USBM Contract No. HO122026

SURVEY OF ELECTROMAGNETIC AND SEISMIC NOISE RELATED TO MINE RESCUE COMMUNICATIONS

VOLUME II

SEISMIC DETECTION AND LOCATION OF ISOLATED MINERS

Robert L. Lagace – Project Leader

John J. Ginty, Martyn F. Roetter, Richard H. Spencer

Special Seismic Consultants

Robert Crosson Roy Greenfield

Francis Crowley John Kuo

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ARTHUR D. LITTLE, INC.

C-73912

USBM CONTRACT FINAL REPORT (Contract No. HO122026)

JANUARY 1974

DEPARTMENT OF THE INTERIOR

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WASHINGTON, D. C.

Arthur D. Little, Inc.

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FOREWORD

This report was prepared by Arthur D. Little, Inc., Cambridge, Massachusetts under USBM Contract No. H0122026. The contract was initiated under the Coal Mine Health and Safety Research Program. It was administered under the technical direction of the Pittsburgh Mining and Safety Research Center with Mr. Howard E. Parkinson acting as the technical project officer. Mr. Francis M. Naughton was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period August 1971 to December 1973. This report was submitted by the authors in January 1974.

VOLUME II

SEISMIC DETECTION AND LOCATION OF ISOLATED MINERS

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EMERGENCY AND OPERATIONAL MINE COMMUNICATIONS

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INTRODUCTION

This final report documents the work done by Arthur D. Little, Inc. (ADL) on behalf of the U.S. Bureau of Mines, Pittsburgh Mining and Safety Research Center (PMSRC), on Contract H0122026 (which began in August of 1971). Under this contract ADL provided technical assistance to the Bureau on a task basis on virtually all aspects of the Bureau's programs related to present and planned emergency and operational communications and miner location systems for underground coal mines. The work consisted of independent investigations, analyses, experiments, breadboard and prototype hardware development, workshops and technology transfer seminars on mine communications, and on-going evaluations and guidance related to the Bureau's contracted programs on electromagnetic noise, mine communications systems, and trapped miner location. This final report documents the work in two volumes, Volume I, "Emergency and Operational Mine Communications," and Volume II, "Seismic Detection and Location of Isolated Miners." The Tables of Contents of both Volumes are included in each Volume.

Phase I of the contract was devoted to performing an in-depth assessment of electromagnetic noise measurements taken by several contractors and other investigators, and then defining a new noise measurement program and instrumentation system tailored to obtain the necessary but missing noise data. These data are required for use in the design of new emergency and operational communication systems. This work, and the follow-on coordination and guidance activities of ADL on this noise measurement program in subsequent phases of the contract, are treated in Part One of Volume I.

The latter part of Phase I and part of Phase II included preliminary performance predictions related to through-the-earth electromagnetic communication systems. These predictions were based on available theoretical signal propagation results and on recently acquired noise data at several coal mines. This work is treated in Part Two of Volume I.

In Phases II, IV and V, investigations were conducted related to wire, guided-wireless and wireless communications systems for communicating with roving vehicles and personnel underground. This work is documented as follows. Part Three of Volume I treats guided wireless communications via leaky coaxial cable; Part Four treats wireless communications in mine tunnels at UHF frequencies; Part Five treats guided wireless communications down deep hoist shafts; Part Six treats aspects of trolley wire communications; and Part Seven treats a new mine pager telephone to public telephone interconnect system.

Another aspect of Phase V included tasks for providing assistance related to technology transfer seminars on mine communications and to a workshop on through-the-earth electromagnetics. Part Eight of Volume I treats this work. Under Phases II, IV, and V, ADL also provided a wide variety of short-term technical support and consulting services not discussed in the above mentioned Parts. This short-term work is treated in Part Nine of Volume I.

In Phase III of the contract, ADL performed another in-depth assessment on a compressed time schedule, to provide PMSRC with independent technical judgments regarding the potentials and limitations of seismic methods and systems for detecting and locating isolated miners. Volume II of this report is devoted entirely to the treatment of this work.

During the course of this contract we prepared over forty working memoranda, technical reports, seminar papers, and workshop summary reports, in addition to many informal memoranda and the monthly technical reports, to keep PMSRC informed of the progress and findings of our work as they developed. This final report is based on these previous memoranda and reports.

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EXECUTIVE SUMMARY

Arthur D. Little, Inc.

I. PURPOSE AND APPROACH

This Volume documents the Phase III effort on the Seismic Detection and Location of Isolated Miners on Contract H0122026 undertaken during the fall of 1972 by a task team composed of ADL staff and several seismic consultants. The team was assembled specifically to work together on complementary tasks, at an accelerated level of effort for four months, to meet the Bureau of Mines' time schedule for obtaining independent, objective, technical judgments regarding seismic methods and systems for detecting and locating isolated miners. The impetus for this work resulted from a compilation and analysis, during the first half of 1972, of new experimental data obtained from a series of in-mine field tests conducted by Westinghouse Corp.† using the CMRSS* interim seismic location system. The Bureau of Mines took advantage of the availability of these new data to reassess the potential and limitations of various seismic methods and systems, and to direct its seismic system improvement program accordingly.

ADL assisted the Bureau in this reassessment by drawing on the skills of seismic consultants from industry, universities and government, to supplement the skills of the ADL project team. The consultants were principal resources of broadly-based and detailed technical expertise in the areas of seismic signal-source and signal-propagation characteristics, natural and cultural seismic noise, seismic sensors and field instrumentation, seismic signal and data processing for detection and location, and overall seismic system utilization in the field under operational emergency conditions. Specifically, the participating consultants were: F. Crowley, Air Force Cambridge Research Laboratories; W. Dean, Teledyne Geotech, Alexandria Laboratories; R. Greenfield, Pennsylvania State University; J. Kuo, Columbia University; D. Peters and R. Crosson, University of Washington; and F. Pilotte, U.S. VELA Seismological Center. The principal ADL participants were J. Ginty, R. Lagace, M. Roetter, and R. Spencer.

† Westinghouse Contract H0210063 with the Bureau of Mines.

* Coal Mine Rescue and Survival System.

Guidance and assistance related to the general suitability and applicability of recommended techniques and procedures to actual mine environments were provided by H. Parkinson and J. Powell of U.S. Bureau of Mines Pittsburgh Mining and Safety Research Center.

The overall objective of the Phase III effort was to perform a short intensive study to identify what could be done by seismic methods and systems, and how well, to:

- detect live signaling miners
- locate such miners to within the confines of a 600-by-600 foot section; and
- locate such miners to within a 15-foot entry width.

Both general and specific ground rules were established, with the assistance of the Bureau, to focus the study on the primary and fundamental aspects of the miner detection/location problem. The general ground rules are listed in Table 1 below for convenient reference. The specific ground rules related to the miner and his signal, the signal transmission path and noise environment, and the signal detection/location activity on the surface, are given in Part Twelve of this Volume.

Table 1

SEISMIC DETECTION AND LOCATION SYSTEM

General Ground Rules

- System hardware field suitable and rapidly deployable.
- System constrained to present state-of-the-art techniques and hardware.
- System operation from the surface.
- System self-contained in its operation and calibration.
- System capable of producing timely location estimates.
- System operation compatible with and complementary to overall rescue effort.
- Signal sources readily available and reasonable - no special devices carried by the miners.
- No wide-area search required by the surface team - likely areas for trapped miners given.
- Surface team will have benefit of mine maps.

Specific task areas, including output objectives and corresponding input components, were also defined, as outlined in Table 2, and assigned to the study participants. These ground rules and tasks allowed the project team to:

- obtain "best" estimates, based on available data, of the ability to detect and locate miners trapped beneath real mine overburdens;
- define the requirements imposed on the surface seismic system by operational field conditions for successfully executing the detection and location operations;
- assess how the above estimates are influenced by system complexity and cost; and
- determine what is still needed in terms of basic data, analyses, and experiments to improve and/or verify these estimates.

Parts Two through Six of this Volume address in detail the major output objectives of detection, arrival time estimation, location, and field utilization. Similarly, Parts Seven through Eleven treat the input components -- seismic signal source and transmission characteristics, earth models, seismic noise, signal-to-noise improvement techniques, and seismic detection/location instrumentation, which influence the ability to achieve the above output objectives. Part Twelve presents copies of the visual aids used in the initial ADL briefing given to the seismic consultants regarding the relevant background, ground rules, major problem components, and identification of specific tasks to be addressed; and those used in the ADL oral presentation of results of this study to PMSRC. The authorship of each Part is designated to appropriately acknowledge the major contributions of each seismic consultant. Consultant F. Crowley also provided key assistance to ADL in its role of overall definition, coordination, and integration of the study effort within the compressed time schedule. The following sections of this Part briefly summarize the principal findings and conclusions of the study regarding the main objectives of detection and location of isolated miners. These findings and conclusions are supported in the subsequent Parts of this Volume.

TABLE 2 TASK AREAS

INPUT COMPONENTS ↓ / OUTPUT OBJECTIVES →	DETECTION	PARAMETER ESTIMATION	LOCATION	EFFECTIVE FIELD UTILIZATION
	MAJOR INPUT COMPONENT CHARACTERISTICS AFFECTING OUTPUT OBJECTIVES			
SIGNAL SOURCES Fn of: Type : Man : Impact Area : Tunnel	• Strength • Directional and Coherence Charac. • Pulse Shape • Rep. Rate	• Strength • Directional and Coherence Charac. • Pulse Shape • Rep. Rate	• Directional Charac.	• Site Environment - Physical - Operational • Field Crew • Hardware • Deployment and Operation Procedures • Overall Rescue Operations ↓
TRANS. MEDIUM. CHARAC. Fn of: Layers (Type, Thick, Angle, etc.)	• Attenuation • Signal Modification - Freq. Response - Time Domain - Spatial Coh.	• Attenuation • Signal Modification - Freq. Response - Time Domain - Spatial Coh.	• Earth Model (Detailed)	
NOISE Fn of: Sources - Sig. Induced - Rescue Sources - Basic Bgrd. - Altered Mine - Message - System	• Spectrum Levels • Time Charac. i.e. Stationarity Impulsiveness • Spatial Coherence	• Spectrum Levels • Time Charac. i.e. Stationarity Impulsiveness • Spatial Coherence	• Noise Weighting of Parameters	
SENSORS Fn of: Depth : Coupling	• Sensitivity • Array Gain/ Directionality • Dynamic Range • Polarization	• Sensitivity • Array Gain/ Directionality • Dynamic Range • Polarization	• Array Geometry and Location	
SIGNAL PROCESSING	• Candidate Detection Methods	• Candidate Estimation Methods		
DATA PROCESSING AND COMPUTATION			• Location Algorithms • Mine Maps	

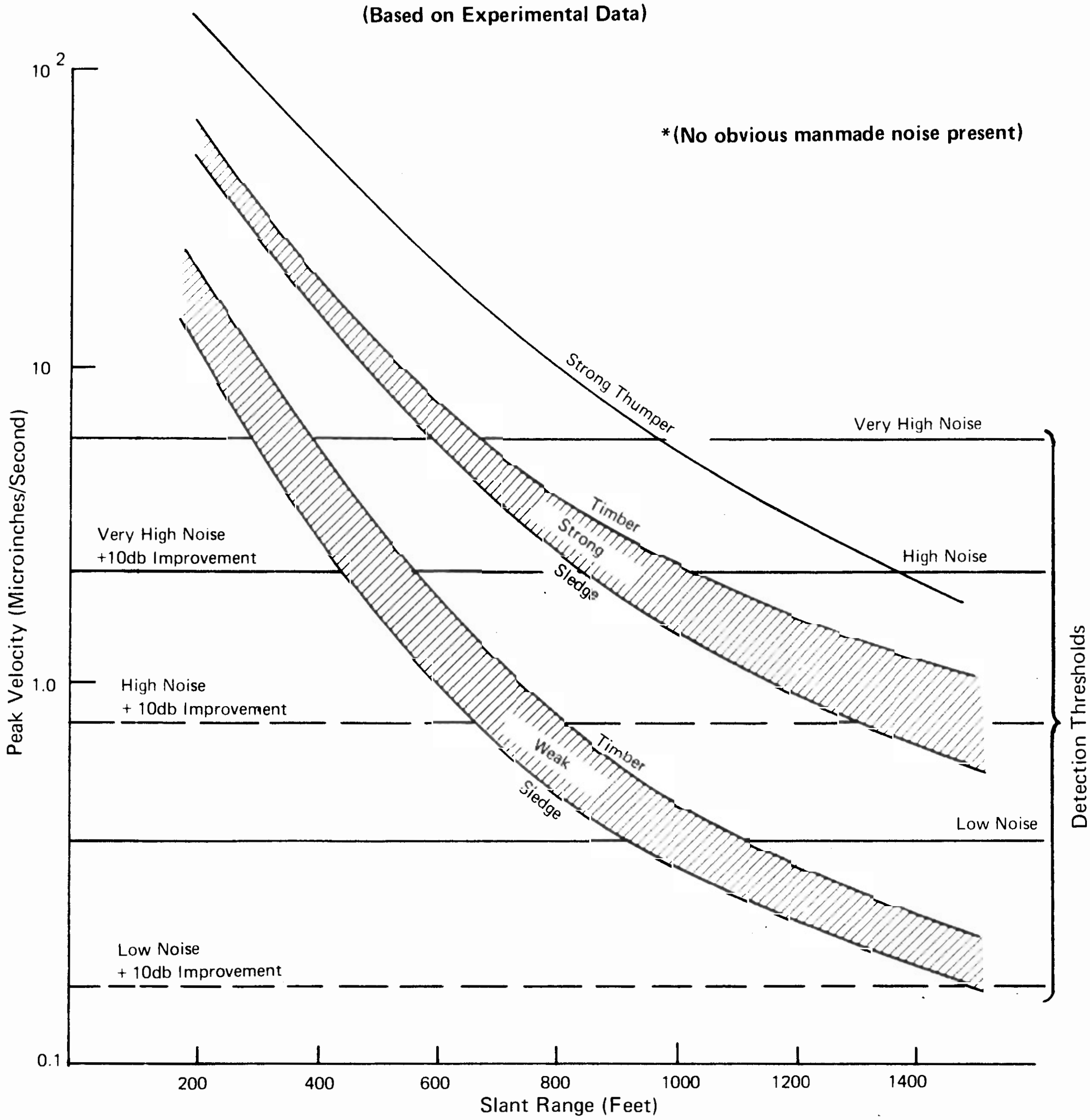
II. SUMMARY OF RESULTS

A. DETECTION OF A MINER

A surface deployed seismic system utilizing conventional signal-to-noise ratio improvement techniques can provide the capability of detecting miners signaling with timber or sledge sources, to slant ranges on the order of 1000 feet, under most natural seismic noise conditions in which no man-made noise sources are present. Under such noise conditions, these ranges should allow more than adequate coverage of typical mine sections. However, to obtain these noise conditions, surface rescue operations and activity in the vicinity of the detection area must be severely restricted and possibly prohibited. This may not be compatible with present mine rescue operations. Though more experimental noise data must be obtained and analyzed before definitive estimates can be made of the reduced detection ranges in the presence of man-made noise of the type and level present during uncontrolled rescue operations, it is highly likely that the presence of such noise will make the detection of a signaling miner impossible with a surface seismic system.

The dependence of detection range on the type of signaling source and on the levels of naturally occurring seismic noise is shown in Figure 1. Figure 1 depicts the variation of received signal strength with type of source and slant range above the source, derived from data taken at several mines. The horizontal lines denote signal detection thresholds for three representative natural noise conditions, with and without the benefit of a conservative 10 dB improvement in signal-to-noise ratio. These natural noise conditions are based on published data taken at several locations other than above mines. Only a limited sample of suitable noise data taken above mines at quiet times was available for comparison. These noise levels at mines were not inconsistent with the more comprehensive natural noise data used.

FIGURE 1 COMPOSITE PLOT FOR ESTIMATING DETECTION RANGES UNDER NATURAL NOISE CONDITIONS*
(Based on Experimental Data)



Detection ranges are obtained by noting the intersection of the signal curves with the corresponding detection thresholds of interest in Figure 1. Noise levels and corresponding detection thresholds for uncontrolled rescue operations are expected to far exceed those for the very high natural noise condition, thereby drastically reducing detection ranges to unacceptable levels. Table 3 presents, for convenient reference, a summary of detection ranges derived from the curves of Figure 1. Table 4 summarizes those signal-to-noise improvement techniques judged most and least useful for detecting and locating isolated miners.

To improve these detection range estimates and to better evaluate the utility of the signal-to-noise improvement techniques identified as most useful, a series of careful seismic noise and signal strength measurements should be performed in Eastern coal mining regions by field crews well-experienced in seismic and geophysical field work. This work should be supported by theoretical analyses to better understand the generation and propagation behavior of signals produced by practical signaling sources available to miners during emergencies in coal mines. Detailed treatments on detection range estimation and signal-to-noise improvement techniques are found in Parts Two and Ten, respectively.

B. LOCATION OF A MINER

The above described detection process, being inherently limited to slant ranges on the order of 1000 feet, in itself provides a coarse location of a trapped miner that in many cases may be sufficient to direct the efforts of a rescue team. However, should greater accuracy be required, location of a miner to within a section is a realistic objective. In fact, location accuracies to within 100 feet for miners down to depths of 1000 feet appear attainable with surface deployed systems, but only when the required conditions are met. Namely, when an adequate seismic representation (model) of the earth beneath the surface seismic system is available, the depth of the miner is known from a good mine map, and as in the case of detection, the surface rescue operation and activity

TABLE 3
MAXIMUM SLANT RANGES (In Feet) FOR DETECTION-UNDER NATURAL NOISE CONDITIONS**

Source	Low Noise		High Noise		Very High Noise	
	W/O-S/N I*	W-S/N I	W/O-S/N I	W-S/N I	W/O S/N I	W-S/N I
Strong Thumper	>2000	>2000	1400	>2000	950	1400
Strong						
Timber	>2000	>2000	1050	>1500	650	1050
Sledge	>1500	>2000	900	1250	550	900
Weak						
Timber	1100	>1500	550	800	375	550
Sledge	900	>1400	450	625	300	450

* W/O - S/N I = Without 10dB Signal-to-Noise Improvement
W - S/N I = With 10dB Signal-to-Noise Improvement

** No obvious manmade noise sources

Table 4

SIGNAL-TO-NOISE IMPROVEMENT TECHNIQUES

Most Useful

For Detection	For Arrival Time Estimation
. Bandpass Filtering . Burial of Sensors . Subarrays: - size optimization - delayed or direct sum - weighted sum	. Same as for Detection . Summing (Stacking) of Repeated Signals

Least Useful

For Detection and Arrival Time Estimation

. Remode Processing
. Linear Phase Filtering of Multicomponent Data
. Matched Filtering
. Multichannel Maximum Likelihood Array Processing
. Multichannel Wiener Filtering
. Single and Multichannel Prediction Error Filtering

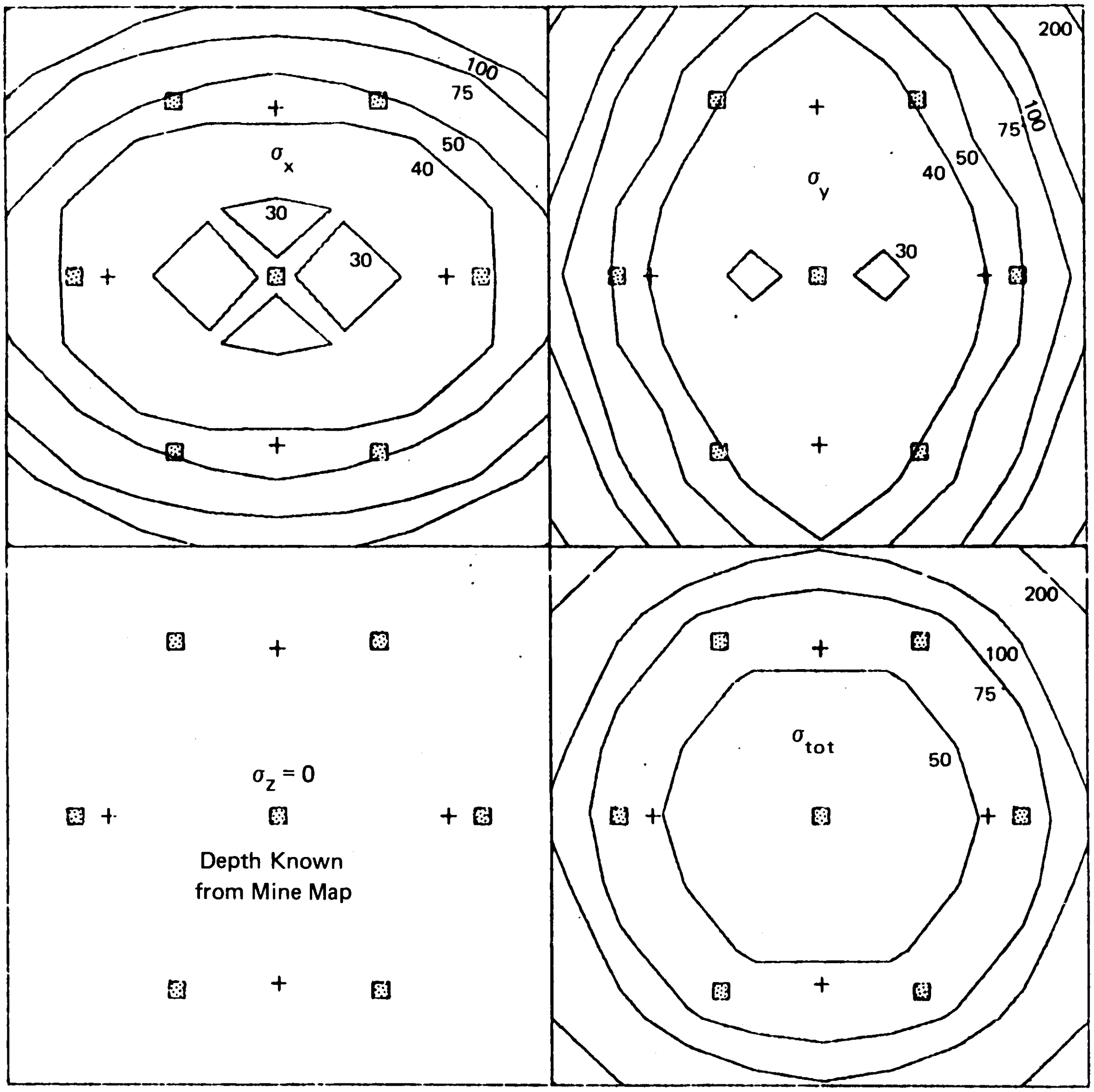
in the vicinity of the location area has been severely restricted and possibly prohibited, which again may not be compatible with present rescue operations. Indeed, for accurate miner location, signals will have to be received on several seismometers surrounding the miner's location, and signal-to-noise ratios well in excess of those for detection will also be required to adequately estimate to sufficient accuracy the signal arrival times needed for computing location coordinates. Specifically, the above estimate of location accuracy applies only to favorable, controlled conditions:

- when the signals are strong enough to allow arrival times to be measured to within 1-5 milliseconds, and
- when the earth at the local mine site can be adequately represented by a set of laterally homogenous horizontal layers with different seismic velocities, and these parameters can be specified to within about 5% by refraction surveys from the surface.

Though available geological information tends to support the reasonableness of the type of seismic earth model assumed, data from refraction surveys performed directly over representative coal mines, together with controlled location experiments using strong signal sources, are still needed to confirm the general applicability of this kind of model. Figure 2 is an example of the location error contour maps generated during the study to form a basis for drawing conclusions on attainable location accuracy with surface seismic arrays. These contours are based on an error analysis applied to the well-established location method of non-linear, least squares iterative inversion. The contours in each square represent the estimated standard location errors in x, y, and z (one standard deviation, σ, of a normal distribution) for a source so located relative to the array geometry.

The location results indicate that earth model errors of 5% will be the dominant contributors to miner location errors when arrival time errors fall between 1-5 milliseconds, but that arrival time errors become the major contributors and seriously degrade location accuracy when these

FIGURE 2 EXAMPLE OF LOCATION ERROR CONTOUR MAPS



4 Layer Model
$\sigma_v = 5\%$
$\sigma_t = .001$

σ_{tot}min. = 41.0

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET
7-ELEMENT HEXAGONAL ARRAY

timing errors reach 15-20 milliseconds. Errors of this magnitude can be introduced by low signal-to-noise ratios and by the variable thickness of low-velocity weathered layers under different seismometers in the location array. Hence it is important to account for such sources of large timing errors in the field.

The further objective of directly locating a signaling miner to within an entry width with a surface seismic system appears to be an unrealistic goal. Only under the most favorable but improbable circumstances, namely, noise conditions similar to or better than those described above, and an even more accurate representation of the earth or shallower mine depth (300 feet or less), do location accuracies of about 30 feet appear attainable. With the aid of a good mine map, these accuracies could allow the surface team to identify the entry in which the miner is located. However, the only method that is likely to produce accuracies of this order in practice is a more costly reference event method. This method relies on the prior calibration of the seismic properties of the earth over the mine by initiating and recording seismic reference events on a regular periodic basis. Detailed treatments of the location algorithms examined in this study; namely, non-linear least squares iterative inversion, Westinghouse program "Miner", and reference events, together with the suggestion of even more advanced algorithms that allow iterative improvement of the earth model as well as the predicted location, are found in Parts Three, Four, Five and Seven.

C. FIELD UTILIZATION

The nature of mine emergencies, the experience gained with the present interim seismic location system, and applicable experience of our consultants related to the deployment of small, highly mobile, operational seismic teams, lead to several guidelines and recommendations regarding the field utilization of the seismic equipment and the composition of the seismic team. The seismic system should be transportable and deployable in various configurations, depending on the mine location and on the needs of the detection and/or location operations. The range of field requirements extend from the need for simple detection processes in quiet remote locations, to complex detection and location processes in areas of relatively easy access with unfavorable noise environments.

Therefore, the system should be configured in modular form that allows deployment in phases. For example, on notification of a mine emergency, the initial deployment could include only a simple portable detection system capable of being easily transported by commercial or private aircraft, automobile, or a small truck to the mine, and back-packed to specific locations over the mine workings if necessary. This simple detection system would be composed of a small array subsystem, an array control unit, an oscilloscope, and possibly a multichannel strip chart recorder. These units are sufficient to obtain not only initial detection of miners, but also first-order location of these miners in the vicinity of the sites chosen for initial investigation. A more comprehensive, easily transportable, van processing center and additional subsystems could be deployed shortly thereafter, or as required by the particular emergency situation.

The equipment must be made simple, weather tight, rugged, modular, and temperature insensitive. In addition, because the location of miners requires calibrated signals and test and repair facilities may not be readily available, calibration and check-out of the system must be easy to do on site. Since power may not be available, battery operation is a must for the portable field equipment. Furthermore, because emergency conditions require quick response, not only must the equipment be quickly and easily deployable at the site, but speed in the acquisition and processing of the seismic data is essential once the system has been deployed. Indeed, overall processing times of received data should be measured in minutes rather than hours. Table 5 summarizes some of the important hardware requirements for a flexible, fieldable seismic detection and location system. These requirements can be met by appropriately integrating and packaging present off-the-shelf components and equipment.

Table 5

HARDWARE REQUIREMENTS FOR SEISMIC DETECTION/LOCATION SYSTEM

- Compact light-weight, rugged, modular, proven hardware
- Simple and easily deployable
- Combination vertical seismometer/amplifier unit capable of burial
- Water proof non-ambiguous cabling and array control unit
- Seismometer calibration device
- 12-channel tape recorder
- Multichannel hard-copy-output recorder
- Accurate, recoverable time codes on tape, or paper output
- Continuous time reference on tape, or paper output
- Selectable time base displays
- Variable filtering and gain
- Battery operation of portable subsystems
- Radio communication for crew
- Tools
- Van processing center with disk pack and mini-computer

The final essential element required to ensure the successful utilization of the system during a mine emergency is the composition and experience of the seismic team. The minimum requirement is a three-man cadre that is trained to work together under such emergency conditions, being completely familiar with all aspects of the system and its operation and each others duties. This cadre should include an operator/analyst an electrical technician, and a field technician. The operator/analyst will be the team chief and should also be an experienced geophysical engineer. This cadre would utilize additional but inexperienced mine personnel at the site to expedite deployment of the system. The key man of this cadre is the team chief who should also be a mature individual who is thoroughly familiar with mining operations and practices, can interface effectively with the overall resuce coordinators, and successfully direct the seismic detection/location operation in the face of confusion and possibly conflicting rescue requirements. Detailed treatment of the instrumentation and its field utilization requirements will be found in Parts Six and Eleven.

III. CONCLUDING REMARKS

As stated in the Purpose and Approach Section of this Part, the purpose of this study was to provide results to help the Bureau of Mines in the formulation of future policy and plans of action related to the detection and location of isolated miners by the application of seismic methods. In this regard, an additional.question was posed by the Bureau, for consideration by the ADL seismic team during the course of this task. Namely, which of the following alternative courses of action appear to be most feasible and appropriate at this time:

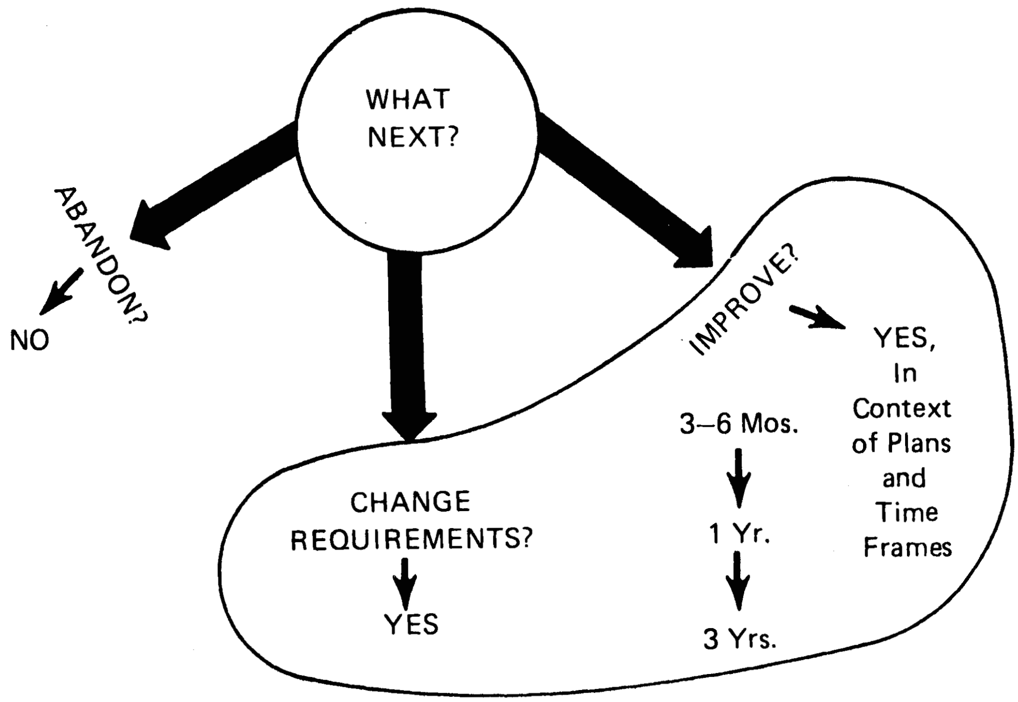
- Abandon the seismic system and rely on electromagnetic or other methods?
- Change the performance requirements of the seismic system - for example, by only requiring positive location to within the dimensions of a working section?
- Improve the system and seismic methods employed?

Figure 3 summarizes the three alternatives and the corresponding ADL responses in a graphic format. Expansions on these responses follow.

No, it would not be appropriate to abandon seismic detection and location methods at this time, in spite of their shortcomings. Until viable electromagnetic miner location equipment is developed, produced in quantity, and utilized by the mining industry, seismic methods still remain the only means presently available for detecting the presence of live signaling miners and determining their location from the surface.

Yes, it is definitely feasible and appropriate to change the performance requirements for a seismic system, particularly regarding the required accuracy of location. Location accuracies to within one or two coal pillars, and even to within dimensions of a working section, when used in conjunction with a good mine map, will be extremely valuable and in many cases, be more than sufficient to direct the efforts of both in-mine rescue teams and surface drilling crews. However, it should be remembered that rescue operations and activity in the vicinity of the location area may have to be severely restricted, and possibly prohibited temporarily, to achieve these location results.

FIGURE 3 ALTERNATIVES



Yes, it is definitely required, feasible, and appropriate to improve the system and seismic methods employed to detect and locate isolated miners. However, the type and extent of these improvements need to be determined by the Bureau in the context of its overall plans and associated time frames related to its miner location programs. In this regard, the Bureau will find that some quick-fix and minor improvements will be suited to 3-6 month schedules, while others that are major or that require additional fundamental investigations may require schedules of 1 to 3 years.

Each of the improvements referred to above will require investments of one kind or another that will impact on both cost and performance. Table 6 briefly summarizes the expected impact on system performance and cost for several possible kinds of investments. Finally, in order to more accurately estimate the performance limits and potentials of seismic miner detection and location systems, further investigations are still required to characterize the following items in a more quantitative manner:

- Seismic signals from sources available to miners.
- Seismic noise in coal mine regions.
- Seismic propagation attributes of coal mine overburdens.

These investigations will be largely based on experimental work in the field.* Several of these are described in more detail in the body of this Volume.

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* Selected improvements in the seismic system hardware have since been made by PMSRC, and experimental investigations related to the above three areas have been conducted by Continental Oil Co. for the Bureau of Mines under Contract H0133112.

Table 6

EXPECTED IMPACT OF INVESTMENTS ON SYSTEM PERFORMANCE AND COST

IMPACT of ↓ on →	Improving Overall Performance	Increasing Overall Cost
. Truly Fieldable Hardware	High	Low
. Trained Experienced Field Crews	High	Moderate
. Site Pre-Calibration Preparation*	High	High
. Improved Seismic Earth Models*	High	Low
. Conventional S/N Enhancement Methods	High	Low
. Sophisticated S/N Enhancement Methods	Low	High
. Controlling Site Man-Made Noise	High	Low

* Applicable mainly to miner location, as opposed to miner detection and location.

PART TWO

DETECTION RANGE AND ARRIVAL TIME ESTIMATES

PART TWO

DETECTION RANGE AND ARRIVAL TIME ESTIMATES

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PART TWO

DETECTION RANGE AND ARRIVAL TIME ESTIMATES

Roy Greenfield
Pennsylvania State University

I. SUMMARY

Estimates are given for the distance from a seismometer at which a miner can probably be detected. The procedure in making these estimates was to first establish the natural noise levels at the output of a surface seismometer for the 25 to 100 Hz frequency passband. The noise levels give the range of values which may be expected in areas with no man-made noise. For each noise level, we give the detection threshold which, when exceeded, indicates that a signal has been received. Based on the signals recorded by Westinghouse, curves are given which show the peak signal amplitude as a function of source-to-receiver distance (slant range). Curves are given for the Westinghouse seismic thumper, a 50-pound timber, and a sledge. For a given type of source, the receive signal strength depends more strongly on slant range than on any other factor. However, there is approximately a five-to-one scatter in the amplitudes. Thus, further study of factors affecting the signal amplitude might allow better estimates to be made for any particular geological setting.

Combining the signal amplitude with the detection thresholds for the different noise conditions gives the distances at which a miner should be detected. These are given in Table 1* below.

Table 1
Maximum Range (in Feet) at Which a Miner Could be Detected
For a Single Sensor--Before Signal-to-Noise Improvement Techniques
(Natural Noise and Average Signal Strength Assumed)

	Natural Noise Condition		
Source Type	Low	High	Very High
Thumper	1600	1000	700
Timber	1400	800	500
Sledge	1200	700	400

The text also gives the increase in detection ranges which should occur if steps are taken to increase S/N by 10 dB. We feel that 10 dB is a conservative estimate of the improvement possible.

During an actual rescue operation, the seismic crew and system should be capable of making on-site estimates of their detection capability, based on measurements of the site noise, and upon the best available estimates of the

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

signal strengths to be expected. This will allow the seismic rescue crew to estimate the likely coverage area of the seismic system, for detection of a signalling miner under the prevailing noise conditions, which will in turn assist the rescue team to determine appropriate search strategies for the entrapped miners.

The effects of noise on the estimates of signal arrival times are also discussed. The arrival times should be picked by an analyst from stacked signals from all available signal repetitions. It is shown that for low to moderate noise situations, the signal arrival time at each subarray can be determined to within a few milliseconds. However, when the noise is comparable to the signal, errors of 10 to 15 milliseconds can occur, and in some cases, it might be possible to pick a signal arrival time which is 50 to 100 milliseconds after the true arrival time.

II. INTRODUCTION

In this Part estimates, based on experimental data, are made of the natural noise levels encountered for surface seismometers, and a model for signal levels, based on Westinghouse data,*is developed as a function of slant range and source type. The natural noise level estimates are applicable to the range of conditions encountered when no man-made noise sources are present. These natural noise levels may be representative of the levels experienced during a mine emergency rescue operation at those times when care has been taken to control the rescue activity's seismic disturbances. Further experimental data is needed in order to characterize the man-made noise environment created by rescue operations.

Using the above results, estimates have been made for the detection range which can be obtained. All work is done for a 25 to 100 Hz bandpass. Most of the signals observed by Westinghouse have most of their energy in that band. It remains (as noted in Part Nine) to determine the noise levels above 100 Hz before it is possible to determine if the band above 100 Hz will aid in detection. Initially detection ranges are determined for a single sensor with no signal processing. Some estimates also are made of detection ranges if signal enhancement is successful. After the detection discussion, a chapter will consider how noise levels affect estimates of signal arrival times for use in the subsequent location process.

III. NOISE LEVELS

We desire to determine a detection threshold, which when exceeded indicates that a signal is present at the output from a single sensor. In the Appendix to this Part, we show a reasonable detection threshold level as 3 times the noise RMS level. This will lead to approximately 1 false alarm each 100 seconds on a single trace, and very rare false alarms if coincidence detection is used on the outputs of several subarrays.

To estimate, within the time available, the surface noise levels to be expected, we concentrated on the noise data of Frantti[1] 1963 rather than the noise measurements made by Westinghouse. This was done because the contamination of the Westinghouse earth noise data by system noise weakened our confidence in their noise data (see Parts Nine, Ten). The Frantti data are for locations free of obvious man-made noise sources. Frantti measured peak-to-peak average envelope values at the output of a 1/3 octave filter. In cases where this envelope average was compared to the RMS noise level, the

* Westinghouse Contract H0210063 with Bureau of Mines.

envelope average was slighly higher. In (A 6) of the Addendum we show this is to be expected, but the difference, a factor of 1.7, is not important because RMS noise levels can be expected to fluctuate over more than an order of magnitude at different times and locations.

We used 47 of Frantti's noise curves (data for deep mines and a site near the ocean were excluded). For each curve the spectral level was read at 25, 50, and 100 Hz. Histograms (Figures 1, 2, and 3) were formed for each frequency. The RMS noise levels exceeded 75% of the time (low noise) were determined for each frequency, and marked on the histograms. This was also done for the RMS noise levels exceeded only 25% of the time (high noise). As a comparison, the range of levels found by Westinghouse during their mine field test program are also included on these Figures. The Westinghouse levels are not inconsistent with the levels predicted by Frantti.

To proceed from the RMS noise spectral estimates to the noise RMS output level of a 25 to 100 Hz filter, we used

$$RMS_{75\%} = \left[\int_{25}^{100} A^2 (f)\, df\right]^{1/2} \qquad (1)$$

for the "low noise" level condition. The RMS (amplitude) spectrum, A(f), used is plotted on Figure 4. The signal detection threshold was then set at 3 times the noise RMS output level. The same calculations were made for the (25%) "high noise" level condition. The results are given in Table 2.

Table 2

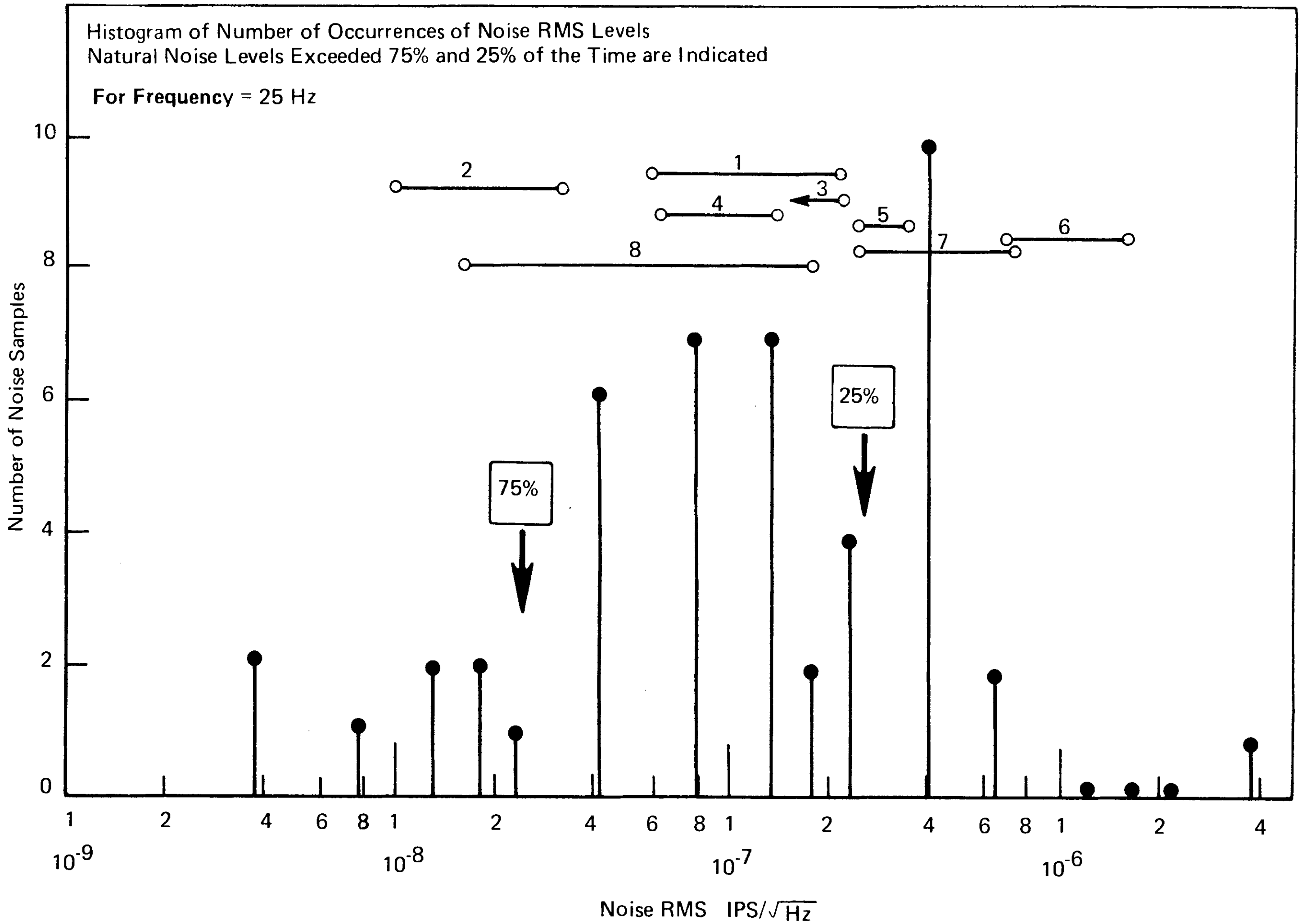
RMS Noise Output and Detection Threshold

Of a 25 To 100 Hz Filter

	(μIPS)
RMS Level Exceeded 75% of Time (Low Noise)	0.22
RMS Level Exceeded 25% of Time (High Noise)	1.5
Detection Threshold (Low Noise)	0.66
Detection Threshold (High Noise)	4.5

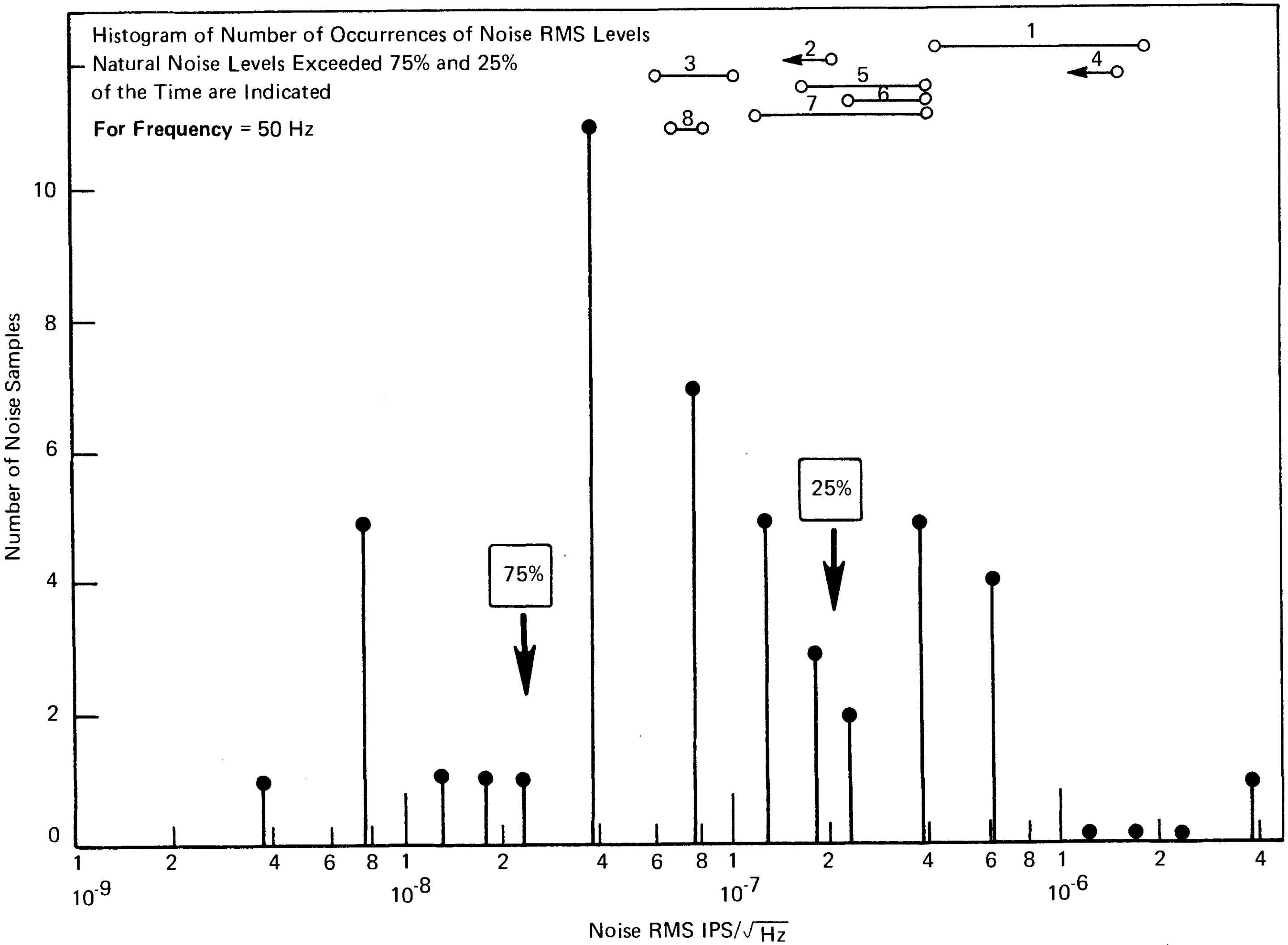
IV. SIGNAL LEVELS

The basis of our estimates of the seismic signal levels is the Westinghouse data. The maximum zero-to-peak amplitude levels for the signals are plotted as a function of slant range in Figure 5. The sources of data are given in the Figure. Curves have been drawn as estimates of the strong



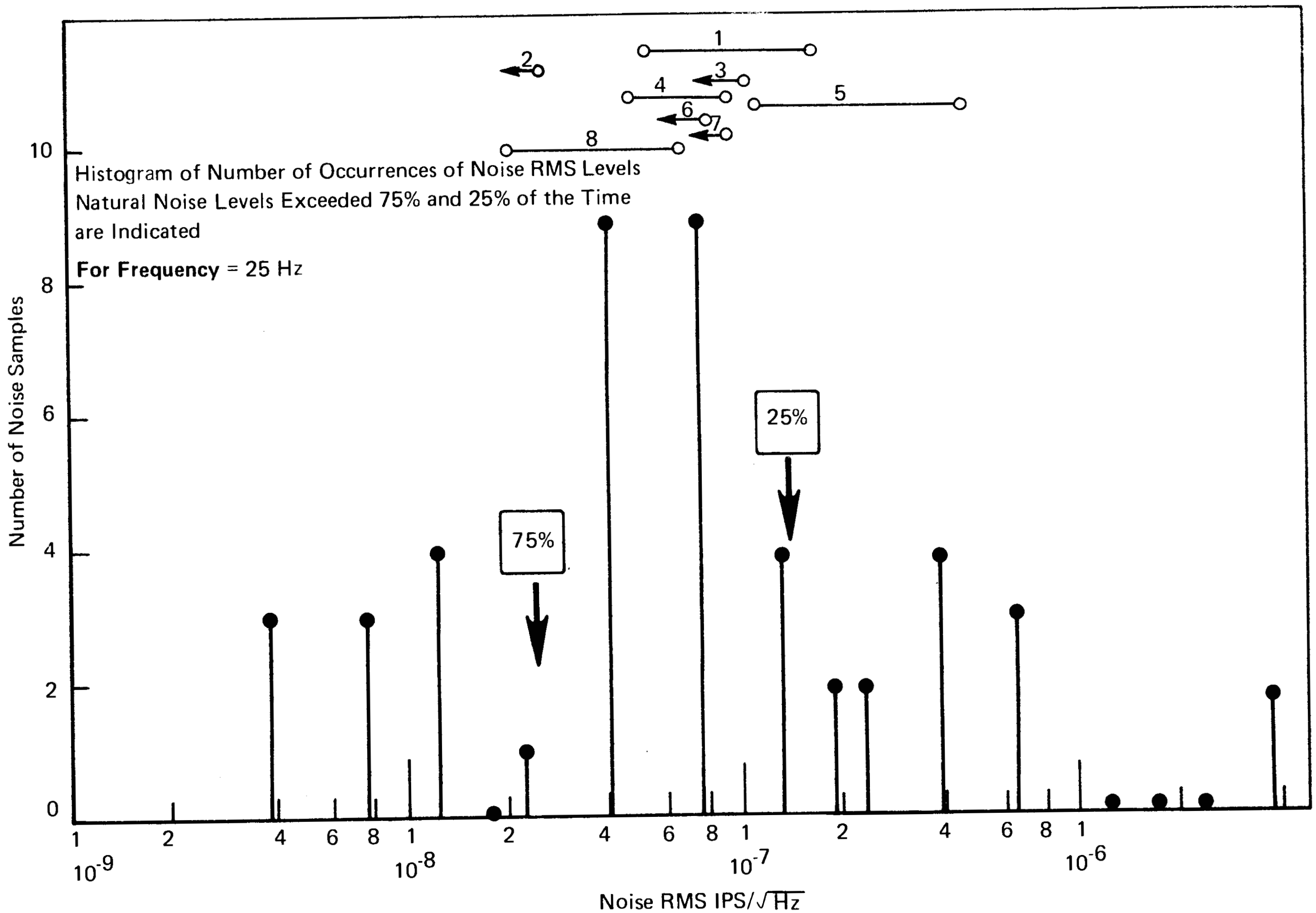
Westinghouse data for individual mines are included for comparison, and maximum and minimum noise levels are shown as open circles connected by lines. Ignore the vertical axis in relation to these data. Arrows pointing to the left indicate that system noise limited noise estimates for low noise periods. The Westinghouse data are taken from the Westinghouse Report Table 2-4. The order of the mines, going from the top of the figure to the bottom data points, corresponds to the field report numbers for the mines.

FIGURE 1 NATURAL SEISMIC NOISE LEVELS: BASED ON FRANTTI DATA WHEN NO MAN-MADE NOISE IS PRESENT



Westinghouse data for individual mines are included for comparison, and maximum and minimum noise levels are shown as open circles connected by lines. Ignore the vertical axis in relation to these data. Arrows pointing to the left indicate that system noise limited noise estimates for low noise periods. The Westinghouse data are taken from the Westinghouse Report Table 2-4. The order of the mines, going from the top of the figure to the bottom data points, corresponds to the field report numbers for the mines.

FIGURE 2 NATURAL SEISMIC NOISE LEVELS: BASED ON FRANTTI DATA WHEN NO MAN-MADE NOISE IS PRESENT



Westinghouse data for individual mines are included for comparison, and maximum and minimum noise levels are shown as open circles connected by lines. Ignore the vertical axis in relation to these data. Arrows pointing to the left indicate that system noise limited noise estimates for low noise periods. The Westinghouse data are taken from the Westinghouse Report Table 2-4. The order of the mines, going from the top of the figure to the bottom data points, corresponds to the field numbers for the mines.

FIGURE 3 NATURAL SEISMIC NOISE LEVELS: BASED ON FRANTTI DATA WHEN NO MAN-MADE NOISE IS PRESENT

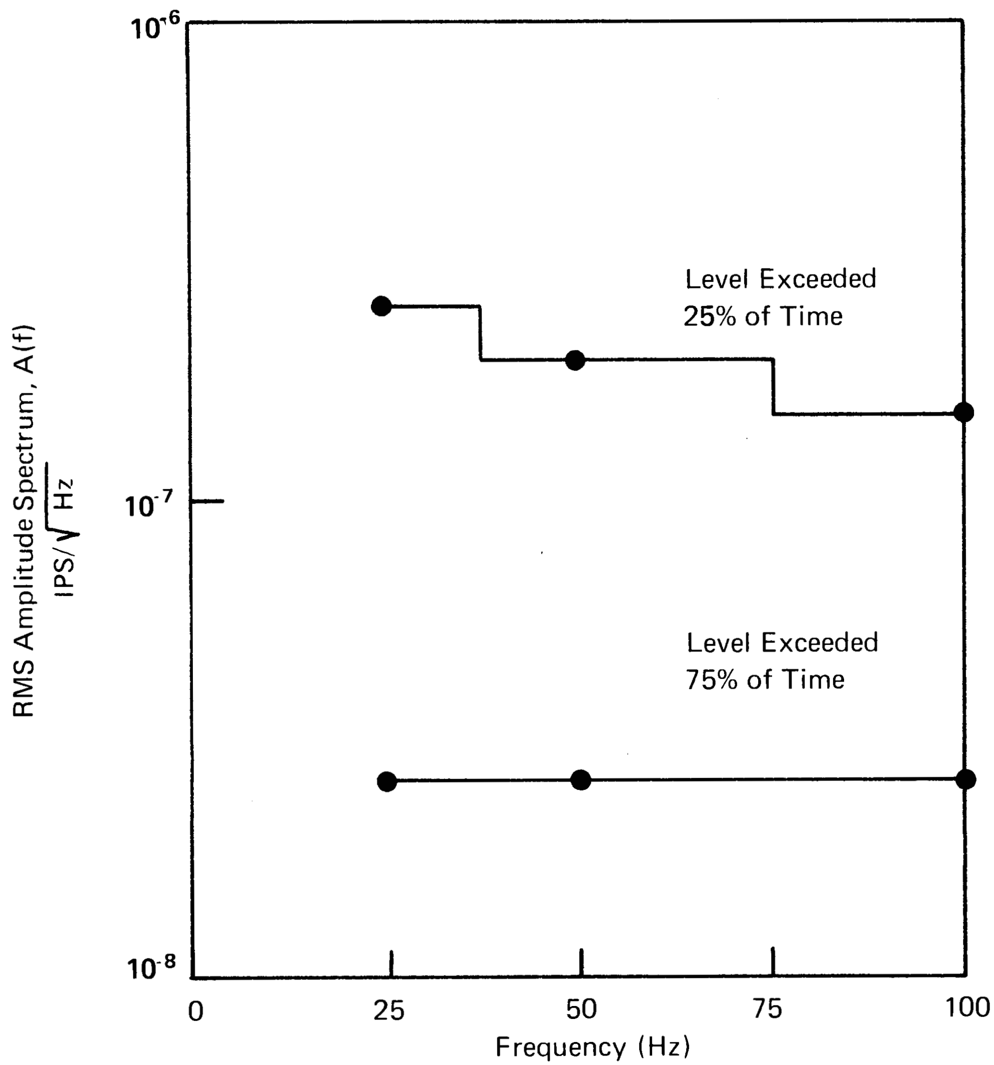
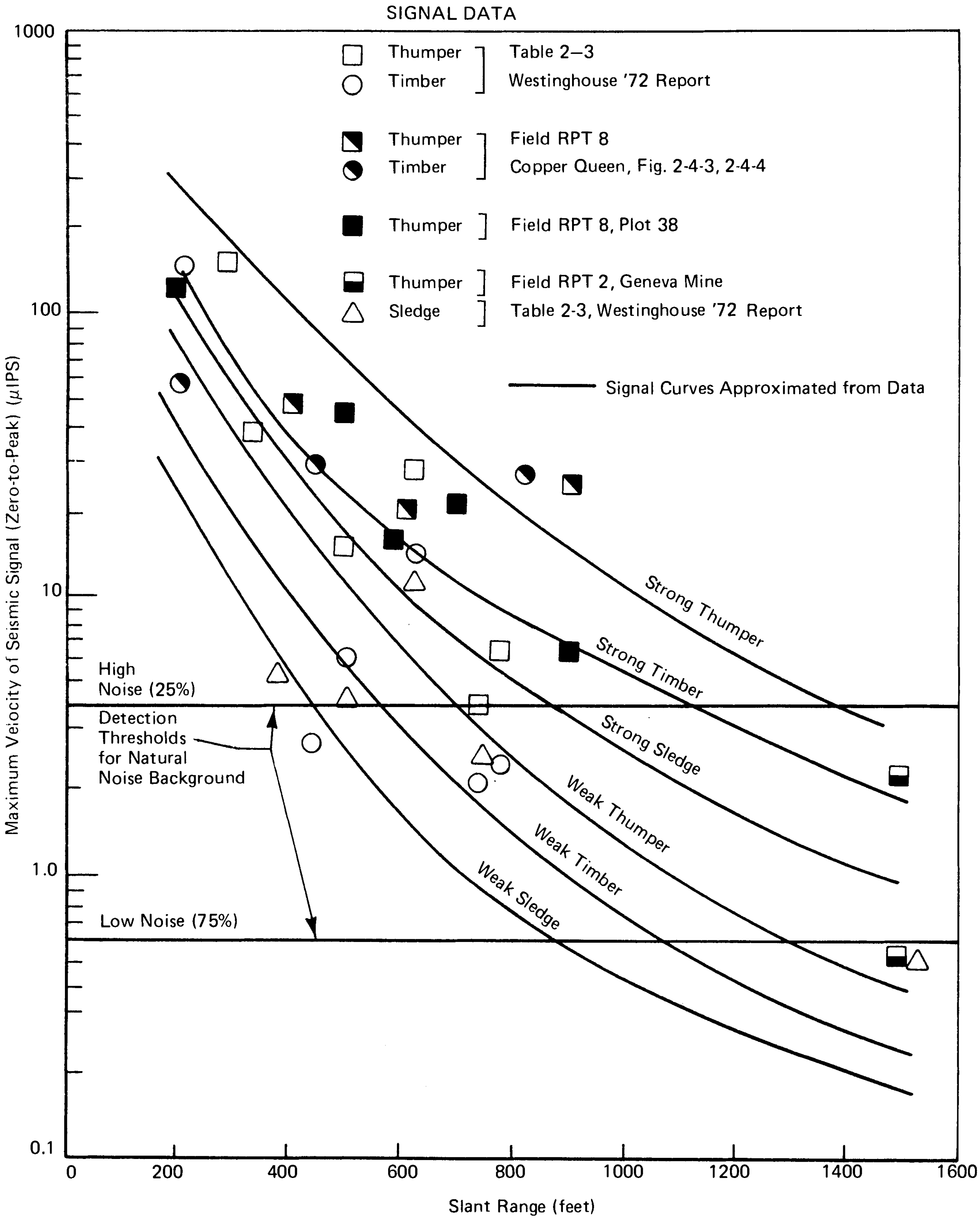


FIGURE 4 NATURAL SEISMIC NOISE LEVELS BASED ON FRANTTI DATA WHEN NO OBVIOUS MAN-MADE NOISE IS PRESENT (RMS AMPLITUDE SPECTRA)



(Largest Zero to Peak Amplitude on Vertical Traces, Plotted for Three Sources, Thumper, Timber, Sledge Hammer.)

Signal Data from Westinghouse 1972 Report, Estimated Detection Thresholds also shown for **Natural Seismic Noise Background** (Noise Data from Frantti, 1963).

FIGURE 5 SEISMIC SIGNAL AMPLITUDE PLOTTED VERSUS SLANT RANGE FROM TYPICAL SOURCES

and weak signals for the thumper, timber, and sledge sources. These curves enclose the majority of the data, and are the basis of the detection range discussion in the next chapter. We believe that Figure 5 represents the best estimates of signal level that we can make at this time, based on experimental data available to us.

A scatter of a factor approximately 5 exists in the amplitude data. However this is not unexpected. Scatter of this magnitude is quite common in seismic data around 1 Hz, and can reflect any one of a number of factors. In the case of the Westinghouse data these factors probably include source coupling, propagation effects, the source radiation pattern, and variation of the low velocity alluvium thickness at the seismometer.

We have attempted to assess the source radiation pattern effect using the data from Field Report 8*, Copper Queen Mine, Figures 2.4.3 and 2.4.4, compiled in Table 2.4-3 of that report. In Table 3, we show their amplitude readings for both first motion and for maximum trace amplitude. Only the vertical seismometer is used. Also shown is the theoretical amplitude, V_m, of the vertical component for a point vertical source in an infinite medium. The V_m for such a source is of the form (Love, 1944, p. 304-305).

$$V_m = \frac{A}{r} \cos^2 \theta \tag{2}$$

where r is slant range

θ is the angle between the vertical and the source-to-receiver direction

and A is a constant

The formula given is strictly valid only if the receiver is many wavelengths from the source. This requirement is <u>not</u> well met in the present experiment. We have set A to fit the observed amplitude at the seismometer on the surface directly above the source, receiver 1. The source and receiver locations are shown in Figure 6. Values for a 1/r variation are also given. Again we normalized to receiver 1.

The results in the Table are not conclusive. However in general, the 1/r fit is closer than the V_m fit. The V_m often greatly underestimates the amplitude.

The data, on Figure 5 obtained from plot 38 of Field Report 8*, (plot 38 is reproduced here as Figure 7a) is of interest. These data were obtained for a thumper source put in the Copper Queen Mine, 900 feet below the surface.

* Ibid.

Table 3

Source Pattern Effects (Copper Queen Mine)

a) First Motion Peak (μIPS)

	Receiver 1	Receiver 2	Receiver 3
Source (1), Timber			
Observed	54.	11.8	6.7
Theory, V_m	54.	5.3	0.58
1/r Variation	54.	24.	13.
Source (2), Thumper			
Observed	26.6	20.	8.6
Theory, V_m	26.6	8.	2.6
1/r Variation	26.6	17.	11.6

b) Maximum Trace Amplitude (μIPS)

	Receiver 1	Receiver 2	Receiver 3
Source (1), Timber			
Observed	58.3	29.8	27.1
Theory	58.3	5.6	0.67
1/r Variation	58.3	26.	14.2
Source (2) Thumper			
Observed	38.0	20.0	26.6
Theory	38.0	17.0	3.7
1/r Variation	38.0	34.0	17.

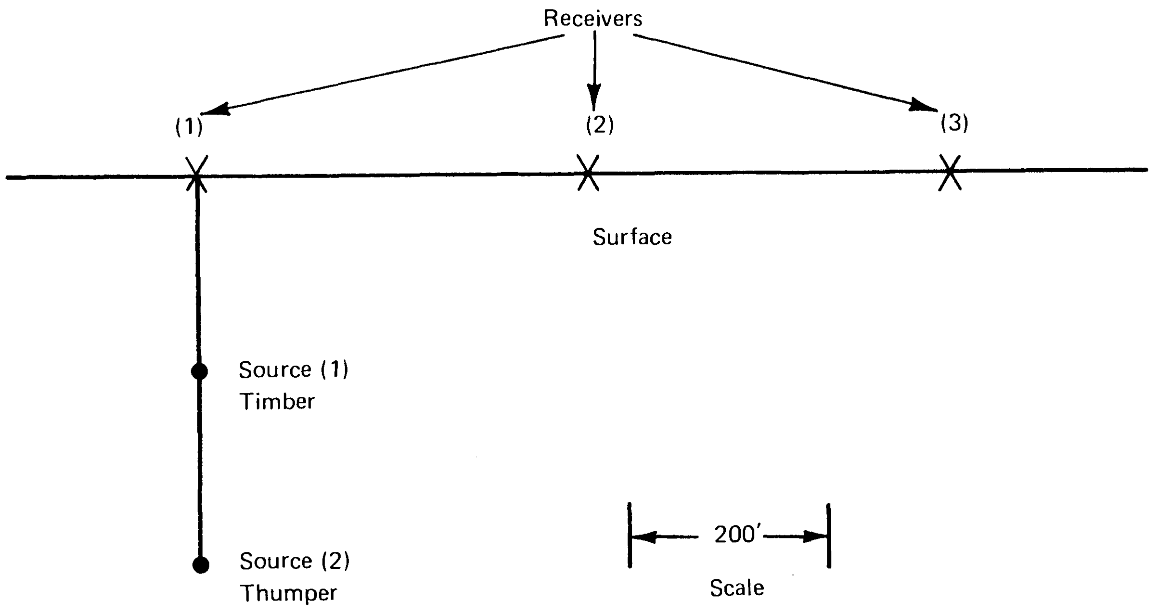


FIGURE 6 SOURCE-RECEIVER LOCATIONS FOR COPPER QUEEN MINE WESTINGHOUSE SIGNAL STRENGTH EXPERIMENT

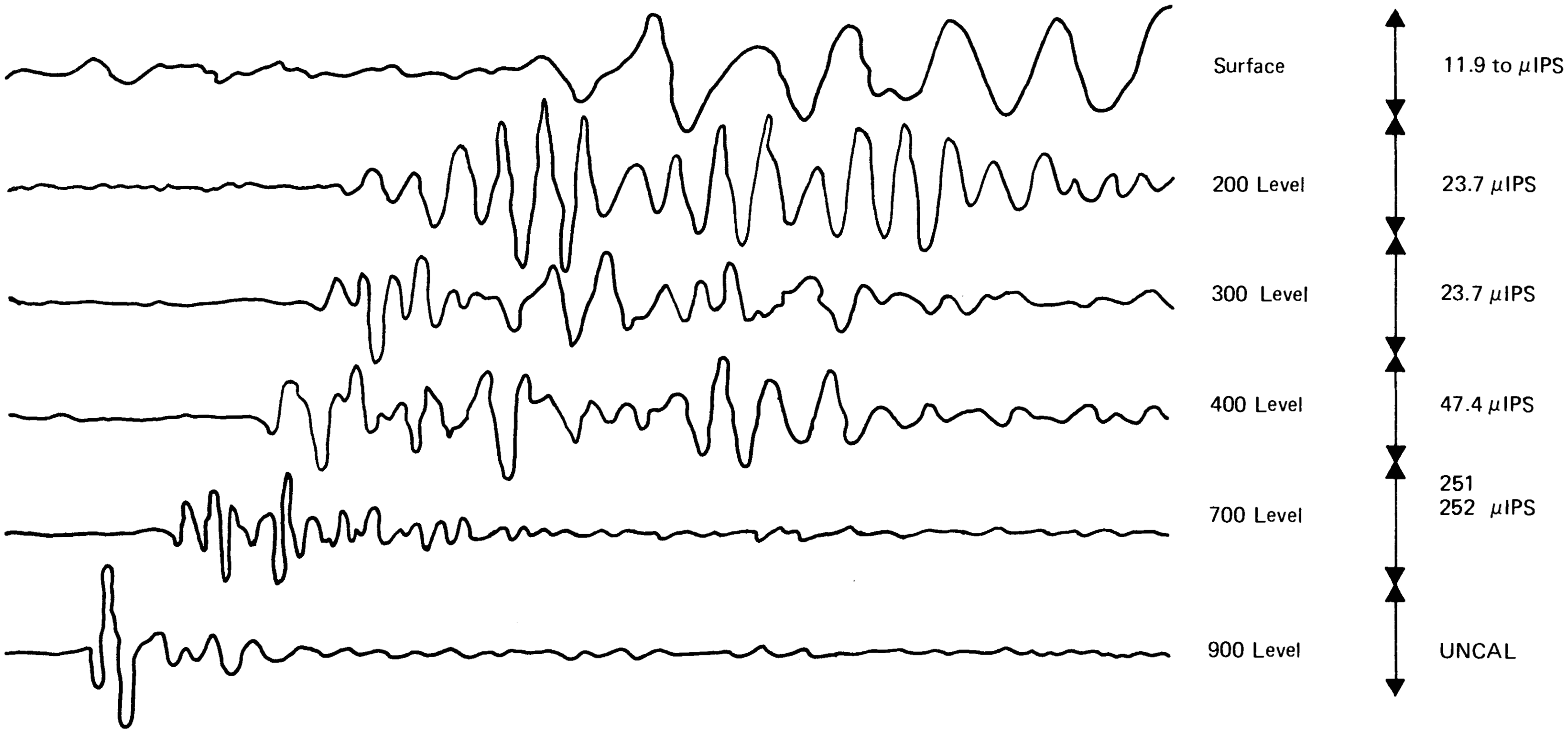


FIGURE 7(a) PLOT 38 FROM WESTINGHOUSE FIELD REPORT NO. 8
(Uplink Velocity and Attenuation – Thumper on 900 Level – 17 Blows)

Seismometers were at the 700', 400', 300', 200', and surface levels directly above the source. The fall-off of amplitude is slightly greater than 1/r. Another important observation is that the surface seismometer has a peak frequency of about 50 Hz while the peak frequency on the below-surface seismometer (at 200 feet) is about 100 to 125 Hz.

The amplitude on the surface seismometer is only about 1/3 that of the seismometer at the 200' level. The reason for the change in amplitude may be either attenuation in the low velocity surface layer or a resonance effect on the waves due to the low velocity surface layer. There is some indication that the latter is the major factor. Namely, plot 39 of Field Report 8* (reproduced as Figure 7b) reveals that an initial ∿100 Hz signal is propagated downward through the surface layer from a surface source to the below-surface seismometers. However, the initial part of the signals are followed in time by ∿40 Hz energy leaking downward from the resonant surface layer.

It is felt that further systematic experiment, and theoretical analysis of relevant models of source and propagation effects, are required to improve estimates of the signal strength and character in various mine situations.

V. DETECTION RANGES - BASED ON EXPERIMENTAL DATA

The initial discussion of detection range will be for a single sensor. It is based on Figure 5 which gives estimated signal levels and the detection thresholds required under two noise conditions. The detection level is set to give one false alarm every 100 seconds on a single subarray trace, so at this level it will be necessary to detect on perhaps three subarrays to safely conclude that a true signal has been received. Consistent relative arrival times on the subarrays will be a strong indication of a repeated source at a fixed location.

In Table 4 we give the maximum slant ranges for detection for different combinations of source and noise conditions. The values in the Table are the best estimates of detection range we can make at this time based on the experimental data available.

* Ibid

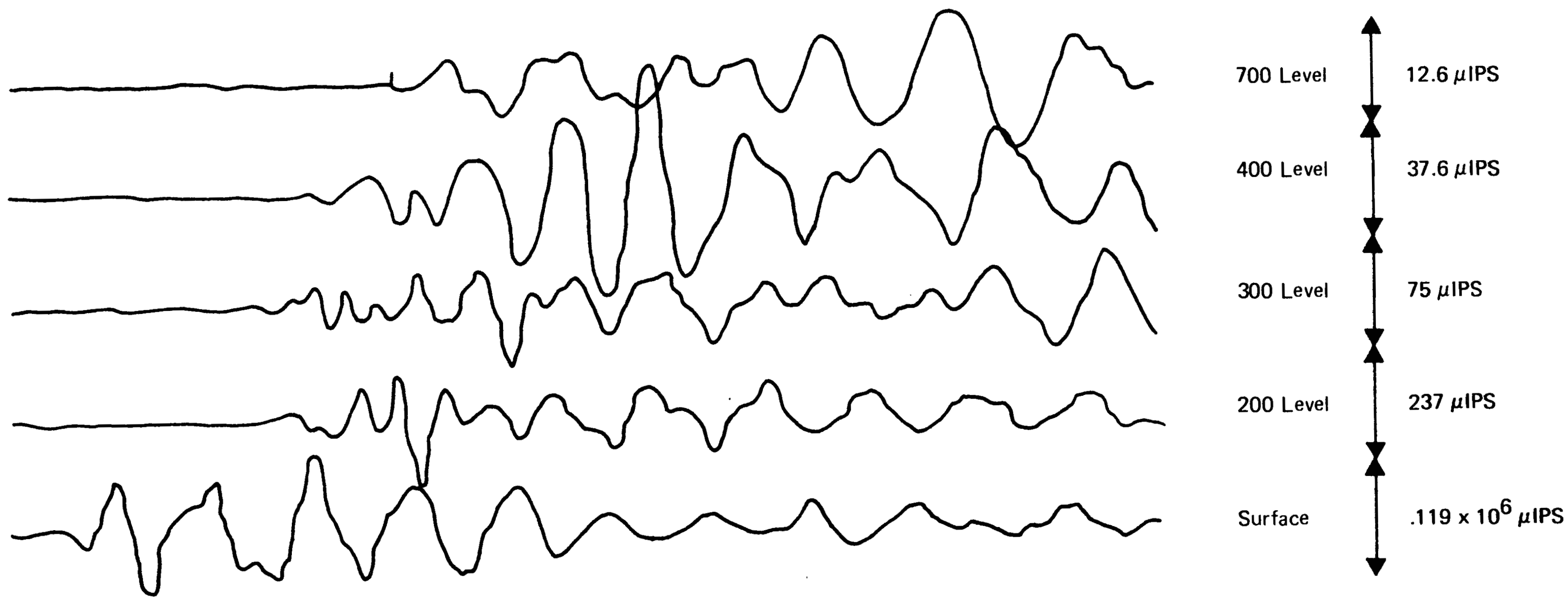


FIGURE 7(b) PLOT 39 FROM WESTINGHOUSE FIELD REPORT NO. 8
(Downlink Velocity and Attenuation – Timber on Surface – 10 Blows)

Table 4

Maximum Slant Range for Detection (Feet)

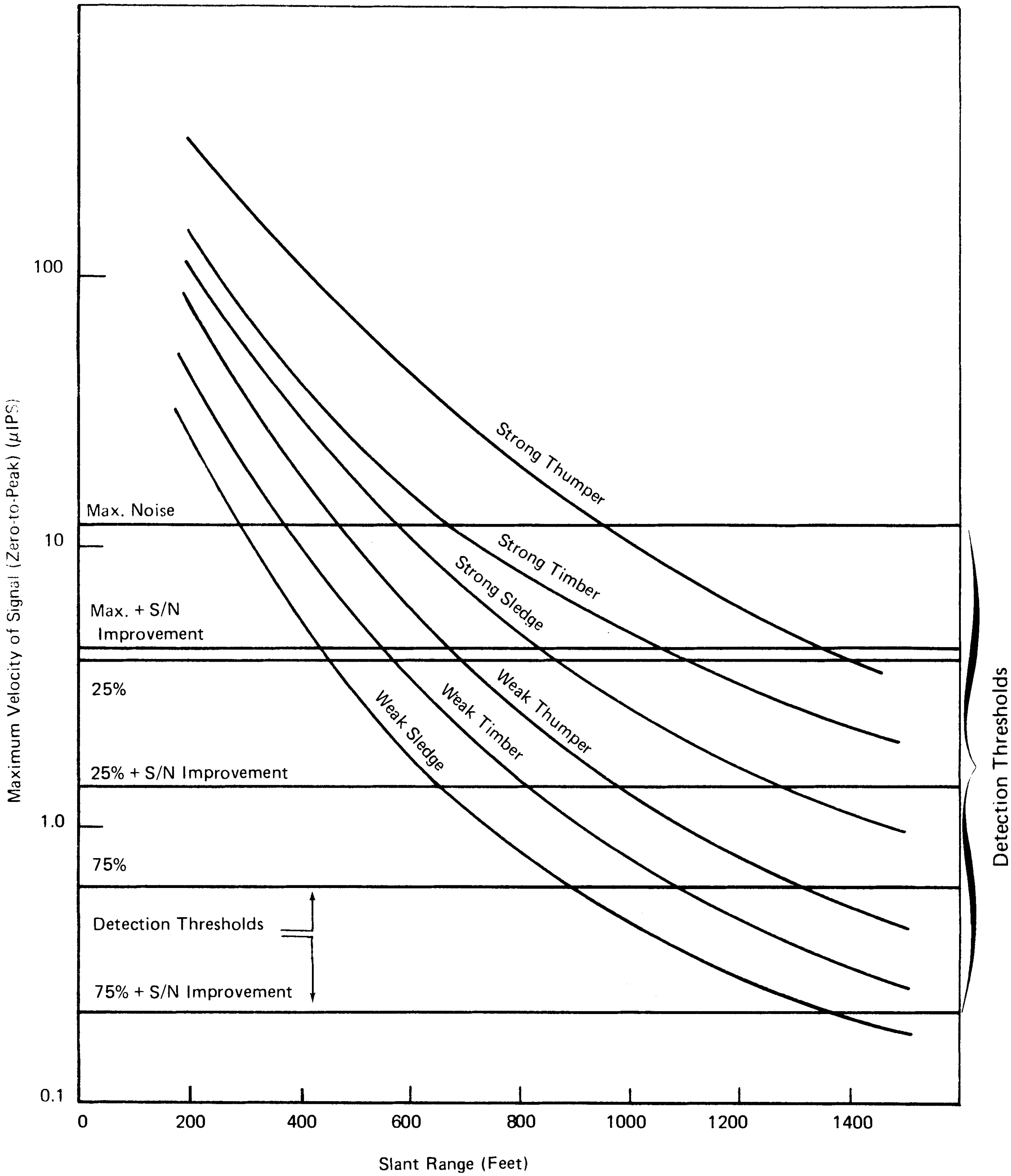
For a Single Sensor--Before Signal-to-Noise Improvement Techniques

(For Natural Noise Conditions)

Source	Natural Noise Condition Low (75%) Threshold	 High (25%) Threshold
Strong Thumper Signal	> 2000.	1400.
Weak Thumper Signal	1300.	700.
Strong Timber Signal	> 2000.	1050.
Weak Timber Signal	1100.	550.
Strong Sledge Signal	> 1500.	900
Weak Sledge Signal	900.	450.

At this point we make some speculative estimates of the detection thresholds required under conditions for which the noise data base is weak, namely for "maximum" natural noise conditions. By inspection of Figures 1, 2, and 3, it appears that the natural noise level rarely rises about 3 times the 25% detection threshold of Figure 5. This threshold,denoted as Max., is shown on Figure 8. Also shown are the signal level curves. We speculate that S/N improvement techniques can give a gain of 10 dB at all three noise levels. The figures of 10 dB would be the S/N gain against uncorrelated noise for a 10 element subarray. Gain obtained by burial could also be significant. In high levels of natural noise due to wind or rain the gain by burial could be considerably above 10 dB. Since there is presently no data to assess these gains we have taken the modest value of 10 dB between the two. On this basis we also put curves for the three noise level conditions with 10 dB S/N improvement on Figure 8. For these conditions, the estimated detection ranges are given in Table 5.

Further experimental data must be analyzed before we can make any estimate of the detection ranges in the presence of man-made noise of the type and level which might be present during uncontrolled rescue operations. However it is highly probable that heavy man-made noise would make detection impossible, using only surface seismometers, if the signaling miner is more than tens of feet to a few hundred feet from the seismometer.



Seismic Signal Amplitude Estimates Plotted Versus Slant Range from Typical Sources; Detection Thresholds for Three Natural Noise Conditions With and Without Benefits of 10 dB Signal-to-Noise Improvement

FIGURE 8 COMPOSITE PLOT FOR ESTIMATING DETECTION RANGES

Table 5

Maximum Slant Range for Detection (Feet)

(For Natural Noise Conditions Only)

Source	Natural Noise Conditions Max.	Max. +	25% +	75% +
Strong Thumper Signal	950	1400	>2000	>2000
Weak Thumper Signal	425	700	1000	>2000
Strong Timber Signal	650	1050	>1500	>2000
Weak Timber Signal	375	550	800	>1500
Strong Sledge Signal	550	900	1250	>2000
Weak Sledge Signal	300	450	625	>1400

(+) Indicates: +10 dB S/N Improvement

VI. EFFECT OF NOISE LEVELS ON ARRIVAL TIME ESTIMATION ACCURACY - BASED ON EXPERIMENTAL DATA

The two limits on the accuracy of the location of the miner are the accuracy of the velocity model and the accuracy of the reading of the arrival time of the P wave. The effects of deficiencies in the velocity models are discussed elsewhere. Here we concentrate on errors in arrival time measurement due to the presence of seismic background noise. Higher signal-to-noise ratios are needed for accurate estimates of arrival times than that needed to simply detect a miner-generated signal. Therefore, it is assumed that the signal-to-noise ratio is improved by stacking repeated signals, if signal repetitions have been received.

