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DESIGN, EVALUATION, AND CONSTRUCTION OF TEXESS AND LUXESS, AND RESEARCH IN MINI-ARRAY TECHNOLOGY AND USE OF DATA FROM SINGLE STATIONS AND SPARSE NETWORKS: PHASE IV

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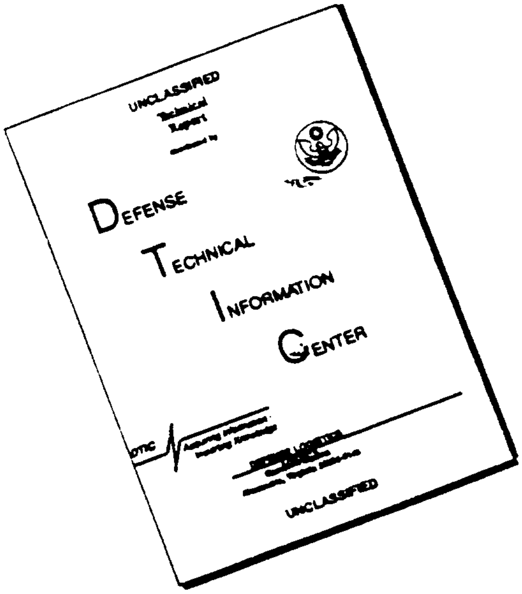

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13. ABSTRACT *(Maximum 200 words)*

Objectives are : (1) conduct research in seismic mini-array technology and single stations and sparse networks data, (CLIN 1) and (2) design, evaluate, and construct TEXESS, in Southwest Texas, and LUXESS, northeast of Luxor, Egypt, (CLIN 2), along the lines of a GSE Alpha Station. TEXESS was installed by SMU personnel in August 1993, and the first event was a local recorded on 31 August. With de-installation on hold awaiting diplomatic agreements, work has been directed to CLIN 1 research.

Research on time-domain processing of array data has resulted in a significant decrease in the standard deviation of azimuths as compared with *f-k* processing. For example, a reduction of azimuthal standard deviations from ± 15 degrees with f-k processing to ±1.4 degrees with time-domain processing. The M_s:m_b method is an effective and transportable discriminant for shallow events at teleseimic distances with m_b greater than 4.75. SMU has been successful in reducing the detection threshold for fundamental mode Rayleigh waves using signals at regional distances for body wave magnitudes as low as 3. Autoregressive (AR) modeling on Lg data has resulted in the ability to discriminate small economic explosions from small earthquakes.

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SUMMARY

Personnel contributing to this contract are: (1) Dr. Eugene Herrin, Principal Investigator, (2) Paul Golden, Director of Geophysical Laboratory, (3) Karl Thomason, Chief Engineer, (4) Nancy Cunningham, Director - Computer Laboratory, (5) David Anderson, Systems Analyst, (6) Dyann Anderson, Administration, (7) Dick Arnett, Consultant, (8) Herbert Robertson, Consultant, (9) Jack Swanson, Consultant, (10) Billie Myers, Consultant, and (11) Dr. Gordon G. Sorrells, Consultant. Ph. D. students include: (1) Chris Hayward, (2) Relu Burlacu, (3) Zenglin Cui, (4) Jessie Bonner, and (5) Ileana Tibuleac.

Objectives

Objectives of the contract are twofold: (1) to conduct research in seismic-array technology and use of data from single stations and sparse networks, and (2) to design, evaluate, and construct two experimental arrays, TEXESS in Southwest Texas and LUXESS (Luxor Experimental Seismic System), which is northeast of Luxor, Egypt. These two tasks are dubbed CLIN 1 and CLIN 2.

The original CLIN 1 objectives were to: (1) conduct research in the use of single station and sparse network data in detecting and identifying small seismic events, (2) conduct research to develop optimum configurations and processing techniques for a nine-element experimental array, and (3) to continue development of an unmanned intelligent seismic station. These objectives have been revised by the Project Office in April 1994 as described on page 4 under Implications for Further Research. The contract has subsequently been revised to include acoustical research as a CLIN1 objective.

CLIN 2 objectives are to: (1) acquire hardware and software, (2) install TEXESS, (3) perform site surveys and choose location for LUXESS, (4) test TEXESS and perform verification tests prior to de-installation, (5) de-install TEXESS, (6) complete civil work in Egypt, (7) install and test LUXESS, (8) de-install data acquisition, analysis and archiving equipment and ship to Helwan, Egypt, data center, and (9) install and test data acquisition, analysis and archiving equipment at Helwan data center. The contract is in the process of being extended to include additional tasks under CLIN2 regarding the establishment of the Egyptian array. TEXESS has recently been designated TXAR, which will be used when appropriate in the remainder of this report.

Technical Problem

The German Experimental Seismic System was dedicated in 1992 and represents an upgrade for regional arrays. Although GERESS was technologically advanced over NORESS and ARCESS, which were earlier regional arrays, because of greater sensitivity and wider dynamic range, there was a considerable effort that resulted in increased costs for pier and vault construction and trenching for power cabling. Now, in TXAR, innovations in emplacement techniques, such as the installation of sensors in shallow boreholes instead of vaults and the use of solar power at each site to eliminate cabling from a central-power source, that have reduced array-installation costs by an order of magnitude. Other innovations are discussed below. TXAR is, therefore, a proposed design for a GSE-Alpha station because of these cost-cutting innovations. In addition to design, construction, installation, and operation, of TXAR, research will be undertaken to develop new means of taking data and handling the data.

General Methodology

In GSE/US/84, February 1993, entitled "Technical Concepts for an International Data Exchange System," the GSE established the design goals of a future system. Goals are as follows:

1. Provide prompt access to all essential data
2. Provide convenient access to all available data
3. Provide direct access to all data at authorized national and global facilities
4. Accomplish goals with realistic manpower and budget resources.

The new concept of a global system for data exchange calls for an Alpha Network of 40-60 stations, primarily arrays; plus much greater than 60 Regional or Beta Stations; plus Local and National Networks or Gamma Stations.

SMU began research on experimental-array technology in 1991 on a previous contract. The proposed design was along the lines of an Alpha Station consisting of an array containing nine sites. Advancements over the GERESS design included the following:

1. The placement of seismometers and electronics in boreholes to greatly reduce construction costs for piers and vaults
2. The use solar power at each site rather than a central-power source
3. The use GPS receivers for time data at each seismometer site to replace central timing from the Hub
4. The employment of radio links from seismometer sites to the Hub to replace cable links and associated construction costs
5. The use of modular equipment to facilitate the installation and maintenance of the array.

Four shallow boreholes about 7 meters deep and 11-5/8 in. in diameter were drilled and cased with standard 8-in. pipe. Special equipment and techniques were developed to lower and level seismometers in the boreholes. A prototype solar power array and directional antenna were also developed for installation at LTX.

Technical Results

The limited program described above was successful and SMU was granted a contract to design, evaluate, and construct two nine element experimental arrays: TEXESS and LUXESS.

Important Findings and Conclusions

The SMU mini-array research program that was begun in 1991 under the previous contract proved the feasibility of the proposed design and methodology described above.

Significant Hardware Development

Preliminary research has led to the following hardware developments:

1.The development of seismometer emplacement techniques in boreholes, including remote seismometer locking eliminated the need for vaults

2.Advancements in computer applications and radio modems allow all necessary electronic components to fit inside a 8-in. casing to provide physical protection and a more stable environment for the electronics

3. The use of Global Positioning Satellite (GPS) receivers to obtain timing accurate to within 10 ms of world time assuring time synchronization of the array

4. The use of modern digital radio modems allows the system to perform as a local area network referred to as a RAN (Radio Area Network); radio polling software provides wide bandwidth intra-array communications while requiring two base-station radios; the need for expensive buried fiber-optic cable is eliminated

5. A NEMA enclosure is mounted on top of the borehole and is used to house the batteries and as a mount for the solar-power array; the GPS receiver and radio antenna are mounted above it.

Special Comments

The task of adapting the solar-panel arrays at Lajitas to the LUXOR environment is simplified somewhat in that both TXAR and LUXESS are at approximately the same latitude, 30 deg North; both are in arid climatic zones; and both have about 3,500 annual hours of sunshine. As a result, there would be no need to modify the prototypic TXAR design because of differing environmental conditions at LUXESS.

Implications for Further Research

CLIN 1 objectives were revised by the Project Office in April 1994 to: (1) conduct research to develop optimum configurations and processing techniques for nine- and sixteen-element short-period arrays, (2) conduct research in discrimination of nuclear events using autoregressive (AR) modeling techniques on Lg data, and (3) conduct research in measuring 20-

second Rayleigh waves at regional distances using high-resolution, wide-dynamic-range, short-period, seismic-array data and broadband KS 36000 data.

CLIN 1 -- RESEARCH

Array Research

Conduct research to develop optimum configurations and processing techniques for nine-and-sixteen element short-period arrays,

In Scientific Report No. 1, PL-TR-94-2106, we discussed the problems of the large scatter of the order of ± 15 deg of azimuth estimates at GERESS after f-k processing. In order to address this problem, SMU research has concentrated on developing a time-domain processing techniques to reduce this statistic using the nine-element TXAR array. The array-processing technique is similar to that described by Bernard Massinon in his paper entitled "The French seismic network -- current status and future prospects," which he presented at the GERESS Dedication and Symposium on 24 June 1992. The processing algorithm developed by SMU using GERESS D-ring data, which approximates the proposed 9-element TEXESS array, was presented in SMU-R-92-396, p. 14-17.

In Scientific Report No. 2, PL-TR-94-2258, ADA292546, array-processing research is described in Appendix 1. Specifically, Appendix 1 describes work on time-domain processing of GERESS and TXAR data to decrease azimuthal-error statistics with respect to that obtained by *f-k* processing. Time-domain processing has resulted in a reduction of azimuthal standard deviations from ± 15 degrees with *f-k* processing to ± 1.4 degrees with time-domain processing of TXAR data. The plan is to integrate the time-domain process with a detector that is being designed by Chris Hayward of SMU in order to automate array processing.

M_b=5.6 Western Texas Earthquake of 14 April 1995

Felt in much of western and central Texas, the epicenter was about 30 miles southeast of Alpine, Texas and 10 miles northwest of Marathon in the Glass Mountains. Origin time was 7:32 p. m. CDT. It was felt as far east as San Antonio and Dallas-Fort Worth and as far west as Roswell, New Mexico. There was damage in the Alpine-Marathon area, and two people were slightly injured. However, there was no damage to either TXAR instrumentation or facilities. After the Valentine, Texas, M_b=6--7 [estimated] quake of 1931, which was about 70 miles to the northwest, this Western Texas highland was still until April 14th.

Figure 1 shows the event as recorded by the array. As you will notice, the event was clipped in the amplifiers. By 19 April, the USGS reported 14 aftershocks including a M_b=4 at 7:33 a. m. on 15 April. However, many more aftershocks were recorded by the array. Figure 2 is the record of this aftershock. As this event wasn't clipped, it will be used for analysis purposes.

Calibration Studies

Calibration is generally required in order to reduce bias in location and magnitude determinations at regional to near-teleseismic distances using seismic array data. Calibration is particularly important at TXAR because the array is located near the boundary between two geophysically different regions, the Mid-Continent and the Basin and Range Provinces. A modified version of the correlation method described by Cansi, Plantet and Massinon was used to estimate azimuth and horizontal phase velocity of 36 events recorded at TXAR for which we had USGS m_b values. At some azimuths the first arrivals from regional events had phase velocities normally associated with Pn (less than 8.5 km/sec) but to the northwest the first arrival was always an upper mantle refraction. Phase identification is essential in order to select a suitable magnitude scale. Observed bias in estimated azimuth as large as 15° was found to be dependent on both distance and true azimuth. Appendix A is a recent poster session describing the method.

Discrimination Research

Conduct research in discrimination of nuclear events using autoregressive (AR) modeling techniques on Lg data

In the framework of a Comprehensive Test Ban Treaty (CTBT), discrimination between low-yield or decoupled nuclear explosions, economic explosions and small shallow earthquakes using the characteristics of the seismic waves becomes very important. Some of the economic explosions are multiple-source events with a time and space pattern dependent upon the type of application. The superposition of the seismic motion in the time domain leads to regular amplification and suppression of spectral power in the frequency domain. As, in general, single events (single explosions or earthquakes) do not exhibit spectral modulations, their presence can be used in the discrimination between single and multiple events. The aim of the present study is to develop a fast and robust method of discriminating between earthquakes and economic explosions based on differences observed in the spectral content of the regional waveforms. The method is based on the parametric estimation of the power-spectral density (PSD) using the autoregressive (AR) Burg algorithm of order 3, which provides a fast method to emphasize the spectral differences.

