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VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

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Texas Instruments, Incorporated

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FINAL REPORT

VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

TEXAS INSTRUMENTS INCORPORATED
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Post Office Box 6015
Dallas, Texas 75222

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Alexandria, Virginia 22314

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Work performed on Contract F08606-74-C-0033 has been reported in detail in a series of fourteen technical reports. This final report summarizes the material covered in each of the technical reports and discusses the conclusions obtained. The five tasks in the program included a final evaluation of the Very Long Period Experiment (VLPE) stations and an evaluation of the detection and discrimination capabilities of a seismic

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Work performed on Contract F08606-74-C-0033 has been reported in detail in a series of fourteen technical reports. This final report summarizes the material covered in each of the technical reports and discusses the conclusions obtained. The five tasks in the program included a final evaluation of the Very Long Period Experiment (VLPE) stations and an evaluation of the detection and discrimination capabilities of a seismic network composed of the VLPE stations and the VELA long-period arrays in Alaska (ALPA) and Norway (NORSAR). The other tasks were studies concerning techniques for signal detection and signal estimation, discrimination methods for first-zone events, and various analyses of a future worldwide seismic surveillance system.

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SECTION I
INTRODUCTION

This final report summarizes work performed under Contract Number F08606-74-C-0033, entitled VELA Network Evaluation and Automatic Processing Research, by Texas Instruments Incorporated at the Seismic Data Analysis Center (SDAC) in Alexandria, Virginia. The program, which was conducted during the period from 1 November 1973 to 31 December 1974, consisted of the following six tasks:

- Continued evaluation of the stations of the Very Long Period Experiment (VLPE)
- Continued investigation of seismic network detection and discrimination capabilities
- Investigation of various signal detection methods including power detectors, Fisher detectors, and incoherent beam detectors
- Evaluation of adaptive filtering techniques for separating interfering signals
- Investigation of discrimination techniques for first-zone events
- Simulation of a worldwide seismic surveillance system and development of interactive graphics processing techniques for such a system.

The detailed results obtained for these tasks have been presented in a series of fourteen Technical Reports. This final report summarizes the results in Sections II through VII, references are given in Section VIII, and a list of all reports issued under this contract is given in the Appendix.

SECTION II

VLPE STATION EVALUATION TASK

The results of the VLPE station evaluation are presented in four reports. Technical Report No. 1 discusses the measurement of Rayleigh wave group velocities over several Eurasian travel paths. Technical Report No. 3 discusses the ambient seismic noise characteristics measured at the VLPE stations. The effects of various parameters on the indirect estimation of station detection thresholds by noise level measurements are discussed in Technical Report No. 4. Finally, in Technical Report No. 5, matched filters and the three-component adaptive processor are evaluated using VLPE data. Summaries of these reports are given in the following subsections.

The discussion of the detection and discrimination capabilities of the individual VLPE stations is deferred to Section III where they are presented in Technical Report No. 7 as parts contributing to an overall multistation capability.

A. Technical Report No. 1: Observed Rayleigh Wave Group Velocities and Spectral Amplitudes for Some Eurasian Paths

The establishment of the Very Long Period Experiment (VLPE) provided a small network of high gain, high quality, long-period digital seismographs at various locations throughout the world. Further, the availability of a list of confirmed and well-located events occurring during the International Seismological Month (ISM) provided the opportunity to determine and compare Rayleigh wave group velocities of several continental travel paths in Eurasia to those determined by others.

For this study, we selected three central Asian events which occurred during the ISM and were recorded at several VLPE stations located in Eurasia. Fundamental Rayleigh wave group velocities and spectra were determined using narrowband filters to minimize possible noise, multipath, and higher mode effects.

The spectra were corrected for geometrical spreading and effective attenuation. Turnbull et al. (1973) using Tryggavason's method (1965) determined the effective attenuation for a selected path from Sinkiang to Chang Mai, Thailand (CHG).

The group velocities are compared to those determined by Santô and Satô (1966) for various tectonic regions in Eurasia and to those determined by Brune and Dorman (1963) and McEvilly (1964) for the mid-continental United States. A summary of the results from the analysis of these three events is as follows.

The group velocities measured over the range of periods from 15 to 60 seconds are sampling the crust and upper mantle structure to depths up to 300 kilometers. Thus, differences in the observed group velocity curves relative to CANSD or McEvilly's reference group velocity curve can be explained by variations in thicknesses and elastic parameters of the crust and upper mantle.

Ten different paths were examined in this report. The observed group velocities for paths 1 through 6 (paths through platform regions) show slightly lower velocities at periods of 50 to 60 seconds than McEvilly. This suggests that the low velocity zone in the upper mantle is thicker than the indicated 58 kilometers by McEvilly. It is probable that the thickness of 200 kilometers shown for the CANSD model would have provided more appropriate velocity values for these longer periods.

The observed group velocities for path 7 which crossed the Caspian and Black Sea regions reflects the thickening of the low velocity surfacial layer, thinning of the crust and lower moho velocity. Here, the short-period velocities are significantly lower, the slope for the intermediate periods is comparable, and the overall velocity curve is lower than that observed for the platform regions.

Path 9 is a complicated path which crosses the Alpine-Himalayan fold system, Caspian Sea region and the Russian platform. For this path we observed significantly lower group velocities but little or no unusual variations in amplitude levels. Since the observed group velocities are averages of the structures traversed, we can only suggest that the Alpine-Himalayan fold system portion of the path was small in distance compared to the rest of the path. This caused lower group velocities but had little effect on the effective attenuation of the Rayleigh wave.

Paths 8 and 10 are extremely complex in that path 8 traverses the Alpine-Himalayan fold system and path 10 crosses the central Asian, central China fold systems and a portion of the Tibet platform. The fold systems result from the collision of continents according to the theory of plate tectonics (Metz and Hammond, 1974). The Himalayas are thought to have formed when the Indian subcontinent collided with the Eurasian continent. Little is known about mountain building caused by continental collisions since vertical motions are almost as rapid as horizontal motions.

Thus, the cross section used for the Alpine-Himalayan and for the other fold systems is an over simplification of the true structure. However, it does provide an explanation for the observed low group velocities and amplitudes by indicating large crustal thicknesses totaling about 75 kilometers.

These are the overall conclusions of this study.

Eurasia is comprised of vast platform structures. The observed Rayleigh wave group velocities indicate that the structure of the crust and upper mantle for these regions is similar to that of the central United States. Various authors have written that all continents have essentially the same crust and upper mantle structures. Thus, these results were as expected.

However, for paths encompassing fold systems such as the Alpine-Himalayan, central China, and central Asian, we found a significant decrease in the Rayleigh wave group velocities and amplitudes, indicating high effective attenuation properties. Further, for path 10 multipathing is evident.

B. Technical Report No. 3: Earth Noise at Very Long Period Experiment Stations

This report presents the results of a study of broadband earth noise at Very Long Period Experiment (VLPE) stations. The specific objectives of this investigation were:

- The determination of the long-term (seasonal) behavior of the vertical component noise field
- The investigation of the three component noise spectra
- The calculation of intercomponent coherence.

These objectives were accomplished by processing and examining 1503 one-hour vertical component noise samples and 846 one-hour three component noise samples from all VLPE stations for the period from January 1972 through March 1973.

The main results and conclusions from this study are summarized below:

Data Base

- For the period from January 1972 through March 1973, 2734 hours of noise data from all VLPE stations were available. Only 1503 (55%) had usable vertical component data and 846 (31%) had usable three component data. Thus, overall data quality was relatively poor.

- In order to avoid visual inspection of large numbers of plots acceptance criteria on the basis of RMS amplitudes and power densities were developed. However, an estimated 10% of the noise samples passing the criteria still contain non-seismic noise. Station EIL was subjected to less stringent acceptance criteria in order to obtain enough samples for analysis.

Vertical Component Noise Analysis

- The average base levels in the 17-25, 20-40, and 30-40 seconds period bands of the vertical component noise data for all VLPE stations were 14.5, 10.1, and 4.5 $m\mu$, respectively, showing the stable minimum at 30-40 seconds periods observed in previous studies.

- The approximate ordering of VLPE stations from quietest (lowest vertical component RMS amplitudes) to noisiest (highest vertical component RMS amplitudes) was as follows: ZLP, CHG, KIP, ALQ, FBK, TLO, EIL, MAT, KON, OGD, and CTA.

- The small quantity and uneven distribution of the vertical component noise data prevented conclusive statements about the long-term (seasonal) variations in the RMS amplitudes at any VLPE stations except station KON which showed definitely increased RMS amplitudes during the winter periods.

Three Component Noise Analysis

- Variability of the RMS amplitudes appeared constant throughout the period range of 13.5 to 62.5 seconds for all components, which is contrary to previous results. This difference probably is due to the more stringent acceptance criteria and the larger data base.

- Within the average minimum noise band of 22-42 seconds, the horizontal component spectra were remarkably similar to the vertical component spectra in amplitude, variability, and spectral shape. Outside this band the horizontal RMS amplitudes were generally one to four times larger than the vertical RMS amplitudes.

- Assuming time stationarity of the noise observations, all components of all VLPE stations were only weakly coherent, suggesting that the average long-term noise field is composed of mainly isotropic noise.

C. Technical Report No. 4: Estimating a Seismic Station's Detection Capability from Noise. Application to VLPE Stations

In monitoring earthquakes and underground nuclear explosions one is interested in the detection capability of a seismic station, array or network. This detection capability is usually expressed as the probability of detecting a seismic event of a given magnitude in a certain region. One method to determine the detection capability is to compute the percentage of events actually detected for each of several magnitudes. The maximum likelihood approach to this so-called direct method fits a Gaussian probability of detection curve to the detection percentages (Ringdal, 1974). The direct method requires a large population of events and consequently, establishing the detection capability of a station, array or network takes considerable time.

Another method estimates the detection capability based on the ambient noise levels at a station (Lacoss, 1969; Harley, 1971; Harley and Heiting, 1972). In this method it is assumed that an event signal can be detected when its maximum amplitude exceeds that of the surrounding noise by a certain margin, e.g., 3 dB. We may then assign a magnitude to the maximum noise amplitude (A) occurring in a certain time gate, using some period (T) and some epicentral distance (Δ). For surface waves this magnitude is (Harley, 1972):

$$M_{s_{noi}} = \log A/T + \log \Delta + 1.12 + C_1$$

where $\log \Delta + 1.12$ represents the distance correction, and C_1 is a detection criterion margin, e.g., $C_1 = 0.15$ for a 3 dB margin. The probability of detecting an event of given magnitude $M_{s_{sig}} = x$ then is assumed to be given by the probability that the noise magnitude is less than or equal to x :

$$P(\det M_{s_{sig}} = x) = P(M_{s_{noi}} \leq x) .$$

Usually, collecting noise data (for instance, an ensemble of daily noise samples) is a much faster process than gathering data from actual events, and if noise amplitude distributions are stationary with time the detection capability can be established in a relatively short time period. This is particularly important in evaluating new or proposed seismic station sites.

In the above formulae some of the parameters involved have not been studied in detail, and so their effects in estimating detection capabilities have not been fully specified. Also, Lambert observed from his Very Long Period Experiment (VLPE) data that the noise peak-amplitude-over-RMS ratio at the seismometer output was relatively constant for the individual stations as well as from station to station (Lambert et al., 1973), and he raised the possibility that 50% detection thresholds may be estimated from average RMS noise levels.

The analytical and empirical investigation of the above topics are the subject of this report. Analytically, the probability of detection is developed into validity conditions for the application of detectability estimation methods, and differences between the estimation from noise and direct estimation are discussed. Empirically, the method of estimating detection capabilities from noise assuming a Gaussian probability of detection is applied to stations of the VLPE network, and the results are compared with maximum likelihood direct estimates for those stations. The study has been confined to surface wave detection threshold estimates derived from the vertical Rayleigh wave component, but could be extended to include horizontal Rayleigh wave, Love wave, and/or bodywave detection threshold estimation.

A summary of the pertinent results and conclusions from this study are as follows.

If detection of a seismic event at a given station is based on the surface wave signal-to-noise ratio (SNR) the probability of detecting an event given its 20-sec reference magnitude is given by the probability distribution function of a random variable (r. v.) M :

$$P(\det \bar{M}_s(20) = x) = P(M \le x) = F_M(x) ,$$

where

$\bar{M}_s(20)$ is the 20-sec reference magnitude for the event concerned;

x is the numerical value of the reference magnitude;

$F_M(x)$ is the probability distribution function of the r. v. M .

The r. v. M is described by

$$M = M_N + d(T) - b ,$$

where

M_N is the so-called 'noise magnitude';

d(T) is the 20-sec minus T-sec magnitude difference;

T is the period of the maximum event signal amplitude at the seismometer output;

b is the station magnitude variation about the reference magnitude.