We discuss the errors in arrival time with reference to the schematic generalized signal shown as Figure 9. This signal illustrates several features of the signal waveforms which can affect the measurement of signal arrival time. Several examples of these features are shown in Figures 10a, b, and c, which are tracings of actual seismic signals taken from the Westinghouse Field Reports* (see Table 6 for identifications). The signal in Figure 9 has a frequency of 50 Hz (period, T = 20 ms) which is an average frequency for the signals observed by Westinghouse.

* Ibid

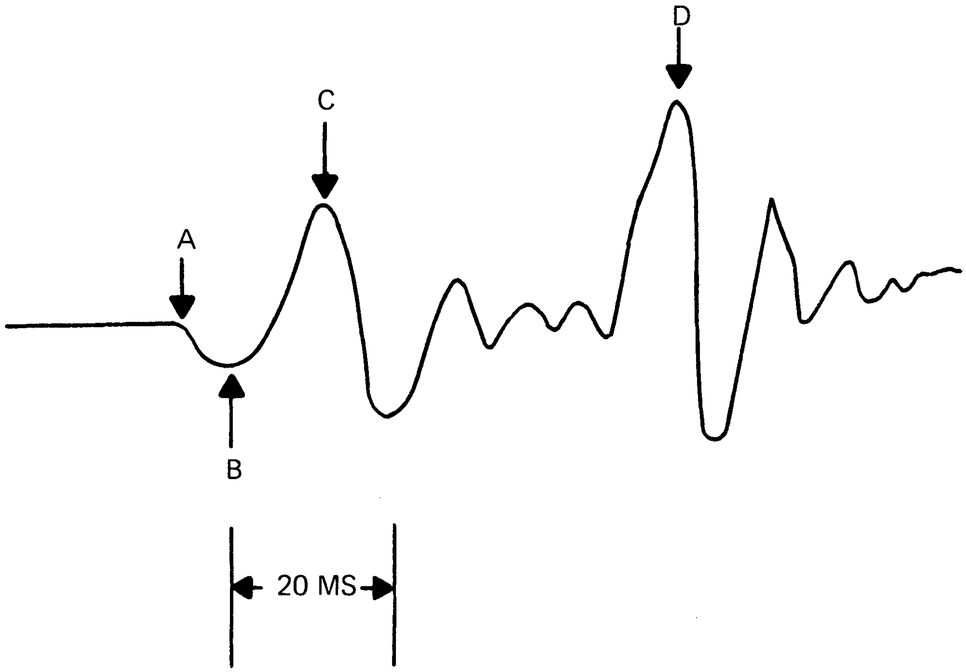


FIGURE 9 SCHEMATIC GENERALIZED SEISMIC SIGNAL (Applicable to Mine Data Obtained to Date)

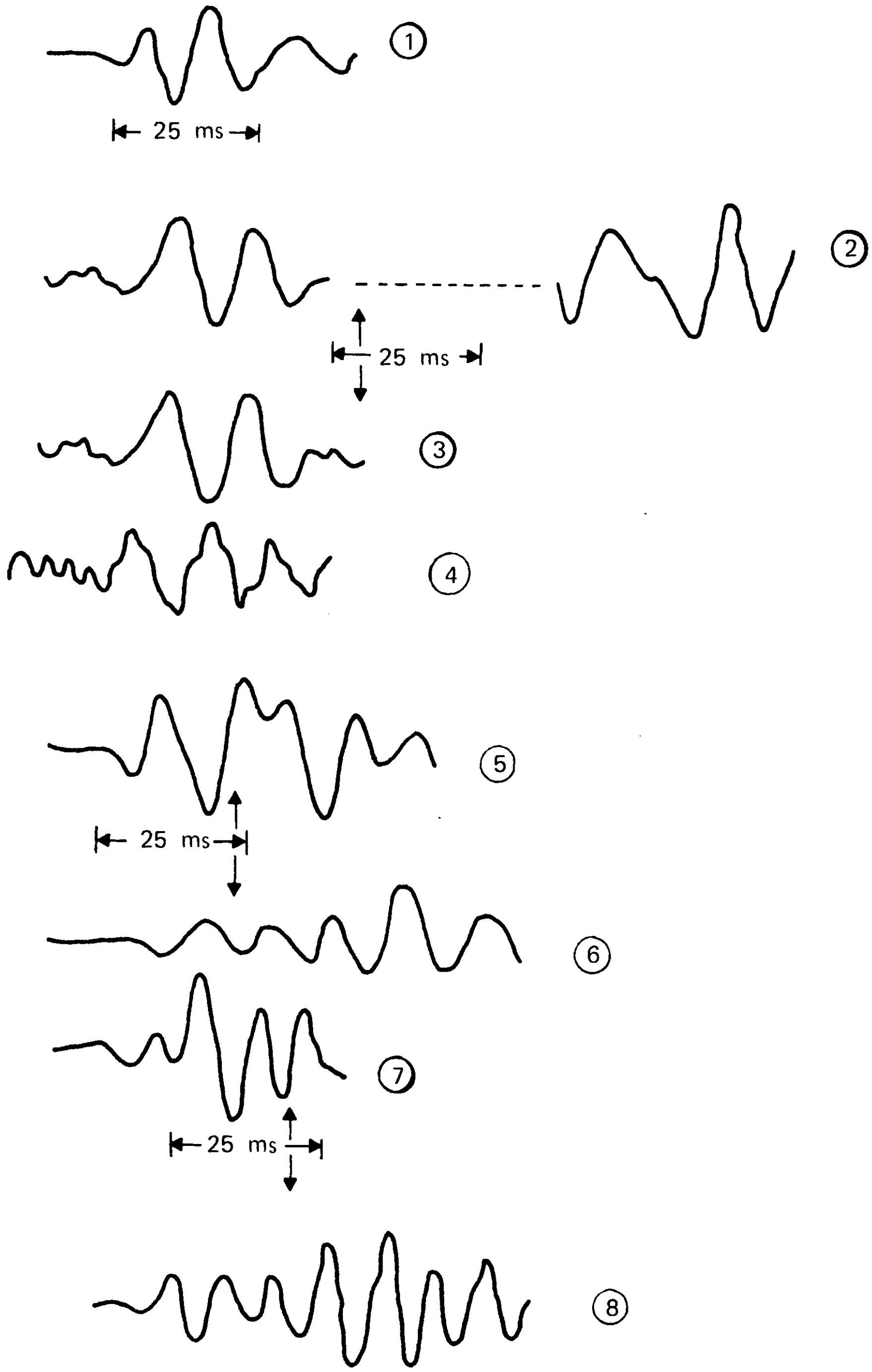


FIGURE 10(a) TRACINGS OF ACTUAL SUMMED SIGNALS FROM WESTINGHOUSE FIELD REPORTS

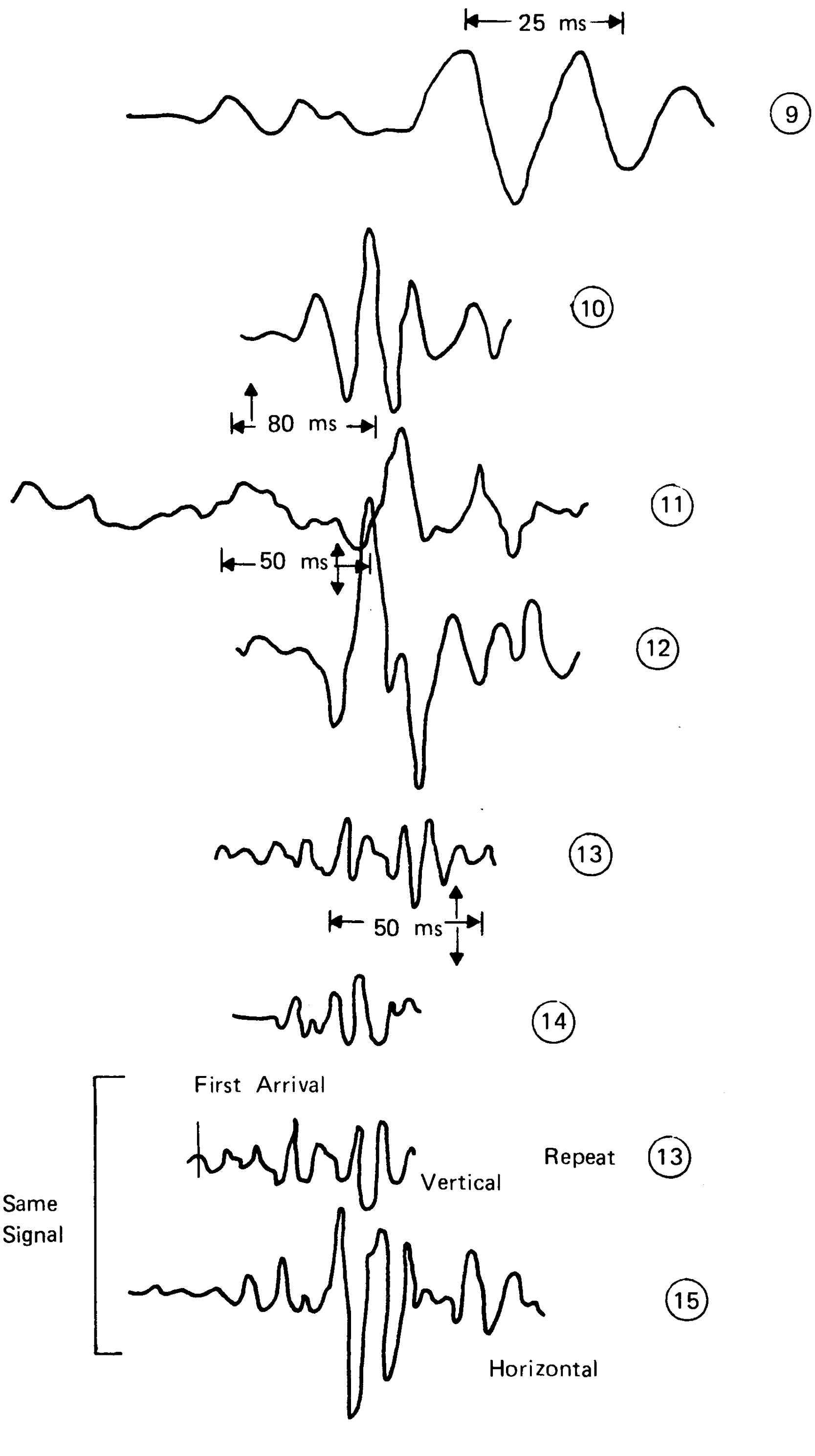


FIGURE 10(b) TRACINGS OF ACTUAL SUMMED SIGNALS FROM WESTINGHOUSE FIELD REPORTS

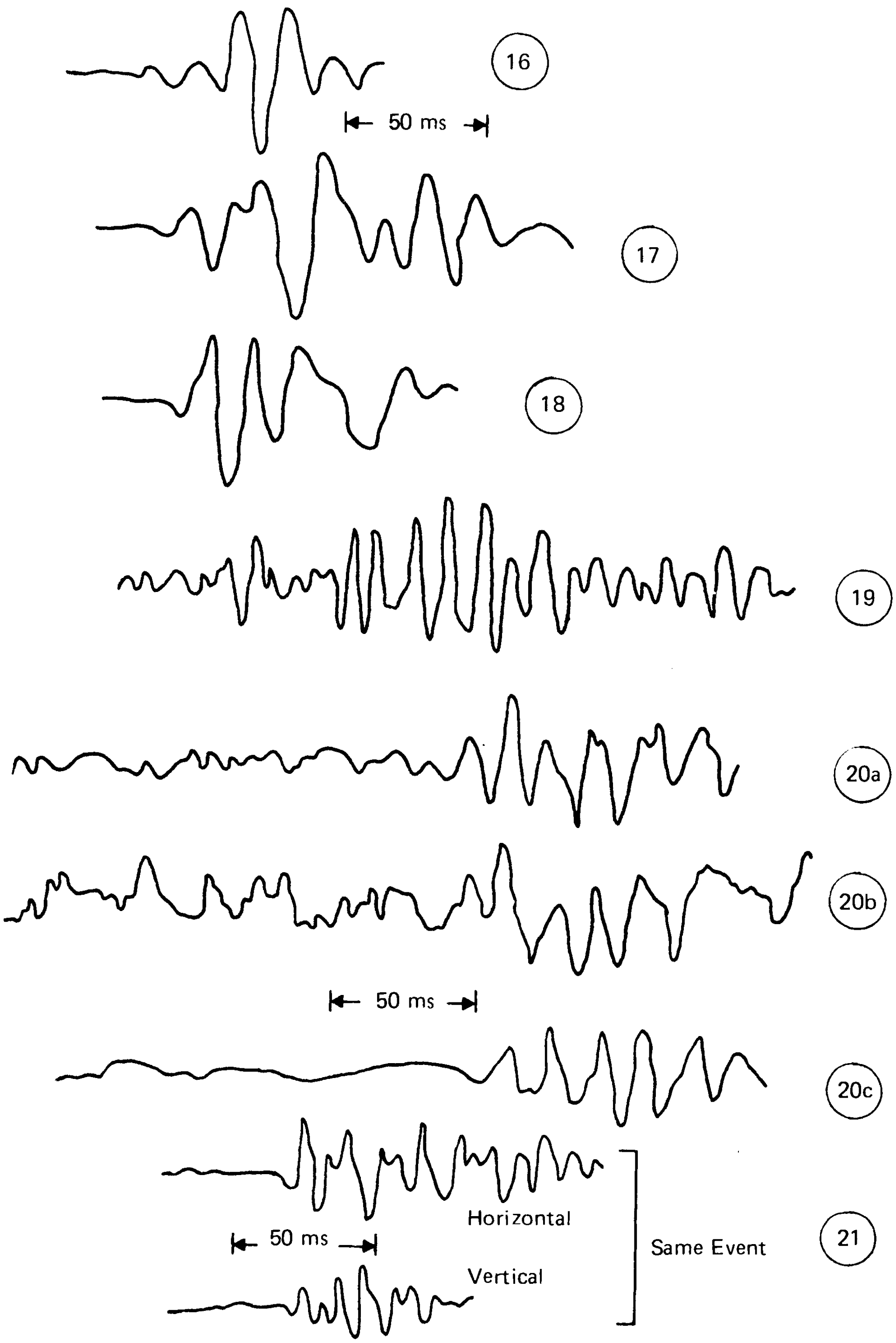


FIGURE 10(c) TRACINGS OF ACTUAL SUMMED SIGNALS FROM WESTINGHOUSE FIELD REPORTS

Table 6

Legend for Tracings of Actual
Summed Signals Shown in Figures 10a, b, & c

Tracing No.				
1.	Plot 23 F.R. 6 - 13 element subarray,	30 blows		Figure 10(a)
2.	Plot 35 F.R. 4 - 7 elements	, 50 blows		Figure 10(a)
3.	" " - 1 vertical	, " blows		Figure 10(a)
4.	37 - 1 vertical	, 30 blows		Figure 10(a)
5.	Plot 37 F.R. 7 - Array (subarray?)	2, 30 blows		Figure 10(a)
6.	Plot 41 " - Array	7, 30 blows		Figure 10(a)
7.	Plot 42 " - Not known	30 blows		Figure 10(a)
8.	Plot 39 " - Array 5	" blows		Figure 10(a)
9.	Plot 36 " ?	" blows		Figure 10(b)
10.	Figure 17, F.R. 2, ch. 5, South	100 blows		Figure 10(b)
11.	Figure 22, F.R. 2, ch3, 19 Hex array	31 blows		Figure 10(b)
12.	Figure 24, F.R. 2, 7 elements	100 blows		Figure 10(b)
13.	Plot 15, F.R. 8, ch 5	15 blows		Figure 10(b)
14.	" " ch 2	" blows		Figure 10(b)
15	" " ch 7, Horizontal	"		Figure 10(b)
16.	Plot 17 " ch 7,	30 blows		Figure 10(c)
17.	" " ch 4,	"		Figure 10(c)
18.	Plot 55 " ch 6,	25 blows		Figure 10(c)
19.	Plot 57 " ch 3, Array K, 700' level, 29 blows			Figure 10(c)
20.	Plot 36 " comparison of small arrays and single geophone, a) single channel, b) parallel, c) series correction			Figure 10(c)
21.	Plot 15, F.R. 8, ch 2 and 3, horizontal and vertical, 15 blows			Figure 10(c)

We assume that the arrival time is picked by a trained analyst, and we discuss the arrival time errors which might arise for different levels of noise. The true arrival time of the signal is T_A. [T_A is the time of the signal at point A and the other times used (T_B, T_C, T_D) are similarly defined.] If the noise level is very low, the analyst will pick the arrival time, denoted by AT, within 1 ms of T_A. The first peak B of the signal is usually small compared to the second peak C. If the noise level is only low enough to recognize peak B, then he picks T_B as the arrival time. This gives an error of about 4 ms. However, it would be better to assume that $T_B = T_A + T/4$. If this is done the error in AT will probably be reduced to on the order of 2 ms.

A much larger error in arrival time can occur in cases when peak D is larger than peak C, and the noise level is such that the analyst misses peak C, but can pick peak D. Examples of signals where peak D is larger than peak C are shown in Figure 10 as traces 6, 8, and 13. Peak D may be 6 dB above peak C. By picking T_D, several cycles of the signal have been missed and the error in arrival time will be 50 to 100 ms. If T_C is picked on some subarrays and T_D on others, very poor locations will result.

There are fortunately some telltale indications if the initial few cycles of the signal have escaped detection, and T_D was picked as the arrival time by mistake. First if T_D is picked on only one or two of seven subarrays, these times will show up as large, late residuals on the least squares fit for the source location. A second indication is that a very large signal may occur on the horizontal seismometers at T_D. An example of this large horizontal motion is shown on Figure 10, traces 13 and 15 and 21. We believe the large late arrivals may be the direct S (shear wave), or a shear wave generated when the P wave hits the base of the alluvium layer below the receiver. A better understanding than we presently have might allow a better possiblity of telling whether the first arrival picked by the analyst is a T_D type late arrival.

VII. EFFECT OF ALLUVIUM ON ARRIVAL TIME ESTIMATION ACCURACY

The surface alluvium has a very low P wave velocity. The velocity can be 2000 feet/sec. or even less. Suppose at a mine we have 50 feet of alluvium under subarray A and no alluvium under subarray B. Let the rock P wave velocity be 10,000 feet/sec. Then the traverse time through the alluvium at subarray B will be 5 ms. Thus if a location is made with these arrival times with no correction for the presence of the alluvium at A, the 20 ms extra delay at A will have the effect of a 20 ms arrival time reading error.

A example of this delay can be observed directly in Figure 11. In Field Report 8*, data is given for a source at 900 feet depth with receivers at various depths and on the surface. In our figure the arrival times are plotted versus distance from the source. If the travel time curve is extrapolated from the straight line fit to the last 3 underground arrivals, the time predicted for the surface arrival is 16 ms earlier than the observed arrival time at the surface.

This problem of the error in arrival time due to the alluvium can be corrected by determining the thickness and velocity of the alluvium at each subarray. This can probably best be done by an easily run shallow refraction survey using either a timber or perhaps a seismic thumper as a source. Reflection seismic methods, using special equipment, might also be useful. Another method which might prove useful,which we have used at Penn State,is to use the dispersion properties of the Rayleigh waves set up with a sledge source.

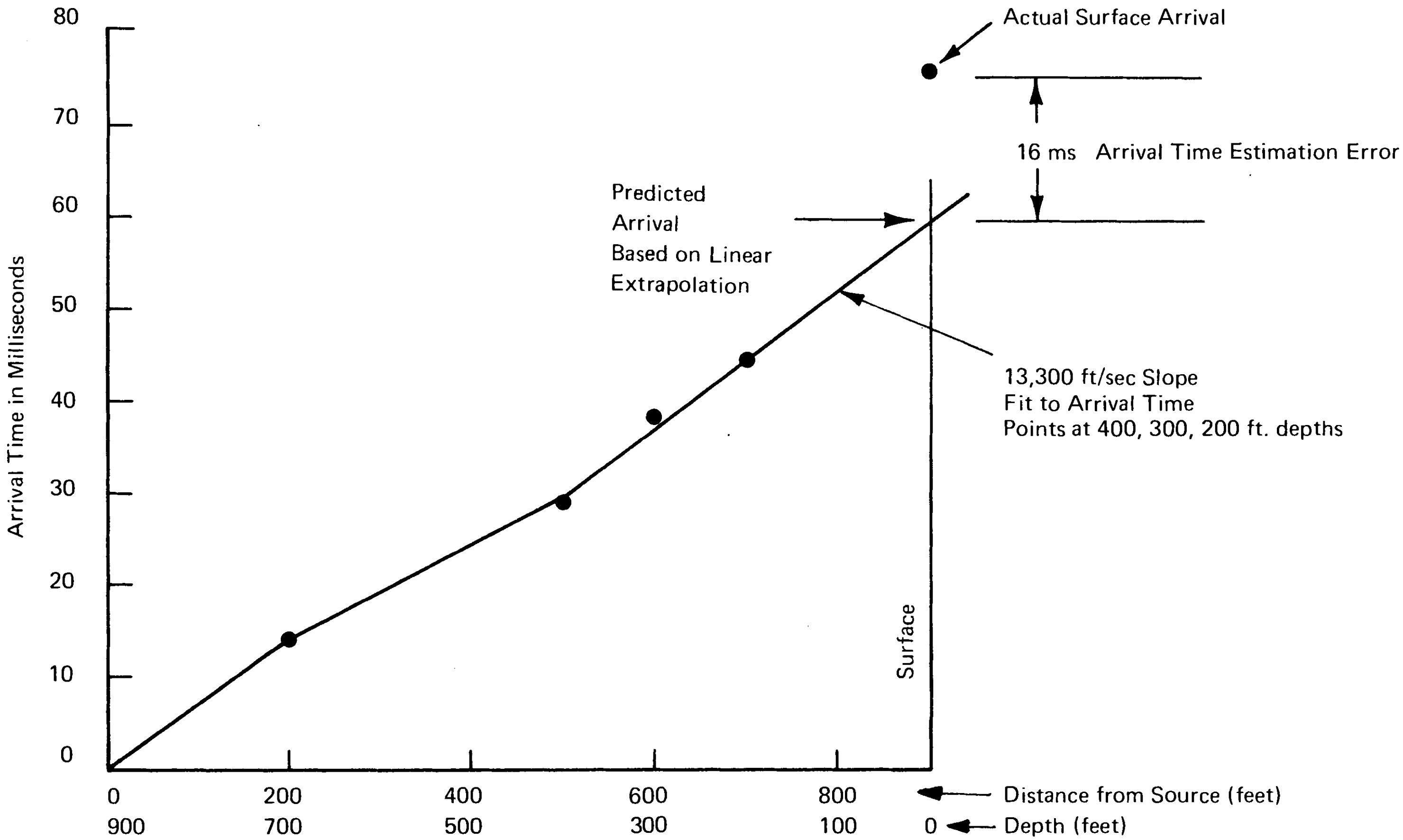
VIII. RECOMMENDED PROJECTS

In order to improve the performance estimates presented in this Part; to better evaluate the utility of signal-to-noise improvement techniques such as seismometer burial, bandpass filtering, subarrays, and signal stacking; and to develop more effective signaling and detection strategies; the following experimental and theoretical efforts are recommended.

- Perform a series of careful seismic noise and signal strength measurements in Eastern coal mining regions. These measurements should be performed by crews well-experienced in seismic and geophysical field work. At each of the sites care should be taken to determine the geological/seismic structure of the overburden material, so that the experimental results can be compared with those predicted by different theoretical models.

- Seismic noise measurements should be performed in representative Eastern mining areas that are "quiet", i.e. not dominated by manmade noise sources; and in areas and under circumstances that are representative of those encountered during mine emergencies or disasters. Noise spectrum levels should be obtained up to a frequency of 300 Hz. The spatial coherence properties of the noise should be studied as a function of seismometer spacing,[4,5] together with the utility of looking at individual seismometer outputs as opposed to that from a whole subarray. The impact of the depth and method of seismometer

* Ibid



Data from Field Report 8, Plot 38.

FIGURE 11 EXAMPLE OF TIME DELAY CAUSED BY SURFACE WEATHERED ALLUVIUM LAYER

burial on the received seismic noise should be examined by careful experiments at sites with different surface materials. At sites over mines where both signal and noise measurements are planned, the effect of seismometer burial on both received signal and noise levels should be determined. Lastly, representative manmade sources encountered during mine emergencies should be characterized, together with some of the likely disaster noise sources in the mine, such as fires, running water, cracking rocks, and roof falls.

- Controlled, systematic seismic signal experiments should be performed with the thumper, timber, sledge, and perhaps other practical sources, in several Eastern coal mines that are representative with respect to depth, overburden geology, and surface topography. Signal properties, such as strength and frequency content, of single source blows or pulses should be examined as a function of type of source, entry cross-sectional dimensions, position and composition of the impact area in the entry, source and seismometer depths, slant range, near-surface layers, and seismic velocity profile. The measurement band should extend up to a frequency of about 300 Hz, to check whether useful signal frequency content above 100 Hz may have been masked by system noise or lossy surface layers in past measurements.

● Perform supporting theoretical analyses to better understand the signal generation and propagation behavior expected for practical miner sources in coal mines. Items of particular interest are: the efficiency of seismic signal excitation, the effect of the mine entry cavity and the source impact point in it, the effects of layering in general and the surface layer in particular. Preliminary analysis indicates that it should be possible to model the mine entry problem as a point source applied to the surface of a cylindrical cavity; and that surface layering effects can be examined using Haskell[6] matrix techniques.

● Develop automatic detection procedures that will choose only the most "interesting" seismic energy arrivals, or probable miner signals, for detailed examination by a trained analyst. An automatic detection or event screening procedure need not be complex, and in its simplest form could be based on the exceedance of a preset threshold on one or more seismometers or subarrays, and set according to the prevailing noise condition. This should ease the large data processing burden that otherwise would be imposed on analysts under emergency conditions. However, it is not intended to replace the trained analyst, for he is the one who will be best qualified to assess the likely cause of the received waveform, and to subsequently ascertain its "arrival time", after any required signal-to-noise ratio enhancement.

- Develop an ability to determine, in a timely manner on site, the thickness and seismic P-wave velocity of the alluvium directly under each of the subarrays. This is needed in order to compensate the signal arrival times for the likely substantial and different amounts of time the signal has spent in this low-velocity, variable-thickness, surface layer to get to each subarray.

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APPENDIX A

RELATION OF PEAKS OF NOISE ENVELOPE TO RMS LEVELS

The envelope of narrowband noise is given by the Rayleigh distribution (e.g. Horton, 1969, p. 96). The results we give below have experimentally been found to fit wideband seismic data, (see Capon et al. 1969). The probability density function is given by:

$$P(R) = \frac{R}{\sigma^2} \exp\left(-R^2/2\sigma^2\right) \qquad \text{(A 1)}$$

where R is the zero to peak amplitude of the envelope.

Over one cycle, the mean square (MS) value is

$$\frac{1}{T} \int_0^T y^2(t)\, dt = \frac{1}{2} R^2 \qquad \text{(A 2)}$$

Thus the MS value of narrowband noise is

$$\begin{aligned} MS &= E\left[y^2(t)\right] = \frac{1}{2} E\left(R^2\right) \\ &= \frac{1}{2} \int_0^\infty P(R)\, R^2\, dR \\ &= 2\sigma^2 \qquad \text{(A 3)} \end{aligned}$$

$$\text{or } RMS = \sqrt{2}\,\sigma \qquad \text{(A 4)}$$

The probability of R exceeding R_o is

$$P[R > R_o] = e^{-R_o^2/2\sigma^2} \qquad \text{(A 5)}$$

If we take $R_o = 3$ RMS

$$P\left[R > (3RMS)\right] = e^{-9} = .000123 \qquad \text{(A 6)}$$

Then the chances of the envelope exceeding 3 RMS on a single trial is about one in .000123. We take 3RMS as a reasonable single channel detection threshold. We note that for a bandwidth of 75 Hz we get an independent sample of R every 1/75 sec. Therefore we go about 100 seconds between false alarms on each channel.

A useful relationship in evaluating Frantti's (1963) method of spectral estimation is that

$$E\,[2R]/E\,[RMS] \;=\; 2 \int_0^\infty R\,P(R)\;dR/E\,[RMS]$$

$$= \sqrt{\pi} \;=\; 1.77 \qquad \text{(A 7)}$$

PART THREE

ESTIMATES OF MINER LOCATION ACCURACY: ERROR ANALYSIS IN SEISMIC LOCATION PROCEDURES FOR TRAPPED MINERS

PART THREE

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PART THREE

ESTIMATES OF MINER LOCATION ACCURACY:

ERROR ANALYSIS IN SEISMIC LOCATION PROCEDURES FOR TRAPPED MINERS

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I. SUMMARY

A method of error analysis has been applied to the location technique of non-linear least squares iterative inversion in order to evaluate the resolving power of several seismic array configurations with various assumed earth models and errors and inaccuracies in arrival times.

The results obtained demonstrate that lateral accuracies of location are improved significantly when the depth of the miner is known. Lateral location to within 100 feet appears achievable in many instances. If it is possible to refine earth models significantly beyond what has normally been assumed in this work by the use of on-site data, or if the mine is shallow (300 feet or less), accuracies of about 30 feet or so may be attainable.

Inaccuracies in earth models of about 5% are found to contribute much more heavily to these location inaccuracies than errors of a few milliseconds in picking arrival times; however, arrival time errors of 15-20 ms or above will dominate these model inaccuracies.

The expected accuracy of location is found to fall off very rapidly as the miner moves outside the array. The strength of this effect depends markedly upon the geometry of the array configuration and can be reduced by careful design. Also, as the size of the array is increased, expected location errors within the array are not altered much, but continue to match the error associated with the smaller array over a larger area (assuming that all stations can still pick up the miner's signals).

Better location accuracy, especially with respect to depth control is achievable in an earth where the velocity is depth-dependent (increasing with depth) than in one which is homogeneous. This is an advantage since the

actual earth is clearly closer to the former situation. Models where the seismic velocity increases linearly with depth can be found which are excellent approximations to a layered earth for the purposes of location.

It has to be emphasized that the location accuracies predicted in this work are subject to the major assumption that the actual behavior of the earth can be represented reasonably accurately by the models selected. If this is not the case, then location inaccuracies resulting from the use of these models may be much larger than those predicted here; new classes of models may have to be developed.

It can be concluded, however, that the location accuracies predicted for the non-linear least squares iterative inversion technique make it appear promising for use as a miner location algorithm. Alternative and potentially better location techniques remain subjects for future investigation. These may, for example, include different weighting schemes for the seismometers in an array, or allow the possibility of iterating and improving the earth model used, as well as the predicted location.

II. INTRODUCTION

Procedures for determining the location of impulsive seismic sources in the earth have been the object of studies by seismologists for many years. Recent expansion of the use of dense networks of detection stations and high frequency sensors and recording apparatus, particularly for the study of very small earthquakes, has stimulated the development of high-precision location techniques. The accuracy and resolving ability with which a given array of sensors can locate a seismic source depend on the closeness with which the model represents the real earth as well as on the array configuration; errors in the input parameters such as arrival times; and the particular algorithm used in the calculations. For the standard technique of non-linear least square iterative inversion, a method of error analysis has been developed which is very useful in evaluating the resolving power of a given station configuration with known model and arrival time errors (Peters and Crosson, 1972). The method is based on a procedure known as prediction analysis

(Wolberg, 1966), and it allows error predictions to be made without actually carrying out the inversion calculations. For the seismic location problem it is convenient to diagrammatically represent the error structure by mapping the errors onto the array geometry by means of contour maps.

The work reported in this Part is a direct application of the error analysis procedure to the problem of locating a trapped miner who is able to communicate seismically with the surface by means of producing small impulsive seismic disturbances. Given basic input data such as the arrival times of a discrete event at a series of detectors located at the surface, and known input in terms of an earth model, the problem is virtually identical to the local earthquake problem except for scaling. In the case of the trapped miner, source depth may be known quite accurately and the earth model may also be known relatively well compared to the typical earthquake investigation.

The limited objectives of this Part are to evaluate the effects on location errors of such factors as model uncertainties, timing errors, array geometry, and different classes of models. To carry out such evaluations we have calculated standard error maps, contoured in the horizontal plane, for three classes of models, three array geometries, and various combinations of input parameter errors. The results should be interpreted not so much as absolute error predictions but as resolution maps showing the relative effects of various assumptions. Caution is required in interpretation because systematic bias in, for example, model assumptions with respect to the real earth, may produce systematic errors not accounted for by the error analysis. On the other hand, relative resolving power of the given configuration is properly indicated.

III. METHOD OF CALCULATION AND PRESENTATION

The method of error prediction is described by Peters and Crosson (1972). A velocity model is chosen from which pulse travel times can be calculated. The normal equations are formed for the non-linear least squares solution for the source at a given location, and the source location errors are calculated. The process is repeated for a number of locations in an x-y grid and the resultant values are contoured.

Statistical weighting is used so that data with large relative errors do not influence the calculations as strongly as data of higher accuracy. Thus, in the least squares method each station in the array is weighted with the reciprocal of the square of its associated uncertainty, which is a function of the errors in the model parameters and the derivatives of the travel time to that station with respect to these parameters. All velocity models used in these calculations are laterally homogeneous, velocity varying only with the z coordinate. The catalog of resulting contour maps numbered 1 through 24 is included in this Part. A standard format with four machine-plotted maps for each case is presented. The four plots are respectively σ_x, σ_y representing rms error in x and y coordinates, σ_z representing rms error in z when z is not fixed, and σ_{tot} representing the rms error in all three coordinates.

$$\sigma_{tot} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \qquad (1)^*$$

The σ's are to be understood as estimated standard errors or one standard deviation of a normal distribution, so that the probability is 68% that the estimated value lies within σ of the true value (and 95% that it lies within 2σ of the true value). The x coordinate is toward the top of each diagram and y is toward the right side. Where σ_z contours are not plotted, the depth was assumed known and fixed at 600 feet. All calculations are based on a source depth of 600 feet. A scale in feet is indicated on each diagram and all error values are in feet. Crosses mark 500 feet from the array center in both x and y for each diagram, and squares indicate station locations. Contours are labeled with their respective error values and it should be pointed out that contour intervals are variable to better illustrate a wide range of error characteristics. Thus, care must be exercised in directly

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

comparing different diagrams. Contours are plotted in multiples of 10, 25 or 100 feet. Thus, for example, if the minimum error contour in a plot is 40 feet, the error never falls to 30 feet, but may be as low as 31 feet at some points.+ Each diagram is labeled as to the velocity model used and the errors incorporated into the calculations. Note that where a 5% model error is used it means that 5% error was assumed in all model parameters. For example, with a layered model both layer velocities and interface depths are included. For the linear velocity model both the surface velocity and the velocity gradient are included. An error of p% in the data means they are assumed to have been selected from a normal distribution about the true value which has a standard deviation of p%.

+ The minimum total error is shown in each plot.

Note: Due to an error in scaling for the plotter, the x and y scales in Runs 1, 2, 5, 6, 8, 9 and 12 differ by a ratio of 5:4. This is of no significance in interpretation.

IV. DISCUSSION OF ERROR MAPS

Run 1 shows the error distribution for a constant velocity model with no model error and 1 millisecond time error. It is useful for comparisons with other cases utilizing the hexagonal array. Errors increase rapidly outside the array margin. Differences in x and y plots result from small differences in the symmetry about these two directions. The general features of Run 1 are found in all the hexagonal array analyses.

A. Time Errors

If there are no model errors, i.e., the model is known exactly, then the relative effect of arrival time errors is large. For example, a comparison of Run 9 with 5 millisecond time error and Run 1 with 1 millisecond time error shows, as would be expected, an increase in location error by a factor of 5. On the other hand, if model error is present, a change from 1 to 5 millisecond time error has a much smaller net effect, as illustrated by a comparison of Runs 10 and 3 for a linear velocity case. The conclusion to be drawn is that compared to probable model errors, a few milliseconds of arrival time error have a small effect.

However, once arrival time errors rise to 10 ms and above, they begin to dominate model errors. Location inaccuracies again rise roughly linearly with arrival time errors once these have risen to 15-20 ms or so (Runs 21-23).

B. Model Errors

Model errors exert strong control on the resolution capability of a given configuration. Comparison of Runs 1 and 12, where the only differences are in error assigned to the constant velocity model, illustrates this feature. Similarly, a comparison of Runs 2 and 3 illustrates the same effect for the linear velocity model. The total error almost quadruples at the array margin when going from no error to 5% model error.

C. Model Differences

The differences in error structure as a function of changing models are not large in most cases. Generally, models with velocity increasing with depth, such as a linear velocity or layered model, offer superior resolution compared with a constant velocity halfspace, especially with respect to depth. Since the real earth is perhaps closer to the linear or layered models, some advantage is gained. The total error diagrams for Runs 1 and 2 illustrate the model dependent effect between the constant-velocity and linear-increase models, when the models are assumed to be exact. Note that the linear velocity increase model yields better resolution within the array proper than the uniform halfspace model; however the rate of deterioration of location accuracy outside the array is more rapid than for the halfspace. Examination of the layered model results of Run 14 shows behavior similar to that of the linear model.

D. Depth Known

Several cases were calculated to show the resultant increase in resolution when it is assumed the depth is known, as it could well be in the case of trapped miners known to be at specific levels. Run 4 compared with Run 3 shows the fairly marked effect of fixing depth for two otherwise identical cases. Resolution within the boundaries of the array becomes very uniform. Comparison of σ_{tot} for these two cases is not really meaningful since σ_{tot} for the z unknown case is dominated by σ_z. The same kind of improvement is noted for all fixed vs. free depth comparisons such as Runs 14 and 16, and Runs 7 and 8. However, this result, as discussed in Section IV-G, appears to be invalid if a homogeneous earth model is used, when a variable depth allows a better lateral location accuracy to be achieved.

E. Changing Array Dimensions

Previous resolution studies suggest that improved control may be obtained if an array does not have a high degree of symmetry. The explanation for this phenomenon is that arrival time data from a highly symmetrical array may be largely redundant and thus lacking in location "information". Less symmetrical configurations are illustrated in Runs 11 and 13, both for a linear-velocity model, and in Run 15 for a layered-model. In Run 11, a modified "H" array shows significant improvement over the highly symmetric hexagonal array used in Run 3. Similarly, the "stretched" hexagonal array used for Run 13 shows slight improvement over the hexagonal array of Run 3. Thus array configuration is an important factor in the design of the system.

F. Layered Models

Runs 14 through 19 are comparative cases run on both 2- and 4-layer models. The results are not dramatically different from similar cases run with the linear model which was chosen as a reasonable representation of the 4-layer model. Since, for all cases, the source lies in the deepest layer, the improved depth control effects noted in earthquake studies when refractions occur (Peters and Crosson, 1972) are not observed here. However, in contrast to the linear model, model errors varying as a function of depth could be represented effectively in a layered model.

G. Calibration of Earth Models

A relative calibration of earth models is exhibited in the results of computed locations shown in Table 2. Arrival times from seismic events at a fixed depth of 600 feet but varying lateral positions relative to the hexagonal array were generated using a 4-layer model as follows:

TABLE 1

4-LAYER MODEL

Depth	P-Wave Velocity
0 ↓ 10	2,000 fps
10 ↓ 100	4,000
100 ↓ 300	8,000
300 half-space	12,000

The locations for these events were then computed using two simpler "best fit" models.

(i) Homogeneous half-space, $V_p = 8{,}500$ fps

(ii) Linear velocity model, $V_p = 4{,}200 + 500z$ fps

The term "best fit" in this context means that these models best fitted a travel time curve for the 4-layer model in a least-squares sense over distances of interest to this experiment.

It can be seen from Table 2 that the linear velocity model provides an excellent fit to the "real" 4-layer earth both inside and outside the hexagonal array; the homogeneous half-space is a much less satisfactory approximation for location purposes, deteriorating particularly rapidly at the boundaries of the array. Interestingly, the homogeneous half-space model always provides a more accurate lateral fix when the depth of the seismic event is allowed to vary from its true value rather than when it is fixed. This is only true for the linear velocity model when the seismic event falls within the array. When the depth is allowed to vary, there is a corresponding inability on the part of the approximate models to match the true time of occurrence of the seismic event, as shown in Table 2.

Preliminary conclusions that may be drawn from these results are that in practical terms a linear velocity earth model, which is computationally much easier to handle, may be used to represent a layered earth for location purposes without introducing serious errors; secondly, if a homogeneous earth model is used, it may be wiser to let the depth vary even if it is known, since errors in arrival times will predominantly introduce an error in the computed z coordinate which, if not left free to "compensate" for this, will cause larger errors in the x and y coordinates.(As the seismic event moves away from the center of the array, arrival times become more sensitive to the x and y coordinates; hence, this reasoning eventually breaks down, as shown by the results obtained for the linear velocity model.)

V. REFERENCES

Peters, D.C. and Crosson, R.S. (1972). Application of Prediction Analysis to Hypocenter Determination Using a Local Array, Bull. Seis. Soc. Am., v. 62., pp 775-788

Wolberg, J.R. (1967). Prediction Analysis, D. Van Nostrand Co., Inc., Princeton, N. J.

TABLE 2

COMPARISON OF LOCATION ERRORS FOR TWO APPROXIMATE MODELS

Arrival Times Generated Using 4-Layer Earth Model-Event Locations Computed Using "Best Fit" Constant Velocity Half-Space and Linear Velocity Models with Assumed Model Errors of 5%

Location Array: 7 Seismometer
Hexagonal Array: 600 ft. side

Actual Event Location (feet)		Computed Event Location (feet) Const. Vel. Depth Varied	Const. Vel. Depth Fixed	Lin. Vel. Depth Varied	Lin. Vel. Depth Fixed
x	100	92.8	86.9	100.5	97.8
y	0	0	0	0	0
z	600	694.9	600	632.3	600
t	0 secs	-0.009	0	-0.001	0
x	300	291.8	258.2	301.1	291.6
y	0	0	0	0	0
z	600	706.6	600	629.1	600
t	0 secs	-0.015	0	-0.001	0
x	500	523.5	423.4	495.3	485.6
y	0	0	0	0	0
z	600	717.7	600	613.6	600
t	0 secs	-0.026	0	0	0
x	700	758.2	599.0	666.7	683.8
y	0	0	0	0	0
z	600	724.6	600	587.3	600
t	0 secs	-0.036	0	0	0
x	900	955.3	781.2	818.0	913.4
y	0	0	0	0	0
z	600	729.1	600	554.3	600
t	0 secs	-0.042	0	0.006	0

TABLE 3

SUMMARY OF ERROR DIAGRAMS

Run #	Array Type	Station Spacing, ft.	Velocity Model	Parameter Error σ_v(%)	σ_t(sec.)	Depth Fixed?
1	Hex	600	Con	0	.001	
2	Hex	600	Lin	0	.001	
3	Hex	600	Lin	5%	.001	
4	Hex	600	Lin	5%	.001	*
5	Hex	1200	Con	0	.001	
6	Hex	1200	Lin	0	.001	
7	Hex	1200	Lin	5%	.001	
8	Hex	1200	Lin	5%	.001	*
9	Hex	600	Con	0	.005	
10	Hex	600	Lin	5%	.005	
11	H	600	Lin	5%	.001	
12	Hex	600	Con	5%	.001	
13	Mod Hex	450	Lin	5%	.001	
14	Hex	600	2 Lay	5%	.001	
15	H	600	2 Lay	5%	.001	
16	Hex	600	2 Lay	5%	.001	*
17	Hex	600	2 Lay	5%	.005	*
18	Hex	600	4 Lay	5%	.001	*
19	Hex	600	4 Lay	5%	.005	*
20	H	600	Lin	5%	.001	*
21	Hex	600	Lin	5%	.010	*
22	Hex	600	Lin	5%	.015	*
23	Hex	600	Lin	5%	.020	*
24	Hex	600	Lin	1%	.005	*

* indicates depth fixed for error computations.

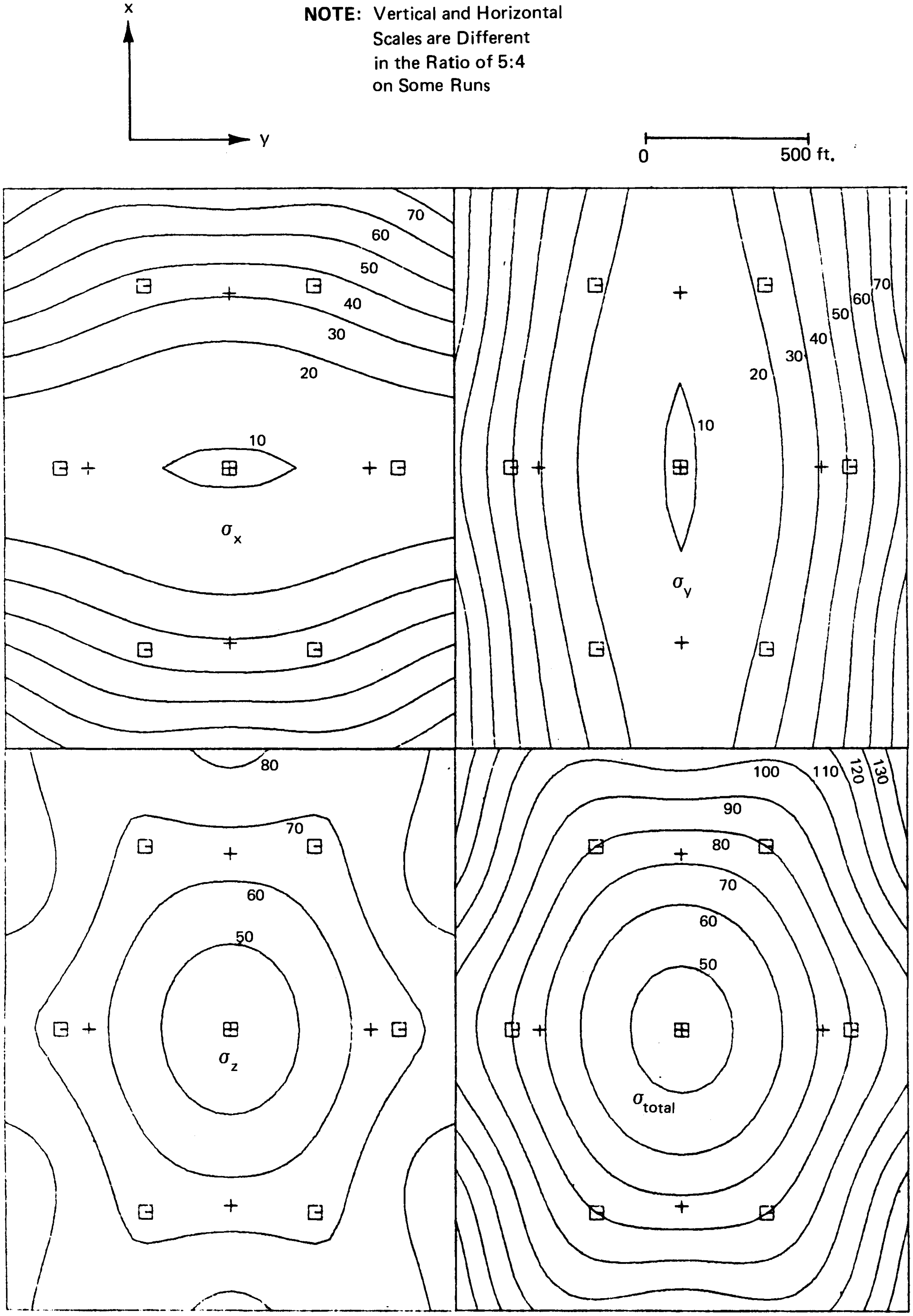
TABLE 3 (Continued)

Con -- Constant Velocity Model: V_p = 12,000 fps

Lin -- Linear Velocity Model: V_p = 5,000 + 18 fps

	Depth, ft.	Velocity, fps
2 Lay -- Two-Layer Model:	0-200	6,000
	200 +	10,000
4 Lay -- Four-Layer Model:	0-10	2,000
	10-100	4,000
	100-300	8,000
	300 +	12,000

NOTE: Vertical and Horizontal Scales are Different in the Ratio of 5:4 on Some Runs



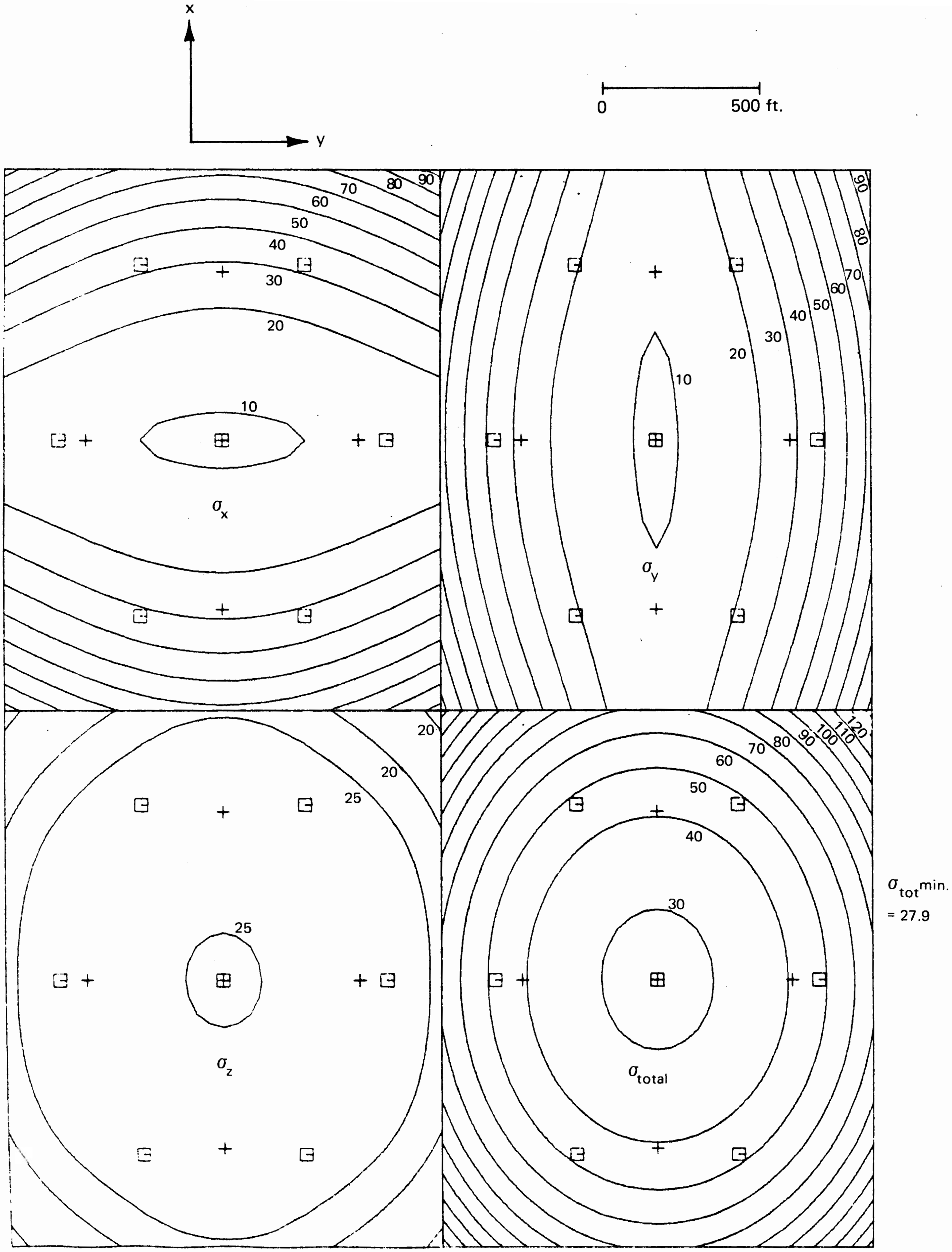
σ_{tot} min. = 46.4

MODEL: Constant Velocity
v = 12000 fps
σ_v = 0%
σ_t = 1 ms

Note Large Effect of Time Error when Model is Known

RUN 1

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

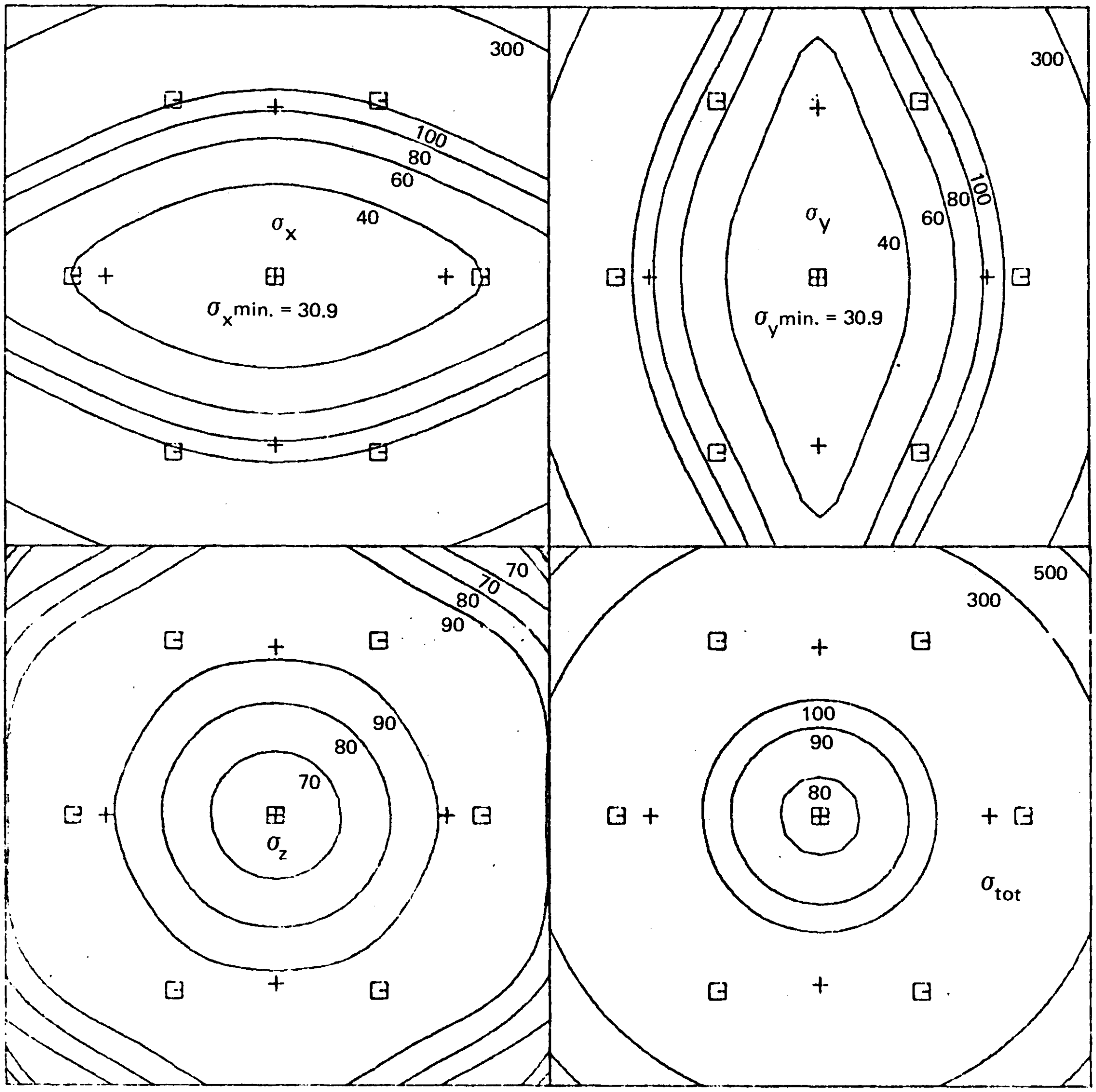


MODEL: Linear Velocity
$v = 5000 + 18z$
$\sigma_V = 0$
$\sigma_t = .001$

Linear Velocity
Gives Much Better
Depth Control

RUN 2

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

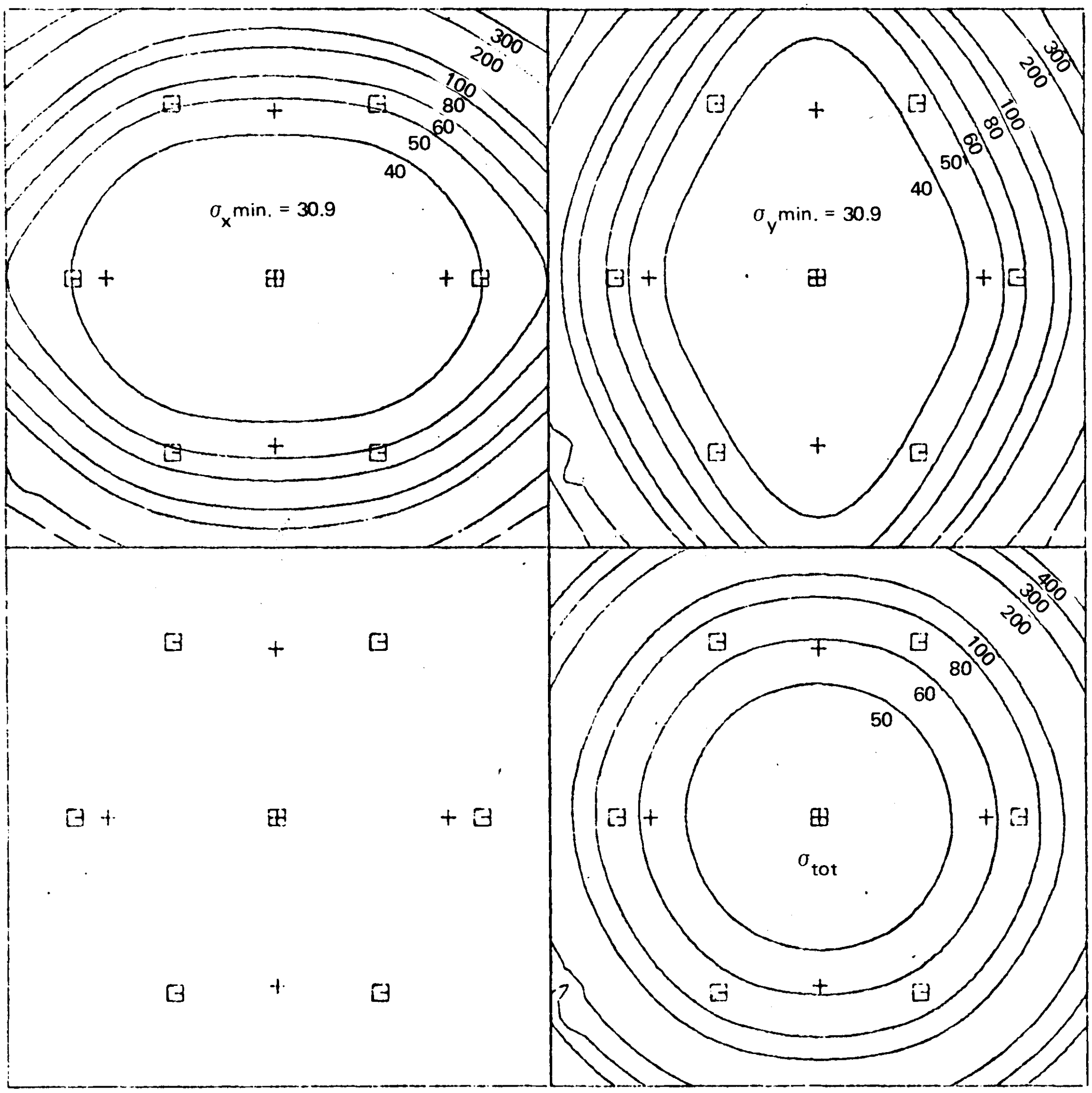


v = 5000 + 18z
σ_v = 5%
σ_t = .001

σ_{tot}min. = 77.6

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 3

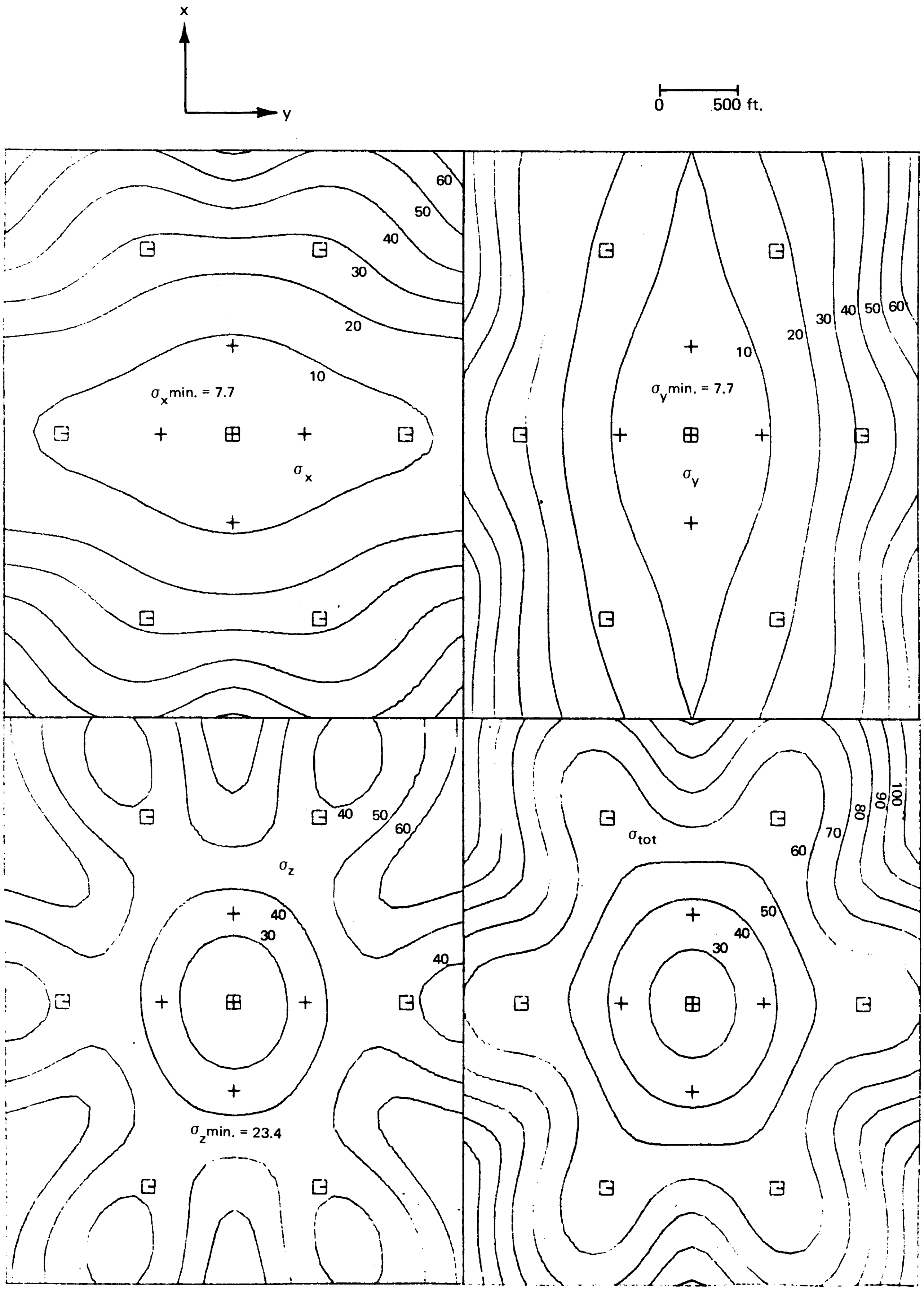


v = 5000 + 18z
σ_v = 5%
σ_t = .001

σ_{tot}min. = 43.7

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

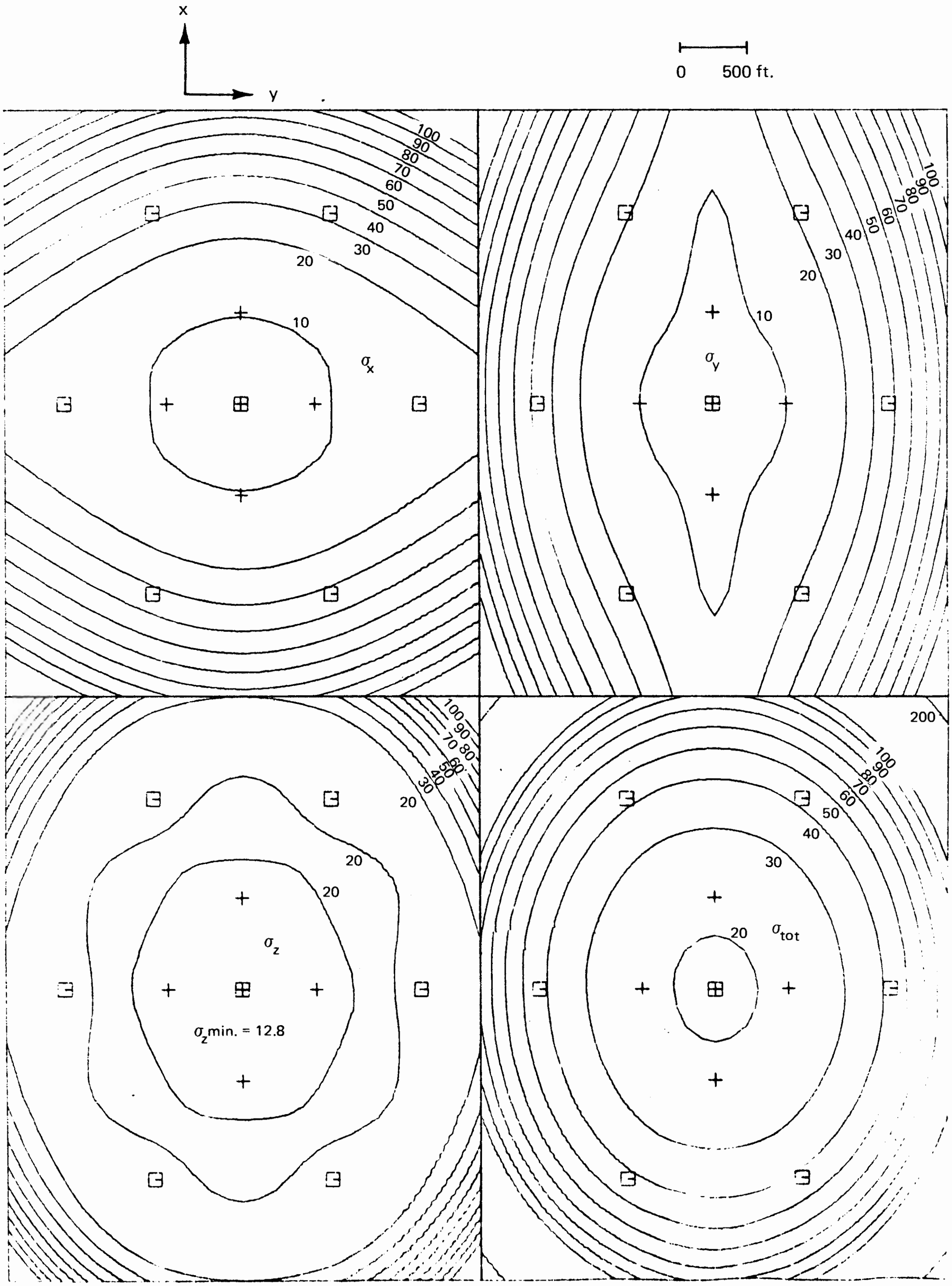
RUN 4



v = 12000
σ_v = 0
σ_t = .001
ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

