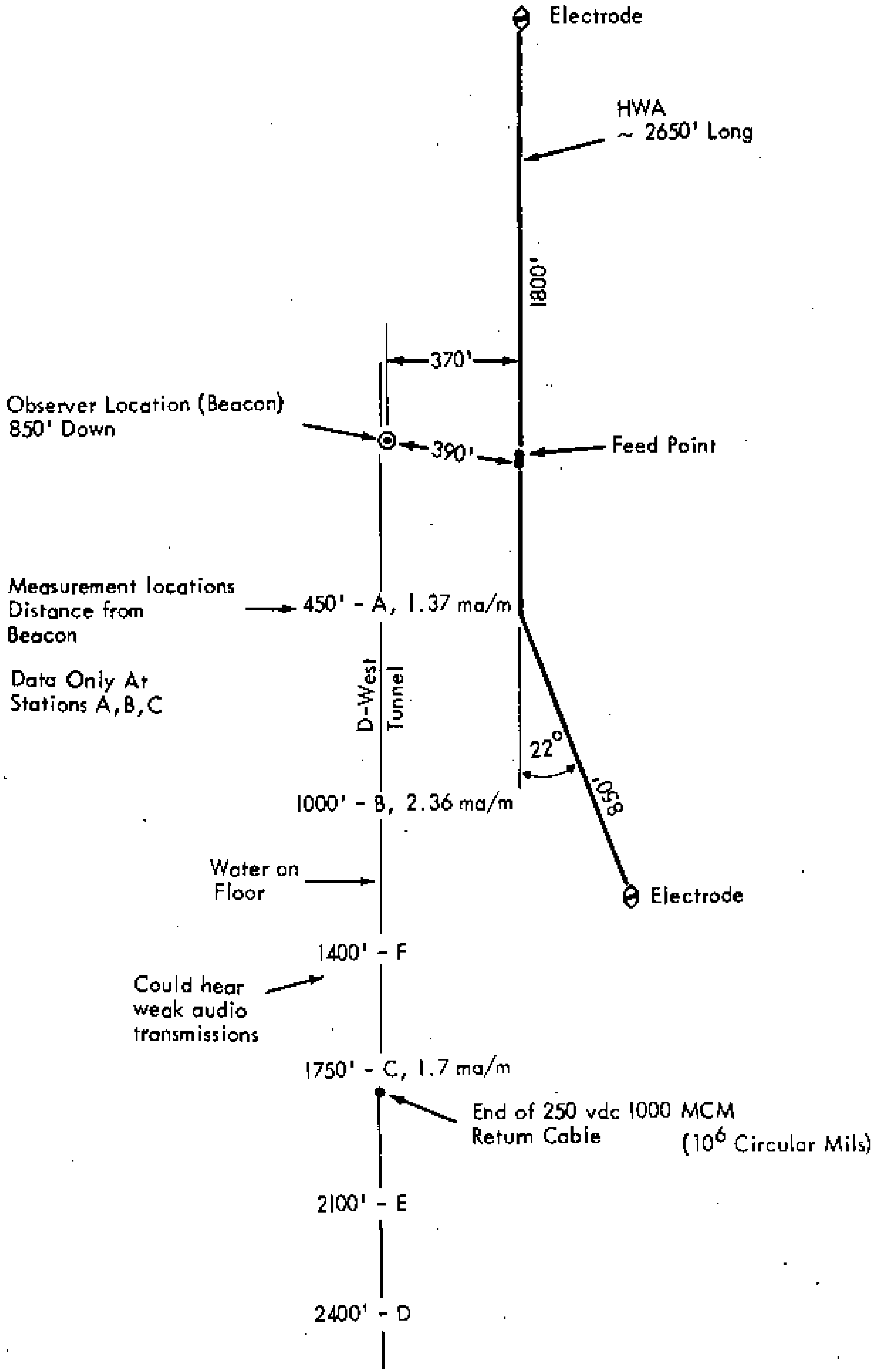


Figure 2.1-16. Geometry of Horizontal Wire Antenna, Beacon Location, and Measurement Points; Cambria Slope Mine No. 33

Conductivity Cases			
	A	B	
σ_1	0.041	0.034	mho/m
h_1	4.1	4.3	m
σ_2	0.0046	0.006	mho/m
1.37 to 2.36 ma/m in D-West tunnel			

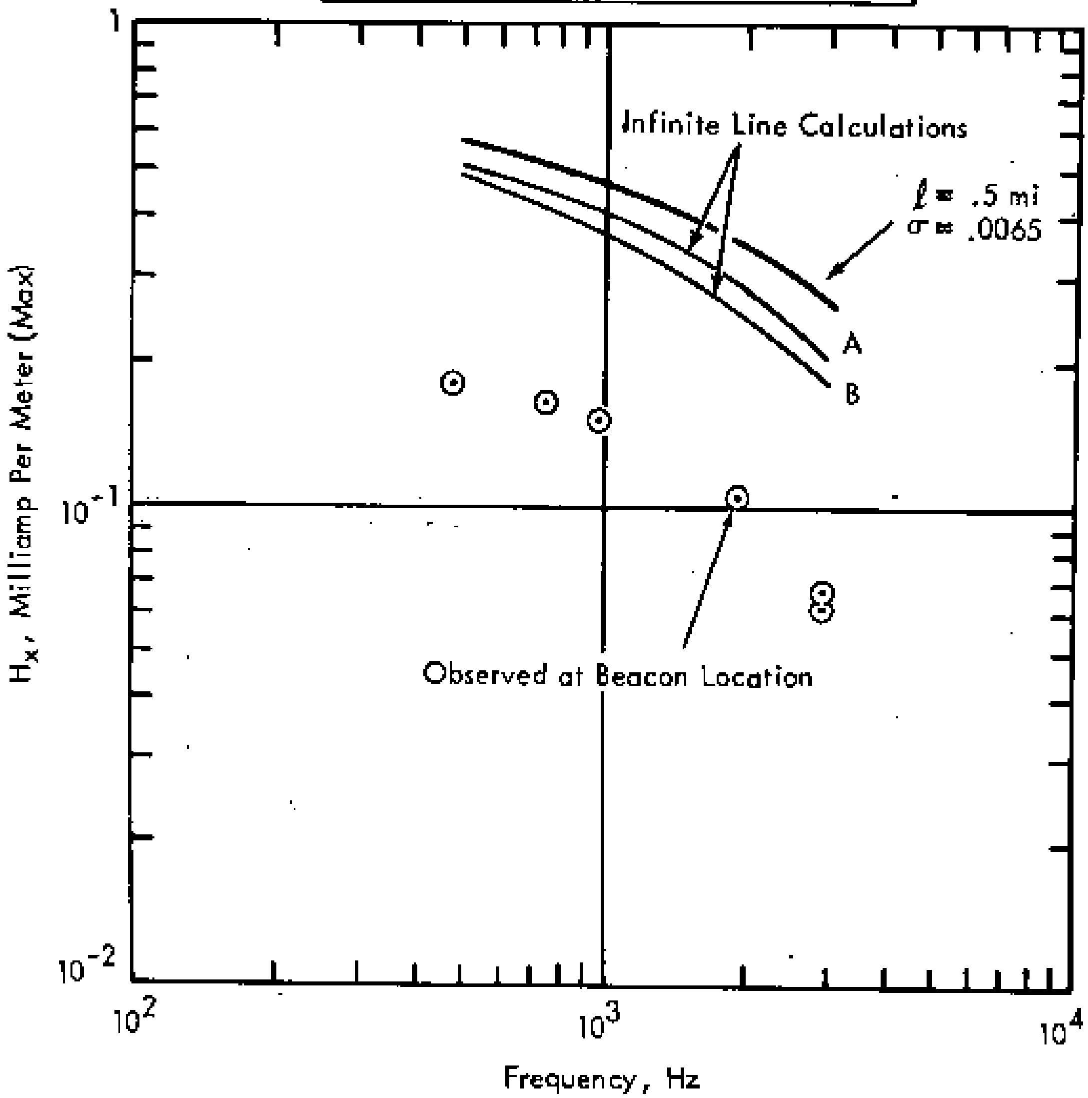
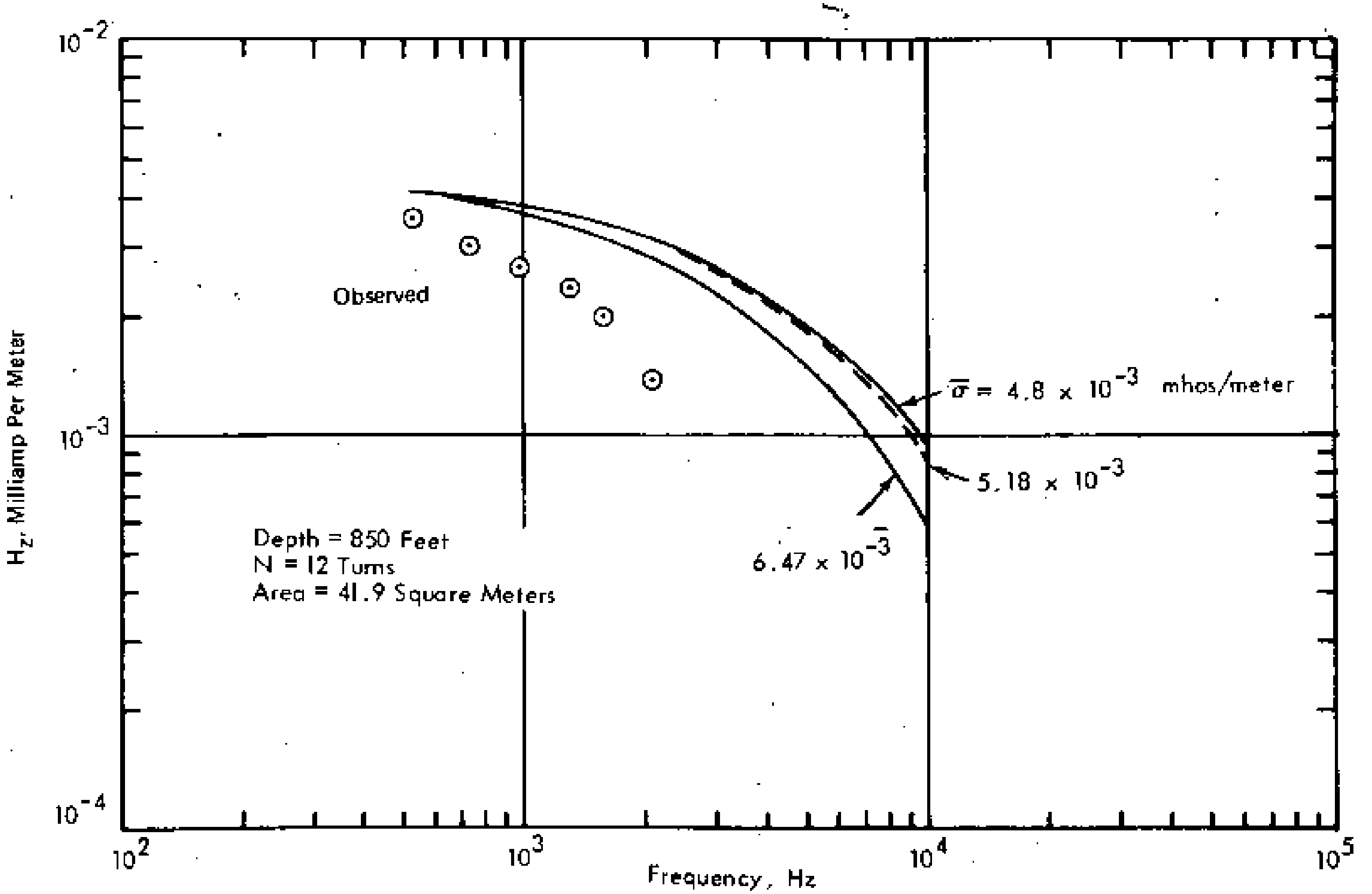
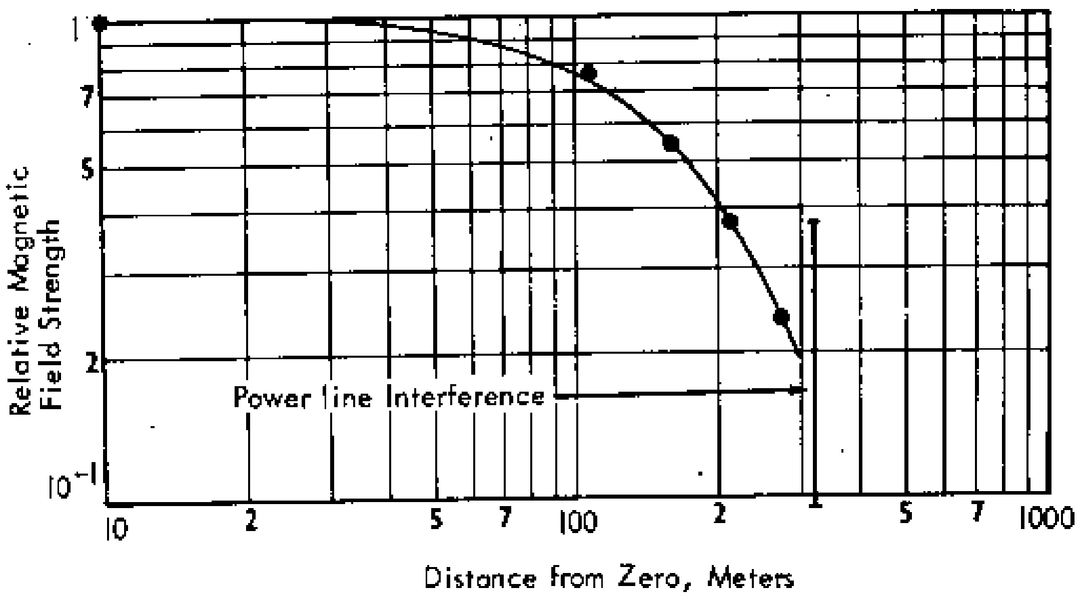


Figure 2.1-17. Observed and Calculated Field Strengths From HWA at Cambria Slope Mine



71-1331-VB-4

Figure 2.1-18. Comparison of Calculated and Observed Field Strength at the Surface Over the Beacon Transmitter at Cambria Slope Mine No. 33



f = 1280 Hz

Figure 2.1-19. Relative Beacon Field Strength (Maximum) Versus Distance On The Surface, Cambria Slope Mine No. 33

2.1.4 Electromagnetic Predesign Summary

The theoretical formulations, which were based on published analyses, first considered uplink propagation where it was shown that a VMD will be a more efficient source than an HMD for the typical case where the depth to the mine is less than 5 skin depths. For larger depths, the reverse is likely to hold.

For downlink propagation, programs were developed to calculate the fields from a horizontal wire antenna (HWA) for the case of a finite line on a homogeneous earth, or an infinite line on a layered earth. In the field, the line may be considered as infinite if the receiver depth is small compared to the distance to the nearest end of the wire.*

Electromagnetic man-made noise was measured in the Clyde Mine and in the Cambria Slope Mine in Pennsylvania, but was not observed in the Imperial Mine in Colorado because it was not in operation at the time. In the Pennsylvania mines, the significant interference frequencies were 360 Hz and its harmonics caused by power rectifiers. In mines where motor generators are used, the noise frequency components will depend on the characteristics of the motor generators. During an emergency, however, the trolley power is generally turned off and the man-made noise is greatly reduced.

Intelligible downlink voice transmissions were received at all three mines (depths of 290, 800 and 850 feet). Quantitative measurements of the antenna pattern below the surface have not been made; however some qualitative observations can be discussed. It was determined that the length of the antenna is not a major factor as long as the depth to the observer is less than (e.g., about one-third) the length of the line. Thus, for a 1000-ft deep mine, the horizontal antenna length should be at least 3000 ft. It was also found that the measured magnetic field was directly proportional to the transmitting current. The theoretical model for an infinite line was found to be satisfactory for predicting field strengths over simple earths. Geology and mine workings can cause unpredictable effects on electromagnetic signals. The horizontal wire antenna should be laid out across the mine area where the coverage is desired. If the receiver is using a vertical magnetic dipole antenna, it is desirable to use a vertical magnetic antenna as the surface transmitter. In the tests in the eastern mines, mine noise prevented extensive subsurface field strength measurements; however intelligible voice recordings were made at two mines with average transmitting currents of 1 to 2 amperes, using an HWA transmitting antenna.

Beacon uplink transmissions were successfully received at all three mines. Surface noise limited the maximum range of coverage on the surface; however it was possible to make measurements two or three hundred yards from directly over the beacon. The maximum vertical magnetic field strength, H_z,

---

* This condition is sufficient if the total field is being observed. It is not necessarily true for certain field components.

at the surface was relatively constant for a radius of about 50 to 150 feet around the center point. The center point could, however, be found by observing the location of nulls in the horizontal H_y field. This indicates a potential method for locating Beacon Transmitters. The theoretical calculations using a homogeneous earth model (the characteristics of which were calculated from an average conductivity) compared favorably with measurements at the Imperial Mine (depth 290 feet), while they were too low at the Clyde Mine (691 feet) and too high at the Cambria Slope Mine (850 feet). At 2750 Hz, the transmitting current was generally between 1 ampere and 3.5 amperes.

2.2 DESIGN AND FABRICATION

Based on the results of predesign field experiments, theoretical calculations, and data from the literature, the design of the EM Communications System proceeded as outlined in the following subsections.

2.2.1 Design Goals and Guidelines

Design goals were:

a. To utilize off-the-shelf components wherever possible without sacrificing performance or reliability.

b. To minimize cost, particularly for the subsurface units.

c. To minimize size and weight of the equipment to be carried by the individual miner. A weight of less than 1 pound for the Manpack Voice Receiver was believed acceptable.

d. To use good "Human Engineering" practices to ensure that subsurface equipment was readily operable by unskilled personnel, even when injured or under stress.

e. To achieve a high degree of flexibility in the operating configuration of the surface units and to accommodate a wide variety of operating conditions dictated by rugged terrain, widely separated working areas, and the inaccessibility of ideal locations.

2.2.2 Make or Buy Decisions

In keeping with the design goal of using off-the-shelf components, a survey was made of readily available major components and equipments. This survey indicated that only the power amplifier for the voice downlink transmitter was available as an off-the-shelf item, but this required some modification.

2.2.3 Description of Equipment

The EM Communications System is specifically designed to provide three primary functions.

- Downlink Voice Communications from rescue operations on the surface to men trapped in the mine.
- Uplink Coded Beacon Communications from men trapped in the mine to the surface.
- Uplink Telemetry of seismic signals received in the mine to aid in the seismic location process.

Figure 1-1 shows in a pictorial and simple block diagram form, the equipment and subsystems required to perform these three functions. Both electromagnetic (EM) and seismic techniques are employed. Major subsystems are described below.

Subsurface Communications Equipment

The EM Communications Subsystem developed includes equipment to be installed in survival chambers, caches or barricade locations within the mine. This equipment is indicated as the "chamber or barricade system" in Figure 1-1, and includes a Beacon Transmitter, a seismic amplifier, an Electromagnetic (EM) Habitat Voice Receiver, a seismic signaller, two antennas, and a geophone.

The subsurface equipment permits EM downlink voice reception, uplink code transmission, and a seismic back-up system for each function. The EM Voice Receiver is the trapped miners' primary equipment for downlink communications. As a back-up for downlink communications, the miner may listen for seismic signals generated by detonating explosives on the surface. These may be directly audible, or can be amplified using a geophone and seismic amplifier operating through his voice receiver.

The primary subsurface component of uplink communication is a coded Beacon Transmitter which transmits six selectable coded signals. The code is generated automatically by square wave keying the transmitted signal at six different on-off repetition rates. A seismic signaller is provided as a back-up for uplink communications. Figures 2.2-1 through 2.2-3 show the subsurface equipment to be installed at a barricade or chamber. The Habitat Voice Receiver and Beacon Transmitter, shown in Figure 2.2-1, have been designed for ease and simplicity of operation. In response to questions received on the voice receiver, the miner may reply with one of the six answers by simply pushing the appropriate button shown at the bottom of the Beacon Transmitter. With properly phrased questions from the surface, considerable information may be obtained with this system. A geophone can be connected to the voice receiver at the geophone plug shown in Figure 2.2-1. With the receiver in SEISMIC mode (the seismic button pushed) amplification of seismic signals from an implanted geophone is possible. These signals can also be relayed to the surface electromagnetically using the Beacon Transmitter (also switched to SEISMIC mode). A narrow band FM modulator is used in this mode in the Beacon Transmitter. A narrow band FM discriminator in the Beacon Receiver on the surface provides demodulation and reconstructs the original seismic wave form.

Figure 2.2-2 shows the seismic signaller (Thumper) which can be used as a back-up system to the EM uplink at the barricade or chamber locations. This Thumper uses compressed gas (liquid CO_2) to lift up to 400 pounds of lead weights. Upon opening a relief valve, the lead weights drop and strike the base plate, generating a seismic signal which can be detected with geophones on the surface. With proper coding, the same six answers available from the beacon transmitter may be transmitted with this device. For instance, one thump could mean yes, two - no, three - unknown, etc. Multiple thumps would occur in groups whose spacing is limited by the reset time of the device.

The entire Subsurface Communications Subsystem, including the seismic thumper solenoid, is operated from a single 12-volt supply consisting of a Leesona-Moos Model BB527/U zinc-air battery. This battery has provision

Figure 2.2-1. Subsurface Components of Communications/Location Subsystem (less antenna and geophone)

for mechanical recharging simply by replacing the internal zinc plates. Consequently, it is ideally suited to mine rescue operations since the plates can be stored indefinitely in their sealed containers and activated only when an emergency has occurred. It is capable of either a 24-volt output at 48 amp hours life or a 12-volt output at 96 amp hours life. Using the 12-volt connection, the battery is capable of providing power to the entire subsurface system for a two-week period on a single set of battery plates.

Light-Weight Personnel Equipment

Since miners could not conveniently carry the equipment described above during the normal performance of their duties, it is important that they be provided a man-pack, or other readily available means of communication in the mine. This reception capability is provided by the personnel system shown in Figure 2.2-3. A small light-weight combination voice receiver and seismic amplifier, with an antenna and geophone, is provided for each man. The geophone case contains a small preamplifier which receives power and couples its signal into the voice receiver through a connector located on the top of the battery case. This is shown in Figure 2.2-4. The antenna for the Manpack Voice Receiver is built into the case, whereas the antenna for the voice receiver used in the barricade system is larger and must be deployed in an open area. This Manpack Voice Receiver and seismic amplifier, which weighs less than one pound, is attached to and powered by the miner's lamp battery to ensure that each miner may receive downlink communications during an emergency. The unit requires so little power that a lamp battery which was fully charged at the beginning of an 8-hour shift will have sufficient power at the end of an 8-hour shift to power the receiver for up to two weeks, provided no other equipment is being powered by the battery. In order to transmit signals to the surface, the miner trapped away from the barricade or chamber location must use a hammer, piece of rail, wooden post or something of a similar nature with which he can pound on the floor or ceiling of the mine to generate seismic signals.

Operational Interfacing Between Seismic and EM Systems

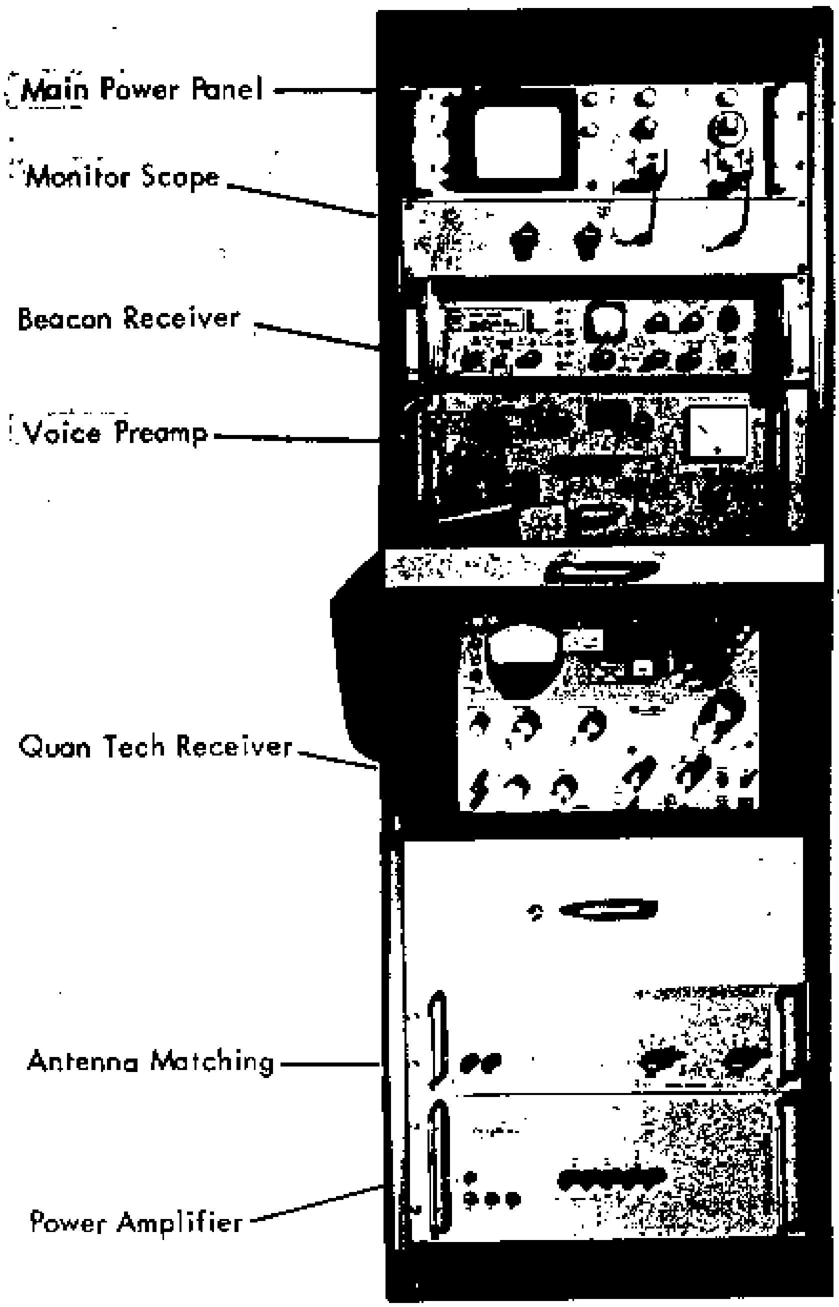
The EM Voice Receiver and coded Beacon Transmitter located at barricades or chambers, can perform an important function in conjunction with geophone preamplifiers and the location system in a manner which improves the probability of determining a lost miner's location. The signals generated by an individual miner pounding on the mine floor or roof propagate with less attenuation horizontally at the mine level than vertically to the surface. It was demonstrated during field tests that useful signals may be received on subsurface geophones installed in the mine and then transmitted to the surface by the Beacon Transmitter. Reception of seismic signals relayed from multiple beacon locations could increase the probability of successfully locating an individual miner. This potential could be realized from unmanned locations by providing a means of turning on the Beacon and Voice Receivers from the surface, having initially preset them to relay seismic signals.

Surface Equipment

The surface equipment required for downlink and uplink communications includes the Voice Transmitter and the Beacon Receiver as shown in Figure 2.2-5.

The Beacon Receiver provides reception of uplink communications signals and has six lights corresponding to the six replies which the men in the mine can transmit. The coding is performed by circuitry which on-off keys the carrier frequency at six different frequencies. Decoding at the surface is accomplished by a bank of narrow band filters in the Beacon Receiver tuned to the six different keying frequencies and connected to a bank of indicator lights. The beacon receiving antenna consists of a 1000 turn 24" square loop which is normally deployed in a horizontal plane lying on the earth's surface. The voice preamplifier, the power amplifier and the antenna matching unit, connected to a long horizontal wire antenna laid out on the surface of the earth and grounded at both ends, provide the primary downlink communications.

The geophone arrays and the Seismic Location System, in addition to their locating function, provide the means for a back-up seismic uplink communications system. The back-up downlink communications system using seismics consists of an explosive firing device and explosives placed in shot holes on the surface. Up to 200 lbs. of explosives may be fired for each shot to ensure that the signals can be heard over a wide area in the mine. The miners will be instructed to pound with a hammer or other heavy object whenever they hear a specified sequence, for example three explosive shots. Two shots could indicate to them that their pounding has been heard and five shots could indicate that the location system had determined their position. This allows



71-1331-BB-16

Figure 2.2-5. EM System Surface Equipment a minimum level of communications which is adequate for the most important messages and can be used to signal the miners even if they have no equipment whatsoever. Two hundred pounds of explosives detonated on the surface can usually be heard without any amplification device at a two thousand foot depth or slant range, but this is a function of the character of the overburden.

2.2.4 Performance Specifications

Tentative specifications for the EM Communications Subsystem were established, based on the performance requirements to provide two-way communications between the surface and a 1000 ft deep mine with overburden conductivity of $\sigma = 10^{-2}$ mhos/m and typical surface and subsurface noise levels as discussed previously. These preliminary specifications are listed below.

Voice Transmitter:

Frequency Response:	300 - 3000 Hz (3 dB)
Antenna Current into Horizontal Wire Antenna:	1 - 4 amps
Antenna Matching:	4 - 100 ohms
Primary Power:	115 volts ac @ 60 Hz

Habitat Voice Receiver:

Sensitivity:	Approximately 1 µA/m for $\frac{S}{N} = 0$ dB
Frequency Response:	500 - 3000 Hz (3 dB)
Output:	Speaker and Headphones
Primary Power:	24 volts dc @ min. current
Other Features:	Squelch, beacon blanking, geophone input

Manpack Voice Receiver:

Sensitivity:	Approximately 50 µA/m for $\frac{S}{N} = 0$ dB
Frequency Response:	500 - 3000 Hz (3 dB)
Output:	Earphone
Primary Power:	4 to 4.5 volts dc from miner's lamp battery with minimum power drain
Other Features:	Small size, less than 1 pound weight, geophone input

Beacon Transmitter:

Frequency:	1375 Hz and 2750 Hz

Modulation:	Square wave ICW @ frequencies of: 1.25 Hz, 1.96 Hz, 2.75 Hz, 4.58 Hz, 6.875 Hz, and 13.75 Hz
Antenna:	Horizontal, series tuned, large area multi-turn loop
Antenna Current:	1 - 3 amps
Primary Power:	24 volts dc @ min. current
Auxiliary Features:	FM seismic uplink
<u>Beacon Receiver:</u>	
Frequency:	500 - 4000 Hz
Bandwidth:	50 - 500 Hz (3 dB)
Sensitivity:	Less than 1 μA/m for $\frac{S}{N}$ = 0 dB
Output:	Visual readout of coded replies, plus earphone
Primary Power:	115 volts ac @ 60 Hz, or battery
Other Features:	Rack mount and portable

2.2.5 Breadboarding and Testing

Individual circuits such as preamplifiers, filters, squelch circuits, voltage regulators, etc., were breadboarded and tested before inclusion into the design drawings.

Circuits which exhibited the desired performance characteristics at room temperature were subjected to as low as 30°F to as high as 150°F temperature extremes. If performance was severely degraded at the temperature extremes, the circuit was redesigned. It was later determined that low temperature operation down to 0°F would be required for some of the surface EM equipment, particularly the Beacon Receiver when operated outside of the van.

2.2.6 Final Design Considerations

The results of the predesign studies, breadboard performance tests, and performance specifications provided the basis for developing hardware specifications which were submitted to an in-house design review board. Some of the basic design decisions are discussed in the following paragraphs.

Voice Downlink

Laboratory tests performed at WGL showed that for the voice downlink a speech bandwidth of 300 - 3000 Hz gave intelligible results of good quality. Subsurface noise measurements made during the predesign field tests showed that large amounts of power line generated noise may exist in the 60 to 500 Hz range, particularly at 360 Hz. These noise fields could easily exceed the lower frequency components of the voice signals from a reasonable sized transmitter. The decision was made, therefore, to restrict the passband of the voice receivers to the range 500 to 3000 Hz.

The final design of the Manpack Receiver antenna represented a trade-off between electrical performance and physical requirements. The physical size in this instance was restricted to a package about 1-1/2" x 1-3/4" x 6" which could mount on the side of a miner's lamp battery case. It would contain all the electronic circuitry and the antenna.

Beacon Uplink

On-off keying of the carrier was selected over frequency shift keying as the method of information transfer for reasons of simplicity in both the Beacon Transmitter and Receiver, and because an interrupted carrier would be easier to distinguish from the interference caused by power line harmonics on the surface.

The beacon transmitter was designed to operate in the steady state low voltage mode as opposed to a high voltage pulse mode in order to meet the permissibility requirements.

For the EM seismic uplink, the time of occurrence of a seismic event was the critical parameter to be considered in designing the circuitry. Frequency modulation was selected as the most practical means of conveying the time information to the surface, since it would be less sensitive to interference and dynamic range limitation than amplitude modulation.

2.2.7 Design Reviews and Design Modifications

Design reviews were held to discuss design trade-offs and make final design decisions. The decisions reached by the in-house design review board are listed below:

Voice Transmitter

It was decided to provide two separate antenna matching circuits so that the two-channel capability inherent in the audio power amplifier selected could be retained. This would provide the flexibility of being able to retain one channel as a spare (for system reliability), or to use both channels to provide coverage of two widely separated areas.

The relative merits of both long horizontal wire and large horizontal loop antennas were discussed. An antenna matching circuit was designed to accommodate either configuration.

Habitat Voice Receiver

The automatic gain control originally planned for the voice channel was eliminated to reduce circuit complexity.

Manpack Voice Receiver

Various packaging configurations involving locations on the miner's helmet, lamp, lamp battery, and belt were discussed. Mounting of the entire receiver in a package on the lamp battery case was selected as the logical solution, since the unit was to be powered by the battery and could be permanently or semi-permanently attached. Owned and maintained by the mine owner, lamp batteries are always charged and always available to underground personnel.

Beacon Transmitter

It was decided to incorporate an interruption in the NORMAL mode beacon transmission sequence to facilitate listening for voice transmissions. Automatic termination of SEISMIC mode transmissions was also incorporated. This feature prevents jamming of voice transmissions for uncontrolled periods of time, should the beacon operator become disabled after switching to the SEISMIC mode.

Beacon Receiver

The principal decision affecting the design of the Beacon Receiver was whether to use continuously variable tuning or fixed tuning in the rf stage. Since the developed system is experimental in nature, it was decided to use variable tuning for increased versatility.

An air core loop antenna, identical to the one used for the Habitat Voice Receiver, was selected because of its inherent compatibility with the design requirements. The only adaptation required was the inclusion of a preamplifier providing additional gain and capable of driving 1000 feet of lead-in cable.

Design Specifications

The final design specifications selected were as follows.

Voice Downlink Transmitter:

Inputs:	Microphone, External
Outputs:	2 independent power amplifiers and antenna matching channels
Power Out:	200 watts per channel
Antenna Impedance Matching:	4 to 128 ohms in binary steps
Frequency Response:	300 to 3000 Hz at 3 dB points
Other Features:	Alert signal, Time ticks built-in cassette tape player
Power Required:	115/230 volts, 60 Hz @ 800 watts

Habitat Voice Receiver:

Inputs:	Air core loop antenna, Geophone
Outputs:	External speaker, Headphones
Sensitivity:	1.6 μA/m for $\frac{S}{N}$ = 6 dB
Frequency Response:	See Figure 2.2-6
Output Power:	250 milliwatts
Power Required:	12 volts dc @ 150 mA

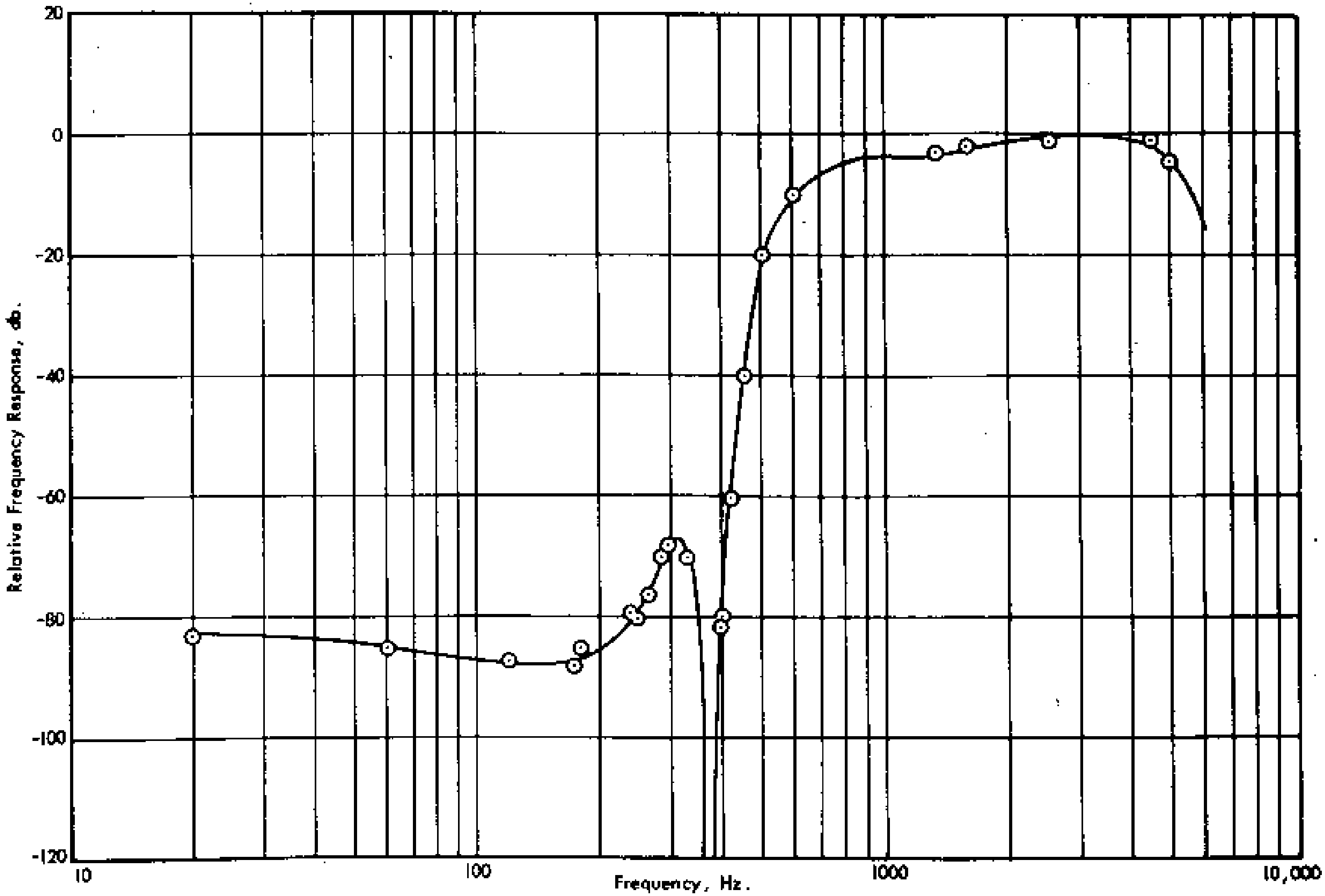


Figure 2.2-6. Habitat Voice Receiver Channel Frequency Response

Manpack Voice Receiver:

Inputs:	Geophone
Outputs:	Earphone
Sensitivity:	50 μA/m for $\frac{S}{N}$ = 6 dB
Frequency Response:	See Figure 2.2-7
Power Required:	4.5 volts dc @ 10 mA

Beacon Uplink Transmitter:

Inputs:	Seismic input from Habitat Receiver (FM Mode)
Antenna:	Air core loop, 12 turn, 100 ft perimeter flexible cable
Power Out:	4 watts, 1.2 amperes into antenna
Frequency:	2750 Hz
Operating Modes:	Normal (Beacon), Fixed Reply (6), Morse Code
Power Required:	12 volts dc @ 1.5 A

Beacon Receiver:

Inputs:	Air core loop antenna, 24" square, 1000 turns
Outputs:	Earphones Seismic Output Jack (FM Mode)
Sensitivity:	0.11 μA/m for message discrimination
Tuning:	Continuously variable 500 to 4000 Hz
Frequency Response:	See Figure 2.2-8 for passband characteristics
Display:	Lights for each fixed reply (6)
Power Required:	115 volts, 60 Hz or internal rechargeable batteries

2.2.8 Fabrication and Assembly

Fabrication and assembly of the various units of the communications subsystem employed standard model shop techniques. All metal forming and circuit card fabrication were performed by hand on an individual unit basis.

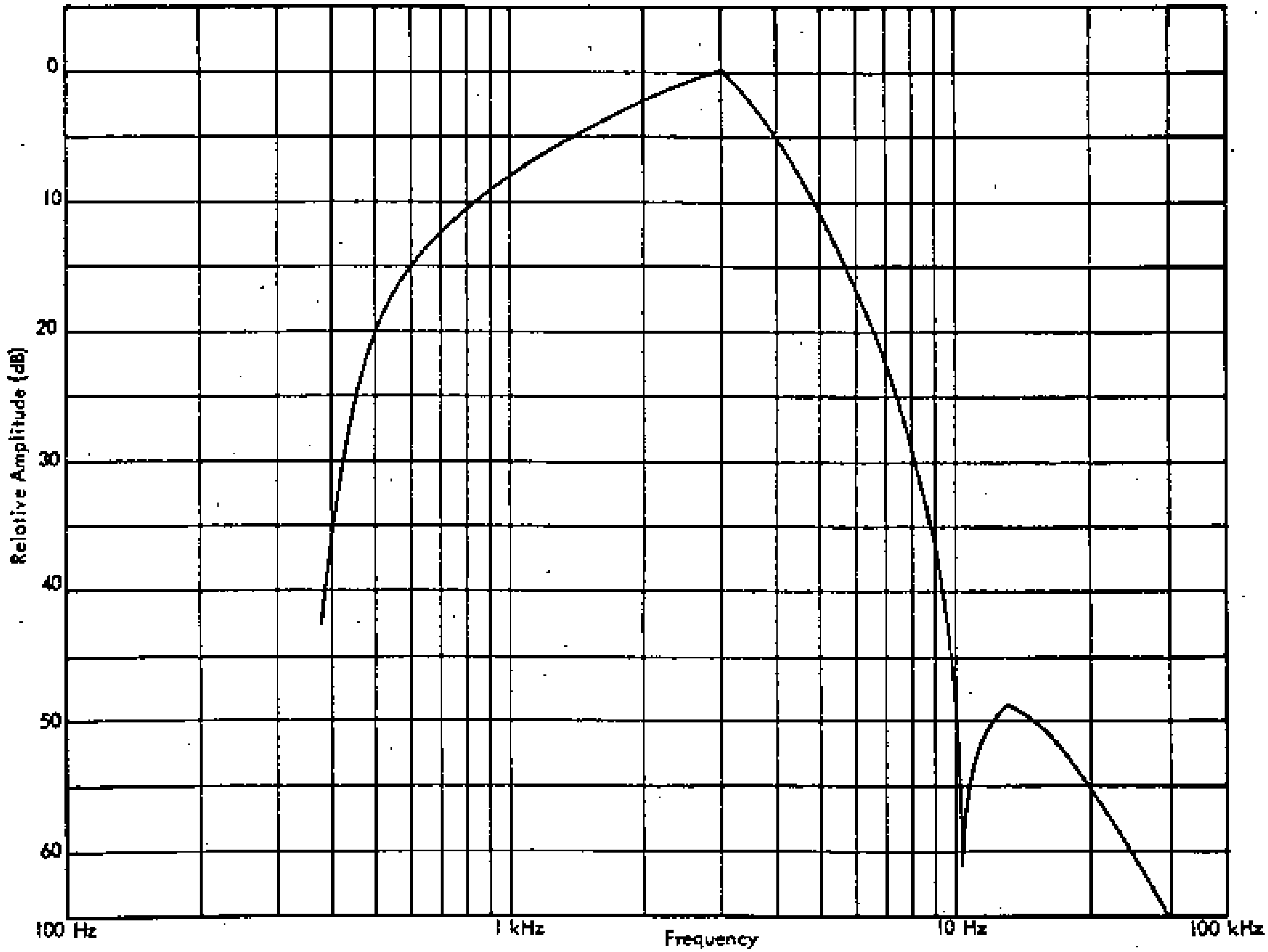


Figure 2.2-7. Frequency Response Manpack Receiver S/N 001

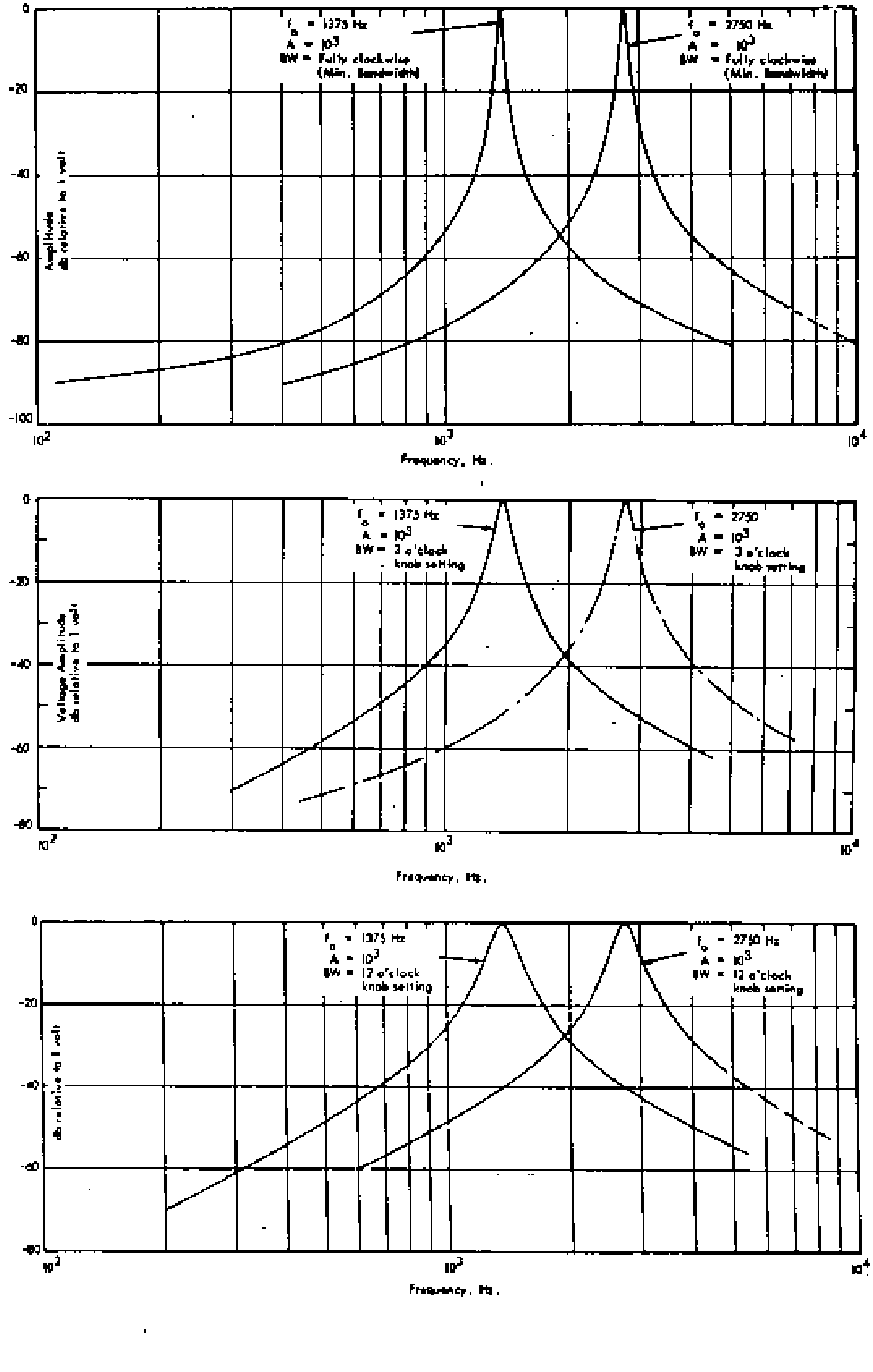


Figure 2.2-8. Beacon Receiver, Measured Frequency Responses

2.3 PREDEMONSTRATION TESTS

Predemonstration tests included both laboratory tests and checkout of the total system followed by field testing in the mine environment.

2.3.1 Laboratory Tests

Before shipping the EM Communications System to West Virginia for the predemonstration test, a series of laboratory tests were performed to ensure that the equipment was operating according to design specifications. Frequency response and gain characteristics were obtained on the beacon receiving loop and preamp, the Beacon Receiver, the Habitat Receiver, and each of the Manpack Receivers. Temperature tests from 30°F to 150°F were conducted on the voice downlink and beacon uplink equipments to verify performance in the expected operating environment.

When these tests were completed, the EM Communications equipment was packed for shipment to Charleston, West Virginia, for predemonstration testing at the Harewood Mine.

2.3.2 Field Tests

The Harewood Mine, operated by Semet Solvay Chemical Co. and located near Gauley Bridge, West Virginia, provided sufficient overburden to give both the EM uplink and downlink systems a valid performance test. It also had several seams being worked, with some mined out areas between the surface and the active workings. The mine to surface vertical separation was about 650 feet.

The conductivity of the overburden was 0.6×10^{-3} mhos/m. No attempt was made to determine conductivity layering at depth. However, the low conductivity measured at the surface probably continues down to the depth of the mine since coal outcrops were seen on the surface.

The long-wire voice transmitting antenna configuration was deployed in the shape of a large horseshoe that followed the road using 2000 feet of wire. This produced signals that could be clearly heard in the mine. The antenna terminal impedance was approximately 90 ohms. Four ground stakes were used at each end to terminate the antenna. At one end they were driven into the ground and at the other they were laid horizontally in puddles of water. Twenty pounds of salt were added to both terminations to improve electrical contact with the earth.

Voice Downlink Performance

The 64 ohm transformer output tap on the antenna matching unit was used and this gave 1 amp undistorted RMS sine wave current into the transmitting antenna. The maximum power of 200 watts was not realized due to the impedance mismatch between transmitter and antenna. However, the transmitted power was sufficient to establish good quality voice signal reception on both the Manpack Receivers and the Habitat Receiver in the mine.

The orientation of the voice receiving loop did affect the quality of reception. The loop usually was oriented for minimum interference rather than maximum signal. A 360 Hz tone was heard on the receivers at all of the working mines visited.

Beacon Uplink Performance

The beacon uplink system met performance requirements during the predemonstration tests conducted at the Harewood Mine, W. Va. The Beacon Transmitter power used in these tests was about 25 watts. Beacon uplink communications were tested at carrier frequencies of 1375 Hz and 2750 Hz. The 1375 Hz signal strength at the surface was stronger than at 2750 Hz, but the background interference was also greater causing an overall degradation in performance at 1375 Hz. The functional operation of the beacon uplink was satisfactory using only the six preselected push button replies; however, the additional provision of the MANUAL CW button proved to be extremely useful whenever the subsurface personnel desired to initate a message to the surface. To ensure that the MANUAL CW operating capability could be utilized by personnel unfamiliar with Morse Code, a plastic laminated card containing the International Morse Code was inserted in the cover of the Beacon Transmitter carrying case.

2.3.3 Design Modifications

Immediately following the predemonstration phase at the Harewood Mine, a meeting was held with the Bureau of Mines Approval and Testing Group, Technical Support Center, Pittsburgh, Pennsylvania, to discuss the subject of permissibility for all subsurface electrical equipment. As a result of this meeting the Beacon Transmitter was modified so that its electrical operation in the mine would be intrinsically safe and therefore not require explosion proof components for permissibility. This modification required reducing battery voltage from 24 volts to 12 volts, limiting the current from the battery with series resistors, and limiting the transmitted current into the primary of the beacon output transformer with a series resistor. These modifications reduced the output power of the Beacon Transmitter from 25 watts to 4 watts resulting in an 8 dB loss of signal level. All subsequent EM testing was performed with a Beacon Transmitter output power of 4 watts.

2.4 DEMONSTRATION TESTS

2.4.1 Site Description

The mine chosen for the "simulated disaster" CMR&SS demonstration was the U.S. Steel Mine No. 14 at Munson near Gary, West Virginia. The terrain in this area is extremely rugged and there was nearly 800 ft of overburden between the area of mine entrapment and the communications van on the surface. Subsequent paragraphs describe the operational parameters of the site and the performance of the Voice and Beacon Communications Subsystems at Mine No. 14. The operational procedures followed during the demonstration are described in Appendix A.

2.4.2 Ground Conductivity

Measurements of ground conductivity were made along a road over the mine beginning at the communications van and extending out to a distance of 350 meters. The apparent ground conductivity observed was nearly the same at each of the 5 dipole separations used, indicating fairly homogeneous electrical characteristics of the overburden. The conductivity measurements ranged from a low of 2×10^{-3} mhos/m at a dipole separation of 300 meters to a high of 3×10^{-3} mhos/m at a dipole separation of 200 meters. The mean conductivity of the strata down to a depth of roughly 500 ft was 2.4×10^{-3} mhos/m. It was assumed that the conductivity remained essentially constant from the surface down to the mine level. Based on a mean conductivity of 2.4×10^{-3} mhos/m, the "skin depth" (δ) of the conducting material at 2750 Hz is 195 meters (640 ft). The EM signal attenuation observed at this depth was due primarily to the inverse distance relationship (z^3) as shown in Figure 2.1-3. Since the maximum frequency of the voice downlink system is about 3 kHz, this analysis will apply similarly to the downlink propagation characteristics.

2.4.3 Signal and Interference Comparisons of Voice Downlink

Figure 2.4-1 shows the subsurface signal and noise field intensity observed at the habitat location in the mine. Most of the background noise in the mine was associated with 3-phase rectifier ac harmonics carried on the dc trolley bus. The noise curve is based on interference peaks received at the significant harmonic frequencies of the 60 Hz primary power and the 360 Hz rectifier harmonics. The received signal from a 410 mA transmitter current on the surface is also plotted on this same figure. In the frequency band of interest (500 to 3000 Hz), the received signal from a 410 mA transmitter current is above the interference peaks. The 360 Hz interference was reduced by filtering in the Habitat Receiver and did not adversely affect the reception of the voice signals in the mine.

2.4.4 Signal and Interference Comparisons with Beacon Uplink

The noise and interference seen on the beacon receiving system (see Figure 2.4-2) was generally caused by local power line harmonics. The beacon field intensity was measured down the mountain from the communications van and at two locations on the strip mining bench. (See map, Figure 2.4-3.) The received signal strength was appreciably greater than the background interference at all locations.

The temperature at the beacon receiving site was below 32°F most of the time and occasionally dipped below 0°F. Throughout the demonstration, the beacon antenna preamp and battery supply were exposed to these temperatures, yet continued to function satisfactorily. The Beacon Receiver was exposed to cold temperatures during the installation and deployment phase of the demonstration and the remainder of the time was housed in the equipment rack in the communications van. Under exposed low temperature conditions detuning was evident in the message display light circuits causing an erratic display on some of the messages. This was due in part to the 30° to 150°F range of the integrated circuit amplifiers. These amplifiers have since been replaced with their corresponding mil-spec counterpart. The rf and audio portions of the receiver functioned satisfactorily under all conditions.

2.4.5 Results of Voice Downlink Tests

The quality of the voice reception in the mine with transmitter antenna currents averaging 0.5 amps, was excellent with both the Habitat Receiver and the Manpack Receivers. One hundred percent message intelligibility was maintained on both receivers throughout the test and usually the quality permitted indentification of individual speakers. The irregular shape of the

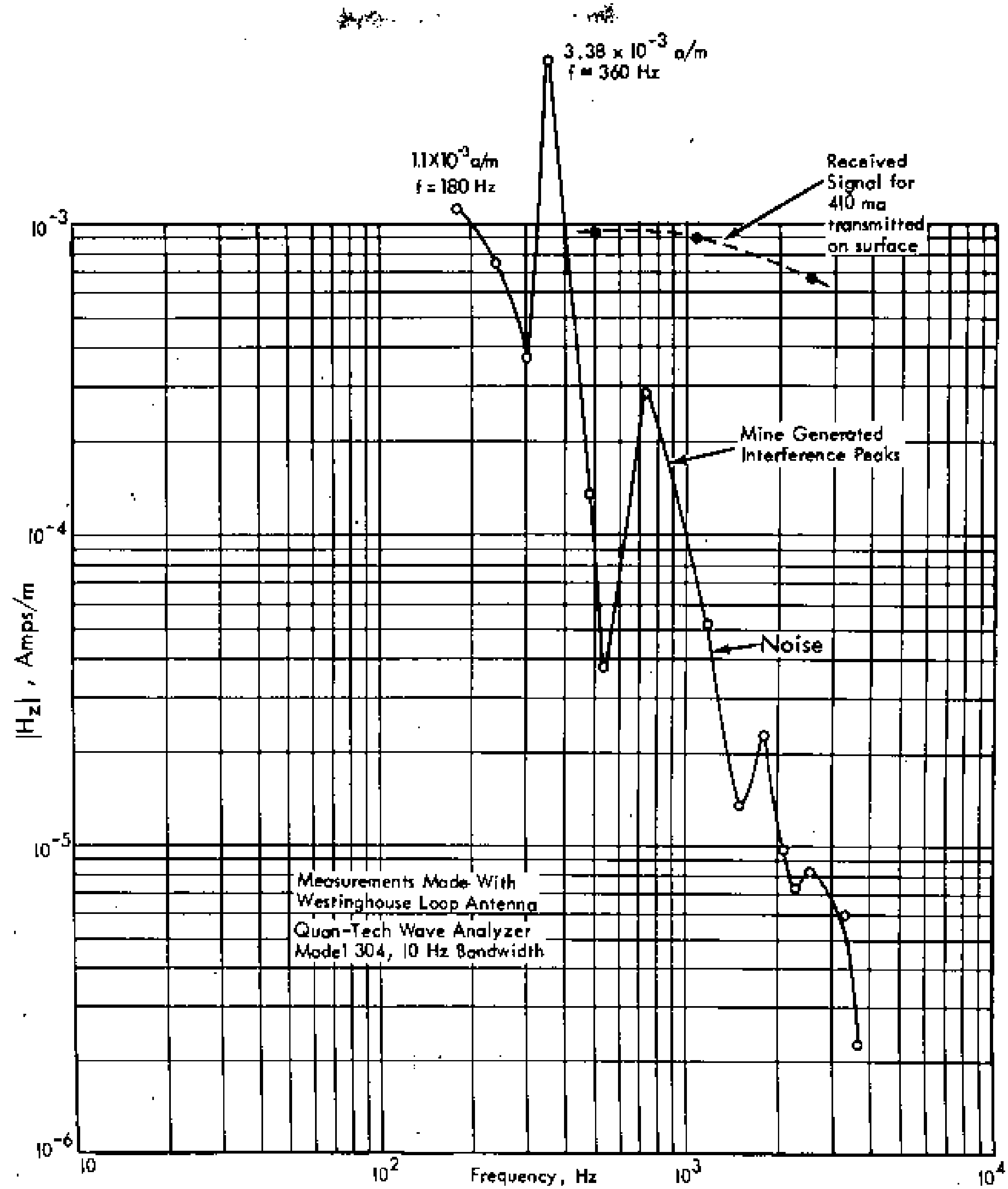


Figure 2.4-1. Subsurface Signal and Noise Field Intensity Measurements (Munson Mine No. 14)

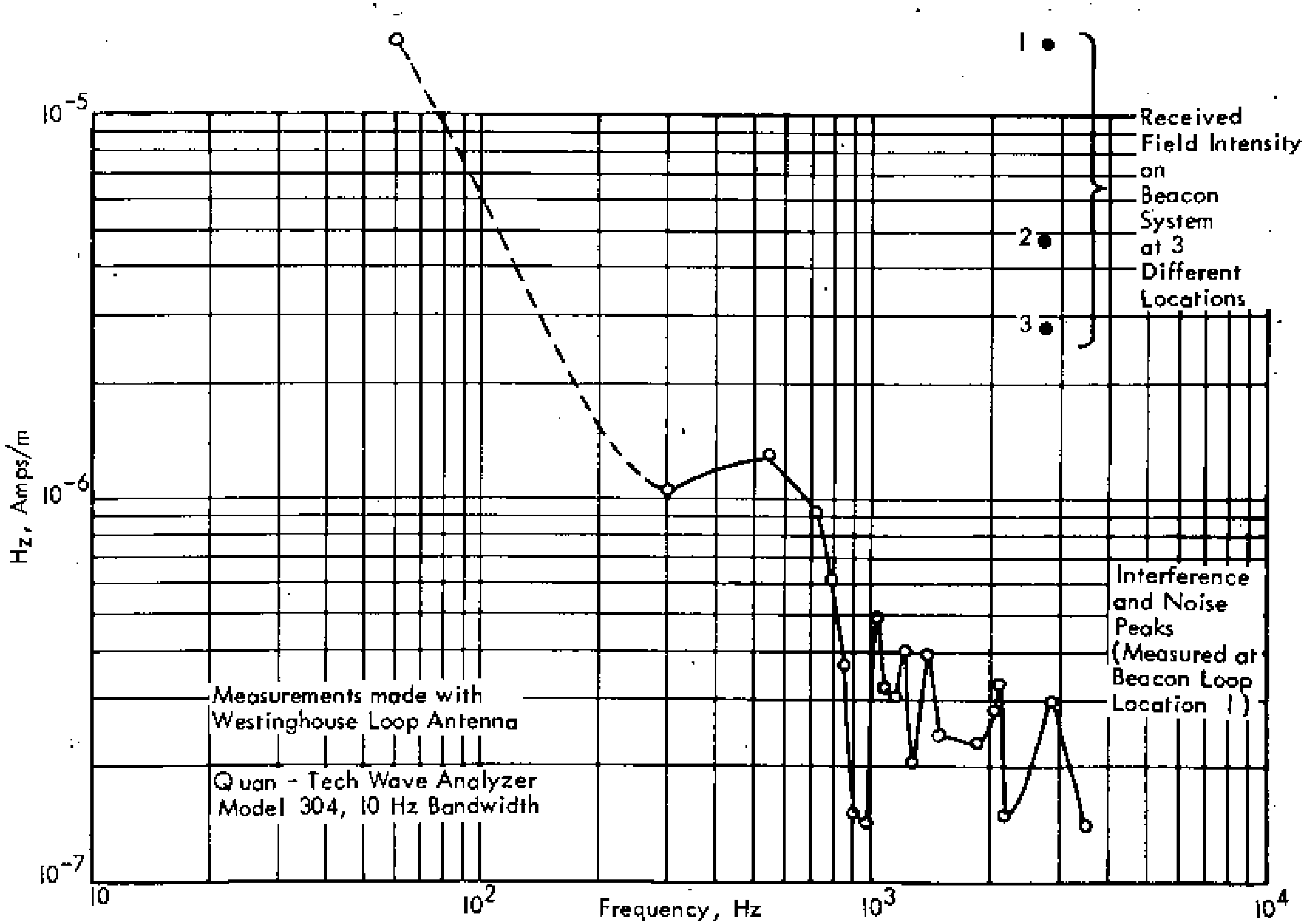


Figure 2.4-2. Surface Signal and Noise Field Intensity Measurements Beacon Receiving Location, Munson Mine No. 14

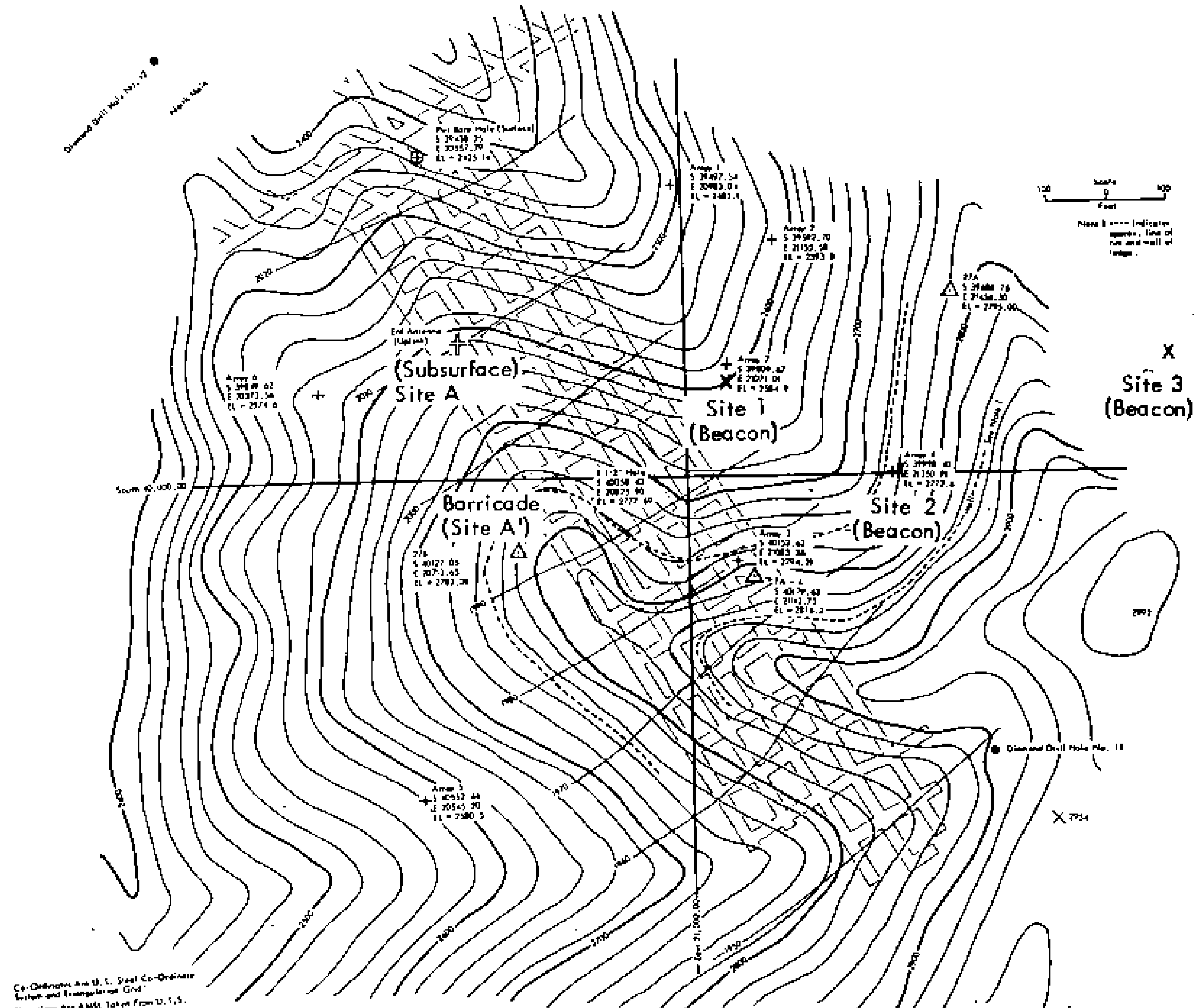


Figure 2.4-3. Area of CMRS Demonstration, U.S. Steel Mine No. 14 Munson, W. Va.

surface transmitting antenna prevented valid quantitative comparisons of measured and theoretical field strengths. The measured field strengths were 10 dB higher than predicted assuming a straight antenna.

Normally voice communications were maintained between the communications van on the surface and either the Beacon Transmitter location (A) or the simulated barricade location (A1) in the mine. On one occasion, reception of voice signals was attempted using the Manpack Receiver at other locations farther away. Table 2.4-1 summarizes qualitatively the results of these experiments. The table shows that intelligible voice communications could be established with transmitter currents of approximately 0.5 amps at a slant range of 1454 ft but not at 2843 ft. At a slant range of 1021 ft, high quality voice reception with 100% intelligibility was continuously achieved.

2.4.6 Results of Beacon Uplink Tests

The coded message transmission and decoded message receiving sections of the beacon uplink system met performance requirements except under extremely low temperature conditions. The beacon/seismic data uplink required a modification of a resistor value in the Beacon Transmitter to prevent overloading and thus permit its signals to be utilized by the Seismic Location System. This modification was made shortly after the test began and the beacon/seismic uplink system was then used as a synchronizing input to facilitate the processing of geophone signals recorded on the surface.

Beacon field strength measurements were made at three different locations and their measured values compare favorably with calculated values using the measured ground conductivity of 2.4×10^{-3} mhos/m. Table 2.4-2 shows the comparison between measured and predicted field strength measurements at sites 1, 2 and 3 in Figure 2.4-3.

Reliable beacon communications were achieved with a transmitter power of 4 watts over a maximum through-the-earth slant range of 1544 ft.

2.5 PERFORMANCE EVALUATION

The results of the predesign tests (Section 2.1), predemonstration and demonstration tests (Sections 2.3 and 2.4) show how the EM communications performed at the five mines visited. These results can also be used to evaluate the system's capability in general, and extrapolate its performance to a wide variety of mines with different physical and operational characteristics. Sections 2.5.1 and 2.5.2 provide curves and tables which can be used to estimate, in advance, the EM System's operational capabilities in any mine whose geophysical and physical characteristics are known.

2.5.1 Voice Downlink

Figure 2.5-1 shows the predicted horizontal magnetic field directly under a long horizontal wire antenna carrying 1 ampere at a frequency of 1000 Hz.