The 'noise magnitude' is given by

$$M_N = \log A_{N_{out}} - \log T \cdot G(T) + \log \Delta + C ,$$

where

$A_{N_{out}}$ is the maximum peak-to-peak noise amplitude at the seismometer output;

T is the signal period defined above;

G(T) is the instrument response for the period T, scaled so that a 40-sec output amplitude represents true ground motion in millimicrons, G(40) = 1;

Δ is the epicentral distance for the event and station concerned;

C = 1.12 + a SNR detection margin (e.g., 0.15 for a 3 dB margin).

The term 'noise magnitude' is not quite appropriate since it consists of a noise parameter ($A_{N_{out}}$) on the one hand, and event signal parameters (T, Δ) on the other.

The above model of the detection mechanism does not presume any special statistical characteristics, and therefore may serve as a model for any method of estimating a seismic station's detection capability. Based on this model two methods of estimating detection capabilities and two approaches to each method were discussed:

- Estimation from actual detection percentages
  - not assuming statistical characteristics (the so-called direct method)
  - assuming a Gaussian probability of detection (the maximum likelihood approach to the direct method).
- Estimation from noise
  - not assuming specific statistical characteristics;
  - assuming a Gaussian probability of detection.

Available data indicates that the probability of detecting an event given its magnitude can be considered to be approximately Gaussian, if the relative distance range, Δ/Δ_o, is kept small (e.g., $\Delta_o = 50^\circ$, $35^\circ < \Delta < 80^\circ$; $\Delta_o = 100^\circ$, $70^\circ < \Delta < 160^\circ$).

The Gaussian probability of detection then is described by:

$$F_M(x) = 0.5 + \text{erf}\ \frac{x - \mu_M}{\sigma_M}$$

where μ_M and σ_M are the mean and standard deviation, respectively, of the r.v. M. In this case the detection thresholds are determined by μ_M and σ_M.

In estimating detection capabilities from noise the statistics of each term constituting the r.v. M, i.e., the statistics of noise amplitude, event signal period, event epicentral distance, and station magnitude bias, are combined to yield the detection probability distribution function $F_M(x)$. In the general case the entire $F_M(x)$ curve must be established; in the Gaussian case we only need to determine the mean and standard deviation of M.

Instrument output RMS noise values may be used instead of maximum noise amplitudes in this method if the average maximum-amplitude-over-RMS ratio is known for the station concerned. This ratio was approximately equal among four out of six VLPE stations.

Based on the analysis of the two methods and their approaches it was concluded that for the non-Gaussian as well as for the Gaussian case there should be little difference between the estimates obtained from actual detection percentages and those obtained from noise samples. This conclusion was supported by an empirical evaluation performed on six stations of the VLPE network, by comparing detection capabilities estimated from noise, assuming a Gaussian detection model, with estimates obtained by the maximum likelihood method. The 50% detection threshold estimates of the two methods agree in general within 0.2 magnitude units. Since the M_s variances used to determine the maximum likelihood detection curves were derived from m_b variances and differ from the M_s variances established for detection capability estimation from noise, the 90% detection thresholds differ correspondingly. The minimum statistical population for estimating detection capabilities from noise appears to be in the order of 30 valid noise samples, and a station's detection capability may be established within one or two months for a well-performing instrument.

This technique, however, requires a prior knowledge of the statistics of the periods of maximum signal amplitudes, the epicentral distances, and the station magnitude bias. For an existing station these statistics may be obtained from previously processed events. For a new or proposed site the distance statistics can be established from the seismicity in the region of interest. The other statistics may be estimated from the event processing performed for other stations of a similar physical configuration. Furthermore, the estimates obtained from noise may require seasonal adjustments.

Finally, it is pointed out that if the statistics describing the detection model are not Gaussian, this will introduce corresponding errors in the maximum likelihood estimates and in the estimates obtained from noise. Agreement between these two methods, therefore, does not necessarily guarantee that these estimates are correct with respect to the actual detection capabilities.

Related topics that need further investigation are the distributions and mutual correlations of signal period, epicentral distance, and station surface wave magnitude bias; procedures for the selection of valid noise samples; extension of this study to bodywave magnitudes and the surface-wave horizontal components; and comparison of non-Gaussian detection capability estimation from noise with the non-Gaussian detection estimates of the direct method.

D. Technical Report No. 5: Evaluation of Matched Filters and the Three-Component Adaptive Processor for the VLPE Stations and VLPE Network

Surface waves often arrive at stations located at teleseismic distances from the epicenter with amplitudes at or below the noise level. In order to detect such signals and determine their magnitudes, special processing techniques must be employed. Three such techniques are evaluated in this report using data from the Very Long Period Experiment. They are: chirp matched filters (CMF), reference waveform matched filters (RWMF), and the three-component adaptive processor (TCA). These techniques were applied to events from two regions, Greece-Turkey (GTUR) and central Asia (CENA).

The specific goals of this study were:

- To estimate potential signal-to-noise ratio gains of each of these techniques.
- To evaluate the effectiveness of these three techniques in increasing the surface-wave detection capability of the VLPE stations.
- To apply the signal-to-noise ratio improvement estimates to the calculation of surface-wave magnitudes for events which were not detected on the bandpass-filtered trace.

- To compare the relative effectiveness of the three techniques.

A preliminary evaluation of these techniques as applied to VLPE data was presented by Lambert et al. (1973) where the application of each technique to events having epicenters in a small region of Sinkiang Province, China was discussed. Conclusions were limited by the small amount of observational data available. The preliminary evaluation did indicate that appropriate chirp matched filters performed essentially the same as reference waveform matched filters when matched with Rayleigh waves. The use of matched filters decreased the number of non-detected events by 36 percent. Both chirp and reference waveform matched filters yielded signal-to-noise ratio improvements of 3.5 dB for earthquakes and 3.7-3.8 dB for presumed explosions. The three component adaptive processor yielded detection results comparable to those for the chirp matched filter.

Analysis of data recorded at the Alaskan Long Period Array (ALPA) (Strauss, 1973) indicated that chirp matched filters were slightly more effective than reference waveform matched filters, that matched filters reduced the number of non-detected events by 20 percent, and that the greatest change in the detection versus bodywave magnitude plots caused by inclusion of these detections occurred at the 50 percent detection level.

Analysis of data recorded at the Norwegian Seismic Array (NORSAR) (Laun et al., 1973) indicated that reference waveform matched filters were slightly more effective than chirp matched filters, that matched filters reduced the number of non-detected events by about 10 percent, and that inclusion of these detections in the detection versus bodywave magnitude plots decreased the detection levels between the 30 percent and 80 percent detection levels. (The three-component adaptive processor was not applied to ALPA or NORSAR data.)

One of the methods of comparing the performance of the three data enhancement techniques under consideration was in terms of signal-to-noise ratio improvement over the equivalent bandpass filter (0.023-0.059 Hz) signal-to-noise ratio. The signal-to-noise ratio improvement of a matched filtered trace over the corresponding bandpass filtered trace, expressed in decibels, is:

$$\text{IMPROVEMENT (dB)} = 20 \log_{10} \left[(S_M/N_M) / (S_{BP}/N_{BP}) \right].$$

Or, in a more convenient computational form:

$$\text{IMPROVEMENT (dB)} = 20 \log_{10} \frac{S_M}{S_{BP}} + 20 \log_{10} \frac{N_{BP}}{N_M}$$

where S and N are the peak signal and the RMS noise amplitude, respectively, the M subscript denotes matched filter, and the BP subscript denotes bandpass filter.

Since the manner in which the VLPE data was edited often precluded the existence of a noise sample of suitable length on the edited signal trace, the values of N_{BP} and N_M in the above equation were determined from a noise sample of the same day.

Each of the three data enhancement techniques was evaluated in terms of signal-plus-noise-to-noise ratio (SNNR) improvement (expressed in dB), detection level improvement, and surface-wave magnitudes.

The mean SNNR improvements and associated standard deviations for each technique were measured for both regions, CENA and GTUR. In each region the best technique was judged to be that one which displayed the largest mean SNNR improvement with the smallest associated deviation. Using this criterion the best technique for SNNR enhancement, by region was:

CENA - The chirp matched filter technique outperformed the other two.

GTUR - The chirp matched filter technique outperformed the other two. However, the reference waveform matched filter technique was almost as good.

In another comparison of the three techniques, approximately 75 percent of the central Asia test events showed higher chirp SNNR improvements than reference waveform SNNR improvements, and approximately 67 percent of the central Asia test events showed higher chirp SNNR improvements than three-component adaptive processor SNNR improvements. Greece-Turkey test events yielded about the same SNNR improvements on chirp and reference waveform matched filters, while approximately 85 percent of the test events from this region showed higher chirp SNNR improvements than three-component adaptive processor SNNR improvements. Therefore, by this criterion, chirp matched filters outperformed both the reference waveform and three-component adaptive processor on central Asia events. For Greece-Turkey events, chirp and reference waveform matched filters outperformed the three-component adaptive filter by the same amount. This is in agreement with the preceeding judgment made on the basis of mean SNNR improvement and associated standard deviation.

The second point of comparison was the relative ability of the three techniques to detect signals which were not detected on the bandpass filter response. For the combined region, use of chirp matched filters resulted in a 130 percent increase in the number of events detected and use of reference waveform matched filters resulted in a 140 percent increase in the number of events detected. The use of the three-component adaptive processor resulted in only a 10 percent increase in the number of events detected. Thus, in terms of the increase in the number of events detected, use of chirp or reference waveform matched filters more than doubled the number of detections, while use of the three-component adaptive processor resulted in very little improvement in the number of detections.

For the combined region, an increase in the number of detections resulted in a decrease in the maximum likelihood detection levels. The results indicated that use of chirp or reference waveform matched filters decreased the 50 percent detection level by approximately 0.7 m_b units and the 90 percent detection level by approximately 0.3 m_b units. The changes in the 50 and 90 percent detection levels due to use of the three-component adaptive filter were too small to be significant.

It has been noted previously (Lane, 1973) that a SNNR improvement of 6 dB implies a reduction of about 0.3 in the bodywave magnitude at which 50 percent of all events are detected (the 50 percent detection level). This in turn implies a doubling of the total number of events detected. In this report, we have noted that use of chirp or reference waveform matched filters results in SNNR improvements of about 3 dB, a reduction of about 0.7 in the 50 percent detection level, and a factor of about 2.4 increase in the total number of events detected. The explanation for these apparent anomalies is as follows. First, the low mean SNNR improvements (less than 2 dB) computed at some stations probably do not represent the SNNR improvement produced when a station-event which was not detected on the bandpass response becomes visible on a matched filter response. This must be true for central Asia station-events of this type which are detected by reference waveform matched filters at Stations 2 and 11, since the mean SNNR improvements in these cases are negative. Thus, the SNNR improvements are probably higher than the approximate 3 dB improvement previously computed. Next, we recall that an event is considered to be detected only if it is detected at two or more stations. Those events which were detected on the bandpass filter response at only one station (a total of 19 events) were therefore listed as non-detected events. Therefore, a detection by a matched filter at only one station other than the one at which it was detected on bandpass will change the detection status from non-detected to detected. Since it is more likely to detect an event using matched filters at one station than at two for a given SNNR improvement, we see that for the VLPE network, it is possible to more than double the number of detections using matched filters when the mean SNNR improvement is less than 6 dB.

The factor of 2.4 increase in the total number of events detected through use of chirp or reference waveform matched filters implies a reduction of 0.4 m_b units in the 50 percent detection level. For this particular data base, however, we had a 0.7 m_b unit reduction in the 50 percent detection level. To resolve this anomaly a larger data base is needed, especially at the lower bodywave magnitude values.

Since the chirp and reference waveform matched filters yielded approximately the same improvement in detection levels, let us consider what happens if the detection results are combined. In addition to the detection criteria used previously, an event is now considered to be detected if it is detected on either the chirp or reference waveform matched filter response. Twenty of the 79 events of the combined region were detected on the bandpass filter response. Use of this new detection criterion results in a total of 35 additional detections. This indicates that under this criterion, the 50 percent detection level is 3.74 $\pm$ 0.12, and the 90 percent detection level is 4.51 $\pm$ 0.17 for the combined region. Thus, the detection levels are lower significantly (about 0.3 to 0.4 m_b units) relative to those where detection is by chirp or reference waveform matched filter alone.

The point of comparison for surface-wave magnitudes derived from each of the techniques was the linear fit made to each set of M_s - m_b data, where the M_s values were for events not detected on the bandpass filter. For the combined region the equations for these linear fits are:

$$M_s = 0.25\ m_b + 1.94 \quad \text{for CMF data}$$

$$M_s = 0.28\ m_b + 1.81 \quad \text{for RWMF data.}$$

(No linear fit was computed for the TCA data, since only 12 data points were available.) From these equations, we see that the two matched filter methods produce values for surface-wave magnitudes which have essentially the same M_s - m_b relationship. The small differences between the two relationships are mostly due to inaccuracies in the dB SNNR improvements.