In Scientific Report No. 2, PL-TR-94-2106, AR modeling is described in Appendices 2 and 4. The initial data set (see Table 1 of said report) includes about 30 mine explosions and earthquakes from the Vogtland area of Czechoslovakia about 200 km northwest of GERESS. The frequency and reciprocal pole position of the complex pole in the AR (3) models were calculated using the Lg arrival for the Vogtland events recorded at GERESS in Table 1 of Scientific Report No. 3, PL-TR-95-2023. Figure 1 of Scientific Report No. 3, shows a clear separation of explosions and earthquakes with the latter having broad spectra with "weak" poles above 6 Hz whereas the explosions all show much "stronger" poles at frequencies less than 5 Hz. The AR (3) method appears to be an effective discrimant for small explosions and small earthquakes. Further work will be to answer questions regarding the method: (1) its effectiveness in other areas such as the Middle East, (2) its effectiveness using larger events, and (3) why the method works as well as it does?

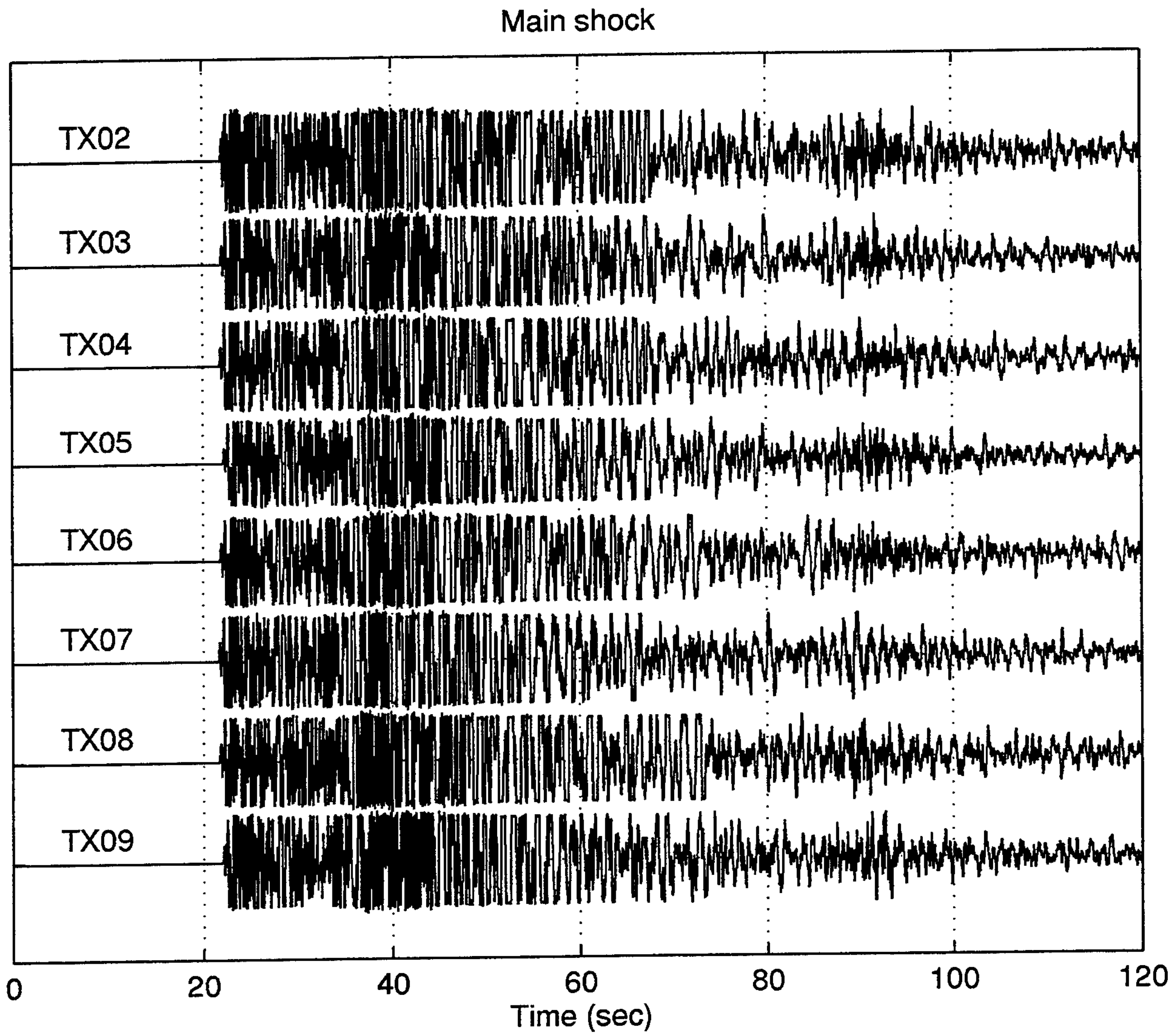


Figure 1 -- Recording of Western Texas M_b=5.6 earthquake of 14 April 1995 by TXAR array.

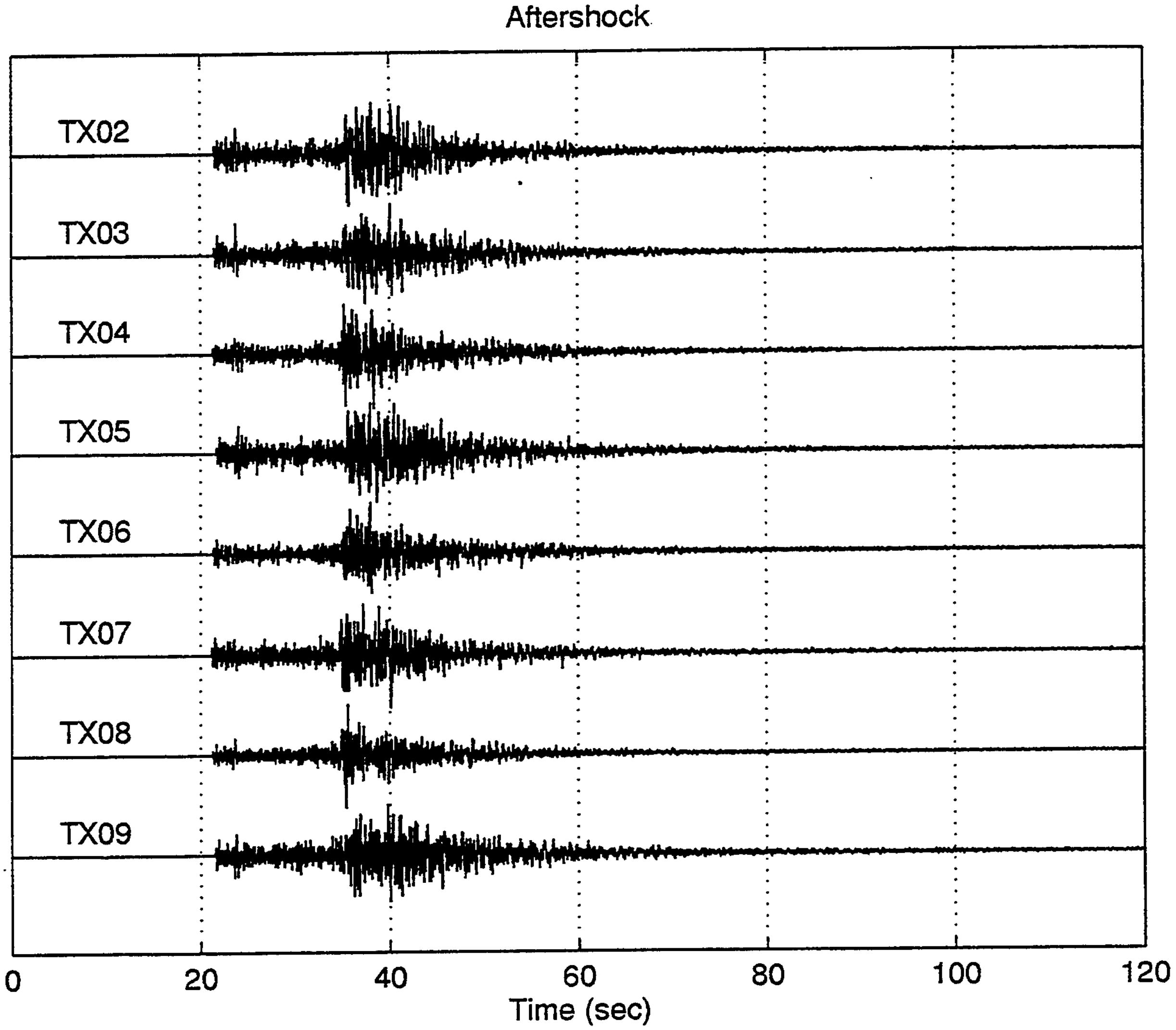


Figure 2 -- Recording of Western Texas M_b=4 aftershock of 15 April 1995 by TXAR array.

Conduct M_S:m_b research by measuring 20-second Rayleigh waves at regional distances using high-resolution, wide-dynamic-range, short-period, seismic-array data and broadband KS 54000 data.

The M_S:m_b discriminant has been investigated by a number of researchers for both regional and teleseismic events and explosions. Bases for the discriminant are (1) that explosions emit more energy in the form of high-frequency body waves and (2) that earthquakes emit more energy in surface waves having low frequency radiation; therefore, an Ms:m_b plot displays a significant separation of the two populations. The problem with the method is that of identifying small explosions; that is, the problem boils down to seismograph sensitivity. With the installation of new high-dynamic-range seismographs at TXAR, planned research includes the determination of Ms from small earthquakes at regional distances using the TXAR array data recorded by short-period GS-13 seismometers and a posthole, broadband KS 54000 seismometer. In Scientific Report No. 2, M_S:m_b studies were described in Appendices 3 and 4, and were excerpted in this section of Scientific Report No. 3, PL-TR-95-2023.

PROPOSED ACOUSTIC RESEARCH

In the present context of the CTBT, there is a stipulation for microbarographic monitoring of low altitude atmospheric nuclear events. Such monitoring involves the deployment of arrays of microphones or microbarographs to detect the atmospheric acoustic waves generated by such explosions. Plans are to deploy microbarograph arrays adjacent to the Alpha arrays in order to better detect and locate sources of low altitude atmospheric nuclear explosions with yields about one kiloton.

Dr. Gordon G. Sorrells has suggested the use of the existing facilities at Lajitas to investigate the possibility of designing an acoustical detector using a seismic array that would have greater sensitivity than a microbarographic pipe array. If this research proves as successful as theoretical work suggests, it would be unnecessary to utilize and deploy microbarographs thereby saving substantial resources. Appendix B is a plan for the research program.

CLIN 2 -- DESIGN, EVALUATION, AND CONSTRUCTION OF TXAR AND LUXESS

Experimental-Array Program

Information on the experimental-array program at SMU on the previous contract was presented in SMU-R-92-396, and in Scientific Report No. 1, PL-TR-94-2106, ADA284580.

TXAR AND LUXESS

Information on CLIN 2 has been presented in Scientific Report No. 1, PL-TR-94-2106, Scientific Report No. 2, PL-TR-94-2258, ADA292546, and Scientific Report No. 3. Since the submission of Scientific Report No. 3, an extension to the contract has been been granted to install LUXESS because of unavoidable delays. As a result, six additional tasks have been added.

Acquisition of Hardware and Software

The First and Second Quarterly R & D Status Reports cover the acquisition of hardware and software. TEXESS and LUXESS equipment are discussed in Scientific Report No. 1, PL-TR-94-2106. Instructions for the installation of the Posthole 54000 seismometer are presented in Appendix 5 of Scientific Report No. 2.

Array Hardware

Hardware is discussed in the Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Computer Hardware

Computer equipment is discussed in the Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Software

Acquisition of software was addressed in Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Install TXAR

Layout

TXAR layout is discussed in Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Installation

Installation is discussed in the Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Because of high noise levels at C1 owing mainly to road traffic along Farm Road 170, the site was relocated about 5 km to the west of the original site, and about 2 km northwest of C2.

Information about TXAR, which has been compiled by Chris Hayward of SMU, can now be accessed on Internet via the World Wide Web at:
http://inge.css.gov:65123/WebIDC/About_TXAR/

Perform Site Surveys and Choose Locations for LUXESS

As mentioned in Scientific Report No. 3, two locations have been identified from satellite photos and maps for LUXESS, which are on granitic bodies located north of the road between Luxor and Quseir. Figure 4 of Scientific Report No. 3 is a digitally-enhanced LandSat image of the two circular granitic intrusions. The specific site for LUXESS will be selected by a team composed of SMU and Egyptian scientists.

Test TXAR Prior To De-installation

TXAR has been operational since 30 August 1993, but outages as discussed in this section of Scientific Report No. 3, have led to reconfigurations as discussed in this report, which should improve overall reliability.

Addition changes at TXAR have recently been made to test LUXESS equipment prior to transportation. During the week of 26 February 1995, a concrete pad was laid at the hub for a borehole GS-13 and the posthole KS 54000. Conduit was also run from the the pad to the CIM hut. The plan is to test the LUXESS KS 54000 in this borehole, then move the TXAR posthole KS to the pad borehole.

De-install TXAR

The present plan is to de-install all equipment except the seismometers, and transport said equipment to LUXESS. Equipment tagged for shipping includes the AIMs, radios, antennas, solar panels, batteries, NEMA enclosures, CIMs, and UPS.

