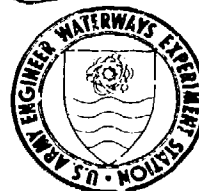


AD A121447



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TECHNICAL REPORT GL-82-9

TUNNEL DETECTION

by

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September 1982

Final Report

Approved For Public Release; Distribution Unlimited



Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Project No. 4A762719AT40, Task CO
Work Unit 007

NOV 15 1982

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report GL-82-9	2. GOVT ACCESSION NO. AD-A121447	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) TUNNEL DETECTION		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert F. Ballard, Jr.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Geotechnical Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 4A762719AT40, Task CO, Work Unit 007
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE September 1982
		13. NUMBER OF PAGES 94
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22151		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Geophysical exploration Tunnel detection Military operations Tunnels Seismic investigations		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This study evaluated numerous geophysical techniques to determine their applicability to the detection of clandestine tunneling activity, either in progress or completed, which is directed against field fortifications. The first priority was to develop a rapid and reliable approach for detecting tunneling at shallow depths (less than 50 m) in rock. The course of this investigation operated under the premise that a rapid reconnaissance survey using only surface geophysical methods (Continued)		

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EDITION OF 1 NOV 65 IS OBSOLETE

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20. ABSTRACT (Continued).

would first be performed followed by a detailed or high-resolution survey in which strategically placed boreholes would be included. Two well-documented test sites, both located in the State of Florida, were chosen for evaluation of the methods. The Medford Cave test site, near Ocala, Fla., was an air-filled cave system located about 20 to 30 ft below the ground surface. The second test site near Chiefland, Fla., was a state park called Manatee Springs. This site differed from Medford Cave in that the cavities were located approximately 100 ft below the ground surface, were water-filled, and were mapped by cave divers.

In addition, two existing seismic triangulation systems developed by the U. S. Bureau of Mines were also evaluated for application to the tunnel detection problem. One permanently installed system is located at the CONOCO-owned Loveridge Mine in West Virginia. The second system is portable and was observed in operation at a mine site in Kentucky. Both systems concepts were considered to be well suited (with minor modifications) for the detection of clandestine tunneling.

Those geophysical methods determined to be best suited for a tunnel detection reconnaissance survey were: (a) ground-probing radar, (b) electrical resistivity (Wenner array), (c) conventional seismic refraction, (d) seismic refracted wave form, (e) seismic refraction fan-shooting, and (f) microgravity.

The methods considered best for a detailed high-resolution survey were: (a) crosshole radar, (b) crosshole seismic, (c) borehole microgravity, and (d) surface electrical resistivity (pole-dipole).

PREFACE

The study reported herein was performed by personnel of the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES) during the period 1 October 1980 through 30 June 1982. The investigation was sponsored by the Office, Chief of Engineers (OCE), U. S. Army, under Project No. 4A762719AT40, Task CO, Work Unit 007, entitled "Tunnel Detection in Rock." The OCE technical monitor was Mr. C. A. Meyer.

The project was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, GL, and under the direct supervision of Dr. A. G. Franklin, Chief, Earthquake Engineering and Geophysics Division (EE&GD), GL. The report was prepared by Mr. R. F. Ballard, Jr., EE&GD. Other EE&GD personnel actively involved in this and related projects were Messrs. J. R. Curro, Jr., S. S. Cooper, D. K. Butler, and D. H. Douglas.

COL Tilford C. Creel, CE, was Commander and Director of WES during the preparation of this report. Mr. Fred R. Brown was Technical Director.



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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
gallons (U. S. liquid)	3.785412	cubic decimetres
inches	2.54	centimetres
miles (U. S. statute)	1.609347	kilometres
square miles	2.589998	square kilometres

TUNNEL DETECTION

PART I: INTRODUCTION

Background

1. Since the mid-1960's, the U. S. Army Engineer Waterways Experiment Station (WES) has been actively involved in tunnel detection beginning with the Vietnam conflict. After the first Korean tunnel was discovered in 1975, the WES participated in a review of the U. S. Army Mobility Equipment Research and Development Command (MERADCOM) tunnel detection plan of attack. At this time, the Corps was also beginning research on cavity detection with the CWIS Project, "Improvements of Geophysical Methods," later evolving to "Remote Delineation of Cavities and Discontinuities in Rock." In the summer of 1977, WES hosted a Symposium on the Detection of Subsurface Cavities attended by more than 100 people from all over the United States. In 1978, WES and MERADCOM established an interagency committee (now consisting of 12 Federal agencies) on "Engineering Geophysics Research and Cavity/Tunnel Detection." Involvement with this interagency committee has enabled WES to maintain an awareness of up-to-date technology regarding tunnel detection. In 1979, the third Korean tunnel was discovered, and WES made an on-site evaluation of a seismic triangulation system permanently installed at Loveridge Mine, W. Va., intended to locate activity or distress signals from the mine. The system was developed jointly by the Continental Oil Company (CONOCO) and the U. S. Bureau of Mines (USBM).

2. WES first received funding specifically for tunnel detection research in 1979. During 1979 and 1980, some 28 different geophysical methods were tested for their ability to detect and trace cavities or tunnels at three different test sites. In 1981, WES participated in a tunnel detection symposium sponsored by MERADCOM at the Colorado School of Mines.

3. The thrust of tunnel detection research at WES during the final year of this project, FY 82, included the evaluation (for military

applications) of a portable triangulation system developed by the USBM for locating mine cave-ins or trapped miners at depths exceeding 1500 ft.* It was felt that this system should also be able to locate clandestine tunneling activity. Related projects funded by MERADCOM will continue after this project has been completed. An evaluation of a focused current borehole resistivity technique developed at WES will be conducted at a mine in Idaho Springs, Colo. Another crosshole borehole method using induced random seismic spectra originating from a downhole vibrator will also be evaluated at the Idaho Springs site.

4. Tunnel detection by aerial and satellite remote-sensing methods has proven to be relatively ineffective. Use of satellite photography, infrared imaging, etc., can be used to detect spoil areas; however, deep-based tunneling activity has thus far eluded state-of-the-art remote-sensing technology. While WES has not participated in a firsthand evaluation of remote-sensing methods, WES contacts with MERADCOM, the Engineering Topographic Laboratory, U. S. Geological Survey, and other agencies involved in remote sensing substantiate the fact that no clandestine tunneling activities have been remotely detected.

5. In the course of this study, voluminous amounts of data were obtained. Some 28 geophysical techniques were evaluated and documented. Much of these data obtained were wholly or partially financially supported by other projects having a common need for geophysical data acquired at well-documented test sites. This approach resulted in the savings of thousands of dollars by preventing costly duplications of effort, particularly in site selection, documentation (drilling and geologists), data acquisition, data reduction and processing, and data interpretation. Each of the following projects, active during FY 80, made substantial contributions to the objectives of this project:

* A table of factors for converting U. S. customary units of measurement (SI) units is presented on page 3.

<u>Sponsor</u>	<u>Title</u>	<u>Objective</u>
OCE (CWIS)	Remote Delineation of Cavities and Discontinuities in Rock	Improve existing or develop new systems for detecting cavities
OCE (AT22)	Downhole Geophysical Exploration Techniques	Determine feasibility of using downhole geophysical techniques to sense voids or poor-quality rock
MERADCOM	Tunnel Detection - Resistivity	Determine changes in electrical properties as a result of tunneling activity
MERADCOM	Tunnel Detection - Cross-hole Methods	Evaluate electromagnetic and sonic crosshole methods for tunnel detection resolution capability
OCE (AT22)	Analytical and Data Processing Techniques for Geophysics	Develop or improve techniques for handling and interpreting large quantities of geophysical data
WES (ILIR)	Evaluation of Microgravity for Geotechnical Use	Evaluate microgravimetry for detection of cavities
NRC	Siting of Nuclear Facilities in Karst Terrains and Other Areas Susceptible to Ground Collapse	Survey state of the art in prediction, detection, and engineering treatment of conditions potentially leading to ground collapse

Final reports on many of the above projects have already been published. This report relies heavily on information contained within those reports, which in turn have benefited from information obtained under this project.

Objective

6. The primary objective of this test program was to evaluate and refine the geophysical technology needed to detect clandestine tunneling activity by means of field tests at well-documented field sites. The first priority was to develop a rapid and reliable approach to detect tunneling at shallow depths (less than 50 m).

Approach

7. In an effort to reach the stated objective systematically, a five-step approach to the problem was adopted:

- a. Select candidate geophysical techniques best suited for tunnel detection.
- b. Select representative test sites for evaluation of the method.
- c. Thoroughly document the test sites.
- d. Conduct a suite of geophysical tests.
- e. Evaluate each technique, determining its optimum deployment, advantages and limitations for military field use, and possible countermeasures which could be taken by an enemy force to disrupt the survey.

Scope of Report

8. Those techniques showing greatest promise of success for tunnel location will be treated in greater detail than those methods which do not. A primary assumption is that an investigator will first perform a general tunnel detection reconnaissance survey using only surface methods followed by a detailed (high-resolution) survey of a suspect area (identified in the reconnaissance survey) in which strategically placed boreholes will be included.

PART 11: SITE DESCRIPTIONS AND TESTS CONDUCTED

Medford Cave

Site description

9. Medford Cave test site is located approximately 12 miles north of Ocala, Fla., in an area of karst topography and has been a local spelunker attraction for a number of years. The cave system exists in limestone covered by about 3 to 6 ft of soil and has known passageways whose roofs range from 10 to 22 ft below the ground surface. Figure 1 is a plan view of the Medford Cave system as mapped by personnel of the Southwest Research Institute (SwRI), showing the grid system used for geophysical surveys at the site. The general geology of the area and of Medford Cave site in particular is covered in a report by Mr. William D. Reves, which is included as Appendix A in Butler (in preparation).

Surface methods

10. In the course of planning the field investigation at Medford Cave, it was determined that at least nine geophysical surface methods might be applicable to the problem of tunnel or cavity detection. The surface methods used are presented first because they would most likely be employed as a reconnaissance measure at a site where tunneling activities are suspected. Following the reconnaissance survey, a highly detailed survey would likely be conducted in selected suspicious areas. These methods, in all likelihood, would require boreholes. Consequently, the philosophy of this report will be to separate the reconnaissance survey (surface methods) from the detailed survey (methods requiring boreholes).

11. Conventional seismic refraction. The conventional surface seismic refraction survey, in principle, consists of measuring the travel times of compressional and sometimes shear waves generated by an impulsive energy source to points at various distances along the surface of the ground (Redpath, 1973; Department of the Army, 1979). The energy source is usually a small explosive charge or an impact

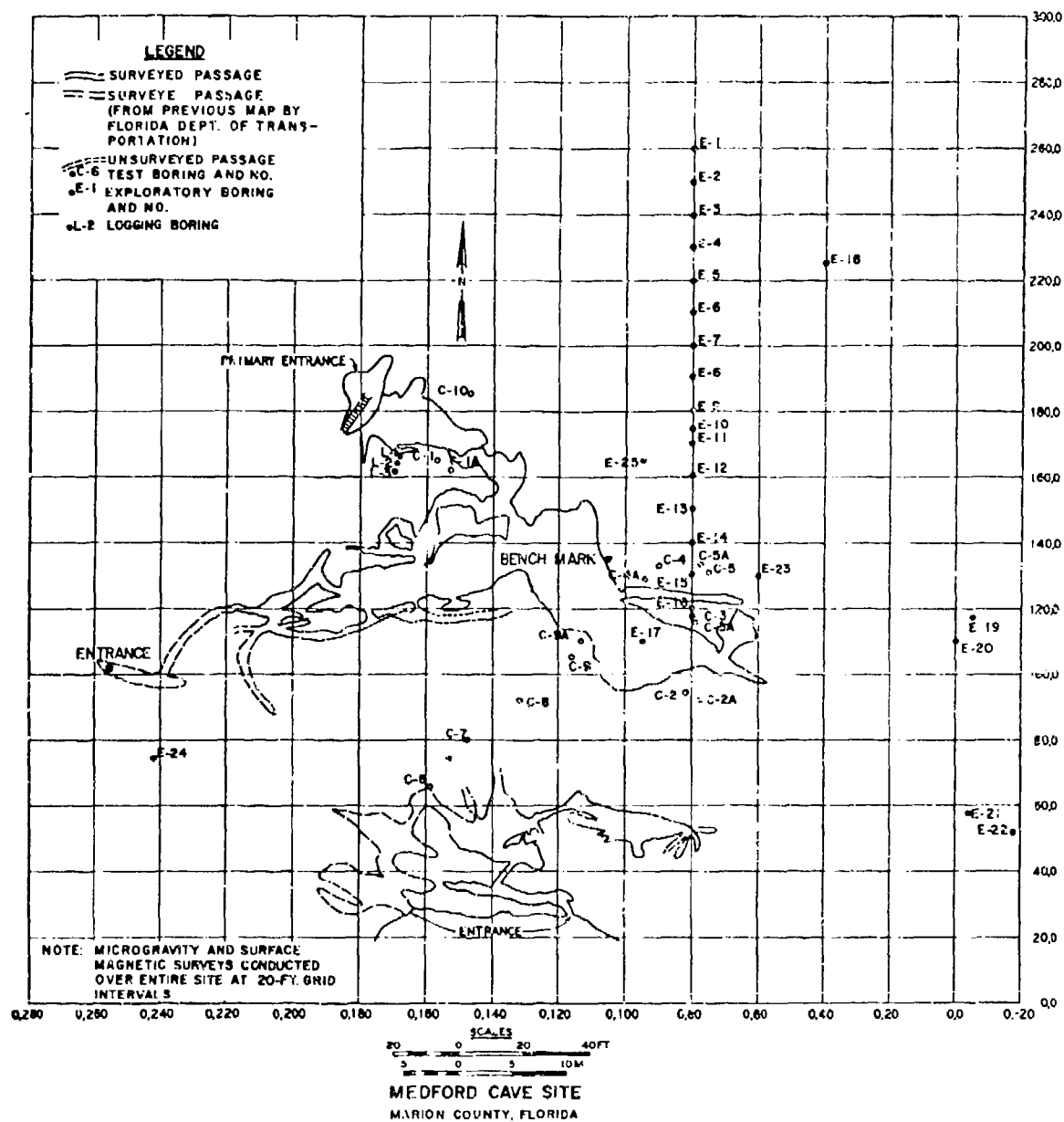


Figure 1. Plan view of Medford Cave site

delivered by a sledgehammer. Energy is detected, amplified, and recorded so that its time of arrival at each point can be determined. The zero time, which is that instant of initiation of impact or explosion, is also recorded along with the ground vibrations arriving at the detectors (geophones). The raw data consist of measured travel times and distances, the travel time being the interval between the zero time and the instant that the detector begins to respond to the disturbance. This time-distance information is then processed to obtain an interpretation of the velocity of wave propagation and the structure of the subsurface strata. This method is extremely useful as a rapid means for performing a site reconnaissance.

12. The following factors are vital considerations in the conduct of a seismic refraction investigation:

- a. Topography. A seismic refraction traverse should be oriented to avoid radical changes in site topography. When abrupt changes occur, it is necessary to determine accurately the elevation of each geophone.
- b. Distance. Surveying must be accurate in order to make correct depth determinations of the refractor.
- c. Geophone spacing. Geophone spacing and overall length of the seismic traverse are dictated by the required amount of detail and depth of investigation. In all cases, however, velocities of the near-surface materials must be obtained. As a general rule, the overall length of the traverse should be four to five times the desired depth of investigation.

13. The above factors are not all-inclusive, but must be given prime consideration when the surface refraction seismic method is to be used for detection of an anomaly such as a tunnel.

14. Eight seismic refraction lines, three 240 ft in length and five 120 ft in length, were run at the Medford site and are reported by Curro (in preparation). The tests were conducted by two men in approximately 10 hr (20 man-hours), equating to about 15 man-hours per 1000 ft linear coverage.

15. Refracted wave form. The refracted wave form seismic technique can be conducted in its simplest form using a sledgehammer as a seismic source in conjunction with a single geophone receiver. The

method could be employed when tunneling activity is suspected to be at fairly shallow depths, i.e., less than 50 ft.

16. In practice, a distance is chosen between the source and receiver which will be about four times the desired depth of investigation. The seismograph amplifier is then adjusted so that a single hammer blow will be displayed with an unclipped trace. The source and receiver are then moved in tandem a short distance, say 5 ft, maintaining the same spacing (25 and 50 ft were used at Medford Cave). Without adjustment to the amplifier or the time scale, a second recording is then taken. By repeating this procedure along a given line, numerous records will be obtained which can be directly compared to one another, noting not only differences in arrival times but characteristic changes in signature, such as amplitude or frequency. Obviously, under relatively homogeneous conditions, all of the records obtained in this manner would be similar. When an anomalous condition such as a cavity or tunnel occurs, its presence is usually readily apparent. Although anomalies in wave form signature may be associated with many different kinds of subsurface conditions, once an operator has obtained some "ground truth" information, he can often relate the signature with some confidence to a limited range of anomalous subsurface conditions. The refracted wave form test can be conducted rapidly, but it is depth-limited to about 50 ft unless a high-energy seismic source is used. Three test lines were run at the Medford Cave site, concentrated in areas of known geologic conditions (Curro, in preparation). The tests were conducted by two men in approximately five hours (10 man-hours) equating to 18 man-hours per 1000 ft linear coverage.

17. Refraction fan-shooting. The refraction fan-shooting technique is somewhat similar to the constant-spacing refracted wave form technique previously described, but covers a much greater areal extent. To conduct these tests, all seismic detectors are located in semicircular fashion the same distance from an explosive or other high-energy source. Consequently, seismic wave arrival times will be the same at each detector if subsurface conditions are the same. Should a tunnel be present between source and detector at a depth less than about

25 percent of the source-geophone distance, the time of wave arrival will be delayed and other elements of the seismic signature changed. Figure 2 illustrates the geometry of the fan-shooting tests performed at Medford Cave. The tests were conducted by two men in about 15 hr (30 man-hours) equating to the same time to cover 1000 lin ft assuming 200 ft between source and geophones.

18. Refracted shear wave. The refracted shear (S) wave method is very similar to the conventional seismic refraction technique. It is conducted in a similar manner with the major exception being the use of a seismic source chosen to have a large part of its energy concentrated in shear wave motion and horizontal rather than vertical geophones. Whereas the conventional refraction seismic survey places emphasis on the detection of the first, or primary (P), wave arrival, the refracted shear wave survey places its emphasis on detection and timing of the shear wave, which arrives at a later time. The seismic shear wave source can be as simple as a sledgehammer striking the end of a large board laying on the surface of the ground, perpendicular to the line of horizontal seismic detectors oriented perpendicular to the source. The board is struck alternately on first one end and then the other to generate horizontally polarized shear waves of opposite phase in order to aid in the interpretation of their first arrival. Data reduction is inherently more complex than in the P-wave refraction survey because the shear wave arrives at a later time and often in the midst of an ongoing compressional wave train. Data are interpreted in the same way as the conventional refraction survey.

19. Four S-wave refraction lines were run at the Medford Cave site in about eight hours by two men (16 man-hours), equating to about 15 man-hours per 1000 ft linear coverage. While the tests were being conducted, poor data quality was evident and further tests suspended.

20. Seismic reflection. Seismic reflection surveying, in its simplest application, uses the principle of reflection occurring when interfaces between layers or zones have a high P-wave velocity and/or density contrast. For example, when a water table, bedrock surface, or an air-filled void (such as a tunnel) is encountered by stress waves

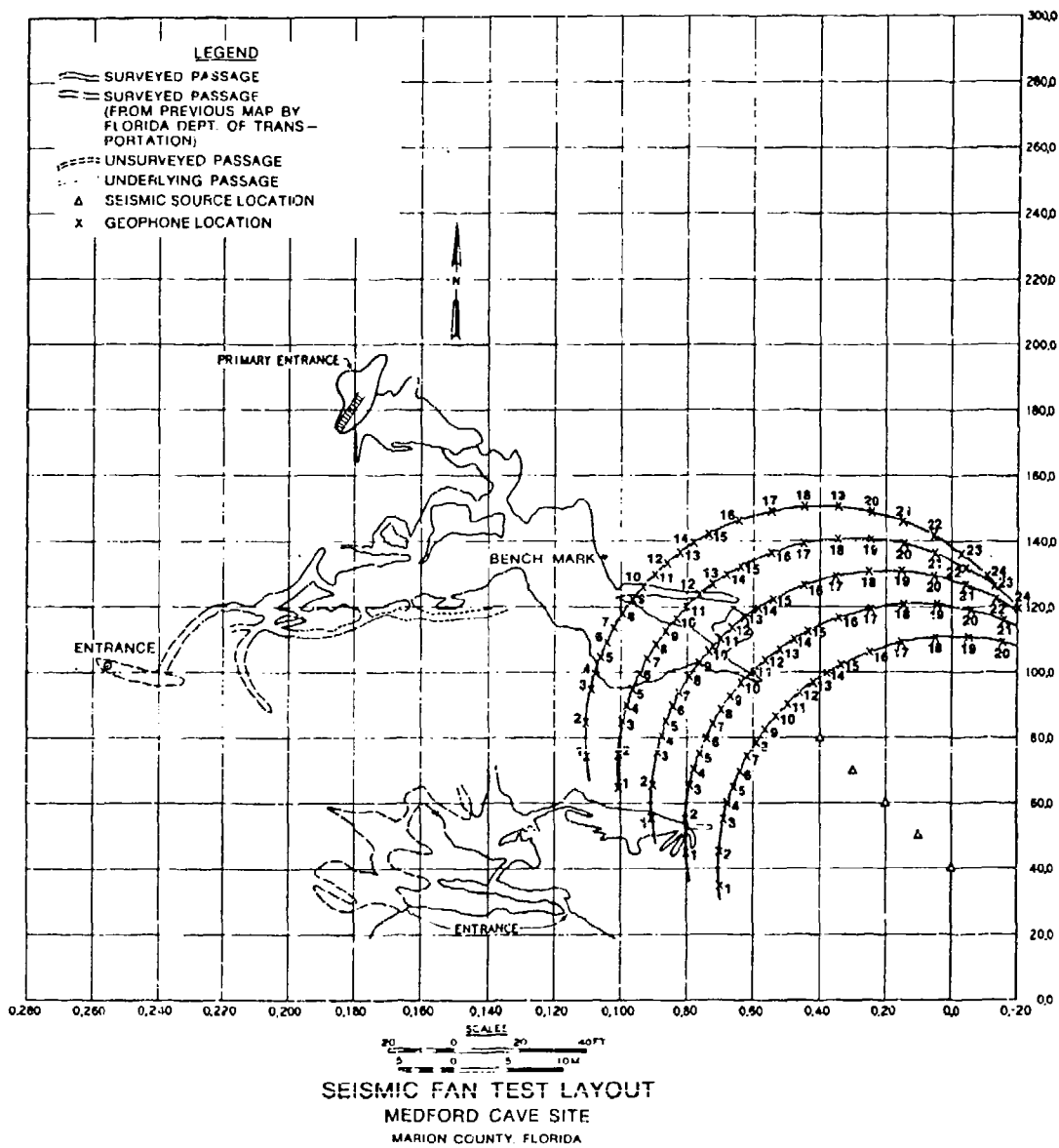


Figure 2. Seismic fan-shooting test layout

propagating downward through soil materials, upward propagating reflected P-waves will be generated at that interface. If subsurface vertical velocities are known, the time of arrival of these reflected waves at surface geophones can be used to determine the depth of the interface.

21. Interpretation of reflected P-wave arrivals is difficult in shallow surveys because available energy sources, such as explosives, sledgehammers, or drop weights, produce characteristic wave trains whose wavelengths are large with respect to the depth and dimensions of the target. Identification of the reflected arrival time from shallow targets is often masked by the presence of surface waves. If an extremely short duration source can be used, arrivals can sometimes be better separated and more easily identified.

22. Seismic reflection surveying was performed at 81 stations along 6 lines at the Medford Cave site by Technos, Inc. Results were reported in Curro (in preparation). An experimental technique developed by Mooney (1977) designed to enhance shallow reflections was used.

23. Electrical resistivity. One of the geophysical methods used in the investigation at Medford Cave showing promise from a reconnaissance as well as a detailed survey standpoint was the surface electrical resistivity method. Surface electrical resistivity surveying is based on the principle that the distribution of electrical potential in the ground around a current-carrying electrode depends on the electrical resistivities and distribution of the surrounding soils and rocks. In usual field practice an electrical current is applied between electrodes implanted in the ground and a measurement of the difference of potential is made between two additional electrodes that do not carry current. Variations in the geometry of electrode arrays are often employed to enhance particular features. A detailed explanation is given in EM 1110-1-1802 (Department of the Army, 1979).

24. Two different array configurations were used at Medford Cave. One was the Wenner electrode array, and the second was the Bristow (pole-dipole) electrode array. Both methods were used in the profiling mode; i.e., the entire array is moved in increments along a profile line using a fixed electrode spacing. By so doing, one will

obtain a profile of apparent resistivity representative of a more or less uniform depth of investigation. The Wenner array was used with an electrode spacing of 10 and 40 ft in an effort to show the effects of the overburden material and the entire cavity system. The Wenner array is well suited for locating fairly large size anomalous features when conducting a reconnaissance survey.