A comparison of M_s values computed from TCA data with those computed from matched filter data showed that all but one of the TCA surface-wave magnitudes were higher than either of the corresponding matched filter surface-wave magnitudes. Since it is believed that the matched filter M_s values were representative of the events detected, it will be necessary in future work to re-examine the manner in which M_s is computed from TCA data.

In summary, the major conclusions of this evaluation of the chirp matched filter, reference waveform matched filter, and three-component adaptive processor data enhancement techniques are:

- In the two seismic regions the chirp matched filter technique outperformed the other two techniques in terms of overall mean LR SNNR improvement. (Since the standard deviations of the mean improvements were large, it is not meaningful to attempt a quantitative statement of relative performance.)
- Even though the overall mean LR SNNR improvement for a given technique applied to events from a given region may be low, the improvement in detection may be good.
- In terms of the increase in the number of events detected, the two matched filter techniques performed equally well and far outperformed the three-component adaptive processor techniques.

- In terms of the detection level improvement of the network considered in this report, the two matched filter techniques performed equally well and far outperformed the three-component adaptive processor technique. When applied to the data set of this report, both yielded a 0.7 m_b unit reduction in the 50 percent two-station detection level and a 0.3 m_b unit reduction in the 90 percent detection level.

- When dealing with M_s values of events detected only by a matched filter, M_s values comparable to those from bandpass filtered data can be expected for m_b values below the 50 percent bandpass filter detection level. The M_s values for events detected only by a matched filter can be expected to be much lower than the M_s values determined from bandpass filtered data with comparable m_b values.

- Overall, there is no clear superiority of one matched filter technique over the other for the set of stations considered in this report. Both are superior to the three-component adaptive processor technique as it is presently used.

- The poor performance of the three-component adaptive processor is due not to some intrinsic flaw in the method but to the unmatched instrumental phase responses between the horizontal and vertical components of the VLPE stations.

We suggest that the following points be considered in any future work along the lines of this report:

- The data base should be increased -- more events and stations should be investigated to better assess the capabilities of these techniques for presently defined regions. Furthermore, analysis of another region should be implemented to assess the capabilities of these techniques over a larger geographical event distribution.

- When sufficient data are available, the eastern Kazakh test region should be studied in terms of these data enhancement techniques.
- SNNR improvements for LQ should be determined.
- Individual stations need to be investigated in detail in terms of dB SNNR improvement and detection capability improvement due to use of these techniques.
- Mean delay times and associated standard deviations for matched filter responses should be determined. These are needed to improve the detection criteria.
- Before the TCA processor is used again the phase and true amplitude responses of the stations must be determined and corrected for. The question of optimum overlap and gap length should also be resolved.
- More reliance could be put on the detection levels if the number of test events in the range $3.5 \leq m_b \leq 4.5$ were greater. Therefore, it is suggested that data from a local network or array be used to increase the number of test events.
- The PDP-15 interactive computing system should be implemented to expedite the matched filter data processing.

SECTION III

NETWORK EVALUATION TASK

A. INTRODUCTION

The goal of the network analysis task was to determine the ability of a network consisting of the Very Long Period Experiment (VLPE) single stations and the NORSAR and ALPA arrays to detect and discriminate Eurasian seismic events. Since the task culminates a three-year evaluation effort, Technical Report No. 7 includes and reviews all of the results from the period and discusses our conclusions about them.

The purpose of the VLPE is to improve discrimination and detection capabilities with the use of a network of high-gain, long-period digital seismographs at various locations throughout the world. Technical Report No. 7 presents a final evaluation of the discrimination and detection capabilities of the VLPE single stations, the VLPE network, and the VLPE-ALPA-NORSAR combined network. Further, a summary is presented of the important results pertaining to the studies of long-period earth noise, and the application of matched filters and the three-component adaptive processor to VLPE data.

The VLPE instrumentation has been described in detail by Pomeroy, et al. (1969), and studies of the data from the station at Ogdensburg, New Jersey have been presented by Savino, et al. (1971). A general review of eight of the long-period stations with their capabilities and the application of various filter techniques on digitally recorded data have been given by Savino, et al. (1972). Two reports, one by Benno (1972) and the other by Harley (1972), have presented a preliminary evaluation of the VLPE network.

A more recent report by Lambert and Becker (1973) presented the preliminary detection and discrimination capabilities of nine VLPE stations, the VLPE network, and the VLPE-ALPA-NORSAR combined network. Further, Lambert, et al. (1973) expanded the data base and presented a preliminary evaluation for eleven VLPE stations and various VLPE networks.

The data base for this report includes and expands upon the VLPE data base given in the latter report and now consists of 1280 Eurasian events for a total of 5962 event-station combinations. This large data base covers the following periods of time: 1 January - 20 March, 1 June - 31 August, 1 November - 31 December of 1972, and 1 January - 30 April, 1973. The ALPA and NORSAR data base was also expanded to cover the corresponding 1280 Eurasian events for a total of 2520 event-station combinations. Those data are used in this report.

The specific goals of this study were to examine:

- Discrimination capability of single VLPE stations, the VLPE network, and the VLPE-ALPA-NORSAR combined network as functions of M_s versus m_b, Love to Rayleigh wave amplitude ratios, and discrimination based on negative evidence.
- Maximum likelihood estimates of detection based on m_b for VLPE single stations, the VLPE network, and the VLPE-ALPA-NORSAR combined network.
- Maximum likelihood estimates of detection for VLPE single stations and the VLPE network based on M_s for surface-wave detections at ALPA and NORSAR, and ALPA and NORSAR M_s values corrected for station-path effects.

B. SUMMARY OF RESULTS

To provide an overview of the detection and discrimination capabilities of the VLPE stations and networks, we summarize from this and other reports the important results pertaining to the following subjects.

- Experimental problems and limitations.
- Long-period earth noise.
- Discrimination and detection capabilities of the VLPE single stations, VLPE network, and the VLPE-ALPA-NORSAR combined network.
- Evaluation of the chirp filter, the reference waveform matched filter, and the three-component adaptive processor as applied to VLPE data.

1. Experimental Problems and Limitations

We encountered several important experimental problems throughout this evaluation. These are as follows:

- Unreliable VLPE station data limited the quantity and quality of the long-period data from any given station. Specifically, only about 55 percent of the available digital data tapes had usable vertical component data while only about 30 percent has usable three component data. These statistics were compiled for the period January 1972 through March 1973 by Prahl (1974). This condition prevented a conclusive assessment of long-term noise trends and the detection and discrimination capabilities for specific station-source region combinations.
- A fixed set of VLPE stations recording reliable seismic data was not available for the network evaluation studies. For

example, the Fairbanks station (FBK) discontinued operation sometime in April 1972, La Paz (ZLP) and Matsushiro (MAT) became operational in November and December 1972. Further, virtually all of the other stations were having intermittent operational problems during the time from January 1972 through April 1973.

- At some stations there are indicated large instrumental gain and system response variations. Initially the system response data was supplied by the Lamont Doherty Geological Observatory and, from about mid-year 1972 to the present time, by the Albuquerque Seismological Center (ASC), Environmental Research Laboratories of the National Oceanic and Atmospheric Administration. Many stations show large static gain and instrumental response changes. We do not know whether these changes were made immediately before calibration by ADC personnel or whether they occurred because of natural instrumental characteristics. From our data observations and measurements we believe the latter reason to be the case.

2. Long Period Earth Noise

Recently, Prahl (1974) studied the long-period earth noise utilizing VLPE data, and included in his report is an appropriate bibliography of previous work. The data base used for analysis consisted of a total of 1503 one-hour noise samples from the vertical components and 846 one-hour noise samples with three-component data. The important results of the study are as follows:

a. Vertical Component Noise Analysis

- At each of the VLPE stations, minimum RMS amplitudes of earth noise were observed in a 22 to 42 second period band,

and within this band the lowest noise values occurred between 25 and 35 seconds period.

- The approximate order of the quietest to the noisiest VLPE station was: ZLP, CHG, KIP, ALQ, FBK, TLO, EIL, MAT, KON, OGD, and CTA.

- The intermittent distribution in time of the vertical component data prevented conclusive statements concerning long-term (seasonal) variations of earth noise. The exception was station KON. Here, there was a significant increase in earth noise during winter months. Similar increases in earth noise were observed at NORSAR (Laun, et al., 1973).

- RMS amplitudes in three period bands (17-25, 20-40, and 30-40 seconds) were highly correlated. Thus, appropriate noise sources excite seismic noise in at least the entire 17 to 40 second period band.

b. Three Component Noise Analysis

- Horizontal RMS amplitudes were generally one to four times larger than the vertical RMS amplitudes. However, within the average minimum noise band of 22-42 seconds, the horizontal component spectra were remarkably similar to vertical component spectra in amplitude, variability and spectral shape.

- For all stations the noise among components was only weakly coherent. This suggests that the average noise field is comprised of mainly isotropic noise.

3. Discrimination and Detection Capabilities of the VLPE, the VLPE Network, and the VLPE-ALPA-NORSAR Combined Network

In this report we attempted to overcome the experimental difficulties discussed above primarily by expanding the data base to obtain average capability estimates.

Attempts were made to analyze all available data. In order to evaluate the individual stations and network discrimination and detection capabilities by surface-waves, the horizontal instruments were rotated analytically to form vertical, transverse and radial components. The seismograms were filtered in the frequency domain with a filter having a bandpass of 18 to 42 seconds and then transformed to the time domain for visual analysis that included detection of surface phases and amplitude and period measurements.

a. Discrimination Capabilities

Within this experimental and analytical framework, we obtained the following discrimination capabilities.

- Instrumental gain variations caused undue scatter in the M_s estimates; thus, separation between presumed explosions and earthquakes in terms of M_s versus m_b was not clear at single stations. However, separation of the presumed explosions relative to the means (best fit straight lines) of the earthquake was consistent with that observed by others.

- With the networks having two or more station estimates of M_s clear separation is achieved between eastern Kazakh and Novaya Zemlya presumed explosions and earthquakes except for the two eastern Kazakh events 626 and 797. Marginal separation is present for presumed Ural explosions. These results are consistent with those published by Marshall and Basham (1972).

- The VLPE network and VLPE-ALPA-NORSAR combined network M_s - m_b relationships (best fit straight lines) for Eurasian earthquakes agree closely with those determined by others.
- Average LQ/LR amplitude ratios ($T \approx 30$ seconds) determined from three or more values for shallow central Asian earthquakes were generally greater than 1.00. Six LQ/LR values from five eastern Kazakh presumed explosions yielded an average of 0.77. All earthquake values were greater than this 0.77 value from the presumed explosions.
- We show theoretically and experimentally that over 80 percent of all LQ/LR ratios ($T = 30$ seconds) will be greater than those observed for the presumed explosions from eastern Kazakh.

b. Detection Capabilities

We used the maximum likelihood procedure for estimating detection capabilities of the individual VLPE station and networks. We applied this model to both bodywave and surface-wave magnitudes. Detectability estimates are given relative to M_s estimated from 1105 earthquakes detected at ALPA and NORSAR. In addition, these ALPA and NORSAR M_s values have been corrected for station-path effects to form a base of approximately 'true' M_s values. The results are as follows:

- The direct single station detectability estimates for m_b and M_s at the 50 percent probability level are in good agreement to those of Lambert, et al. (1973) and those determined from ambient noise by Unger (1974). The average 50 percent detection threshold for eleven VLPE stations is $m_b = 4.58$ and $M_s = 3.70$.
- We believe that the estimated single station 90 percent detection thresholds for M_s are too high due to large standard deviations

(σ) ($M_s(90) = M_s(50) + 1.28\sigma$). σ is affected by such variables as: epicentral distances, signal periods, noise amplitudes, propagation paths and instrumental responses.

- The VLPE network 50 and 90 percent detection estimates in terms of m_b of 4.17 and 5.15 compare closely ($\pm$ 0.07) to the average of those previously determined for three VLPE networks (Lambert, et al., 1973).

- The VLPE network 50 percent detection threshold of 3.18 in terms of 'true' M_s value compares closely to that estimated indirectly (extrapolated from m_b detectability estimates by Lambert, et al., 1973).

- The VLPE network 90 percent detection estimate of $M_s = 4.21$ is greater (+ 0.39) than that previously reported by Lambert, et al. (1973).

- We observe for the VLPE-ALPA-NORSAR combined network that the 50 and 90 percent detectability estimates in terms of m_b are 3.62 and 4.65. The 50 percent level of 3.62 is about 0.3 m_b units lower than that observed for ALPA alone, while the 90 percent level is about the same.

- Separate network detectability estimates have been determined where we require at least two operational stations and two stations detecting for a detection decision.

- The probabilities of mixed events occurring at VLPE networks are also measured. Based on 1252 events with at least one operational station we classify 22 percent of the events as mixed events.