Additional Tasks

Training

There are four training tasks for representatives from Egypt as follows:

1.Training in computer usage including Unix Operating System on the SUN SPARCstation platform

2. Training in the use of Science Horizons Incorporated (SHI) software for seismic data acquisition and processing, XAVE and VISTA

3. Training in the construction and installation of the Egyptian array, which is described in the literature as the ARPA Model 94 Seismic Array

4. Training in the operation and maintenance of the Egyptian array.

Spare Parts

Spare parts for the array will be provided as follows: (1) one GS-13 seismometer, (2) one SHI Model AIM24-1, (3) one Repco Model SLQ96 radio, (4) two solar panels, and (5) two 12 vdc batteries.

After operating TXAR for a year and a half, we have learned from experience that the hub electronics in the remote operations facility (ROF) should be fully redundant because of the possability of lightning damage as mentioned in Scientific Report No.3, PL-TR-95-2023, p. 18,. As a result, there will be two spare radios, a spare CIM, and additional lightning-protection equipment.

Broadband System

Equipment will be provided for a 3-component broadband seismic data acquisition system based on a posthole KS 54000 seismometer such as that installed at TXAR.

APPENDIX A -- CALIBRATION STUDIES AT TXAR

Ileana Tibuleac, Eugene Herrin, and Paul Golden

INTRODUCTION

Calibration is generally required in order to reduce bias in location and magnitude determinations at regional to near-teleseismic distances using seismic array data. Calibration is particularly important at TXAR because the array is located near the boundary between two geophysically different regions, the Mid-continent and the Basin and Range Provinces. A modified version of the correlation method described by Cansi, Plantet and Massinon was used to estimate azimuth and horizontal phase velocity of 36 events recorded at TXAR for which we had USGS m_b values. Modifications to the correlation method include Fourier interpolation of the data by a factor of 8 to obtain a virtual sample rate of 320/sec, use of an L-1 technique (least absolute deviation) to obtain estimates of azimuth and phase velocity, and a moving window display to indicate those portions of the waveform that show strongest correlation across the array.

The panels in this poster illustrate the use of the modified correlation method for processing data from a sparse array and summarize calibration results to date for TXAR. At some azimuths the first arrivals from regional events had phase velocities normally associated with Pn (less than 8.6 km/sec) but to the northwest beyond about 1600 km the first arrival was always an upper mantle refraction with phase velocity greater than 8.6 km/sec. Phase identification is essential in order to select a suitable magnitude scale. Biases in estimated azimuth as large as 15° were found to be dependent on both distance and true azimuth.

ARRAY DATA PROCESSING

- Digital array data were loaded.
- Data from excessively noisy channels were discarded.

- Data were band-pass filtered between 0.75 and 10 Hz with the exception of two events. (Oklahoma, 1-3 Hz and Wyoming, 0.5 - 5 Hz).
- A 3.2 second window was selected.
- Data were Fourier interpolated by a factor of 8 to obtain a virtual sampling rate of 320/sec.
- A complete correlation matrix was computed.
- A complete lag matrix was computed by calculating the lag-times of the maxima of the cross-correlation functions. This matrix must be skew-symmetric.
- The lag matrix was corrected for differences in station elevations within the array.
- In the absence of noise and computational errors, the lag matrix is Toeplitz.
- Median values were used to estimate the elements of the Toeplitz matrix.
- An iterative L-1 method (minimum absolute deviation) was used to estimate azimuth and horizontal phase velocity using the elements of the estimated matrix.
- The 3.2 second window was advanced 5 data points (125 millisec) and the correlation process repeated.
- Estimates of phase velocity and azimuth and the normalized sum of the absolute errors of fit were plotted as a function of window start time.
- A "best" window was selected based on stability of estimates and minimum estimation error.
- The array beam was computed based on estimates from the "best" window.

Table A1 -- List of Events Used in This Study

1.	2.	3.	4.	5.	6.	7.	8.	9
1.	01/17/1994	6.4	1504.9	295	291	8.6	18	Pn
2.	02/05/1994	4.2	1612.3	52	55	9.9	16	Pm
3.	09/01/1994	6.6	2343.2	307	298	13.1	10	Pm
4.	09/12/1994	5.2	1806.7	310	307	9.9	5	Pm
5.	10/25/1994	4.3	2859.3	313	296	14.8	10	Pm
6.	10/27/1994	4.9	710.3	237	234	8.0	10	Pn
7.	10/27/1994	5.6	2626.7	313	300	13.2	10	Pm
8.	10/29/1994	4.5	1425.2	163	167	8.2	33	Pn
9.	12/06/1994	4.2	1497.6	295	285	8.4	10	Pn
10.	12/09/1994	6.5	1257.9	168	169	8.0	33	Pn
11.	12/20/1994	5.0(Ml)	1736.6	299	287	9.4	10	Pm
12.	12/26/1994	5.2	2247.5	310	299	12	20	Pm
13.	12/26/1994	5.1	2654.8	136	136	11.7	33	Pm
14.	12/27/1994	4.8	837.5	243	238	7.8	10	Pn
15.	12/28/1994	5.1	2973.3	134	147	12.2	33	Pm
16.	01/04/1995	2.7(mbLg)	635.2	90	92	8.3	5	Pn
17.	01/05/1995	4.6	1881.2	147	159 152	8.6 10	33	Pn Pm
18	01/06/1995	4.6	1803.7	310	312	9.0	5	Pm
19.	01/06/1995	4.1	986.5	275	260	8.4	10	Pn
20.	01/07/1995	4.3	2055.5	139	155 153	8.3 10	33	Pn Pm
21.	01/09/1995	5.1	3391.5	153	152	11.4	33	Pm
22.	01/09/1995	4.9	2261.8	140	153	9.7	33	Pm
23.	01/10/1995	4.9	3393.7	153	154	11	33	Pm
24.	01/10/1995	4.8	3410.9	151	151	10.6	33	Pm
25.	01/11/1995	3.9	1158.8	289	283	8.5	10	Pn
26.	01/11/1995	4.4	2284.3	308	297	12.3	20	Pm
27.	01/11/1995	5.1	3439.2	154	159	11.8	33	Pm
28.	01/18/1995	4.0(mbLg)	818.9	44	45	8.5	10	Pn
29.	01/19/1995	6.4	4206.6	124	127	14	33	Pm
30.	01/25/1995	4.4	2109.7	147	157	9.2	0	Pm
31.	01/28/1995	4.6(Ml)	1953.5	333	334	12.7	5	Pm
32.	01/29/1995	5.0(Ml)	2578.3	326	327	13.4	15	Pm
33.	01/31/1995	3.5(mbLg)	262.8	212	211	8.3	10	Pn
34.	02/03/1995	5.4	1468.3	340	343	10.5	10	Pm
35.	02/08/1995	6.5	4014.2	130	136	14	70	Pm

where
1. Number of the event;
2. Date of the event;
3. m_b(USGS)
4. The epicentral distance (km);
5. Calculated azimuth (USGS) (degrees);
6. TXAR azimuth (degrees);
7. Phase velocity (km/s);
8. Depth (km);
9. Type of the arrival.

CORRELATION ANALYSIS PANELS

Subplot 1	Shows the filtered beam and the 3.2 seconds window used to estimate azimuth and phase velocity.
Subplot 2, 3	Shows the waveforms parameters, velocity and azimuth, as a function of the start time of successive 3.2 second windows. The dotted line shows the accepted estimates.
Subplot 4	Shows the normalized sum of the time residuals as a function of the start time of the 3.2 second windows.

