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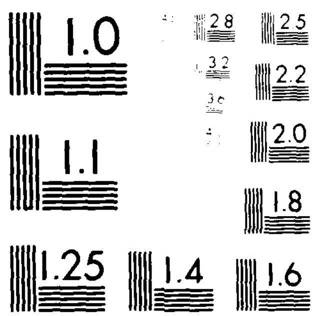

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1 June 1980

FINAL REPORT

VELA NETWORK AND AUTOMATIC PROCESSING RESEARCH

PREPARED BY
THEODORE J. COHEN AND TECHNICAL STAFF

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

The work performed on Contract Number F08606-79-C-0014 has been reported in detail in a series of nine technical reports and one technical memorandum. This final report summarizes the material covered in each technical report and the technical memorandum prepared in FY79, and the conclusions drawn from this material. Eight major task areas were covered as follows:

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19. (continued)

Data base organization
Coda characteristics
Automatic signal detectors
Beamforming
Seismic Research Observatories (SRO) Abbreviated Seismic Research Observatories (ASRO)

20. (continued)

- Extended and completed the evaluation of SRO and ASRO stations to determine the detection and discrimination capability of the stations, and to determine the performance characteristics of the detector used at the stations.
- Integrated and evaluated the short-period ABF with an automatic signal detector, and evaluated the short-period ABF's capability to separate mixed signals. In addition, developed a long-period ABF algorithm, and evaluated the long-period ABF's capability to separate mixed signals.
- Assembled long-period signal extraction (filter) subroutines and combined these subroutines into interactive and batch processing programs. Tested combinations of the various filter techniques in cascaded sequences and determined SNR improvement. In addition, determined noise and signal losses produced by various combinations of the filter techniques used. Also, determined improvements achieved in detection and discrimination capabilities using SRO-Eurasian data base.
- Evaluated capabilities of short-period polarization filter techniques to extract the regional waveforms Pn, Pg, Sn, Sg, Lg, and Rg. Determined filter performance for each propagation mode as well as the waveform degradation produced by the various filters.
- Developed and integrated multivariate, event-identification system and tested this system on a data base. Evaluated the performance of the refined identification system which was developed as part of the Event Identification Experiment.
- Developed a program for the DEC PDP-11/70 to write on disk, from tape, files of seismic signal measures which were used in the unclassified portion of the Event Identification Experiment.
- Developed a technique to detect source-related periodicities in the codas of seismic events, and demonstrated that such periodicities might be useful in providing yield estimates for explosions.
- Reviewed four seismic detectors developed and/or evaluated by Texas Instruments (TI) and ENSCO.

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by AFTAC/VSC, Patrick Air Force Base, FL 32925, under Contract Number F08606-79-C-0014.

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Project Manager:	Theodore J. Cohen (703) 548-8666

SUMMARY

The work performed on Contract Number F08606-79-C-0014 has been reported in detail in a series of nine technical reports and one technical memorandum. This final report summarizes the material covered in each technical report and the technical memorandum prepared in FY79, and the conclusions drawn from this material. Eight major task areas were covered as follows:

- Extended and completed the evaluation of SRO and ASRO stations to determine the detection and discrimination capability of the stations, and to determine the performance characteristics of the detector used at the stations.
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TABLE OF CONTENTS

Cont'd pg. v,

TABLE OF CONTENTS
(continued)

LIST OF FIGURES

LIST OF TABLES

SECTION I
INTRODUCTION

This final report summarizes the work performed under Contract Number F08606-79-C-0014, entitled VELA Network and Automatic Processing Research, by ENSCO, INC., at the Seismic Data Analysis Center (SDAC) in Alexandria, Virginia. This work was conducted during the period 11 December 1978 to 1 June 1980, and consisted of the following major task areas:

- Extended and completed the evaluation of SRO and ASRO stations to determine the detection and discrimination capability of the stations, and to determine the performance characteristics of the detector used at the stations.
- Integrated and evaluated the short-period ABF with an automatic signal detector, and evaluated the short-period ABF's capability to separate mixed signals. In addition, developed a long-period ABF algorithm, and evaluted the long-period ABF's capability to separate mixed signals.
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- Developed a technique to detect source-related periodicities in the codas of seismic events, and demonstrated that such periodicities might be useful in providing yield estimates for explosions.
- Reviewed four seismic detectors developed and/or evaluated by Texas Instruments (TI) and ENSCO.

The detailed results obtained for these tasks have been presented in a series of nine technical reports and one technical memorandum. This final report summarizes these results in Sections II through IX. References are given in Section X, and a list of all reports issued under the instant contract is given in the Appendix.

SECTION II
SRO/ASRO EVALUATION TASK

The results of this task are presented in Technical Report No. 4. The contents and conclusions are summarized below.

Technical Report No. 4
An Evaluation of the Seismic Research
Observatories: Final Report
SAR(01)-TR-79-04

A. THE EVALUATION TASK

The specific goals of this evaluation are:

- To estimate the data quality from, and reliability of, selected stations.
- To investigate the short-period and long-period noise field characteristics of selected stations.
- To estimate the detection capability of selected stations.
- To summarize the results of the four-year study and to determine the detection capability of the combined SRO-ASRO network.

B. SUMMARY OF RESULTS

1. Station Reliability

Reliability factors for each station are summarized in Table II-1. Reliabilities were calculated from the results of an analysis of each station's detection capability event data base, where the reliability factor is defined as:

$$R = 1 - \frac{N_d + N_m}{T}$$

where

R = Reliability factor

N_d = Number of events for which no data were recorded

N_m = Number of events for which the data indicated an instrument malfunction

T = Total number of events.

The average station reliability is approximately 0.9. Reliability would be expected to improve slightly as stations are brought to optimal operating efficiency.

2. Station Noise Characteristics

Short- and long-period noise samples were collected from each station every fourth station day over time periods of from six months to one year. Analyses yielded mean RMS noise amplitudes, noise magnitudes, and long-period mean RMS noise amplitude spectra. All values presented are without correction for instrument response. Mean short- and long-period RMS noise values are presented in Table II-2.

TABLE II-1
STATION RELIABILITY

Station	Short-Period	Long-Period
ANMO	0.91	0.87
ANTO	0.88	0.94
BOCO	0.98	0.91
CHTO	0.85	0.84
GUMO	0.76	0.70
MAIO	0.89	0.92
NWAO	1.00	0.91
GRFO	1.00	0.94
SHIO	0.53	0.83
TATO	0.94	0.90
SNZO	0.94	0.80
CTAO	0.99	0.99
ZOBO	0.98	0.99
KAAO	0.93	0.89
MAJO	0.71	0.66
KONO	0.74	0.96
Average	0.88	0.88

TABLE II-2

MEAN RMS NOISE AMPLITUDES IN MILLIMICRONS (mμ)