- The actual number of events that remained as mixed events for the total network is 74. Since there was a total of 1252 events examined, we conclude that the probability of an event being mixed at all stations is 0.06.

4. Evaluation of the Chirp Filter, the Reference Waveform Matched Filter and the Three-Component Adaptive Processor as Applied to VLPE Data

Recently, Strauss and Tolstoy (1974), applied matched filters (chirp and reference waveform) and the three-component adaptive processor to VLPE data for an event ensemble of 53 earthquakes from central Asia and 28 earthquakes from Greece-Turkey.

The important results of this study are as follows:

- For the two seismic regions considered, the chirp filter technique outperformed the other two techniques in terms of mean signal-to-noise improvements. However, the authors indicated it was not meaningful to quantify the relative performance since the standard deviations were large.
- Even though the overall mean signal-to-noise improvement may be low, the improvement in detection was good. Specifically, each of the matched filter techniques increased the number of events detected by 130 to 140 percent over those detected by the simple bandpass filter. This gives a factor of about 2.4 and implies a reduction of 0.4 m_b units in the 50 percent detection level.
- The use of the three-component adaptive processor resulted in only a 10 percent increase in the number of events detected. However, this poor performance of the processor is not due to

some intrinsic flaw in the method but to the unmatched instrumental phase responses between the horizontal and vertical components of the VLPE stations.

- Determination of detection thresholds using the maximum likelihood method for either of the matched filter applications, yielded a 0.7 m_b unit reduction in the network 50 percent detection level and a 0.3 m_b unit reduction in the 90 percent detection level. It should be noted that for this network, it was required that at least two stations be operational and two stations detecting for a detection decision.

C. DISCUSSION AND CONCLUSIONS

During the analysis of the bandpass filtered VLPE records, it was observed that for Eurasian events the largest Rayleigh wave amplitudes occurred at periods of about 20 to 30 seconds. Forty-second waves were observed for some events and measured when possible. However, detection of small events was principally due to the relatively larger amplitudes at either 20 or 30 second periods. A stable earth noise minimum is present at all stations between 22 and 42 second periods. For the purpose of improving the detection capabilities of the VLPE stations, the VLPE instrumental amplitude response which now peaks at 35 to 40 second periods should be reset to peak at periods from 25 to 30 seconds.

The discrimination capabilities of the VLPE have been evaluated in terms of Love wave to Rayleigh wave amplitude ratios, surface-wave radiation patterns, and the important M_s versus m_b criterion. In general, these results were as expected and are consistent with theoretical and experimental studies by us and others.

Detection levels for single stations and various networks were determined. Single station 50 percent detectabilities are on the average m_b = 4.58 and M_s = 3.70. The VLPE network 50 percent detectabilities are m_b = 4.17 and M_s = 3.18 where one station detection is required, and for the two station detection requirement, m_b = 4.55 and M_s = 3.62. Combining ALPA and NORSAR with the VLPE network reduces the 50 percent m_b detectabilities to 3.62 for one station detection and 4.11 for two station detection. If either of the matched filter techniques were routinely applied to the VLPE data, we would expect a further reduction in the network 50 percent detectability of 0.4 to 0.7 m_b units.

For the VLPE-ALPA-NORSAR combined network with two station detection required and with routine application of either of the matched filters to the VLPE, we would expect a 50 percent detection level of $m_b \approx 3.7$. Extrapolation to M_s using the relationship: $M_s = 1.18\, m_b - 1.66$ yields a 50 percent level of $M_s \approx 2.7$. Estimation of the 90 percent detectability level yields $M_s \approx 3.5$ (i.e., $M_s(90) = M_s(50) + 1.28\sigma$, $\sigma = 0.67$).

Thus, for such a network we could expect discrimination with good confidence between Eurasian earthquakes and explosions utilizing the important M_s versus m_b criterion down to an $M_s \approx 3.5$.

The VLPE networks in this study had on the average four operational stations per event. If instead of single instruments, there had been four small arrays consisting of nine instruments, the single site 50 percent detection levels could be decreased by about 0.5 magnitude units (i.e., $\log \sqrt{9}$ = 0.48), or $m_b \approx 4.1$ and $M_s \approx 3.2$. Forming a network of these small arrays and requiring two of the four for a detection decision would yield approximately the same detectability levels as for the single arrays (i.e., $m_b \approx 4.1$ and $M_s \approx 3.2$). Application of either type of matched filters to the VLPE decreased the m_b 50 percent detection level by 0.2 m_b units. We believe this small gain relative to the VLPE to be due to the lack of a complete and accurate measure of the seismicity for Eurasia. That is, for ALPA and NORSAR, the number of undetected events after beamforming is much smaller than the number of undetected events of equivalent magnitudes for the VLPE bandpassed results. In other words, the number of detected events with matched filters at ALPA and NORSAR is constrained or controlled by the data base. Conversely, the detection capability of the bandpassed VLPE data is so poor that there is no constraint imposed by the data base on the number of undetected events that could possibly be detected by matched filtering. Conservatively then, we can assume that matched filters will yield a further reduction in the 50 percent detection level of about 0.4 m_b units. Converting the M_s 90 percent detection level in a manner similar to that discussed above for the combined VLPE-ALPA-NORSAR network, yields an $M_s \approx 3.5$. Therefore, four small arrays strategically located in Eurasia could be expected to have a 90 percent M_s detection level equivalent to that of the VLPE-ALPA-NORSAR combined network.

Although superficially this hypothetical network appears no better than the VLPE-ALPA-NORSAR combined network, there would be several important advantages:

- Each of the small arrays could be located within 50 degrees of epicentral distance to several seismic and aseismic regions of interest in Eurasia. This could yield an additional decrease of 0.2 to 0.4 magnitude units in the detection levels at the appropriate sites.
- Small arrays would also provide opportunities to apply more sophisticated signal enhancement techniques such as: Wiener type multichannel filters, f-k spectra, and time-varying adaptive filters.

- Mixed event probabilities are the same for arrays as for the single VLPE sites; for four sites, the probability of the same event being mixed at all four stations is 0.05. Thus, over a long time period, a significant number of events would appear mixed at all stations. Additional array processing such as adaptive beamforming (ABF) techniques could be applied to reduce this number.

In conclusion, we believe that a number of small arrays strategically located throughout the world would prove to be the best possible basis for a seismic surveillance system. The number and size of these arrays would, of course, be dependent upon predetermined standards and requirements.

SECTION IV
SIGNAL DETECTION TASK

Two studies were made under the signal detection task. The first study involved further development of a technique for obtaining a maximum likelihood estimate of detection thresholds from a given set of measured detection statistics. This study is discussed in Technical Report No. 2. The second study, discussed in Technical Report No. 9, was a comparison of the conventional beam power detector and the Fisher detector using data from the Korean Seismic Research Station . Summaries of the results of these two studies are presented below.

A. Technical Report No. 2: Estimation of Seismic Detection Thresholds

The detection capability of a seismic station or network for events from a specific region is usually referred to in terms of its incremental detection probability. This is defined as the probability of detecting an event, given the event magnitude. In particular, the 90 percent detection threshold is often quoted as a measure of performance; this is the magnitude at which the station is expected to detect 90 percent of all events.

Several methods have been devised to estimate the detection probability function of a seismic system. In general, such methods can be assigned to one of three main classes:

- Estimates based on seismic noise studies - By measuring the seismic noise level, estimating the signal-to-noise ratio required for detection, and assuming a signal variance, one can predict reasonably well the actual detection performance of a system.

- Estimates based on seismicity and observed detection performance - This is a two-step procedure. First the seismicity of a region is estimated by extrapolating the observed data, using the exponential magnitude-frequency relationship. Then the observed number of events is compared to the estimated seismicity in order to establish detection thresholds.

- Estimates based on comparison to a reference system - A set of events reported by an independent reference system is first selected. The percentage actually detected at each magnitude by the station in question is then used to obtain threshold estimates. This is usually referred to as the direct method.

The main topic of this report is to present a new approach to the direct method of estimation, using a maximum likelihood technique. Examples of application are included, and the results are compared to those obtained by other methods.

A model of the detection probability function which has been found useful for threshold estimation is established. In this model, the probability of detecting an event of a given magnitude m is assumed to be a cumulative Gaussian distribution function:

$$P(\text{Detect } m) = \Phi\left(\frac{m-\mu}{\sigma}\right)$$

where μ and σ are unknown parameters. It is shown that the parameters should be interpreted differently according to which method of estimation is being used. This has the very important implication that different methods of estimation may be expected to produce different results. Thus, a careful interpretation is necessary.

The likelihood function for the direct estimation method is developed, and approximate confidence limits for the estimated parameters are computed. The validity of the approximations is examined by applying a simulation model. A brief description of a maximum likelihood method for the indirect estimation problem, as developed by Lacoss and Kelly (1969), is also included. We choose an approach which is slightly different from theirs in order to show that no hypothesis of Poisson distribution of natural seismicity is required to develop the likelihood function.

In order to define the detection curve of a seismic station or network as a function of magnitude, the following observations of detection behavior were noted:

- Under reasonable assumptions, the detection curve of a single station (or seismic array) for a limited region can be approximated by a cumulative Gaussian distribution function. In this Gaussian model, then, the parameters μ and σ of the distribution completely define the detection curve.
- The Gaussian model theoretically does not apply to seismic networks, but may still be useful as an approximation to the network detection curve within limited magnitude ranges.
- A very important observation is that the detection curve of a seismic system varies with the choice of reference magnitudes. Thus a detection curve estimated from a station's own magnitudes tends to give a significantly lower 90 percent detection threshold than if a different station's magnitudes are chosen as reference.

Evaluation of the maximum likelihood method produced these observations:

- A simulation experiment showed that the asymptotic confidence limits were good indications of the stability of the estimates in a test case with 100 reference events (of which 75 were detected). A test case with 20 reference events (10 detections) indicated that the method should be used only with caution for data samples of this size.

- It is emphasized that the estimation procedure is only as valid as the model. The method is sensitive to 'bad' data points, such as a large event that is not detected or a very low magnitude event that is detected. A careful data screening is necessary to eliminate observations that either violate the independence requirement or have questionable reference magnitudes. Thus, as an example, the lack of consistency in PDE m_b estimates suggests that LASA and NORSAR may in many cases be better suited as reference systems than PDE.

In comparison, a simulation experiment showed that the method of indirect maximum likelihood estimation developed by Lacoss and Kelly (1969) gave reasonably stable estimates in a test case with an expected number of 133 events. Data screening in this case would be easier than for the direct estimation, and the major concern would be to make appropriate limitations to the seismic region considered, so that the Gaussian model is valid.

Finally, examples of applications were shown, with emphasis on the direct method. For two earthquake aftershock sequences, a comparison was carried out between the direct and indirect estimation method. The result was found to be in agreement with the theoretical considerations regarding the detection curves.

In conclusion, it is felt that maximum likelihood estimation is a feasible approach to obtaining estimates of the detection thresholds of seismic stations and networks. When choosing between the direct and the indirect methods of estimation, we observe that the latter method has the following two major disadvantages:

- The seismicity estimates by the indirect method are based upon detections by the station itself and may not always be reliable. For example, suppose we want to estimate the NORSAR operational detection capability for a region with poor beam coverage. The seismicity estimates for this region based on NORSAR detections will then clearly be biased low, thus causing the indirect method to estimate too high detection probabilities.

- The indirect method fails to take the signal variance into account when estimating detection thresholds. Therefore the 90 percent thresholds found by this method will always be significantly lower than the 'true' threshold when estimating station detection capability.

For the above reasons, we feel that the direct method of estimation is a superior approach to obtaining reliable detection threshold estimates. This method has the added advantage of giving easy visual control of the results. However, the direct method does require that a good reference network or station be available. In the hypothetical case of a 'perfect' reference network, the resulting estimates from the direct method would represent the 'true' detection probabilities. In practical situations, the variance of the reference magnitude estimates must be considered when evaluating the results.

As in all applications of statistical estimation theory, it is necessary to do a careful data screening prior to applying the mathematical tools. It is important to remember that the estimators, being random variables, sometimes will produce results that deviate significantly from the true parameter values. Thus, a careful interpretation of the results is required when applying the techniques described in this report.

B. Technical Report No. 9: Study of Two Automatic Short-Period Signal Detectors

This report presents results of a study of two seismic signal detectors, the Fisher detector and the conventional power detector. These detectors have been described in an earlier report (Lane, 1973), where their performance on long-period data was studied. The present report is concerned with their response to short-period data at the Korean Seismic Research Station (KSRS).

A total of 185 events were processed by the detectors and the results used to estimate a probability of detection for magnitudes greater than 3.0. A number of hour-long noise samples were also processed to find false alarm rates. A simple quality-control algorithm was devised to remove spiked and dead channels.

The following is a summary of the conclusions derived from this work.

