UNIVERSITY OF CALIFORNIA, BERKELEY

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO | SANTA BARBARA • SANTA CRUZ

SEISMOGRAPHIC STATION
DEPARTMENT OF GEOLOGY AND GEOPHYSICS

BERKELEY, CALIFORNIA 94720

01 October 1979

Director, ARPA
1400 Wilson Boulevard
Arlington, Virginia 22209

Attn: Program Management

TECHNICAL REPORTS 1 - 4, 01 Oct 1978 - 30 Sep 1979

ARPA Order No. 3291-21
Program Code 9F10
Grantee: The Regents of the University of California
Effective Date of Grant: 01 October 1978
Grant Termination Date: 30 September 1980
Amount of Grant: $102,520
Grant No. AFOSR-F49620-79-C-0028
Principal Investigators: T. V. McEvilly (415)642-4494
L. R. Johnson (415)642-1275
Program Manager: William J. Best (202)693-0162

Short Title of Work: BROADBAND DISCRIMINATION STUDIES

T. V. McEvilly

L. R. Johnson

Sponsored by
Advanced Research Projects Agency (DOD)
ARPA Order No. 3291
Monitored by AFOSR Under Contract No. F49620-79-C-0028

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER Technical Reports 1-4	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Broadband Discrimination Studies	5. TYPE OF REPORT & PERIOD COVERED Technical Reports 1-4 01 Oct 1978-30 Sep 1979
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) T. V. McEvilly L. R. Johnson	8. CONTRACT OR GRANT NUMBER(s) AFOSR-F49620-79-C-0028
9. PERFORMING ORGANIZATION NAME AND ADDRESS Seismographic Station University of California Berkeley, California 94720	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AO 3291-21 9D60 61101E
11. CONTROLLING OFFICE NAME AND ADDRESS ARPA 1400 Wilson Boulevard Arlington, Virginia 22209	12. REPORT DATE 01 Oct 1979
	13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) AFOSR Bolling Air Force Base Washington, D.C. 20332	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

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

discrimination
explosion
elastic waves
seismology
array

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Current studies of the manner in which elastic waves are generated by buried explosions, such as the moment tensor approach, require high-quality broadband ground motion data. In order to obtain such data at distances of a few kilometers from the source, a method or recording the ground motion with force-balance accelerometers and triggered event recorders has been developed and tested. The two NTS events EMMENTHAL and FARM -

DD FORM 1 JAN 73 1473

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. continued

were recorded in the distance range 0.5 - 10 km. A few problems with the method were identified and corrected, and it now appears to be an excellent method of acquiring data from NTS explosions at small distances.

The data recorded from EMMENTHAL and FARM illustrate quite clearly a phenomenon that has been observed on records of previous events but still not very well understood. This is the matter of significant energy on the transverse component of motion, some of it arriving at the time of the P wave. This appears to be an important problem worthy of further study. Its resolution could affect the interpretation of the phases that appear on the radial and vertical components of motion.

A number of specific experiments have been outlined which have the purpose of gathering critical data capable of providing answers to some remaining questions about the generation and propagation of elastic waves from underground explosions. These include making better measurements of the low-frequency part of the ground motion at small distances, studying the generation of the transverse component of motion from explosions with a small array, obtaining more data which can be used to estimate the moment tensor of explosive sources, and testing the utility of a small array at regional distances.

The response of a small array having seven elements and a maximum dimension of about 1 km has been examined with respect to its ability to aid in the interpretation of phases recorded at small to regional distances. The results show that such an array could be designed with a resolution in wavenember sufficient to separate P and S phases and with no significant spatial aliasing problems. Sources within such an array could possibly be located with an uncertainty of a few tens of meters.

TABLE OF CONTENTS

I. SUMMARY

Current studies of the manner in which elastic waves are generated by buried explosions, such as the moment tensor approach, require high-quality broadband ground motion data. In order to obtain such data at distances of a few kilometers from the source, a method of recording the ground motion with force-balance accelerometers and triggered event recorders has been developed and tested. The two NTS events EMMENTHAL and FARM were recorded in the distance range 0.5 - 10 km. A few problems with the method were identified and corrected, and it now appears to be an excellent method of acquiring data from NTS explosions at small distances.

The data recorded from EMMENTHAL and FARM illustrate quite clearly a phenomenon that has been observed on records of previous events but still not very well understood. This is the matter of significant energy on the transverse component of motion, some of it arriving at the time of the P wave. This appears to be an important problem worthy of further study. Its resolution could affect the interpretation of the phases that appear on the radial and vertical components of motion.

A number of specific experiments have been outlined which have the purpose of gathering critical data capable of providing answers to some remaining questions about the generation and propagation of elastic waves from underground explosions. These include making better measurements of the low-frequency part of the ground motion at small distances, studying the generation of the transverse component of motion from

explosions with a small array, obtaining more data which can be used to estimate the moment tensor of explosive sources, and testing the utility of a small array at regional distances.

The response of a small array having seven elements and a maximum dimension of about 1 km has been examined with respect to its ability to aid in the interpretation of phases recorded at small to regional distances. The results show that such an array could be designed with a resolution in wavenumber sufficient to separate P and S phases and with no significant spatial aliasing problems. Sources within such an array could possibly be located with an uncertainty of a few tens of meters.

II. RECORDING OF NTS EXPLOSIONS AT SMALL DISTANCES

The manner in which elastic waves are generated by buried explosions is still not completely understood. One part of the research supported by this grant has been to estimate the first-order moment tensor for explosive sources and to ascertain if this approach provides a useful means of characterizing explosive sources. The method has already been applied to existing data recorded at small distances from the explosions HANDLEY, JORUM, and PIPKIN, and the results were encouraging. These initial experiments also served to point out how experiments could be designed so as to allow the best determination of the moment tensor.

The next logical step in the research was to apply the method to data from more explosions. An attempt was thus made to record data at small distances from two more buried explosions at the Nevada Test Site in late 1978. The two explosions were

EMMENTHAL

Origin time: 15h 25m 0.00s 02 Nov 1978

Location: 37.287N 116.296W

Magnitude: 4.3 M_L BRK

FARM

Origin time: 15h 30m 0.00s 16 Dec 1978

Location: 37.273N 116.409W

Magnitude: 5.5 M_L BRK

Both explosions were in the Pahute Mesa region of Nevada Test Site.

The recording network consisted of seven stations of three-component accelerometers. The accelerometers (which were the same ones used in the AFOSR Near Field Experiment in Bear Valley, California) were the force-balance type with corner frequencies in excess of 100 Hz. The sensors were buried in the soil between 1 and 2 feet below the surface. The recording system consisted of Sprengnether DR-100 digital event recorders which were borrowed from the Lawrence Berkely Laboratory (DOE) for these experiments. These recorders were operated in a triggered mode and 12-bit digital samples were acquired at a rate of 200 samples per second on each channel. A single automobile battery was sufficient to provide the power for a station for about one week.

The network used in these experiments had several advantages over the systems with FM telemetry and analog tape recorders which had been used to record several previous NTS events. These include the speed and ease of installation and the increased dynamic range. However, switching to this new mode of operation meant that new experience had to be acquired concerning such matters as proper settings for trigger levels and amplifier gains, accuracy of timing, effects of noise, and operation of digital cassetts in unusually hot or cold weather.

A data analysis system had to be developed for the new mode of operation. This turned out to be fairly straightforward. An input channel was constructed for the minicomputer in the Seismographic Station so that data recorded on digital cassetts in the field can be simply transferred to the core of the minicomputer and from there to disk or digital magnetic tape. The necessary software was also developed so that the data analysis procedure for data acquired on digital cassetts is now much more efficient than the previous system where data was acquired on analog magnetic tape. The fact that the data are digitized in the field at the seismometer also means that the new system produces more accurate data with a greater dynamic range than the previous system.