Station	Short-Period 0.5-4.0 Hz		Long-Period 0.023-0.059 Hz					
	Vertical		Vertical		North		East	
	Mean	S.D.*	Mean	S.D.*	Mean	S.D.*	Mean	S.D.*
SRO								
ANMO	0.38	0.09	9.73	3.61	8.80	3.67	10.01	3.32
ANTO	3.46	0.96	8.37	4.88	8.62	4.31	16.42	40.50
BOCO	3.88	0.81	13.50	16.00	20.02	48.89	14.60	19.13
CHTO	1.67	0.67	11.13	6.30	12.93	7.35	11.87	6.49
GUMO	40.25	16.83	11.25	3.45	17.20	5.34	18.23	5.34
MAIO	0.57	0.17	7.70	2.96	7.80	2.73	8.07	2.91
NWAO	7.69	2.80	13.44	4.85	17.29	5.67	11.61	4.79
GRFO	5.01	2.57	12.48	6.38	14.36	7.34	13.05	7.41
SHIO	1.62	0.42	8.42	3.01	8.08	2.94	7.50	3.18
TATO	20.61	8.66	14.22	6.04	15.65	7.14	18.12	9.56
SNZO	28.92	11.05	45.92	17.28	27.26	14.22	30.17	14.41
ASRO								
CTAO	5.55	2.27	9.41	3.29	9.90	3.02	8.78	3.18
ZOBO	1.02	0.36	7.57	3.07	8.06	2.97	8.75	3.53
KAAO	1.94	0.69	9.06	3.51	9.05	3.02	11.86	4.56
MAJO	3.53	1.31	8.40	3.22	10.20	4.08	10.85	9.75
KONO	12.64	4.27	10.34	4.23	12.94	6.17	11.59	4.84

*S.D. = Standard Deviation

The stations, based on their RMS noise levels, may be divided into a high noise group represented by the coastal stations GUMO, TATO, SNZO, and KONO; a low noise group represented by the inland stations ANMO, CHTO, MAIO, SHIO, ZOBO, and KAAO; and a medium noise group composed of the remaining inland and coastal stations. Without exception, the stations in the high noise group are located in areas which subject them to severe ocean storm activity.

Table II-3 lists the means and standard deviations of measured $\log_{10}$ peak noise amplitudes. Short-period and long-period measurements were made at periods of 1.0 ± 0.2 and 25 ± 2 seconds, respectively. A comparison between SRO and ASRO peak noise amplitudes reveals, as was expected, that short-period standard deviations appear reduced for the buried SRO instruments. This evidence, together with comparisons of the typical SRO and ASRO long-period noise spectra (shown in Figure II-1), demonstrates how instrument burial reduces and stablizes the ambient noise field.

Figures II-2 and II-3 present the theoretical short- and long-period capabilities of at least one station in the SRO/ASRO network to detect an m_b 4.5 event. The program used was developed by M. H. Wirth (1970) and assumed that both signal and noise are lognormally distributed. Snell (1976) modified that program to consider station reliability. The numbers on the figure contours were calculated as follows:

$$\log_{10} \frac{P_D}{1-P_D}$$

TABLE II-3

MEAN LOG PEAK NOISE AMPLITUDES IN MILLIMICRONS (mμ)

Station	1 Second Period		25 Seconds Period					
	Vertical		Vertical		North		East	
	Mean	S.D.*	Mean	S.D.*	Mean	S.D.*	Mean	S.D.*
SRO								
ANMO	-0.06	0.16	1.33	0.16	1.28	0.17	1.35	0.16
ANTO	0.82	0.17	1.26	0.15	1.32	0.14	1.44	0.34
BOCO	0.87	0.13	1.50	0.24	1.52	0.33	1.45	0.28
CHTO	0.37	0.18	1.28	0.20	1.38	0.18	1.33	0.20
GUMO	1.85	0.14	1.62	0.16	1.73	0.15	1.73	0.17
MAIO	0.06	0.15	1.28	0.15	1.28	0.16	1.29	0.16
NWAO	0.95	0.20	1.54	0.15	1.59	0.15	1,43	0.17
GRFO	0.72	0.18	1.42	0.16	1.45	0.17	1.44	0.18
SHIO	0.43	0.19	1.34	0.14	1.30	0.17	1.30	0.12
TATO	1.49	0.17	1.59	0.15	1.63	0.18	1.68	0.19
SNZO	1.79	0.17	2.10	0.16	1.84	0.17	1.88	0.16
ASRO								
CTAO	0.61	0.26	1.26	0.22	1.32	0.13	1.30	0.20
ZOBO	0.10	0.20	1.24	0.16	1.29	0.12	1.33	0.15
KAAO	0.46	0.21	1.32	0.17	1.35	0.15	1.44	0.18
MAJO	0.56	0.21	1.33	0.15	1.44	0.22	1.34	0.15
KONO	0.83	0.23	1.36	0.14	1.50	0.14	1.46	0.15