If the overburden conductivity is known and one assumes that the mine generated noise is insignificant, it is possible to determine the maximum depth of operational communications for both the Westinghouse Manpack Receiver and the Habitat Receiver using Figure 2.5-1. The limiting field strength required for satisfactory operation of the Manpack Receiver,

TABLE 2.4-1

SUMMARY TEST RESULTS (At Subsurface Location)

Voice Receiving Location	Vertical Displacement from Transmitter Van	Horizontal Displacement from Transmitter Van	Total Displacement from Transmitter Van	Intelligibility of Voice Reception	Quality of Voice Reception	Receivers Used
A (Beacon Transmitter Location)	787	650	1021	100%	Very good	Habitat & Manpack
B	760	1240	1454	95%	Fair	Manpack only
C	760	2740	2843	0%	None	Manpack only

TABLE 2.4-2

FIELD STRENGTH MEASUREMENTS (At Surface Location)

Beacon Receiving Loop Site	Vertical Displacement from Transmitter	Horizontal Displacement from Transmitter	Total Displacement from Transmitter	Calculated Vertical Magnetic Field (H_z)	Measured Vertical Magnetic Field (H_z)
1	600 ft	317 ft	679 ft	15.07 μa/m	15.23 μa/m
2	787 ft	768 ft	1100 ft	4.75 μa/m	4.76 μa/m
3	787 ft	1329 ft	1544 ft	2.30 μa/m	2.85 μa/m

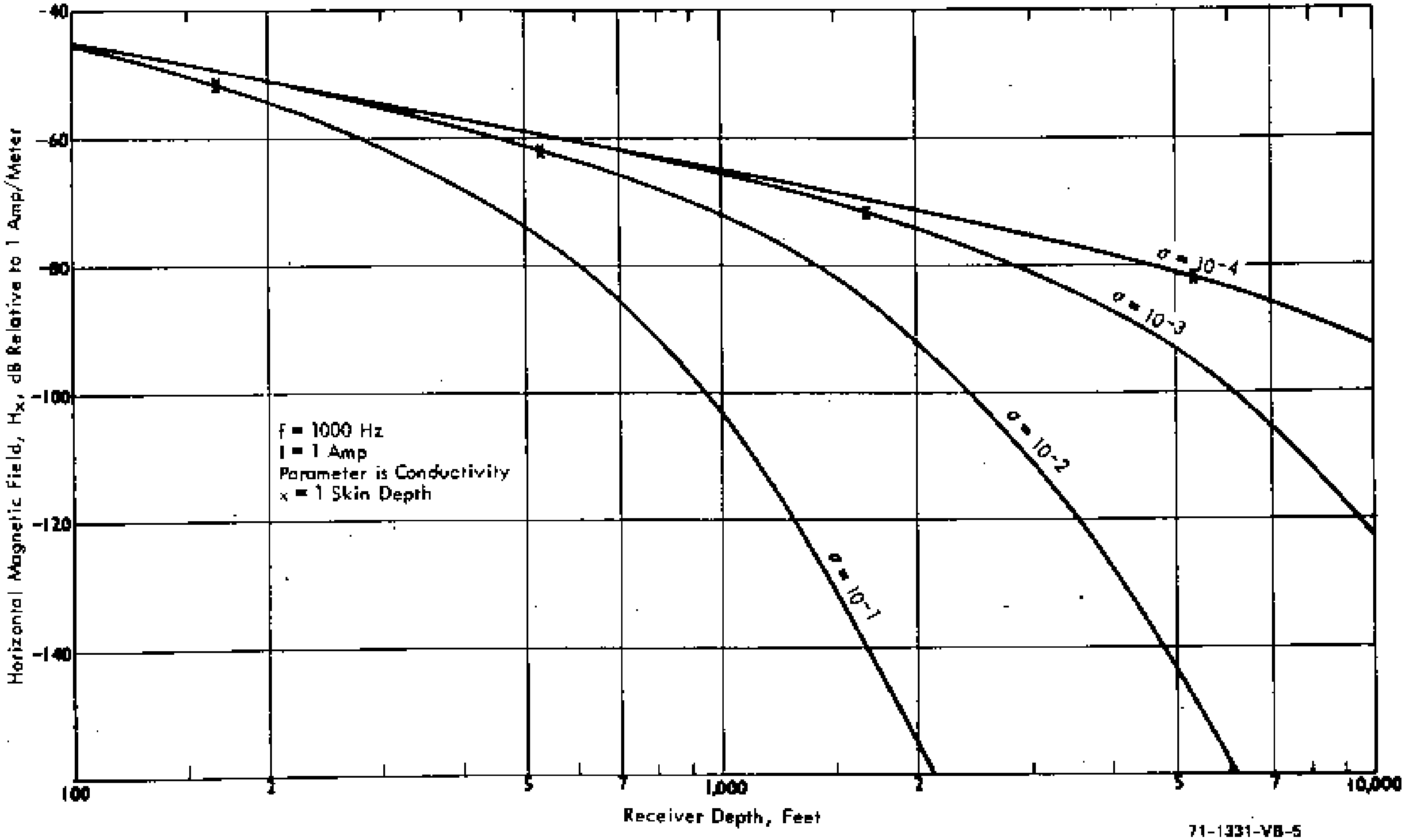


Figure 2.5-1. Horizontal Magnetic Field Directly Under an Infinite HWA

assuming that only receiver thermal noise is present, is -86 dB relative to 1 a/m and for the Habitat Receiver it is -116 dB relative to 1 a/m. Thus, for a mine with an overburden conductivity of $\sigma = 10^{-2}$ mhos/m, and a long HWA transmitting current of 1 ampere, the maximum useable depth for the Manpack Receiver is 1600 ft and for the Habitat Receiver 3200 ft. These depths are optimistic because they assume no mine generated external noise. It is difficult to predict what the mine generated noise will be for a given mine since it varies widely as a function of the location and current demand of electrical equipment in the mine. Also, the movement of electric trolleys has been observed to generate considerable interference. In emergency situations, however, the mine interference should be negligible, and the maximum depths for communications stated above should be achievable.

Referring to the noise curve in Figure 2.1-12, we note that a field strength of at least -60dB relative to 1 amp/m is required to override most of the harmonic noise peaks as seen in a large working mine such as the Clyde Mine in Pennsylvania. Taking this as a typical condition for a large working mine, the maximum useable depth for the two receivers under full scale operating conditions would be about 450 feet. Subsurface noise, as it relates to communications performance is undergoing continuing investigation.

Figure 2.5-2 shows essentially the same data as Figure 2.5-1 with the curves being parametric in magnetic field strength rather than conductivity. Both of these curves can be used effectively to predict the system's performance at any mine for which the pertinent parameters such as conductivity, depth, and background noise are known.

Figure 2.5-3 shows the magnetic field degradation observed by moving horizontally away from a point directly beneath the line at depths of 500, 1000, 1500, and 2000 feet and for voice frequencies of 300 Hz and 3kHz. It is apparent that for these voice frequencies the attenuation vs. horizontal distance out to distances of 500 feet is almost negligible for the two layer earth model used.

Table 2.5-1 shows the approximate maximum operating depth for both the Habitat and Manpack Receivers to achieve the indicated signal-to-noise ratios in conductivity environments of 10^{-1}, 10^{-2}, 10^{-3}, and 10^{-4} mhos/m. The assumption is again made that mine generated noise is negligible and that receiver front end noise is the limiting factor on performance. These figures are based on an excitation frequency of 1 kHz which, logarithmically, is the midpoint frequency of the voice band used in this equipment.

2.5.2 Beacon Uplink

The performance of the beacon uplink system can be predicted for a wide variety of mines using the electromagnetic field strength curves in Figures 2.5-4 and 2.5-5. In most cases, the major component of contaminating noise and interference on the surface will be man-made interference from power lines and nearby industrial facilities. It is difficult to predict what the man-made interference will be at a given site without measuring it. However, it is possible to evaluate the beacon system performance under the condition that it will be atmospheric noise limited, a quantity that can be predicted

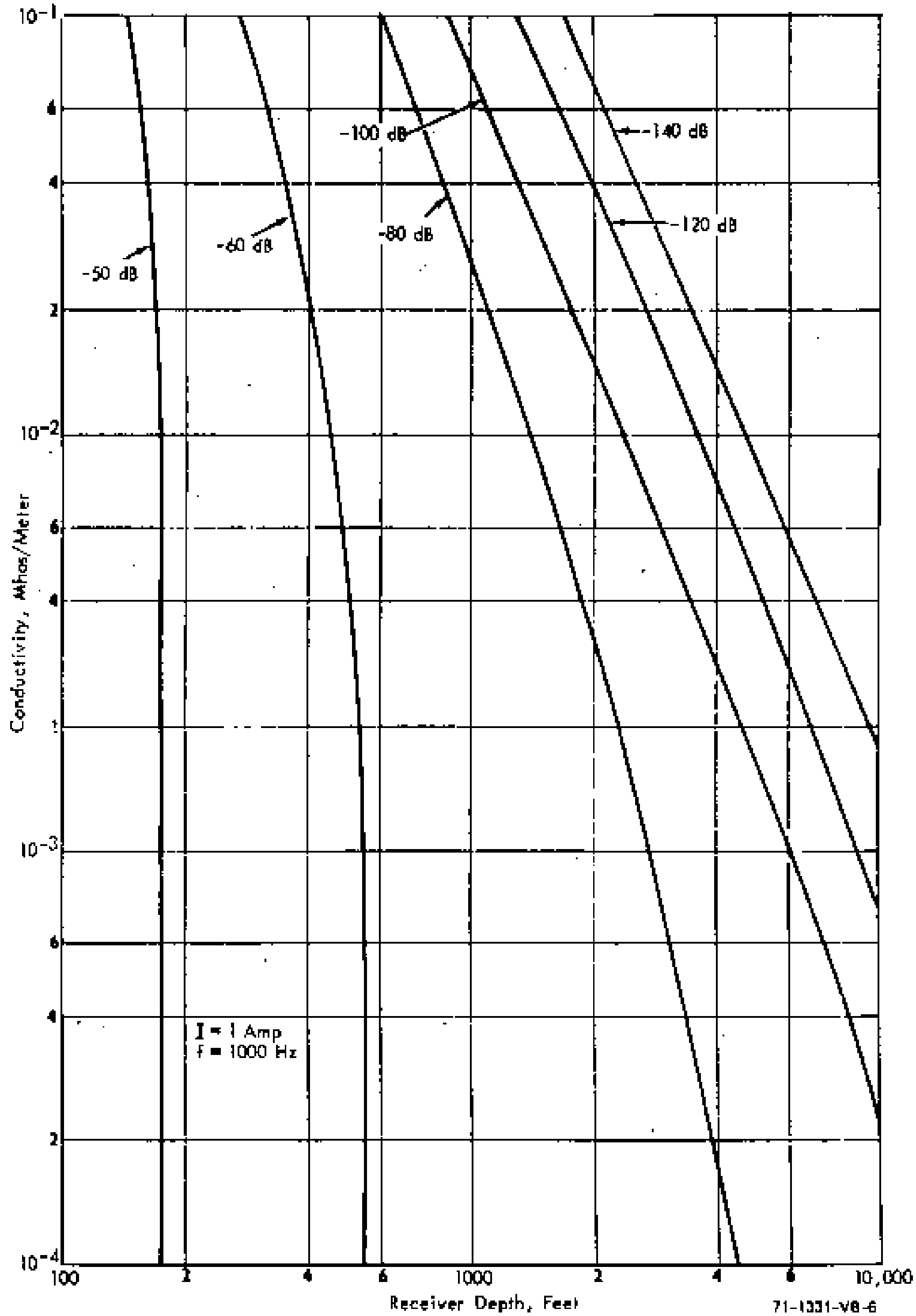


Figure 2.5-2. Horizontal Field Strength (H_x) (dB Relative to 1A/m) Directly Under an Infinite HWA

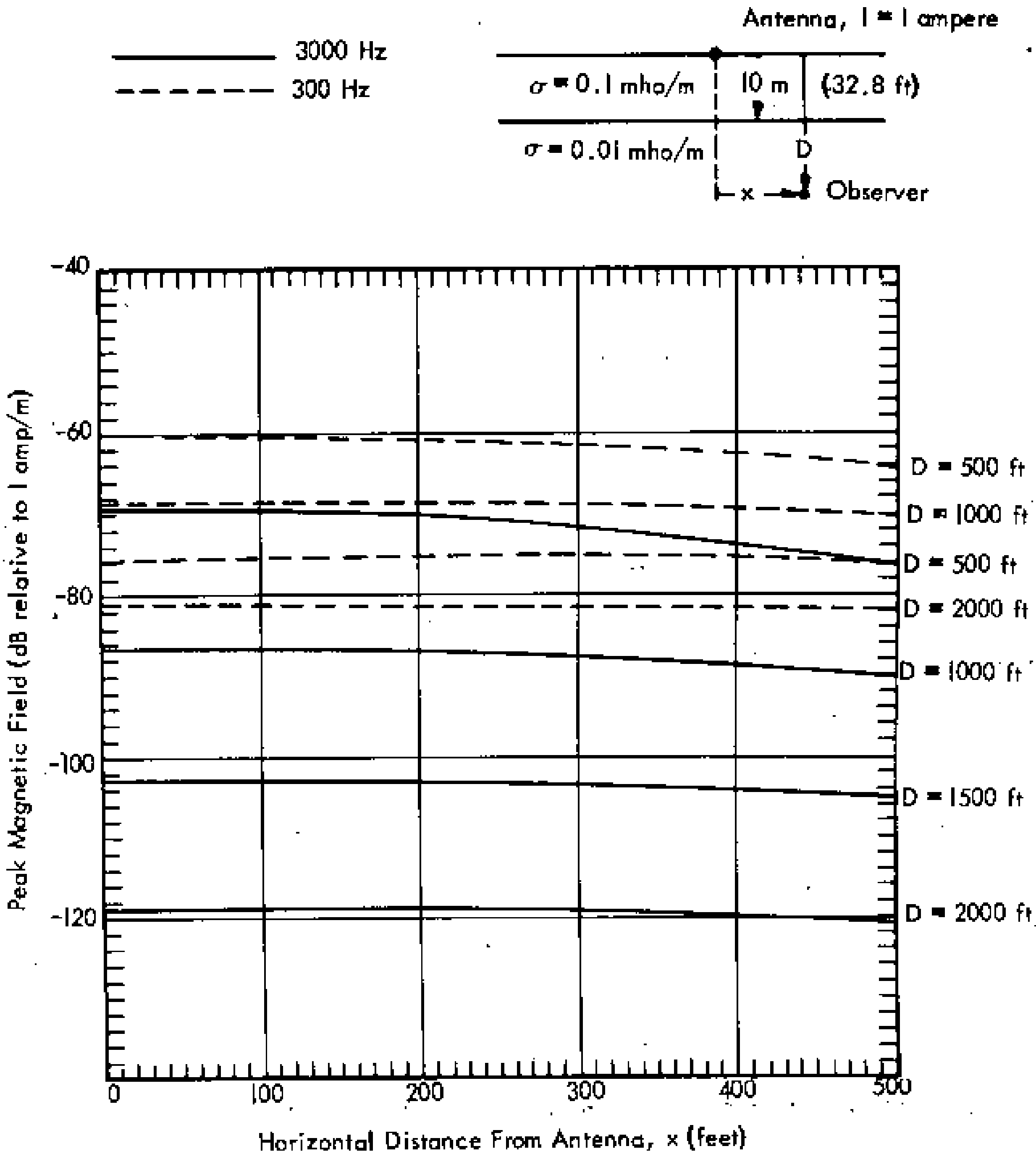


Figure 2.5-3. Magnetic Field Strength in a Two Layer Earth from an Infinite Horizontal Wire Antenna at the Surface

TABLE 2.5-1

APPROXIMATE DEPTH FOR SIGNAL RECEPTION (DOWNLINK) FOR HABITAT/MANPACK RECEIVERS

S/N dB / σ mhos/m	5	10	20	30
10^{-4}	*	*	*	~ 6000
	~ 6000	2000	850	240
10^{-3}	7500	6500	4800	3400
	3200	1500	620	240
10^{-2}	3000	2600	2000	1600
	1500	940	500	230
10^{-1}	1100	950	800	680
	660	450	310	170

For each conductivity, the upper line is the depth for the Habitat Receiver and the lower line is for the Manpack Receiver.

I = 1 amps

BW = 2500 Hz

f = 1000 Hz

Transmitting antenna length - assumed to be long enough such that the horizontal distance between the observer and the nearest end is greater than the observer's depth.

σ = Effective earth conductivity, mhos/meter

N = Noise

Mine equipment turned off

Depth, in feet

* Requires special theoretical consideration

Sensitivity: Habitat Receiver $S/N_T \geq 5$ dB, H = -116 dB rel to 1 A/m

Manpack $S/N_T \geq 5$ dB, H = -86 dB rel to 1 A/m

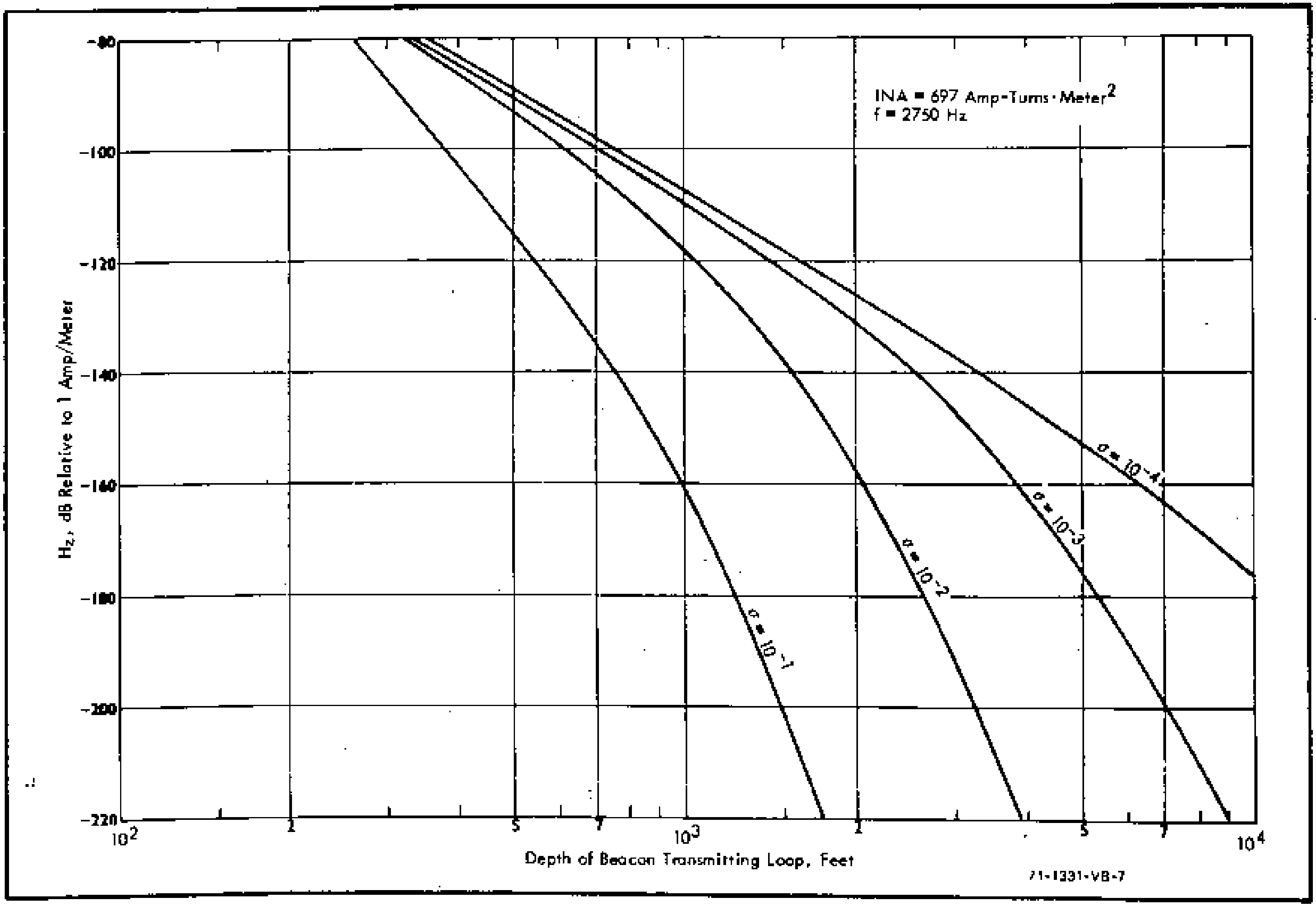


Figure 2.5-4. Vertical Magnetic Field Strength on Surface, Directly Over Transmitting Loop

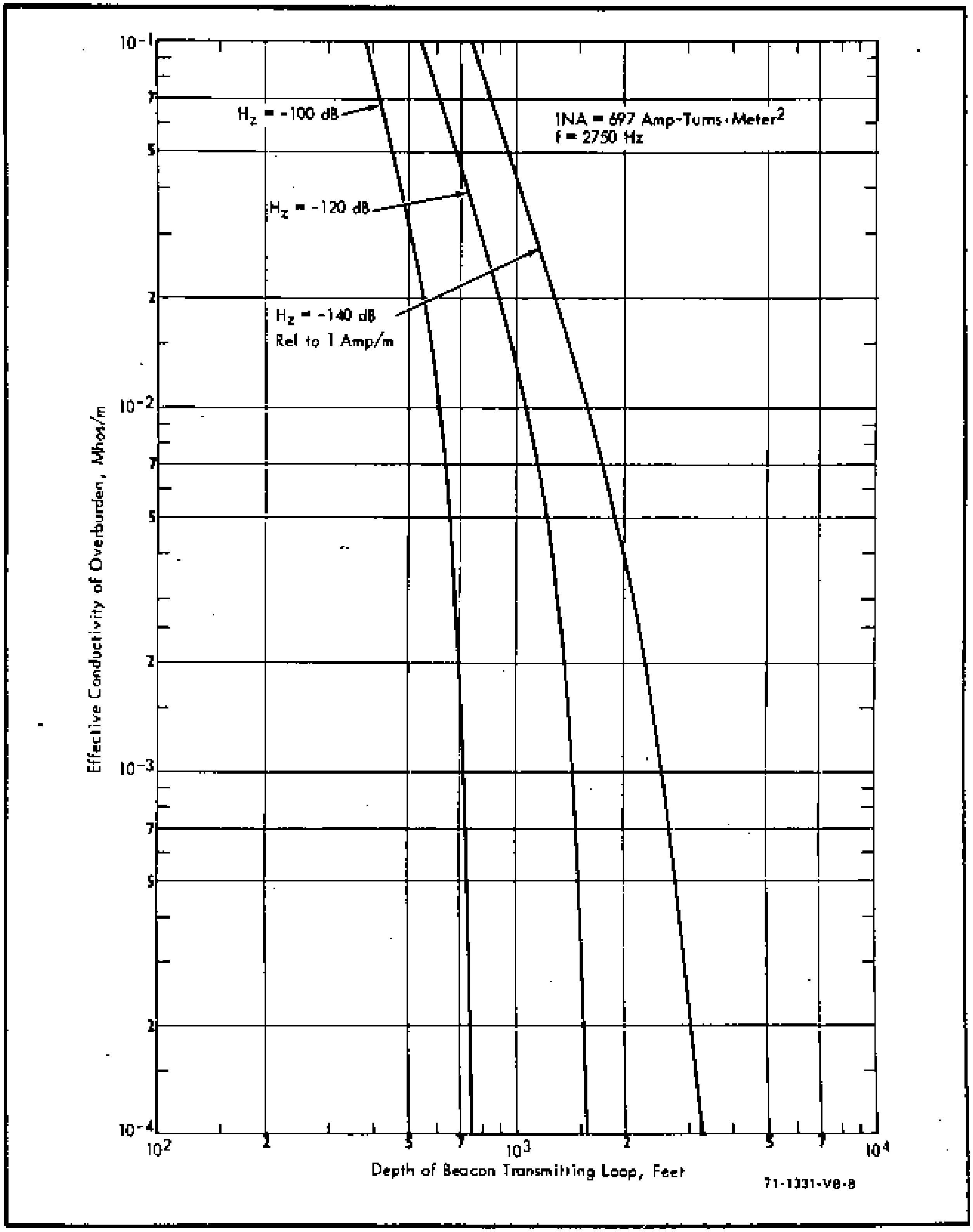


Figure 2.5-5. Magnetic Field Strength Directly Over Beacon Transmitting Loop

with reasonable accuracy. Based on statistical noise data in the literature, and Westinghouse's past experience in the measurement of low frequency noise, a typical value of magnetic field noise at 2750 Hz was assumed to be on the order of -166 dB relative to 1 a/m in a 1 Hz bandwidth.

In order for the beacon decoding circuitry to work properly, the signal-to-noise ratio should be at least 6 dB. Thus, the limiting signal strength for reliable performance of the Beacon Receiver is roughly -139 dB or .11 μa/m in a 50 Hz bandwidth. Using Figure 2.5-4, one can determine the maximum operating depth of the beacon system as a function of the overburden conductivity. For example, for an overburden conductivity of $\sigma = 10^{-2}$ mhos/m, the -139 dB intercept occurs at a depth of 1500 ft. Figure 2.5-5 shows the data in a slightly different manner, and Table 2.5-2 shows the maximum operating depth in tabulated form as a function of desired signal-to-noise ratio for conductivities from 10^{-1} to 10^{-4} mhos/m. It must be kept in mind, however, when using these curves and tables to predict beacon performance, that they represent ideal conditions and that under normal conditions the system performance will be degraded by whatever amount of man-made interference is present.

TABLE 2.5-2

DEPTH TO BEACON WITH TYPICAL ATMOSPHERIC NOISE AT SURFACE

σ (mho/m) \ S/N_A (dB)	0	10	20	30
10^{-4}	4400	3100	2200	1500
10^{-3}	3100	2500	1900	1400
10^{-2}	1700	1500	1300	1050
10^{-1}	880	750	630	530

f = 2750 Hz
Bandwidth = 50 Hz (17 dB)
Avg. H_n = -166 dB rel to 1 A/m/ Hz
= 149 dB rel to 1 A/m in 50 Hz
Depth, in feet

3. SEISMIC LOCATION/COMMUNICATIONS SYSTEM

The purpose of the Seismic Location System is to detect and locate trapped miners who have no means of communicating to the surface other than by generating seismic vibrations which can be received on the surface. The uplink Seismic Communications System is necessarily established as a result of the Seismic Location System since communication requires only detection of the signals at one point, but location requires a means of initial estimation of signal parameters at three or more separated points. The seismic communication system, then, required only development of a downlink to establish two-way communications, since the location system would serve as the uplink. Throughout this section, little attention will be paid to the seismic communications uplink for the above reasons. The seismic communications downlink, which consists of explosive charges on the surface and unaided aural detection by individual mining personnel, will be treated only briefly. The majority of the material will deal with seismic location.

At the outset of this study it was realized that a seismic location system would be difficult to implement with current technology. The work described below is the result of a nine month program to provide the best possible use of the state-of-the-art. Further improvement and research is acknowledged to be required to provide a suitable system for miner location.

It was demonstrated by the National Academy of Engineers (NAE)* that a seismic signal generated by a miner pounding with a 3 pound hammer on roof timbers could be detected by geophones on the surface. However, the received signal was weak, its time of arrival was not definable, and the experiment was performed in a western Colorado mine with only 210 feet of overburden. The NAE suggested that the use of multiple element arrays of geophones and better electronic filtering, would increase the signal-to-noise ratio by 20 dB. However, since the signal and noise both fell within approximately the same band, Westinghouse did not expect to realize significant improvement by filtering. In addition, multiple element arrays do not always improve signal-to-noise ratio to the extent predicted theoretically, so the improvement expected was felt to be somewhat optimistic.

Westinghouse proposed to construct a state-of-the-art location system to empirically test the feasibility of an operational seismic location system. The proposed system would be at least as sensitive and noise-immune as any system known to be in existence and, more importantly, it would take advantage of repetitive signals, in addition to spatial and electronic filtering, in order to improve signal-to-noise ratios.

Also it was proposed to implement some type of simple but reliable downlink communications. Since the electromagnetic system would perform the

* "Mine Rescue and Survival," NAE Committee Report, November 1969.

primary downlink communications function, seismic communications would serve only as a "back-up" system. However, since downlink EM communications require that miners have receivers, and this will not be the case immediately, a back-up downlink was required which could be used even when the miners have no special equipment.

3.1 PREDESIGN TASKS

The purpose of this section is to summarize the initial work which led to specifications and design of the seismic location system. It includes both theoretical work and field tests.

3.1.1 Data Base

The purpose of the geophysical data base was to determine the range of variation and the minimum, maximum, and typical values of geophysical parameters so that the system could be designed with enough margin to operate in any coal mining region in the United States. The seismic parameters of interest are:

(1) Seismic (compressional) P-wave velocity for both the mine overburden rock and the surface weathered layer.

(2) Attenuation of P-waves.

(3) Natural seismic noise levels.

The accomplishment of this task required specifying general geological characteristics and then deducing geophysical properties since no directly applicable data was found. The data was assembled in general form and specific cases were analyzed to assure that the general specifications were valid. A brief example of the data derived from various sources is given in Tables 3.1-1 and 3.1-2. The United States is divided into major coal regions, and geophysical parameters are listed for each. The complete results of the data collected and the sources are given in Appendix D. It is not to be expected that this data base will specify the geophysical parameters at any given mine, since there can be significant variation between mines in the same region. However, the data does indicate the values of parameters which will most likely be encountered at a mine in a given area.

3.1.2 Detection Study

A brief theoretical study was made to attempt to predict the signal transmitted to the surface from a hammer blow underground.

Background

Assume that a point force, $Gg(t)$, where $g(t)$ represents the shape of the force function and G its amplitude, is applied in an unbounded solid as shown in Figure 3.1-1. White* has shown that the radial particle displacement is

$$u_r = \frac{G \cos \phi}{4\pi \rho V^2 r} \, g\left(t - \frac{r}{V}\right) \qquad (3\text{-}1)$$

*White, J. E., Seismic Waves; Radiation, Transmission, and Attenuation, McGraw-Hill Book Co., New York, N.Y., 1965, pp. 214-216.

TABLE 3.1-1

GEOLOGICAL CHARACTERISTICS

Region	Age	Structure	Thicknesses	
			Overburden, ft.	Weathering, ft.
No. Appalachian	Pennsylvanian	Only Gentle Dips	0-1000	10-50
So. Appalachian	Pennsylvanian	Only Gentle Dips	Up to 1500	0-50
Michigan Basin	Pennsylvanian	Gentle Basins	300-600	100-150
Illinois Basin	Pennsylvanian	Gentle Dips	600-800	Less than 50
Western Interior	Pennsylvanian	Regional Dip	0-300	50-100
So. Rocky Mtn.	Cretaceous	Almost no Dip	Up to 1500	Over 150
No. Rocky Mtn.	Cretaceous	Slight Dip	300-600	Over 150
West Coast	Eocene	Slight Dip	300-600	50-100

TABLE 3.1-2

REGIONAL GEOPHYSICAL PARAMETERS

Seismic Characteristics

Region	Overburden Velocity (1) (ft/second)	Wx Layer Velocity (ft/second)	Specific Atten. (2)	Background Noise (3) (in/sec/Hz)
No. Appalachian	9000-15000	1000-4000	70.0	7.8×10^{-5} to 3.9×10^{-8}
So. Appalachian	9000-15000	1200-4000	66.0	7.8×10^{-5} to 3.9×10^{-8}
Michigan Basin	10000-15000	1500-1700		7.8×10^{-4} to 3.9×10^{-8}
Illinois Basin	7000-10000	2000-3500	48.0	3.9×10^{-5} to 3.9×10^{-8}
Western Interior	7000-10000	2000-3500	70.0	3.9×10^{-5} to 7.8×10^{-9}
No. Rocky Mtn.	9300-11000	2000-4500	300	7.8×10^{-6} to 7.8×10^{-8}
So. Rocky Mtn.	9300-11000	2000-4500	250	3.9×10^{-5} to 7.8×10^{-9}
West Coast	7100-10000	3000-3300		7.8×10^{-6} to 7.8×10^{-8}

(1) For sandstone and shale.

(2) Average for sandstone.

(3) Range for 0.1 to 100 Hz.

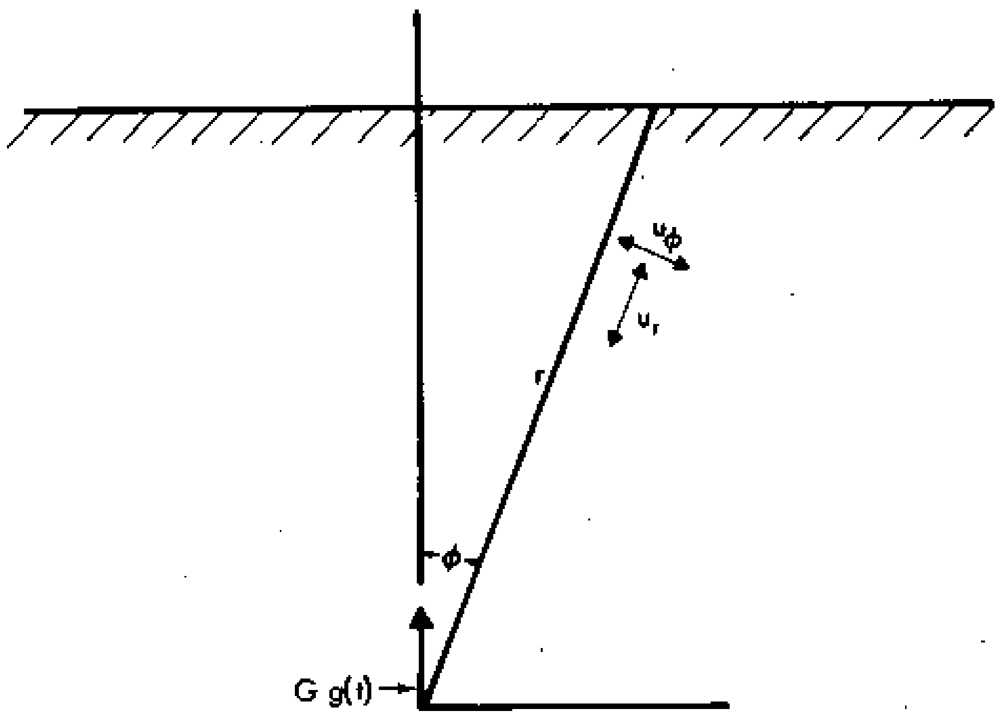


Figure 3.1-1. Geometry of Point Source in Unbounded Solid

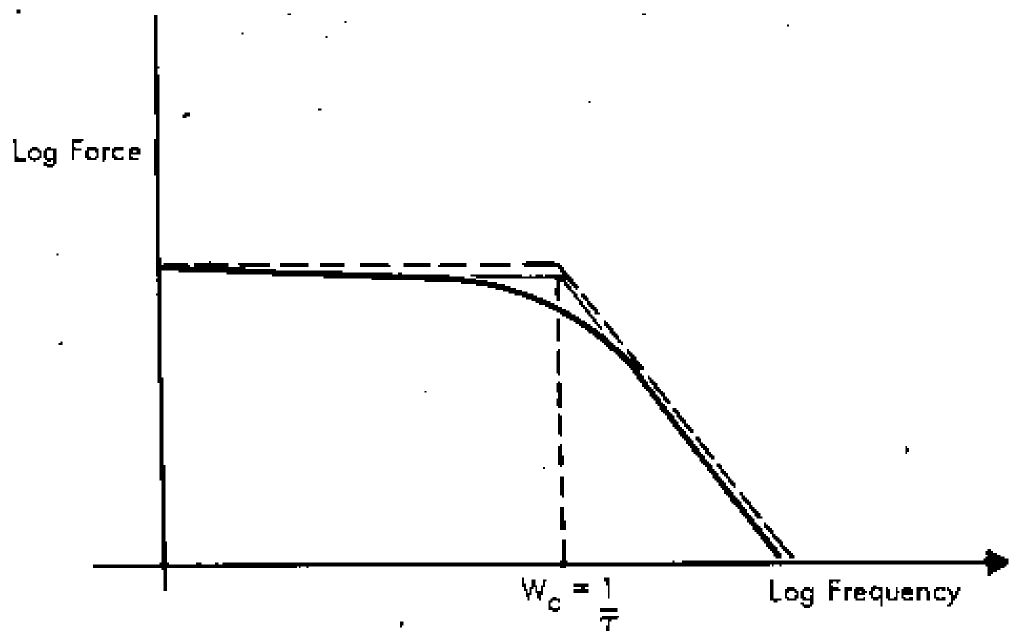


Figure 3.1-2. Expected Spectrum Characteristics from a Hammer Blow

where the point of interest is far enough from the source to neglect "near field" components and frictional attenuation is not included. In the above equation, ρ is the density of the solid and V is the speed of compressional P waves. The expression does not include attenuation and so should give a maximum expected signal. In addition, since the wave reflects at the free surface, the displacement doubles and Equation (3-1) should be multiplied by a factor of 2.

If we let the force be

$$g(t) = \exp(-t/\tau), \tag{3-2}$$

where τ is the decay time of the force, the only unknown variable in Equation (3-1) is G, the magnitude of the force. That magnitude may be determined as follows. The integral of the force from a hammer blow is equal to the change in momentum of the hammer. That is,

$$\int_0^\infty G\, g(t)\, dt = Mv - 0 \tag{3-3}$$

where M is the mass of the hammerhead and v is its velocity at impact. Substituting g(t) from Equation (3-2) and solving for G results in

$$G = Mv/\tau. \tag{3-4}$$

The assumption of the force function as shown in Equation (3-2) results in a spectrum for the hammer blow as shown in Figure 3.1-2 and written as

$$G(i\omega) = \int_0^\infty \exp(-t/\tau)\exp(-i\omega t)\, dt \tag{3-5}$$

$$G(i\omega) = \frac{1}{i\omega + \frac{1}{\tau}} \tag{3-6}$$

The decay time, τ, is related to the cutoff, or corner frequency, by

$$\omega_c = \frac{1}{\tau} \tag{3-7}$$

Then, the decay time, τ, may be estimated by estimating the highest frequencies likely to be induced into the earth by a hammer blow.

Received Signal

Using Equations (3-2) and (3-4), Equation (3-1) becomes

$$u_r(t) = \frac{2\, Mv \cos\phi}{\tau\, 4\pi\rho\, rV^2} \cdot \exp\left[-(t-r/V)/\tau\right]. \tag{3-8}$$

Since a geophone responds to particle velocity rather than particle displacement, Equation (3-8) must be differentiated to obtain a form similar to a geophone output. It is noted that a geophone does not respond to arbitrarily low frequencies as a simple differentiation would indicate; however, the objective here is to try to predict the order of magnitude of the response and neglecting the low frequencies is not a limiting or a serious approximation. The differentiation of Equation (3-8) results in:

$$v_p(t) = \frac{-2}{\tau^2}\frac{Mv \cos\phi}{4\pi\rho r V^2} \exp\left[-(t-r/V)/\tau\right]. \qquad (3\text{-}9)$$

Evaluation

The peak received signal is the multiplying term on the exponential in Equation (3-9), and is evaluated as follows.

- M: Assume a 10 pound hammer (.311 slugs).
- v: Assume a velocity twice that of simple free fall from height of 4 feet (32.2 ft/sec).
- ρ: An average rock density is 156 pounds per cubic foot (4.85 slugs/ft^3).
- ϕ: 0 degrees
- r: Use (1000 ft.).
- V: Use (1000 ft/sec).
- τ: Use (.01 sec). This implies that ω_c = 100 radians per sec and that $f_c = \omega_c/2\pi$ is 16.7 Hz.

The evaluation results in a peak response of

$$V_p = .394 \times 10^{-6} \text{ in/sec}. \qquad (3\text{-}10)$$

Note that this result is relatively sensitive to the choice of the variable, τ. If the depth of the force were reduced by half to 500 feet the magnitude of received signal only doubles, but if the hammer spectrum were assumed flat to 167 Hz, the received signal would go up by a factor of 100. However, as the spectrum extends to higher frequencies, the omission of attenuation (Equation 3-1) becomes a more severe limitation of the analysis.

Since the analysis proved to be very sensitive to the input hammer blow spectrum as would be expected, it was not pursued any further. It was also noted that in a field situation, precisely controlled data would be hard to obtain since it is not easy to submerse a receiver in a medium without causing other serious effects. Also, signals received on the surface would be contaminated by multiple effects and also would not give precise information about the hammer blow spectrum near the point of impact. Since a major research effort was indicated here, and the time span allotted did not permit this effort, the decision was made to concentrate on the actual received data and to optimize the system as much as possible using empirical methods.

An important point of this analysis is that it shows that the received signals from a hammer blow are on the order of natural background seismic noise. (See Appendix D.) The received signals could not be expected to be orders of magnitude above or below the noise. This indicates that: 1) a seismic location system could not be an extremely simple system, since it would have to be able to receive and measure arrival times of signals which could be buried in the noise, and 2) implementation of a seismic location would likely not be a completely futile effort, since the signals could be expected to be large enough to be measurable at least at some mines.

3.1.3 Location Solutions and Error Study

This section describes the mathematics of solving for the miner's location given the arrival time differences of the seismic waves received on the surface. It also summarizes the results of an error study undertaken to obtain an estimate of the accuracy of the solution for imperfect data and a two layered earth. The solution derived here was implemented for computer solution in a program named "MINER," which is described in Appendix B along with the detailed results of the error analysis.

Location Solutions

An impulse source of seismic wave energy is located at some unknown point (x, y, z) in a homogeneous earth with P-wave velocity V. An array of geophones (or a collection of subarrays combined to yield one signal per subarray) is located on the earth's surface at the points (x_i, y_i, z_i), i = 1, 2, . . ., N, with $N \geq 3$, and with the z coordinate reckoned positive downward. If the source location is unrestricted, one can calculate its location from a measurement of the time of arrival of the transient waveform at each of four, five, or six geophones. If the source depth is known, then three measurements are sufficient. If six signal arrival times are available, the calculations also yield the velocity. In the equations which follow, the following definitions apply:

$V \equiv$ P-wave velocity (feet/sec)

$(x_i, y_i, z_i) \equiv$ coordinates of the ith geophone (lengths in feet)

$(x, y, z) \equiv$ coordinates of source (lengths in feet)

$R_i \equiv \left(x_i^2 + y_i^2 + z_i^2\right)^{1/2}$ (feet)

$t_i \equiv$ time of arrival of the signal at the ith geophone (all times are in seconds relative to an arbitrary, but fixed time reference)

$T \equiv$ time of instigation of the source pulse, an unknown (sec)

$\Delta t_i \equiv$ travel time required for the signal to propagate from the source to the ith geophone, an unknown $\Delta t_i = t_i - T)$ (sec)

Since the solutions using three and six arrival times are closely related to those using four and five, these latter cases are summarized first.

a. Using four arrival times

This solution has been given by Wang [1965]*. In this and all solutions which follow, the basic relations relate distance traveled to velocity and travel time:

$$\left[(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2\right]^{1/2} = V\,(t_i - T);\; i = 1,2,3,4 \qquad (3\text{-}11)$$

(Note that the ordering of the geophones is completely arbitrary.) By squaring each equation and subtracting the first from the other three, we obtain a linear system. In Wang's notation (Ibid.):

$$\alpha_i x + \beta_i y + \gamma_i z = \xi_i + \eta_i T;\; i = 2,3,4 \qquad (3\text{-}12)$$

where:

$$\alpha_i \equiv x_i - x_1;\; \beta_i \equiv y_i - y_1;\; \gamma_i \equiv z_i - z_1$$

$$\xi_i \equiv \tfrac{1}{2}\left[R_i^{\,2} - R_1^{\,2} - V^2\left(t_i^{\,2} - t_1^{\,2}\right)\right]$$

$$\eta_i \equiv V^2\left(t_i - t_1\right)$$

Now, solve for (x, y, z) in terms of the unknown T:

$$x = (M_1 + N_1 T)/D \qquad (3\text{-}13)$$

$$y = (M_2 + N_2 T)/D$$

$$z = (M_3 + N_3 T)/D$$

*Wang, "Local Hypocenter Determination in Linearly Varying Layers and Earthquakes in Denver Area," Ph. D. thesis, Colorado School of Mines, Golden, Colorado, (1965).

where:

$$D \equiv \begin{vmatrix} \alpha_2 & \beta_2 & \gamma_2 \\ \alpha_3 & \beta_3 & \gamma_3 \\ \alpha_4 & \beta_4 & \gamma_4 \end{vmatrix}$$; M_i is a determinant like D,

but with the ith column replaced by ξ_2, ξ_3, ξ_4; N_i is also like D, but with the ith column replaced by η_2, η_3, η_4. Equations (3-13) are now substituted back into the first of the set (3-11) to yield a quadratic in T:

$$AT^2 + 2\,BT + C = 0 \tag{3-14}$$

where:

$$A \equiv N_1^{\,2} + N_2^{\,2} + N_3^{\,2} - (VD)^2$$

$$B \equiv M_1\,N_1 + M_2\,N_2 + M_3\,N_3 - D\,(x_1\,N_1 + y_1\,N_2 + z_1\,N_3) + (VD)^2\,t_1$$

$$C \equiv (M_1^{\,2} + M_2^{\,2} + M_3^{\,2}) - 2D\,(x_1\,M_1 + y_1\,M_2 + z_1\,M_3) + D^2\,(R_1^{\,2} - V^2\,t_1^{\,2})$$

Equation (3-14) yields two values of T. If the measured times are <u>exact</u>, one of the values could always be discarded by virtue of its being greater than one or more of the t_i (hence implying negative travel times). However, with realistic data (t_i accurate to $\sim\pm 1$ msec), two physically possible values for T may emerge, and the source location is not specified uniquely, although one location is usually unreasonable. Otherwise, the one meaningful T is substituted directly into (3-13) to yield x, y, and z. (The effects of timing, velocity, and coordinate inaccuracies are discussed later.)

b. Using five arrival times.

This solution is somewhat simpler than the previous one because we can avoid solving for the parameter T. It is essentially the same as the method reported by Leighton* [1970]. The starting point is the same as (3-11), except that i = 1, 2, 3, 4, 5, and it is convenient to deal directly with travel times Δt_i:

$$\left[(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2\right]^{1/2} = V \cdot \Delta t_i;\ i = 1, 2, 3, 4, 5 \tag{3-15}$$

*Leighton, Fred and Wilson Blake, "Rock Noise Source Location Techniques," U.S. Bureau of Mines, Report of Investigation, RI 7432, 1970.

Squaring and subtracting, as before, we obtain

$$2x(x_1-x_i) + 2y(y_1-y_i) + 2z(z_1-z_i) + R_i^2 - R_1^2 = V^2(\Delta t_i^2 - \Delta t_1^2). \quad (3\text{-}16)$$

Now define:

$$V \cdot \Delta t_i \equiv d_i;\ V(\Delta t_i - \Delta t_j) = d_i - d_j \equiv d_{ij}.$$

Equations (3-16) are then written as

$$d_i + d_1 = \frac{2x(x_1 - x_i) + 2y(y_1 - y_i) + 2z(z_1 - z_i) + R_i^2 - R_1^2}{d_{i1}} \quad (3\text{-}17)$$

By subtracting the i = 2 equation from the remaining three in (3-17) and rearranging, we obtain the final linear system:

$$x\left[2d_{21}(x_1-x_i) - 2d_{i1}(x_1-x_2)\right] + y\left[2d_{21}(y_1-y_i) - 2d_{i1}(y_1-y_2)\right] +$$

$$z\left[2d_{21}(z_1-z_i) - 2d_{i1}(z_1-z_2)\right] = d_{i2}\,d_{21}\,d_{i1} + d_{i1}(R_2^2 - R_1^2) - d_{21}(R_i^2 - R_1^2);$$

$$i = 3, 4, 5 \quad (3\text{-}18)$$

the "differential distances" d_{ij} are expressed in terms of the measured times t_i:

$$d_{ij} \equiv d_i - d_j = V(\Delta t_i - \Delta t_j) = V(t_i - T - t_j + T) = V(t_i - t_j).$$

Hence (3-18) may be solved directly for (x, y, z).

In addition to the above, it should also be noted that a four geophone solution may be carried out in much the same manner, i.e. without solving for T, if one of the source coordinates is specified. (Program MINER allows for the option of using four arrival times and a specified source depth.)

c. Using six arrival times

In this case the same procedure is followed as in b), except that V is considered unknown. The linear set becomes, using $t_{ij} = \Delta t_i - \Delta t_j$:

$$x\left[2t_{21}(x_1-x_i) - 2t_{i1}(x_1-x_2)\right] + y\left[2t_{21}(y_1-y_i) - 2t_{i1}(y_1-y_2)\right] +$$

$$z\left[2t_{21}(z_1-z_i) - 2t_{i1}(z_1-z_2)\right] - V^2 t_{i2}t_{i1}t_{21} = t_{i1}(R_2^{\,2} - R_1^{\,2}) -$$

$$t_{21}(R_i^{\,2} - R_1^{\,2});\; i = 3,4,5,6 \qquad (3\text{-}19)$$

Equation (3-19) is solved directly for x, y, z, and V^2.

d. Using three arrival times

In this case a unique solution is possible only if one of the source coordinates is known. For the miner location problem, it is most reasonable to assume that we will have a good estimate of the source depth, z. By assuming that z (and V) is known, the solution proceeds as in part a. The linear system becomes

$$\alpha_i x + \beta_i y = \xi_i + \eta_i T; \quad i = 2,3 \qquad (3\text{-}20)$$

where α_i, β_i, and η_i are the same as previously, but

$$\xi_i \equiv \frac{\left[R_i^{\,2} - R_1^{\,2} - V^2(t_i^{\,2} - t_1^{\,2})\right]}{2} - z(z_i - z_1)$$

The quadratic in T has the same form as in (3-14), but now

$$A = N_1^{\,2} + N_2^{\,2} - (VD)^2$$

$$B = N_1M_1 + N_2M_2 - D(x_1N_1 + y_1N_2) + t_1(VD)^2$$

$$C \equiv M_1^{\,2} + M_2^{\,2} - 2D(x_1M_1 + y_1M_2) + D^2\left[x_1^{\,2} + y_1^{\,2} + (z-z_1)^2 - V^2t_1^{\,2}\right]$$

and

$$D \equiv \begin{vmatrix} \alpha_2 & \beta_2 \\ \alpha_3 & \beta_3 \end{vmatrix}, \quad M \equiv \begin{vmatrix} \xi_2 & \beta_2 \\ \xi_3 & \beta_3 \end{vmatrix}, \text{ etc.}$$

The solutions for x and y then have the same form as in (3-13).

In all of the above solutions, it has been tacitly assumed that the geophones are placed such that not all the x_i nor all the y_i nor all the z_i are identical. Should this be the case, the final set of linear equations for x, y, z degenerate and are no longer independent. For example, if in the five-geophone solution we were to have $z_1 = z_2 = z_3 = z_4 = z_5$, the coefficients of the unknown z in (3-18) are all identically zero, and hence the matrix of coefficients has no inverse. In situations like this, we simply solve the first two linear equations for x and y. These values are then substituted into the following expression:

$$\left[(x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2\right]^{1/2} - \left[(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2\right]^{1/2} - V(t_2 - t_1) = 0 \qquad (3\text{-}21)$$

which is solved for z by a simple iteration scheme (Newton-Raphson method; iteration stopped when the absolute value of the expression on the left-hand side is less than 0.1 feet).

Error Analysis Summary

A great number of computer simulations were carried out to determine the effect of source location relative to the array and propagation velocity, geophone coordinate and time-of-arrival errors. Example calculations for one hypothetical array under a variety of conditions are given in Appendix B. Results are summarized in the following paragraphs.

In general, the source location error (S. L. E.) increases rapidly as the source point moves outside of the array spread. The sample calculations also show that time-of-arrival errors of ±2 ms yield S. L. E. of less than 20 feet when propagation velocity and array coordinates are accurately known and the source point is within the array spread.

Uncertainties in propagation velocities of ±25% can be tolerated when the other data is accurate. The cumulative effect of all inaccuracies tend to average out since they tend to be randomly distributed. This averaging process requires redundancy in the data so a number of calculations can be made.

The general conclusions derived from theoretical error analyses, an analysis of the effects of a low velocity overburden and array/source geometry are:

(1) The source should be within the array spread.
(2) The array spread should be greater than one third the source depth.
(3) The array spread must be great enough so that the difference in arrival times between the two nearest geophones is considerably greater than the maximum anticipated timing uncertainty.
(4) Errors due to layering effects are minimized when the array is nearly square and the source lies near the center.
(5) Adequate accuracy can usually be obtained with:
    velocity error ≤20%
    coordinate errors ≤ 5 ft
    arrival-time errors ≤ 2 ms.

(6) The five and four arrival-time calculations are usually the most accurate. When $N \geq 7$, the six arrival-time solutions are mainly useful for verifying the assumed velocity.
(7) If the source depth is known accurately (± 10 ft), the four arrival-time solution with specified depth is often the most accurate.

System Accuracy

Different methods can be used to define the accuracy of a location system, such as rms distance error, or circular error probability. These are based on a statistical measure of locations using the system and comparing results with locations known to be accurate by some independent means. A meaningful measure of accuracy requires many measurements at many different places to account for the spatial variations which might be encountered.

In this report (Sections 3.3 and 3.4) we have used location accuracy in a somewhat different context. Data has been obtained at only a few mines and a statistical sample is not available; therefore the system accuracy cannot be specified at this time.

The location accuracy obtained for a single test at one location at a given mine can be defined. We have shown in the previous paragraphs how the location problem can be solved in a variety of ways when a multiple point geophone array is used.

In the real world situation, velocity errors, coordinate errors, and arrival time errors may exist, resulting in several different solutions. For example: for a six-point array, and using four arrival times per solution, there are (see Appendix B) 15 possible solutions, each of which can yield different predictions of source coordinates. Rather than define location accuracy as the rms distance error to each of these source coordinates, an arithmetical average of the x and y coordinates is obtained to yield a single predicted coordinate. This averaging process has been found to be an effective means of minimizing the sensitivity of the final location prediction to measurement error.

The surface location error (SLE) is then given by $\left[(x-x_p)^2 + (y-y_p)^2\right]^{1/2}$ where x_p, y_p are the averaged predicted source coordinates in the x-y plane and (x, y) are the true coordinates.

A computer program called MINER has been developed to predict locations and average the coordinates. The user may eliminate from the averaging process locations which are not credible and average only the remainder. Correlation of calculated source locations to an accurate mine map is useful in this process. Examples of calculations are given in Appendix B.

The SLE computation is generally used to define location accuracy in this report. Final system accuracy specifications cannot be given until sufficient data has been obtained at many more locations, and the location prediction computation process is further refined.

3.1.4 Predesign Field Tests

The concept of the predesign field tests was to obtain preliminary data on source (hammer) characteristics, wave transmission and reception, and background noise levels. For the first tests, the Westinghouse Georesearch

Laboratory (WGL) contracted Globe Universal Sciences, Inc., (G. U. S.), Advanced Projects Division, El Paso, Texas. G. U. S., under the direction of J. E. White, performed preliminary tests at the Imperial Mine, WGL then performed some limited testing at the Imperial Mine, followed by limited tests at the Cambria Slope #33 Mine and at the Clyde Mine. A discussion of each of these tests follows.

3.1.4.1 G.U.S. Tests at the Imperial Mine

Five categories of major test were performed. They were Site Characterization, Coherent Noise, Uplink Tests, Underground Tests, and Downlink Tests. The purpose, and results of each of those tests are discussed below. A map of the Imperial Mine showing locations of various tests is shown in Figure 2.1-5 for reference in subsequent sections. The overburden at this mine is indicated in Figure 3.1-3.

Site Characterization

The purpose of this test was to determine the geophysical characteristics of the test site, i.e. seismic wave velocities and strata layering. The test was conducted by performing a standard refraction survey using a 50 foot spacing and an explosive source as shown in Figure 3.1-4. A plot of the travel times versus distance is shown in Figure 3.1-5. The survey showed the overburden at the Imperial Mine to consist of two layers as shown in Figure 3.1-3. The interpretation procedure is given in Dobrin [1960].*

Coherent Noise

The purpose of this test was to determine the predominate spectral distribution and travel velocity of spatially coherent seismic waves. The test was performed by receiving signals from a short geophone spread with 10 feet spacing. The signals were excited by one pound charges of DuPont Nitramon at distances of 60 feet and 650 feet from the spread. The test showed that the excited Rayleigh waves traveled with an observed phase velocity of 1450 feet per second and that the frequency spectrum of a noise trace was largely confined to the 10-20 Hz region, as shown in Figure 3.1-6. A convenient way to present this information is to draw amplitude contours on a frequency wavenumber plot as shown in Figure 3.1-7. The coherent noise appears as a band of energy along the 1500 ft/sec line.

A 120 foot subarray diameter was chosen for subsequent tests based on multiple seismometer theory as discussed by Lombardi [1955], Smith [1956], Verma and Roy [1970], and Graebner [1960].**

---

*Milton B. Dobrin, Introduction to Geophysical Prospecting, 2nd Ed., McGraw-Hill Book Co., Inc., New York, 1960, pp. 70-100.

**Leonard V. Lombardi, "Notes on the Use of Multiple Seismometers," Geophysics, Vo. XX, No. 2, (April, 1955), pp. 215-226.

Mark K. Smith, "Noise Analysis and Multiple Seismometer Theory," Geophysics, Vol. XXI, No. 2, (April, 1956), pp. 337-360.

Rajni K. Verma and Amalander Roy, "A Graphical Method for Computing Geophone Group Response," Geophysics, Vol. 35, No. 4, (August 1970), pp. 707-717.

R. J. Graebner, "Seismic Data Enhancement - A Case History," Geophysics, Vol. XXV, No. 1, (February, 1960), pp. 283-311.

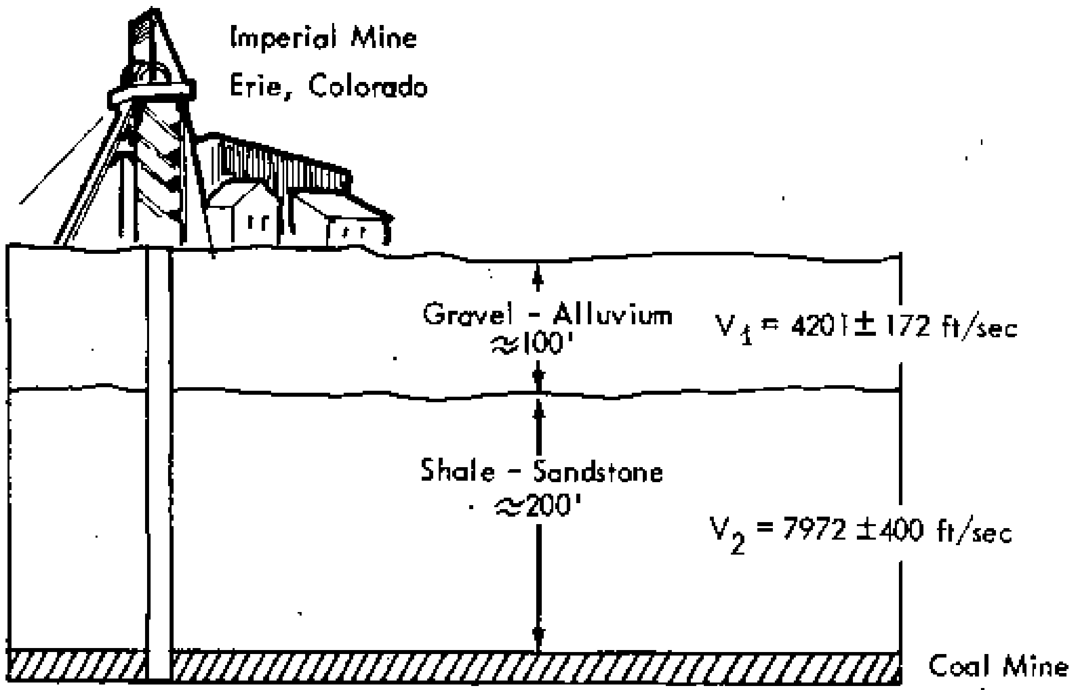


Figure 3.1-3. Overburden Characteristics at Imperial Mine

Multiple geophone subarrays enhance the signal to noise ratio (S/N) in two ways.

Against non-coherent noise, and assuming that each geophone contributes equal amounts of signal and noise, a multiple array improves S/N by a factor of $\sqrt{n}$ where n is the number of elements in the array. For example a seven element array improves S/N up to 8.5 dB.

Against coherent noise, multiple element arrays perform "spatial" or "wavelength" filtering. A discussion of wavelength filtering is given by Graebner [1960].* An insert in Figure 3.1-8 shows the configuration of the subarrays which should be used if coherent noise is non-directional.

A plot of the response of this array to a signal arriving from the directions shown by the arrow is given in Figure 3.1-8. This response is periodic with a period of $d/\lambda_a = 2$, meaning that the complete response repeats as d/λ_a increases. (d = element spacing as shown and λ_a = apparent wavelength).

*Ibid

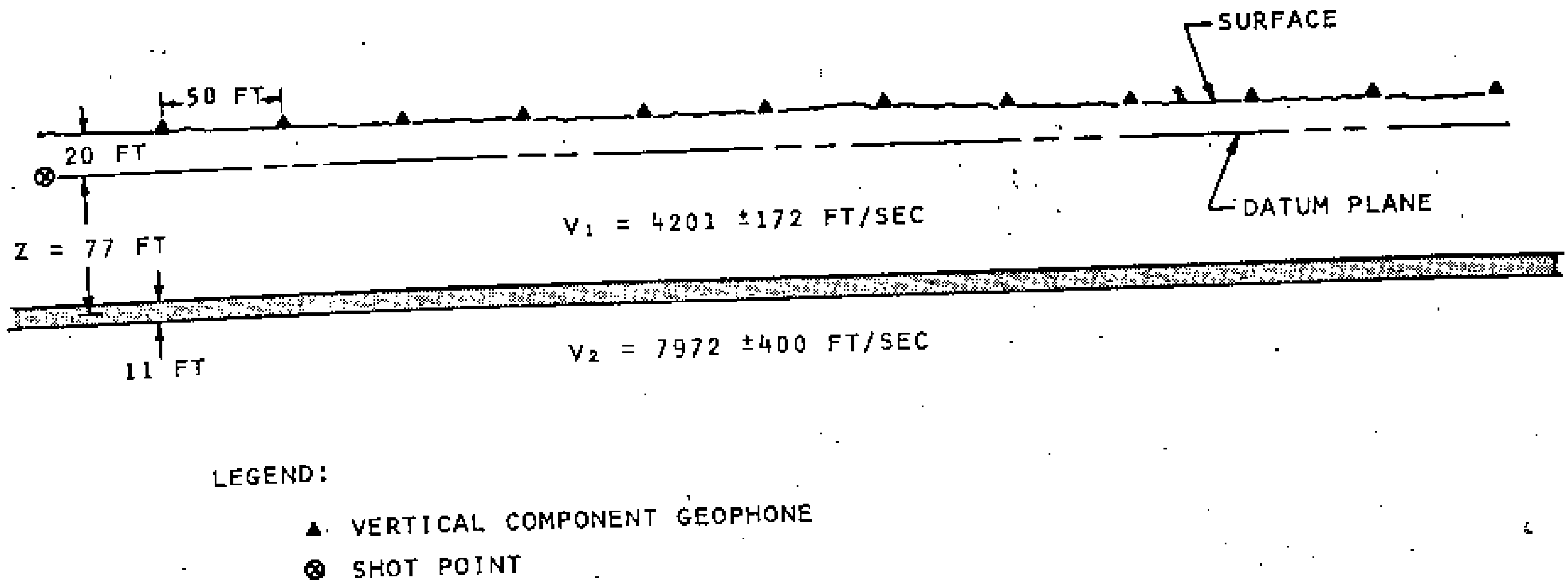


Figure 3.1-4. Geological Environment at Imperial Mine

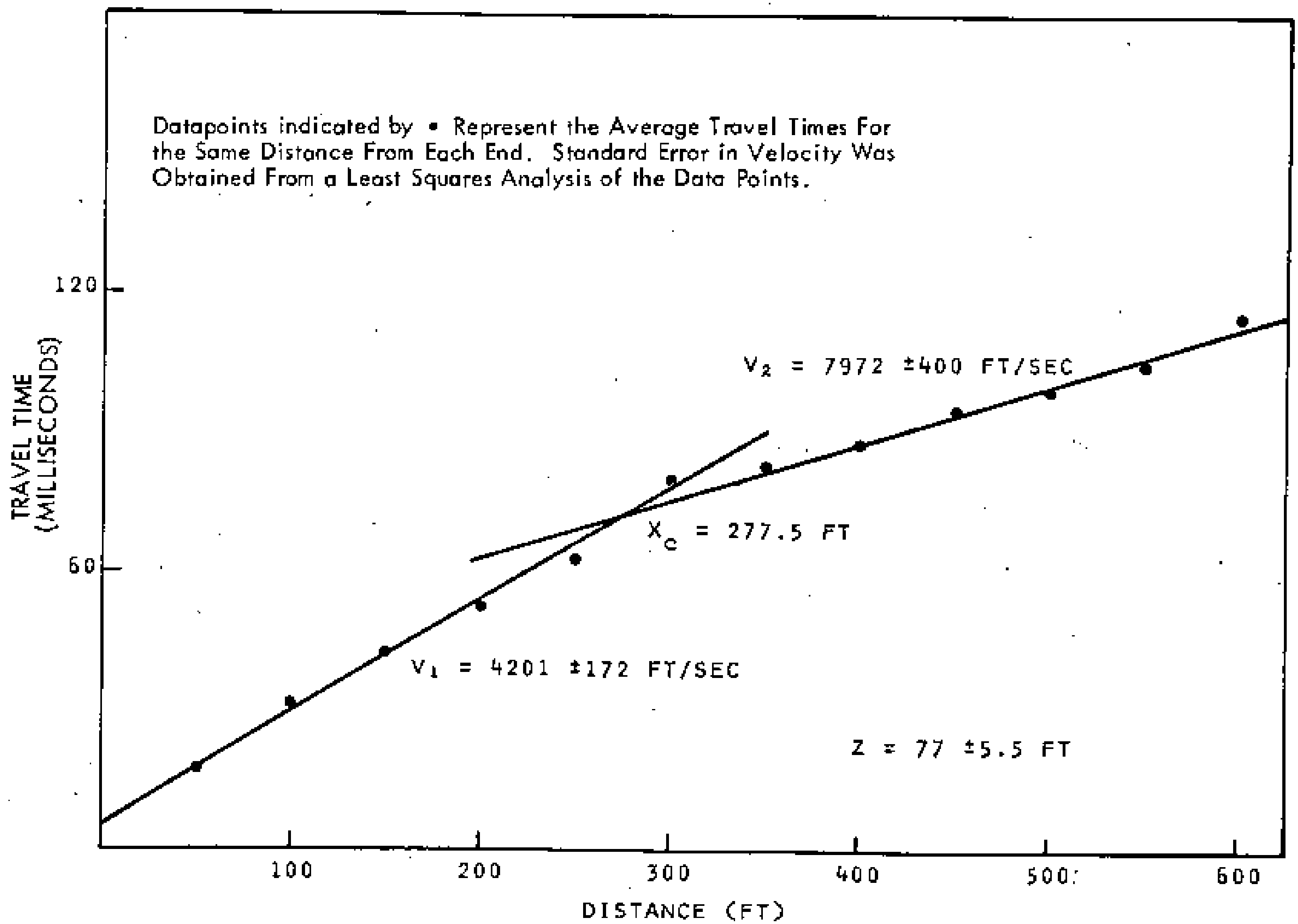


Figure 3.1-5. Geophysical Environment: Time-Distance Plot of Refraction Data Taken at Both Ends of a Linear Spread of Geophones

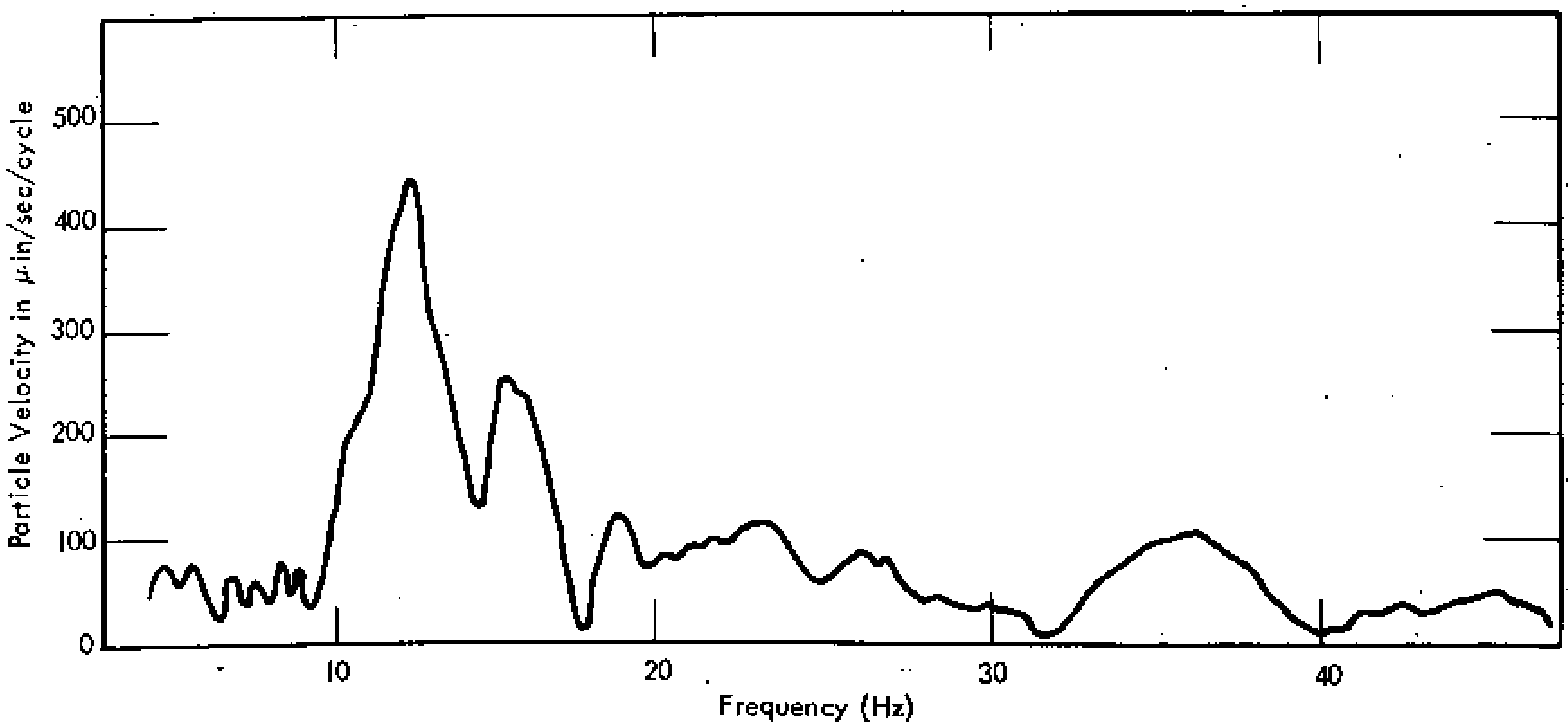


Figure 3.1-6. Spectrum of Coherent Noise at the Imperial Site

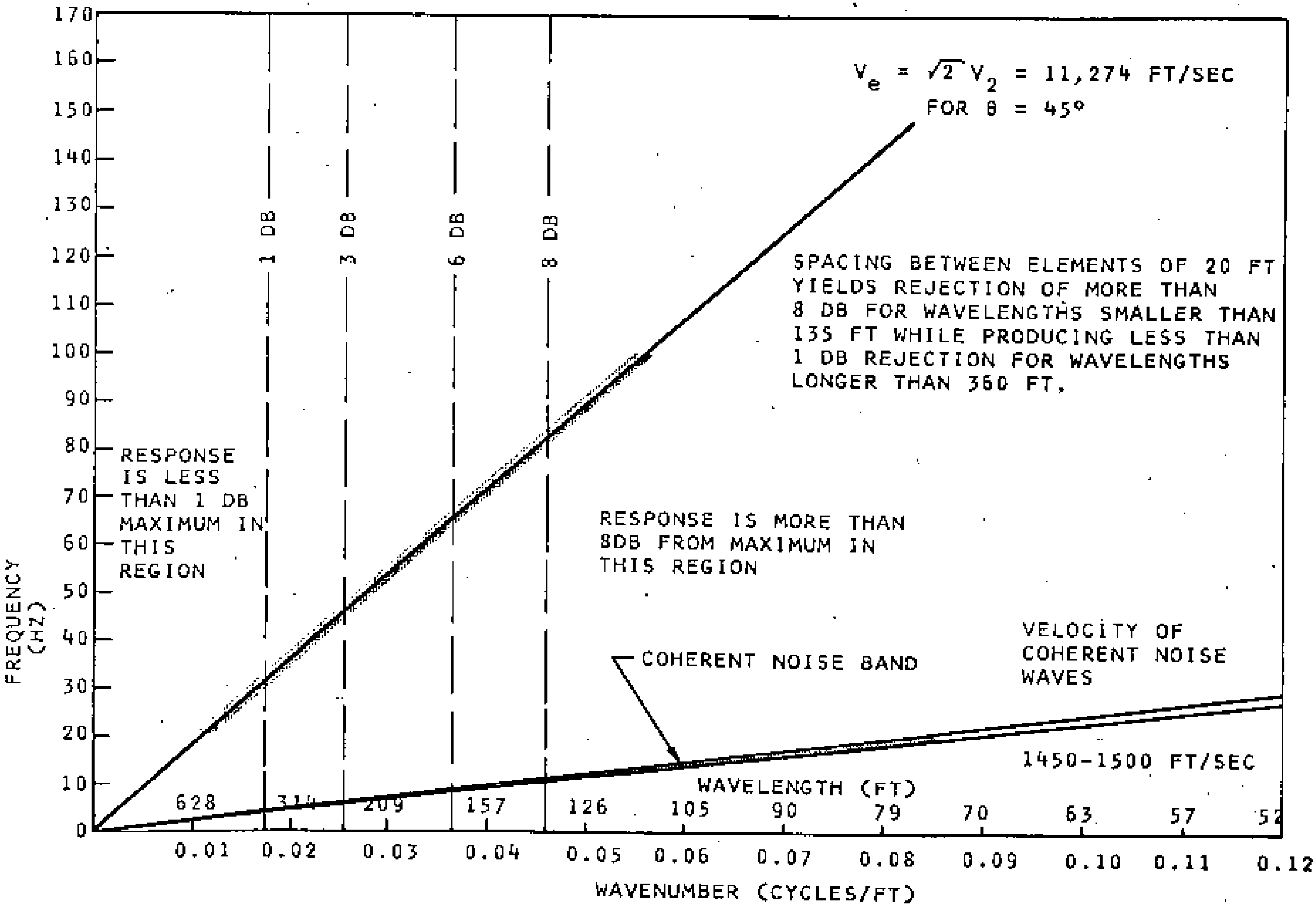


Figure 3.1-7. Geophysical Environment: Frequency-Wavenumber Plot Showing Coherent Noise at the Imperial Mine

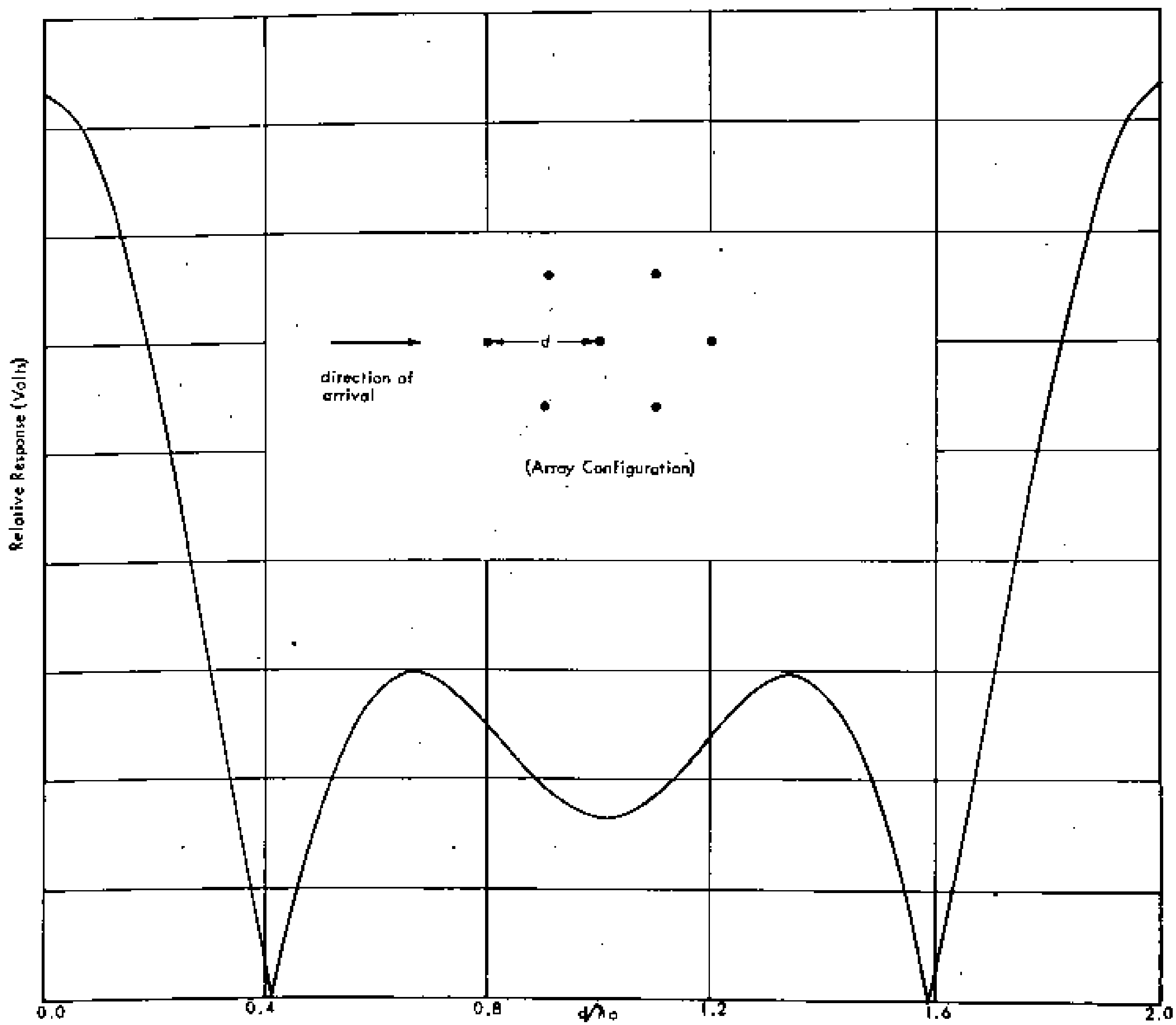


Figure 3.1-8. Response of 7 Geophone Hexagonal Array

In order to calculate the optimum spacing to be used between geophones in the subarrays, the following procedure is recommended.

a. Determine the minimum desired frequency to be attenuated. This may be estimated or measured from a signal already received.

b. Using the weathered layer velocity determine the maximum desired wavelength (λ) to reject using the relationship:

$$\text{Wavelength } (\lambda) = \frac{\text{Velocity}}{\text{Frequency}}$$

c. A signal arriving from below the plane of the array will have a larger apparent wavelength than a signal arriving in the plane of the array. Determine the minimum angle from horizontal with which a signal is expected to arrive. Then the maximum apparent wavelength, λ_a is:

$$\lambda_a = \frac{\lambda}{\cos\theta}$$

where θ is the angle from horizontal (or from the plane of the array if terrain is not horizontal).

d. By referring to the response curve in Figure 3.1-8, select the attenuation desired for that apparent wavelength. A reasonable choice is about 5 dB where $d/\lambda_a = .3$. Longer apparent wavelengths will be attenuated less and shorter apparent wavelengths attenuated more.

e. The array spacing, d, is then determined from $d = k\lambda_a$ where k is the value of d/λ_a read from the response curve, Figure 3.1-8.