25. The pole-dipole array can be used in a survey procedure which actually combined horizontal profiling and vertical sounding concepts. The method is well suited for the detection of localized anomalies, such as cavities and tunnels. A graphical interpretation procedure, such as described by Bates (1973) and Fountain, Herzig, and Owen (1975), can be used to detect anomalous subsurface conditions. The pole-dipole technique has been successfully used for a number of investigations in karst regions (Bates, 1973; Butler, 1980c; Cooper and Bieganousky, 1978; Fountain, Herzig, and Owen, 1975) and also for tunnel location in hard rock (Fountain, 1975). During the conduct of tests at the Medford Cave site, it was noted that a drawback to the pole-dipole survey is the time required to conduct the field tests and process and interpret the data. Three men were used to conduct the field survey in about eight hours (24 man-hours), equating to about 18 man-hours per 1000 ft linear coverage.

26. Radar (Technos and SwRI). In the early 1950's, experiments were conducted using electromagnetic (radar) waves as a means of probing through solids. It was quickly recognized that the wave speed and its amplitude as a function of distance through the solid could vary drastically from one material to another. Factors which control the velocity and absorption characteristics of a radar wave are generally related to conductivity, which is strictly defined only for a material which obeys Ohm's law, and is equal to the ratio of current density to the electrical field vector. The most commonly used unit is the mho/cm (conductivity is the reciprocal of resistivity). In terms of radar wave penetration or reflectance, it should be noted that as conductivity increases, higher losses of electromagnetic (EM) signals are normally experienced. Consequently, materials with high conductivities, such as

clays, actually become barriers to electromagnetic signals beamed into the earth.

27. A second parameter which greatly influences the characteristics of EM propagation is the dielectric constant of the material. The dielectric constant is defined as that property of a material that determines the electrostatic energy that can be stored per unit volume for a unit potential gradient. When the ratio of the dielectric constant of a material to that of a vacuum is used, the term is referred to as the relative dielectric constant. As the dielectric constant increases, it signifies that more EM energy can be absorbed consequently resulting in less penetration.

28. When using radar as a geophysical tool for ground penetration, many resolution requirements demand that the use of short radar wavelengths (generally less than 30 ft) be used. Since many ground materials are highly absorbent of short wavelength EM energy, there is a tradeoff between resolution and penetration. Generally, the absorption characteristics of geological materials are such that radar wavelengths greater than about 2 ft are required to gain appreciable penetration. An EM wave's attenuation can be described mathematically and the absorption can be expressed in decibels per metre. The absorption coefficient is highly frequency-dependent and is a function of the electrical conductivity, magnetic susceptibility, and relative dielectric constant of the medium. Such mathematical expressions can be found in Morey et al. (1978) and Von Hippel (1954).

29. Since penetration depth or distance is generally one of the first questions addressed by the user, it must be realized that it is quite difficult to estimate a radar system's capability to penetrate to a certain depth before a survey is actually run. If beforehand knowledge of the material type is available to the investigator, however, rough estimates can be made. Reported results using ground penetration pulsed radar document penetration depths of greater than 75 ft in the glacial delta composed of water-saturated sands in Massachusetts (Morey et al., 1978). A depth of greater than 230 ft has been measured in a antarctic ice shelf; however, penetrations of only 5 ft or considerably

less in wet clays are commonly expected. In some rock materials or in dry sands, penetration depths of 100 ft or so might be expected.

30. The surface ground-probing radar investigation conducted at Medford Cave by Technos used a Geophysical Survey Systems, Inc. (GSSI) Model 4700P radar system. This is a pulsed system used with two antennas. The first was a bistatic shielded antenna having a center frequency of about 300 MHz (3-nsec pulse). Data quality was recognized as being extremely poor with this antenna, and conversion was made to a monostatic, nonshielded antenna having a center frequency of about 100 MHz (10-nsec pulse). The system was deployed in a towed traverse mode providing a continuous near real-time graphic record by scanning the antenna across the surface of the ground. Data were also recorded on magnetic tape on most of the traverses for later processing.

31. Some sampling was done with the antenna stationary providing a static record of reflecting horizons. In one instance, a metal foil reflector was placed inside the secondary entrance and attached to the roof of the cave. The radar transmitter/receiver was then located on the ground surface immediately above the reflector. Overburden thickness at this location was 9 ft. A very weak return was noted at this location, thereby proving penetration to at least a depth of 9 ft. Figure 3 shows the location of radar traverses made at the Medford Cave site. Three Technos men conducted the radar survey covering more than 3000 lin ft in about 4 hr (12 man-hours); however, only two men are necessary to perform a survey. Assuming that a survey could be conducted towing the antenna at a speed of about 2 mph, only 0.2 man-hours would be required per 1000 ft.

32. The ground-probing radar system used by SwRI was designed and built in their laboratory. The system is quite versatile and can be used from the ground surface in the reflection mode or in a borehole-to-borehole configuration for crosshole testing, as will be discussed later. During the operation, the SwRI system emits 10-nsec-duration EM pulses (100 MHz) from the transmitter. The full wave form of the EM pulse is received, converted to a low-frequency replica of the real time

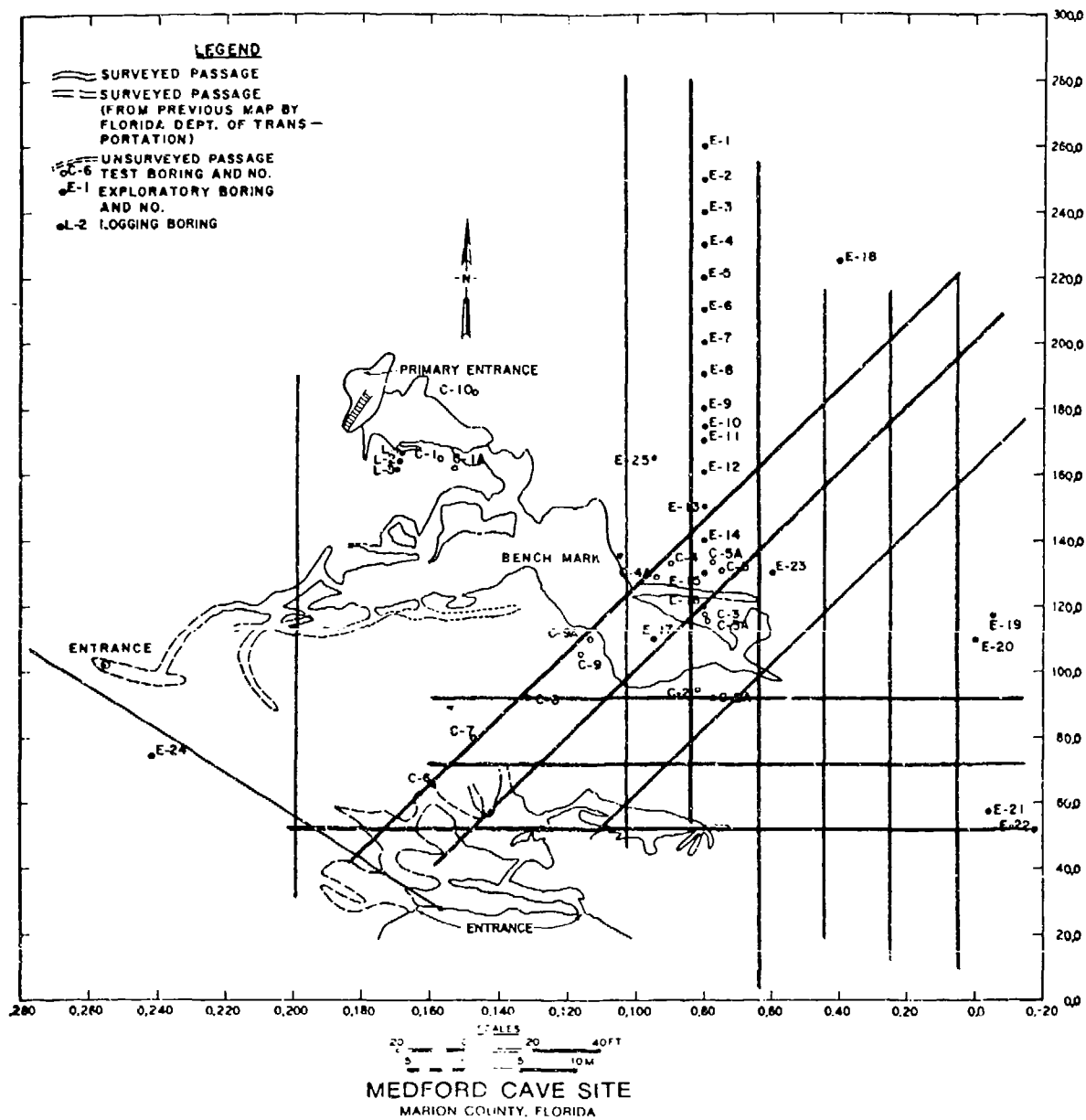


Figure 3. Location of ground-probing radar traverses

pulse by a time-domain sampler, and recorded in either analog or digital form for analysis. A conceptual illustration of the ground-penetrating EM system developed by SwRI is shown in Figure 4. It will be noted that the same system, using borehole antennas, can be used for crosshole applications (described later). Surface ground-probing radar traverses were conducted in the same locations at Medford Cave used by Technos.

33. Magnetic. For tunnel detection, the magnetic survey is a logically chosen technique because the presence of man-made ferrous metal objects would be expected to produce large magnetic anomalies. Depending on how a tunnel is constructed, metal objects such as tools, rock bolts, liners, rails for mucking carts, etc., could be inside.

34. In a magnetic survey the strengths of various components of the earth's magnetic field are measured. The presence of magnetic materials in the subsurface perturb or produce anomalies in that measured field. In the case of a nonmetallic air-filled cavity, such as a tunnel in limestone, granite, or other nonmagnetic rock, little influence could be expected on the existing magnetic field. As a result, it is felt that the magnetic technique would be useful only when man-made metals are present in the tunnel.

35. The survey conducted at Medford Cave was performed by Butler (in preparation), using a hand-held flux gate magnetometer which is sensitive to the vertical component of the magnetic field and must be kept level while making measurements. Data were acquired on the project grid system, mostly at 10-ft intervals along north-south profile lines separated by 20 ft in the east-west direction. A total of 250 stations were measured. Butler reoccupied base stations at the beginning of each profile to determine whether secular variation or drift was occurring. None was noted. The entire survey required about 8 man-hours over a two-day period equating to slightly more than 3 man-hours per 1000 ft.

36. Microgravity. Microgravity methods have been used for the detection of cavities in Europe since the 1960's. The technique, as used at the Medford Cave site, consisted of making relative measurements of the vertical component of gravity in a grid pattern. After the normal corrections and adjustments to the data were made, a contour map of

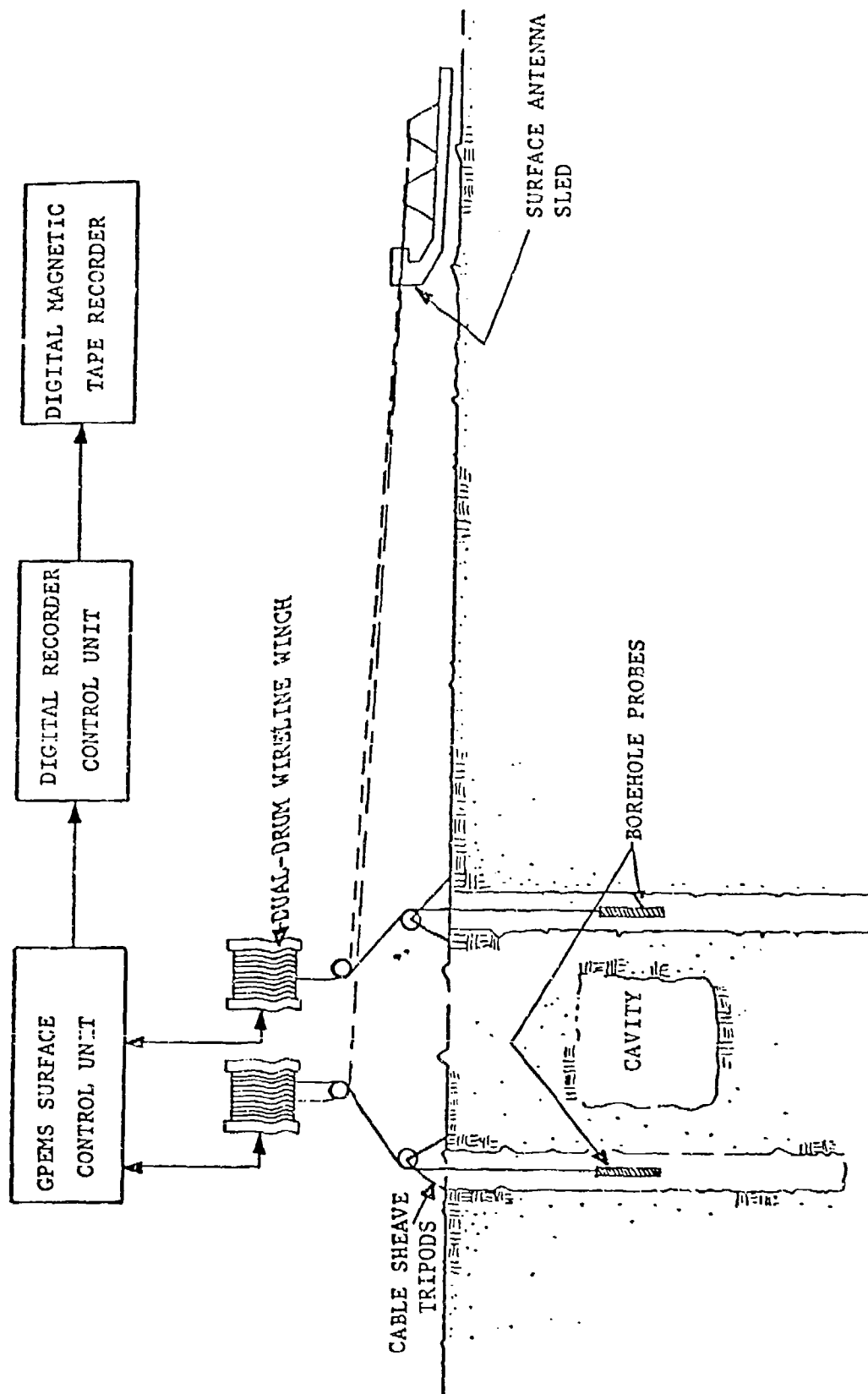


Figure 4. SwRI radar concept schematic

gravity anomalies caused by density variations in the subsurface was produced. Gravimetry, like the magnetic method, is a potential field method. Gravity anomalies occur when lateral density contrasts are present in the subsurface. Most of the gravity measurements at the Medford Cave site were taken along the grid lines at 10-ft intervals. Some 420 stations were occupied with a LaCoste and Romberg Model D-4 gravity meter. The Model D-4 gravity meter has a sensitivity of about 1 μ Gal and relative gravity values in a survey can be determined with a precision and accuracy in the range of 3 to 6 μ Gal (Butler, 1980a). A detailed description of the requirements of microgravimetric surveying are given in Butler (1980a, b).

37. The microgravity technique was selected for application to the tunnel detection problem because the air-filled void produced by the presence of a tunnel has the net effect of producing a low density zone. Whether or not that feature is detectable depends not only on the sensitivity and accuracy of the gravity meter, but on the size, density contrast, and depth of the anomaly below ground surface. In practical terms under average conditions, a sphere having a radius of about 10 ft should be detectable at a depth of about 30 ft. Consequently, the microgravity technique will likely have an application for tunnel detection at relatively shallow depths, i.e., 20 to 40 ft (assuming a 10-ft-diam tunnel), dependent upon site density contrasts. The rate at which tests were conducted at the Medford Cave site would indicate that approximately 30 man-hours per 1000 ft linear coverage are required to conduct a microgravity survey.

Methods requiring boreholes

38. Seismic crosshole. The seismic crosshole method is normally intended to provide a designer or investigator with seismic wave velocities of the subsurface materials (Woods, 1978), or simply for the determination of anomalies that might exist between boreholes.

39. The seismic crosshole system used at the Medford Cave site consisted of a vibratory borehole energy source, used to generate vertically polarized S-waves, and small explosive charges which were used to generate P-waves. Crosshole tests were first conducted between

borings C6, C7, and C8 in an area where no known anomalies existed. Data obtained at these locations were to be used for a relative comparison with data obtained between borings C1 and C10 which were placed on either side of a prominent mapped feature of Medford Cave. Figure 5 shows the test locations.

40. Tests were conducted by placing the seismic source in one borehole at a specified elevation and receivers in adjacent boreholes at the same elevation. The seismic source was repeatedly activated at different elevations and the times of arrival of the specific wave type were noted at the receivers at corresponding elevations.

41. When competent rock is displaced by an anomaly such as an air-filled tunnel or cavity, the arrival time at the receiver point will be lengthened by an amount that is related to the size of the void between the source and receiver. In addition to changes in arrival times, the seismic signature is usually affected by a decrease in amplitude and an increase in the predominant period of the signal. The seismic crosshole method was selected as a candidate for tunnel detection for the above reasons and because the equipment is relatively straightforward to operate and readily available. Based upon the time required to conduct the seismic crosshole tests at Medford Cave site and other WES experience, it is estimated that a 200-ft-deep survey will require about 8 man-hours.

42. Crosshole radar. Crosshole radar tests were conducted at Medford Cave by the SWRI using equipment previously described. In the hole-to-hole method of operation, 10-nsec-duration EM pulses were emitted from the ground-penetrating EM system transmitter in a borehole located on one side of the tunnel/cavity target. The receiver was positioned in another hole located on the opposite side of the target to detect the transmitted pulse. During typical operation, the transmitter and receiver were first located at the same depth below the suspect cavity region. The two probes were then hoisted together, maintaining a common depth while through transmission pulse wave forms were continuously monitored at about 3-ft-depth intervals within the boreholes.

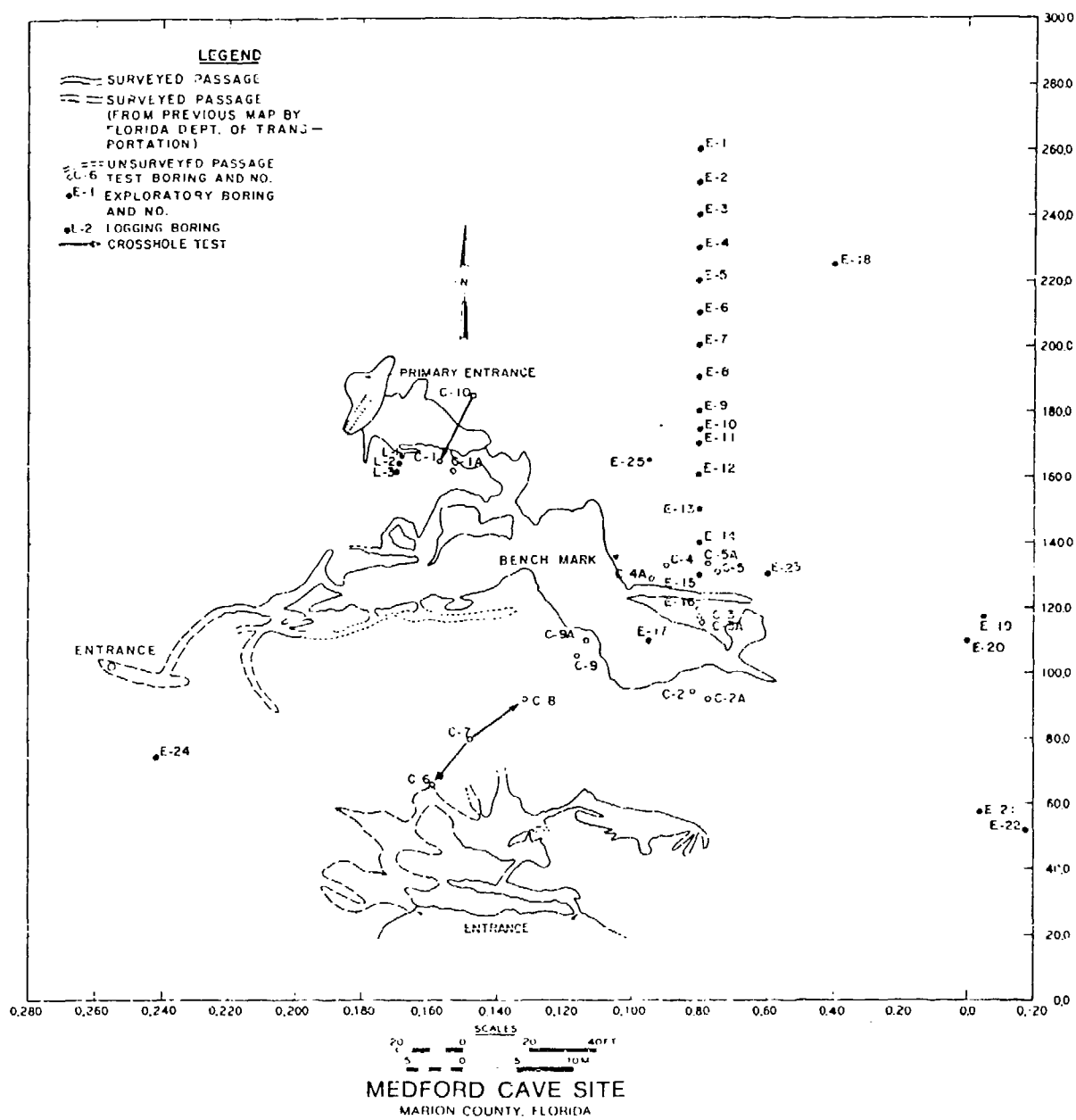


Figure 5. Crosshole seismic test locations

43. The borehole EM system was operated in 10 hole pairs at Medford Cave. Data were collected in two ways: with transmitter and receiver antennas at a common depth and with the antennas offset at different depth increments. Specific information of interest includes the EM pulse propagation time between the holes and the amplitude attenuation of the radiated pulse as it passes through the geologic structure between holes. An air-filled cavity or tunnel between the holes should typically cause a reduced transmission time because of the higher propagation velocity of an EM signal in air. Additionally, signal amplitude and transmission time may vary in the vicinity of the cavity as a result of diffraction and scattering effects (Fountain and Herzig, 1980). Based upon this series of tests and other SwRI experience, it is estimated that about 2 man-hours will be required to survey between borings 200 ft deep.

44. Uphole refraction seismic (wave front). According to Franklin (1980), the uphole refraction method provides the same information as the surface refraction seismic method but adds to it observations of the effects of vertical displacements of the shotpoint. Thus, it provides another dimension in the information obtained about subsurface conditions. The method was thought to be applicable to the tunnel detection problem because presence of a tunnel or void can be expected to influence the transit times of the seismic signals whose ray paths they intercept. The uphole refraction survey conducted at Medford Cave was located along the zero 80 grid line with each of 24 geophones located as shown in Figure 6.

45. The test was conducted by firing a small explosive charge at a predetermined depth in the borehole. The time required for the signal to reach each geophone was then noted. The same procedure was repeated as shots were fired at progressively shallower depths in the borehole. The number of data points acquired will be equal to the number of shots fired times the number of geophone receivers. Since the uphole refraction method produces more information about subsurface conditions than does the surface refraction method, it offers the possibility for detecting anomalies invisible to the test conducted on the ground surface.