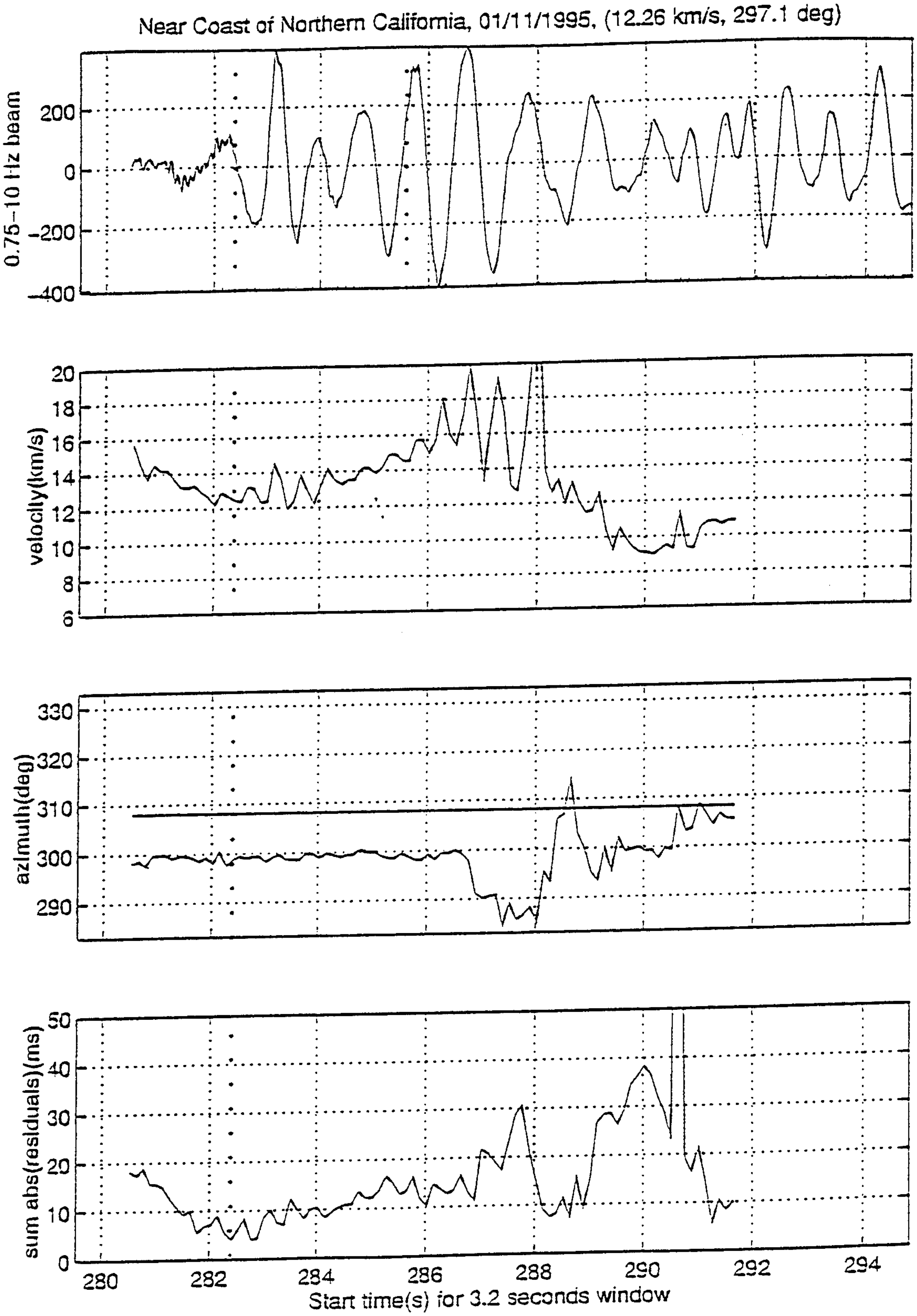


Figure A1 -- NEAR COAST OF NORTHERN CALIFORNIA, m_b=4.4

Origin Time: 01/11/95 13:53:28.1

Distance: 2884.3 km Azimuth: 308°

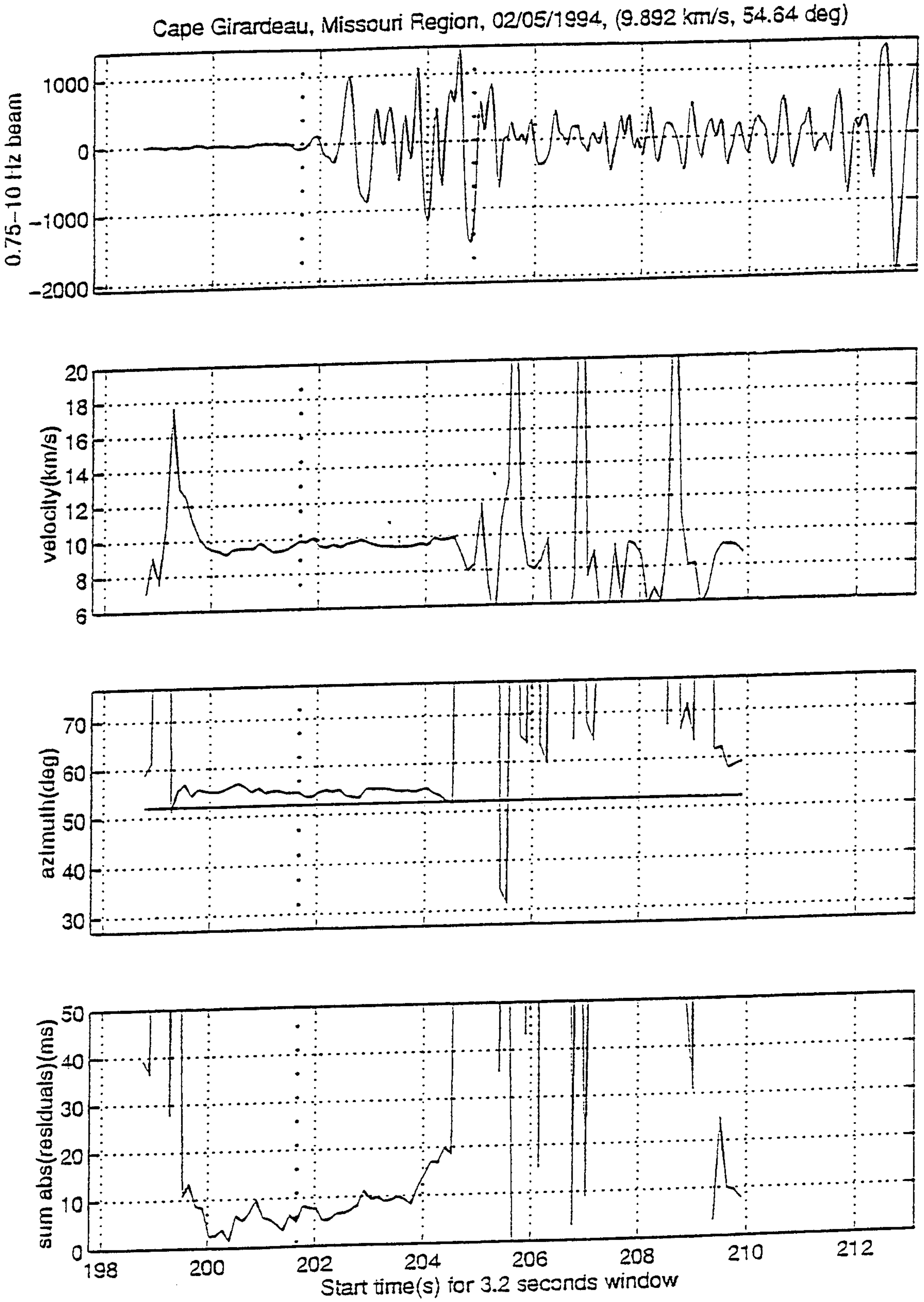


Figure A2 -- CAPE GIRARDEAU, m_b=4.2
Origin Time: 02/05/94 14:55:37
Distance: 1612 km Azimuth: 52°

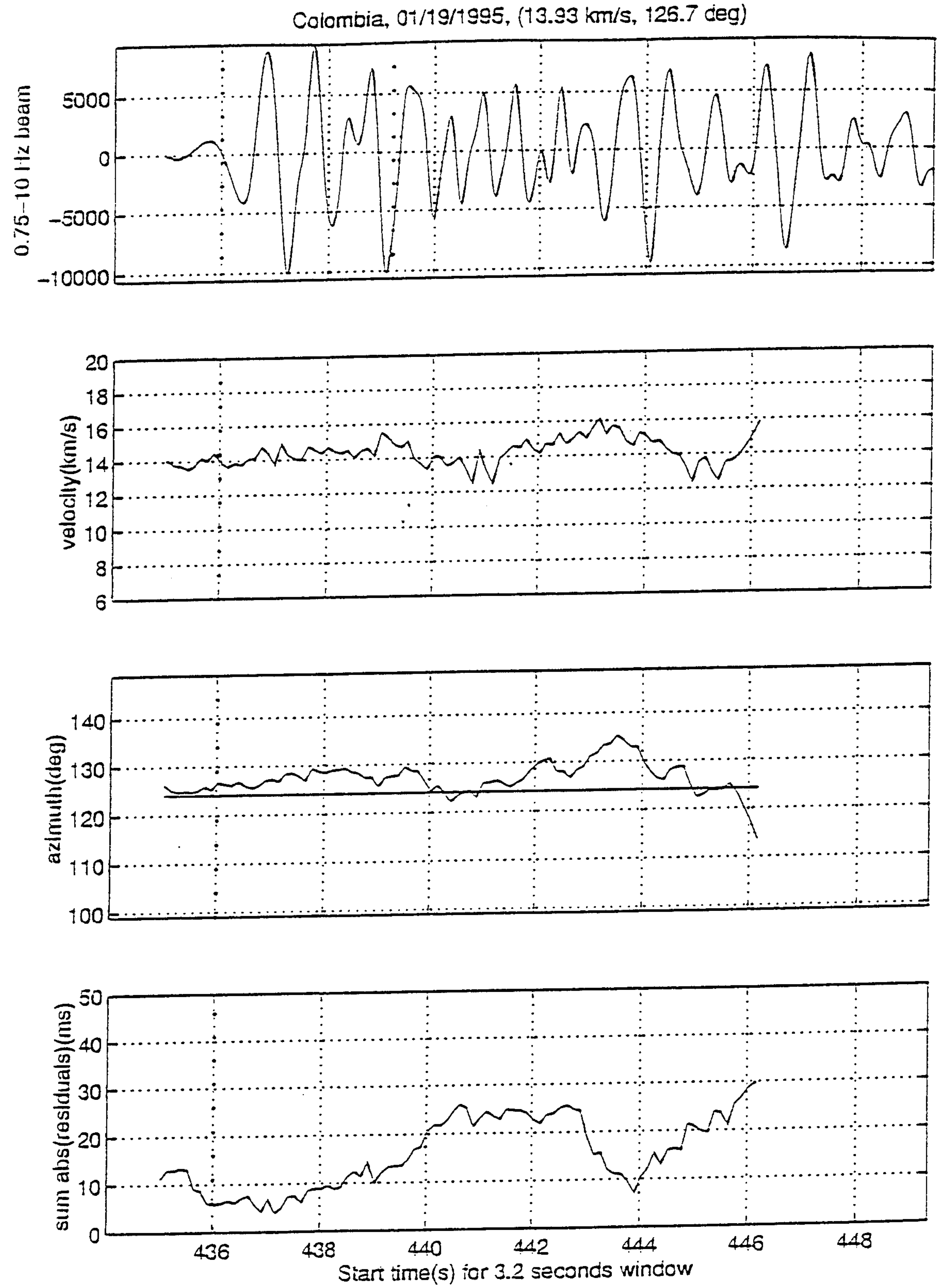


Figure A3 -- COLOMBIA, m_b=6.4

Origin Time: 01/19/95 15:05:04

Distance: 4207 km Azimuth: 124°

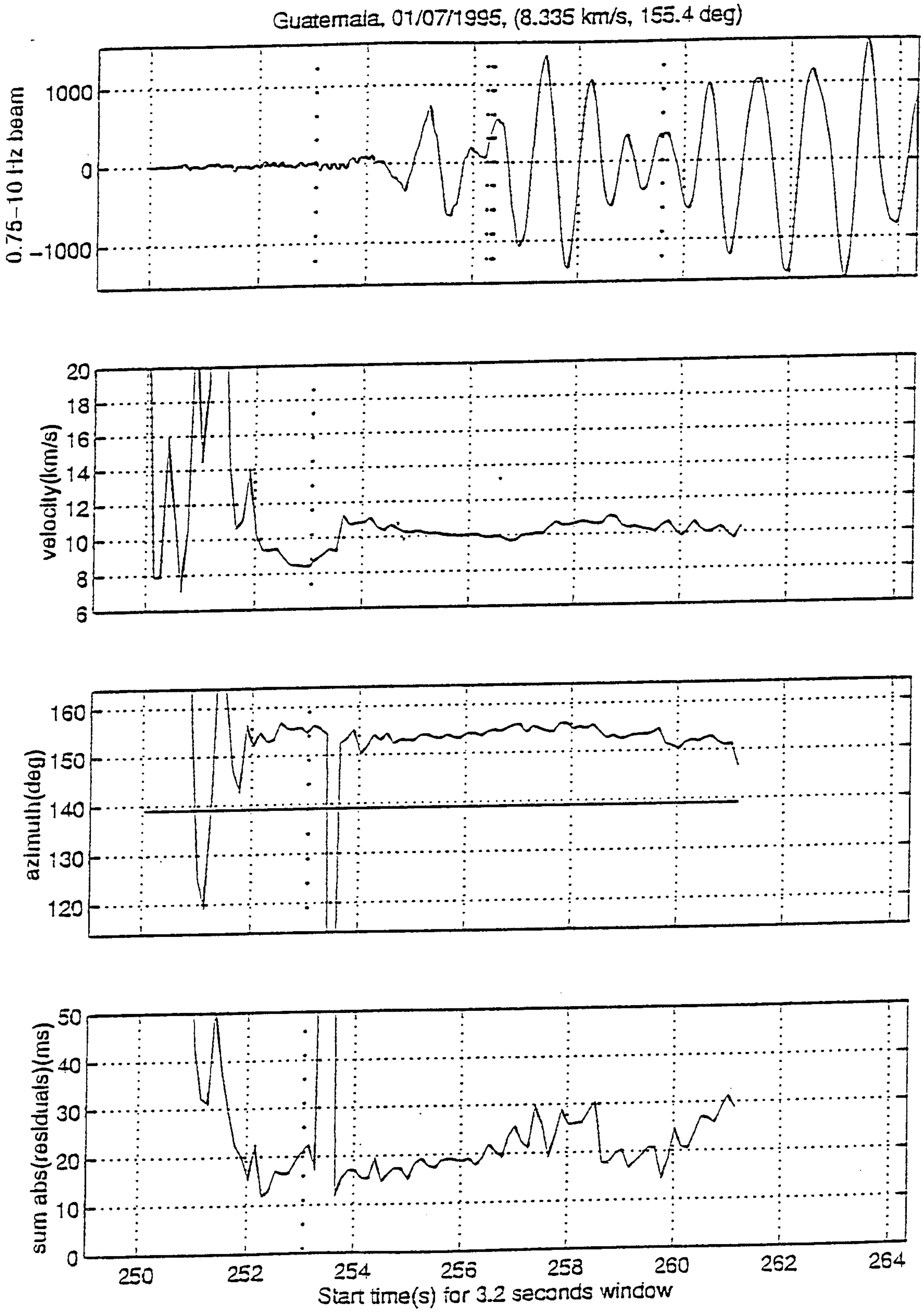


Figure A4 -- GUATEMALA, m_b=4.3
Origin Time: 01/07/95 02:36:32.4
Distance: 2055 km Azimuth: 139°