For a 24 element hexagonal subarray (a 19 element array is similar), the following is true, where λ is the (horizontal) wavelength and D is the subarray diameter:

(1) For $\lambda/D > 3$ response is within 1 dB of maximum.

(2) For $\lambda/D < 1.1$, response is more than 8 dB down, with an "average" of 14 to 16 dB.

(3) For λ/D near 0, rejection exceeds 20 dB.

For a subarray diameter of 120 feet, 1, 3, 6, and 8 dB contours are shown in Figure 3.1-7. Also shown is a 11,274 ft/sec line. That velocity is obtained by calculating the "apparent" velocity of a wave arriving from underground at an angle of 45^o. Then, if a hammer blow were received with principal energy between 20 and 100 Hz, the energy received would lie on and to the left of the shaded portion of the 11,274 ft/sec line. It is clear from this plot that the higher frequencies extend into the wavenumber region covered by the coherent noise, which means that any pattern which will suppress the noise will also reduce the high frequency content of the signal for signals arriving at 45^o. Below 50 Hz, the pattern selected does not substantially reduce the 45^o signals and for angles of 30^o or less (apparent speed of 16,000 ft/sec or higher), the degradation of frequencies below 70 or 80 Hz is minor.

<u>Uplink Tests</u>

The purpose of this test was to examine the signals arriving at the surface from hammer blows underground, to obtain data useful for performing location calculations, and to evaluate the improvement in signal to noise from multiple element subarrays.

An array of five subarrays was laid out as shown by the five outermost points in Figure 2.1-5. At each location, subarrays of one, seven, and nineteen element arrays (hexagonal pattern, 120 feet diameter) were tested. Also a three component geophone was installed in the bottom of a 100 ft deep hole by lowering the unit to the bottom and then packing the hole with pea gravel. That hole was located 50 ft due southwest of the center of the five point array. The source location used in the mine is shown by the triangle in Figure 2.1-5 near the center of the array.

These tests are believed to have been severely limited by the sensitivity of the G.U.S. equipment. The signals shown in Figure 3.1-9 are barely detectable in themselves to say nothing of the detectability of the first onset of the signal. The signal from the vertical component of the three component buried geophones is, of course, the best of the group, but the center subarray, which should have been the most sensitive of the surface subarrays did not respond as well as the east subarray. Some of the surface arrays show a predominant noise component of somewhere around 70-80 Hz. The origin of that noise component is unknown. Observers felt it was due to electrical noise originating in the G.U.S. equipment while the operating personnel felt it was seismic noise from an underground pump.

The multiple element subarray tests were inconclusive. At the north array location, the single element subarray outperformed both the 7 and 19 element subarrays. At the center array location, the 7 and 19 element subarrays performed approximately equally and both were slightly better than a single element. At the east array location, the 19 element array performed best, and the single performed worst, as would be expected. At the south and west arrays, signal was so weak that no analysis could be made. These rankings were made on the basis of the ratio of peak to peak signal over "average" noise between pulses.

A conclusion, of sorts, was drawn from measurements of the peak to peak particle velocities taken from some of these same records. That conclusion is that the calibration procedure, or the equipment, used by G.U.S. was not accurate or stable. Filtered versions of the signals were made by digitizing the signals and noise, Fourier Transforming the signals and noise, setting to zero the spectrum outside of the range 30-80 Hz, and inverse transforming back to the time domain. The maximum peak to peak particle velocity from the filtered records was then measured and is shown in Table 3.1-3. Again, the records did not show that the multiple element subarrays performed according to theory. Also the signal from the "constant" buried geophone was not the same from test to test.

The primary conclusion to be drawn from these tests is that the amplitude of signals from hammer blows as received on the surface is on the order of ones or a few tens of micro inches per second and corresponds to that calculated in Section 3.1.2. Combining that with the noise data in Appendix D indicates that hammer blow signals should be detectable and measurable but not easily so.

A number of records were taken to compare various methods of coupling hammer blow energy to the earth. The couplers included a metal plate, a spike, a rail on the main track, and ambient rock formations. Inspection of those records showed, qualitatively, that striking a metal plate on the floor or striking the rail gives stronger signals than striking a spike in the wall or a spike in the ceiling.

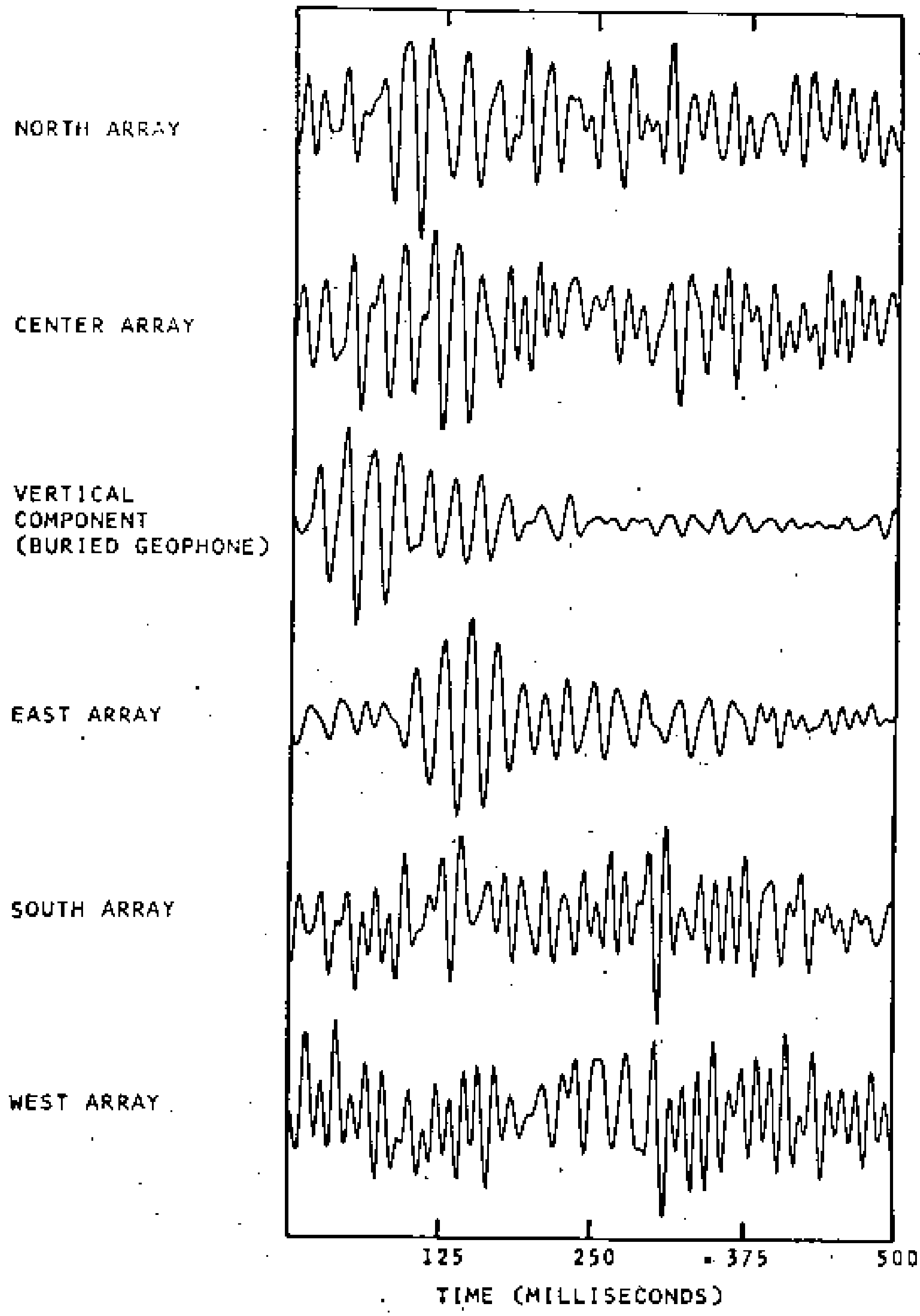


Figure 3.1-9. Signals From a Hammer Blow on a Plate on the Mine Floor 300 Ft Under the Center Array as Recorded on the 19-Geophone Surface Arrays and the Vertical Component of the Buried Geophone. (Preliminary Work Done at Imperial Mine by Globe Universal Sciences)

TABLE 3.1-3

PEAK TO PEAK PARTICLE VELOCITIES
OF FILTERED HAMMER BLOW SIGNALS (μ in/sec)

	19-Geophone Subarray	7-Geophone Subarray	1-Geophone Subarray
Buried Geophone	6.0	6.0	9.2
Center Subarray	24.8	7.0	7.6
North Subarray	3.2	2.1	3.5
East Subarray	0.6	1.0	0.7

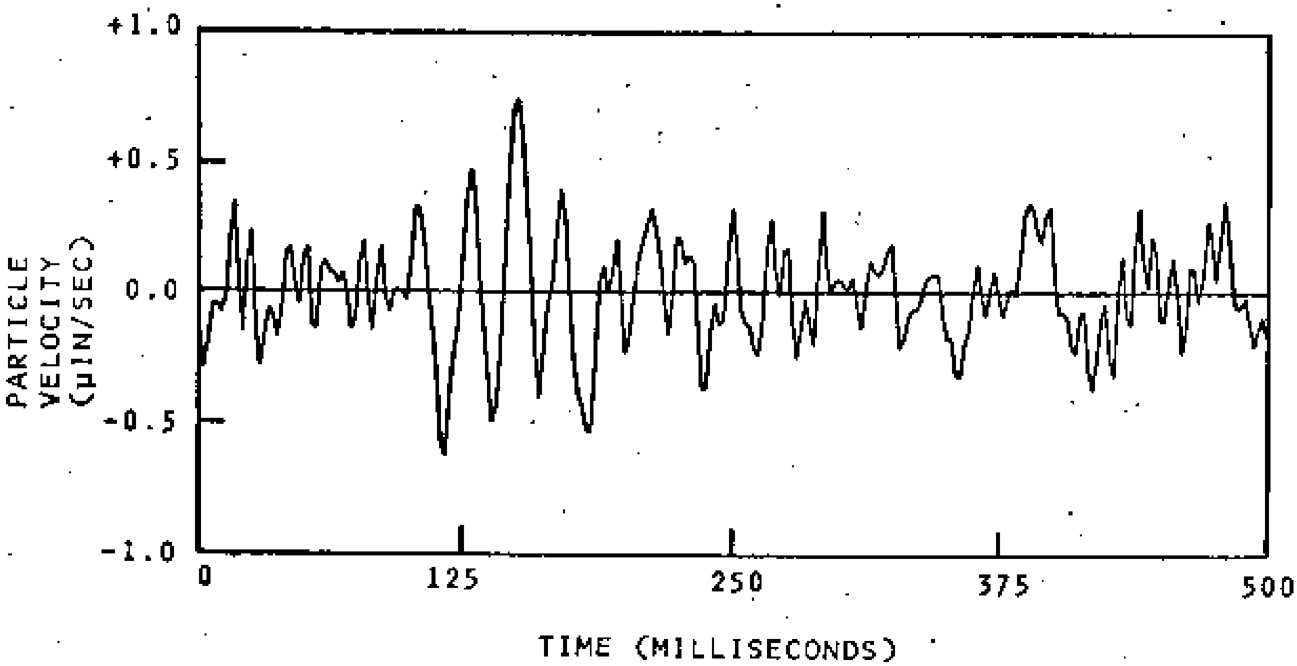
Frequency spectrums were made to determine the spectral component of the signal arriving at the surface. A signal and its spectrum from the center subarray (corresponding to the traces in Figure 3.1-9) are shown in Figure 3.1-10. It shows that the signal energy, for this case, is predominately contained in a 40-50 Hz band.

Cross correlation of signals between arrays had been proposed as a possible method of measuring the arrival time differences of the signals. Cross correlation of the received signals was performed using the signal from the east subarray as the reference. The results of that analysis showed the cross correlation function to be very oscillatory as expected. The center subarray and the vertical component of the buried phone were the only ones which produced a detectable peak in the cross correlation function and those peaks were measured to show 57.1 and 59.1 millisecond time differences, respectively. If these time differences are used to calculate travel velocities, the result is an apparent velocity for P-waves. This discrepancy apparently points up that other waves than P waves are contaminating the cross correlation function although it is possible that noise is the real villain. The major result to be noted is that cross correlation may not be a suitable method of measuring the time difference information, unless the wave types could be definitely separated.

Underground Test

The primary purpose of this test was to provide an indication of the frequency spectrum of a hammer blow. A line of 16 geophones was installed in the mine, along the Main North entry, eight of them on the floor and eight on the roof. The farthest floor geophone was located approximately at the intersection of 3 West and from there floor and roof geophones alternated with 100 foot spacings. In Figure 3.1-11, trace 24 is the southernmost floor geophone and trace 1 is the southernmost roof geophone.

The coupling of the geophones to the mine surface was not consistent. Some of the geophones were mounted with hose clamps to spads driven into the rock or coal suggesting the possibility of cantilever vibration, while others were mounted with the geophone spike driven into cracks in the coal suggesting poor geophone to rock coupling. These plants produced different frequency signals as shown by traces 5, 6, 7, and 23 in Figure 3.1-11. The signals shown are the best that were obtained in this test. They were generated with an 8 pound sledge hammer on an isolated 20 ft section of rail



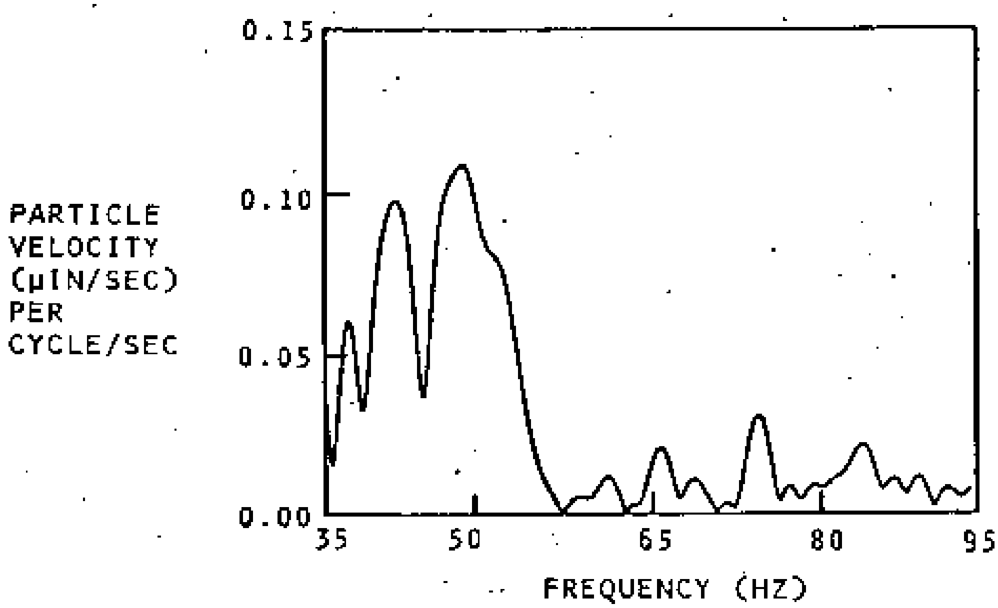


Figure 3.1-10. Signal and Spectrum of Hammer Blow Recorded at the Surface by Globe Universal Sciences at Imperial Mine.

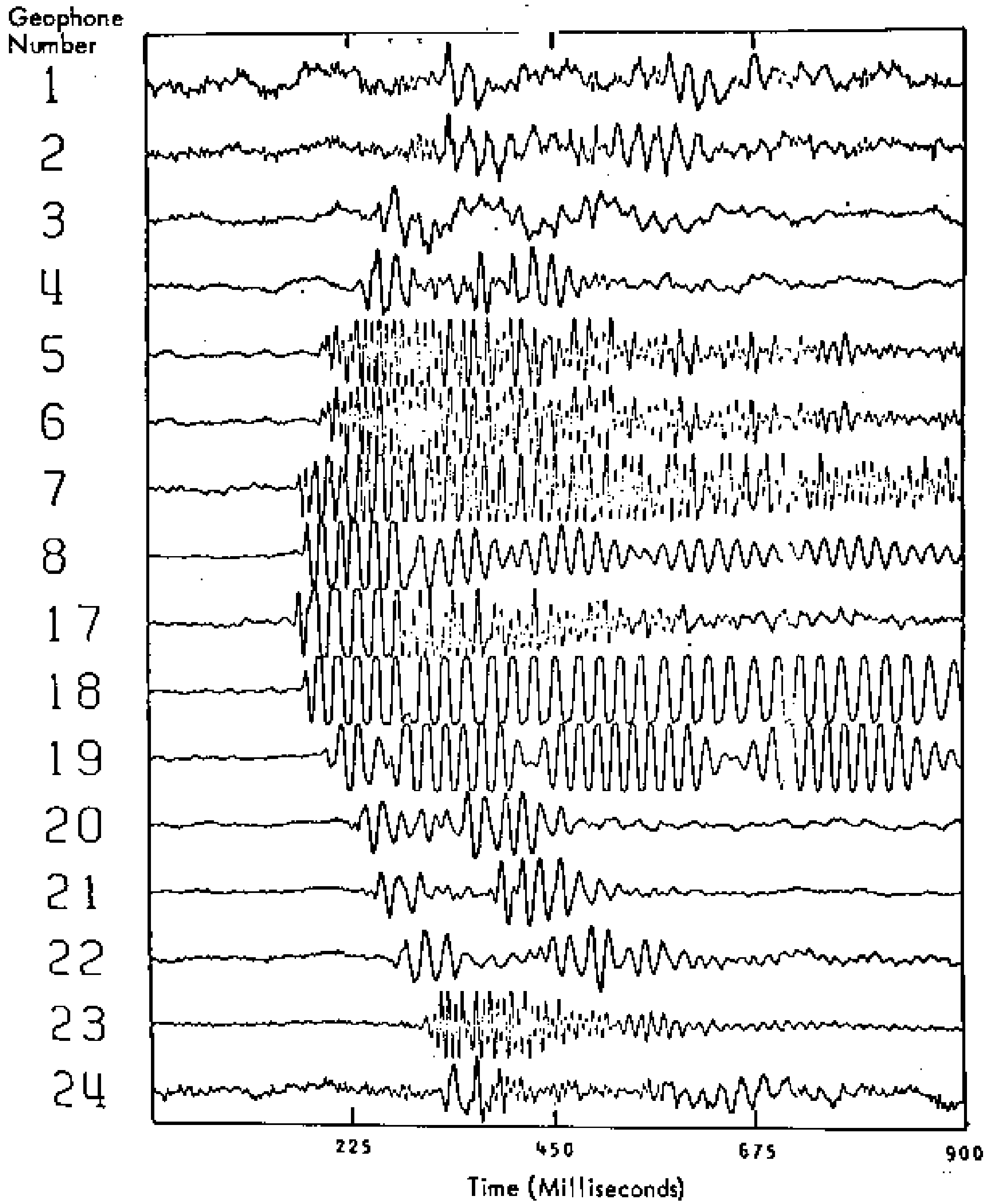


Figure 3.1-11. Signals From a Hammer Blow on an Isolated Section of Rail 155 Ft From Geophone 17 and 1475 Ft From Geophone 24. (Preliminary Work Done at Imperial Mine by Globe Universal Sciences)

located approximately 155 ft east of geophone 17 (a siding in 9 East). Other couplers did not perform nearly as well.

Although, the plant of the geophones is suspect, a signal and its frequency spectrum are shown in Figure 3.1-12. That signal shown was generated by an 8 lb hammer blow on the floor and recorded by a floor geophone 100 ft away. It shows a much higher frequency spectrum than indicated in the uplink tests and is probably due to a bad geophone plant.

Other records showed that striking a hard or a soft formation on the floor of the mine at one location resulted in a surprisingly small difference, but that striking the wall of the mine created a much weaker signal (at least for these vertically sensitive detectors).

Downlink Test

The purpose of this test was to determine the feasibility of using explosives for "crude and simple" downlink seismic communications. The objective was to determine if explosives, implanted in shallow holes on the surface, could be detected by personnel underground having no special equipment or listening devices.

The experiment utilized DuPont Nitramon S blasting agent which was packed in a six inch diameter, 20 ft. deep hole. The experiment showed that a one pound charge was audible directly under the source and no further tests were performed using the G. U. S. crew. More extensive blasting tests at the Imperial Mine were performed later in predemonstration testing.

The following conclusions were drawn from the G. U. S. tests:

(1) Standard "geophysics industry" equipment of the type used is not adequate for gathering the required data. The detection of low amplitude signals, in the presence of noise, requires greater sophistication in hardware over the equipment used at Imperial. A large effective dynamic range over a wide band of frequencies appears to be needed. Equipment should be chosen for its quiet operating characteristics. The signals being detected in our application are orders of magnitude smaller than those normally detected by conventional exploration equipment.

(2) Geophones must be balanced to reject the strong interference created by 60 Hz line voltages and harmonics. This proved to seriously limit the usefulness of the data gathered at the Imperial Mine.

3.1.4.2 WGL at Imperial Mine

Shortly after the G. U. S. tests at the Imperial Mine, WGL undertook a program to obtain more predesign data. The tests were limited in scope because only enough laboratory equipment was available to take data from a single geophone or a single subarray. The prime objective of the tests was to make certain that equipment whose characteristics were known, was sensitive enough to respond to low level ambient seismic noise and not limited to amplifier noise. Also, the data taken was aimed at obtaining approximate indications of the signal frequency spectrum and levels under a few different geological conditions.

The equipment used consisted of a commercial Princeton Applied Research Model 113 low noise preamplifier, a Krone Hite 3202A 24 dB/octave filter, a P. A. R. Model 110 Tuned Amplifier and a Honeywell Model 906 Oscillograph. Geophones - 14 Hz, 4000 Ω, GSC-11 D(Geospace Corporation), with balanced coil were used to pick up the seismic signals.

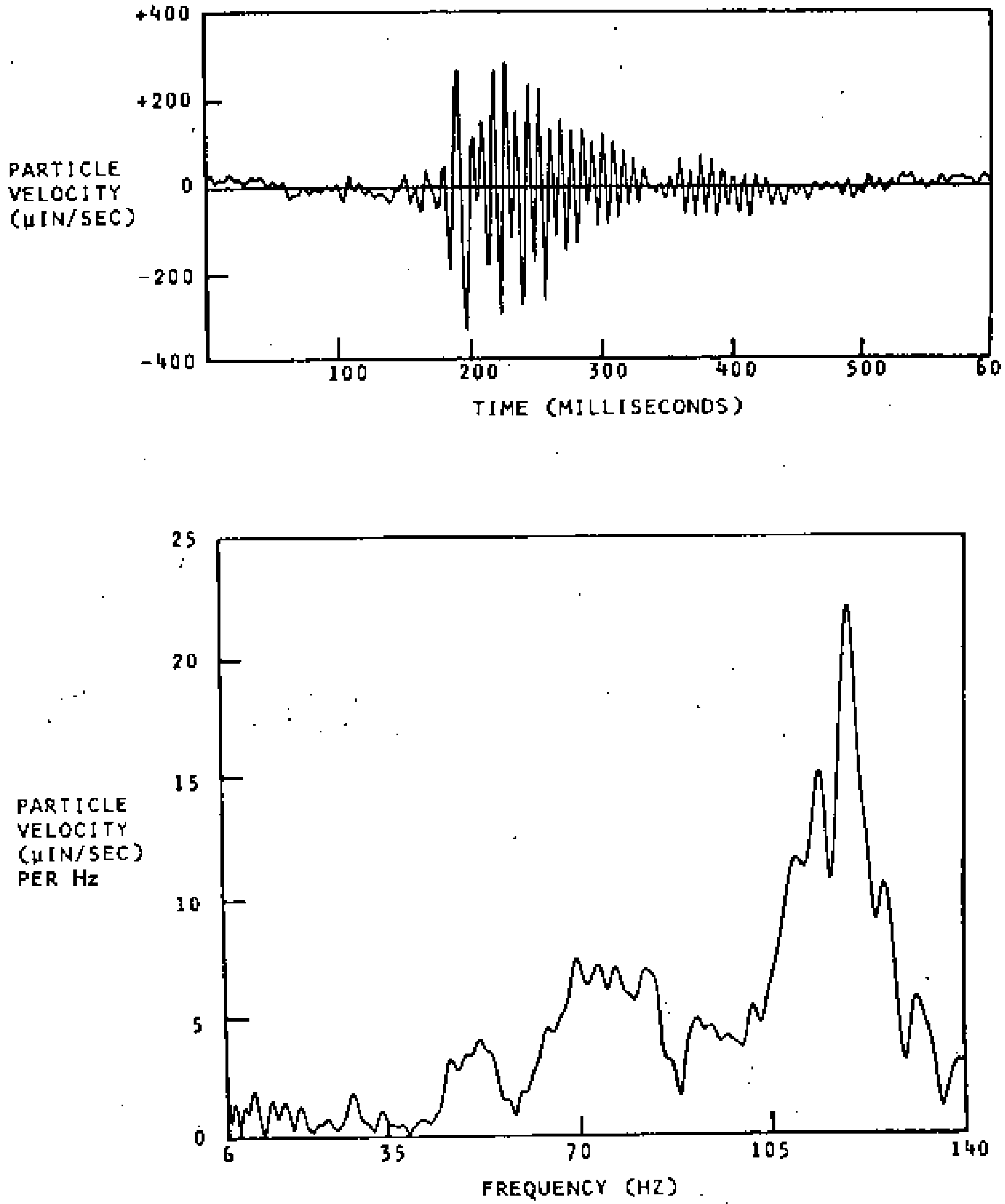


Figure 3.1-12. Signal and Spectrum of a Hammer Blow Recorded Below the Surface at the Imperial Mine.

The P.A.R. preamplifier provided a maximum noise figure of 8 dB with a 4000 Ω source at frequencies above 10 Hz. The Krone Hite filter provided adjustable 24 dB/octave high pass and low pass sections with Butterworth (maximally flat) responses, and the feature of cascading the sections for bandpass operation. The P.A.R. tuned amplifier provided calibrated gain and variable frequency, variable Q, narrow band filtering.

Figure 3.1-13 shows one record taken with this equipment, using a single geophone, at the Imperial Mine. Conditions for this record were somewhat similar to the conditions for the center subarray of the G.U.S. work with the source directly under the subarray and using a hammer on the ceiling. The record shows an obvious improvement in signal-to-noise ratio and an absence of interfering signals.

Frequency content of some of the signals was roughly estimated by varying filter settings until an approximate maximum was obtained. The WGL tests at Imperial gave the same general indication of frequency content at the surface as that obtained by G.U.S., i.e., that most signals tended to have most of their energy around 40-50 Hz.

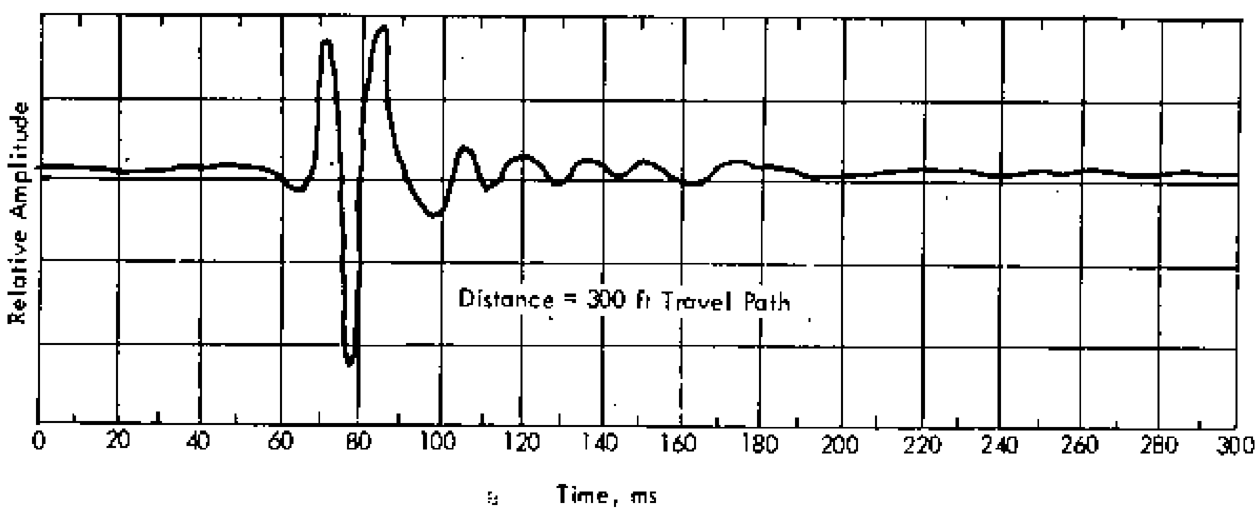


Figure 3.1-13. WGL Observation at Imperial Mine

3.1.4.3 Clyde Mine, Pennsylvania

This mine is described previously in Section 2.1.3 and test locations shown in Figures 2.1-10 and 2.1-11. Figure 2.1-12 shows the geologic section obtained from bore hole data.

Two refraction soundings were made using a fixed geophone (receiver) and a moving source. An 8-pound sledge was used as a source at various distances up to 460 feet from the receiving geophone. A layer interpretation of this data is shown below.

Layer Thickness, ft.	Velocity, ft/sec	Strata
10	2300	Weathered Layer
38	4000	Subweathered, soft Clay and Lime
	>10000	Hard Clay and Lime/Sandstone

Reasonable success was achieved during the up-link tests. An 8 pound hammer was used to pound in various parts of the mine for the seismic source. In all cases, propagation was through about 700 feet of sandy shale with a high average velocity (12,000 - 12,500 feet/second). These rocks seem to be good transmitters of seismic energy. Results of the up-link tests are as follows:

a. In almost all cases, regardless of filter settings, the signal was detectable on the Visicorder records.

b. Generally the best signal-to-noise ratios were obtained in the frequency bands shown below.

(1)	Coupler	Rock
	Response	6.5×10^{-5} in/sec
	Frequency Band	75-200 Hz
(2)	Coupler	Rock Bolt
	Response	3.4×10^{-5} in/sec
	Frequency Band	100-300 Hz
(3)	Coupler	Casing
	Response	1.7×10^{-5} in/sec
	Frequency Band	70-150 Hz

Table 3.1-4 gives the tabulated results of all the measurements made in the Clyde Mine.

Figures 3.1-14, 3.1-15, and 3.1-16 show sample records of the data listed in Table 3.1-4. The figures, in order, correspond to records 6, 13, and 25, respectively.

3.1.4.4 Cambria Slope Mine, Pennsylvania

This mine was described previously in Section 2.1.3 and test locations shown in Figure 2.1-15. The choice of operating locations for the seismic measurements was again dictated by the availability of a telephone link from the surface to the mine plus the availability of 110 volt ac power at the surface. These conditions were satisfied at the two locations shown in Figure 2.1-15. The first site, Site 1, was at a depth of about 670 feet, while the second site, Site 2, was at a depth of 700 feet. Noise levels were very high owing to mining operations and precluded recording good hammer blow signals.

There are only two records from this mine that show a detectable signal from pounding on roof bolts. The first, reproduced as Figure 3.1-17, was at a depth of about 670 feet. The second, reproduced as Figure 3.1-18, was at 700 feet. Both indicate that good response may be obtained during idle mine operations.

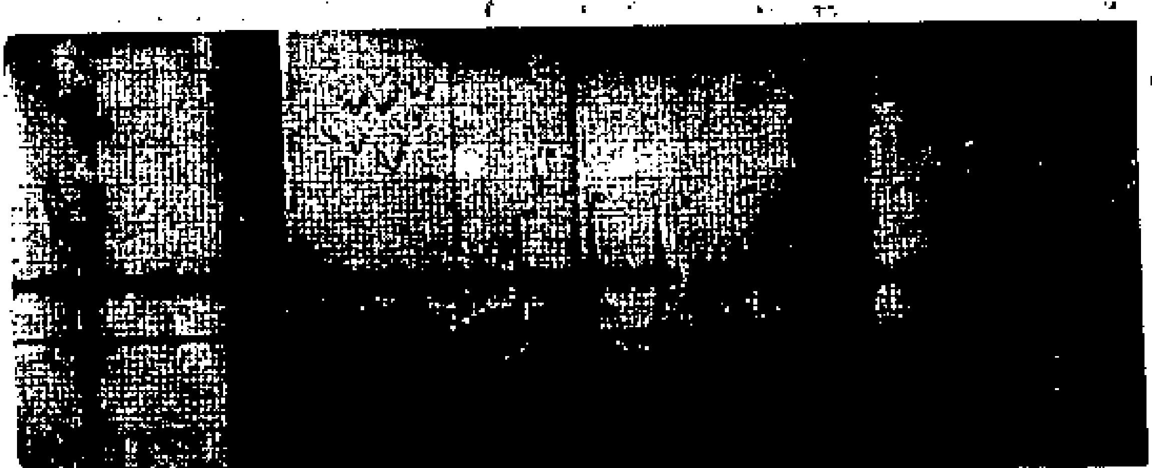
TABLE 3.1-4

RECORDS OF SEISMIC UPLINK SIGNALS AT THE CLYDE MINE USING AN 8-LB. HAMMER ON VARIOUS OBJECTS

Source	Record Number	Bandpass		Center Frequency	Response in/sec	Approx. (S+N)/N
		Low	High			
Well casing	3	40	60	50	5.0×10^{-6} (?)	1
	5	--	--	500	1×10^{-6} (?)	1
	6	200	300	250	1.1×10^{-5}	5.5
	7	200	300	250	1.3×10^{-5}	3
	8	150	300	Flat	1.4×10^{-5}	2.5
	9	150	400	Flat	1.5×10^{-5} (?)	3
Roof bolt	10	70	90	80	4.9×10^{-6} (?)	1.2
	12	200	300	250	5.2×10^{-6}	1.5
	13	100	200	150	5.9×10^{-6}	5
	14	70	130	100	6.5×10^{-6} (?)	2
	15	100	300	Flat	1.9×10^{-5}	3
	16	100	300	Flat	3.4×10^{-5}	1.8
	17	200	500	Flat	1.6×10^{-5}	4
Rail	18	150	250	200	3.9×10^{-6}	1.5
	19	250	350	300	--	--
	20	75	125	100	5.9×10^{-6}	2
	21	30	70	50	3.8×10^{-6} (?)	1 +
	22	120	180	150	2.3×10^{-6} (?)	≤ 1
	23	50	100	75	4.2×10^{-6}	1.5
	24	75	150	Flat	1.1×10^{-5}	1
	25	80	130	100	6.6×10^{-6}	2
	26	70	150	100	1.7×10^{-5}	1.5
Roof rock (silt-stone)	27	80	125	100	1.9×10^{-5}	6
	28	150	300	200	4.8×10^{-6}	2
	29	30	80	50	3.6×10^{-6}	1
	30	75	200	Flat	6.6×10^{-5}	5
	31	75	200	Flat	5.9×10^{-5}	2.2

71-1331-BB-17

Figure 3.1-14. Hammer Blows on Well Casing, Clyde Mine



71-1331-BB-18

Figure 3.1-15. Hammer Blows on Roof Bolt, Clyde Mine

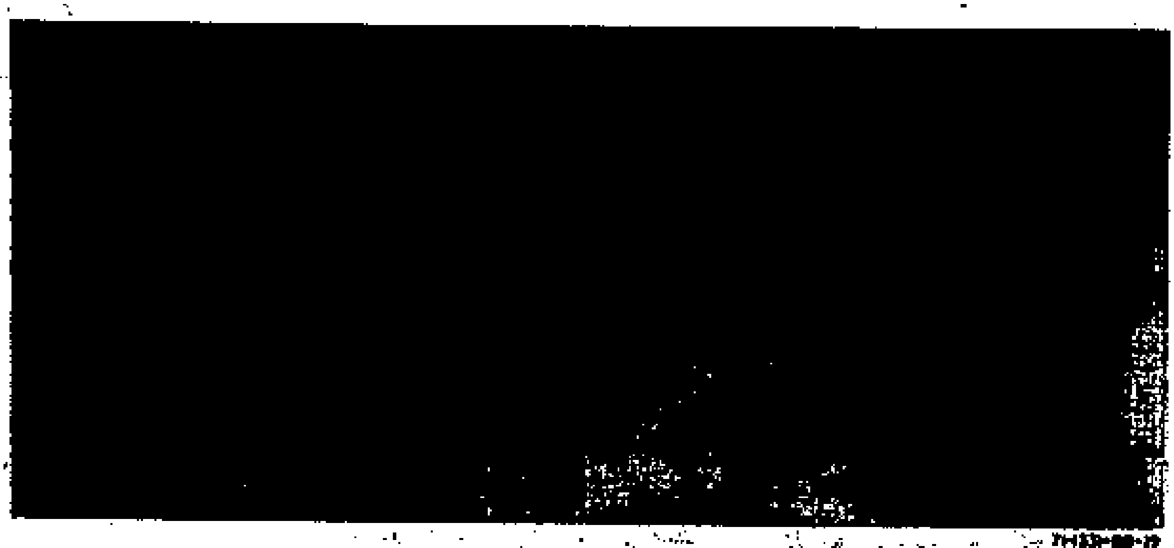


Figure 3.1-16. Seismic Record of Hammer Blows on Rail at Clyde Mine, Pa.

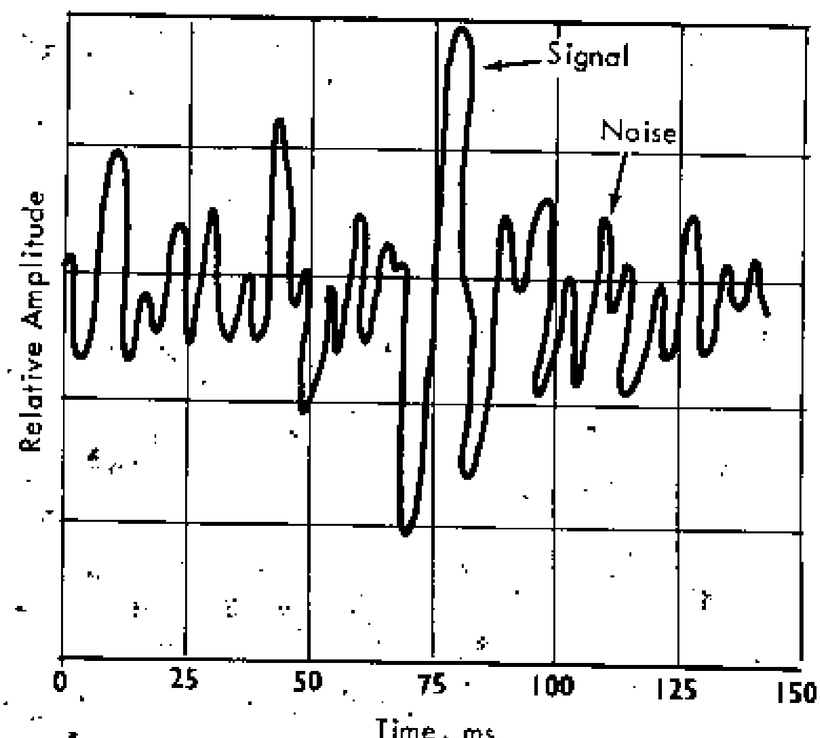


Figure 3.1-17. Signal from Cambria Slope Mine, Site 1 (Traced from Original Records)

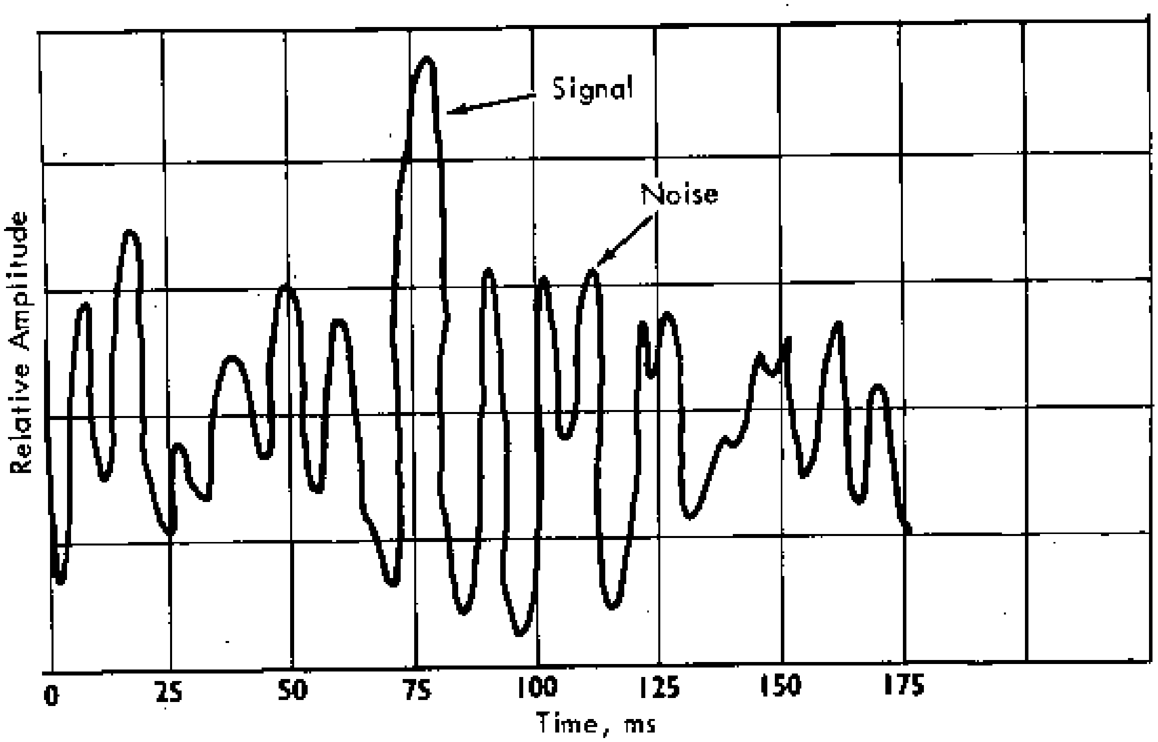


Figure 3.1-18. Signal From Cambria Slope Mine, Site 2a (Traced From Original Records)

3.1.5 Summary of Results

The predesign tasks involved both theoretical and experimental investigations to determine the basic design parameters for the seismic location system. Some general specifications for the system were derived as the results of these tasks. These are briefly summarized here for each predesign task.

Data Base

The lower limit for system sensitivity is established by the seismic noise background level resulting from natural and man-made microseismics. This limit was established from existing data which indicated levels were usually greater than 10^{-7} cm/sec/Hz above 100 Hz and increased around 6 dB per octave with decreasing frequency below 100 Hz.

Detection Studies

Theoretical analysis indicates that the detection of hammer blows under typical situations would require fairly sophisticated hardware and signal processing techniques since the received signals have amplitudes on the same order as background seismic noise, and frequencies of the signal and noise also fall within approximately the same band.

Location Program and Error Analysis

The error analysis using a computer program developed to solve the location problem indicated that the time of arrival of signals should be measurable to within ± 2 millisecond or better in order to achieve reasonable accuracies (20 feet) with the system. Location calculations are relatively insensitive to inaccurate estimates of velocity. A 20% velocity error, 2 millisecond timing error, and 5 foot coordinate error usually give accuracies of less than ± 25 feet.

Predesign Field Tests

The work performed at the Imperial Mine by Globe Universal Sciences showed that requirements for equipment demand a detection system more sophisticated than currently used in the exploration industry. This mine featured relatively thick layers of low velocity weathered material making the detection of subsurface hammer blows at the surface a difficult task for travel paths greater than 400 feet. Indications were that it may be necessary to implant the geophones in shallow holes below the weathering layer.

The energy spectrum from hammer blows at the Imperial Mine was concentrated around 40 Hertz. The lack of higher frequency components is partly attributable to the low velocity weathered layer.

In Pennsylvania, the results were encouraging. A complement of high quality laboratory instruments was used which provided good control of gain, frequency, and bandwidth. The best results were obtained at the Clyde Mine where recordings were made of hammer signals on rock, roof bolts, rail and borehole casing at a depth of 700 feet. The maximum energy frequencies were three to four times higher than in the Imperial Mine owing to geological differences. These tests demonstrated the feasibility of small signal detection, the type of equipment required, and provided signal and noise data with which to refine the design of the signal processing subsystem.

Seismic down-link tests indicated that explosive charges of reasonable size and properly placed could be used to provide a means of signaling to trapped miners since they could be heard by the ear with no additional aids.

The advantages of multiple subarrays was investigated and shown to be useful against certain types of seismic noise. Tests were conducted using multiple geophones placed in an hexagonal configuration but results were inconclusive.

Powerline interference (60 Hz and its harmonics) limited the usefulness of some of the data.

3.1.6 Specific Conclusions

It was concluded that the seismic detection and location of hammer blows from trapped miners would require fabricating a system whose performance exceeded that of conventional systems presently in use if a reasonable degree of success were to be achieved.

The detection problem alone would be difficult. The tests showed that the signals could often be lost in the background noise, and could cover frequencies from 30 to 300 Hz. Maximum frequency components could vary depending on source and coupler used. This indicated adaptive narrow band filtering might aid the detection problem.

Multiple geophones properly spaced in subarrays might improve signal-to-noise ratios. Special signal processing techniques such as cross-correlation, signal averaging, and Fourier transforms of repetitive signals might also be used on multiple hammer blows to enhance the signal.

Computer simulations showed that the location problem could be solved using relative time of arrival at spaced geophones or spaced subarrays of geophones if the time of arrival can be accurately resolved to within one or two milliseconds. Time of arrival measurements with this resolution and accuracy further complicate the detection problem since high signal to noise ratios are essential.

A performance evaluation of the various signal enhancement techniques could only be accomplished by designing, fabricating a complete system which was capable of processing signals in different ways and adaptable to a variety of situations which might be encountered. The design and fabrication and the testing of this system is described in the following sections.

3.2 DESIGN AND FABRICATION

The procedure followed in design and development of the Seismic Location System is summarized as follows:

a. Predesign tasks provided detailed formulation of system requirements based on the evaluation of the data base and results of preliminary measurements in the field.

b. Phase two was the actual design of the location system. Wherever commercial equipment could meet system requirements, it was used in lieu of fabricating instruments. Emphasis was then placed on interfacing the subsystem components to achieve optimum performance.

c. Phase three, fabrication and assembly, required packaging commercial equipment for field use, construction of preamplifiers, notch filters, geophone cabling and system integration.

d. The final phase was testing. The equipment was tested as individual units, then cabled together and tested as a system. Bench tests were run and the equipment was then installed in a van and field tested before delivery to Charleston, West Virginia.

3.2.1 Design Goals and Guidelines

The ultimate design goal was to provide a "state-of-the-art" system which would be flexible enough to be adapted to unforeseen problems without costly redesign.

The short delivery time of the system dictated the purchase of commercial equipment not requiring development and construction time. A guideline for the selection of commercial equipment was that it provide at least the minimum specifications required to accomplish the desired goal.

Human engineering aspects must be considered for operational ease, fast deployment, and maintainability.

A high degree of flexibility in operating configurations and processing techniques was desirable to insure successful performance under a variety of operating conditions. Since powerline noise could not necessarily be silenced following a mine disaster and seismic arrays could not always be moved far enough away from interfering lines, the system design concept must provide voltage gain at the array and balancing and shielding of all cables.

3.2.2 Make or Buy Decisions

The decisions to make or buy, were always based on the following: If the desired specifications could not be obtained using off-the-shelf commercial equipment, then the only alternative left was to design and construct the equipment.

3.2.3 Description of the Equipment

A block diagram of the seismic location system is shown in Figure 3.2-1. Seven geophone arrays with up to seven geophones per array are deployed and seven amplifiers are used to amplify these signals for recording on a seven track magnetic tape recorder. The amplified signals are simultaneously filtered and displayed on an oscillograph record. That oscillograph record serves to detect the signals when they appear as regularly spread pulses. The functions performed by the system are illustrated in Figure 3.2-2. After the signals are recorded, they are processed by a small computer which is an integral part of the signal processing equipments. The

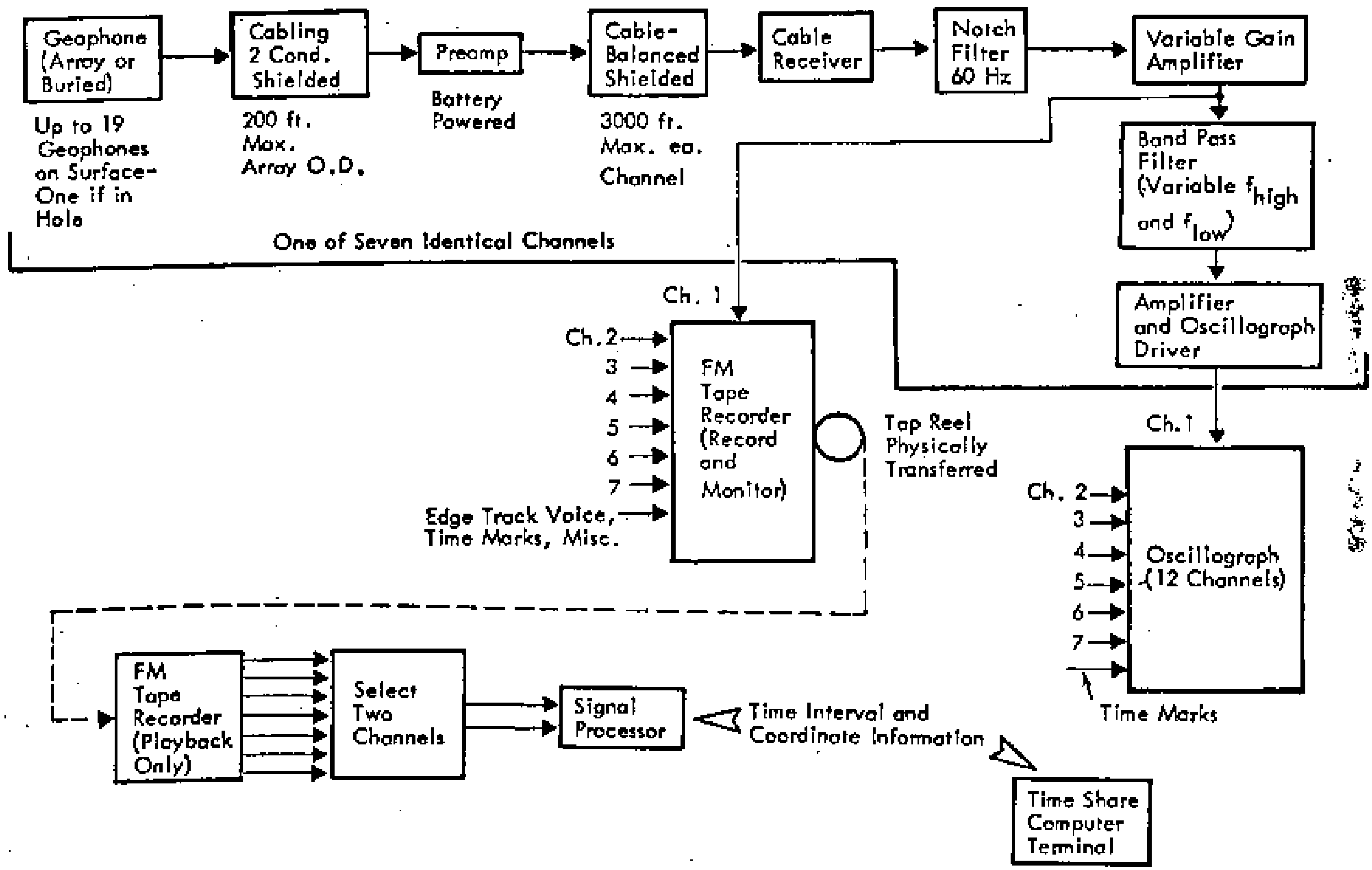


Figure 3.2-1. Seismic Location System (Hardware Block Diagram)

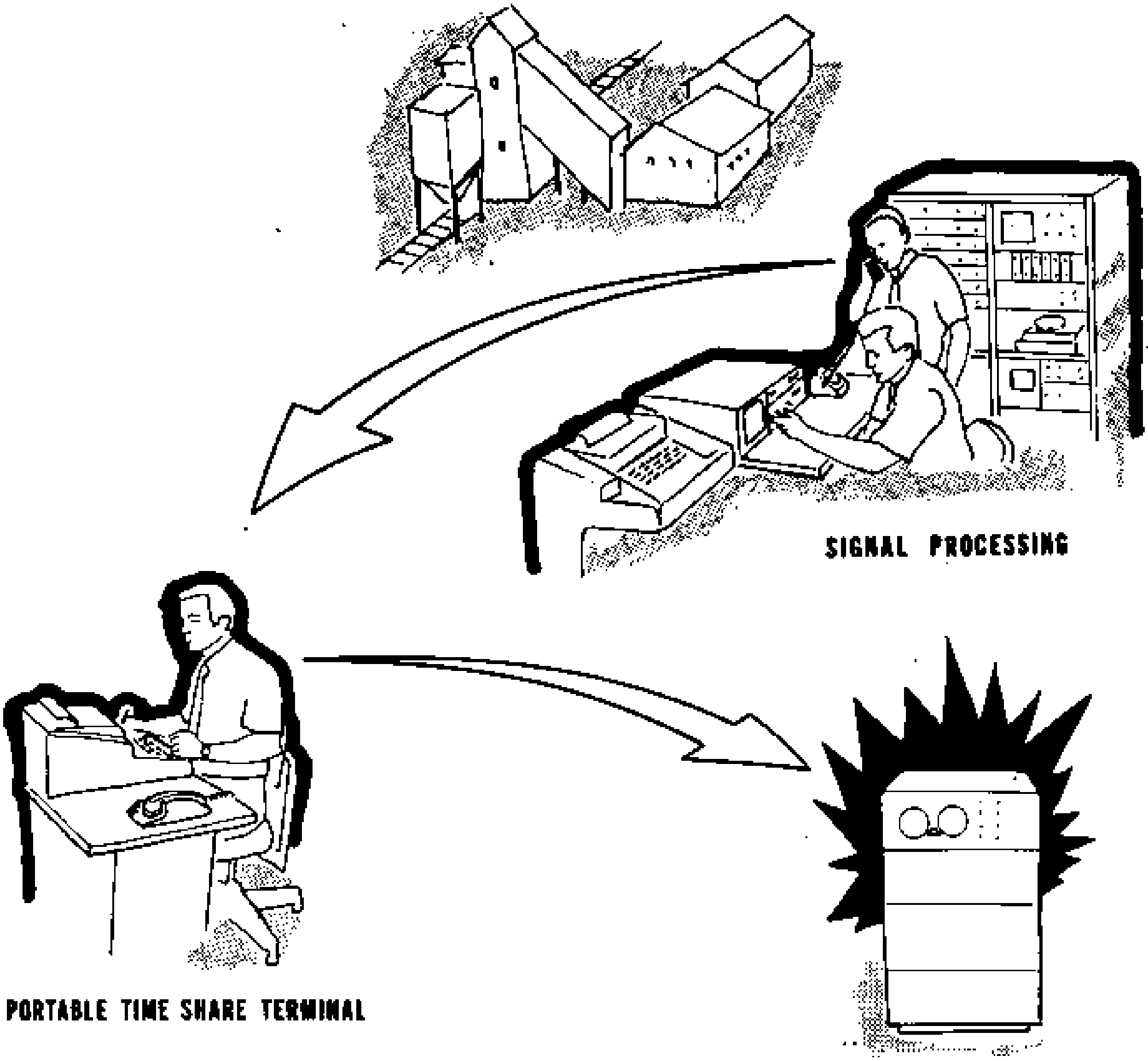


Figure 3.2-2. Seismic Location System – Miner Location Computing

final results of this signal processing are the arrival times of the seismic signals generated by the trapped miners within the mine. These arrival times and the exact position of the geophone arrays are then fed into a time-share computer via a portable time-share terminal which is part of the Seismic Location System. The location program, previously stored in the time-share computer, is then executed to compute the probable location of the signal source. This system, though complex, has performed well and is the primary means of locating miners trapped, or in barricades away from survival chambers. Figure 3.2-3 shows the amplifiers, filters, oscillograph tape recorders, and peripheral equipment which comprise all of the signal processing equipment with the exception of the signal processing computer and time-share teletype.

3.2.4 Equipment Specifications

The block diagram of equipment (Figure 3.2-1) was formulated and passed through a WGL design review. Specifications are presented below for each block.

3.2.4.1 Environmental and Physical Specifications

Geophone Subarray (each)

Weight of seven geophones and cables on a hasp: 25 lbs.
Weight of preamp: 15 pounds
Weight of 1500 feet of cable and chest reel: 45 pounds
Total cable available: 3,000 ft. (2 reels)
Maximum array diameter: 200 feet
Operating temperature range: -4° to 122° F
Humidity: 100%

Van Mounted Equipment

Includes 2 racks of equipment, signal processor and one teletype
Total weight: 1,050 pounds
Operating temperature range: 50° to 104° F
Power consumption: .3kW, single phase, 60 Hz, 115 volts
Size: Requires 7 X 3 X 6 feet (L X W X H) plus table 3 ft. X 3 ft.

3.2.4.2 Seismic Detection Subsystem Specifications

Geophone Subarrays

Geophone type: Geospace Corp. GSC-11D, Model M-3
Geophone electrical characteristics: Dual coil "Humbucking" loaded to 70% critical damping
Sensitivity: 1.5 volts/inch/second
Natural resonant frequency: 14 Hz

Subarray Cabling

Cable type: Belden type 8413, shielded, twisted pair
Maximum diameter of subarray: 200 feet
Number of geophones per subarray: 7
Maximum distance from subarray to signal conditioning/processing van: 3,000 feet each subarray

Preamp

Input: Balanced, transient protected
Input impedance: 100 kΩ minimum
Common mode rejection: 80 dB minimum
Input noise: Less than 0.04 $\mu V/\sqrt{Hz}$
Gain: 40 dB
Output: Transformer coupled, balanced, transient protected
Frequency response: 2 to 3,000 Hz (± 1 dB)

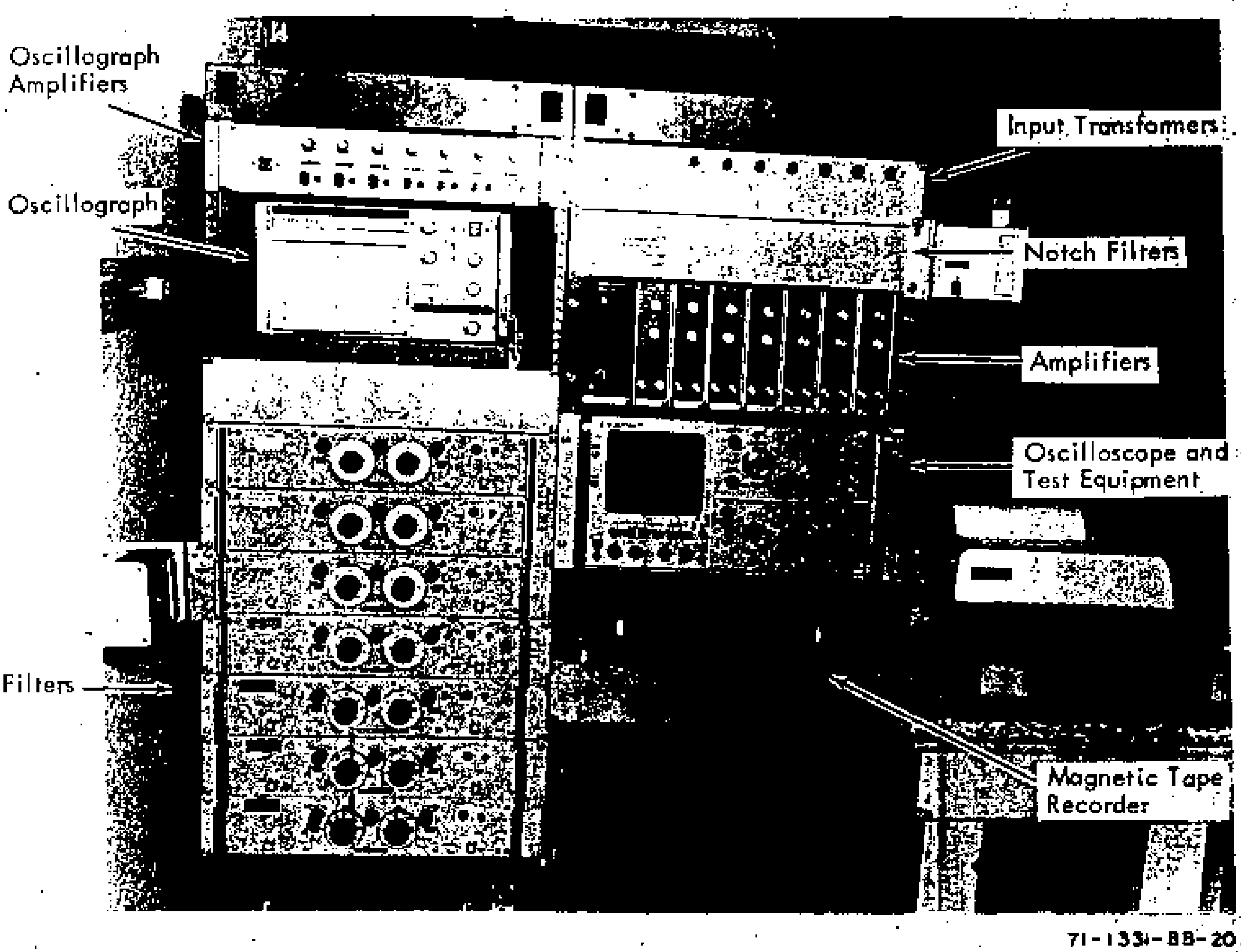


Figure 3.2-3. Rack Layout, Seismic Location System Signal Processing

3.2.4.3 Signal Conditioning Subsystem Specifications

Input Transformers (7 each in one cabinet)

Frequency response: 2 to 3,000 Hz (± 1 dB)

Hi-Gain Amplifiers (7 each in one cabinet)

Type: Ithaco Model 454

Input: Single ended

Input Impedance: 1 M Ω shunted by 100 pf

Gain: -10 to + 90 dB variable in 1 dB steps

Noise: See manufacturer's manual

Frequency response: 1 Hz to 100 kHz (-3 dB)

Variable Filters

Type: Krohn Hite Model 3550

Response characteristics: Selectable low pass, high pass, bandpass, and reject

Attenuation slope: 24 dB/octave

Response type: Selectable Butterworth or low-Q (no overshoot)

Frequency range: 3 dB corner frequencies continuously adjustable 2 Hz to 200 kHz

Oscillograph and Oscillograph Amplifier

Type: Oscillograph - Honeywell Model 2206
Amplifiers - Honeywell Model 112

Frequency response: DC to 2,000 Hz (±5%) using Honeywell M 3300 fluid damped galvanometers

Number of traces: Seven plus one spare - fourteen traces possible with addition of more amplifiers and galvanometers

Paper speed range: .02 - 80 inches per second

Timing lines: .01, .1, 1, 10 seconds or external

Event marker: Front panel push button

Amplifier gain range: 1 - 1000 in steps of 1, 2, 5 plus 1/200 attenuator plus vernier

Magnetic Tape "Record"

Options: 7.5 inches per second tape speed
7 track, FM, record
Voice track
1 switchable channel reproduce
AC power supply
Footage counter

3.2.4.4 Signal Processing Subsystem Specifications

Magnetic Tape "Reproduce"

Type: Lockheed Model 417

Options: 7.5 inches per second tape speed
7 track, FM, reproduce
Voice track
AC power supply
Footage counter

Variable Filters

Type: Krohn Hite Model 3550

Response characteristics: See above

Playback Amplifiers

Type: Honeywell Model 112

Input impedance: 1 MΩ minimum

Frequency response: DC to 20 kHz

Gain: 1-1000 in steps of 1, 2, 5 plus 1/200 attenuator plus vernier

Signal Processor

Type: Computer Signal Processors, Inc., Model CSS-3

Options: 2 channel input, 8192 word memory

Block size: up to 2048 words

Sampling period: 200-10,000 μ sec

Input impedance: 10 KΩ

Display: Cathode ray tube

Output: CRT display or plot using X-Y recorder

X-Y Recorder

Type: Hewlett-Packard Model 7005 B

Chart: 11 x 17 inches

Notch Filters

Type: TT Electronics - Model R-20 - passive

Notch: Greater than 40 dB, 58 to 62 Hz
Less than 3 dB for frequencies outside 48 to 72 Hz

3.2.4.5 Location Processing Subsystem Specifications

Time Share Terminal

Type: Anderson Jacobsen - Model AOT-233

Consists of: ASR-33 teletype with acoustic coupler packaged in a portable case

Time-Share Computer

Type: Any large digital computer equipped for time-share operation and remote access control via telephone lines

Location Software

Loaded on time-share computer

3.2.5 Breadboarding and Testing

The only component of the Seismic Location System which required breadboarding and testing was the preamp. No commercially available preamplifiers were found which would meet the requirements of low noise, battery power, and severe environmental operation. However, component amplifiers needing only a case and power supply and meeting desired specifications were found. Several were tested and the Intech Model A-200 finally selected.