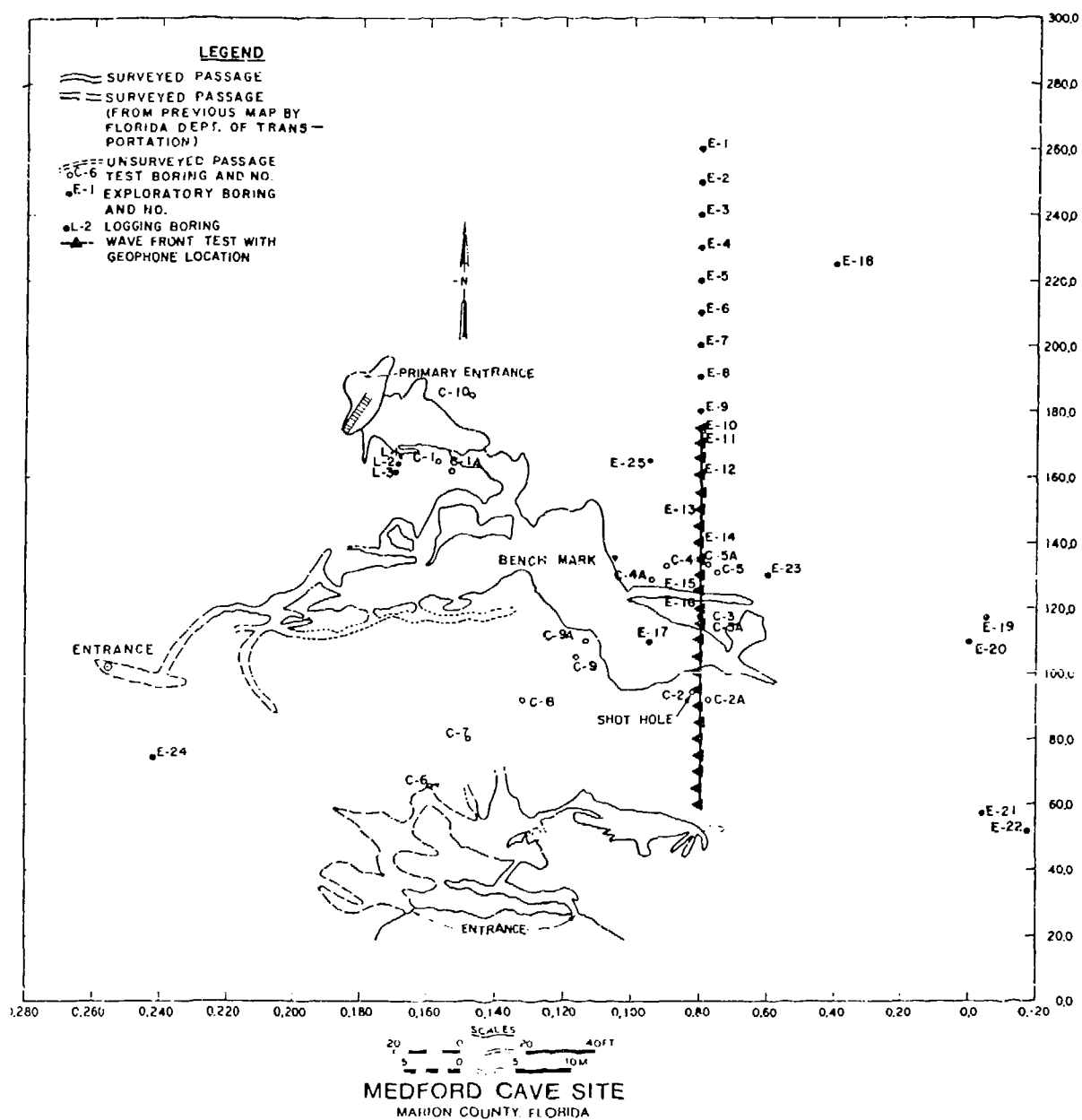


Figure 6. Location of seismic wave front test

Data are ordinarily displayed in the form of a contoured two-dimensional grid matrix. A complete discussion of data handling and processing is given by Franklin (1980). The uphole refraction seismic method was selected as a candidate technique for tunnel detection because the presence of a void or tunnel should appear as an anomalous feature when the travel times between source and receivers are not compatible with the geologic model being used.

Manatee Springs

Site description

46. The second test site, also located in the State of Florida, near the town of Chiefland, is a state park called Manatee Springs. This site differs from the Medford Cave site in that the cavities are located approximately 100 ft below the ground surface, are water-filled, and were mapped by cave divers. In view of the fact that Manatee Springs is a state park, permission was secured from the State of Florida to conduct tests within the boundaries of the park. The site chosen and gridded for geophysical surveys is located near the mouth of the subterranean system. The volume of flow at this point is approximately 82,000 gpm.

47. The Manatee Springs cave system extends several miles to the southeast of its mouth, and approximately 10,000 lin ft has been mapped by the cave diving section of the National Speological Society. The Manatee Springs site was chosen because it met the requirements of several geophysical investigation programs. Contrasted to the Medford Cave site, its cavity system was considerably deeper and offered the challenge of geophysical data acquisition in the presence of rapidly flowing water.

48. With regard to tunnel detection, Manatee Springs met the requirement for obtaining data at depths representative of tunneling activity suspected at some military outposts.

49. The area chosen for high-resolution (methods requiring boreholes) geophysical studies was discovered by cave divers on a

reconnaissance mission while looking for a continuous feature having dimensions approximating those of a tunnel. Figure 7 shows a plan view of this feature, the surface grid system, and the exploratory borings which were placed to provide geological information and support the geophysical testing program. Geologists were on site throughout the entire exploration program and documented the site in detail. Their report is contained in Part III of the report by Butler et al. (in preparation).

Surface methods

50. Microgravity. A microgravity survey was conducted at Manatee Springs in a manner similar to that previously described at Medford Cave. A complete documentation of the survey is reported by Butler et al. (in preparation). The site chosen for the microgravity survey is about midway between the mouth of the spring and the first large water-filled sink. A gridded rectangular survey area 120 to 400 ft was chosen perpendicular to the local trend of the cavity system.

Methods requiring boreholes

51. Crosshole radar. Crosshole radar tests were conducted at the Manatee Springs site by SwRI and by the Lawrence Livermore National Laboratory (LLNL). The SwRI system has previously been described under the Medford Cave test site section and will not be repeated here. A detailed description of the SwRI radar study at Manatee Springs is presented by Herzig and Suhler (1980); only a summary of the test program will be presented in this report.

52. SwRI conducted crosshole radar tests between holes C2 and C5 to provide a basic reference point because no cavities were known to exist between these two borings. The second series of tests were conducted between borings C2 and C3 spaced approximately 30 ft apart and straddling a known cavity feature. A final series of tests were conducted between borings C3 and C4.

53. Crosshole radar tests were conducted by the LLNL during the summer of 1980 and documented by Laine (1980). The LLNL ground-probing radar equipment operates on a slightly different principle than that used by SwRI. Where the SwRI system uses a short rise-time pulse and a

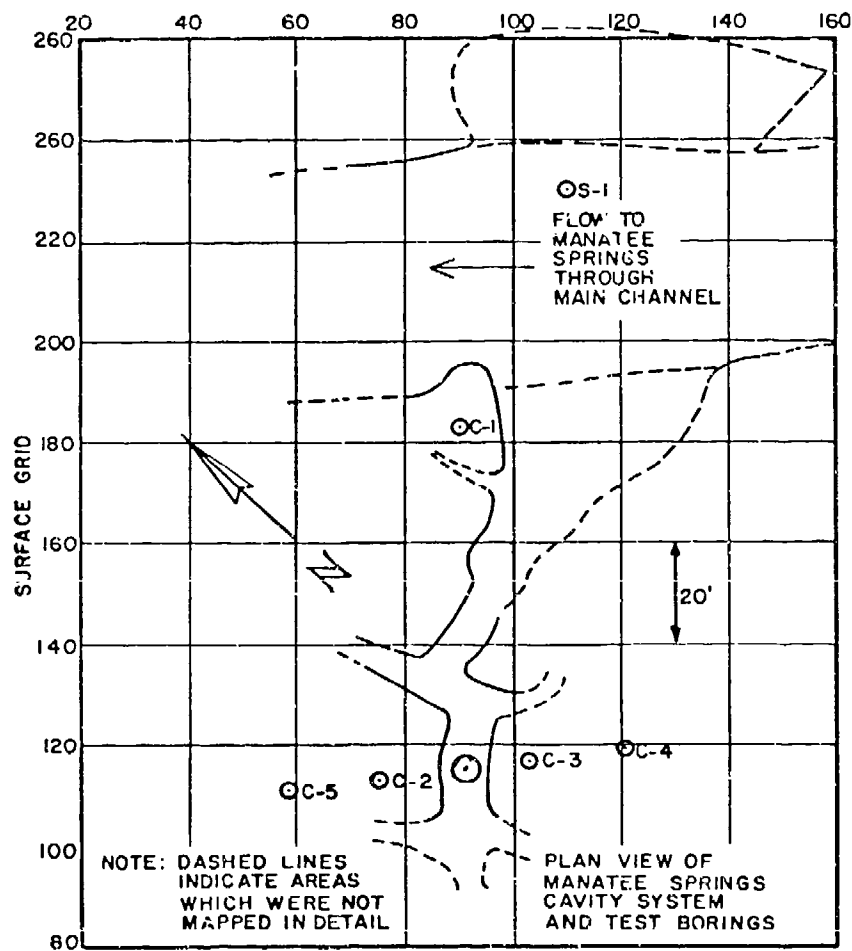


Figure 7. Plan view of Manatee Springs site

receiver which monitors the transmission time of the pulse and its signature, the LLNL approach is to use a swept frequency or a frequency scan to determine that discrete frequency best suited for probing the area between boreholes. The swept frequency is not ordinarily used by LLNL because it requires considerably more time to conduct the test. Rather, a single frequency restricted to narrow bandwidth, typically 1 kHz, brings system noise levels down to the point where signals as low as -110 dbm can be analyzed.

54. In practice, once a frequency has been chosen, the LLNL transmitter power amplifier is carefully controlled to provide a constant power output. The receiver signal is then observed for appearance of prominent nulls in the signal level as a function of depth. When signal losses are observed at a particular depth, the transmitter and receiver can be offset (held at different depths) so that a "skewed" run may be made to determine the geometry of the anomaly in two dimensions.

55. Scans were made between boreholes C3 and C2 with the transmitter in C3 and the receiver in C2. Other cross borehole testing was done with the transmitter in borehole C4 and receivers in holes C3 and C2. In this particular case, receiver C3 was used as a reference for the spectrum analyzer and receiver C2 as the test input. In this way, phase changes representative of the change in relative dielectric constant of the media provided the means for determining the dielectric constant.

56. Seismic (acoustic) crosshole. Three independent crosshole acoustic studies were conducted at the Manatee Springs site by Tennessee Valley Authority (TVA), Sigma Industrial Systems, Inc., and Sonex. Results from two of these studies and detailed descriptions of test methods are contained in the reports by TVA (1980) and Sigma Industrial Systems, Inc. (1981). Test results obtained by Sonex were reported in a letter report to NERADCOM (Sonex, Ltd., 1982).

57. The acoustic study performed by TVA provided little tangible data because the high-energy sparker source malfunctioned. The TVA signal source basically consists of a bank of capacitors which can be discharged across two electrodes encased in a borehole sonde. After

failure of the high-energy source, three crystal energy sources, which are normally used for conventional single-borehole logging, were tried in the crosshole mode but could not project a detectable signal to the receiver located about 30 ft away.

58. The second study, which was conducted by Sigma Industrial Systems, Inc., met a similar fate. Their seismic source also failed before testing was done in the area of interest. Slightly more than one year later (October 1981), Sonex, Ltd. successfully completed an acoustic crosshole test program. Tests were first conducted between borings C5 and C2 to provide a reference standard before a survey was made between borings C2 and C3, straddling the anomaly. The Sonex system consists of a high-energy sparker delivering a seismic impulse in the 2- to 10-kHz region, which is received by a compatible transducer.

59. Data are analyzed in terms of arrival time, signal strength (amplitude), and frequency content. Theoretically if an anomaly, such as a tunnel or cavity, is located at the same elevation between the seismic source and detector in an otherwise homogeneous medium, its presence should cause a change (lengthening) in arrival times of seismic signals and an alteration in the amplitude and frequency content of the seismic signature.

60. Crosshole resistivity. Crosshole resistivity measurements at the Manatee Springs site were jointly funded by the USBM (80 percent) and WES (20 percent) and carried out by LLNL (Laine, 1980) using an LLNL approach. The crosshole resistivity method typically requires fluid-filled holes or scraper pads. The LLNL test is conducted by inducing an electric field by energizing a downhole current electrode with commutated DC current. (The other current electrode is located on the ground surface at some remote distance from the borehole.) The electric potential produced in the subsurface strata is then monitored by a voltmeter connected between the downhole and surface potential electrodes. The downhole current electrode is held in the fixed position while the downhole potential electrode is moved up or down in the adjacent borehole. Using this procedure, measurements were made at 1-ft-depth increments between borings C2 and C3 for the depth interval of 89 to 138 ft.

The crosshole resistivity method was thought to be applicable to the tunnel detection problem because presence of a void, air- or water-filled, should cause a detectable change in the apparent resistivity of the medium. Only the LLNL method was evaluated, but it should be noted that other crosshole resistivity concepts are currently in the development process.

Passive Techniques

Concepts

61. Most of the geophysical methods previously described are referred to as "active." The term "active" is derived from the fact that a given technique induces into the earth medium and measures changes which occur in the process of conducting the test. Examples are: seismic and electrical techniques.

62. "Passive" techniques, on the other hand, rely upon the measurement of changes in natural phenomena such as the earth's magnetic field or variations in gravity. Other items included in the passive category would be the measurement of signals produced by the target of interest. For example, construction of a tunnel will inherently produce noise, electrical power within a tunnel might create a magnetically induced field, ventilation blowers might create a resonance effect, etc., all of which are remotely detectable provided signal-to-noise ratios are favorable. The most noteworthy passive technique for tunnel detection is perhaps seismic triangulation.

63. Tunnel construction (10-ft-diam or larger) is generally accomplished by drilling and blasting, tunnel boring machines (TBM), or in rare instances, pick and shovel. In all of these cases, measurable seismic disturbances are created. Additional seismic disturbances not associated with construction are also likely to occur. These are roof cave-ins and vehicular or personnel traffic. Since an appreciable amount of seismic activity can be associated with the construction or maintenance of an existing tunnel, the seismic triangulation concept

could prove to be one of the most reliable and reasonable approaches to the detection of clandestine tunneling activity.

64. The location of a target which generates seismic activity can be accomplished by considering the simplest case of three geophone detectors configured such that a geophone is placed at each of the vertices of an equilateral triangle whose sides are oriented to a specified reference. Signals from the geophones are simultaneously recorded on a system which has an accurate common time base. Assuming that an explosive charge is detonated during the construction of a tunnel, a seismic wave originating at that point will arrive at some later time at the detector array. By determining the phase shift or difference in arrival time of the seismic wave train received at each geophone, the direction to the target can be calculated. The target which created the disturbance can then be located in two-dimensional space (Cress, 1976).

65. In order to increase the accuracy of target location, several improvements can be added to the basic concept. These are:

- a. Increase the number of geophone detector stations.
- b. Replace individual geophones with subarrays consisting of several geophones summed at a common output point (Durkin and Greenfield, 1981). This approach will tend to cancel random noise thereby improving signal-to-noise ratio.
- c. Bury and grout the geophones to rock at the soil-rock interface. This eliminates most unwanted surface noise sources such as wind or traffic.
- d. Place an additional array of geophones underneath an existing array at greater depth. By having detectors at different elevations, preferably some well below the elevation of the suspected target, triangulation can be accomplished in three dimensions.

Implemented systems

66. In the course of this study, two implemented seismic location systems were closely observed. Both systems are traceable to USBM and were designed to meet the needs of the mining community. Even so, the basic concepts and hardware are applicable to the military situation. These two systems, one permanent and one portable, are intended

for deployment above mining activity and are designed to monitor cave-ins and locate trapped miners in the event of a disaster.

67. CONOCO seismic location system. The Loveridge Mine, owned and operated by CONOCO, is located near Fairview, W. Va. The permanent seismic detection system deployed at this site was brought to the attention of military authorities by CONOCO after publication of an article on clandestine tunneling, which appeared in the 6 November 1978 issue of U. S. News and World Report. Since this system was thought to be applicable to the tunnel detection problem, representatives of CONOCO invited interested parties to a site visit and subsequent demonstration in April 1979.

68. The Loveridge Mine system consists of nine geophones buried and grouted about 40 ft deep at various locations over a 15-square-mile area, amplifiers, associated hardware required to transmit signals (over telephone lines) to the main office, and the central processing unit programmed to detect and locate seismic activity. The system was installed during the period June to September 1974 under partial sponsorship of the USBM at an approximate cost of \$100,000. Once minor problems associated with the original installation were solved, the system has remained in virtually continuous operation and has required very little maintenance. The system has detected roof falls in the "room and pillar" areas of the mine and has located blasts as small as one-quarter pound of dynamite. Location accuracy has typically been within about 250 ft of known sources. This level of accuracy derives in part from an extensive P-wave velocity survey conducted by CONOCO to determine a typical wave propagation velocity for the shale rock at the site (P-wave velocity equals 14,000 fps), which lies between the coal seam and the surface. Surface topography in the area is irregular with hills and valleys of about 400 ft relief. The coal is about 600 ft below the valleys and it is at this depth that most of the activity being detected has taken place. The system and subsequent modifications are described in Fowler (1973, 1974a, 1974b, and 1975). Some of the 40-ft-deep geophones are grouted in soil, while others are grouted in rock and are located in a somewhat random pattern above the mine. Automatic gain

control (AGC) amplifiers, 60-cycle notch filters, and modulation circuitry are installed in metal boxes on poles on the ground surface above each geophone, as shown in Figure 8. AC power is provided along with small back-up batteries. Current draw is so low that the system could run on batteries alone if they were replaced every few months. The biggest technical problem has been 60-cycle electrical noise emanating from overhead power lines in the near vicinity. For all practical purposes, this noise has been eliminated by the inclusion of 60-cycle notched filters. The AGC circuits of the amplifiers automatically suppress many steady-state signals after allowing passage of their initial arrivals, thus tending to minimize the number of false alarms.

69. The system works on the following principle. Signals from nine geophones spread out over the 15-square-mile area are monitored. Arrivals above a preset threshold voltage are counted. If arrivals from three or more different geophones occur in a 500-msec interval, an event is said to have occurred and all the arrival times plus the known location of the geophones and the seismic velocity of the rocks are used by a digital computer to triangulate the source. A map of the area is displayed on a cathode-ray tube (CRT) screen and the location of the source is marked on the display by one of several symbols which indicate how many different geophones recorded the event, providing an indirect indication of the strength of the event and establishing a confidence level. The computer program computes sources for seismic signals originating outside the mine but does not report them to the operator. The same logic could be used in military theaters to eliminate surface signals generated by friendly forces in rear areas behind the geophone arrays. Finally, the computer prepares a report of source coordinates and times of occurrence for each 24-hr period in tabular and map form. Comparison of the map output for several days by someone knowledgeable about construction, vehicular, or explosive surface activity in the area will readily expose quasi-linear patterns of sources which tend to move in a linear fashion as a function of time in areas of very little surface activity. These patterns can identify tunneling operations in rock.



Figure 8. Signal-conditioning equipment used in the CONOCO seismic location system

70. MSHA seismic system. The Mine Safety and Health Administration (MSHA) has implemented a seismic detection system conceived through USBM research efforts. Portability and automation are the primary differences between the MSHA system and the permanent system installed at the Loveridge Mine in West Virginia. In accordance with its operational concept, the MSHA seismic detection system is maintained in a state of readiness at a facility near Aliquippa, Pa. Upon notification of a mine disaster, the equipment and operations personnel are sent to the scene of the disaster to aid in the location of trapped miners. The equipment is highly mobile and in its present configuration the electronics are housed in a metal cab which can be detached from the back of a flat-body truck. Figures 9 and 10 are photographs of the equipment cab and its interior, respectively. When detached, the equipment can be shipped by an aircraft such as an Air Force C-130 or equivalent to any chosen destination and deployed in about 3 or 4 hr time. Its basic concept is shown in Figure 11.

71. In order to maintain a state of readiness, the equipment is periodically checked out above various mines located throughout the country. When fully operational, the MSHA system uses an array of seven seismic stations whose coordinates have been established by survey. Each of the seismic stations, deployed in a manner illustrated in Figure 12, consists of a subarray of seven vertical geophones whose output is summed into a single telemetry channel and then beamed toward the receiving station located at the instrumentation van (see Figure 13). The telemetry system has been carefully calibrated and compared to a variety of hard-wired installations to be certain that arrival times and phase relations are not distorted. The configuration of each 15-ft-diam subarray is similar to that shown in the inset in Figure 12. By configuring the subarrays in this pattern, as opposed to using a single geophone, several decibels signal-to-noise ratios can be gained because random surface noises and seismic surface waves are not in phase and consequently will tend to be cancelled when summed. Typically, the distance between subarrays will be 800 to 1000 ft depending upon terrain conditions.