Fisher and conventional beam power seismic event detectors similar to those reported on previously have been developed for short-period data and subjected to a preliminary analysis on short-period data from the Korean Seismic Research Station.

It was found that the false alarm rates produced by the Fisher detector when using fixed detector thresholds varied by as much as a factor of 20 from day to day. For the conventional detector, however, variations in the false alarm rate were smaller and occurred less often. The Fisher detector threshold level for a given false alarm rate was consistently lower than that for the conventional detector. Increased noise power generally resulted in lower Fisher detector false alarm rates, but caused little change in the conventional detector alarm rate. Increasing the integration time of the detectors decreased the false alarm rate in a regular manner.

A total of 185 events which occurred in the spring of 1973 were analyzed with both detectors. Detection curves for a few fixed threshold levels and integration times were developed taking into account the possibility of incorrect detections at small magnitudes. These curves suggest that neither the conventional detector nor the Fisher detector is affected by changing the integration time while keeping the false alarm rate constant.

The wide variation in false alarm rates at a fixed detector threshold means that a detector operating with a fixed threshold will not be optimum. It also means that the performance of such Fisher and conventional detectors cannot be compared directly. Optimum detectors, which maintain fixed alarm rates, could be used for this purpose. At a constant alarm rate, whichever detector had the higher probability of detection would unambiguously be the better detector.

SECTION V
SIGNAL ESTIMATION TASK

The signal estimation task consisted of two studies. The first study investigated the use of envelope beamformers using incoherent rather than coherent channel summation to reduce the signal loss from beamforming regional events and events having significant higher frequency energy. The results of this work are discussed in Technical Report No. 6. The second study was an investigation into the use of adaptive time domain beamforming for separating interfering signals. This work was an extension of an earlier study and featured an evaluation of a new adaption algorithm. The results of this study are presented in Technical Report No. 8. Summaries of the results of these reports are given below.

A. Technical Report No. 6: Comparison of Coherent and Incoherent Beamforming Envelope Detectors for NORSAR Regional Seismic Events

This report presents the results of a study of envelope detection on short-period array beams from the Norwegian Seismic Array (NORSAR) which had been formed through either incoherent summation or conventional coherent summation techniques. Coherent beamforming of a large short-period array does not yield the theoretically predicted signal-to-noise ratio improvement due to imperfect signal similarity across the array. This signal dissimilarity is frequency dependent with the most pronounced drop in signal coherence occurring at frequencies above 2 Hz. Thus, high frequency signals suffer the largest losses in signal-to-noise ratio. At NORSAR, this type of signal originates from near-regional events and Eurasian presumed explosions, particularly those from western Russia (Ringdal et al., 1972).

Signal loss also may occur even with well-equalized and similar signal waveforms if the regional corrections are not known or if the signal arrives slightly off-azimuth from the direction of a preformed beam. Whenever signal dissimilarity is severe enough to cause appreciable loss in signal-to-noise ratio during conventional coherent beamforming or when beaming parameters are in slight error, incoherent beamforming using the sum of the rectified sensor or subarray output may allow partial recovery of the signal loss.

The objective of this study was to investigate systematically the performance of the envelope detector in detecting underground explosions and near-regional earthquakes. The following steps were undertaken to accomplish this objective:

- Measuring the false alarm probability of coherent and incoherent envelope detectors.
- Computing the detection probability of coherent and incoherent envelope detectors for presumed underground explosions and near-regional earthquakes.
- Comparing the operating characteristics of the detectors.

The results of this study are based on the analysis of 91 events including 36 presumed explosions. The beamformer detectors were analyzed in terms of false alarm rate, detection performance, and operating characteristics. The false alarm performance results are:

- The false alarm probability density function from either the coherent or the incoherent detector output closely follows a Gaussian distribution. This indicates that the amplitude distribution of the envelope of the noise beam can be modeled by a lognormal distribution.

- For the coherent envelope detector, the 1.5-2.5 Hz passband had a higher false alarm probability than the 3.0-4.0 Hz passband for a given decision threshold.
- For the incoherent detector, the opposite is true. For a given decision threshold, the 3.0-4.0 Hz passband had a higher false alarm probability than the 1.5-2.5 Hz passband.
- The detectors using true envelopes computed with Hilbert-transform yielded higher false alarms than the STA-envelope detectors because the former did not incorporate any smoothing through integration.
- In order to achieve false alarm rates less than one per beam per day, the decision threshold for detection must be larger than 9 dB for the coherent detector in both passbands. For the incoherent detector, the thresholds are 3 dB in the 1.5-2.5 Hz passband and 4.5 dB in the 3.0-4.0 Hz passband.

This summary on detection is based only on the detector output for the presumed explosions and near-regional earthquakes without taking into account the detector's false alarm rates.

- For the operational mode detectors using a running STA/LTA ratio, the coherent detector output was 2-3 dB higher than the incoherent detector in both passbands for the presumed-explosion ensemble. For the earthquake ensemble, it was 5-6 dB higher.
- For the frozen-LTA-mode detectors using $(STA)_{max}/\overline{LTA}$, the coherent detector yielded a 10-11 dB higher output than the incoherent detector in the 1.5-2.5 Hz passband and 7-8 dB in the 3.0-4.0 Hz passband.

- The average detector output for diversity-stack beams using Hilbert transform pairs was 7.3 dB and 4.1 dB higher than the STA-envelope average for the $(STA/LTA)_{max}$ and $(STA)_{max}/\overline{LTA}$ coherent detectors, respectively, and 5.1 dB and 2.1 dB higher for the $(STA/LTA)_{max}$ and $(STA)_{max}/\overline{LTA}$ incoherent detectors, respectively, for four events.

- The simulation study where the scaled signal amplitudes were buried in noise suggested that the coherent detector operating in the 1.5-2.5 Hz passband yielded the best detection among the various detectors studied. However, for the 3.0-4.0 Hz passband the incoherent detector yielded better performance than the coherent detector.

- A detector where the LTA is delayed relative to the STA or E(t) envelope can reduce signal contamination in the LTA and thereby provide a better signal-to-noise ratio measurement.

- The diversity-stack beams had a higher detection probability than the adjusted-delay beams for both coherent and incoherent detectors.

With consideration for both detection capability and false alarm rate the following are the conclusions about the overall performance of the coherent and incoherent beamformer detectors.

- The incoherent detector yields better performance than the coherent detector in both the 1.5-2.5 Hz and the 3.0-4.0 Hz passbands.

- Both coherent and incoherent detectors yield better performance in the 1.5-2.5 Hz passband than in the 3.0-4.0 Hz passband.

- The envelope detector using Hilbert transformation operating at a given level produced a larger false alarm rate but an even better detection performance than the STA type of detector at the equivalent level. Thus the actual operating characteristic of the Hilbert transform envelope detector was superior to the STA envelope detector.

In conclusion, for detecting underground explosions and near-regional seismic signals at NORSAR, the incoherent beamforming envelope detector is superior to the coherent beamforming envelope detector, as expected. For teleseismic events, however, it may not be expected that the incoherent detector would still yield the better performance. Hence, it is worthwhile to use the incoherent detector as a supplement to the coherent detector in order to maintain good detection performance for events at all distances.

B. Technical Report No. 8: An Evaluation of Adaptive-Beamforming Techniques Applied to Recorded Seismic Data.

The adaptive processing task of this program has as its objectives:

- Continued improvement of adaptive-processing gains relative to beamsteering for unmixed long-period seismic events in the presence of background noise.
- Evaluation of potential adaptive-beamforming detection improvement over beamsteering for both long-period and short-period signals buried in off-azimuth interfering events.

This report deals with results obtained from operating a maximum likelihood adaptive beamforming system on ALPA long-period data and Korean short-period data. To synthesize interfering events by adding and scaling two different recorded data samples, a new computer program employing floating-point arithmetic was developed to achieve the objectives of this study. This program has the capability of processing long-period data from NORSAR and LASA as well as ALPA data and Korean short-period data.

Multichannel filtering is a form of array processing in which multiple channel inputs undergo individual frequency-shaping and phase-shift filtering prior to the channel-summation operation which produces the beamformer output. The computer program developed under this task also incorporates the option to preprocess the transducer outputs before they are input to the multichannel beamformer. Examples of preprocessing are frequency filtering (most commonly with identical frequency responses on all channels) and time shifting to align waves emanating from a particular direction. The preprocessed transducer outputs become the input channels to a multichannel filter set, where individual filters (generally different from channel to channel) are applied to the input channels. These filters are implemented as convolution filters in time-domain processing or as complex-valued multiplicative filters in frequency-domain processing. The multichannel filter output is created by summing the individual filtered channel outputs.

In systems where second-order statistics (crosscorrelation functions and crosspower spectra) are used to describe interrelationships among the input channels, there are two basic forms of multichannel filtering. In Wiener-Kolmogorov multichannel filtering, the average squared error between the desired signal and the multichannel filter output is minimized. To minimize the mean square error, the crosscorrelation functions or crosspower spectra between the input channels and the desired signal are required. In maximum likelihood multichannel filtering, the average squared output from the multichannel filter set is minimized subject to signal-preservation constraints which place some suitably-chosen frequency response on the signal.

For maximum likelihood multichannel filtering, unlike Wiener-Kolmogorov filtering, only the direction of the signal needs to be specified, but not the signal-to-noise ratio.

Multichannel filtering can be employed with fixed or time-varying filter sets. When the filters are updated as new data inputs enter the multichannel processor, the process is called adaptive filtering. Adaptive-filtering algorithms with significant computational advantages over fixed multichannel filtering are available. When the inputs to the multichannel processor are time-stationary (in the wide sense), these algorithms yield filter sets which converge in the mean to the corresponding fixed multichannel filter sets. After adaptive filter sets reach the vicinity of the corresponding fixed filter sets, they fluctuate about the fixed-filter solution in the presence of time-stationary data: the adaptive filters converge in the mean in the sense that the average position of the fluctuating adaptive filters is identical to the fixed-filter solution. When the statistics of the data entering the multichannel processor slowly change with time, adaptive filtering can react to the changes in a semi-continuous manner. If fixed filtering is used in this situation, newly-designed filters change in a more abrupt fashion. When, as in this case, the statistics of the data shift with time, the adaptive-filter solution lags behind the fixed-filter solution corresponding to the instantaneous statistics. The extent of the lag can be controlled by changing the adaptation rate. The choice of an adaptation rate involves a tradeoff between misadjustment (higher-than-optimum error or power due to the adaptive-filter fluctuations) and the lag behind the optimum instantaneous fixed-filter solution. A different kind of lag occurs when fixed filter sets are periodically redesigned: statistics must be accumulated over a design interval so that, as a result, the fixed-filter solution cannot be implemented until the next design interval.

In the conventional technique of array processing, simple time delays or phase shifts are applied to the input channels before summing to generate the beam output. Optimum multichannel filtering introduces considerable new flexibility into the beamforming process. Since it is possible to weight the input channels differently, channels with higher signal-to-noise ratios can be emphasized at the expense of noisier channels. When well instrumented arrays are utilized, this capability is generally of minor importance. A far more consequential feature of adaptive filtering is the ability to form array antenna patterns which optimally pass a signal while simultaneously rejecting propagating noise. Deep nulls can be aimed toward off-beam noise sources. When strong off-azimuth noise sources are present, the creation of such nulls is an automatic result of the optimality of the multichannel processor. The conventional time-shift-and-sum or phase-shift processor, in contrast, has a beam pattern determined solely by the steer direction and the array geometry.

In most cases, the potential improvement of optimum multichannel filtering relative to beamsteering is determined by the coherence of the noise field across an array: the greater the similarity of the noise field from channel to channel, the greater is the optimum-multichannel-filter improvement over beamsteering. When, on the other hand, noise is completely uncorrelated between sensors and identical signal and noise power levels are encountered at all array sites, there is no potential for improvement: in this case, the optimum filter set is a beamsteer processor. The decision to employ or not to employ an optimum-filter technique of processing depends critically on measurements of the noise field at any given array. Once these measurements are available, the additional cost of implementing an optimum-filter system can be quantitatively weighed against the advantages of greater noise suppression relative to the conventional beamsteer processing technique.

The report discusses the effect of some changes made since the previous adaptive processing study in the procedures used to implement time-domain maximum likelihood adaptive multichannel filtering. The criterion for evaluating these changes is the adaptive-beamforming signal-to-noise gain relative to beamsteering for unmixed long-period seismic events in the presence of background noise. The first topic examined is the effect of replacing the previously-employed adaptive update algorithm, which speeds up in the presence of a signal, with a new adaptive update algorithm which slows down in the same situation. Next, using the new adaptive algorithm, adaptive beamforming improvement over beamsteering for the full ALPA array is compared with that obtained with closely-spaced six-channel partial ALPA arrays. Finally, the effectiveness of a new prefilter for the individual vertical-component channels input to the beamformers is assessed in terms of its detection capability. This assessment of the new prefilter utilizes adaptive filter lengths of both 31 and 15 points per channel in order to determine whether any meaningful processing loss occurs with the shorter filter length, which halves the computational load.