*S.D. = Standard Deviation

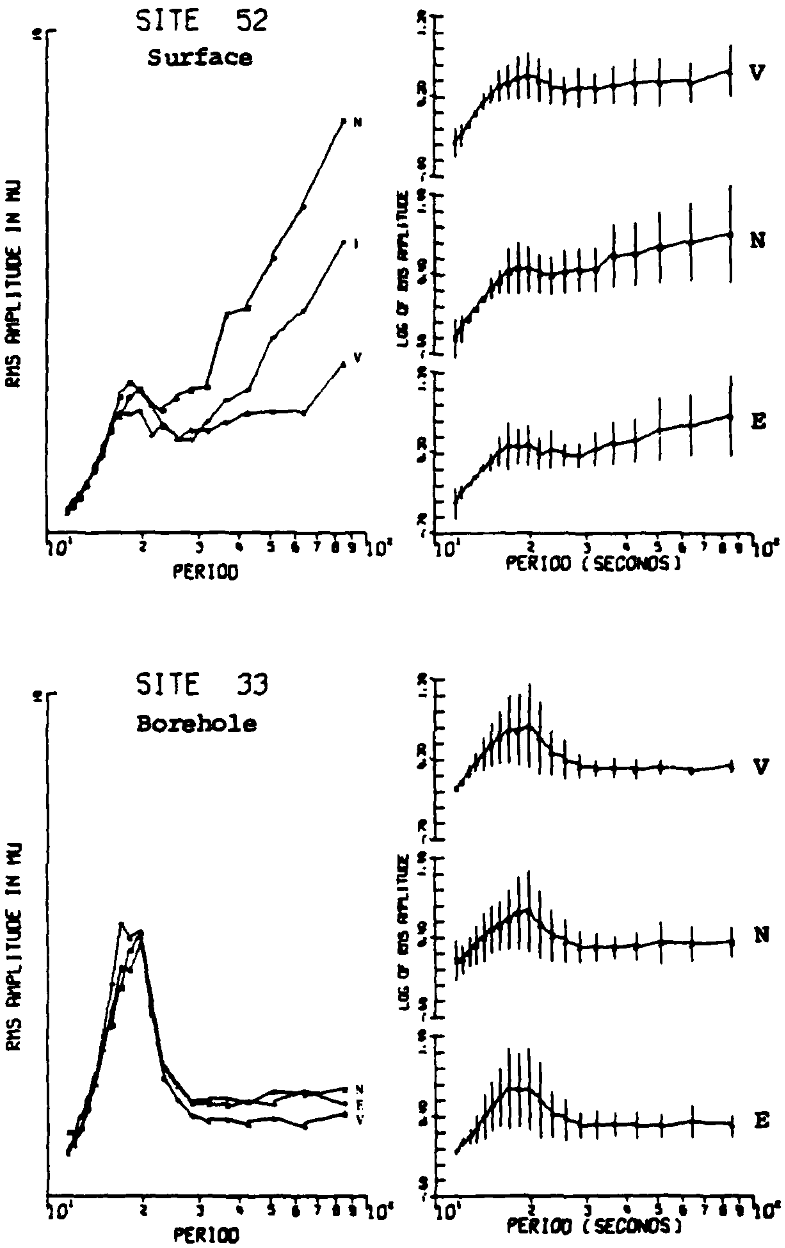

FIGURE II-1

LONG-PERIOD NOISE SPECTRA FROM SURFACE AND BOREHOLE INSTRUMENTS

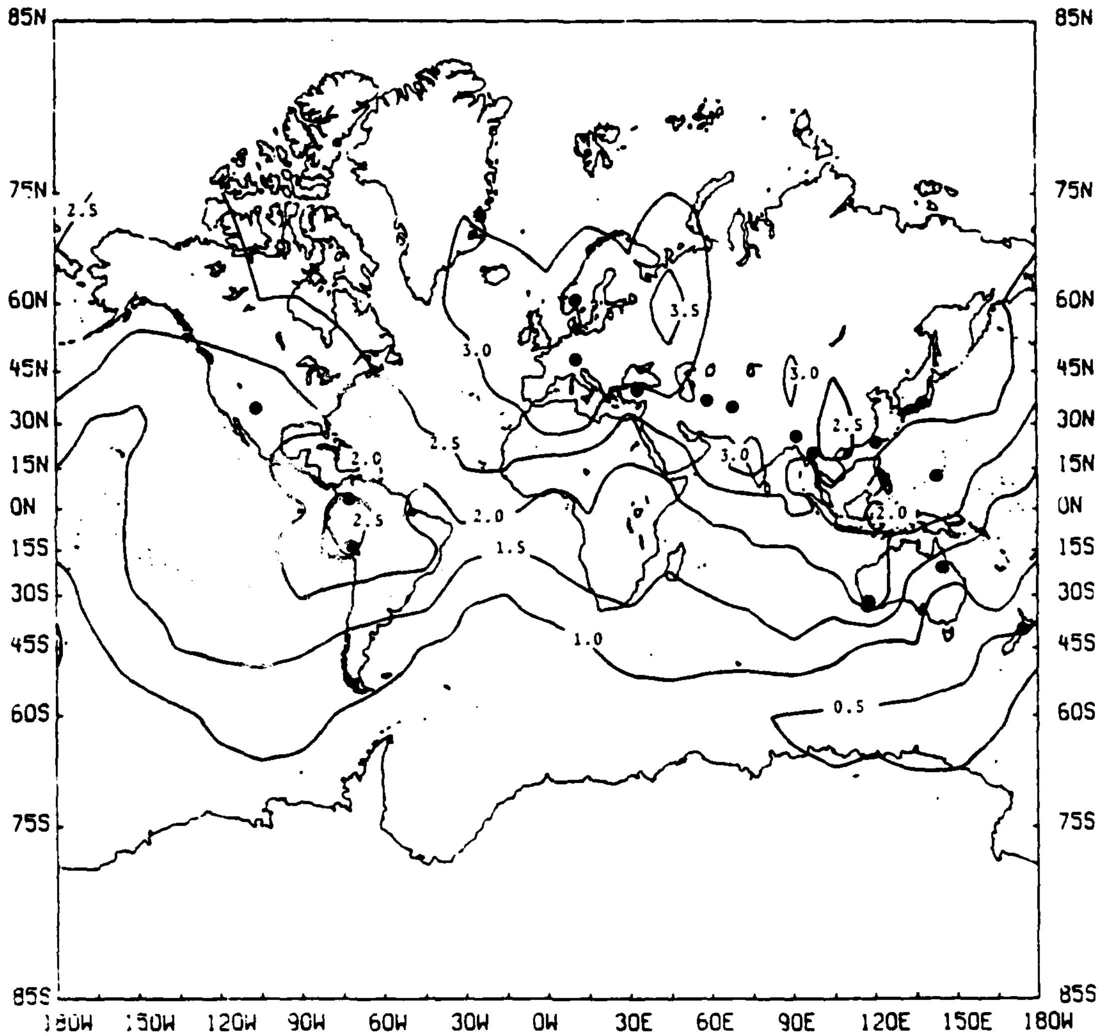

FIGURE II-2

THEORETICAL NETWORK SHORT-PERIOD DETECTION CAPABILITY WITH REGARD TO AN m_b 4.5 EVENT

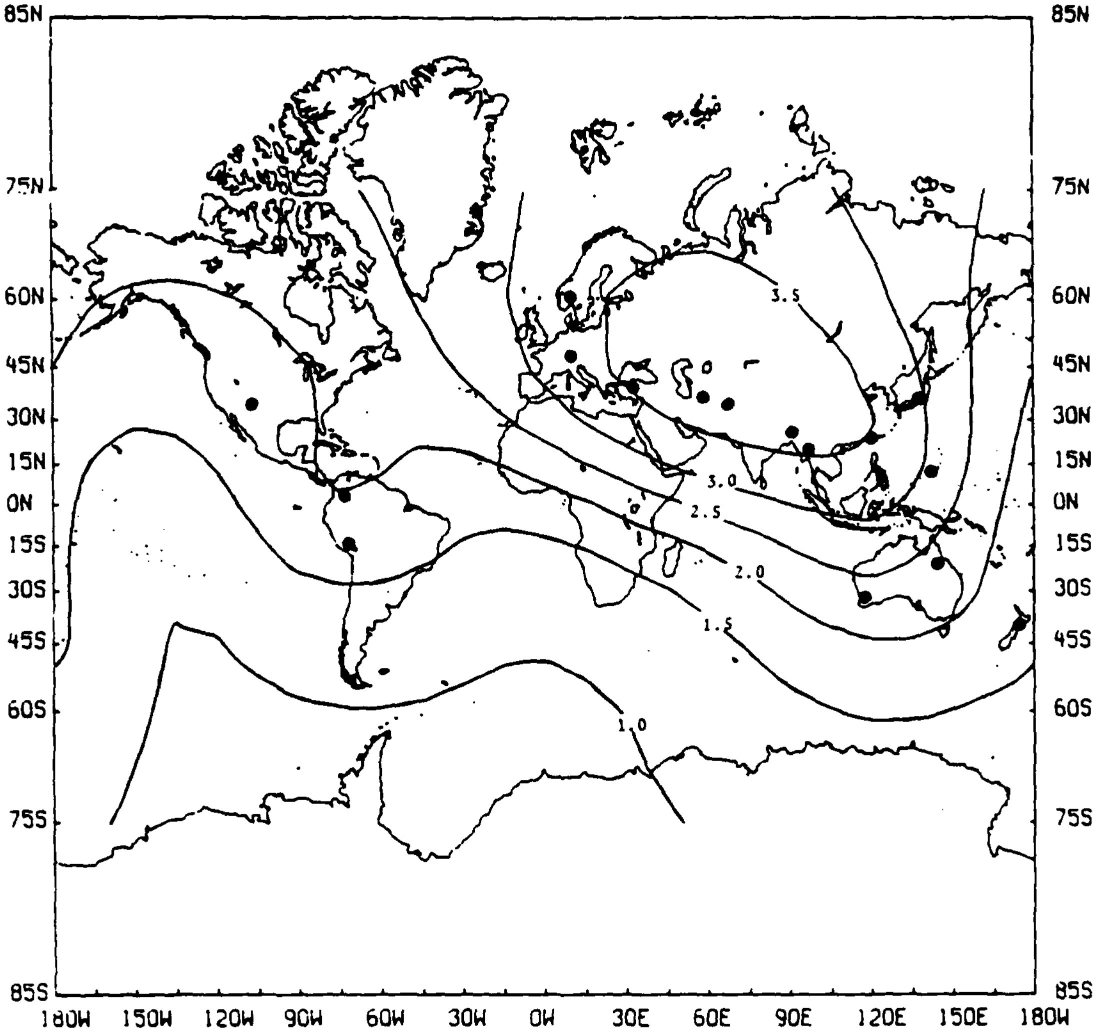

FIGURE II-3

THEORETICAL NETWORK LONG-PERIOD DETECTION CAPABILITY WITH REGARD TO AN m_b 4.5 EVENT where P_D is the probability of detection. The contour values are translated into detection probabilities in Table II-4. The probability of detection must never reach one or the logarithm would be infinite, and so, the last detection probability listed in Table II-4 may actually be calculated as 0.99997. Figures II-2 and II-3 show that the SRO/ASRO network can detect medium magnitude events with certainty.

Short- and long-period detection capabilities for each station are presented in Table II-5. These capabilities were estimated by the analysis of event data bases which were constructed from available event lists. The region of interest for all except two of the stations was Eurasia. Stations BOCO and ZOBO, which are distant from Eurasia, were evaluated with regard to their South American detection capabilities.

The ideal and actual detection capabilities differ in their treatment of signals for events which were undetected due to their masking by other signals, equipment malfunction, or equipment failure. These events were ignored in the ideal estimates and were counted as nondetections in the actual estimates.

The ideal detection capabilities, with few exceptions, reflect station noise levels and the mean epicentral distances of the events in the station's evaluation data bases. Based on these two factors alone, the two South American stations detect better than their Eurasian counterparts, illustrating the regional dependence of detection capability.

In general, the SRO/ASRO instruments are considered reliable and are thought to produce high quality seismic

TABLE II-4

CORRESPONDENCE OF DETECTION CAPABILITY CONTOURS WITH DETECTION PROBABILITY

Contour	Probability Of Detection
0.5	0.7597
1.0	0.9091
1.5	0.9693
2.0	0.9901
2.5	0.9968
3.0	0.9990
3.5	0.9997

TABLE II-5

m_{b50} SRO/ASRO DETECTION CAPABILITY

	Short-Period		Long-Period		$\bar{\Delta}$* (degrees)
	Ideal	Actual	Ideal	Actual	
SRO					
ANMO	4.8	5.1	4.6	5.0	92 ± 16
ANTO	5.0	5.1	4.7	4.8	32 ± 2
BOCO	5.2	5.2	4.3	4.6	42 ± 16
CHTO	4.6	5.0	4.6	4.9	46 ± 20
GUMO	>6.0	>6.0	4.5	5.1	63 ± 30
MAIO	4.7	4.8	4.1	4.6	38 ± 22
NWAO	6.1	6.1	4.9	5.2	87 ± 17
GRFO	5.0	5.0	4.6	4.8	46 ± 4
SHIO	4.4	5.2	4.4	4.6	21 ± 6
TATO	5.5	5.7	4.1	4.5	44 ± 24
SNZO	>6.0	>6.0	5.0	5.3	120 ± 28
ASRO					
CTAO	5.4	5.4	5.0	5.2	86 ± 26
ZOBO	4.7	4.7	4.2	4.5	49 ± 17
KAAO	4.3	4.4	4.1	4.5	39 ± 24
MAJO	4.9	5.3	4.4	5.0	42 ± 29
KONO	5.3	5.5	4.6	4.6	45 ± 5

* Mean and standard deviation of station-to-epicenter distances

data. The studies confirm that instrument burial results in a significant reduction of, and increased stability in, the recorded noise field. Consequently, these stations are valuable assets for use in event detection, location, and discrimination.

SECTION III

SIGNAL DETECTION AND EXTRACTION USING ADAPTIVE BEAMFORMING (ABF) TECHNIQUES

The results of this task are presented in Technical Report No. 8. The contents and conclusions are summarized below.

Technical Report No. 8
Evaluation of Short- and Long-Period