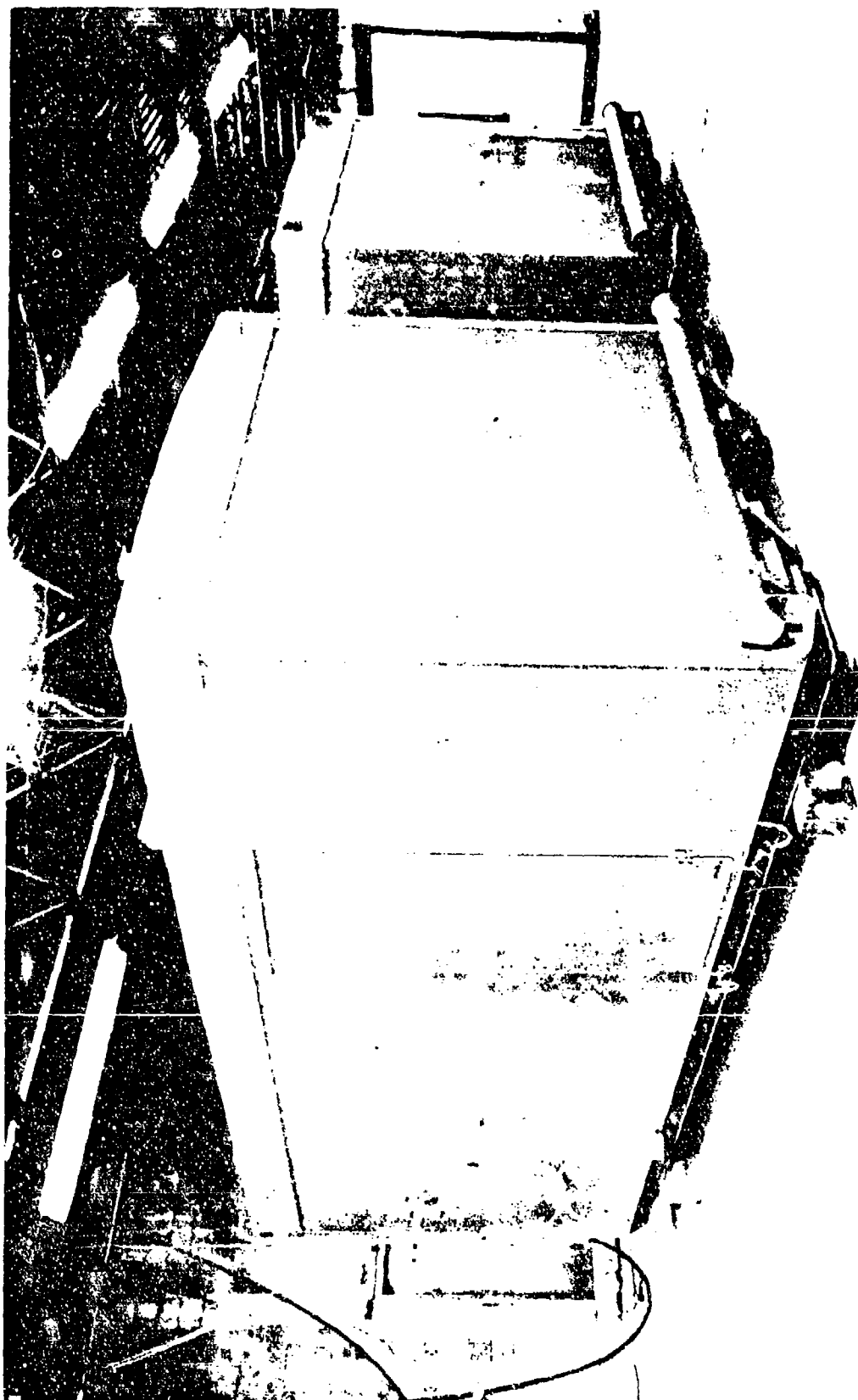


Figure 9. Metal cabs housing MSHA seismic system

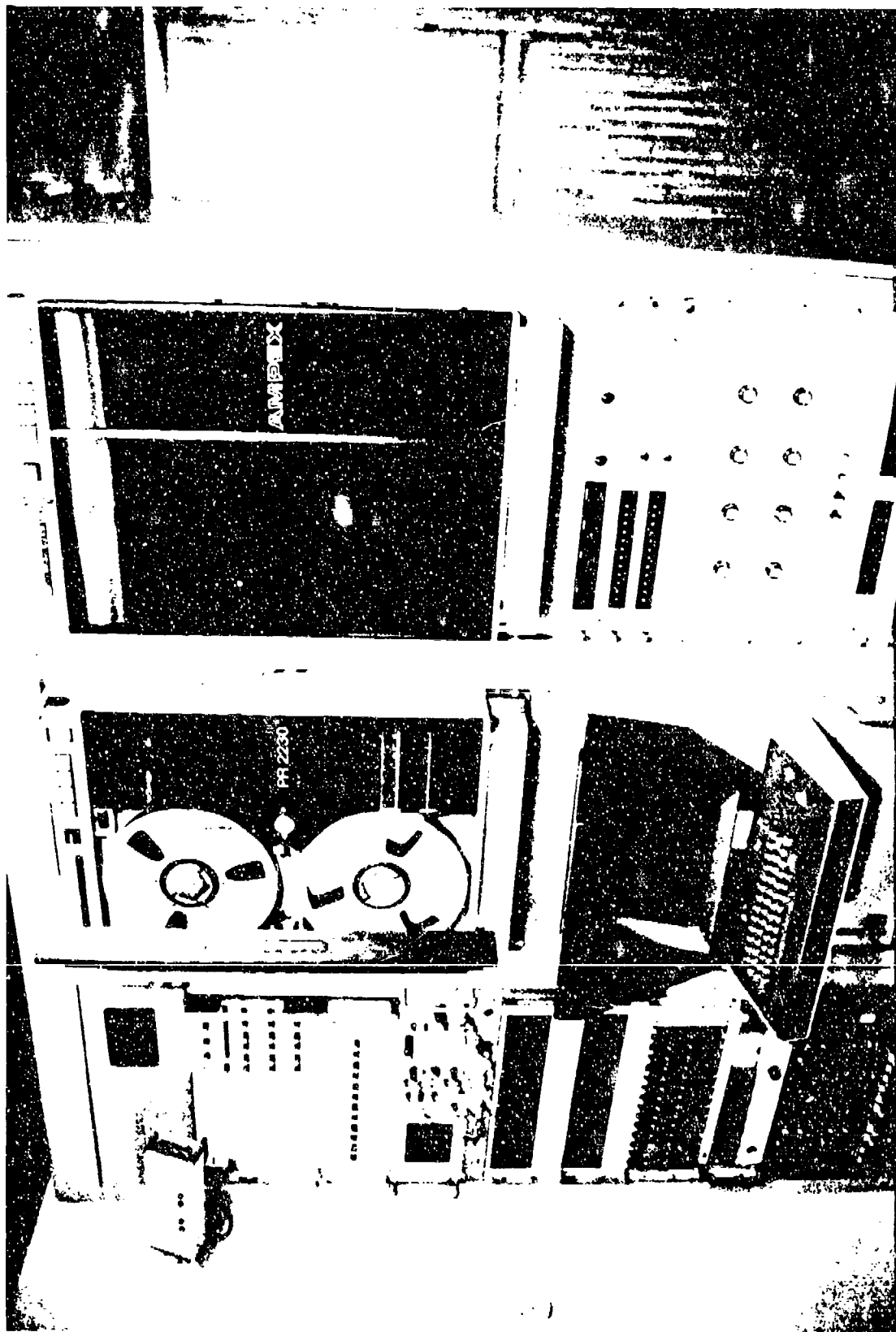


Figure 10. MSHA data acquisition equipment

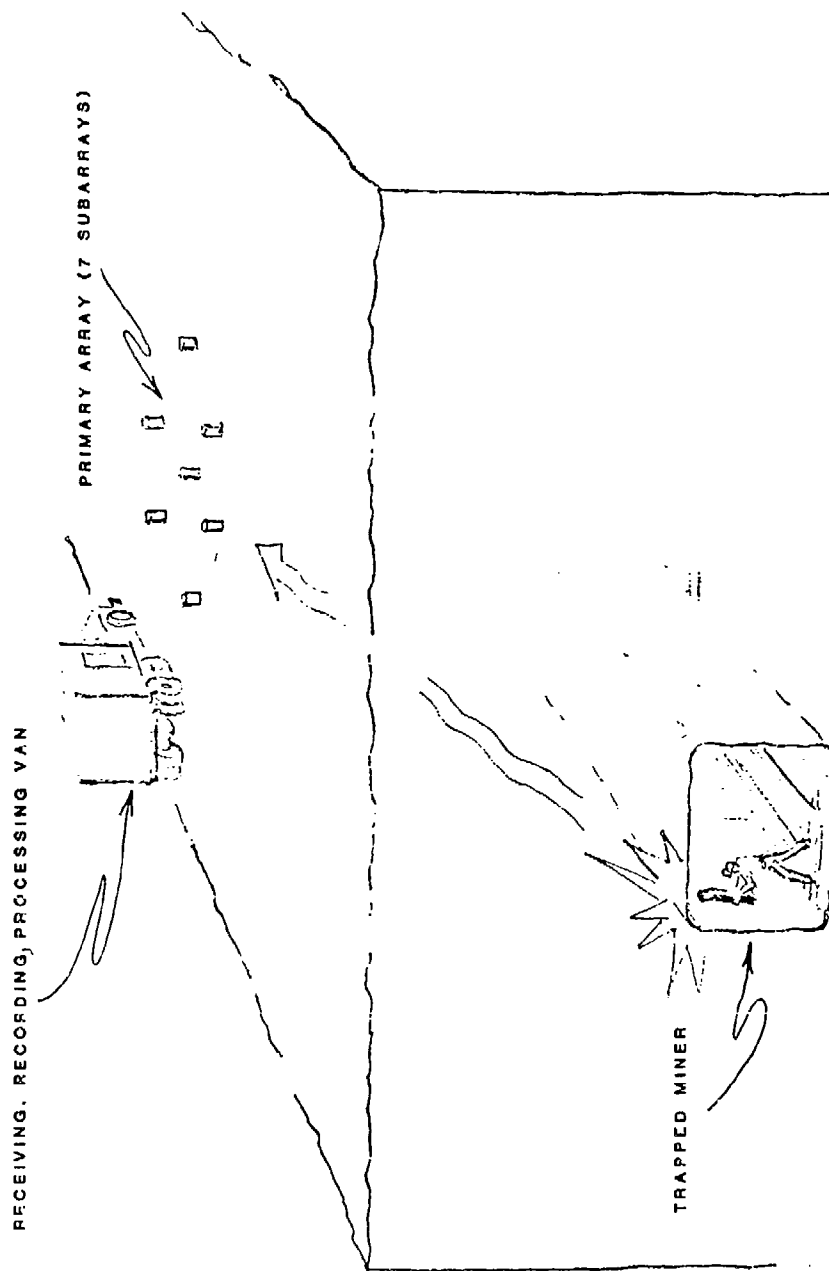


Figure 11. Basic concept of MSHA seismic detection system

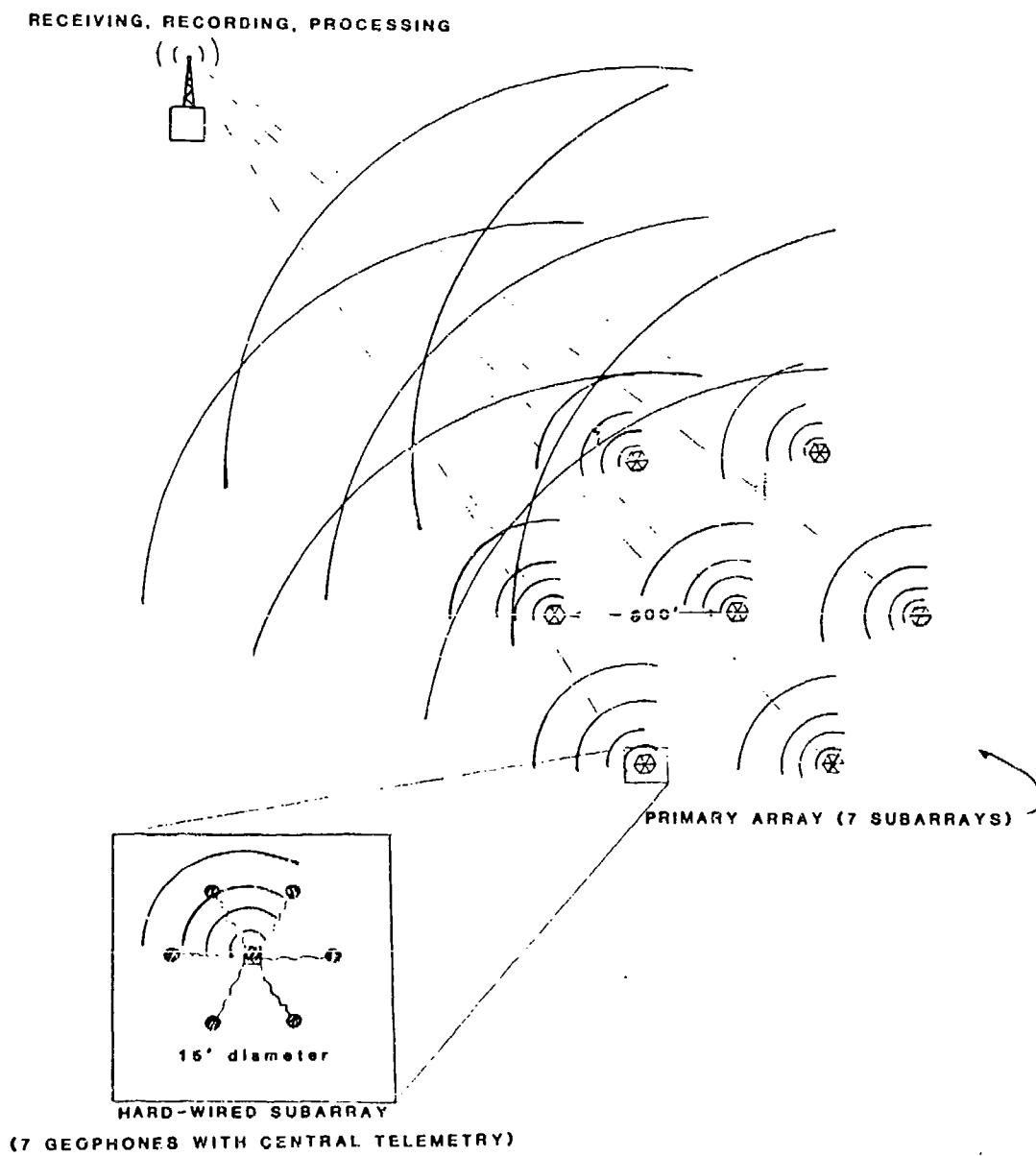


Figure 12. Telemetry data acquisition, MSHA seismic detection system

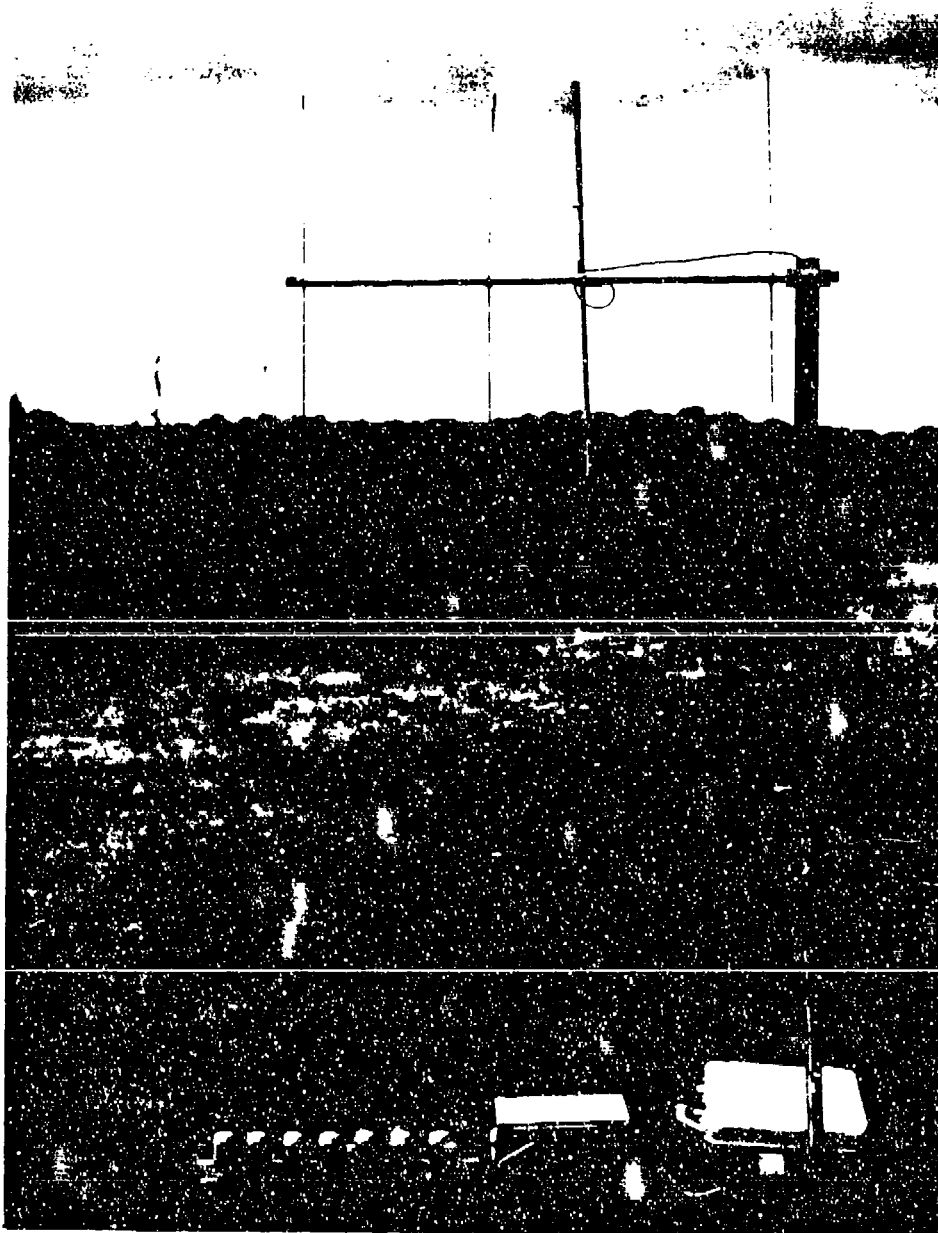


Figure 13. MSHA subarray components and telemetry system

72. As soon as the system is in a state of readiness, the surface crew detonates three explosive charges which can be easily heard underground by a trapped miner. After hearing these shots, the miner is instructed to pound 10 times on a part of the mine, preferably the roof or roof bolt with any heavy object he can find. Following this, the miner is to rest 15 min, then repeat the process until he hears five shots from the surface which will indicate that his signal has been heard and help is on the way. During the location process, a technique known as stacking is used to enhance the signal level. In theory, and in practice, this leads to an increase of $\sqrt{N}$ in amplitude signal-to-noise ratio, where N is the number of pulses stacked. The present system relies on the operator's ability to determine when a signal has occurred. Manual detection of the signal can be unreliable due to the low signal-to-noise ratio often encountered and the ability of the operator to maintain peak performance over extended periods. At present, efforts are being made to automatically detect the miner's signal by computer using seismic event algorithms similar to those used by CONOCO, thus eliminating possible human error (Durkin and Greenfield, 1981).

73. If tunneling activity is suspected in a given area, the MSHA system, in its present state, could likely triangulate and locate the source of activity provided it could be deployed directly over the activity. If, however, the tunneling operation occurs some distance outside of the array, location accuracy will be appreciably hampered. Modifications of computer software can probably overcome this deficiency. The software triangulation package contained in the present MSHA system calculates the target location from arrival times measured on stacked seismograms. This program combines the individual subarray arrival times either three or four at a time to find the location. The program can use a known depth for the source (which is often the case in coal mines) or can fit data for the source depth. Alternate methods of location based on the least-squares principle are often times used in seismic location work and can also be used here. Durkin and Greenfield (1981) tabulated the results of numerous field exercises in which simulated trapped miners pounded on the ceiling at a location unknown to

the search team, but known to the "miners." Results of 12 tests showed that in four cases the error range was less than 50 ft. In six cases, the error range was less than 100 ft, and in two cases, the error range was approximately 150 ft.

74. In a contract report (Dyson, 1981) prepared for the USBM, the feasibility of employing automated processing and detection techniques in the mine disaster communication problems is demonstrated. Efficient processing methods were developed. These methods were demonstrated both in laboratory and in a field environment. Evaluation of existing MSHA computer capacity was given along with recommendations for expansion. Techniques evaluated included digital filtering and Fast Fourier transform, Wiener and Kalman filtering, prefiltering correlation, and stacking. A request for proposal to upgrade the system accordingly has been issued by the USBM and will be implemented by MSHA. These modifications will also greatly enhance the potential military use of this portable seismic detection system for locating underground activity.

PART III: TEST RESULTS

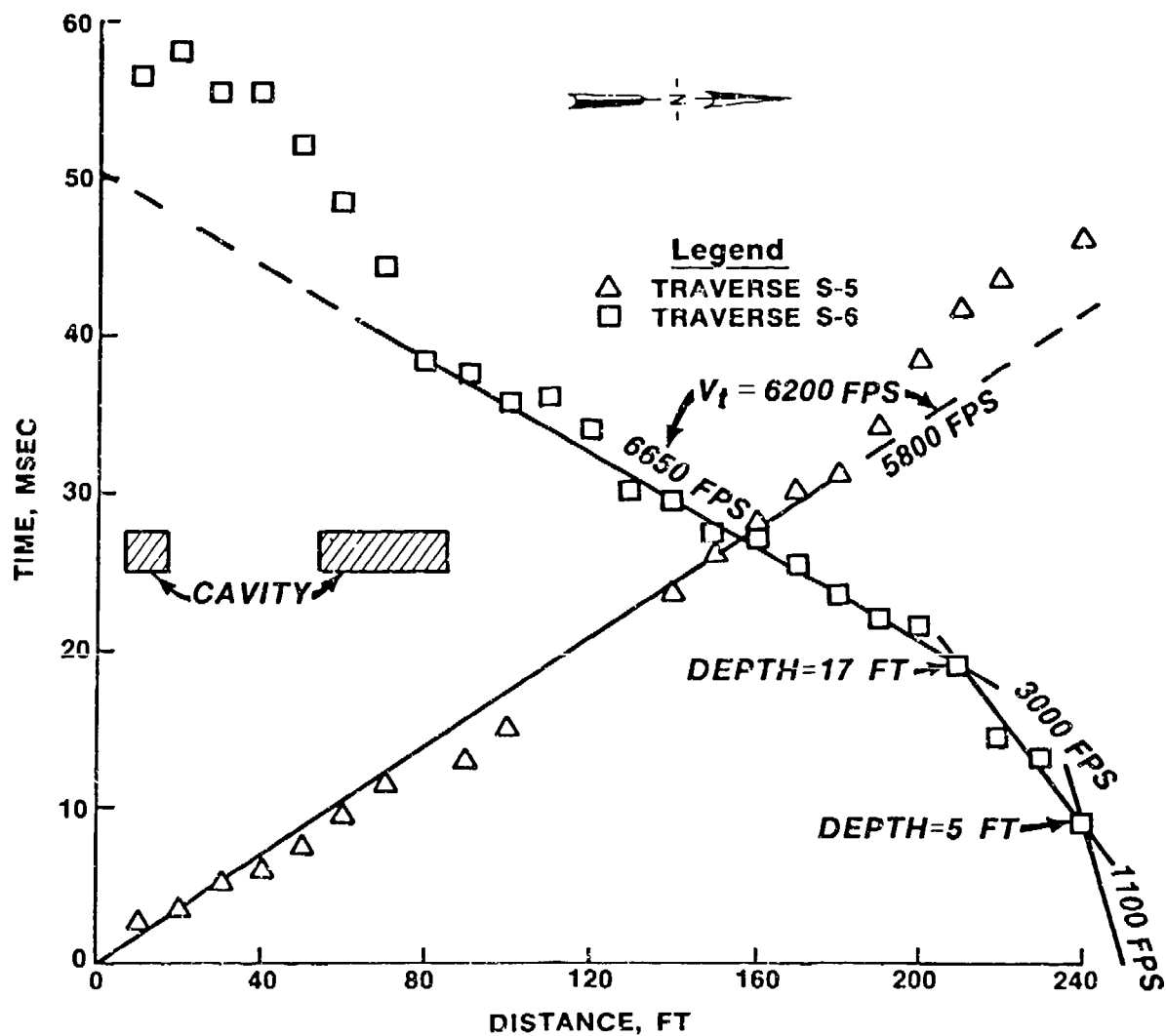
75. The results of tests conducted will be limited to chosen typical examples which serve to show the advantages and limitations of the various test techniques. Complete data can be found in the references. Greatest emphasis will be placed on those methods which show promise when applied to the problem of tunnel detection. Those methods concerned with rapid reconnaissance surveys are presented first, following by the methods which would be used to conduct a high-resolution survey based on findings of the reconnaissance.

Medford Cave

Surface methods

76. Conventional seismic refraction. Eight conventional seismic refraction lines (18 traverses) were run at the Medford Cave site. The lines were purposely located so that areas where no known cavities existed and areas with known cavity features of various sizes could be investigated. Data were plotted in the conventional manner as P-wave arrival time versus distance. Apparent velocities and depths to refracting interfaces were then determined. A detailed description of the interpretation is given by Curro (in preparation).

77. As expected, many of the time-distance plots showed anomalous data in the form of delayed, early, and undetermined arrival times. In summary, it was determined that departures from expected arrival times might be caused by the presence of subterranean cavities. Six out of the seven seismic lines which were located over known cavity features showed either delayed arrival times or no data due to the extremely poor signal quality. The seventh seismic line also displayed somewhat erratic arrival times, but not such that one could positively say that the presence of the cavity was noted. Figure 14 was selected as a typical example of data obtained over a known cavity. The delayed arrival times toward the end of traverse S-6 correlates well with the known cavity features. On the reverse traverse, S-5, there is no



REFRACTION SEISMIC TEST RESULTS

Figure 14. Time versus distance plot for traverses S-5 and S-6

indication of late arrival times in the area of the cavities. This was probably the result of the shotpoint for S-5 being too close and too shallow to produce delayed arrival times. The delay times at the end of traverse S-5 were found to have been caused by an increase in overburden (17 ft compared to less than 1 ft near shotpoint S-5). This can also be seen from the first two segments of the time-distance curve for traverse S-6.

78. Refracted wave form. Test results obtained during the conduct of the seismic refracted wave form (constant spacing) technique proved to be quite interesting. As described previously, the refracted wave form is intended to provide information beyond the conventional determination of arrival times. That information is contained in the total seismic signature, i.e., amplitude and frequency variations.

79. In addition to the "quick look" analysis done on site, the data were digitized to aid in a more quantitative assessment. These data, along with a Fourier spectrum analysis of each wave shape, are presented by Curro (in preparation).

80. In summary, in several areas where frequencies and amplitudes of the signal decreased, cavities were found to exist. Generally speaking, when consistent arrival times, high frequencies, and amplitudes were present in the seismic signature, no cavities were found. Since all of the known cavities at this site were fairly shallow, the effect of cavity depth on detection success still remains a question. However, the technique shows promise for the detection of shallow tunnels (less than 50 ft).

81. Refraction fan-shooting. Referring to Figure 2, the fan test layout, one will observe that test No. 1 was intended to be conducted in an area where no known cavities existed. Arrival times determined from this test showed appreciable delays (Figure 15), beginning with geophone 20 and continuing through geophone 24 or beyond the eastern edge of the grid system. Boring E21, located between the seismic source and geophone 20, detected numerous small cavities in the depth range from 10 to 40 ft, but it is also known that the thickness of overburden material increases in an easterly direction. As a result, one must

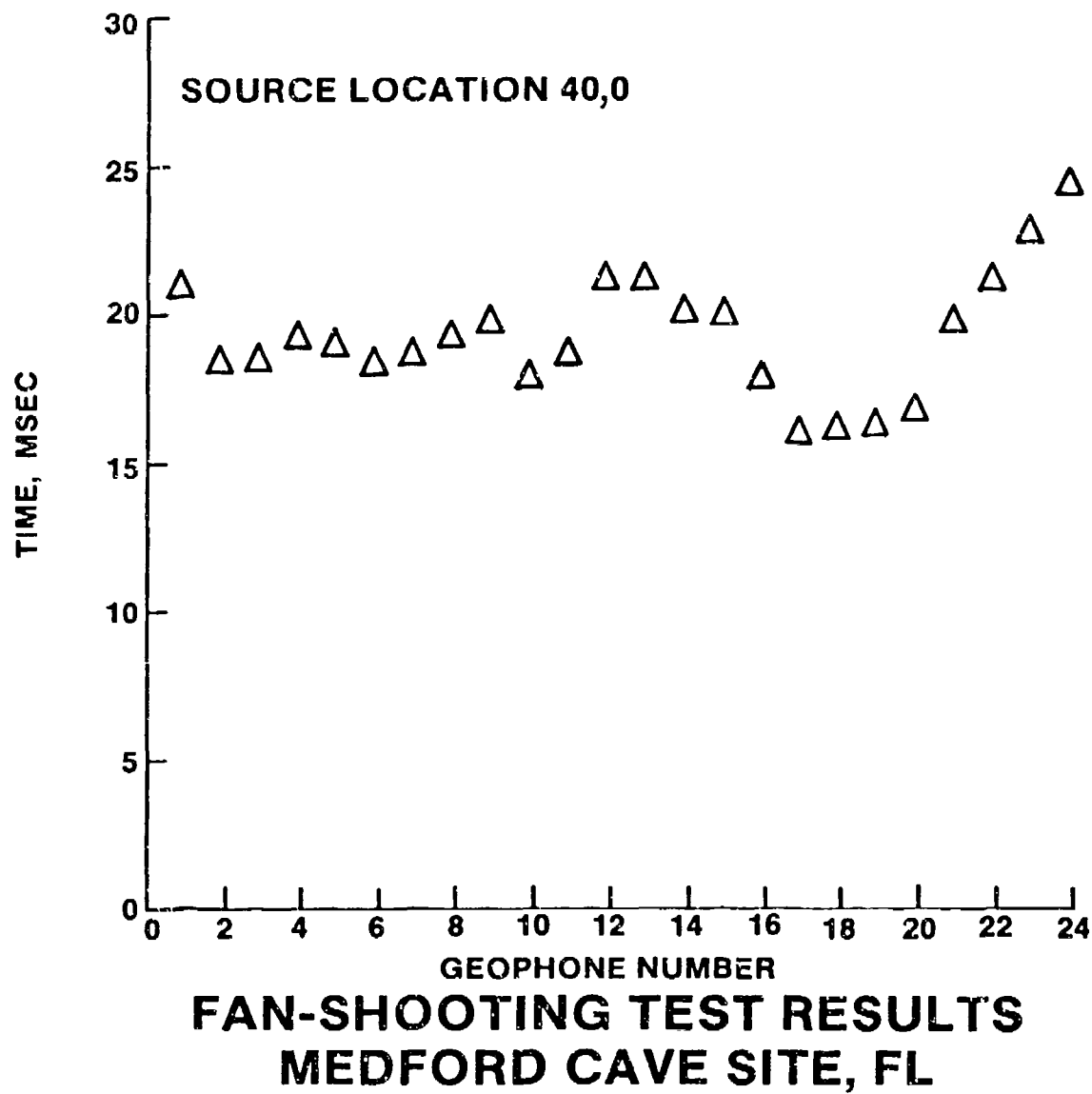


Figure 15. P-wave arrival time versus geophone number
for fan test 1

acknowledge that the delayed arrivals could be caused by one or a combination of both circumstances.