Figure 1 and Table 1 give the station locations and other information for the EMMENTHAL event. The acceleration records of the four stations which operated properly are shown in Figures 2, 3, and 4. Unfortunately, the intensity of the ground motion was underestimated for this overburied event and all of the records were clipped. Thus the maximum accelerations listed in Table 1 are actually lower bounds on the maximum accelerations.

Figure 5 and Table 2 give the station locations and other information for the FARM event. The acceleration records of the four stations which operated properly are shown in Figures 6, 7, and 8. In the process of analyzing these data it was discovered that the input amplifier of the digital recorder was overloading the output of the accelerometers, and this caused a slight nonlineararity at large values of acceleration.

The two primary purposes of these experiments were to test the method of recording NTS explosions with triggered event recorders and to obtain useful seismological data at the same time. The first purpose was successfully achieved and valuable experience was obtained. Problems which caused loss of data during the recording of these two events have all been identified and hopefully solved. The digital event

Table 1. Network data for EMMENTHAL

Station	Epicentral Distance (km)	Azimuth (deg E of N)	Elevation (km)	Velocity of first arrival (km/sec)	Maximum Accelerations			Notes on Operation
					Z	R	T	
E1	3.03	175	2.073					Electronics in recorder failed.
E2	1.32	197	2.127					False triggers. Tape ran out.
E3	0.80	203	2.140	1.19	0.20g	0.13g	0.13g	All channels clipped.
E4	0.57	234	2.134	1.11	0.20g	0.13g	0.13g	All channels clipped.
E5	0.37	272	2.127					Bad trigger electronics.
E6	0.74	297	2.140	1.19	0.20g	0.13g	0.13g	All channels clipped.
E7	1.74	353	2.085	2.03	0.10g	0.07g	0.07g	All channels clipped.

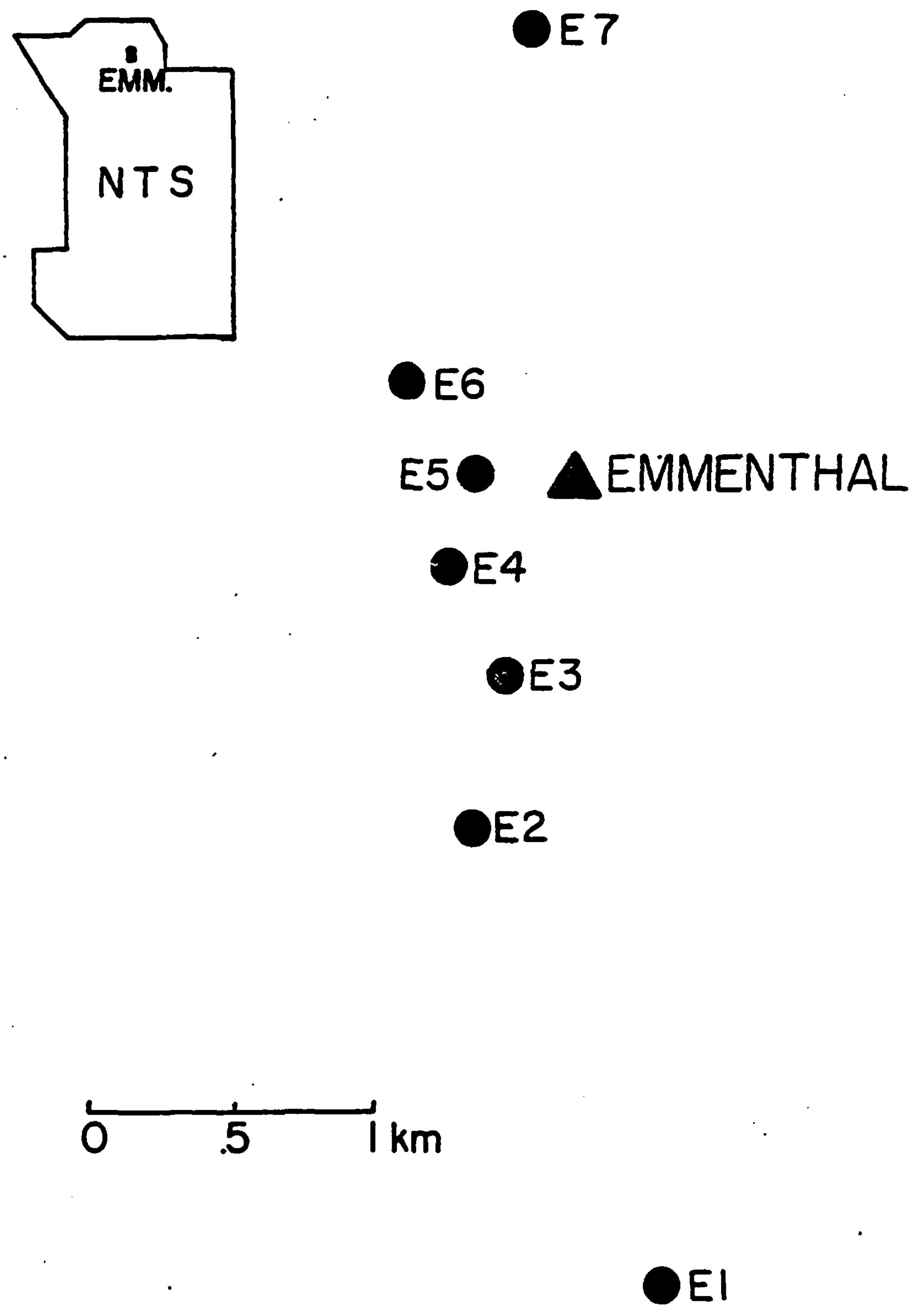

Figure 1. Location of recording sites for the explosion EMMENTHAL.