Expanded array
Compare to 1; σ_{tot}min. = 25.9

RUN 5

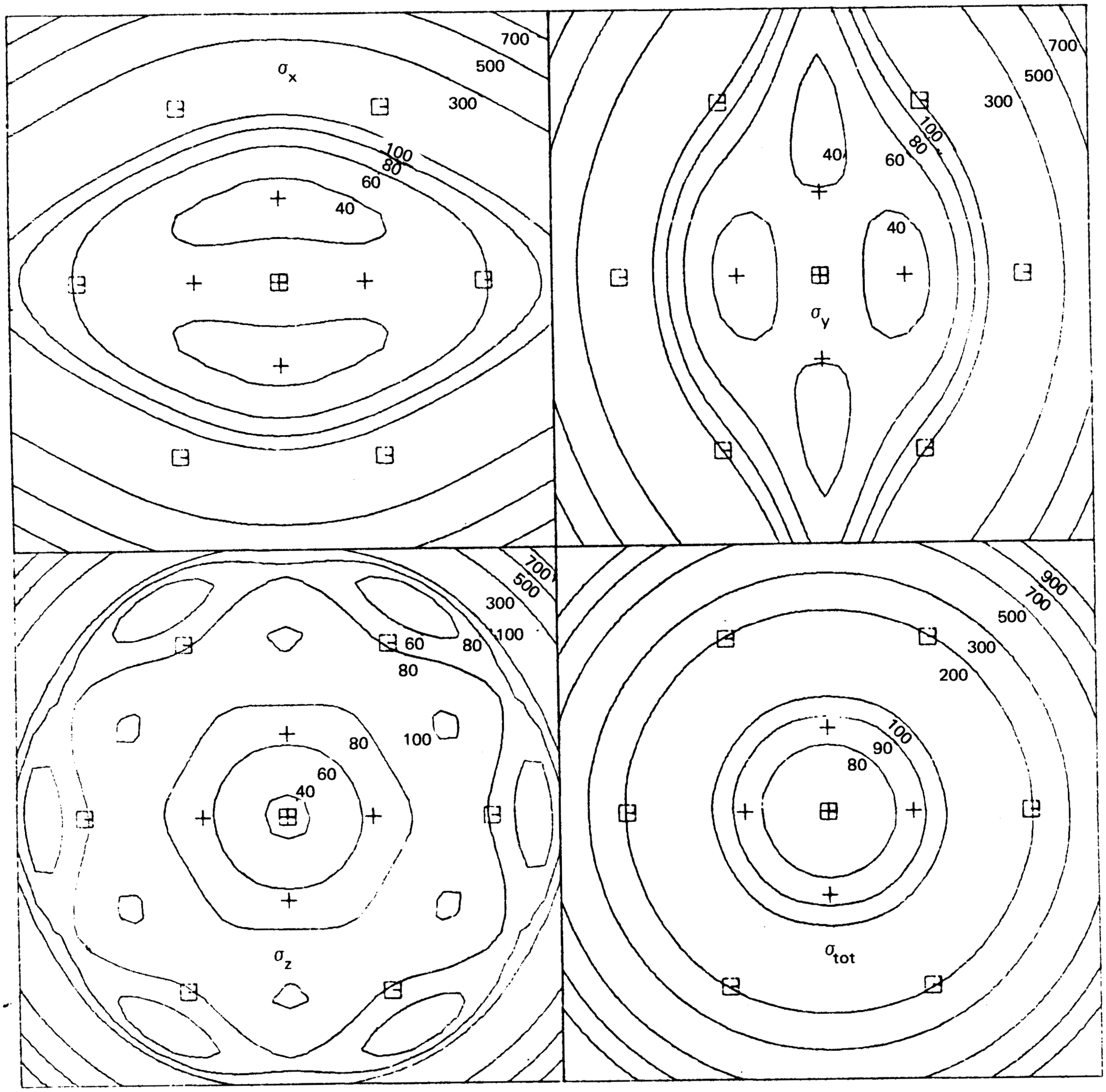


v = 5000 + 18z
σ_v = 0
σ_t .001

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

Expanded Array
Compare to 2; σ_{tot}min. = 18.7

RUN 6

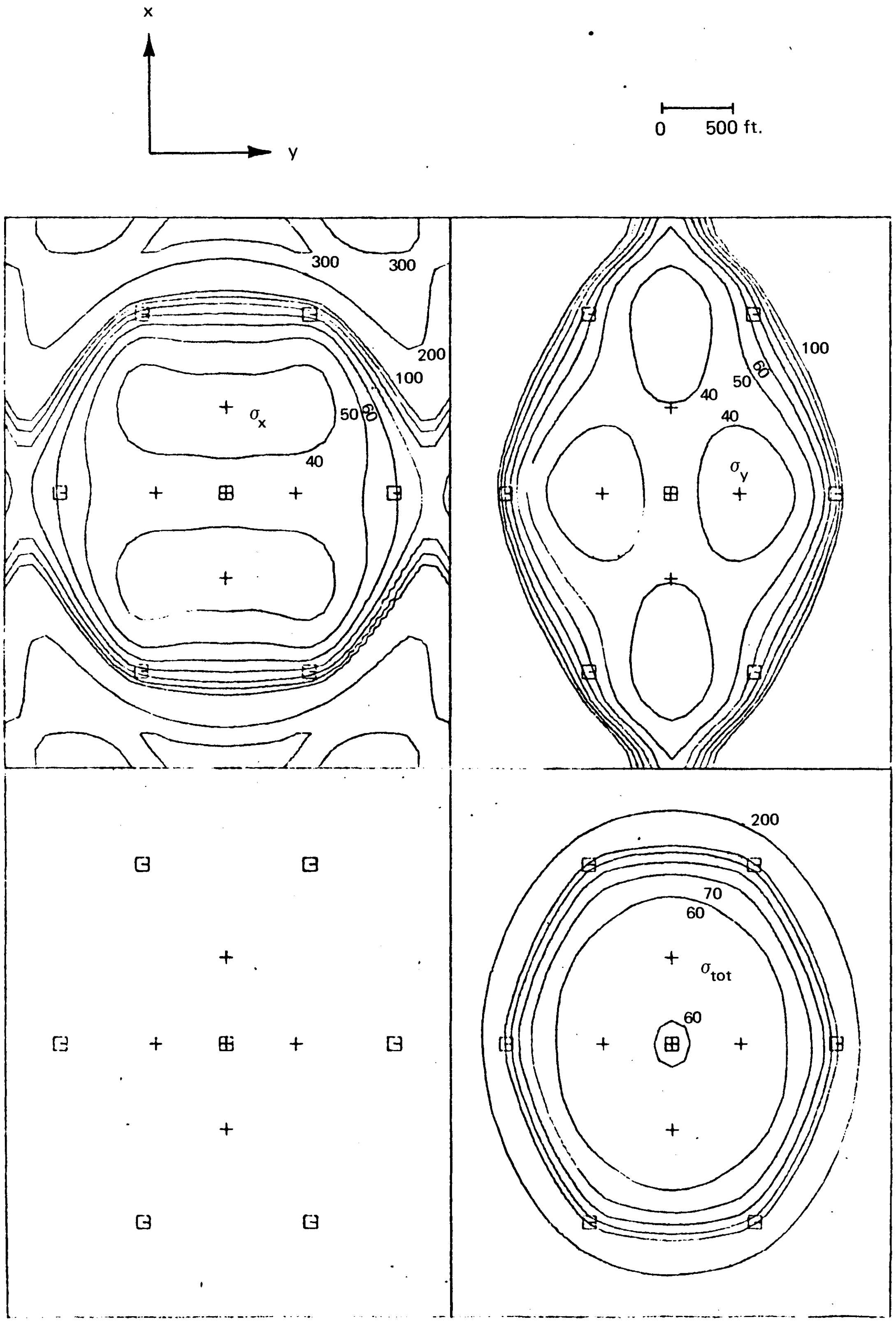


v = 5000 + 18z
σ_v = 5%
σ_t = .001
Double Array Dimensions

σ_{tot}min. = 71.7

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 7

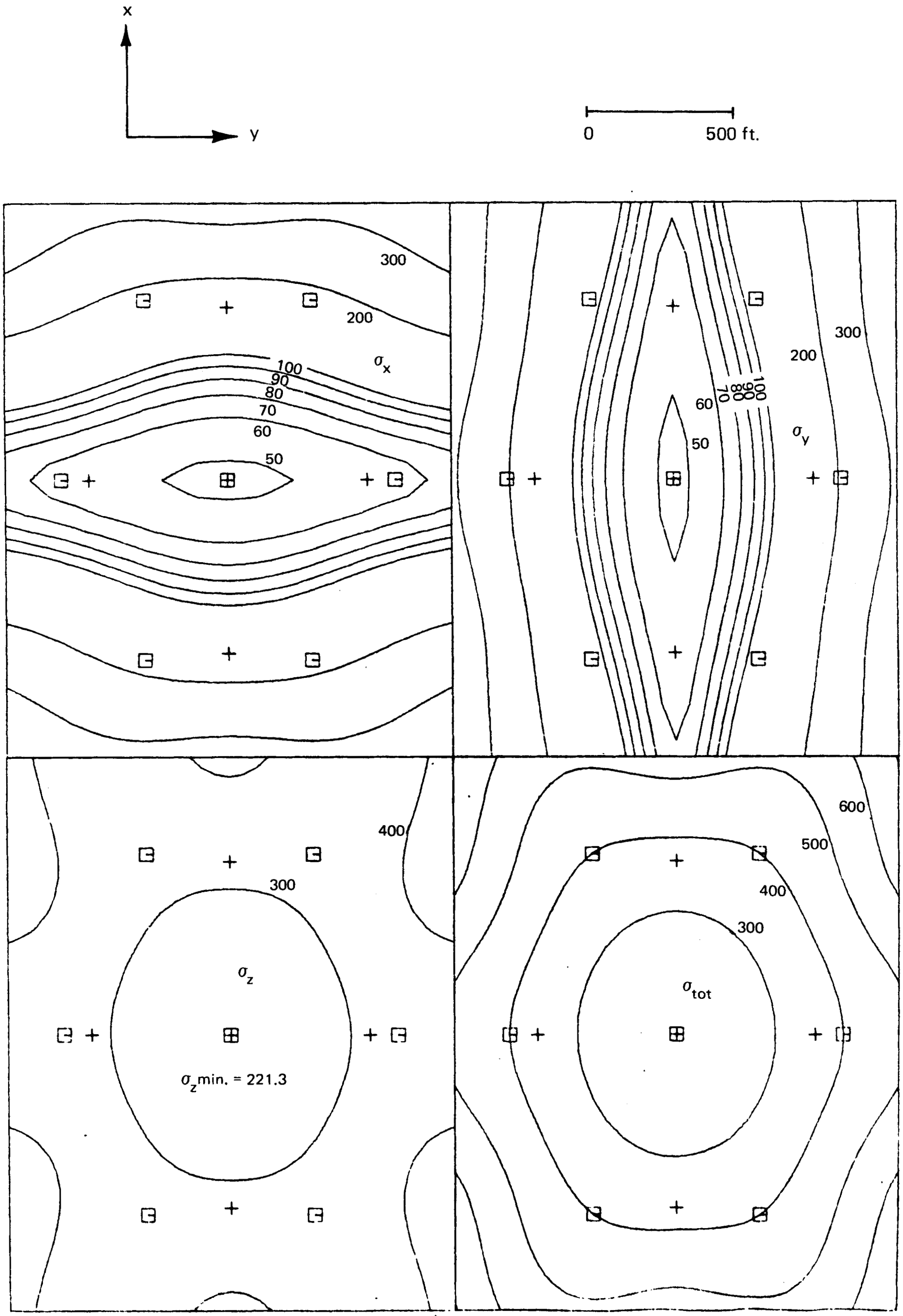


$v = 5000 + 18z$
$\sigma_v = 5\%$
$\sigma_t = .001$
Depth Fixed

Expanded Array
Compare to 4; σ_{tot}min. = 54.0

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 8

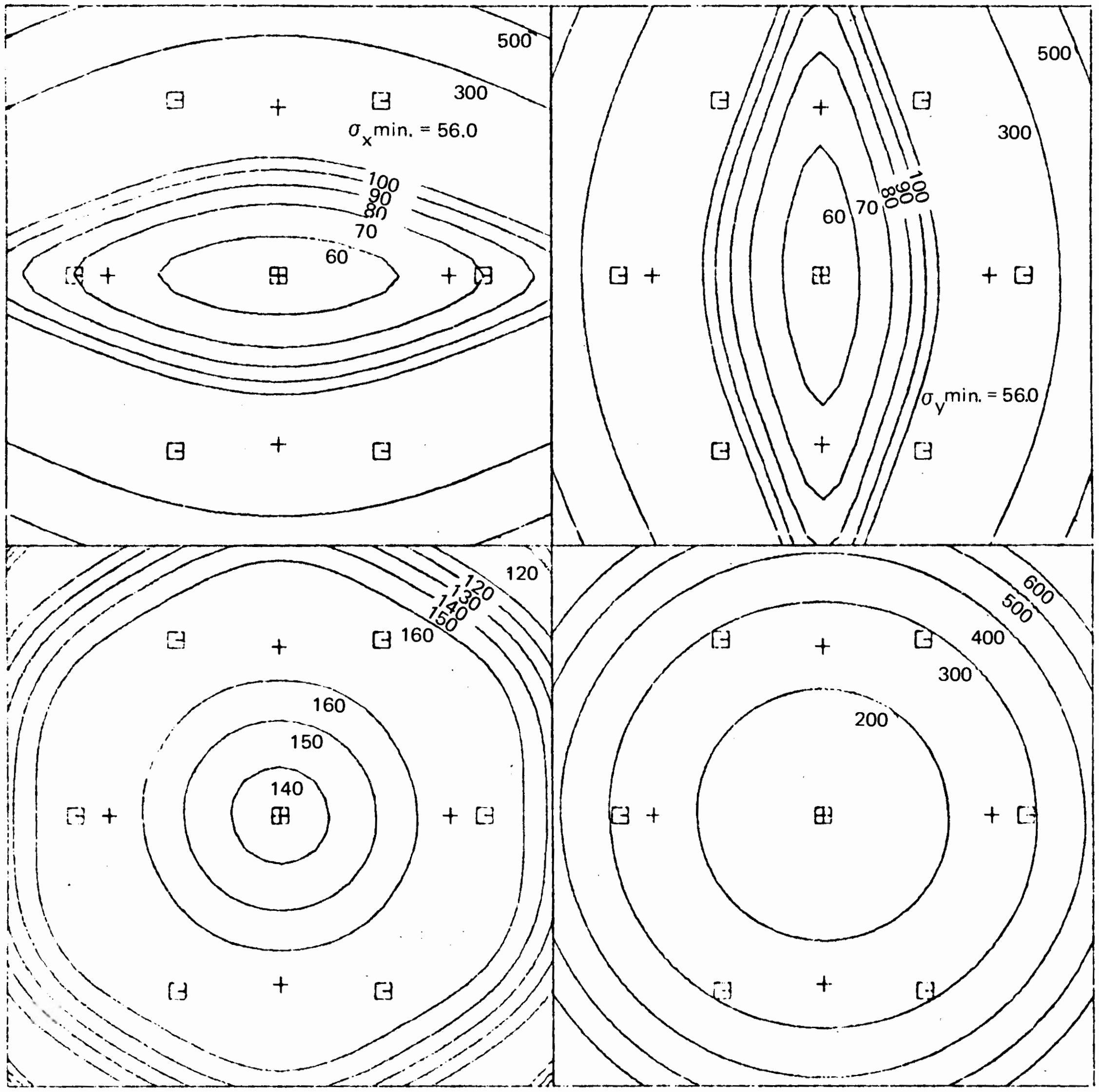


v = 12000
σ_v = 0
σ_t = .005

$\sigma_{x_i} = 5 \times \sigma_{x_i}$ (plot 1)
σ_{tot}min. = 231.9

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 9

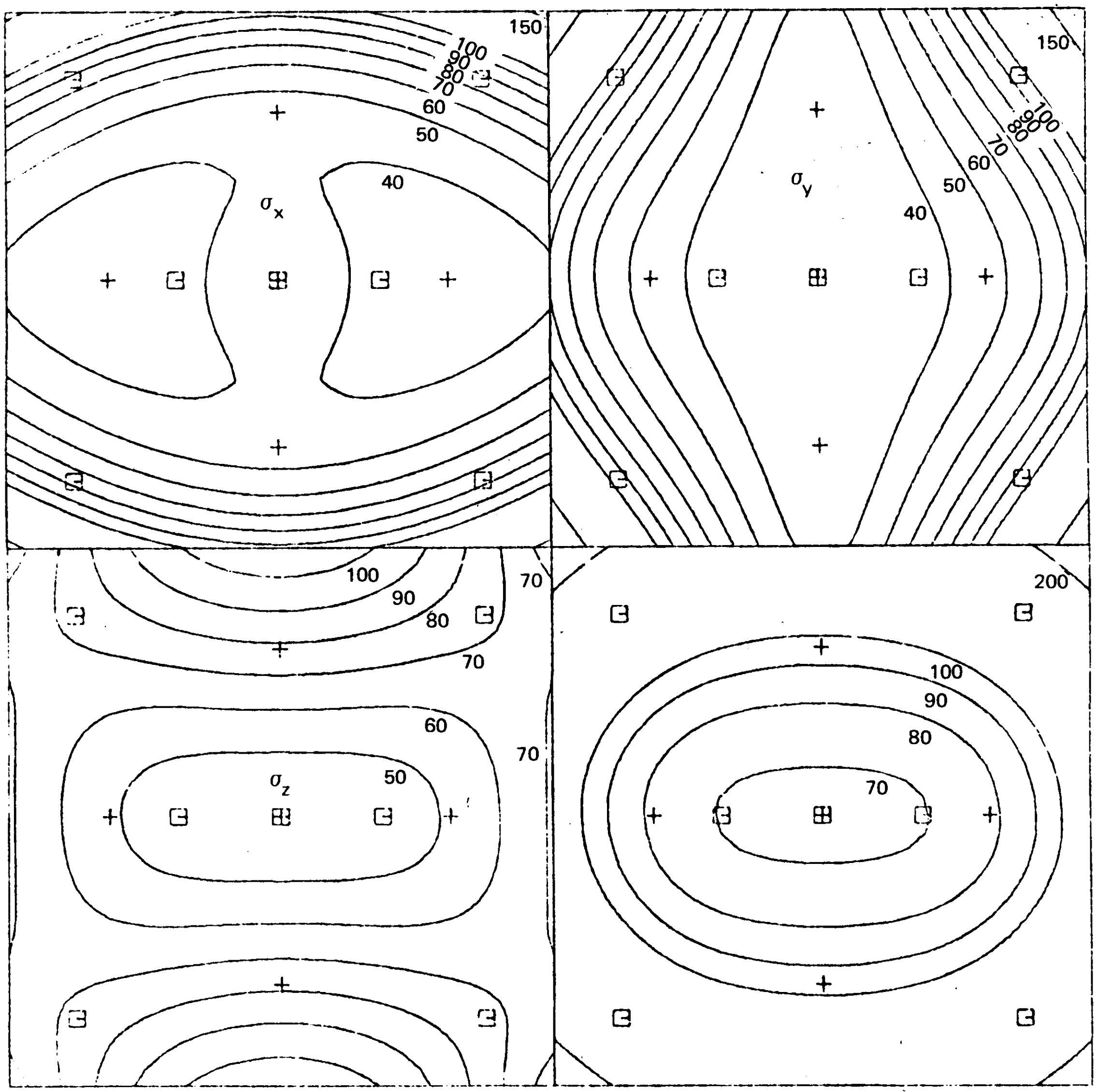


v = 5000 + 18z
σ_v = 5%
σ_t = .005

σ_{tot}min. = 156.0

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 10



$v = 5000 + 18z$

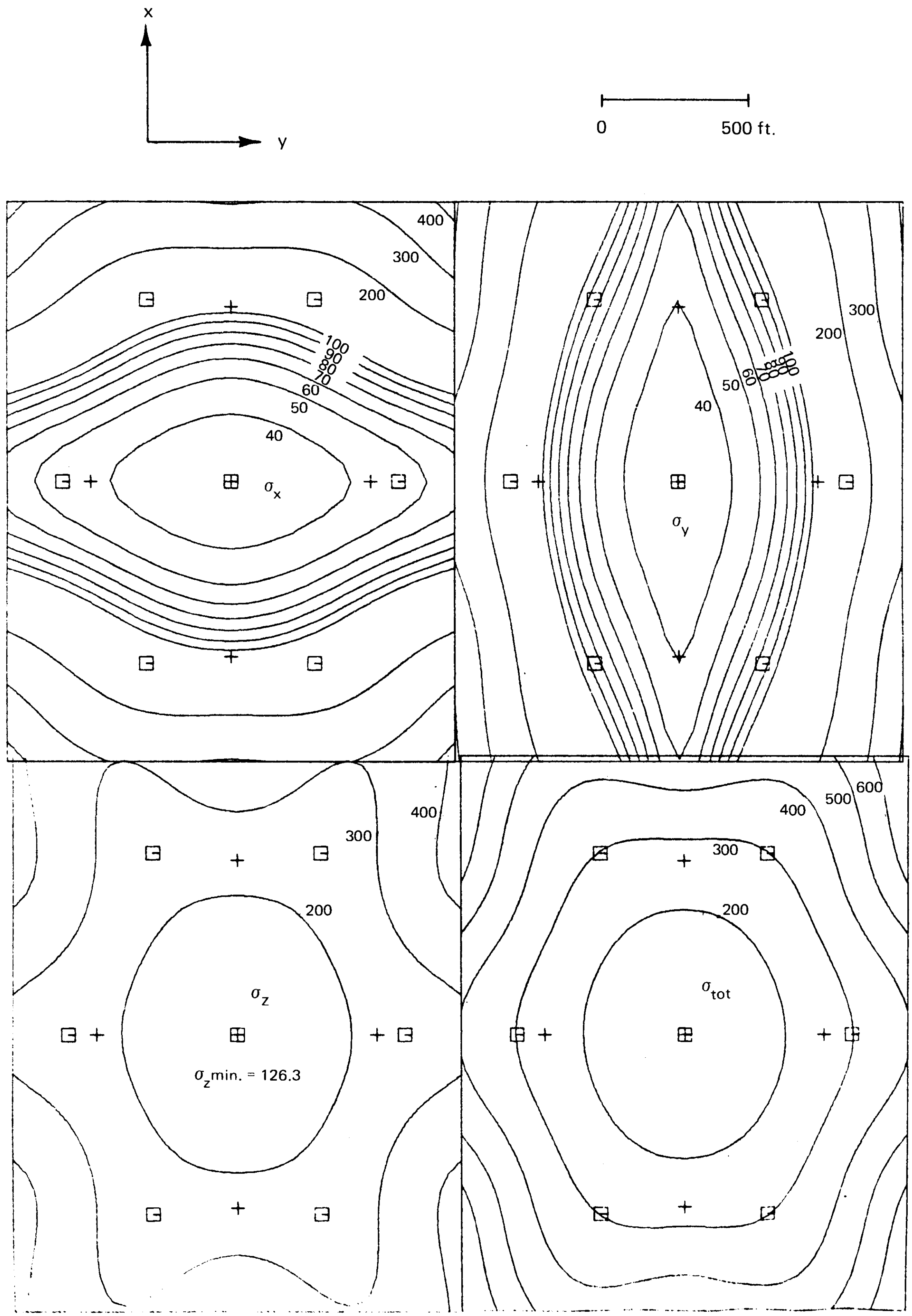
$\sigma_v = 5\%$

$\sigma_t = .001$

σ_{tot}min. = 67.7

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 11

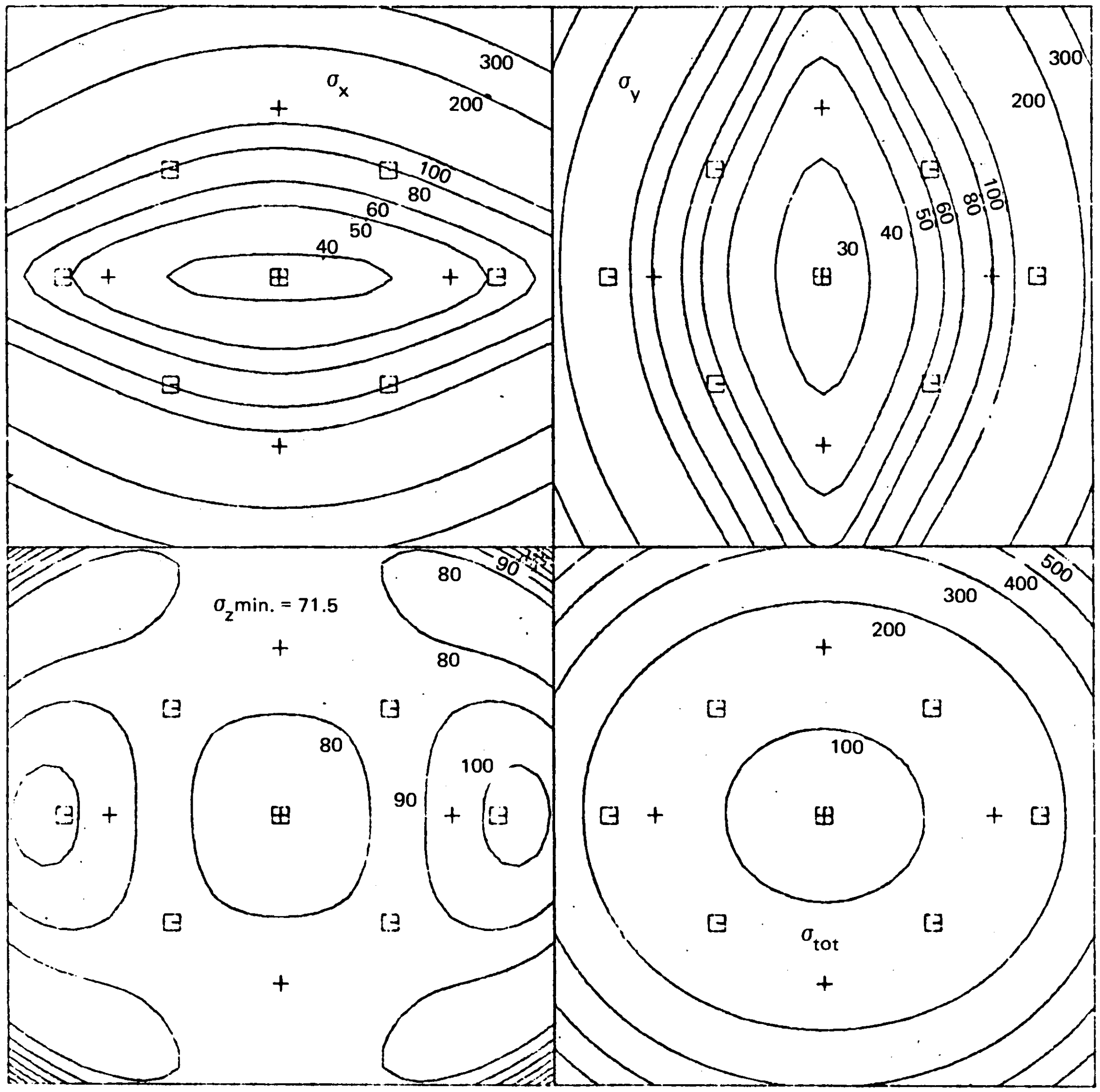


v = 12000
σ_v = 5%
σ_t = .001

Compare to 1, 3, 9
σ_{tot}min. = 136.2

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 12



$v = 5000 + 18z$

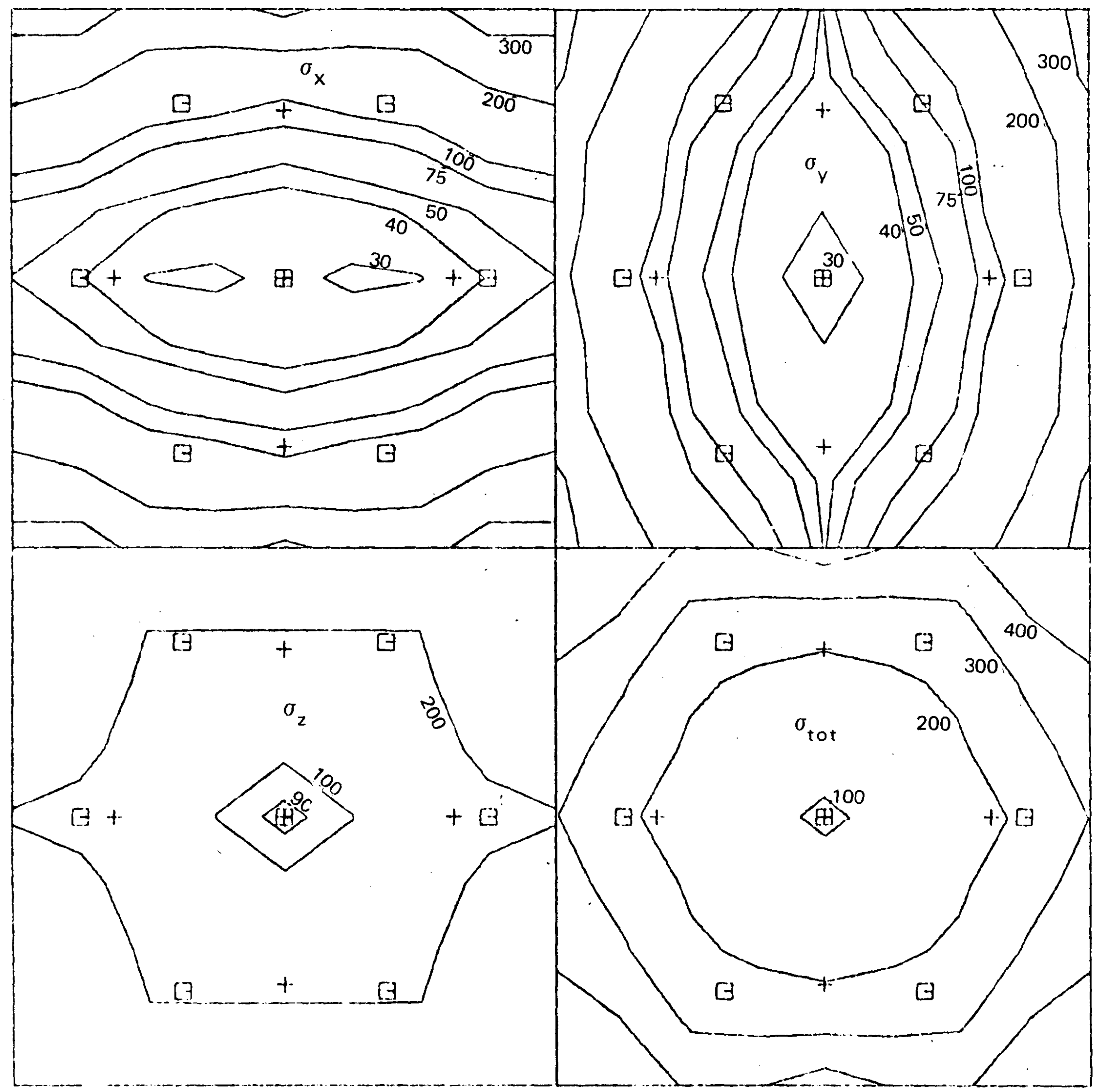
$\sigma_v = 5\%$

$\sigma_t = .001$

σ_{tot}min. = 85.8

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 13

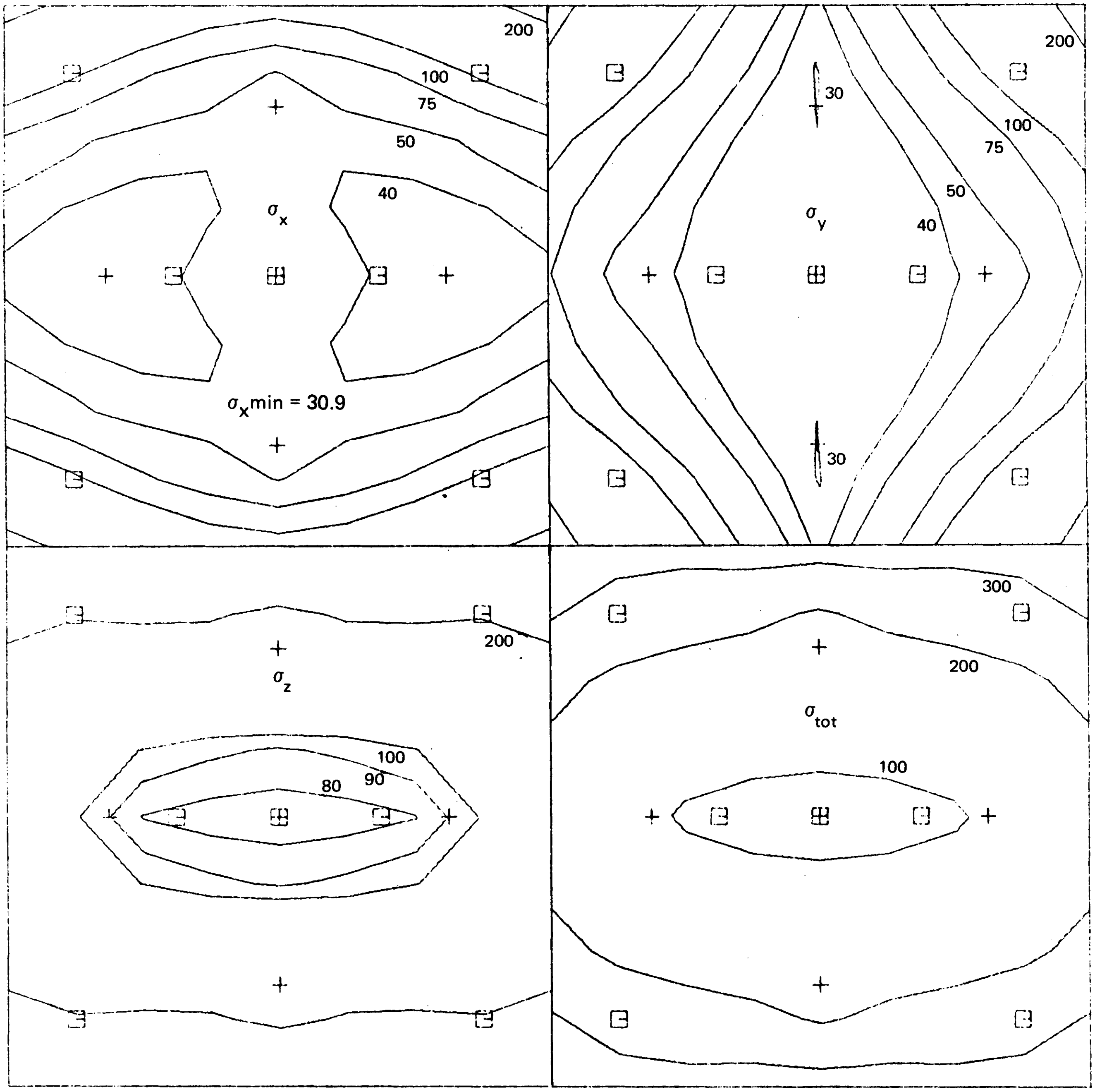


2 Layer Model
$\sigma_v = 5\%$
$\sigma_t = .001$

σ_{tot}min. = 95.2

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 14

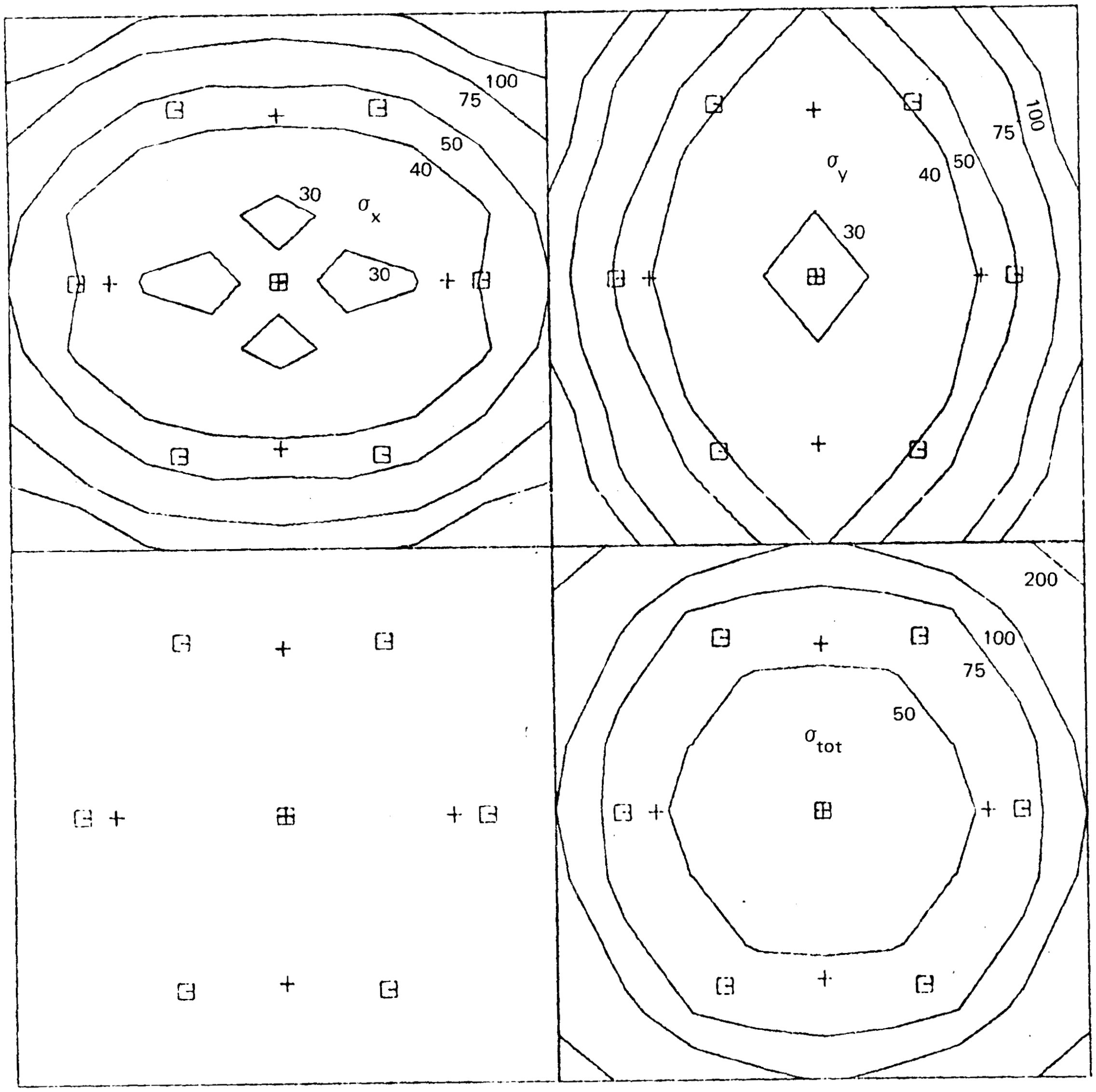


2 Layer Model
σ_v = 5%
σ_t = .001

σ_{tot}min. = 93.4

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 15

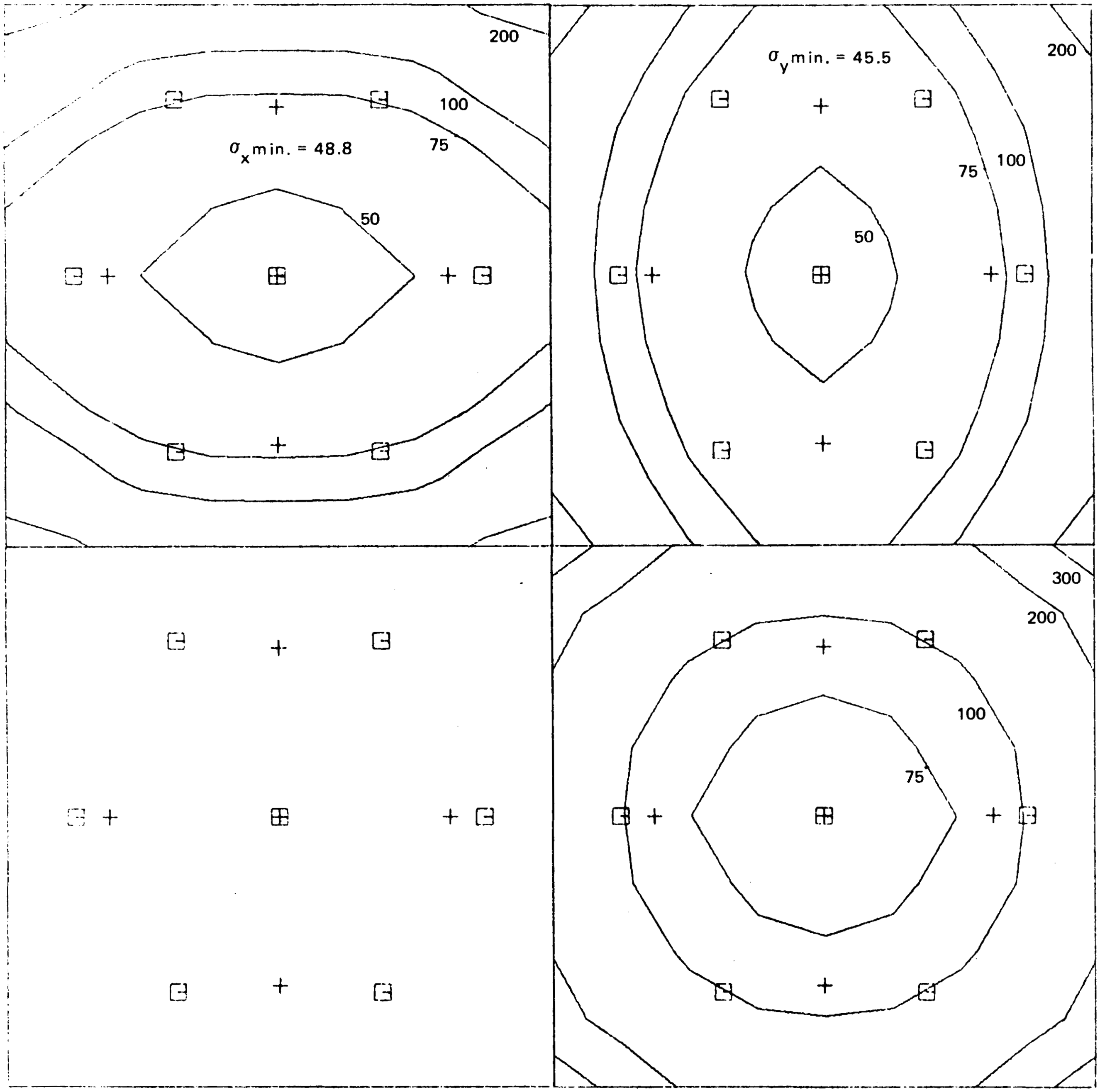


2 Layer Model
$\sigma_v = 5\%$
$\sigma_t = .001$

σ_{tot}min. = 41.8

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 16

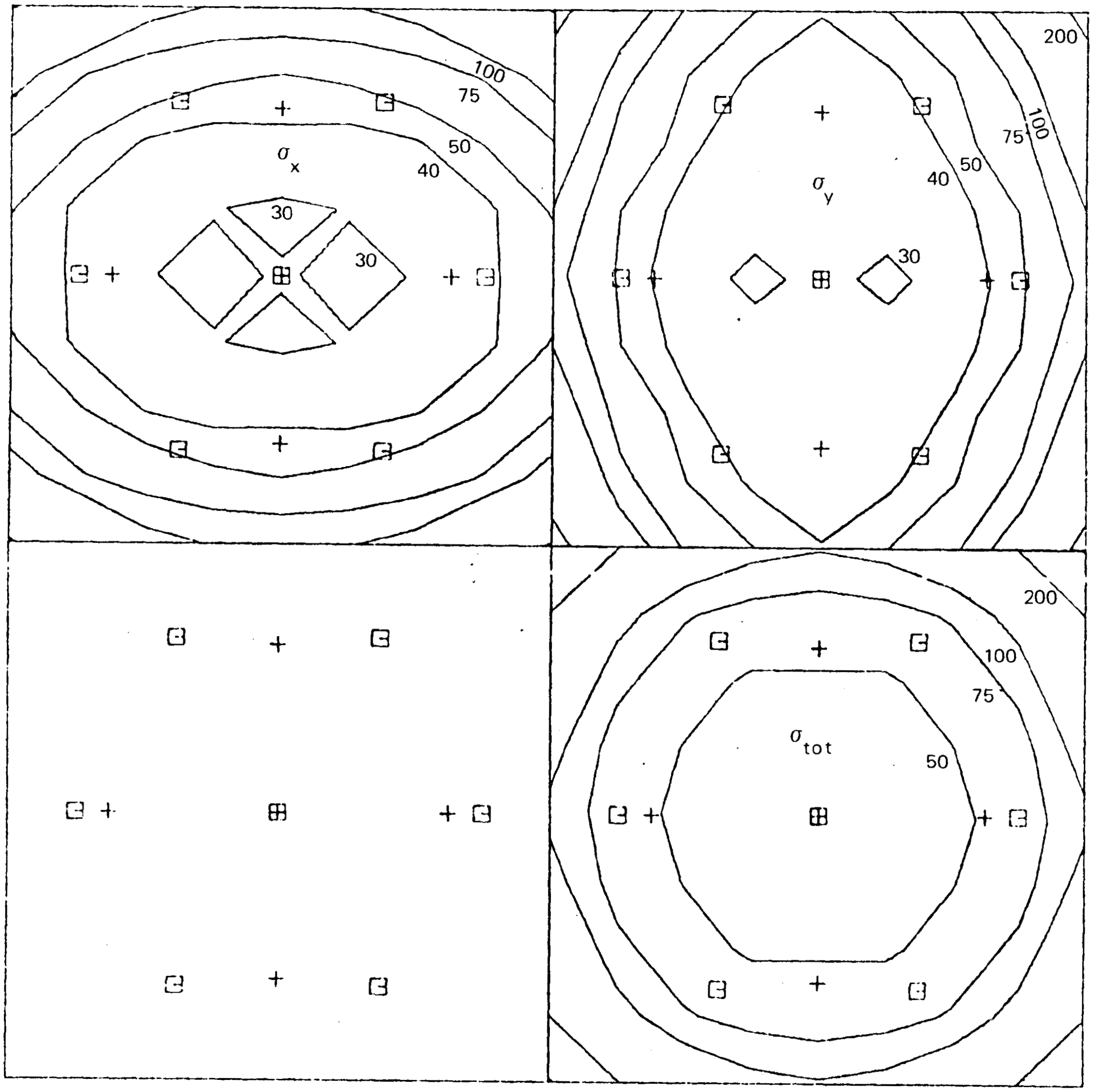


2 Layer Model
σ_v = 5%
σ_t = .005

σ_{tot}min. = 66.7

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 17

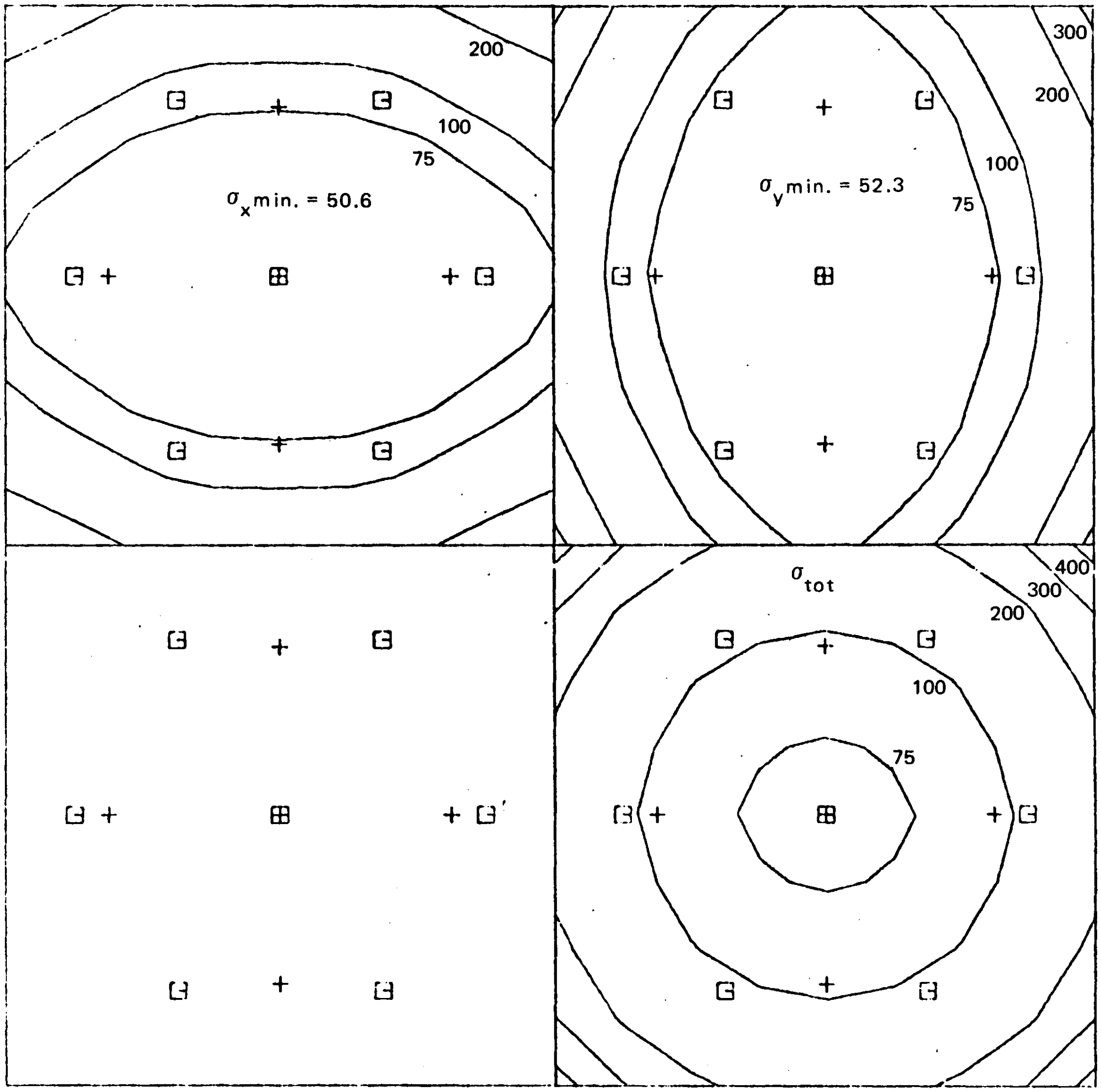


4 Layer Model
σ_v = 5%
σ_t = .001

σ_{tot}min. = 41.0

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 18

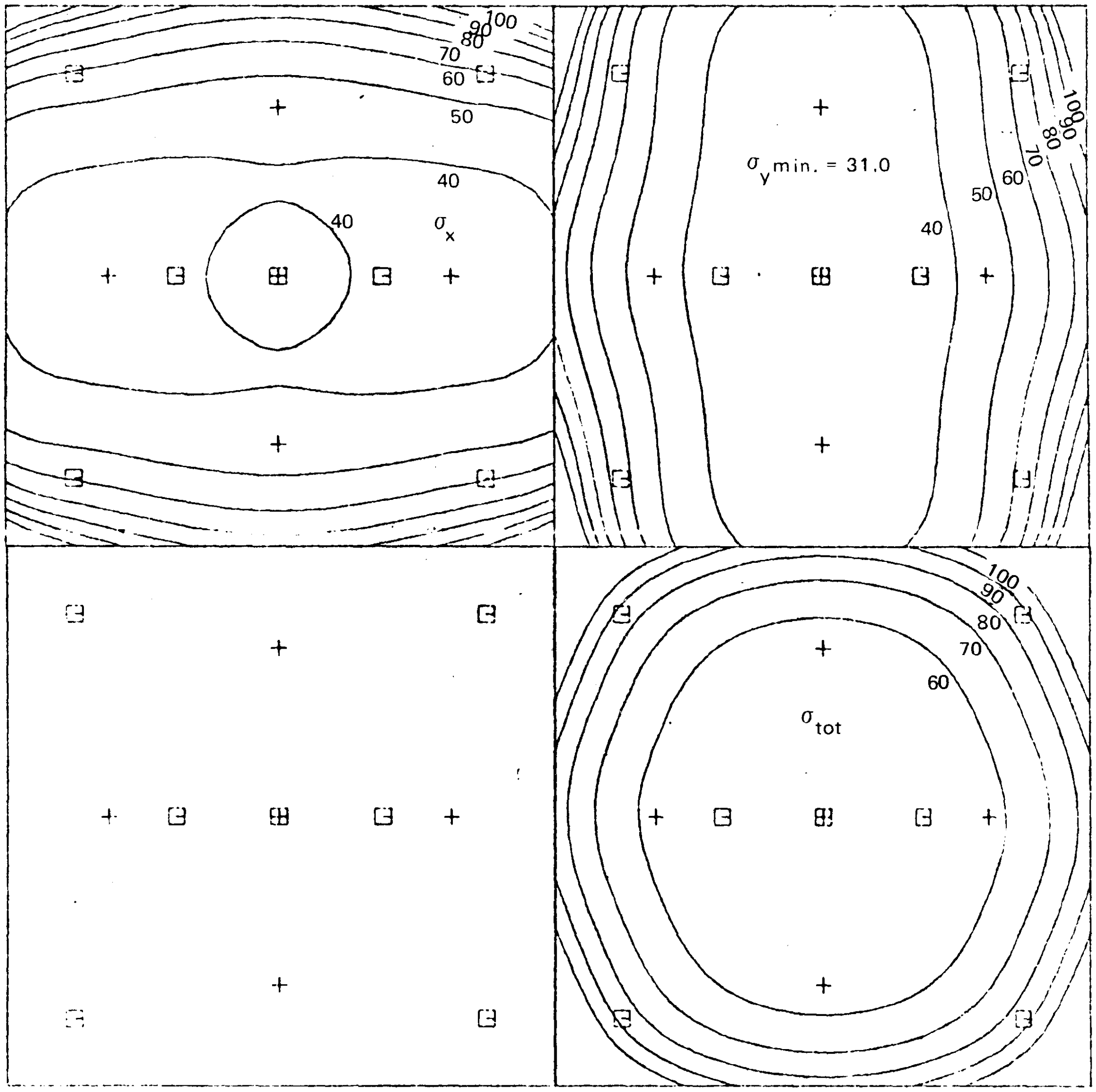


4 Layer Model
σ_v = 5%
σ_t = .005

σ_{tot}min. = 72.7

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 19

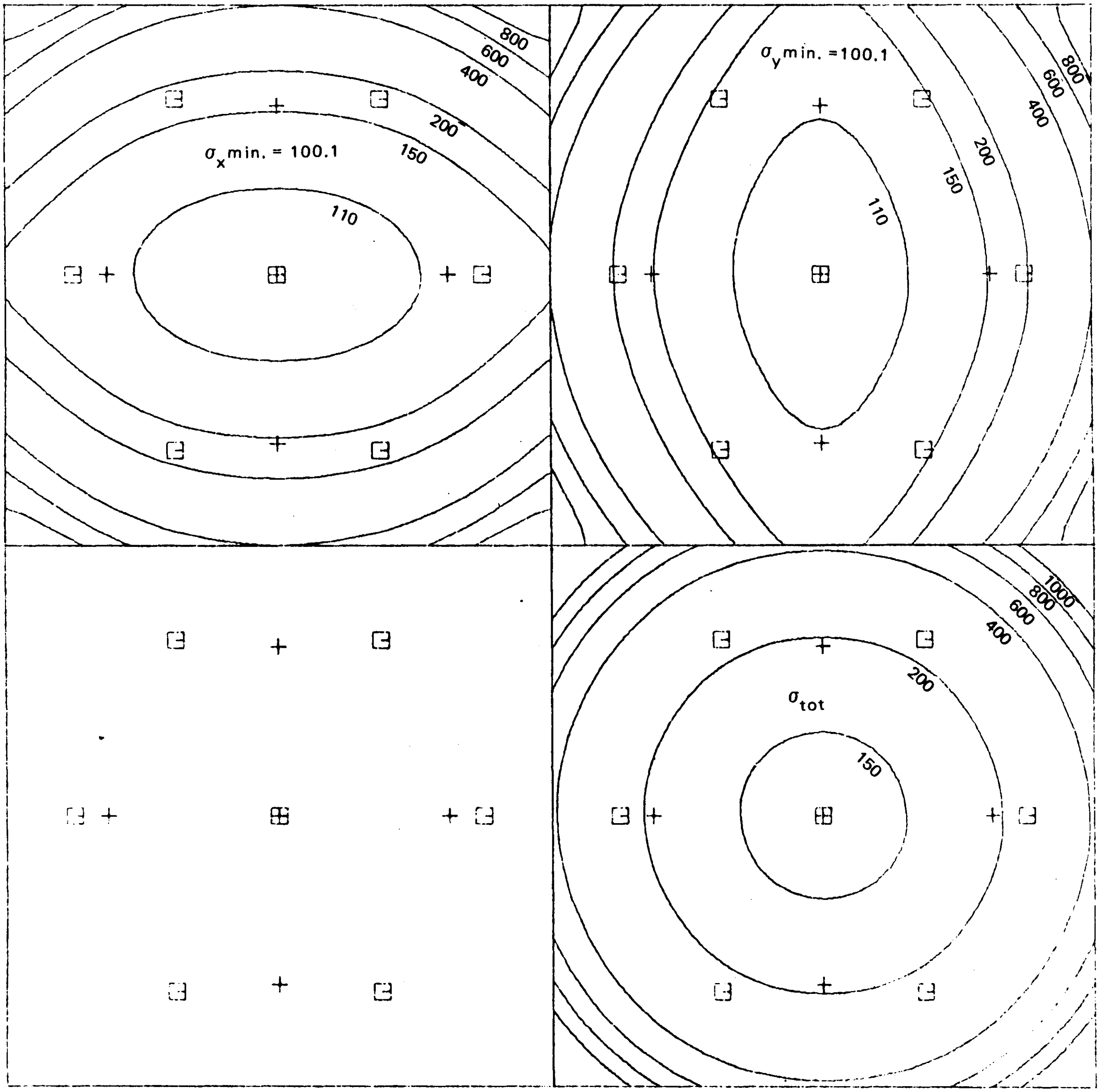


v = 5000 + 18z
σ_v = 5%
σ_t = .001

σ_{tot}min. = 51.0

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 20

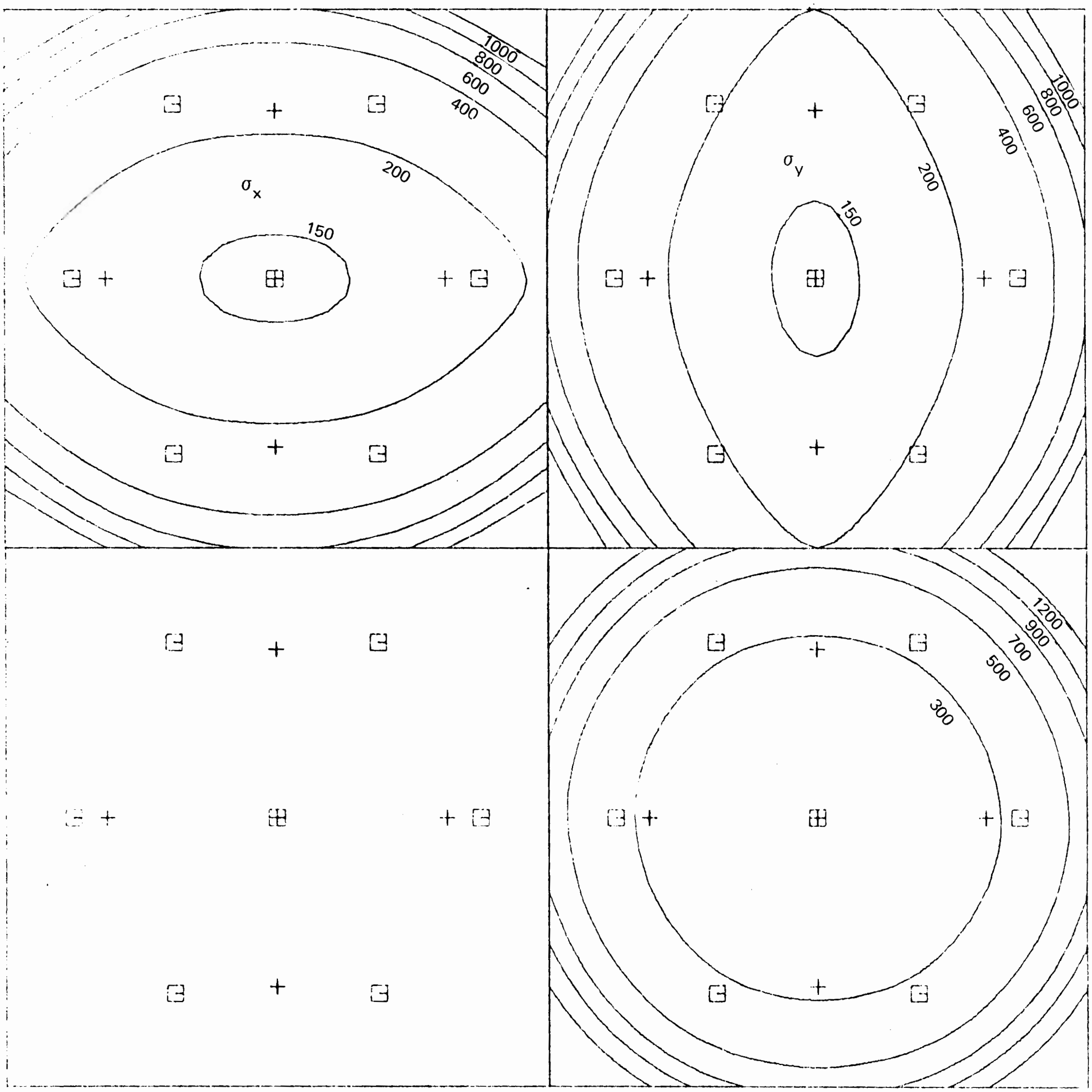


v = 5000 + 18z
σ_v = 5%
σ_t = .010

σ_{tot} min.=141.6

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 21



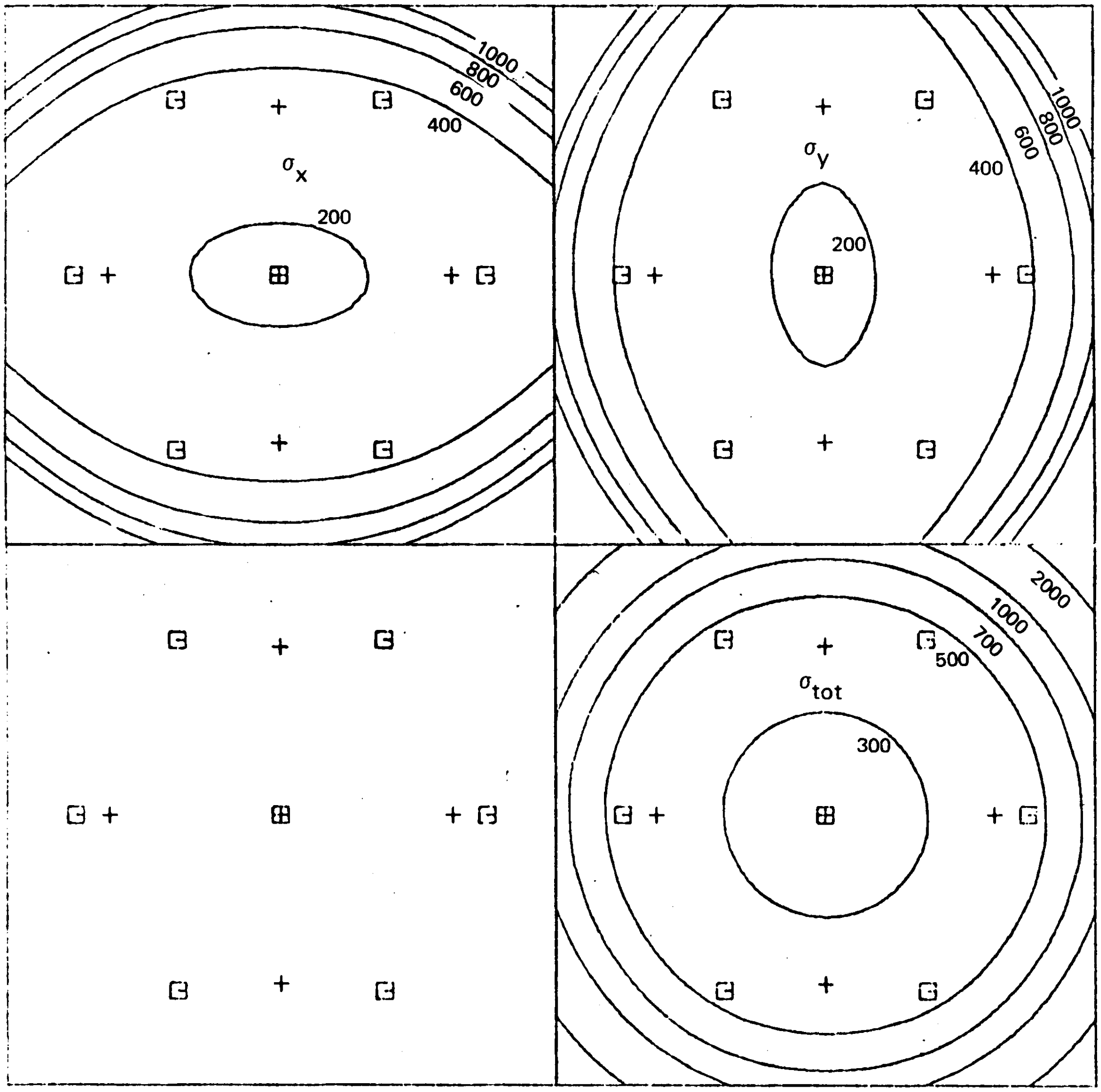
$v = 5000 + 18z$ σ_{tot}min. = 207.2

$\sigma_v = 5\%$

$\sigma_t = .015$

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 22



v = 5000 + 18z

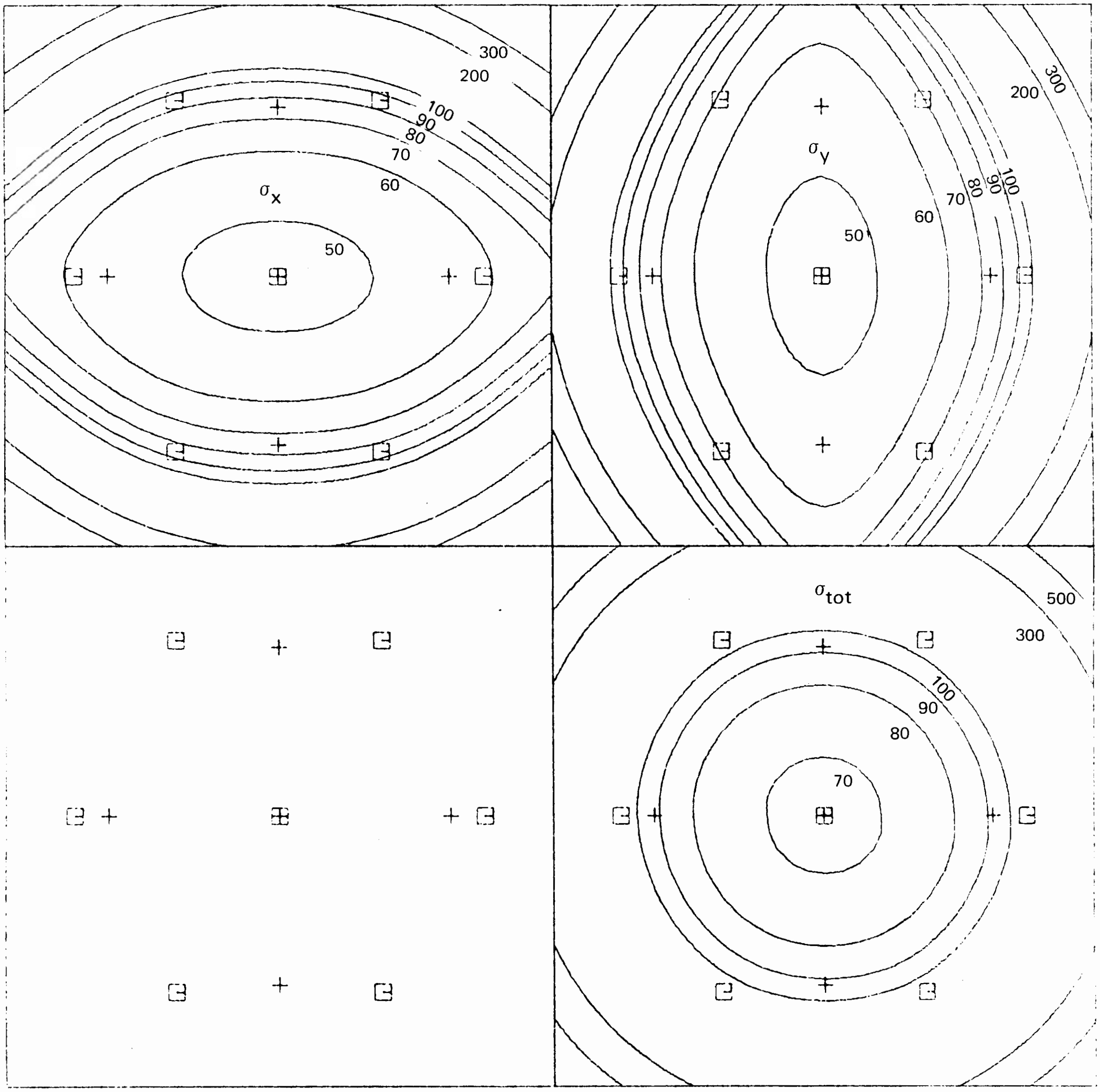
σ_v = 5%

σ_t = .020

σ_{tot}min. = 273.8

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

RUN 23



$v = 5000 + 18z$

$\sigma_v = 1\%$

$\sigma_t = .005$

σ_{tot}min. = 68.1

RUN 24

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET

PART FOUR

ESTIMATES OF MINER LOCATION ACCURACY:
WESTINGHOUSE LOCATION PROGRAM "MINER"

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PART FOUR

ESTIMATES OF MINER LOCATION ACCURACY: WESTINGHOUSE LOCATION PROGRAM "MINER"

Arthur D. Little, Inc.

I. INTRODUCTION

Crosson and Peters treat the errors that result in miner location due to errors in the overburden earth model used for computing location. A parallel effort by J. Powell of PMSRC is discussed here, where the location method used is that of the Westinghouse location program - "Miner". This location program was tested by Powell by using arrival times generated from the overburden earth model of Table 1* rounded to the nearest millisecond. Location computations were then made using 3 geophones at a time. The average location is tabulated for all geophone triplets except when 3 geophones are in line. Geophone arrays were as shown in Tables 2 and 3. The manner in which the test was done is illustrated in Figure 1.

II. SUMMARY OF RESULTS

The arrival time differences, based on the Table 1 earth model, together with geophone locations based on the array geometries of Tables 2 and 3, were entered into the computer, together with a stated depth of 700 feet and an estimated overburden seismic velocity of 10,000 feet per second. These parameter values were processed by the location program - "Miner". Figure 2 illustrates the interpretation of the plots and data. The tabular data and plots of Table 4 and Figures 3, 4, and 5 illustrate the location error results obtained.

These plots indicate that for sources within the array, the errors are considerably less than the measured errors obtained during field tests of the present location system. The possible reasons for this discrepancy are noted in Part Eight (Earth Models).

*References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

The work summarized here is based on arrival time differences resulting from one particular representation of the earth. Other representations of the earth will yield other results. When hard data has been developed on the real seismic properties of coal mine overburdens, much more definitive results concerning the location accuracy of program "Miner" can be developed.

It is further noted that the present test of "Miner" did not make any use of the overspecification of location that results from the use of seven arrival times to vary the model velocity used in computation. Figure 5 does illustrate the behavior of errors for an array judged to be too small for the known depth of source. For this example the dependence of location error on input velocity is shown.

Table 1

Earth Model

Layer Number	Layer Thickness (ft.)	Layer Velocity (ft/sec)
Surface		
1	5	1,500
2	15	2,000
3	30	3,000
4	50	4,500
5	100	6,000
6	200	8,000
7	300	11,000
Source		

Table 2

"L-Feet Hexagon" Array

Geophone No.	X	Y
1	0	0
2	L	0
3	L/2	.866 L
4	-L/2	.886 L
5	-L	0
6	-L/2	-.886 L
7	L/2	-.886 L

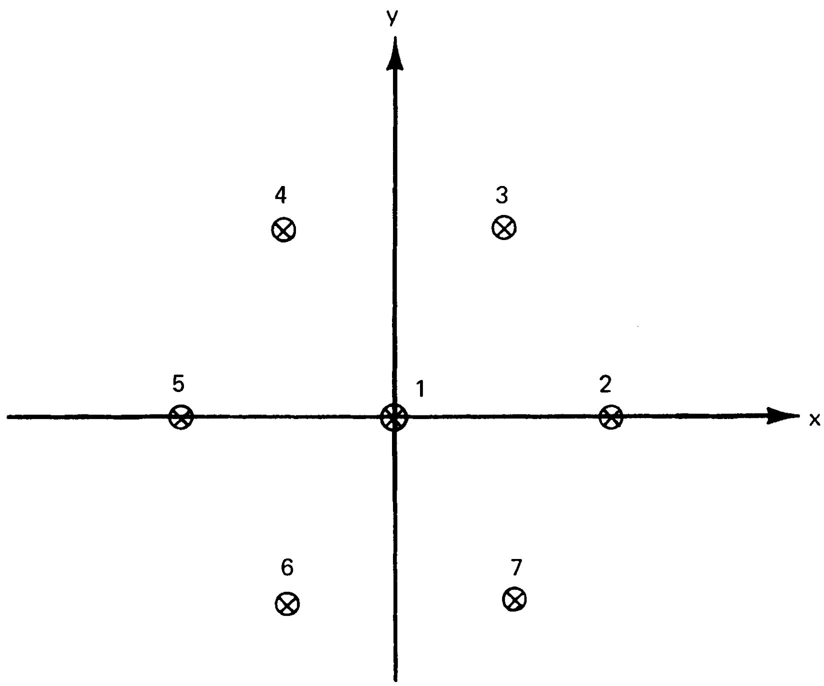
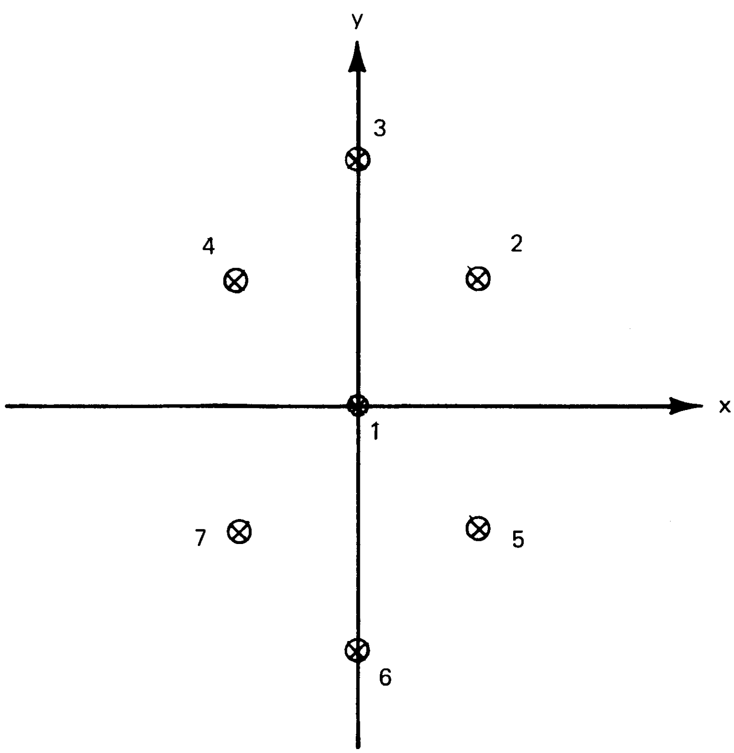


Table 3

"L-Feet Double-Square" Array

Geophone No.	X	Y
1	0	0
2	L	L
3	0	2L
4	-L	L
5	L	-L
6	0	-2L
7	-L	-L



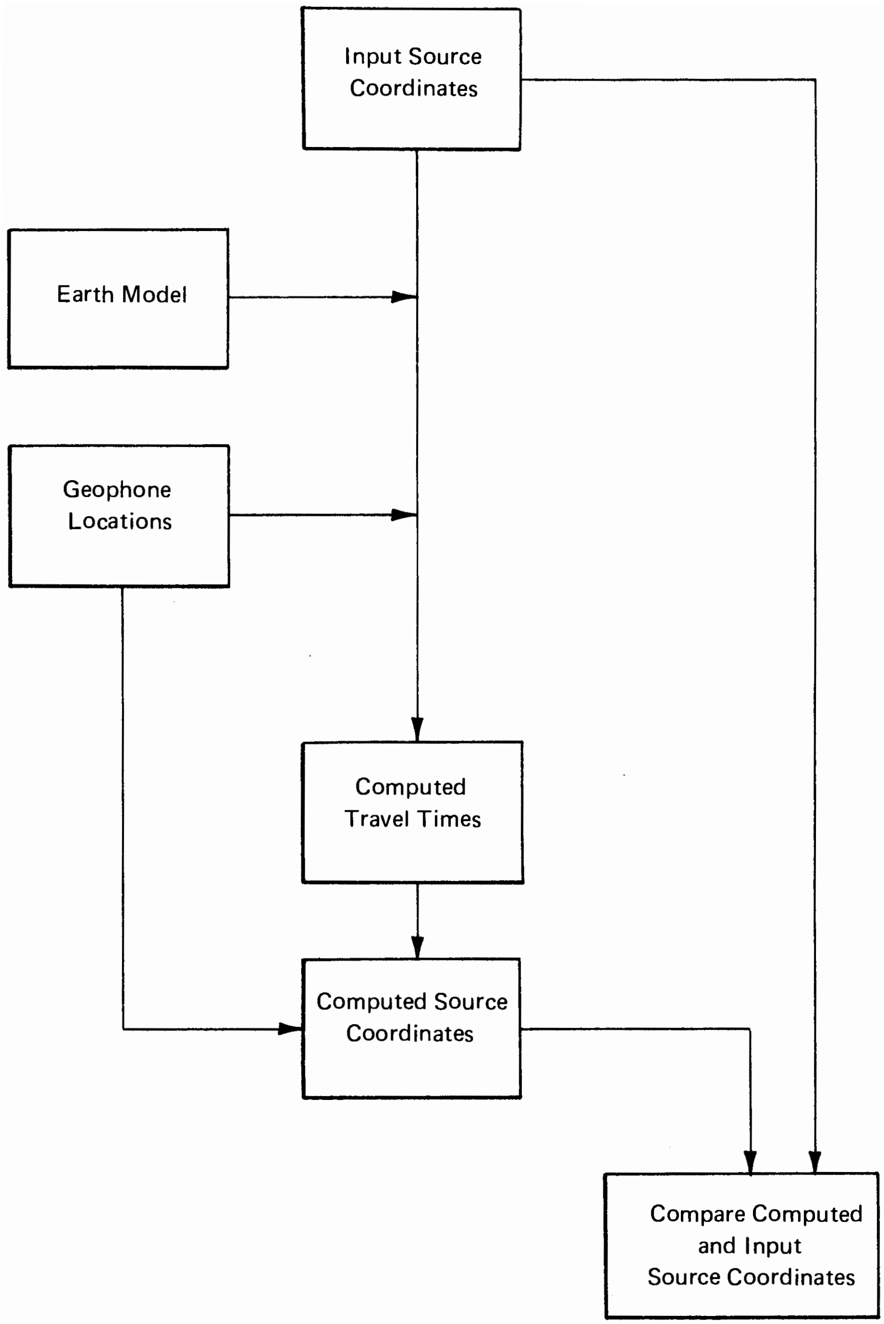
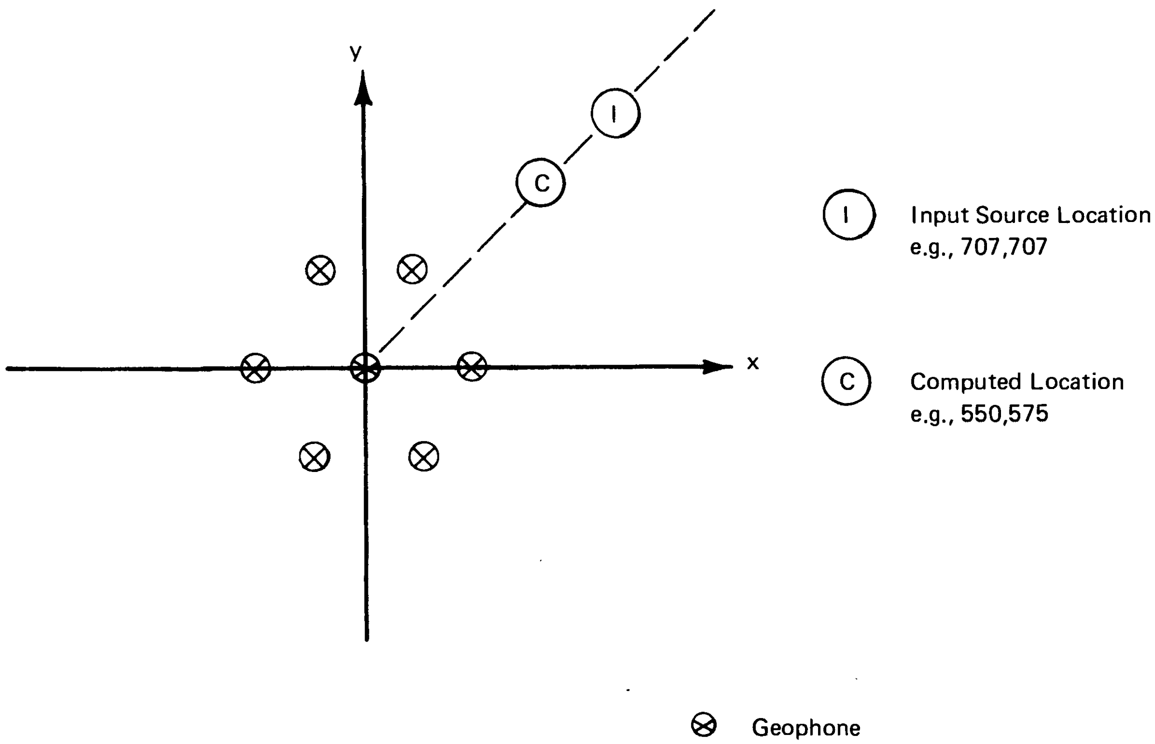


FIGURE 1 BLOCK DIAGRAM OF COMPARISON TEST



Note that:

1. The origin of the coordinate system is at the center of the array
2. The origins, I, and C are almost in a straight line
3. The distance from origin to I exceeds the distance from origin to C, so error is negative.

FIGURE 2 NOTATION USED IN ERROR GRAPH

Table 4

Error Data From "Miner" Location Program

Assumed Velocity = 10,000 Ft/Sec
True Depth = Assumed Depth = 700 Ft
D Refers to Error as Source Moved Along a Diagonal
X to Error as Source Moved Along X Axis
Y to Error as Source Moved Along Y Axis

a) Errors for 300 Feet Double Square Array

Source Distance (Feet) From Array Center	Error (Feet) in Computed Location		
	D	X	Y
2000	-1010	-354	-503
1400	154	-143	-123
1000	64	43	64
700	72	103	91
450	62	63	59
300	59	55	52
200	28	24	26
150	19	14	17
100	14	7	14
50	4	-2	-2
5	2	-7	-2

b) Errors for 400 Feet Hexagon Array

Source Distance (Feet) From Array Center	Error (Feet) in Computed Location		
	D	X	Y
2000	-373	-569	-532
1400	-106	-51	-124
1000	57	99	44
700	98	112	69
450	77	84	85
300	57	56	59
200	31	34	35
150	27	31	32
100	16	18	20
50	7	5	10
5	-5	-	-5

Table 4 (Continued)

Error Data From "Miner" Location Program

X Errors (Feet) for 3 Different Assumed Velocities
As Source Moved Along X-Axis
True Velocity Less than 8000 Ft/Sec
True Depth = Assumed Depth = 700 Ft

c) Effects of Assumed Velocity on Location Error for 150 Ft Double Square Array

Source Distance(Feet) From Array Center	Assumed Velocity in Ft/Sec		
	10,000	8,000	6,000
2000	-534	-1263	-1540
1400	-163	-713	-963
1000	-10	-407	-610
700	147	-143	-330
450	93	-55	-175
300	63	-31	-108
200	35	-21	-70
150	29	-12	-50
100	26	-3	-30
50	1	-13	-4
5	-5	-7	-8

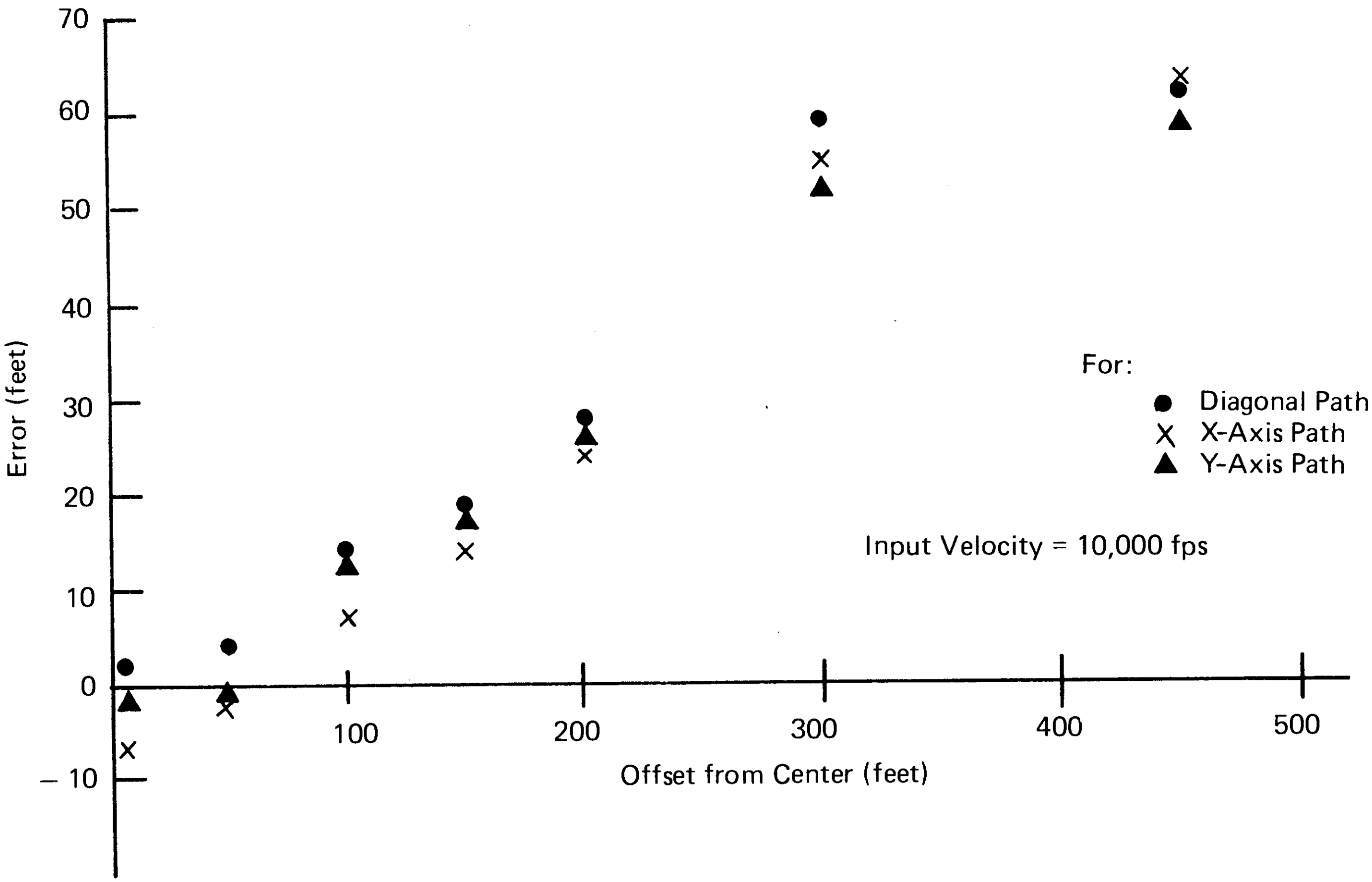


FIGURE 3 "MINER" LOCATION ERROR
300 FOOT DOUBLE SQUARE

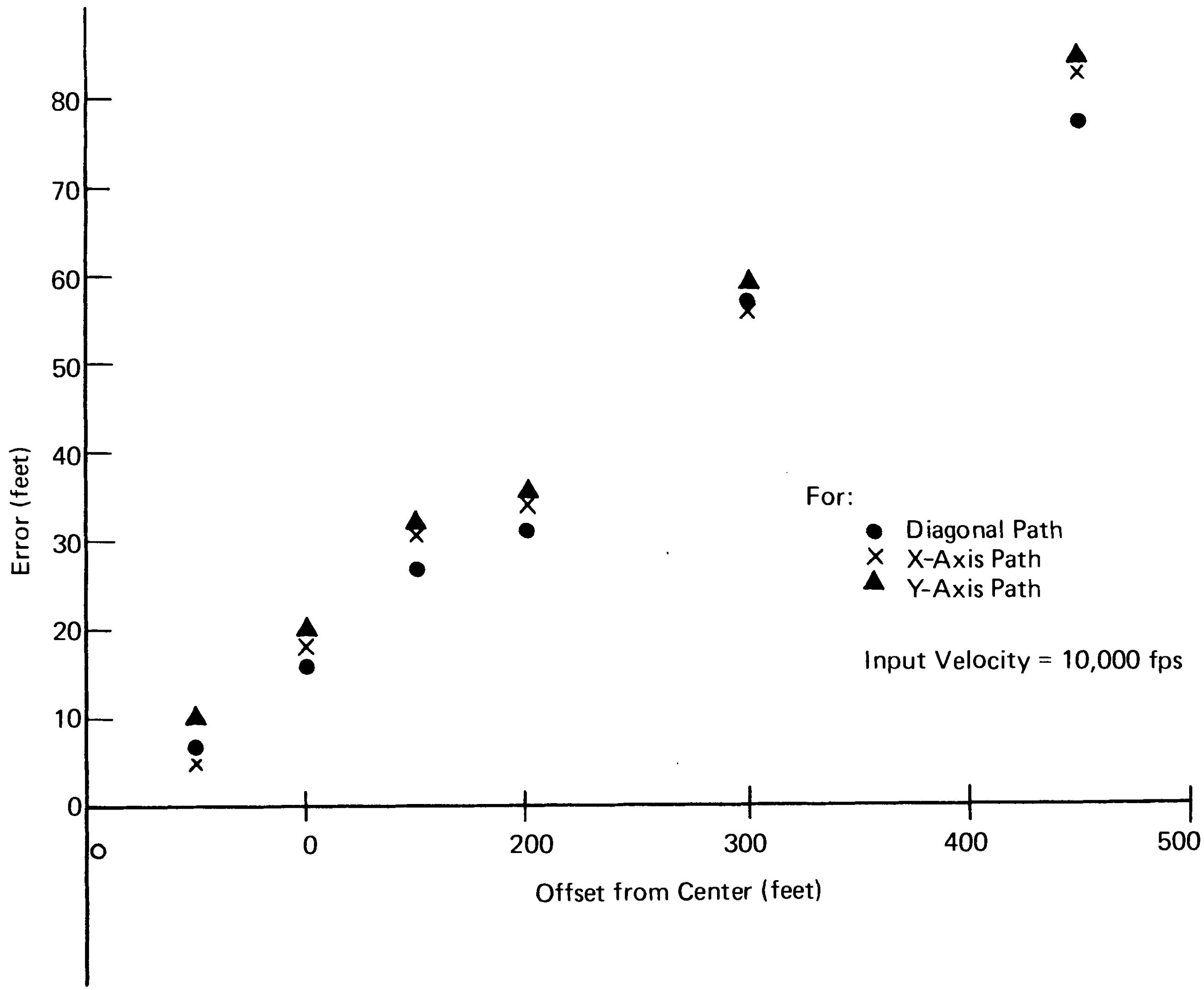


FIGURE 4 "MINER" LOCATION ERROR
400 FOOT HEXAGON

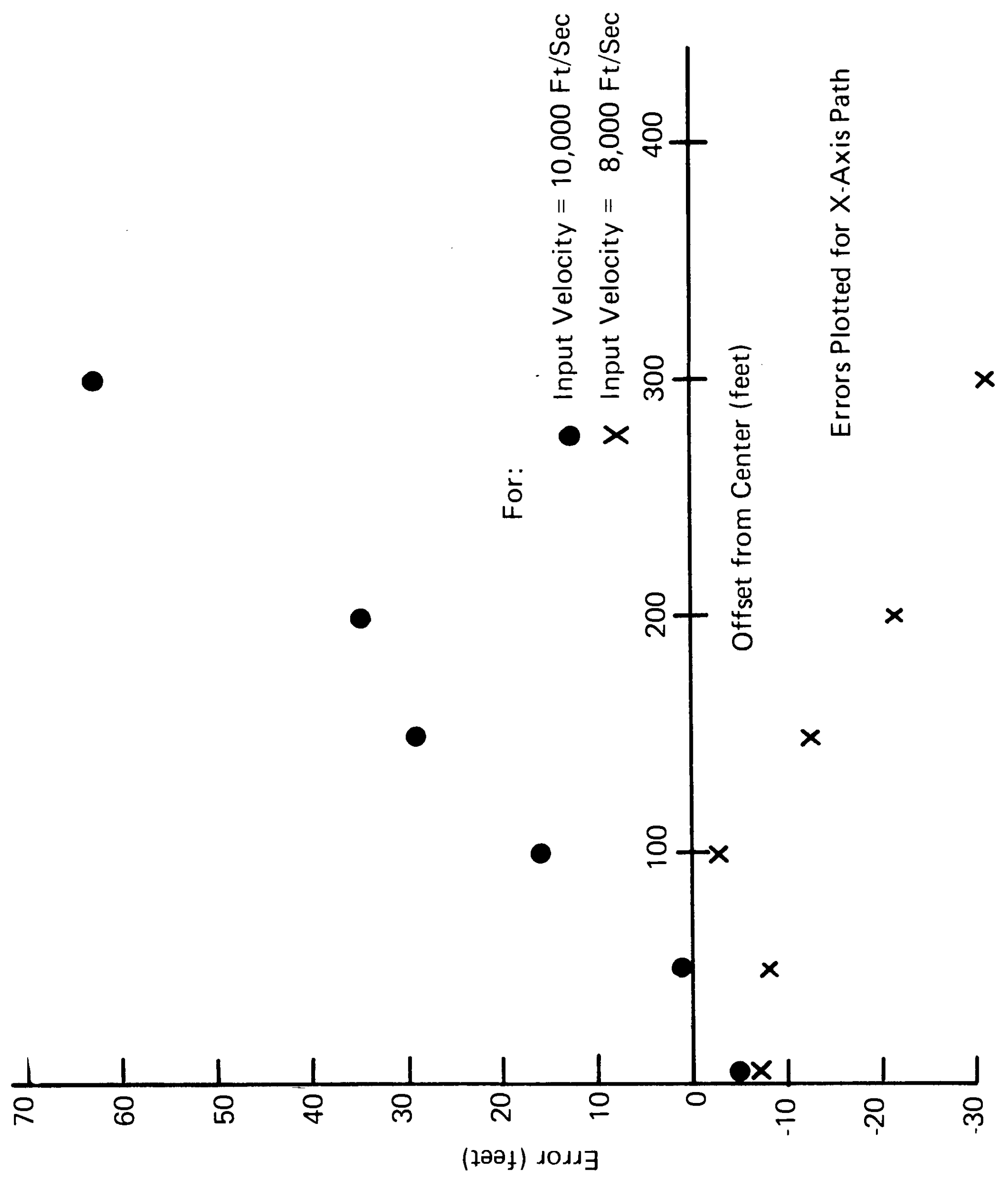


FIGURE 5 "MINER" LOCATION ERROR
150 FOOT DOUBLE SQUARE

PART FIVE

THE REFERENCE EVENT METHOD OF SEISMIC LOCATION FOR MINE RESCUE SYSTEMS

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PART FIVE

THE REFERENCE EVENT METHOD OF SEISMIC LOCATION FOR MINE RESCUE SYSTEMS

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I. SUMMARY

The location of trapped miners from their seismic signals will be inaccurate if we assume the P-wave propagation velocity is a constant. P-wave velocities are anything but constant in regions about mines, so some calibration is necessary to obtain more accurate seismic locations. The reference event method compares the time arrivals of signals generated by the miners with those previously recorded from a reference or calibration event in the vicinity of the miners. This method locates the miners' position relative to the calibration source. Hence, the location of the miners is absolute if the reference event position is known absolutely, usually from surveys and mine maps.