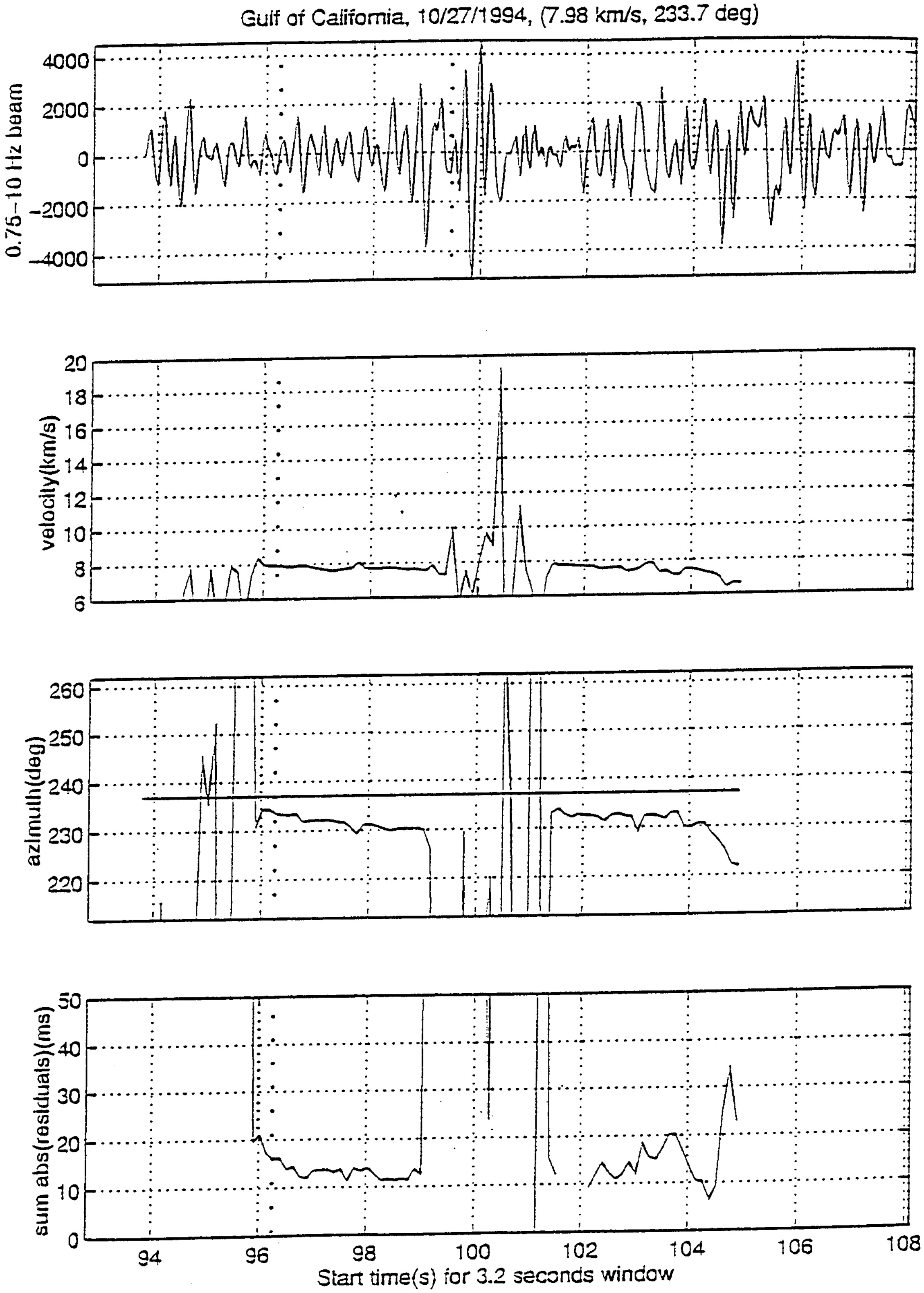


Figure A5 -- GULF OF CALIFORNIA, m_b=4.9

Origin Time: 10/27/94 09:14:35

Distance: 710 km Azimuth: 237°

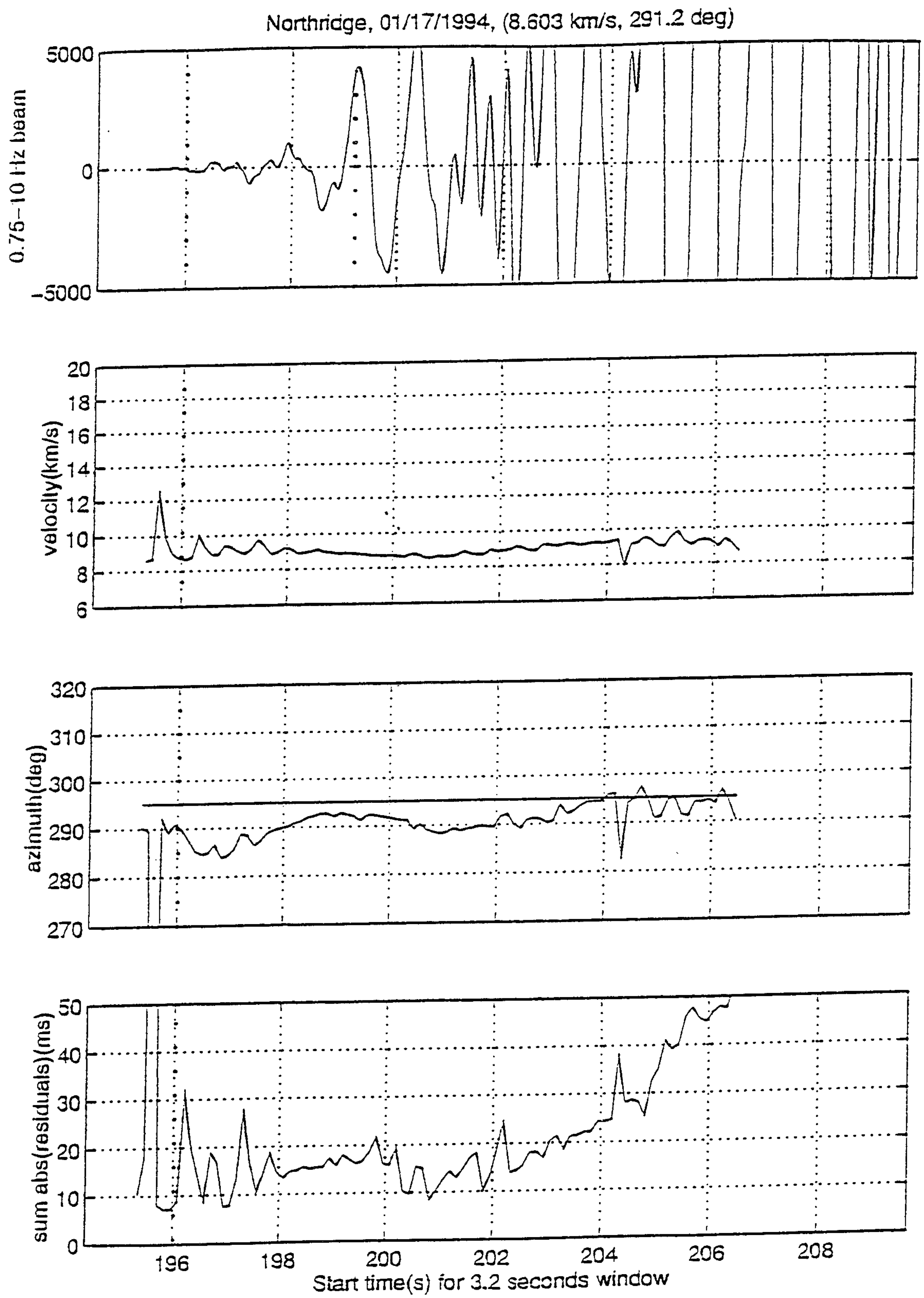


Figure A6 -- NORTHRIDGE, m_b=6.4

Origin Time: 01/17/94 12:30:55.3

Distance: 1505 km Azimuth: 295°

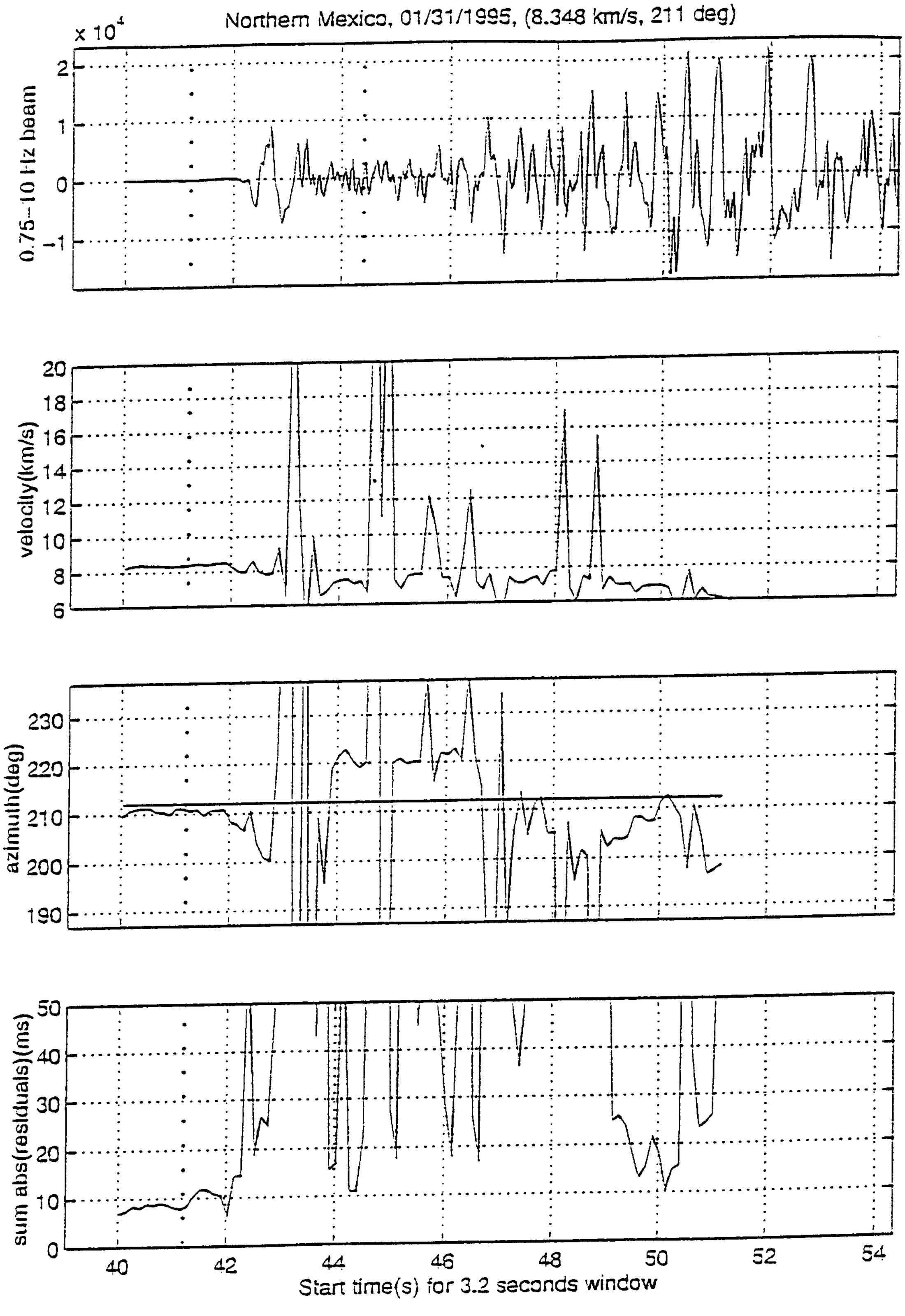


Figure A7 -- NORTHERN MEXICO, mb(Lg)=3.5

Origin Time: 01/31/95 11:33:47

Distance: 263 km Azimuth: 212°

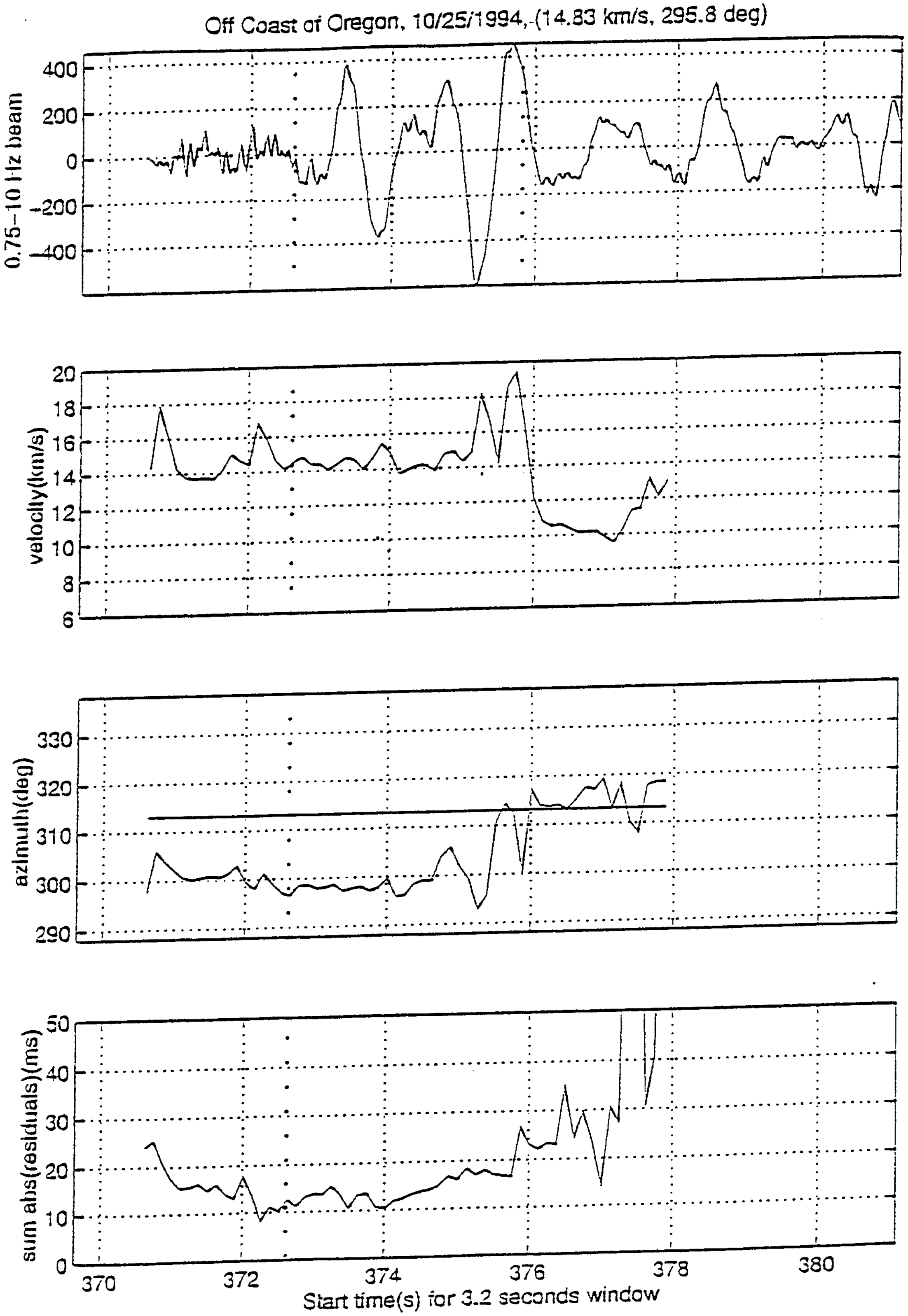


Figure A8 -- OFF COAST OF OREGON, m_b=4.3