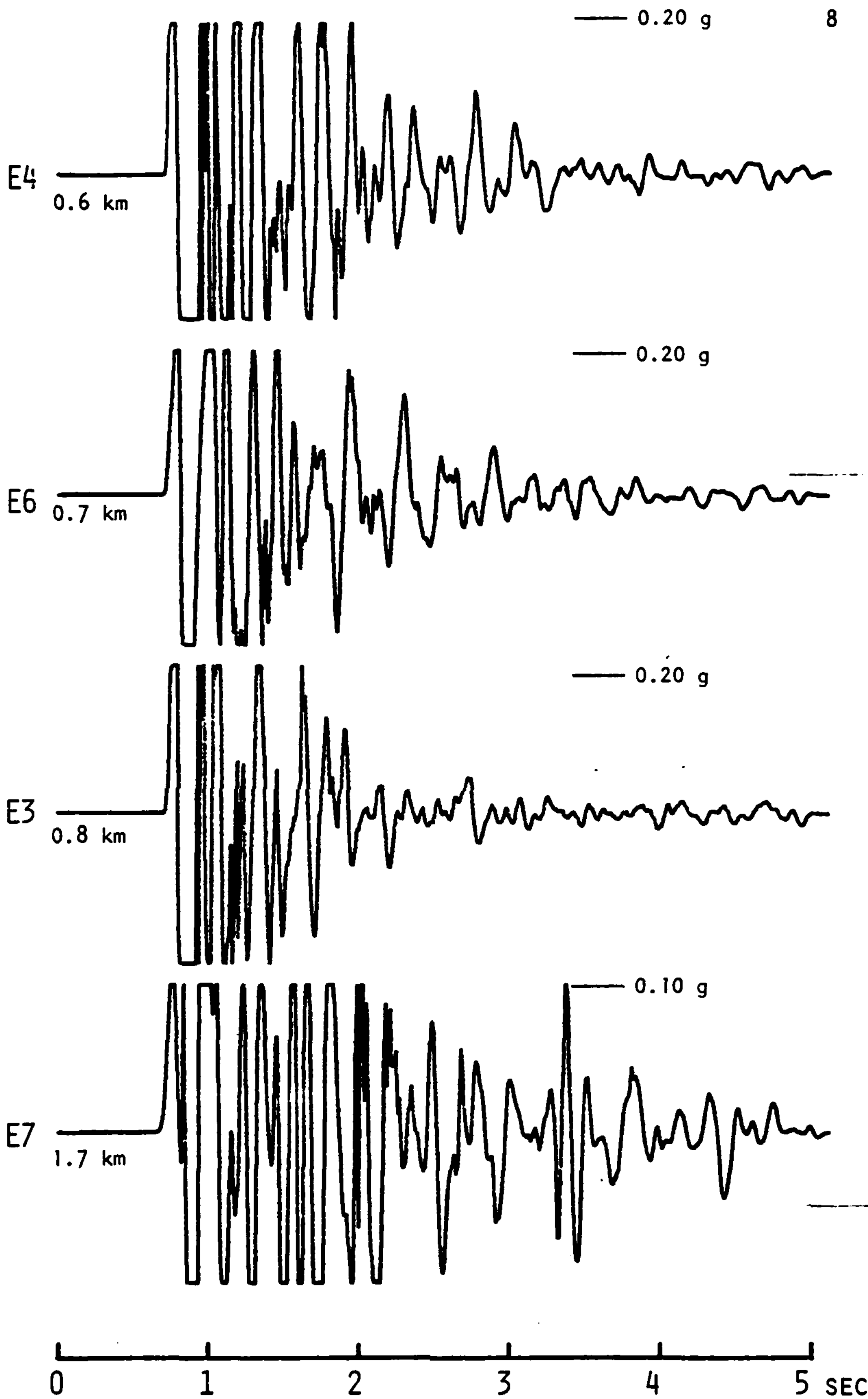

Figure 2. Vertical components of acceleration recorded from the explosion EMMENTHAL.

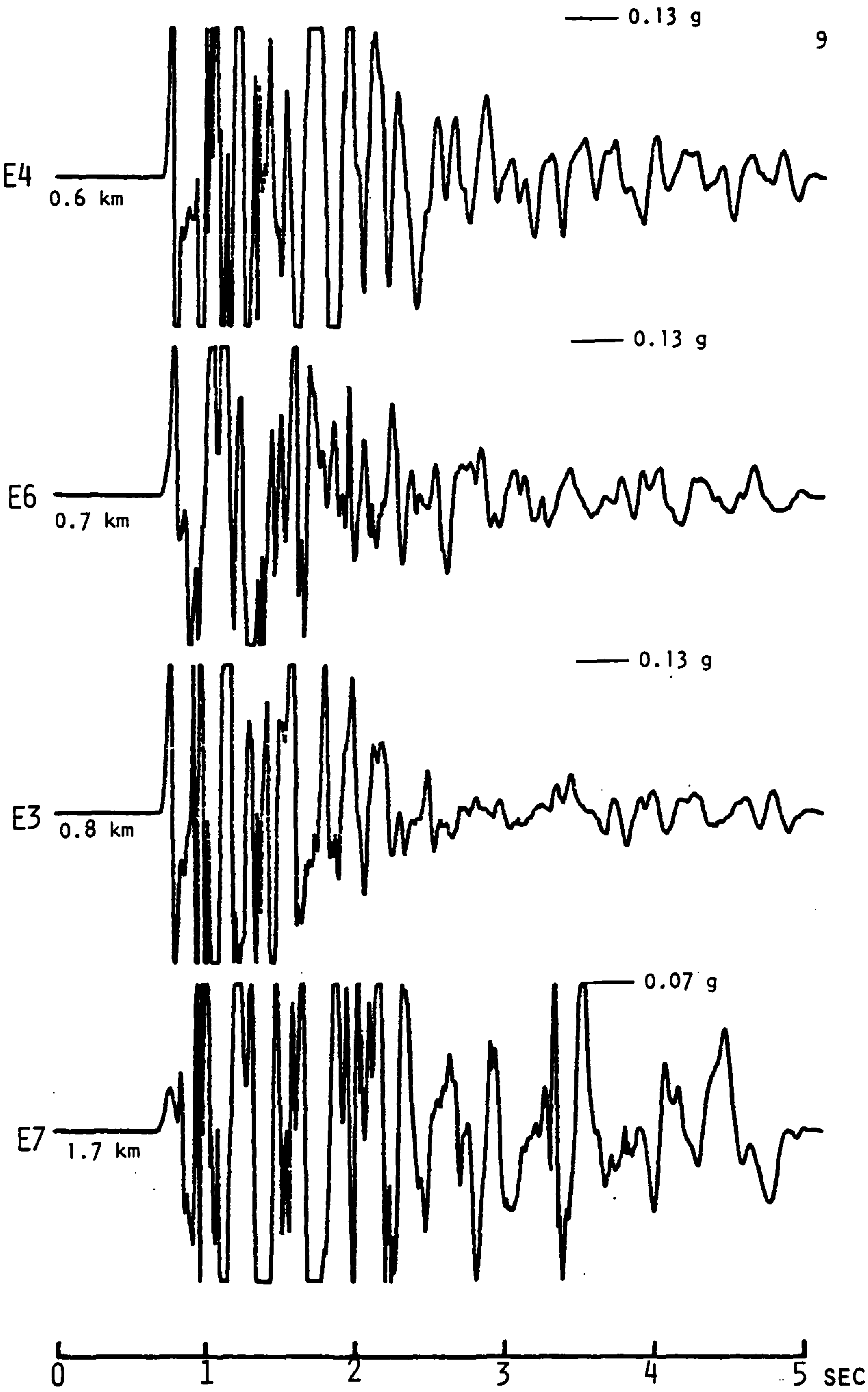

Figure 3. Radial components of acceleration recorded from the explosion EMMENTHAL.