Advantages resulting from the system, besides greater accuracy, are locations independent of the velocity model assumed, the same solution from the full array and from any subset of four or more seismometers in the array (three if the miners' depth is known), fewer seismometers required, and no complex computers required for analysis.

VELA Uniform experience shows that the accuracy of locations of teleseismic explosions and earthquakes is improved by an order of magnitude over locations computed from average travel time curves.

Each calibration event is applicable only over a limited range. We recommend a field test of the method at a mine to measure its location accuracy, the range of effectiveness for each calibration event, the number of seismometers needed, and the number of reference events required per mine.

From these experiments we could decide whether the reference event method was useful and, if so, what form a practical rescue system would take.

II. INTRODUCTION

To date the seismic location system for locating miners trapped underground has been applied assuming a uniform isotropic earth. The use of this assumption leads to errors of one to several hundred feet in the seismic locations (Westinghouse 1972).* Under favorable conditions we should expect time reading errors on the order of one tenth of a cycle of the dominant signal period. With the 80 Hz to 100 Hz signals, the 1 to 2 millisecond time reading errors could account for mislocations on the order of 10 to 20 feet, assuming no errors in the earth model. Thus the errors experienced by Westinghouse can only be accounted for by the inappropriate velocity model of the geologic region around the mine.

If seismic locations to within less than a few hundred feet are to be attained, then one of two approaches must be followed. Either the geologic structure defining the velocity about the mine must be determined by a refraction survey or some other means, or reference events must be used to calibrate the P-wave travel times to pre-set seismometer locations. The purpose of this work is to develop the reference event theory and discuss its application for the mine rescue systems; refraction surveys and more sophisticated velocity models are discussed elsewhere in this report.

III. THEORY

The concept of the relative event approach is fairly simple. Since accounting for the variations in the velocity of propagation is necessary for accurate seismic locations, why not measure the signal delays from source to seismometers directly with a test event? Repeated sources from the same location will reproduce the same propagation delays. Moreover, sources only slightly displaced from the reference event location will nearly reproduce the same propagation delays. To compute the change in location of the new (unknown) event from that of the reference event, we can use any velocity model we wish since most of the path (and hence, most of the propagation delay) from source to seismometer almost duplicates that from the reference event. Thus by computing the small displacement accurately from the known test event, we can determine accurately the location of the unknown event.

* Westinghouse Contract H0210063 with Bureau of Mines.

In earthquake seismology the standard location method (Geiger 1910) minimizes the sum of the squares of the residuals between measured P-wave arrivals, t_i, and the calculated arrivals, F_i, based upon some velocity model

$$t_i - F_i(u) = e_i \qquad i = 1,2, \ldots, n. \tag{1*}$$

The calculated time, F_i, for a P-wave to travel from some particular event to the $i^{\underline{th}}$ seismometer is a function of the event coordinates, u, (actually $u_1 = x_o$, $u_2 = y_o$, $u_3 = z_o$, and $u_4 = t_o$) and the $i^{\underline{th}}$ seismometer coordinates x_i, y_i, z_i, as well as well as the P-wave velocity between the two.

$$F_i(u) = F_i \quad (x_o, y_o, z_o, t_o / x_i, y_i, z_i) \tag{2}$$

F_i is a non-linear function of the space and time coordinates of the seismometers and events. This is true even if the velocity is assumed to be uniform. Hence, the equations are easier to solve in a least squares sense if we expand F_i in a Taylor's series and neglect the higher order terms.

$$F(u) = F(u^*) + \frac{\partial F}{\partial u_1}(u_1 - u_1^*) + \frac{\partial F}{\partial u_2}(u_2 - u_2^*) + \frac{\partial F}{\partial u_3}(u_3 - u_3^*) + \frac{\partial F}{\partial u_4}(u_4 - u_4^*) + \ldots.. \tag{3}$$

The approximation is good when the new location, u, is in the vicinity of u* for which F(u*) is presumably known.

Now the equation (1) can be written as

$$\sum_{k=1}^{4} \frac{\partial F_i}{\partial u_k} (u_k - u_k^*) = t_i - F_i(u^*) = R_i \tag{4}$$

---

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

or in matrix form

$$B\ \delta = R \tag{5}$$

where B is the condition matrix

$$B = \begin{vmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \frac{\delta F_i}{\delta u_1} & \frac{\delta F_i}{\delta u_2} & \frac{\delta F_i}{\delta u_3} & \frac{\delta F_i}{\delta u_4} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{vmatrix} \tag{6}$$

δ is the displacement vector between a new (u), and our original (u*) source position.

$$\delta = \begin{vmatrix} u_1 - u_1^* \\ u_2 - u_2^* \\ u_3 - u_3^* \\ u_4 - u_4^* \end{vmatrix} \tag{7}$$

and R is the vector of residuals between the calculated and measured time arrivals, $t_i - F_i^* = e_i$.

The least squares solution of these equations is

$$\delta = (B'B)^{-1} B' R. \tag{8}$$

For the development of the method and its associated errors see Flinn (1965).

To apply the Geiger method we merely have to choose coordinates of an arbitrary event location, $u^* = (x_o^*, y_o^*, z_o^*, t_o^*)$, and perform the matrix multiplication iteratively until the solved-for-displacement vector, δ, goes to zero.

In the usual case the least squares solution still leaves us with residuals ($\Sigma_i\ R^2_i$) which are too large. Moreover the resulting location estimates from any of the n-1 or n-2 subsets of the seismometer network can be quite different than the location estimate of the full n-seismometer network. Consequently, weak sources and strong sources with identical locations are apt to be located apart from each other.

The situation is quite different if the first location estimate, ($u^* = x_o^*, y_o^*, z_o^*, t_o^*$) is from a calibration source in the vicinity of the unknown. In this case several advantages result:

1. The least square residuals are small.

2. The accuracy of the method is relatively independent of the velocity model we assume in the vicinity of the source.

3. Any subset of four or more seismometers in the network give a location as accurate as the full network. As a result weak event locations are frequently as accurate as those of strong events.

4. Fewer seismometers are needed in the network to yield accurate locations.

5. The waveforms at a particular seismometer from the calibration event and the unknown event often are quite similar to each other. Thus relative timing between the events is much easier since it is not limited to first motions but can make use of large dominant features later in the P-wave train.

6. Utilizing the reference event method a computer can identify which of n seismometers have had reading errors and by how much, as long as no more than a third of the seismometer readings are in error.

IV. VELA UNIFORM EXPERIENCE

For several years the VELA Uniform program has made use of the reference event method for locating teleseismic earthquakes and underground explosions. In a study using various networks from 4 to 13 stations, Chiburis 1968, compared the accuracy of teleseismic locations both with and without travel time corrections for 17 underground explosions at the Nevada Test Site. The stations ranged from 2000 to 9000 kilometers from the epicenter. Chiburis compared both the travel time residuals, which is the method we have described in the previous section, and travel time anomalies, which calibrates the difference in arrival times between pairs of seismometers using reference events. The accuracies of the travel time anomaly method and the travel time residual method are essentially the same. There are operational advantages to travel time anomalies, since the method is independent of the time origin of either the reference event or unknown event.

Figure 1 shows the location error in kilometers for 17 NTS explosions versus the number of recording stations both with and without travel time corrections. These results imply that the location accuracy is independent of the number of stations.

Figure 2 shows the location errors for NTS explosions versus the azimuth of the network. The network azimuth is measured as the widest angle drawn from the epicenter to all pairs of stations. Location accuracy improves as network azimuth increases both with and without travel time corrections. Similar data for Asian explosions and earthquakes in Figure 3 show the same trends. These experiments show that the reference event method improves locations by an order of magnitude over the uncalibrated least squares locations.

We can make an estimate of the ultimate accuracy attainable for relative locations of teleseismic earthquakes from the spectral considerations. For wide-aperture networks the timing accuracies of signal arrivals are approximately 0.1 second with the signal spectra peaked near 1.0 Hz.

From the timing error and velocity we have

$dt = 0.1$ seconds, expected timing inaccuracy.

$v = 15$ km/sec, apparent (average) P-wave velocity at earth's surface.

$du = v\ dt = 1.5$ km, expected location error.

Thus the 1-to 2-kilometer relative location accuracy achieved by the wide-aperture VELA networks as indicated in Figure 3 approaches the asymptotic limit of location accuracy we can expect.

V. FIELD METHODS FOR MINE RESCUE

We consider here three ways in which the influence of the earth may be accounted for in computing the location of trapped miners seismically: 1) the uniform velocity approach; 2) the refraction survey approach; and 3) the reference event approach. Each method may be applicable in different circumstances.

The first approach involves little sophistication in attempting to improve the seismic location accuracy. Upon detecting seismic signals from trapped miners, the approximate location of their source is computed assuming a uniform, isotropic earth. Then if the seismic array does not surround the

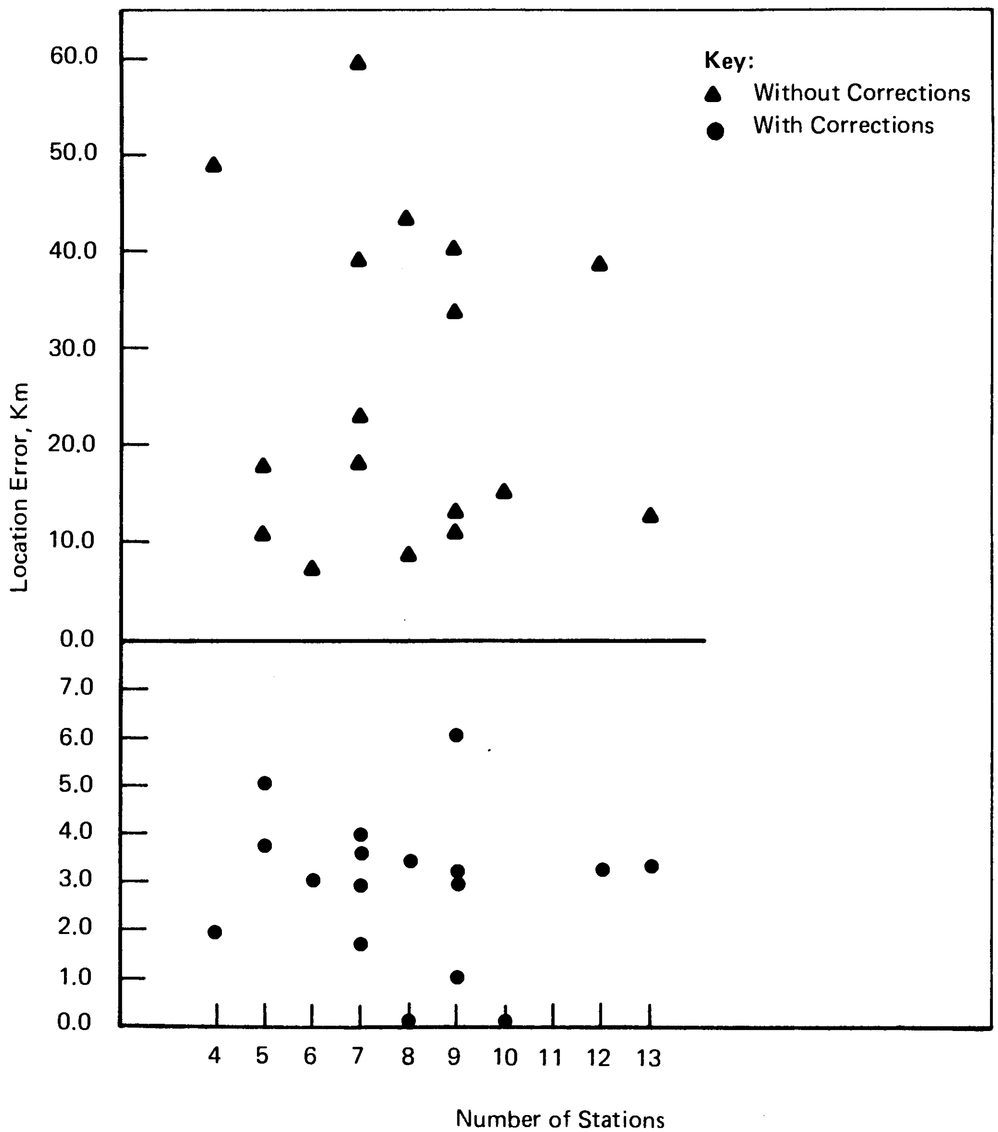

FIGURE 1 LOCATION ERROR VERSUS NUMBER OF RECORDING STATIONS

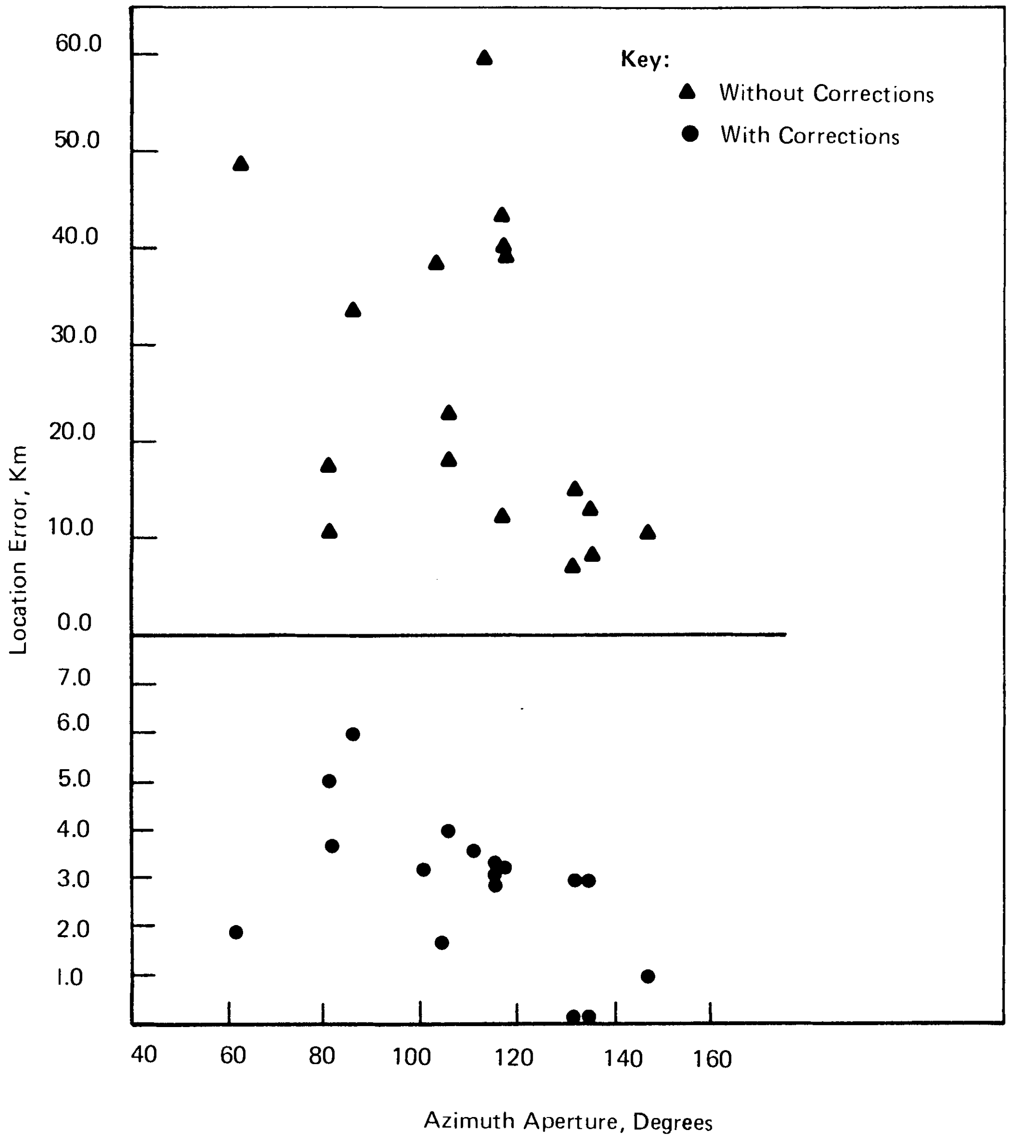

FIGURE 2 LOCATION ERROR VERSUS AZIMUTH APERTURE

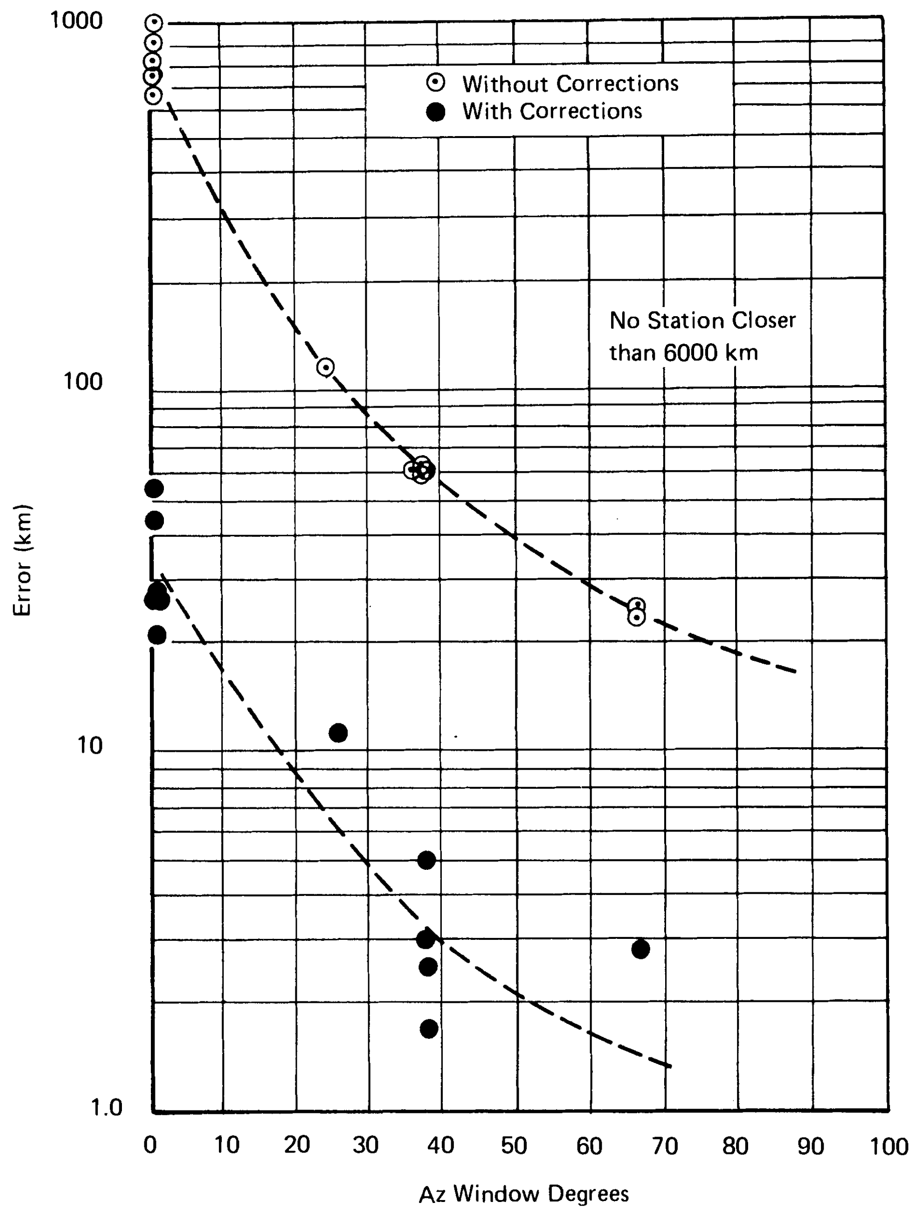

FIGURE 3 LOCATION ERROR VERSUS NETWORK AZIMUTH APERTURE

miners' position, or if the dimensions of the seismic array are too large, the seismometers may be redeployed in a smaller array surrounding the miners. Subsequent signals from the miners may then provide a more accurate location estimate. However, we would not place any confidence in the seismic location for positioning a drilling rig for a life-support hole. Rather the drilling rig location would be based only upon mine maps and companion surveys on the surface of the ground. Seismic locations would indicate approximate locations of trapped miners. In this way seismic location errors as large as 200 feet or more may be acceptable.

Advantages of this approach are that it is simple and that it requires no precalibration of the mine.

Disadvantages of this approach are that rescue operations may have to depend upon a more accurate seismic location and that there may not be time nor subsequent signals from the trapped miners to make redeployment of the seismometers practical.

The second approach is to calibrate the geology surrounding the mine with a refraction survey. Then the uniform isotropic earth assumption is discarded for a more realistic model. Powell (1972) illustrated the magnitude of location errors arising when a uniform velocity was used instead of the true structure in a few three-layer models. In optimum cases we may improve the location accuracy by an order of magnitude, but perhaps somewhat less in practice. The reason is that, although the refraction survey may describe the first order variations in the seismic velocities about the mine, it may not be detailed enough to measure the secondary features (velocity anomalies, faults, fractures, etc.) in the vicinity of the seismometers. These secondary variations in geology may cause the test array of seismometers to behave differently than the array deployed in an emergency.

There are trade-offs to be considered in this situation, in terms of the complexity of the velocity model envisaged and the extent and analysis of the refraction survey required. The size of the uncertainties remaining in coal mining environments will have to be resolved by experiment. If the refraction survey is carried out at the mine following a disaster rather than in a pre-calibration exercise, the importance of having trained, experienced personnel to perform it cannot be underestimated. For the interpretation of the data, they will require at least a general knowledge of the geological structure of the region. In principle, it is also possible to improve the location accuracy by iterating the velocity model as a result of a preliminary location; the improvements obtainable with this approach remain to be determined.

Advantages of approaches relying on calibrated geology are that a reduction of the expected seismic location errors by factors of 2 to 5 may provide sufficient accuracy for positioning a drilling rig in the most favorable circumstances or at least allow a miner to be located to within a dimension of a pillar. However, several actual or potential disadvantages still remain. The locations may still be inaccurate but the inaccuracies unknown. The proper velocity model may be applied inaccurately, perhaps due to the lack of trained personnel, during an actual emergency. Finally, the emplacement of seismometers during the refraction survey may be sufficiently different from those used during the location procedure, that the velocity model may not apply well enough to the location array.

The third approach is the reference event method which requires a seismic array permanently installed (or seismometer positions chosen in advance of disasters) and pre-di· aster calibration of the mine with seismic signals from different parts of the mine.

Advantages of this approach include improved location accuracy by at least an order of magnitude over uniform velocity models, elimination of the need of refraction surveys, and no fancy data processing techniques.

Disadvantages of the method include the need for precalibration of the mine, permanently installed seismometers (or permanently assigned seismometer locations), and perhaps more calibration signals than we might wish, especially as the mine dimensions increase.

The density of calibration signals required, the number and placement of seismometers, and the costs of the method are questions to be resolved by experiment.

Several designs of the seismic location system utilizing the reference event approach are possible. One is to install seismometers, cables and recording instruments permanently around the mine. Fire drills (test seismic signals) are taken periodically from different parts of the mine as the mine dimensions expand. These recordings, clearly labeled as to source location, can be reproduced on clear plastic overlays for easy comparison with signals recorded during an emergency. In this way good seismometer locations would be assured (buried for improved signal-to-noise ratio) and the equipment would demonstrate its reliability as calibration (reference) events were recorded about the mine. Signals could be read and approximate locations determined by analysts without the need for a computer. With or without a computer, mine personnel could acquire training in operating the system as calibration data were collected.

A second design would be to locate test seismic sources (small explosives or weight drops) throughout the mine which can be triggered from the surface. When a seismometer array has been deployed during an emergency, and an approximate location of trapped miners determined from their signals assuming a uniform velocity model, then test seismic sources would be set off in that section of the mine. The signals from the miners and those from several test sources would be compared. Then the relative location of the trapped miners would be determined from the test signals which most closely matched those generated by the miners.

The characteristics of the three types of systems, utilizing the uniform velocity, the refraction survey, and the reference event methods, are summarized in Table 1.

VI. FIELD EXPERIMENT

The reference event method should be tested by a controlled experiment at a mine. The Westinghouse data taken to date do not provide data from a multitude of close to widely spaced sources received by a fixed seismometer array. The objectives of such an experiment will be (1) to demonstrate whether the relative event method, which has been so successful for locating teleseismic earthquakes, can also be applied to seismic sources in mines, and (2) to determine the calibration range of applicability of the reference events.

The field experiment should comprise from 10 to 15 well-placed seismometers. These sensors should be buried below the weathering layer in drill holes if necessary. Every effort should be made to attain good signal sensitivity on single sensors so array summations are not necessary. Different

TABLE 1

SEISMIC LOCATION METHODS

1. Uniform Velocity Method

Features:	Installation	- after disaster is reported
	Precalibration	- none
	Location Accuracy	- several hundred feet
	Drill Locations By	- mine maps for precise placement, seismic locations indicate section of mine.

Advantages:
Simple
No precalibration
No capital outlay prior to disaster
Minimum training of mine personnel required

Disadvantages:
Seismic locations can indicate only general area of miner
Deployment of extra seismometers after first signals detected may be desirable

2. Refraction Survey Method

Features:	Installation	- after disaster is reported
	Calibration	- refraction survey to model velocity structure around mine
	Location Accuracy	- will vary on complexity of geology and thoroughness of refraction survey; probably to within 100 feet
	Drill Location By	- mine maps for precise placement, seismic locations narrow search.

Advantages:
More accurate locations than uniform velocity model

Disadvantages:
Location accuracy may be unknown
Velocity model may be incorrectly applied in an emergency
Calibration required

3. Reference Event Method

Features:	Installation	- predisaster; permanent
	Precalibration	- tests made throughout mine as mine dimensions expand
	Location Accuracy	- 10 to 50 feet with high confidence
	Drill Locations By	- mine maps and seismic locations jointly

TABLE 1 - Continued

3. Reference Event Method - Continued

Advantages:	Accurate locations No refraction surveys required Data processing required fairly simple System in place when emergency arises Mine personnel familiar with system from mine Calibration tests
Disadvantages:	Predisaster mine installation, tests, and costs Necessary system tests required as mine dimensions expand Some mine personnel must be trained on system

types of sources should be used (e.g., timber on mine floor, sledge on roof bolts) at each source location so the method can be demonstrated with reference and unknown events of the same and different types. Minimum source displacements may be on the order of 25 to 50 feet. Maximum source displacements should be 1000 feet or more if possible. Different sections of the mine should be tested including ones for which the seismometer array surrounds the event location (360^{o} aperture) and ones for smaller apertures. One value of having a sufficient number of seismometers is that partial arrays (but more than 3 or 4 sensors) with varying apertures can be compared with the full array.

Costs of running seismic exploration crews within the United States average between $30,000 and $50,000 per month including costs for dynamite and drilling shot holes. Although we propose to use 10 to 15 sensors all in bore holes, the holes will not be deep (average depth 50 feet) so drilling costs for the mine tests should not exceed those of a normal exploration crew. The cables, sensors, and instruments required would be available or easily obtainable by an exploration crew. Hence, a geophysical service company should be able to conduct a field test of the relative event method for $1,000 to $2,000 per day and complete it within two to four weeks.

As a result of this experiment we should be able to indicate:

1) whether the reference event method works in mines,
2) over what range a reference event is applicable,
3) the source location accuracy of the method,
4) the number of reference events needed per mine,
5) the minimum number and placement of sensors required in a workable field system,
6) the analysis procedures to be followed, and
7) an estimate of the capital and operational (emergency, calibration, and testing) costs in a practical field system.

VII. CONCLUSIONS

1. We have considered two alternative seismic approaches to improve the accuracy of seismic locations for miners trapped underground over methods which assume a uniform P-wave velocity in the earth. The first approach uses seismic measurements, such as a refraction survey, to calibrate the velocity

structure about the mine. The second approach calibrates the source-to-seismometer travel paths with reference events at known locations in the mine.

2. The method yielding the most accurate seismic locations is the reference event method. When the displacement between the unknown and reference events is small, the location accuracy will be limited only by the timing accuracy of the signals.

3. The reference event method provides absolute rather than merely relative location accuracy since calibrations are tied to surveyed (non-seismic) locations. Methods based upon purely seismic measurements may provide accurate relative locations (small least squares error) but still contain absolute biases (lateral shifts between true and calculated locations).

4. The reference event method has the disadvantages of requiring calibration events, permanently installed seismometers or prelocated calibration sources triggered from above ground, and several reference events per mine for complete calibration.

5. A field installation utilizing the method has several operational advantages. As well as accuracy, these include readiness in the event of a disaster, fire-drill testing of the system by calibration events, familiarity with the system on the part of mine personnel, and no complex computers or analysis required.

6. We recommend field tests to verify the method. Key questions to be answered include the range of effectiveness of each reference event and the number of reference events required to completely calibrate a mine.

7. A field test could be conducted at a mine over a period of two to four weeks for costs not exceeding those incurred by Westinghouse in previous seismic experiments at a mine. Total costs should be in the $25,000 to $50,000 range, or less.

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PART SIX

FIELD UTILIZATION OF SEISMIC SYSTEMS

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FIELD UTILIZATION OF SEISMIC SYSTEMS

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PART SIX

FIELD UTILIZATION OF SEISMIC SYSTEMS

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I. SUMMARY

Proper design characteristics for a seismic system to locate miners during a mine disaster are considered in terms of a total system concept. Field hardware, processing equipment, operating personnel, deployment, training, and supportive R and D are necessary elements of the total system. Each of these elements is discussed and an indication given as to the requirements necessitated by each one.

Hardware must be portable, rugged, and fieldworthy. Processing equipment must be simple to operate, expandable for future processing improvements, and ruggedized for field use. A small well-trained team must be available for quick response in times of emergency. Alternative deployment procedures are necessary to allow for a variety of situations including both ground and air delivery. Supportive R and D is used to support training and upgrading of the system.

II. INTRODUCTION

Here we discuss a set of design characteristics that would result in an improved seismic system for miner location following a mine accident. The system, when implemented as proposed, will be an adaptable multi-purpose seismological array packaged in hand-portable sized containers for use under severe field conditions. The system will be capable of monitoring up to 12 individual sensors, recording on magnetic tape, providing visual displays, and accomplishing some data processing and analysis.

In selecting individual items, great emphasis should be placed on the use of equipment which has been design tested and proven under operational field conditions. Special design modifications should be used only as required to meet special needs of remote and severe field operations; for example, the use of modular-type moisture-proof-container packaging for seismometers and field amplifiers.

In order to specify the design of this equipment, it is necessary to assume the following:

1. Optimum location accuracy requires calibrated and timed signals.
2. Power may not be obtainable at the various remote locations where the system will be deployed.
3. Measurements will be made under field conditions where electronic test and repair facilities are not readily available.
4. Emergency conditions will exist at the time of deployment and quick response is absolutely essential.
5. Personnel making the measurements must be able to evaluate the data within a short length of time.
6. The system should be expandable to meet future requirements of improved analysis.
7. Maximum use of off-the-shelf components.

To operate under these assumptions, the system should have the following features:

- The basic system should contain an accurate calibrating device. The calibrator should apply an impulse of known polarity to verify seismometer polarity, and sine waves of known amplitude at any desired frequency to the seismometer calibration coil to obtain a frequency response at a known gain.

- The sensing system should be a vertical seismometer-amplifier combination capable of direct burial. The seismic signals would be fed to a recording and processing system powered by the same source powering the amplifier.
- Monitoring and field analysis will require a playback unit capable of producing the data at either .5mm/ms or 1.0mm/ms on a paper strip recorder. A monitoring oscilloscope should also be provided.
- The tape recorder should be able to record up to 12 channels of data plus time and compensation channels. A time code should be encoded on the tape. Additional design provisions should be made for inserting operational amplifiers, modules, attenuators, and filters as desired.
- The whole system should be as compact and lightweight as possible, and sufficiently rugged to withstand transport under the worst field conditions. Simplicity, mobility, ruggedness, and ease of setup and operation are prime design goals.

III. REQUIREMENTS

To minimize the interference of nearby cultural (man-made) and weather-induced noise, seismic surveys usually employ either seismometer burial or small array techniques. In the mine disaster case, the rescue team will often be hampered by the absence of favorable surface geology at the points where the particular deployment must be made. Of the two possible techniques, seismometer burial appears to be the simpler solution. A seismometer capable of operating at shallow depth will enable the rescue team to pick any desired point for measurement and then drill (possibly with a hand auger) until reaching some suitable foundation materials. Even at the shallow depths reached by hand drilling, the seismometer should have a considerably reduced response (compared to a surface site) to locally induced cultural noise (seismic and acoustic). In addition, if relatively solid foundation material can be reached, some signal attenuation may be avoided.

In many situations, the simplest, most direct method to determine a location will be for the operator analyst to read relative signal arrivals from the individual array elements. Being able to record such signals from each element of the array on an identical, selectable time basis will greatly improve the operator's response time and the precision of the location. The sought-after objective is the ability to record under <u>any</u> field conditions with a completely independent portable system capable of highly accurate, dependable results.

<u>It is proposed that both the seismometer and amplifier be packaged in the same case.</u> This will result in a single, easily transportable instrument package that can be placed in a constant environment away from molestation.

The time encoder should be a highly accurate digital device capable of providing several different frequency standards in order to broaden the overall capability of the system. Of particular importance is a 100-Hz signal on the compensation trace. This frequency is then used as a reference to obtain an accurate time-based playout in high speed visual reproductions.

A properly equipped field analysis and processing center is essential if rapid response and adaptability are to be provided to what will surely be a fluid situation. During the course of a location attempt, it will frequently be necessary to make judgments regarding seismometer emplacement and coupling, noise characteristics in the area, transmission quality, and signal reception. Thus, it may be necessary to vary bandpass filters and apply other processing techniques. For this reason, inclusion of a playback unit in addition to a monitoring oscilloscope is necessary.

The package for the filters, attenuators, and operational amplifiers should be designed with plug-in cards to provide for rapid changes in the data circuits.

Power will be provided by public power facilities when available; however, battery backup should be provided to maintain system operation if the primary power source fails or if a primary source is not used. The battery pack should have sufficient capacity to maintain operation for at least twelve hours. A battery charger should be included to recharge a fully discharged battery bank within two hours.

All interconnecting cables should be prefabricated. Connections should be waterproof and should be designed so that improper connections cannot be made. System cabling should be designed for maximum portability.

Sufficient accessory items like hand tools, test equipment, and spare parts should be carried to and from the field by operating personnel. The accessory kit would possibly include its own power supply so that the operation of this equipment would not use power from the principal source.

A well-coordinated field exercise is impossible without reliable communications. This factor is paramount where time is a critical factor during an emergency. To meet this need, special radio communications can be provided as part of the total system to assure efficient operation of the crew.

Major attributes of a field system which have to be emphasized are ruggedness, simplicity, portability, and reliability. While there need not be a one-to-one correspondence, useful guidelines for the criteria to be placed on a field system can be obtained from Military Specifications for field equipment. The cost of a field system is likely to be on the order of $100,000.

The crew required to operate the seismic detection and location equipment must be considered a part of the total system. As much care and attention must be given to the selection and training of the team as to the design and construction of the equipment.

IV. OPERATIONAL PERSONNEL

To successfully perform under emergency conditions, the seismic detection and location equipment (SDLE) must be manned by a team trained and experienced with its deployment and use. As a minimum requirement, a three-man cadre trained to work together who are completely familiar with all phases of the equipment and its operation should be available to deploy the SDLE in the event of an emergency. Additional men needed to expedite the setup and calibration of the equipment could be provided by the mine company involved in the disaster.

The three-man cadre would consist of the following:

- An operator/analyst (team chief)
- An electronic technician (second in command)
- A field technician

The team chief should be a geophysical engineer or someone with an equivalent background whose responsibility includes interfacing with the disaster/rescuer coordinators (mining and/or Government officials), deploying the SDLE, and making final processing and location decisions. He should be a mature individual who is thoroughly familiar with mining operations and practices. The overall success of the mission will depend on his ability to preserve the integrity of the whole team and to direct its operation in a confused situation.

The electronic technician should be qualified and trained to set up and operate the entire field system. He must be able to troubleshoot and repair most system electrical and mechanical malfunctions or failures. In the absence of the team chief, he will substitute as data analyst.

The field technician should be experienced in geophysical field work and capable of directing the efforts of temporary field workers acquired on site. He must be familiar with the use of hand portable and light drilling equipment. His principal responsibility will be to install the seismometers, lay cables, and assist in setting up the analysis center.

Training and practical experience in the use of the seismic equipment are the keys to successful field operations under emergency conditions. Selected personnel should be trained to operate as a team and, as such, be deployed on "operational" missions several times a year. As many of the pressures associated with a real disaster as possible should be simulated during these training excercises.

V. DEPLOYMENT OF SYSTEM

Transportation from the staging area to the field presents special problems. Emergencies may occur at any time and in the most remote areas. Several different contingency plans are necessary to meet the demand for rapid deployment. For use near the staging areas, a suitable four-wheel-drive truck should be available. The truck should be outfitted with appropriate racks and accessory gear such that the field equipment could be installed within one-half hour and dispatched to the field. In addition, the field equipment should be so packaged that it could also be hand portable or cart portable for air movement by either commercial or private aircraft. Consideration should be given to the use of contract or military helicopter for direct delivery to the field site. On delivery to the field, a truck might be made available or the packing crates used to form the analysis center enclosure.

VI. SUPPORTIVE R AND D

Field R and D should serve two purposes. Each R and D field trip could start as a training exercise to improve the performance of the team and to expose areas of weakness or deficiency in the operating procedures. The second objective would be to test a new procedure or possibly gather data to evaluate some point of theory. Certain ideas suggested elsewhere in this report need clarification and evaluation. For example, more data are needed to estimate the calibration range and absolute location accuracy associated with the reference event technique, signal attenuation through various media, calibrated noise measurement for optimization of signal passband, and efficiency of signal generators.

PART SEVEN

THEORETICAL SEISMIC SIGNAL SOURCE
AND TRANSMISSION CHARACTERISTICS

PART SEVEN

THEORETICAL SEISMIC SIGNAL SOURCE AND TRANSMISSION CHARACTERISTICS

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PART SEVEN

THEORETICAL SEISMIC SIGNAL SOURCE AND TRANSMISSION CHARACTERISTICS

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I. SUMMARY

The miner's seismic source strength can be approximately estimated on the basis of a single force acting in an infinite medium. Because of the uncertainty involved in estimating the amount of conversion from mechanical energy to seismic energy, the source strength thus estimated may be in error by as much as a half-order of magnitude. Calculations of wave transmission must take into account geometrical spreading, dissipation of energy by internal friction, and energy partition due to reflection and refraction of waves impinging on interfaces in the layered earth.

Theoretically derived peak-to-peak particle velocities in microinches per second (μIPS) are given for two models; viz: (i) 50-feet thick and (ii) 100-feet thick 4000 ft/sec layers with $Q = 20$, overlying a half-space of 10,000 ft/sec material with $Q = 50$;for the cases of a hammer blow and a timber impact, at the frequencies of 50 Hz and 100 Hz. Comparison of the theoretically derived peak-to-peak particle velocity with experimental data taken at the Copper Queen Mine indicates that the theoretical particle velocity may be overestimated.

A discussion of the distortion of seismic wavefronts by mine tunnels indicates that it is unfavorable to use a seismic source impact on the floor of the tunnel, since deceptive delays in arrival time are liable to occur at the surface.

A program of parallel theoretical and experimental work is required to clarify uncertainties still associated with the nature and strength of the miner's seismic source signal which cannot be resolved within the approximations of this work. Its major components include theoretical investigations of the

(1) Wave diffraction and scattering of an impact source on a face of a cylindrical cavity.

(2) Impact of an elastic object on an elastic medium.

Experimental measurements of the signal spectrum under carefully controlled conditions are also necessary in order that the frequency spectrum of the source be determined accurately; it is virtually impossible to determine the source strength near or at the source since the problem of the efficiency of conversion of mechanical to seismic energy is extremely difficult to handle.

For the initial detection of a surviving miner in a disaster struck mine, a "low-frequency" source of considerable strength is desired. It is proposed that experimental efforts be devoted to the development and test of such a source, in conjunction with the concept of a coupler to enhance the conversion of mechanical energy into seismic energy.

II. INTRODUCTION

The thrust of this work is confined to the surface seismic detection and location of trapped miners in a coal mine. It is imperative that the procedure of locating trapped miners be as unsophisticated to operate as is feasible; the final system should ideally be as close to a "push button" type as possible.

The investigation of the problem of the detection and location of a trapped miner starts from the following initial conditions:

(i) A relatively weak but high-frequency seismic source

(ii) Seismic-wave transmission in an inhomogeneous medium generally capped by an extremely lossy weathering layer of variable thickness.

(iii) Relatively high background noise in the frequency band of the signal.

(iv) Limitations in the resolution of currently employed seismic methods in both the time and frequency domain.

The following analysis is designed to shed light on items (i) and (ii).

The results obtained in this investigation of seismic sources are consistent with being able to detect miners at ranges up to on the order of 1000 feet, and to measure arrival times to within a few milliseconds. Hence under the most favorable signal-to-noise and geological conditions, it is conceivable (see Appendix B) that the location of a miner to within 30 feet should be achieved by seismic means, and a reasonable expectation in a range of situations would be location accuracies to within 100 feet.

III. SOURCE STRENGTH AND SOURCE SPECTRUM

It is reasonably certain that the miner detection and location system has to depend predominantly upon the compressional wave, certainly for location purposes, as neither shear waves nor surface waves offer the necessary resolving power. Suppose that a hammer blow (or a timber impact) on the roof, rib or floor in a given mine can be approximated by a single force in an infinite medium. Such an approximation is only good for estimating the order of magnitude of the source strength. More precise estimates demand a rigorous theoretical treatment of the problem. Neglecting the distortion of the wave front, due to a system of cavities, which will be discussed in a later section, the radial component of the particle displacement for near-field, as shown by White (1965), is given by

$$u_r = \frac{G \cos \phi}{4\pi\rho r} \left[\frac{1}{V^2} g(t-\frac{r}{V}) + \frac{2}{rV} g^{I}(t-\frac{r}{V}) + \frac{2}{r^2} g^{II}(t-\frac{r}{V})\right] \qquad (1)^*$$

where G is the magnitude of the force, ρ is the density of the medium, V is the compressional wave velocity, and ϕ is the angle between the source and the point of observation with respect to the vertical.

Fortunately, for the present application of Equation (1) to the seismic detection and location of a miner, the distance from the source to the observation point is generally large, in the order of at least several wavelengths, e.g., a frequency of 75 Hz and a velocity of 8000 ft/sec corresponds to a wavelength of 106 feet, whereas the observation point is typically located at least 400 feet away from the source. From that point of view, the first term in the right-hand side of Equation (1) is predominant, as the second and third terms decay very rapidly at large distances. However, the efficiency of the conversion of the mechanical energy into seismic energy at the immediate point of impact is extremely difficult to estimate accurately, as an appreciable amount of energy is dissipated at the point of impact due to fracture and plastic deformation of the rock.

For a crude estimate of the particle displacement at an observation point located sufficiently far away from the source, Equation (1) may be written as

$$u_r \approx \frac{G \cos \phi}{4\pi\rho V^2 r} g\ (t-\frac{r}{V}) + 0(\frac{1}{r^2}) \qquad (1a)$$

which is also used by Westinghouse (see Westinghouse Final Report (1971),† Volume II, p. 78-83). It is possible to extrapolate the particle displacement back to the source in a half-theoretical and half-empirical fashion to obtain values for the source strength and frequency characteristics.

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

† Westinghouse Contract H0101262 with Bureau of Mines.

Introducing the dissipation of energy by internal friction, Equation (1a) may then be written as

$$u_r \approx \frac{G \cos \phi}{4\pi\rho V^2 r} g(t- \frac{r}{V}) e^{-\alpha r} + 0(\frac{1}{r^2}) \tag{1b}$$

where α is the dissipation coefficient. The radial component of the particle velocity can then be obtained by differentiating Equation (1b), neglecting the terms higher than $1/r^2$.

$$\dot{u}_r \approx \frac{G \cos \phi}{4\pi\rho V^2 r} \dot{g}(t- \frac{r}{V}) e^{-\alpha r} \tag{2}$$

There is a factor of two increase in the displacement if the detection of the motion is made on the surface of a half-space. In addition, the vertical displacement usually detected is a component of the radial particle displacement so that equation (2) should be multiplied by a factor of 2 $\cos\phi$.

Instead of letting the force be of the form

$$g(t) = e^{-t/\tau} \tag{3}$$

as used by Westinghouse, a closer representation of the real source, as recorded through the Westinghouse seismic system, may be given by

$$g(t) = e^{-at} \sin bt. \tag{4}$$

The force function g(t) has the form shown in Figure 1. The integral of the force from a hammer blow or a timber impact is equal to an approximation of an impact of very short duration for the case of an inelastic collision, I, such that

$$I = \int_0^\infty G g(t)\, dt = Mv \tag{5}$$

where M is the mass of the impact object and v is the impact velocity.

Substituting g(t) from Equation (4) into (5) and solving for G, we have

$$G = Mv\left(\frac{a^2 + b^2}{b}\right) \tag{6}$$

The Fourier Transform of Equation (4) thus gives the spectrum for the impact (a hammer or timber upon the roof, rib or floor) as follows

$$\begin{aligned} G(i\omega) &= \int_0^\infty e^{-at} \sin bt\, e^{-i\omega t}\, dt \\ &= \frac{b(a^2+b^2-\omega^2-2i\omega a)}{(a^2+b^2-\omega^2)^2 + 4\omega^2 a^2} \end{aligned} \tag{7}$$

Assuming that $a = \frac{b}{n}$ where n is either an integer or a non-integer, equations (6) and (7) become, respectively

$$G = \frac{Mv\ (n^2 = 1)\ b}{n^2} \tag{6a}$$

and

$$G(i\omega) = \frac{n^2(1+n^2-\Omega^2 - 2i\Omega)}{b[(1+n^2-\Omega^2)^2 + 4\Omega^2]} \tag{7a}$$

where $\Omega = \frac{n\omega}{b}$.

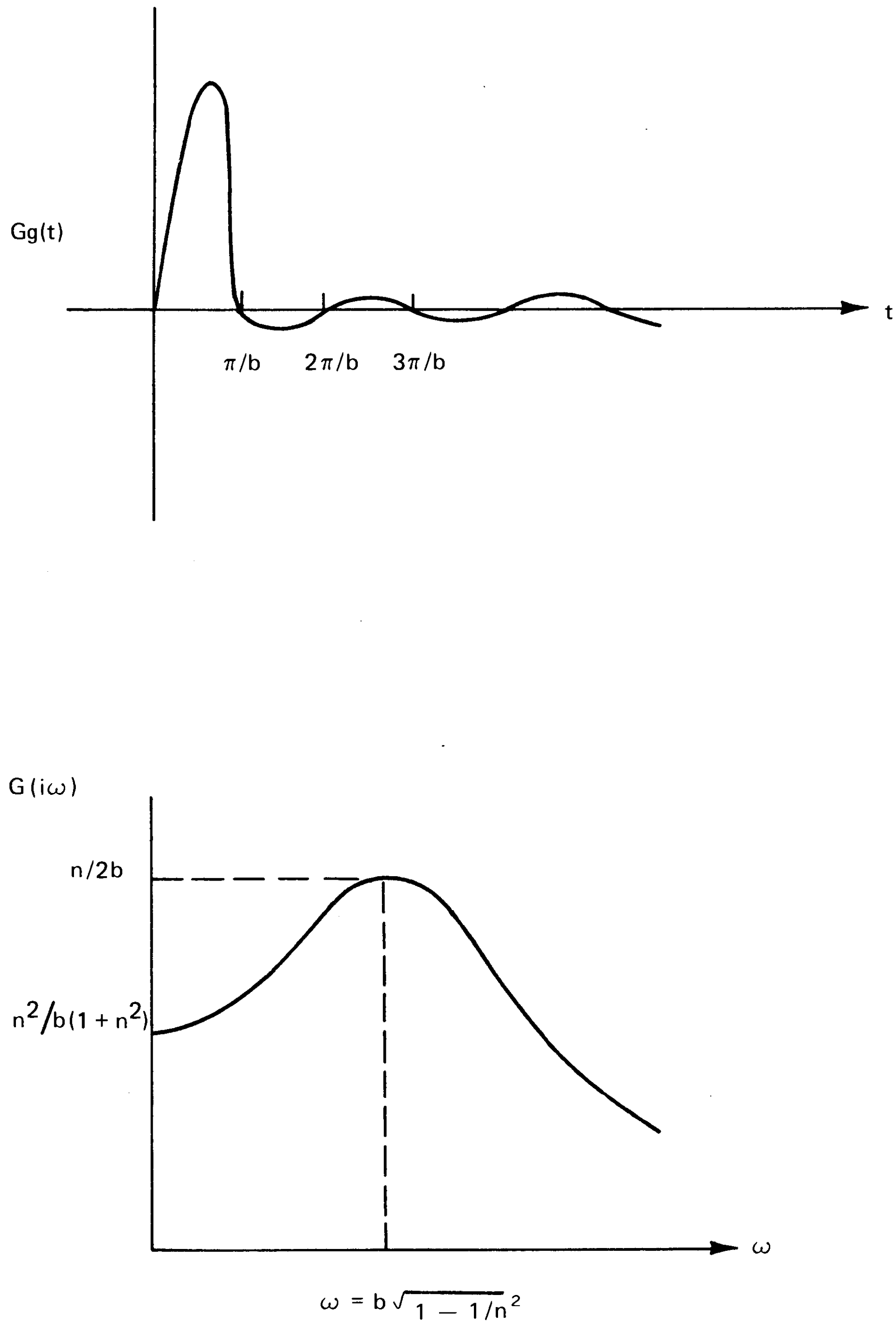


FIGURE 1 THE FORCE FUNCTION AND THE FOURIER TRANSFORM

It follows that

$$|G(i\omega)| = b\ \{[b^2(\frac{1}{n^2} + 1)-\omega^2]^2 + \frac{4b^2\omega^2}{n^2}\}^{-1/2} \tag{8}$$

The maximum value of $|G(i\omega|$ thus occurs at

$$\omega = b\sqrt{1 - \frac{1}{n^2}} \text{ for } \omega>o \tag{9}$$

with a corresponding value, $|G(i\omega)| = \frac{n}{2b}$.

At $\omega = 0$, we have

$$|G(i\omega)| = \frac{n^2}{b(1+n^2)} \tag{10}$$

The ratio of $|G(i\omega)|_{\omega=b\sqrt{1-\frac{1}{n^2}}}$

to $|G(i\omega)|_{\omega=o}$ is thus

$$\frac{|G(i\omega)|_{\omega = b\sqrt{1-\frac{1}{n^2}}}}{|G(i\omega)|_{\omega=0}} = \frac{1}{2}(\frac{1}{n} + n) \tag{11}$$

Experimental results are needed to determine the spectrum for various sources under various rock types.

The spectrum of the hammer blow or timber impact has the form of Figure 1; thus as n approaches one, the spectrum approaches that assumed by Westinghouse, as depicted in Figure 2 below;

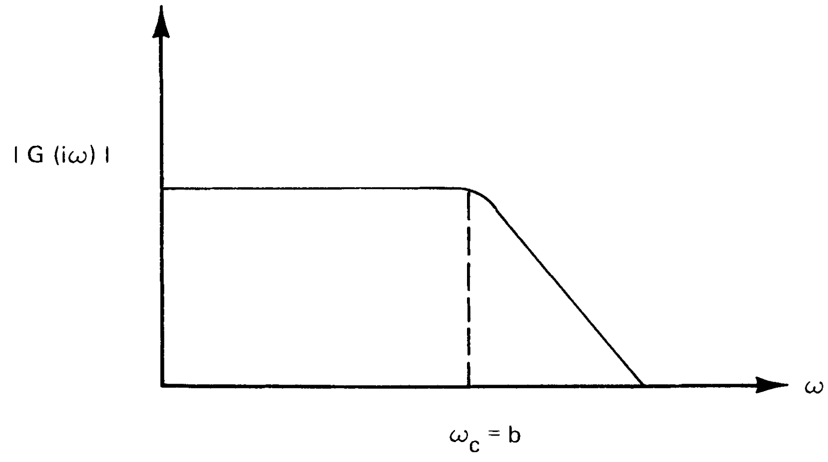


FIGURE 2 SOURCE IMPACT SPECTRUM ASSUMED BY WESTINGHOUSE

i.e., flat from DC to the corner frequency ω_c .

Therefore the radial component of the particle velocity of Equation (2) becomes

$$\dot{u}_r = \frac{Mv\ (a^2+b^2)^2\ \cos\phi}{4\pi b^2 \rho\ V^2 r}\ \dot{g}\left[\frac{a^2+b^2}{b}\ (t-\frac{r}{V})\right] e^{-\alpha r} \qquad (12)$$

for $a \neq b$

and

$$\dot{u}_r = \frac{Mv\ (n^2+1)b\ \cos\phi}{4\pi n^2 \rho\ V^2 r}\ \dot{g}\left[\frac{(n^2+1)b}{n^2}\ (t-\frac{r}{V})\right] e^{-\alpha r} \qquad (13)$$

for $a = \frac{b}{n}$

For a multilayered model, the radial component of the particle velocity, by virtue of equation (12), becomes

$$\dot{u}_r = \frac{Mv(a^2+b^2)^2 \cos\phi}{4\pi b^2 \rho V_1^{\,2} R}\, \dot{g}\left[\frac{a^2+b^2}{b}\left(t - \sum_1^n \frac{r_n}{V_n}\right)\right] e^{-\sum_1^n \alpha_n r_n} \times T_n(i) \qquad (14)$$

$$\text{as } R = r_1 + r_2 + \ldots. + r_n$$

where V_1 is the compressional wave velocity of the medium in which the source is located, and T_n is the transmission coefficient through the multilayered medium.

IV. NATURE OF THE MINER'S SOURCE

Consider the impact of an elastic rod of length, ℓ, upon a rigid half-space. At the impact, $t = t_o$, $v = v_o$, and $\sigma_o = v_o\sqrt{E\rho}$ where t is the time, v_o is the velocity of the impact, σ_o is the stress, E is Young's modulus of the rod, and ρ is the density.

Later, for $t > t_o$, if the contact duration is sufficiently long, we have

$$A\rho(\ell-ct)\frac{dv}{dt} + \sigma A = 0 \qquad (15)$$

$$\text{as } v = \frac{\sigma}{\sqrt{E\rho}} \text{ and } c = \sqrt{\frac{E}{\rho}}$$

$$\frac{\rho(\ell-ct)}{\sqrt{E\rho}}\frac{d\sigma}{dt} + \sigma = 0 \qquad (16)$$

$$\frac{(\ell-ct)}{c}\frac{d\sigma}{dt} + \sigma = 0.$$

Therefore the stress exerted on the rigid medium is

$$\sigma = A' \left(\frac{\ell}{c} - t\right). \tag{17}$$

$$\text{At } t = t_o,\ \sigma = \sigma_o$$

and we have

$$\sigma_o = A' \left(\frac{\ell}{c} - t_o\right)$$

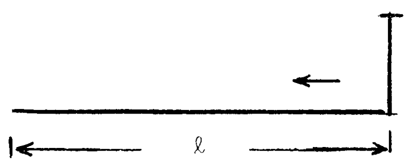
$$A' = \frac{\sigma_o\, c}{\ell - c\, t_o} \,. \tag{18}$$

Hence the stress on the rigid medium is

$$\sigma = \frac{\sigma_o}{\ell - c\, t_o} (\ell - ct). \tag{19}$$

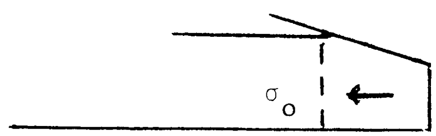
The behavior of equation (19) may be summarized as follows:

(1) at $t = t_o$



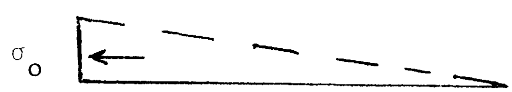
$$\sigma_o = v_o\sqrt{E\rho}$$

(2) at $t_o < t < \frac{\ell}{c}$

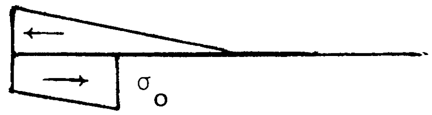


$$\sigma = \frac{\sigma_o(\ell - ct)}{\ell - ct_o}$$

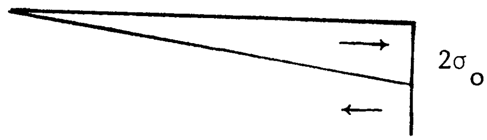
(3) at $t = t_o + \frac{\ell}{c}$



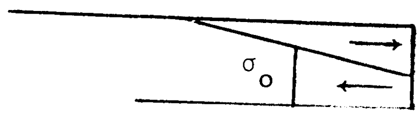
(4) at $t_o + \frac{\ell}{c} < t < t_o + \frac{2\ell}{c}$



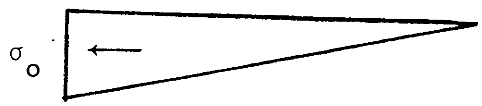
(5) at $t = t_o + \frac{2\ell}{c}$



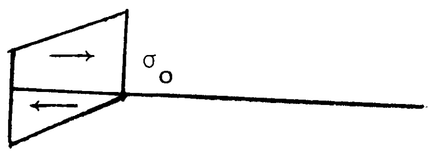
(6) at $t_o + \frac{2\ell}{c} < t < t_o + \frac{3\ell}{c}$



(7) at $t = t_o + \frac{3\ell}{c}$



(8) at $t_o + \frac{3\ell}{c} < t < t_o + \frac{4\ell}{c}$



Therefore, if the impact duration is sufficiently long, the longitudinal vibration of the rod is of importance to the stress on the impact medium. It is anticipated that for the case of the impact of an elastic object such as a timber on an elastic medium, the stress should be a function of E_1, E_2, ρ_1, and ρ_2, and furthermore, the initial impact stress might be a function of E_1, E_2, ρ_1, and ρ_2, as well as of V_o. This might explain why a timber impact, in addition to its heavier mass, generates lower frequency as well as larger signals than a hammer blow.

V. SIGNAL ATTENUATION

Attenuation of seismic waves is attributed principally to

(1) geometrical spreading

(2) energy dissipation

(3) energy partition due to reflection and transmission at the interfaces of a layered medium.

A. Geometrical Spreading

According to equation (1a), in the far-field the particle displacement is simply inversely proportional to the first power of the distance between the source and the observation point.

B. Energy Dissipation

The dissipation function Q^{-1} for compressional waves propagated in common rocks may be given by (Futterman, 1963)

$$Q^{-1}(\omega) = \frac{1}{2\pi}\left[1 - e^{-4\pi\alpha V/\omega}\right], \qquad (20)$$

where α is the attenuation coefficient.

For small dissipation such that $\frac{4\pi\alpha V}{\omega} << 1$,

equation (20) may be approximated by

$$Q^{-1}(\omega) \approx \frac{2\alpha V}{\omega}, \qquad (21)$$

so that the attenuation coefficient in terms of Q^{-1} is

$$\alpha \approx \frac{\pi f}{VQ}^{*}, \qquad (22)$$

where f is the frequency in Hz.

*This expression differs by a factor of 2 from that given in the Westinghouse Final Report (1971), Section II, p. D-16.

Therefore, the attenuation coefficient is a function of ω as shown in Figure 3. Basic physical considerations indicate that the attenuation should disappear at some low frequency cut-off ω_o , which has accordingly been included in Figure 3, although reliable estimates of its values are not yet available.

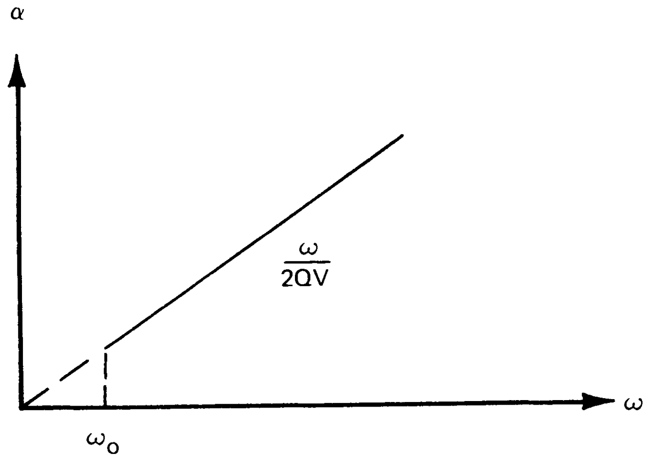


FIGURE 3 ATTENUATION COEFFICIENT VERSUS FREQUENCY WITH A LOW-FREQUENCY CUT-OFF

Valuable information on the value of Q for Eastern Coal Province, Southern Appalachian field, Interior Coal Province, and Rocky Mountain coal regions is given by Westinghouse (Final Report II, p. D16-18).* Average values of Q for various rock types are approximately given in (without specifying the frequency range) Table 1.

TABLE 1

AVERAGE VALUES OF Q

Rock Type	Q
Cap rock	50
Dolomite	200
Limestone	120
Marlstone, sandstone, shale and siltstone	50

* Ibid.

Since the coal region is generally covered by weathering layers and soils, the following are values of Q for soils for compressional waves in the frequency range of interest (Table 2):

TABLE 2

Q's FOR TYPICAL WEATHERING LAYERS

Formation	Frequency Range	Q	Source
Pottsville sandstone	100-900 Hz	7	Collins and Lee (1956)
Pierre shale	50-450 Hz	23	McDonal *et al.* (1958)

The average values of α are approximately (Table 3):

TABLE 3

AVERAGE VALUES OF ATTENUATION COEFFICIENT, α

Rock Type	Compressional wave velocity ft/sec	Q	Frequency Hz	α nepers/ft
Dolomite	16,000	200	100	9.82×10^{-5}
Limestone	14,000	120	100	1.87×10^{-4}
Sandstone	8,000	50	100	7.85×10^{-4}
	10,000	50	100	6.28×10^{-4}
Weathering zone	4,000	15	100	5.24×10^{-3}
	2,000	10	50	7.85×10^{-3}

C. Energy Partition

The fraction of the energy incident in a plane wave upon a plane interface, separating two semi-infinite media, that is carried away in each of the reflected and refracted waves, can be directly calculated on a computer. Among various authors, e.g., Costain *et al.* (1963), McCamy *et al.* (1962)*, etc., Nafe (1957) has expressed the Knott equations (1899) in common coordinate system for the four separate problems of incident P (or SV) waves from either side of the interface in a symmetrical form, which is convenient for numerical calculation.

*There is an error in sign in McCamy *et al.*'s (1962) paper. Consequently, their results are incorrect.

Referring to Figure 4, if the incident waves are assumed to have unit amplitude, the sixteen equations for the amplitudes may be expressed as the matrix product:

$$MX = N \tag{23}$$

where

$$M = \begin{bmatrix} 1 & \tan\sigma & -1 & \tan\sigma' \\ -\tan\delta & 1 & -\tan\delta' & -1 \\ \mu q & -2\tan\sigma & -\mu' q' & -2\mu'\tan\sigma' \\ 2\mu\tan\delta & \mu q & 2\mu'\tan\delta' & -\mu' q' \end{bmatrix} \tag{24}$$

$$X = \begin{bmatrix} (P,P) & (P,S) & (P,P') & (P,S') \\ (S,P) & (S,S) & (S,P') & (S,S') \\ (P',P) & (P',S) & (P',P') & (P',S') \\ (S',P) & (S',S) & (S',P') & (S',S') \end{bmatrix} \tag{25}$$

$$N = \begin{bmatrix} -1 & \tan\sigma & 1 & \tan\sigma' \\ -\tan\delta & -1 & -\tan\delta' & 1 \\ -\mu q & -2\mu\tan\sigma & \mu' q' & -2\mu'\tan\sigma' \\ 2\mu\tan\delta & -\mu q & 2\mu'\tan\delta' & \mu' q' \end{bmatrix} \tag{26}$$

where μ' and μ are rigidities, and q and q' are equal to $(\tan^2\sigma - 1)$ and $(\tan^2\sigma' - 1)$, respectively.

The notation of (P,S') or (P',P) refers to the outgoing wave by the first letter, and the incident wave by the second letter.

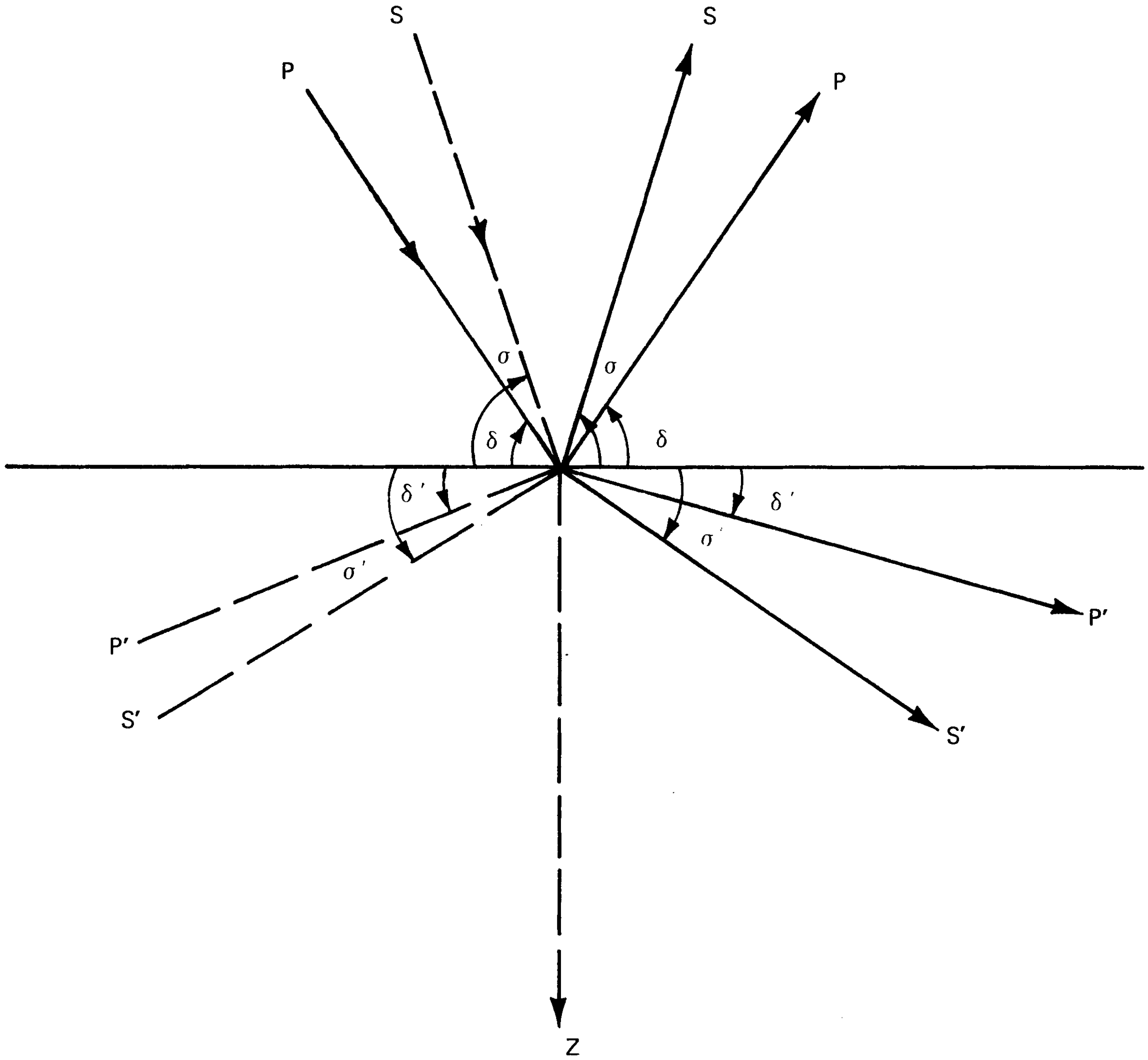


FIGURE 4 FOUR INCIDENT PLANE WAVES ARE SHOWN APPROACHING A PLANE INTERFACE. ANY ONE OF THESE PRODUCES FOUR OUTGOING WAVES, P, S, P', S'. THE ANGLES OF EMERGENCE FOR SHEAR WAVES ARE σ AND σ', AND FOR COMPRESSIONAL WAVES, δ AND δ'. THE UPPER MEDIUM IS UNPRIMED. (After Nafe, 1957).

The cases for the velocity ratios of 1:2, 1:2.5, and 1:3, and the densities 2.3 and 2.8, which are directly applicable to the present requirements of a weathering zone in contact with sandstone or limestone, are shown in Figure 5 for the range of incident angles from 0 to 60^{o}.

The present results can be easily applied to the case of plane waves in a multilayered medium used to represent the geological structure of a coal mine region. A similar analysis was performed by Haskell (1962) in treating crustal reflection of P and S waves in a layered medium. However, the problem of calculating reflection and transmission coefficients for a point source located in a layered medium requires further investigation.

VI. DISTORTION OF SEISMIC WAVE FRONT FOR AN IMPACT SOURCE IN A MINE OPENING

Evidently, the assumption of a simple force in an infinite medium for a hammer blow (or a timber strike) on either the roof or the ribs of a mine opening is not adequate. The radiation pattern generated by a simple force in an infinite medium is spherical, whereas that of a simple force impacted on a cavity has a distorted spherical shape. Figures 6a and 6b give a comparison of these two wave front patterns.

Because of the general complexity of a mine section including a grid of tunnels, it is virtually impossible to represent the wave front generated by a source under actual mine conditions. Fortunately, the wave length we are dealing with is generally large in comparison with at least the cross-section of an opening. Unless the impact is on the floor, the approximate spherical wave front of the impact on either the roof or the rib would not be significantly distorted as it impinges on the surface, as shown in Figure 6b.

It must be cautioned, however, that when the impact is on the floor the wave front is severely distorted. The degree of its distortion naturally depends upon the dimensions of the opening as shown in Figure 7; for a floor impact the first arrival of P waves on the surface should be expected to have a considerable time delay. Figures 8, 9 and 10 represent the wave distortion in sections A-A' and B-B' for a three-dimensional representation of a long tunnel with impact on the roof, the rib and the floor.