Adaptive Beamforming Processors (U)
SAR(01)-TR-79-08

A. THE EVALUATION TASK

The purpose for performing the adaptive beamforming (ABF) detector study was fivefold:

- To integrate the adaptive beamforming processor with an automatic short-period seismic signal detector.
- To determine the detection capability of the combined processors.
- To investigate the feasibility of extracting explosion signals from the coda of earthquakes.
- To develop a long-period version of the ABF.
- To examine its applicability to the problems of long-period seismic wave extraction and mixed-signal separation.

An adaptive beamformer (ABF) is a multiple-point, multiple-channel filtering processor. The design goal for this type of processor is to minimize the filtered output through the use of constraints which, theoretically, only pass energy propagating from an array-steered location.

The ABF algorithm described is based on an L_1-norm criterion of estimating signals. This criterion minimizes the residual noise in a manner which is insensitive to large, unknown errors in the signal model (such as those related to amplitude anomalies and to signal distortion across an array). For this ABF processor, the time-varying adaptation rate updates the multichannel filter at each point by weighting deviations from the beamform inversely as the signal-to-noise ratio of the ABF output. As a result, large deviations from the signal model used to estimate an incident signal do not cause the ABF algorithm to annihilate signals exhibiting such amplitude deviations. Studies have shown that this action is critical to the operation of the ABF if the detection of weak P-wave signals is to be enhanced. Further, signal losses caused by the ABF have been greatly reduced through the use of the time-varying algorithm.

The ABF processor was developed for use in real-time so that it could be used in an operational front-end detection system. The objective in using this processor is to increase the detection capability of a short-period or a long-period seismic array. The ABF processor requires only a signal propagation model; it does not require a reference waveform or noise statistics for implementation. As such, it can be used to extract a signal exhibiting an unknown waveform.

B. CONCLUSIONS AND RECOMMENDATIONS

1. Short-Period ABF Performance

Single Sensor (SS) performance, as well as Conventional Beamformer (CBF) and Adaptive Beamformer (ABF) performance, were gauged using data recorded by a 19-element, 8-kilometer-aperture array. Performance was determined by counting the number of events detected visually from a set of 126 events previously detected and located by the NORSAR array. At the 70% detection level, it was determined by visual analysis that using a single sensor, events greater than NORSAR magnitude m_b=5.07 could be detected; using a CBF, the threshold was lowered to NORSAR magnitude m_b=4.53; and using an ABF, the threshold dipped to NORSAR magnitude m_b=4.03. These results are similar to those published by Shen (1978). Note that the results obtained in the current study pertain to events which are approximately 45^o distance from the array. By analyzing events from a region which is nominally 45^o epicentral distance, later phase association problems were avoided. This follows since such later phases as PP and PcP occur at least several minutes later than the P phase.