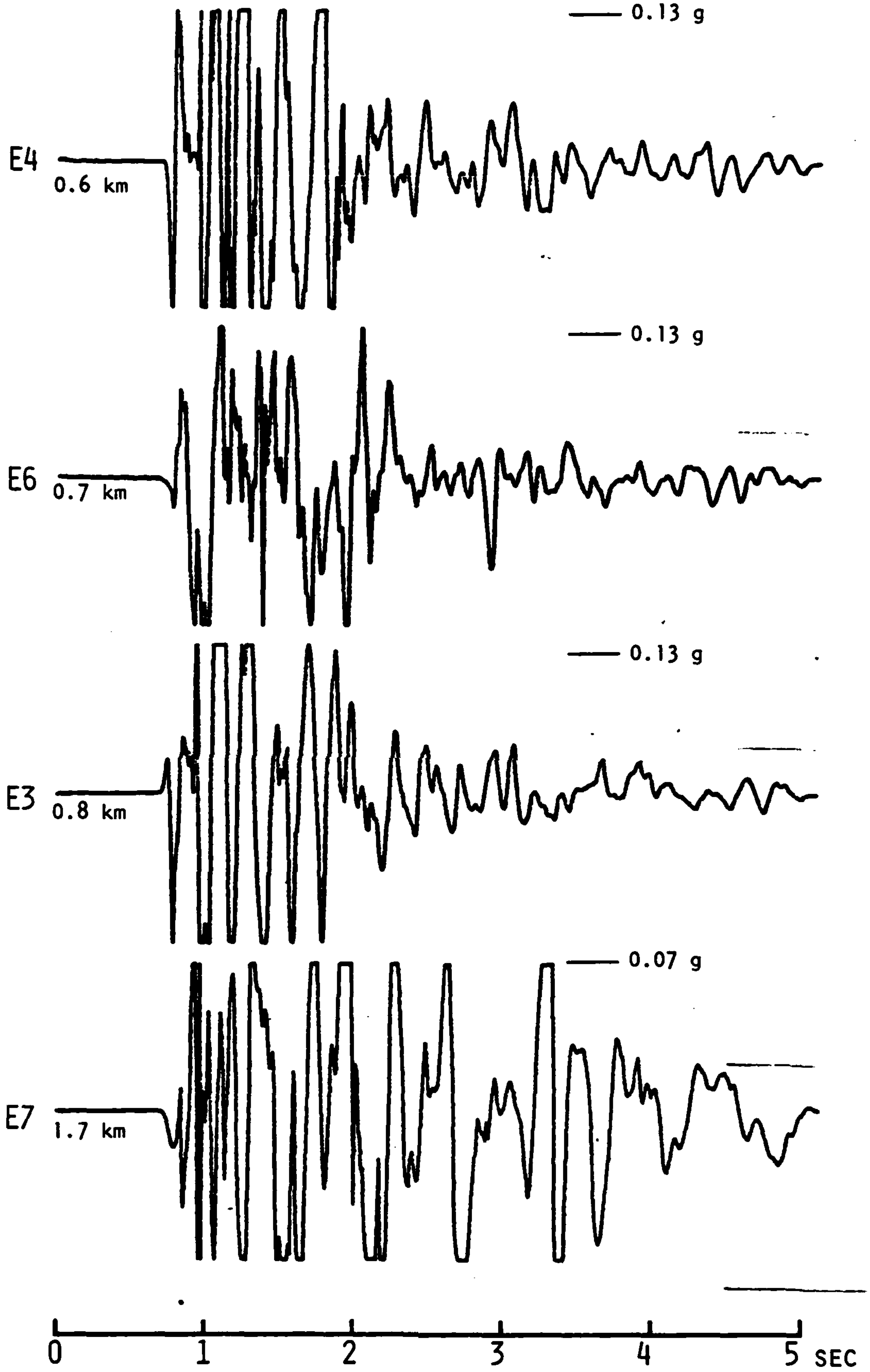

Figure 4. Transverse components of acceleration recorded from the explosion EMMENTHAL.

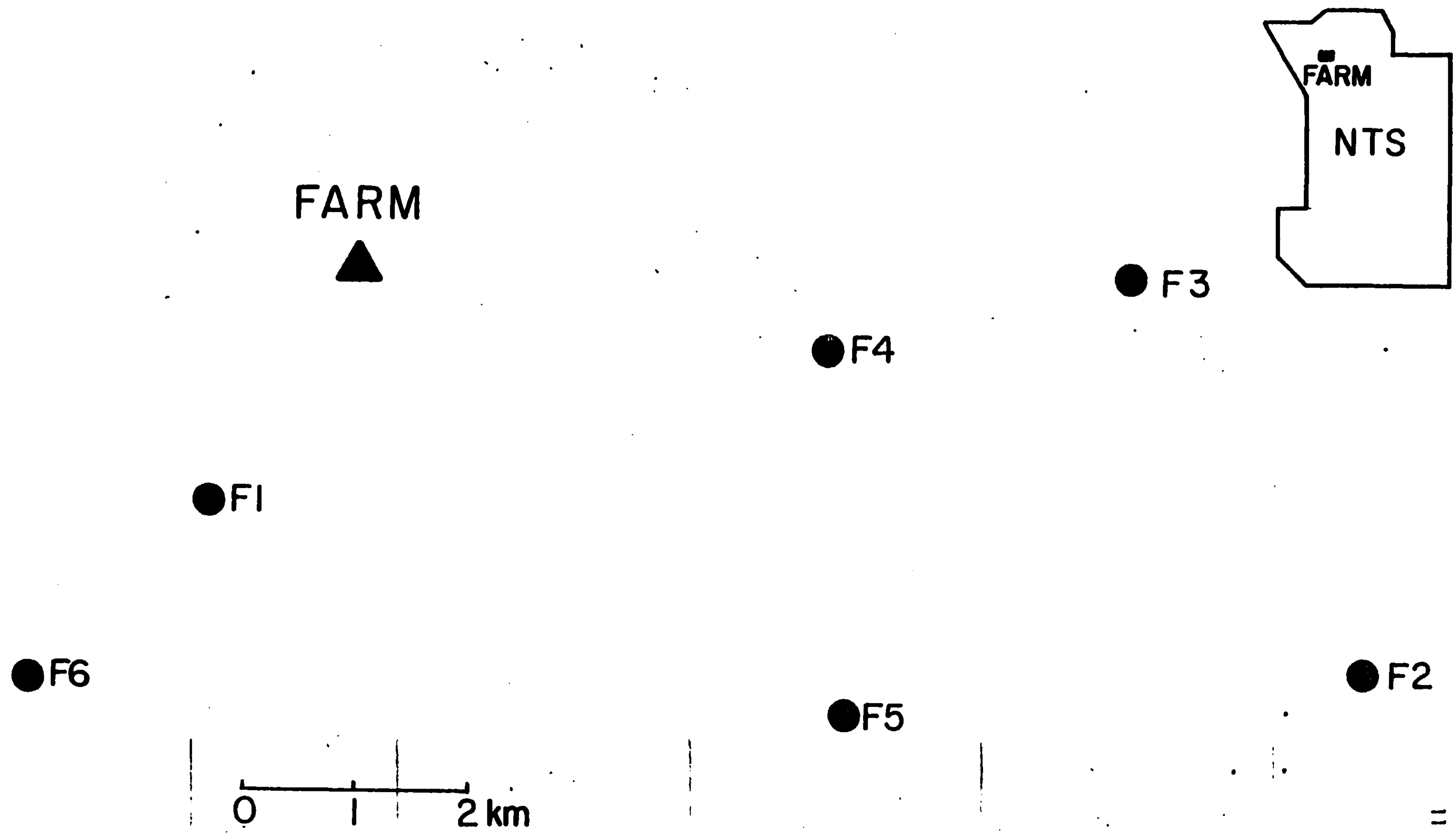

Figure 5. Location of recording sites for the explosion FARM.

Table 2. Network data for FARM

Station	Epicentral Distance (km)	Azimuth (deg E of N)	Elevation (km)	Velocity of first arrival (km/sec)	Maximum Accelerations			Notes on Operation
					Z	R	T	
F1	2.66	213	1.966					Capstan froze.
F2	9.67	113	2.134	3.45	0.13g	0.10g	0.15g	
F3	6.77	94	2.063					Bad accelerometer connector.
F4	4.20	104	1.990	2.77	0.71g	0.37g	0.46g	
F5	6.34	136	2.048	3.19	0.56g	0.35g	0.33g	
F6	4.68	221	1.929	3.13	0.43g	0.31g	0.21g	