The possibility is examined that adaptive beamforming can detect signals buried in off-azimuth interfering events when the conventional time-shift-and-sum processor is unable to do so. To simulate mixed events, two separately-recorded data samples are scaled and summed to create a composite sample used in the adaptive-filter update procedure. Beam outputs are computed for both data samples individually to ascertain the effect of the adaptive beamforming process on each sample in the composite data sample. Then the beam outputs for both samples in the composite sample are summed in order to observe the result of combining the two samples. The detection capability of adaptive processing is determined from a visual examination of the composite beam-output trace. This investigation of the ability of adaptive multichannel filtering to detect signals masked by off-azimuth interfering events employs both long-period ALPA data and Korean short-period data. The preliminary results presented should assist those people interested in improved separation of mixed events.

Although a large amount of data has not yet been analyzed, significant results have been obtained already. A summary of these results and their implications is presented below.

For unmixed long-period seismic events in the presence of background noise, the new adaptive algorithm produces much higher signal-to-noise ratio improvement than the old adaptive algorithm used in the previous adaptive beamforming study (Barnard, 1973). The improved results with the new adaptive algorithm are due to a slowing of the effective adaptation rate in the presence of on-azimuth signals. For events with good signal similarity between sites, signal degradation with the new adaptive algorithm is dramatically reduced at high convergence rates. Since noise reduction increases significantly as a function of convergence rate, the best signal-to-noise gains occur at high convergence rates with the new adaptive algorithm. In contrast, severe signal degradation at high convergence rates causes the maximum signal-to-noise gains for the old adaptive algorithm to occur at low convergence rates near $\mu = 0.005$.

When the full ALPA array is used as input to the beamformers instead of a closely-spaced six-channel array, the measured noise reduction relative to beamsteering is lower at all convergence rates. Differences in measured signal degradation, however, are highly variable. At rapid convergence rates, signal degradation is 2 dB higher for one event and 2 dB lower for another event. In most cases, the estimated signal-to-noise gain relative to beamsteering is less with the full array because of the decreased noise reduction.

The new signal-enhancement prefilter is a definite improvement over the old prefilter. Not only is detection gain achieved by the frequency response of the new prefilter, but also the new prefilter's emphasis on the more coherent energy at low frequencies increases ABF noise reduction relative to beamsteering for the full array by more than 3 dB compared with the old prefilter. This additional noise reduction occurs with both 31-point and 15-point adaptive-filter lengths. The difference in noise reduction is only 0.3-0.4 dB for the two adaptive-filter lengths. For two events with good signal similarity, the difference in signal degradation is less than 0.1 dB, so that the loss in estimated signal-to-noise gain is 0.3-0.4 dB with the shorter filter length. On the other hand, signal degradation for one event with poor signal similarity is more than 2.1 dB lower with the 15-point-long adaptive filter, so that the estimated signal-to-noise gain is actually 1.8 dB higher. The significantly diminished computational load probably justifies the use of the shorter adaptive filter length in any on-line implementation of adaptive beamforming.

When vertical-component data from the full ALPA array are passed through the new prefilter, the signal-to-noise gain over beamsteering falls within a 3-to-8 dB range for an adaptive filter length of 15 points per channel. Normally, a 6 dB gain might be expected in this operational mode. Thus adaptive beamforming could conceivably lower the Rayleigh wave detection threshold at ALPA by 0.3 magnitude units.

Off-azimuth events are strongly suppressed by adaptive beamforming at $\mu = 0.5$, the same convergence rate where the maximum gain over beamsteering is achieved for on-azimuth events. Some off-azimuth events are almost totally annihilated. Ordinarily, the strongest off-azimuth events are attenuated the most. For some signals 30^o to 60^o from the steer direction, however, considerable energy leaks into the adaptive beams, even for the strongest events. The new prefilter reduces off-azimuth event suppression somewhat. Even with the new prefilter, however, the attenuation of off-azimuth events is considerable. Thus the beam-narrowing capability of adaptive processing can provide greater directional resolution at ALPA and other similar long-period arrays.

Until now, we have discussed adaptive-processing results for single seismic events in the presence of background noise. The remainder of this discussion deals with mixed-event simulations where two data samples, each containing a signal, are summed to create a composite sample containing an interfering event. The mixed-event results in this report are preliminary and extend over only a limited range of the situations possible.

For the two mixed-event simulations where two different data samples are added, adaptive beamforming achieves significant detection gains over beamsteering. These gains, which are realized at high convergence rates, occur in a peculiar way. Before the on-azimuth signal arrival, the off-azimuth interfering event is strongly attenuated. After the signal arrival, adaptive beamforming cannot produce immediate mutual interfering-event cancellation. The energy burst coinciding with the on-azimuth signal arrival permits a signal detection.

In the first mixed event simulation, the time-shift-and-sum beam pattern in the off-azimuth event direction is much lower than normal (-21 dB). The off-azimuth event is 18 dB stronger than the on-azimuth signal at the single sensor level. The beamsteer amplitude rise after signal onset is -2 dB. For the adaptive beam at a 0.2 convergence rate, the amplitude rise is 6 dB. This 8 dB difference occurs despite the excellent beamsteer response toward the off-azimuth event.

The beamsteer response toward the off-azimuth event is -15 dB in the final mixed-event simulation. At a 12 dB event separation level, the beamsteer amplitude rise is 8 dB, and the on-azimuth signal is just detectable. At a 24 dB event separation level, the amplitude rise on the composite-sample adaptive beam at $\mu = 0.2$ is also 8 dB. Thus, adaptive beamforming produces the same detection results as beamsteering when the event separation is 12 dB greater.

In those cases where detections are made with adaptive beamforming, the maximum peak-to-peak amplitude on the composite-sample beam furnishes a good estimate of the on-azimuth signal's maximum peak-to-peak amplitude. The maximum amplitude on the composite-sample adaptive beam is never much more than 2 dB lower than that of the on-azimuth signal.

The mixed-event results show definite promise in lowering detection thresholds for Rayleigh wave arrivals masked by off-azimuth events. Beamsteering seldom reduces the detection threshold more than 0.6 to 0.9 magnitude units (12 to 18 dB) below that of a single seismometer. Adaptive beamforming may further reduce the detection threshold more than 0.6 magnitude units (12 dB) below the beamsteer detection threshold. However, these results are quite limited in scope. Many additional simulations are needed to determine the factors affecting adaptive-processing performance in the mixed-event situation. Furthermore, adaptive beamforming needs to be tried at smaller long-period arrays such as the Iran Long-Period Array.

A Wiener filter, where the design goal is to minimize the mean square difference between the filter output and the on-azimuth signal, might provide better detection performance than the maximum likelihood adaptive algorithm, which sometimes produces mutual cancellation of the interfering events.

SECTION VI
FIRST-ZONE DISCRIMINATION TASK

A. INTRODUCTION

The investigation into the behavior of discriminants derived from first-zone seismic events is discussed in Technical Report No. 10. Only a small amount of data was available for this analysis during the past year, therefore, the results, which appear promising, must be considered preliminary. A summary of the background to this work and the results obtained are given below.

In the past several years teleseismic signals from Eurasian events have been studied extensively using data from seismic arrays around the world. Sophisticated signal enhancement techniques have been developed to lower the thresholds for detecting and discriminating small magnitude events. However, many low magnitude events which occur within the Eurasian continent remain undetected simply because their signals are so weak at teleseismic distances that present processing techniques cannot extract them from the noise.

Thus it is desirable to have detection and discrimination techniques which are tailored to data from non-teleseismic events so that these events can be used to lower the detection and discrimination thresholds.

The purpose of this study was to determine the parameters best suited for distinguishing between shallow earthquakes and presumed underground explosions occurring in Eurasia at less than teleseismic distances from the observer. These discrimination parameters will be used for small magnitude Eurasian events detected at small distances (most likely by only one station).

Clearly, lowering the discrimination threshold requires smaller distances just for event detection. Further, these near-source seismograms contain most of the information required for crustal studies.

In this study we are mainly concerned with the distance range at which the primary wave (first arrival) is refracted horizontally below the Mohorovocic discontinuity (Pn). The distance range at which the Pn is the first arrival has been found by Pasechnik (1970) to be $\Delta \leq 800$ to 1200 km which he terms 'first-zone'. The range of $1200 \leq \Delta \leq 2000$ km, he terms the 'second-zone'. Carder (1952), on the other hand, uses the term 'near-regional' for $150 \leq \Delta \leq 650$ km and 'regional' for $650 \leq \Delta \leq 1600$ km. We use the terms 'first-zone' and 'regional' interchangeably throughout this report but meaning distances within the general range of $150 \leq \Delta \leq 2000$ km.

First-zone studies in Eurasia have been principally reported by Pasechnik (1970). He observed that both earthquakes and explosions from the same region have the same phases and travel-times but that the dynamic characteristics of the phases were different. His first-zone information is concerned mainly with travel-times and phase identification.

First-zone studies from the Nevada Test Site, on the other hand, are quite extensive. Because the epicenter locations and times were well known, a large data base was available for both earthquakes and explosions. The results of these studies have been used here to delineate the first-zone problem areas and to decide on the more effective discrimination measurements. Some of the first-zone problems of interest are the following:

- The first-zone seismograms are quite complex because of the presence of many wave phases. These phases have only small differences in their travel times.
- First-zone seismograms are highly dependent on local crustal structure, and thus, the amplitude and travel-time curves are variable.

- Magnitude measurements in the first-zone have not been as reliable or consistent as the corresponding teleseismic estimates.

Three discriminants that appeared most promising for single station first-zone discrimination were:

- Depth estimation - Use of possible depth phase travel-times.
- Phase energy and amplitude ratios - Explosions will presumably generate less shear or surface-wave energy than earthquakes.
- Spectral splitting - Source spectrum studies suggest spectral differences between earthquakes and explosions of equivalent magnitudes.

An accurate assessment of these discriminants requires that broadband data covering the spectrum of the event be used. The most convenient source providing data of this type was the NORSAR array. For this report, NORSAR data from a single short-period site and a corresponding nearby long-period site were used.

B. SUMMARY OF RESULTS

In general this investigation of regional events was hampered both by the classical seismic problem of inaccurate epicenter location and origin time, and by the larger estimates of m_b using first-zone data rather than teleseismic data. Successful solutions to similar problems were developed in the first-zone studies of the western United States and the Nevada test site, but they were predicated upon having accurate travel-time curves which presently don't exist for the NORSAR first-zone. The PDE epicenter information appears adequately accurate for most of the first-zone studies, but the same parameters from the NORSAR bulletin are not satisfactory. These relatively poorer location and origin time data affect every portion of the analysis.

The small data base included here is sufficient to permit only a trial of the various measurements considered, but these results do define the problem areas. The lack of accurate travel-time curves prevents calibrating the magnitude measurements so that they are consistent with corresponding teleseismic estimates. Further, the lack of positive S wave and depth phase identification prevents any reliable estimation of depth.

The phase energy ratios appear to be effective discriminants even for such broad velocity windows used here. The addition of similar discriminants computed from long-period data should improve considerably their effectiveness.

The spectral splitting discriminant will require more data from earthquakes and explosions of similar magnitude before the most effective spectral bands can be determined,and before the effectiveness of this discriminant can be determined.

The absence of the Pg phase and the missing first arrival on one event indicate potential problem areas in the constructing of travel-time curves for the NORSAR first-zone area.

An event selection process has been set up so that in the future data for these events can be ordered from NORSAR on a regular basis. The analysis will emphasize the use of events with accurate origin times and locations so that accurate travel-time curves can be constructed. Array beams will be formed using S wave velocities as well to improve the signal-to-noise ratio of the S wave and thus,the reliability of their identification.

The development of travel-time curves for P, S and possibly other phases for the NORSAR region will allow a reformulation of first-zone m_b measurements which conform to teleseismic estimates.

As a check on the accuracy of the first-zone travel-times and to permit the prediction of phases on the first-zone seismogram, a crustal model will be developed using the calculated travel-times and incorporating the various published crustal models into a unified crustal model of the NORSAR first-zone.

SECTION VII

SEISMIC SYSTEM STUDIES TASK

The seismic system studies task was oriented toward the investigation and development of particular aspects of a future worldwide seismic surveillance system. A comprehensive analysis by Texas Instruments Incorporated of the overall requirements, configurations, and capabilities that such a system might have was reported on earlier this year (Sax and Staff, 1974).