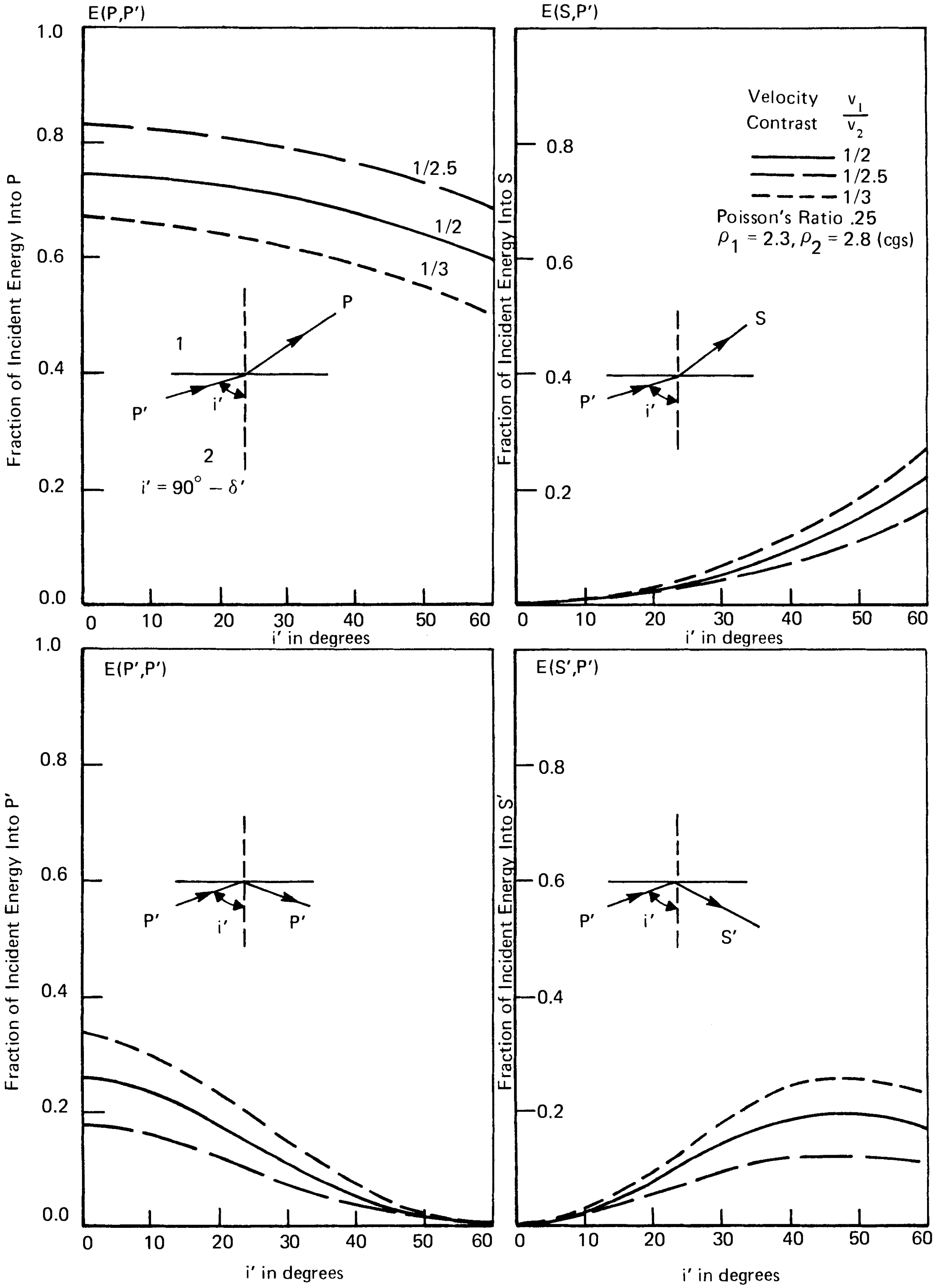
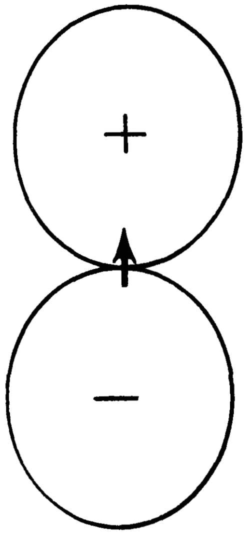
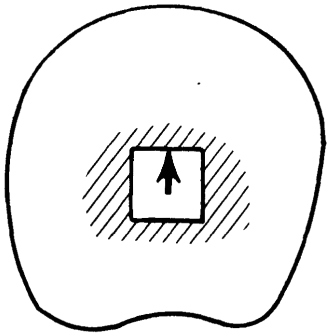


FIGURE 5 FRACTION OF INCIDENT ENERGY CARRIED AWAY IN REFRACTED (P, S) AND REFLECTED (P', S') WAVES



(a) A simple force in an infinite medium



(b) A simple force in a mine opening

FIGURE 6 RADIATION PATTERNS OF A SIMPLE FORCE IN (a) AN INFINITE MEDIUM AND (b) A MINE OPENING

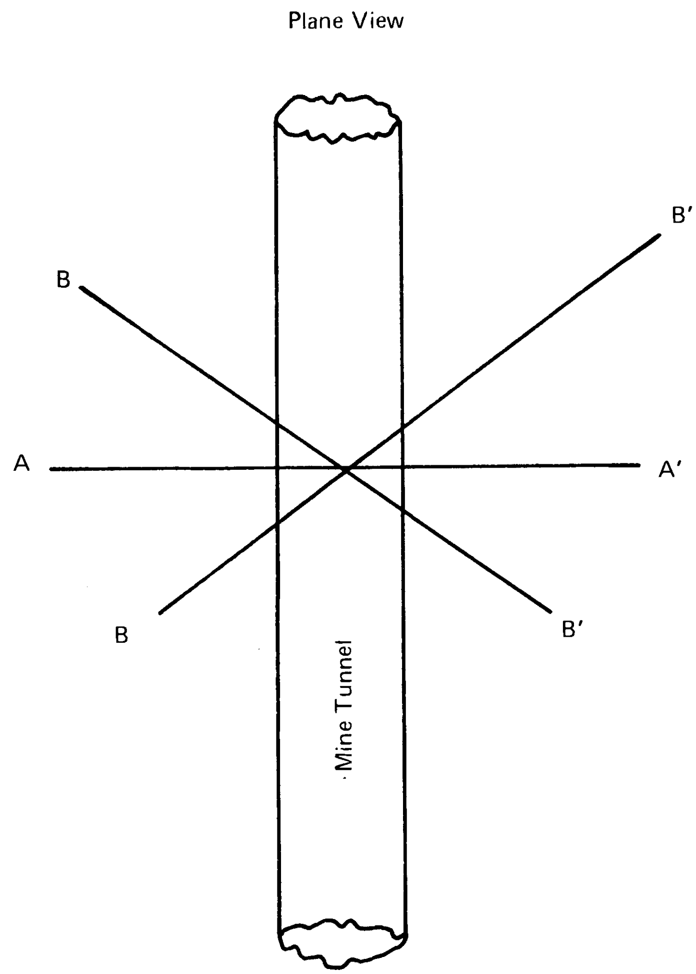


FIGURE 7 PLANE VIEWS FOR MINE TUNNEL

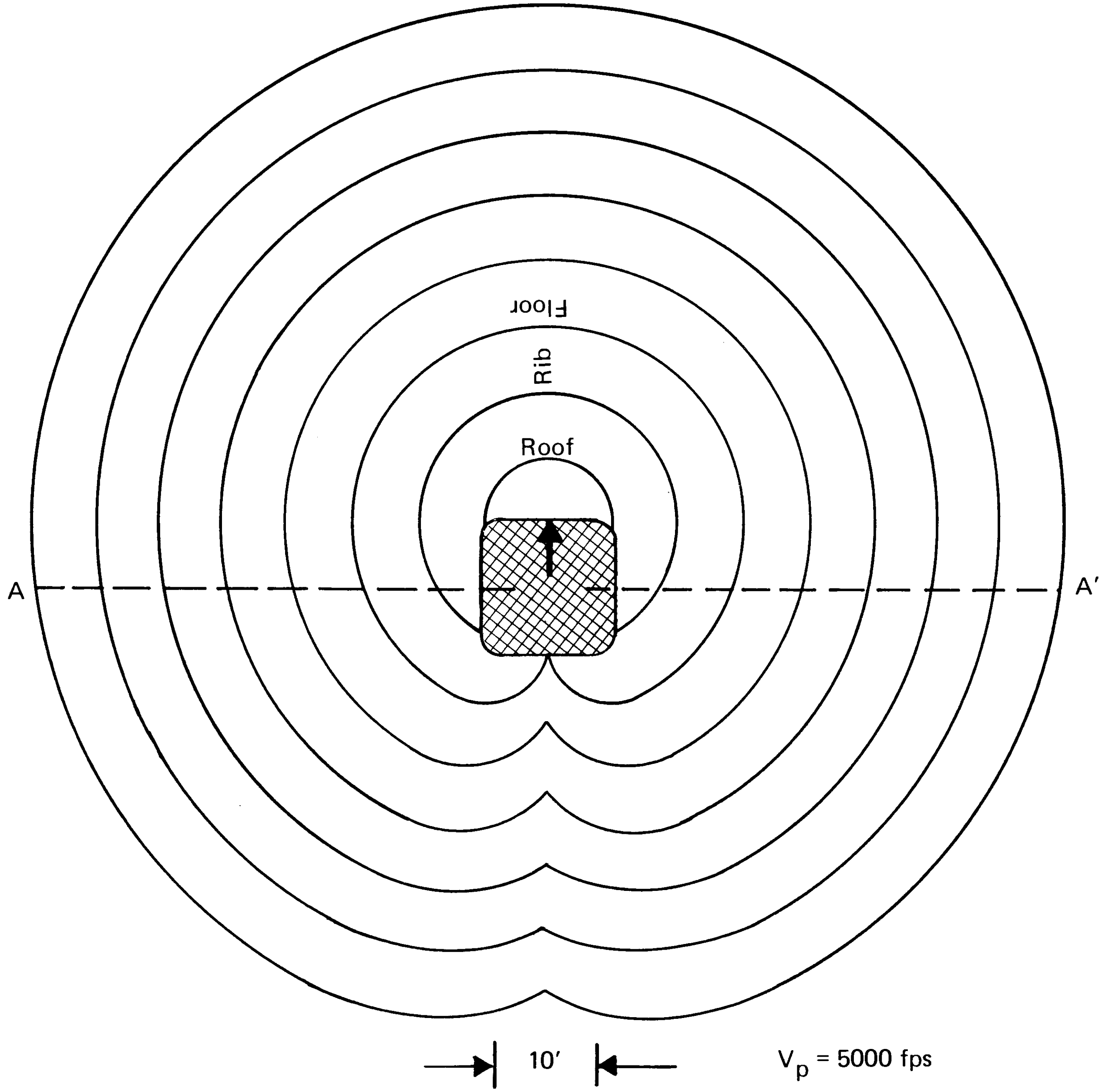


FIGURE 8 DISTORTED WAVE FRONTS OF A VERTICAL SECTION A-A′

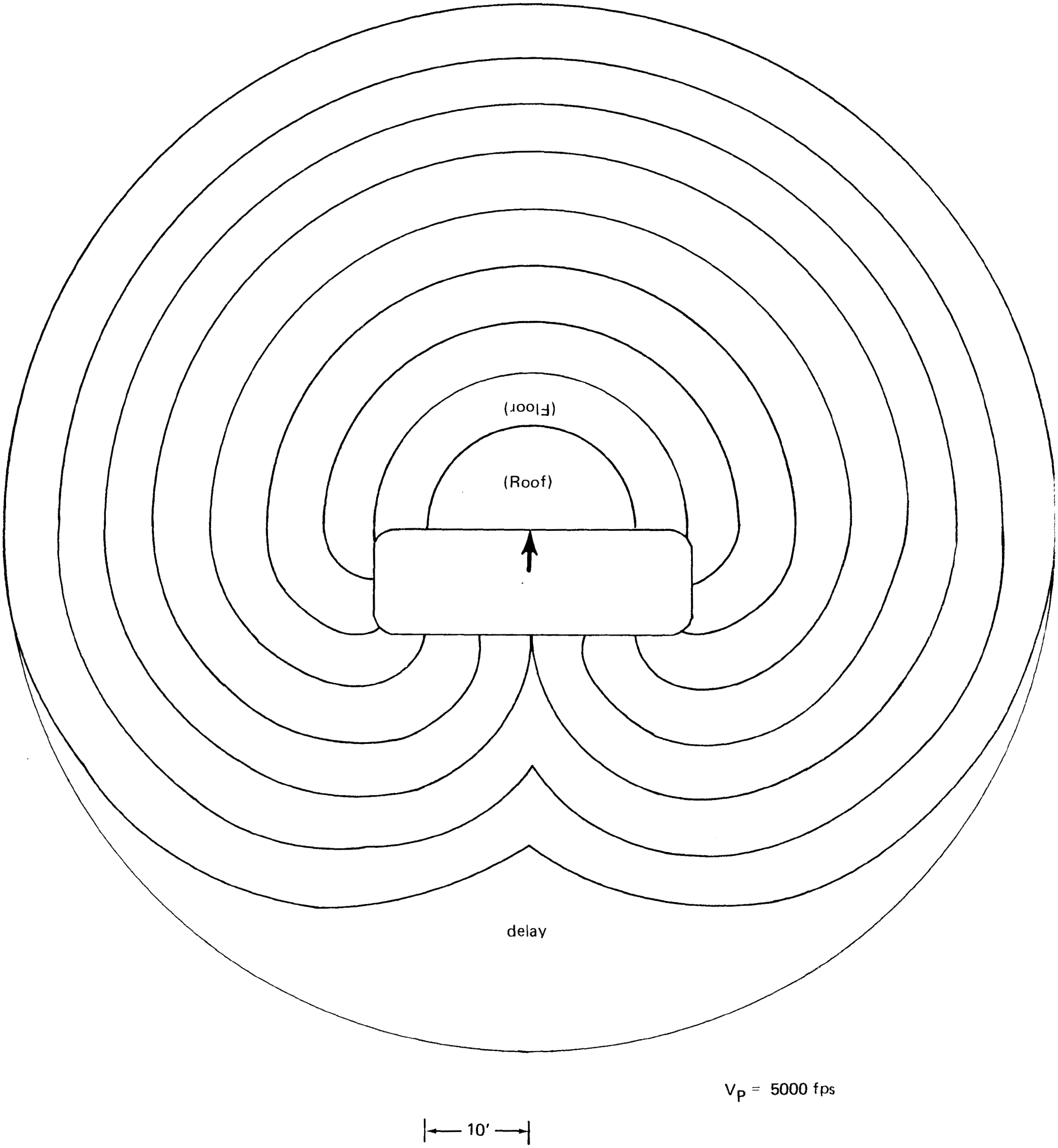


FIGURE 9 DISTORTED WAVE FRONTS OF A VERTICAL SECTION B-B'

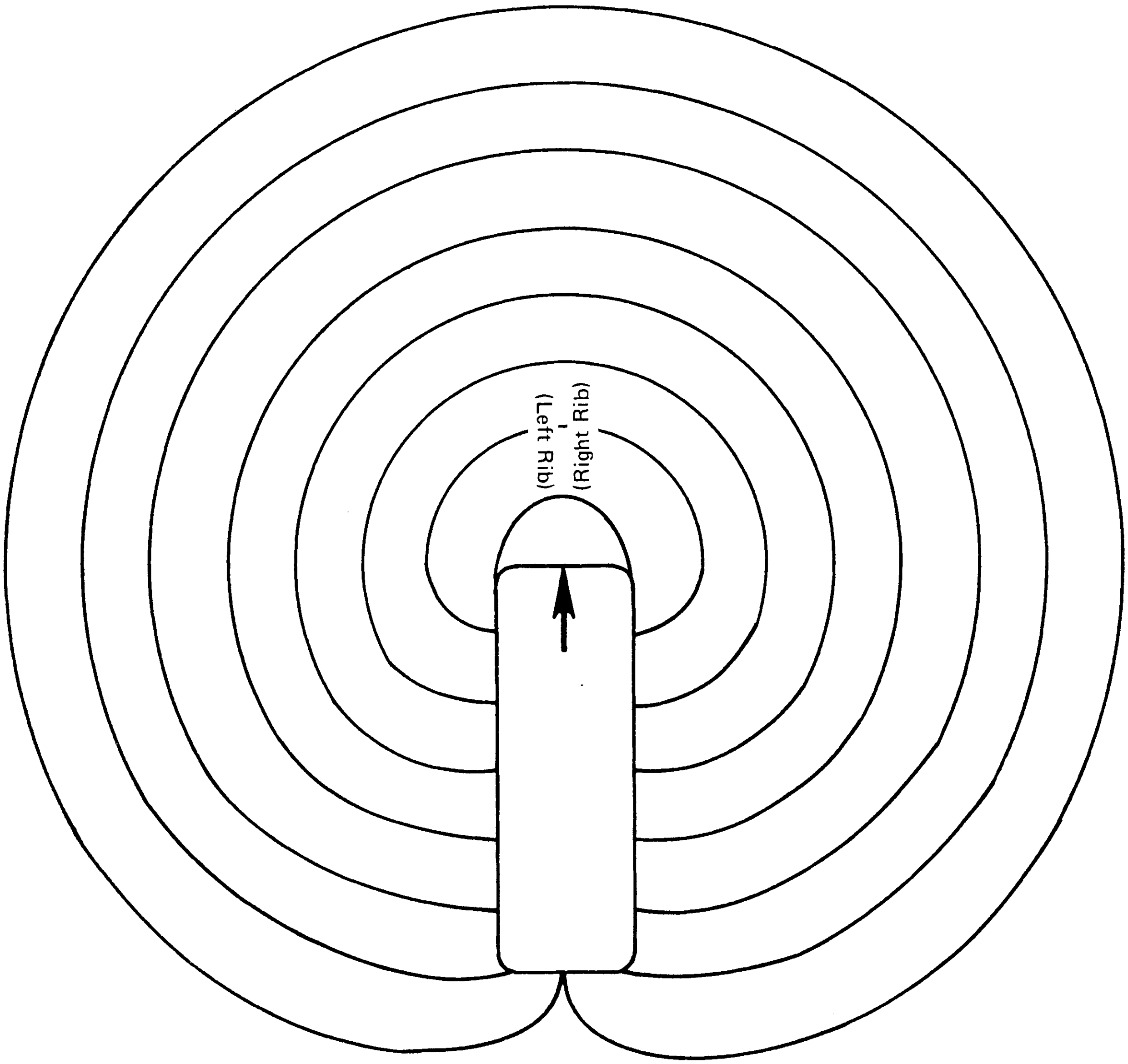
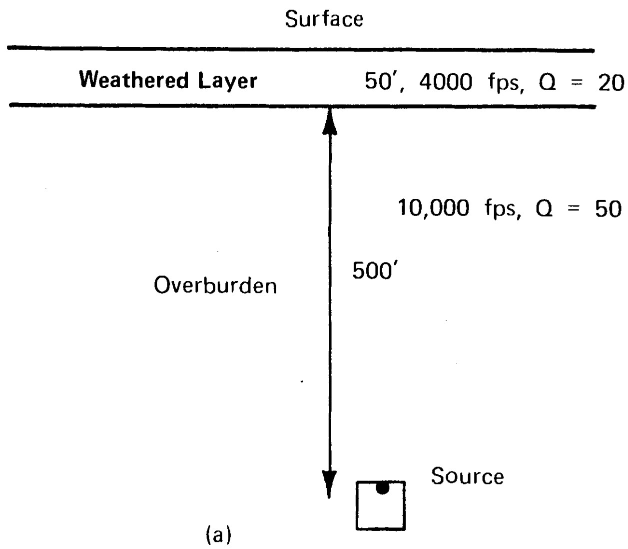


FIGURE 10 DISTORTED WAVE FRONTS OF A VERTICAL SECTION B-B' FOR AN IMPACT ON RIB

VII. THEORETICAL ESTIMATION OF THE SIGNAL LEVEL AS A FUNCTION OF RANGE

Neglecting the effect of noise on the signal, the particle velocity may be approximately calculated by Equation 13. The remaining problem is then to estimate the efficiency of energy conversion from mechanical impact to seismic-wave transmission, which naturally depends on the dimension, elastic properties and the velocity of the impact body, and the stress thereby induced in the impact medium. Such an estimation, without controlled experimental data, involves a high degree of uncertainty. We will assume a 70% effective elastic collision as a hammer strikes the rock in a mine opening.

As a specific example, we use the models of Figure 11, which are close to the geological model at Imperial Mine (Westinghouse Final Report II,* Figure 3.1-3, p. 92)



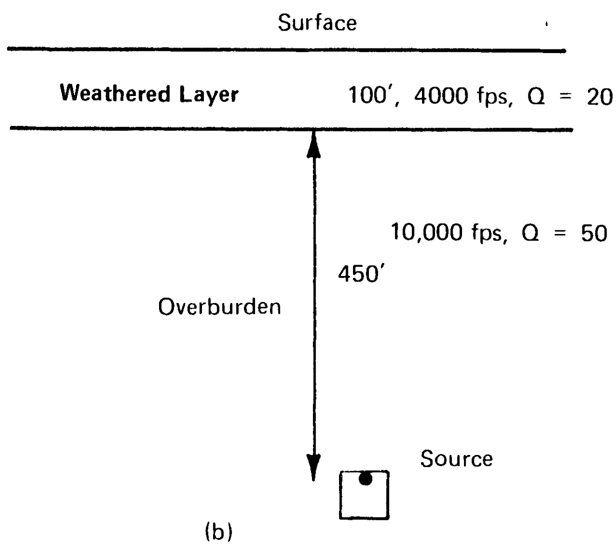


FIGURE 11 MODELS FOR ESTIMATING SIGNAL LEVELS ON THE SURFACE

* Ibid.

and the values of

M = a 10-lb sledge hammer; a 40-lb timber

v = 16.1 ft/sec for hammer; 11.5 ft/sec for timber

ρ = 2.67 gm/cm^3 for 10,000 ft/sec half-space

Taking into account all the factors of the geometrical spreading, energy dissipation, and energy partition at the interface as described in the preceding section, the vertical component of the peak-to-peak particle velocity on the surface of the model is given in Figure 12 for the cases of 50 Hz and 100 Hz as a function of slant range for a hammer blow and a timber impact.* The up- and -down-link experimental data for the frequency range of 70 to 83 Hz (Table 2.5.3-1, Westinghouse Field Report 8)† at Copper Queen is also plotted in the Figure. The rates of decay for the theoretically calculated and the experimental data agree rather closely. The theoretical magnitude of the peak-to-peak particle velocity seems somewhat overestimated for a hammer blow, as the source used at Copper Queen is a thumper for uplink and a timber for downlink. This is an unfair comparison, as the geological models vary between the theoretical situation and that of Copper Queen, since the geology at Copper Queen is complicated by faults and irregular distribution of alluvial materials. Nevertheless, it does provide evidence of the applicability of such a crude approximation in theoretical calculations.

VIII. DEVELOPMENT OF LOW-FREQUENCY SEISMIC SOURCE FOR THE DETECTION OF SURVIVING MINERS

Present seismic detection methods are handicapped because only very weak signals can be generated by a trapped miner with available tools such as a sledge hammer or a timber. The detectability of a trapped miner should be greatly enhanced if a suitable low-frequency source can be developed. Since the option of what a miner may be able to carry is rather limited, it appears not altogether unreasonable to consider a permanent installation of a mechanical source generator of the simplest kind. An electrically or electronically driven transducer is ruled out because of its requirement for either sophistication or power. It seems that heavy-weight simple pendulums can be installed in strategic locations in an actual mine section. As the signal strength for an impact source is directly proportional to the mass of the impact body, a "lead" sphere type of simple pendulum may be appropriate. Such installations cost relatively little. The support of the pendulum can be anchored either to the roof or to the rib as

* A relatively large value of n has been assumed, so that the source signal strength (see Figure 1) is noticeably higher at 100Hz than 50Hz.

† Westinghouse Contract H0210063 with Bureau of Mines.

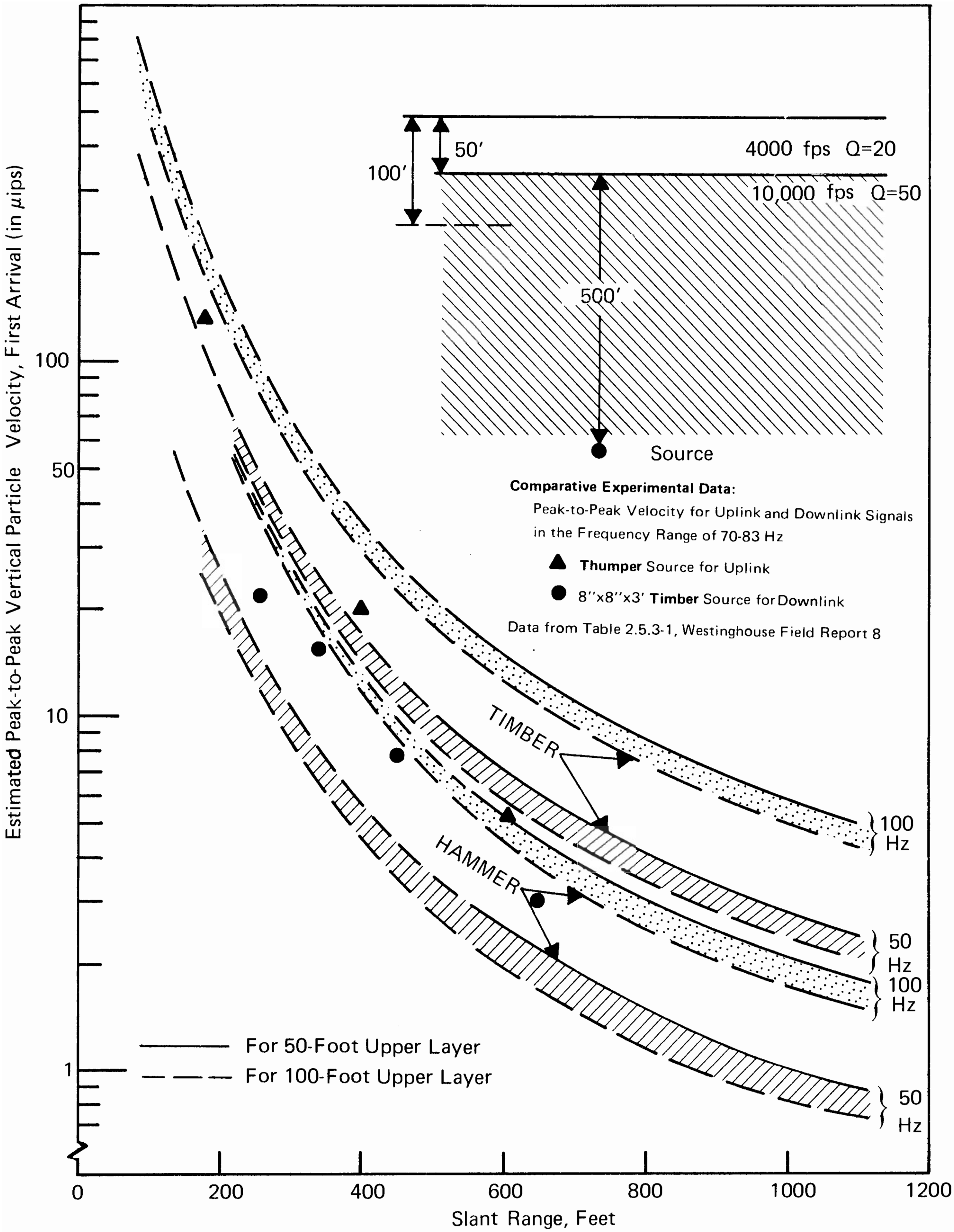


FIGURE 12 ESTIMATED PEAK-TO-PEAK VERTICAL PARTICLE VELOCITY FOR THE FIRST P-WAVE ARRIVAL (BASED ON THEORETICAL CONSIDERATIONS)

the following diagram (Figure 13) illustrates.

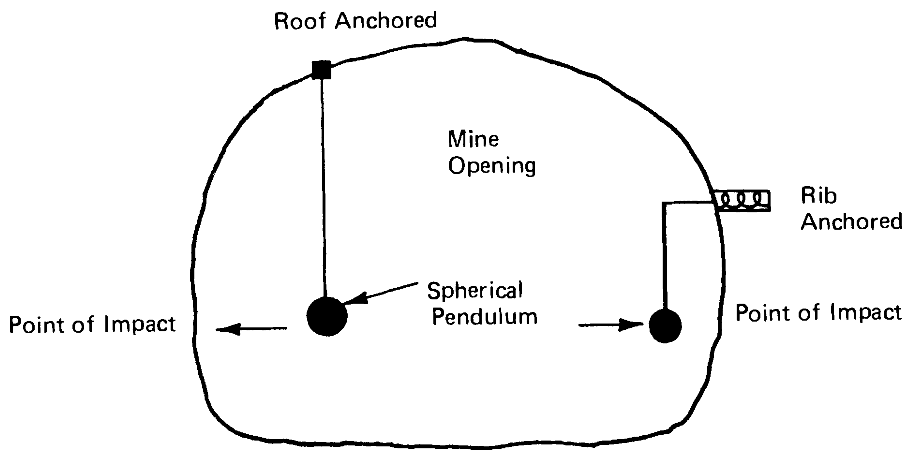


FIGURE 13 PERMANENT INSTALLATION OF A PENDULUM

The signal can be generated repeatedly without great effort on the part of a trapped miner. Furthermore, the particle velocity is also directly proportional to the impact velocity. If the impact of a timber is comparable to that of a hammer blow, the magnitude of the particle velocity due to the impact of a lead sphere would be about an order of magnitude higher than that due to a 10-lb sledge hammer blow. If the impact is made on a floor filled with soft earth material or in a coal seam, a coupler may be installed at the point of impact to enhance the conversion of mechanical energy into seismic energy without much energy loss in permanent deformation of the medium. Experimental results of impact on sand and sand-silt clay show a great deal of promise for eliminating energy loss from plastic deformation and heat generation (Appendix A and Mereu et al. (1963)).

For the initial detection of surviving miners in a disaster-struck mine, a positive, immediately identifiable signal of yes/no would be of great value for subsequent operation. Since the high frequency components of a signal attenuate rapidly in earth materials, particularly in weathering layers such as alluvium and soil, as is clearly demonstrated in Figure 14, a "low-frequency" source is preferred, i.e., with a peak frequency in the neighborhood of 10 Hz. A hammer

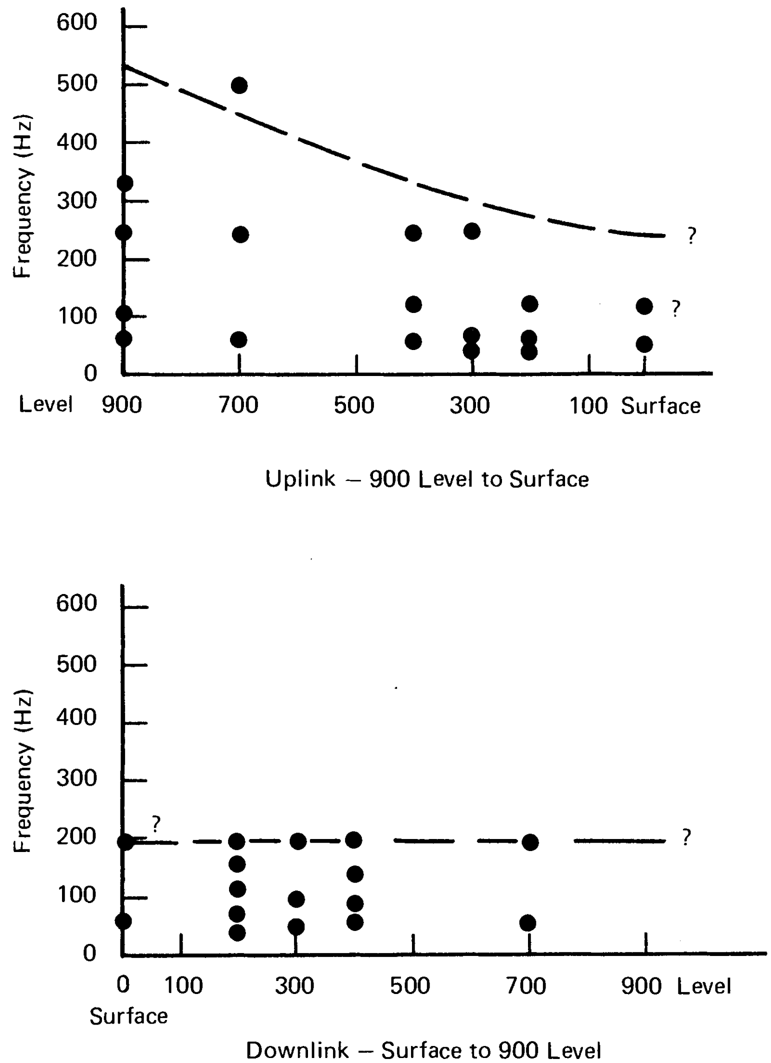


FIGURE 14 ATTENUATION OF HIGH FREQUENCIES THROUGH WEATHERING LAYERS AS DEDUCED FROM PLOTS 38 AND 39 OF REPORT 8, COPPER QUEEN

or a lead sphere with a spring mount as shown in Figure 15 promises to generate lower frequencies of this order. Future efforts toward developing a low-frequency source could be very worthwhile.

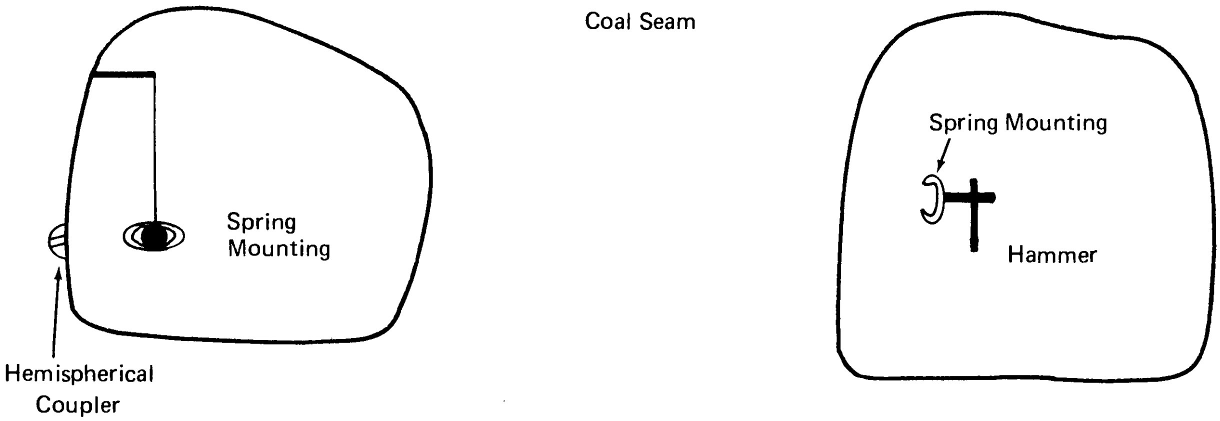


FIGURE 15 EXAMPLES OF LOW FREQUENCY SOURCES

In the time domain, a repeated low-frequency signal received on the surface should have the following forms (Figure 16).

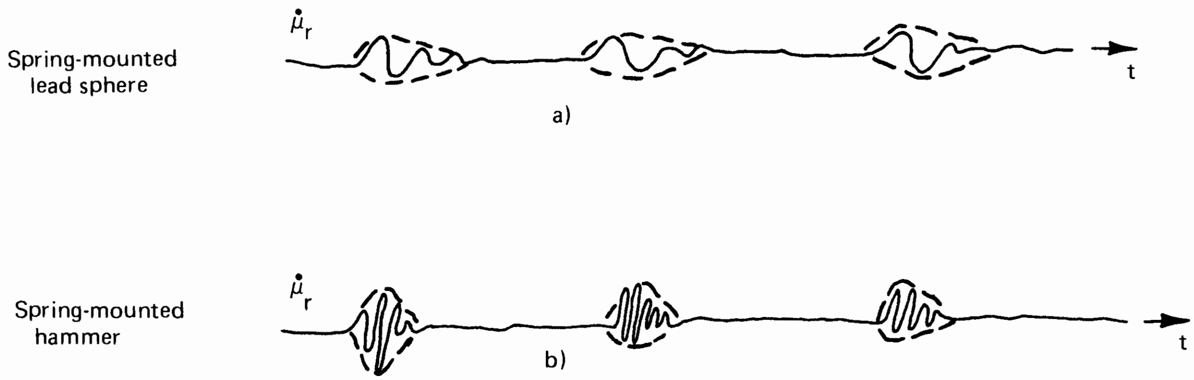


FIGURE 16 REPEATED LOW-FREQUENCY SIGNALS AS RECEIVED ON THE SURFACE

It should be of great value to analyze the envelopes of the signals in the frequency domain, instead of the actual signals themselves. The spectra of the time series of these envelope signals should contain the low frequency energy of repeated sources. If the signals are sufficiently strong, their envelopes could themselves offer direct visual identification of the presence of surviving miners. Once surviving miners have been successfully detected, a down-link signal can be sent to tell survivors to use a high-frequency source with a shorter range of transmission for the purpose of accurate location.

IX. FUTURE INVESTIGATIONS

(1) Wave diffraction and scattering of an impact source on a face of a cylindrical cavity.

(2) The impact of an elastic object on an elastic medium.

(3) Spectrum of the source, sufficiently far from the source to determine $G(i\omega)$ as a function of frequency. This information should be of great value for more accurate determination of the source strength, as it is virtually impossible to determine the source strength near or at the source because the conversion of mechanical energy to seismic energy remains a difficult problem.

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APPENDIX A

USE OF A COUPLER IN THE CONVERSION OF IMPACT ENERGY INTO SEISMIC ENERGY

Mereu *et al* (1963) presented an interesting paper on the efficient transfer of impact energy into seismic energy in soil-covered areas by means of a falling weight-coupler system. This concept is equally applicable to the present problem of impact on a coal seam or on a floor generally covered with rock debris or soils. Through their theoretical and experimental model studies on sand and clay-silt sand, the authors concluded that for compressional waves:

(1) A coupler such as a plastic steel hemisphere embedded in the medium at the impact point can increase the amplitude of the seismic output by reducing plastic deformation at the point of impact, i.e.,

$$A \sim M^{2/3} V_c \qquad \text{(A1)}$$

where A is the amplitude of the seismic signal, M the mass of the coupler, and V_c the maximum velocity of the coupler.

(2) The seismic energy is not proportional to the source energy.

APPENDIX B

QUADRATURE WEIGHTING METHOD FOR MINER LOCATION ARRAYS*

In principle it is possible to cope with the problem of bias in location estimation by using a different station weighting procedure than that adopted in Part Three. The stations in each quadrant are considered in separate groups. When an approximate location has been determined, the residues for each station in a group are computed, and obviously "abnormal" stations are rejected. Subsequently, an average residue is calculated as

$$\bar{R} = \frac{1}{N} \sum_i R_i \qquad \text{(B1)}$$

where N is the number of stations in the group.

It is assumed that residue values follow a Gaussian distribution about this mean value, to which a weighting factor of unity is assigned. Finally a weighted residue is computed for each station by using a weighting factor which corresponds to the position of the original residue on the Gaussian distribution.

Appropriate quadrants for the miner location problem might be as follows (Figure B1).

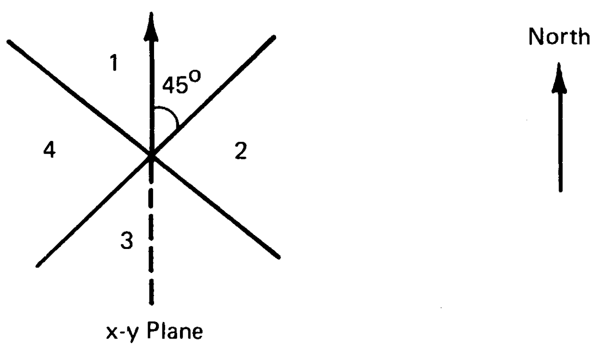

FIGURE B1 QUADRANT GEOMETRY

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*This method has been in common use at the Lamont Geological Observatory for earthquake focus relocations (Kuo et al.).

PART EIGHT

EARTH MODELS

PART EIGHT

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EARTH MODELS

Arthur D. Little, Inc.

I. INTRODUCTION

The question of earth models has repeatedly arisen in our work. An accurate representation of the seismic properties is required for three reasons:

1. To be able to determine from a set of received arrival times, the location of a seismic source in the earth, and secondly the degree of accuracy required in the model used for calculating source location from the set of arrival time differences.
2. To be able to determine the expected arrival times at an array of geophones produced in response to a hypothetical source in the earth.
3. To be able to estimate received signal strengths more accurately.

The work reported here on earth models is based on information from several consultants and from others who expressed an interest in the problem and supplied information to us.

II. COAL MINE GEOLOGY

On one of our earlier assignments for the Bureau of Mines, Earth Science Research Inc. of Cambridge, Massachusetts prepared for us a short description of the lithology to be expected at coal mine sites. This description follows, together with the ranges of compressional seismic velocities **(Figure 1*) associated** with typical materials comprising the layered structure of a coal mine area.

Coal is primarily associated with fresh water sediments including sandstones, shales, and clays, and occasionally may be metamorphased to varying degrees. In the Appalachian Basin the coal beds occur within cyclical sequences of non-marine shales, sandstones, conglomerates, limestones, and clays. The beds range in thickness from a few inches to 60 feet, averaging between 2 feet and 10 feet. They have generally broad areal extent, occasionally up to 5,000 square miles, and have an overall tabular or lens-like shape. Within a particular lens, local changes in thickness are normal.

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

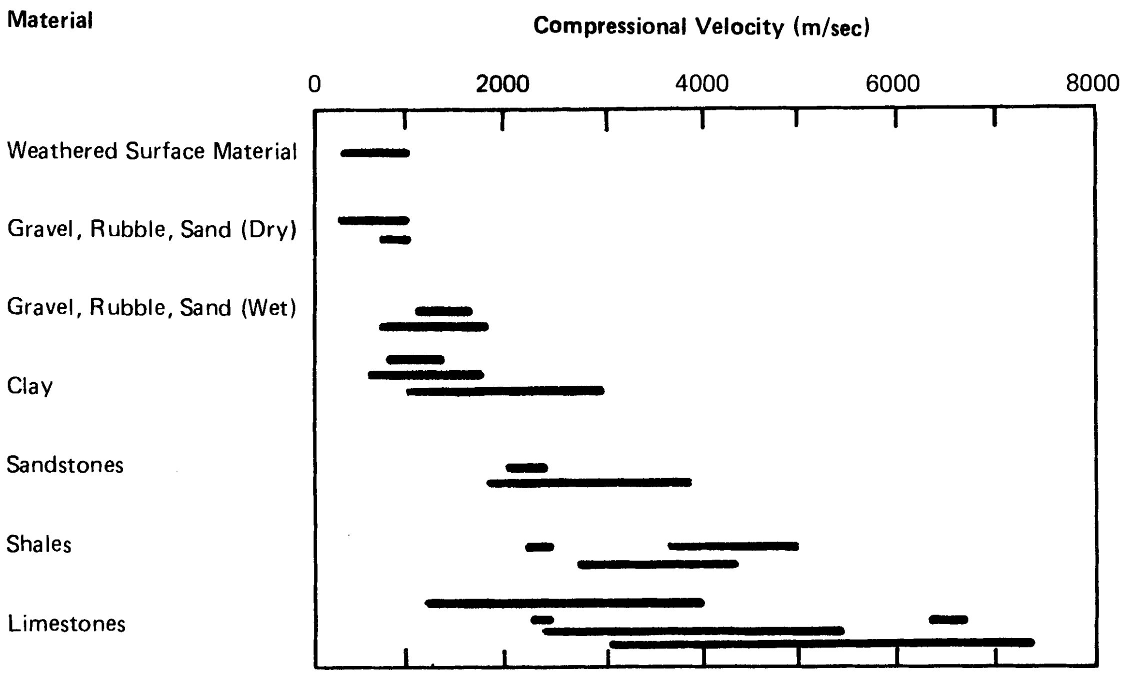

FIGURE 1 COMPRESSIONAL VELOCITIES FOR TYPICAL OVERBURDEN MATERIALS

Coal beds typically contain thin bands of clay, shale, fine grained or nodular pyrite, marcasite, and siderite. Graphite is also prevalent with the content depending on the degree of metamorphism. In the steeply folded rocks of the anthracite region in northern Pennsylvania, which have undergone dynamic metamorphism, the graphite content is above average.

Cyclothems are cyclical sequence deposits which repeat in succession throughout the geologic column of a coal basin. When ideally developed, a typical cyclothem, starting with the oldest beds, is as follows:

1. Fine grained micaceous sandstone and siltstone grading into conglomerate varying from thin to massive bedded, in which occasional plants are found.
2. Grey sandy shale which often contains ironstone concretions.
3. Fresh water limestone occurring as nodules or discontinuous beds.
4. An underclay, medium or light grey in color and somewhat calcareous.
5. Coal seam.
6. Grey shale with pyritic nodules and ironstone concretions towards the base. Fossils are rare.
7. Marine limestone.
8. Black laminated shale with large concretions and often fossiliferous.
9. Marine limestone with fossils.
10. Grey sandy shale or shaly sandstone often grading into conglomerates. The shales may have fossils and sometimes ironstone concretions.

Part or all of this sequence may be repeated many times in the coal series.

J. Powell of the U.S. Bureau of Mines has conducted an investigation of coal mine geology for this present investigation. Utilizing data obtained from References (1), (2), and (3) and information supplied by Mr. George Smith, a geologist with U.S. Steel, Powell concludes:

1. Geologic strata are usually horizontal, a slope of 100 feet per mile would be unusually large.
2. Although the strata are horizontal, they often pinch out or grade into different rock types.
3. The outstanding example of this pinch-out would be sand and gravel deposits laid down in stream beds. In cross section, a bed may be tens of feet thick in one spot and have disappeared completely a few hundred feet away as shown in Figure 2.
4. Geologic cross sections keep their general characteristics for distances of several miles. For example, if most of the overburden at point A is limestone, most of the overburden at a point 2 miles east of A will probably be limestone.
5. Geologic sections can change considerably over a distance of ten miles. To continue the above example, the overburden at a point 10 miles east of A could well be shale.
6. Items 4 and 5 above indicate that for many mines (i.e., those which could be contained within a square a few miles on a side) there exists much common geology.
7. In Pennsylvania and northern West Virginia, there is little faulting. As one goes south faulting becomes more common. In western Kentucky faults with vertical displacements of tens of feet are not unusual.
8. Coal is one of the most persistent beds; that is, in general a coal bed will continue for greater distances than other rock beds.

Source: *Some Appalachian Coals and Carbonates,* Figure 4, W. Va. Geologic and Economic Survey, 1969, Geology Department of West Virginia.

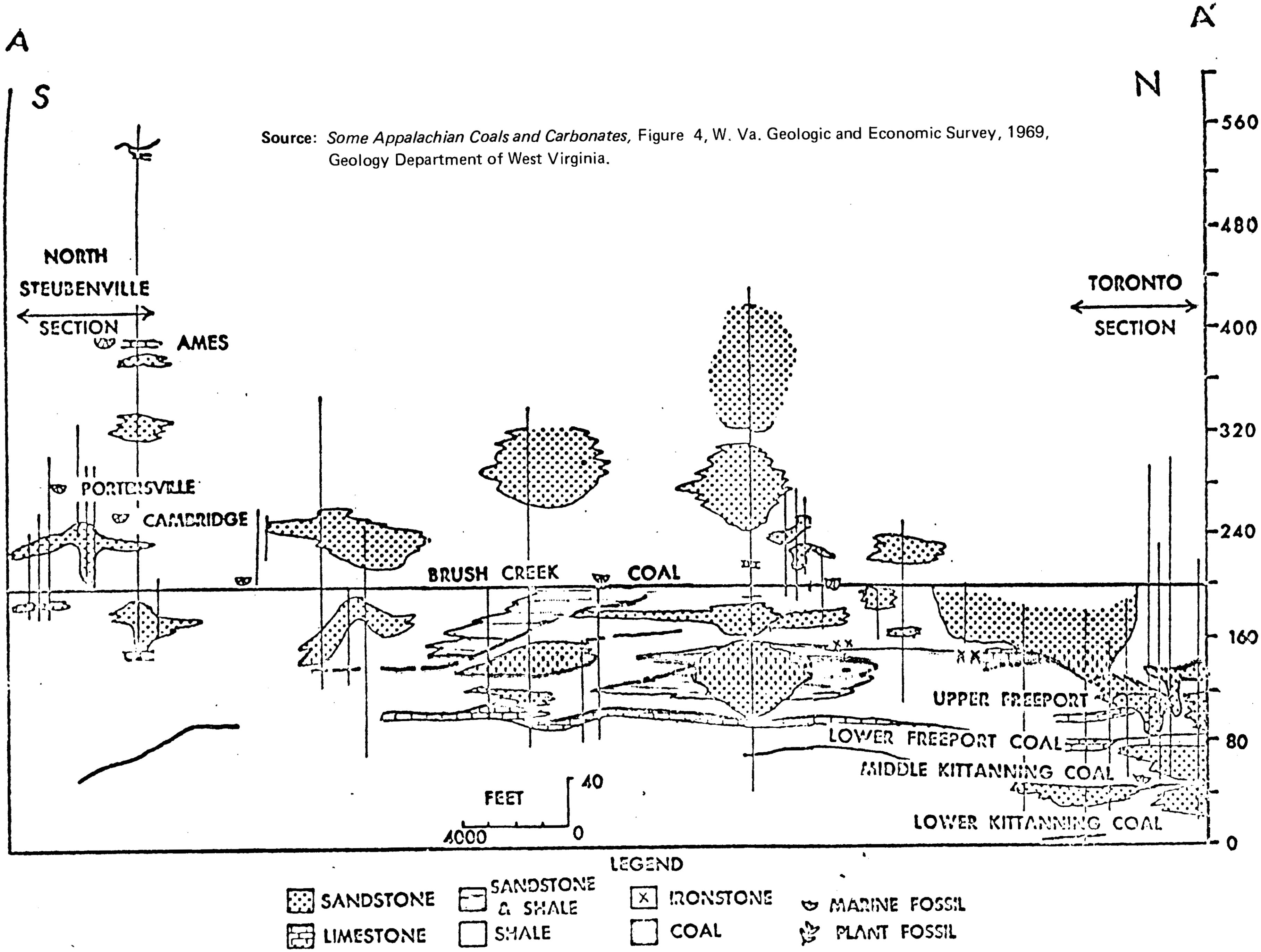

FIGURE 2 STRATIGRAPHIC CROSS SECTION FROM STEUBENVILLE TO TORONTO USING THE BRUSH CREEK COAL AS THE DATUM

From these data and descriptions some general comments can be made. Seismic compressional velocities in the regions of the earth through which a miner's signal must travel, from the mine tunnel area to the surface, will range from that of limestone (as high as 14,000 feet per second) to that of the weathered layer (as low as 500 feet per second). It will generally be true that the higher velocities will be encountered at the greater depths and the lower velocities near the surface. The extreme range of compressional velocities encountered suggests that accurate knowledge of the velocity profile in the region under which the miner is trapped may be required in order to perform accurate location calculations based on arrival time differences.

III. BASIC SEISMIC DATA REQUIRED

If the arrival times are perfectly obtained, then the accuracy of the location is dependent on the accuracy of the model used to represent the earth in the computation of location. Elsewhere in this Volume, Crosson and Peters, and Powell, treat the effect of model errors on location errors. These analyses compare hypothetical laterally homogeneous, horizontally layered earths represented by similarly layered models or continuous models where the seismic velocity increases linearly with depth, and homogeneous half-spaces. These two studies show that the location errors that can be assigned to model errors of this class are much less than the errors experienced with the present seismic location system. This suggests several possibilities:

1. Horizontally layered earth models may be inadequate to represent the real earth.
2. Gross timing errors may have been introduced by the system instrumentation and/or by operator misinterpretation of the seismic recordings.
3. The depth of the weathered layers under the receiving geophones may not be properly taken into account with the present system.
4. Source cavity-produced errors may be present and unaccounted for.
5. Survey errors may have been large.

We are concerned here only with the possible inadequacies of the earth models used to date. It is not possible to say at present what effects gross model errors have, because the seismic properties of the real earth over coal mines are not adequately known. This lack of knowledge emphasizes the need for comprehensive seismic surveys at a few eastern coal mine sites.* These comprehensive tests would reveal what properties of the real earth need to be included in the model, in order to make the model errors small enough to reach the desired location accuracy. The survey tests are outlined elsewhere in this report but would include:

- Surface refraction surveys configured to yield layer data to at least the working depth of the mine.
- High resolution vertical reflection surveys to substantiate the refraction survey and/or identify spatially varying layer properties.
- Core holes with geological logging.
- Core hole to core hole velocity measurements to substantiate larger velocity properties.
- Arrival time plots from mine located impulsive sources as an additional confirmation of seismic properties.
- Precise measurement of weathered layered thickness at seismometer positions.

One of the objectives of this comprehensive seismic survey is to establish if a surface seismic survey can provide adequate detail for the preparation of a sufficiently accurate earth model for location computation purposes. Our discussions with persons experienced in surface refraction surveys[4] indicates that a careful refraction survey done by an experienced survey team can identify well defined layer boundaries to within a few feet to depths near a thousand feet, and that seismic velocities can be measured to within a few percent. The work of Crosson and Peters indicates the degree of location accuracy that would result for models of this accuracy. In addition to undertaking conventional refraction surveys, it may be desirable to consider the technique of Donath and Kuo[5] as discussed below.

The method of refraction surveys for determining the seismic velocity structure of the earth, which is based on fitting straight lines through sets of points on a distance versus arrival time plot, is geared to the specification of plane layered models of the earth. It will not pick up features such as varying layer thicknesses or fractures. However, it is possible to interpret refraction survey data in a more sophisticated manner to reflect, if appropriate,

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* See Appendix A.

the complex nature of the underlying structure. The construction of wavefront diagrams (Donath and Kuo) enables observed travel-time curves to be fitted well when discontinuities or tilts in the topography are present. This type of interpretation of refraction data can be accomplished by a computer program implementable on a minicomputer.

It should be noted that refraction methods do not always give a unique solution and that their interpretation depends on knowledge of the general geological environment as well as on geometrical solution of the travel-time curves. The accuracy with which velocity models can be determined in Eastern coal mining regions, and the need for the wavefront, as against the straightforward, methods of interpretation of refraction surveys in these areas, are matters ultimately to be resolved by controlled field measurements. It can be estimated however, that velocity models should be measurable to within a few percent.

The conduct of the comprehensive seismic survey and the analysis of the data obtained should provide answers to a number of questions that have been raised. Among these questions are: Are earth properties other than horizontal layering of importance to location? Is there any velocity anisotropy of importance? What ranges do the velocity profiles occupy? Can a simple earth model suffice for most mines? Is a simple surface survey adequate to characterize the underlying region?

IV. AN INTERIM EARTH MODEL

Based on available information, and recognizing the uncertainty of important data, Powell has developed a seismic earth model which can be expected to be typical of eastern soft coal regions. The model is not intended to be one for use in the location of miners at a mine disaster, but is rather one which can be used to determine the behavior of arrival times for hypothetical source locations in an earth that has the structure of the model. From such sets of arrival times the accuracy of various location earth models can be established, and a grasp of how accurately the location earth model must approach the real earth can be obtained. As such we consider this model to be an interim one, which can be used for theoretical analyses of location earth model performance, and can be varied to determine the sensitivity of alternative location earth models. The model, which is composed of laterally homogeneous horizontal layers, is described in Table 1. Crosson and Peters, in Part Three of this Volume, use earth models based on this interim model, but simplified to cases of 2 and 4 layers and the case of a continuous velocity variation.

TABLE 1

INTERIM EARTH MODEL

Layer number	Layer thickness (ft)	Layer velocity (ft/sec)
Surface		
1	5	1,500
2	15	2,000
3	30	3,000
4	50	4,500
5	100	6,000
6	200	8,000
7	300	11,000

V. CONCLUSIONS

A comprehensive seismic survey at a number of coal mine sites is recommended as a means of obtaining data to the accuracy necessary for further miner location, earth model development, including a comparison of alternative models. An interim seismic velocity earth model is suggested on the basis of general geological properties of soft coal regions. This model is based on laterally homogeneous horizontal layers, which may be inadequate to properly describe a real mine environment. Its accuracv can onlv be determined when all potential sources of error in arrival time measurements have been accounted for.

VI. REFERENCES

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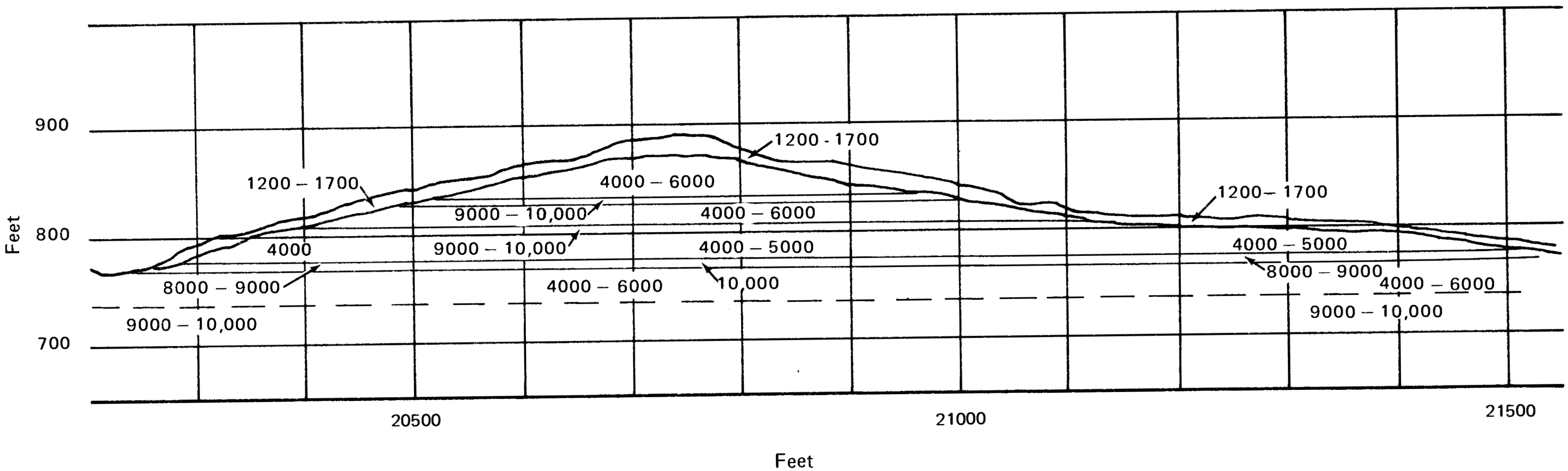
2. U.S. Geologic Survey, Professional Paper 621.
3. Press, Frank, in Handbook of Physical Constants, S.P. Clark, Jr., editor. Geological Society of America, New York, 1966.
4. Mr. Vincent Murphy of Weston Geophysical Engineers and Rev. Daniel Linehan of Weston Observatory.
5. Donath, F.A. and Kuo, J.T. (1962) Geol. Soc. Am. Bull, 73 429-434.

APPENDIX A

SEISMIC SURVEY OVER THE CLARION 4A COAL SEAM

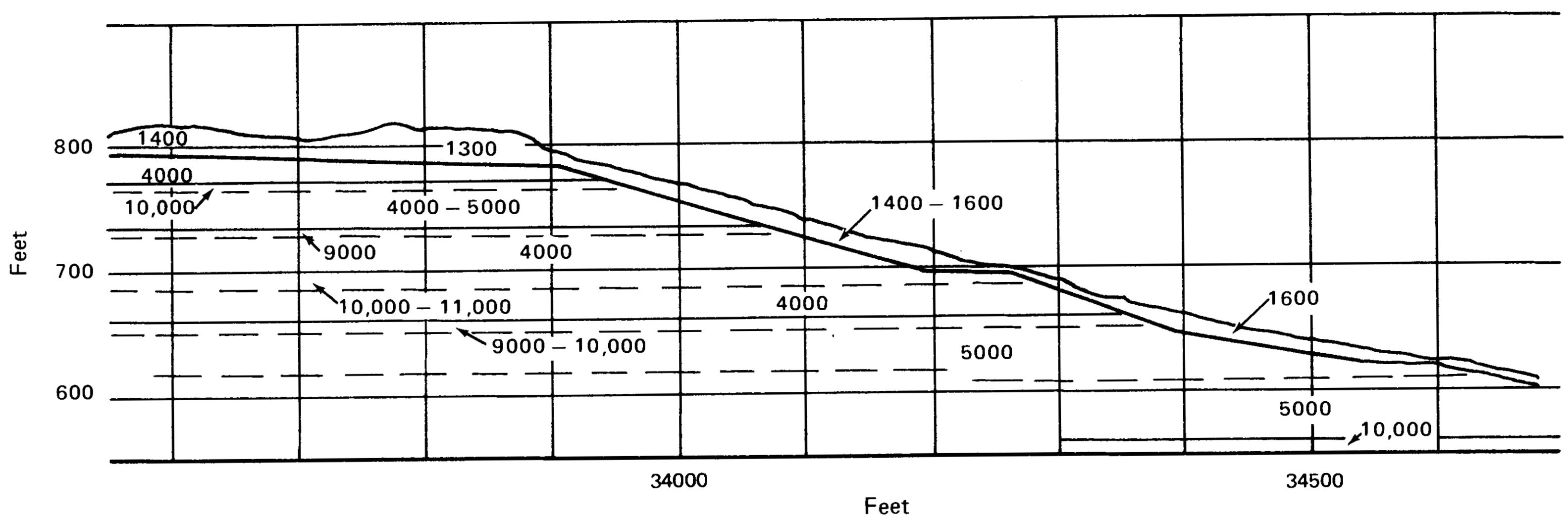
Since the completion of the work upon which this report is based, we have obtained seismic velocity profiles through the good offices of Mr. Dennis Rubin of American Electric Power Service Corporation. These profiles were taken for AEP by Weston Geophysical Engineers, Inc. of Weston, Massachusetts. These profiles were taken in the Meigs County area of Ohio over the Clarion 4A coal seam. Elevations and distances on these profiles are scaled with major divisions equal to 100 feet. Velocities are in feet per second. The profiles are shown in Figures A1, A2, A3, and A4.

These data provide part of the needed base for developing good earth models as noted in this Part. The nature of these data also emphasize the need for further data, to greater depths and higher accuracy over other coal seams.



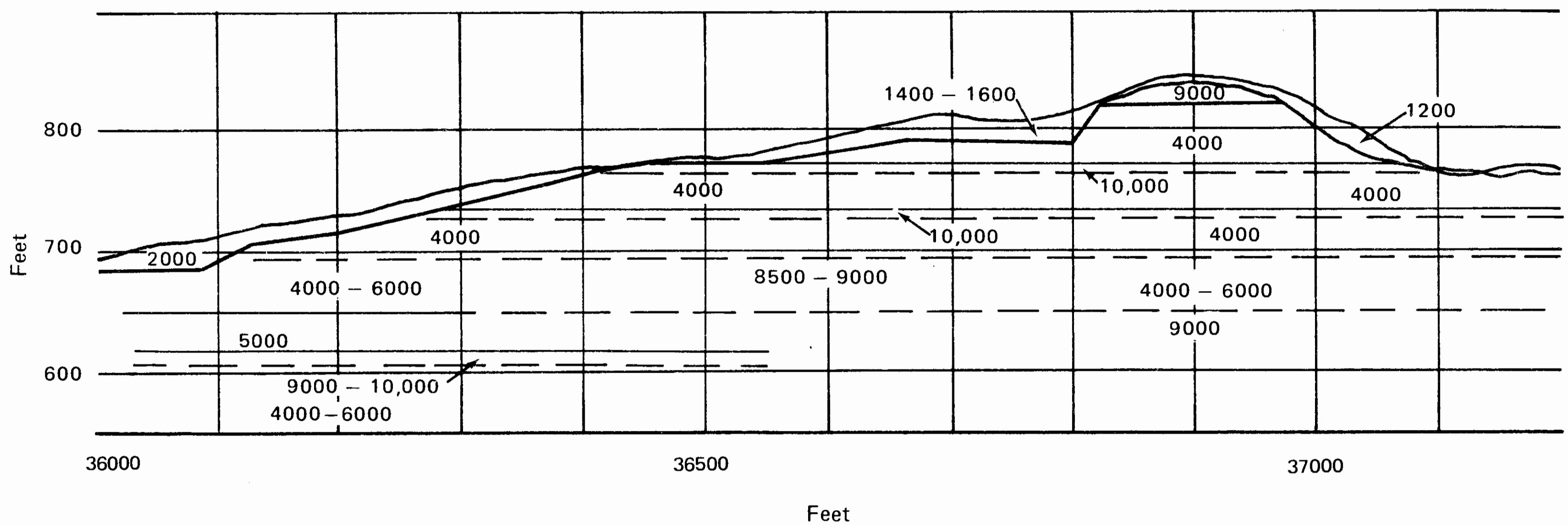
Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A1 SEISMIC VELOCITY PROFILE



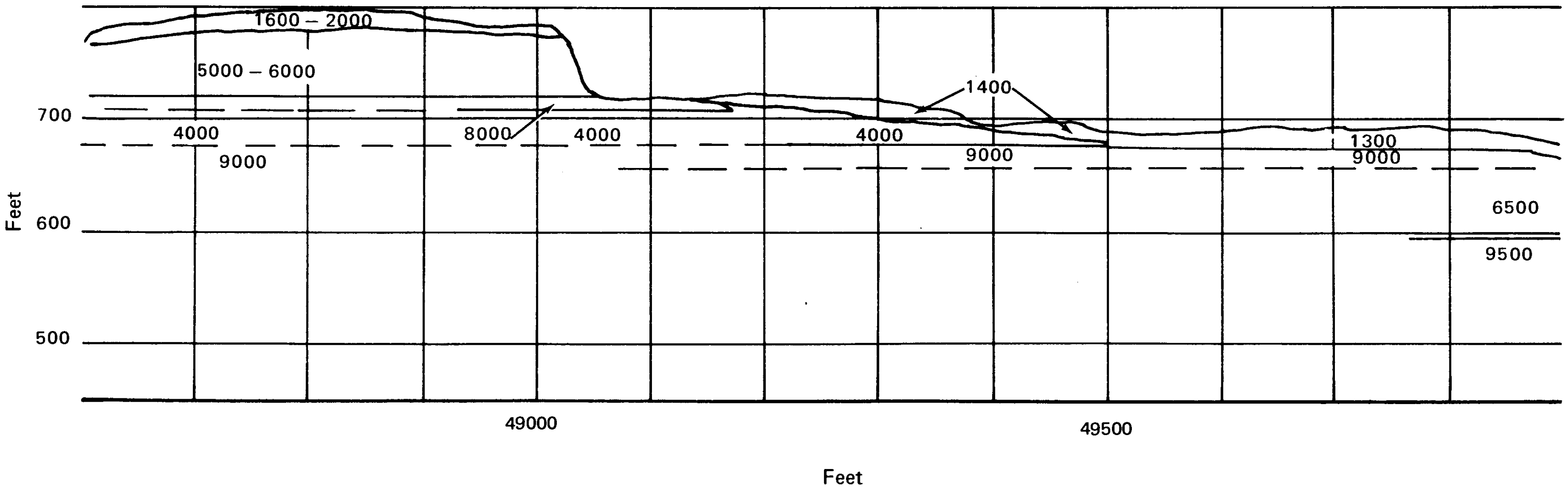
Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A2 SEISMIC VELOCITY PROFILE



Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A3 SEISMIC VELOCITY PROFILE



Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A4 SEISMIC VELOCITY PROFILE

PART NINE

SEISMIC NOISE CHARACTERISTICS

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PART NINE

SEISMIC NOISE CHARACTERISTICS

Francis Crowley
Air Force Cambridge Research Laboratories

I. SUMMARY

Elementary concepts of seismic wave properties are reviewed to establish a framework for discussing seismic noise and its suppression. A liberal number of references is included for those who wish to pursue the topic in detail. A base motion noise level is established for a single surface seismometer. It is argued that simple array processing and seismometer burial should regularly permit us to approach this base noise level which is found in areas free of conspicuous man-made seismic noise sources.

The sensitivity of the base seismic level to a number of common disturbances is presented. Solutions that promise to hold the "effective" seismic noise at a site near the base level are given for acoustic, meteorological and fixed local surface sources. Guidelines are suggested for controlling other local man-made sources, e.g. vehicular traffic, by keeping them at sufficiently large distances away from the seismometers to keep noise at permissible levels. These guidelines are speculative and conservative. They should be the subject of future study.

The ability to process against general local activity, drilling, and intramine sources is limited. Certainly no dramatic gain is to be expected. When strong man-made and/or intramine noise sources are not controllable, detection may well be impossible to achieve, unless the seismometer can be moved close enough to the suspected miner position, i.e. via very deep holes, to compensate for the likely vast differences in strength of the miner signal and the uncontrollable man-made noise sources. However, many intramine sources, e.g., falling water, rock bursts, explosions, etc., may well preclude the existence of a hale miner in their vicinity, and therefore any need to attempt detection of a miner at such locations.

The following recommendations are made to enhance the detection and location of a miner signaling seismically. They are:

1. Seismometer burial in slim holes.
2. Narrow band detection, using multiple narrow band filters to cover the likely signal band.
3. Broadband recording and analysis for time-of-arrival estimation.

II. INTRODUCTION

A. Some Seismic Elementals

The bulk of seismic noise is the aggregate of propagating seismic waves. Being waves, each coherent elemental contribution can be represented as

$$u = U(k\ell - \omega t). \qquad (1)^*$$

Here the motion, u, appears to have constant phase when an observer moves at a velocity $c = \omega/k$. The angular frequency ω is 2π times the number of cycles of a periodic element sensed by a stationary observer per unit time, while k, the wave number, is 2π times the number of cycles observed at an instant over a unit distance. The amplitude of the wave is determined by the source and path attributes.

In the far field and for small source dimensions, u attentuates as $1/R$ in its body phases.[1] Body waves are the only waves that exist in a homogeneous, isotropic, elastic body of infinite extent at small motion levels.[2] They are of two kinds, a P wave whose particle motion is directed along the propagation path and an S wave whose motion is normal to this path. Typical parameters of body waves are given in Table 1.

The p wave displacement $\vec{u}$ due to a localized force F (t) observed in the far field in a medium of velocity V_p and density ρ is given by:

$$\vec{u}_p = \frac{F(t-R/V_p)}{4\pi\rho V_p^2 R} \qquad (2)$$

The velocity of motion at a point $\dot{\vec{u}}$ is a complete replica of $\dot{\vec{F}}(t)$ delayed in time by the propagation delay, R/V_p. Far field particle velocity ratios of soil to rock for a common F(t) and distance are then

$$\frac{\dot{u}_S}{\dot{u}_R} = \frac{\rho_R}{\rho_S}\frac{V_{pR}^2}{V_{pS}^2} \approx 100 \qquad ; \text{ where } \begin{array}{l} S = \text{soil} \\ R = \text{rock} \end{array} \qquad (3)$$

Looking ahead to our discussion of seismic noise levels, we should expect motion levels in soils to be substantially larger than those in rock, when the distributions of sources and source strengths are roughly equivalent.

An alteration of seismic body waves always occurs at a boundary. The waves are converted in kind; boundary phases develop. Techniques for computing the transmissivity of layered media have been the aim of much theoretical work (3,4).

---

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

TABLE 1

TABLE OF SEISMIC VELOCITIES FOR COMMON MATERIALS

Material	Vp ft/sec	Vs ft/sec	
IGNEOUS AT SHALLOW DEPTH			
GRANITE	15,750 - 18,500	9,420 - 10,600	***
DIORITE	19,000	10,000	***
GNEISS	11,500	6,050	***
SEDIMENTARY ROCKS			
LIMESTONE	5,580 - 23,200	9,940	***
MARBLE	12,300 - 22,750	6,625 - 12,660	***
CHALK	8,465	3,510	***
SLATE	14,000	9,380	***
UNCONSOLIDATED SEDIMENTS			
WETCLAY	4,920 - 5,413	375 - 1,150	***
SAND (TIGHT)	1,970 - 6,073	1,150 - 1,340	***
SAND (LOOSE)	655 - (min. meas.)		
SOIL	360 - 656	254 - 298	***
ALLUVIAL CLAY	--	150 - 484	*
ALLUVIAL SAND	--	390 - 650	*
TALUS	262 - 853	--	**
WEATHERED LAYER	980 - 2,950	--	***

* SHIMA (37) ** WATKINS (38) *** GEOLOGICAL SOC. OF AMER, MEMOIR 97 (39)

We speak of waves observed on the earth's surface that attenuate as R^{-1} in the far field as body waves, and those that attenuate as $R^{-1/2}$ as surface waves, each also having different phase velocities. Between these two lie the so-called leaky modes. For horizontally stratified media, leaky mode behavior should dominate the miner's signal[3]. Normal or locked mode transmission should govern an area's noise attributes when excited by distant surface sources[4,36].

Much of the analysis of seismic wave transmission to date achieves mathematical success only when applied to the complexities met on a small scale near the earth's surface. Computational tools are only now becoming generally available to deal with these complexities[27] in a more general fashion.

For a regularly layered area and large distances from the source, surface waves exhibit the following properties:

(1) An attenuation with distance as $1/\sqrt{R}$

(2) An attenuation from the surface in terms of k

(3) A highly selective enhancement of the motion in k,ω space

(4) A phase velocity dependence on k,ω (Dispersion)

For this case, u, is not a delayed version of F(t). Indeed path attributes heavily mask the true history of the source. Schematically we can view the earth as a highly complicated filter that delays and colors the source.

In summary the earth is a linear, passive, time invariant, realizable filter with the following properties:

(1) Adding inputs, adds outputs

(2) Measurements between the source and receiver are coherent (in the absence of noise)

(3) Filtering is multi-dimensional in k,ω.

(4) Reciprocity exists between the source and receiver.

(5) When the collective source attribute is gaussian, the output is gaussian.

B. The Representation of a Seismic Wave

We define $G(\omega)$, the spectral estimate of our motion measured at a stationary point as

$$G(\omega) = \text{F.T.}\{\overline{u(t)\cdot u(t+n\Delta t)}\} \qquad \underline{\text{time average}} \qquad (4)$$

In like manner G(k) is

$$G(k) = \text{F.T.}\{\overline{u(x)\cdot u(x+n\Delta x)}\} \qquad \underline{\text{space average}} \qquad (5)$$

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In like manner G(k) is

$$G(k) = \text{F.T.}\{\overline{u(x)\cdot u(x+n\Delta x)}\} \qquad \underline{\text{space average}} \qquad (5)$$

$$\text{and } G(k,\ \omega) = \text{F.T.}\{u(x,t)\cdot\overline{u(x+n\Delta x, t+n\Delta t)}\} \tag{6}$$

spatio-temporal average

(F.T. = the Fourier Transform)

($\overline{\quad}$ = complex conjugate)

Let us now represent the attributes of an impulse in a non-dispersive medium for these various representations. The impulse is

$$u = \delta(kx-\omega t). \tag{7}$$

The representations are shown in Figure 1.

C. Elementary Array Processing

Arrays are space filters. Their response H(k) is determined by their arrangement in space. For a uniform distribution of seismometers about a point, seismometer summing has the effect of low pass filtering. Hankel transforms apply in this simple case[30]. The response of a seven element, hexagonal array is given in Figure 2[6].

If we now combine frequency and spatial filtering we can pass or reject certain regions in ω, k (Figure 3). For a general discussion of arrays in detection, see Part Ten.

D. Signal Representation

The presumed features of the miner's signal are:

(1) High apparent velocity, $c = \omega/k$ large

(2) Repetitive coherent wavelets

a) F(t) Impulsive: the frequency of the maximum particle velocity[7] $\sim$ to the reciprocal of the half period of the contact time .

b) Path invariant

(3) Proportionately large vertical component (P wave and flat layering)

(4) A lowering of peak frequency with distance due to

1) Internal layering[32]

2) Inelastic response, especially in surface alluvium

(5) Quarter wave leaky resonance of upper layer can enhance the signal wavelet at discrete frequencies[3].

(6) The signal appears coherent only over a small area at the surface[8].

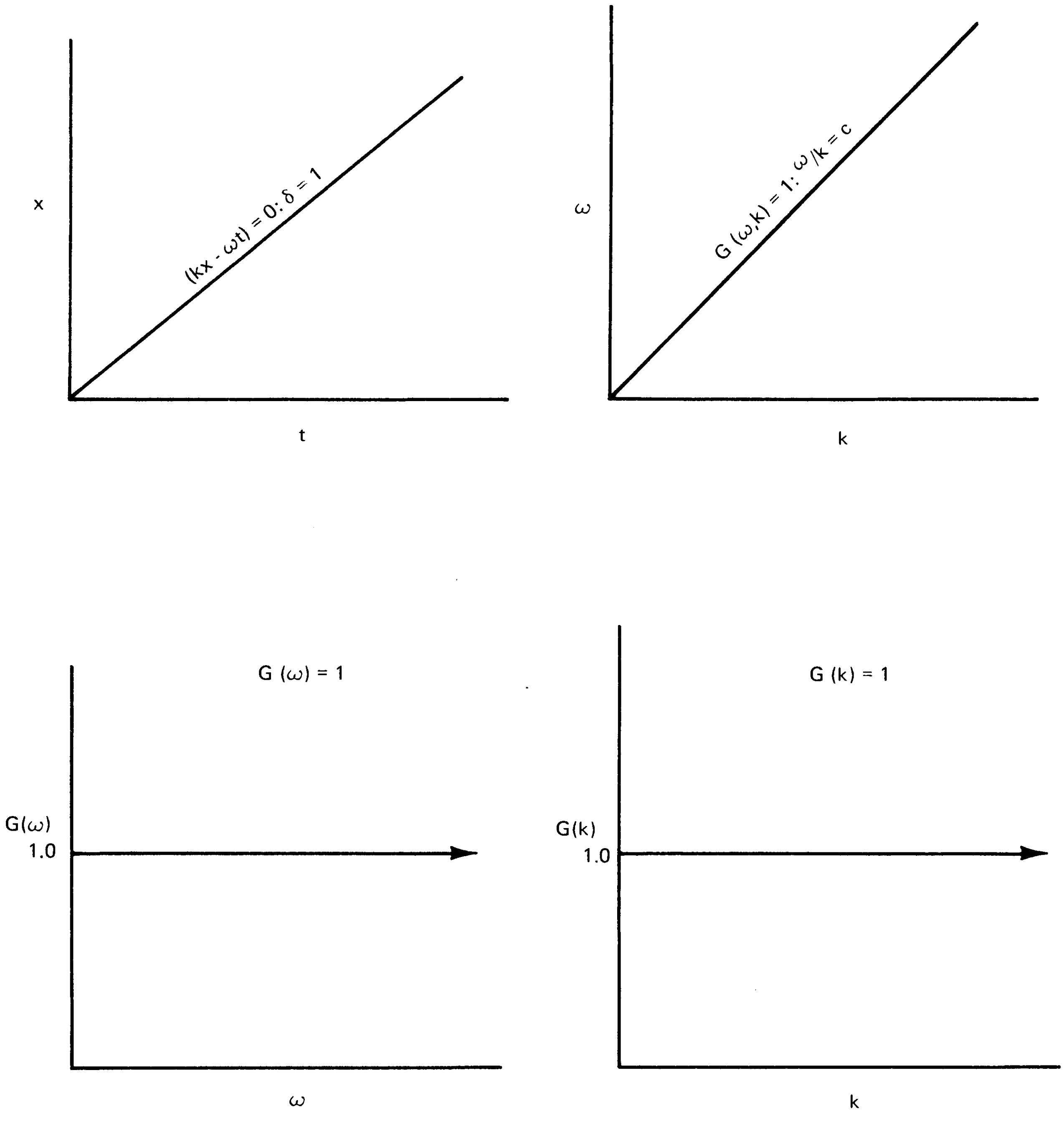


FIGURE 1 REPRESENTATION OF AN IMPULSE

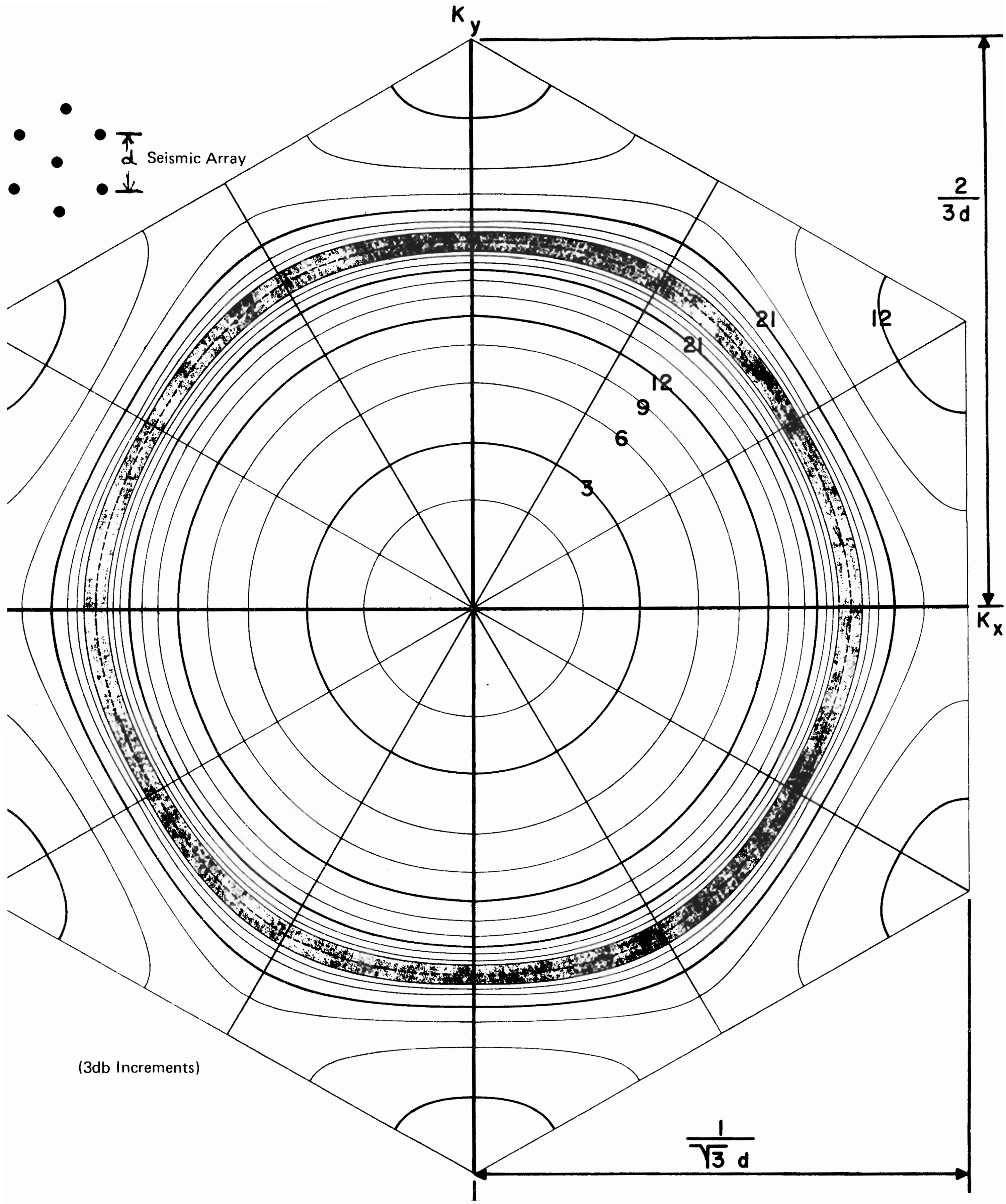


FIGURE 2 K PLANE RESPONSE FOR EQUALLY WEIGHTED 7-SEISMOMETER HEXAGONAL ARRAY WITH SEISMOMETER SPACING d

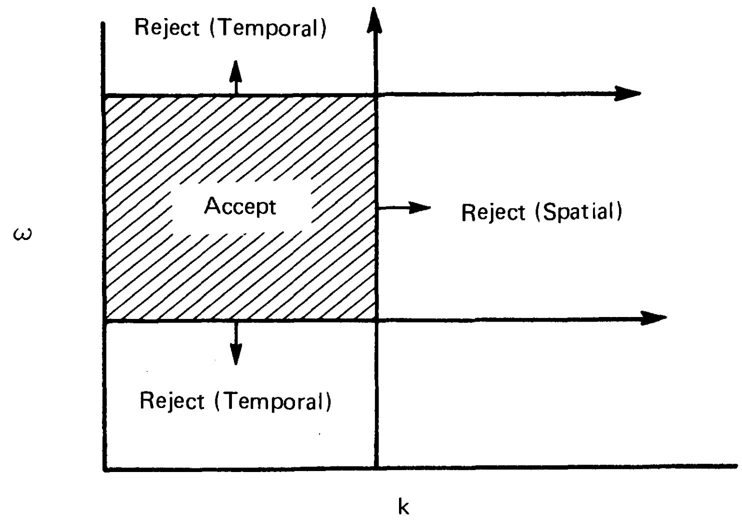


FIGURE 3 SPATIAL AND BANDPASS FREQUENCY FILTERING

The approximate location of the miner's signal in the ω, k plane is shown in Figure 4.

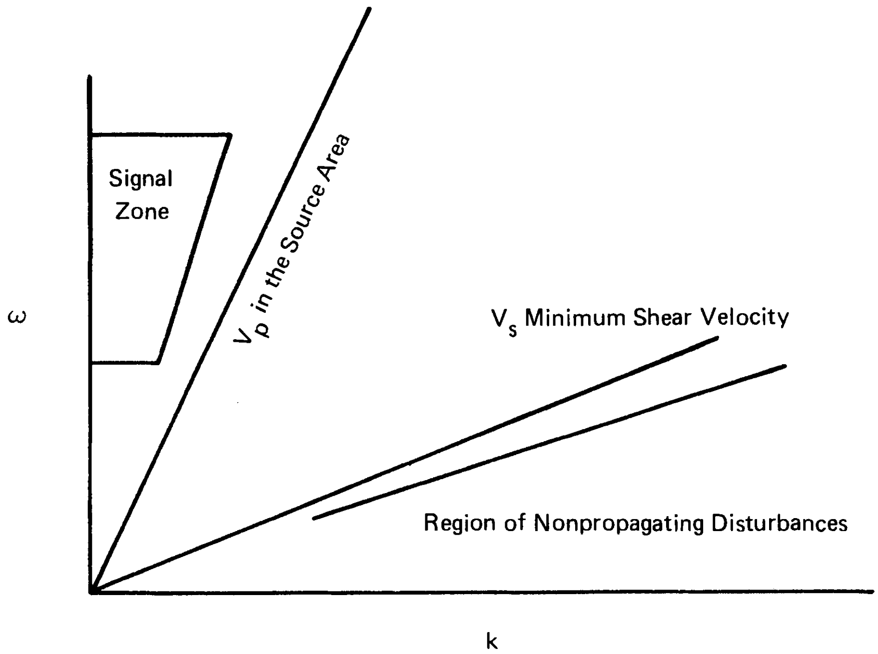


FIGURE 4 LOCATION OF THE MINER'S SIGNAL IN (ω,k) PLANE

III. BASE SEISMIC NOISE LEVEL

A. Statistical Class

In the main, seismic sources have been found to be random and independent[18]. In the absence of a conspicuous source, limit-in-the-mean theorems apply so that the motion level at a point has gaussian attributes. For the case at hand, there is little to suggest either experimentally or conceptually that motions cannot be effectively treated as gaussian variates. As such all the probability information of the motion of a point is given by its covariance or its Fourier transform spectra (mean = 0). The treatment of seismic noise fields for detection is a natural extension of the treatment of random scalar processes. The subject is well developed. For our immediate purposes, spatial sampling allows us to preferentially accept elementary wave components in the signal region. The effectiveness of arrays fundamentally rests on our proper recognition of the propagation attributes of the noise and signal in the ω, k plane.

B. Data Analysis and Estimation of Base Noise Levels of Motion Between 10-100 Hz

Seismic noise above 10 Hz is not a well developed topic, and the bulk of the open literature that does exist requires some interpretation before being compared to periodograms or spectra.