Other equipments and interface components were tested when received to insure manufacturer's specifications were met.

3.2.6 Design Trade-offs and Design Decisions

A discussion for each instrument is given below:

Geophones - Geophones could be selected with a range of senstivities and self-resonant frequencies. A geophone with a self-resonant frequency of 14 Hz was selected, since it could be expected to respond to frequencies as high as 500 Hz without introducing spurious responses, for example, internal spring resonance. A trade-off was required when selecting sensitivity and geophone impedance level. The highest available impedance was selected since that provides the most sensitivity and all geophones investigated were at a lower impedance level than needed to provide optimum thermal noise performance. Transformer coupling between the geophones and preamp was investigated but discarded when no transformer could be found that would improve the calculated noise performance. The relative response of the geophone used is shown in Figure 3.2-4 for undamped conditions and in Figure 3.2-5 as installed in the plastic case for field use.

Cabling - It was desired to make the cable some bright color so that it could be more easily spotted at night. Also it was desired that the cable jacket be tougher than normal laboratory cable in order to reduce repairs. Two manufacturers were requested to bid on shielded pair cable with plastic jackets capable of remaining flexible in cold weather. The manufacturer that responded had an excessive price and delivery time. Therefore ordinary microphone cable was selected.

Preamplifier - Selecting the actual amplifier used in the preamp was discussed in paragraph 3.2.5. The costs of other items in the preamp, excepting batteries, did not merit spending further design time. Diodes with surge ratings of 300 amps were selected for lightning protection. The output transformer was selected to be compatible with frequency response, levels, and the required balanced output. The batteries selected were alkaline type since alkalines perform better in cold environments than most batteries. Maximum preamp drain, and 336 hours continuous operation at room temperature were used as the criteria for selecting battery size. Also, it was kept in mind that the batteries should not be "rare" or hard to buy. Alkaline "C-cell" size batteries, 1.25 volts, were selected.

Cable Receiver - Transformers and diodes identical to those used in the preamp were selected for the interface at the seismic equipment terminal.

Notch Filters - A short market search revealed only TT Electronics as a supplier of passive filters meeting the required specifications. They designed and tested two prototypes and sent specifications to WGL for selection. One had only a 20 dB notch and the other had fairly wide 3 dB points with a 40 dB notch. The second filter was selected on the basis that engine generator sets, which were a likely source of power, would not be well frequency regulated. In addition, the notch filters were a back-up item which were not expected to be used under normal circumstances.

Variable Gain Amplifiers - Several amplifiers were investigated and, as a result, the ones that were selected were Ithaco Model 454. These provided the best noise performance (of those that specified noise performance) and the lowest price of those that met specifications.

Band Pass Filters - Since seven variable bandpass filters were to be purchased, cost was a major consideration in the market search for filters. Only the one selected had a moderate price tag and versatility over the required frequency range.

Oscillograph and Oscillograph Amplifiers - The oscillograph was selected on the basis that it was "portable" and should therefore be rugged enough to withstand the shock and vibration of a vehicle installation. Only the oscillograph and tape recorders were given much attention in this area, since they are the only "mechanical" instruments. The oscillograph driver amplifiers were selected for compatibility with the oscillograph and galvanometers. The galvanometers were selected to be fluid damped for ease of installation and for high frequency response.

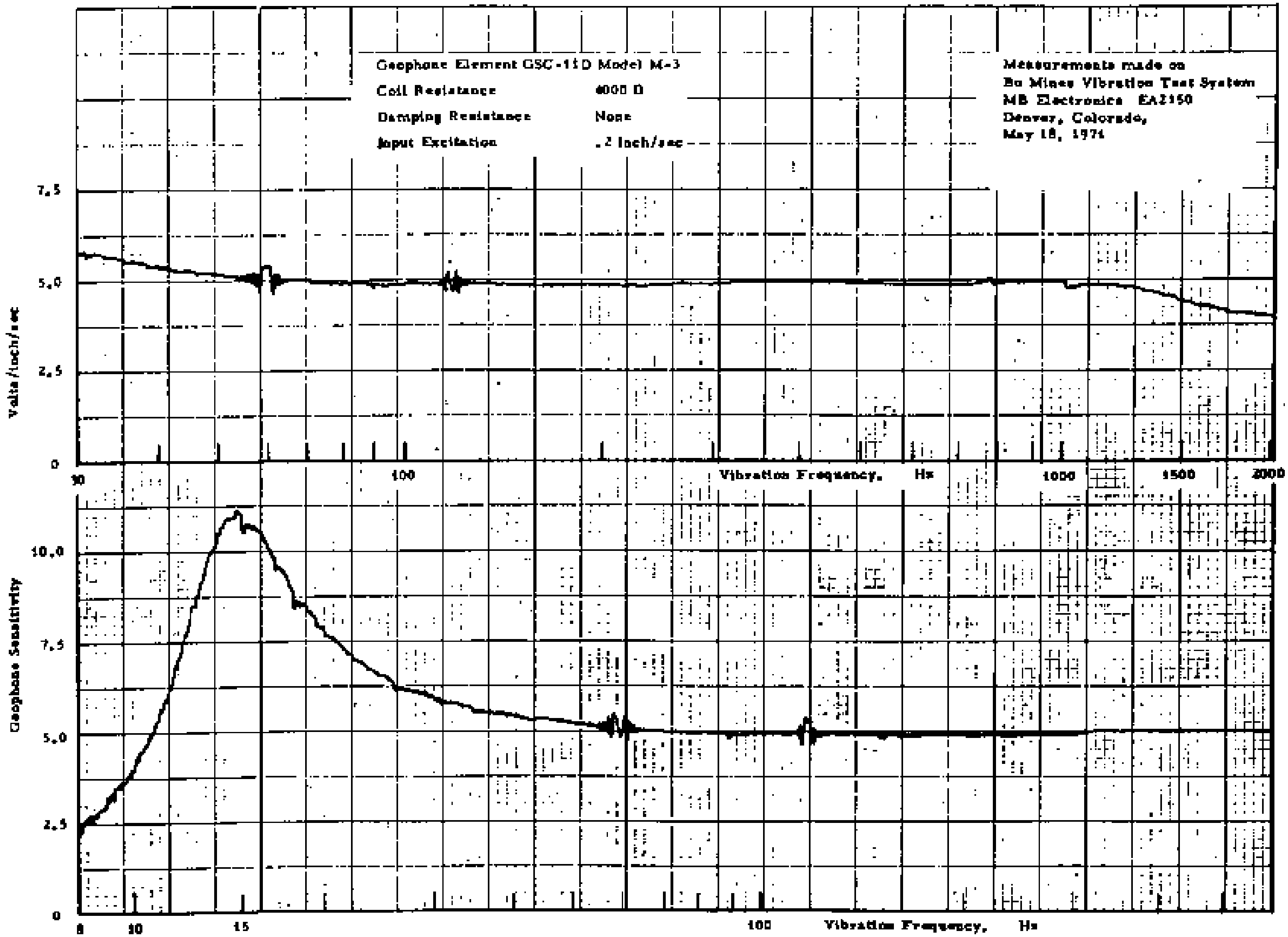


Figure 3.2-4. Frequency Response of Undamped Geophone Element

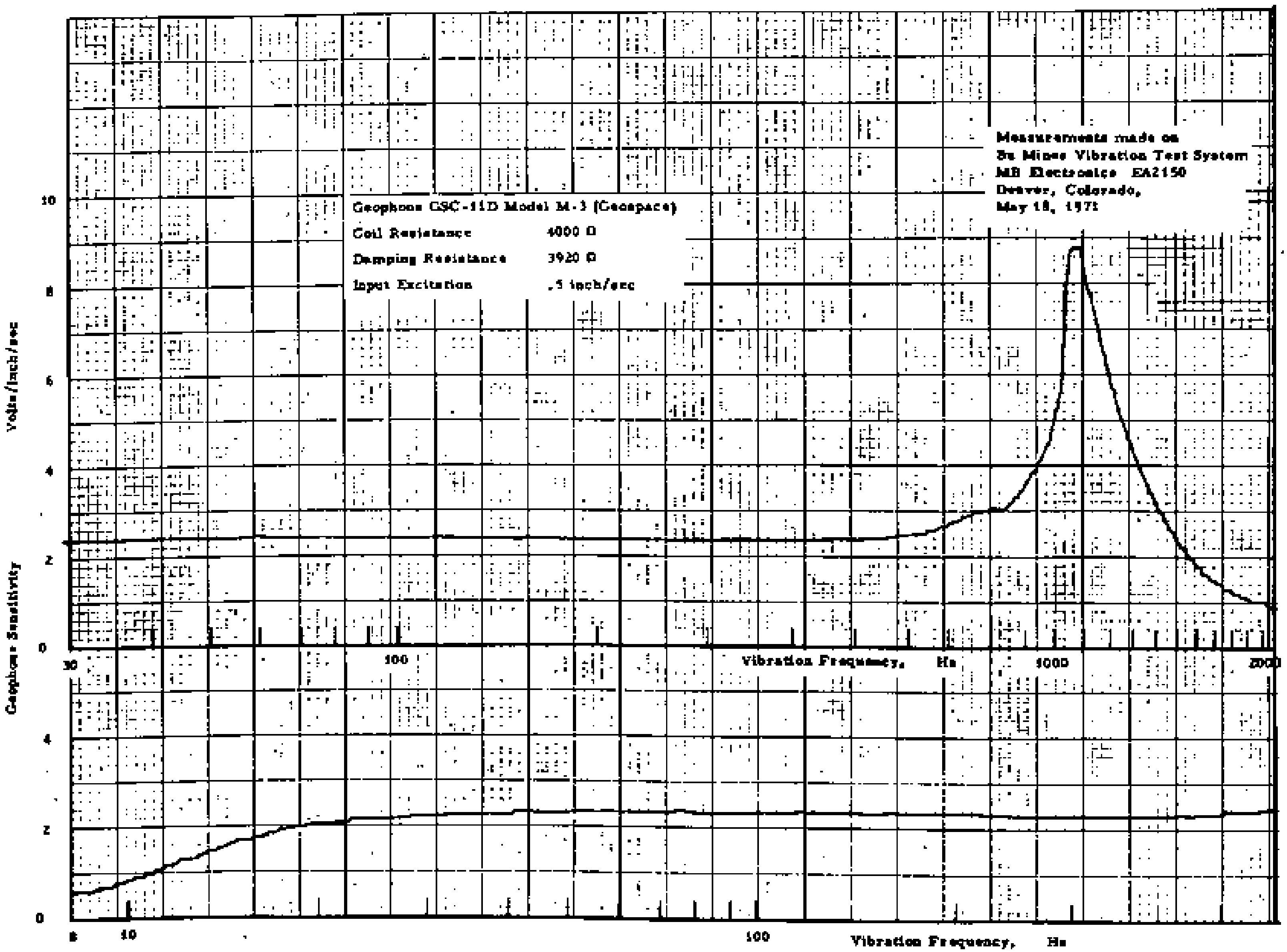


Figure 3.2-5. Frequency Response of Critically Damped GSC-11D Geophone in Plastic Case

Magnetic Tape Recorders - Three different portable tape recorders were investigated, Pemco Model 110, Honeywell Model 5600, and Lockheed Model 417. The Pemco (the least expensive) significantly degraded time interval information and the Honeywell Model (the most expensive) could not be delivered on time. The Lockheed recorders were thus selected.

Signal Processor - Three signal processors were investigated. A discussion of each and the basis upon which they were evaluated is given below. They are:

- Time Data: T/D 100
- Computer Signal Processors, Inc. (C. S. P. I.): CSS-3
- Hewlett-Packard: 5450A

The systems were evaluated on the following basis, in order of priority.

(1) Versatility - The ability to do many types of signal processing. This includes simple and complex operations on the data and such factors as operating on data in "real time."

Since many consecutive hammer blows must be added up in order to obtain adequate signal-to-noise ratios, the "real time" capability was considered important but not absolutely necessary. "Real time" here implies the ability to buffer input data while operating on previously taken data.

(2) Cost and Delivery - Four months' rental and 30 day delivery was considered adequate.

(3) Operator Interface - With systems that do complex signal processing, it is important that data inputs and outputs can be interpreted by the operator without undue difficulty.

Factors one and three are discussed in the following paragraphs.

Time/Data 100 - The Time Data machine is the least versatile of the three since it performs only a fixed set of computations. It allows input buffering and is fast enough to perform signal processing for this application in real time if the final type of signal processing required is within its capabilities. It is a hard wired processor and capabilities cannot be added to this system as with the others. Important functions this system lacks are conversions to and from polar coordinates, division, and subtraction. The T/D 100 has a good operator interface but this interface is simplified with respect to the other two systems because the machine does less sophisticated processing. CSS-3 - This system is based on software and a Varian 620I computer.

CSS-3 - This system is based on software and a Varian 620I computer. It is potentially the most versatile of the three systems since C. S. P. I. can be contracted to write additional software to perform nearly any type of signal processing. Input buffering is allowed, and the system is fast enough to meet the application in real time. It performs all of the basic Fourier analysis and mathematical operations and many more. However, these standard operations cannot be linked together except by separate commands from the operator. A disadvantage is that the system works in whole numbers but not in mixed numbers. The operator must take care that mathematical operations of fractions result in fractions and similarly for whole numbers. All commands to this system are entered through an ASR-33 teletype rather than by "push button" command. The operator must learn the conversational language of this system.

Hewlett-Packard 5450A - The H. P. system consists of a keyboard with standard arithmetical operations and basic signal processing applications. Complicated signal processing routines are generated by first programming sequences of basic routines. The system then executes the entire routine automatically. However, the system cannot do things such as choosing the largest value in a spectrum without special programming from H. P. This system is significantly slower than the other two and cannot buffer input data unless it is coupled to the 16K memory computer. For real time processing, this system would require the larger computer and some method of slowing down real time such as magnetic tape recording at a fast speed and playing back at a low speed. The operator interface of this system is the best of the three systems since data is manipulated automatically and scale factors are automatically computed and displayed.

The T/D 100 was eliminated since it could not be expanded to do non-standard routines. The H. P. system is more costly than the CSS-3 and has greater versatility standard, but could pose serious problems in real time analysis. Therefore, the CSS-3 system was selected.

Time-Share Computer Terminal - Two terminals were investigated but one was eliminated when it was found that the supplying company was not stable. It was desired to find a terminal other than an ASR-33 teletype since teletypes are not extremely reliable when exposed to shock and vibration. However, no other terminals could be found and an ASR-33 with acoustic coupler was selected.

3.2.7 Design Reviews and Design Modification

No changes were made in the Seismic Location System at its final design review. The system was implemented as discussed above.

After initial field testing it was found that filtering and gain were required between the playback recorder and the signal processor. This did not hinder field testing since two of the filters and the amplifiers used in the system can be used for signal processing. However, in a disaster, when signals must be recorded concurrently with signal processing, those filters and amplifiers could not be used. As a result, two more filters and amplifiers were purchased. The filters were selected to be identical to previously purchased filters in order to provide redundancy. The amplifiers selected were identical to the oscillograph amplifiers for reasons of cost, redundancy, and adequate performance.

3.2.8 Fabrication and Assembly

No problems were encountered during fabrication and assembly. WGL assembled only geophones, cables and connectors, preamps, cable receivers, and notch filters. The commercial equipments were installed in standard relay racks as shown in Figure 3.2-3. Tests were then conducted at Boulder to gain familiarization with the equipment, to optimize equipment usage and to investigate various operating procedures.

The equipment was installed in a 12 foot truck mounted van for field testing. The racks were bolted directly to the floor of the van. Shock mounting was considered and rejected because of the possibility of shock mount resonances. Other experience with electronic equipment of this type in vehicles indicated direct bolting to be desirable. This method of installation proved reliable throughout the tests.

3.3 PREDEMONSTRATION TESTING

Testing of the Seismic Location System was conducted in several areas. Laboratory tests were conducted at Boulder to gain familiarization with the equipment, to optimize equipment usage and to investigate various operating procedures. Predemonstration field tests were conducted in Colorado, Pennsylvania and West Virginia.

3.3.1 Laboratory Testing

Laboratory tests were conducted at the WGL Base Station following the installation of the Seismic Location System in a truck mounted van. These tests were performed to test the equipment after installation, investigate the usage of various configurations of multiple element arrays, and to measure seismic noise and powerline interference. No formal data was collected but the tests showed that ambient or natural noise levels were far above calculated thermal noise levels and that the system was resistant to power line interference.

3.3.2 Imperial Mine, Erie, Colorado

The Imperial Coal Mine at Erie, Colorado, was chosen for tests for several reasons. Among these was the existence of previous work done during the predesign phase of this contract. As a result of the previous work, the geological and geophysical environments were characterized.

Using this knowledge of the environment, tests were conducted to test equipment performance, to optimize the use of geophone tranducers, to test seismic source performances, to experiment with processing techniques, and to test location accuracies. Because of the predesign work done at this location, comparisons were available to show system improvements and performance.

The geophones were planted at the same locations used previously, as shown in Figure 3.3-1. Five of these locations included 30 foot holes for deep geophone comparisons. The seismic transmitter thumper was used underground as were hammers, rails, and various other sources.

Figure 3.3-2 shows an obvious improvement in hammer blow data over that recorded during predesign work by G.U.S. (Figure 3.1-9). The signal-to-noise improvement indicates that some degree of optimization has been achieved in signal reception, signal conditioning, and signal processing. A typical pulse with noise discarded, and its spectrum are shown in Figure 3.3-3 and should be compared with Figure 3.1-10 to show signal-to-noise improvement for a hammer blow. The response is more impulsive and centered around 45 Hz.

Noise attenuation experiments, using single and multi-element surface arrays versus buried geophones provided some useful results. It was not easy to plant "retrievable" geophones firmly in the bottom of holes; thus the use of buried geophones was determined to be impractical. This decision is supported by the fact that in cases of rugged terrain, such as West Virginia, it is not feasible to drill holes at selected locations. In most cases, the buried geophone was much noisier than its surface counterpart due primarily to inadequate plants. A comparison of relative noise levels is shown in Figure 3.3-4.

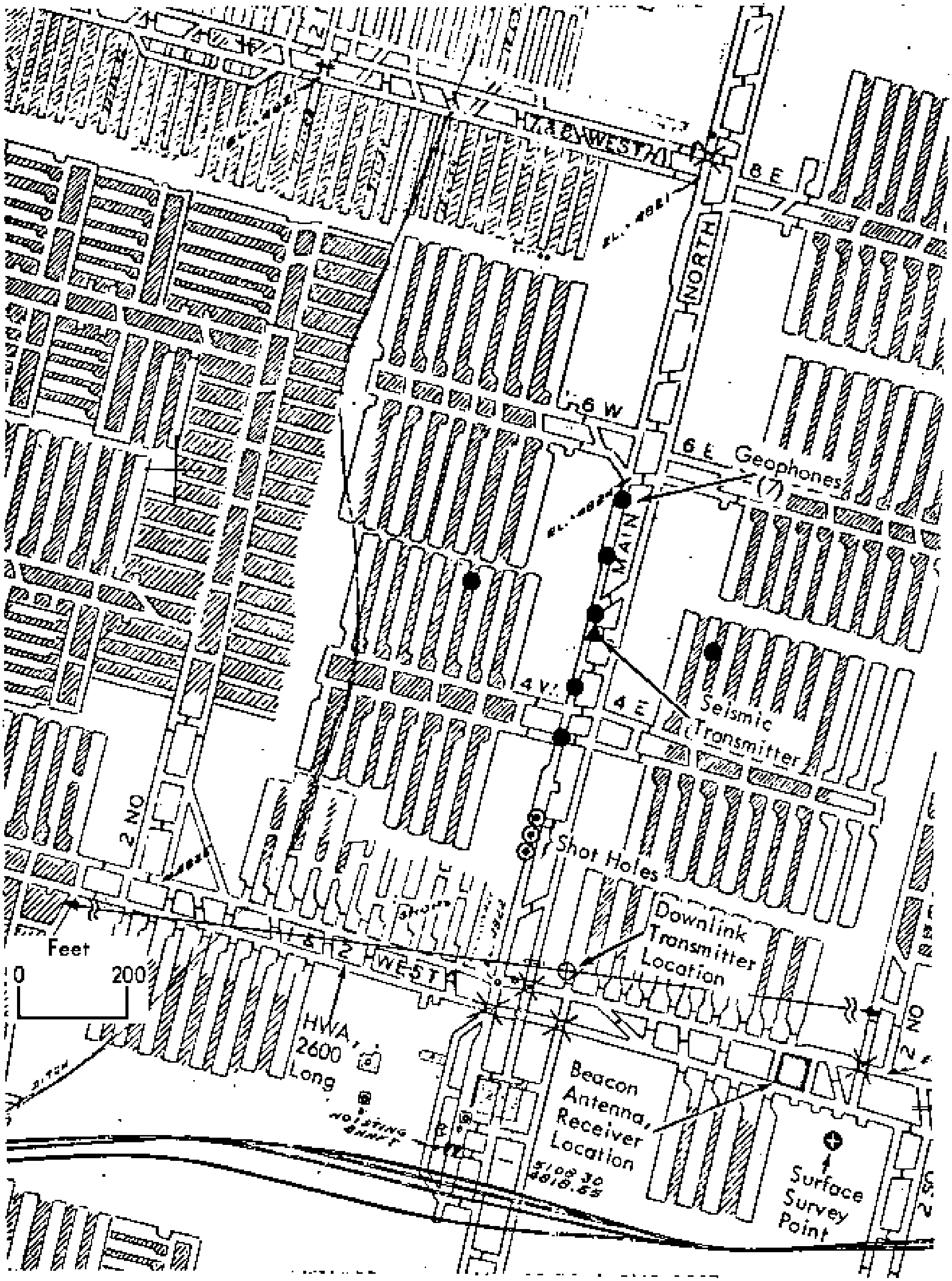


Figure 3.3-1. Map of Imperial Coal Mine Showing Locations of Seismic Measuring Points

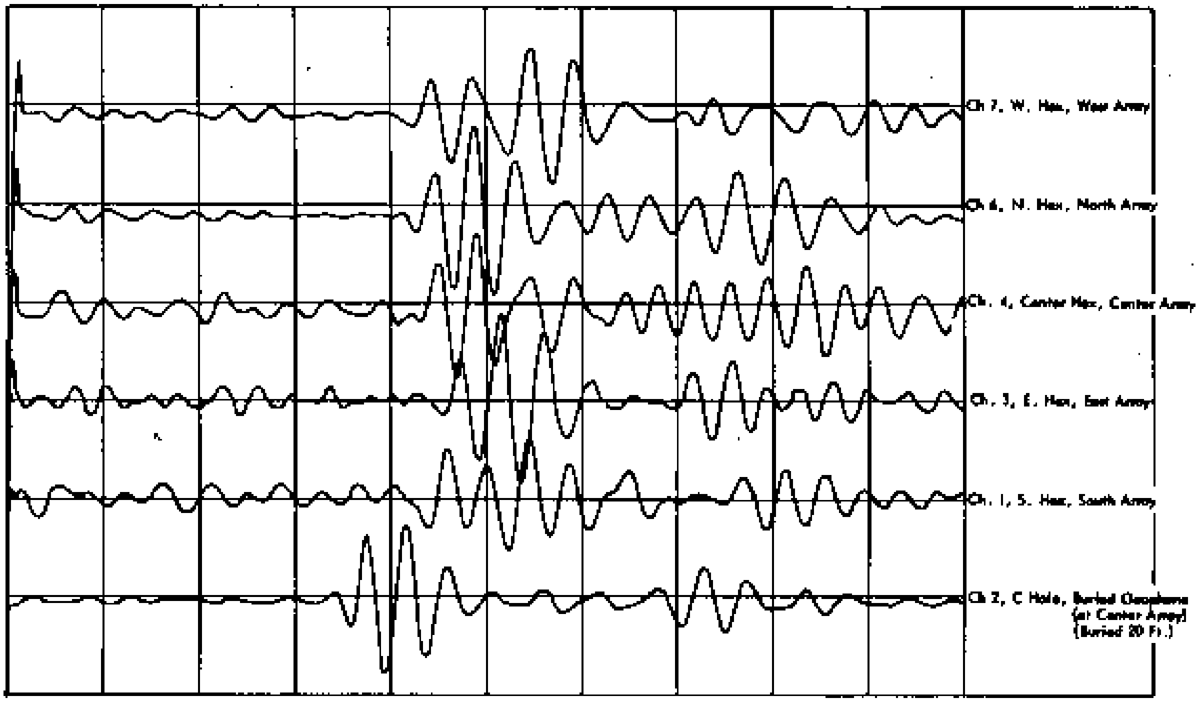


Figure 3.3-2. Signals Received at Imperial Mine - 11-25-70

Experimentation with sources performance indicated that for this mine, overhead beams were excellent couplers where roof rock was relatively firm, Pounding on rails gave inaccurate location results believed to be due to propagation of the signal down the rail.

This was the first time in the field that signal enhancement using repetitive blows was tried. A requirement of this method is that a trigger signal be generated to be in close synchronization with each individual hammer blow. It had been realized previously that there may be one or more signals received on the surface which would be strong enough to establish that trigger, but that the point in time at which the trigger would occur would be too late to allow an examination of the first arrival of that signal. Therefore, Computer Signal Processors, Inc., the suppliers of the signal processor, had been contracted to write a routine which would allow the computer's memory to be used as a type of delay line.

The processor continuously samples input signals, keeping a "current" block of data. Then when a trigger occurs the processor averages that block of data, (containing samples of the signal up to the time of trigger), into another section of memory which contains previously taken data. The effect is that data blocks are averaged together where the trigger point in time occurs at the end of each data block, whereas for normal signal averaging, the trigger occurs at the beginning of data blocks.

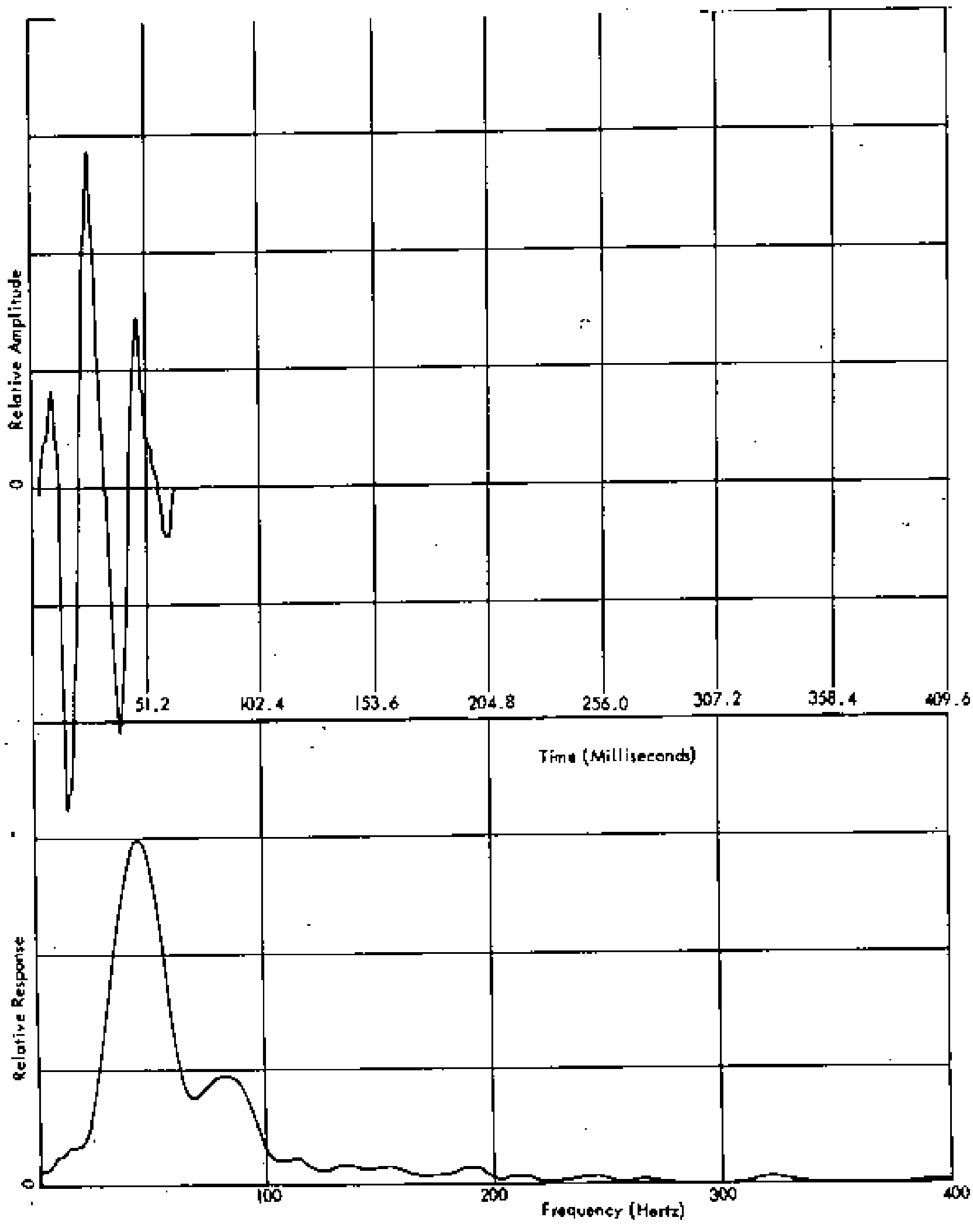


Figure 3.3-3. Signal and Spectrum of Hammer Blow Recorded by WGL 11-25-70

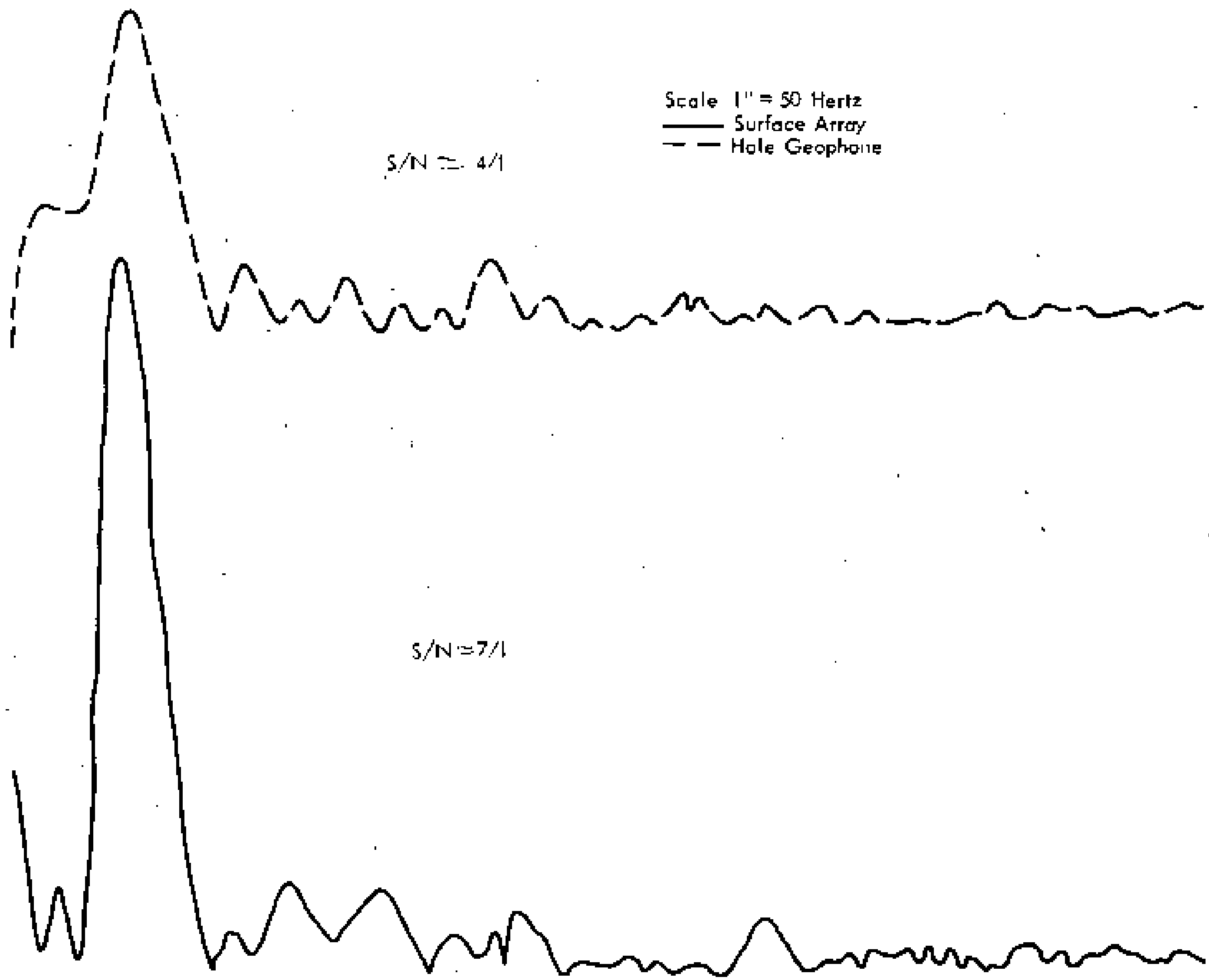


Figure 3.3-4. Comparison of Signal Response (Hammer Blow)

The trigger for the signal processor is generated by the delayed trigger output of the oscilloscope which can be adjusted to follow (in time) any normal trigger of the oscilloscope, (see manufacturer's data for Hewlett Packard 1421A time base plug-in). Then, combining sweep rate with delay time allows a point in time to be established which is in synchronization with the scope trigger and adjustable so that each data block in the processor contains a complete signal from one blow underground.

A trigger signal for input to the oscilloscope, can be generated by any one of three ways: 1) Use of a single signal received on the surface which has a signal-to-noise ratio, after filtering, large enough to allow identification of the same point on each pulse (the actual signal-to-noise ration required is variable depending on the shape of the pulse transient and the characteristics of the noise), 2) Use of a signal received by a geophone underground (in an emergency, this geophone may be installed in the mine at a point as close as possible to the believed area of entrapment, or in the mine through a borehole, or in a borehole drilled only partially to the mine), and 3) Use of a signal received by a geophone underground and transmitted to the surface by the EM beacon.

The use of a signal received on the surface as a trigger was demonstrated qualitatively during predemonstration and demonstration testing. In the interests of performing more location and source studies, specific data was not taken which would allow comparison of data averaged with a "perfect" trigger to data averaged with other triggers. However, some of the data shown in later sections was averaged using signals received on the surface, some was averaged using the EM beacon uplink and some was averaged using an underground geophone.

The data shown in Figure 3.3-5 is the average of 31 pulses from the seismic thumper using an underground trigger and is the best data obtained at the Imperial Mine. The locations computed using this data are shown in Figure 3.3-6. The methodology employed is discussed in Section 3.1.3 and elsewhere. The data points plotted result in an average location. If points which are obviously not grouped with the others are eliminated, the mean location is even closer to the actual source. One source of error is the inability to select the arrival of the first energy to within two milliseconds. This is due primarily to the low frequency of the processed signal. The accuracy of the original mine survey may also be questionable.

3.3.3 Clyde Mine, Fredricktown, Pennsylvania

The environment at the Clyde Mine was very much different from that in Colorado. Topography was very hilly, overburden was much thicker, and the mine workings were more extensive. Since previous data at the Clyde Mine was scarce, a refraction survey was run to characterize the environment. The test site at the Clyde Mine is shown in Figure 3.3-7. At this site, in addition to testing location accuracies, tests were performed on source performance and array optimization. Because of the continual high humidity and the subfreezing temperatures that persisted during the tests, an opportunity arose to evaluate the environmental capabilities of the system.

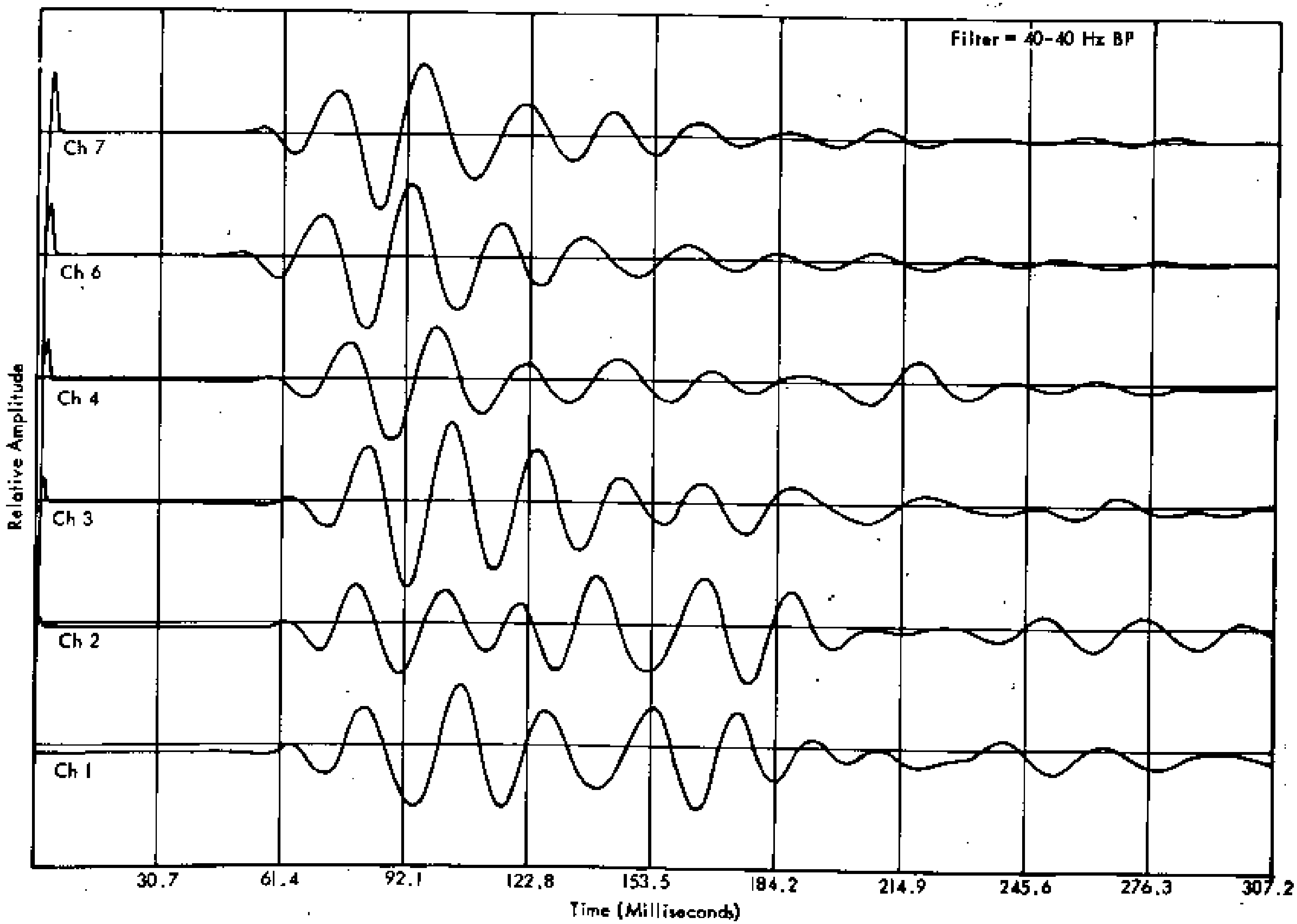


Figure 3.3-5. Imperial Mine Signals - Seismic Transmitter/Used for Locations 12-1-70

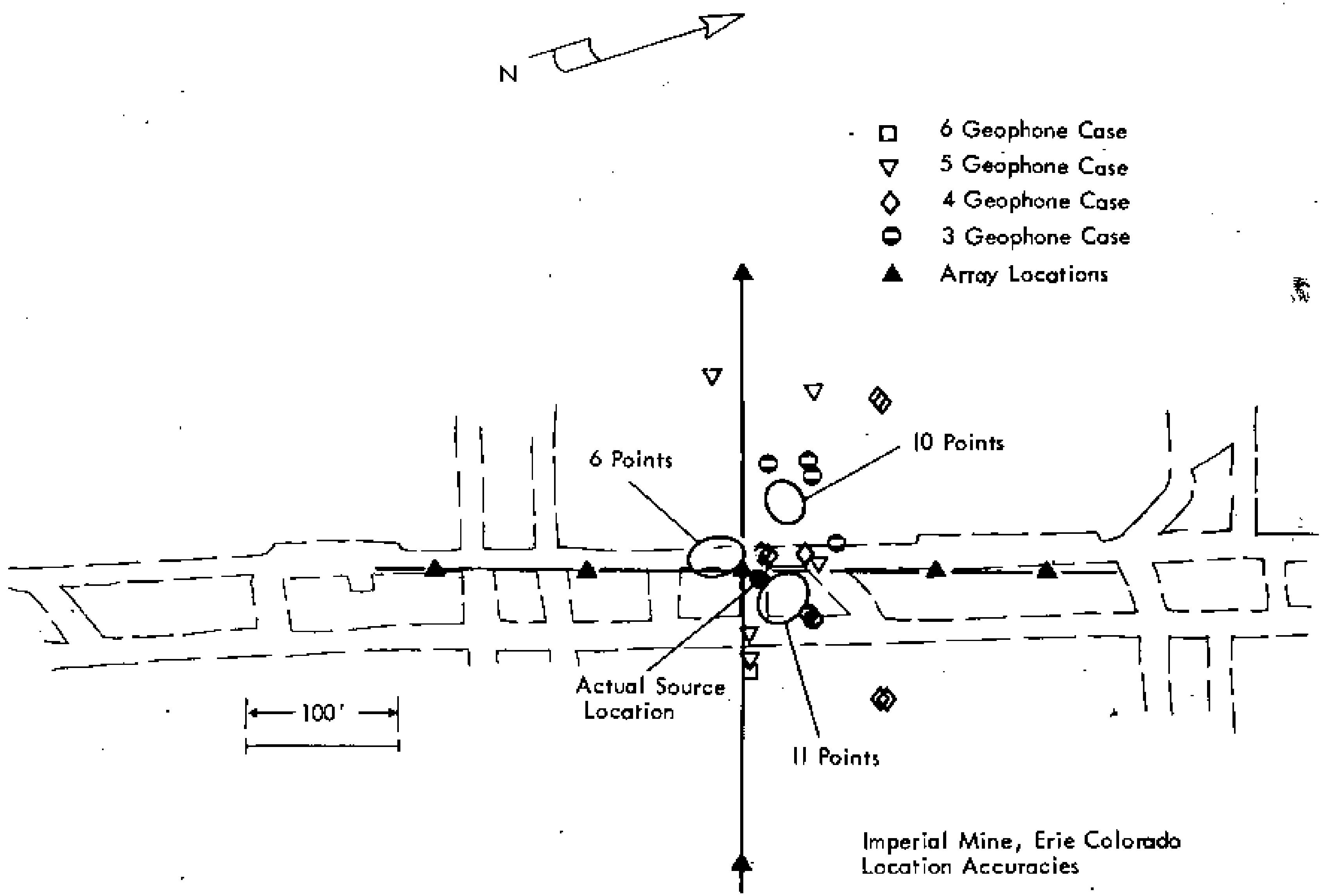


Figure 3.3-6. Locations Obtained at Imperial Mine

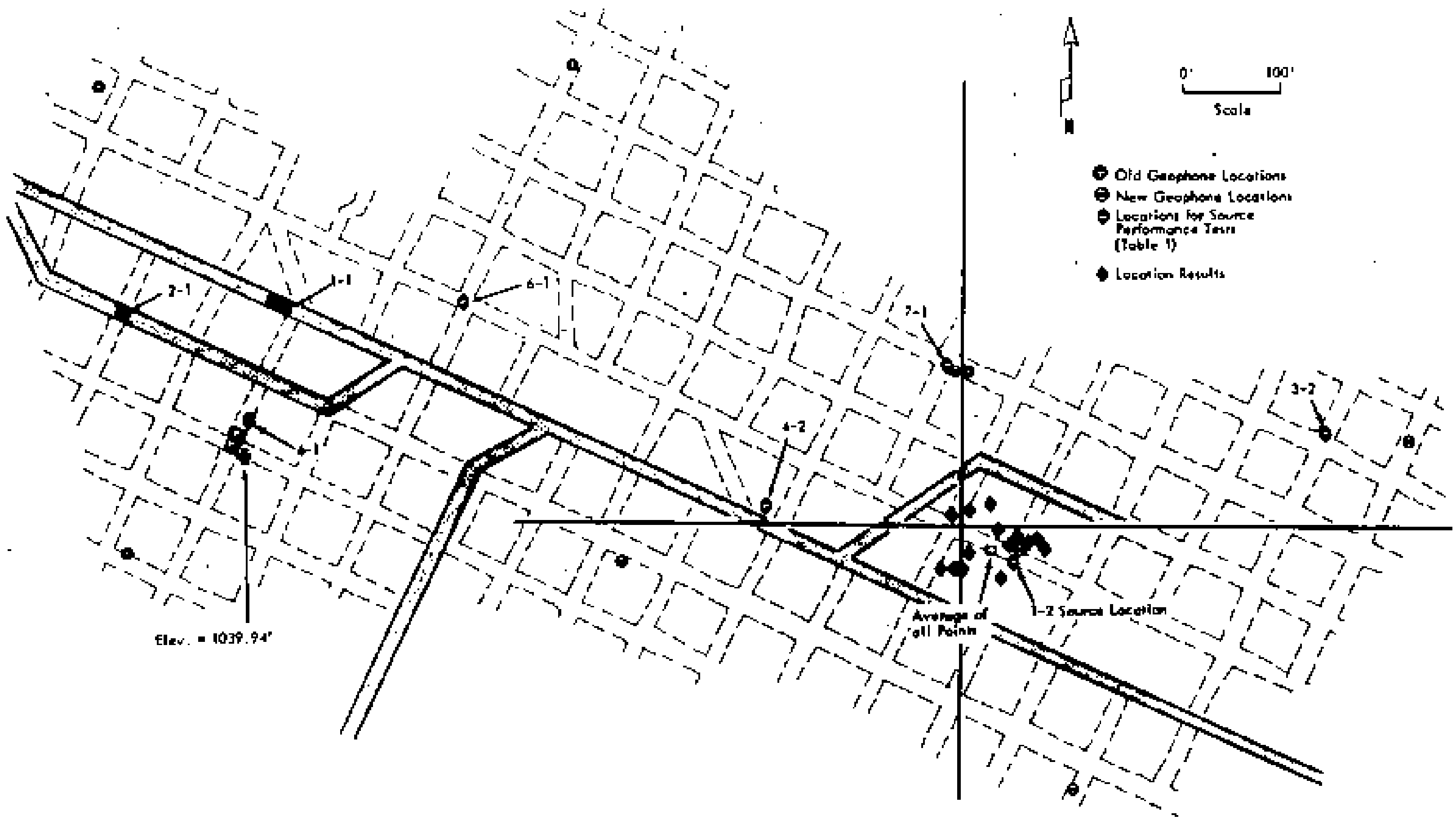


Figure 3.3-7. Clyde Mine Array and Source Locations

The tests performed at the Clyde Mine were similar to those at the Imperial. The major change in procedure was the abandonment of drill holes for buried geophones. At the Clyde Mine, the depth was almost twice that at previous mines, as a result background noise created more problems than during prior tests. Because of the proximity of the test site to cultural noise sources, two sets of array locations were used.

A refraction survey was run to characterize the geophysical and geological environment. The data was resolved into the various seismic wave phases on the time-distance plot shown in Figure 3.3-8. The velocity of the principal noise wave is shown. This velocity was used to determine an array dimension of 20 feet outside diameter. The geological interpretation of the refraction data is given in Figure 3.3-9.

Array experimentation involved comparison of a single geophone, a seven element hexagonal array, and a nineteen element hexagonal array. One plot of the results is shown in Figure 3.3-10 where no improvement is apparent. Additional data collected showed no consistent trends comparing single to seven to nineteen element arrays. However, a seven element array usually performed as well as or better than a single geophone.

Source performance results are shown in Table 3.3-1. An 8 pound hammer was used to pound on the couplers indicated in the Table, except where noted otherwise. The most reliable coupling for hammer blows in the Clyde Mine was found to be a roof bolt, although other sources provided detectable signals.

Figure 3.3-7 shows the location of arrays and sources at the Clyde Mine. Also shown is the accuracy of location trials for the data shown in Figure 3.3-11. The accuracy of locations here was on the same order as at the Imperial Mine, with the average value about twenty-five feet from the actual location, again using the methodology described in Section 3.1.3.

Based on data collected at the Clyde Mine several important observations could be made. With regard to the array comparisons, it appeared that no consistent improvement in signal-to-noise ratio was achieved using nineteen element arrays. The nineteen element array usually did not perform according to theory during these tests. Possible reasons for these results is that the wavelengths and frequencies of coherent noise were estimated inaccurately or that the geophone plants were not consistent. In addition, coherent noise appeared to predominate so that no improvement over random noise could be seen.

One important result of the Clyde Mine testing was the evaluation of the operation of deployed equipment under high humidity and subfreezing temperatures. Conclusions were that the system responses were not altered by weather conditions.

3.3.4 Harewood Mine, Longacre, West Virginia

Tests at the Harewood Mine were much more demanding than at previous sites due to rugged West Virginia topography. Tests were conducted at two sites, chosen for their accessibility. Both sites were on strip mine roads where weathered covering was negligible. As a result, a refraction survey was not run.

At Harewood, as at previous sites, the major objectives were to evaluate array usage, source performance, and location accuracy. Working conditions were much different in that the mine had low roofs (36 - 48"), which made many areas inaccessible for experimentation and hampered seismic.

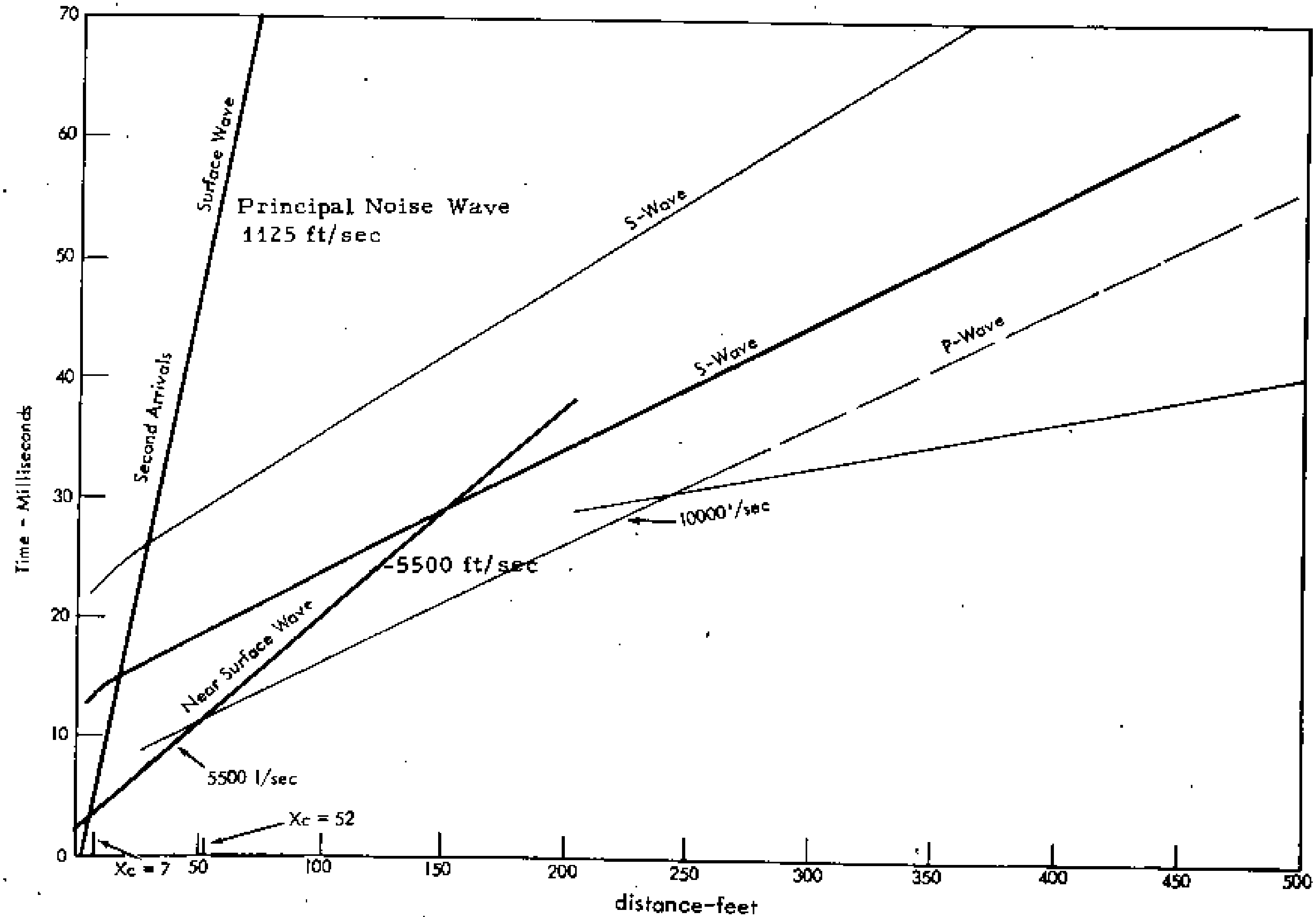


Figure 3.3-8. Clyde Mine - Seismic Waves from Refraction Survey

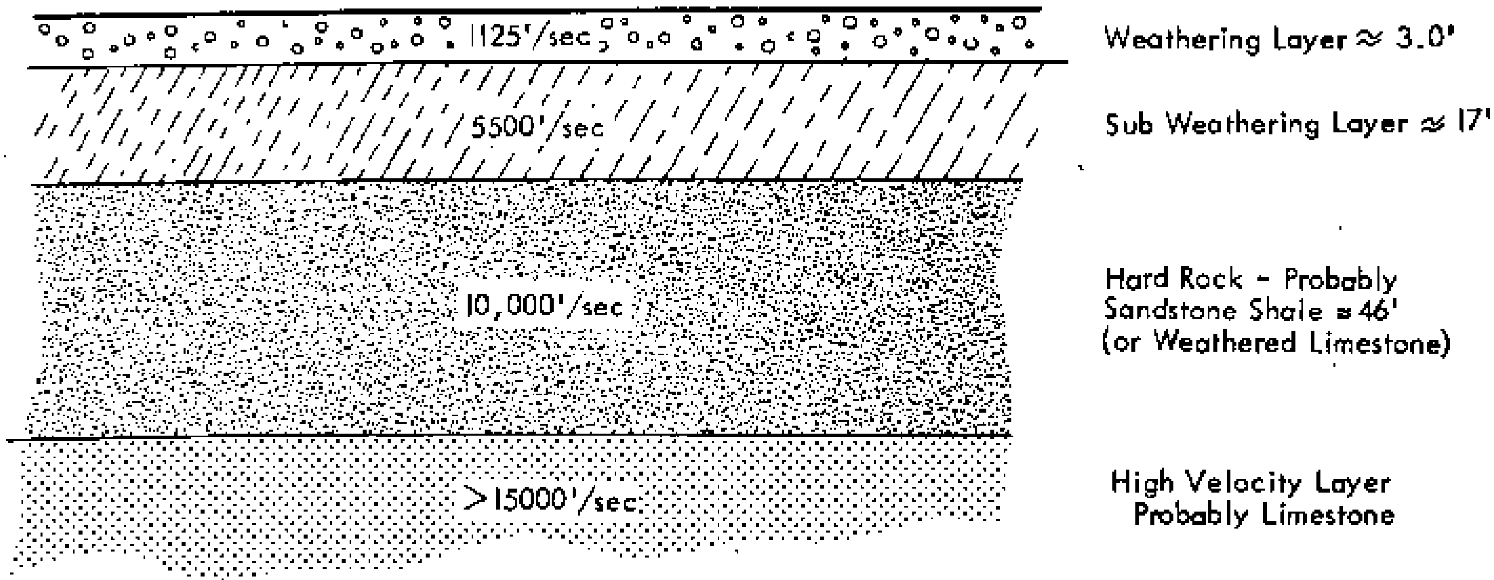


Figure 3.3-9. Interpretation of Refraction Survey - Clyde Mine

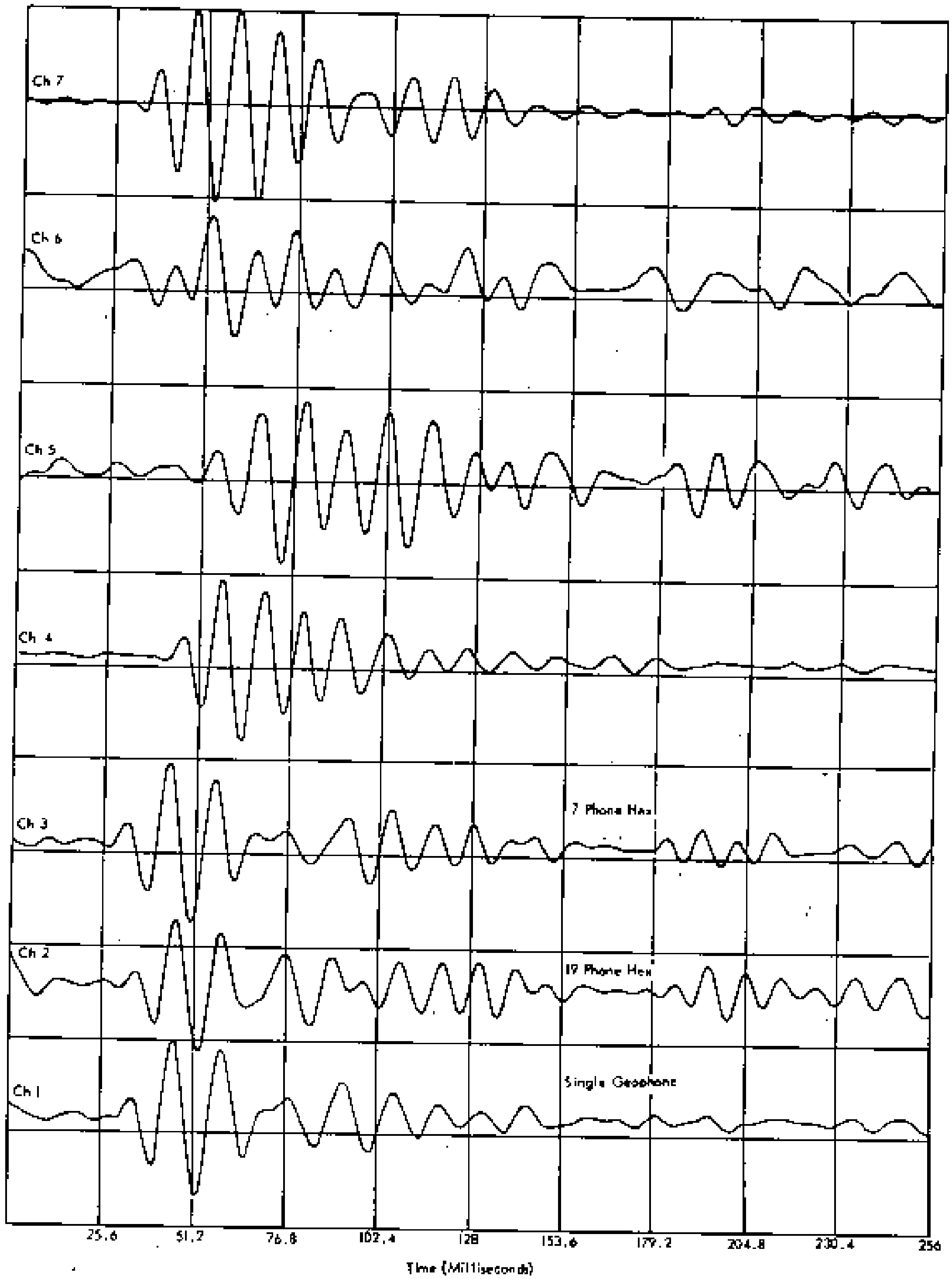


Figure 3.3-10. Clyde Mine, Miner Signals Used for Array Comparison 12/10/70

TABLE 3.3-1

SOURCE PERFORMANCE EVALUATION - CLYDE MINE

Source	Map Location	Filter Setting (bandpass) Hz	Channels with Visible Signal	Channels without Visible Sig.
		First Array Locations		
Empty car	1-1	100-400		All
Rail	1-1	150-150	4, 5, 7	1, 2, 3, 6
Roof Bolt	1-1	100-400	2, 3, 4, 5, 7	1, 6
Rail	1-1	100-400		All
Roof Bolt	2-1	100-400	7	1, 2, 3, 4, 5, 6
Rail	2-1	100-400		All
Elevator	4-1	100-400		All
Roof Beam	6-1	400-1000		All
Timber on wall	6-1	400-1000	4	1, 2, 3, 5, 6, 7
Roof Bolt	7-1	100-400	2, 3, 4, 5	1, 6, 7
		Second Array Locations		
Seismic transmitter	1-2	75-125	1, 2, 3, 5, 7	4, 6
Roof Bolt	1-2	75-125	1, 2, 3, 5	4, 6, 7
Rail	1-2	75-125	2, 7	1, 3, 4, 5, 6
Empty car	2-2	75-125		All
Roof Bolt	2-2	75-125	1, 2, 3, 4, 5	6, 7
Rail	2-2	75-125	3, 7	1, 2, 4, 5, 6
Conveyor housing	3-2	75-125		All
Roof Beam	3-2	75-125		All
Wall with timber	3-2	75-125		All
Roof Bolt	4-2	75-125	1, 2, 3, 4, 5, 6	7

Visible Signals are those visible on the monitor record prior to signal averaging. In nearly all cases signals could be detected using the signal averaging technique.

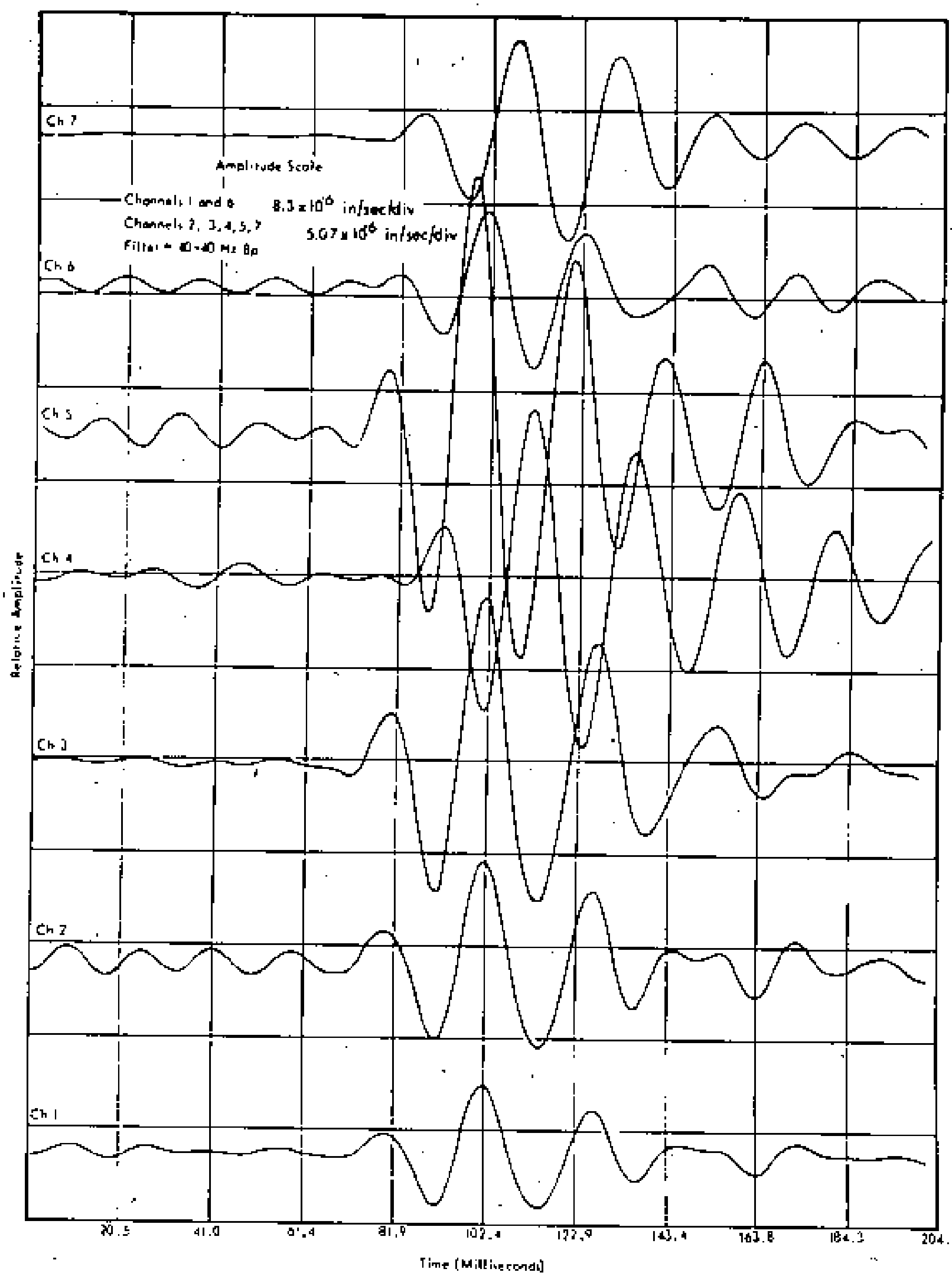


Figure 3.3-11. Clyde Mine, Miner Signals Used for Locations 12/12/70

signalling efforts. Figure 3.3-12 shows the geophone and source locations at the Harewood Mine.

The results from array comparisons were similar to those obtained at the Clyde Mine, i.e., the increase from seven to nineteen elements showed little improvement in signal-to-noise ratio.

Table 3.3-2 is a compilation of source performance results obtained at the Harewood Mine. A spectrum of a hammer blow indicated that the signal response was much the same as that in the earlier Colorado tests; however, the presence of other mine noises was more noticeable in this area. The spectrum is shown in Figure 3.3-13.

TABLE 3.3-2

SOURCE PERFORMANCE AT HAREWOOD MINE

Source	Map Location	Filter Setting (bandpass) Hz	Channels with Visible Signal	Channels without Visible Sig.
Seismic transmitter	1-2	50-500	1,2,3,4,5	6,7
Rail	1-2	50-500	2,3	1,4,5,6,7
Roof	1-2	50-200		All
Timber on roof	1-2	50-200		All
Roof Bolt	2-2	50-100		All
Rail	2-2	50-100		All
Full Car	3-2	50-100		All
Roof	4-2	35-75	3,4	1,2,5,6,7
Full Car	4-2	35-75	3,4	1,2,5,6,7
Roof	5-2	35-75	1,2,4	3,5,6,7
Floor	5-2	35-75	1,2,4,5	3,6,7
Wall	5-2	35-75	1,2,5	3,4,6,7

Visible Signals are those visible on the monitor record prior to signal averaging. In nearly all cases signals could be detected using the signal averaging technique.