Origin Time: 10/25/94 15:59:44

Distance: 2859 km Azimuth: 313°

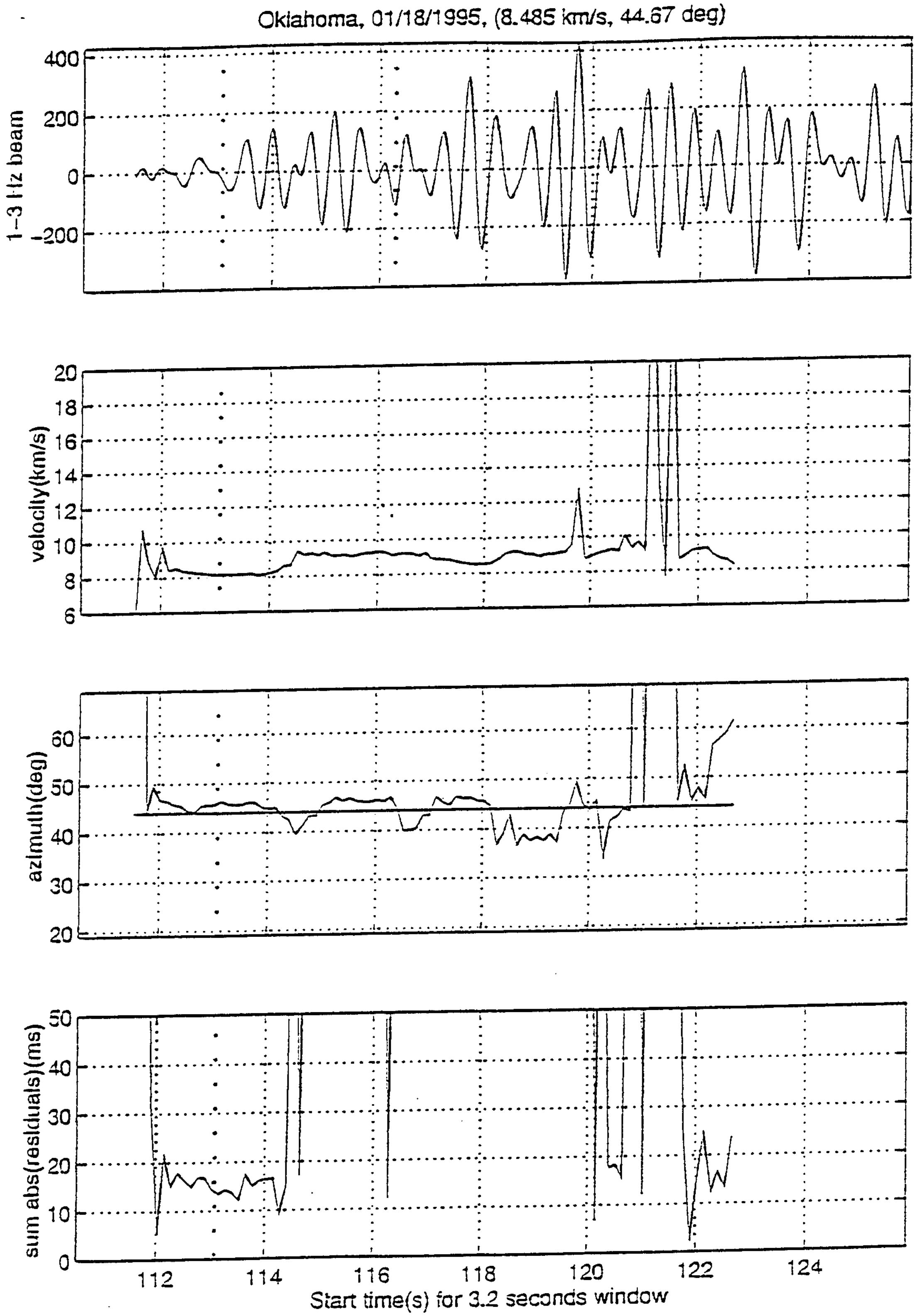


Figure A9 -- OKLAHOMA, m_b=4.0 (m_b Lg)

Origin Time: 01/18/95 15:51:37

Distance: 819 km Azimuth: 44°

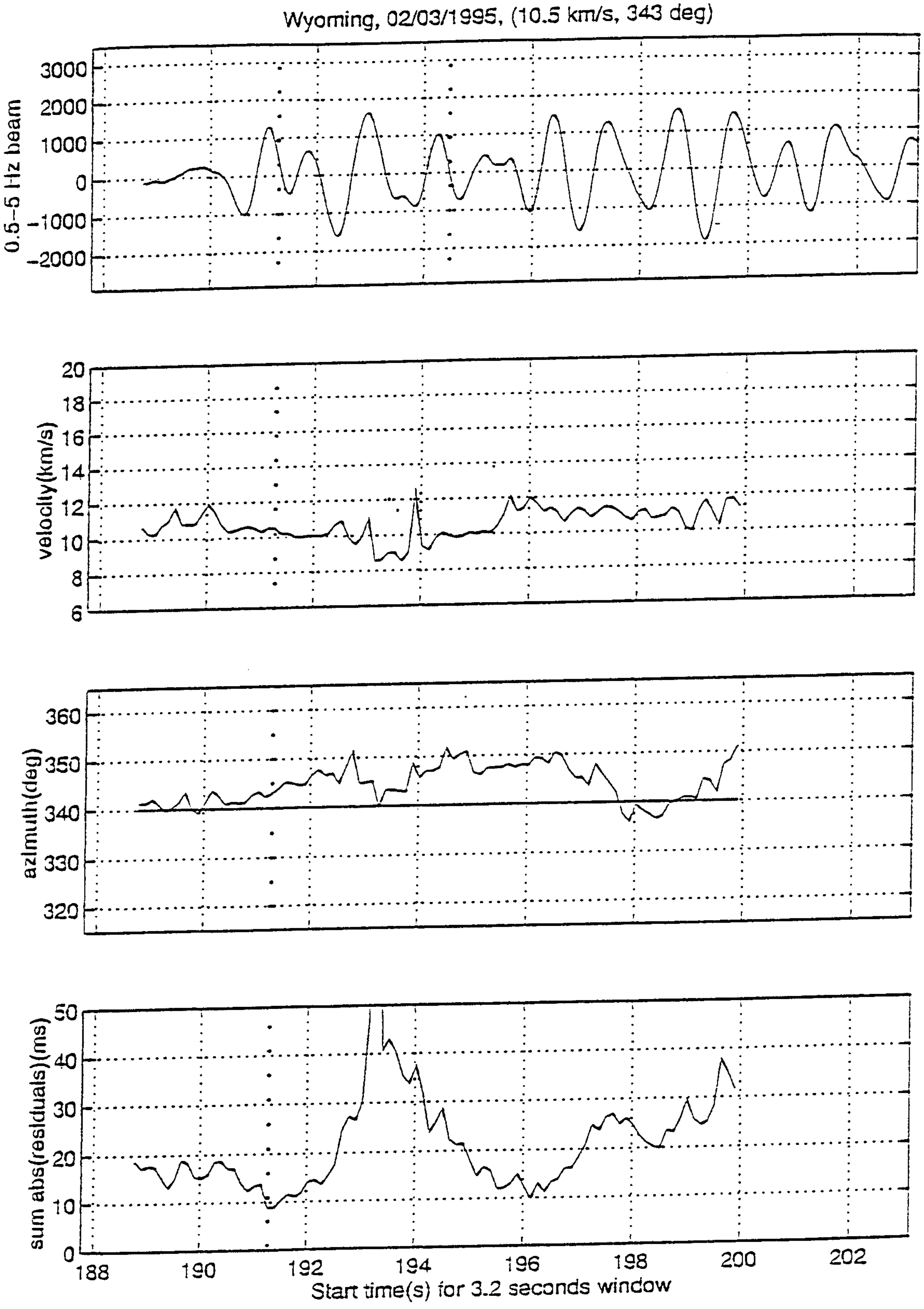


Figure A10 -- WYOMING, m_b=5.4

Origin Time: 02/03/95 15:26:11

Distance: 1468 km Azimuth: 340°

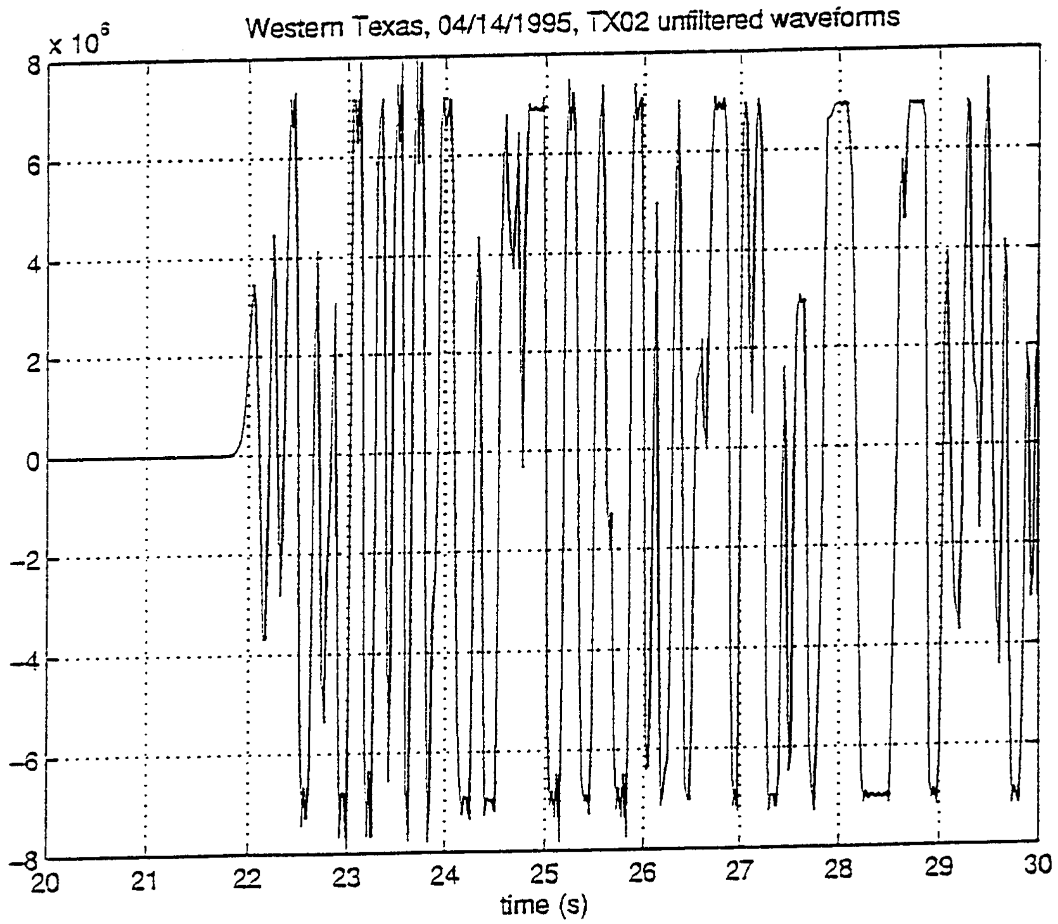


Figure A11 -- WESTERN TEXAS, m_W=5.8
Origin Time: 04/14/95 00:32:54
Distance: 107 km Azimuth: 19°