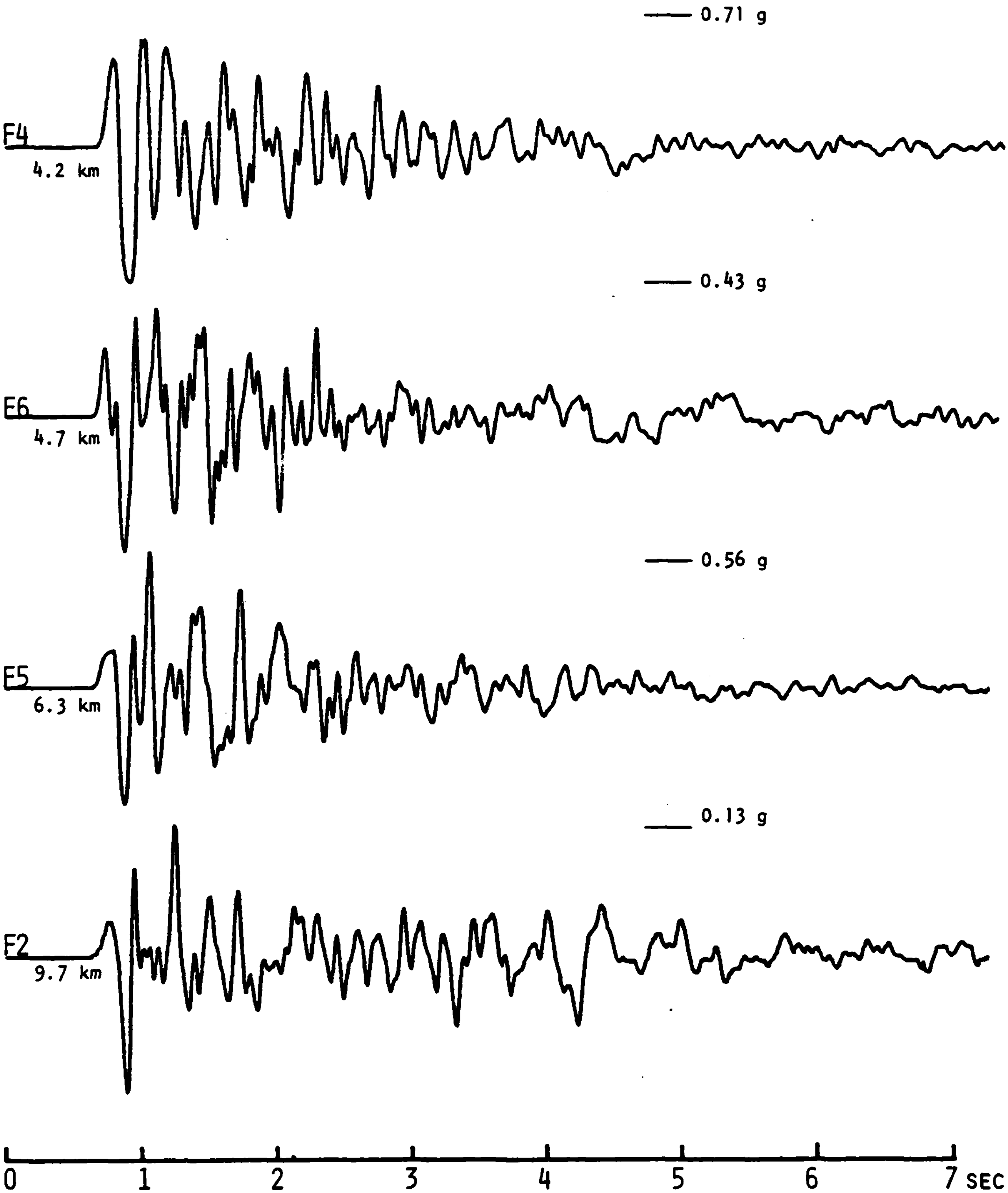

Figure 6. Vertical components of acceleration recorded from the explosion FARM.

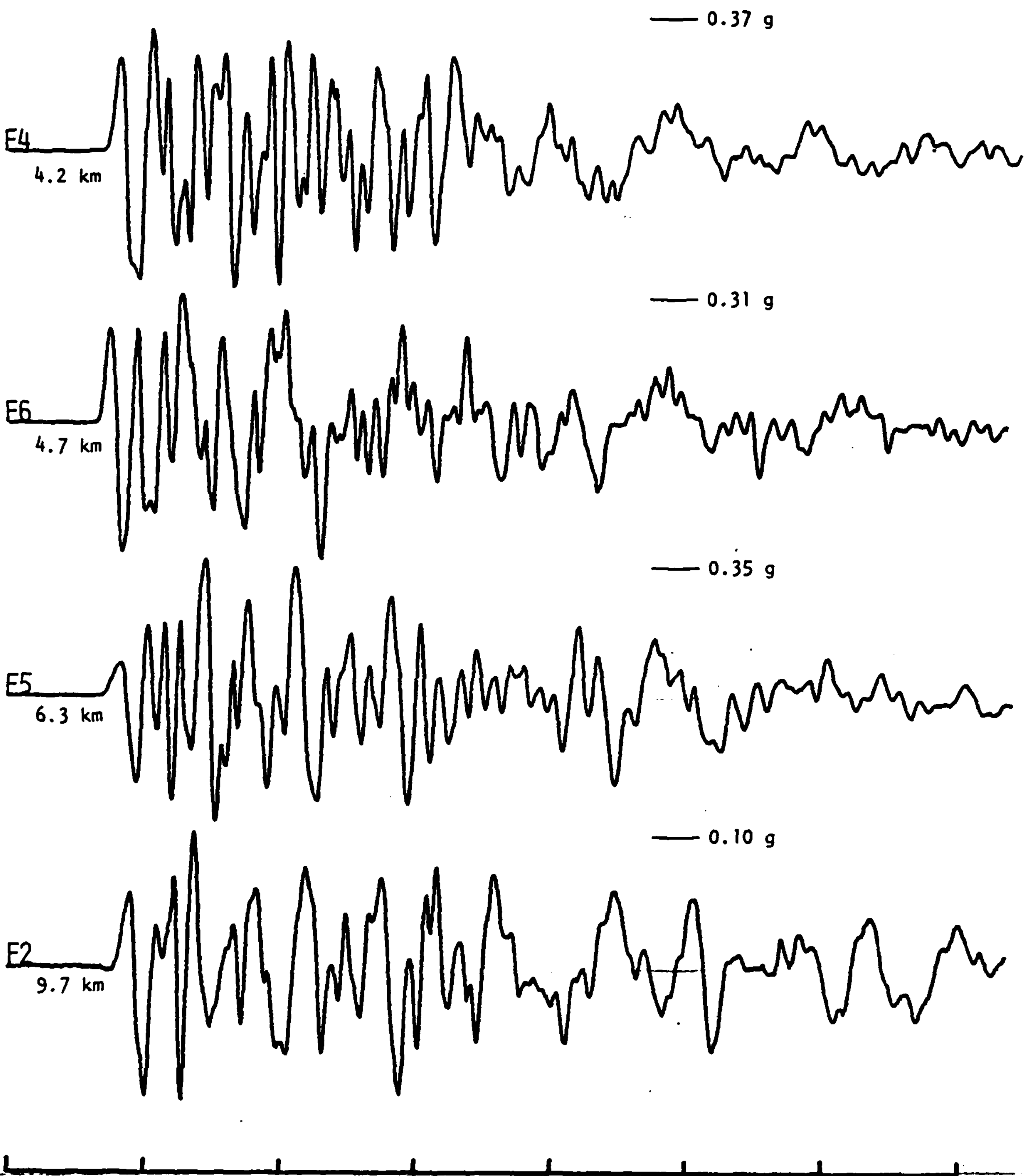

Figure 7. Radial components of acceleration recorded from the explosion FARM.