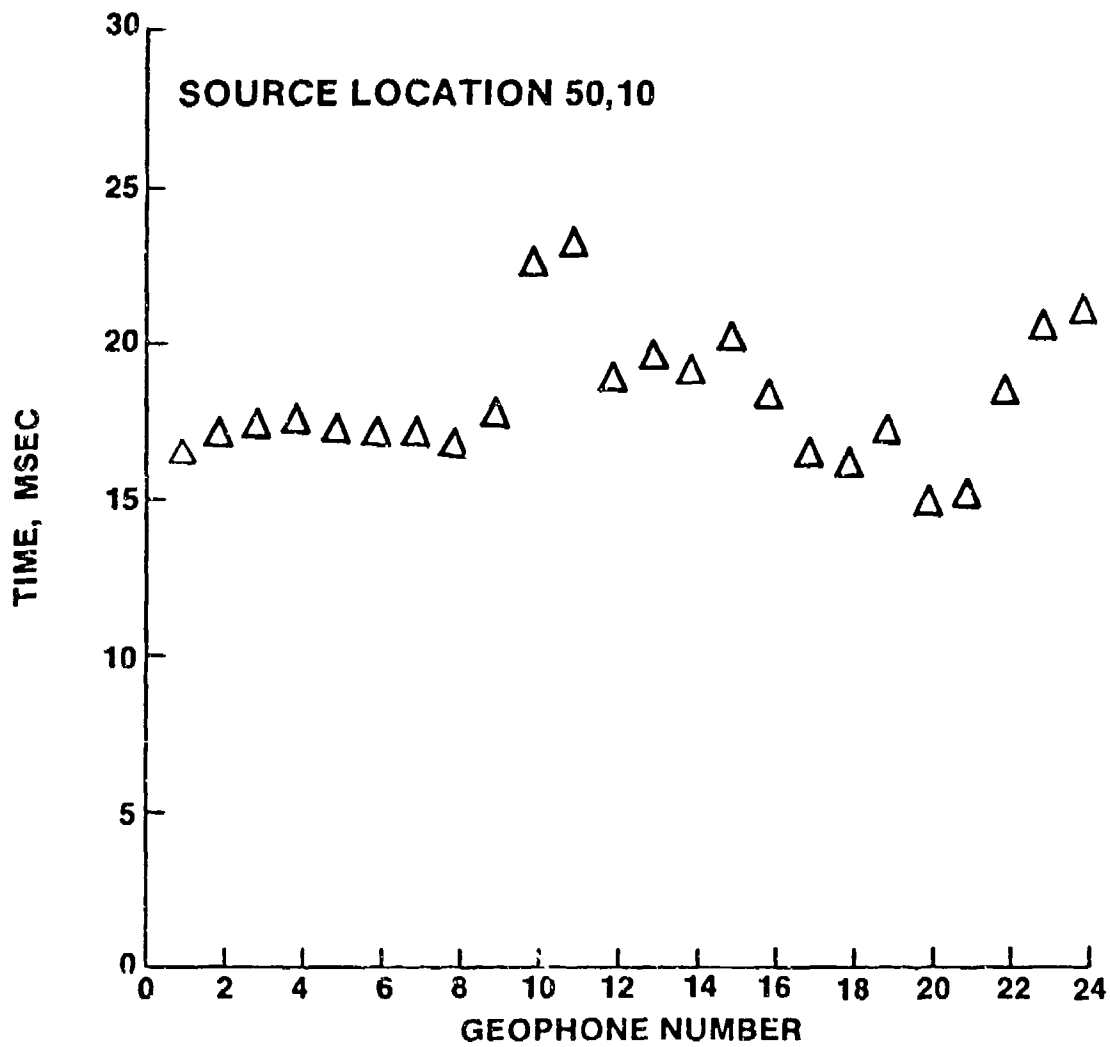
82. As the test sequence progressed in a northwesterly direction, some of the geophones were purposely located over known cavity features. Observing Figure 16, which is the plot of arrival time versus geophone number at sta (50,10), it will be seen that the arrival times at geophones 10 and 11 are appreciably delayed. These geophones were located over mapped parts of the cavity system. As testing continued, inconsistent data were obtained in several instances. Geophones located directly over cavity features in test No. 3 did not indicate any anomalous delayed times; however, one bit of consistency was noted in every test case. The last four geophones (those located on the eastern portion of the grid) showed appreciable time delays. It was concluded after exploratory drilling that these were likely related to the combination of increased overburden in that area and cavity features.

83. In summary, results of the fan test present no conclusive evidence of anomalous arrival times being cavity-related; however, if the gains on the seismograph had been set lower so that the entire signature had been visible on the record, other clues such as amplitude and frequency content might have provided greater insight into the subsurface conditions.

84. Refracted shear wave. Results of the refracted shear wave tests were considered to be inconclusive because the seismic source (sledgehammer) did not provide adequate energy for confident data analysis.

85. Reflection seismic. The reflection seismic tests were first conducted in areas with no known cavities and in areas with known cavity features of various sizes. Data were acquired and analyzed by Technos, Inc., using a procedure advocated by Professor Harold Mooney (1977) and described by Curro (in preparation).

86. Even though seismic reflection techniques are well understood and used on a regular basis by petroleum exploration companies, shallow reflection procedures are still being developed. Little, if any, data exist in the literature documenting the successful mapping of



**FAN-SHOOTING TEST RESULTS
MEDFORD CAVE SITE, FL**

Figure 16. P-wave arrival time versus geophone number
for fan test 2

strata shallower than 20 ft in depth. The reflection data obtained at the Medford Cave site should be viewed with that caveat in mind.

87. The interpretation presented by Technos showed considerable scatter in the reflection picks; however, some trends were noted. It appears that rock strata are horizontal or near horizontal at the site and the shallowest reflectors could be as shallow as 9 ft or as deep as 22 ft, depending upon the velocity chosen for the interpretation. In summary, the data from the reflection lines do not provide any positive indication of correlation with a known cavity system and at this stage of development, use of the method to detect either cavities or tunnels would be highly questionable.

88. Resistivity (Bristow and Wenner). The Bristow (pole-dipole) resistivity array was used to profile several lines at the Medford Cave site. Results of the survey along the 80W north-south grid line were chosen as representative of site conditions and because more geologic information was obtained along this line than any other. Figure 17 (Butler, in preparation) shows the pole-dipole sounding results for six locations of the current electrode (C_1) along the profile line using a 30-ft spacing. Butler described the test and results in the following manner. The potential electrodes were moved out to a distance, $X = 80$ ft, on each side of each C_1 station, where X is the distance to the center of the potential electrodes. The distance between potential electrodes P_1P_2 was 10 ft and X is incremented by 5 ft between measurements. The distance between C_1 stations is selected as 30 ft; this procedure allows an anomaly near the surface to be defined by as many as seven intersecting hemispherical shells. The general trend of the sounding data is increasing apparent resistivity as a function of depth. In order to pick anomalies, linear trend lines are used as indicated in Figure 17. High resistance zones, falling above the trend line, are related to air-filled voids, while the low resistance zones are associated with clay-filled voids or depressions. According to Butler (in preparation), the degree of success that can be expected using this technique will depend a great deal on the experience of the interpreter and on having considerable redundancy of the data. Test

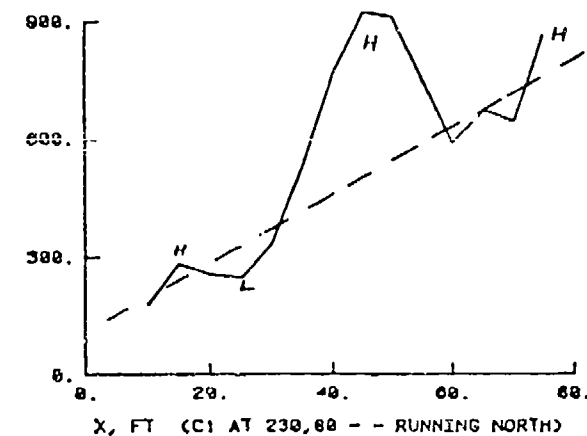
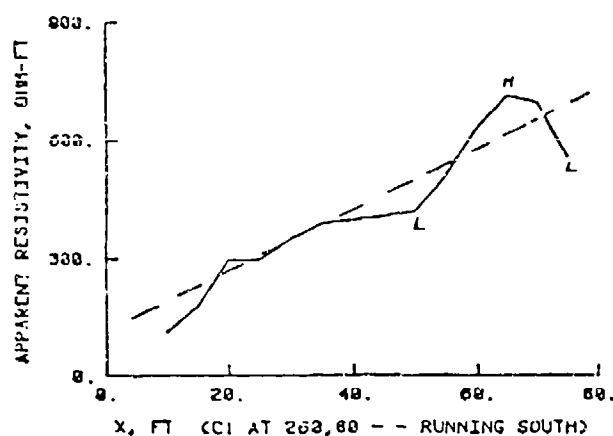
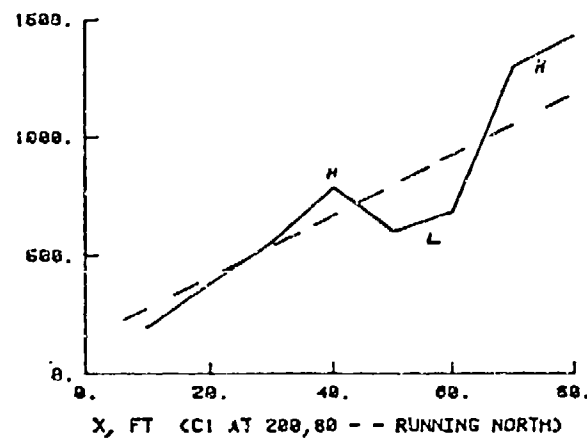
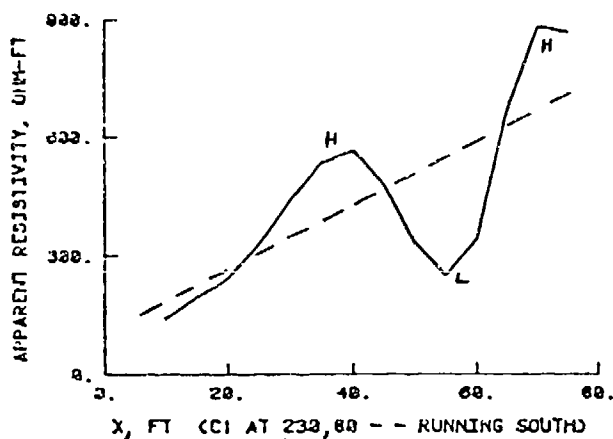
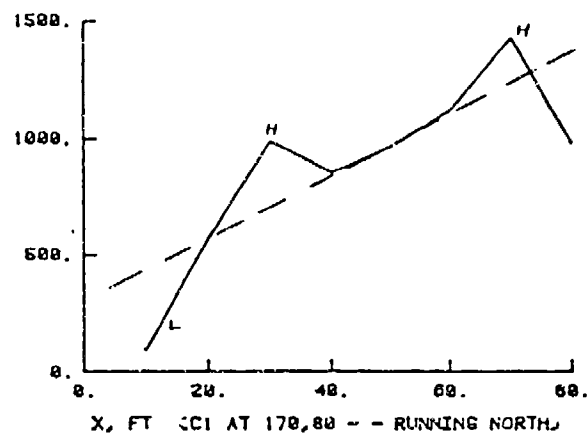
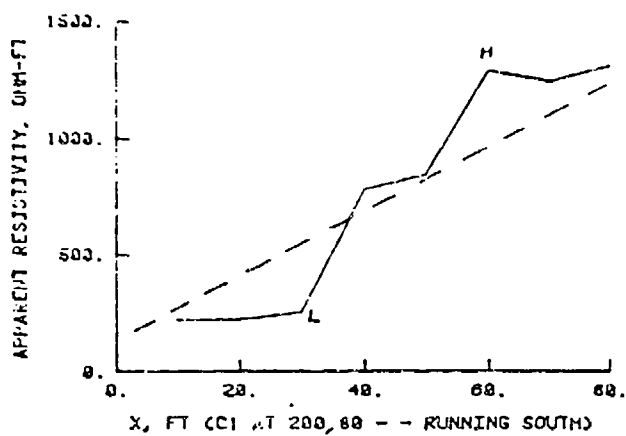


Figure 17. Six pole-dipole sounding curves at 30-ft spacing along the (0,80) to (260,80) line at the Medford Cave site (Butler, in preparation)

results obtained by the geometric method are shown in Figure 18 (Butler, in preparation). Comparisons with the near-surface geologic cross section defined by drilling are quite good. Varied hatching patterns denote the number of arc intersections in a particular zone, hence a confidence level can be established.

89. Since the field procedure is relatively slow, the SwRI, with funding from MERADCOM, has developed an automated resistivity data acquisition system (Fountain and Herzig, 1980). Data are digitally recorded and graphically processed. This procedure has been used by MERADCOM under actual field conditions in an effort to locate existing tunnels. To this date, no new tunnels have been found by this procedure, but an existing tunnel was detected. Consequently, it is worthy of future consideration.

90. The Wenner array was used with electrode spacings of 40 and 10 ft at the Medford Cave site. The 40-ft spacing allowed the depth of investigation of the resistivity survey to include the effects of the entire known cavity system. The apparent resistivity contour map (Figure 19, Butler, in preparation) definitely shows the presence of the cavity system. Assuming a baseline resistivity to be about 400 to 600 ohm-ft, the cavity system produces a resistivity anomaly of about 1000 ohm-ft. The Wenner array can be considered as a viable reconnaissance method. Table 1 can be used to determine deployment requirements.

91. Radar (SwRI and Technos). A complete documentary of the results obtained using the SwRI surface ground-probing radar is presented by Duff and Suhler (1980). Tests were conducted along lines chosen to be representative of cavity areas and noncavity areas. Just prior to running the traverses, one test was conducted to determine the propagation velocity of the medium. The velocity must be known in order to analyze the returns of the pulse-echo radar in terms of depth to the target. The velocity was determined by placing a small receiver antenna on the roof of the large room of the cave and recording the transmitter as it traversed overhead on the ground surface. The two-way propagation time determined at this depth of 10 ft was 60 nsec. Velocity (EM) is then determined by dividing the distance by the travel time.

POLE-DIPOLE RESISTIVITY ANOMALIES

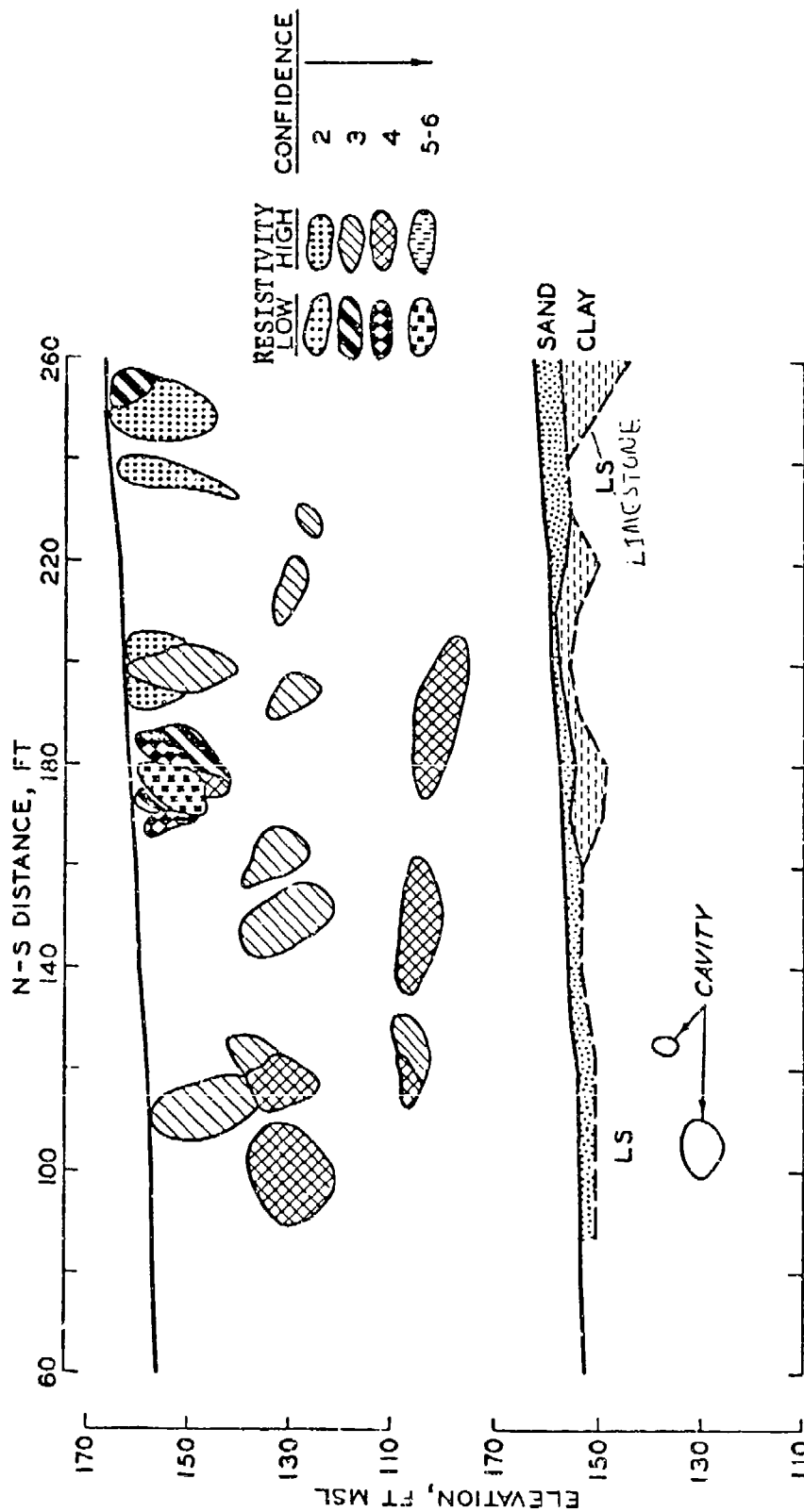


Figure 18. Interpreted pole-dipole resistivity cross section compared with known geology along the (0,80) to (260,80) line at the Medford Cave site (The numbers indicating increasing confidence levels correspond to the number of arc intersections which define the anomaly (Butler, in preparation.)

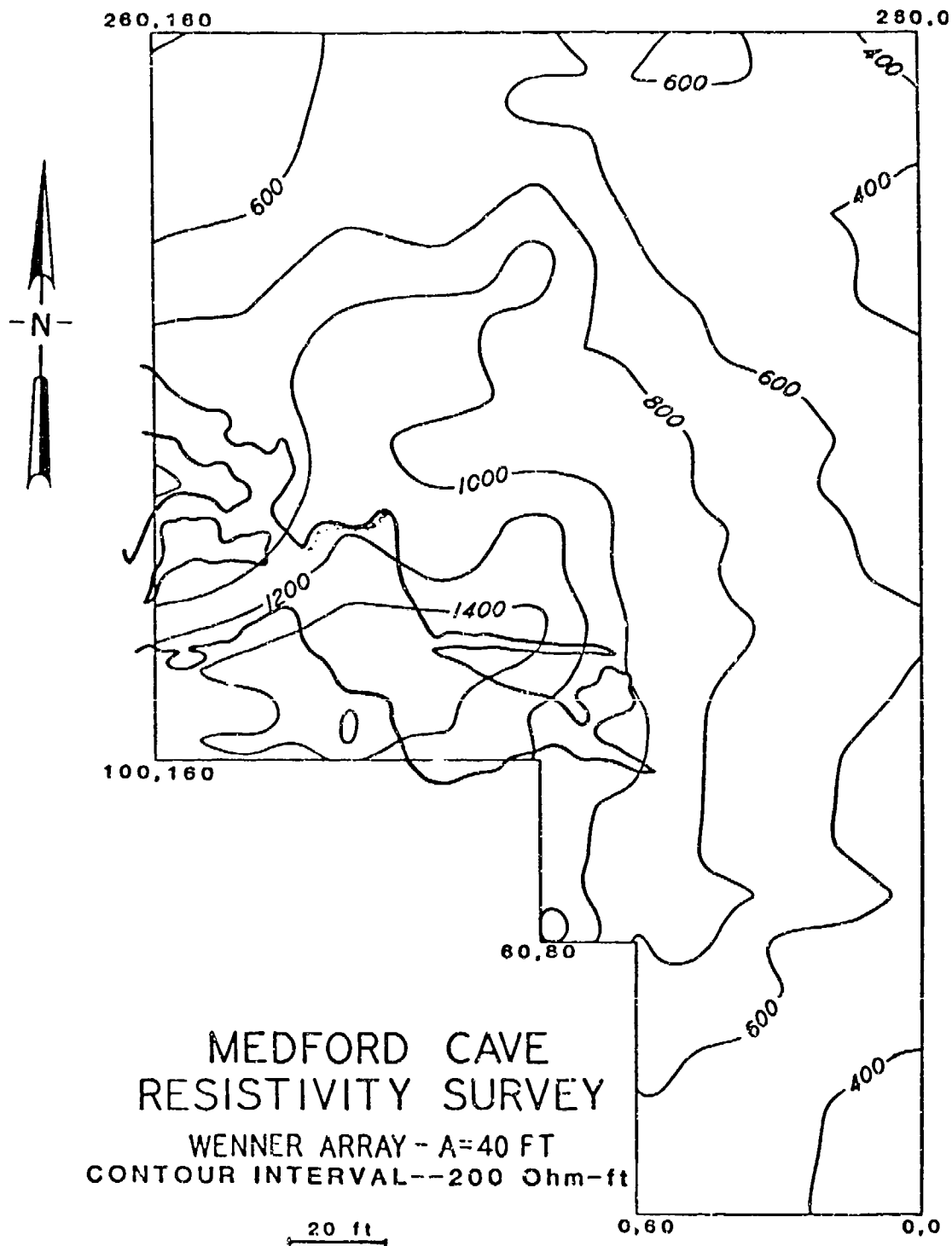


Figure 19. Resistivity contour map for a portion of the Medford Cave site, Wenner electrode array with 40-ft electrode spacing (Butler, in preparation)

Table 1

Geophysical Methods for Tunnel Detection, Surface Methods

Requirements to Survey 1000 Lin Ft Optimized for 150-Ft Depth									
Surface Method	Personnel		Time Required			Maximum Depth (Ft) for Detection of 10-Ft-Diam Tunnel (90% Confidence)			
	Field	Analysis	Training		Field Survey	Data Analysis	Host Material	Actual Data	Projected to 1987
			Months	Man-hr					
Seismic Conventional Refraction	2 (HS)	1 (BS)	1	6	15	4	Soil Rock	-- 25 (Curro, in preparation)	150 50
Seismic Refracted Wave Form	2 (HS)	1 (BS+)	1	6	18	6	Soil Rock	-- 9 (Curro, in preparation)	50 20
Seismic Refraction Fan-Shooting	2 (HS)	1 (BS)	1	6	30	8	Soil Rock	-- 25 (Curro, in preparation)	130 50
Electrical Resistivity Wenner Array	3 (HS+)	1 (BS)	1	2	12	4	Soil Rock	-- 20 (Cooper, 1978)	20 30
Pole-Dipole Array	3 (BS)	1 (BS+)	1	4	18	8	Soil Rock	-- 75 (Cooper et al., 1982)	75 100
Ground-Probing Radar	2 (HS+)	1 (BS+)	2	4	0.2 (2 mph)	1	Soil Rock	25 (Duff & Suhler, 1980)	100 150+
Microgravity	2 (HS)	1 (BS+)	1	6	30	20	Soil Rock	-- 25 (Butler, in preparation)	60 80

* HS = high school graduate; BS = Bachelor of Science degree; + indicates some education beyond indicated level.

Cannot directly detect tunnel below top of refraction horizon. Degree of resolution inversely related to increasing velocity.

Geologic and/or stratigraphic changes can affect seismic wave form. Optimum use is with sledgehammer as source, usable distance between source and receiver should not exceed 200 ft limiting depth of penetration to about 50 ft.

Same as conventional refraction seismic. Localized near-surface conditions. Could affect arrival times and alter seismic signature.

Large resistivity changes and/or complex geology of host material. May mask presence of tunnel. Resolution diminishes with increasing depth.

Depth of investigation controlled by dielectric constant and conductivity of host material. Resolution is directly proportional to increasing frequency.