The most important conclusion is that in this case, the effectiveness of the system was severely limited. There was no data suitable for location trials obtained at the first site evaluated. After signal averaging the data, signals became detectable only to the extent that their presence could be noted. Peak-to-peak velocities were on the order of 2×10^{-6} cm/sec, which is slightly above seismic noise levels. The probable reasons for the inability to sense seismic events at the first location were: 1) the travel paths from source to receivers were long, the shortest was 850 feet and the longest was 1900 feet, 2) the existence of two mined-out seams directly above the source points probable caused some energy loss (see Figure 3.3-12), 3) the strip mine road on which the geophones were planted was probably fractured due to the large explosions involved in the strip mining operation. If this were the case, then frictional energy losses existed here, too. Figure 3.3-14 shows the results from the first series of tests at Harewood Mine.

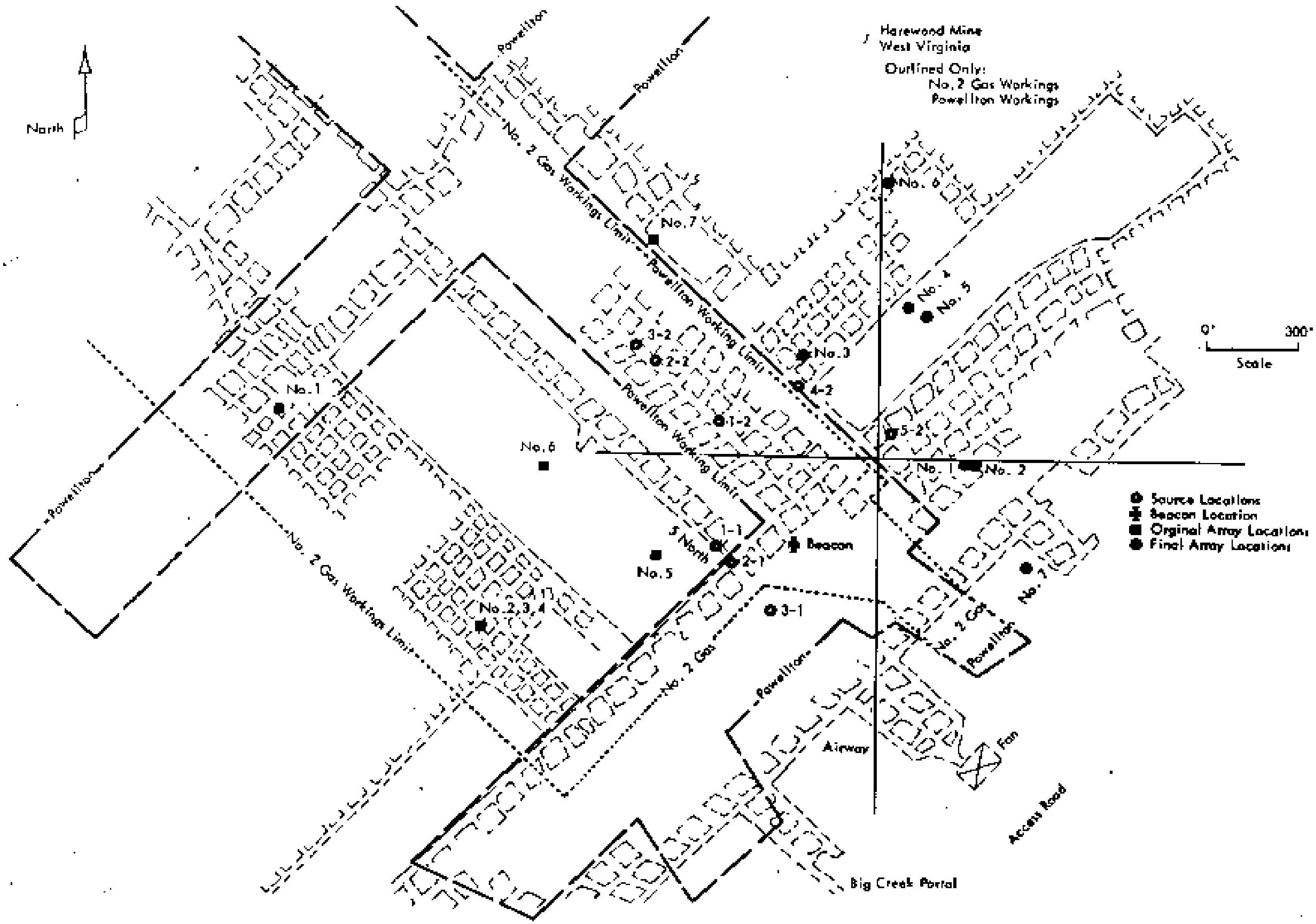


Figure 3.3-12. Harewood Mine Array and Source Locations

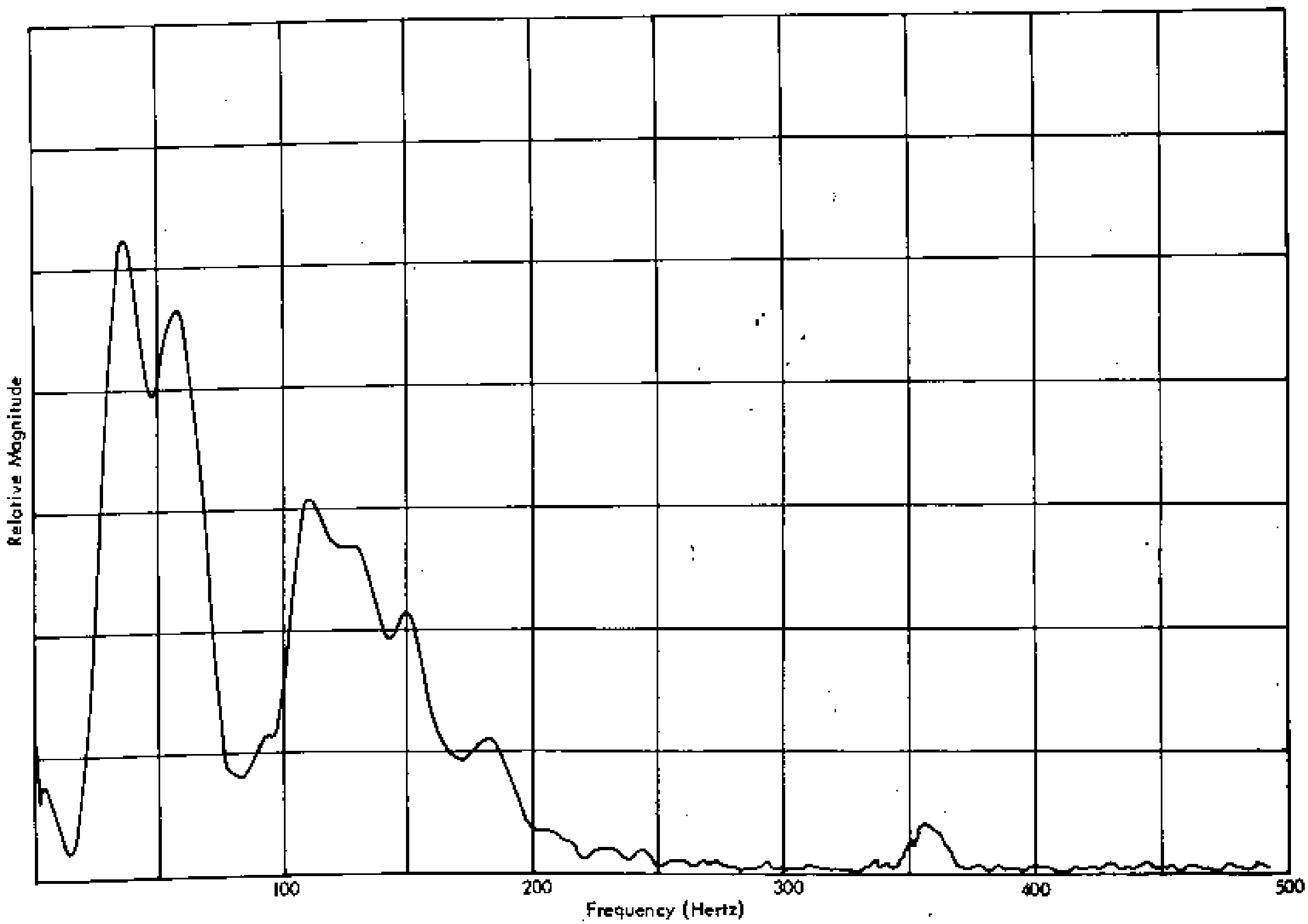


Figure 3.3-13. Harewood Mine - Spectrum of Hammer Blow 12/19/70

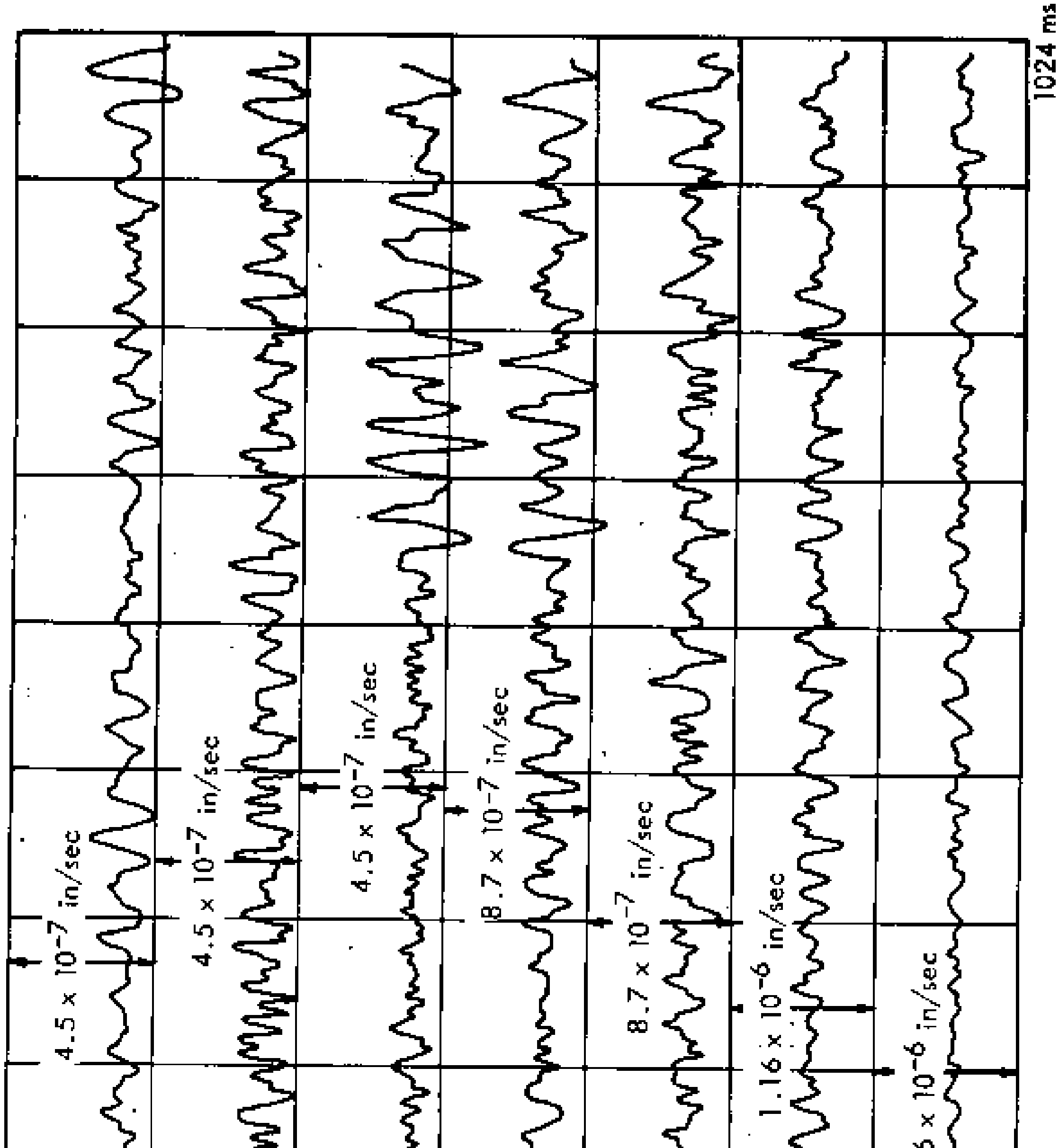


Figure 3.3-14. Results from 1st Set-Up at Harewood Mine 12/20/70

The second location for tests at the Harewood Mine proved more successful. Here again, the arrays were deployed for accessibility reasons on a strip mine road or on the hillside above the road. However, the thickness of overburden was less, ranging to about 300 feet.

The source location was calculated using signals shown in 3.3-15. Since time did not allow an accurate survey the sensor positions were determined with Brunton and chain. Results, although they did not coincide with the actual source location, did group together similar to data from other mines. No location accuracy number was obtained because of the lack of survey tie points to the subsurface.

3.4 DEMONSTRATION TESTS

The testing of the Seismic Location System under simulated disaster conditions can be described in two phases: the Game Plan Phase extending from the initial alert on January 16 to 3:00 AM on January 18 and the Test or Demonstration Phase which followed. The latter produced the most useful data, although the former did accentuate many of the problems involved in use of the Seismic Location System in a large scale rescue operation.

3.4.1 Phase I - Chronology

Equipment Deployment - Movement of the Communications Subsystem equipments from the staging area in Charleston, West Virginia, to the U.S. Steel Mine #14, near Gary, West Virginia, was begun about 2:20 PM on 16 January when the Rescue Director directed the Communications Subsystem van to proceed to the mine site. This van arrived on site at 7:50 PM on the same day.

The first group from WGL arrived at the demonstration test site at about 1:00 AM January 17, and reported immediately to the Rescue Director for a briefing on the disaster situation and the actions taken by the rescue crews.

WGL personnel examined the mine workings map showing the location of the rock falls blocking tunnels, the beacon transmitter, and where the miners were presumed to be trapped. A topographic overlay was compared with the mine workings map to determine possible locations for the surface components of the Communications/Location Subsystem. The desired location was approximately over the beacon on a strip mining shelf road near the 2800 foot contour. (See Figure 2.4-3.)

The Communications/Location System equipment van had already been parked on the strip mining road at a point about one-half mile from the desired location. WGL requested the communications van be moved to the desired location as soon as the road could be made passable and a tractor found.

Installation of geophones began by midmorning of January 17. All of the geophone arrays were installed by the time the communications van was moved to the new location. This initial installation covered the entire possible area of entrapment, since the Rescue Director had indicated there were no regions within this broad area which were more probable areas of entrapment. U.S. Steel miners as well as Bureau of Mines and Westinghouse personnel assisted in the deployment of these geophone subarrays.

At 6:40 PM seismic testing began using the seismic thumper located with the beacon transmitter in the mine. Signals from the thumper were received and recorded on the geophone receiving equipment. The reception of these signals indicated that equipment was working satisfactorily and that reception of miners' signals should not be impossible. These signals were of

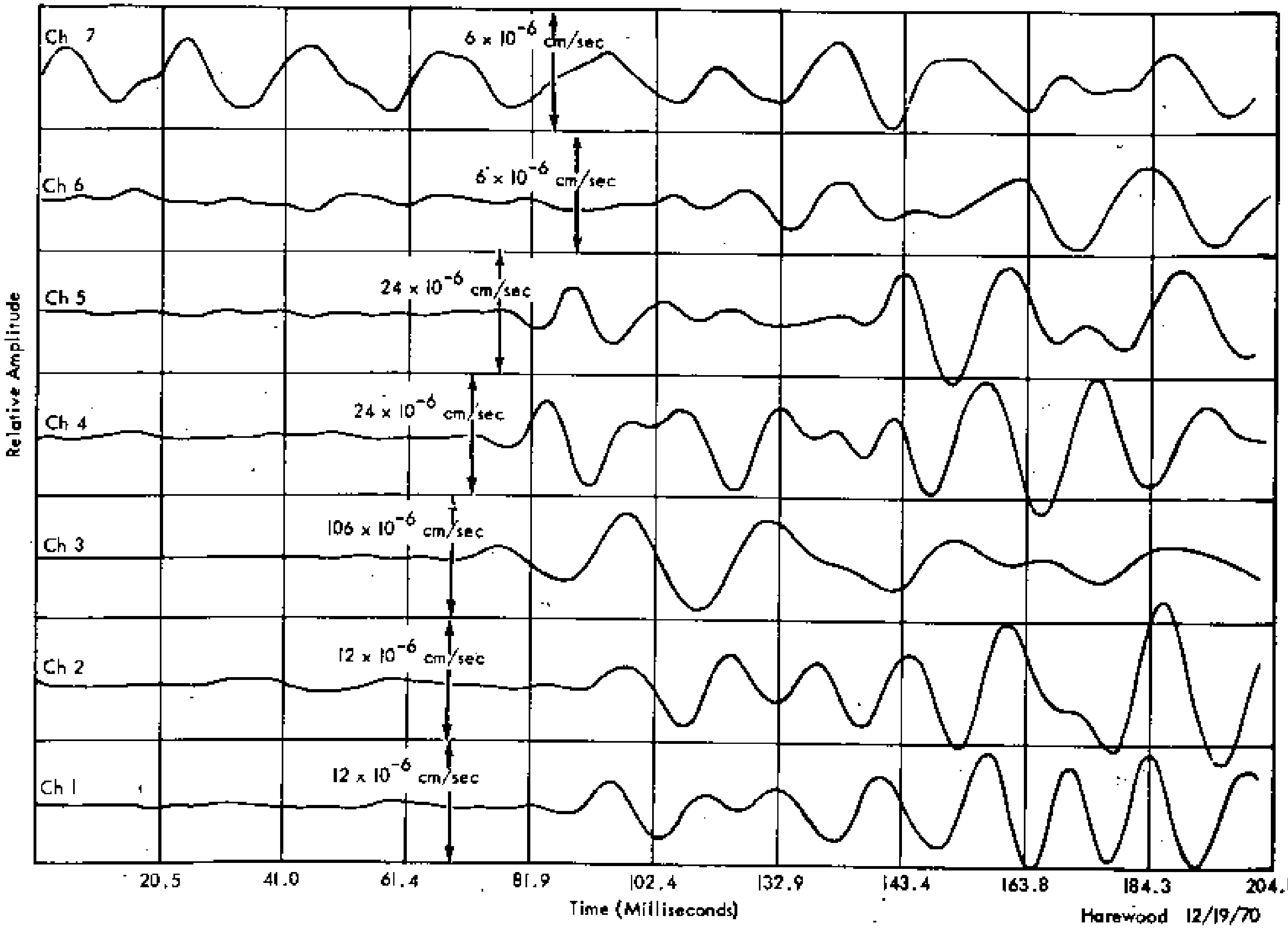


Figure 3.3-15. Harewood Mine - Miner Signals Used for Locations

minimal strength and could not be used to determine the location of the point of emanation. However, three geophone arrays did provide signals of usable strengths. At approximately 3:00 AM, January 18, the game plan was changed to use the mine map and survey data to determine where the probe drill should be located. The trapped miners' location was revealed and four subarrays were moved to closer points over that area. This was accomplished by 8:00 PM, January 18, and signals from the miners as well as the seismic thumper were received. After receipt of the geophone survey early January 20, calculations locating the thumper and miner signals were completed.

Several interruptions occurred as the result of cables being broken by vehicular traffic, the failure of the ground survey team to provide a survey of geophone locations on a timely basis, and the lack of manpower to quickly redeploy geophones as needed were contributing factors in the decision to proceed with the drilling operation without waiting for results of the seismic location process.

Since the decision to deploy the drilling rigs meant the use of heavy equipment and traffic in the vicinity of arrays, seismic testing was conducted only at those times when the Rescue Director arranged silent periods. The sporadic spacing of these periods throughout the following two weeks provided time for data and location analysis. This data is discussed in the following sections.

3.4.2 Engineering Tests

Tests were performed to evaluate three basic aspects of the system which affect performance. These are (1) Site Characterization, (2) Seismic Transmitter Detection and Location, (3) Source Evaluation. The tests provided an opportunity to evaluate a phase of the Seismic Location System and to define areas requiring investigation.

3.4.2.1 Site Characterization

Due to the rugged terrain and the similarity of the site to others encountered during predemonstration testing, it was deemed unnecessary to run a refraction survey. The required geophysical parameters were estimated.

The first parameter determined was seismic velocity. Using a geophone lowered down the 8-1/2" probe hole as a time break, it was possible to determine absolute travel times and thus calculate the velocity to each array. Table 3.4-1 contains the velocity measurements for each array. Vertical velocity was determined during drill string location tests. The average total velocity computed after location of the source is very close to what was estimated for location calculations. Overall velocities are slower than would be expected for the rocks of this coal region. A possible explanation is that the time picked on the averaged records is relative to a shear wave event and not a faster traveling compressional wave, which is probably attenuated as a result of long travel paths.

The second geophysical parameter measured was the attenuation. Attenuation was determined from comparisons between the signal received from the downhole geophone and surface measurements. Actual particle velocity from each array and for the downhole geophone are shown in Table 3.4-2. Table 3.4-3 shows the comparison of measured and predicted attenuation. The attenuation for the predicted response was determined using the Multiple

TABLE 3.4-1

Array Number	Vertical Velocity	Horizontal Velocity	Total Velocity
1	7595 ft/sec	8482 ft/sec	8119 ft/sec
2	7595 ft/sec	7992 ft/sec	7784 ft/sec
3	7595 ft/sec	8103 ft/sec	7649 ft/sec
5	7595 ft/sec	9910 ft/sec	8775 ft/sec
6	7595 ft/sec	7962 ft/sec	7750 ft/sec
7	7595 ft/sec	6995 ft/sec	7448 ft/sec

These velocities average as shown below:

Average Total Velocity = 7920 ft/sec
Average Horizontal Velocity = 8241 ft/sec
Average Vertical Velocity = 7595 ft/sec

TABLE 3.4-2

PARTICLE VELOCITY

Array	Peak to Peak
1	3.1×10^{-5} in/sec
2	2.8×10^{-5} in/sec
5	6.25×10^{-5} in/sec
6	2.96×10^{-5} in/sec
7	5.69×10^{-5} in/sec
Downhole Phone	8.4×10^{-2} in/sec

TABLE 3.4-3

ATTENUATION COMPARISONS

Array	Length of Travel Path	Measured Attenuation	Predicted Attenuation
1	766 feet	68 dB	64 dB
2	834 feet	69 dB	65 dB
5	823 feet	62 dB	65 dB
6	771 feet	69 dB	64 dB
7	695 feet	63 dB	62 dB

Axis Tradeoff Curve, Figure D-12 in Appendix D. The attenuations are computed using an average velocity of 7900 feet/second, a source frequency of 30-50 Hz, and an average specific attenuation factor (Q) of 50.

The MATO curve in Appendix D includes losses from both spreading and attenuation. The calculated and measured values show a reasonable correlation. The difference is due to the uncertainties involved in trying to compute attenuation from an average model.

The geological cross-section in the area is shown in Figure 3.4-1 from information from two U.S. Steel diamond drill holes. The locations of the diamond drill holes are shown on the rescue site map (Figure 2.4-3). The cross-section shows that the geology is relatively uncomplicated with gradual regional dip to the south and the associated thickening of beds in the basinward direction.

3.4.2.2 Seismic Transmitter Signal Detection — Lost Miner Location

Signal detection at the demonstration proved to be difficult. In most of the early attempts at seismic signalling, detectable signals could be seen on only one or two channels. After the geophone arrays were redeployed to an area more directly over the barricade location, signals became visible on all channels. With the establishment of a triggering signal via the EM Beacon, detection was enhanced by signal averaging.

The signals shown in Figure 3.4-2 were used for location of the "trapped miners." These were produced by averaging 90 pulses from the seismic transmitter (thumper) using a signal trigger (channel 7). Arrival times were picked from this data and based on an estimated 7750 feet/second velocity, locations were calculated using both 3 and 4 arrival time combinations.

The results of location trials are shown in Figure 3.4-3. The locations shown in Figure 3.4-3 can be used to evaluate the system performance in terms of location accuracy for this particular situation. If all the points shown are considered equally probable source fixes then the rms distance error is 237 feet. Using various combinations of 3 arrival time measurements and the known source depth from mine survey maps the rms distance error is 252 feet and for 4 arrival time measurements, 216 feet. When all the location points which fall outside probable areas of entrapment (outside mine working area) are eliminated, then the rms distance area is reduced to 97 feet. One method for determining a single location from the results of numerous calculations is to average the coordinates of all points which are closely concentrated together. (See Section 3.1.3.) In Figure 3.4-3, this eliminates 15 of the 34 possible answers and the averaged location is 20 feet from the actual source location.

The rms distance error has not been evaluated for other cases because averaging clusters of most likely points gives considerably better system accuracies. This selection and averaging process has not been fully developed. In general it seems reasonable to select a certain percentage of points, say 50%, which fall within the smallest possible circle and then average only their coordinates to establish a single location from all points. Techniques such as this could also be computerized, but this as yet has not been accomplished nor evaluated. The major source of error is believed to be caused by the low frequency of the processed data (30-50 Hz) which makes selection of an arrival time to with two milliseconds very difficult. Some of the scatter results from array/source geometry, which degrades accuracy with certain combinations of arrays used to calculate locations.

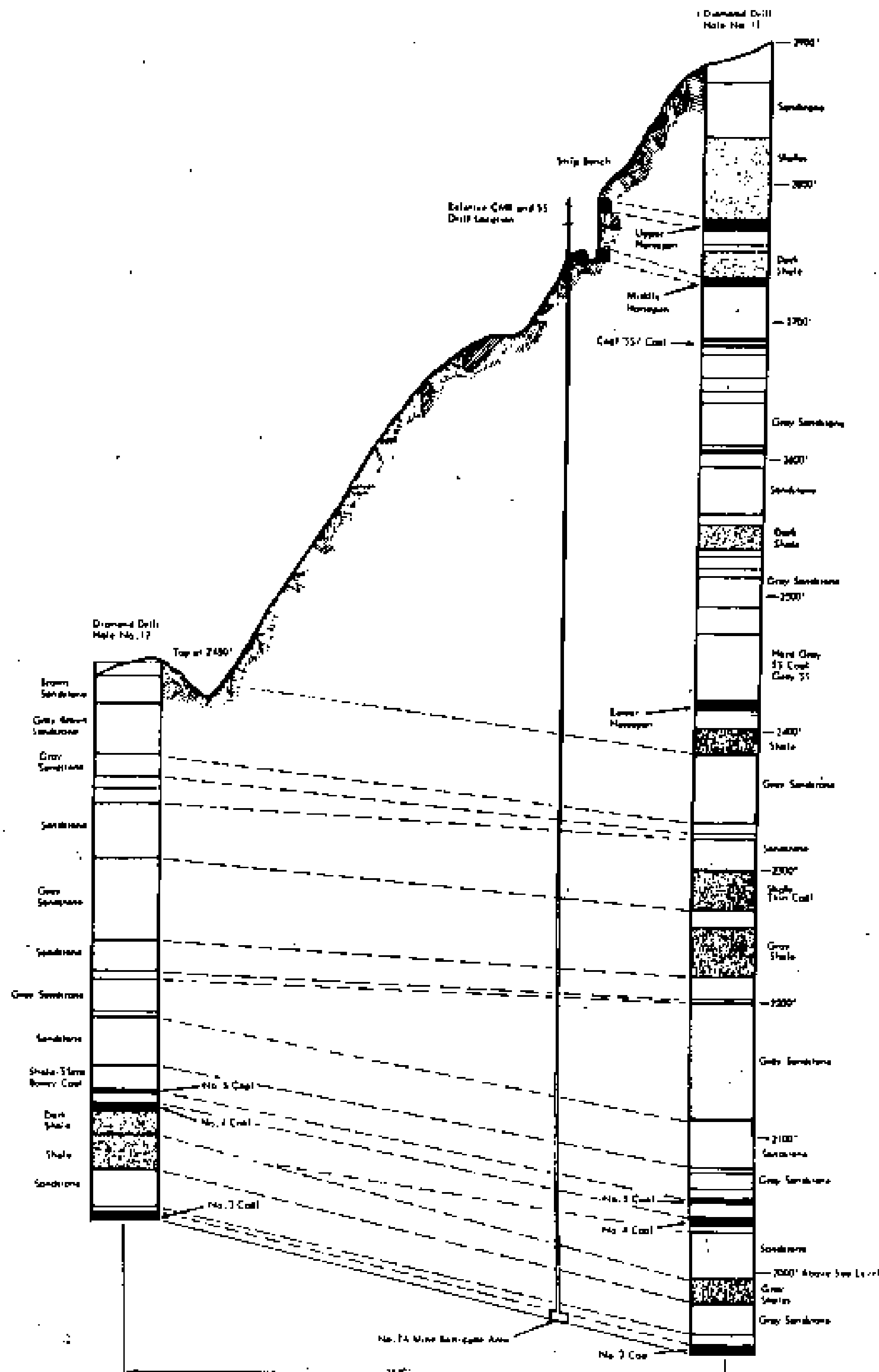


Figure 3.4-1. Geologic Cross Section No. 14 Mine Barricade Area

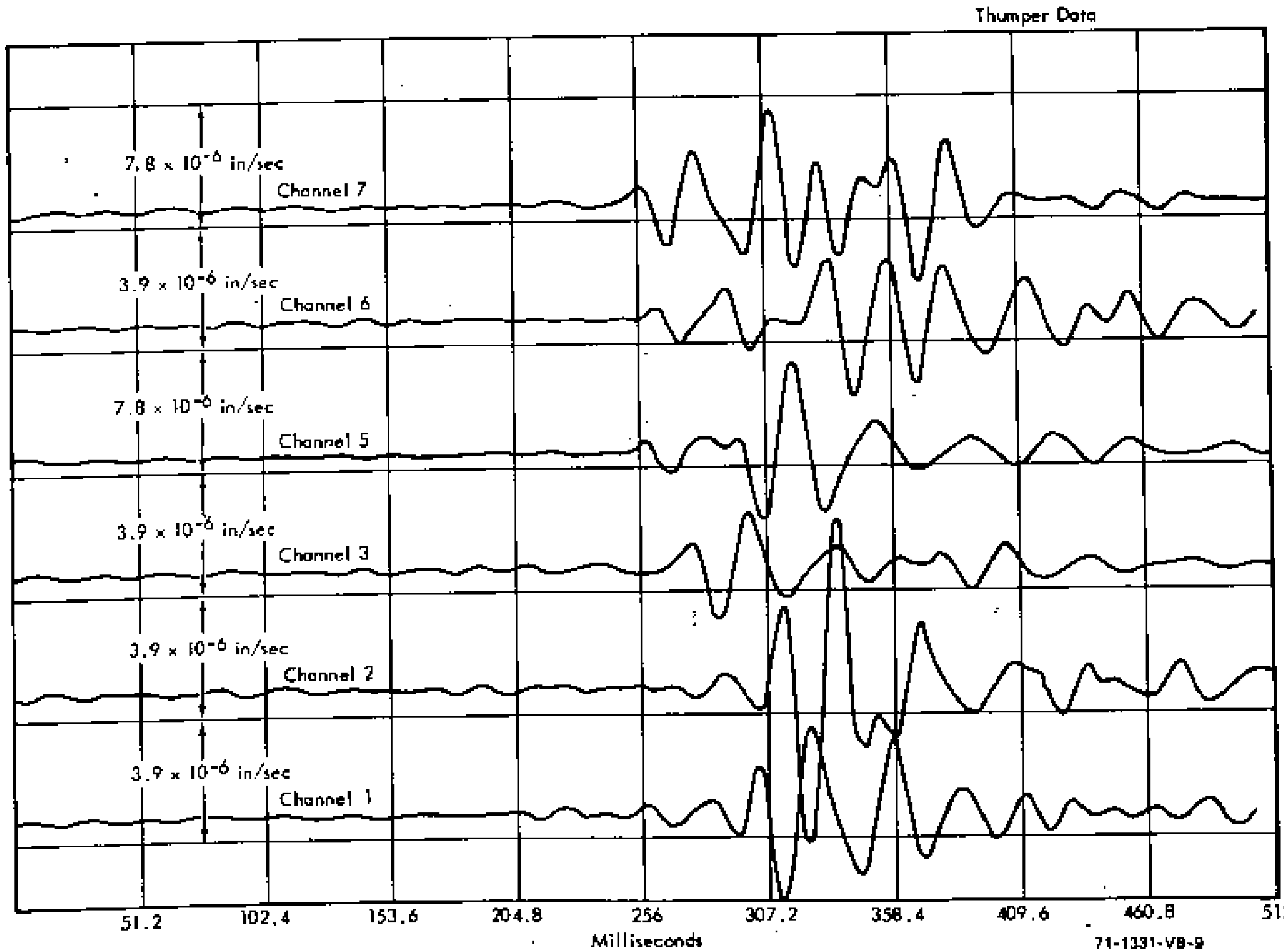


Figure 3.4-2. Signals Used for Location of Barricade Area at CMRSS Demonstration

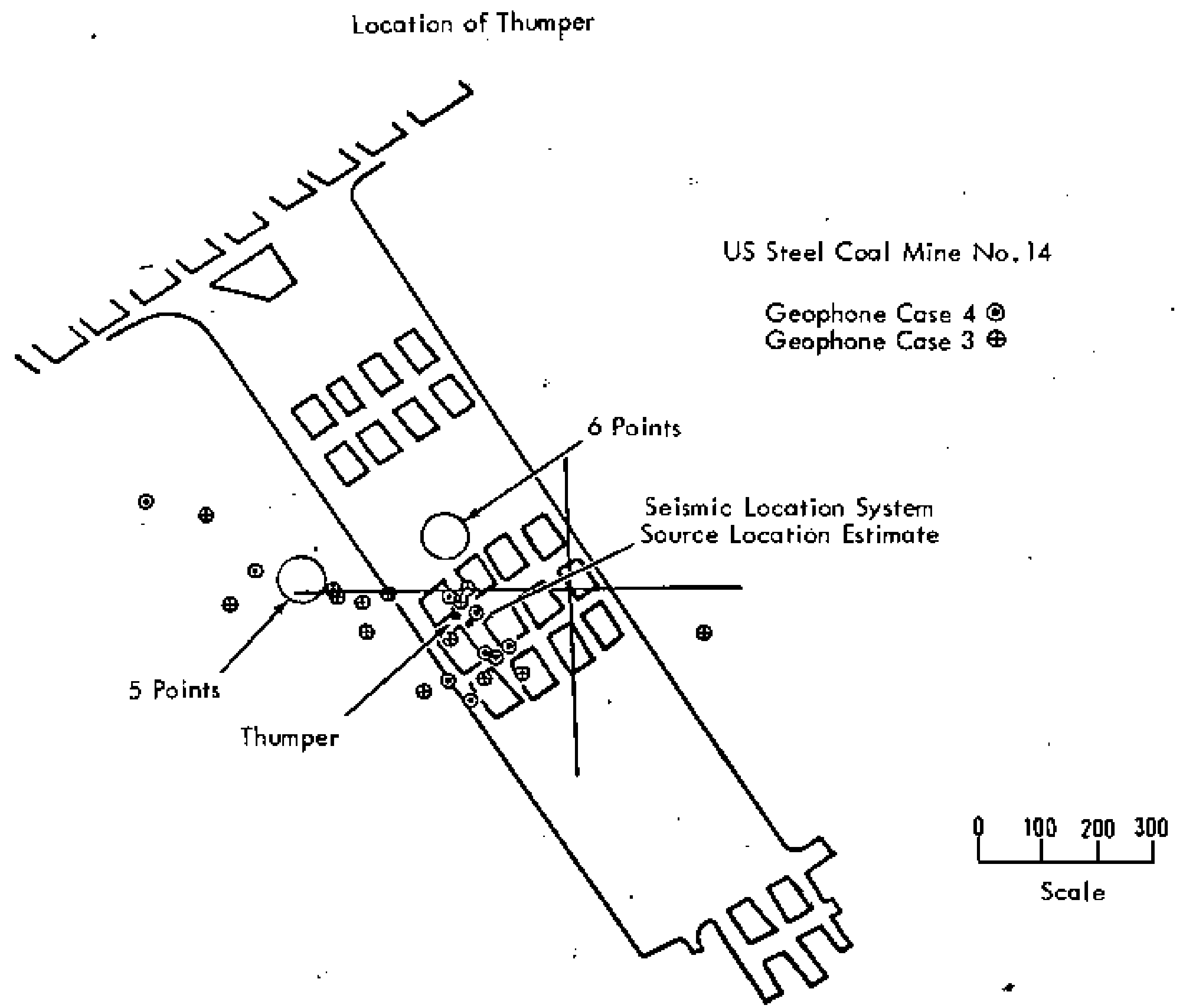


Figure 3.4-3. Location Calculations Using Seismic Transmitter and Signal Averaging

3.4.2.3 Source Evaluations

Extensive tests were conducted to evaluate various types of seismic sources. The performance of the sources in terms of generating detectable signals is summarized in Table 3.4-4. Locations were computed for several of these sources. In all cases except those using the seismic transmitter as a source, it was necessary to use a trigger signal from the beacon seismic uplink signal or from a downhole geophone for signal processing. In cases where the same data is presented twice, locations were calculated on different arrival time picks in each case. Locations were calculated and are shown for the following sources:

Source	Figure Number
Timber on plate	3.4-4
Timber on roof	3.4-5, 3.4-6
Seismic Transmitter	3.4-7
Seismic Transmitter	3.4-8
Sledge Hammer on Roof	3.4-9, 3.4-10
Rail on plate	3.4-11
Rail on plate	3.4-12, 3.4-13

The data used for calculating the locations shown includes only that where some points tended to cluster. Other location calculations were made using data with much smaller signal-to-noise ratios. These showed no patterns or groupings. Here, as before, the most probable source of error is the inability to select arrival times to an accuracy of one millisecond.

3.4.3 Summary of System Performance

The performance of the Seismic Location System during the Demonstration Tests can be evaluated from two viewpoints. From the viewpoint of rescue operations, the results from Seismic Location were very slow. This result was affected not only by system performance, but to a large degree by the logistics that must necessarily accompany a location and rescue attempt. Such factors as surveying, geophone redeployment, terrain, and weather tended to impede location efforts.

From the viewpoint of an engineering exercise, the Seismic Location System performance was a success. The concept of signal averaging as a signal-to-noise enhancement technique proved to be an important factor in determining the location of the "lost miners." An example is Figure 3.4-14. This is a monitor record made during source evaluation tests. Observing the six data channels, there are no obvious signals that could be assumed man-made. However, using the Beacon Uplink Signal (track 4) as a signal trigger and averaging the fifty pulses, the result is Figure 3.4-9. Signal-to-noise improvement here was sufficient to run a location analysis, the results of which are shown in 3.4-10.

This example indicates the performance achievable even where the signals do not appear to exist on the monitor record. Other sources often produced better signal-to-noise ratios but gave poorer location accuracies. The performance of the Seismic System as evaluated from all phases of work will be discussed in Paragraph 3.5.

TABLE 3.4-4

SOURCE PERFORMANCE EVALUATION - DEMONSTRATION

Test No.	Source	Filter Setting (bandpass) Hz	Channels with Visible Signal	Channels without Visible Signal
1	Seismic Transmitter	30-70	6	1, 2, 3, 4, 5, 7
2	Seismic Transmitter	40-40	6	1, 2, 3, 4, 5, 7
3	Seismic Transmitter (3 weights)	40-40		All
4	Sledge on plate	40-40		All
5	Seismic Transmitter (5 weights)	40-40	6	1, 2, 3, 4, 5, 7
6	Pick on plate	40-40		All
7	Pick on floor	40-40		All
8	Wall w/sledge	40-40		All
9	Wall w/pick	40-40		All
10	Seismic Transmitter	40-40	5, 6	1, 2, 3, 4, 7
11	Sledge on plate	40-40		All
12	Roof bolt	40-40	6, 7	1, 2, 3, 4, 5
13	Pick on ceiling	40-70		All
14	Pick on roof	40-70		All
15	Hammer on wall	40-70		All
16	Pick on wall	40-70		All
17	Roof bolt	40-70		All
18	Seismic Transmitter	30-80	2, 5, 7	1, 3, 4, 6
19	Rail	30-80		All
20	Wooden post	30-80		All
21	Steel between rails	50-80		All
22	Water pipe	50-80		All
*23	Seismic Transmitter†	20-50	1, 2, 4, 5, 6, 7	3
24	Rail on plate†	20-50	1, 2, 4, 5, 7	3, 6
25	Timber on plate†	20-50	1, 4, 5, 6, 7	2, 3
26	Rail on plate†	20-50	1, 2, 3, 4, 5, 7	6
27	Timber on roof†	20-50	1, 2, 4, 5, 6, 7	3
28	Rail on roof bolt	20-50	1, 2, 4, 5, 6, 7	3
29	Timber on roof bolt	20-50	5, 7	1, 2, 3, 4, 6
30	Hammer on plate†	20-50		All
31	Seismic Transmitter	30-120	1, 2, 4, 5, 6, 7	3
32	Pick on plate	30-120		All
33	Sledge on plate	30-120		All
34	Rail on plate	30-120		All
35	2-man rail on plate	30-120	6	1, 2, 3, 4, 5, 7
36	Rail on plate	30-120	1, 6, 4	2, 3, 5, 7
37	Short rail on plate	30-120		All

Tests 1-9, Beacon Location; Tests 10-31, Barricade Location; Tests 31-37, Prepared plate 100' N.W. of Beacon Location.

*Used for Lost Miner Location   †Location Analysis Performed.

NOTE: Visible Signals Refers to Signals Detectable Without Signal Processing.

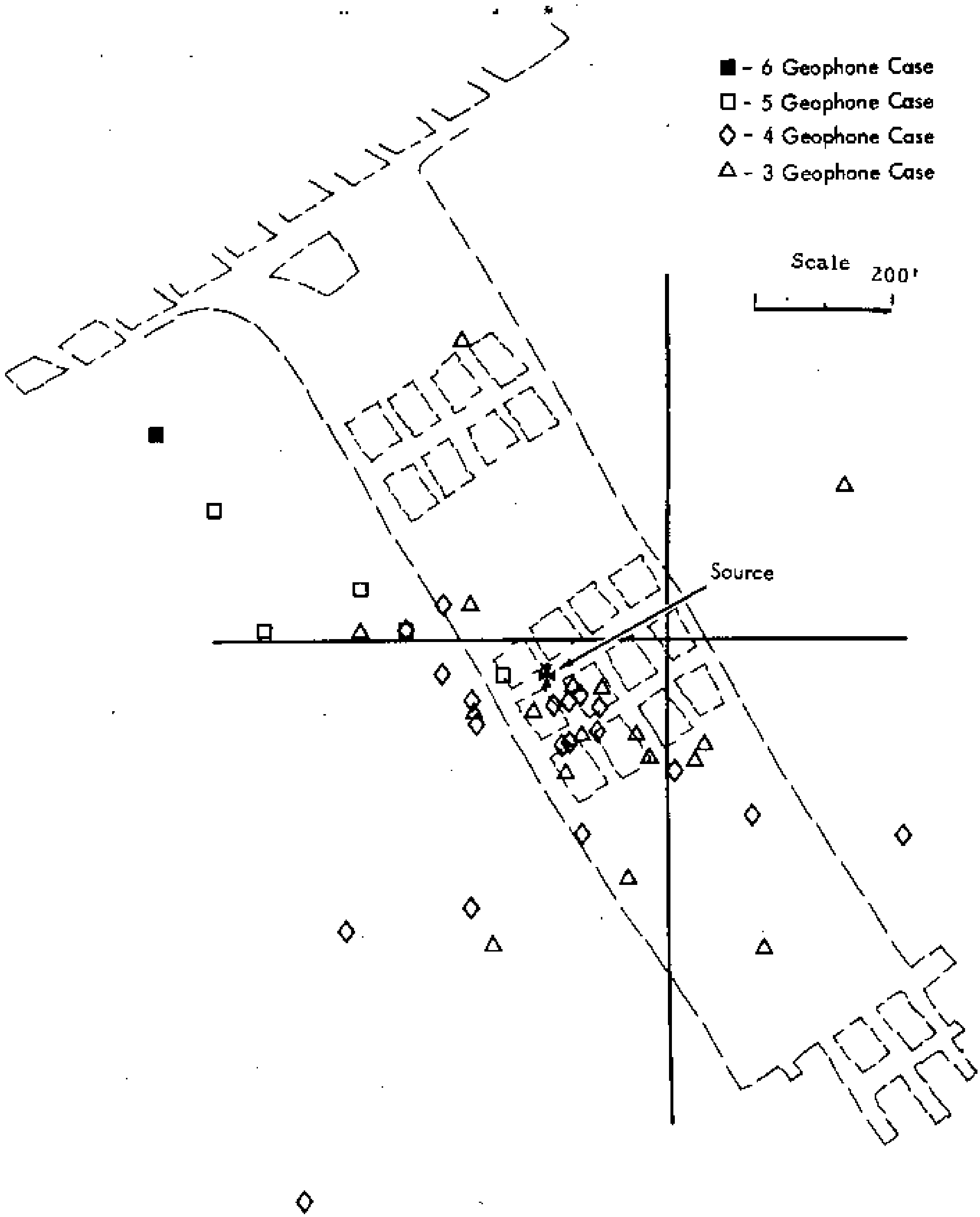


Figure 3.4-4. Gary No. 14 Mine - Location Accuracies - Timber on Plate - Test 25

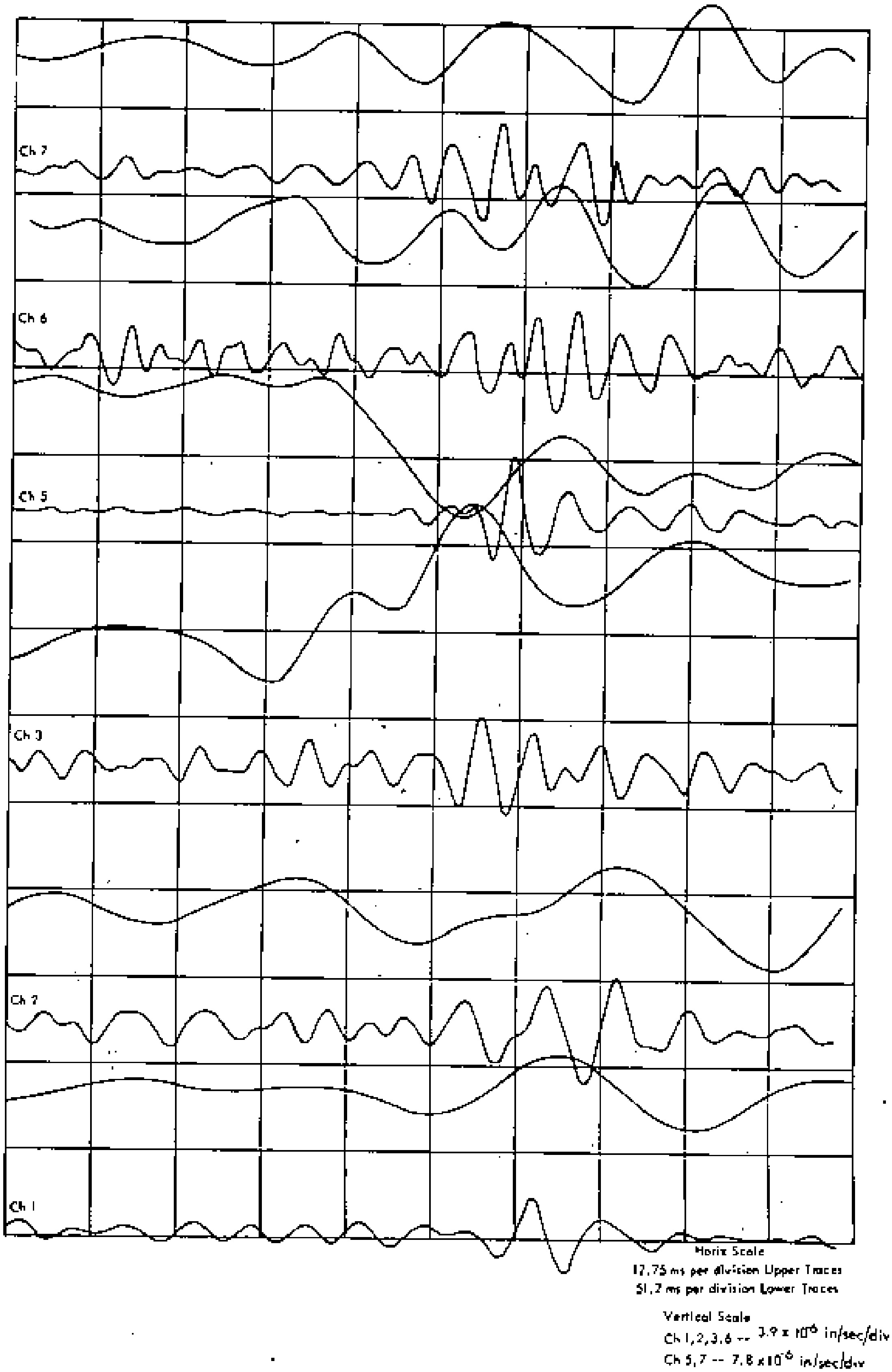


Figure 3.4-5. Gary No. 14 Mine Signals From Timber on Roof
Test 27 - 1/20/71

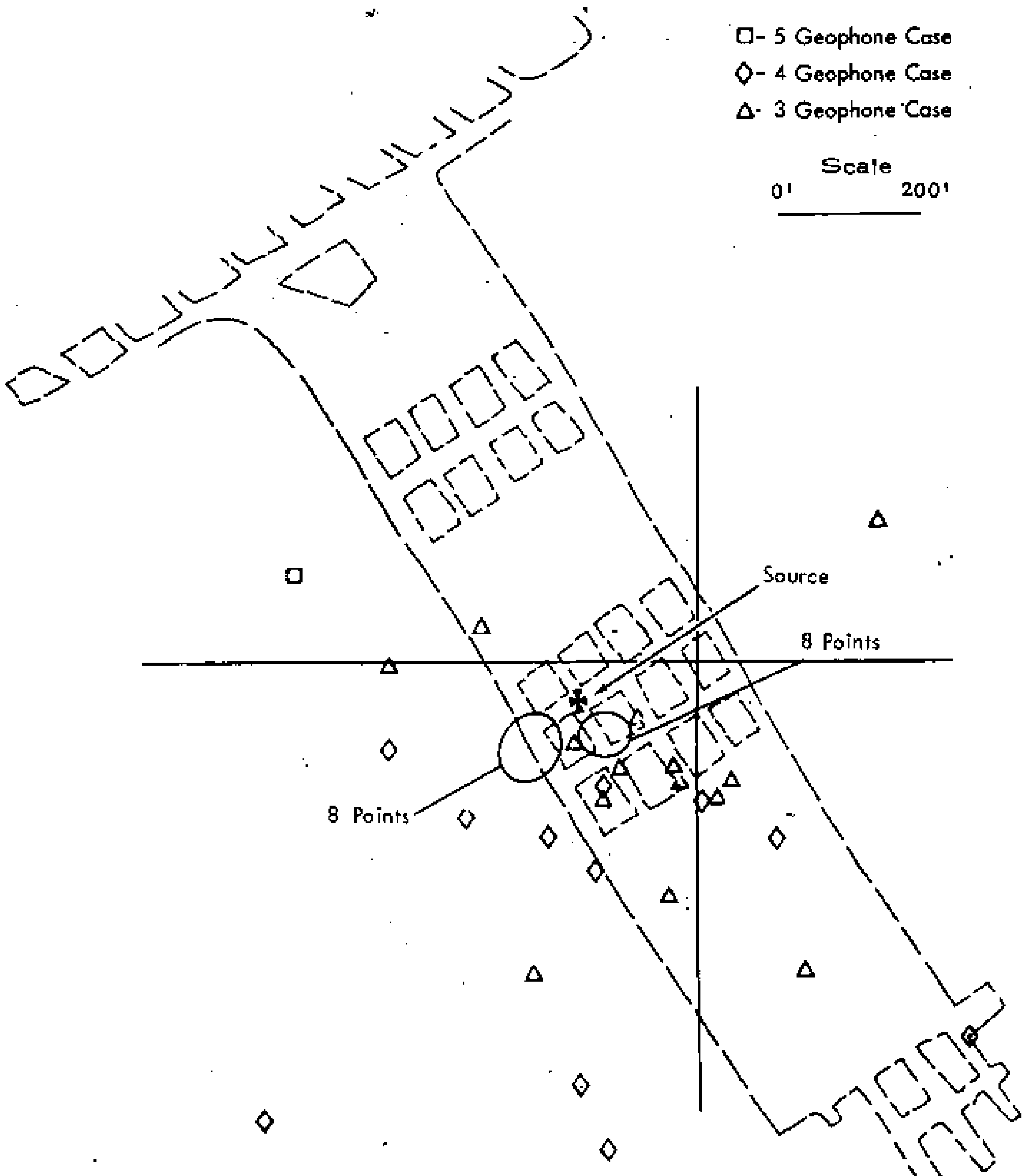


Figure 3.4-6. Location Calculations - Test 27 - Timber on Roof

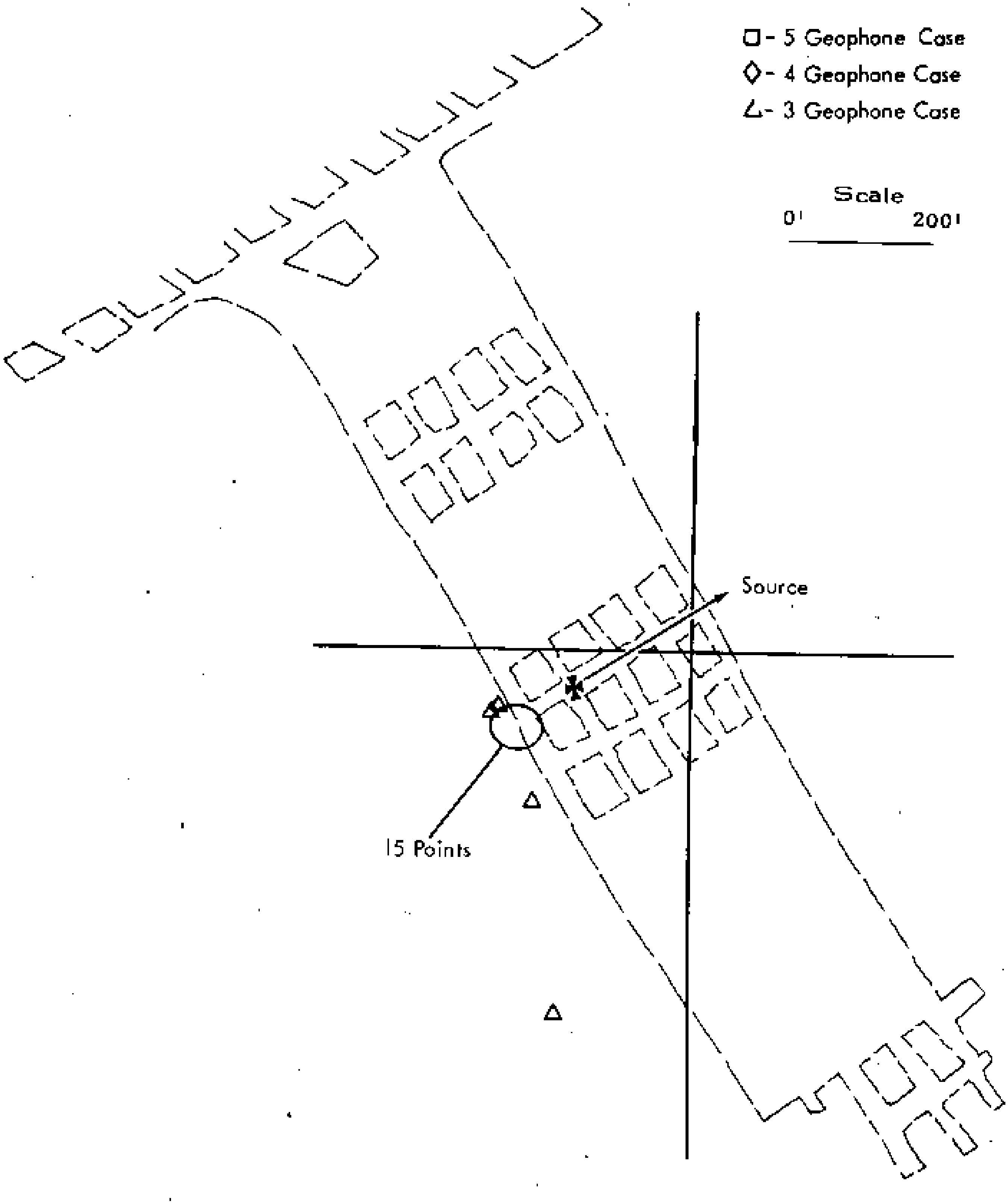


Figure 3.4-7. Gary No. 14 Mine - Location Calculations - Test 23 - A Seismic Transmitter

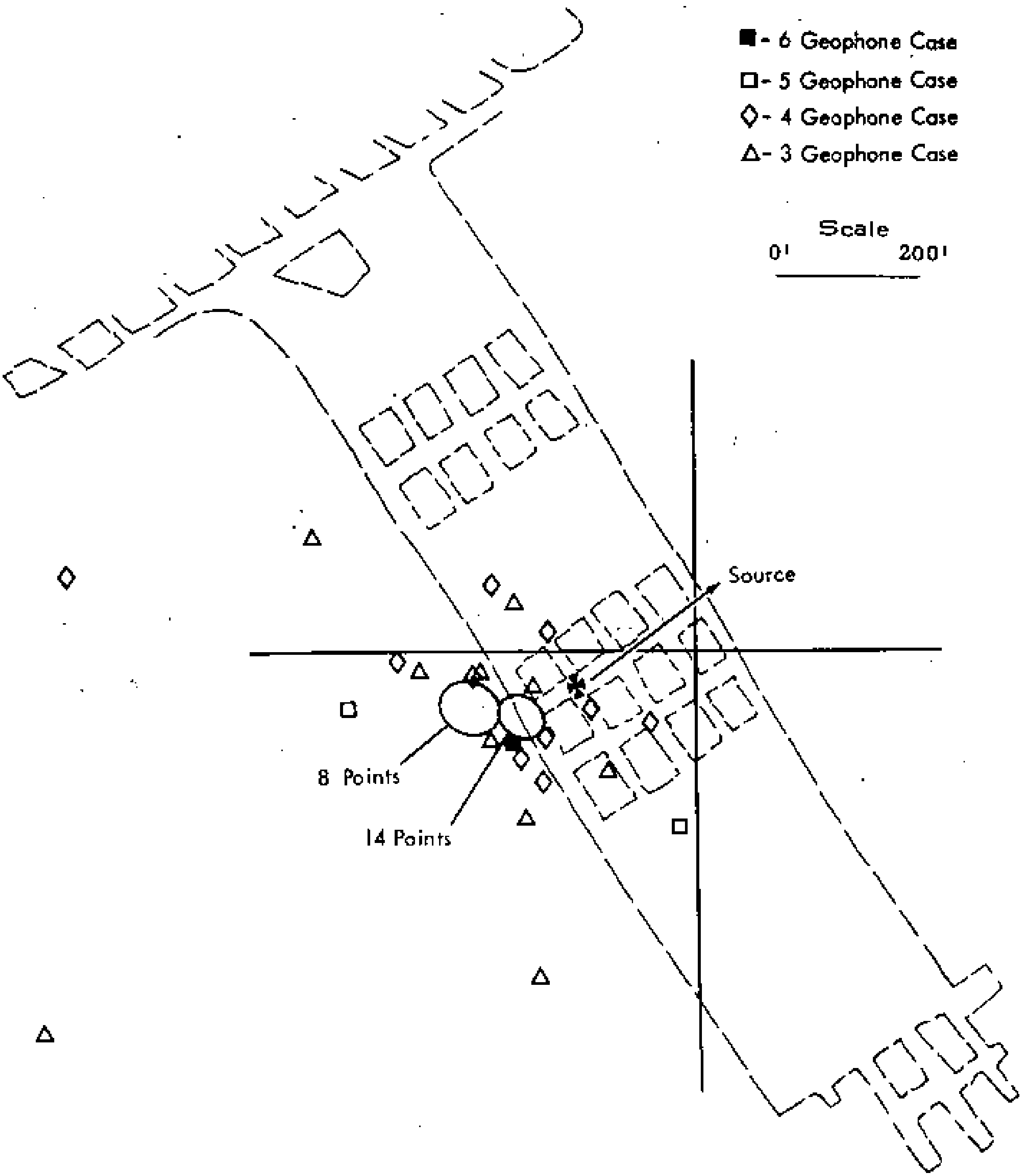


Figure 3.4-8. Gary No. 14 Mine - Location Calculations - Test 23 - Seismic Transmitter

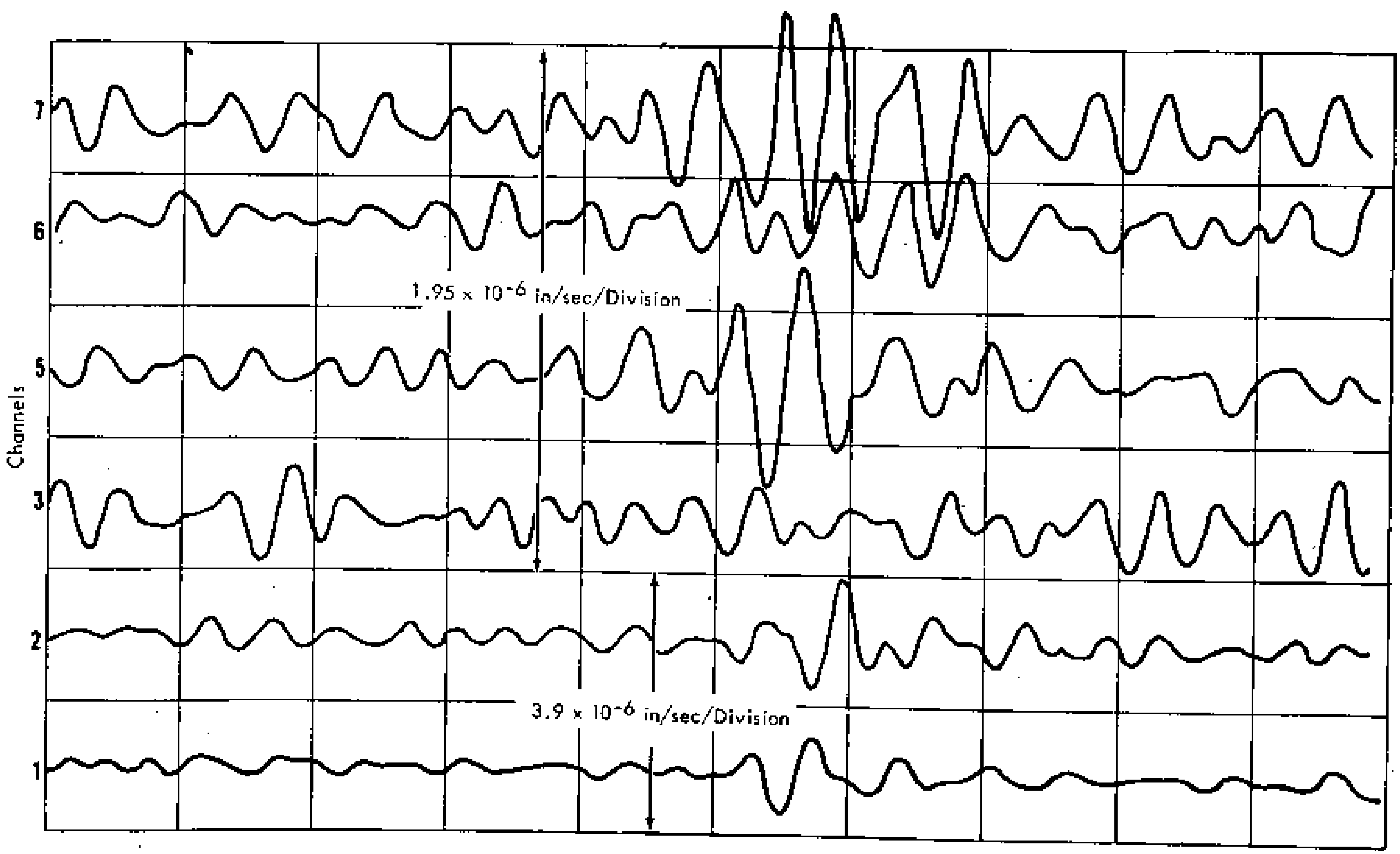


Figure 3.4-9. Gary No. 14 Mine Signals - Test 30 - from 10 lb Sledge on Floor

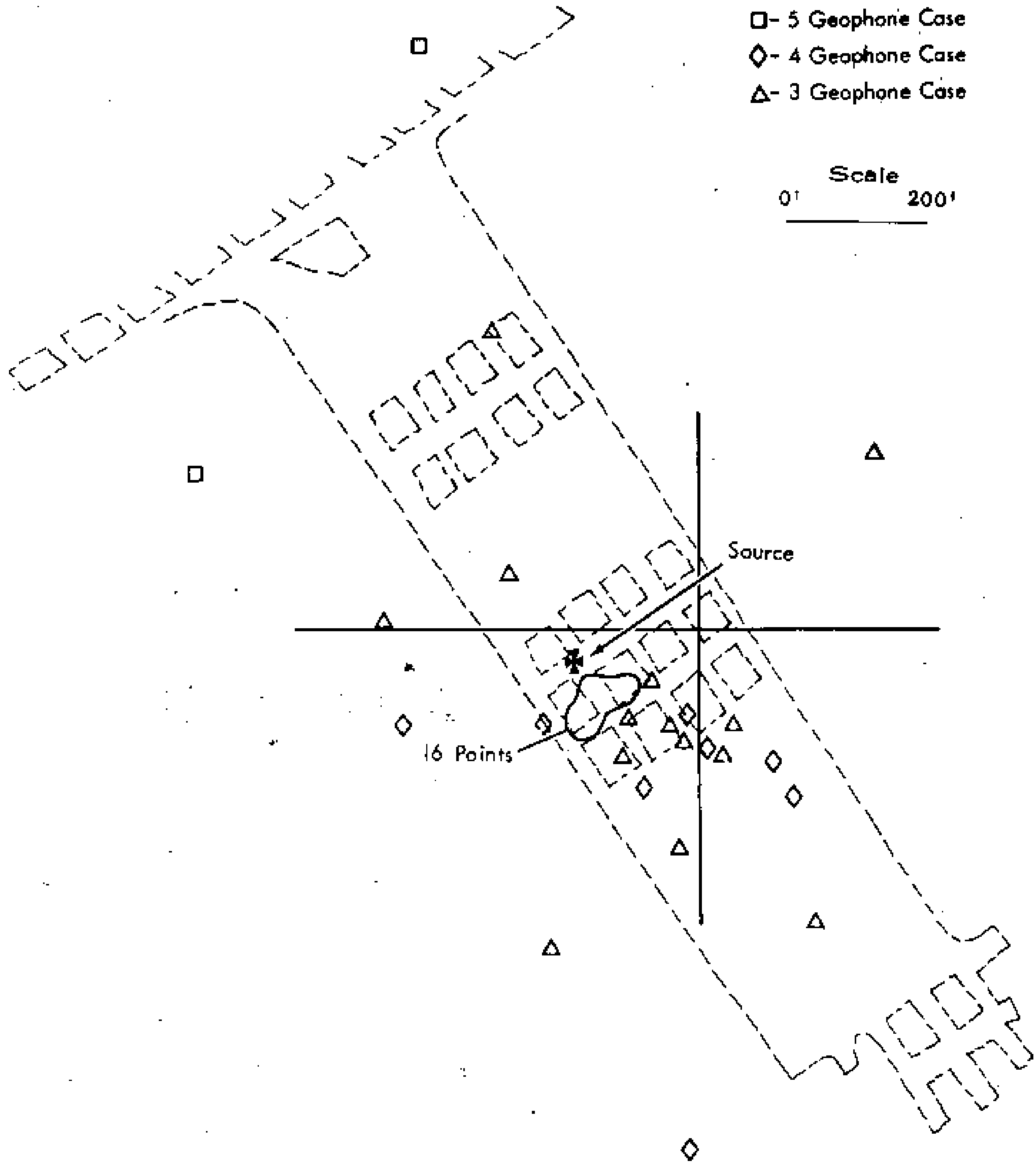


Figure 3.4-10. Gary No. 14 Mine - Location Calculations - Test 30 - 10 lb Sledge on Floor

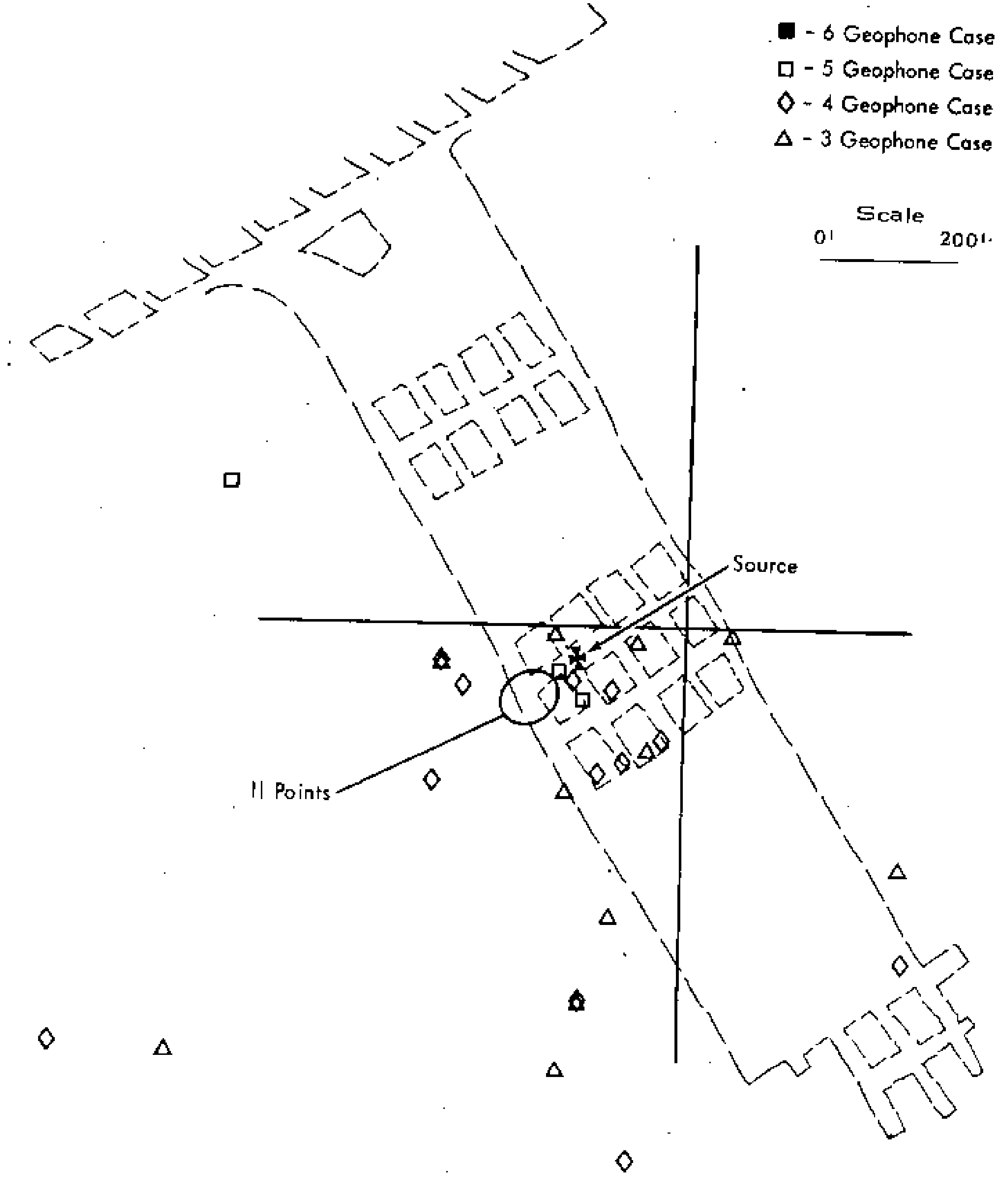


Figure 3.4-11. Gary No. 14 Mine - Location Calculations - Test 24 - Rail on Plate