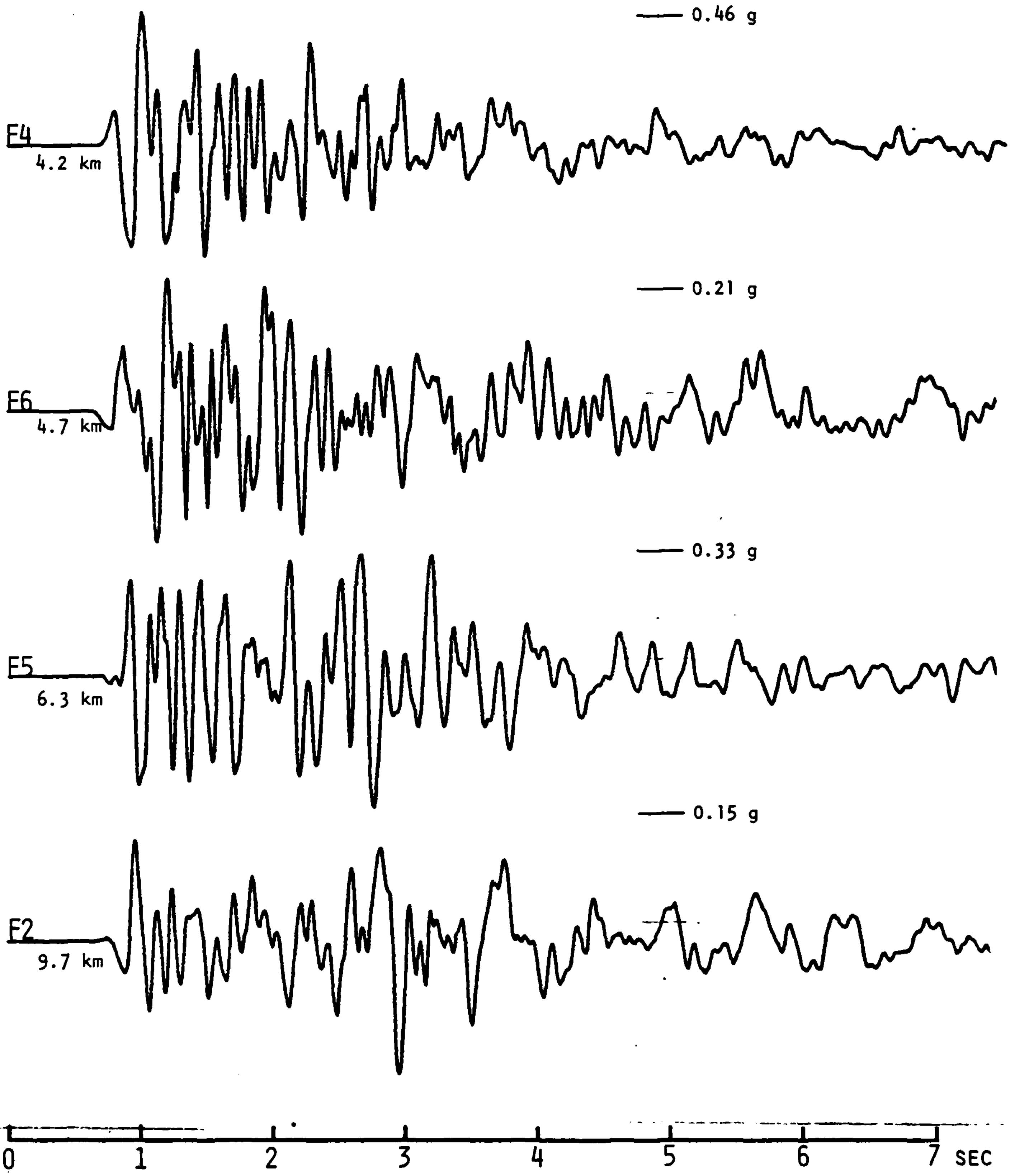

Figure 8. Transverse components of acceleration recorded from the explosion FARM.

recorders provided excellent records with noise at or below the level of the least significant bit. The dynamic range achieved with these recorders is significantly greater than that of the analog tape system used to record previous NTS events. Settings for the trigger levels, amplifier gains, and filter frequencies have not been a problem. Our procedure for estimating expected ground accelerations as a function of yield and distance has been modified and worked well for FARM. The output of the accelerometer packages have been modified to avoid any loading problems. The logistics of working at NTS have been worked out and the procedure for installing the network has been refined. It is now possible for two people to install a 7-10 element network in one day under good conditions and in two days under adverse conditions. The network can be removed in one day. The FARM experiment was performed with snow on the ground and, aside from icy roads, this caused no problems. We are thus confident that we now have the recording method and experience to successfully record accelerations at close distances from NTS explosions. The same method can be used to record aftershock sequences of earthquakes.

The second purpose of acquiring useful data from the explosions EMMEHTHAL and FARM was not so successful because of the problems mentioned above. However, it was not a complete failure and the data acquired have implications for future experiments. The vertical and radial components (Figures 2, 3, 6, and 7) show consistent explosion-like first motion patterns with the vertical component usually the larger of the two. The dominant frequencies are less than 10 Hz. More surprising are the transverse components (Figures 4 and 8) which have accelerations comparable to those on the radial components. Also note that the motion begins at a time close to that of the P-wave arrival and that the direction of first motions changes sign. Simple models of an explosion source in a laterally homogeneous material predict zero motion on the transverse component, so it is of interest to determine how and where these transverse motions are generated. Of course, one could ignore the transverse component and concentrate on the vertical and radial components in analyzing the explosion, but this also ignores the possiblity that the source of the transverse motion may also be contributing energy to the vertical and radial components. It seems clear that the matter of the strong transverse component of motion at close distances is not very well understood and is a problem that should be studied. An experiment is now being designed to do this.

III. PROPOSED SEISMIC MEASUREMENTS FROM UNDERGROUND NUCLEAR TESTS

The following was presented at an AFOSR/DARPA workshop on "Seismic Measurements from Underground Nuclear Tests" which was held in Arlington, Virginia, on 28 June 1979.

This is a brief description of a number of seismic measurement experiments which are proposed for underground nuclear tests at the Nevada Test Site. The purpose of these experiments is to gather critical data capable of providing answers to some remaining questions about the generation and propagation of elastic waves from underground explosions. These questions are germane to the general detection-discrimination problem.

The experiments described below are not intended to be a complete set of recommended measurements, but rather a subset which is based on the particular experience acquired during past and ongoing work on AFOSR grants at Berkeley. This work has been involved primarily with the recording and analysis of broadband seismic data from NTS events and western US earthquakes at local and regional distances. Naturally, these suggested experiments would have to be combined and coordinated with others to form a complete program of research.

EXPERIMENT I

Purpose. Most seismic measurments within a few kilometers of underground nuclear explosions produce recordings of ground acceleration. While such a mode of recording works well for recovering the high frequencies, it is band limited at the low frequency end of the spectrum because of the limited dynamic range of the recording system. Recent experience with 12-bit digital recording of NTS explosions in the distance range of 2-10 km has been a low-frequency limit of recoverable information in the 2-5 sec range. Because of this limitation on the bandwidth, the interpretation of acceleration data generally involves the assumption that periods longer than a few seconds contain no significant additional information about the source. The validity of this assumption should be experimentally checked, and that is the purpose of this experiment.

Accurate knowlege of the explosion source function over a wide frequency band bears upon several aspects of the general detection-discrimination problem. Examples are the relative excitation of body waves versus surface waves and hence the Ms:mb discriminant, the amount of overshoot involved in the source function, and the effect of tilts upon seismic measurements at small distances from the source.

Experimental method. A temporary seven-nine element network of three-component accelerometer stations should be deployed at the surface in the distance range 2-10 km from an explosion in the magnitude range 3.5-5.5. At least two of the stations should also have three-component displacement recordings which could be achieved by double integration of the output of the accelerometer sensors. This method of simultaneously recording acceleration and displacement responses from the same sensor has been used previously for recording earthquakes and shown to be feasible. Both acceleration and displacement channels could be recorded on triggered 12-bit digital recorders. The effective passband of the acceleration channels would be roughly 5 sec to 50 Hz and that of the displacement channels roughtly 20 sec to 5 Hz, giving a combined passband of 20 sec to 50 Hz. Such broadband recording should provide a fairly complete picture of the frequency content of surface displacements near an explosion.

EXPERIMENT 2

Purpose. Essentially all recordings that we have made of underground nuclear explosions in the distance range 2-10 km have revealed a surprisingly strong transverse component of motion. The accelerations on this component are typically 50-100% of those on the radial and vertical components, while theory predicts that there should be no transverse component for a symmetrical explosion in a vertically stratified media. In addition, these strong transverse motions begin at a time very close to that of the first P-wave arrival. The question of where and how these transverse motions are generated should be answered.