The four studies this year include the development and demonstration of a computer program to evaluate the usefulness of an interactive graphics capability for a surveillance system; this is discussed in Technical Report No. 11. The feasibility of having interactive capability in such a system and the role an analyst can play through system interaction is explored in Technical Report No. 12. The extreme difficulty of analytically predicting the operating characteristics of a complex dynamic system driven by numerous random inputs required that the surveillance system performance be measured by Monte Carlo techniques. To this purpose, one configuration of the system was modeled by simulation methods, and the simulator was tested by a realistic model of the earth's seismicity. The results of this simulation are discussed in Technical Report No. 13. Finally, in Technical Report No. 14, the techniques for estimation, feedback, and control of seismic and system parameters are discussed with particular emphasis on detection threshold control and the updating of regional corrections. Summaries of these four reports are given below.

A. Technical Report No. 11: An Interactive System for Long-Period Seismic Processing

This report describes an interactive processing system developed by Texas Instruments Incorporated for the purpose of analyzing long-period seismic signals. The system utilizes the interactive graphics facilities of the PDP-15/50 computer at the Seismic Data Analysis Center (SDAC) in Alexandria, Virginia.

The main intention of the program system has been to investigate the feasibility of utilizing interactive graphics for event detection purposes in a potential world-wide seismic surveillance system. Although the software package is general in nature, an interface to one specific seismic system (the Very Long-Period Experiment (VLPE) network) has been designed, and a preliminary evaluation has been conducted using data recorded by this network as a source.

Interactive processing is today a very important aspect of numerous computer applications. It provides an efficient means for a user to comprehend his data base, to direct a computer in its operations upon that data base, and to examine the results of those operations - all within an appropriate time interval. The principal advantages of interactive processing are:

- It reduces the waiting time between intermediate processing steps, thus increasing productivity
- It reduces the need for hard-copy output because a video display of intermediate results is sufficient in many applications
- It provides an efficient means to retain human judgment in the analysis loop, and thus avoids the problems inherent in fully automating analytical decisions.

Interactive processing is particularly well suited for those applications that are characterized as a series of sub-processes with active intermediate decision points. Seismic signal analysis belongs to this class of problems. Typical intermediate decision points are exemplified as follows:

- Data quality control; elimination or correction of bad data segments.
- Alignment of signal traces for beamforming.
- Selection of the 'best' bandpass filter or matched filter from a filter library.
- Selection of a signal peak for magnitude measurements.
- Selection of time windows for computing quantities such as seismic noise level and the AR and AL discriminants (Brune et al., 1963).
- Rapid visual control of detection/no-detection decisions on individual signal traces.

In addition, several non-routine seismic signal processing techniques may benefit greatly from interactive processing. Examples include the complex cepstrum technique, identification of later phases (such as pP), and detection association techniques for network processing. For a discussion of these and related topics we refer to Sax (1974).

This interactive system is known as the Interactive Long-Period Processing System (ILPPS) and deals primarily with standard processing techniques such as bandpass filtering, linear chirp or reference waveform matched filtering, computation of power spectra and measurements of selected event parameters. Documentation of the developed software has been issued separately from this report (Ringdal and Shaub, 1974). This documentation also contains a user description of the programs, including a step-by-step solution of a sample problem.

The purpose of the ILPPS experiment was to investigate the feasibility of using interactive graphics for processing long-period data in an operational seismic surveillance system. It is felt that the following features of the interactive approach have been definitely demonstrated:

- High quality of results
- Convenience to the analyst
- Minimal intermediate hard copy output
- Short turn-around time compared to batch processing.

The one major question not fully answered is whether interactive signal analysis is efficient enough for the large-scale routine processing required in a surveillance system. The average processing time for one station component during the ILPPS evaluation was 4 minutes, including time for event selection, bandpass and iterative matched filtering and interactive computation of several event parameters. This processing time is probably prohibitive for routine analysis in surveillance mode. However, it is possible to reduce the average ILPPS processing time significantly by the following approach:

- Establish a semi-automated interactive system, in which a fairly extensive default processing may be performed automatically if the analyst so wishes.
- Retain an option to perform extensive interactive analysis of difficult cases or events of special interest.
- Improve computer efficiency by various means (e.g., extensive use of direct access disk operations to reduce wait time).

The time required for this type of routine processing could probably be reduced to about 1 minute per station component. This processing time would seem to satisfy the real-time requirements of a large scale surveillance system, while the indicated approach still retains the desired flexibility to perform extensive analysis of interesting events.

It is therefore recommended that further development of ILPPS be directed toward establishing a semi-automated processing capability to supplement the already existing fully interactive system. The addition of such a capability would probably not require a major software effort. Also, improving efficiency in the computer operations and in providing more analyst conveniences such as hard copy output should be given high priority.

Finally, several additional options may be included in the system at relatively low cost, such as:

- The capability to process short-period data.
- Techniques for data quality control and spike removal.
- Additional processing techniques, such as beamforming, three-component processing, complex cepstrum and multichannel filtering.
- The capability to interface directly with a remote seismic data mass storage, in the event such a system is established.

The implementation of some or all of the above options can be expected to provide more insight into areas within the seismic event detection problem which are well suited to the application of interactive graphics. This information will be valuable both for seismic data processing techniques in general and also for the possible future operation of a global seismic surveillance network.

B. Technical Report No. 12: Feasibility of Interactive Data Processing In a Seismic Surveillance System

The definition of an interactive processing system is that which enables an analyst to efficiently interrupt and modify computer processing. This is done by observing the results of processing and by inputing additional information to influence the results of future processing. In this report, a number of options are described for appropriately using interactive processing to execute selected tasks needed for effective seismic surveillance.

The hypothetical seismic surveillance system under consideration consists of a network of about 25 seismic observatory stations located around the world. It is assumed that each station will collect data from arrays of long-period and short-period seismic sensors and will have the capability to automatically process that data. Also, each station will be connected with communication links over which the data can be sent. By means of this communication capacity, the remote stations will deliver seismic data to a central facility serving as the surveillance system headquarters.

The delivery of seismic data from remote stations to the central facility can either be done selectively, by utilizing low rate communications and on-site data processing at each station, or by sending all of the raw seismic data and doing all of the data reduction at the central facility. In either case, substantially the same processing functions are needed to reduce the data to significant event information. Therefore, the following analysis of interactive processing is relevant to either mode of data collection. In the following, it is assumed that data is sent selectively from remote stations to the central facility. For the case of a centralized data processing system, merely consider that the station processors and storage elements exist in the central facility and are linked to the other central facility processing functions by data channels into a common storage element. The costs, tradeoffs, and design problems associated with either approach were described in an earlier report by Texas Instruments Incorporated (Sax and Staff, 1974).

The following functions are performed on raw seismic data collected at remote stations:

- Collect and hold raw sensor data for a specified length of time.
- Automatically generate bulletins to indicate possible seismic events.
- Forward those detection bulletins from all of the stations to a processor which makes preliminary event locations.
- Reduce each station's raw seismic sensor data to waveform estimates of each event.
- Temporarily retain backup files of the raw seismic data.

The following functions must be performed at the central facility:

- Make a preliminary location of events using the information on station detection bulletins.
- Request waveforms from stations at computed arrival times of possible events.
- Classify those events of special interest. These require recording of all of the array sensors at selected stations and in some cases by records of extended duration.
- Request the seismic data needed to document classified events of special interest.
- Monitor and control the quality of all processes carried out to detect, describe, and classify the seismic events.
- Deposit sets of selected event phases into a data bank and withdraw needed data from the data bank.

To implement the data processing required for the above functions, choices must be made between using 1) an automated processing system, 2) an interactive processing system or 3) a batch processing system. Some combination of all three of these data processing modes should result in maximum efficiency in executing given functions. The degree to which an interactive processing system is needed to accomplish a function depends on the efficiency of data processing and on realizing significant benefits from human interpretation. These choices in designing the data processing system should be considered at all of the major decision points in the analysis sequence which influence the data flow from remote sensors to the data bank. The cost of interactive processing must be justified by the designers evaluation of gains in the efficiency and the capability to detect events. These are the main factors affecting the choice of a data processing system to implement the functions required for seismic surveillance. To improve computational efficiency, interactive processing must effectively trade off the general purpose computer's complexity required to compile any conceivable program for the special purpose computer's prompt execution of interpreter driven pre-stored program modules. To improve the capability of detecting events, the human analyst must intervene effectively between machine processing steps to beneficially influence the selection of desired data and thereby affect the data flow from one place to another.

A summary of the conclusions of this study are as follows. An interactive processing system is most feasible for seismic surveillance data processing at a central facility serving a system headquarters. Conversely, collection of seismic array data and detection of signals can be done entirely by automatic data processing. The functions which could be performed by an interactive processing system at the central facility are:

- Locate the event and obtain event waveforms
- Describe source parameters

- Classify the event and document those events classified as possible explosions
- Deposit or withdraw seismic data from the mass storage of past detected events
- Obtain information on the performance of the system
- Control quality of the automatic processing through the surveillance system.

The feasibility of an interactive processing system for matched filtering of long-period data was demonstrated by Ringdal and Shaub (1974). They showed that successful application of the interactive approach depends critically on the design of suitable software architecture and on the design of the human factors affecting the users of the system. Important features include:

- Flexible interrupt capability
- Convenient record keeping
- Assumed fast recoverability from analyst errors
- The capability for allowing long delays in the analyst's response to permit him to interpret results
- Flexible partitioning between the interactive and fully automatic modes of data processing.

The tradeoff which is made to acquire these capabilities is to give up some of the general purpose computer system's capability of running any conceivable program for the dedicated computer's capability to respond flexibly and rapidly to the analyst's commands. To achieve maximum efficiency, the general purpose system requires specialized computer operators and programmers to intervene between the analyst's need for computed results and the computer's operations on the data. This results in a long turnaround time to accomplish a specific task. The benefits obtained by the interactive system are that processing is limited to only those program modules needed to perform the analyst's highly structured function, and that a command language can rapidly and directly execute any task needed by the analyst. Thus, the development of the interactive processing consists of developing program modules to perform seismic data processing and of developing an operating system controlled by a standard set of analyst commands via a special purpose command language.

One approach followed in developing such a command language was that of Roman (1973). He described a command language called the Numerical Analysis Problem Solving System (NAPSS). Ringdal and Shaub applied this methodology to seismic data processing and demonstrated its feasibility by designing a command language known as Seismic Analysis Problem Solving System (SAPSS). Their system used a set of commands to branch from one program module execution to another and provide needed analyst interactive program control. It also supported easy and nearly foolproof recovery from errors and comprehensive and convenient record keeping.

By using a command language driven system the analyst's requirements for data processing are fully integrated into the computer operation. This provides the analyst with a tool to control and manipulate data as he sees fit within the context of the system design and purpose. The analyst has the capability of adding new functions and combining existing functions in any sequence with branching capability backed up with coordinated access to large shared mass storage devices. The user of the interactive system will rapidly learn to use the command language as it gives him the capability to:

- Invoke program executions in a language with which he is already familiar

- Access files of data labeled by familiar names
- Link programming tasks in any desired sequence with branching controlled by logical tests on computed results
- Obtain fast turnaround of computing necessary to achieve his functional responsibilities.

The interfacing of interactive data processing systems with the overall operation of a seismic surveillance system depends on organizing the data processing workload into a set of command levels. Each command level pertains to the execution of one specific function process to acquire only that seismic data which is needed. The starting point of the processing is to store seismic sensor measurements. The ending point is to put into mass storage sufficient seismic data to interpret each detected seismic event. Four functions were considered as possible applications of an interactive data processing system. These are the association of bulletins describing possible seismic events, source description and classification of seismic events by analysis of the event waveforms, the deposit and retrieval of data into mass storage, and quality control of all data processing by the surveillance system. Each of these function processes was organized by outlining the requirements for automatic processing, by the displays invoked by the analyst, and by the control procedures invoked by an analyst.

There are certain tasks involving the interpretation of seismic information and data wherein an interactive processing system offers absolute advantages over presently known automatic data processing algorithms. Several examples of this were discussed. One of these is to obtain more accurate timing and focal estimation of events by detecting large timing errors due to false associations. Other options for applying interactive data processing involved interpretation of highly ambiguous seismic data. The purpose of the analyst invoked options was to more accurately locate and classify the seismic event. These options involve invoking well known data processing algorithms by the analyst and displaying various information and data. It would therefore appear that an interactive processing system can be feasibly applied to numerous seismic data processing tasks.

C. Technical Report No. 13: Simulation of a World-Wide Seismic Surveillance Network

The simulation study is an extension of earlier work in the design and evaluation of a seismic event monitoring network. A computer program developed by Wirth (1970) estimated the operating characteristics of a network but neglected constraints imposed by response time and the physical system. That program, made more efficient by Wirth in 1971, was applied by Wirth, Blandford, and Shumway to evaluate an automatic network-level detector. Since then, a study by Sax et al. (1974) identified the major functions and the configuration for a cost-effective network. The current study combines and extends these earlier works by providing means for evaluating alternative processes at the subsystem and total system level. It weakens the assumption regarding the physical system and permits evaluation of dynamic behavior, given a procedural or functional alternative.