Approximately 20 years ago Wilson conducted a careful experiment in England to discern the origins and nature of microseisms over the band 4-100 Hz. In his experiments he found ground particle velocity rms noise levels as low as 0.2 μips in chalk areas and as high as 1 μips in clay soil areas, over the 4-100 Hz passband, in the presence of system noise of 0.1 μips. These levels represent the rms noise levels remaining <u>after</u> sources such as vehicular traffic, machinery, aircraft, wind-vegation, rain etc., were removed.

More recently Frantti reported surface measurements in the band 10-100 Hz. His results are presented in a series of reports (11,12,13). Given in Figure 5 are the smoothed results of his 1965 report. Here we have taken the liberty to modify his original plots by restoring the measurements to the peak-to-peak value in a 1/3 octave band by multiplying his spectral value by 1/3 octave. This multiplication is consistent with spectral units. Results are given in terms of the upper and lower quartiles and the median, as found at some 90 locations. He selected sample data "during time periods that appeared to be free from obvious, local anomalous sources of noise near the site at the time of recording". As such his levels should also approximate "<u>base seismic levels</u>."

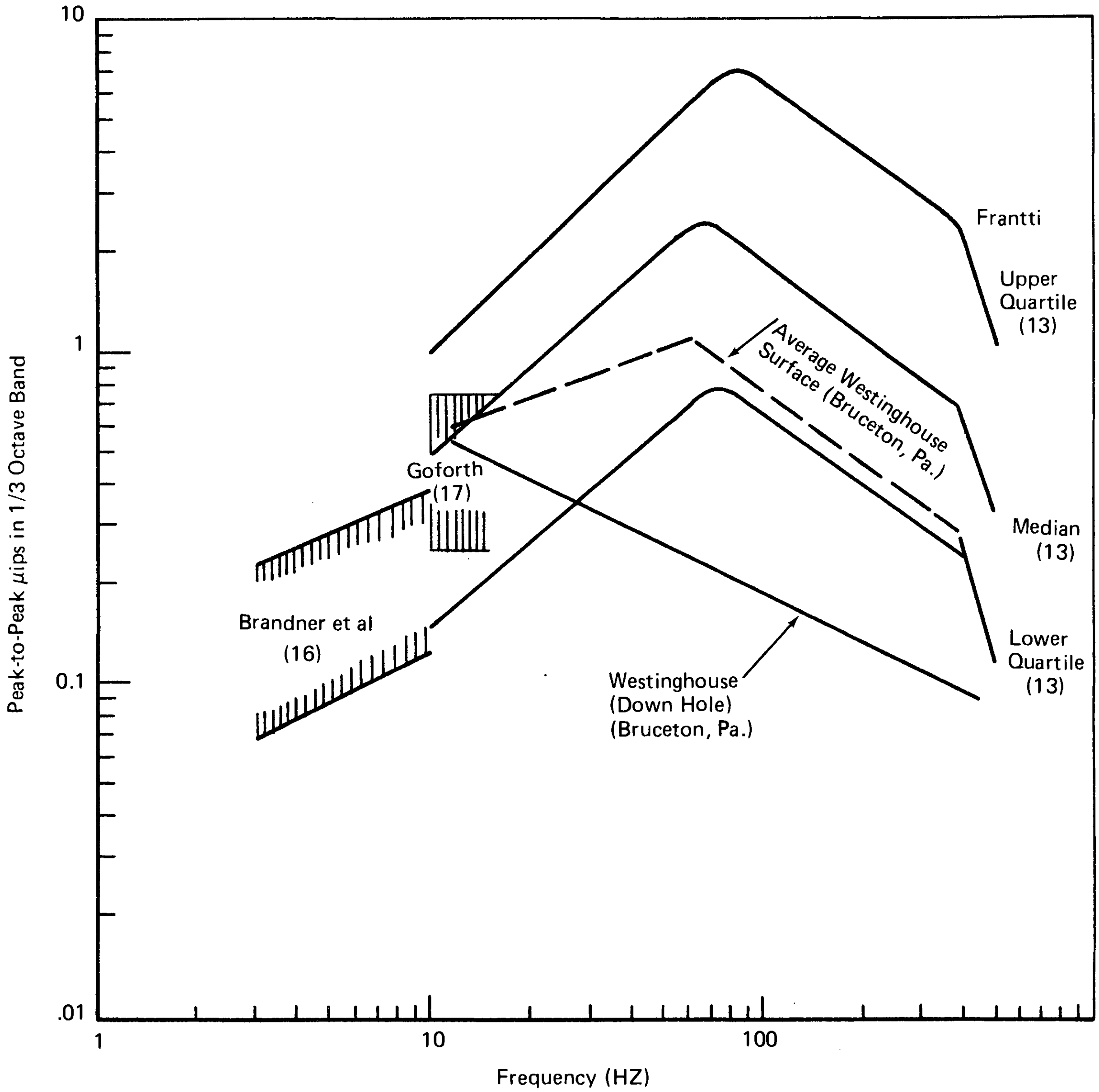


FIGURE 5 SEISMIC BASE LEVELS FOR A SINGLE SURFACE SEISMOMETER

Both Frantti's (1962) and Wilson's data show a strong trend towards clustering the small levels in areas with a surface geology of rock. Both noted a significant increase of level with wind. The upper quartile levels of Figure 5 (after Frantti) are taken to be more suggestive of the base level for alluvial areas. Rock areas in turn are more nearly represented by the lower quartile levels.

Also given in Figure 5 are Westinghouse spectra taken at the USBM experimental mine at Bruceton, Pa.[(8)†] Again we have converted the data to the peak-to-peak value to be found in 1/3 octave bands, by summing the spectra over 1/3 octave and converting to a peak-to-peak estimate by multiplying the rms value by 1.7. These Westinghouse values fall between Frantti's median and lower quartile values in the range 10-100 Hz. Above 100 Hz we have only this Westinghouse data*. For this region Frantti's estimates are extrapolated beyond 100 Hz using the slope of the Westinghouse data taken at Bruceton mine above 100 Hz. This portion of the spectra above 100 Hz must be considered quite speculative.

Also shown in Figure 5 are data taken by Bradner *et al.*[(16)] and Goforth[(17)]. The Bradner values are taken near the ocean. Using Frantti's regional distribution[(13)] of seismic levels Bradner's results appear low, the explanation probably lying in the care used by Bradner in installing the seismometers. By contrast the Goforth data are well represented by the Frantti data. As with Wilson, Goforth has presented a base value. The upper value can be associated with a local anomaly caused by geothermal activity known to exist in the area. Having established a base seismic level and its variation under various conditions for a single surface sensor, a judgement must now be made as to how this seismic energy is distributed in the ω , k plane, in order to determine the base level that would be passed by a small array.

Very few investigators have considered the structure of high frequency seismic noise fields. Aki[(18)] in an extraordinarily comprehensive paper on seismic noise has derived the essential tools for treating the problem. In this work he considered the spatial attributes of an isotropic seismic noise field. These concepts were tested by surface observations. Using only a pair of seismometers and negligible computational hardware, Aki constructed a reasonable picture of the noise at his recording site. He found much of the noise to occur as fundamental mode surface waves. In turn Akamatu[(19)] conscious of the work of Wilson and Aki, concentrated

† Westinghouse Contract H0210063 with Bureau of Mines.

*The "seismic" noise levels reported by Westinghouse prior to the Bruceton mine experiment are not used to estimate the distributions in seismic base level noise, because the lower bounds of that noise data were masked by system noise.

on the distribution of seismic waves with velocity. She found the bulk of the noise confined to velocities much less than 3,000 ft./sec. Guided by these two works and the work of Phillips[20] on small shallow buried arrays, the conclusion is that a small array will have little effect on baseband noise in shallow rock areas. In contrast, for alluvial areas direct summing of a small aperture seismometer array will diminish the base level by 6 db or more at the frequencies of interest.

Westinghouse noise data taken at the Bruceton mine can be used to suggest the impact of seismometer burial on base noise. Given in Figure 6 are the motion levels at a 23 ft. depth during a surface high noise condition. The reported value at this depth falls below quiet surface levels by 2-12 db. Also shown are the corresponding high surface noise levels, and the average surface noise levels at that site.

Therefore a combination of shallow burial and the use of arrays might be reasonably expected to attenuate base seismic levels by 10 db in low velocity alluvial areas. In shallow hard rock areas, the attenuation will be substantially smaller if our experience in the 1-10 Hz band remains valid. Consequently the base seismic noise level in the miner's signal band, after burial and array summing, should be reasonably close to values in Frantti's lower quartile. Futhermore, variation about the median should be significantly reduced below the original "untreated" surface noise dispersion.

Estimated base noise peak-to-peak levels, as seen by 1/3 octave passbands have been plotted in Figure 7 for shallow buried arrays. Figure 7 indicates that the upper quartile-to-median noise levels, after burial and arrays, should fall to levels between median-to-lower quartile levels of Figure 6 for a single surface seismometer, over the frequency range approximately bounded by 40 to 120 Hz. This is the band where most of the miner generated signal energy has been found to date. Figure 7 also reveals the flattening of the Figure 6 noise spectrum over the 10-100 Hz range, and the more rapid roll-off above 100 Hz,expected with shallow buried arrays.

The values shown are sensitive to bandwidth. As given, they are directly applicable only to narrow band signal detection. The curves are readily adjusted to larger bandwidths in their flat areas by multiplying the value shown by $\sqrt{n}$ where n is the number of third octave bands in the desired larger bandwidth.

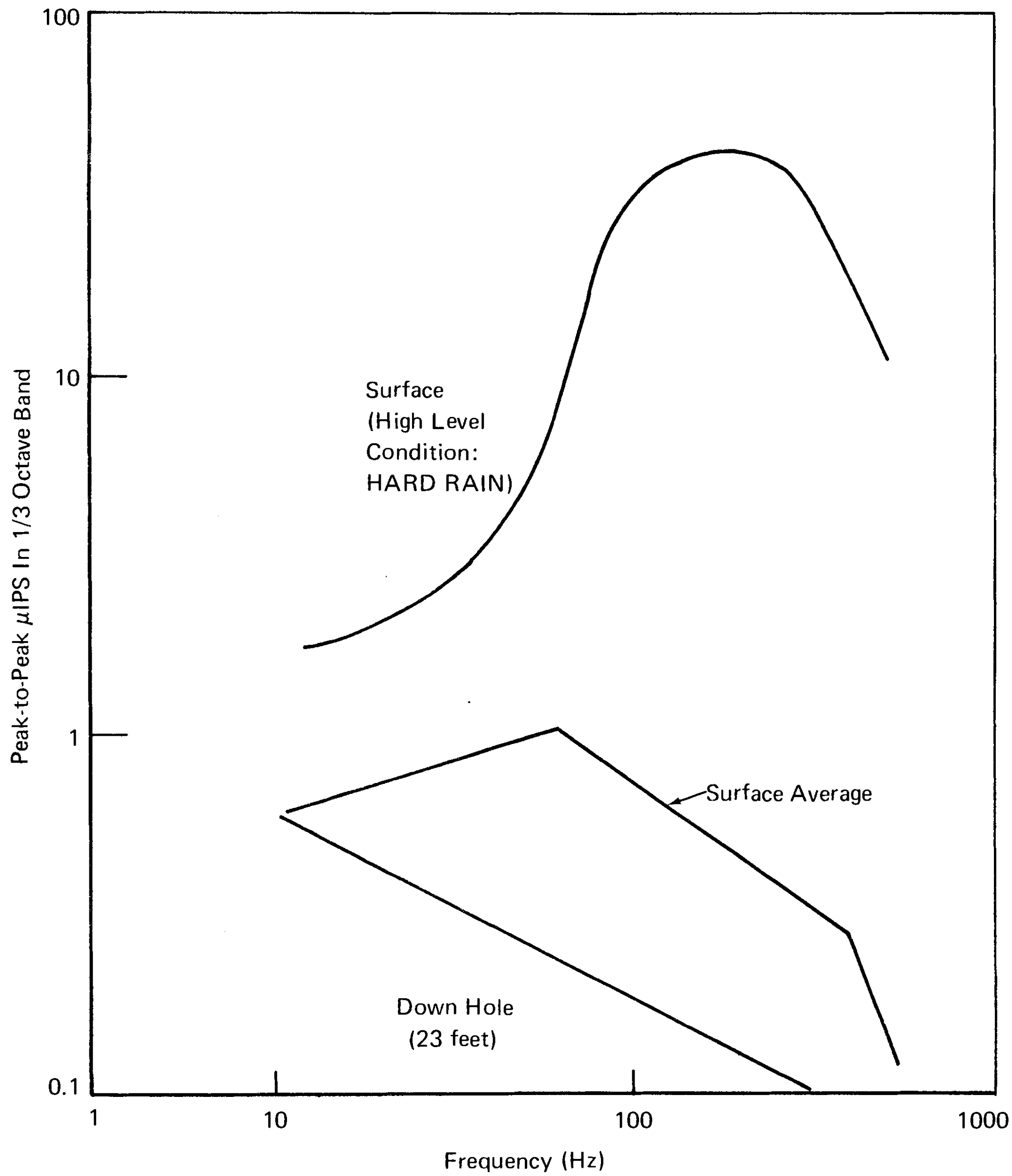


FIGURE 6 WESTINGHOUSE DATA FOR SEISMIC NOISE LEVEL AT 23 FT. DEPTH DURING A HIGH SURFACE NOISE CONDITION (BRUCETON)

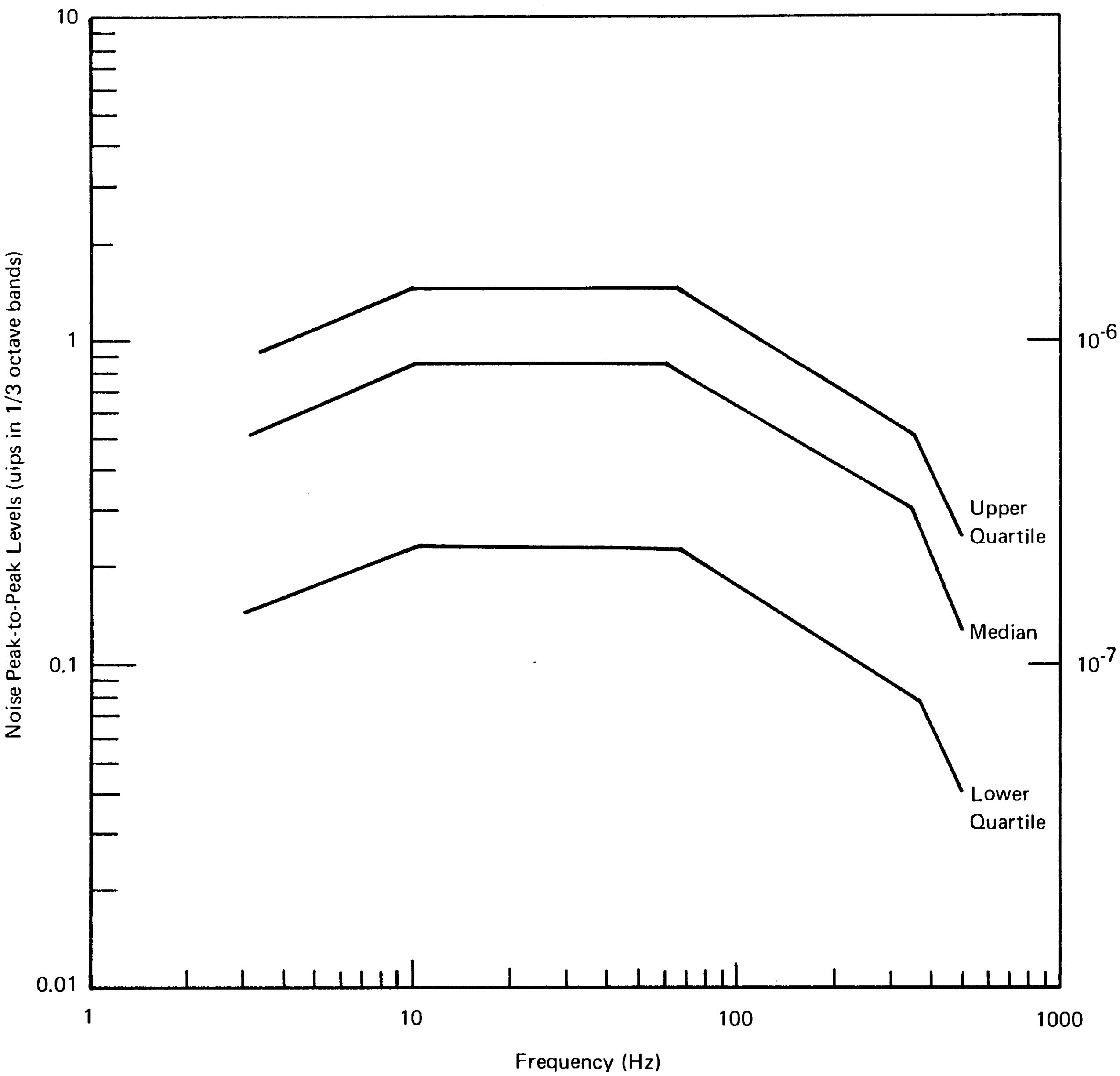


FIGURE 7 ESTIMATED SEISMIC BASE NOISE PASSED BY SHALLOW BURIED ARRAYS

At low frequencies, seismic spectral levels appear to be flat with velocity. At higher frequencies, spectra tend to be flat with acceleration. Since, at very high frequencies, the base level becomes exceedingly small, and system noise is approximately flat with velocity,[8] we can therefore expect that any measuring system will eventually become system-noise-limited, if this spectral trend continues in the base seismic noise.

The Figures 6 and 7 plots represent our best estimates based on the limited noise data available to date in the 10-100 Hz frequency band of interest. As such, they should still be considered speculative base levels requiring verification, particularly for the Eastern coal mining regions.

IV. COMMON NOISE SOURCES

Having established a base seismic noise through our system, the impact of conspicuous noise sources must now be assessed. Three common sources of seismic surface noise are acoustic, wind (rain), and fixed local machinery. Each source will be considered in turn with a method of dealing with it to maintain an overall seismic noise value near our base level.

A. Acoustic: Piston Aircraft

According to Wilson, low flying aircraft are capable of increasing the seismic base level when they close to within about 10,000 ft. In this case, the ground disturbance sensed by the seismometer should take the form of an air coupled seismic surface wave, assuming that the seismometer is sufficiently buried to protect it from the direct air wave. Such disturbances occur when the horizontal phase velocity of the air wave matches that of the seismic surface wave in the ground. In this situation, large motions result (Crowley)[33] but the structure of the disturbance is such that simple array processing should be quite effective. As shown in Figure 8, such behavior occurs at the intersections of the v_a line with the Rayleigh wave curves (1) and (2).

The sensitivity of a site to air-coupled disturbances is best determined by firing a small explosion on the surface. Once the wave number, k, of the air-coupled term is known, an omnidirectional array can be constructed to suppress it by something near 20 db. As aircraft approach closer to the sensor at low levels, at a distance of say 5,000 ft., the air-coupled wave pole in (ω, k) will start to migrate towards the signal zone. Also, the array will cease to suppress the disturbance. At a distance of say 1,500 ft., the disturbance will probably start to saturate any system working at a base seismic level in a uniformly layered area with an alluvial surface geology.

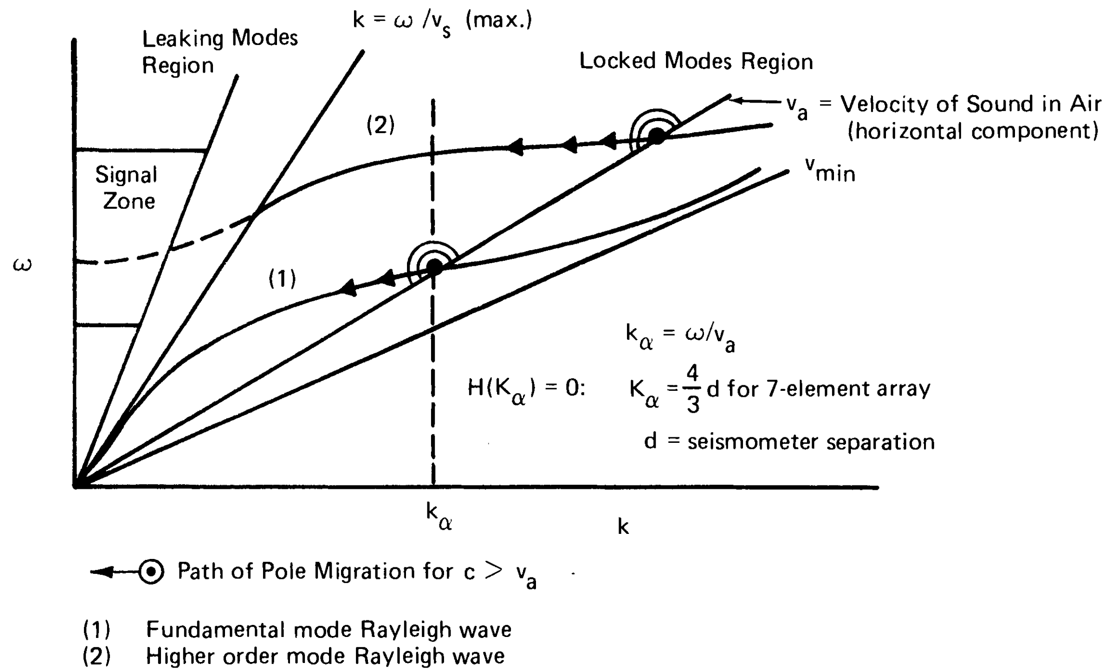


FIGURE 8 AIR–COUPLED SURFACE WAVES IN LAYERED MEDIA

Other sources of acoustic noise, such as diesel generators, can be dealt with by combinations of seismometer burial and coherent processing as discussed in Section C below.

B. Wind and Rain

A single surface seismometer is severely affected by wind and rain. As noted by Wilson, Frantti and Westinghouse our base noise level can be exceeded by two orders of magnitude during a meteorological disturbance. Surface arrays when summed in this condition suppress this type of noise by no better than $\sqrt{N}$. This processing gain is trivial in light of the desired base level. In contrast to array processing, burial appears to be extremely effective. Westinghouse reported a 6 db attenuation by burying to only 0.5 ft. and an attenuation between 20-40 db was achieved by 20 ft. of burial. Modest burial of a single sensor, or shallow burial of a small subarray, should hold most meteorological disturbances to permissible noise levels.

C. Fixed Local Disturbances

Wilson noted pumps disturbed his base level at a distance of less than 10,000 ft. Such disturbances are quite capable of degrading our signal zone as depicted in Figure 9. Normal array processing can be effective only for that portion of the noise exterior to the signal zone. An alternative approach for rejecting these disturbances is offered based on the fact that the noise source area is coherent with the disturbance sensed by the subarray. The problem is schematically represented in Figure 10.

Since the earth is a linear filter, a measurement in the neighborhood of the source will be completely coherent with n_1' (t), i.e., the unpredictability of the motion n_1 (t) is a source attribute, not a transmission attribute. Hence a measurement at p_1 of n_1 (t) can remove the n'_1 (t) contribution sensed at the subarray location p_2. Following Levinson[21] a predictive filter can be constructed between two points even with a minicomputer. The key to the success of this coherent processing is that the dynamic range of the measuring system be sufficient to obtain an adequate representation of n_1 (t).

For the bulk of static sources, e.g., machinery, the resulting disturbance is narrow band. In this case a short prediction operator is adequate. Processing gains of 20 db should be readily attainable.

D. Moving Sources at a Distance

Moving seismic sources, e.g., vehicle traffic, man walking, drilling etc., disturb our signal band in the manner of Figure 9. Neither shallow burial nor arrays offer much hope of a dramatic processing gain. For this case the only

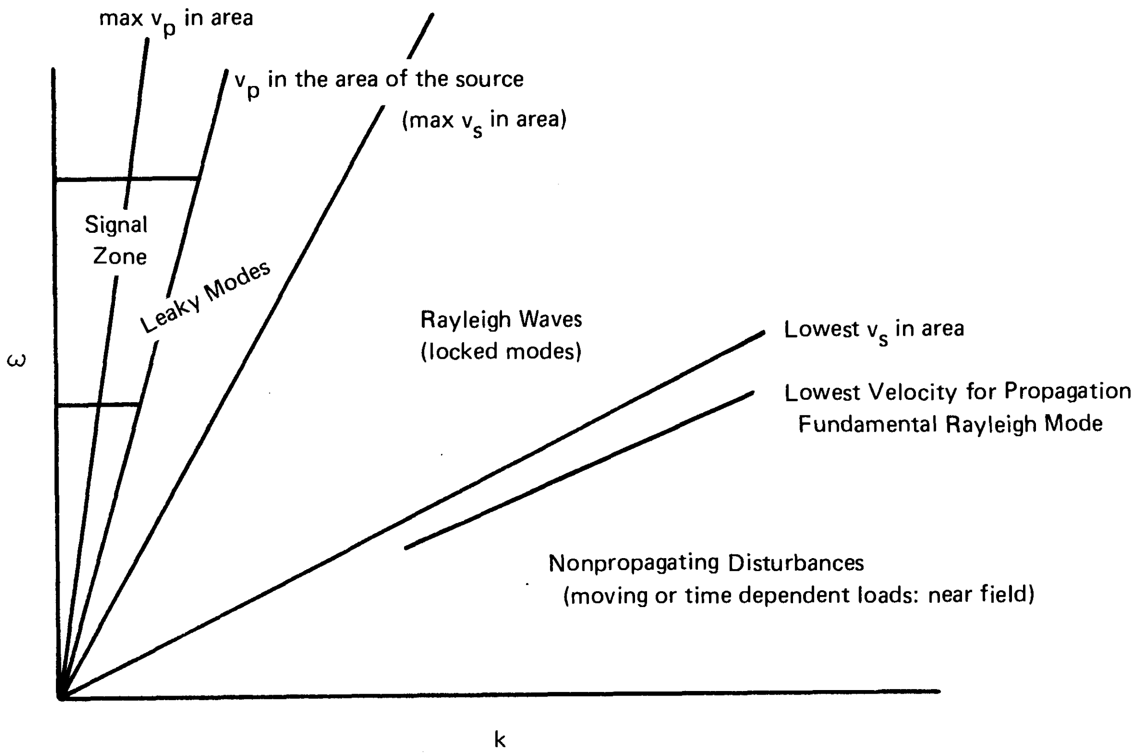
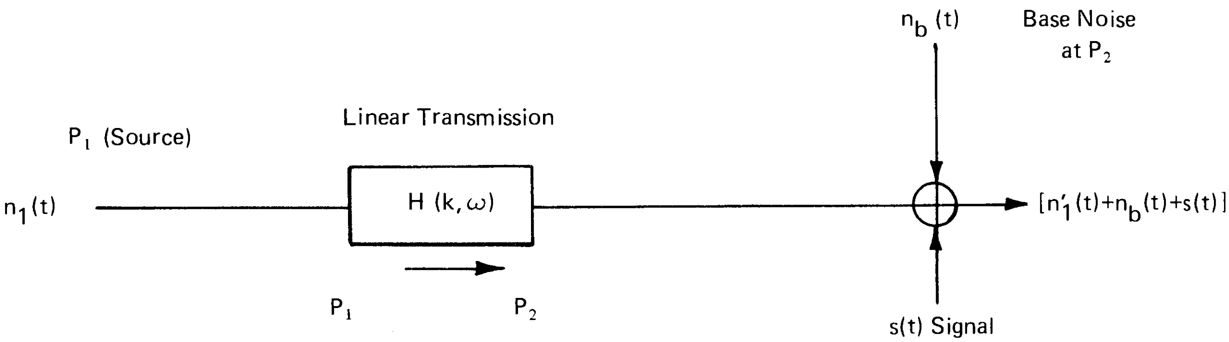


FIGURE 9 SIGNAL AND NOISE ZONES EXCITED BY DISTANT SOURCES IN LAYERED MEDIA



$n_1 * n_1' = h_p^{12} * n_1 * \overline{n}_1$

h_p^{12} = Predictive Operator $1 \rightarrow 2$

$n_1 * \overline{n}_b = 0; n_1 * \overline{s} = 0; n_b * s = 0$

$n_1(t) >> n_b(t)$ near P_1

Note: From reciprocity the noise source and observation point can be exchanged. Such exchanges would provide a basis for evaluating inelastic effects at the miner's source.

FIGURE 10 A REPRESENTATION OF A SINGLE FIXED NOISE SOURCE

way to ensure a S/N gain is to move the detector closer to the source and away from the noise. As a rule of thumb the noise of a surface noise source gives rise to a signal below the surface that is twice that of a point buried source. Hence for a detectable signal ($3 = S_m/S_n$) in the far field for a common path material we have:

$$6(\dot{F}_m/R_m)/(\dot{F}_n/R_n) = 3, \tag{8}$$

i.e., a concentrated noise source at the surface, F_n, must be removed a distance equal to 6 detector distances in order to detect a miner source, F_m, of the same strength, all else being equal.

For the purpose of this discussion we have ignored the possibility of a signal separation in frequency due to the source character, the losses normally met in the surface layer caused by internal reflections, and inelasticity. Our conclusion should be on the conservative side for a deeply buried detector. Clearly, as the detector enters the near field of the source, a large enhancement in the miner's signal occurs since wave losses in this region vary as R^{-3}.

E. Intra-mine Sources

Intra-mine disturbances will produce signals in the miner's signal zone; hence an array processor will tend to pass them. The impact of "hard" noise sources such as these and seismic disturbances caused by deep drilling are difficult to assess. For a comparable source strength, these sources should be removed from the array at least three (3) times the distance of the miner in order not to interfere with detection. In the event that these noise sources are substantially closer, the base noise levels suggested here cannot be maintained. Table 2 is suggested as a guide for controlling noise sources to hold seismic levels near the base values of Figure 7.

TABLE 2

SEPARATION GUIDELINES FOR DEALING WITH MAN-MADE NOISE SOURCES*

Type	Distance	Detector
Light Vehicular	10,000 ft.	Single Phone
	5,000 ft.	Buried Array
Piston Aircraft	20,000 ft.	Single Phone
	5,000 ft.	Buried Array
Lone Trees and Telephone Poles	400 ft.	Single Phone
(heavy wind condition)	150 ft	Buried Array
Drilling	7,500 ft.	Single Phone
	5,000 ft.	Buried Array
Man Walking	1,000 ft.	Single Phone
	500 ft.	Burried Array
Machinery (heavy)	10,000 ft.	Single Phone
	2,000 ft.	Coherent Processing
Intra-Mine Sources	3,000 ft.	Single Phone
(miner equivalent)	3,000 ft.	Buried Array

* The detector scheme and noise source-detector separation distances shown are those which should be sufficient to keep the disturbance of the associated noise source within the "base" noise levels discussed in Chapter III of this Part. These guidelines should be considered both speculative and conservative.

V. HIGH FREQUENCY LOW LEVEL SEISMIC NOISE

The measurement of high frequency low level seismic disturbances will probably always be eventually limited by system noise due to the inherent properties of a seismometer[25], its coupling to the ground[7], and the lossy character of the ground[2]. The problem is depicted in Figure 11.

(1) The free period of the seismometer, f_a (4-20 Hz), depending on choice of seismometer.

(2) The cutoff frequency of the seismometer due to ground coupling (100-300 Hz).

(3) The cutoff frequency due to the seismometer coil inductance (10-70 x f_a)

(4) Parasitic responses of the sesimometer (50-100 x f_a)

Here it is assumed that the seismometer is buried at least to a depth sufficient to suppress direct forces on its case by other than earth motion, i.e., rain drops, wind loading, acoustic. A depth of burial in the range of a few feet should suffice.

For the problem at hand the need to treat ever higher frequencies is eventually limited by the expected performance/cost ratio of the system. It is well known that the impact of horizontal layers on highly incident seismic waves is basically that of a low-pass filter. This loss and losses due to inelastic properties of a real earth serve to force us to consider "low frequency" signals even for impulsive sources at distances of say 1000 ft. Also as we are forced to consider frequencies substantially higher than 100 Hz, uniform, hard coupling of the seismometers to the earth becomes ever more difficult. In addition, data rates rise, and the useful dynamic range of any measuring system is invariably bandwidth-limited. Comparing the reduced expectations for signals suggested by the present observations and the penalties incurred, it is recommended that the upper frequency of a miner's rescue system be no more than 250 Hz.

VI. OPTIMUM ARRAY PROCESSING

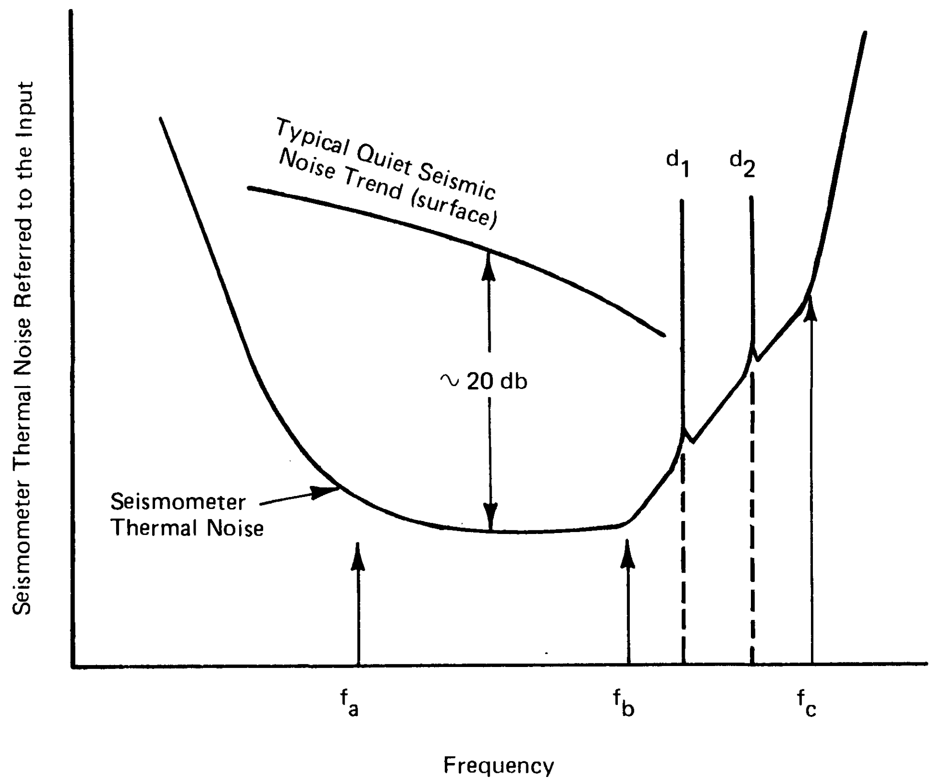
The value of optimum array processing in a general sense cannot be now assessed. However several factors mitigate against normal optimum processing.

(1) The computational burden exceeds the limited capacity of a field-deployable system.

(2) The time required to determine the covariance matrix estimates of the noise field appear excessive.

(3) The nature of the noise field being of man-made origin should exhibit strong non-stationary properties.

(4) The signal character over the sub-array is not well known in advance.



f_a = Free period of seismometer $f_a \sim$ (4-20)Hz depending on choice of seismometer

f_b = Cutoff frequency due to ground coupling, 100-300 Hz

f_c = Cutoff due to coil inductance, $\sim 50 \times f_a$

d_1, d_2 = Parasitic responses of seismometer, $\sim (40\text{-}50) \times f_a$

FIGURE 11 THE PROBLEM OF HIGH FREQUENCY, LOW LEVEL MEASUREMENTS

VII. NARROWBAND DETECTION

As stated by Greenfield in Part Ten, bandpass filtering can improve the signal to noise ratio when the major energies of signal and noise are separated in frequency. Since the response of a layered earth is sensitive to the depth of the source, we can anticipate on seismic grounds that the spectral content of the miner's signal[3] will differ markedly from the noise level spectra caused by surface sources[36]. For example the Westinghouse data from the Geneva mine (Field Rept. 2) exhibit a signal to noise (S/N) ratio variation as a function of frequency which shows maxima near 45 and 150 Hz. Furthermore, the ratio is quite variable over the system passband; i.e., there is a large separation of signal and noise in frequency.

Based on the above result, some form of narrow band envelope detection should be explored as a potentially valuable technique. As envisioned in this technique, data from each subarray would conceptually be filtered through something like 1/3 octave bands. Each elementary band would then be normalized, rectified, and low passed with a filter having a time constant somewhat shorter than the duration of the miner's signal. The resulting levels would then be passed to a variable density, area or event, display to generate exceedence patterns. The statistics for this kind of narrow band signal envelope detection processing are well known.[35]

For the miner detection problem, coincidence of threshold exceedences can be looked for between subarrays. Furthermore, the repetitive characteristic of the miner's signal can serve as the final basis for rejecting false alarms. It is recommended that the potential of narrow band filtering and envelope detection be considered using the existing data base. Clearly, its value should be compared with other detection schemes that are simple, well known, and easily automated.

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PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

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PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

Roy Greenfield

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I. SUMMARY

During the detection phase, several procedures can be used to improve the signal-to-noise ratio (S/N).

- Subarrays of up to 10 seismometers should be used. The apparent failure to obtain improvement in S/N in the Westinghouse subarray work is probably due to excessive noise in the electronics. The spacings needed for sensors in the subarray must still be established.
- The sensors should be buried. Even burial to a few feet will probably give appreciable reduction of noise. A deeper burial will probably further reduce the noise; and, if the seismometers can be put below the weathered layer, the signal level will probably be increased. The reduction in noise by burial will be especially effective during high noise periods due to wind or rain.
- Before attempting detection, the waveforms should be bandpass filtered. The bandpass should go from 25 Hz to an upper frequency of 100 to 200 Hz. Further measurements with a low noise system must be done before the signal-to-noise ratio can be determined for the 100 to 200 Hz range. Any narrow band noise should be removed by notch filters.
- If noise levels differ among seismometers of a subarray, weights inversely proportional to the noise power should be applied to the seismometers.
- Automatic methods of screening data for possible signal arrivals should be developed, but the final determination that the signal on a subarray output appears to be from a miner should be made by an analyst. Detection of "signal" on several subarrays should be required for positive identification.

In the location phase, after detection:

- If repeated signals are received, they should be coherently added (stacked) to give as good a S/N as possible for use in determining signal arrival times, to be used in location computations. The miner should, if possible, repeat the signal 25 to 50 times.

It is probably not worth the increase in system complexity to implement such complex signal processing methods as multi-channel maximum likelihood filtering, linear particle filtering, or prediction error filtering. These will probably not give much signal-to-noise improvement. Matched filtering does not compress the body wave signals in time, and thus will not improve system performance any more than any suitable bandpass filter.

II. BRIEF DESCRIPTION OF TECHNIQUES

A. Linear Phase Filtering of Multicomponent Data [1]

The vertical component of a seismometer is added to a time shifted version of the horizontal component. With proper time shift this processing can accentuate a linearly polarized P wave arrival while suppressing eliptically polarized Rayleigh surface wave noise.

B. Remode [2] [3] [4]

A nonlinear method to accentuate linearly polarized portions of single sensor 3-component seismic data.

C. Delayed Sum

The output of each of a group of seismometers is delayed so that signals traveling at a selected horizontal phase velocity are added coherently. Note that the presently used system of subarray addition is a special case of delayed sum with zero delay between channels. Noise which is uncorrelated is reduced by a factor of 1/N in power where N is the number of seismometers. Coherent noise with phase velocities different from the direction at which the subarray is aimed is also reduced; the amount of reduction depends on the subarray pattern.

D. Weighted Delay and Sum

This processing is similar to delayed sum processing, but amplitude weighting of the channels is designed to maximize the suppression of coherent noise. The weights for this processing can be adaptively designed [5] to optimize suppression of a time varying noise field. The method is also useful if the noise level is unequal among channels.

E. Multichannel Maximum Likelihood Array Processing [6] [7]

The seismometer outputs are first time aligned for the horizontal phase velocity of the signal. Then an individual filter is applied to each channel. This processing is designed to operate where the signal is the same on each channel. Filter design requires extensive digital computation, and the filtering operation itself is costly in computer time. This form of processing can give large S/N improvement when a wideband signal is to be examined and coherent noise is present.

F. Multichannel Weiner Filtering [8]

This form of processing is similar to multichannel Maximum Likelihood Processing; however, the filters are designed for a signal modeled as a stationary multidimensional random process.

G. Single Channel Bandpass Filtering

Bandpass filtering can improve S/N if the major energies of the signal and noise are separated in frequency or if the signal is of narrower band than the noise.

H. Single Channel Prediction Error Filtering [9]

A filter is designed based on the noise to predict the noise ahead in time. The predicted noise is subtracted from the seismometer output, reducing the noise at the output of the filter. At the commencement of the signal the filter does not attenuate the signal, so the S/N ratio can be improved. This type of filter works best when the noise is fairly narrow band, so the filter can do a good job of noise prediction.

I. Multichannel Prediction Error Filtering [10]

The noise on each channel is predicted by applying filters to the noise on all the channels. This noise is subtracted from each channel and a trace produced for each channel. When the noise field is coherent between the channels, this procedure can give better noise reduction than the single channel prediction error filter.

J. Matched Filtering [11] [12]

If the signal waveform is known, a matched filter can compress in time a dispersed waveform by removing the dispersion effect, and thus give an improve-provement of S/N equal to the time bandwidth product. The matched filter is implemented by convolving the signal with a filter whose response is that of the known waveform. In addition, the application of a matched filter acts as a bandpass filter, and thus gives an additional S/N improvement by rejecting out-of - signal-band noise.

K. Design of Subarray Configuration [13] [14]

A configuration of seismometers has a frequency dependent array response pattern. In areas of coherent noise the placement of sensors can be such as to put a low part of the beam response at the horizontal phase velocity of the noise. Spacing of the sensors far enough apart so the noise appears incoherent leads to a $1/\sqrt{N}$ reduction in noise amplitude, where N is the number of seismometers in the subarray.

L. Burial of Sensors [15] [16] [17]

If noise is composed of Rayleigh waves the noise amplitude falls off with depth; burial of sensors can lead to a decrease in noise amplitude. If noise is due to transient surface loading near the seismometer and has a certain correlation distance, then the noise level will also fall off with depth.

III. SIGNAL PROCESSING FOR DETECTION OF A MINER

Detection of a trapped miner by seismic means requires that the presence of a signal is identified in the presence of ambient background noise, and that this signal may be identified as the efforts of the miner. In this detection section we first consider what can be done on the subarray and individual sensor to improve S/N, then discuss how to use the subarray outputs to detect the miner's presence.

A. Signal-to-Noise Improvement on the Individual Sensor Level

Filtering methods which could be considered for application to a single seismometer output include Remode, Linear Phase Filtering of Multicomponent Data, Bandpass Filtering, Single Channel Weiner Filtering, Single Channel Prediction Error Filtering, and Matched Filtering. We now comment on the usefulness of these various methods.

1. Remode - This type of processing will not be useful for several reasons. First it must be designed and applied digitally. For application to 50 sensors at a sampling rate of 500 to 1000 samples per second the computation load would be far too large and not practical. Secondly the filter is designed on the

in-phase property of the P wave on the horizontal and vertical seismometers. From Westinghouse data, it appears that the arriving P wave is almost completely linearly polarized, but in the vertical direction, i.e., no horizontal (see Plot 49, Westinghouse Field Report No. 8).* Because of this, the Remode filter design would not work for P waves. However, it might work on part of the later arrivals. The reason for the vertical polarization is believed to be caused by the ray being bent toward the vertical as it traverses the low velocity material normally near the surface. Thirdly, it has not been established that the ambient noise is elliptically polarized as for a Rayleigh wave. Fourthly, implementation requires addition of horizontal sensors to each channel.

2. Linear Phase Filtering of Multicomponent Data - This type of filter might improve the S/N ratio, by subtracting a properly phase-shifted version of the horizontal from the vertical record. This could remove some of the elliptically polarized noise from the vertical. It is rather hard to estimate, without implementing the filtering on actual data, how well it will work. However, if the noise is predominantly Rayleigh wave from one direction, this method could work where Remode does not. This type of filtering could be done with analog equipment. Again, it would be required to have horizontal as well as vertical sensors.

3. Bandpass Filtering - Most of the signal energy is below approximately 200 Hz, and for many of the signals, it is below 100 Hz. (See Figures 2-11, 2-12, 2-13 of the Westinghouse Fy '72 Report.)* Westinghouse data suggests that significant seismic noise energy may exist out to frequencies of 500 Hz or more (see Figures 2-7, 2-8, 2-9). However, its contamination by electronic system noise lowered our confidence that the data really shows the presence of high frequency seismic noise. If the high frequency noise shown by Westinghouse is indeed seismic noise, bandpass filtering can increase the signal-to-noise ratio. Judging from these figures, the noise could be reduced by 3 to 6 db by low-pass filtering below 100-200 Hz with no significant loss of signal power. If signal detection is done by an analyst looking at clear records, he will do some bandpass filtering by eye so the low-pass filtering will not gain much. However, if detection is done by automatic threshold detection or by looking at a very compressed time scale visicorder record, it is important to remove the high frequency noise. The optimum cutoff

* Westinghouse Contract H0210063 with Bureau of Mines.

frequency will depend on noise spectra and an estimation of the signal spectra expected from the undetected signal. In any given situation a combination of theory and experimental data will allow us to estimate the signal spectra. In general, longer travel paths will lower the average frequency of the signal. It is clear from the Westinghouse results that at some mines narrow band noise sources are present. In such circumstances a notch (or narrow band rejection) filter should be used. Such filters can probably best be implemented with analog equipment.

4. Matched Filtering - Matched Filtering can give an improvement in S/N by compressing the energy of a dispersed waveform in time or by simply acting as a bandpass filter. Work was done by Westinghouse to evaluate matched filter performance. The filter clearly gives a significant S/N improvement. (See Figures 5 and 6, Appendix E of Westinghouse Report.)* However, the time-bandwidth product of the signal is not great and the matched filter does not seem to compress the signal in time. Therefore, it appears that the signal-to-noise improvement obtained by the matched filter is a result only of its bandpass filter characteristics. (The filter used does seem to be a reasonable bandpass filter to use.) It does not appear to predict the signal shape well enough to design a true matched filter, and it does not appear that the signal is dispersed sufficiently to warrant the attempt.

5. Single Channel Prediction Error Filtering - This type of filtering is most useful when the noise is fairly narrow banded. Then it is able to predict the noise ahead fairly well and subtract it from the trace. The spectral data show that the noise is wideband and thus it would not be expected that prediction error filtering could make a large S/N improvement. When tried by Westinghouse the Prediction Error filter provided essentially no improvement (see Westinghouse Fy '72 Report, Appendix E, page 29).*

6. Burial of Sensors - Large S/N improvement may be possible by burying the sensors. Very little information seems to be available in the literature for the frequency range of 30 to 200 Hz. (I also spoke to several people in exploration seismology and was told that because of time and costs, they do not normally bury geophones.) At the much lower frequencies of 1 to 5 Hz burial of a few hundred feet can give noise reductions of 20 to 40 db. (Seriff, A.J., et. al., Seismic Noise in Deep Boreholes, Contract No. AF 19 628-2785, Shell Development Co., Houston, Texas, June 21, 1965.)

* Ibid.

The noise reduction is greater on windy days. Since the surface noise level is high on windy days, even greater S/N gain can be obtained under this condition.

The amount of S/N gain obtainable by burial under various noise conditions cannot be estimated because we presently have no data on the spatial coherence or the depth variation. The theoretical discussion in the Westinghouse Report, Appendix C, discusses some of the possible reasons for the decrease in noise level. It is unfortunate that the experimental program discussed in Appendix C was terminated before data could be analyzed. Before any estimate can be made of S/N improvement, data must be analyzed to get empirical noise reductions and to get the spatial structure of the noise field. If the Westinghouse data is available, examination may allow some estimates of S/N improvements as a function of depth of burial. The only available results are from Section II-4.4 of the Westinghouse Report. Here noise reduction of 19 db at 30 Hz; 44 db at 100 Hz; and 55 db at 250 Hz were obtained for a seismometer in a 23-foot borehole relative to a surface seismometer. The data is from the USBM Safety Research Mine, and is for data taken during a hard rain (see Figure 2.4-4, Westinghouse Report).* addition there are indications (see Part Two, IV) that below a surface alluvium layer the signal may be of considerably higher amplitude than at the surface. It is also indicated that the energy spectra is shifted to higher frequencies for a seismometer below the alluvium. So it is clear that effects on the signal as well as noise reduction resulting from burial should be studied. The experimental and theoretical approach should be combined.

The range of depths which should be studied in the program should extend to as great a depth as it might be feasible to implant seismometers after a mine accident. If it is feasbile to lower or pre-place seismometers in the coal seams, the signals and noise levels in seams should be studied.

I will not at present make a complete discussion of the signal effects of burial. However, there are some conditions under which the signal may also be reduced in strength with burial which should not be overlooked. For example, a sinusoidal P-wave, vertically incident upon a perfectly reflecting interface in a lossless medium can produce a vertical standing wave pattern whose amplitude is given by A cos $[2\pi fz/V_p]$, whre z is depth. For f=100 Hz, and V_p=2000 ft/sec, the first null of this standing wave pattern will occur at z=5 ft.

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* Ibid.

B. Signal Processing at the Subarray Terminal Level

1. Delayed Sum Processing - This type of processing can give gains of 1/N in power (N is number of sensors in the subarray) for 'random' noise, and a gain depending on the beam pattern for coherent noise. Signal loss, because of differences in signal shape must be considered also.

Let us assume that the traces are time aligned so the signals of interest add. The delayed sum output is

$$F(t) = \sum_{i=1}^{N} f_i(t) \qquad (1)*$$

where $f_i(t)$ is the individual sensor output. If the noise of total power, P_{in}, is composed of a coherent fraction C (in power) then the fraction of noise power which is incoherent is (1-C). (We caution that the coherent portion of noise depends on the sensor spacing. For example all noise will appear coherent if sensors are close together, and all noise will appear incoherent if the sensors are moved far enough apart.) If the beam response of the subarray reduces the coherent noise power by a factor of G then the noise on the output is

$$P_{out} = \frac{1}{N} \cdot P_{in} \cdot (1-C) + P_{in} \cdot C \cdot G \qquad (2)$$

If the subarray is large enough the noise reduction will always go to 1/N in power. Failure to obtain 1/N gain is only an indication that the noise is coherent to some extent. The Westinghouse experience with subarray summing is not representative of the improvements that can be achieved with this technique.

Measurement of the noise spatial coherency [13] between sensors as a function of separation can be used to decide the necessary separation between sensors to get close to 1/N noise reduction, larger coherence distances demanding larger separations. The data taken to date above coal mines is insufficient to form a basis upon which I can make a recommendation of subarray element spacing, because the subarray design must reflect the noise field encountered there.

There is another consideration if the distance over which the noise is coherent forces us to a large diameter subarray. If the array is not small

* References to Figures, Table, and Equations apply to those in this Part unless otherwise noted.

compared to the signal horizontal wavelength, signal amplitude decreases and distortion will occur unless the subarray is steered toward the signal. Let us assume that we form the sum with no time delays for a signal of 10,000 ft/sec horizontal phase velocity, and frequency of 100 Hz. Typically an array with seismometers within a circle of diameter d will have less than 3 db signal reduction if $\frac{d.f}{V_n} < 0.25$. Thus d could be as great as 25 ft. for less than 3 db signal loss. In the detection mode, we do not know the direction and horizontal phase velocity of the signal. If it were necessary to go to a larger subarray diameter, or if the horizontal phase velocity were less than 10,000 ft/sec, it might be necessary to form a few delayed sum beams, perhaps 5 at each subarray, in order to prevent excessive signal loss. This type of processing can be implemented with analog equipment.

2. Weighted Delay and Sum - If the noise is unequal and uncorrelated on the seismometers of a subarray, then unequal weight will give a greater noise reduction than equal weighting. This type of weighting is called Brennen combining. If the noise is in the main coherent and coming from a small number of fixed sources, unequal weightings of the seismometers can be used to shape the subarray beam to reject the coherent noise. This type of processing can probably be implemented with analog equipment. [18]

3. Subarray Configuration - If the noise is in the main propagating at a single velocity, such as the Rayleigh wave velocity, proper construction of the subarray geometry may produce an important noise reduction. Namely, the diameter of the array can be chosen to give a near null at the Rayleigh wave velocity. This has been well discussed in the Westinghouse Report. We note that in practice it may be inconvenient to first set up sensors to determine noise properties, then redeploy the sensors to give a better subarray beam pattern.

4. Methods of Multichannel Filtering - It was suggested in Appendix E of the Westinghouse Report that complex signal processing methods might be useful. Such methods include Multichannel Maximum Likelihood, Multichannel Weiner, and Multichannel Prediction Error Filtering. I will not go into detail; however, I do not feel these methods would be appropriate for subarray or full array application. These methods require for S/N improvement that the noise be highly coherent and time stationary, that the signal be highly coherent between sensors,

and that the gains on the various channels be carefully matched. It is probable that some or all these conditions will be violated. These methods require a very large computing facility for the sampling rate under question.

5. Repetition of Source Blows - Summation of repeated source blows will always reduce the noise power by 1/N. This was borne out in Westinghouse's work. They also showed that when the traces could be properly time aligned no significant signal loss occurred. It was also shown that if the traces could not be properly aligned some signal loss occurred, so the S/N gain was not as great as N in power. (See Figure II 2-15, Westinghouse Report.)

In the detection mode if the miner's signal has not been identified on any channel, it will not be possible to time align successive signals for S/N improvement. Thus the measurement of S/N gain will not be available when needed most. However,if a signal is seen at intervals on a single subarray output the method can be used to determine if the signal is on other subarray outputs. This could be useful to verify that the signal on the best channel is in fact due to a signaling miner and not to some unimportant signal source, such as a banging door, near the one subarray.

C. Detection Processing on the Full Array Level

We start with the signal outputs from the separate subarrays. I do not think that any sort of multichannel filtering will be useful for combining the subarray outputs. It will be found, I'm sure, that the noise is incoherent between subarrays. Even simple delay and sum processing will not be practical. There could be as much as 200 ms. delay between subarray arrival times. This delay is not known before detection. To coherently sum sensors with 100 Hz energy they must be properly aligned to within 1 m sec. or better. Thus there are 200 possible relative delays between each pair of subarray outputs. It is clear that delay and sum would impose an impossible computational load.

In the detection mode the array processor must handle a great deal of data. If the processing is done digitally a sampling rate on the order of 1000 samples/sec per subarray is needed. Thus 7000 samples per sec are coming in. Thus it is probable that the signal processing for detection must be fairly simple. The most reasonable way to detect the miner is to use a criteria that a signal be detected on several subarrays within some time window representing the estimated travel time differences between the subarrays. This will be useful if the S/N is not much greater on one of the subarrays than on the others. By use of this 'coincidence detection',a detection can be made at a lower signal threshold for a fixed 'false alarm' rate than would be possible for a single subarray.

The threshold that should be used for a detection on each subarray signal should be set at 3 times the RMS noise level on that channel. If the noise level is not time stationary, the level should be set by, for example, setting the threshold at 3 times the RMS noise level over the last 30 seconds. (Geotech and Lincoln Laboratories have done extensive work on detection criteria for nuclear detection.)

As possible signals are detected, the data for these detections should, of course, be saved for use in the location process.

IV. SIGNAL PROCESSING EFFECTS RELATED TO LOCATION

After a miner has been detected, portions of the data containing signals can be reprocessed to improve arrival time estimates. The summing up of repeated source blows is useful for improving signal to noise.

The summing up of the seismometers of a subarray improves S/N. However, if direct sum with no delays is used, then some slight signal distortion can occur since the signals are added with slight misalignment. A simple sketch of this effect is given in Figure 1. This summing will in general make the first break somewhat less sharp and will distort the waveform slightly. The arrival time reading error which could result might be on the order of 2 ms. It is difficult to say if the noise reduction would compensate for this. The magnitude of the signal distortion will increase as the size of the subarrays are increased. One means of alleviating this effect would be to put in a delay line for each seismometer after the approximate location is found. This would align the traces in the subarray sum.

The matched filter proposed in Appendix E* has some advantage. The S/N ratio is improved. However, as stated previously this is due to the bandpass filtering effect whereby the filter removes high frequency noise. The matched filter does not get S/N improvement by compressing a dispersed wave train. Filtering by the filter constructed in Figure 3 of the Westinghouse Fy '72 Report, Appendix E, changes the signal waveform. Here the signal distortion is not great, as shown

* Westinghouse Fy '72 Report, Contract H0210063.

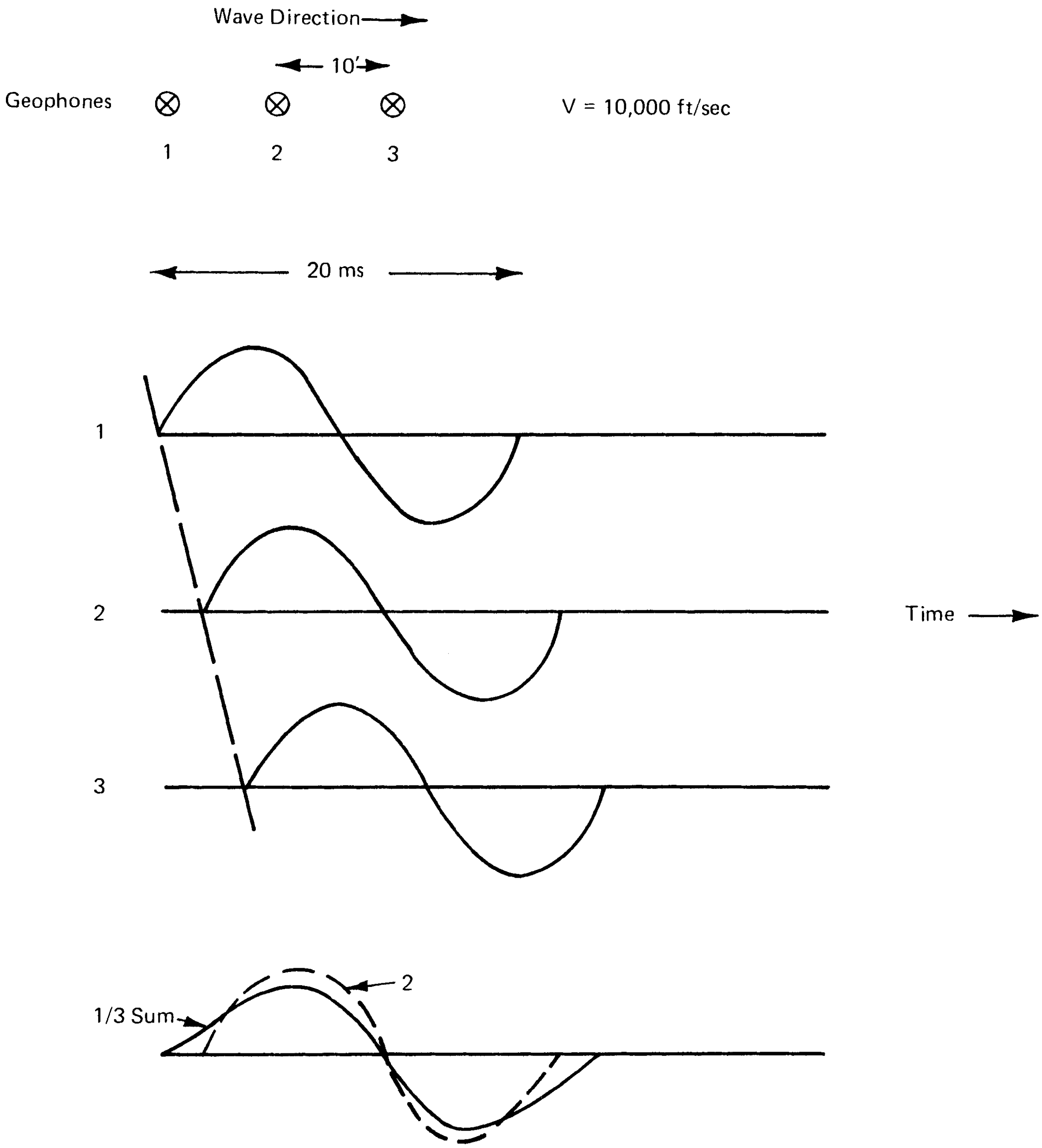


FIGURE 1 EFFECT OF DIRECT SUMMING ON WAVEFORM

in Figure 2. However, an example taken from [11] shows how a slightly different matched filter can change the output waveform and reverse polarization. One set of Westinghouse data was available to determine how time picks on the unfiltered data compared to the picks made on matched filtered data. In Appendix E arrival times were picked on match filtered data, (Appendix E, Table 1). The analyst's time picks on this data, before matched filtering, were found on the input to the computer location program in Field Report No. 4.* For both sets of time picks we calculated the arrival times relative to channel 6. (Only four channels were picked in Appendix E.) Table 1 shows the comparison.

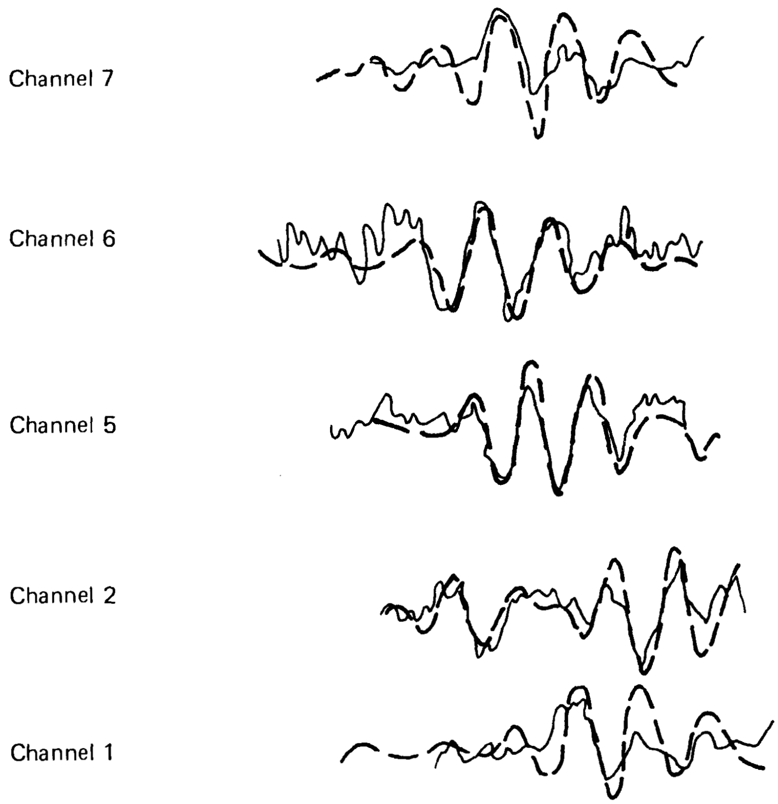
TABLE 1 - COMPARISON OF ARRIVAL TIMES

Channel Number	A-T Matched Filter Signal	A-T Field Report 4	Difference
1	16.25 m. sec.	12.8 m. sec.	+3.4 m. sec.
5	10.30 m. sec.	9.7 m. sec.	1.6 m. sec.
7	14.25 m. sec.	16.3 m. sec.	-2.1 m. sec.

Thus we feel that the time picks from the matched filter output may be in error on the order of 2 m. sec. This is to be contrasted to the RMS scatter of time picks on the matched filtered data of from 1.00 to 0.71 m. sec. (ms) given in Westinghouse, Appendix E.

In general, except in very high signal to noise situations where first breaks can be seen, an error of 1 or 2 ms will probably have to be tolerated. However, if a half cycle is missed, this will introduce approximately a 10-15 ms error. Data processing should probably concentrate on methods to avoid this missing of a half cycle. In particular it may be helpful to determine the polarization to be expected at each site when we have a rough fix on the source location.

* Westinghouse Contract H0210063.



(From Figures 5 & 6 of Appendix E of Westinghouse Report)

Raw Trace
Matched Filtered Trace

FIGURE 2 COMPARISON OF A SEISMIC SIGNAL BEFORE AND AFTER PASSING THROUGH THE WESTINGHOUSE MATCHED FILTER

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PART ELEVEN

SEISMIC DETECTION/LOCATION INSTRUMENTATION

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SEISMIC DETECTION/LOCATION INSTRUMENTATION

Arthur D. Little, Inc.

I. INTRODUCTION

The instrumentation specification in the National Academy of Engineering (NAE) report of March, 1970, set forth some rather general guidelines that the seismic surface system should follow. The fact that there was no comparable equipment in existence at that time, and the need to produce a system from presently available equipment, was spelled out in that document.

The features that the system should include were listed, and included:

- Quick and simple deployment
- Portability
- Battery-powered operation
- All-weather operation
- Computational simplicity and speed
- High reliability and long shelf-life
- Dual service for location and communication
- Adaptability to widely varying seismic velocities, topography, and geologic structures
- Minimum maintenance
- Capability of continuous operation for extended periods, and
- Reasonable cost

Since that report, there has been a substantial amount of field work addressing the trapped miner detection and location problem carried out by Westinghouse Corporation under contract with the Bureau of Mines. Two complete surface systems have been designed, built, and field tested and substantial documentation has been produced on the mine environment and background noise using these systems. These systems, built from off-the-shelf equipment, have been designed with maximum flexibility in mind in order to explore what configuration a field unit should have.

This Part reviews the Westinghouse surface system, reviews the general system specifications in light of present experience, and describes in some detail a recommended system configuration that attempts to meet all the requirements of a truly fieldable system.

II. WESTINGHOUSE SURFACE SYSTEM

Two complete surface systems were built by Westinghouse on contract† with the Bureau of Mines. Since the fabrication of these systems, a substantial amount of field experience has been gained with these units in actual test measurements at a number of working mines in the United States. Improvements and modifications have been made to the original system as field experience has dictated.

The present system is housed in a portable van that can be transported either by a companion 4 x 4 truck to which it is normally attached or via plane (e.g., a C-47). The instrumentation is self-contained except for primary power and telephone service. Geophones and cables for the array are stored inside compartments for easy accessibility. The power signal and telephone connections to the van are made via clearly marked terminal jacks. For field deployment, the system comes with a second truck to transport a portable 6" drill, spare fuel, and a primary power generator.

The van floor plan showing storage room and equipment layout is shown in Figure 1.* The instrumentation and computer system are centrally placed to balance the van for ease of loading and transport. Figure 2 shows the present equipment layout and jackfield location. The use of multiple jackfields, allows for maximum patching flexibility but does require the operator to be careful in setting up the patching arrangement. The use of commercial equipments throughout tends to provide more gain controls than may be required on a field system.

A block diagram of the complete system is shown in Figure 3. The system can be subdivided into four subsystems:

1. Seismic detection;
2. Signal conditioning;
3. Signal processing; and
4. Location processing.

† Contract H0101262 with Bureau of Mines.

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

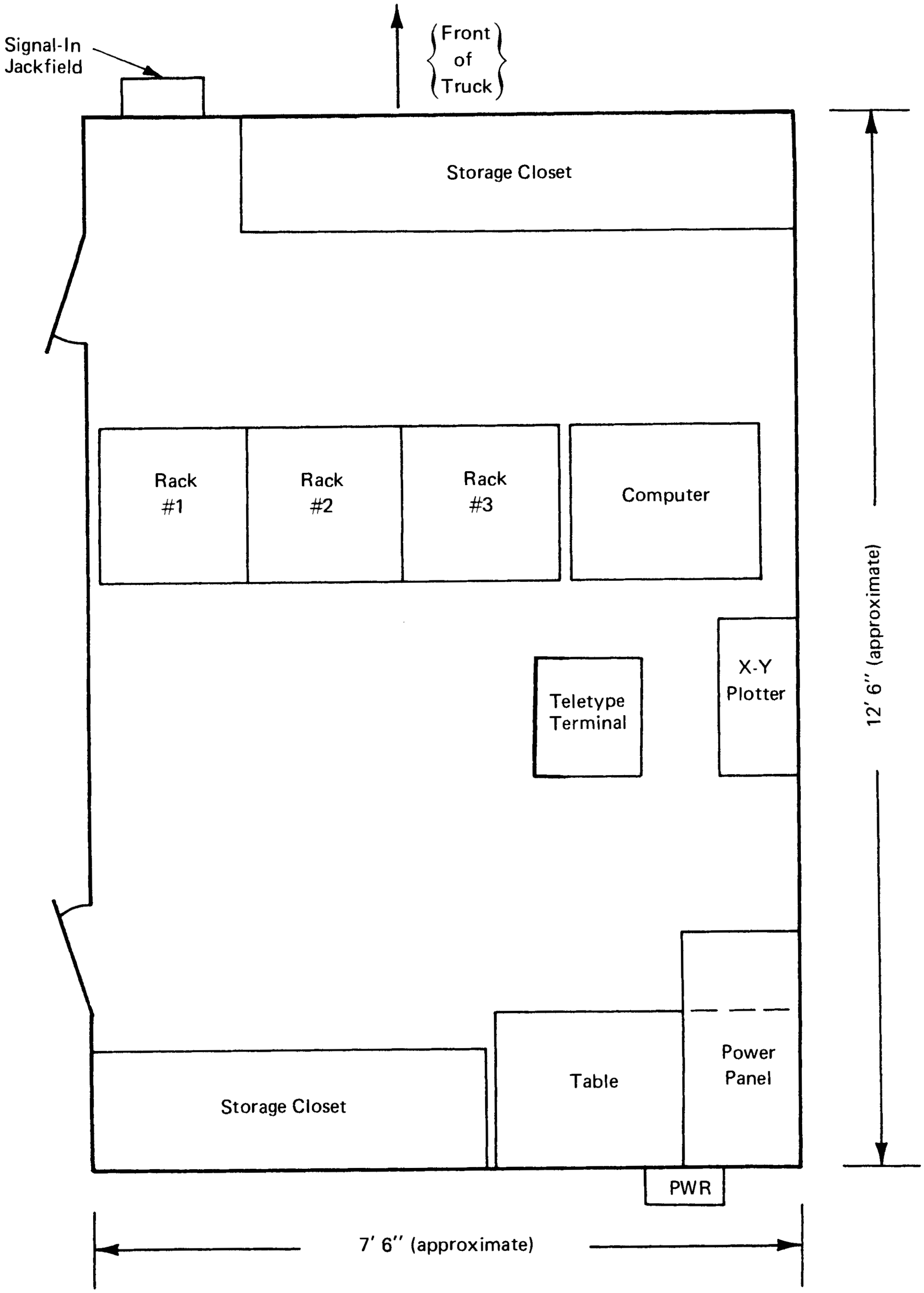


FIGURE 1 PRESENT SEISMIC SYSTEM (Floor Plan)

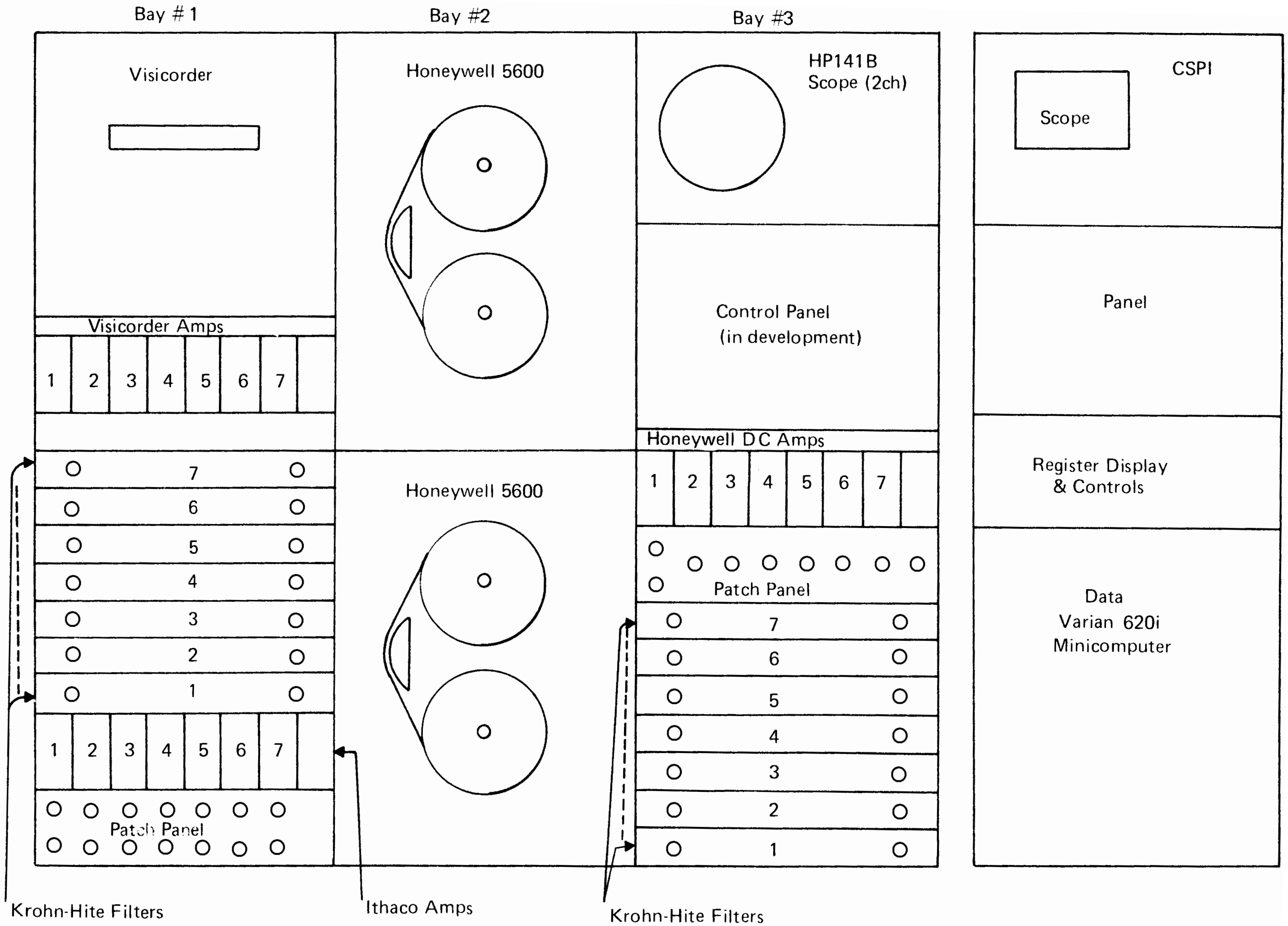


FIGURE 2 EQUIPMENT LAYOUT (PRESENT SYSTEM)

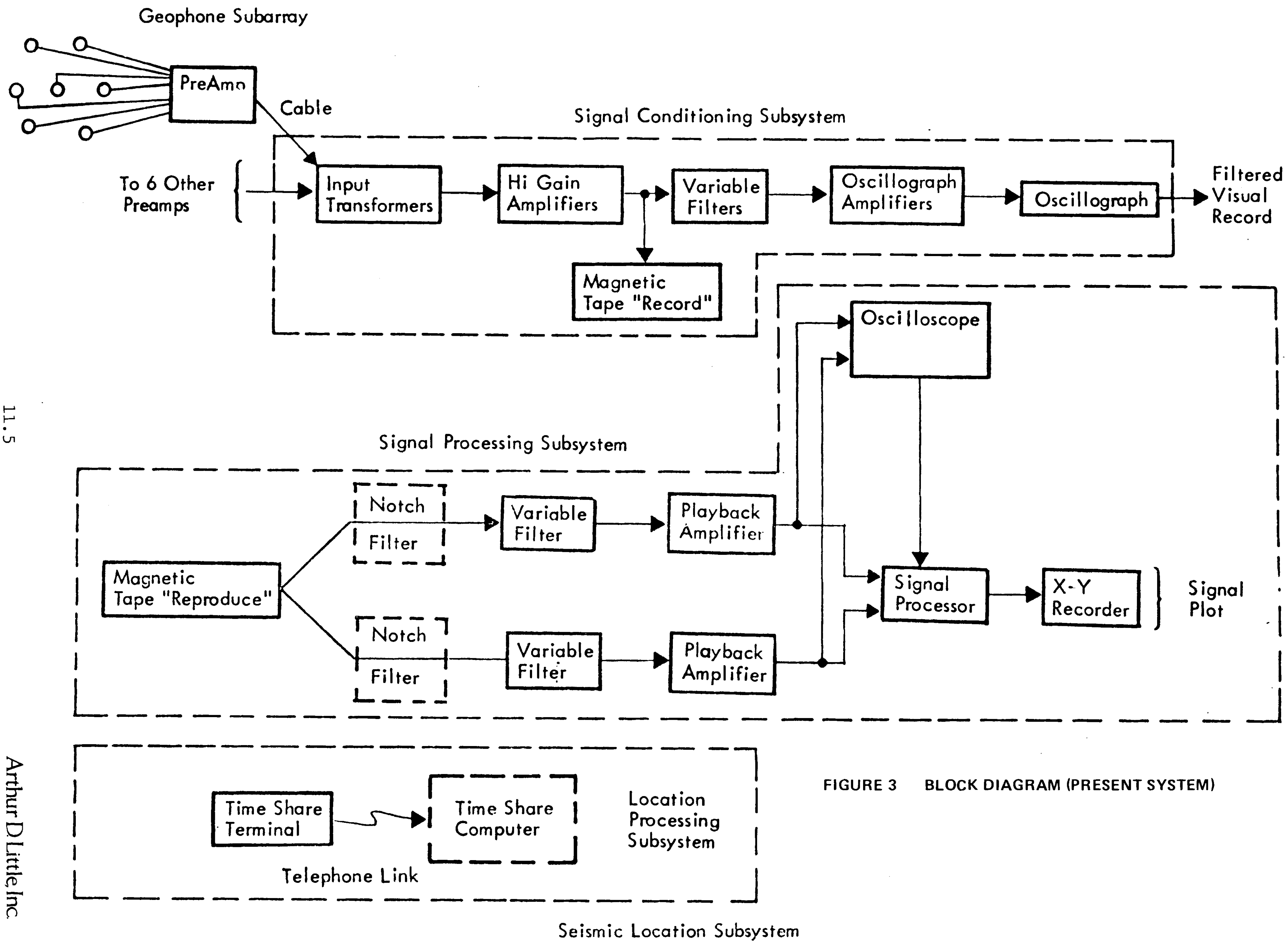


FIGURE 3 BLOCK DIAGRAM (PRESENT SYSTEM)

A. <u>Seismic Detection Subsystem</u>

The seismic detection subsystem consists of the array geophones, associated cabling, and array preamplifiers. The present array configuration is seven array elements each with seven geophones connected in parallel, then connected to a preamplifier. Each preamplifier has a fixed gain of 69db. The output of each preamp is an unbalanced to balanced transformer feeding the signal cable to a connector on the van. The balanced cable system is intended to minimize noise pickup in the system due to external noise fields.

B. <u>Signal Conditioning Subsystem</u>

The input of the signal conditioning subsystem is a balanced to unbalanced transformer matching the array cable to the input high gain amplifiers. Present amplifiers are ITHACO models with an adjustable gain range of -10 to +90db. Nominal gain settings for this amplifier is in the 10 to 50db range producing a signal output of approximately 0.5 volts peak-to-peak (p-p).

In normal field operations this signal is recorded on a seven track Honeywell 5600 tape recorder and/or can be displayed in real-time on a seven track Visicorder.

C. <u>Signal Processing Subsystem</u>

The signal processing subsystem is designed to play out stored data for visual display and/or processing. Processing of the data can be achieved by either varying the filter bandwidth with the Krohn-Hite filter bank, or by processing the signal in the CSPI data processing system for gain enhancement. The CSPI system using the Varian Data 620 i computer can perform fast Fourier transforms on incoming signals or noise, and play out power density spectra on the x-y plotter. On repetitive seismic signals, the computer is programmed to do signal stacking giving a gain enhancement and signal-to-noise improvement over background noise. In the signal stacking mode the oscilloscope trigger circuit is used to detect the signal arrival on one channel and trigger the sampling gate of the computer for the other channels. Two channels at a time are treated in this way. Each channel can be displayed on the x-y recorder for comparative analysis of first arrival times.

D. <u>Location Processing Subsystem</u>

The present location processing subsystem as shown in Figure 3 is not located on-site with the other system. The crew chief now uses the telephone to send first arrival time data, estimated on-site by viewing all seven channels on the play out of the x-y recorder or the Visicorder. A resident location program called MINER is used in a remote time-share computer to compute the estimated signal source location based on array arrival time data.

III. SYSTEM MODIFICATION

The Westinghouse system described above has provided a substantial insight into the system and fieldability problems that are encountered in deploying such a unit and making practical field measurements. Some major modifications were incorporated into the Westinghouse system as deficiencies in system performance were identified. The preamplifiers and the high gain amplifiers were replaced along with the tape recorder.

Present modifications now in process call for an increase in memory capacity of the CSPI processing system. The present capacity of 8,000 16-bit binary words will be expanded to 20,000. This will reduce signal processing time substantially and reduce corrective maintenance time. The number of input channels to the computer will be increased from two to eight to reduce the analysis time.