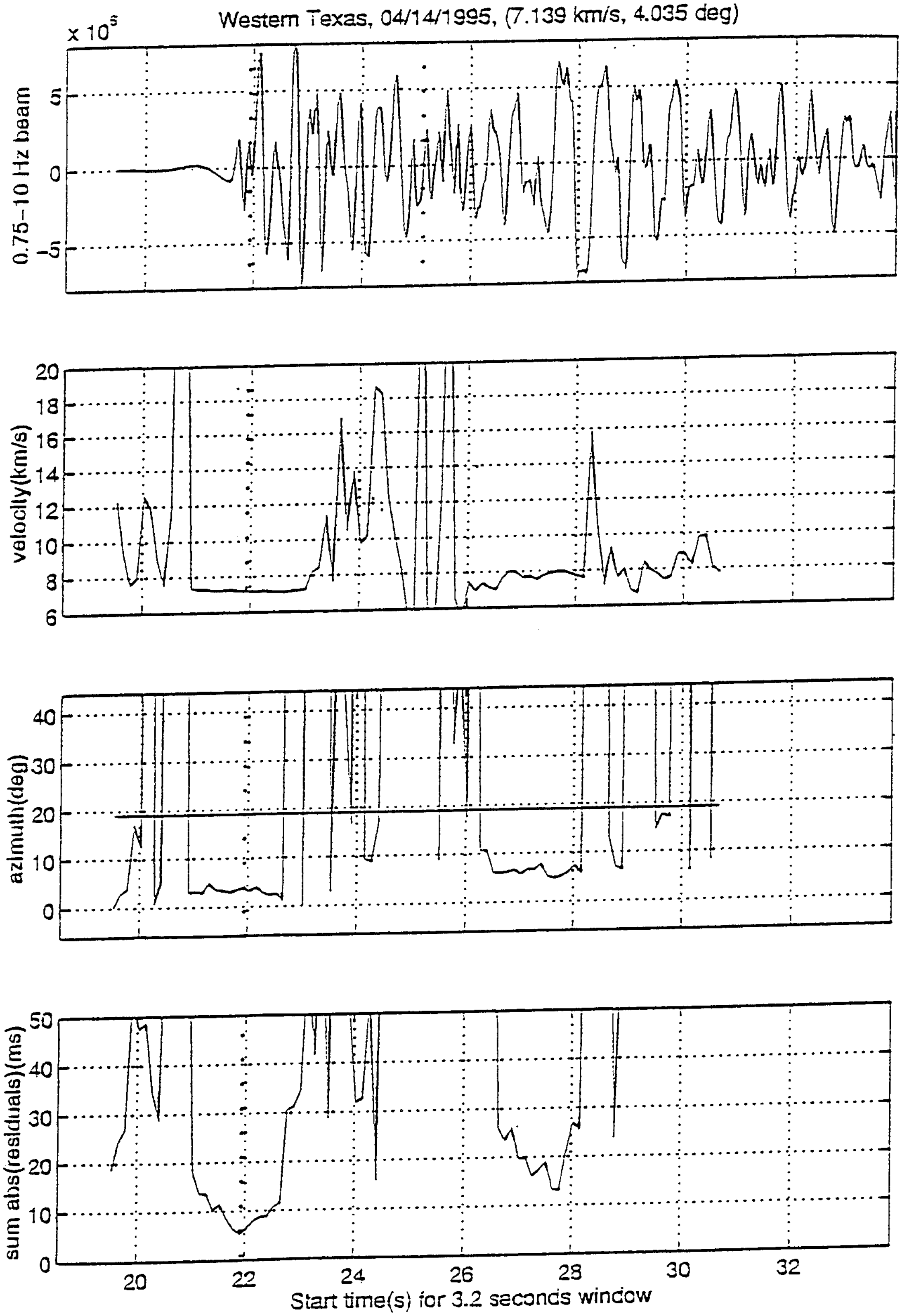


Figure A12 -- WESTERN TEXAS, $m_W=5.8$, showing the correlation method works well with digitally clipped data.

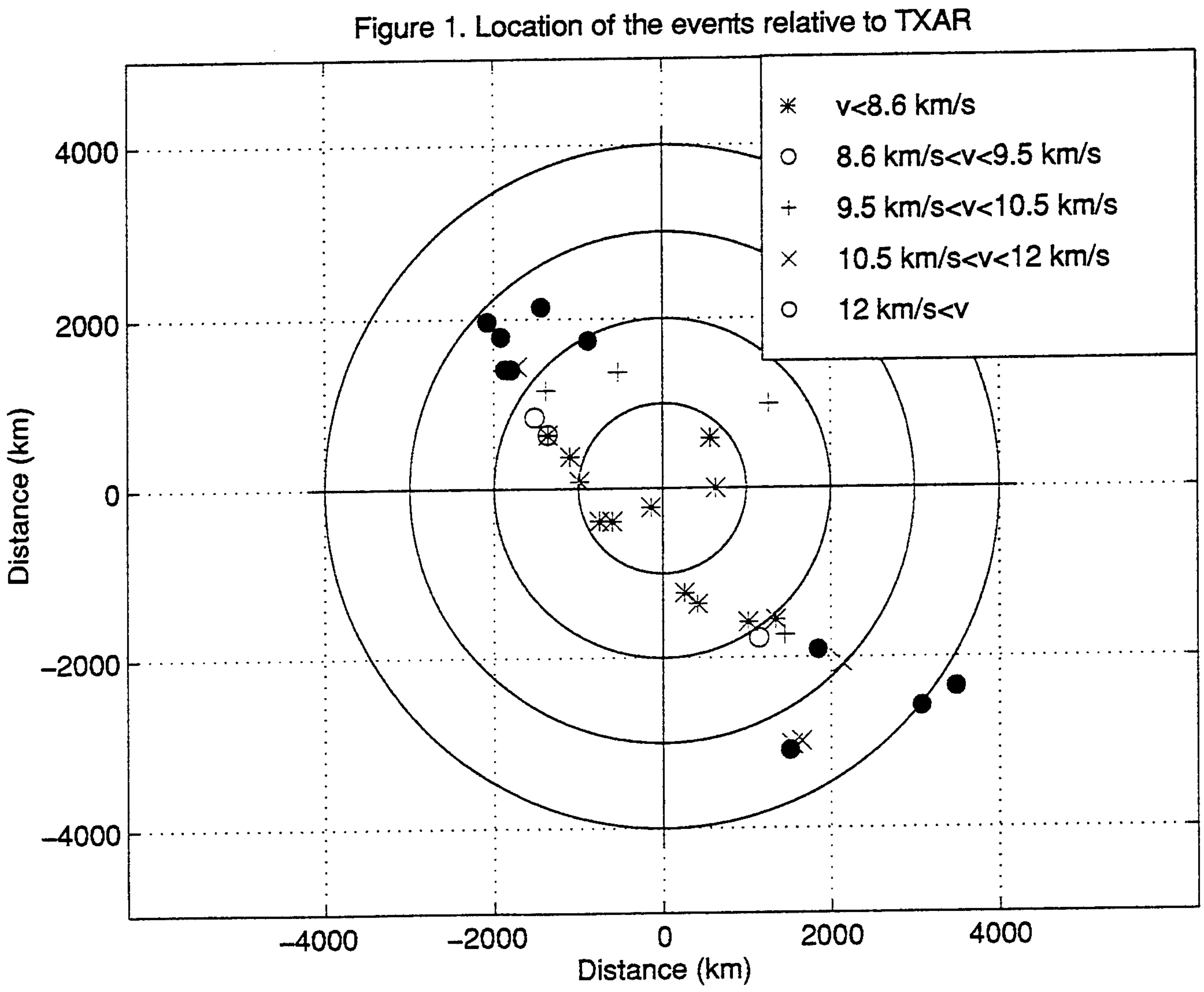


Figure A13 -- Location of events relative to TXAR

MAGNITUDE ESTIMATION AT TXAR

Various magnitude estimates were made for the 35 events shown in the color diagram and compared with USGS m_b. The most reliable estimates were those that used the Denny, Taylor and Vergino formula as follows.

For horizontal phase velocity less than 8.6 km/sec:

$m_b(D) = \log A + 2.4(\log\Delta) - 3.95 + C$
with $C=-0.35$

For horizontal phase velocity greater than 8.6 km/sec:

$m_b(D) = \log A + 2.4(\log\Delta) - 3.95 + C$
with $C=-0.05$

where A is zero to peak amplitude in nanometers
and Δ is epicentral distance in km.

CONCLUSIONS

1. Method results in stable correlation statistics even in the case of clipping.

2. Azimuthal corrections must be made for events whose epicentral distances are about 1, 000 km or greater from TXAR.

APPENDIX B -- SEISMIC DETECTION OF ACOUSTICAL WAVES

Gordon G. Sorrells and Eugene Herrin

INTRODUCTION

In order to verify compliance with the terms and conditions of a future Comprehensive Test Ban Treaty (CTBT), it will be necessary to provide the capability to detect and locate the source of low altitude atmospheric nuclear explosions whose yields are greater than or equal to one kiloton. The conventional approach to this problem is to deploy array of microphones or microbarographs to detect the atmospheric acoustic waves generated by such an explosion. It is well known that the detection of acoustic waves is complicated by the occurrence of turbulent atmospheric pressure fluctuations caused by the surface winds. Pipe arrays (Daniels, 1959) are commonly used to combat this problem. A pipe array is nothing more than a hollow tube with multiple inlet ports which is connected to the input of the microbarograph. The spacing between the inlet ports is chosen to minimize the correlation of the wind generated noise from port to port in the bandwidth of interest; while the aperture of the array is chosen to insure that the signal samples provided by the inlet ports add constructively across the same bandwidth. Therefore if ASNR is the acoustic signal to wind noise ratio at the inlet ports of a pipe array-microbarograph system, and $(ASNR)_m$ at its output, then under ideal conditions

$$(ASNR)_m = K^{0.5} ASNR \tag{1}$$

where K is the number of inlet parts in the pipe array. While it is possible to approach the ideal in narrow frequency bands, broad band gains will be substantially less because the spatial correlation of the wind noise increases as a function of decreasing frequency, while the spatial correlation of the signal decreases as a function of increasing frequency. (Mac Donald et al, 1971, Mack and Flinn, 1971). Therefore, as a general rule.

$$(ASNR)_m < K^{0.5} ASNR \tag{2}$$

An alternative approach to the acoustic wave detection problem, which has the theoretical potential to yield significantly greater gains during windy periods, is described in the following section.

PROPOSED TECHNICAL APPROACH

The corner frequency of the acoustic waves generated by a low altitude one kiloton atmospheric nuclear explosion is expected to be a few hertz (Pierce and Posey, 1971). This expectation is consistent with observations which indicate that at near regional distances, the peak power in acoustic signals triggered by large, surface HE shots is usually found in a bandwidth extending from about 0.5 to 3 Hertz (Stump, Personal Communications). It is significant to the discussion that follows to observe that this bandwidth is roughly comparable to the bandwidth used for the detection of the short period seismic signals generated by underground nuclear explosions.

Research in the early 1970's demonstrated that for atmospheric pressure disturbances which propagate at apparent horizontal phase velocities that are small in comparison to seismic wave velocities, the power spectra of the earth movements caused by these disturbances could be described by an equation of the form

$$P_j = |\mathscr{A}_J|^2 P_p \qquad (3)$$

where P_p is the power spectrum of the propagating pressure disturbances, $\mathscr{A}_J$ is a transfer function that describes the jth component of the earth's near field response to a spatially distributed source which can be characterized by the correlation structure of propagating pressure disturbance and P_j is the power spectrum of the jth component of earth movement (Sorrells and Goforth, 1973). In the same paper it was shown that for partially organized, slowly propagating atmospheric pressure disturbances,

$$\mathscr{A}_z \approx A_z \qquad (4)$$

where A_z is the transfer function describing the vertical component of the earth's near field response to a point pressure load applied at its surface. In addition it was shown (Sorrells, 1971) that at or near the surface of an elastic half space

$$A_z \propto c \tag{5}$$

where c is the apparent horizontal phase velocity of the propagating pressure disturbance. The pressure disturbances caused by the wind propagate at speeds that are approximately equivalent to the mean surface wind speed which is generally less than 10 m/sec. In contrast, the acoustic signal will propagate at apparent horizontal phase velocities that are greater than or equal to about 330 m/sec. It therefore follows from equation 5 that to the extent that the local structure can be approximated by an elastic, isotropic half space, the vertical component of the earth's response to an acoustic signal should be at least a factor of 33 greater than its response to wind noise. Thus, if $(ASNR)_z$ is the acoustic wave signal to noise ratio observed at the output of a short period vertical seismograph during a windy interval expressed in dB then

$$(ASNR_z) \geq ASNR + 20\log(33) - 10\log(1+R) \tag{6}$$

where R is the ratio of the seismic noise power under zero wind conditions to the seismic noise power caused by the wind driven pressure disturbance. Significant increases in vertical short period noise power are commonly observed during windy intervals at frequencies greater than 0.5 Hz. (cf.; Carter et al, 1991). Therefore it is reasonable to assume that during these intervals and in this bandwidth that nominal values for R are less than or equal to 1. Thus,

$$(ASNR)_z \geq ASNR + 24dB \tag{7}$$

and from equation 2

$$(ASNR)_m < ASNR + 10\log(K) \tag{8}$$

Therefore,

$$(ASNR)_z - (ASNR)_m \geq \left(24 - 10\log(K)dB\right) \tag{9}$$

Equation 9 states in effect that in the bandwidth of interest and given the assumption of an elastic, isotropic halfspace, the acoustic wave detection capability of a short period vertical seismograph system will be equivalent to or greater than an ideal pipe array-microbarograph system which contains at least 250 inlet ports. Preliminary research indicates that a pipe array-microbarograph system possessing these performance characteristics does not currently exist and, for the reasons given earlier concerning the correlation structure of acoustic signals and wind noise fields, it seems unlikely that one could be fabricated in the future. Therefore, it is predicted that the condition

$$(ASNR)_z > (ASNR)_m \tag{10}$$

will generally be satisfied in the bandwidth of interest during windy intervals. While equation 10 is based upon the assumption that the local earth structure can be well approximated by an isotropic, elastic half space, there is no reason to believe that it cannot be broadly applied to other areas characterized by more complex local structure. Thus, it has important practical implications with regards to treaty verification. In particular, it predicts that the short period vertical seismographs in the Alpha CTBT arrays have the potential to replace pipe array-microbarograph systems as short period acoustic wave detectors. Realization of this potential would eliminate the need for microbarograph arrays, thereby releasing resources tentatively committed to their acquisition and deployment to address other critical treaty verification requirements. Recommendations concerning actions that should be undertaken in order to fully realize this potential are summarized in the following section.