A constant-false-alarm-rate automatic detector developed by Swindell and Snell (1977) was integrated into the array processing program. The constant-false-alarm-rate characteristics of the array were verified by analyzing 1½ hours of noise data using different detection thresholds. On this basis, thresholds were set at 4 false alarms per hour on the SS, CBF, and ABF channels. The feasibility of operating the detector at an even higher false alarm rate of

8 false alarms per hour was also evaluated for the ABF. The false alarm rates are specified for a single beam focused on the selected source region.

At the 70% detection level and at a false alarm rate of 4 false alarms per hour, the single sensor detected events having NORSAR magnitudes greater than m_b=5.14; for the CBF, the threshold was lowered to magnitude m_b=4.57; and the ABF, the threshold was lower to m_b=3.82. For 8 false alarms per hour, the ABF detected events having NORSAR magnitudes of m_b= 3.63. The confidence bounds on the ABF performance were large (about 0.2 of a magnitude unit), indicating that the improvement in the detection capability at the higher false alarm rate is not significant.

For a data base of 126 events, the ABF, at 4 false alarms per hour, detected all but 25 events; detections included all but one of the 13 events with NORSAR magnitudes between m_b= 3.3 and 3.6. It should be noted that by using the detector peak-power output to determine magnitudes, it appears that smaller NORSAR-magnitude events are not really as small as is indicated. That is, there were large, nevative statistically-valid NORSAR deviations of events with magnitudes derived from the 8 km array between m_b=3.9 and 4.1. Seventy of the 126 events were in this magnitude range so that this interpretation of the NORSAR magnitudes seems credible.

To better assess the detection capability of the automatic detectors, the detection statistics were analyzed in terms of the detector-determined magnitudes at the 50% detection level. For a false alarm rate of 4 per hour, the single sensor detected events having magnitudes greater than m_b=

5.02; the CBF detected magnitudes greater than m_b=4.28; and the ABF detected magnitudes greater than m_b=3.87. An analysis of magnitudes indicated that the detector-determined magnitudes are roughly 0.15 m_b magnitude units larger than the NORSAR magnitudes. That is, on the basis of NORSAR magnitudes, at the 50% detection level, and at a false alarm rate of 4 per hour, the equivalent detection thresholds are: SS, m_b=4.87; CBF, m_b=4.13; and ABF, m_b=3.72. It is interesting to note that at 8 false alarms per hour, the ABF detector threshold is m_b=3.58 (NORSAR). The population standard deviations at 4 false alarms per hour varied between 0.16 and 0.26 m_b units, as would be expected for noise fluctuations. However, at 8 false alarms per hour, the population standard deviation increases to 0.33 m_b units, and the confidence bounds were observed to increase significantly at the 50% and lower detection levels. It would appear, then, that the apparent improvement of the detection capability at 8 false alarms per hour is influenced significantly by the occurrence of false alarms, whereas at the 4-false-alarms-per-hour rate, false alarm interference is not considered a significant factor. Comparing the constant false alarm rate automatic detector to the detection results obtained using visual analysis, it appears that the performance of an automatic 4-false-alarms-per-hour rate detector is approximately equivalent to the results of the visual analysis. On that basis, a threshold setting of 4 false alarms per hour, per beam, would appear to be an optimum setting.

In the course of this analysis, preliminary evidence was obtained which suggested that events from certain small regions may exhibit multiple-source characteristics. For the events examined, the composite signals exhibit a consistent pattern of time delays. Most of the multiple signal arrivals occur at magnitudes near the detector-determined station magnitude, even at time delays of up to one minute. If a multiple-source mechanism is operative, it could be verified by observing the events of interest with two arrays, including the NORSAR. In that case, a source-related multiple time delay pattern should be observed at both sites simultaneously. This effect, if valid, has important implications for event detection, location, and discrimination. Work on multiple events is left as a subject for future research.

2. Extraction of Explosion Signals Hidden in Earthquake Coda

The coda-suppression capability of the ABF processor is useful for detecting and identifying explosion signals which are hidden in what are presumed to be receiver-scattered coda of nearby earthquakes. This result was demonstrated by adding explosion signals to earthquake signals, with the explosion signal delayed 15 seconds and 30 seconds from the onset of the earthquake signals. The results of ABF analysis of these signals showed that explosions 0.7 to 1.1 m_b units smaller than the masking earthquake can be extracted with good preservation of the explosion signal's character.

By comparison, the CBF can only extract explosion signals which are 0.4 m_b units smaller than the masking earthquake. However, the CBF signals are usually distorted by the earthquake coda, and so, the former cannot be readily distinguished from later-arriving earthquake phases.

In general, if a large earthquake was selected to mask an explosion, the earthquake signals will be dominated by energy at significantly lower frequency than the signals from the explosion. Thus, by combining bandpass filtering with ABF processing, earthquake and explosion signals can be separated with little cross-talk or distortion. The use of the ABF processor for this purpose increases significantly the risk for an adversary hiding an explosion in an earthquake unless the earthquake is more than one magnitude larger than the explosion. Note that this result pertains to the 19-element array, which has an aperture of about 8 km.

3. Long-Period ABF Performance

All results below were achieved using the 7-element Iranian Long Period Array (ILPA).

Vertical-component Rayleigh wave extraction by means of the ABF processor using a convergence rate of 2.0; SNR gains of 9.0 dB over a CBF were achieved. For the radial component, a convergence rate of 2.5 appears optimum, and the SNR improvement over a CBF is 7.0-8.0 dB. Transverse Love wave extraction is optimized by a convergence rate of 1.5, and the SNR improvement over a CBF was variable, ranging from 3.0 to 10.0 dB.

The array response pattern measurement for ILPA indicated a 3 dB mainlobe beamwidth of 80 degrees for the CBF, and of 30 degrees to 40 degrees for the ABF.

Regarding the mixed-signal separation of long-period surface waves with seven-channel beamforming, the threshold reduction achieved through the use of ABF, as compared with that for CBF, was 9 dB (0.45 M_s). With four-channel beamforming, the threshold reduction obtained using the ABF instead of the CBF was 6 dB (0.3 M_s). This performance was achieved by separating surface wave signals only 30^o apart in azimuth. Based on aperture, only 3 dB improvement was expected for the ABF using a seven-channel array. The results obtained, however, indicate that the ABF possesses significant coda suppression capabilities. Apparently, the ABF can differentiate a structured, receiver-scattered coda from the onset of arrivals propagating from the source. This hypothesis needs to be tested further by separating mixed signals which propagate from the same direction.

With respect to long-period bodywave extraction, the ABF successfully extracted P and S waves, and secondary phases such as PP and ScS. The estimated processing gain for ABF bodywave extraction was about 10 dB over that achieved using the CBF.

4. Suggestions for Future Research

Although the ABF, combined with an automatic detector, appears to be at a stage where its field implementation as a front-end detector is feasible, this processor is also an important seismic research tool. As such, the following, additional research studies are considered to be important:

- Detect and locate small events by incorporating time anomaly corrections into the large aperture NORSAR array.