In the signal detection subsystem, current plans call for a change in the present parallel geophone arrangement to a series connection and a new transformer in the preamp to match the new geophone connection. This will improve the sensitivity of the subarray.

A high speed paper tape reader will be used with the computer expanded memory to increase the operating efficiency. Additional amplifiers and filters will be added to interface the tape recorder to the computer.

In summation, the above modifications are designed to expand processing capacity, reduce processing time, and improve system sensitivity.

IV. SYSTEM SPECIFICATIONS

The specifications listed above in Section I, as spelled out in the NAE report, are still a valid set of specifications. However, in view of the experience gained in the interim period, a more detailed set can now be made covering the seismic surface instrumentation.

Quick and simple deployment can be specified in relation to deployment by any common means of transport. This is related to the availability of the transportation, and requires a somewhat different packaging concept than used up to now. It relates to portability; where the packages could be hand loaded onto a commercial or private airplane, or on a pick-up truck for over-the-road deployment.

Coupled with the portability is the ability of hand carrying the units over otherwise inaccessible terrain. This requires portable cases with handles and weighing no more than 70 pounds per case.

Battery powered operation is a must in some instances, if the terrain or emergency conditions prevent the use of commercial power.

Experience by the Westinghouse team shows that snow and temperatures around zero require operational units to perform over a wide range of temperature and environment conditions. All units must be weather-tight and not temperature sensitive to expected conditions.

There is a real need for processing speed once the system has been deployed. Processing times of received data should be measured in minutes rather than hours.

Reliability goes with good design. Data acquired should be accurate and reproducible. System operation and checkout should be almost automatic. All systems should be easily checked and calibrated on deployment and periodically recalibrated during the work.

The system should be deployable in various configurations depending on the need for detection and/or location.

The system must be adaptable to the condition expected. For example, there may be occasions when power is not available or telephone communication non-existent. The system configuration must be tailored to operate under almost any condition.

Minimum maintenance and reliable operation is a must if the system is on stand-by at all times. Small portable units incorporating solid state design where possible should meet this criterion. Continuous operation for extended periods of time is feasible with small rechargeable battery operated units.

The concept of small portable units could reduce overall program costs, since specialized equipment may not be necessary.

V. SUGGESTED SYSTEM CONFIGURATION

The need for a truly portable hand carried system has been established in many cases during the extensive field work* in the past two years. Contrasted with this is the requirement of computer equipment to perform signal processing to enhance signal-to-noise in high noise environments. Thus, the suggested system described in this section will attempt to meet these conflicting requirements in addition to all the others stated above.

Our approach to the system configuration is to recognize the fact that there are a wide span of field requirements that must be met. These range from the need for possible simple detection processes in remote quiet areas to a complex detection/location problem in high noise environments with relatively easy accessibility. In one case, a simple hand carried system with hard copy play out may be all that is necessary, where in the latter case a full system with a sophisticated computer system may be required. We have, therefore, taken a modular approach, with each subsystem capable of add-on to meet the existing requirements.

In each of the portable package designs described below, we have considered only equipment that is now available. Little or no major R&D work is required to produce the field package described below, only good equipment layout and packaging design are required. Figure 4 shows the overall block diagram of the suggested seismic detection subsystem. A description of this subsystem and the signal process- and location subsystem will be covered in the following sections.

A. Seismic Detection Subsystem

The seismic detection subsystem consists of the array element geophones, the associated cables, and a hand carried array control unit.

We recommend geophones that can be placed in boreholes, or on the surface if hard rock overburden is encountered. The phones could be of the marine-type, since they are more sensitive than the ones now used. Tests conducted with the Westinghouse system indicated a 6-8 db discrimination to local noise sources with a geophone buried one foot in the ground. The phones should be completely sealed against water since they will frequently be in water.

A hand auger can be used to make the boreholes for easy implantation. A much better coupling could be established to the surrounding earth if dirt were tamped back over the phones, or if some form of integral bellows arrangement could be used to expand the phone casing to the borehole walls.

Integral with each geophone should be a preamp with 70 db of gain, and a calibration coil that induces a known motion to the phone sensing elements.

* Westinghouse Contracts H0101262 and H0210062 with Bureau of Mines.

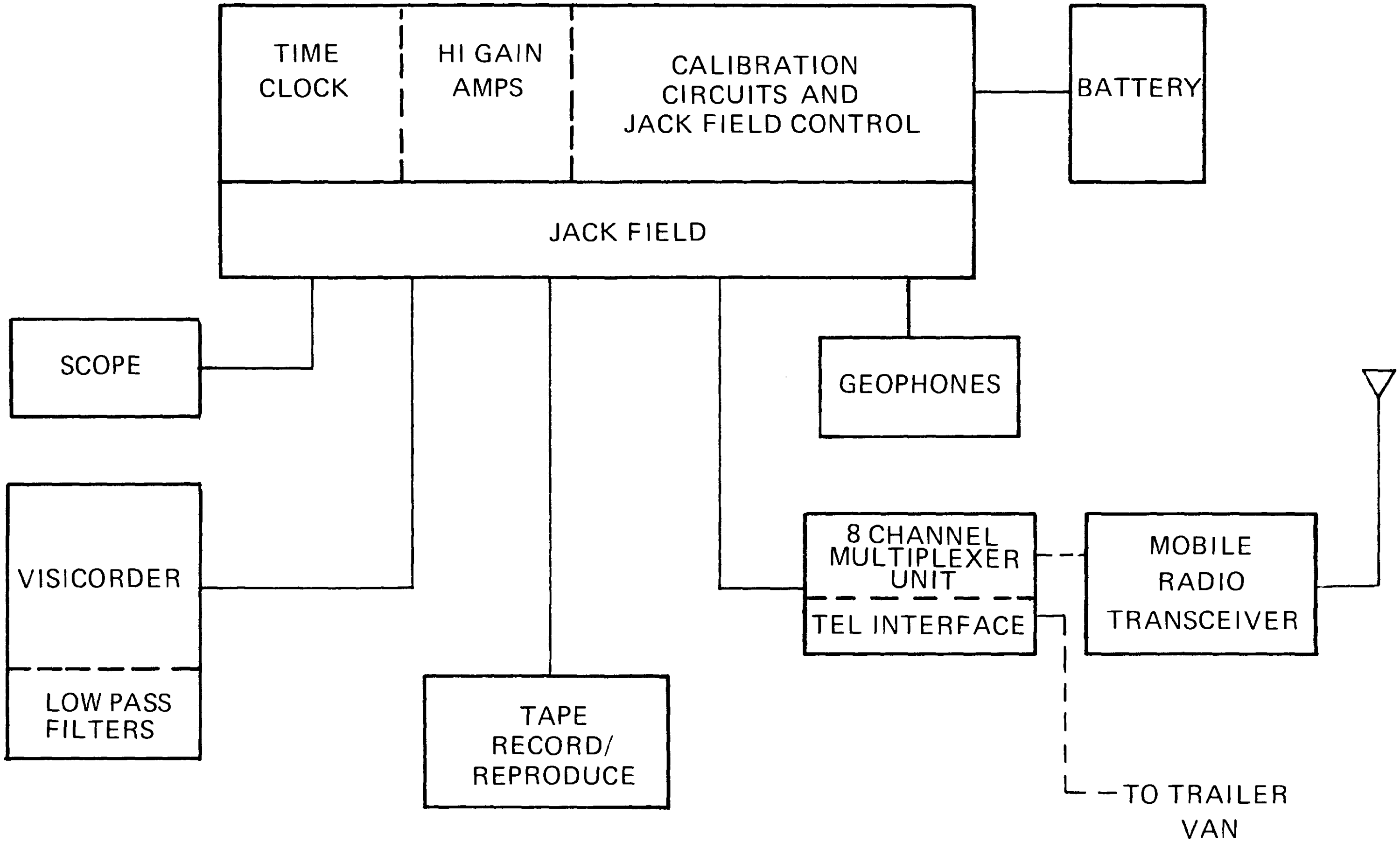


FIGURE 4 SUGGESTED SEISMIC DETECTION SUBSYSTEM

The calibration circuit is necessary to establish the proper operation of each phone in the array, and to reference the relative delay in the system between channels. Should a delay exist, for example, in the tape recorder subsystem as was the case in the Westinghouse system, the delay can be recognized and measured. First-motion picks on seismic signal records could then be adjusted to allow for instrumentation delays.

Should multiple geophones be used for each element array, we recommend they be wired in series for the output signal to achieve greater sensitivity than the present arrangement, and that each calibration coil be connected individually to ensure the proper operation of every phone in the array.

In configuring this system, we considered the use of digital vs. analog geophones. The use of digital geophones has many advantages in field applications. Digital systems are more immune to noise interference than analog systems, and once in digital format, waveforms can be processed in a more convenient manner. An additional advantage is the ability to obtain a greater dynamic range of up to 90 db by utilizing digital formats, geophones, and recorders. The maximum dynamic range of current analog systems is approximately 45 db.

The use of the system for miner detection would require only the array and a portable scope and Visicoder system. Since the signals on the scope and the Visicoder are analog, we see no reason to complicate the front end of the system with A/D and D/A circuits. The need for a large dynamic range in the system has not been demonstrated in the Westinghouse field work. Therefore, with a proper gain setting, a 40 db dynamic range seems adequate for all expected conditions. Considering all the advantages of both systems, we have concluded that for this application, the use of the analog format in the array system is preferable to digital.

The cable connecting each geophone to the control unit should be a three twisted pair cable with a separate external shield. A balanced transformer should be used at the geophone output interface and the control unit input circuit interface. The ground return can be the geophone housing connected to the external cable shield and the control unit case. The third pair of wires are used to power the geophone preamp from the control unit battery supply.

The array control unit should be a hand carried aluminum watertight case approximately 2 x 3 x 1 feet and weighing under 75 pounds. Key elements in this unit are:

a. system time clock,

b. main amplifier and gain adjust unit,

c. control status panel, and

d. battery unit.

There is no stringent accuracy requirement on the system time clock, since the relative signal arrival times are the important information required. The time clock, therefore, should be capable of coding the local time by minutes in a format suitable for placing on the voice channel of the tape recorder. This time code can be used for computer tape search during the processing of data. In addition, to minutes time codes, pulses of 5, 10, and 50 ms should be available on the tape. These pulses will be used to accurately measure arrival times of signals, and gate the computer accurately during the processing phase.

We have reviewed the use of portable tape recorders, and believe that either a portable seven (7) or fourteen (14) track analog system is feasible. Good systems are available that use an FM format and meet all IRIG specifications. These units are more than accurate enough to meet the system requirements. The expected portable package should be no more than 24" x 16" x 12" in dimensions, and weigh approximately 80 lbs.

The main amplifier circuit should be a stable high gain amplifier with a gain adjust over the range of 0 to +90 db. These amplifiers should have two modes of operation; one mode a straight gain where the gain of the system is set by the amplifier control setting. This is used in calibration procedures. A second mode should be an AGC mode where once the system gain has been set for standard output levels, the system can maintain a standard output level of 1.5 volts peak-to-peak under varying input signal levels. AGC can be used effectively since arrival times are of importance and not absolute signal levels.

The control status panel consists of the calibration circuitry, switch control, and output signal switches to display individual channels for oscilloscope viewing, or all channels for magnetic tape recording. Output BNC and/or multipin connectors will be used to connect to companion units such as the portable oscilloscope and magnetic tape recording systems shown in block diagram form in Figure 4.

The hard copy play out unit shown in Figure 4 can be a portable unit equivalent to a Visicoder unit capable of reproducing all seven channels plus the timing track. This will allow first cut estimation of arrival times on each channel, and with the control status panel and array unit, constitute a complete austere field system. Integral with the Visicoder unit would be a switchable low pass filter unit for each channel. Suggested cutoff frequencies are 200 Hz and 500 Hz. A filter roll off of 24 db per octave is recommended.

A key field unit in this system is the 8 channel MUX* and a telephone interface unit shown in Figure 4. This unit is designed to interface directly with the array control unit and works with the standard level output on each channel.

Each channel consists of an input buffer stage coupled to a VCO with a center frequency assigned to allow seven signal channels plus a time channel to be sent over a standard telephone line. The output of each VCO is then combined and buffered to a common output circuit designed to reflect to the telephone system an off-hook telephone set. A standard telephone set is also incorporated in this unit to permit communication between the field crew and/or the data processing center. Should telephone lines be available, the array subsystem, array control unit, oscilloscope, and the 8 channel MUX unit could constitute the entire field system. Data processing could then be performed at any point in the United States (Boulder, Pittsburgh, etc.).

The interface to the telephone line can be a short patch or may be in some cases up to several miles of 20 gauge cable. This cable may in many cases interface on a hard wire basis with the trailer van described later.

An alternative to the telephone hard wire connection could be another hand carried package housing a mobile radio transceiver. This could provide radio transmission of the data to some more accessible location at which point the data could be interfaced with the telephone network or to the trailer van.

B. Seismic Signal Processing and Location Subsystem

The trailer van subsystem is configured as shown in Figure 5. Major components are the minicomputer and associated A/D converter and disk pack, variable filter banks such as the Krohn-Hite, an x-y plotter such as a Calcomp, Visicorder or equivalent for hard copy play out, and a monitoring unit with a memory type oscilloscope.

In addition to the equipment above, an eight channel discriminatory bank and a mobile radio transceiver would be required to interface with the field units. Telephone equipment with signaling capability would be required should the communication link be hard wired.

A more powerful minicomputer, in the PDP-11, class and associated disk pack has the following advantages over the present system:

1. It appears likely that computer programs already in existence for signal processing, and system organization and control may be available to the Bureau of Mines.
2. The disk pack arrangement with digital format is more efficient in interfacing a computer in the signal processing mode. Access time is significantly less, programs are available on data search, and

*MUX = Multiplexer

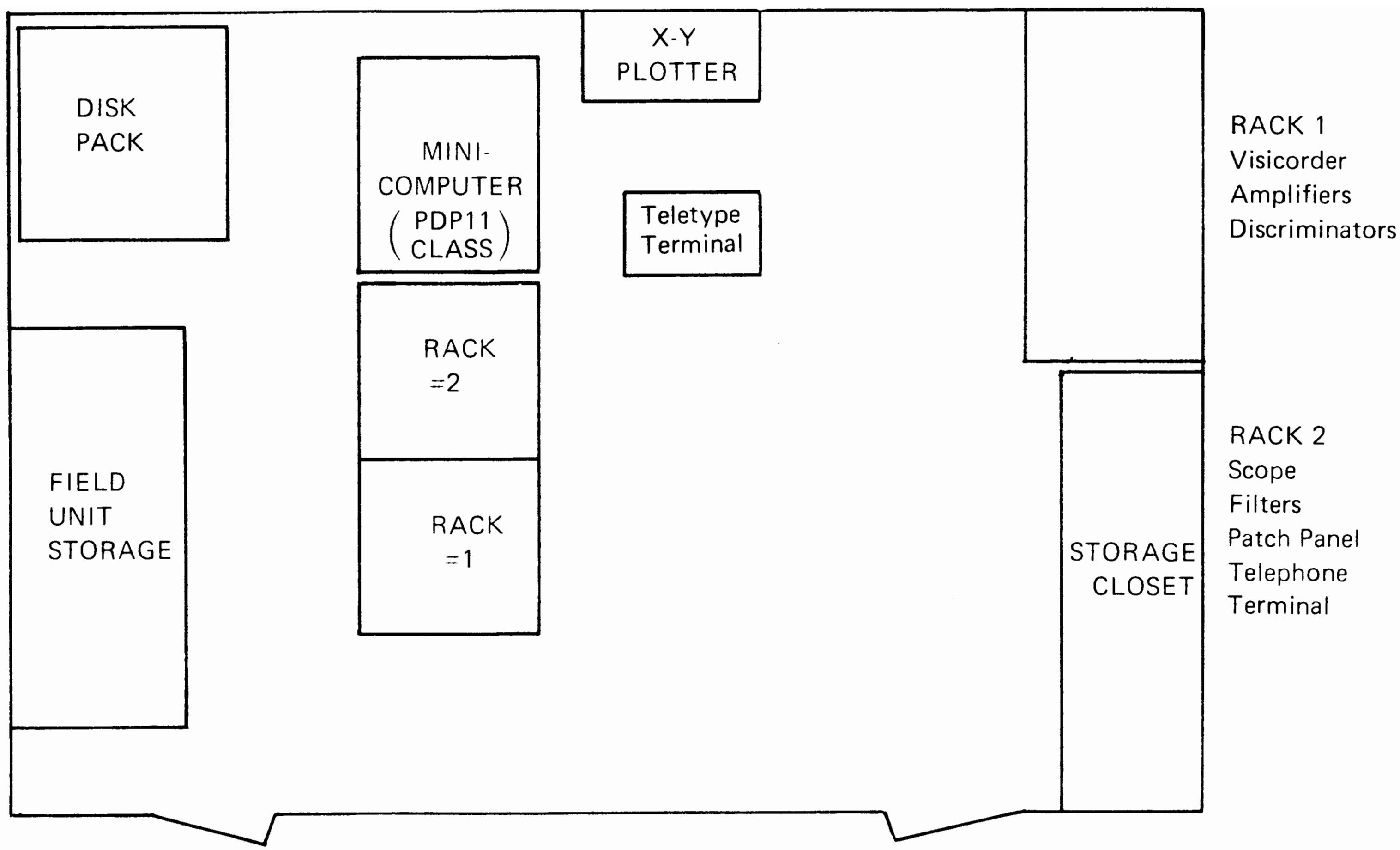


FIGURE 5 SUGGESTED TRAILER VAN SIGNAL PROCESSING AND LOCATION SUBSYSTEM

reproduction costs are also competitive.

3. Location programs such as "MINER" could be incorporated in this system thus eliminating the need for an additional time-share facility.

VI. DEPLOYMENT

The suggested configuration described above solves the critical requirements of portability, rapid deployment, and cost. It is flexible in configuration to satisfy a wide range of needs and is of comparatively low cost for initial purchase and maintenance.

We visualize a possible deployment of this system in phases: on notification of a disaster, the initial deployment would be of the array subsystem, the array control unit, and the scope. These three units are sufficient to perform the initial function of miner detection. They can be hand carried on a commercial airliner or even in a passenger car. They are reasonable in cost so that a number of these could be placed in strategic locations throughout the United States. We expect that such a subsystem could be deployed and begin the miner detection process in several hours. Several variations in this scenario can be made. If telephone lines are known to be available and working, it is conceivable that as a fourth unit only the 8 channel MUX need be deployed and real-time data collection and processing could be performed at Pittsburgh, for example. On the other hand, a full blown system may be more convenient on-site, in which case the trailer van and additional subsystem units could be deployed as soon as possible. The important characteristic of the portable system described in this section is the ability to begin the detection process in a minimum of time, and to deploy the larger and more cumbersome comprehensive location system later when it is needed. In many cases, the van may not even be necessary.

In summary, the suggested system represents a truly portable self-contained system that is self-calibrated, tested, and usable under a wide variety of conditions. It is modular in growth to match every type of disaster condition, and is reasonable in cost. All system units and circuits described are off-the-shelf items that can be integrated and packaged to satisfy the above-described system requirements.

PART TWELVE

BRIEFING CHARTS

PART TWELVE

BRIEFING CHARTS

TABLE OF CONTENTS

PART TWELVE

BRIEFING CHARTS

I. INTRODUCTION

In this Part, we have included copies of the flip charts and overhead projector viewgraphs used in the two briefings we conducted as part of this seismic detection and location task. The first one was an overview and problem definition briefing given to the seismic consultants on September 7, 1972. The second was a formal oral presentation of study results to technical staff members of the Pittsburgh Mining and Safety Research Center on November 21, 1972.

II. PROGRAM BRIEFING FOR SEISMIC CONSULTANTS 7 SEPTEMBER 1972

SEISMIC LOCATION OF ISOLATED MINERS
Arthur D. Little, Inc.

In order to provide the seismic consultants with a clear and concise:

a) definition of the seismic miner location problem;

b) summary of the relevant background information regarding the Bureau's seismic location program to date; and

c) identification and assignment of specific tasks;

we prepared and gave the consultants a comprehensive briefing. This briefing consisted of a flip chart presentation, complemented by the use of film, slides, and viewgraphs, and culminated in an interactive discussion of the problem, specific tasks, and consultants' individual areas of interest and corresponding assignments. In short, the seismic briefing was organized into the six parts listed below, and summarized in this Part by reproductions of the briefing visual aids.

A. OPENING REMARKS - ADL

B. INTRODUCTION TO COAL MINE DISASTERS - BUMINES

C. OVERVIEW AND STATUS OF SEISMIC LOCATION PROGRAM - BUMINES

D. FORMULATION OF THE MINER SEISMIC LOCATION PROBLEM - ADL

E. DESIRED END PRODUCT AND SCHEDULE OF PRESENT EFFORT - ADL

F. IDENTIFICATION AND DISCUSSION OF MAJOR TASKS AND TASK ASSIGNMENTS - ADL/PARTICIPANTS

A. OPENING REMARKS

ARTHUR D. LITTLE, INC. - R. LAGACE

OBJECTIVE

DETECTION AND LOCATION OF MINER BY SEISMIC MEANS

PRESENT EFFORT

DETERMINE:

- HOW AND HOW WELL OUR OBJECTIVE CAN BE ACHIEVED

IN PARTICULAR:

IDENTIFY WHAT CAN BE DONE AND HOW WELL -- BY SEISMIC MEANS -- TO:

- DETECT A MINER
- LOCATE A MINER TO WITHIN A SECTION
- LOCATE A MINER TO WITHIN AN ENTRY WIDTH

B. INTRODUCTION TO COAL MINE DISASTERS

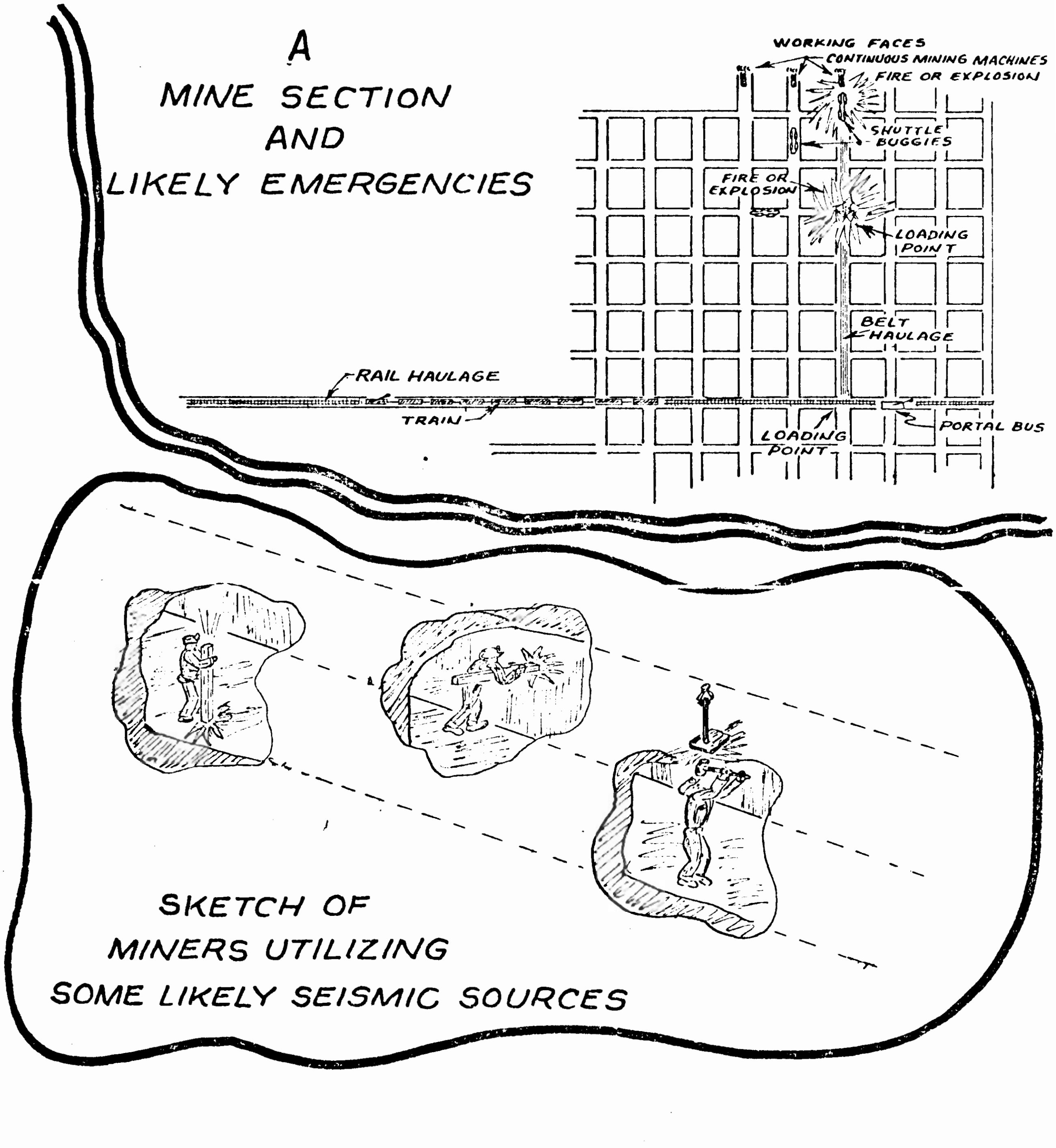
U.S. BUREAU OF MINES - H. PARKINSON, PMSRC

This part of the briefing included:

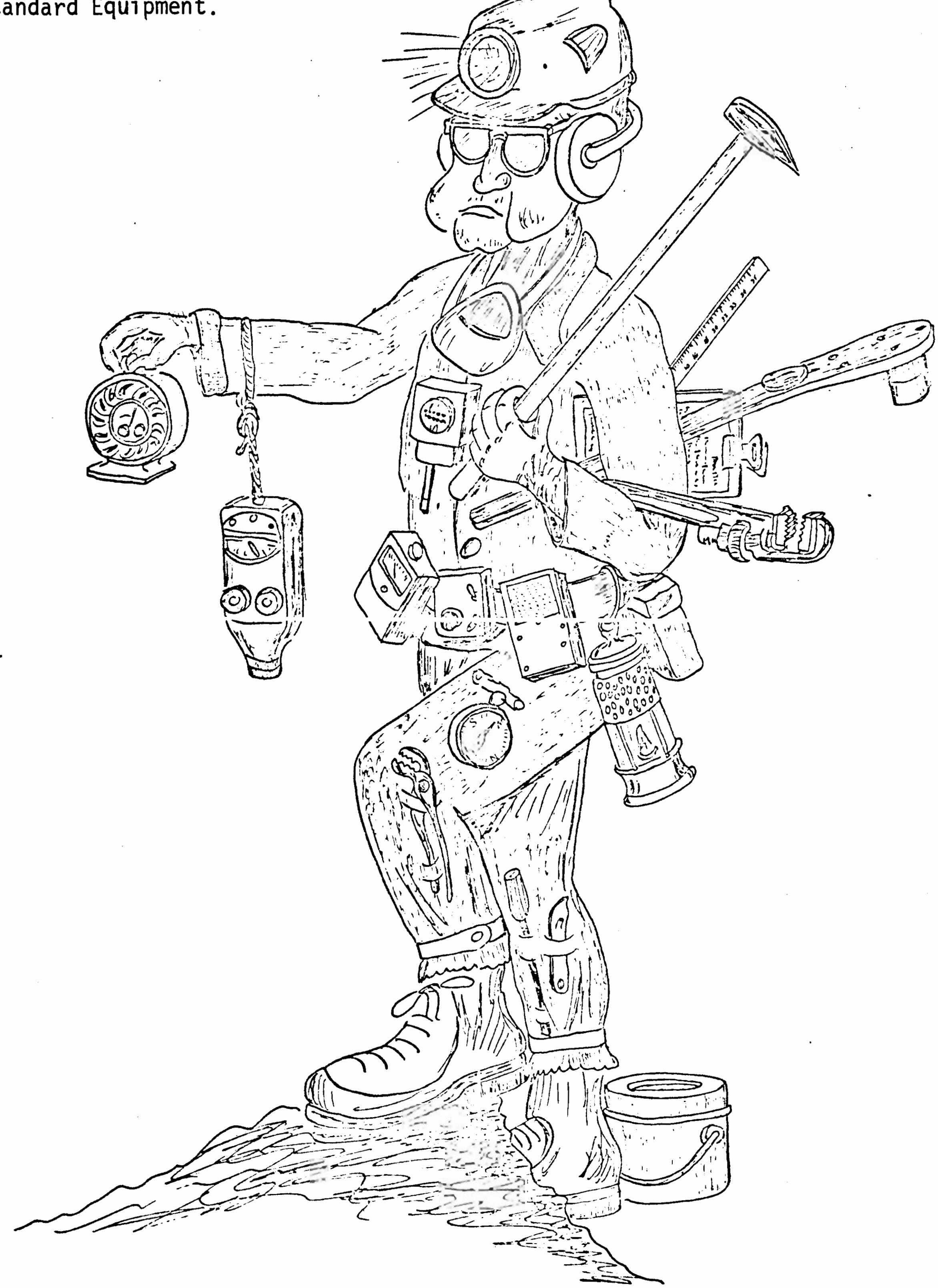
1. Viewing of the Bureau film: SAFETY PRACTICES IN LOW COAL MINES, with special narration by H. Parkinson.

2. Viewing color slides of the U.S. Steel Mine site used for the demonstration of the Coal Mine Rescue and Survival System.

3. Discussion of Coal Mine Layouts, Activities, and Disasters with the Aid of Actual Mine Maps, and the Visuals included in this section.


A
MINE SECTION
AND
LIKELY EMERGENCIES
WORKING FACES
CONTINUOUS MINING MACHINES
FIRE OR EXPLOSION
SHUTTLE BUGGIES
FIRE OR EXPLOSION
LOADING POINT
BELT HAULAGE
RAIL HAULAGE
TRAIN
LOADING POINT
PORTAL BUS
SKETCH OF
MINERS UTILIZING
SOME LIKELY SEISMIC SOURCES

An example in the extreme of what <u>cannot</u> be imposed on the miner. Namely, the miner <u>CANNOT</u> be expected to carry or have attached to his person, a Special Seismic Signaling Device as Standard Equipment.



C. OVERVIEW AND STATUS OF

SEISMIC LOCATION PROGRAM

U.S. BUREAU OF MINES - J.POWELL, PMSRC

O U T L I N E

WHERE ARE WE NOW?

- HISTORY
- PHILOSOPHY AND RATIONALE
- SYSTEM SET-UP
- EXPERIMENTS AND INVESTIGATIONS
- RESULTS

NAE RECOMMENDATIONS

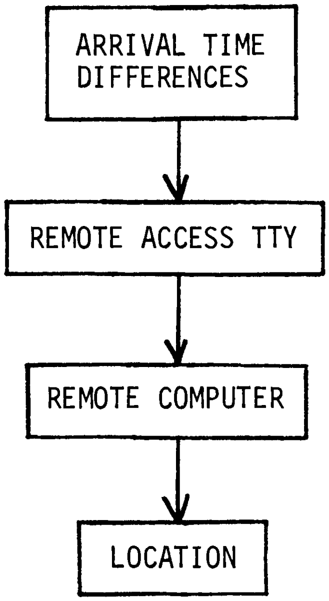
AND

REQUIREMENTS

REQUIRED:	50 FT. ACCURACY
THOUGHT TO BE ATTAINABLE:	25 FT. ACCURACY

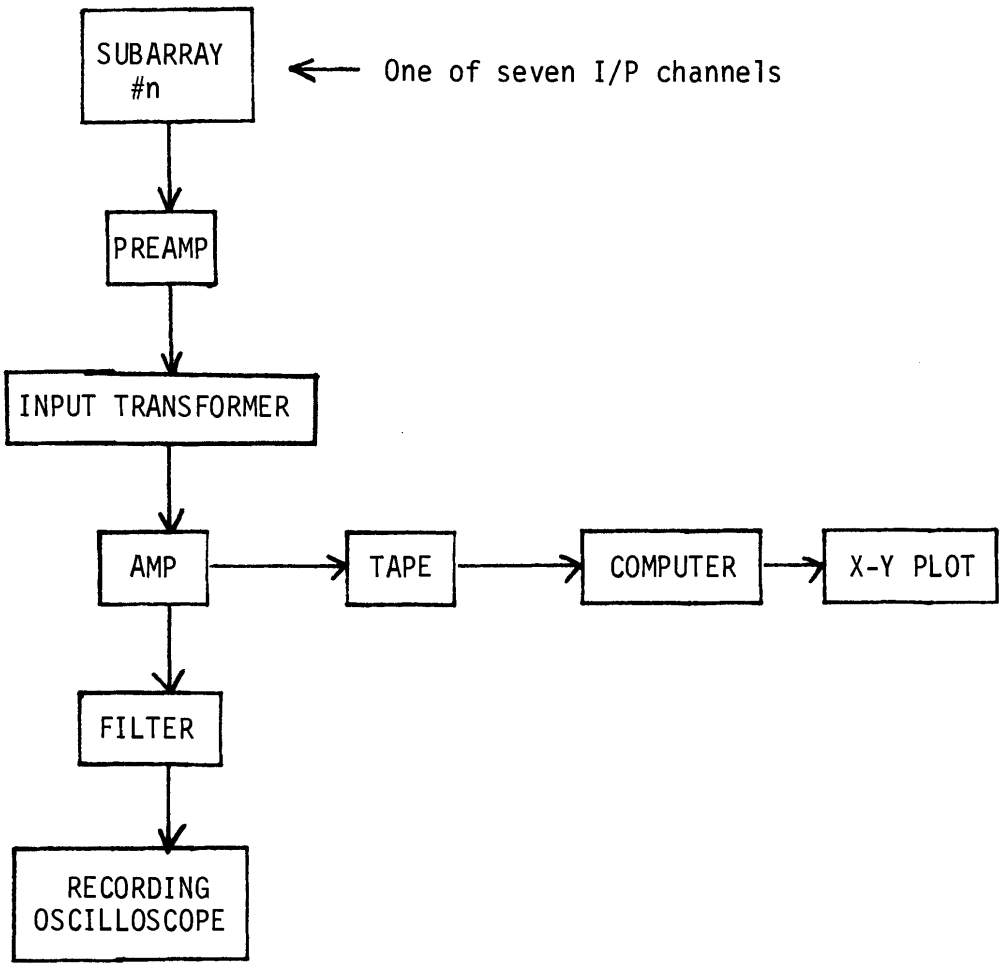
(2 millisec. timing error at 10,000 fps velocity $\equiv$ 20 ft. error)

SYSTEM (LOCATING)

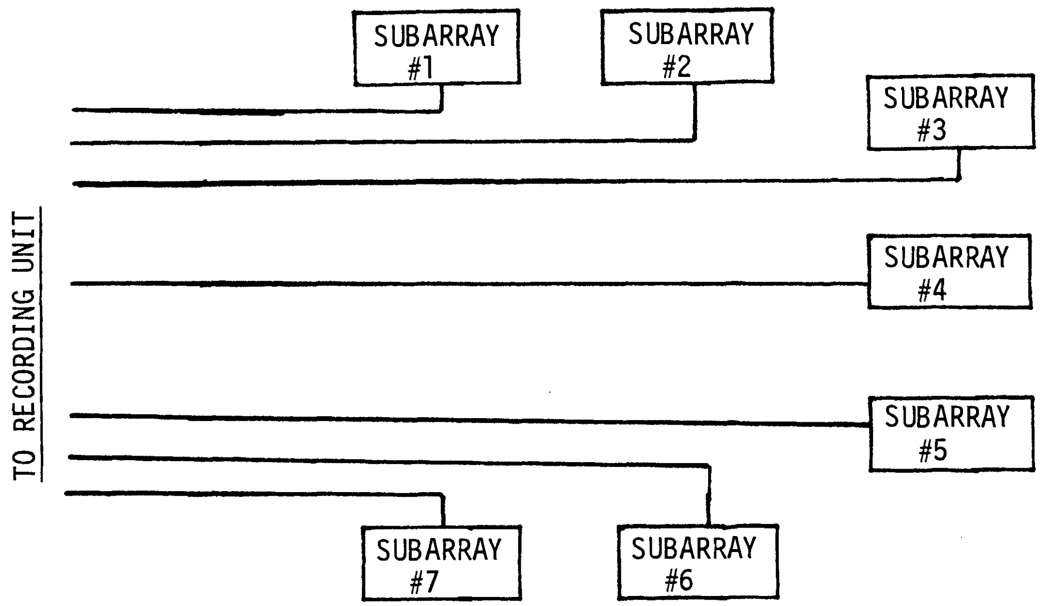


SYSTEM

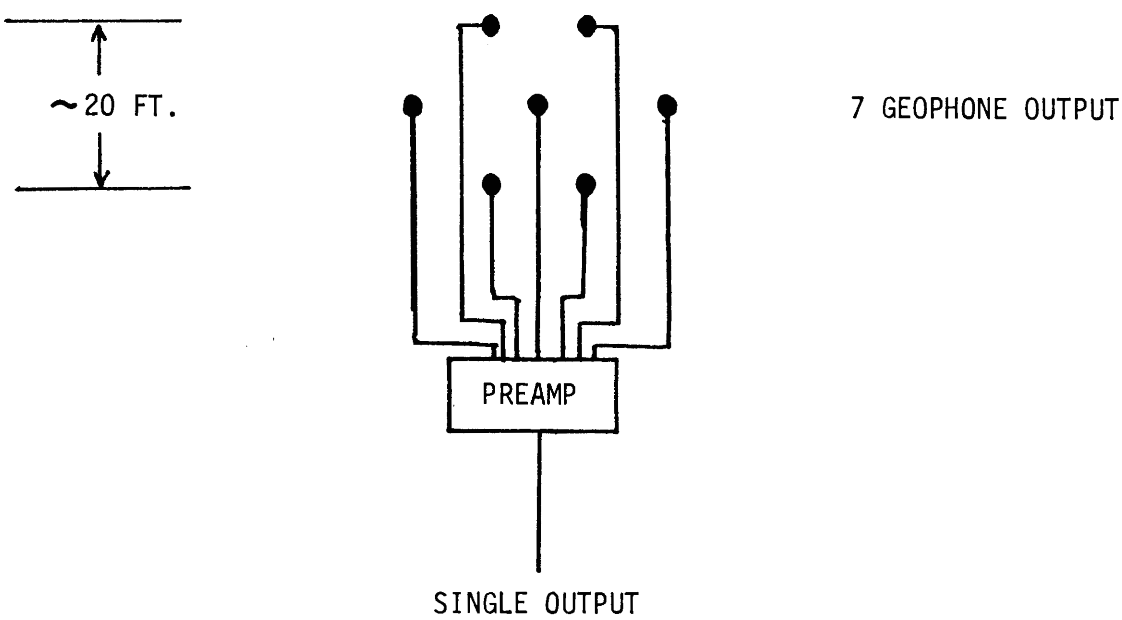
RECORD UNIT, NORMAL MODE



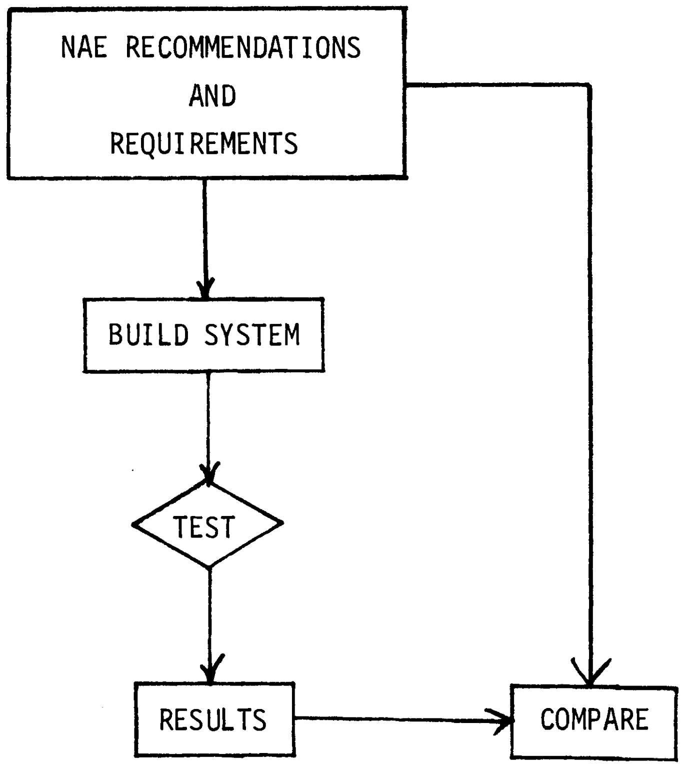
SYSTEM (ARRAY)



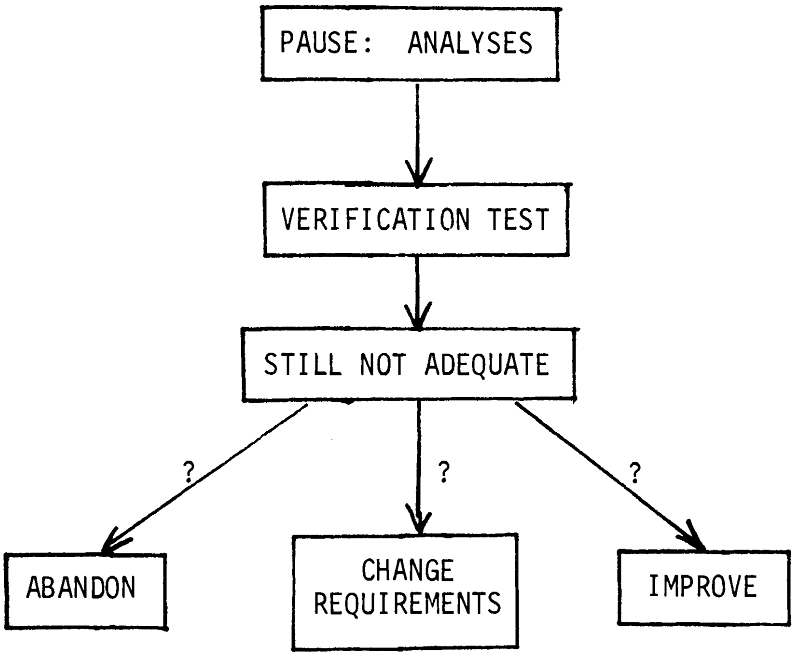
SYSTEM (SUBARRAY)



HISTORY - (A)


NAE RECOMMENDATIONS
AND
REQUIREMENTS
BUILD SYSTEM
TEST
RESULTS
COMPARE

HISTORY - (B)



PAUSE: ANALYSES
VERIFICATION TEST
STILL NOT ADEQUATE
?
?
?
ABANDON
CHANGE REQUIREMENTS
IMPROVE

T E S T

PHILOSOPHY: VARIETY IN

- MINE TYPES
- GEOGRAPHIC AREAS

(ASSUMED SYSTEM WOULD USUALLY WORK)

RESULTS: FAILED NAE REQUIREMENTS

PAUSE - ANALYSES

E.G.,

- THEORETIC EXAMINATION OF SOURCES

- EXAMINATION OF PRE-AMP DESIGN

- COMPLETE LIST IN SEISMIC APPENDIX
  (Westinghouse FY 1972 Report)

VERIFICATION TEST

SIX (6) WEEKS AT EXPERIMENTAL MINE

(50 FT. OVERBURDEN), BRUCETON, PENNSYLVANIA

- Not Always a Realistic Test

WHAT NEXT?

- ABANDON - E.G., RELY ON E.M. METHODS
- CHANGE REQUIREMENTS - E.G., ONLY NEED TO KNOW SECTION
- IMPROVE - Y O U

CHOICE WILL BE MADE WITH YOUR HELP

D. FORMULATION OF THE MINER SEISMIC LOCATION PROBLEM

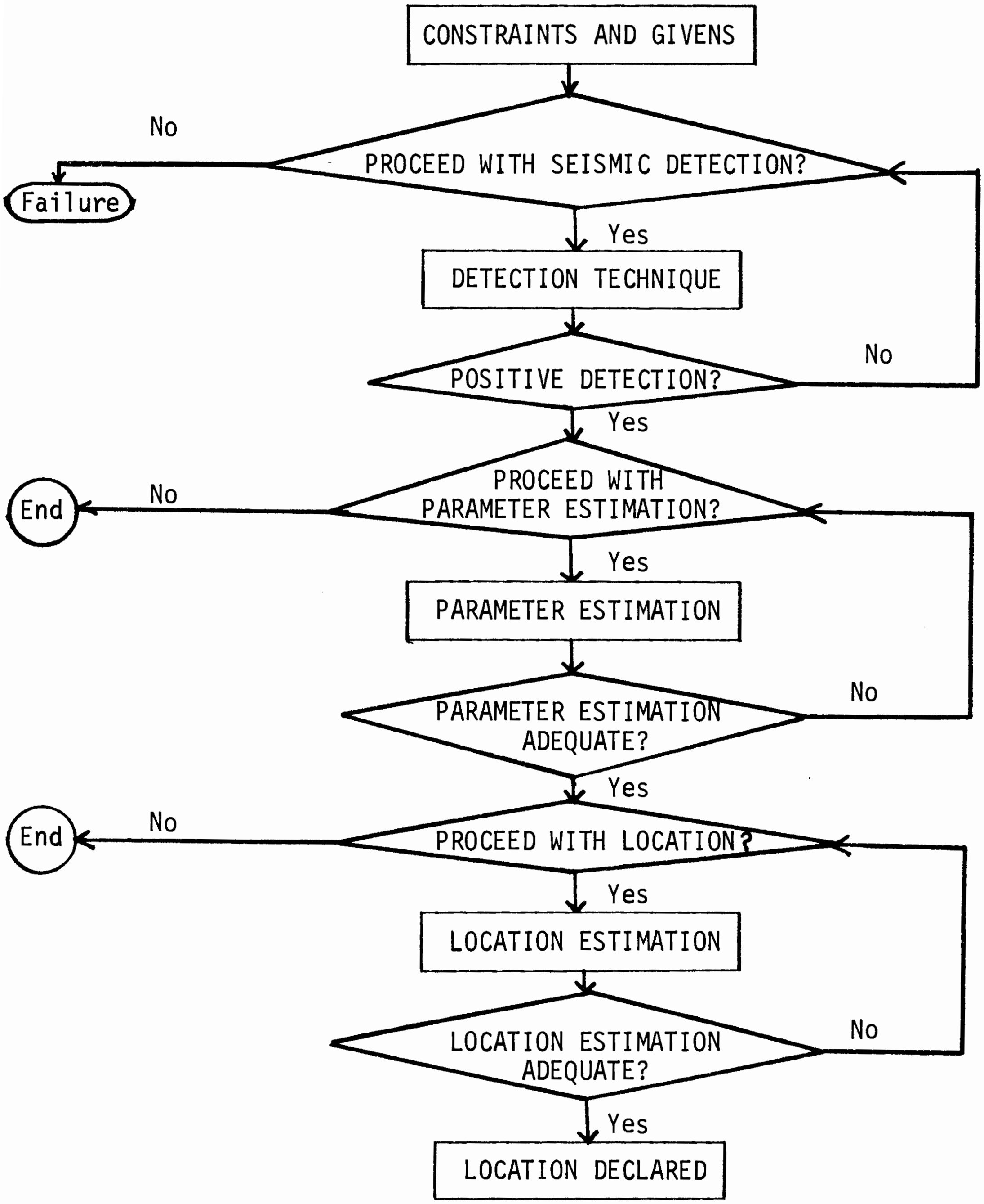
ARTHUR D. LITTLE, INC. - M. ROETTER

CONSTRAINTS AND GIVENS

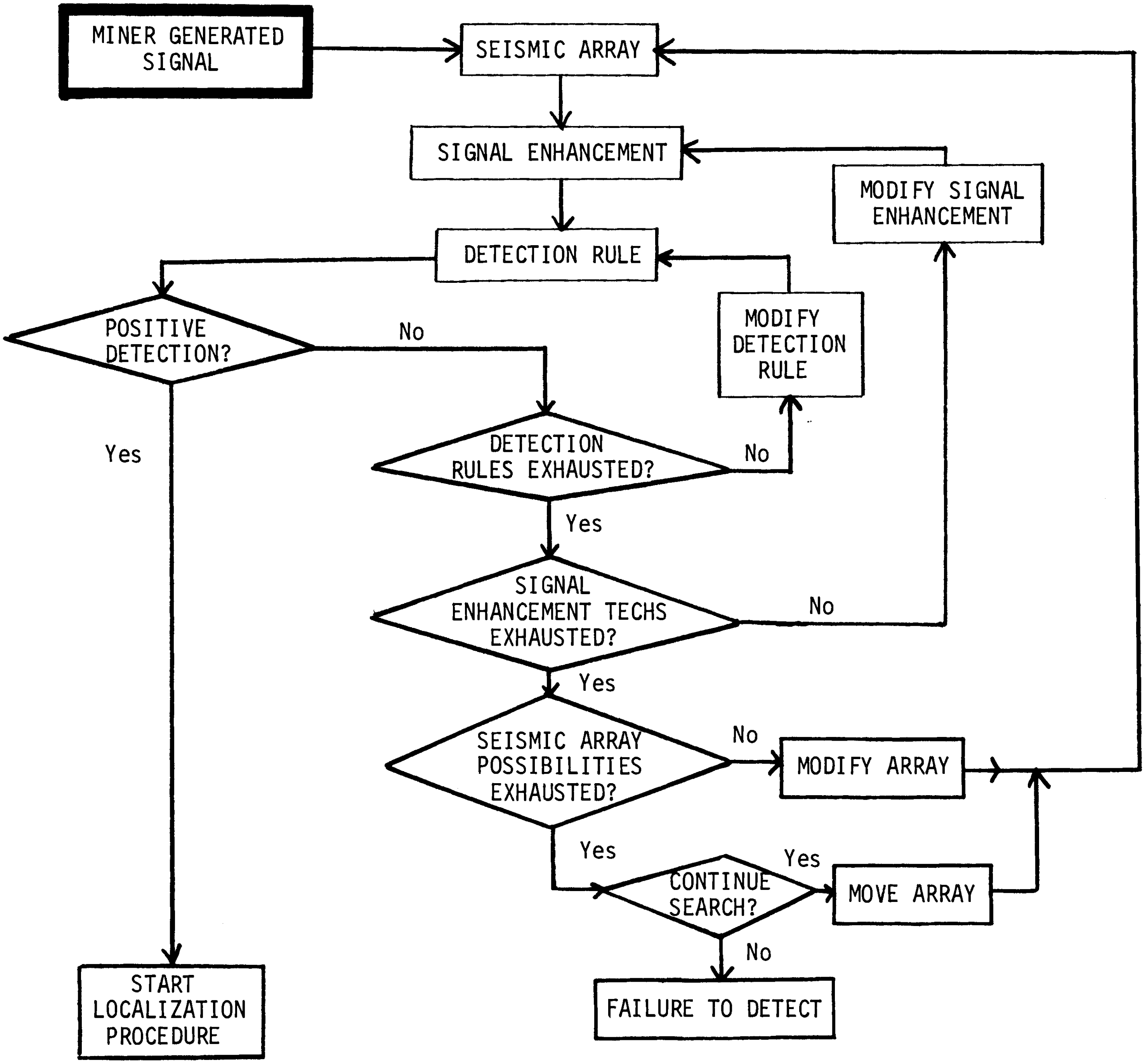
INDUCED BY:

- MINE
- MINERS
- SEISMIC SYSTEM
- OVERALL RESCUE EFFORT

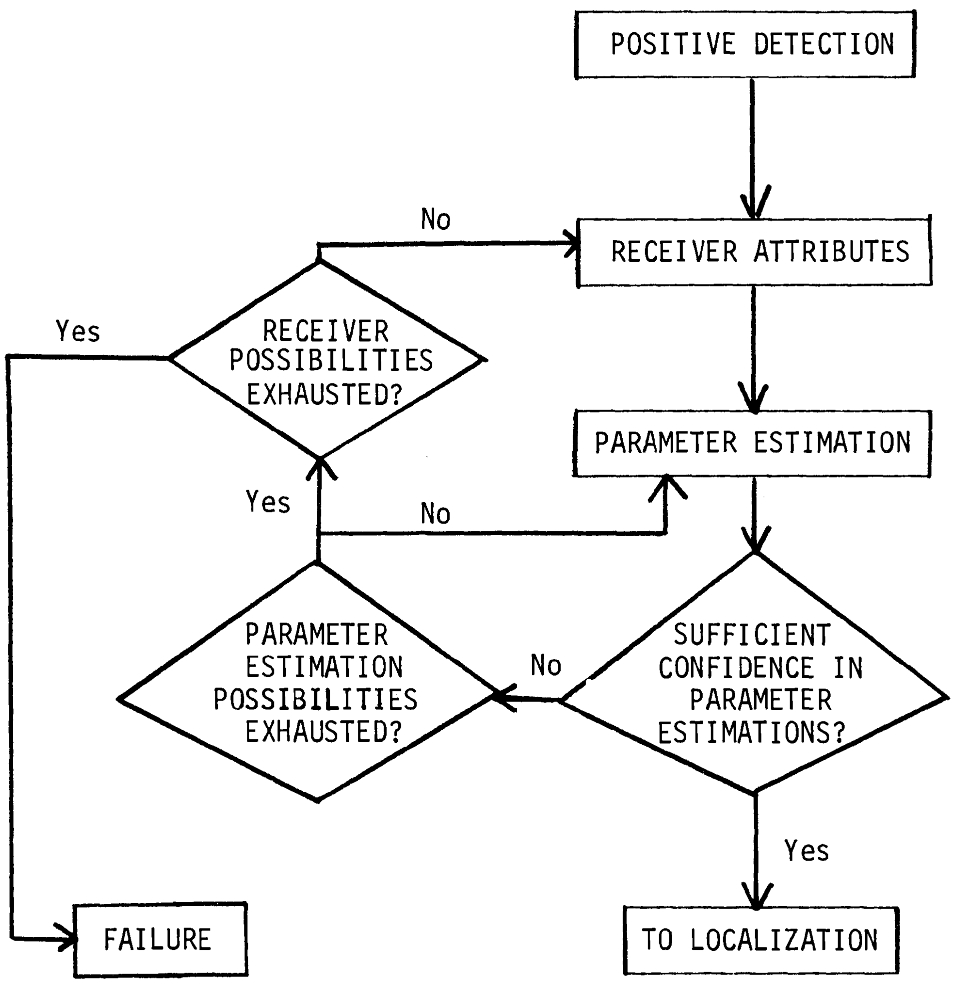
FORMULATION OF PROBLEM



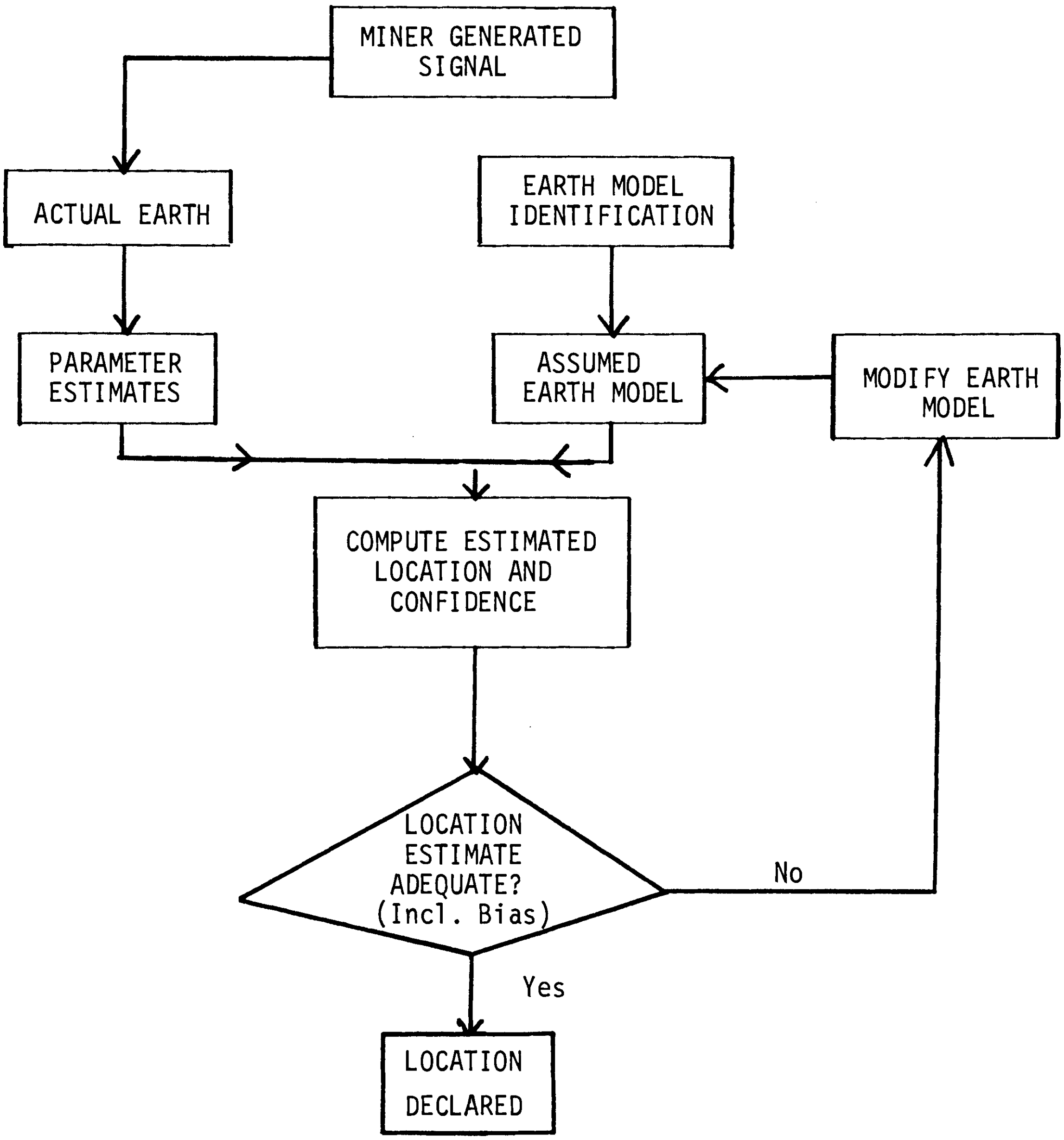
DETECTION OF MINER



PARAMETER ESTIMATION



MINER LOCALIZATION



SEISMIC LOCATION SYSTEM:

GENERAL GROUND RULES

- HARDWARE: FIELD SUITABLE AND RAPIDLY DEPLOYABLE
- SYSTEM CONSTRAINED TO PRESENT STATE-OF-THE-ART TECHNIQUES AND HARDWARE
- SYSTEM OPERATION FROM SURFACE
- SYSTEM SELF-CONTAINED IN ITS OPERATION AND CALIBRATION
- SYSTEM CAPABLE OF PRODUCING TIMELY LOCATION ESTIMATES
- SYSTEM OPERATION COMPATIBLE WITH AND COMPLEMENTARY TO OVERALL RESCUE EFFORT

KEEPING IN MIND THE

IMPACT OF

INVESTMENTS IN

- EQUIPMENT
- TRAINING
- SITE CALIBRATION-PREPARATION

ON

PERFORMANCE

AND

COST

SEISMIC LOCATION SYSTEM:

SPECIFIC GROUND RULES

THE MINER AND HIS MESSAGE

1) The miner has uncertainty as to his true location.
2) The miner's location is fixed.
3) The depth of the miner is known relatively well (σ)
4) Gross location of miner for starting miner detection/location process is given.
5) Only one miner (true signal source) is signalling.
6) The miner has an expectation/certitude of a seismic search.
7) The miner is a limited/non-ideal performer.
8) The miner has imperfect knowledge of time.
9) The miner is unimpaired.
10) The miner's source element must be readily available and reasonable.
11) The source impact area is an undeveloped, but probable feature.

THE MESSAGE TRANSMISSION PATH
AND NOISE ENVIRONMENT

1) The seismic path is initially unknown.
2) The seismic path is linear and time-invariant.
3) Identification of the earth seismic path must proceed from the surface.
4) The surface will most likely be sloped.
5) The seismic noise during a rescue operation is the sum of:
   a) signal induced noise (path scatter)
   b) rescue sources
   c) basic background
   d) altered mine sources
   e) message noise
   f) system noise

THE MESSAGE DETECTION/LOCATION ACTIVITY ON THE SURFACE

1) The surface team will have a mine map and limited mine geological data.

2) The surface team has imperfect knowledge of when signals are transmitted.

3) The surface team has imperfect knowledge of when only noise is present.

4) Use of arrays and burial of seismometers are not mutually exclusive options.

5) Burial to 50 Ft. is an upper bound for the seismometer plant in alluvium.

6) Measurement will not be constrained to the vertical component.

7) The surface team knows the performance of the measuring system.

8) Deep pre-planted sensors may be available at some mines.

9) The search aspects of the problem will be tabled.

E. DESIRED END PRODUCT

AND SCHEDULE OF

PRESENT EFFORT

ARTHUR D. LITTLE, INC. - R. LAGACE

DESIRED STUDY OUTPUTS

- "BEST" ESTIMATES (Based on Present Data) OF:

  THE PROBABILITY OF DETECTION

  and

  THE ACCURACY OF LOCATION

  OF A MINER TRAPPED IN REAL EARTH.

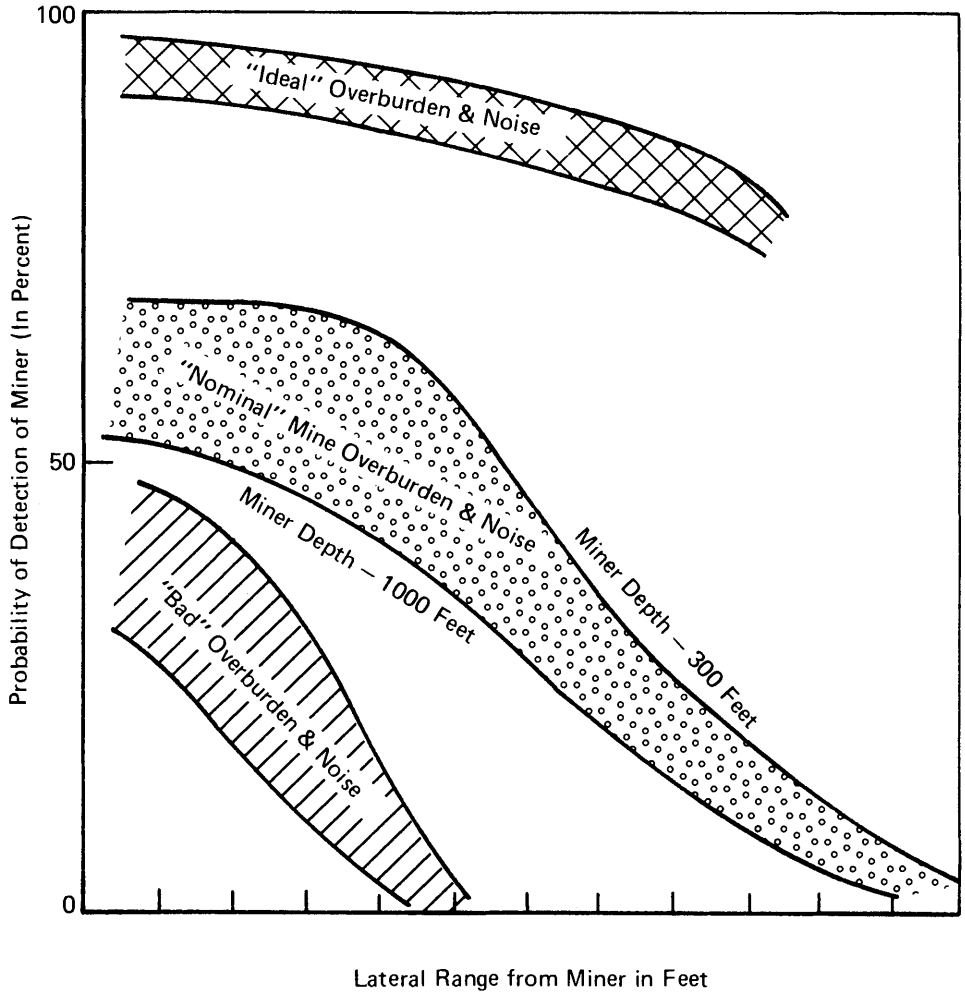
- HOW THESE ESTIMATES CHANGE WITH:

  SYSTEM COMPLEXITY AND COST

- WHAT IS STILL NEEDED IN TERMS OF:

  BASIC DATA
  ANALYSES
  EXPERIMENTS

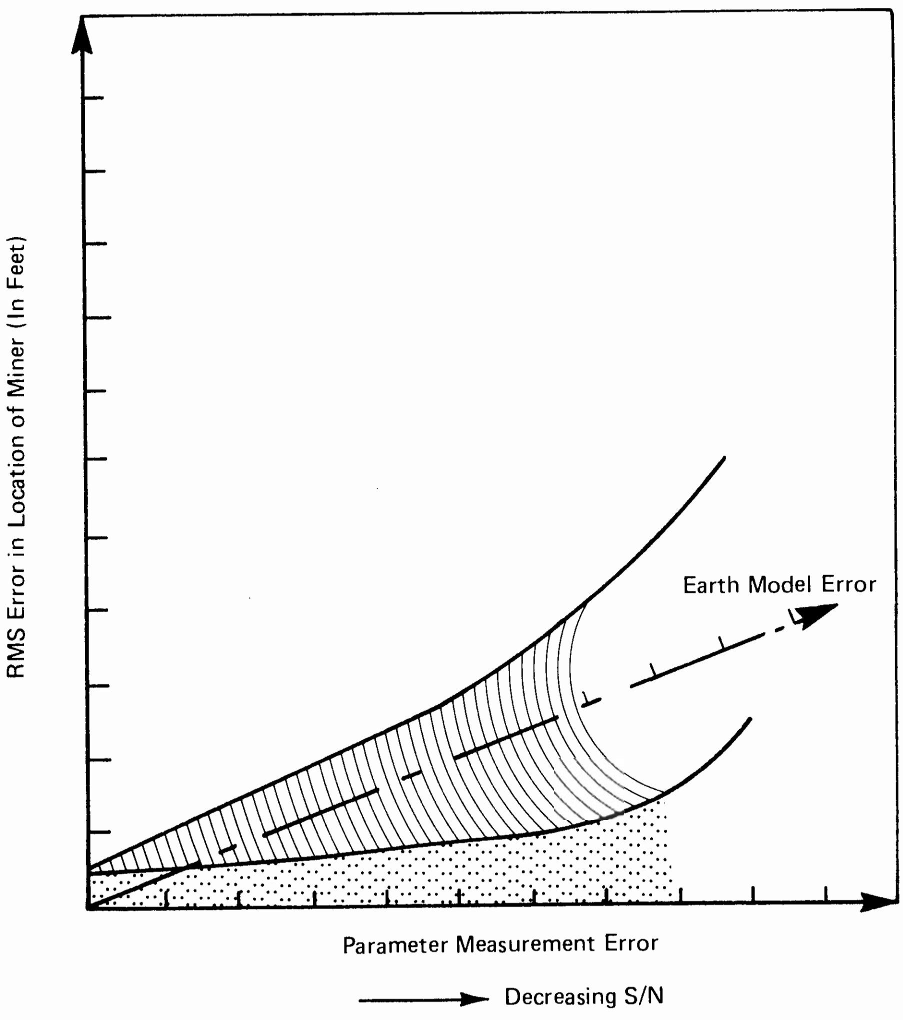
  TO IMPROVE AND/OR VERIFY THESE ESTIMATES



Conditions:

System Configuration —
Miners Source and Message —
Detection Method—

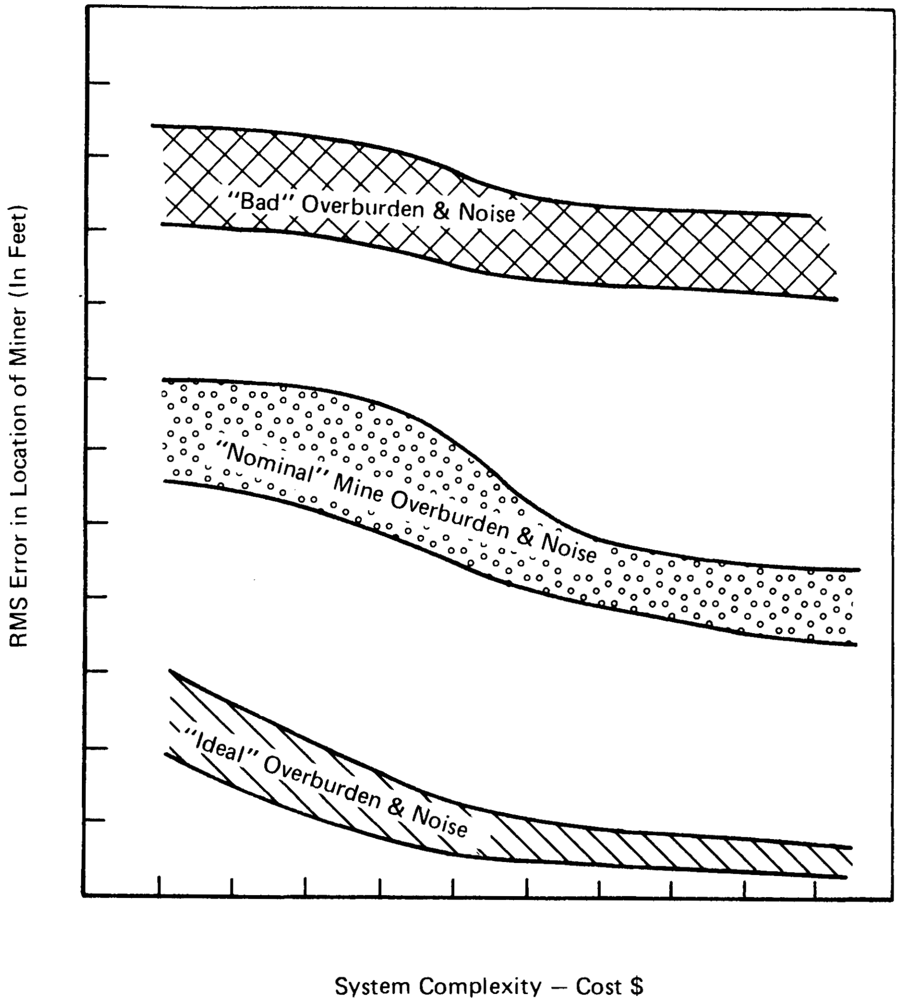
MINER DETECTION
(SAMPLE CONCEPTUAL SKETCH)



Conditions:

System Configuration —
Location Method —
Miner Depth —
Miner's Source and Message —
Overburden Transmission Characteristic —
Noise Environment —

MINER LOCATION
(SAMPLE CONCEPTUAL SKETCH)



PERFORMANCE VERSUS SYSTEM COMPLEXITY—COST (SAMPLE CONCEPTUAL SKETCH)

F. IDENTIFICATION AND DISCUSSION OF MAJOR TASKS

AND TASK ASSIGNMENTS

ARTHUR D. LITTLE, INC. - R. LAGACE

WITH PARTICIPATION BY CONSULTANTS,
AND BUREAU OF MINES
STAFF AND ADL STAFF

CONSULTANTS:

FRANK CROWLEY	-	WESTON OBSERVATORY AND AFCRL
WILLIAM DEAN	-	TELEDYNE GEOTECH
JOHN KUO	-	COLUMBIA UNIVERSITY
ENDERS ROBINSON*	-	INDEPENDENT

BUREAU OF MINES:

HOWARD PARKINSON	-	PMSRC
JAMES POWELL	-	PMSRC

ARTHUR D. LITTLE, INC.

JOHN GINTY

ROBERT LAGACE

MARTYN ROETTER

RICHARD SPENCER

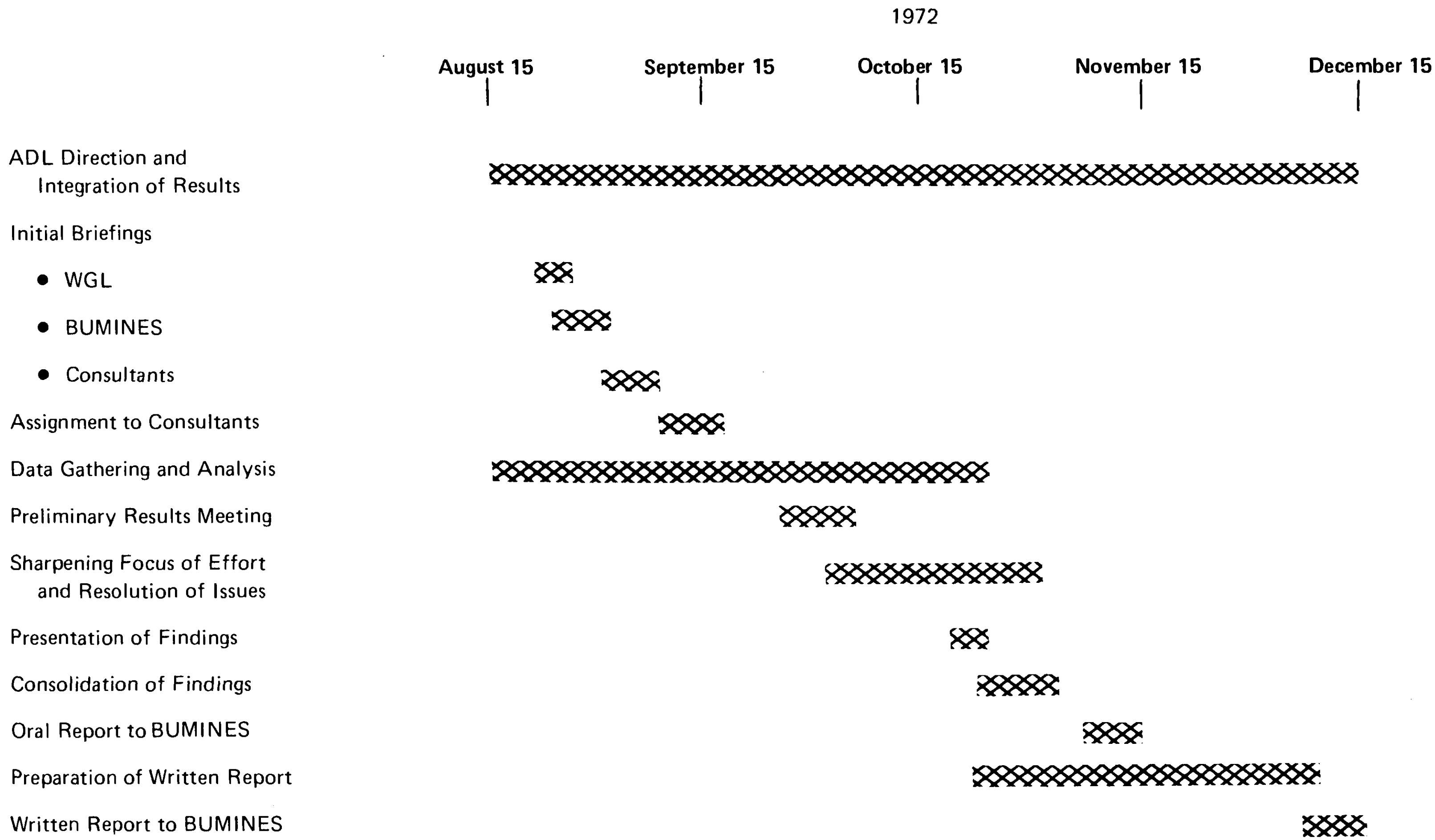
CONSULTANTS: (Who Had to Receive Individual Briefings)

ROBERT CROSSON DAVID PETERS	-	UNIVERSITY OF WASHINGTON
ROY GREENFIELD	-	PENNSYLVANIA STATE UNIVERSITY
FRANK PILOTTE	-	VELA SEISMOLOGICAL CENTER

* Could not participate as originally intended because of scheduling conflicts with prior commitments.

TASKS

	OUTPUTS / INPUTS	DETECTION	PARAMETER ESTIMATION	LOCATION	FIELD UTILIZATION
"FIXED"	SOURCES Fn of: Type : Man : Impact Area : Tunnel	• Strength • Directional and Coherence Charac. • Pulse Shape • Rep. Rate		• Directional Charac.	
"FIXED"	TRANS. MEDIUM. CHARAC. Fn of: Layers (Type, Thick, Angle, etc.)	• Attenuation • Signal Modification - Freq. Response - Time Domain - Spatial Coh.		• Earth Model (Detailed)	
"FIXED"	NOISE Fn of: Sources - Sig. Induced - Rescue Sources - Basic Bgrd. - Altered Mine - Message - System	• Spectrum Levels • Time Charac. i.e. Stationarity Impulsiveness • Spatial Coherence		• Noise Weighting of Parameters	
"VARIABLE"	SENSORS Fn of: Depth : Coupling	• Sensitivity • Array Gain/ Directionality • Dynamic Range • Polarization	✦ Sensitivity ✦ Array Gain/ Directionality ✦ Dynamic Range ✦ Polarization	• Array Geometry and Location	
"VARIABLE"	SIGNAL PROCESSING	• Candidate • Detection Methods	• Candidate • Estimation Methods		
"VARIABLE"	DATA PROCESSING AND COMPUTATION			• Location Algorithms • Mine Maps	



PROGRAM SCHEDULE

III. ORAL PRESENTATION
OF
STUDY RESULTS
TO

PITTSBURGH MINING SAFETY AND RESEARCH CENTER

NOVEMBER 21, 1972

SEISMIC LOCATION OF ISOLATED MINERS

Arthur D. Little, Inc.

(Copies of Flip Charts and Viewgraphs)

A. OVERVIEW AND SUMMARY OF PRINCIPAL FINDINGS

ROBERT L. LAGACE

OBJECTIVE OF STUDY

IDENTIFY:

WHAT CAN BE DONE

AND

HOW WELL

BY SEISMIC MEANS

TO:

- DETECT A MINER
- LOCATE A MINER

TO WITHIN: A SECTION

: AN ENTRY WIDTH

SEISMIC LOCATION SYSTEM:

GENERAL GROUND RULES

- Hardware: Field Suitable and Rapidly Deployable
- System Constrained to Present State-of-Art Techniques and Hardware
- System Operation From Surface
- System Self-Contained in its Operation and Calibration
- System Capable of Producing Timely Location Estimates
- System Operation Compatible with and Complementary to Overall Rescue Effort
- Signal Sources Readily Available and Reasonable - No Special, Carried Devices
- No Wide-Area Search - - Likely Areas Given
- Team Will Have Benefit of Mine Maps

DESIRED STUDY OUTPUTS

- "BEST" ESTIMATES (Based on Present Data) OF:

  THE PROBABILITY OF DETECTION

  and

  THE ACCURACY OF LOCATION

  OF A MINER TRAPPED IN REAL EARTH.

- HOW THESE ESTIMATES CHANGE WITH:

  SYSTEM COMPLEXITY AND COST

- WHAT IS STILL NEEDED IN TERMS OF:

  BASIC DATA
  ANALYSES
  EXPERIMENTS

  TO IMPROVE AND/OR VERIFY THESE ESTIMATES

DETECTION OF A MINER

RANGES

ON THE ORDER OF

1000 FEET

CAN BE ACHIEVED

SUBJECT TO THE CONTROL OF

MANMADE NOISE SOURCES*

This Should Allow More

Than Adequate Coverage

of Typical Mine Sections

* Namely, surface operations and activity over and in the vicinity of the detection area must be severely restricted and possibly prohibited.

LOCATION OF A MINER

TO WITHIN A SECTION

LOCATION ACCURACIES
TO WITHIN
100 FEET
TO DEPTHS OF 1000 FEET
APPEAR ATTAINABLE

SUBJECT TO:

- CONTROL OF MANMADE NOISE SOURCES*
- AN ADEQUATE SEISMIC REPRESENTATION OF THE EARTH

* Namely, surface operations and activity over and in the vicinity of the location area must be severely restricted and possibly prohibited. Signal-to-noise ratios in excess of that for detection will also be required.

<u>LOCATION OF A MINER</u>

<u>TO WITHIN AN ENTRY WIDTH</u>

APPEARS TO BE AN <u>UNREALISTIC GOAL</u>

HOWEVER: UNDER VERY FAVORABLE CIRCUMSTANCES*

ACCURACIES OF ABOUT 30 FEET APPEAR ATTAINABLE

With the Aid of An Accurate Mine Map - This Should Allow <u>Identification</u>

Of the Entry in Which the Miner is Located

---

* For manmade noise, same comments as for previous chart. An even more accurate representation of the earth, or a shallower depth (300 feet or less), will also be necessary.