Equipment delicate and costly. Interpretation tedious. Surface topography influences data. Highly irregular bedrock surface can mask presence of tunnel.

92. An additional, but highly significant finding resulting from the velocity test was the high signal level recorded at a depth of 10 ft. The inference drawn is that the EM signal was capable of penetrating to substantially greater depths at the Medford Cave site. Cave conditions did not permit further verification to determine the maximum depth limitation of the surface-mounted unit. Crosshole radar tests, which will be described later, were conducted to distances of 100 ft.

93. Data obtained during the conduct of 11 different traverse lines tend to indicate localized targets or reflectors. In regions corresponding to known voids, multiple reflections were seen over extended portions of the traverse lines. In all cases but one, when the traverse line extended over a mapped void, characteristic reflections were received at the ground surface. In that exceptional case, the depth to the roof to the cave was estimated to be approximately 16 ft. Reflection returns were very weak and broad and probably would not have been recognized had the presence of the cavity not been known. Strong echo responses were found in several locations not corresponding to mapped portions of the caverns. A recommendation was made by SwRI that exploratory borings be placed at grid coordinates (120,0), (135,40), (125,60), and (160,100). Exploratory borings were later placed at three of the recommended four locations. These were designated as E19 (120,0), E23 (125,60), and E25 (160,100). The fourth boring (135,40) was not placed due to time and cost limitations for the project. Complete logs and descriptions of these borings are contained in Butler (in preparation).

94. A few observations are worthy of note. Boring E19 encountered a massive core loss and some clay from a depth of approximately 11 to 27 ft. Boring E23 encountered a very soft zone and water loss from 13.5 to 17 ft, and boring E25 encountered a cavity from a depth of 8 ft extending to a depth of approximately 10 ft. Therefore, one can conclude that the SwRI ground-probing radar tests were successful at the Medford Cave site and should be considered for both reconnaissance and high-resolution tunnel detection surveys, recognizing that the SwRI ground-probing radar's maximum effective depth of penetration will be dependent on site conditions.

95. The surface ground-probing radar tests conducted by Technos were reported by Benson and Glaccum to WES in an unpublished letter report in 1980. Twelve selected radar traverses were run in areas where known cavities existed and in unmapped areas where the presence of cavities was unknown. In the areas of low conductivity (low clay content in the near-surface), radar profiles produced numerous clear anomalies over mapped cave areas as well as over unmapped areas. In the areas of higher conductivity, the anomalies became less distinct. The 80-MHz antenna achieved much better results than a 300-MHz antenna because of the greater depth of penetration and amplification of the lower frequency antenna.

96. At the beginning of the survey, calibration of the system was accomplished at a small, accessible horizontal cave whose roof was approximately 9 ft below ground surface. An aluminum foil reflector was used in the cave to provide a recognizable target. The 9-ft depth produced a response at approximately 50 nsec comparing favorably with SwRI findings. Other tests were conducted using an aluminum reflector in the main cave entrance where the roof of the cave was approximately 22 ft thick. No detectable reflections were observed at this site. An auger boring was placed in this area, and approximately 7 ft of clay overburden was found overlying the rock surface. This concentration of clay (clay has a high dielectric constant) was probably responsible for the lack of radar response at this location.

97. The GSSI recorder provided a convenient display for use on site. Technos personnel classified the anomalies in two categories: Class I, those which were clearly independent of any EM noise, and Class II, those which were present in zones of noise (particularly overhead noise caused by trees). Only the Class I anomalies were used by Technos in determining the overall pattern of the radar anomaly zones, thus presenting a somewhat conservative interpretation. It was interesting to note the extension of radar anomalies in the easterly direction along the axis of the two main mapped cave sections into what may be incipient cavities or fractured rock zones. A large concentration of radar anomalies occurred in the vicinity of (140,80) and (160,60).

A few of the radar traverses were processed from a magnetic tape record which was obtained on site to remove unwanted low-frequency components, as well as noise generated by overhead tree branches. It was recommended by Technos that exploratory borings be placed at grid coordinates (110,0), (117.5,-5), (60,0), and (165,95). Borings E19, E20, E21, and E25 accomplished this purpose. In each case, the boring logs indicated the presence of cavities or other anomalous features such as soft zones. Figure 20 is the graphic display obtained by Technos along the zero north-south grid line. The targets identified by Technos are indicated by the arrows, and logs of borings E21 and E19 are also shown in the figure.

98. In summary, the results of ground-probing radar at the Medford Cave site show promise for future application in detection of shallow cavities or tunnels at sites where the dielectric characteristics of the overburden materials are compatible with ground-probing radar.

99. Magnetic. Detailed results of the magnetic survey are reported by Butler (in preparation). In several instances, the data obtained were influenced by the presence of metal, such as the ladder used for gaining entrance into the main portion of the cave and a nearby sink which was used as a garbage disposal area. The magnetic data obtained at the site were plotted and contoured on the grid system, but showed little discernible relation to the known geology or known cavities. Consequently, these survey results do not encourage use of the magnetic technique for tunnel detection unless it is known that a high concentration of metal exists in the tunnel system.

100. Microgravity. Details of the microgravity survey conducted at Medford Cave site are presented by Butler (1980c; in preparation). The data were carefully processed and corrected for time variations, latitude, elevation, Bouguer corrections, and terrain effects.

101. After adjusting the microgravity data, Bouguer and residual anomaly maps were made for both 10- and 20-ft station spacings. Four major negative anomaly features were observed, some of which were readily accountable, but others required confirming borings. Those borings based on gravity anomalies were E18, E19, E20, E23, and E25. It will

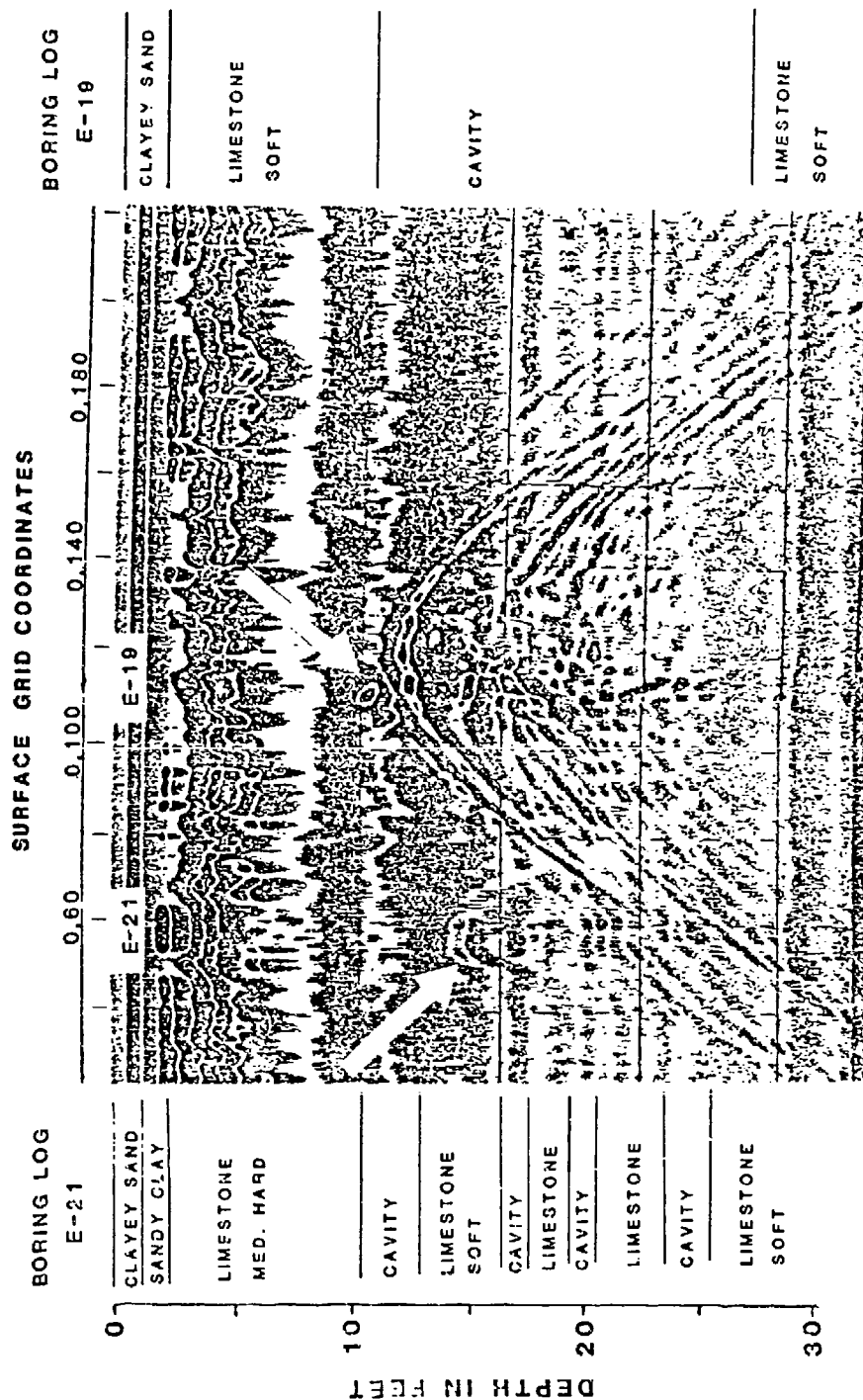


Figure 20. Technos ground-probing radar targets, Medford Cave

be noted that some of these borings coincide with the findings of other geophysical techniques, specifically borings E19, E23, and E25, which were related to findings of the ground-probing radar contractors and various seismic tests. Borings E19 and E20, located at (117,-5) and (110,0), respectively, both encountered cavities which are the probable cause of gravity lows noted in this area. Boring E18, located at grid coordinates (225,40), encountered a partially clay-filled cavity at a depth of 9 ft extending to 14.5 ft. Boring E23, located at grid coordinates (130,60), was placed to investigate the cause of a small gravity anomaly which appeared on the 10-ft spacing map. Boring E23 encountered a clay-filled cavity extending from a depth of about 9 to 18 ft. Additionally, a broad resistivity high occurred over the central part of that position. According to Butler, two factors might account for the resistivity high: (a) a broad region of increased porosity due to solutioning, and (b) the close proximity of the large known cavity system. Other interesting results obtained during the gravity survey can be seen in Figure 21, which is a profile along the north-south 80W grid line. Comparing the microgravity to the geologic profile, one can see that the relative highs and lows can be associated with the geologic features. Particularly, note that the strongest low occurs over the cavity system. Other lows can be attributed to clay-filled depressions in the bedrock. Thus, it would appear that the microgravity method shows a great deal of promise for the location of shallow tunnels to a depth less than four times the diameter of the tunnel. From a military standpoint, however, one must consider that the microgravity method requires considerable expertise and time to conduct and interpret the survey. Table 1 shows these requirements.

Methods requiring boreholes

102. Crosshole seismic. A complete discussion of the results obtained during the crosshole seismic test is presented by Curro (in preparation). To illustrate the applicability of the crosshole test scheme to tunnel detection, only the results of the P-wave tests conducted between borings C1 and C10 will be presented. Figure 22 shows the apparent P-wave velocities and the approximate position of the known

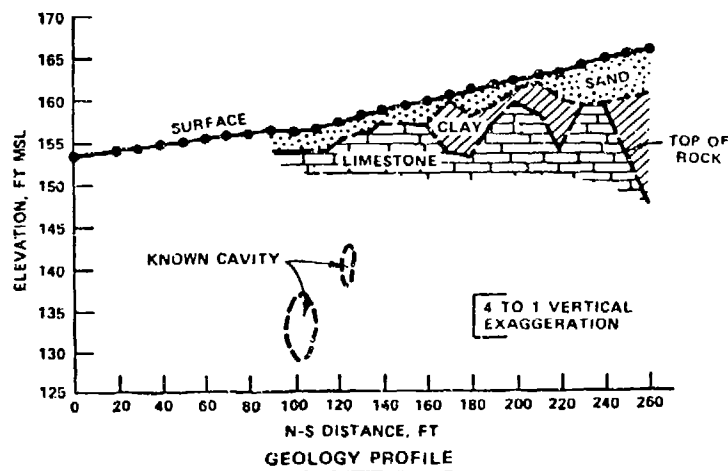
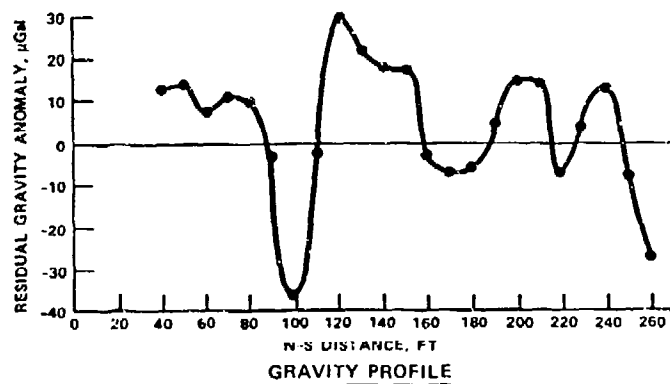
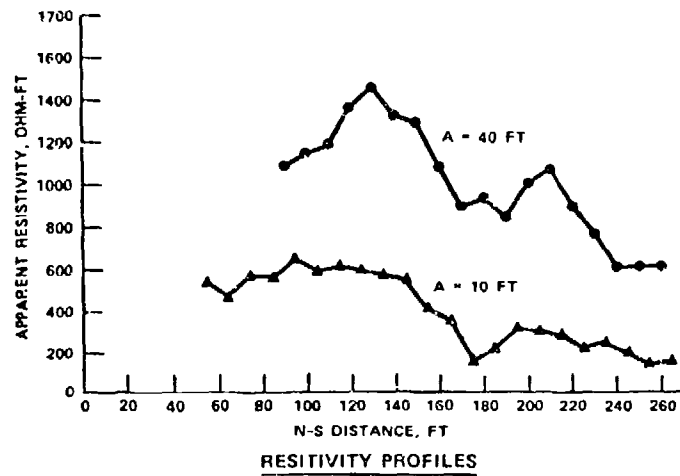
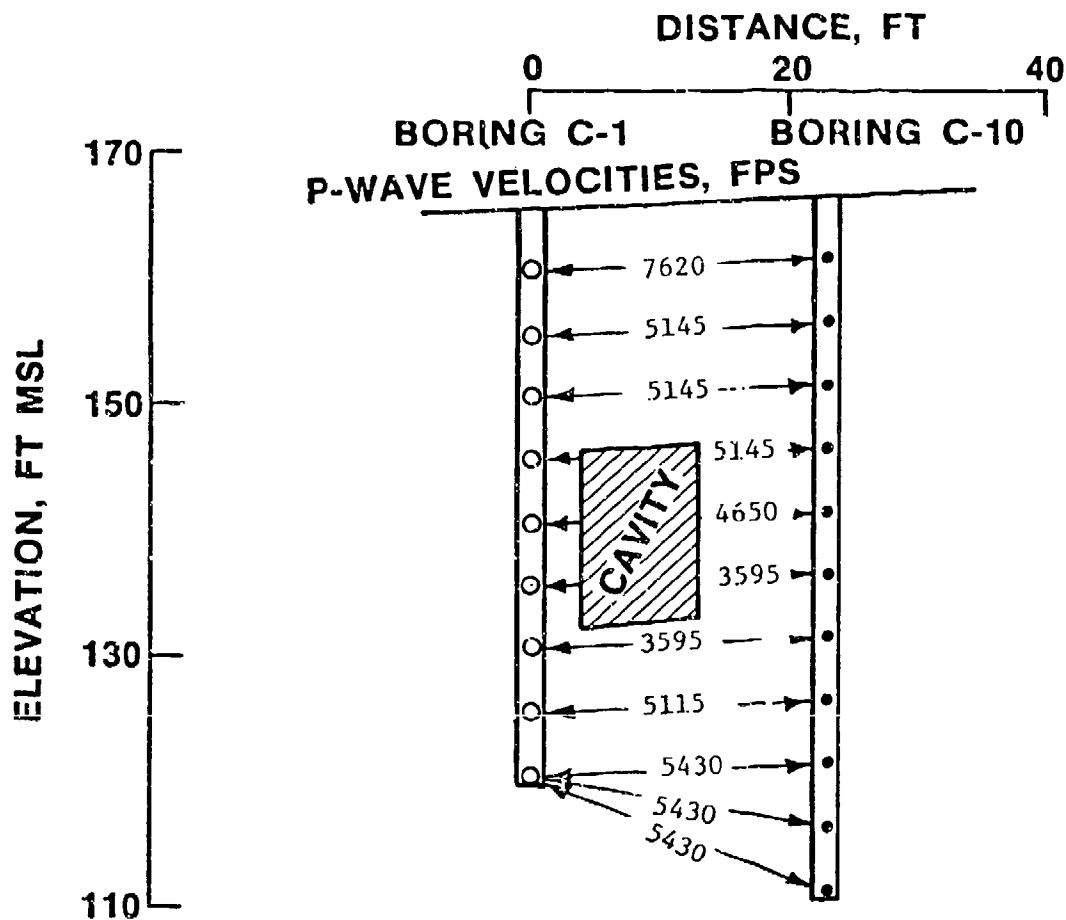


Figure 21. Microgravity and Wenner resistivity profiles along 80W north-south grid line, Medford Cave



LEGEND

- SEISMIC SOURCE LOCATION
- GEOPHONE LOCATION

CROSSHOLE SEISMIC TEST RESULTS

Figure 22. P-wave velocity profile from crosshole seismic test, borings C-10 to C-1

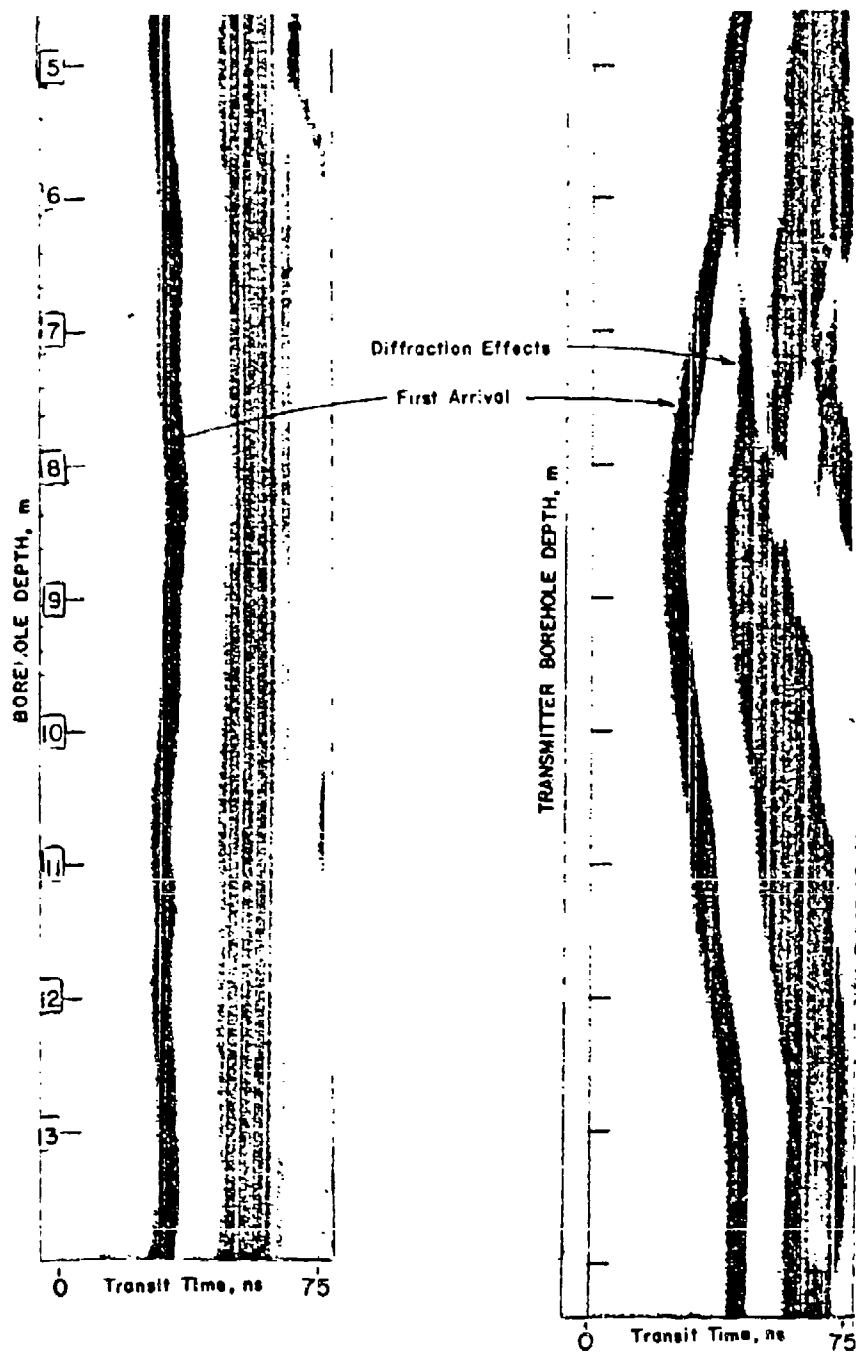
cavity between the borings. From Figure 22, it is quite evident that the lowest apparent velocities (3595 and 4650 fps) were obtained in the cavity region. The 3595-fps value obtained about 2 ft below the cavity is almost certainly cavity-related and probably shows some of the inaccuracies associated with the mapping of the cavity system or indicates a solutioned fractured zone extending to some depth below the mapped cavity. Velocities ranging from 5145 to 7620 fps are related to the more competent limestone formations that exist under the site.

103. Crosshole S-wave tests did not produce valid data simply because signals could not be transmitted between borings when cavities were present. This in itself is an indication that an anomaly exists between two borings and can also be related to the presence of a tunnel. The seismic crosshole method shows promise for tunnel detection during a high-resolution survey.

104. Crosshole radar. Results obtained during the hole-to-hole EM transmission (radar testing) are presented by Fountain and Herzig (1980). The time window for observing received pulses between boreholes was adjusted to cover the range of 50 to 300 nsec. Some data were obtained with transmitter and receiver at the same elevation, while other tests were conducted with the transmitter and receiver offset in depth for the purpose of making a more detailed analysis using tomographic image reconstruction.

105. The data were closely examined for differences in pulse arrival times. The presence of an air-filled cavity between transmitter and receiver causes a speedup in time; whereas, water- or mud-filled cavities should cause a slowdown or longer time of flight of the pulse than through rock without cavities.

106. Figure 23 serves to illustrate that the crosshole radar technique should receive serious consideration for tunnel detection. Figure 23a shows a crosshole record obtained between boreholes C4 and C5, 17 ft apart, with no known cavity between the borings. One will observe that the first arrival times are approximately equal throughout the scan. Figure 23b is a crosshole record obtained between borings C2 and C3, which were 23 ft apart. In this case, a known cavity existed



a. EM Crosshole Record
Boreholes C4-C5, 17ft Apart
Transmitter-Receiver Raised Synchronously
(No known cavity between boreholes)

b. EM Crosshole Record
Boreholes C2-C3, 23ft Apart
Transmitter-Receiver Offset 1m
Raised Synchronously
(Known Cavity)

Figure 23. SwRI crosshole radar tests conducted at Medford Cave site

between the boreholes and its presence is evidenced by the decreased first-arrival times and the diffraction effects which are also visible on the record.

107. Uphole refraction seismic (wave front). A detailed discussion of the results obtained during the conduct of the uphole refraction seismic survey is given by Curro (in preparation). Since Curro's final conclusion was that the results of the uphole refraction tests did not indicate anomalous data caused by presence of cavities, the method should not be used as a cavity or tunnel detector. Certain very large cavity features did affect the travel times of the seismic signals, but smaller features, such as a 10-ft-diam tunnel, would be undetectable in competent rock materials.

Manatee Springs

Surface methods

108. Microgravity. Results of the microgravity survey at Manatee Springs, Fla., are documented by Butler et al. (in preparation). The survey was conducted along an established grid pattern and applied corrections to the microgravity data in a manner similar to that at the Medford Cave site. These test results were presented in the form of a residual gravity anomaly map. Directly above the main channel, Butler observed a region of -20 μ Gal compared to positive readings of 20 to 40 μ Gal noted in other areas of the test site.

109. Several other anomalous features were noted in the microgravity survey, but due to time and fiscal constraints only a very limited number of verification borings were possible. Of the total of 12 borings at the site, the gravity data were consistent with subsurface conditions revealed by all but two of the borings. These two borings were located in the northeast half of the survey area away from the area above the main cavity system and produced no features which could be related to the microgravity survey. The microgravity investigation at Manatee Springs strengthens the conclusions drawn from the survey at Medford Cave. It would appear that the microgravity method is a viable

contender for shallow (depths less than four times the tunnel's diameter) tunnel detection provided site conditions are conducive to this type of survey.

Methods requiring boreholes

110. Single borehole methods. Results of single borehole conventional logging techniques were reported by Cooper (in preparation). He concluded that the maximum volume of material influencing measurements made within a single borehole extended no more than 3 ft (probably considerably less) from the sidewall from the instrumented borehole. Consequently as a method for detecting tunnels, single borehole techniques offer little promise.