- Integrate three-component long-period ABF extraction with polarization filtering.
- Test the composite event hypothesis by simultaneously observing events from Flinn and Engdahl region 716 at NORSAR; also, evaluate depth determinations from such a configuration.
- Test hidden event extraction by applying the integrated ABF and automatic detector to extraction and timing of real multiple explosions, and, if possible, to explosions masked by the coda of large earthquakes.

SECTION IV
LONG-PERIOD SIGNAL EXTRACTION TASK

The results of this task are presented in Technical Report No. 5. The contents and conclusions are summarized below.

Technical Report No. 5
Interactive and Automatic Modes of
Long-Period Signal Extraction
Using Cascaded Filters
SAR(01)-TR-79-05

A. SIGNAL EXTRACTION TASK

The purpose of this work was to develop and evaluate an interactive long-period signal extraction filter suite. Five filters were included in the suite and were applied to test data in a cascaded mode (i.e., the output of one filter served as the input to the next filter). The filters tested were a bandpass filter, a Wiener filter, a chirp matched filter, a polarization filter, and a Gaussian narrowband filter. It was found that for the filters examined, the polarization filter dominates the cascaded filtering approach to signal extraction; specifically, processing gains as high as 14 to 15 dB were realized from the application of cascaded filters which included this filter. Further, tests performed on a Eurasian data set using one specific cascaded filter sequence yielded an improvement in surface wave detection capability equivalent to an improvement in bodywave detectability of approximately 0.6 to 0.8 m_b units. Finally, cascaded filters were found to provide more detected signals from which surface wave magnitudes can be obtained; as such, the use of these filters can enhance an analyst's capability to discriminate between earthquakes and explosions.

B. CONCLUSIONS AND RECOMMENDATIONS

1. Summary of Results

The following conclusions are drawn from this study:

- An effective long-period signal extraction program has been created and tested on data recorded by Eurasian SRO stations. This program exists in both interactive and automatic mode versions.
- Both versions of the program are modularized for ease of insertion of additional signal extraction techniques.
- The polarization filter dominates the cascaded filter process. Cascaded filter sequences containing this filter yielded SNR gains of up to 14 to 15 dB.
- The bandpass filter/polarization filter/Gaussian narrowband filter cascade filter sequence produced an improvement in surface wave detection capability equivalent to approximately 0.6 to 0.8 m_b units.
- Cascade filtering enhanced the discrimination capability, increasing the number of detected signals for which reliable surface wave magnitudes can be estimated.

2. Feasibility and Operability of Applying the Long-Period Signal Extraction Program to a Large World-Wide Data Base

Based on the results of this study, the most feasible approach to applying the long-period signal extraction program to a large world-wide data base would be to have both interactive mode and automatic mode versions resident on the same computer. This would permit one to process the majority of the data using the automatic mode, with the interactive mode reserved for parameter determination and the analysis of time segments of more than usual interest. (It is anticipated that attempts to use the interactive mode on all of the data of a large data base would overwhelm the analyst. Automatic mode processing of the majority of the data should avoid this.)

Initially, it would be necessary to determine the signal suppression of each selected cascade filter sequence at each station providing data to the data base. This is necessary to permit computation of comparable surface wave magnitudes for events detected by different cascade filter sequences, since the degree of signal suppression varies with the choice of cascade filter sequence and the recording station.

3. Suggested Additional Research

Significant gains in detecting and measuring weak surface-wave signals can be achieved by evaluating and optimizing an alternate design for the cascade filter used in the signal editing process. The cascaded bandpass filter/polarization filter/Gaussian narrowband filter (B_1, P, G) evaluated in this study is considered the optimum choice of a processor which automatically edits and measures surface wave signals. It was designed for maximum likelihood detection of at least 85% of the signals which are expected to be observed.

Another cascade configuration, the Wiener filter/polarization filter/chirp filter/Gaussian narrowband filter sequence (W, P, C, G) provides an enhanced capability for extracting weak, hard-to-detect signals which are missed by the B, P, G sequence. The capability of the W, P, C, G processor to detect weak signals at the 15% level of detection results from the higher variance associated with this processor. This is especially the case for the network-related performance of the W, P, C, G processor in that at least one additional detection out of the eight SRO stations used here is expected at the 15% level of detection.

For enhanced network performance, it is proposed that the W, P, C, G cascade filter sequence be operated in parallel with the B_1, P, G cascade filter sequence. It is expected that at least 0.17 units of improved magnitude detection (m_b) capability can be achieved in this way for single-station detections. Considerably more gain is expected to be achieved when parallel processors are used with a network. This can be accomplished (with only a minor increase of computer time) by utilizing the W, P, C, G cascade filter sequence as a back-up to the automated B_1, P, G cascade filter sequence. In this dual mode of operation, the W, P, C, G cascade filter sequence would be used only when signals are not detected after application of the B_1, P, G cascade filter sequence.

SECTION V

EXTRACTION OF SHORT-PERIOD (SP) REGIONAL WAVEFORMS USING POLARIZATION FILTERS

The results of this task are presented in Technical Report No. 3. The contents and conclusions are summarized below.

Technical Report No. 3
Application of the Phase-Difference
Polarization Filter to Short-Period
Regional Data
SAR(01)-TR-79-03

A. SHORT-PERIOD POLARIZATION FILTER TASK

This research effort was intended to refine and test a technique to extract and identify the short-period regional phases Pn, Pg, Sn, Sg, Lg, and Rg. The technique, called phase-difference polarization filtering, was originally developed for long-period teleseismic data (Strauss, 1978). However, with the move toward utilization of three-component single-site stations, and with the increased interest in regional seismic data, it becomes desirable to apply the technique to short-period reigonal phases.

This report presented the results of research on the application of the phase-difference polarization filter to regional short-period data. The specific goals of this study were:

- To design three-component adaptive filters which extract short-period regional phase signals.
- To estimate the effects of such filters on the detection capability of the phases Pn, Pg, Sn, Sg, Lg, and Rg.
- To test the filters on seismic events with epicentral distances between 0° and 20° from the receiver site.
- To outline future, feasible extensions of polarization filter use to the problem of identifying significantly refracted or wave-guided phases which are observed at regional distances (this pertains to source discrimination by correlation with source-region-to-station synthetics).

B. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

The following conclusions were drawn from the work performed on the phase-difference polarization filter:

- Using batch processing, a broadband bandpass filter (in this study, 0.5-5.0 Hz) is more effective as a preprocessor to the polarization filter than is an arbitrary narrowband filter.
- Choice of the processing segment length used in the polarization filter algorithm appears to have a greater effect on the signal-to-noise ratio improvement of short-period regional phases than does the

choice of the trapezoidal pass window half-width parameters for the range of values tested (half widths of 10^{o} to 20^{o}).

- The 'best' results, in terms of signal-to-noise ratio gain, are obtained with a polarization filter processing segment length of 16 points.
- The polarization filter provides signal-to-noise ratio gains of approximately 10 dB for regional compressional and shear waves, and of approximately 8 dB for Lg and Rg.
- Direct estimates of detection capability improvement which result from application of the phase-difference polarization filter for regional P and S waves were found to be approximately 0.6 m_b units.
- In addition to its use as a signal extractor, the phase-difference polarization filter can be used to separate mixed signals and to identify phases.