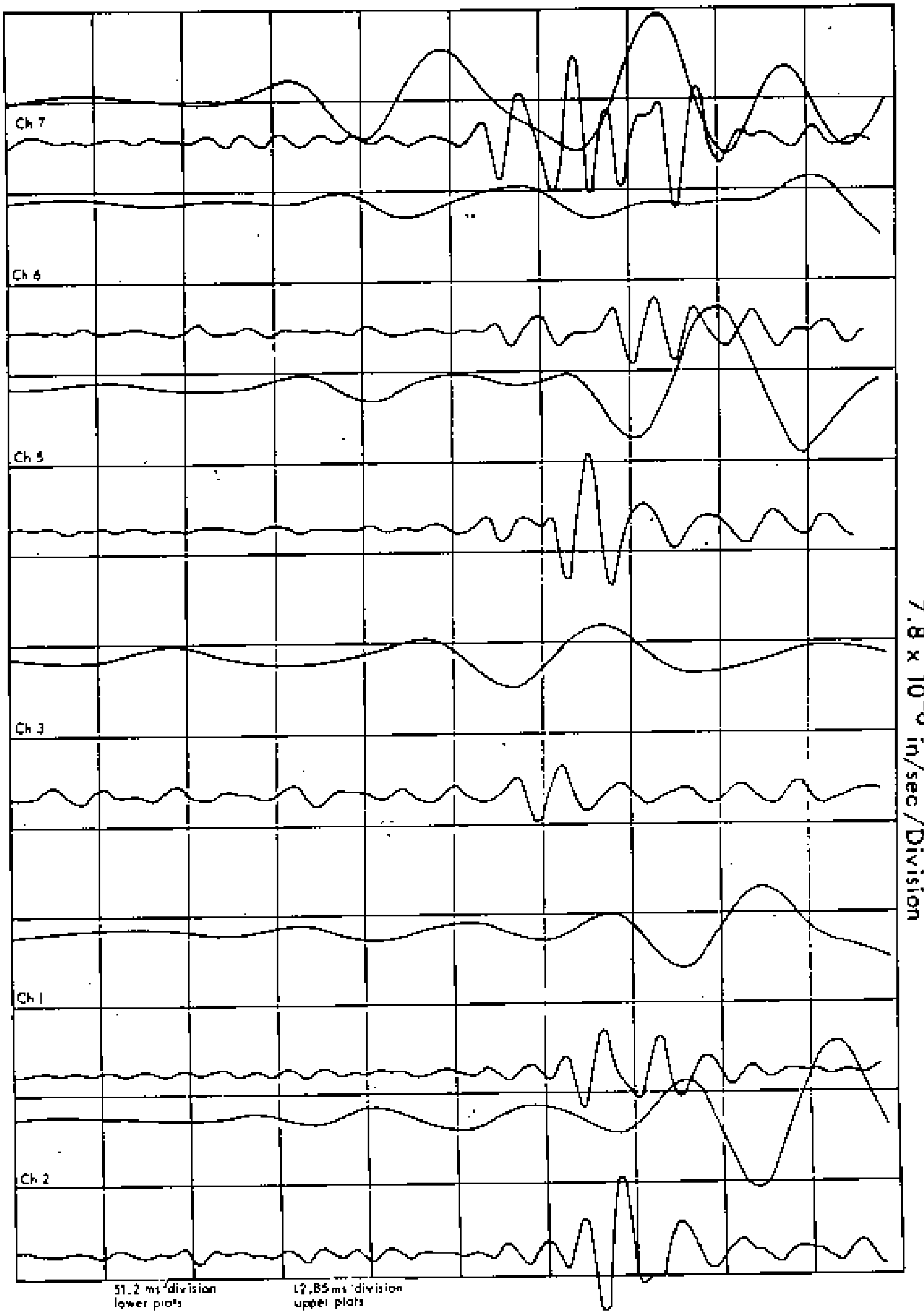


Figure 3.4-12. Gary No. 14 Mine, Signals - Test 26 - from Rail on Plate 1/20/71

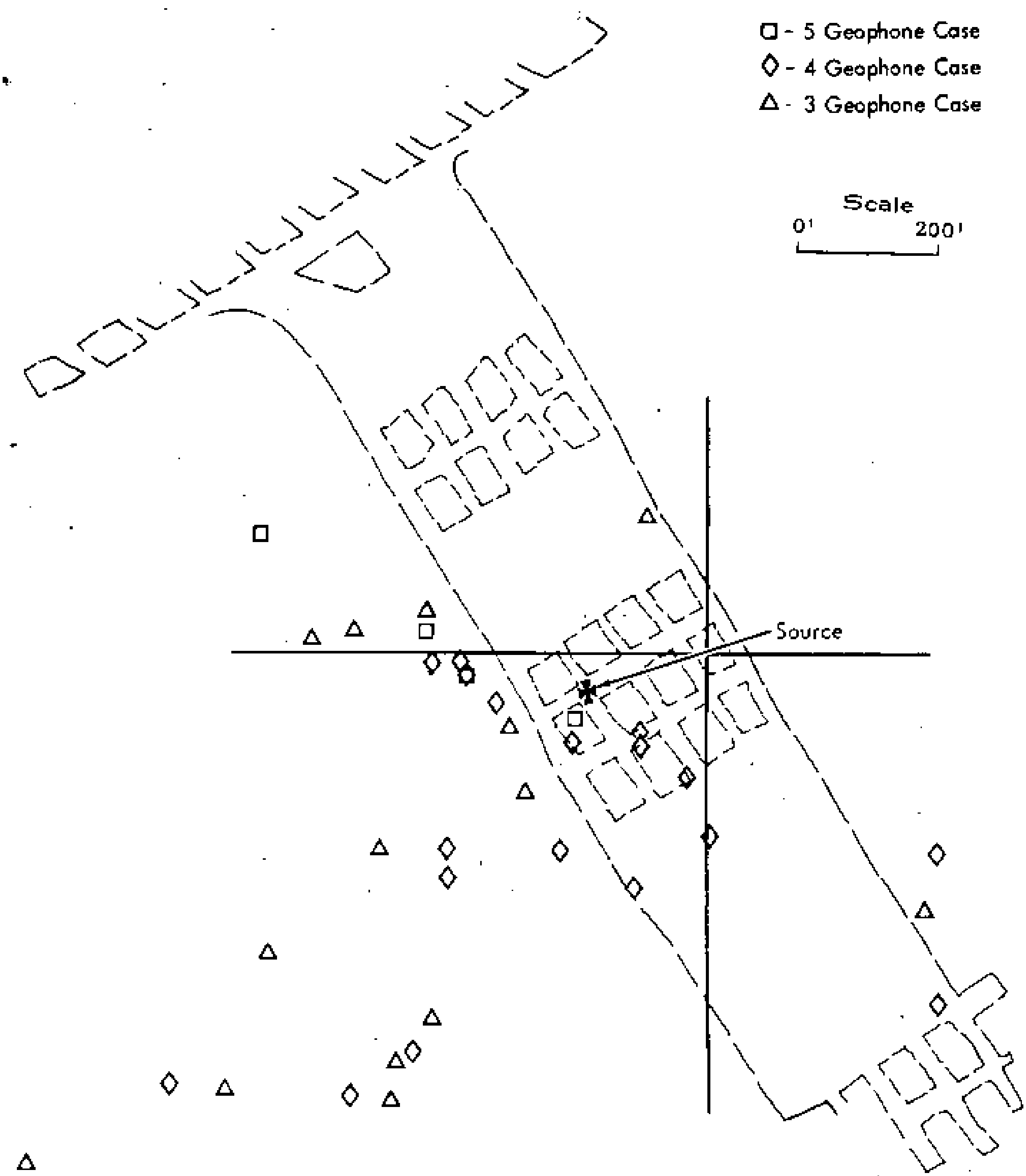


Figure 3.4-13. Gary No. 14 Mine - Location Calculations - Test 26 - Rail on Plate

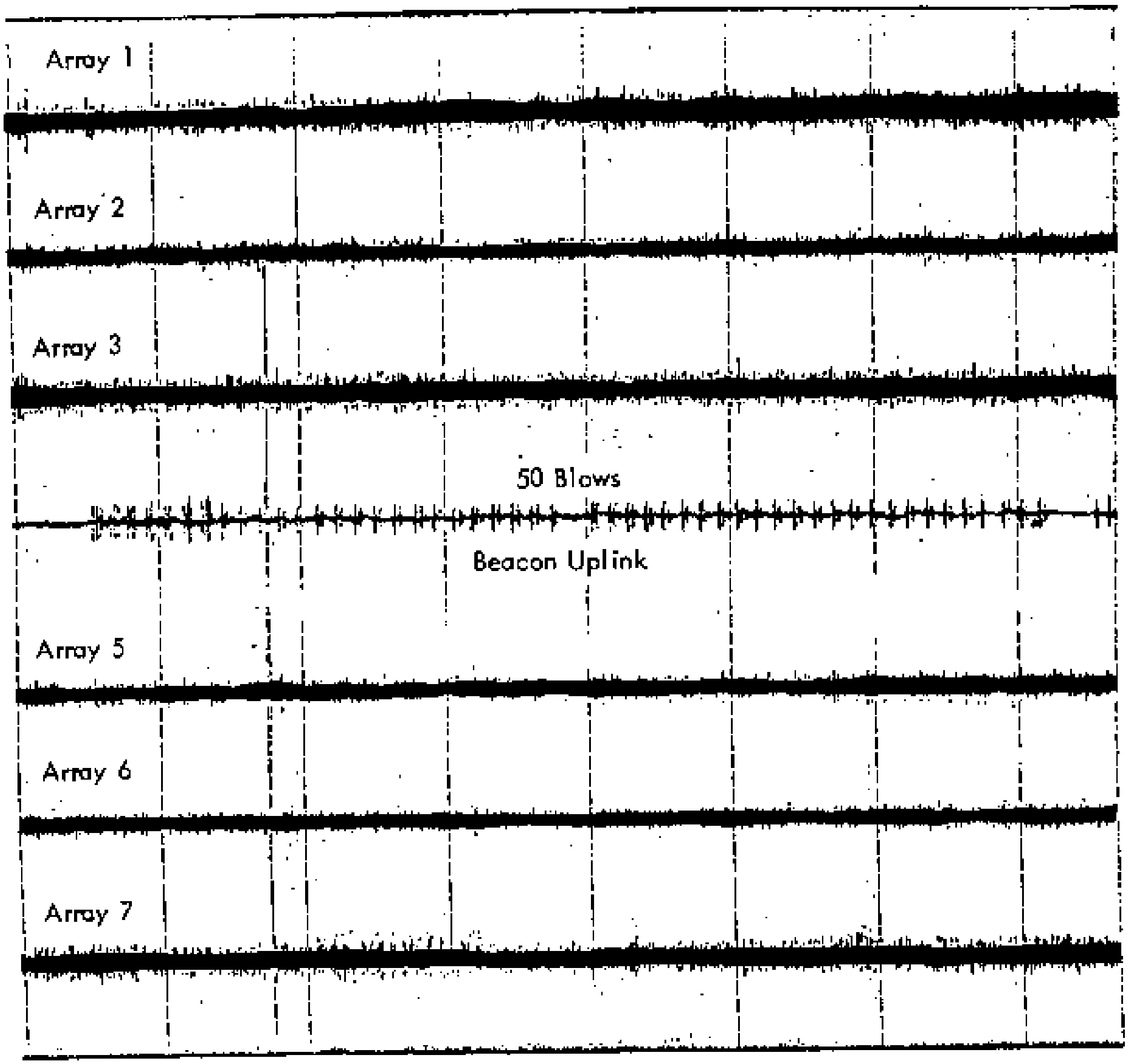


Figure 3.4-14. Facsimile of Oscillograph Monitor Record-Sledge Hammer on Plate

3.5 PERFORMANCE EVALUATION

Design specifications required that the Seismic Location System: 1) be able to locate trapped miners whose only signalling means are seismic signals; 2) be sensitive enough to observe natural noise on the order of 10^{-7} in/sec/$\sqrt{Hz}$; 3) be capable of using multiple hammer blows not necessarily generated at precise intervals; and 4) be capable of real time signal analysis to whatever extent is necessary to optimize signal detection. The degree to which system performance fulfilled these design goals is discussed below.

3.5.1 Summary of Performance

The success of the Seismic Location System must be judged ultimately on its ability to locate underground seismic sources and aid in the rescue of trapped miners. With the current state-of-the-art, this is not possible in every case. In some cases, such as the Harewood Mine, signals from the mine will not be of sufficient strength to be detected. Other times, such as at the Gary #14 Mine, background seismic noise levels will be too high to facilitate signal detection. Still in other cases, geological conditions create anisotropic situations which will cause ambiguities in wave travel paths and consequently confuse location results. The fact that these cases were encountered and recognizable as system limitations is important in defining future efforts. In situations where the system was not working beyond its limitations, performance was sufficient to define the major problem areas. These problems are: 1) Resolution in picking arrival times from records, 2) evaluation of the effects of anisotropic earth situations, 3) adequate seismic coupling, 4) generating a "trigger" signal for data processing. These problems will be discussed in paragraph 3.5.3.

When the overall performance of the system is balanced against the design specifications, the success is apparent. In every case where signals were detectable, locations were run with varying degrees of accuracy. Detection of these signals was enhanced by averaging many signals from a source and by other on-the-spot signal processing techniques. Even in cases where signals could not be detected, the limitation was external seismic noise and not the lack of versatility to perform some type of signal enhancement technique.

The thermal noise level of a single channel is below measured levels of seismic background noise as shown in Figure 3.5-1. Thus the sensitivity of the instrumentation is not a performance limiting factor.

3.5.2 System Results

The results of the field tests are important in evaluating the Seismic System's performance. The most meaningful results are in the areas of array optimization, signal enhancement, and source evaluation.

3.5.2.1 Arrays

Theoretical studies on array optimization indicate that multiple geophones should provide noise reduction. However, the data gathered during testing did not always confirm this. The lack of S/N improvement could be due to any number of factors but the fact that seven geophone arrays usually performed as well as nineteen geophone arrays and better than single geophone arrays indicated that seven element arrays are sufficient until more conclusive data is obtained.

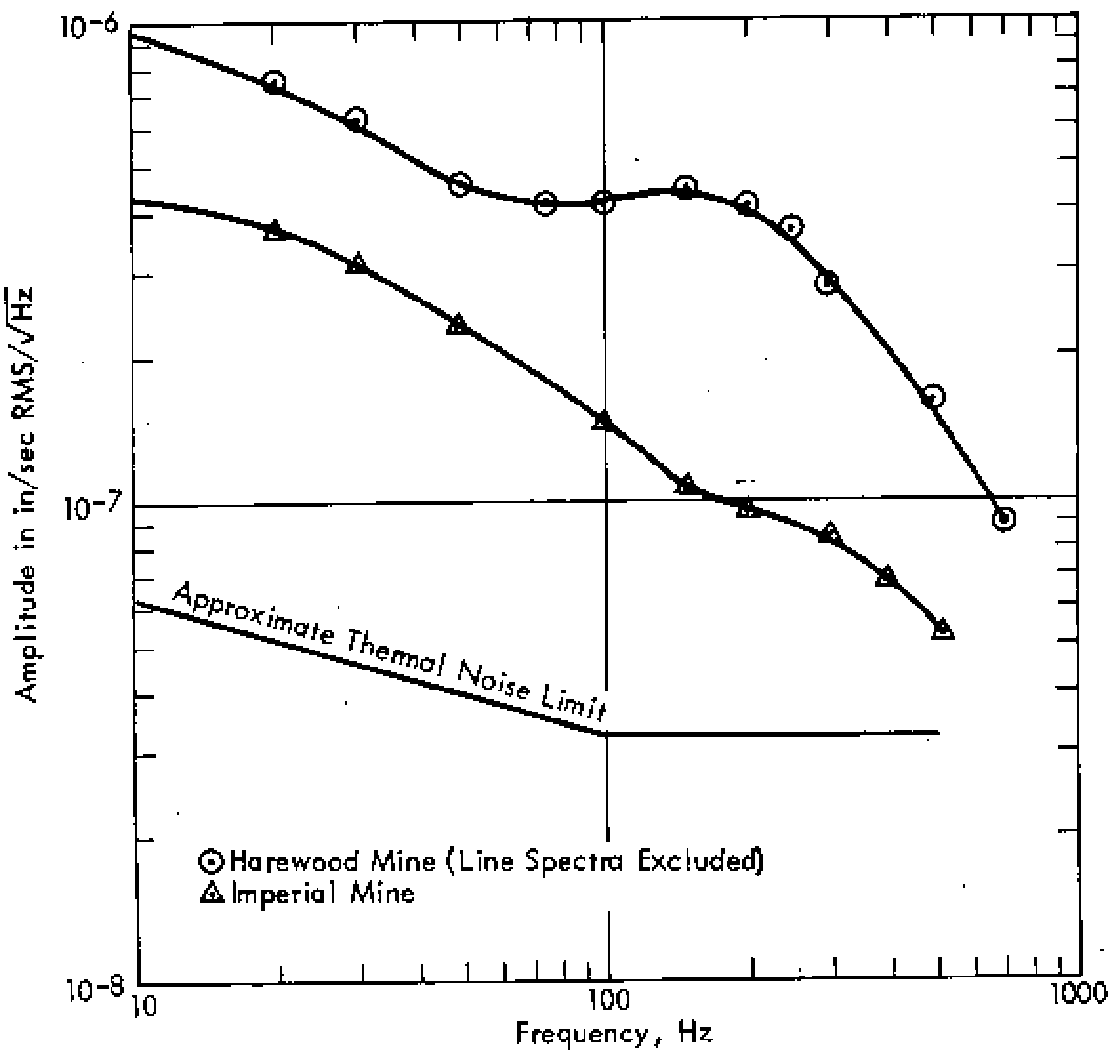


Figure 3.5-1. Seismic Noise Levels Encountered During Predemonstration Testing

Since time did not permit quantitative analysis of array comparisons during predemonstration testing, qualitative estimates were made based on noise spectra and estimated signal-to-noise ratios from processed records. Subsequent use of the system has produced data that does show improvements in signal-to-noise ratio as the number of geophones in an array increases. This is shown in Figure 3.5-2. However, subsequent data has also shown in some cases that multiple element arrays attenuate signals as much or more than noise when deployed according to array size calculations.

3.5.2.2 Signal Averaging

A significant result of system tests was the evaluation of signal averaging techniques. The results shown in paragraph 3.4.3 are excellent examples of the effectiveness of this technique. Detection theory predicts that the amount of signal-to-noise improvement by averaging n like signals is equal to the $\sqrt{n}$. In order to achieve this, signals must be identical and must be summed in phase.

In the tests run using the Seismic Location System, the fact that signal-to-noise ratio was enhanced was obvious even though only qualitative determinations were made. The degree of enhancement was not quantitatively determined, although it is apparently less than theory would indicate. The reason is related to the two requirements that signals be identical and that they be summed in phase. Since the signals are mechanically generated by a method that necessarily fatigues the source mechanism, it is unreasonable to expect that every signal be identical. Likewise, since the signal itself is used to trigger the summing process, differences in signals cause jitter in the trigger and they may not be summed exactly in phase.

Figure 3.5-3 emphasizes these two points. If the 30 signals were all identical to the signal in the upper plot then using a true averaging technique the final signal amplitude would be identical to the amplitude of a single pulse with a $\sqrt{n}$ signal-to-noise improvement. Comparing the peak amplitude of the signals in Figure 3.5-3, it can be seen that the averaged signal (lower trace) is only about 60% the amplitude of a single pulse (upper trace). This is due to not having exactly similar signals and not being capable of in-phase summation.

3.5.2.3 Sources

Source tests were performed at every test site to determine the best method of coupling seismic energy into the rock. The basic conclusion is that there appears to be a correlation between the mass of the striking object and the amount of energy imparted to the rock. Best signals were obtained by signalling with heavy objects (railroad ties, rails, lead weights) that were dropped. These observations are based on qualitative data and need further investigation to determine the optimum source.

3.5.3 <u>Major Problem Areas</u>

There are four specific areas that imposed limitations on the use of the Seismic Location System. These are:

a. Adequate time resolution and associated location accuracies.
b. Anisotropic earth situations to the location problem.
c. Seismic coupling at the source.
d. Generation of a "trigger" signal to facilitate signal averaging.

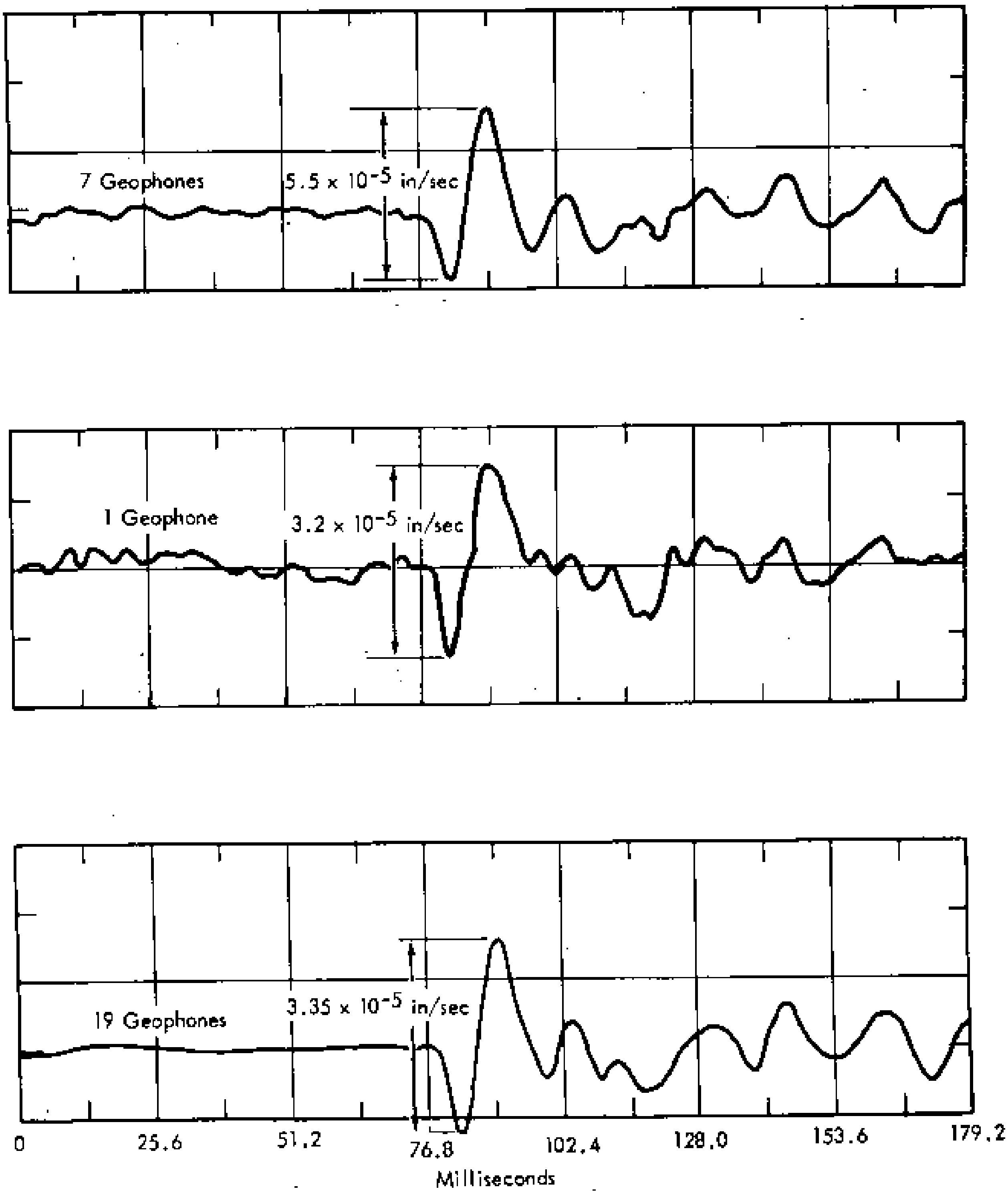


Figure 3.5-2. Comparison of Noise Reduction - 1/7/19

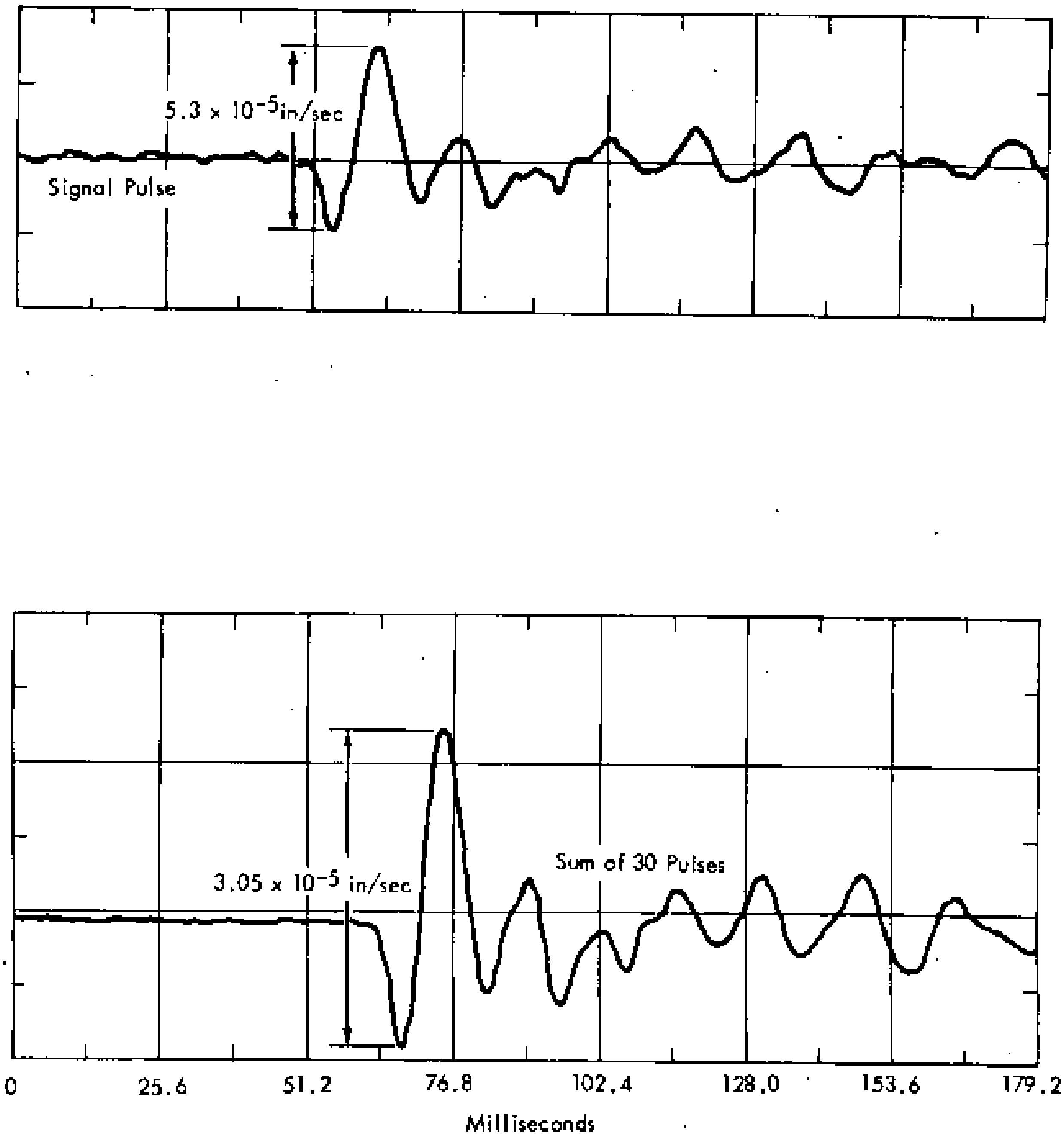


Figure 3.5-3. Comparison of Signal to Noise Improvement Using Signal Summation

3.5.3.1 Time Resolution and Location Accuracies

The most prevalent problem involved with accurately determining the trapped miners' location was the inability to select arrival times to within one or two milliseconds. The problem exists because either the signals are of such a low frequency that the actual "first break" is spread out over five or six milliseconds, or the noise levels are so high that the actual first arrival is obscured on some or all of the traces.

Part of the solution to this problem is the use of the highest frequencies possible, even to the point of degenerating the signal-to-noise ratio if it aids in defining the first break. Another part of the solution is to use human judgment in analyzing the locations returned by the computer. Instead of relying on a purely statistical method of determining the signal source and the error in calculations, obviously bad data points should be discarded. The final part of the solution is to repeat the location computations using other phases of the arriving energy such as the shear wave, with an adjustment in velocity, comparing results with previous data.

3.5.3.2 Anisotropic Earth

One of the problems encountered during the demonstration tests was an apparent anisotropic earth situation. When the theoretical arrival time was calculated using a known source location and velocity, the calculated arrival time at Array 5 was about ten milliseconds slower than the observed arrival time, apparently caused by a velocity higher than the assumed average. By adjusting the time for the average velocities being used, locations were all within ten feet of the source. (See Figure 3.5-4.)

This problem has always been present while using an isotropic earth model, although never to the degree experienced at the demonstration. Since source coordinates are never known for sure until after the fact, such anisotropics can lead to a serious problem.

This problem can be lessened somewhat by estimating the existence of anisotropic conditions from geological reconnaissance and avoiding such situations, and by estimating the magnitude of such travel time errors and making the necessary time adjustments based on a calibration using the seismic transmitter. Other solutions to this problem merit future investigation.

3.5.3.3 Seismic Signal Generation and Coupling

Experience with the seismic system indicates that the sources tried, in general, all provide detectable signals, at varying signal-to-noise ratios. Emphasis to date has been on conventional seismic generators such as the hammer, heavy timbers, and the "thumper" described in earlier sections of this report. These devices are all limited in terms of efficient coupling of the signal to the earth, and there is a need to concentrate future efforts on improving the efficiency of this coupling. Additional, important design constraints include simplicity of operation and maximum portability.

3.5.3.4 Generation of a "Trigger" Signal

The advantages of signal averaging in addition to electronic filtering and array optimization as methods of signal-to-noise enhancement were proven during field tests. The concept has one disadvantage, however, that puts a limitation on its use. In order to signal average recurrent miner pulses, a trigger signal must exist that has precisely the same intervals as the signals to be averaged.

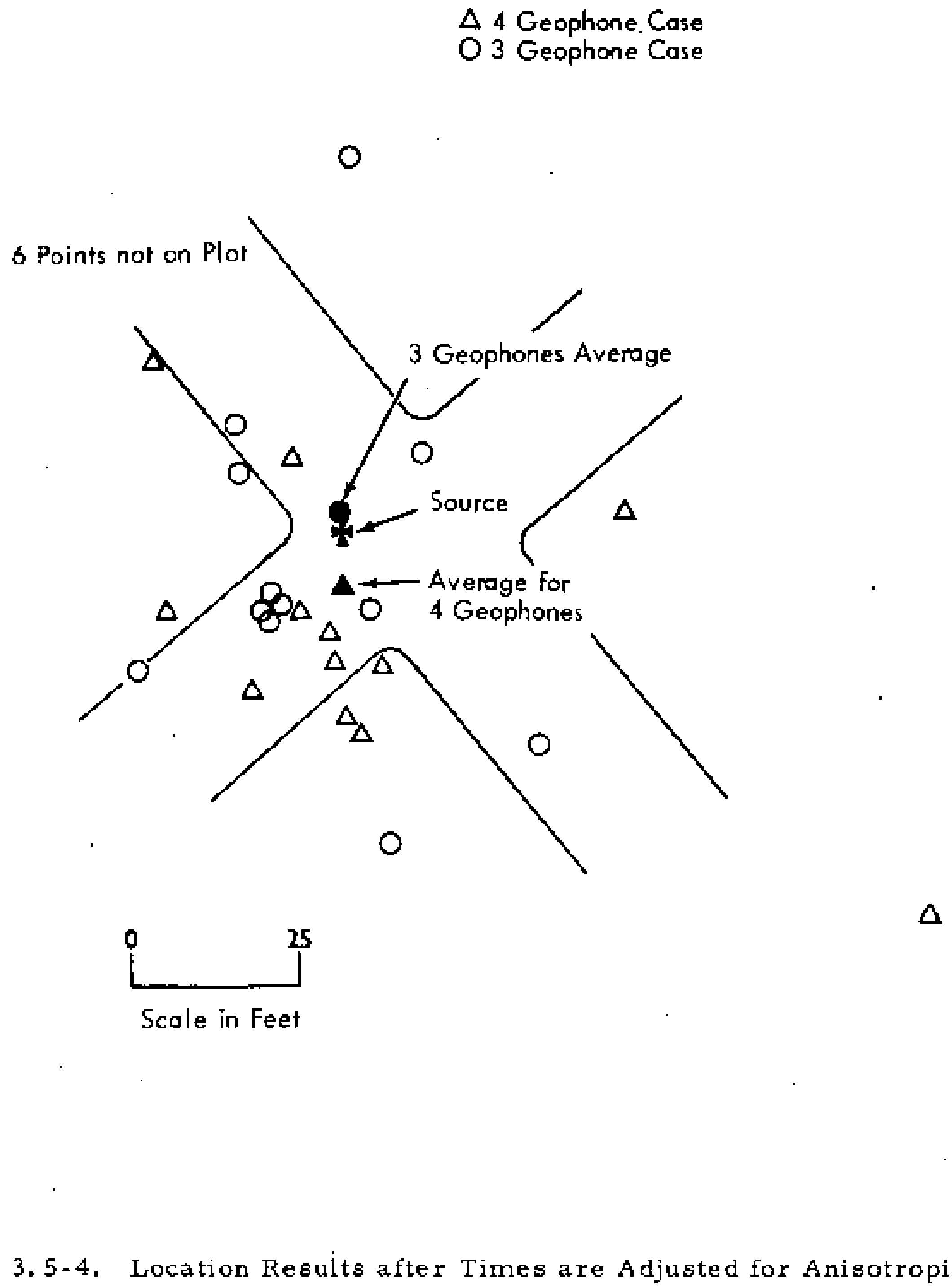


Figure 3.5-4. Location Results after Times are Adjusted for Anisotropic Earth (Compare with 3.4-4)

In the past tests there have been three sources for this signal: 1) A data channel, 2) A geophone planted in the mine and cabled to the surface, 3) The EM beacon seismic uplink. Any one of these must be available in order to facilitate location of trapped miners. If one of these signal sources is not available, little can be done as far as location analysis is concerned until a "trigger" signal can be provided.

4. CONCLUSIONS AND RECOMMENDATIONS

The design, fabrication and testing of the Communication/Location subsystem was completed on schedule and demonstrated in January 1971. A performance evaluation of the electromagnetic and seismic portions of the subsystem is given in Sections 2.5 and 3.5 respectively. Here, the basic conclusions are summarized for both technological areas. These conclusions lead directly to recommendations for further research, development, and evaluation programs designed to improve system utilization, provide training, determine performance limitations and maintain an emergency readiness posture.

4.1 ELECTROMAGNETIC SYSTEM CONCLUSION SUMMARY

The electromagnetic voice downlink and coded beacon uplink was tested and qualitatively and quantitatively evaluated at five different coal mines. Pertinent mine characteristics were:

Mine	Depth (feet)	Apparent Conductivity (mhos/meter)
Imperial, Colorado	290	0.12
Clyde, Pennsylvania	800	0.034
Cambria Slope, Pennsylvania	850	0.0052
Harewood, West Virginia	650	0.0006*
U.S. Steel #14, West Virginia	800	0.0024

Based on the results of these field tests, theoretical studies, and laboratory performance measurements, the following conclusions can be made.

4.1.1 Voice Downlink

Intelligible voice transmission were received at each mine using a horizontal wire transmitting antenna terminated in the ground at each end. The voice frequency rms antenna current varied from mine to mine and depended upon antenna length and termination resistance. The average antenna current, as observed with an average reading meter, was 0.5 amperes or less at each mine. The voice transmitter, however, is capable of supplying one

* This consisted of a single measurement made on a strip mining shelf above the underground coal mine. (The conductivity values obtained for the other mines represent the average conductivity obtained from a complete conductivity sounding at each site.)

ampere of antenna current (200 watts into 200 ohms) if needed. As ground conductivity increases, it becomes increasingly difficult to penetrate the earth with EM waves.

The field strength observed when exciting the antenna with a fixed frequency was proportional to the antenna current and independent of antenna length when the receiver depth is small compared to the distance to the nearest end of the wire. The theoretical model for an infinite line is useful for predicting fields below the surface using up to three layers of horizontal stratification and frequencies where the skin depth is short compared to the length of the antenna. Comparisons between measured magnetic field intensities and theoretical predictions as a function of frequency showed excellent correlation except at the Cambria Slope Mine. Here, the observations were almost 10 dB less than the theory would indicate. This may be attributed to an anomaly in the conductivity sounding, but is not fully understood.

Voice transmissions can be received intelligibly when band limited to between 500 and 3000 Hz. Subjective measurement in the laboratory indicates that a slow distinct speaker can be understood when the signal-to-noise ratio is 6 dB, and the noise is assumed to have a Gaussian distribution.

Quantitative measures of the horizontal wire antenna's pattern below the surface have not been made. However, qualitative observations were obtained in some mines. Intelligible voice was received at slant ranges (perpendicular to the plane of the wire) of 1794 feet in the Imperial Mine and 927 feet in the Cambria Slope Mine using antenna lengths of 2500 feet. The fields drop rapidly beyond the ends of the horizontal wire antenna.

The performance of the system depends on several factors, namely the antenna current, the depth to the receiver, the average conductivity of the overburden, the noise, and the receiver's performance characteristics. Two types of receivers were fabricated, one for use in the Habitat and one for the individual miner's use. The performance of each receiver is limited by the front end thermal noise when no external noise is present. The minimum detectable signal for the Habitat receiver is 1.6 μamps/meter, and for the Manpack receiver is 50 μamps/meter. In the absence of man-made electrical interference, the maximum usable depth is 3200 feet for the Habitat receiver and 1600 feet for the Manpack receiver in mines where the apparent conductivity of the overburden is 0.01 mhos/meter. These depths were calculated using the theoretical model and assuming one ampere of antenna current.

External noise sources were measured below the surface in operating mines. Spectral components of power line harmonics were observed with a maximum magnetic field strength of nearly 40 mA/meter at 360 Hz. Other components existed in the voice band which exceeded 1 mA/meter. The performance of the voice receivers in such a noise environment is severely limited. A quantitative evaluation of the voice performance has not been made because of the extremely variable nature of this noise environment and the limited amount of data available on the man-made noise characteristics in different mines.

4.1.2 Coded Beacon Uplink

Coded beacon transmissions at 2750 Hz and 1375 Hz were detectable on the surface using 25 watts at the Harewood Mine, and 2750 Hz transmissions were detectable using 4 watts at the U.S. Steel #14 Mine in West Virginia. The power output was reduced to 4 watts to ensure permissibility of the system in all mines. A 12-turn, 625-square meter, air core loop was used for the transmitting antenna and a 1000-turn air core loop of approximately 0.4 square meters was used for receiving on the surface.

The external noise environment, both natural and man-made, limits reception at the surface. It was found that in general the maximum magnetic field strength observed on the surface is nearly constant for a radius of 50 meters around the center point. Theoretical predictions of field strength were made for some of the mines and results compared favorably with measured data except at the Cambria Slope Mine. Reliable communications were achieved with the transmitter output power of 4 watts (1 ampere in the antenna) over slant ranges of 1500 feet.

The receiver detection and decoding circuitry requires a signal-to-noise ratio of at least 6 dB. The maximum sensitivity of this system is 0.11 μA/meter in a 50 Hz bandwidth. With an overburden conductivity of .01 mhos/m and 1 ampere in the transmitter antenna, the operating depth of the beacon uplink is about 1500 feet. For a conductivity of 0.001 mhos/meter, the operating depth increases to about 2500 feet. These operating depths would be reduced by significant amounts of man-made noise and interference which limit the performance of the receiver on the surface. Performance is also limited by highly conducting overburden.

The use of Beacon Transmitters for relaying seismic signals to the surface is a valuable feature not only for detecting the presence of trapped miners, but for improving the performance of the seismic location system, by providing a trigger for signal averaging.

4.1.3 General Comments

The EM communications system's performance objectives were realized during the test and demonstration phase of the program. Theoretical and experimental studies indicate that this EM system could be effectively used in rescue operations in about 90% of all coal mines in the United States provided that these mines were equipped with subsurface EM transmitters and receivers. This is based on the fact that 89% of all coal mined in the U.S. is taken from mines less than 1000 feet deep.* The EM system performance, in terms of reliable and intelligible information transfer, can be accurately

* Coal Mine Characterization Study, Westinghouse Defense and Space Center, November 1970.

predicted when the overburden conductivity, the overburden thickness, and the surface and subsurface noise levels are known. The curves and tables given in Section 2.5 apply to the performance capability of the system as designed and built. These performance characteristics could be modified in a variety of ways to meet new and different requirements. For example, the Beacon Uplink System could operate at narrower bandwidths to increase the signal-to-noise ratio. The increase in signal-to-noise ratio is proportional to the square root of bandwidth decrease. However, if the beacon bandwidth were to be decreased, the Beacon transmitter keying rate and thus the data rate would also have to be decreased in proportion to the bandwidth decrease.

For the Voice Downlink System, a decrease in bandwidth is not possible since it would degrade the intelligibility of the voice reception in the mine. To overcome unusually high mine noise environments or to communicate to extremely deep mines and still retain the advantages of voice communications, it may be necessary to increase the transmitter current at the surface. This can be accomplished either by:

a. raising the voltage and the power level of the transmitter,

b. reducing the impedance of the antenna ground terminations to achieve an increase in current for the same voltage, or

c. when using a large transmitting loop, resonate the loop to eliminate the reactive component of antenna impedance, thereby increasing the current.

To implement a practical network of Beacon Transmitters in a mine, each beacon carrier frequency must be separated from each other by at least 100 Hz, so that the Beacon Receiver may select and identify transmissions from each unique transmitting location. The results of the surface noise studies indicate that an optimum frequency range of operation is from about 1.5 kHz to 3.5 kHz. Using a frequency range such as this would permit a mine to have as many as 20 different beacons operating at the same time. It is highly unlikely, even in large mines, that an emergency situation would require simultaneous operation of 20 beacons. Nevertheless, the capability exists, and the receiver is capable of tuning to any frequency in this range.

There are many ways in which the EM System could be improved, and recommendations are given in the next section for additional efforts which should improve the usefulness of the system both from an operational and a technical standpoint.

4.1.4 Recommendations

a. System Evaluation

Operation of the Communications/Location Subsystem by Westinghouse and U. S. Bureau of Mines personnel should be undertaken on a continuing training program.

b. Subsystem Utilization in Emergency Situations

(1) Determine the most effective non-emergency use of the communication equipment in order to assure availability of working equipment and trained operators in the event of an emergency.

(2) Evaluate the performance, merits, and constraints of using the subsystem as part of routine, day-to-day coal mining operations. Operational systems are more likely to be usable in emergency systems than standby systems.

c. Noise and Interference Reduction

(1) Identify the sources and characteristics of the very high EM and seismic noise levels found in operating coal mines.

(2) Develop better methods for reducing this noise and/or its effect on communication links.

d. Increased EM Voice Coverage

Devise and develop new transmitting antenna configurations and coupling techniques to obtain increased, broad and uniform electromagnetic voice coverage in the mine. This would be particularly useful for routine operations.

e. Mine Environment Characterization

(1) Develop and maintain a broad data base on mine characteristics and special installations in more difficult mines in order to have such information readily available for use by rescue teams, and to provide a data base for designing advanced systems.

(2) Design and develop simple, reliable methods of measuring pertinent mine characteristics essential to the implementation of optimum mine communications systems.

f. Surface EM Noise Study

Study surface electromagnetic noise characteristics at typical sites obtaining both short term and long term statistics over a period of several months.

g. Coding Techniques

Conduct a comparison of different coding schemes to determine the most effective way to communicate in a high noise environment.

h. Theoretical Analysis

Extend theoretical analysis to determine complete EM field patterns from horizontal wire antennas (HWA) and vertical magnetic antennas (VMA) on the surface and VMA's below the surface.

i. Transmitter Current Enhancement

Investigate techniques to increase transmitter current in regions of extremely high conductivity or magnetic permeability. This will include investigation of sophisticated methods of obtaining low resistance ground terminations for use with the existing system as well as an investigation of other higher power audio amplifiers.

4.2 SEISMIC LOCATION SYSTEM CONCLUSION SUMMARY

The seismic location system was tested at four different mines as follows:

	Depth to Source
Imperial, Colorado	290
Clyde, Pennsylvania	700
Harewood, West Virginia	850, 300
U.S. Steel #14, West Virginia	800

Based on the results of these field tests and predesign techniques including theoretical studies, computer simulations, and laboratory experiments, the following conclusions can be made.

4.2.1 Signal Detection

Equipments normally used for seismic exploration work do not have adequate sensitivities for the mine rescue application. The predesign studies indicated that special care must be taken to insure sensitivity in order to detect hammer blows generated in most mines. This includes low noise amplifiers and sensitive, balanced geophones to permit reception of signals at least above the normal seismic background noise. This noise background level is approximately 10^{-7} cm/sec/Hz at 100 Hz and increasing 6 dB per octave below 100 Hz. Theoretical studies, neglecting attenuation, indicated that a 10 lb. hammer blow, 1000 feet below the surface would generate a signal whose magnitude was about the same as that of the background noise at similar frequencies. Generally frequencies received were below 100 Hz, although some components were observed up to 300 Hz. Thus it appeared that signal detection would, at best, be difficult. The maximum frequency response was found to be quite variable depending on the geological characteristics, path length and method used to implant the geophones. Adaptive filtering was incorporated into the system to permit the operator flexibility in optimizing signal-to-noise ratios. A spectrum analysis on broadband signals can be obtained using the computer to determine the upper and lower passband characteristics during the initial operational phase.

Additional techniques which would improve signal-to-noise ratio were also investigated. Multiple seismometer theory indicated that subarrays of geophone elements should enhance signal-to-noise ratios, when the noise is noncoherent, by a factor of $\sqrt{n}$ where n is the number of geophones in the subarray. Against coherent noise, the multiple element arrays should also provide spatial filtering of the noise at certain frequencies depending on the spacing of the elements. Initial tests with multiple element arrays did not support or refute the theoretical improvement expected since the data was not consistent. A majority of the results showed some improvement using seven elements instead of one and sometimes improvement was apparent using nineteen elements relative to seven. This data was not sufficient, however, to conclude that additional improvement could be achieved under any circumstances.

Averaging the signals from a series of successive hammer blows, also theoretically, should provide signal-to-noise ratio improvement. This was accomplished by computer processing and found to give substantial improvement, although a quantitative measure of the change in the S/N ratio as a function of the number of blows has not been accomplished. Signal averaging, in the case of extremely weak signals, requires some means of independently triggering the processor. These triggers may be obtained either by transmitting subsurface signals to the surface using the beacon transmitter or, if this is not available, by using a downhole geophone or one of the surface geophones if the signal-to-noise ratio is acceptable.

4.2.2 Location System Performance

The location system performance depends not only on detecting signals on at least three separate geophone locations but also on being able to measure the relative time of arrival of these signals. This arrival time difference is the basic information required to solve the location problem. Computer simulations showed that the relative time of arrival measurements should be within at least 2 milliseconds if $\pm$ 25 foot accuracies were to be realized. This time resolution places a stringent requirement on the signal detection processes since such a measurement requires comparing a signal arrival time to within two milliseconds using weak signals perturbed by noise.

Cross correlation of the signals was suggested as one means of measuring arrival time differences. Some results showed no well defined peak and others showed a peak which was obviously wrong. This is believed to be caused by signal contamination by different seismic waves arriving by different paths and by noise.

Various means have been tried to determine the relative time of arrival of the signals such as zero crossing of identifiable cycles, phase matching half cycles and amplitude peaks. None have proved completely satisfactory, and each of these involves some subjective decisions by the system operators.

4.2.3 System Location Accuracy

The location accuracy depends on a number of factors in addition to the accuracy of the time of arrival measurement. These include:

a. The accuracy of the array survey including the tie point to the subsurface workings,

b. The location of the array as deployed relative to the source of signal being located,

c. The size of the array and the depth of the source,

d. The accuracy of the velocity estimate.

Items b and c relate the array/source geometry. The effects of geometry on location accuracy have not been fully evaluated, although the results of computer simulation studies indicate the following:

a. The source should be within the spread of the array, and this spread should be greater than one-third the source depth.

b. The geophone spacing should be such that the minimum time difference measured is large compared to the timing uncertainties.

The performance of the system in terms of accuracy varied at each location and cannot be defined using the limited amount of available data. From a given set of data, it is possible to calculate several locations using various combinations of geophone signals. Location errors can be reduced by averaging all the points which tend to group together, and rejecting obviously bad points which tend to scatter. Correlation of location points to a mine map is useful in this process. The actual accuracy limits of the system cannot be fully determined until many more locations have been measured at a variety of mine types.

4.2.4 General Comments

The seismic system performance in terms of design specifications was realized during the test and demonstration phase of the program. It is difficult to predict the performance for different geological structure overburdens. Further testing is required to determine potential system accuracy and signal processing gains achievable by various methods available.

The system does have potential applications in the disaster situation and can also serve as a valuable research tool for gathering the data necessary for development of future systems and for improving the existing system.

Electromagnetic systems would be extremely useful in disaster situations but until these are available in the mines the seismic techniques are the only means of detecting and locating trapped miners. Even this requires some knowledge on the part of the miner on signalling techniques to increase his chances of being located.

4.2.5 Recommendations

a. Develop training aids to instruct miners in the most effective way to generate seismic signals.

b. Develop methods for placing geophones in a mine after a disaster (in the absence of permanently installed voice receiver and beacon transmitter equipments). Possible solutions include: use of existing shafts or drill holes; drilling a small hole into the area of entrapment; carrying a geophone, a voice receiver, and beacon transmitter as close to the entrapment area as possible.

c. Investigate and develop methods for obtaining more rapid, accurate surveys of surface geophone locations.

d. Devise and test various methods (for use inside mines) of generating seismic signals and advise mine operators on optimum methods to use.

e. Investigate additional methods for uplink seismic signalling which do not require excessive exertion of energy on the part of trapped miners.

f. Develop means to initiate the operation of automatic subsurface signalling devices from the surface.

g. Identify the sources and characteristics of the very high seismic noise levels found in operating coal mines and develop methods for reducing this noise and for processing signals in this noise environment.

h. Develop and maintain a broad seismic data base on mine characteristics in order to have such information readily available for the use of rescue teams, and to provide a technological base for designing advanced systems.

i. Investigate improved techniques of seismic data processing and source location determination.

APPENDIX A

COMMUNICATIONS/LOCATION SUBSYSTEM OPERATING PROCEDURES

CONTENTS

		Page
1.0	PRIMARY PROCEDURES	A-1
2.0	BACKUP PROCEDURES	A-4
3.0	VOICE COMMUNICATIONS PROCEDURES	A-6

APPENDIX A

COMMUNICATIONS/LOCATION SUBSYSTEM OPERATING PROCEDURES

The procedures described in this appendix were used for the demonstration at the U.S. Steel Coal Mine No. 14 near Gary, West Virginia. They are representative of the procedures which would be used in an actual emergency. These procedures are general in nature and assume that the operators are competent engineers and geophysicists who are thoroughly familiar with the equipment and have had several months of experience in its operation. Successful operation of the Seismic Location System in particular is dependent upon an in depth understanding of seismology and signal processing principles.

As more experience is obtained in the operation of this system, these procedures will likely be modified. They will also be modified if the mine at which the emergency has occurred does not have any previously installed electromagnetic communications equipment. This would require use of seismic signalling techniques initially, rather than as a back-up procedure. It is probable that a voice receiver and Beacon Transmitter could be carried into a mine and installed near the area of the emergency to be used in coordinating in mine rescue efforts and to be used to relay detection of seismic signals in the mine to the surface. Modified and optional procedures should be worked out in the near future to insure successful use of this system in the event of an actual emergency.

1.0 PRIMARY PROCEDURES

A detailed log will be maintained of all actions and reactions of the Communications Subsystem. This log will begin when the director of the Communications Subsystem receives word of the emergency and will end upon the completion of all rescue efforts. The director of this subsystem will keep his own log and will direct that key individuals at other locations maintain logs of their operation. Tape recordings of all transmissions on the voice system will be maintained. This will be very important in verifying the use of adequate procedures.

1) Upon arrival at the emergency location the mine operator and/or rescue director will identify on a mine map the location of the emergency and the location of the beacon in the emergency area.

They will also identify the probable avenues of escape and other regions wherein they might anticipate having trapped men.

2) A survey team will roughly locate, within plus or minus 100 feet, the position on the surface directly above the beacon location. The communications/location trailer or field housing will be moved to this location for initial operations.

3) The beacon receiving antenna will be placed at the position designated, directly over the Beacon Transmitter, and the EM Communications System operator will immediately initiate operation of the Beacon Receiver to listen for transmissions. (Note that the Beacon Receiver can be operated on internal batteries until power has been supplied to the trailer.)

4) Power will be supplied to the trailer either from a tap from a local power line or from a 10 kilowatt power generator placed 1000 to 2000 feet from the trailer in a direction away from the more probable trapped miner regions of the mine. This will be accomplished within 30 minutes after the trailer is in place.

5) The voice transmitting antenna will be deployed in such a manner as to effect communications with men at the beacon location and with other locations wherein men might be trapped. If these locations are widely separated, the voice communication system will be used, first of all to communicate with the beacon location, and thereafter with other possible entrapment areas in an order of priority to be established by the rescue director. (Note that step five and step six will be undertaken in parallel or at the same time as steps seven through nine.)

6) The voice communications system will be used to establish communications with men trapped at the beacon location. This voice communication system will be used to determine the number of men, their condition, condition of the habitat or barricade area, and general conditions within the mine as

best as can be determined.* The presence of men at the beacon location and their condition will be conveyed immediately to the rescue director. Upon completion of these communications the men at the beacon location will be directed to turn the beacon off until they receive further instructions via the voice system.

7) The survey team will be directed to locate and record positions for the geophones and geophone arrays in accordance with instructions provided by the Communications Subsystem director.

8) The auger or small drill crew will be directed to prepare holes for seismic refraction shots to be used in determining velocities of propagation in the weathered and sub-weathered layers above the mine. At the same time, geophone subarrays will be placed in the surveyed positions. These geophones and other geophones will be used in conjunction with the shots to establish velocities of propagation.

9) When the geophones subarrays are in place, tape and oscillographic recordings will be used to record possible signals from trapped miners. A request for quiet conditions on the surface will not be made until suspected signals are observed or until the voice system is available to request signalling from trapped miners.

10) When the voice communications system is ready, it will be used to request trapped miners to begin signalling with hammers or other objects by beating on the mine floor or walls. At this time a request will be made of the rescue director to stop all motion and seismic noise makers within the area while reception of signals is attempted.

11) The signals received by the Seismic Location System, up to this point in time, will be used to compute the location of the signal sources. If the

---

* See Voice Communications Procedures, paragraph 3.0

signal sources are not in an optimum location relative to the geophone subarrays, the subarrays will be moved and steps nine and ten repeated until a reliable source location is obtained. The Communications Subsystem director shall have full responsibility and authority to judge the reliability of any locations computed.

12) The survey team will convert the computed coordinates of the miners' location to a surface position. This position, when judged reliable by the Communication Subsystem director, will be conveyed to the rescue director for positioning of the drill rig. The location position will be coordinated with the mine map to ensure that the drill will be positioned directly over a tunnel.

13) When the search and probe drill has reached a point halfway between the surface and the mine, the location subsystem will be used to track the position of the drill bit. If this identifies an error in the calculated locations, which is possible due to anomalous seismic propagation within the earth, this information will be used to select a correlated location and a new drilling point.

14) When time and drilling operations permit, the Seismic Location System will be used, along with the voice communication system, to obtain information about the condition of the trapped miner or miners. The voice system will be used to ask questions of the miners to which they will respond by striking the mine walls according to instructions given on the voice system.

15) The trapped miners will listen for drilling noise using the geophones and voice receivers. They will communicate via the beacon when they detect the sound of drilling.

2.0 BACKUP PROCEDURES

Various backup procedures, should the primary systems fail to function satisfactorily, are described below.

1) If the beacon signals cannot be received on the surface, the miners at this location will have to use the Seismic Transmitter for communications. (Note also that this Seismic Transmitter may be used for calibration of the Seismic Location System in place of the refraction shots (Step 8).)

2) If signals, seismic or EM, are being received on the surface from within the mine and it becomes evident that voice transmissions are not being received within the mine, explosive charges will be set off on the surface of the mine, according to predetermined codes, to request responses from within the mine. This means of signalling will also be used if no response of any kind from within the mine has been received after repeated operations of the voice communications systems.

3) Prior to establishment of EM communications, or in the event communications are not established; attempts will be made to pick up seismic signals on the hour and half-hour. If signals are not obtained, quiet periods will be required on the hour and half-hour.

4) If electromagnetic voice communications and beacon responses are being received and no positive seismic signals have been received by surface geophones after repeated attempts to do so, the geophones planted at the beacon location will be used to attempt to receive such seismic signals at that point. The Beacon Transmitter and Receiver will be used to transmit the signal to the surface. If signals are received in this manner, these signals could be used to establish the exact times between the miners' blows, to more effectively use the signal processor to improve signal-to-noise ratios for the surface geophones. The signals received by the subsurface geophone would then be used with the best signals received on the surface for computation of location.

3.0 VOICE COMMUNICATIONS PROCEDURES

The following procedure will be used when initiating communications with the beacon location. An alert signal will be sounded during the 30 second off period between NORMAL beacon transmissions to attract the attention of miners at that location. The following messages should then be transmitted:

1) Calling Beacon Alpha - Calling Beacon Alpha (or other name of specific beacon locations), if you can hear this transmission, push the REPLY button and the YES button on your Beacon Transmitter. I repeat, push the REPLY and the YES button on your Beacon Transmitter.

2) Now, push each answer button for five seconds. Start with YES and push the other answer buttons in the order from left to right on the transmitter.

3) Is your reception of our voice signals good or bad? Note: after each of the questions the voice transmitter operator should indicate to the miners the response which he received.

4) How many men are at your location? Push the MANUAL key once for each person at your location.

5) Are you and all of the men at your location in good physical condition? Answer YES or NO. Note: if the answer is NO, message 5a will be transmitted.

5a) Are any of the men at your location seriously or critically injured? Note: if the answer is YES, we will proceed through a series of questions to determine the nature of the serious injury. This should include questions to determine if someone has had a serious loss of blood, is unconscious, is in shock, has broken bones, or has serious burns. Note: if the answer to 5a is NO, then we will inform the miners that we will determine the nature of their injuries in a few minutes.

6) Are you in any immediate danger at your location? Answer YES or NO. Note: if the answer is YES, we will proceed to ask the following questions:

6a) Can you safely remain at your present location for one hour?

6b) Can you remain at your present location for four hours?

6c) Can you remain at your present location for eight hours? etc., etc., until we determine their estimate of the period of time they can remain safely at that location. We will also determine the nature of their immediate danger e.g. fire, water, roof collapse, gas, etc.

7) Do you have adequate food and water? Note: if the answer is NO, we will proceed to determine the period of time which they do have adequate food and water.

8) We will now read a list of names of all men who may be trapped within the mine. We will ask the miner at the beacon location to send a YES or NO after each name is read. YES to indicate the man is at their location, NO to indicate that he is not at that location.

9) We will now read the names for which they replied NO to the previous message and ask them if they have any information about the location or condition of these men. If they respond YES to this question for any of the names, we will then proceed to message 10.

10) We will ask a series of questions to find out what information the men at the trapped miner location have about other men in the mine. These will be questions about the condition and location of other men within the mine, using mine entry designations.

11) At some point in time we will probably ask the men at this location to operate the Seismic Transmitter. We will give them specific instructions as to the number of times they are to operate this Seismic Transmitter. This will be done primarily for calibration of the location system, but also to determine the possible use of this transmitter for transmission of messages.

12) At some point in time we will probably ask the men at the beacon location to put the Beacon Transmitter and the voice receiver on SEISMIC mode for subsurface reception of hammer blows. They will be given specific instructions as to how to accomplish this and for what period of time the system should be left in the SEISMIC operation.

13) From time to time we will inform the men at the beacon location of rescue progress. We would also send them various other messages, such as messages from family to encourage them and to maintain morale.

14) Upon the completion of any series of messages or transmissions, the men at the beacon location will be asked to turn off the Beacon Transmitter and wait for further instructions from the voice receiver. They will also be informed that should an emergency arise such that they need to communicate with the surface that they should put the Beacon Transmitter back in the REPLY mode and then alternately push each answer from YES through BAD for five seconds. They should then wait for fifteen seconds to listen for a transmission from the surface. They should continue to repeat this procedure until they attract the attention of the surface operators. This procedure will alternately light all of the message lights on the Beacon Receiver and should attract the attention of any operator at that control panel.

THE QUESTIONS RELATIVE TO IMMEDIATE DANGER AND THE PHYSICAL CONDITION OF THE MEN SHOULD BE REPEATED AS OFTEN AS DEEMED NECESSARY AS PREVIOUS REPLIES AND KNOWN CONDITIONS WITHIN THE MINE DICTATE. THESE SHOULD BE THE FIRST QUESTIONS ASKED IF AN EMERGENCY SIGNAL IS RECEIVED FROM WITHIN THE MINE.

If the beacon transmissions cannot be received, an attempt will be made to obtain answers at the beacon location with the Seismic Transmitter. The following code will be used:

Messages	Number of Blows
YES	2
NO	4
DON'T KNOW	5
REPEAT	0
GOOD	3
BAD	6

A complete response to any one question using the Beacon Transmitter would consist of the above number of blows repeated three times with ten seconds between each group of blows.

This same message code could be used in obtaining information from an individual miner providing good signals are being received on at least one geophone from his hammer blows.

APPENDIX B

DESCRIPTION OF COMPUTER PROGRAM MINER AND LOCATION ERROR ANALYSES

CONTENTS

		Page
1.0	CONCEPTUAL DESCRIPTION OF MINER	B-1
2.0	EXAMPLE CALCULATIONS	B-2
3.0	THE EFFECT OF A LOW VELOCITY WEATHERED LAYER	B-10

LIST OF FIGURES

		Page
B-1	Example of Array Configuration	B-3
B-2	Ray Refraction Through a Low Velocity Layer ($V_1 < V_2$)	B-11
B-3	Location Errors Due to a Low-Velocity Layer (Source Near Array Center)	B-14
B-4	Location Errors Due to a Low-Velocity Layer (Source Near Array Edge)	B-15

APPENDIX B

DESCRIPTION OF COMPUTER PROGRAM MINER AND LOCATION ERROR ANALYSES

1.0 CONCEPTUAL DESCRIPTION OF MINER

The program is capable of carrying out the mathematics described in paragraph 3.1.3, using six, five, four, or three travel times. The program is executed on a time-sharing computer and input/output is via teletype. There is considerable user-machine interaction during execution. The program first asks:

> How many stations responded?
> (i. e., how many relative arrival times are available.)
>
> What are the arrival times?
> (Input times in seconds.)
>
> What are the array coordinates?
> (Input the x_i, y_i, z_i; i = 1, 2, . . . , N, in feet.)
>
> What is the velocity and estimated source depth?

After the operator has responded to these questions, the basic data needed for performing the location analysis is stored in the computer.

> How many stations per calculation?
> (This is the number of travel times to be used per calculation, M. It must be less than or equal to the total number of stations, N, and lie in the range 3 to 6.)

The program then proceeds to cycle through the N times-of-arrival, taking all possible combinations of M at a time and printing out $N!/[M!\ (N-M)!]$ solutions. The average values of the predicted source coordinates is then computed, and it is this average value which is normally taken as the final answer. There are several ways in which this average may be computed. The program first averages all the results. It then recomputes the average eliminating those points which have a "numerical trouble" flag, and those whose predicted z value is not within ± 60% of the estimated depth. If this procedure yields dubious results, the operator can eliminate any results he wants and average the remainder. Finally, he can change the number of times per calculation, or the velocity V can be changed, and the cycling procedure can then be reinitiated.

This philosophy of cycling through all possible combinations of a redundant number of travel times has been found to be an effective means of minimizing the sensitivity of the final location prediction to measurement error. In addition, the output format is such that there is a good possibility of detecting and identifying which, if any, of the measured times is especially inaccurate. This bad data may then be eliminated and the calculation recycled. If several of the times are very inaccurate, of course, any procedure will fail.

2.0 EXAMPLE CALCULATIONS

A great number of computer simulations have been carried out, but only one hypothetical array is included here. The predicted locations given in the examples are the average source locations calculated by program MINER. The surface location error (SLE) in the x-y plane is defined as:

$$SLE \equiv [(x - x_p)^2 + (y - y_p)^2]^{1/2} \quad \text{(feet)}$$

where (x_p, y_p) are the predicted source coordinates in the x-y plane, and (x, y) are the true coordinates.

Consider the geophone array shown in Figure B-1. The geophones are planted in a shape which approximates a hexagon, with one phone near the center. Two hypothetical source locations are shown -S_1 = (300, 120, 500) and S_2 = (400, 1360, 500). The z coordinates are assumed to be -260, -200, -350, 50, -450, -370, and -280 feet. (Recall that z is reckoned positive downward.) The seismic velocity is assumed to be 12000 ft/sec.

The SLE resulting from random time-of-arrival measurement errors were found by calculating the exact travel times and then adding random perturbations in the ranges ±0.1 ms to ±2.5 ms. The results of such an analysis for source S_1 are given in Table B-1. The RMS arrival time error is the root-mean-square of the seven timing errors, and the second column gives the maximum of the seven errors. The resulting SLE are shown (rounded to the nearest foot) as functions of the number of arrival times (M) used per calculation. (Hence, for M = 6, the predicted location (x_p, y_p) used in the SLE calculation was the average of seven sets of calculated x-y values.)

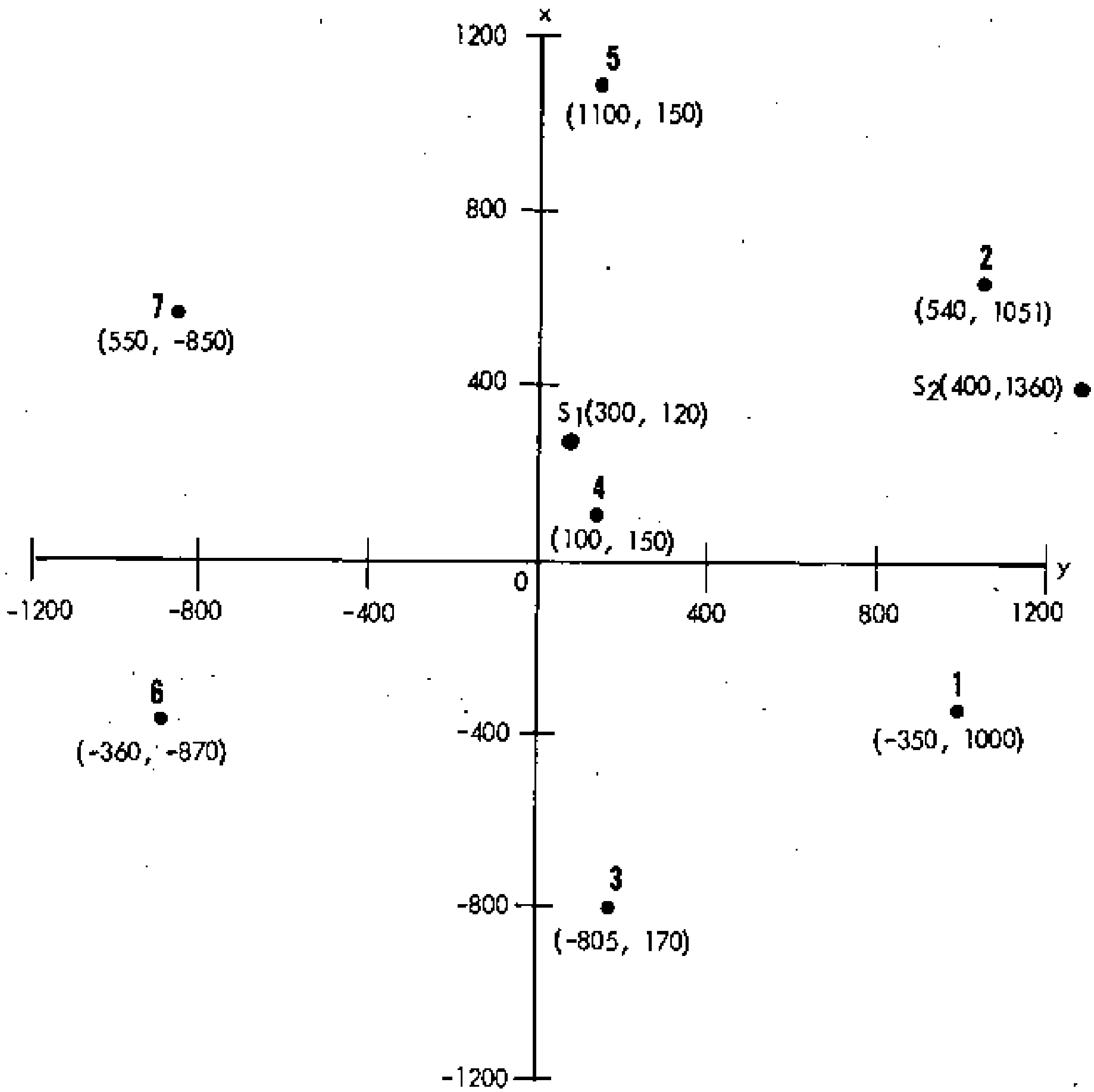


Figure B-1. Example of Array Configuration

TABLE B-1

LOCATION ERRORS VS ARRIVAL-TIME ERRORS FOR SOURCE LOCATION S_1

R.M.S. Arrival-Time Error (milliseconds)	Max. Arrival-time Error (milliseconds)	No. of Arrival Times per calculation	S.L.E. (feet)
0	0	6	0
		5	0
		4	0
.05	.09	6	1
		5	0
		4	0
.17	.25	6	4
		5	3
		4	4
.23	.47	6	9
		5	3
		4	4
.47	.80	6	13
		5	13
		4	11
.81	1.20	6	32
		5	11
		4	8
.99	1.89	6	23
		5	12
		4	8
1.62	2.25	6	49
		5	26
		4	26

In general, the SLE error increases rapidly as the source point moves outside of the array. This is illustrated by Table B-2, which gives results for the source at location S_2. (Only the (M = 5) arrival-time solutions are shown for brevity.)