111. One single borehole technique, however, that was not evaluated by WES during this test series should not be overlooked as a possible contender for tunnel detection--the borehole microgravity method. The borehole microgravimeter is not a widely available tool due to its very high cost and delicacy. Its primary use to date has been in petroleum exploration. Based upon results obtained during surface microgravity testing at both the Medford Cave and Manatee Springs sites, one might expect a borehole microgravimeter to be sensitive to the presence of a 10-ft-diam tunnel 30 to 40 ft away from the borehole. This supposition is partially confirmed by recent borehole microgravity tests conducted at a site near Idaho Springs, Colo. (Exploration Data Consultants, Inc. (EDCON), 1982). EDCON was successful in locating a tunnel approximately 10 ft in diameter at a distance 16 ft from the borehole. The tunnel could not be detected at a distance of 50 ft. Based upon the quality of data obtained 16 ft from the tunnel, EDCON predicted detection to a distance of at least 33 ft. Military deployment considerations can be guided using Table 2.

112. Crosshole radar. Results of crosshole radar tests conducted at Manatee Springs, Fla., showed that electromagnetic wave propagation is indeed influenced by cavities in wet rock. A detailed description of the SwRI radar study at Manatee Springs is available from the literature (Heizig and Suhler, 1980). Cooper (in preparation) also discussed the findings of SwRI. The test sequence was similar to that

Table 2

Geophysical Methods for Tunnel Detection, Methods Requiring Boreholes

Methods Requiring Boreholes	Requirements to Survey Between Two Borings 200 Ft Deep									
	Personnel		Time Required				Maximum Distance Between Boring to Detect 10-Ft-Diam Tunnel			
	Field	Analysis	Field	Analysis	Survey	Data	Host Material	Actual Data	Projected to 1987	Basic Limitations and Remarks
Crosshole Radar	2 (HS)	1 (BS+)	2	4	2	1	Soil Rock	-- 100 (Fountain & Herzog, 1980)	100 150+	Maximum distance between transmitter and receiver controlled by dielectric constant and conductivity of host material. Resolution decreases in direct relation to frequency. Lower frequency limit to resolve 10-ft-diam tunnel will be about 100 MHz.
Seismic Crosshole	2 (HS)	1 (BS)	1	6	8	6	Soil Rock	-- 25 (Curro, in preparation)	100 100+	Maximum distance between borings dictated by geology. Snell's law of refraction must be applied to establish zoning. Repeatable seismic source should be used.
Borehole Microgravity (Single Borehole)	2 (HS)	1 (BS+)	1	6	60	60	Soil Rock	-- 16 (EDCON, 1982)	30 30	Equipment delicate and costly. Interpretation tedious. Surface topography influences data. Terrain correction schemes are in developmental stage.

* HS = high school graduate; BS = Bachelor of Science degree; + indicates some education beyond indicated level.

conducted at Medford Cave in that the radar was first used to survey between boreholes C2 and C5 because no significant cavity features were known to exist in this section.

113. Figure 24 (Cooper, in preparation) provides a straightforward description of the test results. In this illustration, Cooper shows the location of the cavity feature and a zone thought to be a lateral cavity network between borings C2 and C3. Radar and acoustic crosshole test results between borings C5 and C2 (no cavities) are shown to the left, while results obtained between C2 and C3 (with cavities) are shown to the right. It can be seen that the C5/C2 radar pulse travel times are reasonably consistent except for one interval between 101.7 and 105 ft in depth. Here, the radar pulse is attenuated and its arrival time increases only slightly. The 40- to 120-ft-depth interval between borings C2 and C5 is essentially free of cavities and may be considered as competent rock at this site. It is interesting to note that perturbations do appear in the zone 95 to 100 ft and 115 to 120 ft. These, in all likelihood, correlate with poor-quality rock or solutioning which has occurred.

114. Observing the data obtained between boreholes C2 and C3 which straddled the known cavity (Figure 24), it is seen that:

- a. There is a distinct signature change in amplitude and frequency at a depth of 90.2 ft corresponding to the top of the target cavity.
- b. No radar pulse arrivals were detectable below 100 ft in depth, probably due to the presence of the known cavity and related cavity networks.

115. Electromagnetic propagation theories suggest that the presence of water-filled cavities would tend to both increase the travel time through such zones and also severely attenuate signal pulses. Note that the travel time in the air-filled cavity system at Medford Cave decreased.

116. As evidenced by the data obtained by SwRI and LLNL (Laine, 1980), it must be concluded that the crosshole borehole EM (radar) technique must be considered as one of the most promising candidates for

tunnel detection at sites composed of igneous rock (granite) where dielectric characteristics of the substrate are favorable.

117. Seismic (acoustic) crosshole. Of the three seismic (acoustic) crosshole tests conducted at Manatee Springs (TVA, Sigma, and Sonex), only the data obtained by Sonex will be addressed. As stated earlier, equipment failures resulted in little or no data obtained by TVA and Sigma in the zones of interest.

118. Test results obtained by Sonex are also presented in Figure 24 (Cooper, in preparation). Tests were conducted in the same sequence and in the same boreholes used for radar measurements. The left-hand acoustic plot in Figure 24 is the result obtained when the receiver was located in boring C5 and the transmitter located in boring C2. These data are presumed to be representative of the test site where little or no cavity development is expected. The acoustic test results show a uniform P-wave arrival time of approximately 2 msec, thus indicating that no anomalous condition is present.

119. The acoustic cross survey made between borings C2 and C3 can be seen on the right side of Figure 24. Comparing the two plots (C5/C2 and C2/C3), the following details will be noted:

- a. Uniform arrival times, frequencies, and amplitudes are exhibited when no significant cavities are present.
- b. When the cavity is introduced (C2/C3), the crosshole acoustic signals are severely attenuated and changes are noted in frequency along with a delayed signal travel time.
- c. Little or no crosshole signal is received through the cavity zone.
- d. A distinctive diffraction pattern can be observed in the secondary wave train arrivals at the detector in boring C3 above and below the elevation of the target cavity.

120. Cooper (in preparation) used the arrival time data in conjunction with the known dimensions of the cavity between borings C2 and C3 to mathematically prove its reasonableness.

121. Tests were also conducted by Sonex to determine the two-dimensional geometry of the mapped cavity. The source and detector were

offset in depth by several feet and skewed runs were made between borings C3 and C2. Cooper documented these results and concluded that the vertical dimensions of the target cavity were well defined by the offset surveys when the diffraction pattern is used as the standard for comparison.

122. For high-resolution tunnel detection surveys, the seismic (acoustic) crosshole method appears to be a logical choice at sites having a shallow water table or where boreholes can be made to contain water. Coupling with this type of seismic source is extremely critical and it can only function well under water. Since the technique deals with sonic P-wave velocities, it is inferred that any good, repeatable P-wave source (such as an air gun) should be able to function as well.

123. Crosshole resistivity. Results of crosshole resistivity tests conducted at Manatee Springs are presented by Laine (1980) and Cooper (in preparation). In summary, plots of apparent resistivity as a function of depth identified a significant resistivity anomaly in the 114- to 120-ft-depth interval between boreholes C2 and C3. This anomaly is assumed to be the extensive lateral cavity feature intersecting boreholes C2 and C3. No indication of the crosshole target cavity feature was detectable. Cooper (in preparation) concluded that the crosshole resistivity method was not able to detect features other than those intersecting the borehole. Thus, it must be concluded that the crosshole resistivity technique, as conducted by LLNL, would not be well suited for tunnel detection. Alternative electrode configurations as suggested by Cooper may offer more positive results.

Passive Techniques

CONOCO seismic location system

124. Figures 25, 26, 27, and 28 show examples of computer printouts (which are logged practically every day) superimposed on a map of the mine system. Figure 25 shows activity which is thought to be associated with a fault in the mine which has been activated by hydrofracturing in an effort to promote the release of methane gases

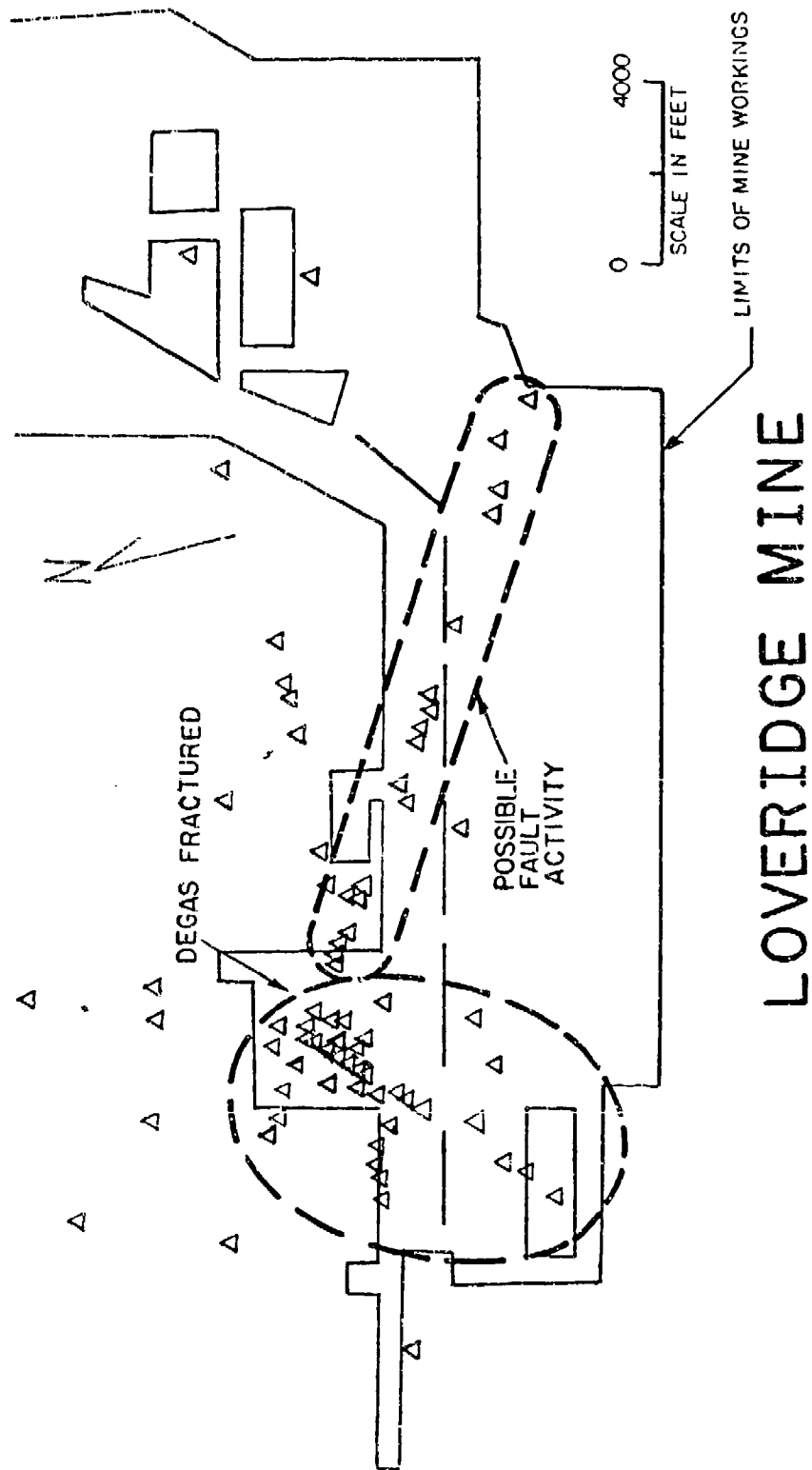


Figure 25. Computer printout of seismic events located by CONOCO triangulation system
(note fault activity stimulated by hydrofracturing)

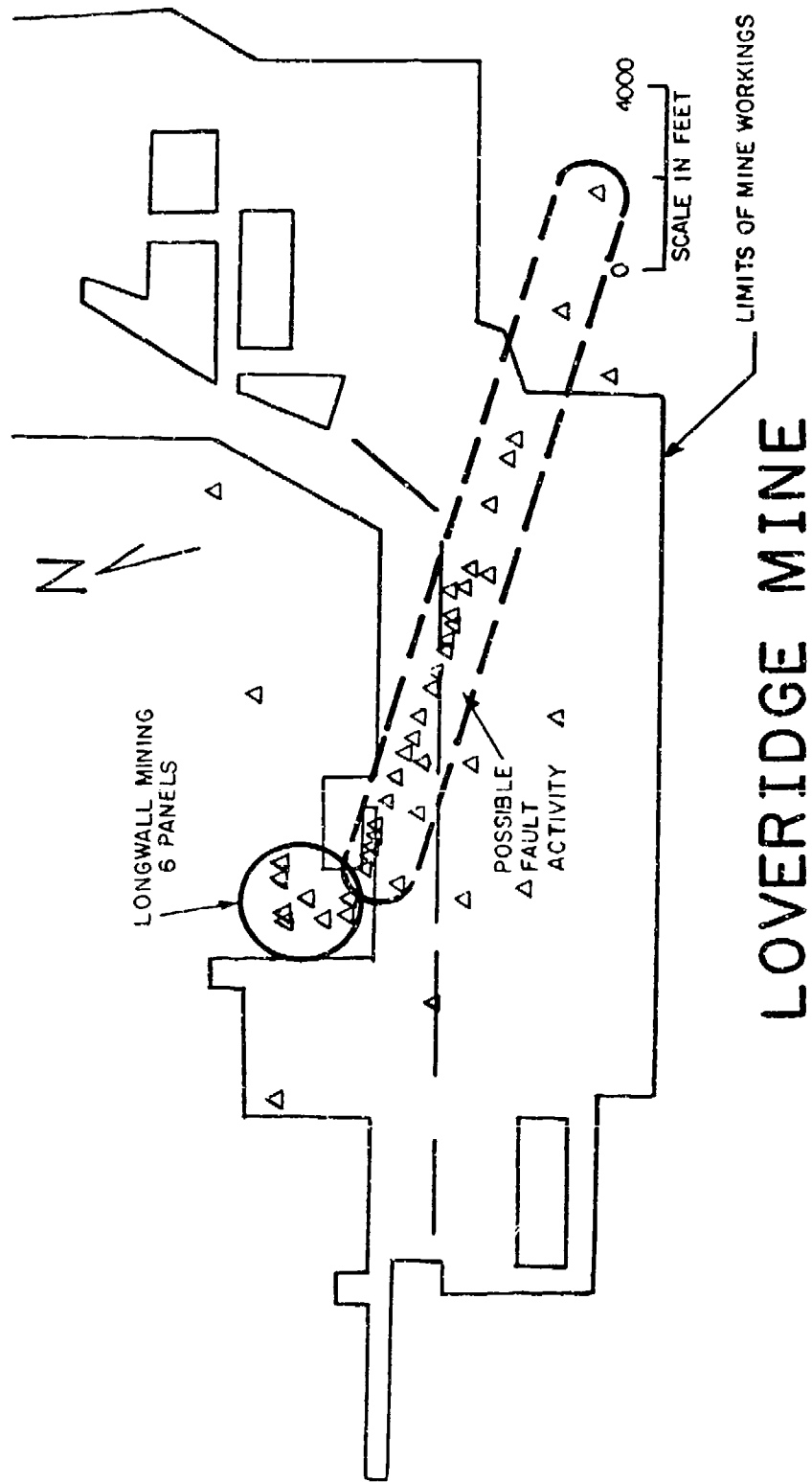


Figure 26. Computer printout of seismic events located by CONOCO triangulation system

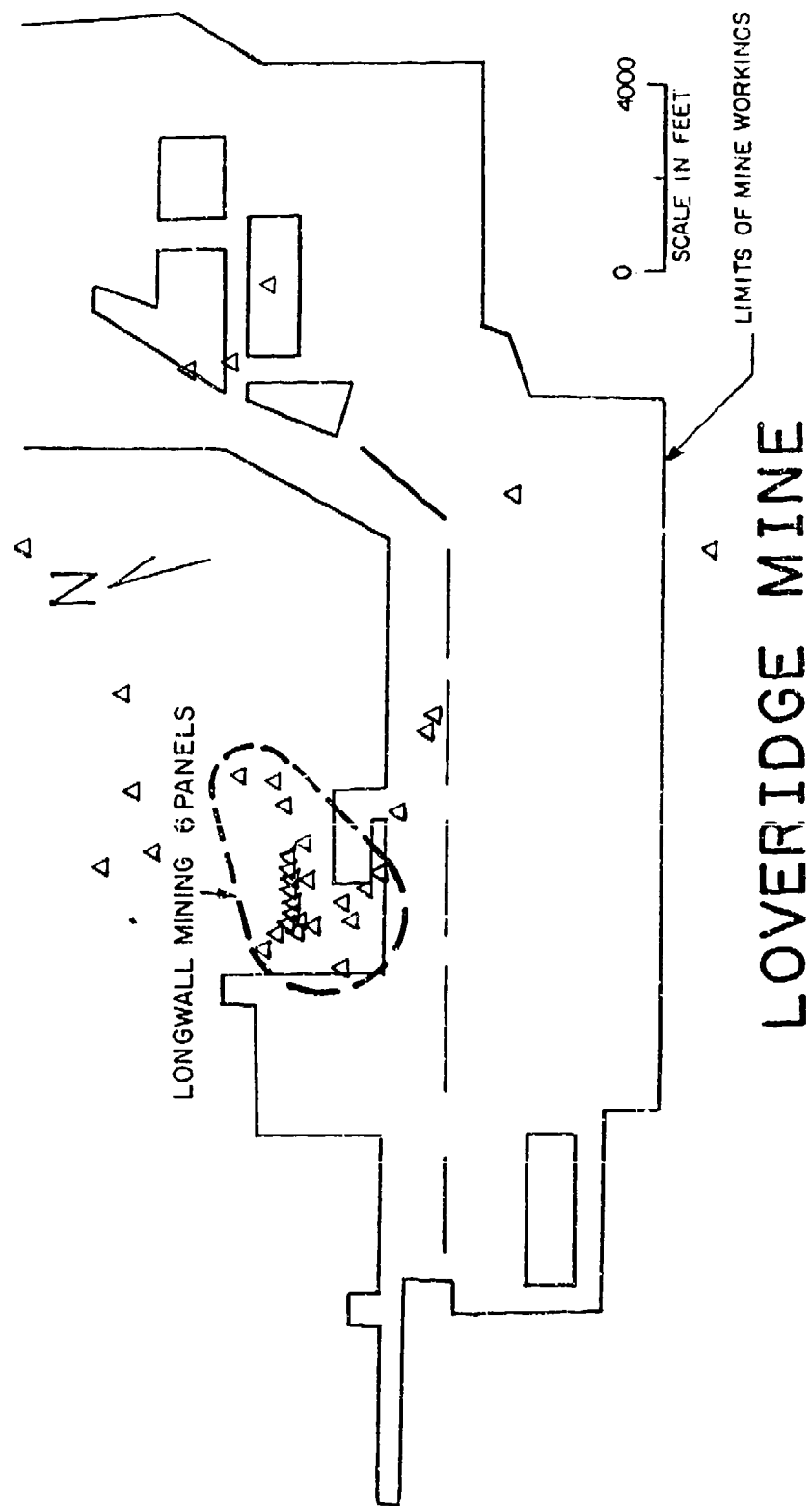


Figure 27. Computer printout of seismic events located by CONOCO triangulation system

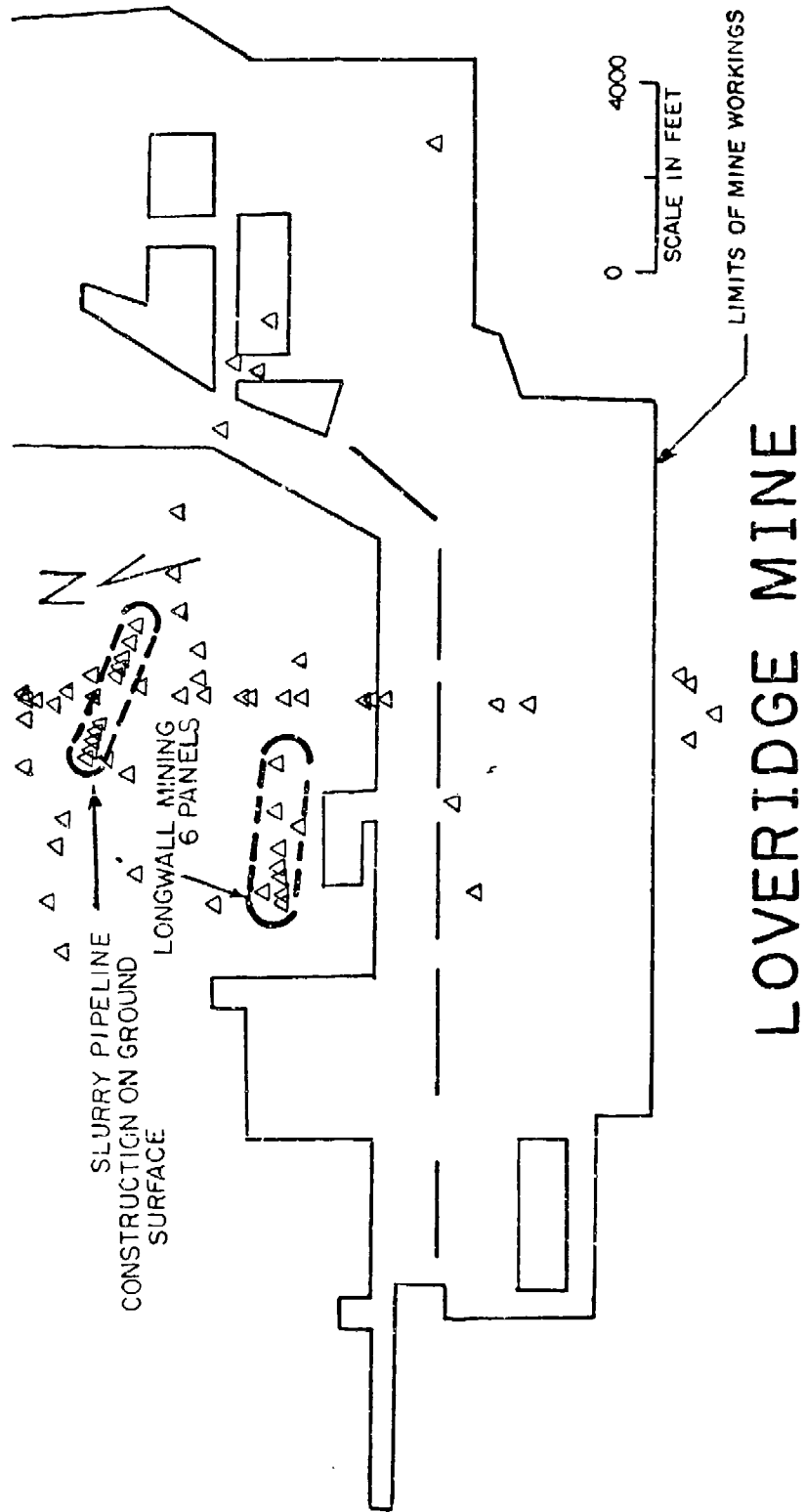


Figure 28. Computer printout of seismic events located by CONOCO triangulation system

from certain zones. Seismic movements caused by the fracturing process are shown in precise detail. Another example (Figure 26) pinpoints "long-wall" six-panel mining process activity and a continuation of fault activity on one particular day. Data depicted in Figure 27 were recorded several days later than that shown in Figure 26. Note the long-wall mining progress. The plots showing fault activity are similar to data which would be expected from a tunneling operation, i.e., straightline progression. Surface activity was also detected and an example is shown where a slurry pipeline was being placed above the mine and its installation tracked by the seismic system (Figure 28). Figure 29 is a photograph of the microprocessor key board and recording system, and Figure 30 is a photograph of the microprocessor and CRT display.

125. In summary, the system's simplicity and outstanding record of reliability is impressive. It is particularly encouraging to note that during the life span of this system none of the buried geophones have required maintenance or replacement. The operational seismic monitoring system installed at Loveridge Mine is readily adaptable, with minor modification, for military and even for some civilian applications.

MSHA seismic location system

126. Seven seismic stations were deployed by MSHA and their coordinates established by survey at the Island Creek Hamilton No. 1 Coal Mine near Waverly, Ky. Each station consisted of a subarray of seven vertical geophones whose output was summed as previously described. In this experiment, the extreme length of the seismic array pattern was slightly less than 2000 ft and the extreme width approximately 1200 ft.