EXPECTED IMPACT OF INVESTMENTS ON PERFORMANCE AND COST

IMPACT OF ↓ ON →	Improving Overall Performance	Increasing Overall Cost
Truly Fieldable Hardware	HIGH	LOW
Trained Experienced Field Crews	HIGH	MODERATE
Site Pre-Calibration Preparation	HIGH	HIGH
Improved Seismic Earth Models	HIGH	LOW
Conventional S/N Enhancement Methods	HIGH	LOW
Sophisticated S/N Enhancement Methods	LOW	HIGH
Controlling Site Manmade Noise	HIGH	LOW

TO IMPROVE AND/OR VERIFY PERFORMANCE ESTIMATES

NEED

BETTER QUANTITATIVE
CHARACTERIZATION OF:

- SEISMIC SIGNALS FROM SOURCES AVAILABLE TO MINERS
- SEISMIC NOISE IN COAL MINE REGIONS
- SEISMIC PROPAGATION ATTRIBUTES OF COAL MINE OVERBURDENS

B. PROBLEM

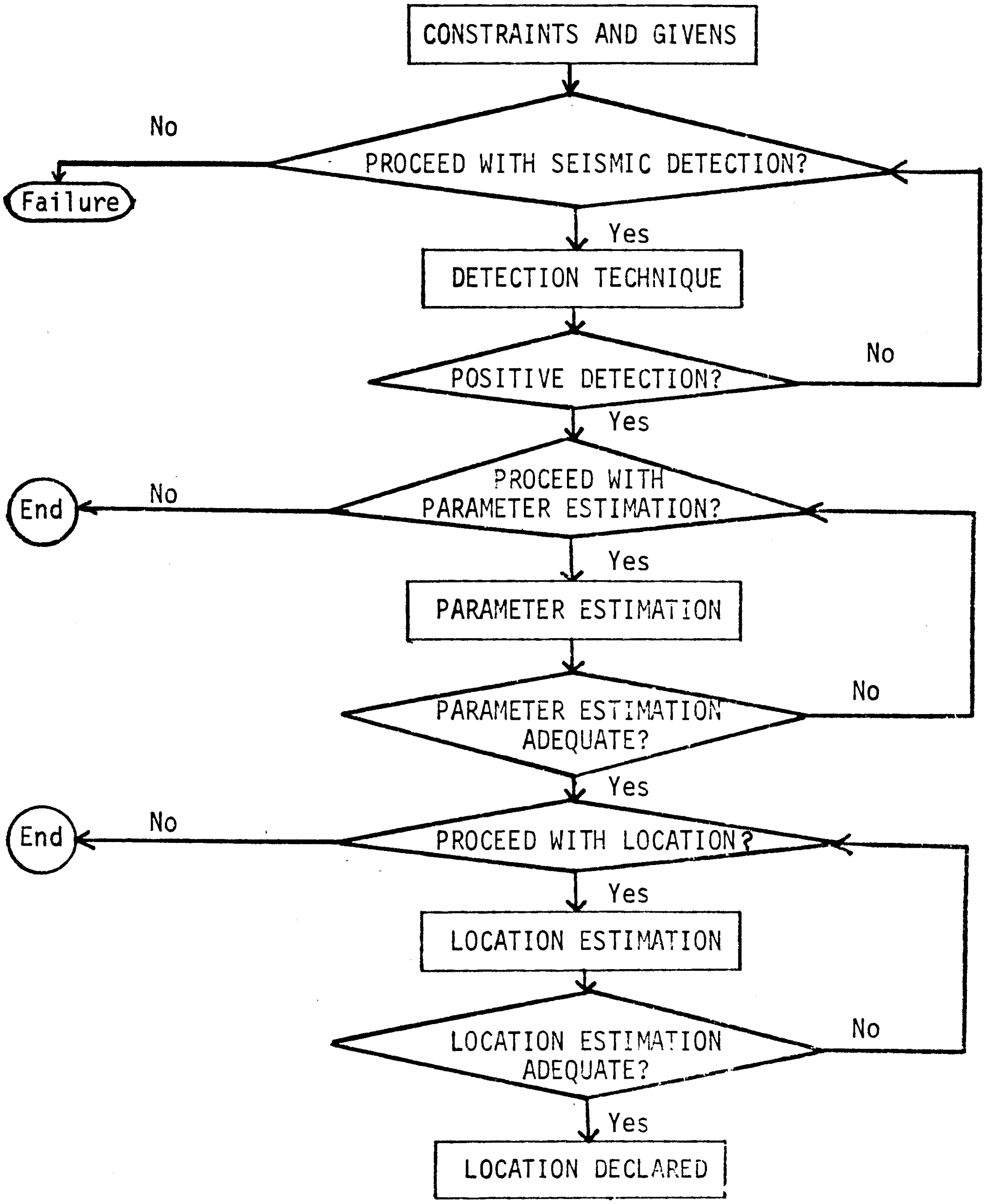
FORMULATION

AND

TASKS

ROBERT L. LAGACE

FORMULATION OF PROBLEM



TASKS

	OUTPUTS / INPUTS	DETECTION	PARAMETER ESTIMATION	LOCATION	FIELD UTILIZATION
"FIXED"	SOURCES Fn of: Type : Man : Impact Area : Tunnel	• Strength • Directional and Coherence Charac. • Pulse Shape • Rep. Rate		• Directional Charac.	
	TRANS. MEDIUM. CHARAC. Fn of: Layers (Type, Thick, Angle, etc.)	• Attenuation • Signal Modification - Freq. Response - Time Domain - Spatial Coh.		• Earth Model (Detailed)	
	NOISE Fn of: Sources - Sig. Induced - Rescue Sources - Basic Bgrd. - Altered Mine - Message - System	• Spectrum Levels • Time Charac. i.e. Stationarity Impulsiveness • Spatial Coherence		• Noise Weighting of Parameters	
"VARIABLE"	SENSORS Fn of: Depth : Coupling	• Sensitivity • Array Gain/ Directionality • Dynamic Range • Polarization	✦ Sensitivity ✦ Array Gain/ Directionality ✦ Dynamic Range ✦ Polarization	• Array Geometry and Location	
	SIGNAL PROCESSING	• Candidate • Detection Methods	• Candidate • Estimation Methods		
	DATA PROCESSING AND COMPUTATION			• Location Algorithms • Mine Maps	

C. DETECTION

OF AN

ISOLATED

MINER

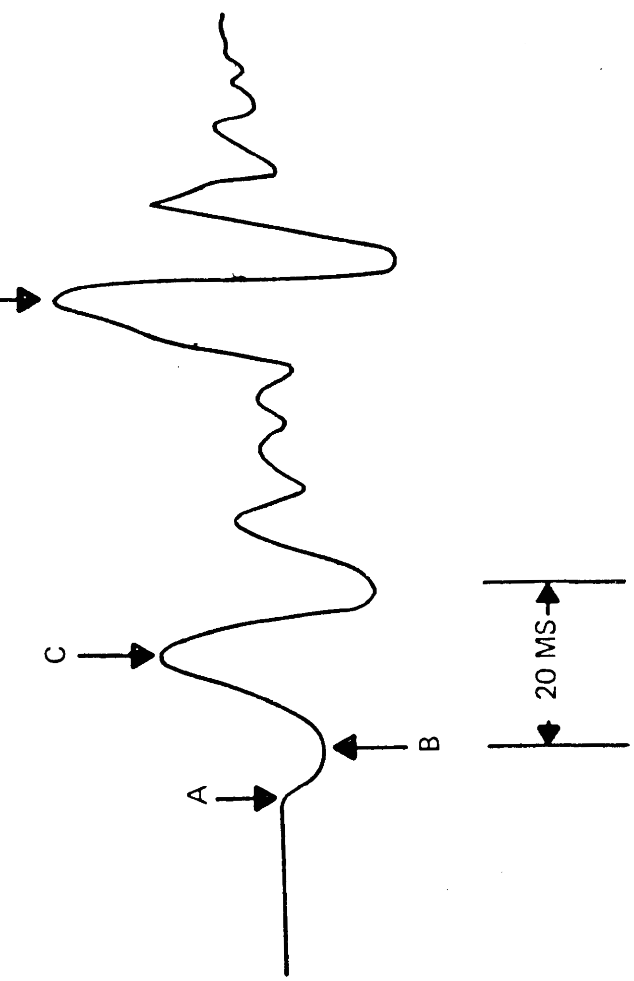
ROBERT L. LAGACE

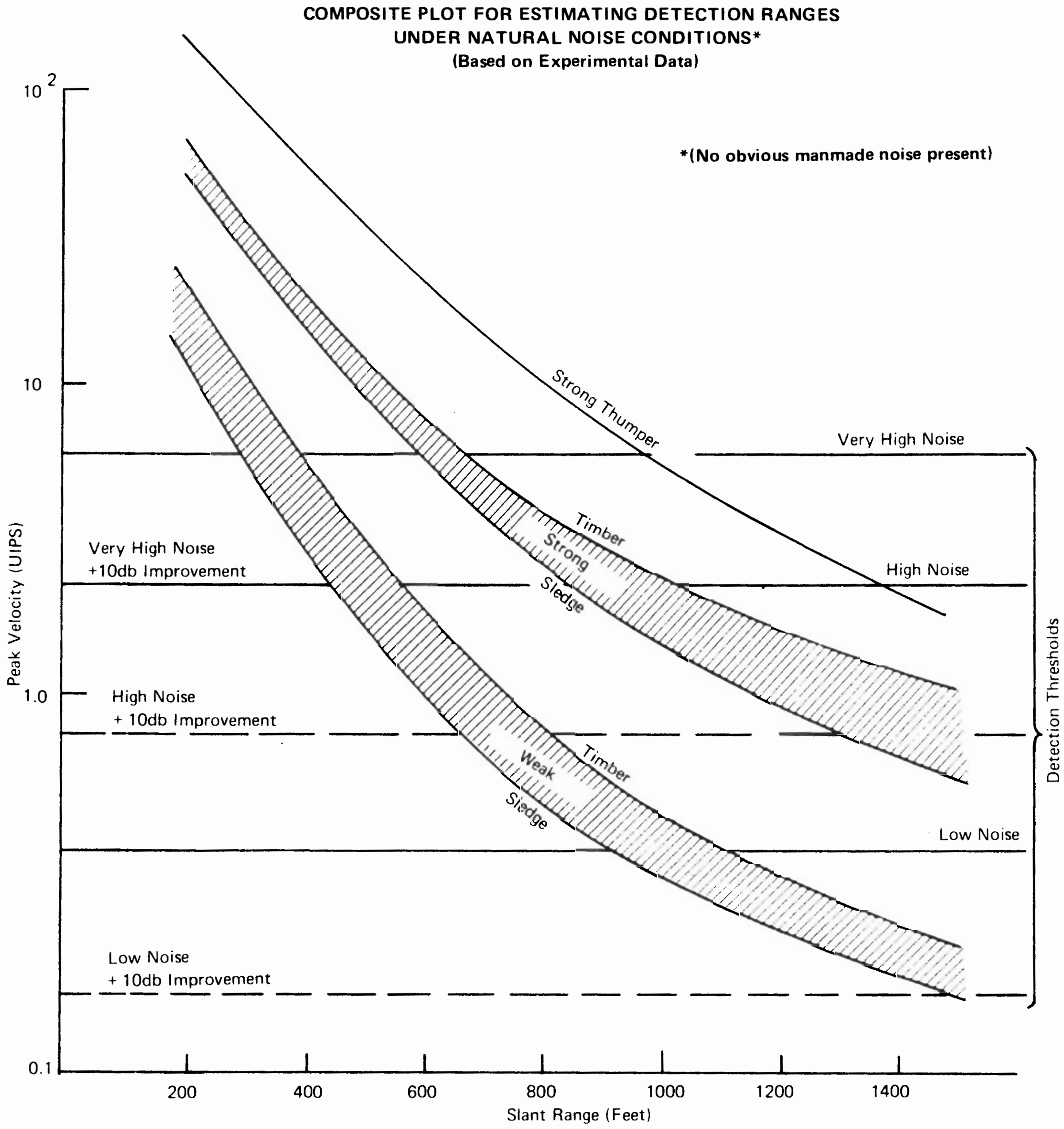
DETECTION OF A MINER

CONSIDERATIONS FOR
ESTIMATING DETECTION RANGES

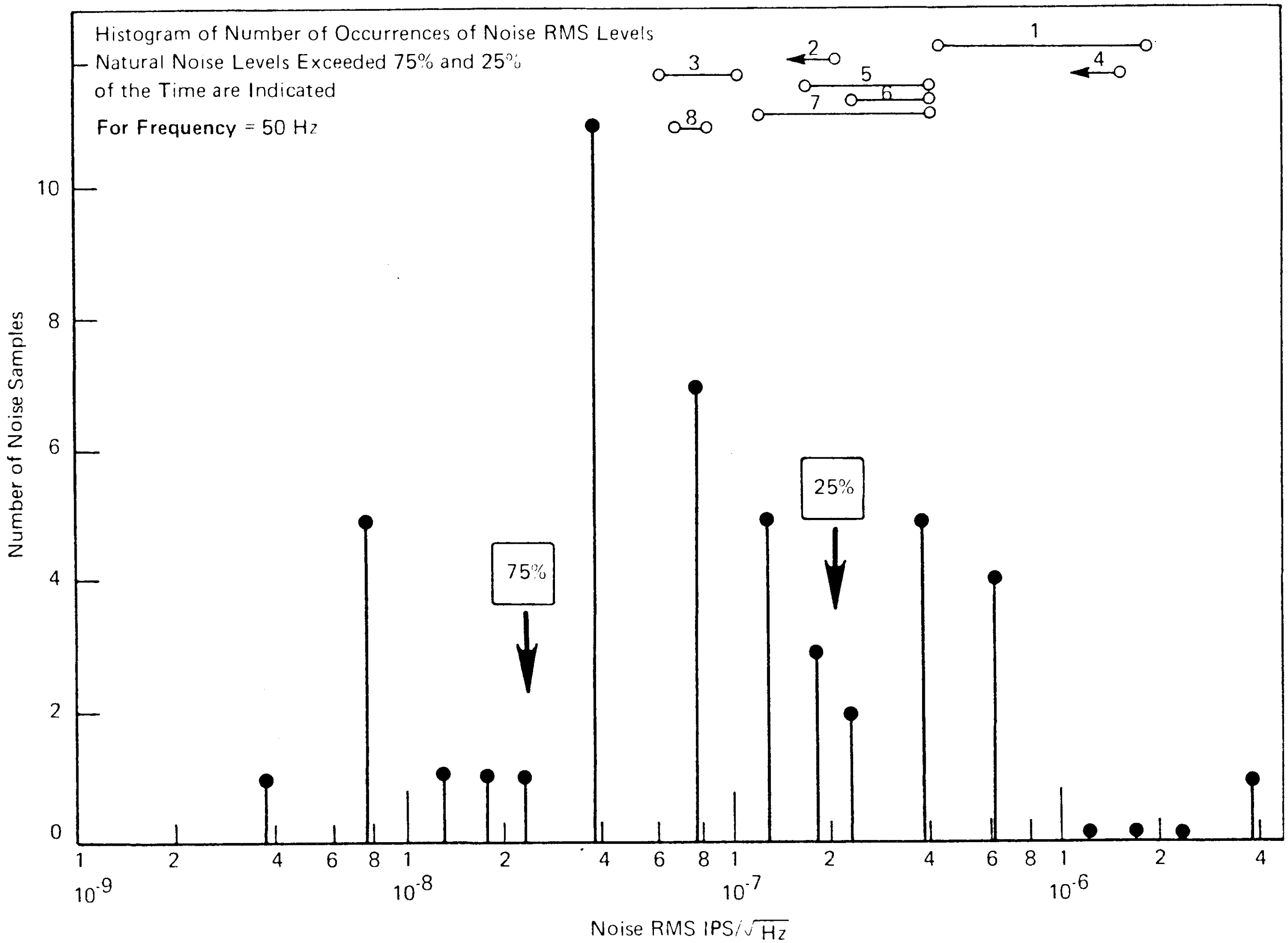
- SIGNAL STRENGTH
  - Source
  - Transmission Loss
- NOISE LEVELS
  - Natural Background
  - Manmade Sources
- SIGNAL-TO-NOISE ENHANCEMENT METHODS
- RANGE ESTIMATION
  - Detection Criteria

SCHEMATIC GENERALIZED SEISMIC SIGNAL
(Applicable to Mine Data Obtained to Date)



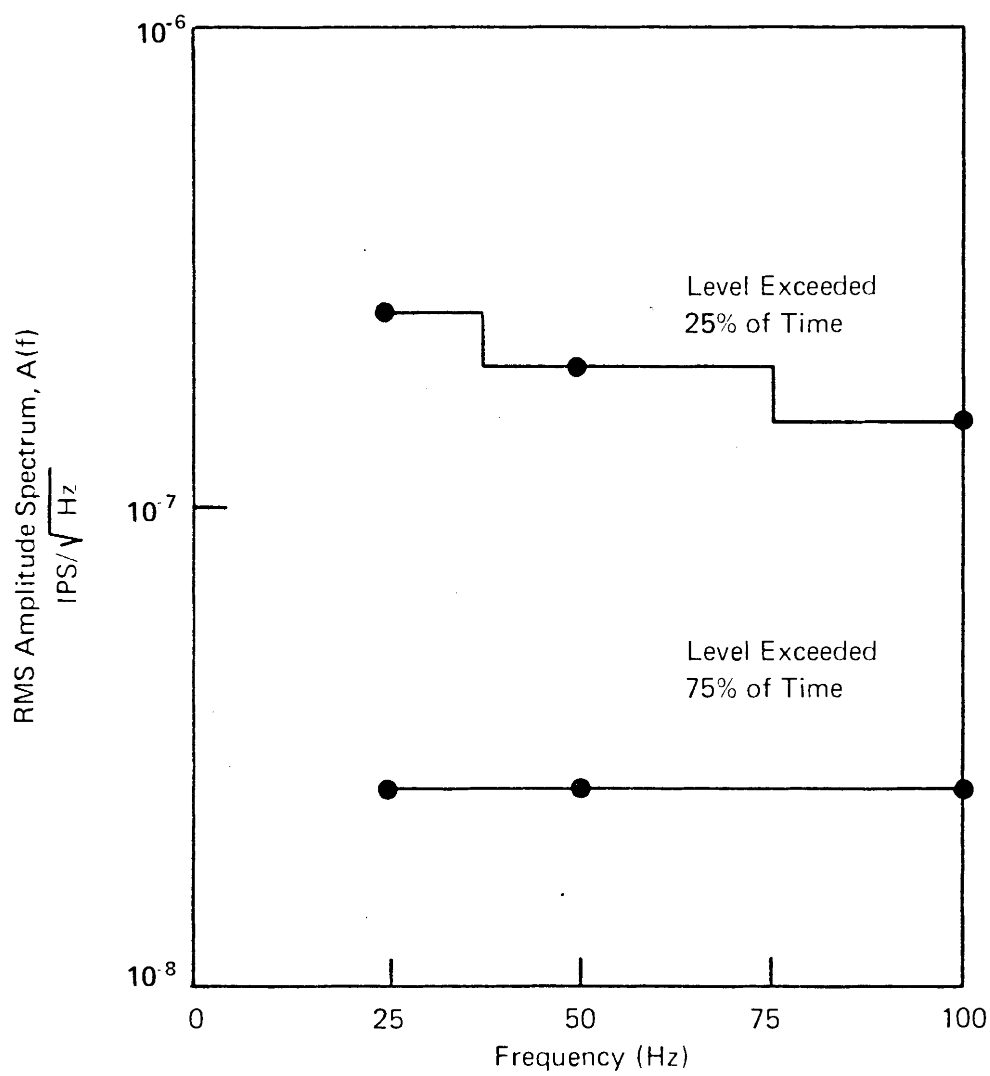


COMPOSITE PLOT FOR ESTIMATING DETECTION RANGES
UNDER NATURAL NOISE CONDITIONS*
(Based on Experimental Data)
*(No obvious manmade noise present)
10^2
10
1.0
0.1
Peak Velocity (UIPS)
Strong Thumper
Very High Noise
Timber
Strong
Sledge
High Noise
Very High Noise
+10db Improvement
High Noise
+ 10db Improvement
Timber
Weak
Sledge
Low Noise
Low Noise
+ 10db Improvement
Detection Thresholds
200
400
600
800
1000
1200
1400
Slant Range (Feet)

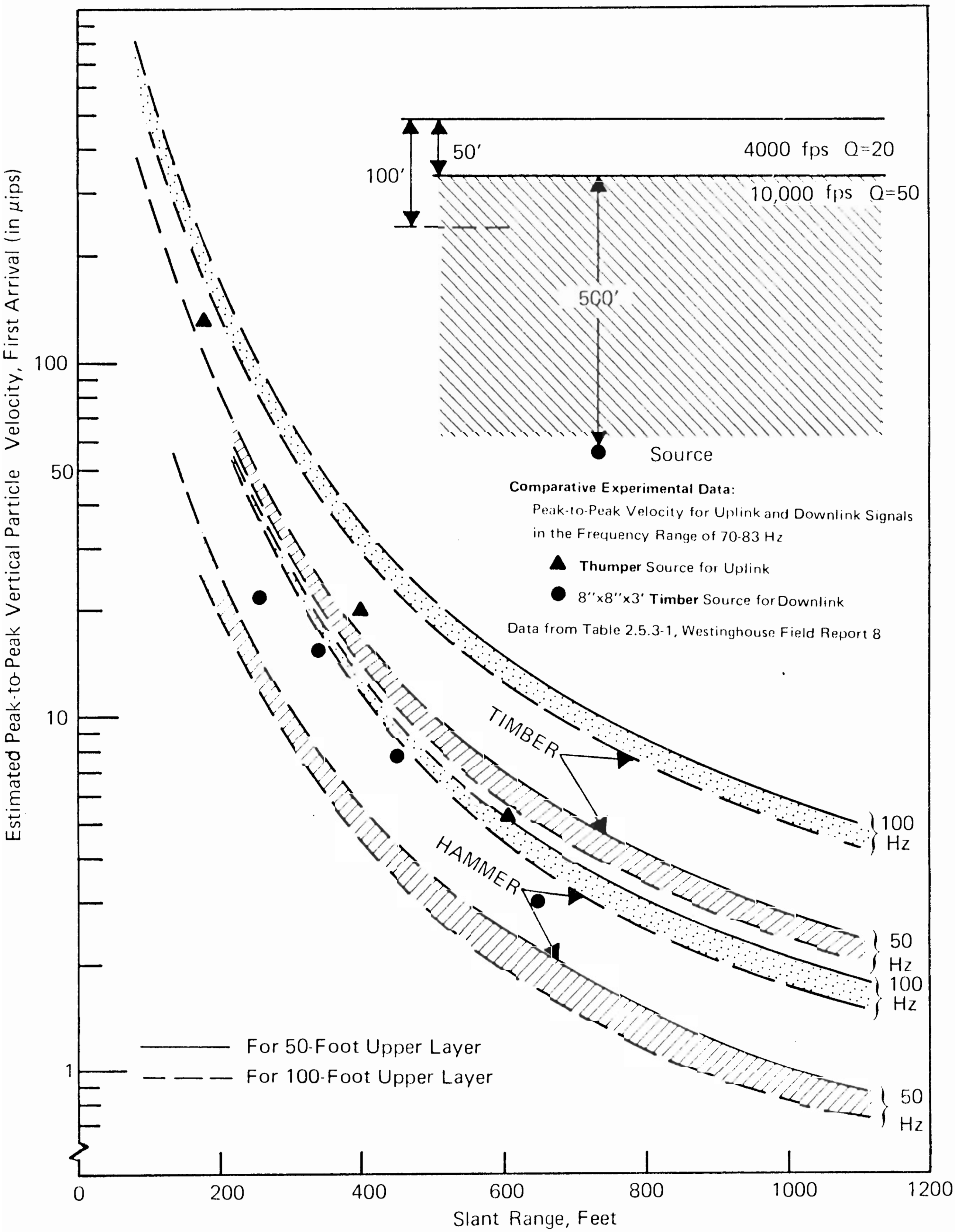


Westinghouse data for individual mines are included for comparison, and maximum and minimum noise levels are shown as open circles connected by lines. Ignore the vertical axis in relation to these data. Arrows pointing to the left indicate that system noise limited noise estimates for low noise periods. The Westinghouse data are taken from the Westinghouse Report Table 2-4. The order of the mines, going from the top of the figure to the bottom data points, corresponds to the field report numbers for the mines.

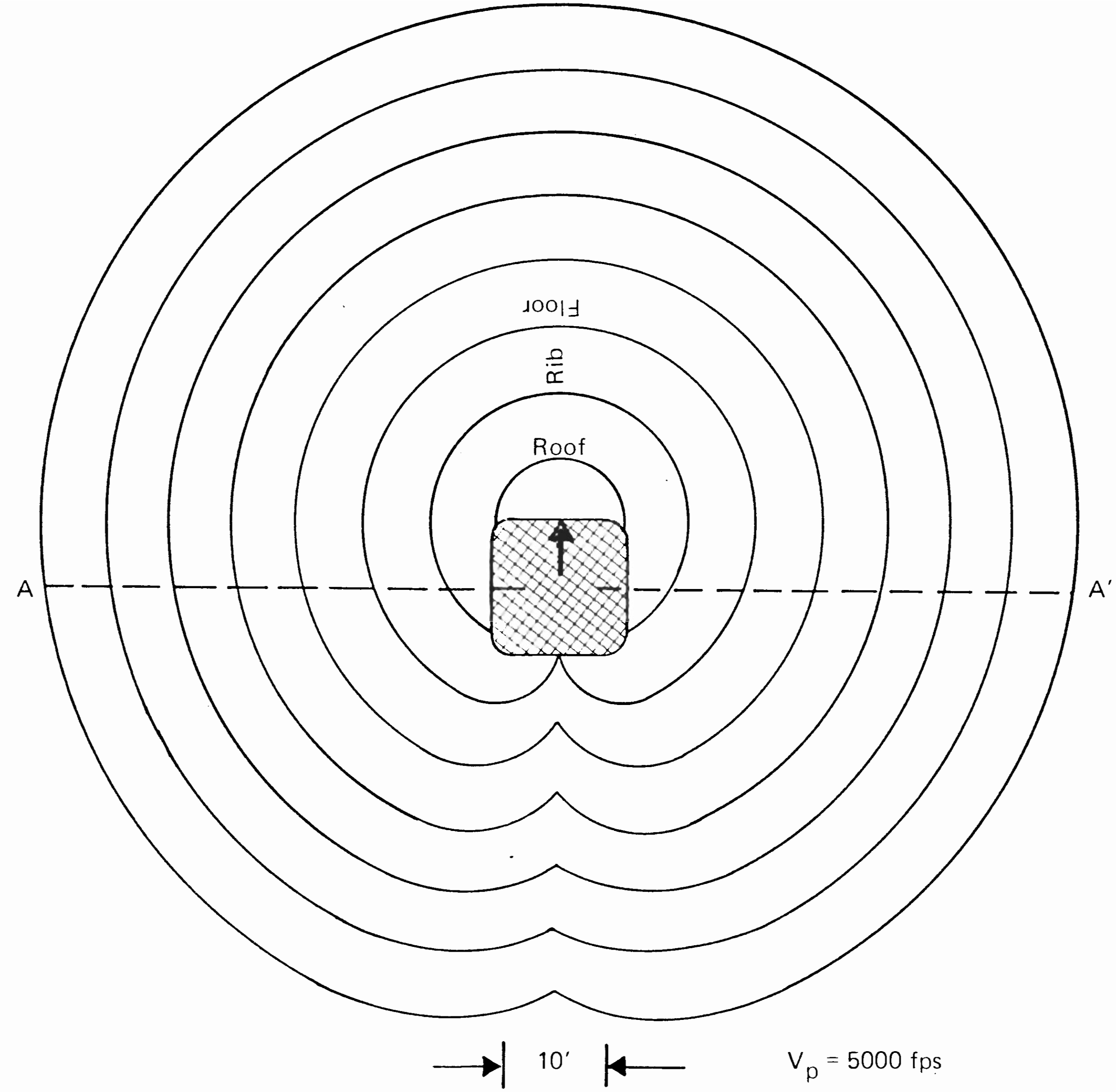
NATURAL SEISMIC NOISE LEVELS: BASED ON FRANTTI DATA WHEN NO MAN-MADE NOISE IS PRESENT



NATURAL SEISMIC NOISE LEVELS BASED ON FRANTTI
DATA WHEN NO OBVIOUS MAN-MADE NOISE IS PRESENT
(RMS AMPLITUDE SPECTRA)



ESTIMATED PEAK-TO-PEAK VERTICAL PARTICLE
VELOCITY FOR THE FIRST P-WAVE ARRIVAL
(BASED ON THEORETICAL CONSIDERATIONS)



DISTORTED WAVE FRONTS OF A VERTICAL SECTION A-A′

SIGNAL-TO-NOISE IMPROVEMENT

METHODS

FOR DETECTION

Most Useful

- BANDPASS FILTERING
- BURIAL OF SENSORS
- SUBARRAYS
  - Size Adjust
  - Delayed or Direct Sum
  - Weighted Sum

FOR ARRIVAL TIME ESTIMATION

Most Useful

- SAME AS ABOVE
- SUMMING (STACKING) OF REPEATED SIGNALS

FOR DETECTION AND ARRIVAL TIME ESTIMATION

Least Useful

- REMODE
- LINEAR PHASE FILTERING OF MULTICOMPONENT DATA
- MATCHED FILTERING
- MULTI-CHANNEL MAXIMUM LIKELIHOOD ARRAY PROCESSING
- MULTICHANNEL WIENER FILTERING
- SINGLE AND MULTICHANNEL PREDICTION ERROR FILTERING

MAXIMUM SLANT RANGES (In Feet) FOR DETECTION-UNDER NATURAL NOISE CONDITIONS**

Source	Low Noise		High Noise		Very High Noise	
	W/O-S/N I*	W-S/N I	W/O-S/N I	W-S/N I	W/O S/N I	W-S/N I
Strong Thumper	>2000	>2000	1400	>2000	950	1400
Strong						
Timber	>2000	>2000	1050	>1500	650	1050
Sledge	>1500	>2000	900	1250	550	900
Weak						
Timber	1100	>1500	550	800	375	550
Sledge	900	>1400	450	625	300	450

* W/O - S/N I = Without 10dB Signal-to-Noise Improvement
W - S/N I = With 10dB Signal-to-Noise Improvement

** No obvious manmade noise sources

SEPARATION GUIDELINES FOR DEALING WITH MAN-MADE NOISE SOURCES*

Type	Distance	Detector
Light Vehicular	10,000 ft.	Single Phone
	5,000 ft.	Buried Array
Piston Aircraft	20,000 ft.	Single Phone
	5,000 ft.	Buried Array
Lone Trees and Telephone Poles	400 ft.	Single Phone
(heavy wind condition)	150 ft	Buried Array
Drilling	7,500 ft.	Single Phone
	5,000 ft.	Buried Array
Man Walking	1,000 ft.	Single Phone
	500 ft.	Buried Array
Machinery (heavy)	10,000 ft.	Single Phone
	2,000 ft.	Coherent Processing
Intra-Mine Sources	3,000 ft.	Single Phone
(miner equivalent)	3,000 ft.	Buried Array

* The detector scheme and noise source-detector separation distances shown are those which should be sufficient to keep the disturbance of the associated noise source within the "base" noise levels discussed in Part Nine. These guidelines should be considered both speculative and conservative.

D. LOCATION OF AN ISOLATED MINER

ARRIVAL TIME ESTIMATES AND LOCATION ACCURACIES USING SURFACE ARRAYS AND EARTH MODELS

MARTYN F. ROETTER

LOCATION ACCURACIES USING REFERENCE EVENT METHOD

RICHARD H. SPENCER

MINER LOCATION

CONSIDERATIONS IN THE ESTIMATION

OF

LOCATION ACCURACIES

ARRIVAL TIME ESTIMATES

- Enhancement of Arrival Time Accuracies

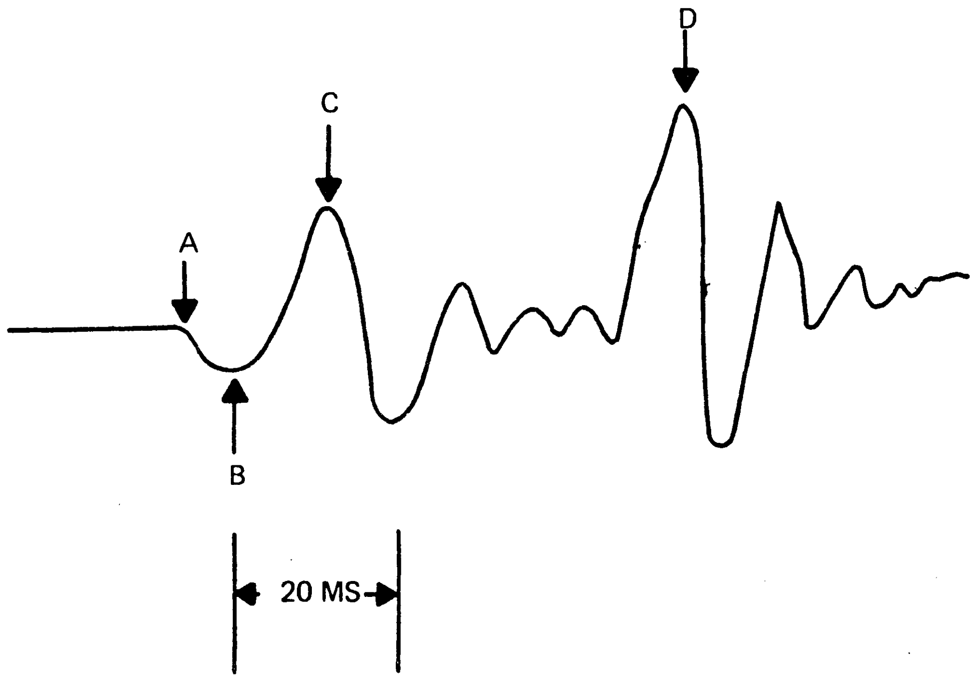
TREATMENT OF THE EARTH

- Model Representation Based on
  - General Geological Knowledge
  - Refraction Survey Data
- "Black Box" Approach with Travel Times Based on Reference Events

1. ARRIVAL TIME ESTIMATES

MARTYN F. ROETTER

SCHEMATIC GENERALIZED SEISMIC SIGNAL
(Applicable to Mine Data Obtained to Date)

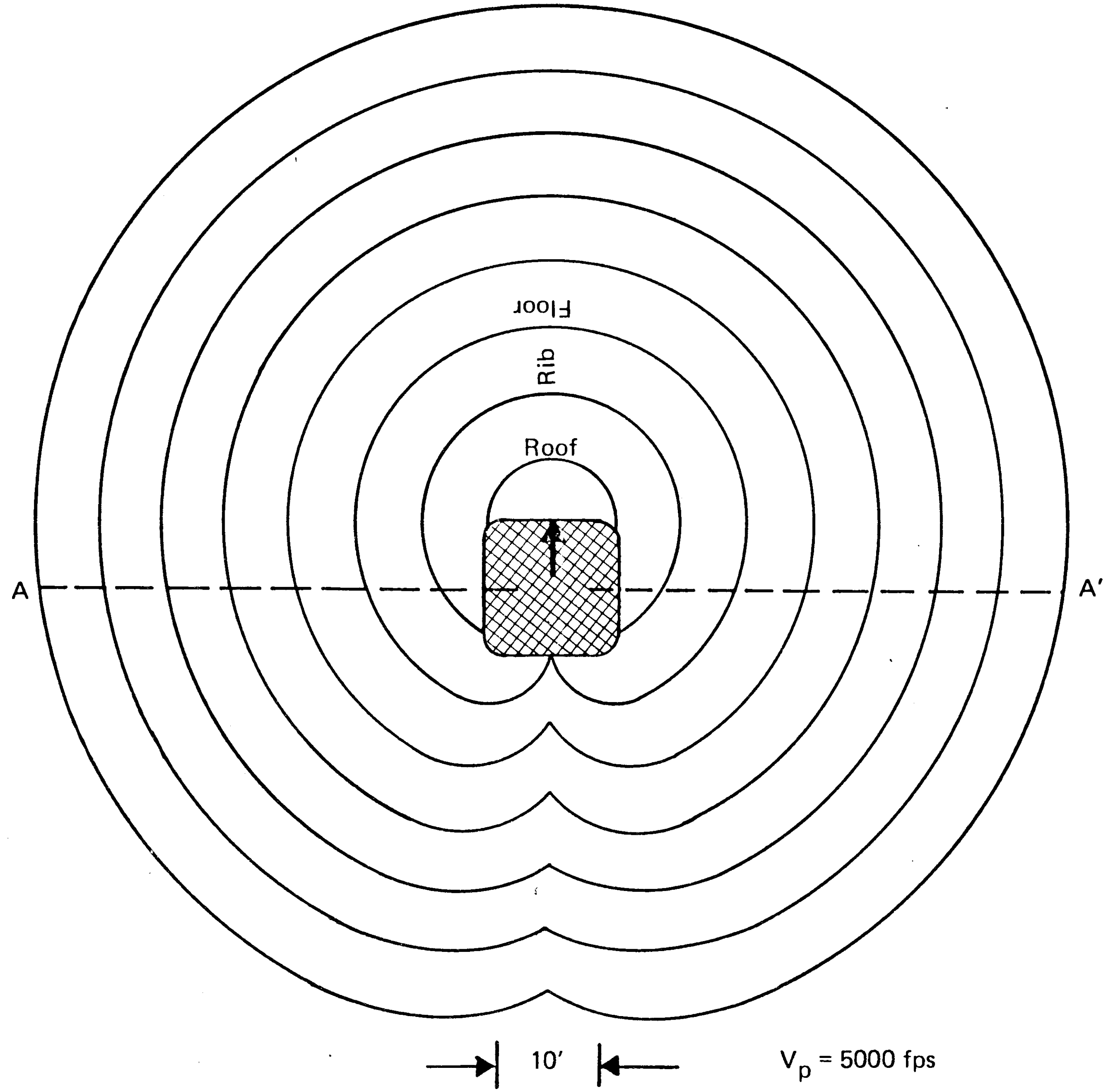


ACCURACY OF ARRIVAL TIMES

SIGNAL ASSUMED TO LIE IN RANGE 50-100 Hz

- $\sim$ 1 ms. ACCURACY IF PEAK OF FIRST ARRIVAL RECOGNIZED
- $\sim$ 5-10 ms. ACCURACY IF PEAK OF A LATER ARRIVAL CHOSEN
- $\sim$ 50 ms. ACCURACY IF SEVERAL CYCLES OF SIGNAL MISSED

DISTORTED WAVE FRONTS OF A VERTICAL SECTION A - A′



2. LOCATION ACCURACIES USING SURFACE ARRAYS AND EARTH MODELS

MARTYN F. ROETTER

COAL MINE GEOLOGY

GENERAL CHARACTERISTICS OF EASTERN U.S. BITUMINOUS COAL MINE ENVIRONMENTS:

- Geologic Strata Usually Horizontal (a Slope of 1 in 50 is Large)
- Strata Often Pinch Out or Grade Into Different Types
- Geologic Sections Tend to Remain Similar Over Distances of 1-3 Miles, But Can Change Considerably Over 10 Miles
- Little Faulting Found in Pa. or Northern W. Va. - Faulting More Common in Southern Areas (Western Ky.)
- Seismic Velocities in Overburden Can Vary From 14000 fps to 500 fps, Generally Tending to Increase With Depth
- The Thickness of the Upper Weathered Layer Can Vary Significantly From One Geophone Subarray to Another

ACCURACY OF EARTH MODELS

ASSUMPTION: The Earth Can Be Represented by a Set of Laterally Homogeneous, Horizontal Layers With Different Seismic Velocities.

THEN: Refraction Surveys Allow The Thicknesses and Velocities of These Layers to be Determined to Within About 5%.

The Errors May be Somewhat Less for the Upper and Lower Layers, and Greater for the Middle Layers.

ACHIEVABLE LOCATION ACCURACY*- I

- LATERAL LOCATION ACCURACIES TO WITHIN ABOUT 100 FEET APPEAR ACHIEVABLE IN MANY SITUATIONS

- UNDER VERY FAVORABLE CIRCUMSTANCES, ACCURACIES AROUND 30 FEET MAY BE ATTAINABLE

* Based on the Crosson and Peters error analysis applied to the location technique of non-linear least squares iterative inversion.

ACHIEVABLE LOCATION ACCURACY*- II

- KNOWLEDGE OF DEPTH IMPROVES LATERAL LOCATION ACCURACIES WHEN THE SEISMIC VELOCITY IS DEPTH DEPENDENT

- EARTH MODEL ERRORS OF 5% ARE MORE SERIOUS SOURCES OF INACCURACY THAN ARRIVAL TIME ERRORS OF 1-5 ms.

BUT

- ARRIVAL TIME ERRORS OF 15-20 ms. DOMINATE EARTH MODEL ERRORS OF 5%

* Ibid

ACHIEVABLE LOCATION ACCURACY*- III

- LOCATION ACCURACY INSIDE AN ARRAY IS NOT A STRONG FUNCTION OF THE ARRAY'S SIZE OR CONFIGURATION

- LOCATION ACCURACY FALLS OFF RAPIDLY OUTSIDE THE ARRAY
  - THE RATE IS SIGNIFICANTLY DEPENDENT UPON THE ARRAY GEOMETRY

* Ibid

ACHIEVABLE LOCATION ACCURACY*- IV

- BETTER LOCATION ACCURACY, ESPECIALLY WITH RESPECT TO DEPTH, IS ATTAINABLE IN AN EARTH WHERE THE VELOCITY IS DEPTH DEPENDENT, RATHER THAN CONSTANT

- LINEAR VELOCITY MODELS ($V = A + BZ$) ARE EXCELLENT APPROXIMATIONS TO A HORIZONTALLY LAYERED EARTH

* Ibid

CONCLUSIONS ON LOCATION ACCURACY

THESE CONCLUSIONS ARE SUBJECT TO THE FOLLOWING CONDITIONS:

- ARRIVAL TIMES CAN BE MEASURED TO WITHIN 1-5 ms.
- MODELS OF THE EARTH CAN BE APPLIED WHICH ARE "ACCURATE" TO WITHIN 5%

EARTH MODEL ACCURACY

MODEL "ACCURACY" IS A FUNCTION OF THE:

1. SEISMIC SURVEY DATA AND ANALYSIS

2. VALIDITY OF THE REPRESENTATION OF THE COMPLEX STRUCTURE OF THE ACTUAL EARTH BY A SIMPLE MODEL FOR TRAVEL TIME COMPUTATIONS

Summary of Error Diagrams†

Run #	Array Type	Station Spacing, ft.	Velocity Model	Parameter Error σ_v(%)	σ_t(sec.)	Depth Fixed?
1	Hex	600	Con	0	.001	
2	Hex	600	Lin	0	.001	
→ 3	Hex	600	Lin	5%	.001	
→ 4	Hex	600	Lin	5%	.001	*
5	Hex	1200	Con	0	.001	
6	Hex	1200	Lin	0	.001	
7	Hex	1200	Lin	5%	.001	
→ 8	Hex	1200	Lin	5%	.001	*
9	Hex	600	Con	0	.005	
→ 10	Hex	600	Lin	5%	.005	
→ 11	H	600	Lin	5%	.001	
12	Hex	600	Con	5%	.001	
→ 13	Mod Hex	450	Lin	5%	.001	
→ 14	Hex	600	2 Lay	5%	.001	
15	H	600	2 Lay	5%	.001	
→ 16	Hex	600	2 Lay	5%	.001	*
17	Hex	600	2 Lay	5%	.005	*
→ 18	Hex	600	4 Lay	5%	.001	*
→ 19	Hex	600	4 Lay	5%	.005	*
→ 20	H	600	Lin	5%	.001	*
21	Hex	600	Lin	5%	.010	*
22	Hex	600	Lin	5%	.015	*
→ 23	Hex	600	Lin	5%	.020	*
24	Hex	600	Lin	1%	.005	*

† Ibid

* indicates depth fixed for error computations.

† Arrows indicate the error diagrams shown in the presentation. They can be found in Part Three.

FURTHER RESOLUTION

OF THE QUESTION OF

ACHIEVABLE

LOCATION ACCURACY

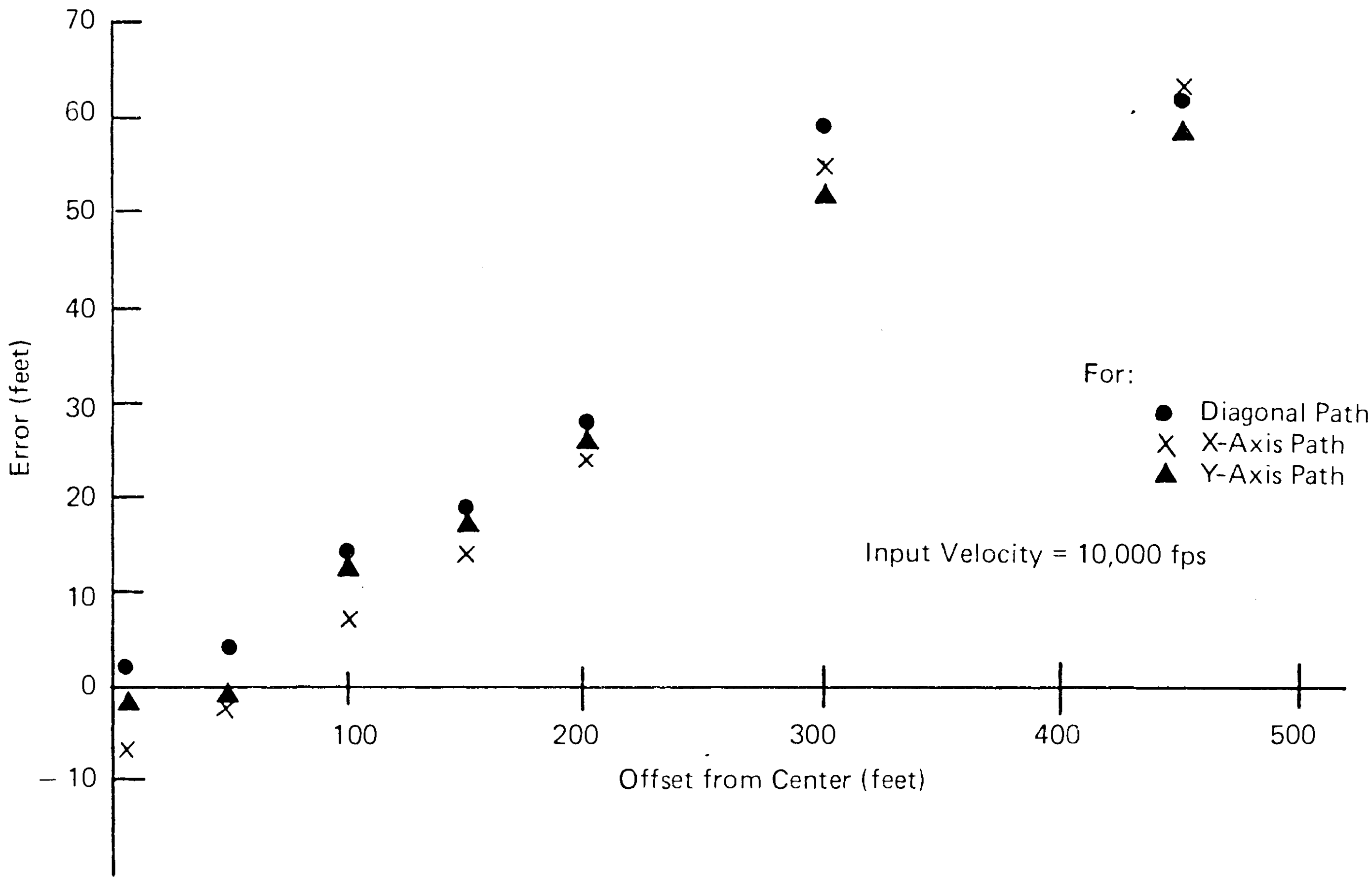
MAJOR PROGRAM COMPONENTS:

- COMPREHENSIVE SEISMIC SURVEY OF REPRESENTATIVE MINE SITE(S) BY EXPERIENCED PERSONNEL

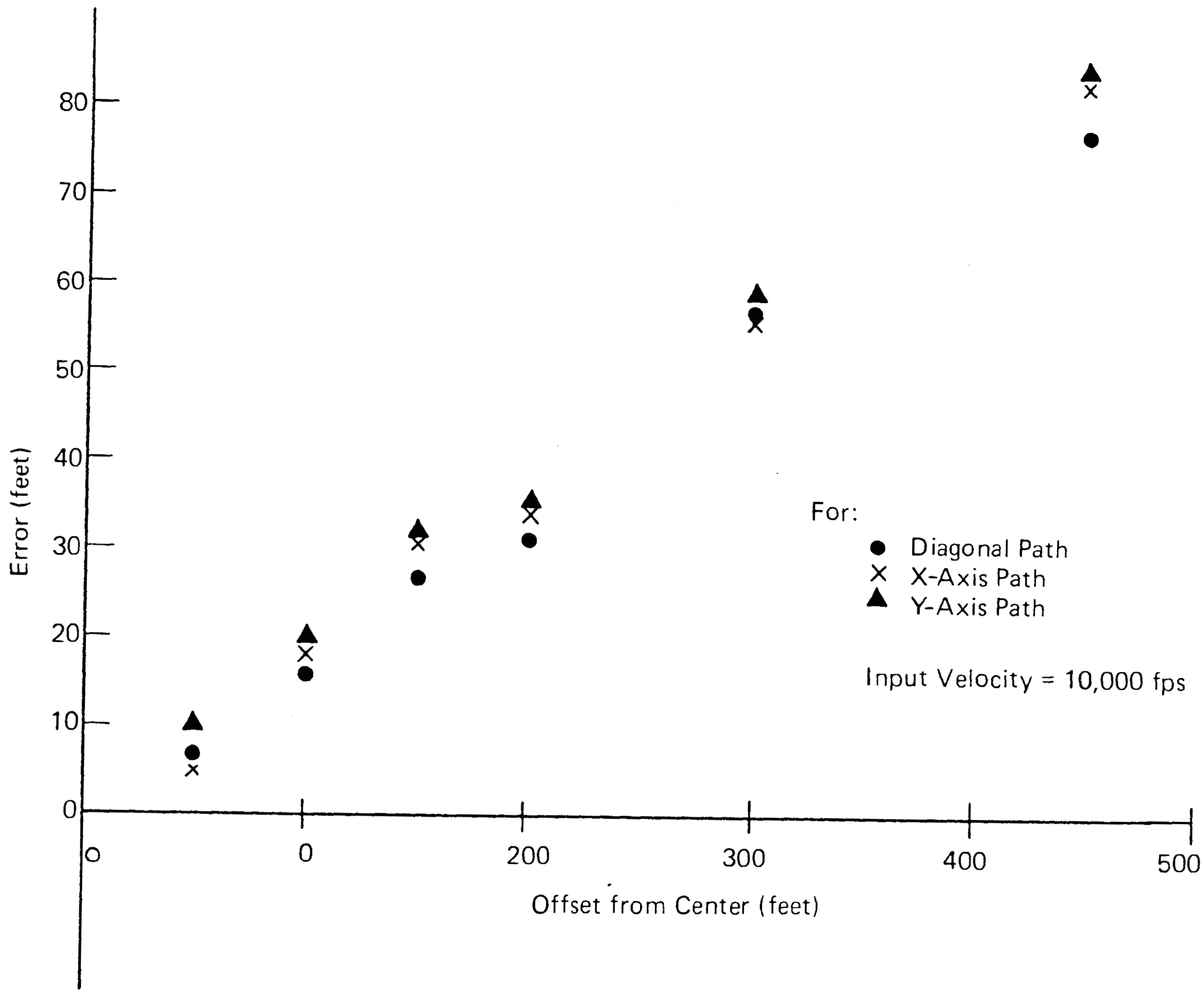
- CONTROLLED (STRONG SOURCE) LOCATION EXPERIMENTS USING:

  1. Actual Measured earth velocity profile

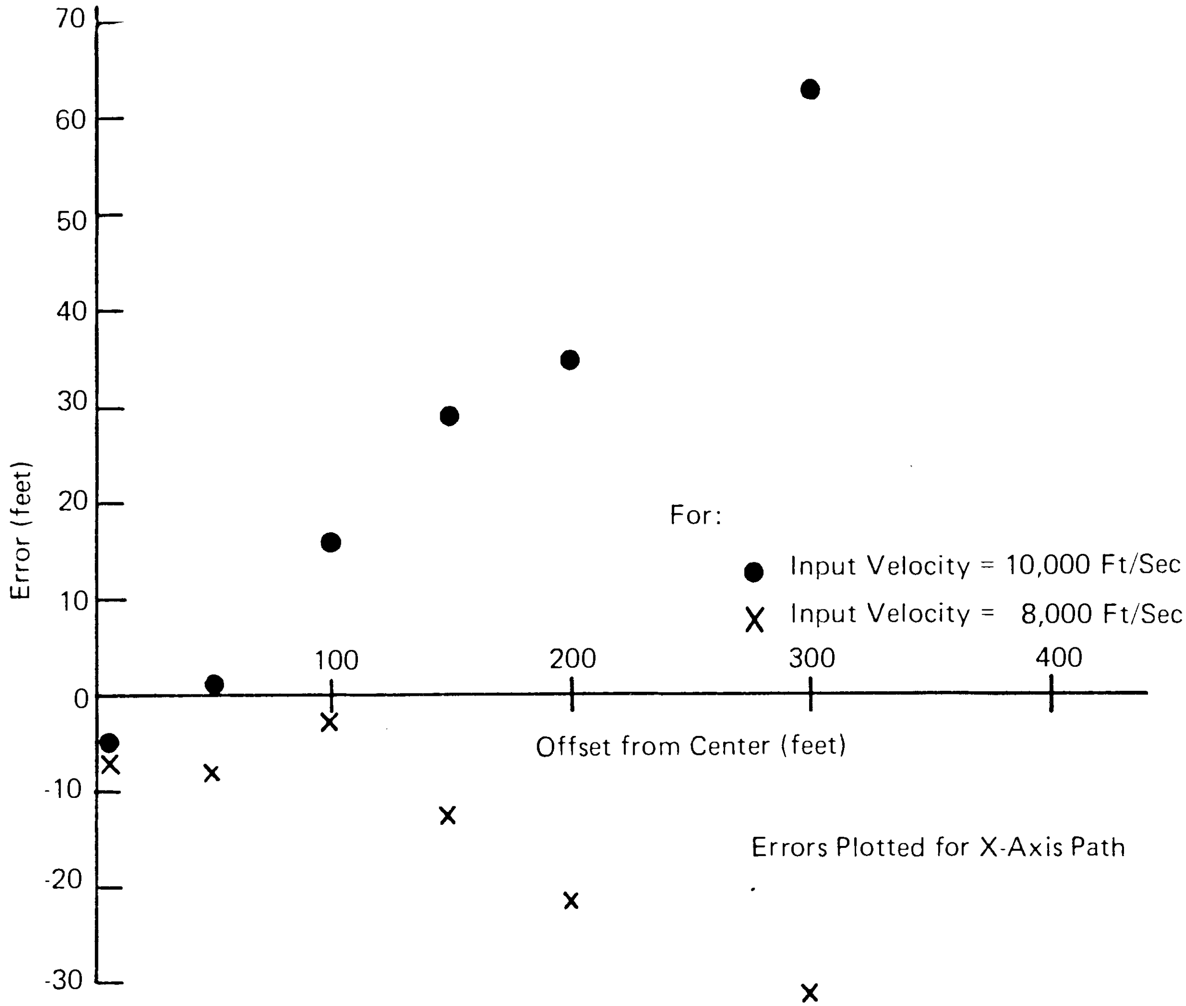
  2. Simple Model Approximations to 1.



"MINER" LOCATION ERROR
300 FOOT DOUBLE SQUARE



"MINER" LOCATION ERROR
400 FOOT HEXAGON



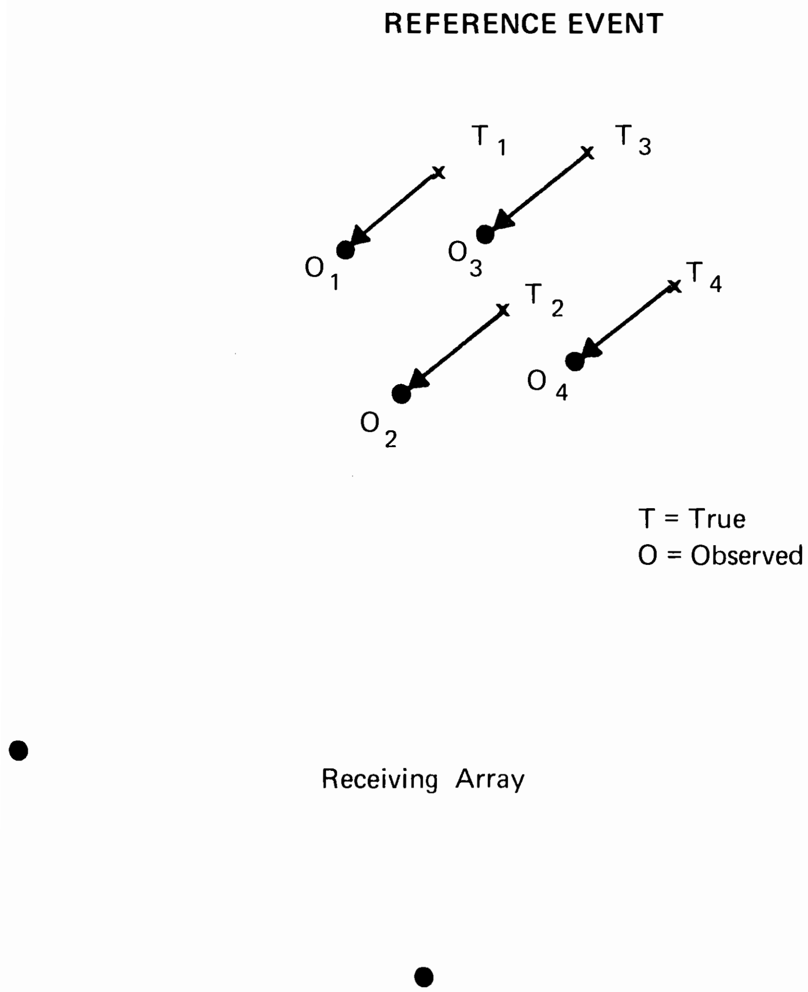
"MINER" LOCATION ERROR
150 FOOT DOUBLE SQUARE

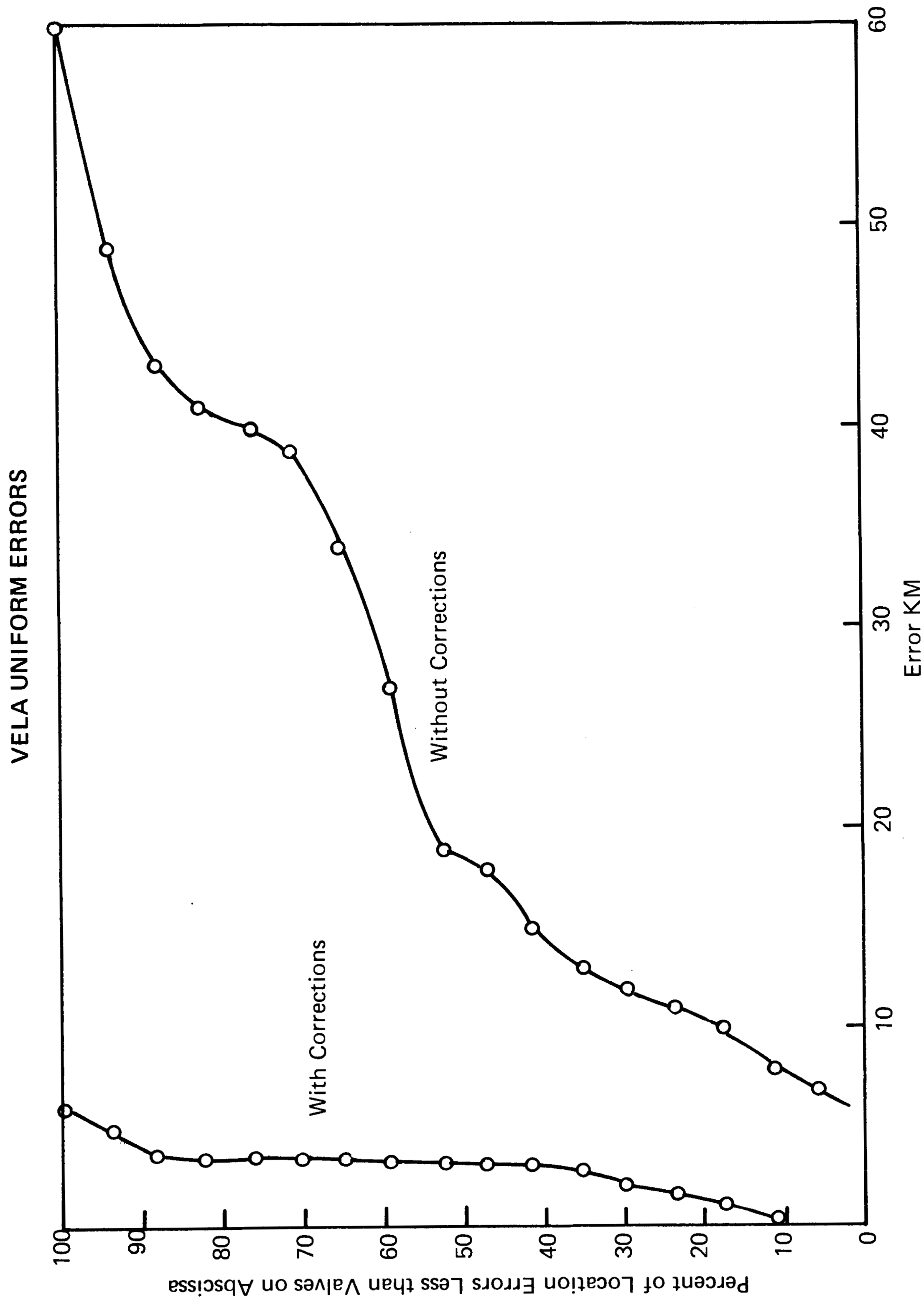
3. LOCATION ACCURACIES

USING

REFERENCE EVENT METHOD

RICHARD H. SPENCER


REFERENCE EVENT
T 1
T 3
O 1
O 3
T 2
T 4
O 4
O 2
T = True
O = Observed
Receiving Array


VELA UNIFORM ERRORS
Percent of Location Errors Less than Valves on Abscissa
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
Error KM
With Corrections
Without Corrections

REFERENCE EVENT

EXPERIMENT

OBJECTIVE: TO DETERMINE ACCURACY AND NUMBER OF CALIBRATION EVENTS REQUIRED

- 10-15 Geophones
- Two or More Sources (Timber, Hammer, Explosives)
- Source Locations - 25' to 50' Grid Running Over 1,000 ft.
  - Accurately Known Locations
  - Time Mark Desired
- Aperture Control
- Must Try in Several Mines

TO BE DONE BY SKILLED GEOPHYSICAL SERVICE COMPANY

DETAILED TEST PLAN TO BE DEVELOPED

E. SEISMIC SYSTEM FIELDABILITY AND INSTRUMENTATION

RICHARD H. SPENCER

F I E L D A B I L I T Y

GIVEN:

- LOCATION REQUIRES CALIBRATED SIGNALS
- POWER MAY NOT BE AVAILABLE
- TEST AND REPAIR FACILITIES NOT READILY AVAILABLE
- QUICK RESPONSE UNDER EMERGENCY CONDITIONS REQUIRED
- OPERATING PERSONNEL MUST BE EXPERIENCED - MUST
  KNOW EQUIPMENT AND ITS CAPABILITIES

HARDWARE:

- VERTICAL SEISMOMETER - AMPLIFIER ABLE TO BE BURIED
- 12-CHANNEL TAPE RECORDER
- ACCURATE, RECOVERABLE TIME CODES ON TAPE
- CONTINUOUS TIME REFERENCE ON TAPE
- SEISMOMETER CALIBRATION DEVICE
- VARIABLE FILTERING - GAIN
- COMPACT LIGHT WEIGHT RUGGED MODULAR SIMPLE
- PROVEN HARDWARE
- SELECTABLE TIME BASE DISPLAYS
- PROCESSING CENTER
- BATTERY OPERATION
- WATER PROOF NON-AMBIGUOUS CABLING
- TOOLS
- RADIO COMMUNICATION FOR CREW

PERSONNEL:

- 3-MAN CREW (MINIMUM)
  OPERATOR/ANALYST - TEST CHIEF-GEOPHYSICAL ENGINEER
  ELECTRICAL TECHNICIAN
  FIELD TECHNICIAN
  ON SITE ADDITIONS

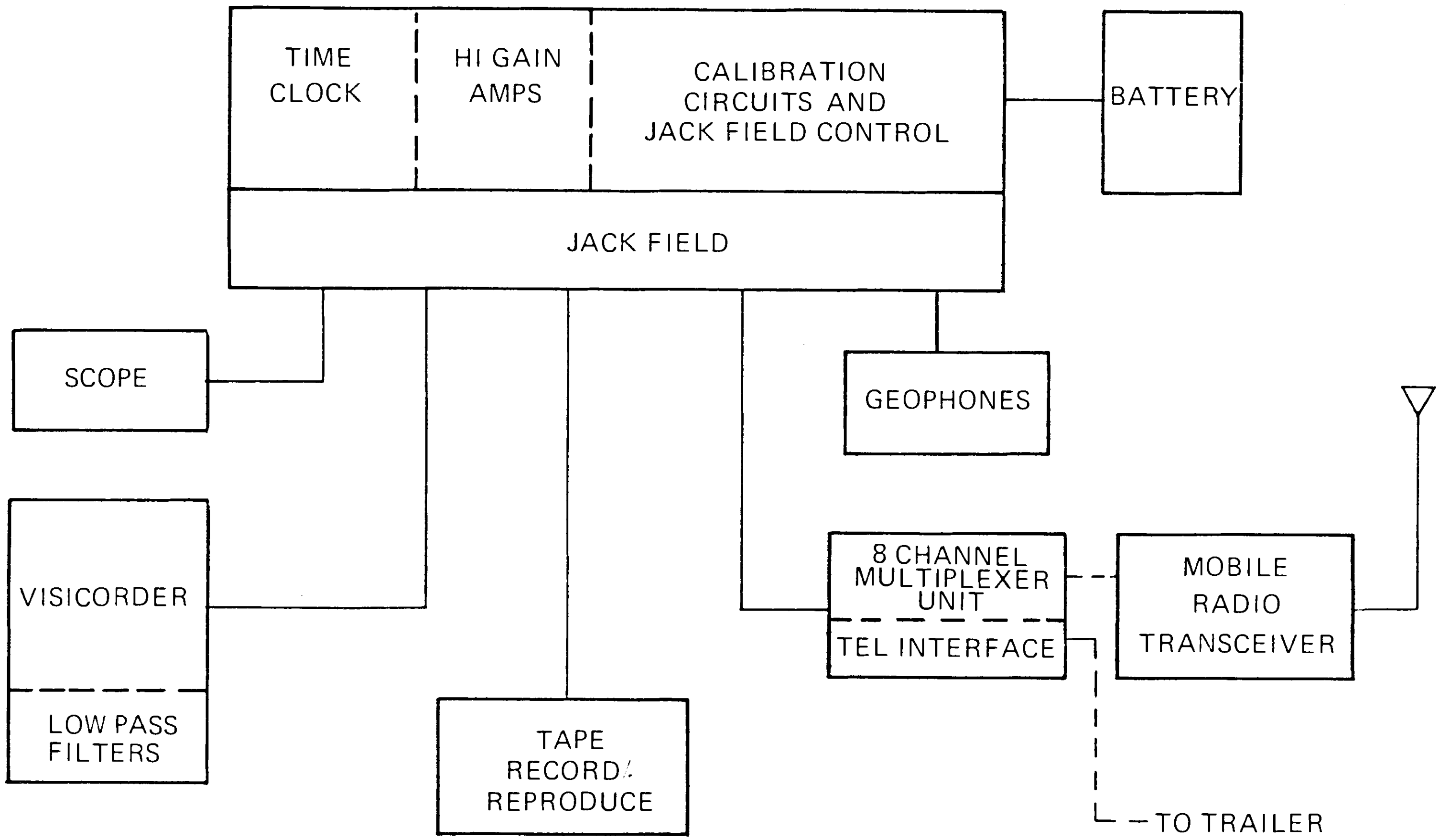
DEPLOYMENT:

- MODULAR PACKING
- PORTABLE PROCESSING CENTER

INSTRUMENTATION

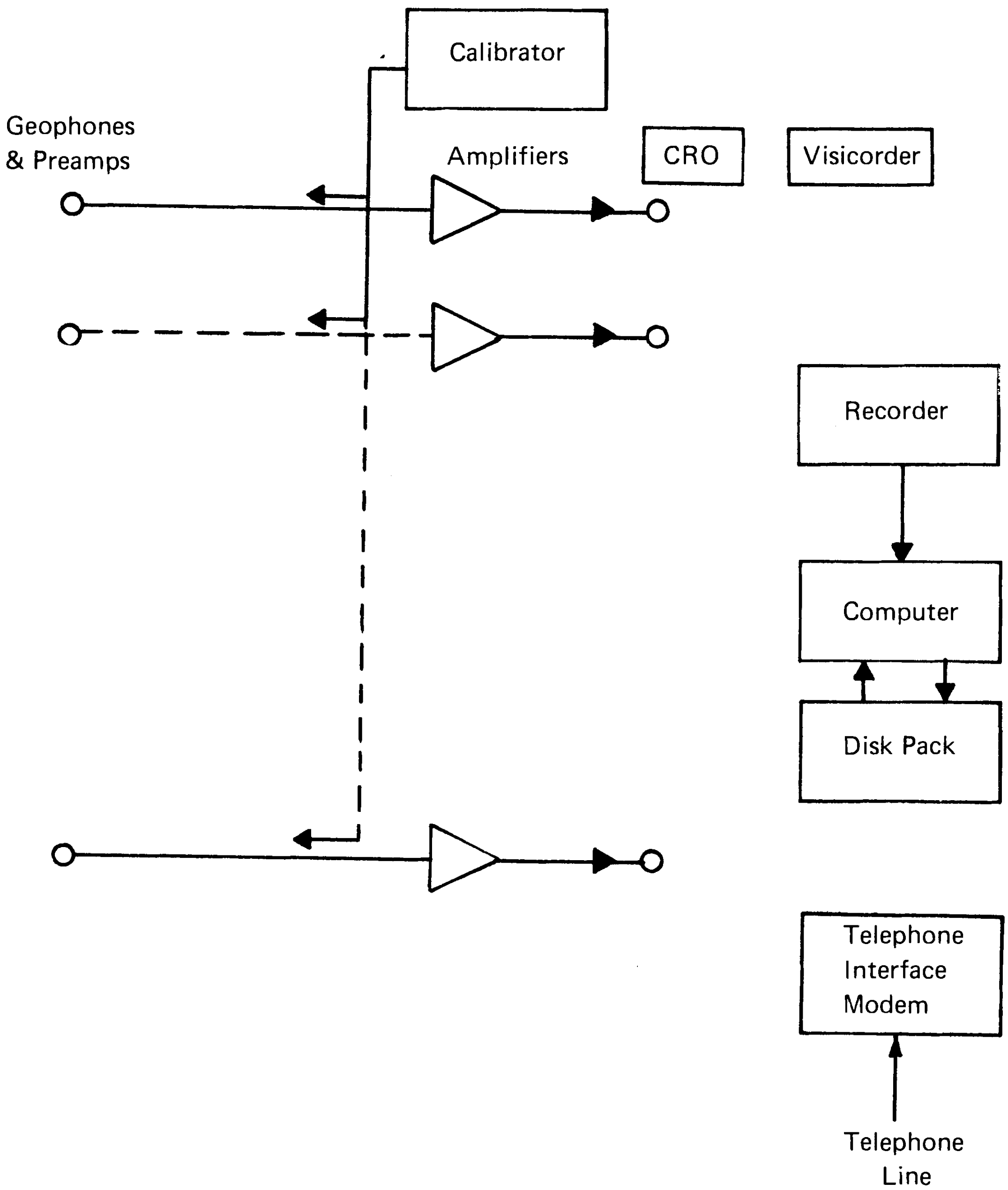
KEY ITEMS

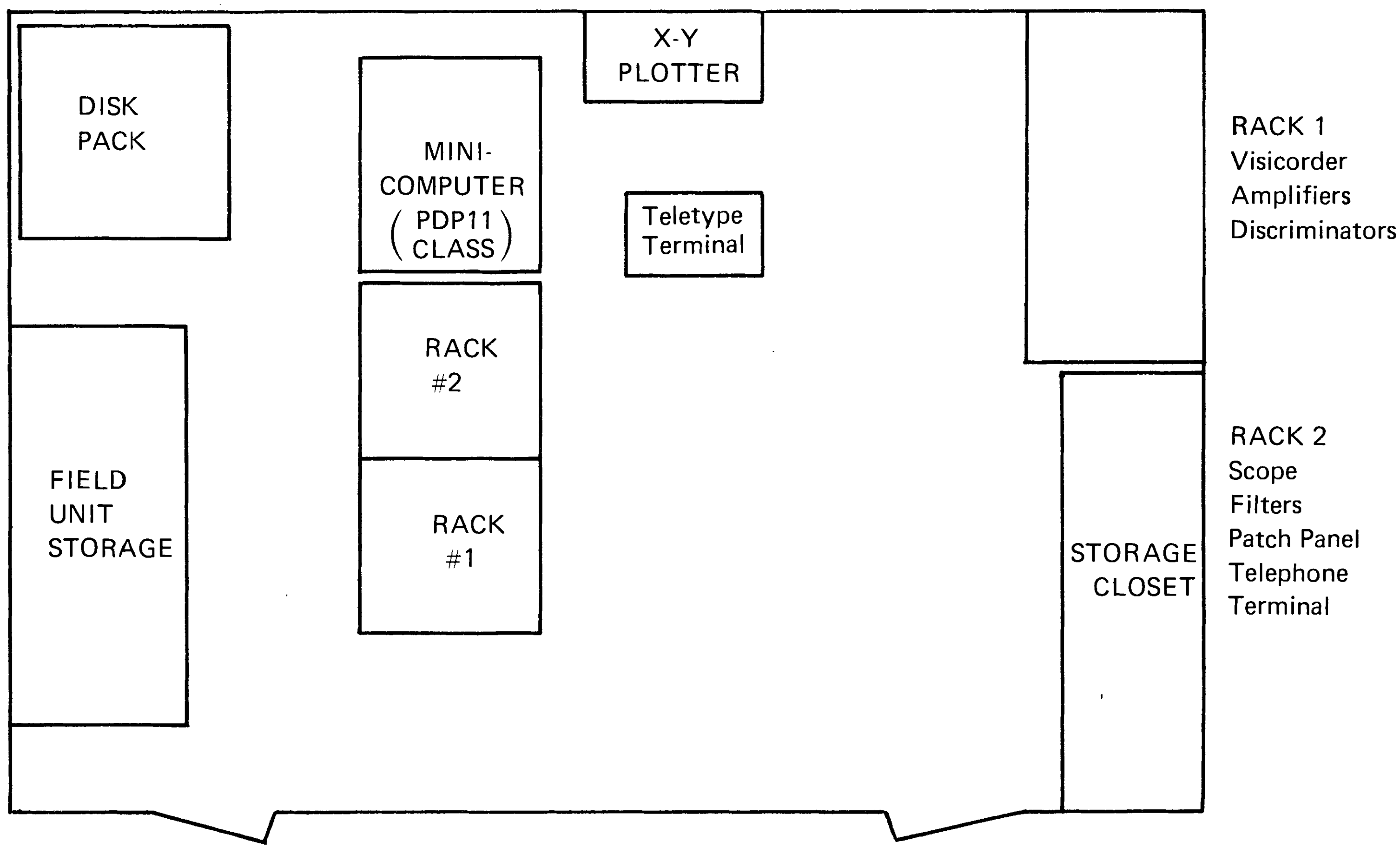
1. RAPID DEPLOYMENT OF DETECTION SUBSYSTEM
2. SELF-CALIBRATING SYSTEM - FRONT END AND FINAL OUTPUT - BOTH SENSITIVITY AND TIME
3. PERFORMANCE LIMITED ONLY BY SEISMIC NOISE
   - Geophone/Preamp Unit
   - Burial of Geophones
4. DISC PACK FOR COMPUTER
   - Fast Programming
   - Extends Capabilities
5. DISPLAYS
   - Real Time
   - Processed



SUGGESTED SEISMIC DETECTION SUBSYSTEM

BLOCK DIAGRAM INSTRUMENTATION

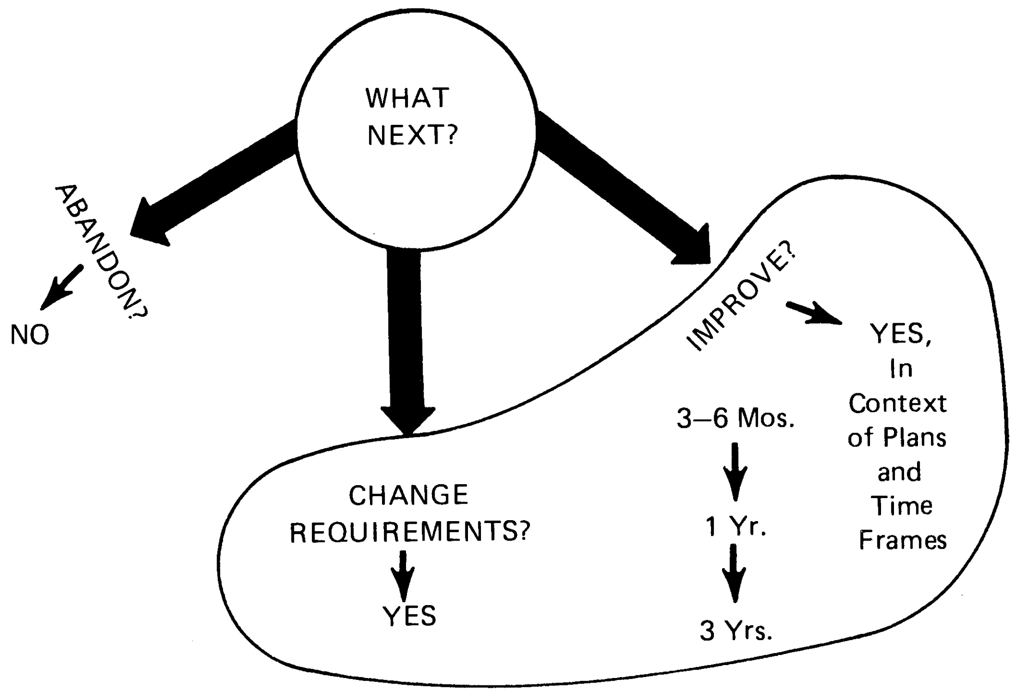




SUGGESTED TRAILER VAN SIGNAL PROCESSING AND LOCATION SUBSYSTEM

F. CONCLUDING REMARKS

ROBERT L. LAGACE


WHAT
NEXT?
ABANDON?
NO
CHANGE
REQUIREMENTS?
YES
IMPROVE?
YES,
In
Context
of Plans
and
Time
Frames
3–6 Mos.
1 Yr.
3 Yrs.

BIBLIOGRAPHIC DATA SHEET	1. Report No. ADL-C-73912-VOL. II	2.	3. Recipient's Accession No.

4. Title and Subtitle SURVEY OF ELECTROMAGNETIC AND SEISMIC NOISE RELATED TO MINE RESCUE COMMUNICATIONS. VOL. II. Seismic Detection and Location of Isolated Miners.	5. Report Date (Preparation) January, 1974 6.
7. Author(s) Robert L. Lagace, et al.	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Little (Arthur D.), Inc. 25 Acorn Park Cambridge, Massachusetts 02140	10. Project/Task/Work Unit No. 11. Contract/Grant No. USBM-H0122026
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15. Supplementary Notes

Initiated under the Coal Mine Health and Safety Research Program.

16. Abstracts Volume II of this report presents the findings of a short intensive assessment performed during the fall of 1972 by a task team composed of ADL staff and seven special seismic consultants, to provide the U.S. Bureau of Mines with independent technical judgments regarding the potentials and limitations of seismic methods and systems for: (1) detecting the presence of isolated signaling coal miners, (2) locating such miners to within the confines of a 600-by-600 foot mine section, and (3) further locating these miners to within a 15-foot entry width. The results of this assessment were obtained by addressing the following major subject areas treated in this volume: the detection of seismic signals and the estimation of their arrival times, the location of the origin of seismic signals, seismic signal source and propagation characteristics, earth models, seismic noise characteristics, signal-to-noise ratio improvement techniques, coal mine operational and emergency environments, seismic detection and location instrumentation and its effective utilization during mine rescue operations. Experimental seismic data gathered by others during a series of mine field tests prior to this task and other relevant seismic data were fully utilized for the assessment reported in this volume.

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

Mines-Coal	Seismic Noise
Coal Mines	Seismic Wave Propagation
Rescue Operations-Mines	Seismic Signal Sources
Miner Location	Seismic Instrumentation
Seismic Location	Through-the-Earth Communications-Seismic
Seismic Detection	

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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