RECOMMENDATIONS

Theoretical Predictions Concerning Acoustic Wave Signal to Noise Ratios Should be Tested

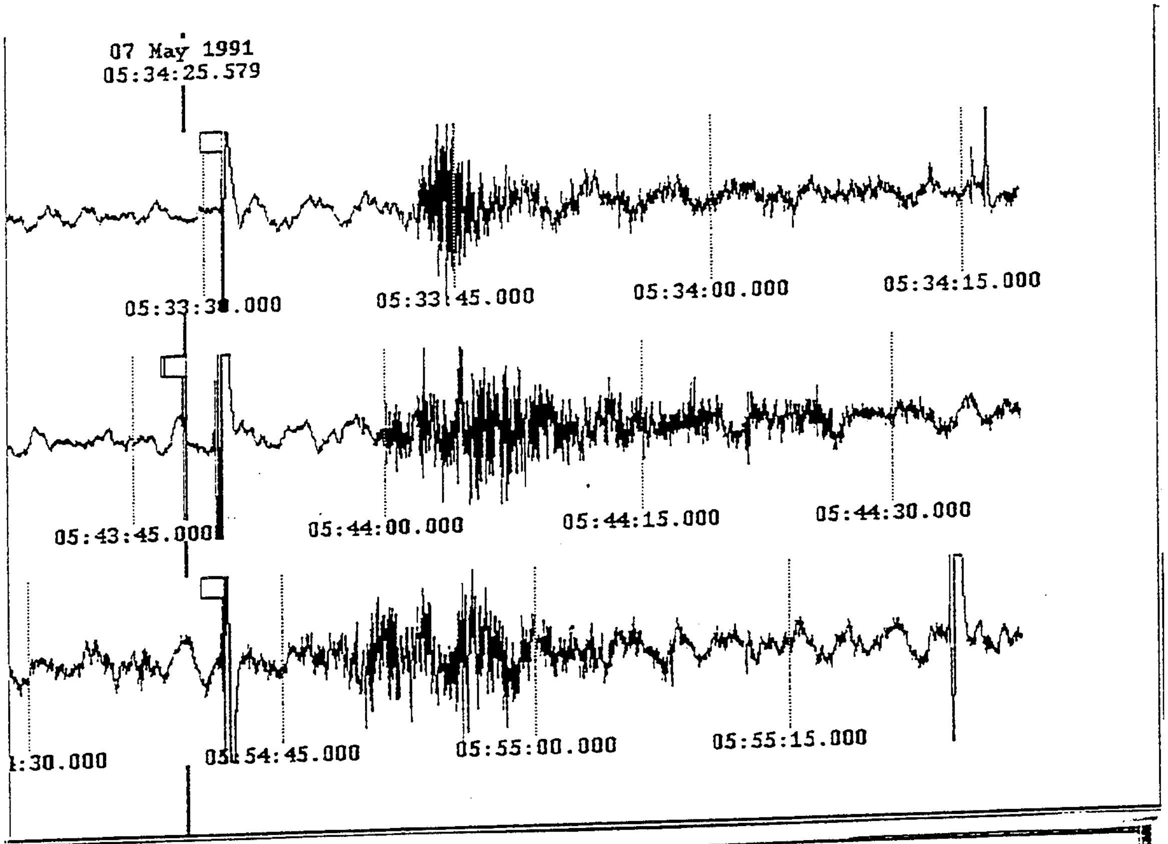
Field experiments should be undertaken to test the hypothesis that during windy intervals and for frequencies greater than about 0.5 Hz, the acoustic wave signal to noise ratio at the output of a short period vertical seismograph, $(ASNR)_z$,will exceed that observed at the output of a co-located pipe array-microbarograph system, $(ASNR)_m$. Since $(ASNR)_z$ is expected to vary as a function of:

1. the local seismic wave velocity distributions in the uppermost few hundred meters of the earth beneath the observation point;

2. the mean surface wind speed; and,

3. the correlation structure of the wind noise and acoustic signal fields.

the field experiments should be designed to test the validity of the hypothesis for demonstrably extreme values of these parameters. Furthermore, in order to minimize data acquisition expenses, these experiments should utilize existing Alpha array seismic sensors and facilities. The TEXESS array near Laitas TX is recommended for this purpose. In addition the experiments should be conducted during time intervals when naturally occurring sources of acoustic wave energy in the 0.5-5.0 Hz. bandwidth are likely to be active. In this regard, it is worth noting that seismic signals caused by acoustic waves with amplitudes of a few microbars should be detectable in this bandwidth at Lajitas, but as a rule, they have usually gone unnoticed and unreported because there has been no independent evidence indicating their origin. The records shown in figure B1a are an exception to this rule. These are short period vertical seismograms and seismic signals that are believed to have been generated by the passage of storm triggered acoustic waves. They were recorded at Lajitas, TX, during an interval when isolated thunderstorms were observed to be active in the region. The signals would have escaped attention



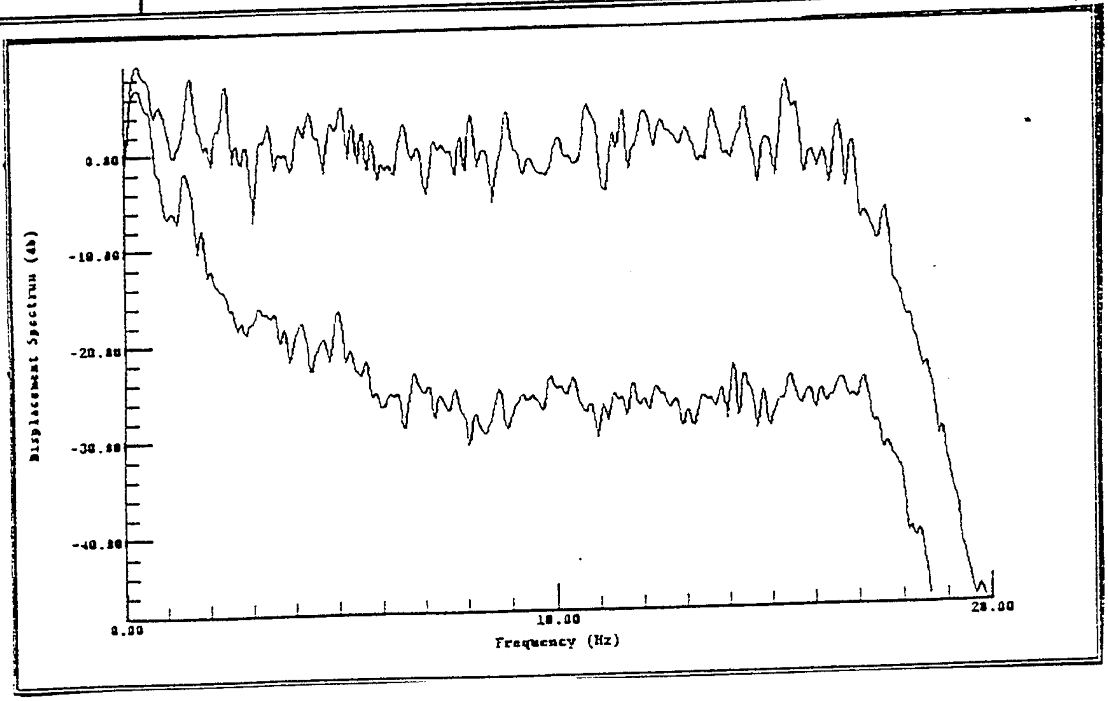


Figure B1a -- Short-period vertical seismograms illustrating lightning-triggered EM pulses followed by seismic signals presumably generated by the passage of the atmospheric waves caused by the lightning. These data were recorded at LTX in 1991 during a period of local thunderstorm activity.

Figure B1b -- Comparison of the ambient-noise spectrum with the spectrum of a representative short-period vertical seismic signal in the middle trace of figure B1a. The comparison shows that this type of source can generate power levels that are substantially above the ambient background at frequencies greater than about 0.5 Hz.

were it not for the fact that during this interval, high electrical noise was observed at the output of the vertical seismometer. The seismometer coil had apparently shorted to the case, and on closer inspection, the source of the electrical noise was identified as the electromagnetic (EM) pulses caused by the lightning associated with the local thunderstorms. Examples of these pulses are shown at the beginning of each record. High frequency seismic signals were invariably found to follow each EM pulse, but at variable time intervals. The arrival time of these signals roughly corresponded to the audible detection of thunder (Golden, Personal Communication). Therefore, they are assumed to be the seismic images of the acoustic waves generated by the lighting pulses. The spectrum of one of the larger signals is compared to the background noise spectrum in figure B1b. This figure indicates that the acoustic waves generated by local thunderstorms can produce seismic signals that are characterized by an essentially white spectrum in the bandwidth of interest and high signal to noise ratios. Thus isolated thunderstorms can serve as a rich source of the short period acoustic waves required to verify the predictions contained in the previous section. Isolated afternoon thunderstorms are an almost daily occurrence at Lajitas in a time period extending from late July through October. However, they are much less common at other times during the year. Therefore, in order to provide an early test of the hypothesis postulated above, the field experiments should be timed to begin no later than mid-July, 1994.

Studies Should be Undertaken to Determine the Feasibility of Extending the $(ASNR)_z$ Bandwidth to Lower Frequencies.

In the previous section $(ASNR)_z$ was predicted to be enhanced with respect to $(ASNR)_m$ only for frequencies greater than about 0.5 Hz. At lower frequencies, the large increase in microseismic noise power is expected to rapidly offset the predicted gains resulting from the large difference between the apparent horizontal phase velocities of the acoustic signal and the wind noise. Since attenuation will shift the peak acoustic signal power to lower and lower frequencies as the source-receiver distances increase, the existence of this microseismic noise barrier imposes a limit on the acoustic signal detection range of a short period vertical seismograph. While experimental studies are obviously required to determine quantitative limits on this range, it is perhaps more important to determine whether or not this barrier can be penetrated. In this regard, it is worth remembering that on the dimensional scale of the Alpha arrays, the noise power at frequencies less than 0.5 Hz will appear to be fairly well organized. In addition, it will be characterized by apparent horizontal phase velocities in the 3-8 km./sec. range (Haubrich, 1969). On the other hand, while the acoustic signal will be less well organized on the same dimension-frequency scale, it will be characterized by a much lower apparent horizontal phase velocities (330-400m/sec). Thus, depending upon their respective organizational states, it can be reasonably anticipated that the acoustic signals and the microseismic noise will be widely separated in (f-k) space. If the results of future studies are supportive of this expectation, then it is possible that adaptive realizations of the existing multi-channel array processing technology could be used to extend the enhanced $(ASNR)_z$ bandwidth to lower frequencies, thereby increasing the effective acoustic detection range of short period vertical seismograph to greater distances. Therefore, experimental studies to characterize the organizational state of acoustic signals and microseismic noises at frequencies less than 0.5 Hz., are strongly recommended. In addition the result of these studies should be used to investigate the feasibility of applying existing array processing technology to extend the $(ASNR)_z$ bandwidth. In order to minimize data acquisition expenses, these studies should use the existing TEXESS array and associated facilities and should be integrated into the field experiments recommended above.

The recommendations listed above are the basis for the proposed research program, which is summarized as follows.

TASK 1. Use the existing facilities at the Lajitas Test Site, supplemented with temporarily installed micro meteorological systems to test the hypothesis that during windy intervals and at frequencies greater than 0.5 Hz, the acoustic wave signal to noise ratio will be greater at the output of a short period vertical seismograph than at the output of a co-located pipe array-microbargraph system. Acquire data as required to identify and document extreme values of:

(1) the seismic wave velocity distribution in the uppermost few hundred meters beneath the observation point.

(2) the mean surface wind speed, and

(3) the correlation structure of the wind noise and acoustic signal fields.

Perform experiments to test the hypothesis under these extreme conditions. Initiate the field experiments on or before 15 July 1994 in order to maximize the opportunity to detect acoustic waves generated by isolated thunderstorms.

TASK 2. Use the short period data currently being acquired at the Lajitas Test Site to investigate the technical feasibility of applying existing multi-channel array processing technology to extend the bandwidth used for the seismic detection of acoustic waves to frequencies less than 0.5 Hz. Undertake studies to investigate the organizational state of the microseismic noise observed at the Lajitas Test Site at frequencies less than 0.5 Hz. Use these data to predict the potential gain in $(ASNR)_z$ that could be realized through the application of existing array processing technology. Where possible, test these predictions using acoustic and seismic data acquired at the Lajitas Test Site. In addition, investigate the use of other array configurations to enhance $(ASNR)_z$ at frequencies less than 0.5 Hz.

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