A proper understanding of the transverse motions may play an indirect but nevertheless important role in the general detection-discrimination problem. In view of their size, it would seem that any attempt at an accurate energy budget for the waves generated by an explosion would have to take these motions into account. The more transverse energy radiated by an explosion, the more it begins to look like an earthquake, and this leads into the general area of evasion.

Experimental method. A small temporary seven element array of three-component accelerometer stations should be deployed at the surface about 5 km from an explosion in the magnitude range 3.5-5.5. The maximum dimension of the array should be about 1 km. The array stations could be recorded on triggered 12-bit digital recorders and the stations could be connected so that all would be triggered simultaneously. The array should be designed with the idea of using frequency-wavenumber processing of the resulting data to determine the direction and apparent velocity of energy arriving at various times on the different components.

EXPERIMENT 3

Purpose. The seismic moment tensor is a useful means of characterizing a seismic source, whether it be an earthquake or explosion. The estimation of this moment tensor has been shown to be a linear problem, and estimates have been obtained from local data for the explosions HANDLEY, PIPKIN, and a collapse of JORUM. The results are interesting and encouraging, but more experience with this approach is definitely needed. The questions that are the focus of experiments 1 and 2 have arisen partly from these investigations of the moment tensor, and any progress in those areas should also help advance the moment tensor method. While most of the analysis so far has been confined to data recorded within a few kilometers of explosions, the method is completely general and could also be applied to regional and teleseismic data. The purpose of this experiment is to continue to apply the moment tensor method to the characterization of underground explosions.

The seismic moment tensor provides a convenient approach to the discrimination problem. The ratio between the isotropic and deviatoric parts of this tensor is a quantitative measure of the relative amounts of explosion and earthquake in a source. It may also provide a means of sorting out the effects that the free surface and spallation have upon the effective source function of an explosion.

Experimental plan. A temporary seven-nine element network of three-component accelerometer stations should be deployed at the surface covering an azimuthal range of at least 180° in the distance range of 2-15 km from an explosion in the magnitude range 3.5-5.5. All stations could be recorded on triggered 12-bit digital recorders. The data should be inverted to obtain an estimate of the moment tensor for the explosion source. In addition, an attempt should be made to collect data recorded at regional and teleseismic distances from the same explosion so that moment tensor inversions could be performed on these data also. It is important to compare moment tensor estimates from local, regional, and teleseismic data and investigate the relative advantages of looking at a seismic source from these different distances.

EXPERIMENT 4

Purpose. In designing a national seismic system to be used in a treaty verification program, it is of interest to consider what could be achieved with a small seismic array. Many of the seismic phases that will be observed at regional distances will have relatively high frequencies and relatively low phase velocities, and thus an array dimension of a few kilometers may be sufficient to allow effective frequency-wavenumber processing.

The seismogram that is recorded at regional distances is often rather complex with numerous crustal phases arriving in overlapping time frames. Any capability of separating these phases on the basis of frequency content, phase velocity, or particle motion could be very useful for both detection and discrimination.

Experimental plan. A small array with about seven elements and dimensions of 1-2 km should be deployed several hundred km from NTS. The sensors could be three-component short-period geophones and the recording mode triggered digital. The array would record not only any explosions at NTS but also any earthquakes in the California-Nevada region with sufficient magnitudes. Standard array processing techniques should be applied to the data with the objective of sorting out and identifying the numerous crustal phases that arrive at regional distances.

DISCUSSION

The experiments described above are relatively simple and could be conducted with standard off-the-shelf equipment. Logistical support required at NTS consists only of a vehicle, several charged automobile batteries, and a few hand tools. The temporary networks can be installed in one or two days and removed in one day. The usual procedure is to install the network two days prior to the shot and remove it one week later. If the shot is delayed more than one week, the batteries would have to be recharged.

Experiments 1 and 2 have been designed so that they could be conducted concurrently on the same explosion. The manner in which experiment 3 is carried out could be affected by the results of experiments 1 and 2. Depending upon the results that emerge, it may be desireable to repeat one or more of these experiments for different source media and different source geometries. For instance, it could prove useful to compare an explosion in granite with an explosion in some other source media, such as tuff. It could also be useful to compare an explosion above the water table with one below the water table and to compare an explosion at normal depth with one that is over buried. Possibilities such as these should not pose a problem with the experiments described above because they are quite flexible in design and are easily mobilized.

For the sake of simplicity, the experiments described above involve instruments at the surface of the earth, which usually means that the sensors are buried only 1-2 ft. A natural extension of these experiments would be to put the sensors down boreholes. With minor modification the surface sensors could be put downhole to a depth of about 20 ft. To go deeper would require special downhole sensor packages, but such an experiment should not present any major difficulties. It may also be possible to take advantage of existing boreholes and downhole instrumentation at NTS when siting the experiments.

The fourth experiment is essentially passive and a convenient site in California or Nevada would have to be selected for this regional array. Some effort would also have to go into the development of appropriate computer codes for processing the array data.

It should also be pointed out that the passive recording of all explosion at NTS by the Seismographic Stations of the University of

California will continue. This involves a number of different instrument types at numerous stations in central and northern California. Also available are the archival recordings at these same stations of essentially all NTS events in the past 20 years.

IV. ANALYSIS OF THE RESPONSE OF SMALL ARRAYS

In Section III it is proposed that a small temporary array be deployed for the purpose of attacking some specific problems, such as the source of the energy on the transverse component at close-in recording sites. An array might help determine if this energy is coming directly from the source region or from some near by scatterer. In addition, it is also suggested that at regional distances a small array might have certain advantages over a single seismometer when it comes to sorting out various crustal and upper mantle phases on the seismograms. Thus some preliminary calculations have been performed with regard to the response of such a small array.

The arrays considered here are quite small with only a few elements and maximum dimensions of a few kilometers, at most. Figure 1 shows a practical 7 element array which has been used for the calculations that follow. It consists of a center element and two nested equilateral triangles.

First consider the response of the array in Figure 1 to a simple harmonic plane wave. This is just the impulse response of the array in wavenumber space and it is contoured in Figure 2.

Two important parameters characterizing the array response can be obtained from Figure 2. The first is the 3 db point of the central peak of the response, which is a measure of the resolution of the array. For this array the value is 2.5 radians. The second parameter is the

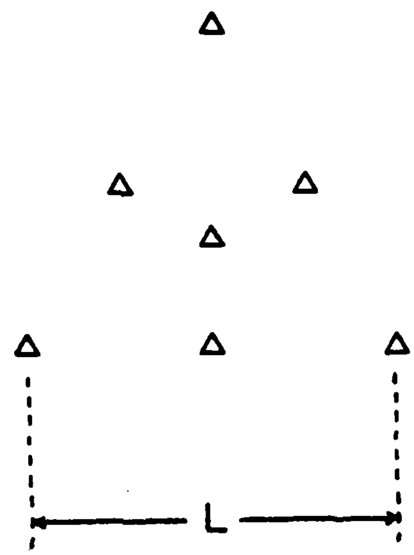

Figure 1. Geometry of a seven-element array. L is the maximum dimension of the array.