2. Recommendations for Future Use

The following recommendations should be considered in any future work involving the phase-difference polarization filter:

- Implement the phase-difference polarization filter in an interactive processing environment.
- Cascade the phase-difference polarization filter with the previously-developed particle-motion polarization filter (Strauss, 1978) which tests on the angle of incidence to create a total model of bodywave polarization.

- Test the phase-difference polarization filter on data recorded at a different station in order to check for regional dependence of program parameters and in order to estimate better the Lg and Rg extraction results.

NOTE:

Advanced applications of polarization filtering should address a more complete interpretation of phase arrival times and of the relation of these arrivals to local crustal structure. Also, the relative excitation and frequency of phases can be used to determine information on source depth and source mechanism. This important application can be facilitated by further development of interactive waveform extraction combined with synthetic studies which would be used to predict the observed wavetrain associated with specific source-region-to-station paths. Results shown here, with a few of the better known phases, indicate interesting possibilities for applying this approach to precise seismic interpretation of observed phases.

Criteria for, and the precision of, source direction and distance determinations should be thoroughly evaluated. The combined use of the phase associations with source distance, direction, and depth estimates may provide the only feasible basis for focal determinations and discrimination of small regional events.

SECTION VI
EVENT IDENTIFICATION TASK

The results of this task are presented in Technical Report No. 6. The contents and conclusions are summarized below.

Technical Report No. 6
Event Identification Experiment
SAR(01)-TR-79-06

A. EVENT IDENTIFICATION TASK

In this study, an experimental Event Identification System (EIS) developed by Sax, et al. (1978) was used to classify, as an earthquake or an explosion, each of 128 events drawn from an Area of Interest (AI) data base. The specific goals of the study were:

- To refine the Event Identification System developed by Sax, et al. (1978).
- To identify the 128 events as either earthquakes or explosions.
- To evaluate the performance characteristics of the Event Identification System.
- To recommend procedures for implementing the Event Identification System in an operational environment.

B. CONCLUSIONS

With our initial, selected set of discriminants, we observed that eight discriminant clusters were needed to separate the different types of earthquakes in the data base. Some of these event clusters were found to have resulted from operational problems (i.e., problems related to our definition of discriminants and to our data processing techniques). Clustering helps to identify operational problems as well as to identify the physical factors responsible for our capability to separate explosions from earthquakes. The most important operational problem observed was that the selected event discriminants exhibited serious magnitude scaling effects. That is, the event discriminants clustered into small, medium, and large magnitude sub-groupings of a group containing deep earthquakes or of another group containing exclusively shallow earthquakes. Then, too, another earthquake cluster probably associated with large ground-displacement overshoots was indicated by substantial high-frequency peaks in the event spectra. Unless they were clustered and treated separately, these unusual earthquakes would have been falsely classified as explosions.

A number of operational problems were identified by the adaptive clustering procedure and are discussed in detail. An attempt was made to resolve these problems, and the results obtained were encouraging.

With respect to the results obtained, one explosion in the data base was misclassified as an earthquake, and another was 'unidentified.' Post-analysis quality control checking of the data for these two events indicated that the data were not properly edited. In particular, large timing errors on the order of 30 seconds, and correspondingly large errors in magnitude measurements (one or two orders of magnitude), suggest that the data for these two events be omitted from the performance evaluation. On this basis, the following detection performance was achieved:

Explosions misidentified	
Explosions unidentified	0%
Earthquakes falsely identified as explosions	4%
Earthquakes which were unidentified	14%

These results indicate that a single explosion cluster effectively separates the explosions, but that improvement is needed to identify more effectively the earthquake events.

We did modify our baseline discriminants by scaling them to remove their observed dependence on network magnitudes. Using the scaled discriminants, we obtained the same partitioning of earthquakes and explosions previously obtained, but with the following difference: <u>all</u> of the earthquakes, which formerly fell into eight clusters, migrated into a single earthquake cluster, (the explosions still fell into a single cluster). This dramatic result indicates that the clustering previously obtained with our baseline discriminants appeared to be an artifact of the magnitude scaling problem.

The modified discriminants, empirically corrected for their dependence on network magnitude, exhibited significant differences in their ability to separate explosions from earthquakes. From this, we learned that it is important to recognize and remove operational problems before judging the efficacy of the individual discriminants. Then, too, by applying the adaptive clustering technique using the modified discriminants, it may be possible to improve event identification performance, especially by more effectively identifying earthquake events and by reducing false alarm explosion identifications.

In sum, the results we obtained in the Event Identification Experiment demonstrate the power in our clustering approach to training with earthquakes and to interpreting residual clusters (which are dissimilar to earthquake clusters) as consisting of possible explosions. Furthermore, our approach of not presuming any prior knowledge of explosion discriminant characteristics, but, instead, of relying on clustering to provide such information, is important in that there is no 'forcing' of solutions which have limited applicability. We further learned that the recognition and solution of operational problems is essential before passing judgement on the efficacy of the discriminants. Otherwise, the interpretation of results could be misleading and lacking in generality. Clearly, then, our work indicates that much remains to be done to improve our data processing techniques before our results can be considered optimum and generally applicable.

SECTION VII
DATA BASE TRANSFER TASK

The results of this task are presented in Technical Report No. 2. The contents and conclusions are summarized below.

Technical Report No. 2
Management of a Signal Management Data Base (SMDB)
SAR(01)-TR-79-02

A. DATA BASE TRANSFER TASK

The purpose of the Data Base Transfer Task was to transfer the Event Discriminant Data Base from the PDP-15/50 to the PDP-11/70, and to do so under the following constraints:

- Preserve the signal measurements for all event-stations processed under Contract Number F08606-79-C-0014.
- Establish an expandable and maintainable Signal Measurement Data Base (SMDB) on the PDP-11/70 that:
  - satisfies the first constraint above
  - may be updated with additional signal measurements for event-station data processed by other contractors.
- Provide FORTRAN-compatible software utilities to:
  - initialize the SMDB Directory and Free-Block File

- update the SMDB by event, station, measurement, or contractor
- access the SMDB for information by event, station, measurement, or contractor.

- Write selected driving programs to demonstrate an:
  - SMDB update with signal measurements discussed in the first criterion
  - SMDB access to list Directory information and signal measurements
  - SMDB access to compute unbiased network averages of signal measurements for a specified event.
- Demonstrate this software contingent on the availability of UNIX operating system utilities provided by the Government.

B. CONCLUSIONS AND RECOMMENDATIONS

An expandable and maintainable Signal Measurement Data Base (SMDB) program suite has been designed and compiled on the PDP-11/70 under the UNIX operating system. Tapes (from the SDAC) which were used in the VELA-sponsored identification experiment, and which were used in the development and test of the SMDB program suite, are:

1. L22882 (IBM 360/44)
2. L13033 (DEC PDP-15/50).

These tapes can be used in future efforts to refine the SMDB program suite.