These results, plus those from many other tests, show that, in general, time-of-arrival errors of ± 2 ms or possibly more can be tolerated and still have a SLE less than 20 feet provided that both the propagation velocity and the array coordinates are known accurately, and that the source point is kept within the array spread.

Table B-3 shows the effects of uncertainties in the propagation velocity, assuming exact time-of-arrival and coordinate data for the source at S_1. These results show that the predicted location is relatively insensitive to inaccuracies in V of as much as ± 25%, provided the other data is highly accurate.

Tests of the type just described are useful in determining the sensitivity of the location scheme to errors in the individual parameters, but obviously the cumulative effect of inaccuracies in <u>all</u> the data must be considered in order to describe the real-world situation. Fortunately, it turns out that those errors which tend to be truly random, such as the errors in arrival times and geophone coordinates, tend to average out to near zero when a redundant number of calculations are available for averaging. As an illustration of this, consider the same array (Figure B-1), assume a true velocity of 12000 ft/sec, and source location S_1. The data given to program MINER was as follows:

x_i = -351, 541, -804.2, 99, 1103, -362, 551

y_i = 1000, 1050.8, 171, 148.6, 151, -871, -851

z_i = -259.2, -198, -348, 49.3, -450, -368, -280

V = 10800 ft/sec

t_i = accurate to within ± 1 ms.

Hence, the coordinates are inaccurate by as much as three feet, the velocity is 10% low, and the arrival-time errors are described by the fifth set of data in Table B-1. Results from MINER are shown in Table B-4. The predicted locations are again the average x and y values calculated as described previously. Note that the three, four and five arrival-time solutions are quite close to the correct location.

TABLE B-2

LOCATION ERRORS VS. ARRIVAL-TIME ERRORS FOR SOURCE LOCATION S_2

(All results for 5 arrival times per calculation)

R.M.S. Arrival-Time Error (milliseconds)	Max. Arrival-Time Error (milliseconds)	S.L.E. (feet)
0	0	0
.08	.10	13
.18	.29	15
.25	.45	54
.60	.91	54
.75	1.30	120
1.36	1.86	46
1.22	1.85	36

TABLE B-3

LOCATION ERROR VS. UNCERTAINTY IN VELOCITY FOR SOURCE LOCATION S_1

(True V = 12000 ft/sec, all other data exact.)

Percent Velocity Error	S.L.E. (feet)
-25	6
-20	11
-15	10
-10	8
-5	5
0	0
+5	5
+10	9
+15	10
+20	14
+25	17

TABLE B-4

ILLUSTRATING THE COMBINED EFFECT OF ERRORS IN ALL THE DATA
(Source Location = S_1 = (300, 120, 500))

No. of Arrival Times per Calculation	Predicted Source xy Coordinates (feet)	SLE (feet)
6	(317, 122)	17
5	(307, 117)	8
4	(301, 109)	11
3*	(293, 114)	9

---

* The source depth was assumed to be known exactly in this solution.

As mentioned earlier, the calculations presented here are only a minute portion of the computer simulations carried out in the development of the location scheme. Generalities about expected accuracies are difficult to state, because each array geometry and source location one considers leads to different results. Obviously, the most critical data are the arrival times, and the accuracy to be expected in measuring them is a sensitive function of the available signal-to-noise ratios, which in turn depend upon the impulse strength and spectrum, the earth medium, the source location, etc. But even for a specified time-measurement accuracy, the location error depends upon the velocity and the source location. The few general conclusions which we have been able to draw from our theoretical studies of measurement error, layering effects (see paragraph 3.0 of this Appendix), and geometrical relations are as follows:

1) The source should be within the array spread.

2) The array spread should be greater than one third the source depth.

3) The array spread must be great enough so that the difference in arrival times between the two nearest geophones is considerably greater than the maximum anticipated timing uncertainty.

4) Errors due to layering effects are minimized when the array is nearly square and the source lies near the center.

5) Adequate accuracy can usually be obtained with:

   velocity error ≤ 20%

   coordinate errors ≤ 5 ft

   arrival-time errors ≤ 2 ms

6) The five and four arrival-time calculations are usually the most accurate (6 or 5 geophones). When N ≥ 7, the six arrival-time solutions are mainly useful for verifying the assumed velocity.

7) If the source depth is known accurately (± 10 ft), the four arrival-time solution with specified depth is often the most accurate.

3.0 THE EFFECT OF A LOW VELOCITY WEATHERED LAYER

The assumption of a seismic velocity V which is constant throughout the earth medium is of course never exactly correct, but, at the depths considered in the coal mine problem, an average velocity may often be used which will yield sufficiently accurate results. There is one important case, however, which departs from the simplest homogeneous model and which is relatively easy to analyze. Figure B-2 shows the geometry used to represent a horizontally layered earth with an upper ("weathered") layer of thickness h_1 and characteristic velocity V_1 over a medium with velocity V_2. The source depth is h feet below the layer boundary, and a ray is shown reaching a geophone after being refracted by an upper layer with $V_1 < V_2$.

The angles θ_1 and θ_2 are related by Snell's law:

$$\sin \theta_2 = \frac{V_2}{V_1} \sin \theta_1 \qquad \text{(B-1)}$$

By expressing the horizontal distance D in terms of h_1, h, θ_1, and θ_2 and using (B-1), there results a transcendental equation for θ_1:

$$\frac{h \sin \theta_1}{(V_1^2 / V_2^2 - \sin^2 \theta_1)^{1/2}} + h_1 \tan \theta_1 - D = 0 \qquad \text{(B-2)}$$

By specifying D, one may solve (B-2) by numerical iteration for θ_1, find θ_2 from (B-1), and hence infer the travel time to each geophone:

$$\Delta t_i = \frac{h}{V_2 \cos \theta_2} + \frac{h_1}{V_1 \cos \theta_1} \qquad \text{(B-3)}$$

A computer program (LAYER) was written to predict the effect of a low velocity layer for specified geophone geometry, layer thickness, velocities, and source location. The calculation proceeds as follows:

1) By means of the ray tracing procedure described above, solve for the actual travel-time to each geophone, Δt_i, $i = 1, 2, 3, \ldots N$.

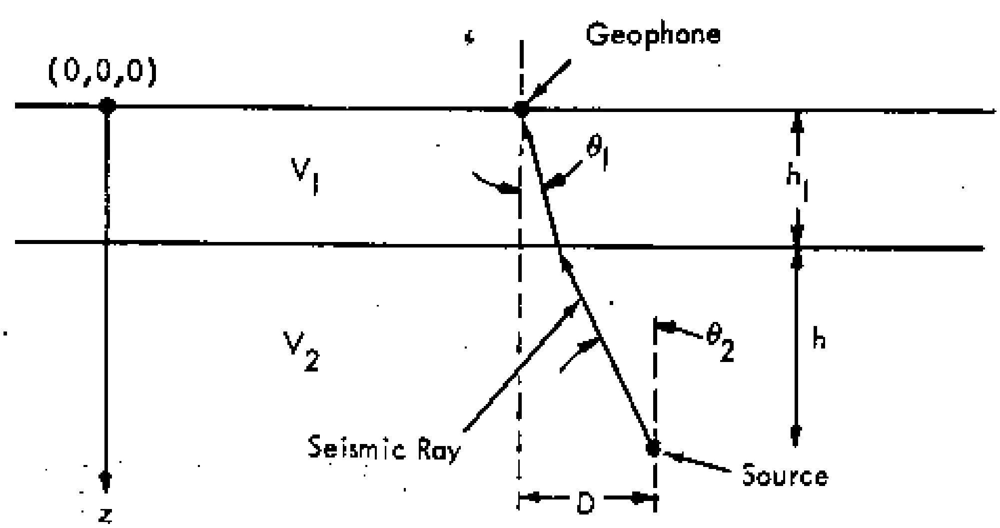


Figure B-2. Ray Refraction through a Low Velocity Layer ($V_1 < V_2$)

2) Add some arbitrary initiation time T to the Δt_i to obtain hypothetical arrival times, t_i.

3) Specify a set of effective velocities, $\bar{V}$, and use the homogeneous-earth procedures outlined previously to predict a source location corresponding to each velocity.

This procedure allowed us to define a "best" $\bar{V}$ which minimizes the error introduced by refraction through the upper layer. (No position-independent $\bar{V}$ exists which can reduce the error to zero.) The effective velocities which were used are:

$$\bar{V}_1 \equiv V_2 \qquad \text{(neglect weathered layer entirely)}$$

$$\bar{V}_2 \equiv \frac{V_1 h_1 + V_2 h}{h_1 + h} \qquad \text{("weighted average" velocity)}$$

$$\bar{V}_3 \equiv \left(\frac{h_1 V_1^2 + h V_2^2}{h_1 + h} \right)^{1/2} \qquad \text{("R.M.S." velocity)}$$

$$\bar{V}_4 \equiv \left(\frac{h_1^2 V_1^2 + h^2 V_2^2}{h_1^2 + h^2} \right)^{1/2} \qquad \text{("modified R.M.S." velocity)}$$

$$\bar{V}_5 \equiv \frac{V_1 V_2 (h_1 + h)}{h_1 V_2 + h V_1} \qquad \text{("time-weighted" velocity)}$$

In all of the many test cases tried, the "modified R.M.S." velocity gave as good or better answers as did any of the other effective velocities.*

---

* Except when the effect of the layer was quite small, in which case using $\bar{V} = V_2$ often gave slightly better results.

Some examples of the reduction in the SLE due to the use of the modified R. M. S. velocity are shown in Figures B-3 and B-4. Note that as the layer thickness, h_1, goes to zero in these figures, the SLE also becomes exactly zero; we are assuming exact timing information here, and hence the location errors shown are due entirely to the presence of the layering.

The SLE are much smaller in Figure B-3 than in B-4. This results from the proximity of the source x-y coordinates to the exact center of the array in the first case. In fact, the SLE would have been exactly zero if the source were directly under the center of the arrays, because in that case the additional time delay caused by the weathered layer would be equal at all the geophones, and hence would cancel-out in the final analysis. This fact tends to reduce the SLE due to a horizontally layered earth situation whenever the source is located in the vicinity of the array center. Although the travel time to any particular geophone may be significantly altered by the layer, the net result in the overall calculation is slight.

In summary, whenever a significantly thick, low velocity weathered layer overlies a higher velocity medium, we use the homogeneous earth analyses described previously, first with $V = V_2$, and then with an <u>effective</u> velocity defined by

$$\bar{V} = \left(\frac{h_1^2 V_1^2 + h^2 V_2^2}{h_1^2 + h^2} \right)^{1/2} \qquad \text{(feet/sec)} \qquad \text{(B-4)}$$

where the estimated layer thickness is h_1, its estimated seismic velocity is V_1, the estimated depth to source is $h_1 + h$, and the estimated lower medium velocity is V_2.

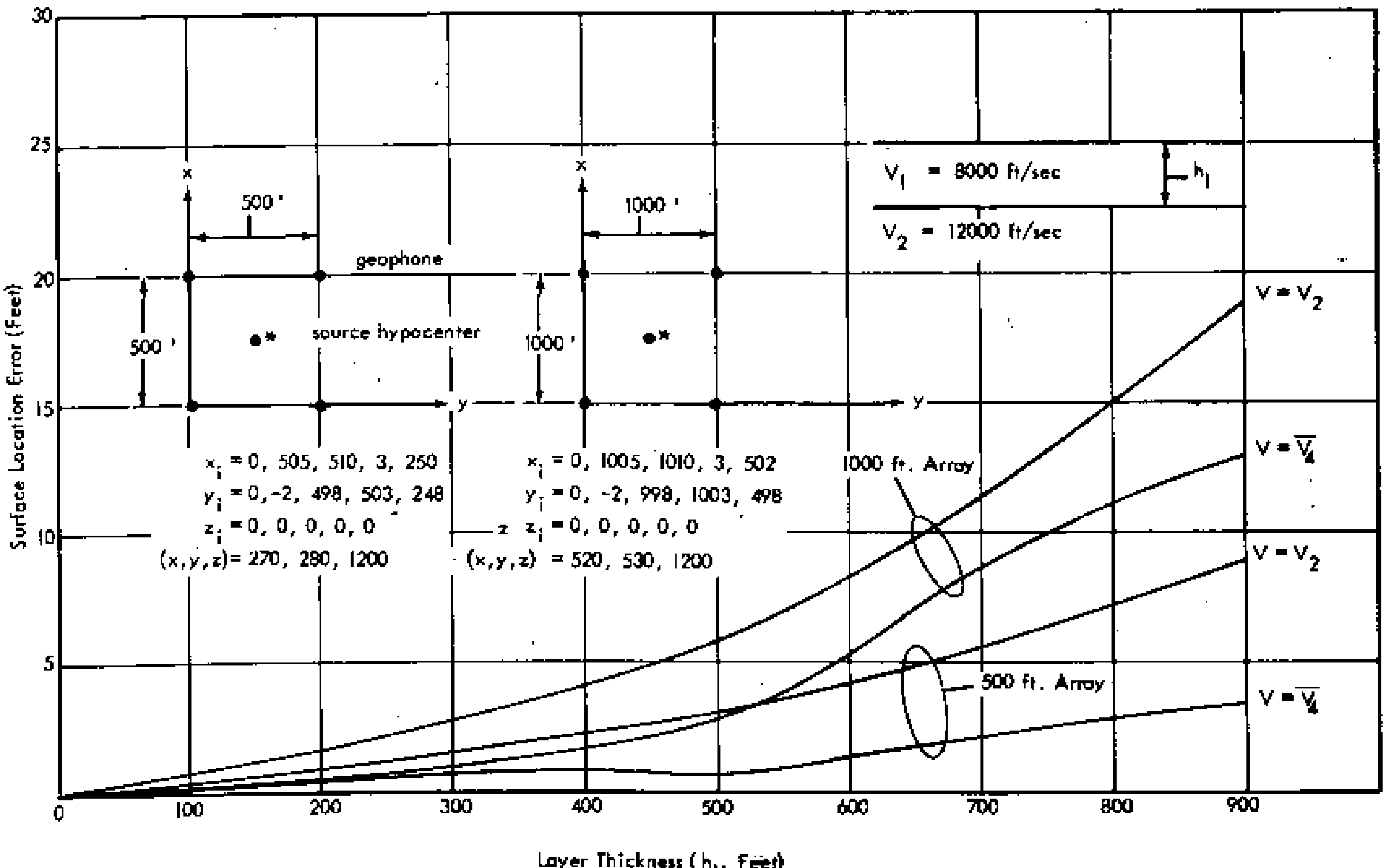


Figure B-3. Location Errors Due to a Low-Velocity Layer (Source Near Array Center)

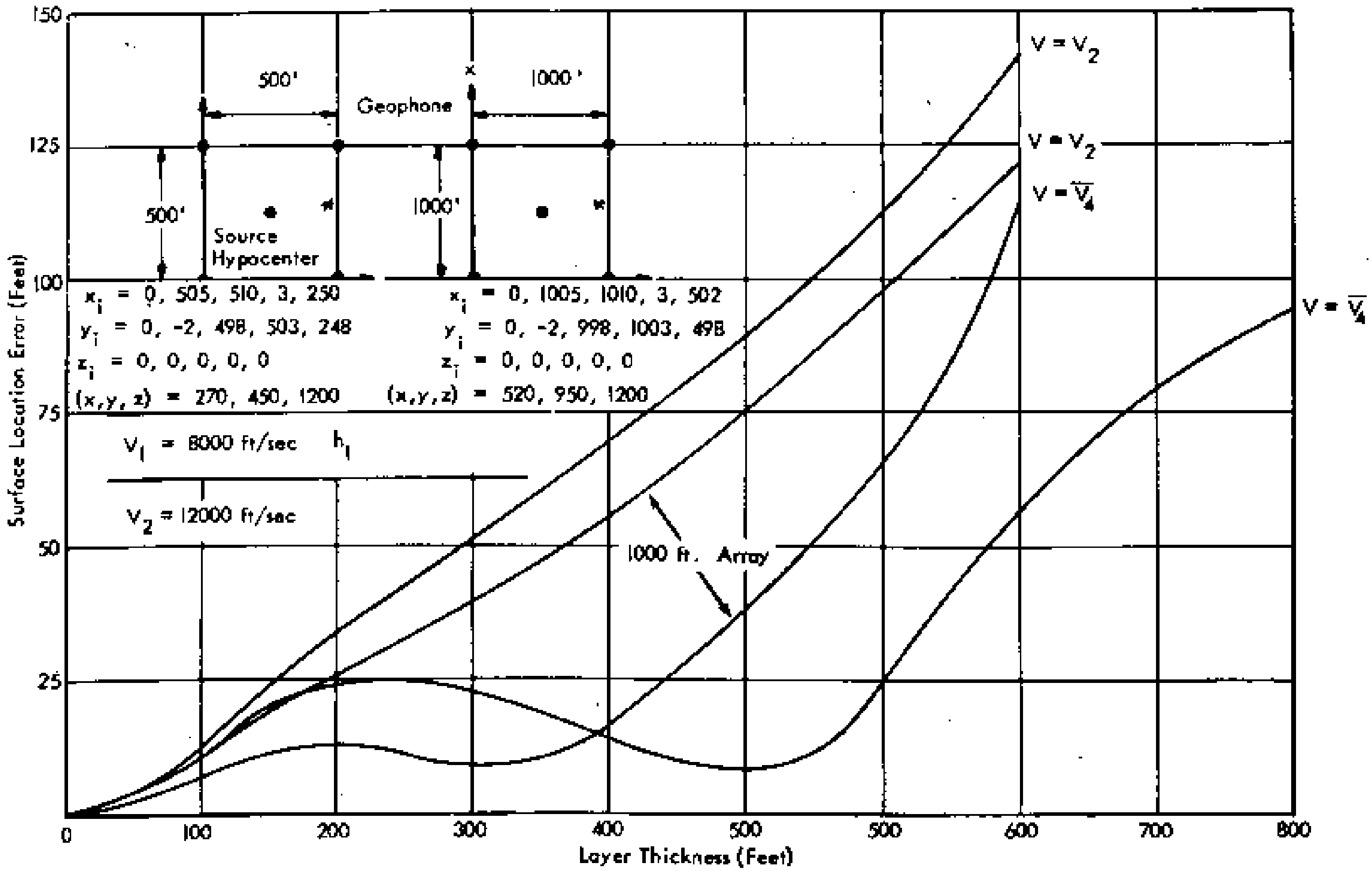


Figure B-4. Location Errors Due to a Low-Velocity Layer (Source Near Array Edge)

APPENDIX C

ELECTRIC BLASTING CAP HAZARDS AND EXPLOSIVE SEISMIC SOURCES

CONTENTS

		Page
1.0	INTRODUCTION	C-1
2.0	ELECTRIC BLASTING CAP HAZARDS	C-2
3.0	SEISMIC DOWN-LINK COMMUNICATION TESTS USING EXPLOSIVES	C-5
4.0	RESPONSE TO INQUIRY TO IME	C-9

APPENDIX C

ELECTRIC BLASTING CAP HAZARDS AND EXPLOSIVE SEISMIC SOURCES

1.0 INTRODUCTION

Two basic problems regarding explosives are considered here. The first relates to the potential electromagnetic hazards to electric blasting caps in mining areas and the second relates to seismic down-link signalling techniques.

It is well known that electric blasting caps can be detonated with radio frequency energy from communications transmitters operating at broadcast frequencies (540 kHz and above) and the Institute of Makers of Explosives (IME) have determined tables of minimum distances to various transmitters for the safe operation of electric blasting caps. It is not known, however, just what hazards if any exist for frequencies between 300 Hz and 3000 Hz where the communications subsystem operates. Paragraph 2.0 discusses this problem and suggests the safe operating distances for both the underground beacon antenna and the surface voice antenna.

Experiments made by Globe Universal Sciences at the Imperial Mine showed that considerable energy would have to be generated at the surface to provide an audible signal in the mine. Explosive charges were selected to meet this requirement. The problem was to determine methods of implacement, the type of explosives to use, how to prime and shoot them, and the amount of explosives necessary in order to communicate to miners below the surface. This work is described in paragraph 3.0.

2.0 ELECTRIC BLASTING CAP HAZARDS

Basic information on the mechanism of RF initiation tables of safe distances, and data on common RF sources are given by the IME.* The tables of safe distances were derived from analytical worst case calculations based upon an assumed 40 mW, no-fire level of commercial blasting caps.

---

* Radio Frequency Energy - A Potential Hazard in Use of Electric Blasting Caps, Inst. of Makers of Explosives, Safety Publication #20.

Westinghouse questioned the IME on several aspects of the problem. The results of this inquiry are included at the end of this Appendix in paragraph 4.0 for reference.

The theory of wave antennas was employed by the IME for electric blasting caps deployed within the fields emanating from various transmitting sources. It was assumed that the field structure from the broadcast band antennas was in the Fresnel (near) zone and that for higher frequencies, the caps were located in the Fraunhofer (far) zone. At the low operating frequencies under consideration, the IME correctly noted that the primary mechanism for induced currents would be simple magnetic induction since the magnetic flux would be the predominant factor.

Regarding the 40 mW, no-fire level, it was noted that members of the IME do not design commercial blasting caps with firing levels below 0.2 amperes, and with a conservative resistance of 1 ohm, the resulting power dissipation is 40 milliwatts. Stray currents caused by dc or 60 Hz ac power sources can deliver power to electric blasting caps very efficiently. For this reason, a safety factor of 5 was imposed by the IME to define the "potential hazard level" for stray sources of current which might come in direct contact with caps. The lowest firing level (0.25 amperes) was reduced to 0.05 amperes for a 1-ohm bridge wire to arrive at the following definition: "a stray voltage source capable of developing 50 mV or more across a 1 ohm resistance constitutes a potential hazard to commercial e.b. caps manufactured in the U.S.A. Note that 50 mV across 1 ohm represents 2.5 mW." The IME goes on to note that at frequencies above 28 MHz, the tables of safe distances are very conservative. The hazards in the broadcast band are less conservative in that "there is one chance in a thousand for premature initiation caused by induced RF in the broadcast band provided 1) the e.b. cap is perfectly matched to the pickup antenna, 2) the pickup antenna is ideal in configuration (tuning) and orientation, and 3) the pickup loop is located at a peak of a fringe in the Fresnel zone. The IME then concluded that "the possibility of simulating such circumstances in the 300-3000 Hz band are even more remote since such long blasting circuits are impractical, e.g., such long leading lines cannot be used to successfully initiate e.b. cap rounds." They recommended, nevertheless, that tests should be conducted to properly assess the hazard. These are described in the following paragraph.

2.1 ELECTRIC BLASTING CAP TESTS

DuPont No. 6 electric blasting caps with 10-foot leg wires were tested under safe conditions in a field near Boulder, Colorado. The caps were inserted into the soil a few inches to permit safe firing, and the lead wires were kept shunted until the test was ready to begin. The instrumentation included a Wavetech signal generator, an amplifier, matching transformer, a sensitive voltmeter, and a 1-ohm resistor with a voltmeter to indicate current level. Tests were run at frequencies of 60, 120, 200, 275, 500, 700, 1000, 2000, 2750, and 5000 Hz. At each frequency, the terminal voltage and line current were recorded at several steps as the voltage was increased to the firing point. From this data, magnitude of impedance and power dissipation in the cap were calculated. Since only 10 caps were used to complete these tests, there is an insufficient amount of data for statistical inference; however, the data for resistances falls within published figures and hence it is felt that these tests will be useful for estimating the potential hazards at ELF(300-3000Hz).

The IME definition that if 2.5 mW is dissipated in the caps, a potential hazard exists, is extremely conservative in the opinion of Westinghouse. It was found, in the Westinghouse tests, that with voltages in the range of 50 mV to 100 mV across the caps, gives a resistance of 1.5 ohms (+ 0.15 - 0.07) for ELF. From this, it was found that 2.5 mV will be dissipated when the current is about 48 milliamps. The Westinghouse tests showed that 100 to 500 mW was required to fire caps with currents in the range 250 to 550 milliamps. The firing voltage was in the range 450 to 900 mV and the resistance at the firing point was about 0.1 ohm higher owing to heating. Thus, even the 40 mW no-fire level is a conservative figure.

2.2 SUSCEPTIBILITY OF CAPS

How close can the electromagnetic communication antennas be to blasting caps? The IME suggests that there does not appear to be an RF initiation hazard in the normal storage and transportation of electric blasting caps, as long as they are in their original carton. The calculations discussed below show further that there is only a remote chance for initiating e.b. caps when they are deployed for maximum coupling to either the underground beacon antenna or the voice antenna on the surface. Therefore, caps which are in the original packaged condition, should never be initiated by electromagnetic radiation from the beacon or the voice transmitter. The calculations are based on the characteristics of No. 6 instantaneous electric blasting caps.

As suggested by the IME, magnetic induction was considered to be the most hazardous mechanism. Considering an electric cap with the lead wires shunted, the maximum ELF induction will occur when the lead wires are arranged in a circular shape so as to enclose a maximum area. The equivalent circuit for each cap is simply the resistance of the wire in series with the resistance of the cap, and if several caps are connected in series and arranged in a circle which is immersed in a uniform magnetic field with flux normal to the loop, the current that is induced into the shorted circuit is given by:

$$I_i = 8\pi^2 \times 10^{-7} \frac{fAH}{R}$$

where

f = frequency, Hz

A = area of loop, M^2

H = magnetic field intensity, amps/meter

R = total series circuit resistance in ohms

This equation was used to calculate the currents induced into various blasting cap configurations using large areas, a frequency of 3000 Hz, and the maximum transmitting currents which may be realized with the beacon and voice transmitter.

In the mine it was assumed that the worst condition would be in conventional mining where a face has been drilled and loaded with 10 shots distributed over the face having an area of 10 feet by 20 feet. Each cap is assumed to have a resistance of 1.5 ohms, and for caps used in the mine with iron leg wires the total resistance is 4.5 ohms for each cap and leg wire. Conditions were calculated under which a current of 40 milliamps would be induced into the cap circuit. It was found that a magnetic field of 2.25 amperes per meter would induce 40 milliamps into the 10-cap circuit. Since the maximum magnetic field generated by the beacon will be less than 3 amps per meter in the center of the loop antenna, the chance for initiating electric caps would be extremely remote. If a single cap with 16 foot leg wires was arranged in a loop inside of the beacon antenna loop for maximum coupling, it was found that a magnetic field of about 1.5 amps per meter would induce about 40 milliamps into the cap loop.

For the voice antenna on the surface, calculations were based on the field next to an infinitely long wire carrying less than 3 amps of current which will generate a magnetic field less than 0.5 amperes/meter per meter of distance separation. Assuming that the electric caps are connected in series to form a loop, then a uniform field of 0.5 amperes per meter in the resulting loop would induce about 100 milliamps. These calculations indicate that it would only be necessary to move the transmitting antenna wire far enough from the shot holes so that the blasts do not break the wire. This should be sufficient spacing to also insure against electromagnetic initiation of the caps by this antenna.

In December 1970, experiments were performed at the Harewood Mine in West Virginia to determine a susceptibility of an electric blasting cap to magnetic fields radiated by the voice antenna. The experiments were conducted at one end of the voice transmitter near the grounding electrode where there would be large conducting earth currents as well as stakes driven vertically into the ground in line with the antenna and separated ten feet.

The ground stakes were salted for good contact, and the surface soil was muddy with standing water in the vicinity. No. 6 instantaneous electric caps were used and inserted into the ground near the center stake of the electrode and separated one foot from it. The lead wires were then arranged in the following five configurations: 1) both lead wires close together and shunted and extended parallel to the antenna, 2) the lead wires were separated to form a circle of wire at the side of the antenna wire, 3) the circle of wire was crossed over the antenna wire, 4) the 40-foot lead wires were separated (shunt removed) and laid out parallel to the antenna wire but not grounded at the ends, and 5) the ends of the 40-foot leg wires were scraped to bare wire for two inches and grounded in wet mud. The voice antenna was carrying one ampere of current at 1000 Hz. A Dupont No. 6 electric blasting cap with 40-foot leg wires failed to detonate under the five different configurations. This confirmed the relative safety of operating the voice transmitter within a few feet of deployed electric blasting caps.

3.0 SEISMIC DOWN-LINK COMMUNICATION TESTS USING EXPLOSIVES

3.1 IMPERIAL MINE

The dropped-weight experiments performed by G.U.S. at the Imperial Coal mine in Colorado showed that a 100-pound weight dropped a distance of six feet at the surface produced signal detectable only by geophones in the mine 300 feet below, whereas explosive charges at the surface were easily heard by the ear at this depth. Based on these results, explosive shots were selected for down-link signalling since the amount of energy imparted to the ground could be readily increased as necessary through the proper use of additional explosives, the choice of types of explosives, and the method of implacement.

The seismic refraction experiments performed by G.U.S. utilized Nitramon S blasting agents as a source. This powder is conveniently packaged into rigid, highly water resistant, charges. Several shots were discharged using loads from 1 pound to 5 pounds per shot with both single and double shots being fired. The powder used was Nitramon S and was loaded in 6-inch diameter holes bored 15 feet into the surface soil. Since the holes had water in them, it was necessary to attach weights to the charges to insure that they would be planted at the bottom of the hole as the unweighted charges tended to float. Clay and loam were put back into the hole around each charge and carefully tamped for a total depth of 2 to 3 feet above the charge. Since the charge column was usually canted in the hole, it was difficult to insure thorough stemming around the charge to improve coupling to the ground.

Observers were positioned in the mine directly below the shot holes (300 feet) and at other locations out to a slant range of 800 feet. The 1 pound and 2 pound shots produced only a light thud at the closer locations and was weakly audible at slant ranges of 500 feet. Two 3-pound shots fired with two-second separation were audible out to 580 feet. A 4-pound shot, which was planted so poorly that the hole blew up, was barely audible directly under the shot hole. The 5-pound shot sounded like a dull thump at a slant range of 800 feet.

The results of these explosives tests indicated: 1) a conformable charge which would have more intimate contact with the walls of the hole would be preferable to the packaged charges like Nitramon S, 2) the use of coded charges will require construction of a switch box with which one blasting machine can be used to set off several charges in sequence, 3) charged holes must be very carefully stemmed to insure that energy will propagate down rather than up, 4) electric firing (e.b. caps) is preferable to firing with safety fuse because the firing sequence can be controlled within seconds, and 5) that additional experiments should be performed in an eastern mine with the assistance of an explosives contractor, 6) future tests will include the use of delay caps.

3.2 HAREWOOD MINE

Additional tests were conducted in December at the Harewood Mine in West Virginia using the services of Explosives Engineering, Inc., South Charleston, West Virginia. The objectives of these tests were to determine the minimum and maximum charge size, the minimum and maximum depths of placement holes, the minimum spacing between shots for audible resolution, and to demonstrate communications using coded shots.

Explosives Engineering personnel recommended that drilling in West Virginia be accomplished with a pneumatic crawler type of drill to facilitate operation in the rugged West Virginia mountains. The 600 cfm drill that was recommended was limited to drilling holes 3 1/2 inch diameter using up to ten 10-foot long steels. They also suggested that the depth should be deep enough to insure that charges would be placed in good competent formations. It was further recommended that a conformable explosive, such as DuPont Pelletol, be used which is easy to pour, provides 100% conformity with the hole, is resistant to water, and is safe to transport. The powder was primed with HDP-3 primers (1/3 pound equivalent) and detonated with DuPont No. 6 electric caps. To insure that a maximum amount of energy be imparted to the ground, it was recommended that each hole be firmly stemmed with soft soil or sand to the top and used only once.

Surface locations were located on an old strip mine bench approximately 650 feet above the Eagle coal seam entry. Two other mined out seams were located between the Eagle and the bench (Powelton), and the No. 2 Gas. The Powelton seam was approximately 150 feet above the Eagle seam and the No. 2 Gas seam was approximately 40 feet above the Powelton. The existence of these mined-out levels may have adversely affected the seismic signal transmissions.

Sixteen holes, each 30 feet deep, were drilled on 15-foot centers using a 3 1/2 inch beaded bit. The holes, penetrating hard sandstone and some thin shale layers, each took approximately 20 minutes to drill. The three observers in the mine were positioned at 500-foot spacings along the entry approximately under the shot location. There was radio communication between the shooting station and the seismic observing vehicle and telephone communications between the vehicle and the observers in the mine. This setup permitted coordinating the surface activities with the mine activities to insure quiet conditions.

The first two shots of 30 pounds and 50 pounds respectively were not heard by any of the observers. The third shot consisted of 120 pounds of Pelletol loaded in two holes and may have been heard by one of the observers. The final shot, 400 pounds of Pelletol loaded in six holes, was heard and felt by two observers and not heard by the third. The stemming was not blown out by any of the shots; however, gases were occasionally vented through unloaded holes giving evidence to some fracturing in the medium.

A telephone conference was held several weeks later with Dr. Ronald Rollins in the University of Missouri, at Rolla, Rock Mechanics and Explosives Research Center. An involved discussion regarding the problem of imparting sufficient explosive energy to the ground so as to be audible in the mine produced the conclusion that one should use the highest velocity explosives obtainable, load the holes to provide good coupling to the earth, and finally use sound probes in the mine to pick up minute vibrations in the rock. DuPont Pelletol, with an explosive velocity of 15,200 feet per second, is considered a relatively high velocity explosive in contrast to many of the permissible type explosives which range from 6,000 to 9,000 feet per second. The Nitramon S, with a velocity of 11,800 feet per second, is fairly high velocity; however it is very difficult to obtain good coupling unless Pelletol would be used to fill the annular space around the Nitramon charge column. Dr. Rollins suggested that various military high explosives, with velocities in the range of 25,000 - 30,000 feet per second, would probably be highly suitable for our uses but are relatively hard to obtain. It was suggested that the use of millisecond delays between individual holes could produce impulses in the mine which may generate more energy in the audible frequency range. Dr. Rollins did not hold high promise for this approach since reflections and interference in the earth will probably affect the waves and mitigate any control which may be initiated with delay firing.

3.3 U.S. STEEL NO. 14 MINE

At the U.S. Steel No. 14 mine near Gary, West Virginia, the geology and physical environment were very similar to those at the Harewood Mine. The shot holes were located 840 feet above the coal seam and offset 1800 feet from the observers giving a slant range of about 2000 feet to the observers. The 3 1/2 inch diameter holes were drilled to a depth of 41 feet. It took 30 to 40 minutes to drill each hole in the hard sandstone and shale formations.

The communications van was in communication with observers stationed at two locations in the mine approximately 500 feet apart. Five different shots were fired with loads ranging from 10 pounds to 220 pounds with the following results. A 220 pound shot was heard at both locations, of two 110 pound shots only the second shot was heard at one location; two 220 pound shots three seconds apart were heard at both locations; a 40 pound shot may have been heard with the geophones, and a 10 pound shot was not heard with the geophones. The 220 pounds per shot required two holes each containing 110 pounds of powder. Two of these two-hole shots were detonated with a delay of 17 milliseconds while the others were detonated instantaneously. Although not conclusive, the instantaneous shots appeared to be louder. One observer listened for shots by placing his ear on the shoring timber and felt this enhanced detectability. The highly competent sandstone formations along with the absence of mined-out layers undoubtedly contributed appreciably to the ability to hear explosive shots in this mine.

3.4 CONCLUSIONS

The following observations and conclusions can be stated regarding the use of explosives for down-link communications.

1. Use the highest velocity explosives obtainable.
2. To obtain maximum coupling between the explosives and the earth, use conformable charges in fully stemmed holes.
3. The presence of mined-out sections between the surface and the observer will probably affect the signal strength.
4. Set off charges where there is the thinnest section of solid earth between the source and observer consistent with the ability to drill holes.
5. There is little to gain in arranging patterns of shot holes or in using delay firing.
6. Observers in the mine should use sounding bars and/or geophone amplifiers to pick up acoustic waves in the rock.
7. In the deeper eastern mines, several hundred pounds of powder per shot will probably be required to insure that signals will be heard in the mine.

4.0 RESPONSE TO INQUIRY TO IME

The following questions and answers are the result of correspondence between Westinghouse and the Institute of Makers of Explosives (IME*).

Question - We anticipate radiating energy in the ELF range, i.e., frequencies below 3000 Hz. Since Safety Publications No. 20 did not cover frequencies below 540 kHz, do you have supplemental information regarding hazards in the ELF frequency range?

Answer - "In the preparation of IME Pamphlet 20, only standard radio communications frequencies were considered. Except for the broadcast band, radiation patterns and field intensities were assumed to follow known formulas applicable to the Fraunhoffer zone in air for which typical blasting circuit configurations might be made sensitive. For the broadcast band, the level of hazards were evaluated at distances from the source antenna which are in the near or Fresnel zone where fringes lead to unpredictable field strengths.

---

* M. M. Champion, IME Technical Committee, 420 Lexington Avenue, New York, N.Y. Letter dated November 30, 1970.

"Although we do not know the greatest linear dimension of the ELF antenna under consideration, we suspect that it will be relatively long, perhaps a quarter wavelength, and that the Fresnel zone would include the underground mine area blast site. At such low frequencies and long wavelengths relative to typical blasting circuits, the primary mechanism for induced currents would be simple magnetic induction since the magnetic flux would be the predominant factor (e.g., power transmission lines are 60 Hz radiating antennas)."

Question - Page 8 of Safety Publication No. 20, mentions that the no-fire power dissipation level for commercial blasting caps is 40 milliwatts. How conservative is this figure, how was it determined, and is it typical for approved coal mine e.b. caps?

Answer - "The no-fire level of 40 mW was evaluated by FIRL as being 99.9% reliable with 95% confidence at both 150 and 450 MHz for domestic commercial e.b. caps. It is applicable to continuous wave radio frequency induced currents since the thermal response time of e.b. caps is very much longer than the reciprocal (period) of the radio frequency. Hence, an e.b. cap does not "follow" the RF amplitude, but responds to the effective or rms induced current. An e.b. cap begins to follow Hertz-induced currents (half-cycle period of ~ 8 ms), since the response time of commercial e.b. cap ignition systems are typically in the order of 5 to 10 ms."

"Typical d-c firing levels for domestic e.b. caps range from 0.25 to 0.5 ampere for one-ohm bridge wire ignition systems. Members of the IME do not design commercial e.b. caps with firing levels below 0.2 ampere, hence the 40 mW no-fire level."

"Stray currents caused by dc or 60 Hz ac power sources can deliver power to e.b. caps very efficiently. For this reason a safety factor of 5 was imposed to define the "potential hazard level" for stray sources of current which might come in direct contact with e.b. caps. The lowest firing level (0.25 amperes) was reduced to 0.05 amperes for a 1-ohm bridge wire to arrive at the following definition: a stray voltage source capable of developing 50 mV or more across one-ohm resistance constitutes a potential hazard to commercial e.b. caps manufactured in the U.S.A. Note that 50 mV across one ohm represents 2.5 mW."

"The efficiency with which higher frequency currents can be induced in e.b. cap circuits is considerably less than 100%. The efficiency of a vertical loop circuit is maximized at approximately 2 MHz. The 0.25 ampere effective current level in a 1-ohm bridge wire represents 2.5 mW. The 40 mW no-fire level corresponds to 0.2 ampere in a 1-ohm resistance. With 40 mV as a basis, theoretical calculations were used to define the maximum safe distances from sources of transverse electromagnetic radiation. The most efficient radiating antenna designs for each frequency were assumed to be lossless, ideally polarized, and have the maximum theoretical effective aperture (maximum gain). Similar ideal situations were applied to the receiving antenna and, in addition, the e.b. cap load circuit was assumed to be perfectly matched to the loop or dipole receiving antenna. These calculated induced power levels were then compared with field measurements conducted under idealized situations at 28.8 MHz, 159 MHz, and 462 MHz, and in each case the measured values were significantly below calculated values by orders of magnitude(factors of 10). Hence the tables of safe distances in these bands are very conservative."

"This is not the case for the broadcast band where measured power levels are essentially equal to calculated levels and did produce 40 mW at the minimum safe distance table. However, the pickup antenna in this case was in the Fresnel region, perfectly matched to the 1-ohm load and was in an ideal configuration. If the 40 mW no-fire level is considered to possess a 0.1% probability for firing with 95% confidence (tested at 150 MHz and 450 MHz frequencies by Bruceton methods) we must conclude that there is one chance in a thousand for premature initiation caused by induced RF in the broadcast band provided: 1) the e.b. cap is perfectly matched to the pickup antenna, 2) the pickup antenna is ideal in configuration (tuning) and orientation, and 3) the pickup loop is located at a peak of a fringe in the Fresnel zone. These circumstances are to be avoided by following instructions in Pamphlet 20."

"The possibility of simulating such circumstances in the ELF band are even more remote since such long blasting circuits are impractical, e.g., such long lead lines cannot be used to successfully initiate e.b. cap rounds. Nevertheless, tests should be conducted in this band to properly assess the hazard. Undoubtedly, losses in the earth will be variable depending on the conductivity of the soil and on the geology of the region."

Question - Can you make any suggestions regarding the field testing of e.b. caps? We have some experience with their use in routine rock blasting.

Answer - "Field tests should not be conducted with live e.b. caps. Squibs (ignition systems) may be used, but the preferred method involves power measurements using a simulated e.b. cap impedance. Bruceton no-fire tests should also be conducted on all commercial e.b. caps at the proposed frequency to establish the sensitivity level."

Question - Are there any other hazardous blasting situations in the coal mine environment which might be endangered by our seismic or electromagnetic equipment?

Answer - 'Relatively high induced voltages in mine shaft equipment, including hoist cables which can cause sparking, are hazardous in terms of igniting mine gas. Overland antennas are also invitations to lightning hazards unless special precautions are taken."

"Radiation of electromagnetic energy is a direct health hazard to personnel at specific (high) power densities and/or field strengths. Safe levels for the EM spectrum are defined by the American Standards Association under C95 Committee activities. Induced voltages in conducting members of hoist cables and the like, are potential electric shock hazards to personnel, and in the ELF band the electric shock would penetrate below the skin to the nerve system, unlike RF burns which are superficial."

APPENDIX D

GEOPHYSICAL DATA BASE

CONTENTS

		Page
1.0	INTRODUCTION	D-1
2.0	GEOLOGICAL CHARACTERISTICS	D-1
3.0	ELECTROMAGNETIC CHARACTERISTICS	D-3
4.0	SEISMIC CHARACTERISTICS	D-8
5.0	BIBLIOGRAPHY	D-30

LIST OF FIGURES

		Page
D-1	Major Coal Regions in the United States	D-2
D-2	Maximum Overburden Thickness for Each Coal Region	D-4
D-3	Thickness of Weathered Layer in Major Coal Regions	D-5
D-4	Typical Structural Section from the Eastern U.S. Coal Regions	D-6
D-5	Distribution of Coal by Age	D-7
D-6	Variation of Typical Atmospheric Noise Spectra with Depth	D-9
D-7	Effective Conductivity Values for the United States	D-10
D-8	Average Conductivity versus Age of Formation for Various Rock Types	D-11
D-9	Resistivity of Coal Relative to Ash Content	D-12
D-10	Average Velocity of Overburden Rocks in the Major Coal Regions	D-14
D-11	Variation of Velocity with Depth and Age	D-15
D-12	Multiple Axis Trade-Off Curve for Estimating Attenuation	D-19
D-13	Noise Waves versus Useful Seismic Information	D-21
D-14A	Seismic Noise for Region No. 1	D-23
D-14B	Seismic Noise - Region No. 1 - Also Wind Noise	D-24
D-14C	Seismic Noise - Region No. 3	D-25
D-14D	Seismic Noise - Regions 5 and 7	D-26
D-14E	Seismic Noise - Regions 6 and 8	D-27
D-14F	Seismic Noise - Region 7	D-28
D-14G	Seismic Noise - Region 8	D-29

APPENDIX D

GEOPHYSICAL DATA BASE

1.0 INTRODUCTION

The Geophysical Data Base contains the information necessary to characterize coal mine environments in the various coal regions of the United States. Although information is not detailed, it does provide a starting point for gathering specific on-site measurements. The geological and geophysical information in the data base will aid in adapting communication systems to the varied coal mine environments that exist.

Areas covered are Geological Parameters, Electromagnetic Parameters and Seismic Parameters for the eight coal regions shown in Figure D-1. The final section of this Appendix contains a list of references to be consulted for more specific data.

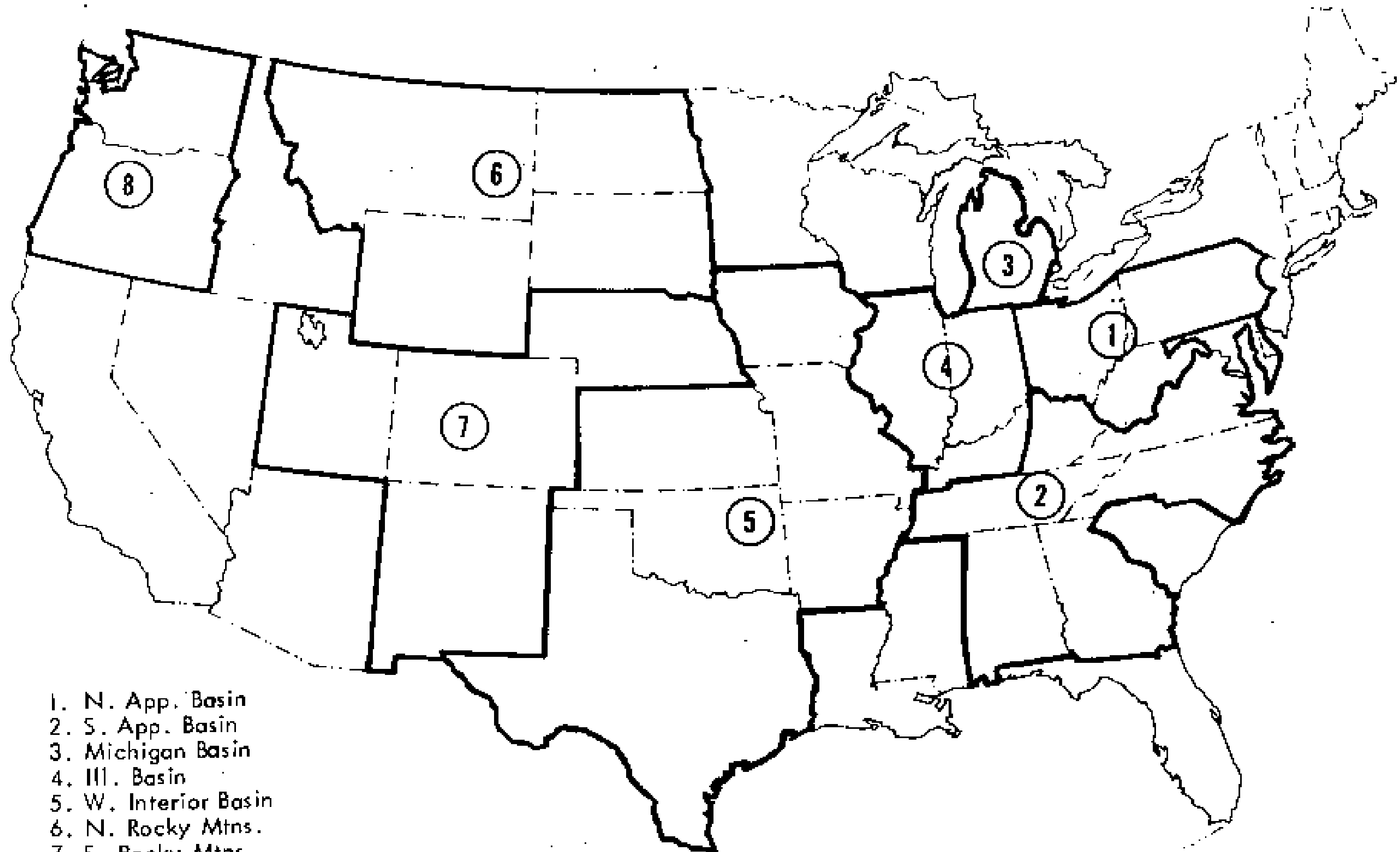
2.0 GEOLOGICAL CHARACTERISTICS

Knowledge of the geology and geologic environment is important for efficient application of electromagnetic and seismic communications. Features such as stratigraphy, structure, lithology, and age are significant from an engineering standpoint since they may determine the limits of effectiveness for a communications system. Each of these is discussed here as they pertain to the coal mining regions and the application of the CMR&SS.

2.1 STRATIGRAPHY AND LITHOLOGY

The stratigraphy and lithology of the overburden in coal mine regions is, for the most part, consistent. Usually the stratigraphic column consists of a weathered layer over a repetitious sequence of sandstone, shale, clay and coal. In many cases, the beds are so intermingled that seismically they appear to have one velocity. This feature is significant because it implies a more continuous travel path for the upward traveling seismic wave. Detailed stratigraphic successions and lithologic descriptions are given in Ⓦ Special Systems Report covering Coal Mine Characterizations.

Perhaps even more important than the actual geologic content of the stratigraphic column in a coal mine region is the thickness of



1. N. App. Basin
2. S. App. Basin
3. Michigan Basin
4. Ill. Basin
5. W. Interior Basin
6. N. Rocky Mtns.
7. S. Rocky Mtns.
8. West Coast

Figure D-1. Major Coal Regions in the United States the rocks overlying the coal and the thickness of the weathered layer. Since seismic energy decays with increasing distance from the source, the overburden thickness may severely limit the usefulness of uplink seismic communications. Similarly, seismic energy decays faster in low velocity medium, such as the unconsolidated soils and gravels lying near the surface. As a result, a thick weathered layer may preclude the use of surface detectors for uplink seismic communications.

The actual attenuation mechanisms of overburden and the weathered layer are discussed later in this section. Maximum overburden thicknesses were tabulated for the data base and are shown on the map in Figure D-2. Similarly, average weathered layer thicknesses are shown in Figure D-3. Weathered layer thickness depends to a large extent on topography. Valleys tend to have thicker weathering deposits than do hill tops. Exact information regarding the weathered layer must be obtained at the disaster site as is needed.

2.2 STRUCTURE

The geologic structural features of a coal mine can be important to through-the-earth. Large dips, as exist in several coal regions, can alter energy travel paths and result in incorrect and inaccurate location calculations. Figure D-4 shows some of the structural configurations for eastern United States coal fields. By far, the majority of coal mines lie in areas where extreme structural features are absent.

2.3 GEOLOGIC AGE

The geologic age of coal formations can imply much about the nature of the overburden. As will be shown later, seismic velocity and conductivity seem to have a direct relationship to geologic age. Figure D-5 shows the distribution of coal bearing formations relative to age.

3.0 ELECTROMAGNETIC CHARACTERISTICS

Consideration of EM characteristics of coal mine environments falls in two categories: actual conductivity values for the overburden material, and background noise. Only general information is given for the EM data base concerning conductivities and background noise. The reasons for this are: 1) although conductivities can be estimated regionally with reasonable accuracy, local anomalies almost always exist, and 2) conductivity readings are easy and inexpensive to make and, should the situation demand, on the site readings can be made quite easily.

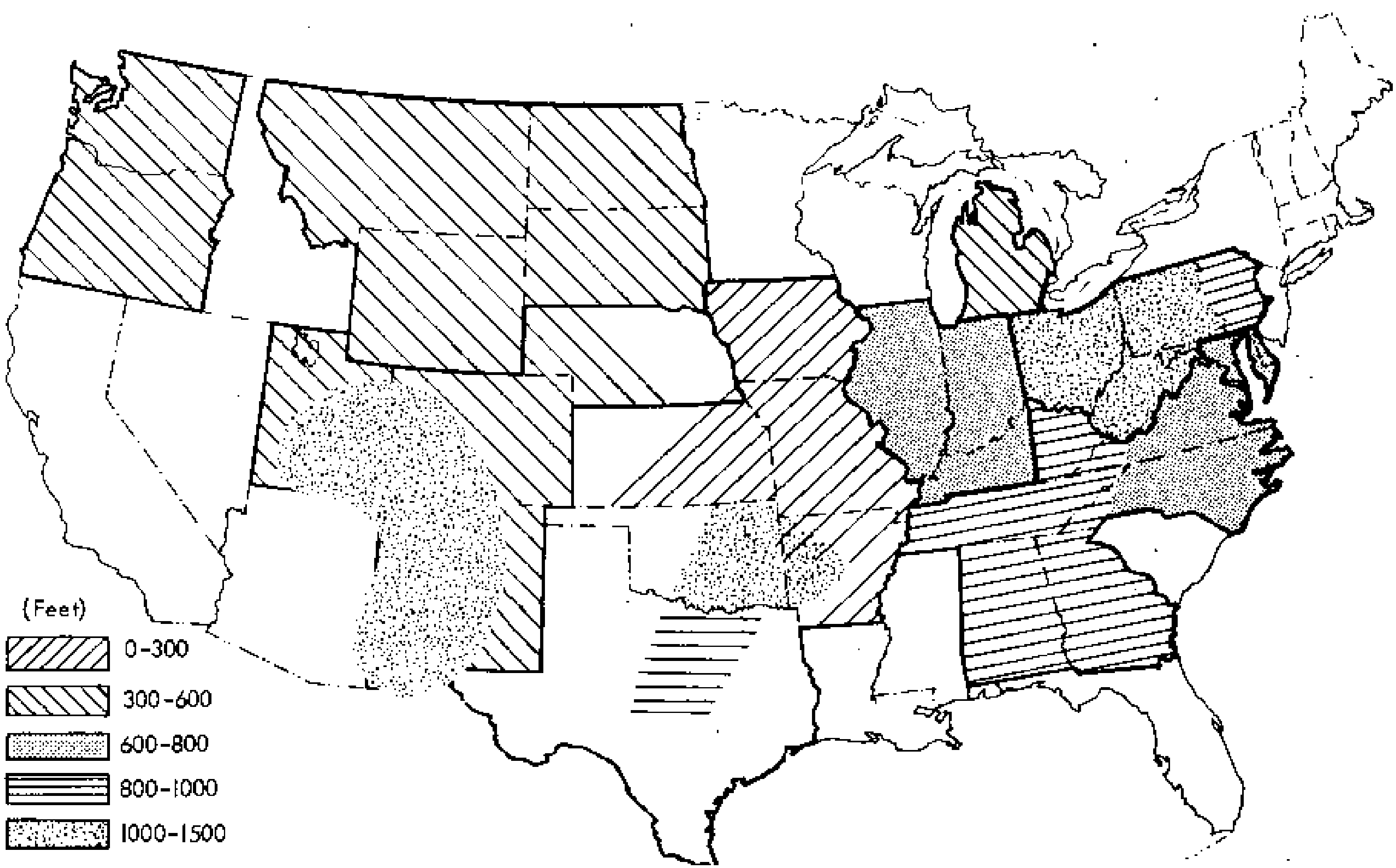


Figure D-2. Maximum Overburden Thickness For Each Coal Region

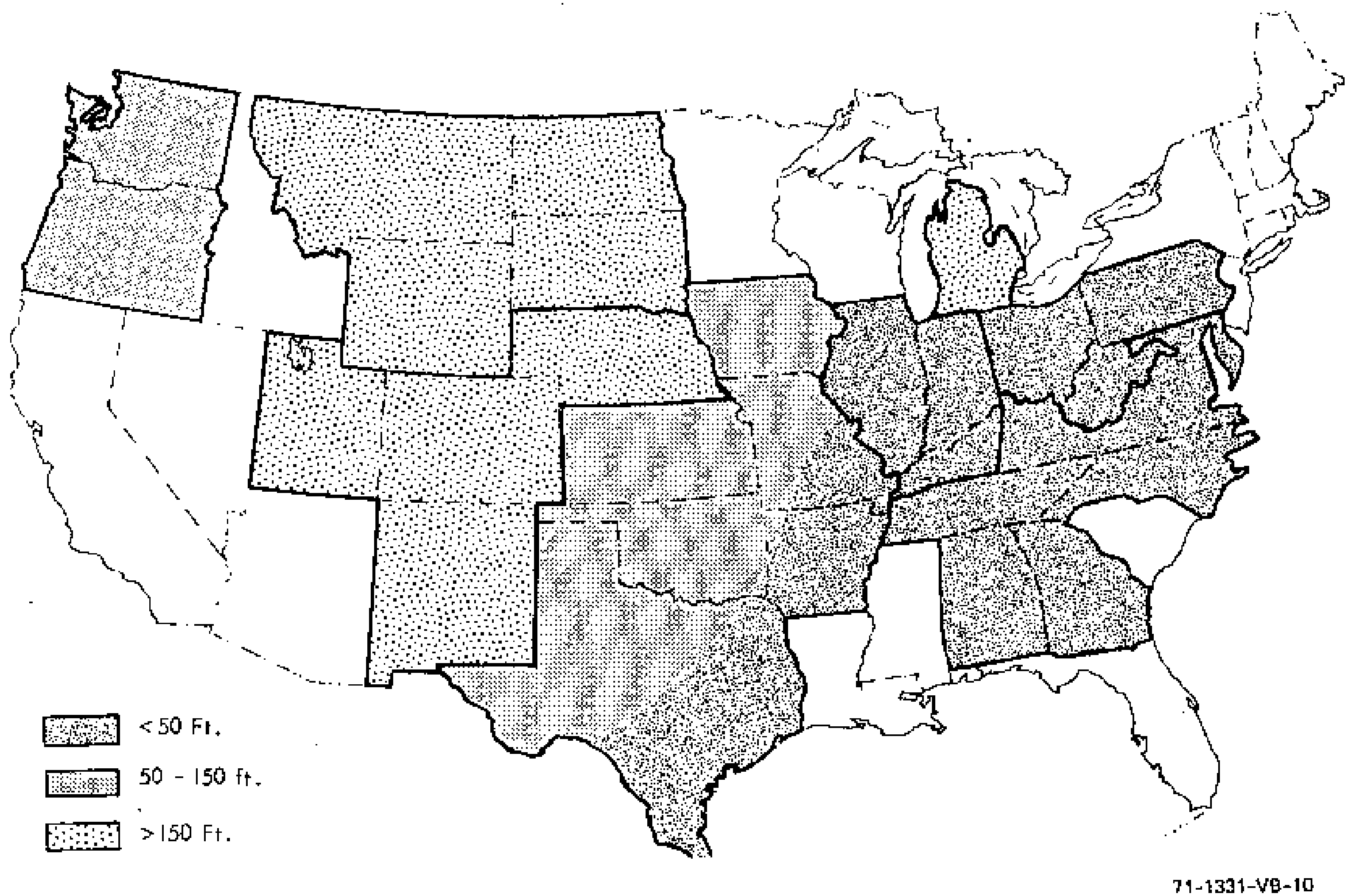


Figure D-3. Thickness of Weathered Layer in Major Cool Regions

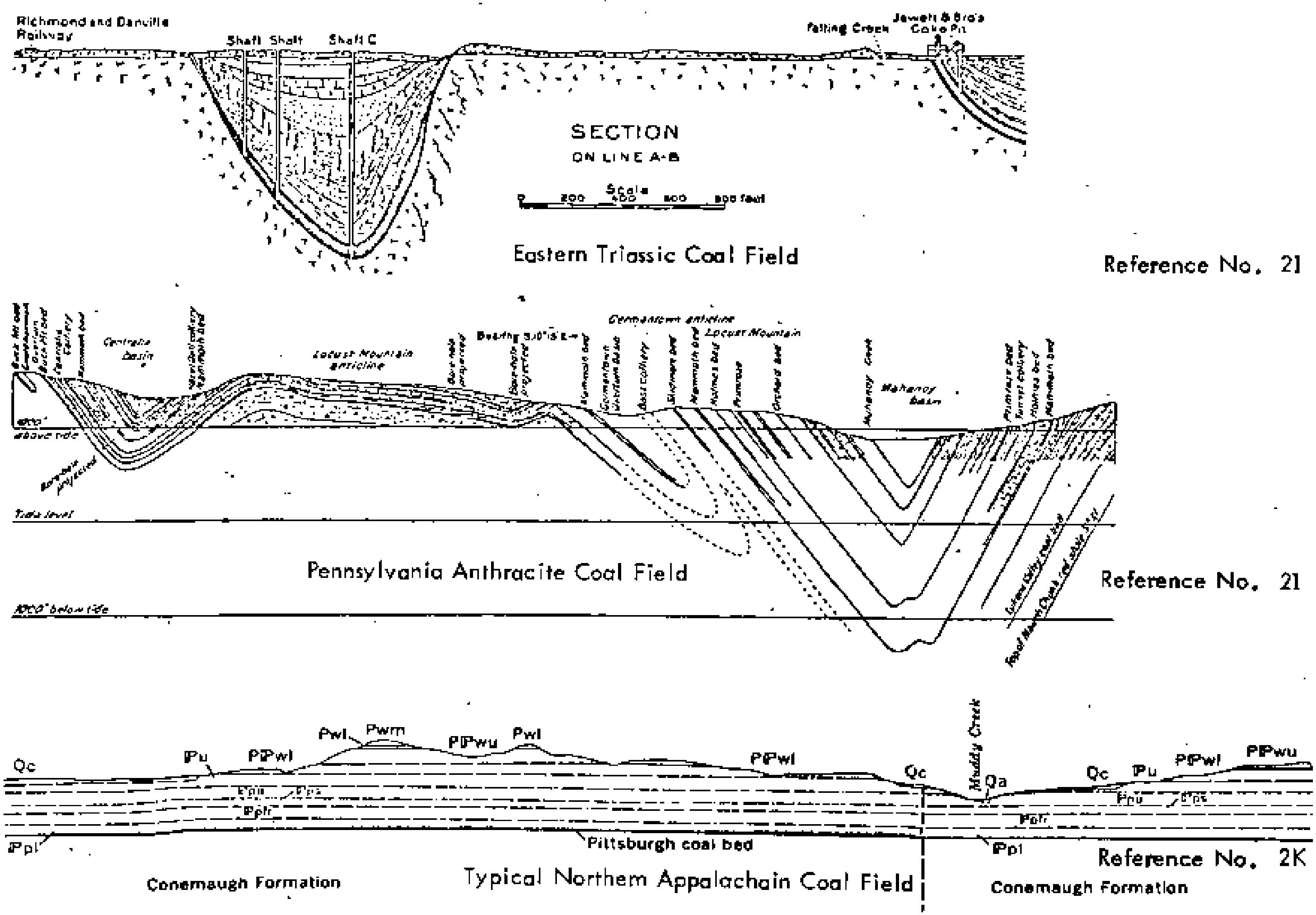


Figure D-4. Typical Structural Section From The Eastern U.S. Coal Regions

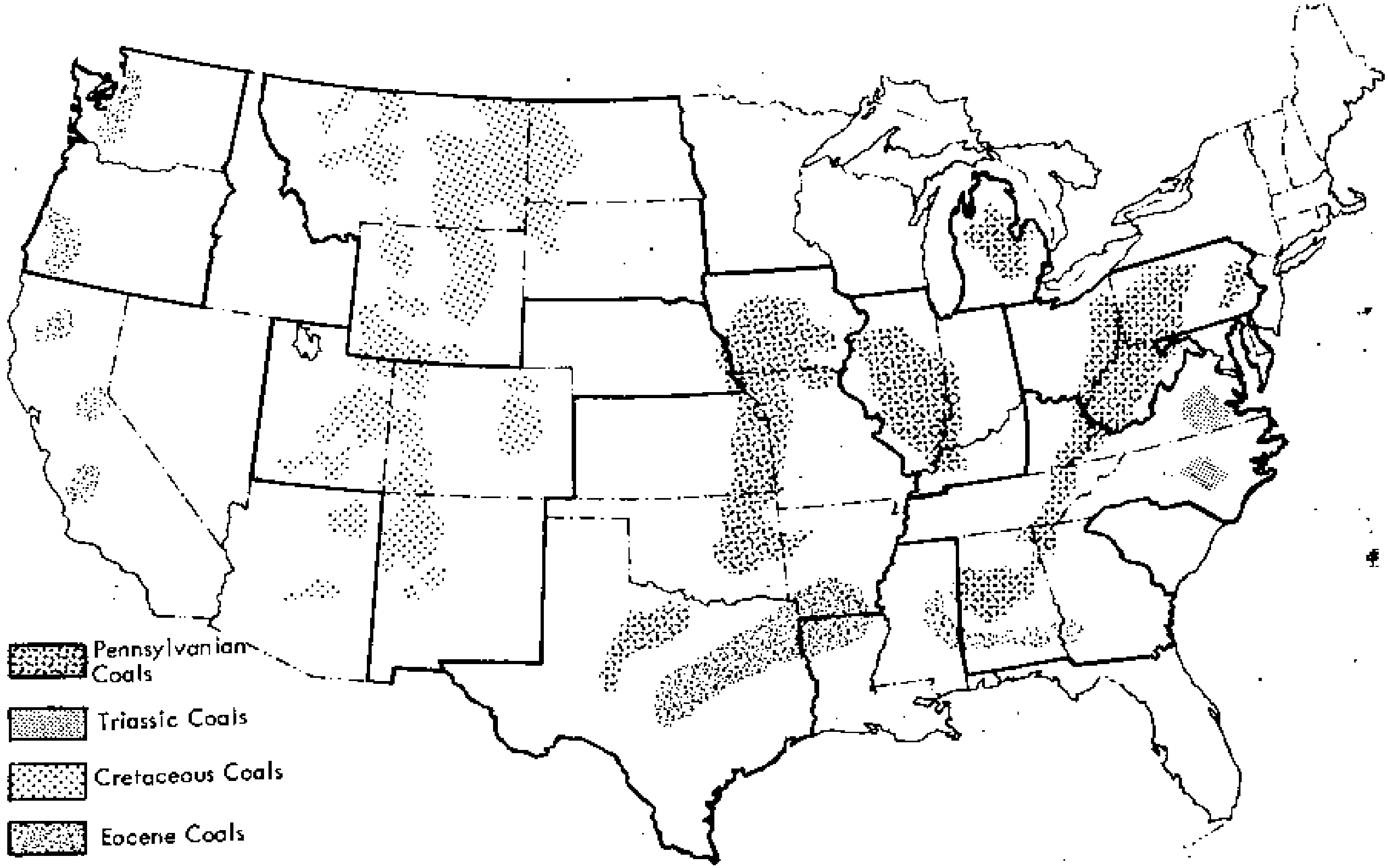


Figure D-5. Distribution of Coal By Age

3.1 ELECTROMAGNETIC BACKGROUND NOISE

One of the limitations of successful EM communications is the level of background noise. EM background noise can be one of two types - natural interference and man-made noise. Natural interference at low frequencies is primarily atmospheric noise caused by world-wide lightning activity. Figure D-6 shows the magnitude of natural atmospheric noise versus frequency at various depths. Even in rural areas this is oftentimes lower than man-made noise fields, at 60 Hz and its harmonics.

The sources for man-made EM noises are numerous. Subsurface noise at a mine site, however, can be categorized in three groups: machinery, rectifiers and transmission lines. The machinery and rectifiers generate noise pulses which are propagated and radiated by transmission lines in the mine. Because of the type and variability of this noise, measurement of man-made background noise on the site may be necessary. Generally, the most prevalent noise in the mine is the sixth harmonic of 60 Hz caused by rectifier spikes carried by the trolley bus. The presence of this noise and some typical examples are shown in the discussion of Predesign and Predemonstration test results.

3.2 EARTH CONDUCTIVITIES

As mentioned above, generalized information on earth conductivities is plentiful and helpful in characterizing a coal mining region, however the actual on-the-site conductivity can only be approximated from this generalized information due to local anomalies that almost always exist. Figure D-7 shows the regional 10 kHz effective conductivity for each coal mining area. In all cases, the conductivity is in the 10^{-3} to 10^{-1} mho/meter range. This agrees with what few measurements have been made at actual mine sites.

Figure D-8 characterizes conductivities in accordance with rock type and age. Here also, the coal bearing rocks of interest fall in the 10^{-3} to 10^{-1} mho/meter range. Figure D-9 further shows conductivity (inverse of resistivity) as a function of ash content of coal formations.