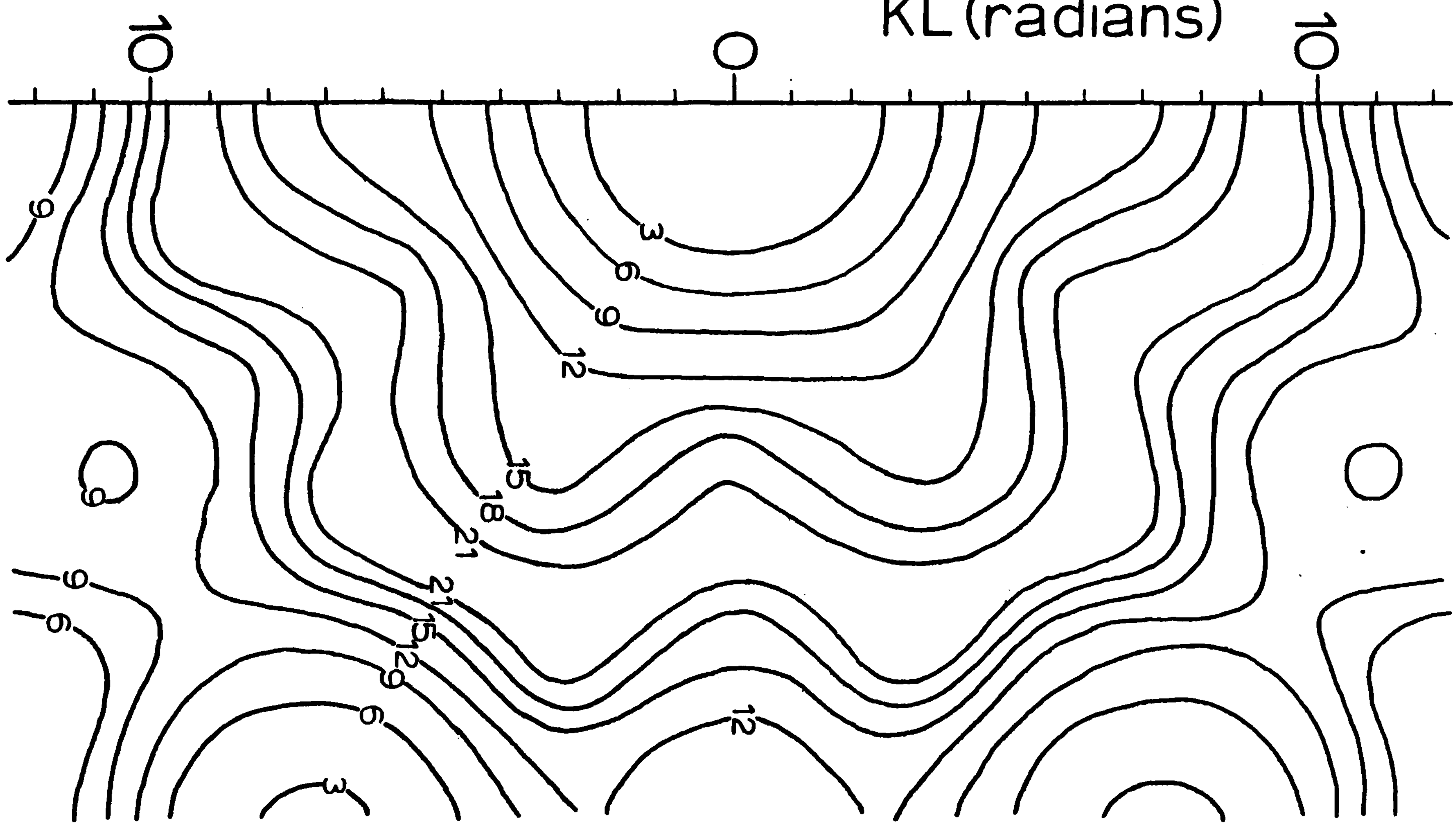

Figure 2. Response of the array in Figure 1 to a simple harmonic plane wave having wave number K in radians/km. The maximum dimension of the array is L in km. The contours are in units of db below peak response.

distance to the closest secondary peak of the response, which controls the spatial aliasing of the array. For this array the value is 15 radians. Given any horizontal phase velocity c, the above two parameters can be used to calculate the upper and lower limits on the range of velocities that can not be distinguished from c with the array (3 db points) and also the first upper and first lower alias velocity. Such results are given in Table 1 for values of c equal to 1.7 and 3.0 km/sec, which are typical of S and P velocities observed at small distances from NTS events, and values of 6.0 and 8.0 km/sec, which are typical of the velocities of crustal and upper mantle P phases observed at regional distances.

Consider the implications of Figure 2 and Table 1 for an array to be placed within a few kilometers of a buried explosion. Velocities of 1.7 - 3.0 km/sec will then be expected for c. From Table 1 it is clear that a value of fL=1 gives insufficient resolution to distinguish between P and S waves, while values of fL=10 or fL=20 begin to encounter alias problems for the lower velocities. A value of fL=5 provides enough resolution to separate P and S waves and aliasing is not a serious problem, so this appears to be a good design choice. The corner frequency of the displacement spectra which are typically observed in this distance range is about 5 Hz with significant energy out to about 10 Hz, so an array dimension of about 0.5 - 1.0 km would be suitable.

Next consider the implications of Figure 2 and Table 1 for an array to be deployed at regional distances where the velocities of crustal and upper mantle P and S phases typically span the range 3.0 - 8.0 km/sec. A value of fL=5 from Table 1 would provide resolution

Table 1. Velocity resolution and spatial aliasing for the array shown in Figure 1.

Velocities are in units of km/sec and are given in the order
-3 db velocity, 1st alias velocity
for both upper limits (+) and lower limits (-). Results are given for four different values of fL where f is frequency in Hz and L is the maximum dimension of the array in km.

		fL = 1	fL = 5	fL = 10	fL = 20
c = 1.7	+	5.3, ∞	2.0, 9.1	1.8, 2.8	1.8, 2.1
	-	1.0, 0.3	1.5, 0.9	1.6, 1.2	1.6, 1.4
c = 3.0	+	∞ , ∞	3.9, ∞	3.4,11.1	3.2, 4.7
	-	1.4, 0.4	2.4, 1.2	2.7, 1.7	2.8, 2.2
c = 6.0	+	∞ , ∞	11.5, ∞	7.9, ∞	6.8,21.4
	-	1.8, 0.4	4.0, 1.5	4.8, 2.4	5.4, 3.5
c = 8.0	+	∞ , ∞	22.2, ∞	11.8, ∞	9.5, ∞
	-	1.9, 0.4	4.9, 1.6	6.1, 2.7	6.9, 4.1

between P and S phases but not between crustal and upper mantle phases. A value of fL=10 or fL=20 is required to obtain good resolution between crustal and upper mantle phases. The phases observed at these regional distances in the western U.S. typically have dominant energy in the frequency band around 2 Hz, and this implies an array dimension between 2 and 10 km.

The foregoing calculations are for one particular array configuration (Figure 1), but the results are not critically dependent upon how the elements of the array are arranged. In general, the resolution of the array depends upon the maximum dimension and the aliasing depends upon the mean minimum distance between elements.

If the source of the seismic waves is close enough to the array so that the wave front has significant curvature as it crosses the array, then the preceeding plane-wave analysis is not valid. This is particularly true for sources within the boundaries of the array. In such a case the method of analysis is similar to that used to locate earthquakes with a network of local or regional stations. Some preliminary calculations have been made along these lines to determine the resolution of the array for near-by sources.

Table 2 gives some results for a shallow source with an epicenter within the array. These results imply that for a 1 km array and sources with depths less than 1 km,the uncertainty in the source location would be a few tens of meters if the arrival times could be read to 0.01 sec. Uncertainties in the velocity structure would inflate the uncertainty in the source location. Nevertheless, it seems apparent that such an array could be quite useful in locating any secondary sources which might be present.

Table 2. Uncertainty in location parameters for the array shown in Figure 1.

The source event is near the center of the array which has a maximum dimension of 1 km. Only P waves were used in the location and the velocity model was of the form

$$v = 1.4 + 3.8z \quad \text{(km/sec)}$$

where z is depth in km. The standard error of the arrival time readings at the array stations is taken to be S_t and has the units sec.

Source Depth (km)	Uncertainty in Origin Time (sec)	Uncertainty in Horizontal Position (km)	Uncertainty in Depth (km)
0.2	0.5 S_t	S_t	2 S_t
0.5	S_t	2 S_t	4 S_t
1.0	S_t	4 S_t	4 S_t