This report records for later reference the methods for seismic network simulation, and describes specific results obtained to date. From the simulation results presented and their analysis, a number of conclusions and recommendations are indicated. These conclusions are given below for the remote facilities, communications system, the central facility, and the overall system.

Although remote facility detector alternatives were not simulated, it is apparent that two factors to consider in selecting between candidate detectors are:

- Significant differences in the low threshold area of the detector operating characteristic
- The impact on the processing time of poor detectors due to increased back communications.

The first point seems obvious except that one is not used to comparing operating characteristics in the extremes. But this area is most important for successful operation of the network processing. The second factor is difficult to evaluate since the station processor design is involved. That is, are waveforms serviced in the background area of the computer, do they interrupt the detection processing, or do they begin processing when the detector is finished? In the last case a poor detector, even if it allows more time for such requests, may fall behind because of more but erroneous waveform requests. If these factors are taken to account, it is possible to select detector alternatives for the network without simulation. Also, the simulator can provide gross statistical models that can be used in such evaluations.

The analyses and measurements from the simulation of the communications system led to the following conclusions:

- A full-duplex (simultaneous two-way transmission) system offers only marginal improvement in the line utilization.
- The performance of the communications system is sensitive to the management of the facility.
- Communications processors should interface with the processing facilities by disk rather than allowing direct access.
- The remote processor should buffer at least one waveform message and use fixed buffer allocation to improve utilization and to simplify the software.

- Multiple access methods at the central facility effect the communications utilization.
- The worst case delay for a low-rate system (50-75 bps) is 10 to 15 hours without optimization.

The improvement offered by the full-duplex system was shown to be about 0. 8 percent, whereas the utilization due to varying loads ranges from 10 to 30 percent. So rather than pay, say twice as much, for the full-duplex system, better management of the half-duplex system is indicated. If greater capacity is needed, however, then wideband half-duplex will maximize the useful capacity.

The communications processors were seen to have time-varying queues so that some buffering by a disk unit is necessary as the queue lengths extended beyond that which could be buffered in a reasonable core memory. In the case of a failure, more buffering is needed beyond that indicated by simulation. At the remote facility at least some waveform messages can be expected and at the central facility at least 20 waveform request messages needed to be buffered. To maintain the system utilization with the simplest software at least one waveform message should be in the remote communications processor (RCP) memory. The RCP, buffered internally by packets, seems to save only memory at the cost of more elaborate software. Similarly, fixed rather than dynamic buffer allocation also will simplify the software.

The results of the central facility simulation are summarized below:

- The number of data path failures per year at the central facility is expected to be 138 before the detection association processor (DAP) and 275 before the event classification processor (ECP), depending on the processing sequence.

- No significant queues or delays were noted at the central facility.
- The DAP utilization was around 7 percent.
- The baseline DAP algorithm used in this study is limited by incorrect associations at a false-alarm rate of 0.57 alarms per hour.

Reliability, while not expected to impact the system performance, may cause management difficulties. Lack of significant queues or delays is due to the under-utilization of the DAP. In the event of a failure queues will develop, but the given central facility configuration would recover easily. Since the DAP capability deteriorates beyond a certain false alarm rate the output waveform request rate for best DAP performance is below the present capacity of the communications system.

Finally, at the total system level, the following conclusions are reached:

- The number of data path failures may reach 400 or so annually. This may present a major problem to the system's management but is not expected to impact the network capability.
- The major time delay in the network is due to the time required to send waveform messages to the central facility. Optimization of this procedure is recommended.
- The major queue in the network is at the remote facility for outgoing waveform messages.
- The four station network detection capability is in the 4.5 to 4.6 m_b range for 90 percent detection probability when averaged over all regions. This is about 0.5 m_b units worse than the theoretical potential of the network.

- The major limitation on the network performance is in the DAP. A better DAP than the one simulated here would allow a significantly improved network detection capability.

Rather than arriving at system specifications at this time, the base-line simulation has indicated the need for further research to improve the design. Network detection processing appeared to be the limiting factor in the simulation. Therefore, further development of this subsystem is recommended. The development should focus on suppressing unwanted waveform messages in addition to improving the processor operating characteristics. Interactive processing may be useful at this point. Also, extension of the association criteria to include magnitude, depth and ellipse rotation should be considered.

Once the network processing limitation is removed, the next limitation is in the quantity of data that can be delivered by the communications system. The most fertile area here is the operating procedures of 1) when to request data, 2) what data to request, and 3) which stations to select. Clarification in this area will allow maximum utilization of the communications. Other optimizations of the communications system are possible such as the best multiple access method, data compression, coding and the like. However, these factors are considered less important in improving overall system performance.

Systems management was, for convenience, omitted from the simulation but the problems involved are not simple. The effect on the on-line system of poor maintenance, over-staffing or under-staffing, and lack of supplies and loss of other control functions could be significant to the system performance. Therefore, some effort to obtain information for control should be an integral part of the system.

The simulator developed for this study may be used to develop fast test-beds for the other research efforts. Therefore, it is recommended that the simulator be extended and updated along with the surveillance system.

To summarize these recommendations, the areas for further research as identified by the simulator are:

- Development of network detection processing methods
- Optimization of the communications procedures, especially the data request protocols.
- Study of the system management problems and requirements.
- Development of fast test-bed simulators.

Finally, it is recommended that the simulator be updated as the system evolves as a guide in this development and for other application objectives.

D. Technical Report No. 14: Aspects of Parameter Update and Information Feedback Design for a Seismic Surveillance System

In 1974 Texas Instruments Incorporated presented the results of a preliminary study of a world-wide seismic surveillance network (Sax and Staff, 1974). That work contains the basic system concepts, the trade-offs between centralized and decentralized systems, the approaches to several basic problems, and estimates of required processing and communications needs. An optimum seismic surveillance system must continuously adapt to changes in its external and internal conditions (e.g., a storm increasing a station's noise level and thereby lowering its detection capability; earthquake swarms causing an increase in data transmission and processing; sensor breakdown). This requires feedback of information from the ultimate information collection and system control points to the lower processing levels, and the updating of signal processing parameters and algorithms. This report discusses the problems anticipated in the design of such a feedback and parameter update technique.

For instance, one of the basic feedback problems is the setting of the station detection thresholds. These determine directly the false alarm and missed detection rates, the system processing and communications loads, and the station and network detection capabilities.

In updating parameters one is concerned with the fact that wave propagation does not necessarily take place along the great circle path between event source and station. Also, wavefronts may not be planar when propagating over an array. The first fact causes anomalies in beam direction, inverse velocity, travel time, sensor delay times, magnitude and spectral contents for each region-station path. The second fact causes additional (usually random) sensor delay time anomalies. For certain station-region relationships, these anomalies are expected to show consistent bias. The system then may be designed to be adaptive so that it can generate corrections to these anomalies to enhance the accuracy and quality of event indicators and estimators utilizing array measurements.

Finally, the system control center needs to be continuously updated on processing and communications loads at the various levels to maintain efficient system performance.

The concepts presented in this analysis are only a choice from several possibilities of approach, and are not necessarily the best. However, they serve the purpose of defining and describing general problem areas inherent in seismic surveillance system feedback and parameter update design. The optimal approach can only be found from more detailed analysis and in particular from system simulation after the overall surveillance system configuration is selected. The following are the results and conclusions for this study.

The threshold control, which determines the network detection capability and the false alarm and missed detection rates, should be optimized and exercised at the highest system level, i.e., by the system control processor. A minimum decision error cost threshold control algorithm for decisions at a station was developed in an open loop concept, i.e., without consideration to information feedback. For that case, the minimum cost threshold is determined by the so-called larger magnitude (the minimum magnitude of events one desires to detect), and by the relative cost of false alarms and missed detections. For the closed loop model, however, the cost of saturating the processing, storage, and communications capacities, and the cost of decision errors involved in detection association, event classification and the sending of waveform requests must be taken into account.

Parameter update compilation and general research and development are conceived to be performed by a special parameter update processor from data deposited in the system's data bank. This processor may also interact with other control facility processors, in particular with the system control processor, to assist in special problems and evaluations. Parameter update algorithm approaches were suggested which predict anomalous wave propagation effects. Parameter updating is estimated to require approximately ten seconds of extra communication per hour, and 75,000 words of additional storage capacity at the central facility and 3,000 words at each station.

The emphasis in this study has been on sketching the scope of problems encountered in seismic network feedback and parameter update design. A good understanding of these problems is essential to the overall system design, in particular, with respect to system capacity, the detection association procedure, and the network configuration. Therefore, more refined studies are needed to focus on specific problems. These problem areas are:

- Threshold control optimization at all processing levels in the system.

- Parameter update optimization (e.g., the problem of regionalization with emphasis on the trade-off between system warm-up time and seismic region size; the development of parameter update algorithms)
- Treatment of the detection problem for various types of non-stationary noise (storms, etc.).
- System quality and efficiency control.

SECTION VIII

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APPENDIX A

LIST OF REPORTS FROM CONTRACT F08606-74-C-0033

A. QUARTERLY REPORTS

1. Quarterly Report No. 1, covering the period 1 November 1973 to 1 January 1974, Texas Instruments Report Number ALEX(01)-QR-74-01, 15 February 1974.

2. Quarterly Report No. 2, covering the period 1 February 1974 to 30 April 1974, Texas Instruments Report Number ALEX(01)-QR-74-02, 15 May 1974.

3. Quarterly Report No. 3, covering the period 1 May 1974 to 31 July 1974, Texas Instruments Report Number ALEX(01)-QR-74-03, 15 August 1974.

4. Quarterly Report No. 4, covering the period 1 August 1974 to 31 October 1974, Texas Instruments Report Number ALEX(01)-QR-74-04, 15 November 1974.

B. TECHNICAL REPORTS

1. Observed Rayleigh Wave Group Velocities and Spectral Amplitudes for Some Eurasian Paths, by David G. Lambert, Texas Instruments Report Number ALEX(01)-TR-74-01, 28 February 1974.

2. Estimation of Seismic Detection Thresholds, by Frode Ringdal, Texas Instruments Report Number ALEX(01)-TR-74-02, 28 May 1974.

3. Earth Noise at Very Long Period Experiment Stations, by Sidney R. Prahl, Texas Instruments Report Number ALEX(01)-TR-74-03, 27 November 1974.

4. Estimating a Seismic Station's Detection Capability from Noise. Application to VLPE Stations, by Rudolf Unger, Texas Instruments Report Number ALEX(01)-TR-74-04, 22 October 1974.

5. Evaluation of Matched Filters and the Three-Component Adaptive Processor for the VLPE Stations and VLPE Network, by Alan C. Strauss and Alexandra I. Tolstoy, Texas Instruments Report Number ALEX(01)-TR-74-05, 10 October 1974.

6. Comparison of Coherent and Incoherent Beamforming Envelope Detectors for NORSAR Regional Seismic Events, by Wen-Wu Shen, Texas Instruments Report Number ALEX(01)-TR-74-06, 31 December 1974.

7. Seismic Detection and Discrimination Capabilities of the Very Long Period Experiment - Final Report, by David G. Lambert, Alexandra I. Tolstoy, and Ervin S. Becker, Texas Instruments Report Number ALEX(01)-TR-74-07, 9 December 1974.

8. An Evaluation of Adaptive-Beamforming Techniques Applied to Recorded Seismic Data, by Thomas E. Barnard, and Leo J. O'Brien, Texas Instruments Report Number ALEX(01)-TR-74-08, 31 December 1974.

9. Study of Two Automatic Short-Period Signal Detectors, by Stephen S. Lane, Texas Instruments Report Number ALEX(01)-TR-74-09, 6 December 1974.

10. Discrimination Techniques for Regional Events at NORSAR Using a Single Site, by Philip R. Laun, and Ervin S. Becker, Texas Instruments Report Number ALEX(01)-TR-74-10, 31 December 1974.

11. An Interactive System for Long-Period Seismic Processing, by Frode Ringdal and Jeffrey S. Shaub, Texas Instruments Report Number ALEX(01)-TR-74-11, 10 December 1974.

12. Feasibility of Interactive Data Processing in a Seismic Surveillance System, by Robert L. Sax, Texas Instruments Report Number ALEX(01)-TR-74-12, 31 December 1974.

13. Simulation of a World-Wide Seismic Surveillance Network, by Edward M. Shoup, and Robert L. Sax, Texas Instruments Report Number ALEX(01)-TR-74-13, 31 December 1974.

14. Aspects of Parameter Update and Information Feedback Design for a Seismic Surveillance System, by Rudolf Unger, Stephen S. Lane, and Robert L. Sax, Texas Instruments Report Number ALEX(01)-TR-74-14, 31 December 1974.

C. FINAL REPORT

1. Final Report, VELA Network Evaluation and Automatic Processing Research, by William H. Swindell and Staff, Texas Instruments Report Number ALEX(01)-FR-74-02, 31 December 1974.