4.0 SEISMIC CHARACTERISTICS

Consideration of the seismic characteristics of coal mine regions, like the EM characteristics, falls into two categories: actual

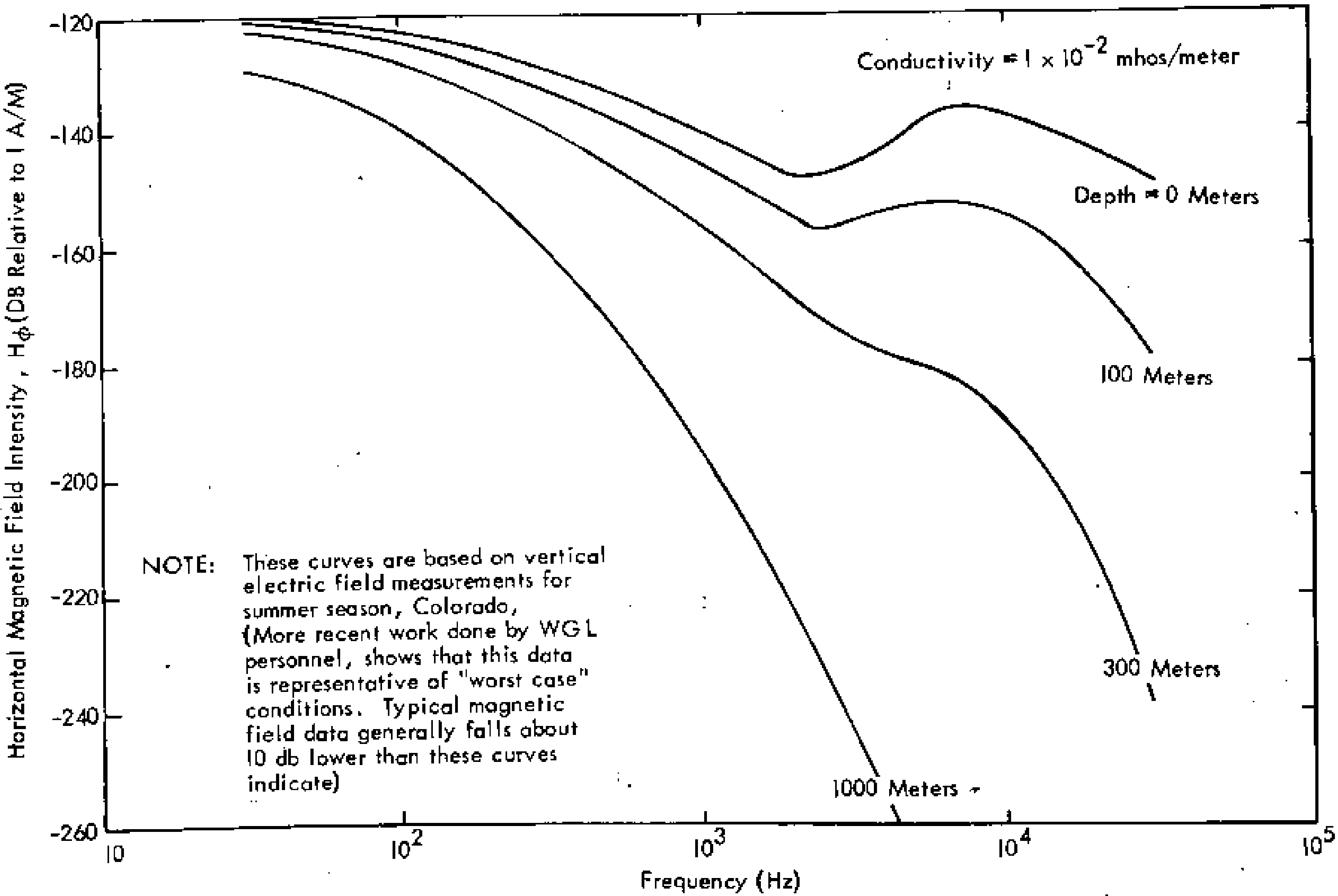
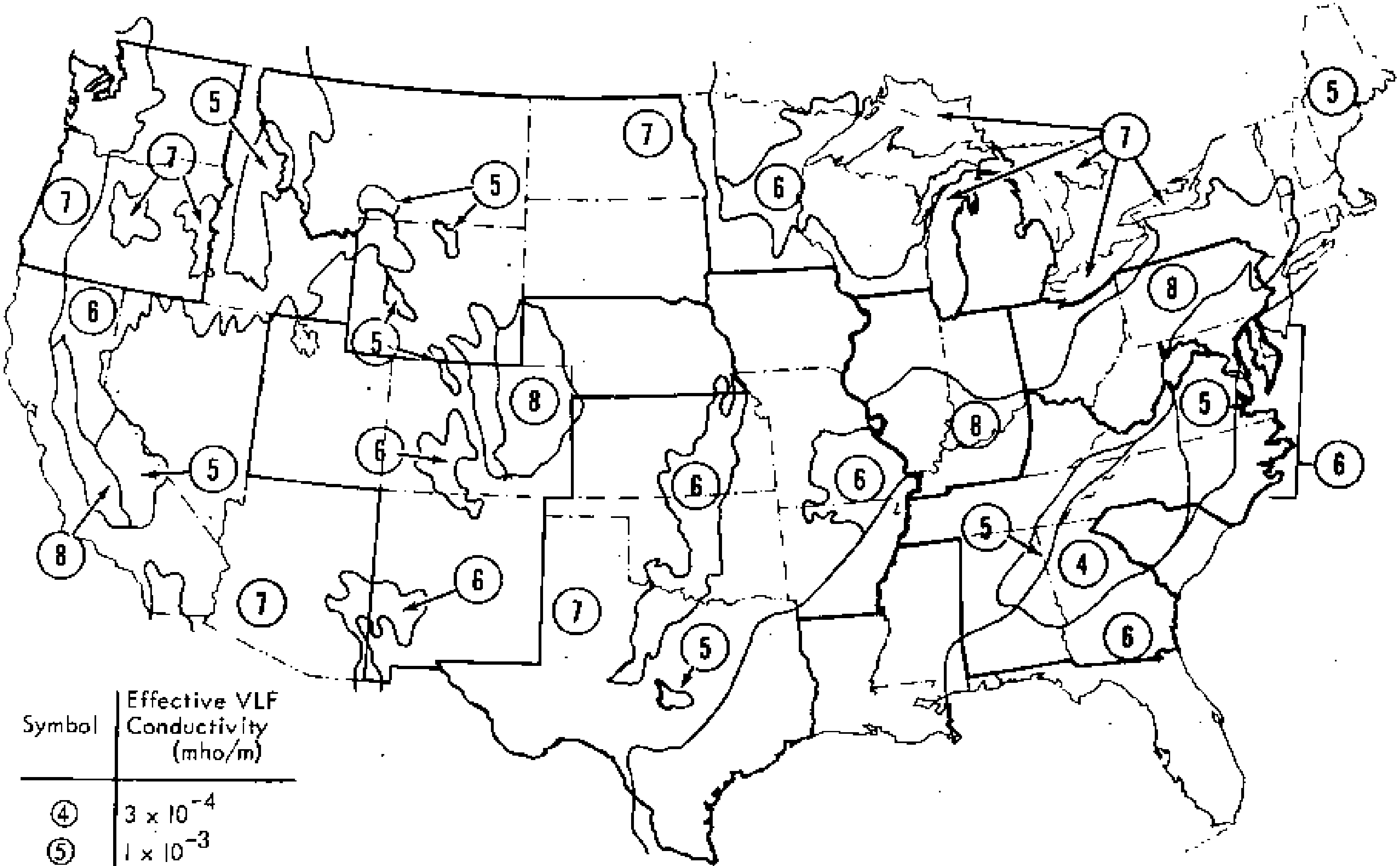


Figure D-6. Variation of Typical Atmospheric Noise Spectra with Depth



Symbol	Effective VLF Conductivity (mho/m)
④	3×10^{-4}
⑤	1×10^{-3}
⑥	3×10^{-3}
⑦	1×10^{-2}
⑧	3×10^{-2}

Figure D-7. Effective Conductivity Values For The United States

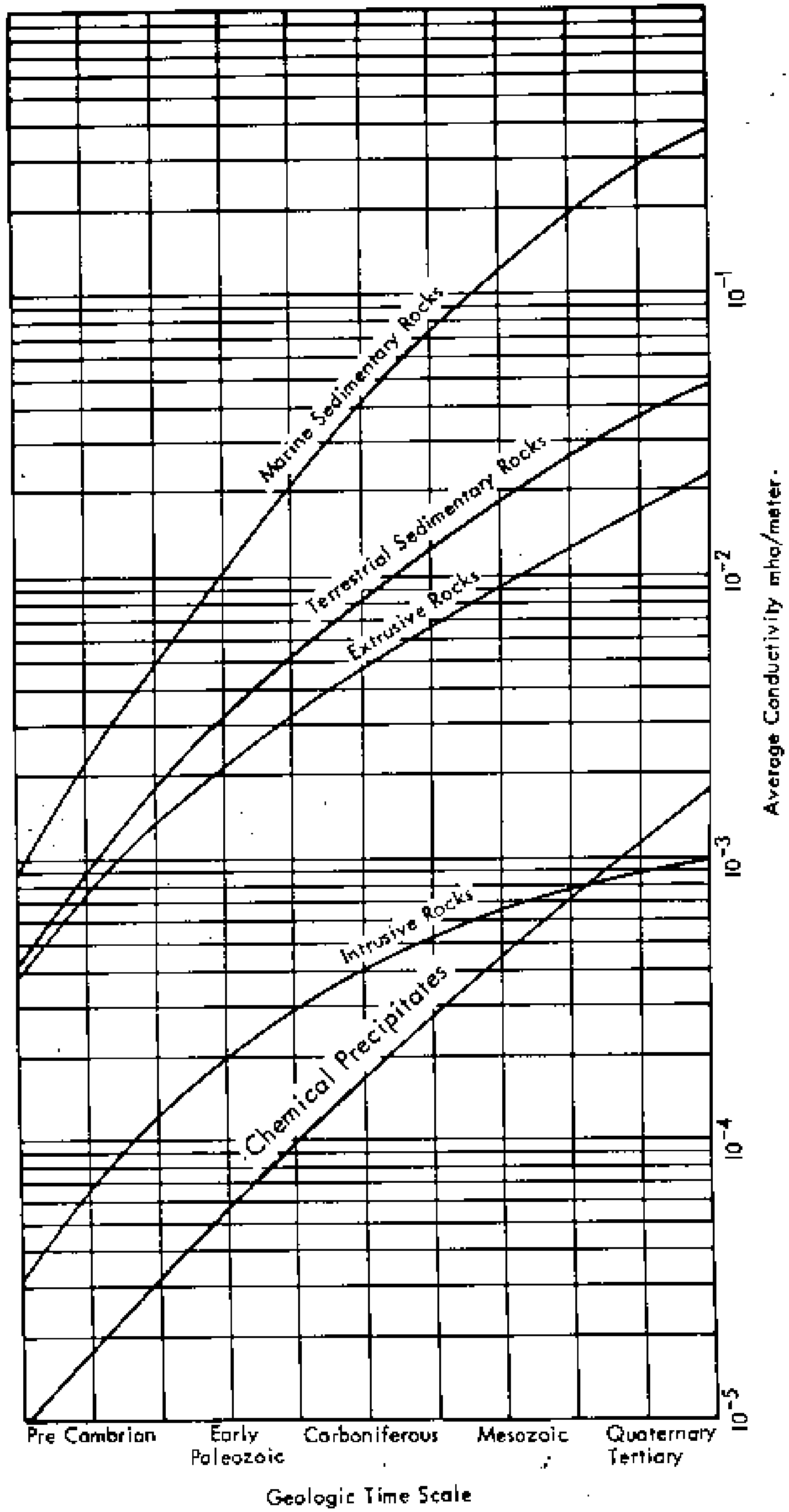
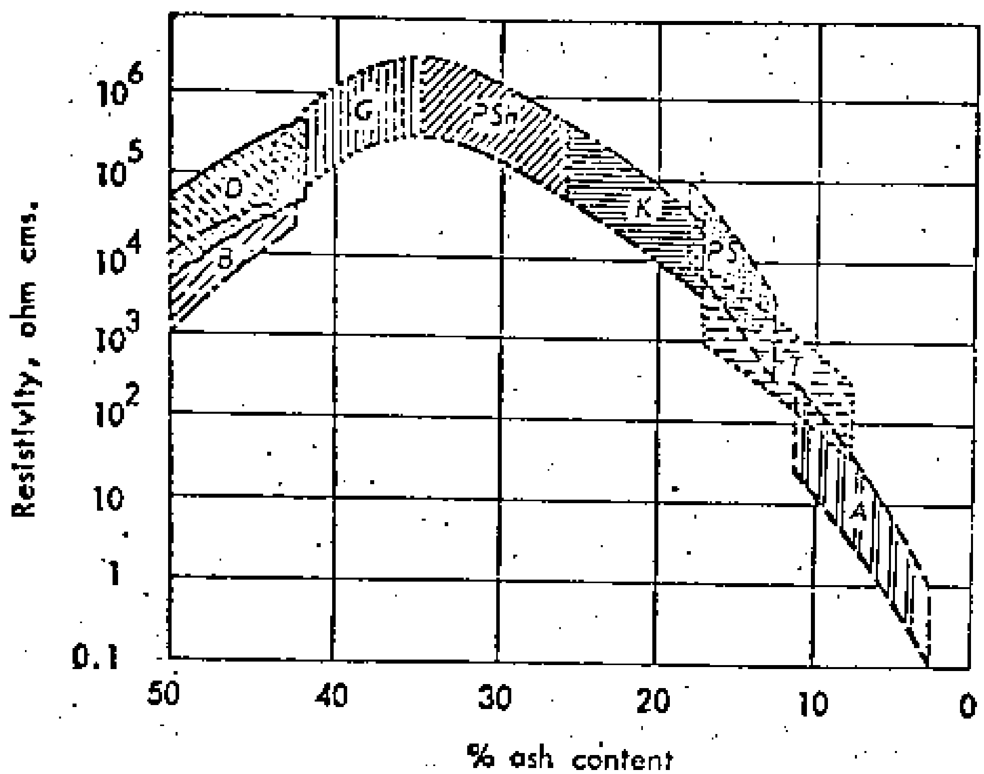


Figure D-8. Average Conductivity Versus Age of Formation for Various Rock Types



A Anthracite

B Brown coal

D Long-burning coal

G Gassing coal

K Coking coal

PS Steam coal (bituminous)

PSh Steam coal (super-bituminous)

Figure D-9. Resistivity of Coal Relative to Ash Content geophysical parameters like velocity and specific attenuation, and seismic background noise. Both are important features of a mine site as far as they concern limitations imposed on seismic communications.

4.1 VELOCITY

The most important seismic parameters to be determined at a rescue site are wave velocity and specific attenuation. Knowledge of velocity and attenuation make possible an estimation of the potential effectiveness of seismic communications. Figure D-10 summarizes the velocity distribution for the various coal mining regions. The values shown on the map vary according to age of rocks and depth of burial although with the relatively shallow range of depth of coal mine activity, the depth factor is negligible. Figure D-11 shows the variation of velocity with age for sedimentary rocks.

As can be seen from published velocity values, only rough estimates can be made for seismic velocity. Actual on-site velocity measurements are more meaningful for several reasons. First, on-site measurements tend to lump all velocities together to give the average velocity necessary for the location calculations. Second, on-site measurements tend to imply the band of best frequency response for seismic communications.

Knowledge of seismic velocity and best frequency of transmission are important in estimating the attenuation properties of an area and as a result, the expected effectiveness of seismic communications and location.

4.2 ATTENUATION

Attenuation of seismic signals can be attributed principally to two causes:

1) Internal energy loss (friction, distance)

2) Energy loss due to spreading (time, distance)

Considering the first phenomena, internal energy loss, the most widely accepted expression of this mode of attenuation is of the form $\exp(-\alpha x)$ where α is an attenuation constant (generally in dB/cm) and x is the distance from the source.

Most researchers in this area agree that for the seismic frequency range, α is proportional to the first power of frequency.

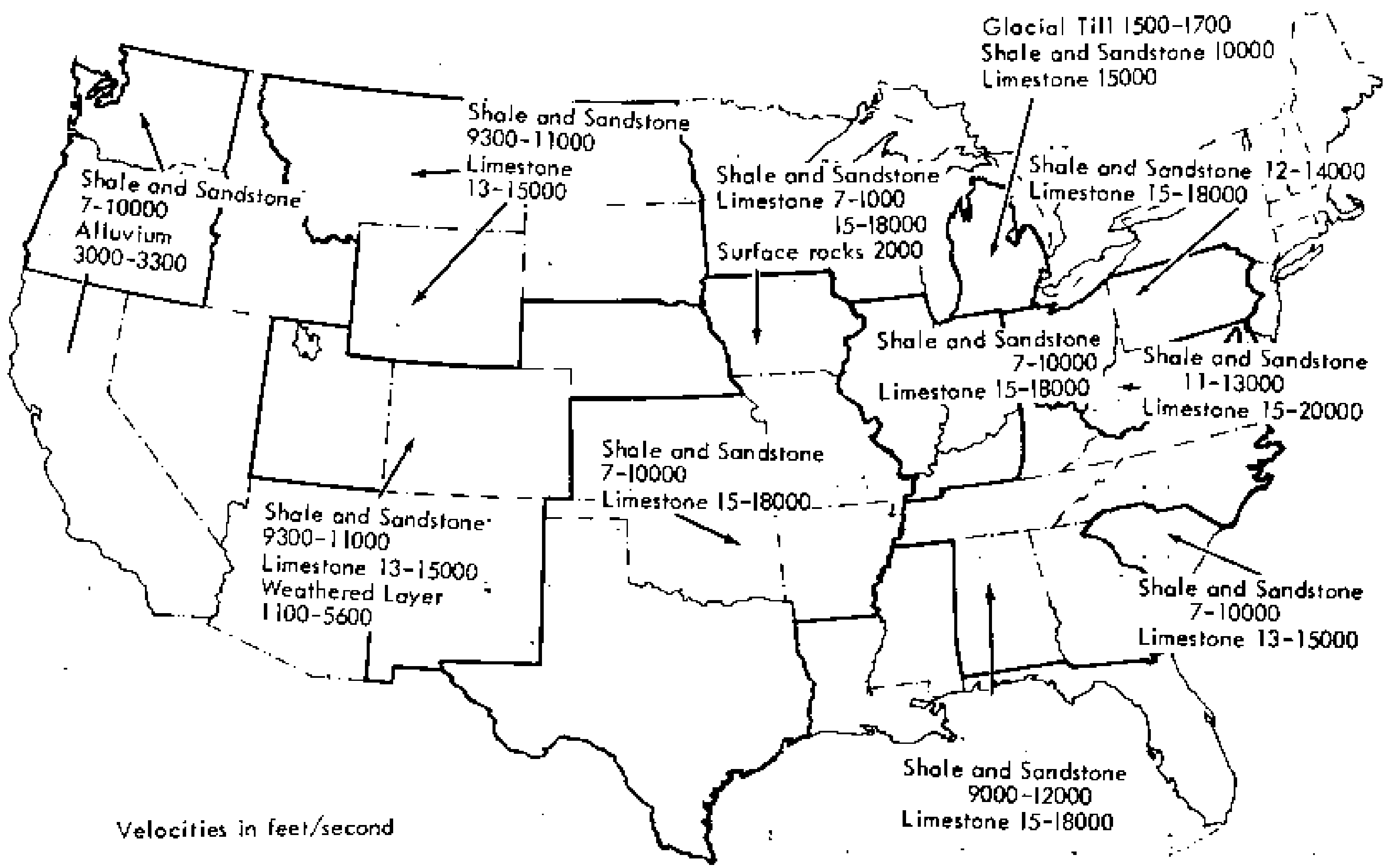


Figure D-10. Average Velocity of Overburden Rocks in the Major Coal Regions

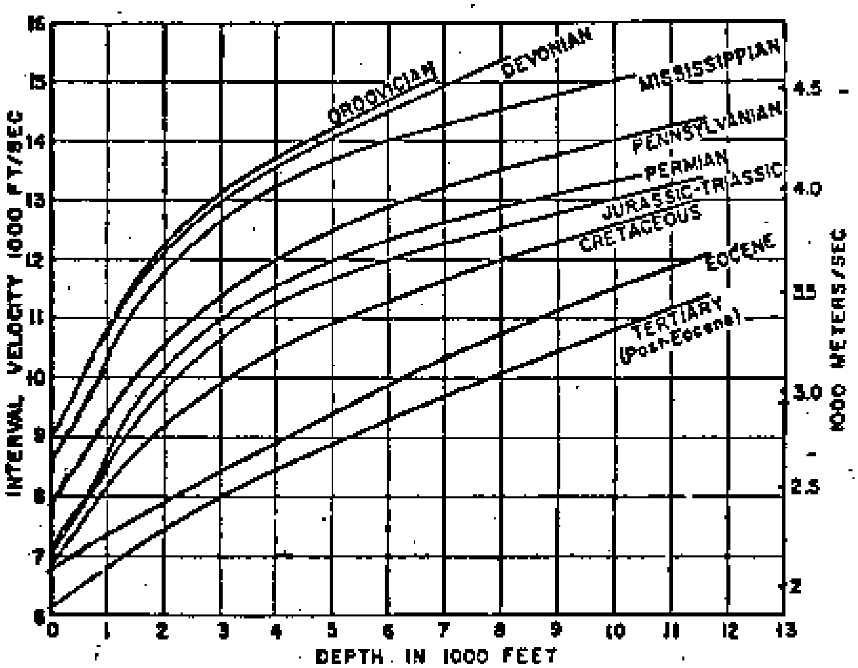


Figure D-11. Variation of Velocity With Depth and Age

Reference 9

A common method of determining α is in terms of the specific dissipation factor $1/Q$ where:

$$\alpha = \frac{2\pi f}{v\,Q}$$ where v = velocity in ft/sec
f = frequency in Hz
α = attenuation in nepers/ft

Since Q is independent of frequency, it is easily determined for various rock types. Various observed and average values of Q are given below for the various coal mining regions. It should be mentioned that Q is related to the rate at which mechanical energy is converted to thermal energy and reflects the physical properties of the rock type (i.e. grain size, porosity, water content, etc.).

Eastern Coal Province

Northern Appalachian Field (Region 1)

Sandstone (Connoquenessing Fm)		Q= 57
Sandstone (Homewood Fm)		Q= 57
Sandstone (Pottsville Fm)		Q= 7
Sandstone (Amherst)		Q= 52
Nonformational sandstones		Q= 52
		Q= 104
		Q= 99
	(quartzitic)	Q= 130
Average - All sandstones Q = 70.0		
Dolomite		Q = 385
Chalk		Q = 157
Limestone		Q = 150
Shale		Q = 70
Siltstone		Q = 36

Southern Appalachian Field (Region 2)

Siltstone with shale		Q = 125
Siltstone with sandstone and shale		Q = 63
Sandstone		Q = 52.3
Sandstone		Q = 62.8
Sandstone		Q = 57
Sandstone	(Average = 66)	Q = 90

Limestone		Q = 209
Limestone	(Average = 183)	Q = 157
Dolomite		Q = 209
Dolomite		Q = 314
Dolomite	(Average = 244)	Q = 209

Interior Coal Province

Mississippi Valley Region (Region 4)

Dolomite		Q = 209
Dolomite		Q = 314
Dolomite	(Average = 244)	Q = 209
Limestone		Q = 418
Limestone	(Average = 313)	Q = 209
Shale		Q = 48

Oklahoma - Texas - Arkansas (Region 5)

Limestone (Hunton)		Q = 65
Limestone (Hunton)		Q = 59.3
Sandstone		Q = 70

Rocky Mountain Coal Region (Regions 6 and 7)

Sandstone		Q = 314
Sandstone (Torpedo)		Q = 241
Sandstone (Tensleep)		Q = 523
Limestone		Q = 628
Limestone		Q = 31.4
Limestone and shale	(Average = 289)	Q = 209
Shale (Pierre)		Q = 23
Shale (Pierre)		Q = 36
Shale (Pierre - at depth)		Q = 91
Shale	(Average = 70)	Q = 126
Marlstone		Q = 45
Marlstone		Q = 57
Marlstone		Q = 29
Marlstone	(Average = 39)	Q = 35

Some average values of Q for various rock types - reflecting various physical conditions (1% moisture content, grain size, etc.) are given below:

Caprock	Q = 47
Conglomerate	Q = 196
Dolomite	Q = 190
Limestone	Q = 119
Marlstone	Q = 43
Sandstone	Q = 61
Shale	Q = 45
Siltstone	Q = 59

Generally, the value of α determined by these measurements of Q is on the order of:

$$2 \times 10^{-6} f \text{ db/cm} \qquad 10^{-3} < f < 10^{8} \text{ (P and Rayleigh Waves)}$$

The other type of attenuation - and the one that is most pronounced, is that due to wave spreading. Seismic wave energy is related to distance (x) from the energy source and is proportional to $\frac{1}{x}$ - that is the wave decays as $\frac{1}{x}$. This attenuation has been superimposed on that from internal friction to give a composite decay curve as shown in D-12. This figure, D-12, is a multiple axis trade-off curve, designed to aid in determining the attenuation in dB for any frequency, velocity, Q and distance relationship within our area of interest.

Use of the curve in Figure D-12, requires explanation as follows:

1) Find desired frequency on left axis.

2) Determine point where horizontal line through this point intersects desired velocity curve (V).

3) Extend this point vertically to intersect the abscissa (This gives wavelength v/f).

4) Determine the proper "Q" curve for the earth materials concerned. Extend the wavelength line vertically until it intersects with appropriate "Q" curve.

5) Read this point to the left (or right) on the ordinate. This is the attenuation coefficient (α).

6) Project this point horizontally to intersect the appropriate (distance) curve.

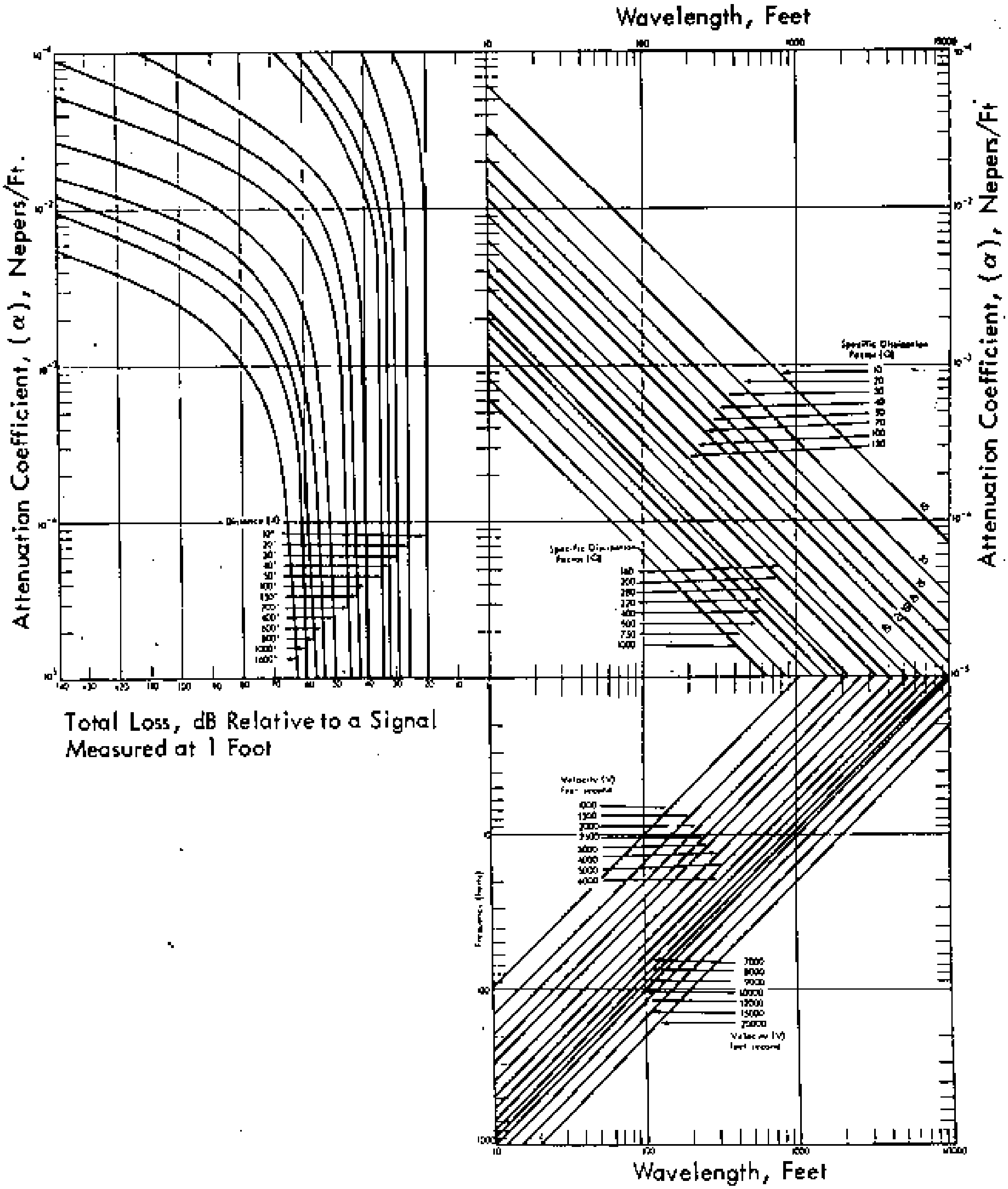


Figure D-12. Multiple Axis Trade Off Curve for Estimating Attenuation

7) Read this point on the dB axis below as dB of attenuation relative to the attenuation at a distance of 1 foot.

4.3 SEISMIC BACKGROUND NOISE

By defining noise as any unwanted signal received by a seismic detector, we can look at the noise as the sum of two components:

1) Microseismic Noise

2) Random Noise.

Microseismic noise is by definition, oscillatory. That is to imply it is a continuous, usually periodic, signal lasting for some length of time, where the duration usually is many times the period of the noise. With this in mind, microseismic noise can be divided into two categories:

1) Natural Microseisms

2) Man-made Microseisms.

Both types have in common several features. First, their mode of propagation is the same - a surface (Rayleigh type) wave traveling at a velocity depending on the geology of the area. Second, their source can usually be determined by studying frequency and duration. Third, their attenuation does not depend as much on distance of travel as it does on the geologic configuration - large geologic disconformities such as mountain ranges attenuate the waves appreciably. Figure D-13 shows the distribution of microseismic noise relative to useful seismic information.

Natural microseisms are still much studied. There is a general concensus that natural microseismic disturbances are associated with storm activity over large bodies of water. Observations have shown that the periods of these disturbances range from 1 to 12 seconds with those in the 3 to 9 second range the most common. Observation also seems to indicate a range of predominant periods for various parts of the country. These are given below:

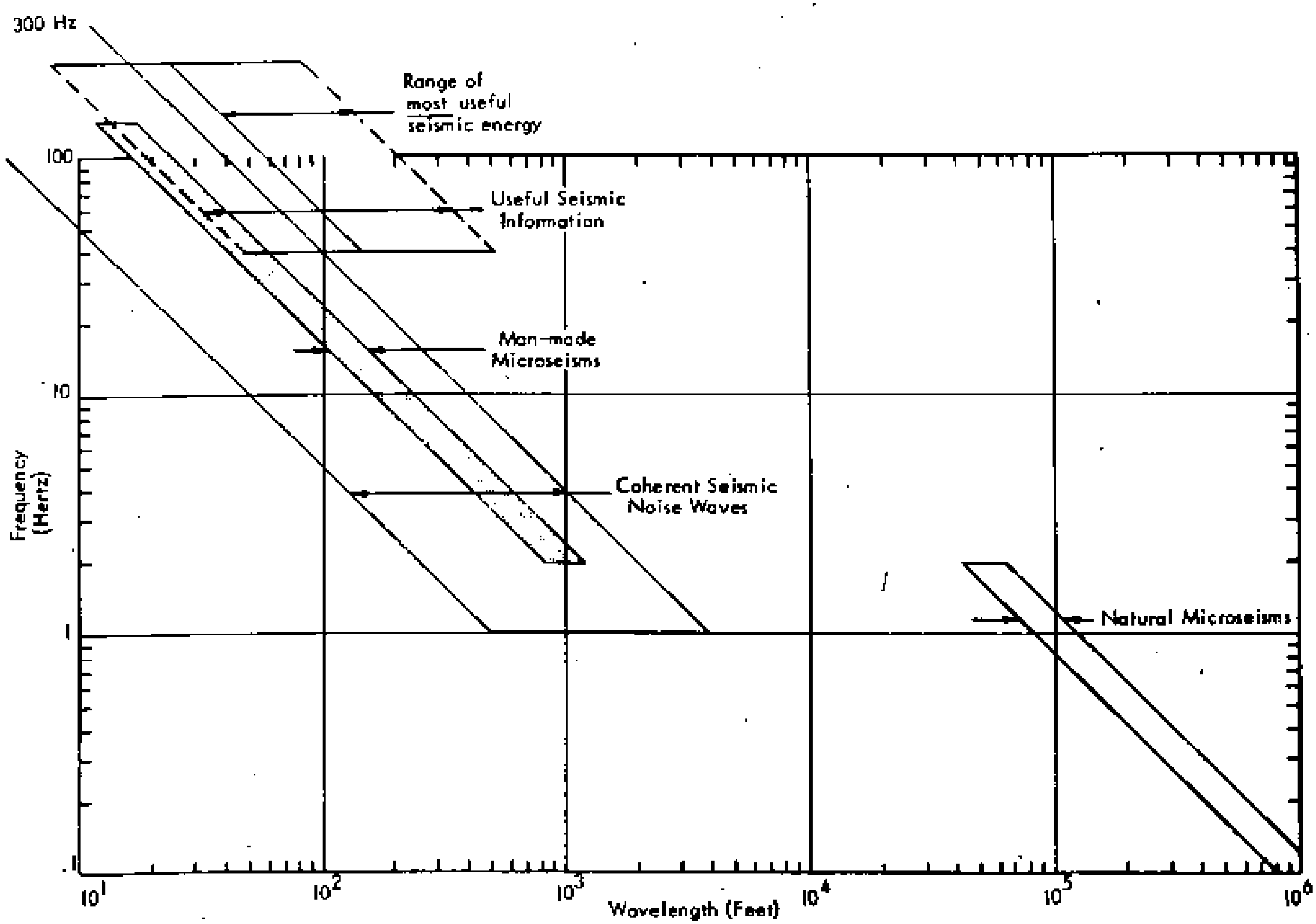


Figure D-13. Noise Waves vs. Useful Seismic Information

Area	Prevailing Period
S.E. Coast	3-5 secs.
N.E. Coast	3-7 secs.
West Coast	3-8½ secs.
Interior	4-9 secs.

The velocities of these natural microseisms appear to be dependent on the period and the surface geology for wavelength less than crustal thickness. An average figure is 10,000 ft/sec.

This data implies that natural microseismic activity of this nature will be of little consequence in recording miner generated signals, since the inherent sensitivity of the system does not include these low frequencies.

Many microseismic observations were made by the University of Michigan at widely scattered parts of the United States. These observations relative to areas of significant coal mining, are shown in Figure D-14A to Figure D-14G. Several conclusions resulted from this data:

1) The similarity of response below 1.5 Hz for the entire region tends to imply that this portion of microseismic noise is due to natural microseisms.

2) Microseismic activity above 1.5 Hz is man-made disturbance. The consistent peak at 2 Hz seems to imply this is the predominant frequency for man-made noise (probably due mostly to traffic - rail and road). Subsequent noise "peaks" appear to be localized and may depend on some local noise source.

3) Microseismic reading taken in a mine show considerably less noise - particularly for the "man-made" part of the spectrum.

4) The majority of the signals appear to originate near the earth's surface and propagate as near surface energy.

Man-made microseisms are less studied than those of natural origin. This is probably due to the fact that they are of relatively low amplitude and they appear to attenuate more rapidly than do natural

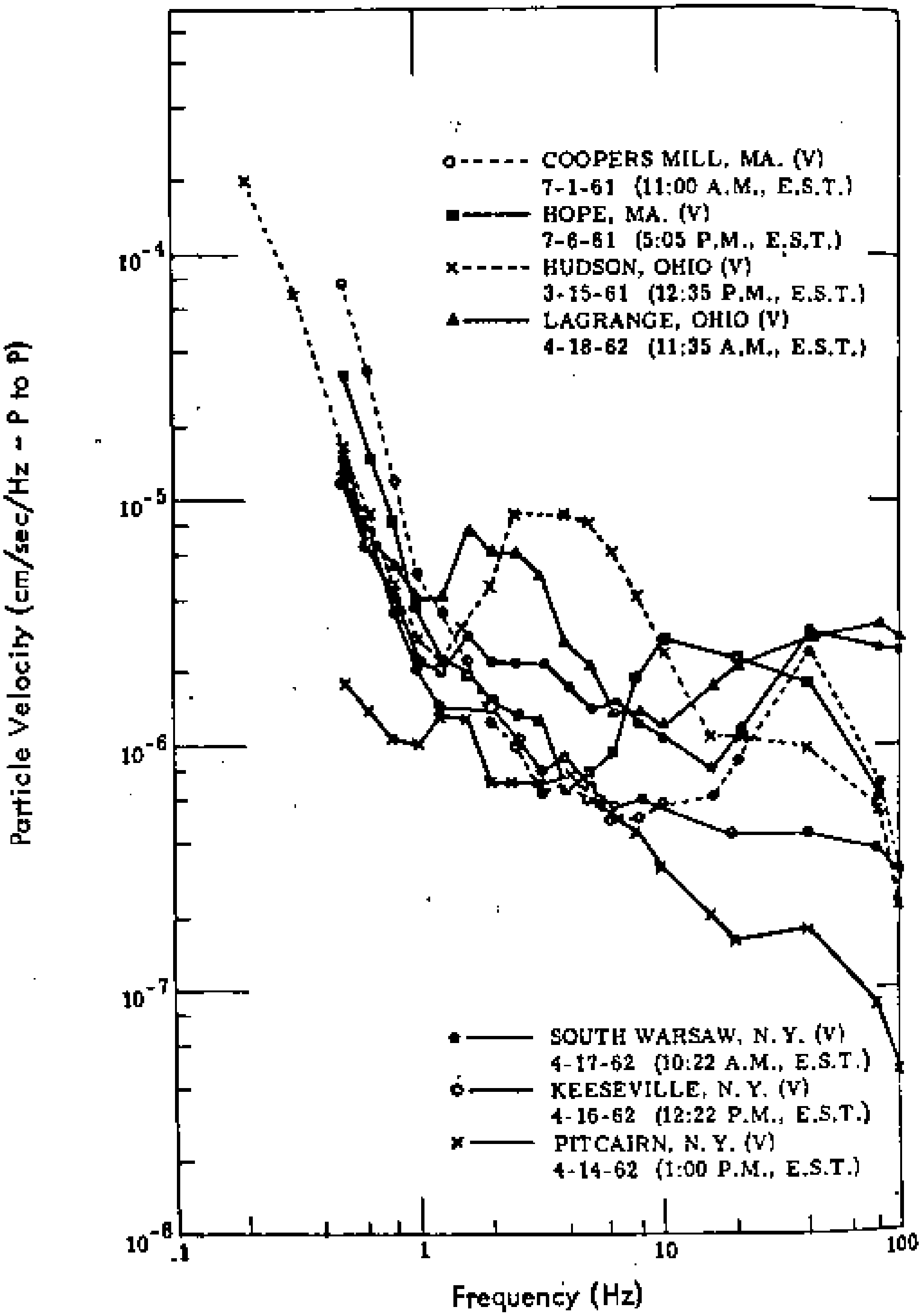


Figure D-14A. Seismic Noise For Region No. 1

Reference 16

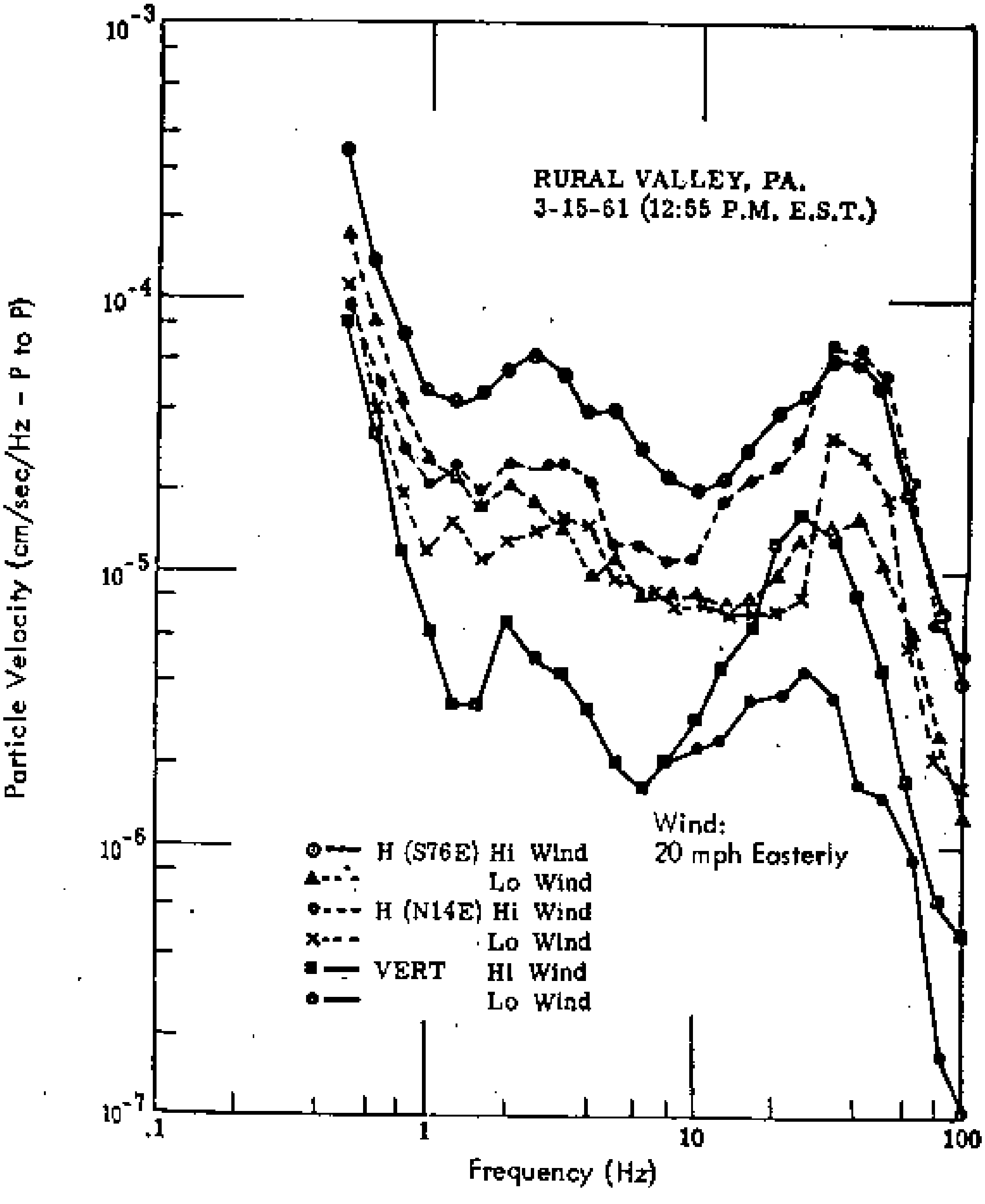


Figure D-14B. Seismic Noise Region No. 1

Also Wind Noise

Reference 16

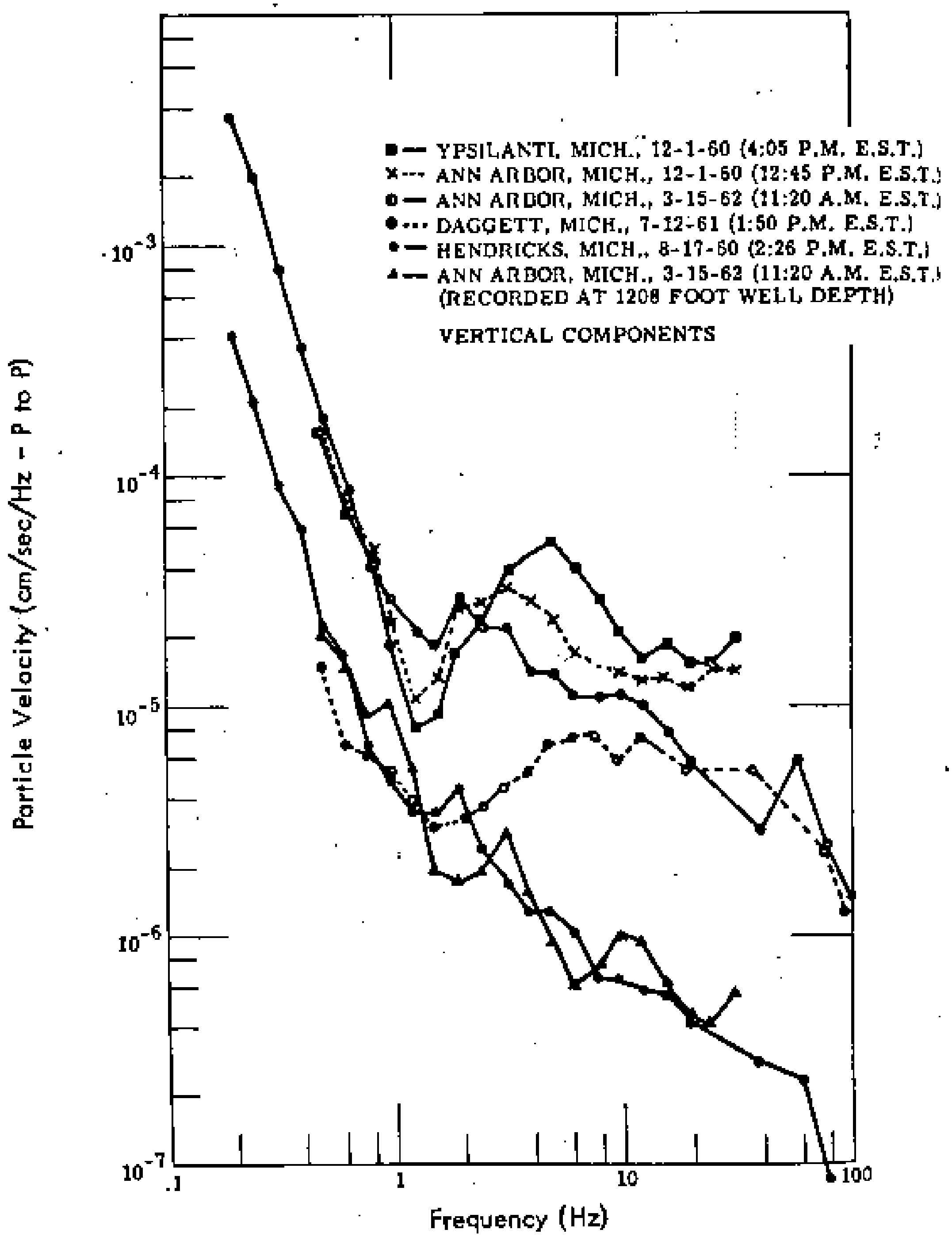


Figure D-14C. Seismic Noise Region No. 3

Reference 16

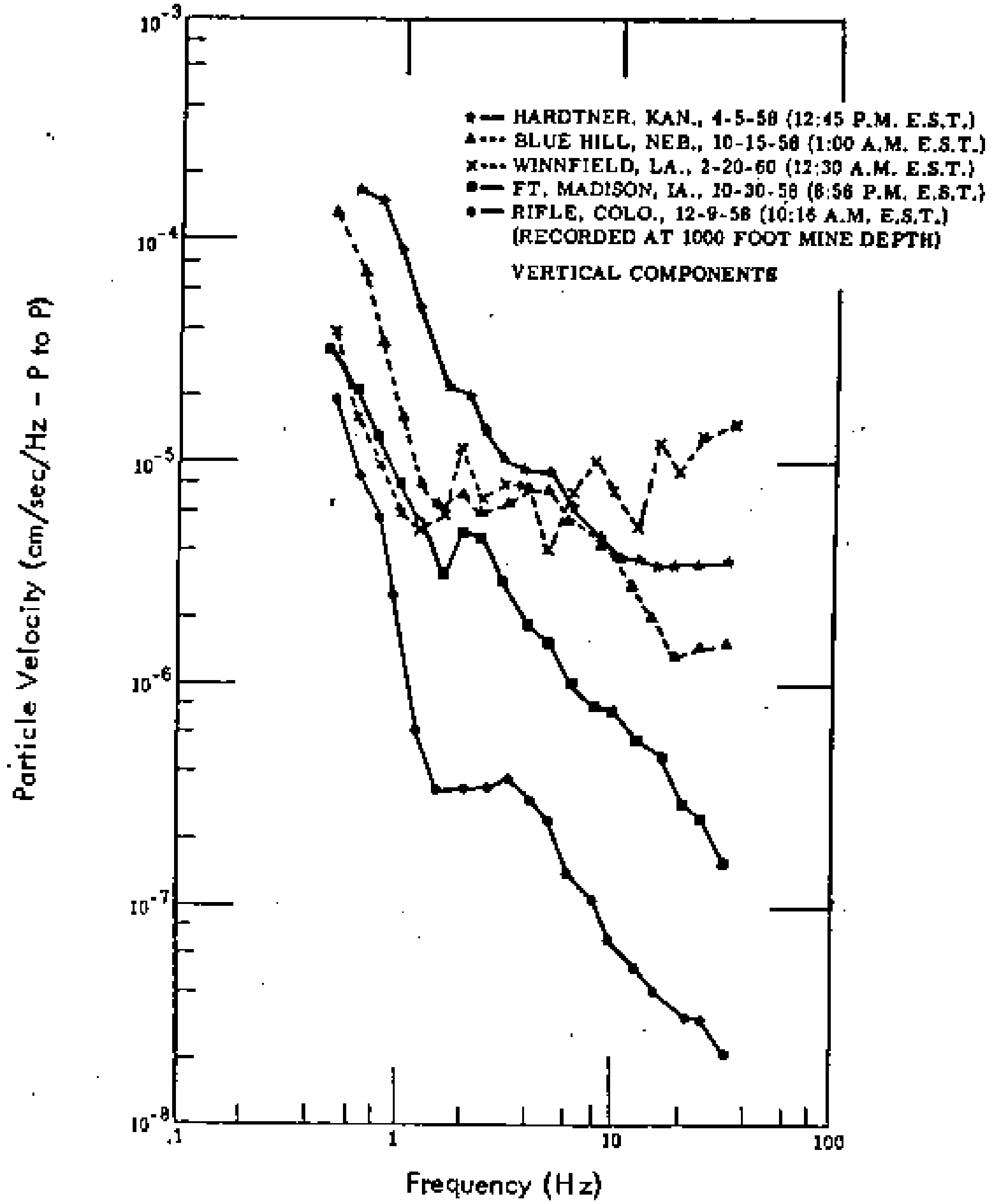


Figure D-14D. Seismic Noise Regions 5 and 7

Reference 16

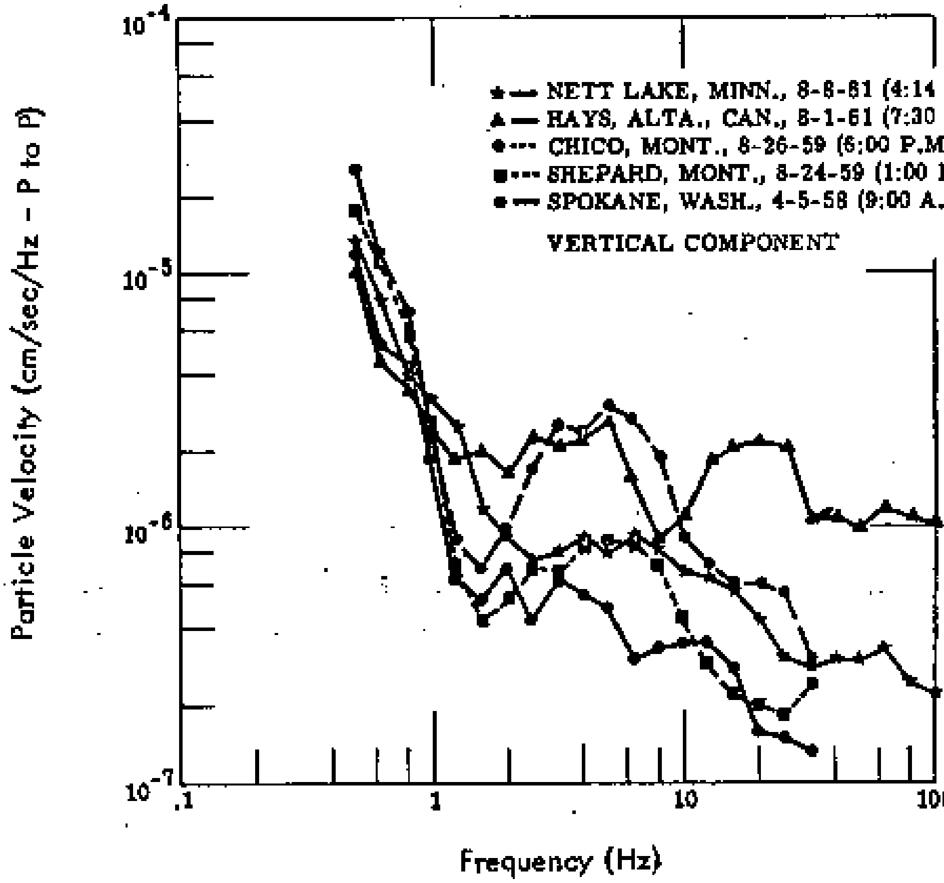


Figure D-14E. Seismic Noise Regions 6 and 8

Reference 16

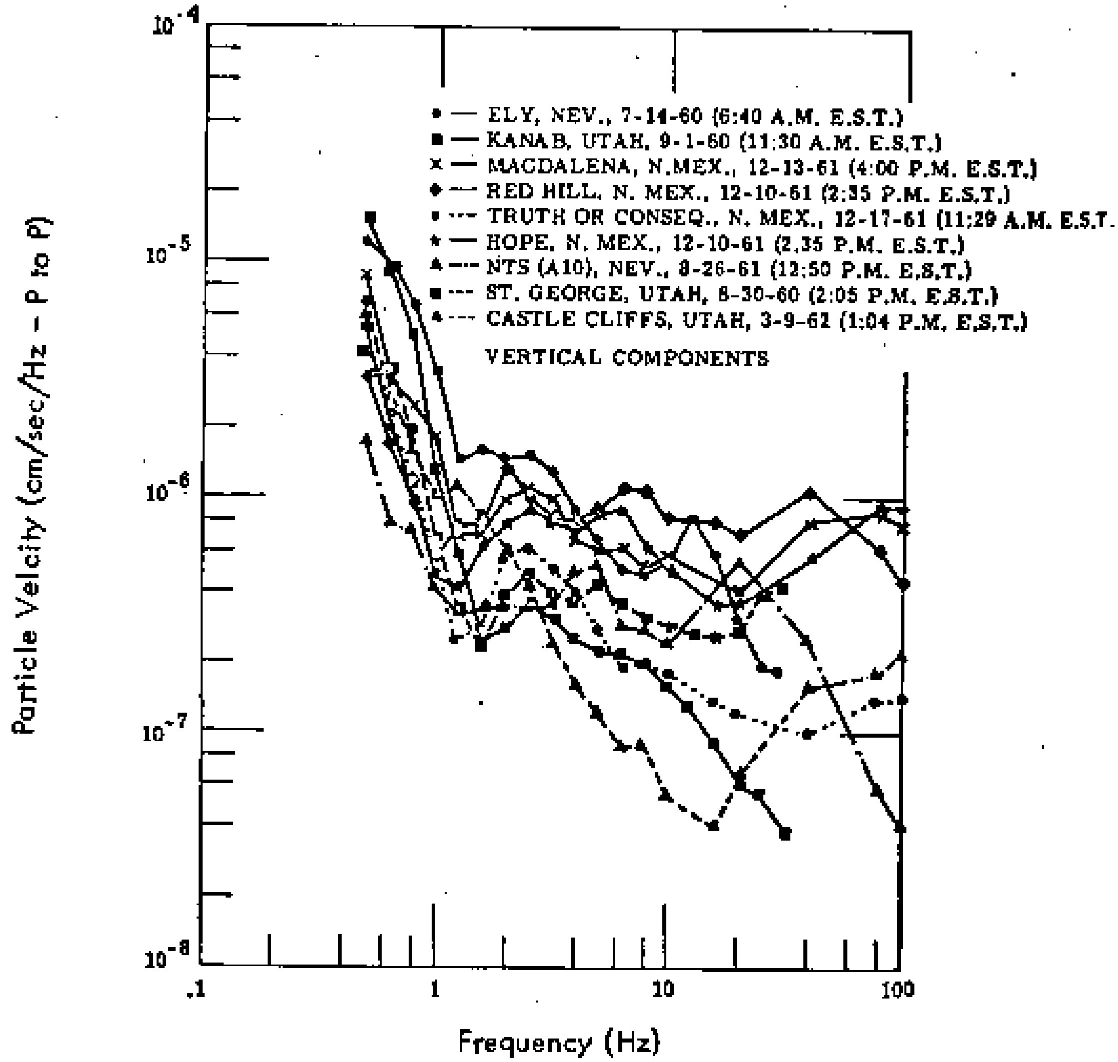


Figure D-14F. Seismic Noise Region 7

Reference 16

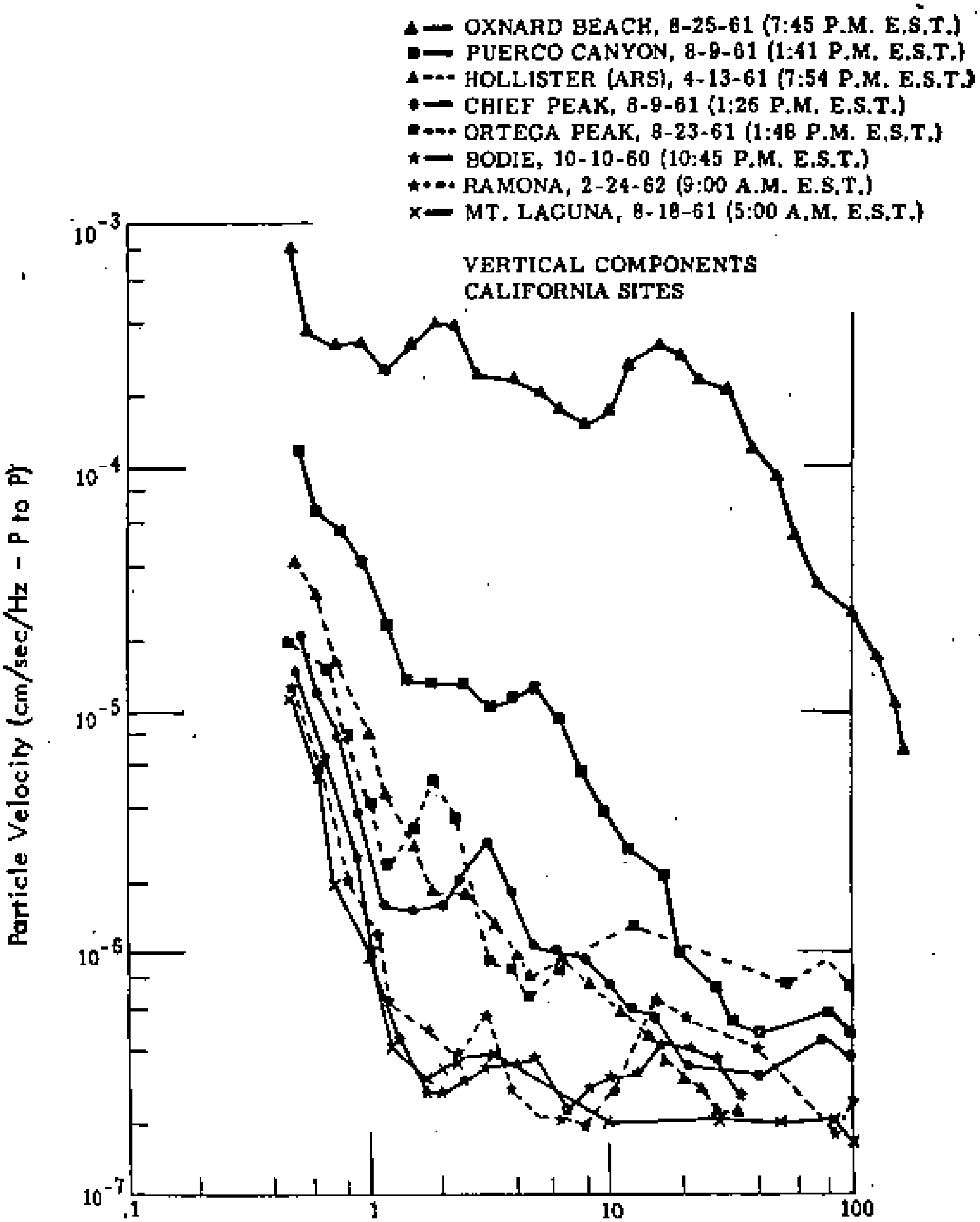


Figure D-14G. Seismic Noise Region 8

Reference 16

seismic disturbances. Tests show that attenuation of man-made microseismic activity is on the order of

$e^{-\alpha D}$ where D = distance from source, and

$1.97 < \alpha < 2.18$ dB/mile.

The other part of the noise spectrum is random noise. This is due to non-oscillatory noise sources in the earth. Such noise is omnidirectional - that is, it appears to have no specific direction of origin. Also, it is not frequency discriminatory - that is, the amplitude versus frequency response curve is flat.

Generally this type of noise is of very low amplitude and it is attenuated by means of signal summation - either at the signal source, geophone, or in signal processing.

5.0 BIBLIOGRAPHY

Listed below are references used in compiling the information in the data base. More detail can be obtained for any coal region by consulting these references. Most are available in the United States Geological Survey Library in Denver, Colorado.

1. Structural Geology of North America, A. J. Eardley, Harper and Row, New York, 1962.

2. United States Geological Survey, Washington, D. C.:

   A. Contributions to Economic Geology, 1906, Part II, Bulletin No. 316.

      1. Pages 76 - 115.
      2. Pages 161 - 173.
      3. Pages 174 - 193.
      4. Pages 212 - 241.
      5. Pages 244 - 260.
      6. Pages 264 - 301.
      7. Pages 302 - 320.
      8. Pages 321 - 337.

9. Pages 359 - 375.

10. Pages 376 - 426.

B. Stratigraphy of the Bituminous Coal Field in Pennsylvania, Ohio, and West Virginia," Israel C. White, Bulletin No. 65, 1891.

C. Contributions to Economic Geology, Bulletin No. 225, 1903.

1. Pages 240 - 258.
2. Pages 311 - 324.
3. Pages 345 - 362.

D. Contributions to Economic Geology, Bulletin No. 213, 1902.

1. Pages 270 - 275.
2. Pages 284 - 293.

E. Contributions to Economic Geology, Bulletin No. 285, 1905.

1. Pages 211 - 225.
2. Pages 226 - 234.
3. Page 240.
4. Pages 241 - 258.
5. Pages 259 - 268.
6. Pages 289 - 302.
7. Pages 316 - 330.

F. Contributions to Economic Geology, Bulletin No. 1042, 1956.

1. Pages 307 - 382.
2. Pages 557 - 584.

G. Geology and Fuel Resources of the Southern Part of the Oklahoma Coal Field, Bulletin No. 874, 1939.

1. Pages 251 - 254.
2. Pages 255 - 298.

H. The Coal Fields of the United States, Professional Paper No. 100, 1929. General Introduction by M. A. Campbell, pages 1 - 33.

I. Twenty-second Annual Report, Part III, 1900 - 1901.

1. Pages 7 - 24.
2. Pages 25 - 54.
3. Pages 55 - 118.
4. Pages 119 - 226.
5. Pages 227 - 264.
6. Pages 265 - 306.
7. Pages 307 - 332.
8. Pages 333 - 366.
9. Pages 367 - 414.
10. Pages 415 - 472.
11. Pages 473 - 514.

J. Coal Investigation Maps.

1. "Geology and Coal Resources of the Gulnare, Cuchara Pass and Stonewall Area, Huerfano and Las Animas Counties, Colorado," G. H. Wood, Jr., R. B. Johnson, G. H. Dixon, No. C-26, 1956.

2. "Principal Coal Beds in the Buckhorn Quadrangle," Breathitt, Leslie and Perry Counties, Kentucky," P. T. Stafford, K. J. Englund, No. C-15, 1953.

3. "Coal Beds of the Troublesome Quadrangle, Kentucky," A. D. Williamson, W. L. Adkison, No. C-18, 1953.

4. "Preliminary Coal Map of the Cornettsville Quadrangle, - Perry, Knott, Letcher, Harlan and Leslie Counties, Kentucky," J. E. Johnston, P. T. Stafford, S. W. Welch, No. C-22, 1955.

K. Miscellaneous Geologic Investigations.

1. "Geologic Map of Part of the Carmichaels Quadrangle Southwestern Pennsylvania," B. H. Kent, 1969, Map I - page 588.

L. Geologic Folios.

1. No. 46, "Richmond, Kentucky," M. R. Campbell, 1898.
2. No. 58, "Elmoro, Colorado," R. P. Hills, 1899.
3. No. 71, "Spanish Peaks, Colorado," R. C. Hills, 1900.
4. No. 102, "Indiana, Pennsylvania," C. B. Richardson, 1904.
5. No. 110, "Letrobe, Pennsylvania," M. R. Campbell, 1904.
6. No. 115, "Kittanning, Pennsylvania," C. Butts, 1904.
7. No. 123, "Elders Ridge, Pennsylvania," R. W. Stone, 1905.
8. No. 133, "Ebensburg, Pennsylvania," C. Butts, 1905.
9. No. 146, "Ropersville, Pennsylvania," F. C. Clapp, 1907.
10. No. 175, "Birmingham, Alabama," C. Butts, 1910.
11. No. 185, "Murphysboro-Herrin, Illinois," E. W. Shaw, T. E. Savage, 1912.
12. No. 186, "Apishapa, Colorado," C. W. Stose, 1912.
13. No. 221, "Bessemer-Vandiver, Alabama," C. Butts, 1927.

3. Seismic Waves: Radiation, Transmission and Attenuation, J. E. White, McGraw Hill Company, New York, 1965.

4. Interpretation Theory in Applied Geophysics, F. S. Grant, C. F. West, McGraw Hill Company, New York, 1965.

5. Elastic Waves in Layered Media, W. M. Ewing, W. S. Jardetzky, F. Press, McGraw Hill Company, New York, 1957.

6. Applied Geophysics for Engineers and Geologists, D. H. Griffiths, R. F. King, Pergamon Press, Oxford, 1965.

7. Handbook of Physical Constants, S. P. Clark, Jr., Ed., Geological Society of America, Memoir 97, 1966, pages 175-144, 195-218.

8. Exploration Geophysics, J. J. Jakosky, Trija Publishing Company, Newport Beach, California, 1940.

9. Geophysical Exploration, C. A. Heiland, Prentice-Hall, Inc., New York, 1946.

10. Physics of the Earth's Interior, Beno Gutenberg, Academic Press, New York, 1959.

11. Geophysics, Society of Exploration Geophysicist, Tulsa, Oklahoma.

    A. Underground Applications of Seismic Measurements in a Saskatchewan Potash Mine, D. J. Gendzwill, Vol. 34(6), 1969, pages 906-915.

    B. Hammer Reflection Seismics in Engineering Geophysics, Tsvi Meidav, Vol. 34 (3), 1969, pages 383 - 395.

    C. Wave Attenuation and Internal Friction as Functions of Frequency in Rocks," P. B. Attewell, Y. V. Ramana, Vol. 31 (6), 1966, pages 1049-1056.

    D. Wave Velocities in Rocks as a Function of Changes in Overburden Pressure and Pore Fluid Saturants," M. S. King, Vol. 31 (1), 1966, pages 50-73.

    E. A Loss Mechanism for the Pierre Shale," C. W. Horton, Vol. 24 (4), 1959, pages 667 - 680.

    F. Attenuation of Shear and Compressional Waves in Pierre Shale, F. J. McDonal, F. A. Angona, R. L. Mills, R. L. Sengbush, R. G. Van Nostrand, J. E. White, Vol. 3 (3), 1958, pages 421 - 439.

    G. Transient Behavior of Patterns, J. E. White, Vol. 23 (1), 1958, pages 26-43.

H. Seismic Reflection Records Obtained by Dropping a Weight, Edwin B. Neitzel, Vol. 23 (1), 1958, pages 58-80.

I. Seismic Wave Attenuation Characteristics from Pulse Experiments, F. Collins, C. C. Lee, Vol. 21 (1) 1956, pages 16-40.

J. Structure of the Noise Background of a Seismogram, C. W. Horton, Vol. 20 (3), 1955, pages 565 - 584.

K. The Form and Laws of Propagation of Seismic Wavelets, Norman Ricker, Vol. 18 (1), 1953, pages 10 - 40.

L. Seismic Data Enhancement - A Case History, R. J. Graebner, Vol. 25 (1), 1960, pages 283-311.

M. Noise Analysis and Multiple Seismometer Theory, Mark K. Smith, Vol. 21 (2), 1956, pages 337 - 360.

N. Notes on the Use of Multiple Geophones, Leonard V. Lombardi, Vol. 20 (2), 1955, pages 215 - 226.

O. A Graphical Method for Computing Geophone Array Response, R. K. Verma, A. Roy, Vol. 35 (4), 1970, pages 704 - 707.

12. Reviews of Geophysics, American Geophysical Union, Richmond, Va.

A. Q, L. Knopoft, Vol. 2 (4), 1964, pages 625 - 660.

13. Transactions of the American Geophysical Union, Richmond, Va.

A. Propagation of Elastic Waves in Limestone, Maurice Ewing, A. P. Crary, Vol. 16, 1935, pages 100 - 103.

B. Seismological Observations on Quarry Blasting, M. Ewing, A. P. Crary, J. M. Cohse, Vol. 15, 1934, pages 91 - 94.

14. Electrical Properties of Rocks, E. I. Parkhomenko, Plenum Press, New York, 1967.

15. Electrical Methods in Geophysical Prospecting, Keller and Frischknecht, Pergamon Press, Oxford, 1966.

16. The Nature of High Frequency Noise Spectra, G. E. Frantti, Geophysics, Vol. XXVIII, No. 4, 1963, pages 547 - 562.

17. An Analysis of the Vibrations Emitted by Some Man-Made Sources of Microseisms, C. D. V. Wilson, Proc. of the Royal Society, A, Vol. 217, pages 188 - 202.

18. Handbook of Geophysics, 1961 Edition, Chapter 12, pages 49 - 50.

19. A Theory on the Origin of Microseisms, M. S. Longuet-Higgins, Phil. Trans. Royal Soc. (London), Vol. 243 A, 1950, pages 1 - 35.

20. A Theory of Microseisms with Geologic Applications, Frank Press and Maurice Ewing, Trans. Amer. Geoph. Union, Vol. 29, No. 2, 1948, pages 163 - 174.

21. World-Wide VLF Effective Conductivity Map, Robert R. Morgan, Westinghouse Report 80133 F-1, 15 January 1968. AD 669-916.