127. A number of different tests were conducted. In one instance, crew members were dispatched into the mine workings some 600 ft below the ground surface. Communication was established by telephone contact and the men were instructed to pound on the roof, roof bolts, wall, floor, or rails using a heavy timber. Comparisons were then made of the amplitude and signature of the received signal. In almost all cases, impulses originating on a roof bolt were considerably

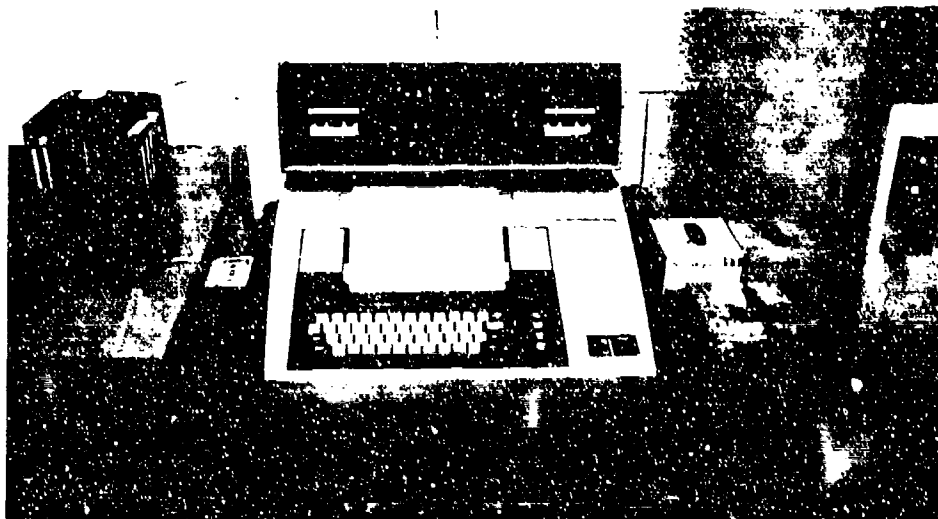


Figure 29. CONOCO seismic location system microprocessor keyboard

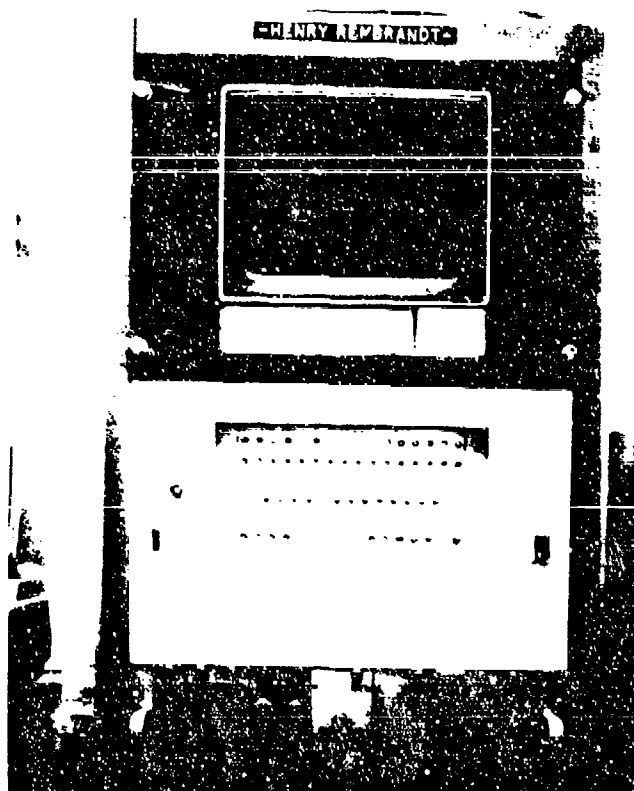


Figure 30. CONOCO seismic location system microprocessor and CRT display

better than those at any other location. These tests showed that the system was operative.

128. A second test was designed to demonstrate the sensitivity and accuracy of the system. This was accomplished by having the underground team pretend to be lost miners. In so doing, the team members pounded on the roof bolt at a location of their own choosing but unknown to the surface team. In less than 15 minutes, the signals received from the "lost miners" had been recorded, processed, and coordinates established for a simulated rescue. After the coordinates had been established, the underground team revealed their location. The seismic system proved to be accurate within 80 ft of the known location.

129. This demonstration was performed without the benefit of a surface refraction seismic survey which is normally performed at each of the substations within the array to establish the overburden velocity and its depth. The refraction seismic survey was later conducted and correction factors applied. This resulted in a location accuracy to within 50 ft of the known location.

130. Other tests were conducted using horizontal geophones in place of the vertical, a second array configuration, and the comparison of a subarray cluster of several geophones as opposed to a single vertical geophone. The effectiveness of the cluster versus the single geophone was amply demonstrated by the improved signal-to-noise ratio when a small charge was detonated in a 5-ft-deep hole approximately 1500 ft from the array.

131. While the MSHA seismic location system was not constructed to detect clandestine tunneling activity, it would appear that with only minor modifications, it could be optimized for that application. Based upon results obtained at the Island Creek No. 1 Coal Mine, the seismic triangulation technique must be considered as a viable approach in locating tunneling operations when active seismic noise is being generated within the tunnel. The concept will be addressed in the following section (Part IV).

PART IV: DISCUSSION

132. The following discussion is predicated on the premise that personnel in a forward military area suspect clandestine tunneling activity and seek to determine its location. Presumably, the method of attack would be to perform a reconnaissance survey using surface geophysical techniques comparable with site characteristics such as geology, topography, and access to the area in question. Six methods are deemed suitable for this purpose. The highest probability of tunnel detection will be achieved by using as many of the methods as possible. Each will be discussed with regard to deployment of the method, its advantages, limitations, and possible enemy countermeasures which could be used to disrupt the survey. Table 1 can be used to compare surface methods when deployed under the same set of circumstances.

133. After conduct of the reconnaissance survey, a high-resolution survey should be performed in questionable areas located by the reconnaissance operation. All of the acceptable high-resolution methods, with the exception of the pole-dipole electrical resistivity technique, require the use of boreholes. Comparisons of these methods are presented in Table 2.

134. In addition to the geophysical search methods proposed for reconnaissance and high-resolution surveys, the location of clandestine tunneling activity can be detected using a passive technique consisting of a permanent seismic surveillance system supplemented by a portable system designed for deployment in the immediate area where signs of activity have been detected by the permanent system. Exploitation of this concept will also be addressed.

Reconnaissance Survey

Conventional seismic refraction

135. Deployment. In an area where tunneling activity is suspected, a surface seismic refraction survey should be conducted in a grid line fashion, i.e., several traverses parallel to each other

supplemented by an equal number of traverses at right angles and overlaying the first series of traverses. The length of each line should be approximately four times the desired depth of investigation and geophone spacing should not exceed 25 ft (10-ft spacing would be preferable if practical). A high-intensity seismic source should be used to generate a good signal-to-noise ratio producing well-defined arrival times. Data should be analyzed to define velocities and refracting layers so that departures from the norm will be apparent in the form of delayed travel times at certain detectors.

136. Advantages. Multiple-channel seismic refraction equipment is readily available and field procedures are well established. Data interpretation is also straightforward. If a minicomputer is used, analysis can be accomplished on the spot. The conventional seismic refraction method will prove to be the most useful where tunneling activity is suspected in soil materials. Soils having characteristically low velocities will exhibit more pronounced delays in arrival times (compared to rock) when a tunnel is present.

137. Limitations. The conventional seismic refraction method could not be expected to directly detect a tunnel existing below the top of a refracting horizon. The degree of arrival time resolution available with most seismographs is generally less than 0.5 msec. If tests are being conducted in a high-velocity material such as competent rock, delays caused by a 10-ft-diam tunnel would probably be on the order of 1 msec or less. Otherwise stated, the degree of resolution is inversely related to increasing velocity. In many instances, it is conceivable that normal bounds of data interpretation would mask the presence of such a tunnel.

138. Enemy countermeasures. The most likely enemy countermeasures taken to prevent acquisition of high-quality seismic refraction data would be the creation of high-level seismic noise which would tend to degrade the determination of first-arrival times.

Seismic refracted wave form

139. Deployment. The seismic refracted wave form method should be deployed only when tunneling activity is expected to be at a depth of

less than 50 ft and when poor-quality rock or soil materials are present. Since the method uses a single-channel seismograph and sledgehammer or drop weight as a seismic source, it can be mobilized very quickly and data interpretation made on site. If shallow tunneling activity is suspected, the seismic refracted wave form method should be used prior to the conventional seismic refraction survey. Tests should be conducted along parallel lines where activity is suspected using a spacing between seismic source and receiver equal to four times the desired depth of investigation. The existence of suspected tunneling will appear as delayed times and alternations in the seismic signature. Most apparent signature changes will be loss of high frequency data and a decrease in signal amplitude.

140. Advantages. The seismic refracted wave form test requires only the simplest form of seismic refraction equipment, that is, a single-channel seismograph and a sledgehammer or drop weight to be used as the seismic source. Once the field team has been trained in conduct of the test, the interpreter should develop a "feel" for the data and immediately recognize anomalous signals.

141. Limitations. Near-surface geologic and stratigraphic changes can affect the seismic wave form. Presence of a tunnel could be masked or confused by such changes. The method is also depth-limited to a maximum of about 50 ft because of its low-energy seismic source.

142. Enemy countermeasures. Conceivably, the enemy countermeasures would be the same used against the conventional surface seismic refraction test.

Seismic refraction fan-shooting

143. Deployment. Optimum use of the seismic refraction fan-shooting method will be realized by conducting the survey along a single straight line in the area of interest. The geophones should be placed in an arc all equidistant from the seismic source. They should be positioned no more than 25 ft apart and at a distance (from the source) equal to four times the desired depth of investigation. Preferable seismic sources would be a large drop weight or an explosive charge. Two sets of data should be obtained at each point--one using high

amplification to optimize first-arrival breaks and the other using low amplification to capture the signature of the entire wave train at each geophone. By so doing, the data can be analyzed from the standpoint of delayed times and by noting characteristic changes in signature similar to the approach used when performing the seismic refracted wave form test.

144. Advantages. The basic advantage of the refraction fan-shooting method is its rapid coverage of a broad areal expanse.

145. Limitations. Localized near-surface conditions can also affect arrival times and alter seismic signatures in the manner described for the refracted wave form test.

146. Enemy countermeasures. The same enemy countermeasures used against the conventional seismic refraction method would also be applicable for fan-shooting.

Electrical resistivity

147. Deployment. During the conduct of a reconnaissance survey, electrical resistivity tests should be performed in the profiling mode along an established grid system similar to that described for the conventional surface seismic refraction. A desirable electrode spacing would be equal to about twice the desired depth of investigation. It should be recognized, however, that this is a basic "rule of thumb." A better estimate of effective survey depth can be obtained from vertical soundings at locations where geological information from other sources might be available if time permits. Also, the spacing between resistivity stations should be smaller than the width of the smallest feature to be detected. Quick looks at the field data should be performed so that anomalous conditions such as extremely low resistivities can be investigated in more detail.

148. Advantages. Resistivity equipment is readily available and inexpensive. A resistivity survey is quite rapid if a field team of three men is employed using a spacing between stations equal to the electrode spacing. In this case, only the rearmost electrode need be moved in preparation for succeeding tests. Data interpretation is straightforward.

149. Limitations. Large resistivity changes or complex geology of the host material may mask the presence of a tunnel. Resolution of the technique diminishes with increasing depth.

150. Enemy countermeasures. Any surface electrical technique could be hampered by enemy induction of sporadic electrical currents or by placing metallic objects in the ground or on the ground surface.

Ground-probing radar

151. Deployment. By far, the fastest of the geophysical reconnaissance methods for tunnel detection is the ground-probing radar. If terrain will accommodate vehicular traffic, the transmitting and receiving antennas should be towed at a speed of approximately 2 mph in a grid pattern traversing the entire area where suspected tunnel activity is occurring. Data should be displayed in variable-density (shades of gray) chart format. If suspicious reflections are noted, the antenna should be detached from the vehicle and pulled very slowly by hand over the area where the reflection was noted.

152. Advantages. Surface ground-probing radar has two primary advantages: (a) speed, and (b) near real-time data reduction and presentation.

153. Limitations. The depth of investigation by ground-probing radar is controlled by the dielectric constant and conductivity of the host material. It is extremely limited in depth if wet clays are present on site. Its resolution is directly proportional to increasing frequency, but high frequencies are normally rapidly absorbed.

154. Enemy countermeasures. One enemy countermeasure tactic could be accomplished by burying reflecting objects in the near-surface materials, thereby creating numerous false targets.

Microgravity

155. Deployment. The microgravity technique should be used only in areas where suspected tunneling activity is no more than 40 ft deep and where radical changes in topography do not exist. A search pattern can be established using a grid system of approximately 20 ft between points. Data should be analyzed on the basis of relatively low or negative gravity readings.

156. Advantages. Where relatively shallow tunnels are suspected and where the presence of the tunnel would drastically alter the density of the medium, the microgravity technique would prove to be extremely useful. Even though the survey should be carefully conducted, well-trained personnel can move quite rapidly.

157. Limitations. Interpretation is tedious and numerous terrain corrections must be made. Surface topography influences data and highly irregular bedrock surfaces could mask the presence of the tunnel.

158. Enemy countermeasures. As a countermeasure, the enemy could conceivably bury heavy metallic objects to influence microgravity readings or create high levels of seismic noise.

High-Resolution Survey

Crosshole radar

159. Deployment. Based upon the results of the reconnaissance survey, 4-in. inside-diameter borings should be placed no more than 100 ft apart along a line where tunneling activity is suspected. The borings should be at least 50 ft deeper than the elevation where tunneling activity is expected. Tests should be conducted by placing the transmitter in one boring and the receiver in an adjacent hole. Data should be acquired at 2-ft intervals, beginning at the bottom of the hole and proceeding toward the top. Signal amplitudes and arrival times should be observed for departures from the norm (both decreasing). If anomalous zones are observed, tests should be conducted with the transmitter and receiver at different elevations, approximately 10 ft apart. This skewed look at the target will aid in establishing the distance to the target and its geometric shape.

160. Advantages. Like the surface ground-probing radar test, the cross borehole radar application is also quite rapid and, provided transmission characteristics are good, the data interpretation is straightforward.

161. Limitations. The maximum distance between transmitter and receiver is controlled by the dielectric constant and conductivity of the host material. Resolution decreases in direct relation to frequency. The lower frequency limit to resolve a 10-ft-diam tunnel will be approximately 100 MHz.

162. Enemy countermeasures. No enemy countermeasures are known.
Seismic crosshole

163. Deployment. Placement of borings to conduct the seismic crosshole test would be identical to the crosshole radar described above except that borings should be no more than 50 ft apart. The seismic source should be placed in one boring near the bottom of the hole and multiple receivers located in adjacent borings at the same elevation to a maximum distance of 100 ft. The test procedure should also be the same as described above. Data should be analyzed on the basis of arrival times and wave train signatures. Delayed times in combination with decreased amplitudes and loss of high frequencies are indicators of the possible presence of a tunnel.

164. Limitations. The maximum distance between borings is primarily dictated by geology. Snell's laws of refraction must be applied to establish zoning. A repeatable seismic source should also be used.

165. Enemy countermeasures. Enemy countermeasures would likely take the form of artificially generated seismic noise.

Borehole microgravity

166. Deployment. The borehole microgravity instrument is deployed in a single borehole having a minimum diameter of 6 in. (The borings used for radar or seismic tests can be reamed to the larger diameter.) Based upon the results obtained to date, the boring sidewall would have to be located within 20 to 30 ft of the center line of a 10-ft-diam tunnel in order to be able to detect its presence (EDCON, 1982). Data should be obtained from the bottom of the hole working toward the top at intervals not exceeding 5 ft. Terrain corrections must be applied to the data before an analysis can be made. After correction, the presence of the tunnel should be apparent from the decrease

in natural gravitational field caused by the apparent density change in the material. If an anomaly is detected, additional borings should be placed in the 40-ft-diam pattern around the test borehole to locate the tunnel.

167. Advantages. The prime advantage of the borehole microgravity survey is the fact that only one boring is required to perform the survey. However, other borings will be needed to actually locate the tunnel.

168. Limitations. The equipment is delicate and costly. Interpretation is tedious and surface topography influences data. The maximum distance between the source borehole and the tunnel, whose presence is detectable, will be limited to about 30 ft. The coordinates of the tunnel cannot be established without additional borings.

169. Enemy countermeasures. The same countermeasures used against surface microgravity are possible.

Permanant Surveillance, Seismic Triangulation

Deployment

170. Deployment of a permanent seismic surveillance system in a forward area should be accomplished using a two-part approach. First, a series of seismic stations should be located no more than 5 miles apart along the perimeter of the forward area. Each station should consist of an array of approximately five (no less than three) triaxis geophones located near the soil-rock interface and, below that array, a second identical array located at some two times the depth of the suspected tunneling activity. By so doing, triangulation can be accomplished in three dimensions. Figure 31 illustrates the deployment concept. Using this concept, the permanent stations would monitor activity on a continuous basis. Secondly, a portable surface-deployed seismic triangulation system similar to the one developed by MSHA should be maintained as a backup. When suspected tunneling activity has been observed by the fixed permanent station and rough coordinates established, the portable system should then be deployed in the immediate target area to pinpoint the activity.

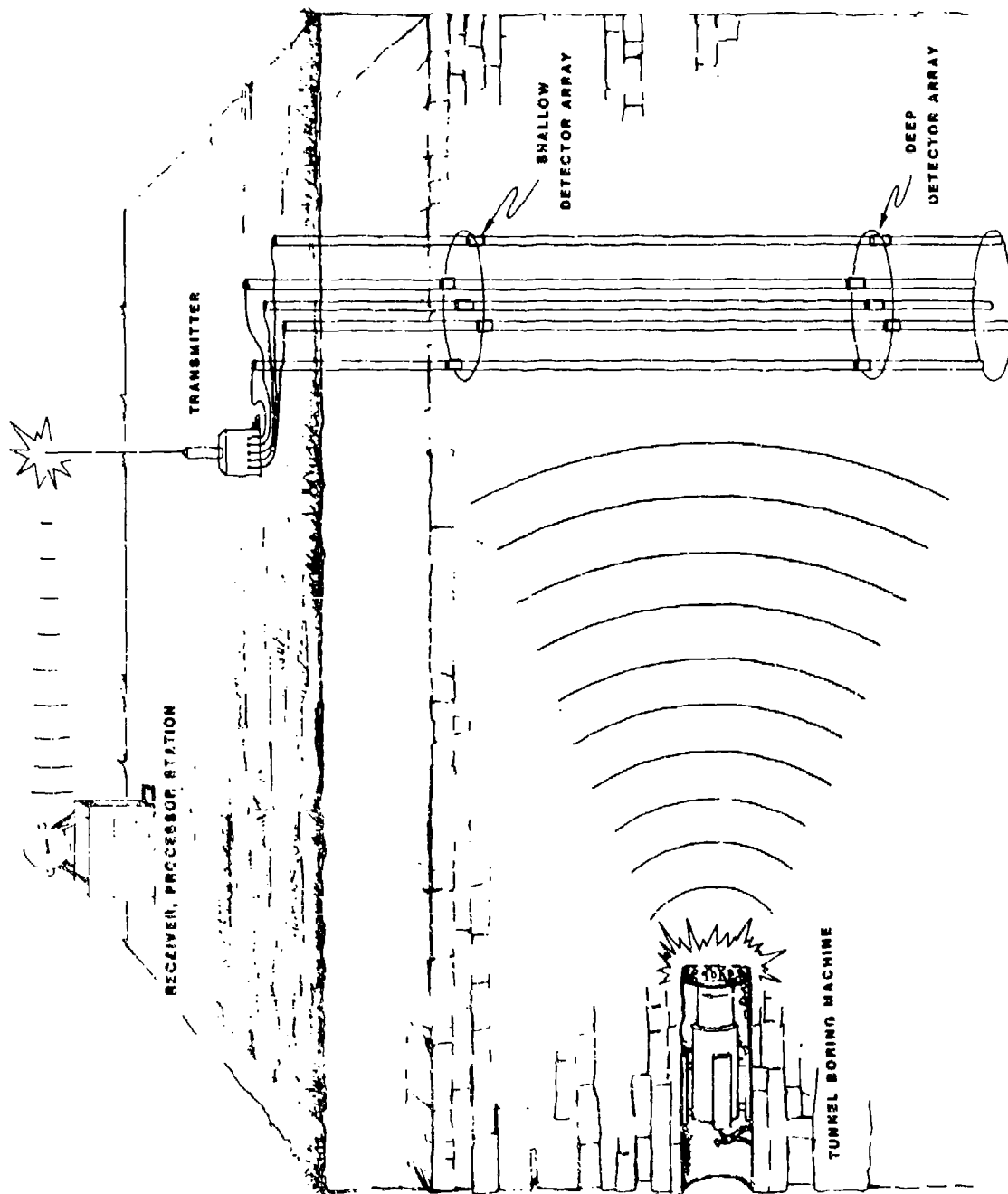


Figure 31. Three-dimensional seismic triangulation concept

Advantages

171. The advantages provided by seismic surveillance are:

(a) near real-time detection and location of subterranean activity, (b) a three-dimensional target location scheme, and (c) a determination of construction rate of progress.

Limitations

172. Seismic triangulation must rely upon activity generated from within the tunnel complex; i.e., if there is no activity, there will be no detection. The degree of location accuracy diminishes with increasing distance to the source. Continuous noise sources such as TBM's require more sophisticated data analysis (possible cross-correlation) which can result in a loss of accuracy.

Enemy countermeasures

173. In order to confuse a permanent seismic surveillance system, an opposing force might generate seismic activity at other locations to mask the tunneling operation. Additionally, low-flying aircraft might be used in an effort to generate an acoustically coupled high-intensity disturbance which would interfere with surface-deployed instruments. These countermeasures, although annoying, should not prove to be a long-term detriment to a permanent seismic surveillance system.

PART V: CONCLUSIONS

174. To some degree, many of the geophysical techniques evaluated could detect the presence of cavities. Recognizing that the complex mechanisms associated with the formation of natural cavities greatly influence a much larger zone than the cavity itself, it was more easily understood why some methods worked when theory based on an idealized model would have predicted otherwise. A tunneling operation, however, would not be expected to influence its host material more than two tunnel diameters away from its center line, making detection a bit more difficult.

175. In view of the fact that the relative success of a geophysical technique is highly site- and interpreter-dependent, it was determined that it would not be practical to rate the recommended methods in order of effectiveness. Rather, it was determined that quantitative and qualitative comparisons could be made between methods given the same set of circumstances. The following techniques, not in order of preference, were concluded to be best suited for reconnaissance surveys:

- o Surface ground-probing EM (radar) - Very rapid. Best suited for shallow investigations. Will not perform well on sites where clay is present.
- o Surface electrical resistivity (profiling and sounding) - Generally good performance under a variety of conditions. Well suited for deep investigations.
- o Seismic refracted wave form - Rapid, but limited to shallow (less than 50 ft) investigations.
- o Microgravimetry - Requires well-trained personnel. Best suited for smooth topography.
- o Conventional surface seismic refraction - Widely used for other purposes. Cannot directly detect cavity/tunnel below top of refracting layer.
- o Seismic refraction fan-shooting - Broad areal coverage of the site. Delayed times readily apparent, though sometimes caused by near-surface conditions.

176. It was further concluded that those geophysical methods best suited for a detailed or high-resolution survey were as follows:

- o Crosshole radar - Excellent results when used at sites having favorable dielectric characteristics.

- o Pole-dipole electrical resistivity - Good results but specialized interpretation is involved and slow.
- o Crosshole seismic - Good results if repeatable source is used.
- o Borehole microgravimetry - Equipment delicate and costly. Data interpretation is tedious. Effective in locating tunnels within a radius no more than four times the tunnel diameter from the borehole.

177. It was also concluded that tunneling activity can be detected using passive seismic triangulation techniques. The permanent system installed by CONOCO in West Virginia was capable of locating sub-surface mining activity over a 15-square-mile area within less than 250 ft. Likewise, the MSHA portable system demonstrated an accuracy of 50 ft when deployed over simulated "trapped miners" 600 ft deep at a site in Kentucky. Enemy countermeasures would likely be directed toward the generation of seismic noise designed to mask tunneling operations. Although this could affect accuracy, a long-term seismic surveillance operation would still prove to be effective by concentrating on data that plots in a straight line.

PART VI: RECOMMENDATIONS

178. It is recommended that technological improvements in existing or newly developed techniques, such as borehole microgravity, crosshole resistivity, and induced random seismic spectra, be monitored.

179. While the MSHA seismic detection system was not constructed to detect clandestine activity in a forward military area, with only minor modifications it could be optimized for that application. In its present configuration, the MSHA system should be duplicated with some modifications. Its estimated cost (with modifications) will approach \$350,000 (FY 82 dollars).

180. Considering tunneling problems in forward areas, the following approach is recommended as a viable tunneling detection scheme. Deploy several permanent seismic stations, locating geophones in an antenna-like array within the bedrock at two depths, near the soil-rock interface and at a depth directly below that array some two times the depth of suspected tunneling activity, as illustrated in Figure 31. By so doing, triangulation can be accomplished in three dimensions. Using this concept, the permanent stations would monitor activity on a continuous basis. When suspected tunneling activity has been observed and rough coordinates established, a system similar to that of the MSHA's would then be deployed in the immediate target area to pinpoint the activity.

181. Those tunnels which are already in existence require maintenance. Personnel traffic, carts, and possibly roof falls are all potential seismic sources. It is entirely likely that their location could also be established.

182. It is also recommended that further tests be carried out using the MSHA system to determine the system's strong points and limitations regarding the detection of boring machines, drilling, blasting, effects of countermeasures, etc.

183. Finally, it is recommended that a site within CONUS where a tunneling operation is just beginning be instrumented to evaluate the advantages and limitations of the three-dimensional triangulation concept.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

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Tunnel detection / by Robert F. Ballard, Jr. (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. ; available from NTIS, 1982.

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"Prepared for Office, Chief of Engineers, U.S. Army under Project No. 4A762719AT40, Task CO, Work Unit 007."

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