It should be noted that several problems were encountered with the UNIX FORTRAN compilers during attempts to implement the SMDB routines. Specifically, the routines were initially coded in a modified version of DEC RT-11 FORTRAN IV (Rottman, 1975). (The UNIX command to request this compiler is FORTRAN.) Difficulties encountered with this compiler included problems which are apparently related to array size and to the argument lists. That is, a routine could be made to generate routine errors, or not to do so, by increasing or decreasing the size of its arrays, respectively. Associated error messages, in general, indicated a bus error or a segmentation violation. Regardless, a solution to this problem was not readily apparent. Further, the number of arguments in a subroutine argument list appeared to be limited to eight. Any additional arguments were not passed. It was possible to circumvent this problem by passing arguments in a named common block.

Toward the end of this task, a new FORTRAN compiler was provided (Anon., 1978). This compiler is based on American National Standard (ANS) FORTRAN 77. (The UNIX command to request this compiler is F77.) An investigation was made into the feasibility of converting the SMDB routines to the FORTRAN 77 standard. Necessary changes would include substitution of the ENCODE/DECODE statements with equivalent statements, modification of the file I/O, modification of character variables, and modification of the code to allow for irregularities in the new compiler. ENCODE/DECODE statements can be replaced with 'reads' and 'writes' to internal files. This replacement is not possible on a one-to-one basis, and some additional program structuring will be necessary to provide for parallel operations. The file I/O initiated using the routines SETFIL and DFILE does not appear to be equivalent to using SETFIL and DEFINE FILE in the original compiler. In particular, it seems that the file to be accessed must already exist in order to be accessed (i.e., the system does not create a new file). This was not the case with the compiler called using FORTRAN. Another difference in file I/O requirements was that the last record written in a file could not be read subsequent to the write to the file. This difficulty may indicate that it is necessary to close and open the file between write and read operations. An example of one irregularity encountered during the investigation of the F77 compiler is the failure to compile a logical expression with a unary minus (e.g., if (IFLG.EQ.-1) go to 100). The same logical expression without the minus sign, however, does compile.

The results of the investigation made indicate that the F77 compiler is sufficiently different from the FORTRAN compiler as to require a significant effort to convert the SMDB from the FORTRAN to the F77 compiler. It will first be necessary to establish the operating characteristics of the new compiler (i.e., the logic sequences necessary to accomplish a given operation). After the methods for performing the desired operations have been established (usually done by the trial-and-error method), the SMDB routines can be restructured (i.e., converted).

At this time, a competent FORTRAN language compiler is not available on the SDAC PDP-11/70. Note, however, that the use of the FORTRAN language is not recommended by the designers of the UNIX operating system for major applications using UNIX.

As a final comment, several additional routines could be added to make the SMDB more versatile. These include a function to delete event and/or station entries in the data base. The design of the SMDB included consideration of these avenues for development.

SECTION VIII
DETECTION OF SIGNAL PERIODICITIES TASK

The results of this task are presented in Technical Report No. 9. The contents and conclusions are summarized below.

Technical Report No. 9
Detection of Signal Periodicities in the
Coda of Seismic Signals (U)
SAR(01)-TR-79-09

A. DETECTION OF SIGNAL PERIODICITIES TASK

The impetus behind this study was, originally, to determine the feasibility of detecting cavity-ringing periodicities in the codas of signals from decoupled nuclear explosions. We reasoned that if by some mechanism, ringing in a cavity produced signals which could be detected at regional or teleseismic distances, the periodicities so detected could yield estimates of the cavity's size and, hence, of the size of the decoupled explosion. We were also intrigued by the possibility that ringing in an explosion-generated cavity might produce characteristic periodicities in seismic records which could be used for yield estimation. On the possibility that source-related effects associated with explosions may produce periodicities which can be detected in the signal codas, we initiated a feasibility study to determine whether such periodicities could indeed be detected and, specifically, whether the periodicities could be related to source yield.

We used several approaches in our attempts to extract periodic components from the codas of seismic signals. These were:

(1) Direct spectral analysis of coda and noise data

(2) Spectral analysis of tapered autocorrelation functions

(3) Spectral analysis of quadcorrelation* functions derived from truncated autocorrelation functions

(4) Visual inspection of bandpass-filtered data.

We also attempted to enhance the detection of masked periodic signals by stacking (averaging) spectra computed from data obtained at different stations for the same explosion.

B. CONCLUSIONS

A technique to detect spectral peaks in the coda of seismic sources was tested using synthetic data, and was applied to explosion data (eleven presumed USSR explosions and four western USA events) and to data for one earthquake. A data base consisting of spectral peaks observed in the codas was compiled. Only peaks occurring in the codas were included; peaks simultaneously observed in the noise and in the associated coda were excluded to eliminate as much as possible the effect of reverberations in the crustal stack at the receiver site. In all, 153 spectral peaks were observed. Eleven out of fifteen explosions emitted what appear to be harmonically

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* The quadcorrelation function is defined here as the autocorrelation of the truncated autocorrelation.

related spectral components. Of 131 spectral peaks observed, 123 could be interpreted as being harmonically related within a $\pm$ 5% frequency matching criteria. The base frequency of the observed harmonics was plotted against m_b. Larger events were associated with lower frequencies, with the relationship varying as $f^{-0.27}$ (f = frequency). Also, by using a relationship between yield and m_b derived using Knickerbocker and Greeley, event yield was mathematically related to the observed base frequencies. In two known cases, for NTS events, predicted yields using the relationship derived in this study were within 30% of announced yields. The preliminary results presented here suggest that measurements of prominent spectral peaks in the codas of signals might provide improved yield estimates for explosions. More observations and modeling are needed to verify and explain the observed data.

SECTION IX
REVIEW OF AUTOMATIC SIGNAL DETECTORS TASK

The results of this task are presented in Technical Memorandum No. 1. The contents and conclusions are summarized below.

Technical Memorandum No. 1
Review of the Seismic Detectors Developed
and/or Evaluated by Texas Instruments
(TI) and ENSCO
SAR(01)-TM-79-01

A. REVIEW OF AUTOMATIC SIGNAL DETECTORS TASK

In this memo we briefly described several seismic detectors, their advantages and disadvantages, and their performance characteristics.

We reviewed the research and development work performed on the following detectors:

- TI* 'Z' Detector
- Allen's Characteristic Function Detector
- Shensa's Power Spectrum Deflection Detector
- Unger's Analytic Detector.

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* Prior to 1978, ENSCO's Systems and Applied Research Division was a part of Texas Instruments Incorporated.

B. CONCLUSIONS

Analytic detectors such as Unger's are in an early phase of development, and they are not yet comparable in detection performance to the TI 'Z' detector. The potential exists, however, to design a robust, maximum likelihood detector on the sound theoretical basis described by Unger. As a step in this direction, Unger (1978) produced a statistical study of short-period noise envelope statistics as a basis for developing an optimum design of such a detector. Some potential also exists for designing a weak signal detector which uses instantaneous phase modulation measurements of signals; for example, this detector would be expected to detect low-amplitude regional phase signals by recognizing abrupt frequency changes.

The applicability of these concepts for precisely timing signals has been amply demonstrated. Unger's detector demonstrated a potential for timing teleseismic P-wave phases with a standard deviation of 0.2 seconds (as compared with analyst picks).

The computer power and storage requirements for the implementation of Unger's detector concepts are believed to be quite modest since 90^{o} phase shifters and envelope formers can be generated with a few multiplications per point by means of time-domain implementation.

SECTION X
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