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VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

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QUARTERLY REPORT NO. 2

15 OCTOBER 1975 TO 15 JANUARY 1976

TEXAS INSTRUMENTS INCORPORATED
Equipment Group
Post Office Box 6015
Dallas, Texas 75222

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Contract No. F08606-76-C-0011
Amount of Contract: $440,000
Beginning 15 July 1975
Ending 30 September 1976

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Alexandria, Virginia 22314

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Program Code No. 6F10
ARPA Order No. 2551

15 January 1976

Acknowledgment: This research was supported by the Advanced Research Projects Agency, Nuclear Monitoring Research Office, under Project VELA-UNIFORM, and accomplished under the technical direction of the Air Force Technical Applications Center under Contract Number F08606-76-C-0011.

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This second quarterly report summarizes progress under the VELA Network and Automatic Processing Research Program, Contract Number F08606-76-C-0011, during the period 15 October 1975 to 15 January 1976. Work in the following areas is summarized:

- Array and network evaluation,
- Signal detection methods,

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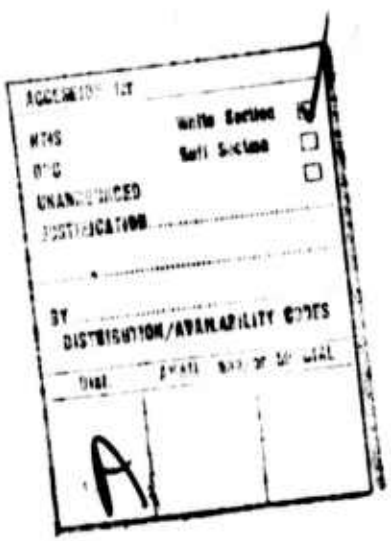
- Signal estimation techniques
- Discrimination.



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SECTION 1
INTRODUCTION AND SUMMARY

This second quarterly report summarizes the progress made during the period 15 October 1975 to 15 January 1976 in the VELA Network Evaluation and Automatic Processing Research program being carried out by Texas Instruments Incorporated at the Seismic Data Analysis Center (SDAC) in Alexandria, Virginia. The four program tasks are:

- Array and network evaluation
- Signal detection methods
- Signal estimation techniques
- Discrimination.

During the last quarter, the necessary software modifications were made and tested on the Very Long Period Experiment (VLPE) edit program to permit editing of SRO data. We are currently using a test tape to formulate an optimum processing scheme to maximize the amount of data handled. Software modifications have begun for the processing of ILPA data with the recent acquisition of the tape formats. Analysis of both SRO and ILPA data will begin when field data are received in the next quarter.

Evaluation of the automatic power and Fisher detectors using KSRS data was continued. Using the November 1974 KSRS data (new data is expected in the next quarter), analysis was completed for 149 events with a 0.8 second integration gate, a 10 per hour false alarm rate, 6 minute warm-up period, and the implementation of a single-sensor optimum detection pre-filter. With the receipt of new data allowing expansion of the data base, we will estimate the performance for the Fisher detector, the conventional power detector (array beams), and single-channel power detector.

The program NETWORTH has been modified to make the results more meaningful in evaluating real networks. This program, NET2, will be used to estimate the performance of a global network of KSRS-like arrays. The objective of this study is to determine which parameters have the greatest impact upon network capability. For example, we wish to determine if having more stations are as useful as having fewer stations which have greater reliability or lower signal-to-noise ratio required for detection. From this parameter study, we hope to set quantitative guidelines.

For the adaptive beamforming (ABF) detector study using KSRS short-period data, seven 'strong' events ($m_b > 5.0$) were processed with three prefilters, which were applied to single-channel input data before beamforming. The ABF high convergence rate (0.5) improvements (over beamsteer) were 5.2 - 9.5 dB for the unfiltered data, 9.3 - 12.4 dB for a low frequency (0.5 - 1.1 Hz) band filter, and 1.8 - 6.3 dB for the KSRS optimum detection filter. (Note: the low frequency band filter was mistaken as 'unfiltered' in Quarterly Report No. 1. This error was the result of an 'unknown' default option in the ABF program.) For 'weak' events ($m_b < 5.0$, S/N ~ 10 dB), the array beam optimum detection filter, applied for prefiltering, yielded the best performance among the prefilters tested. For the next quarter, the processing of 'weak' events will be continued and power density spectra will be computed for ABF and beamsteer outputs.

Software development for the computer program framework of the cascading study is nearly complete. The program allows the analyst to bury a signal in noise at a known signal-to-noise ratio, and to apply three component adaptive filtering, optimum Wiener filtering, and matched filtering in any order. For the next quarter, real signals will be processed with this software at various signal-to-noise ratios.

The task to upgrade the TCA processor is essentially complete. From this study, we conclude that: (1) The most effective form of the new

Love wave proce[illegible] combines rotation of the Love wave frequency components about the vertical axis to the radial azimuth with a limit on the permissible Love wave arrival azimuth; (2) At zero dB true signal-to-noise ratio, we can expect about 6 dB gain for Love waves from the new processor for single site data, and no significant gain when applied to beamsteered data; (3) Application of this processor lowered the 50 percent Love wave detection threshold by 0.3 to 0.4 m_b units. The technical report for this task will be completed during the next quarter.

For the dispersion relation filter task, the software has been completed in its basic form. It is capable of reproducing linear chirp waveforms and of timing their onsets within 4 seconds under noise-free conditions. During the next quarter, the filter will be evaluated under various noise conditions, and the design of a Wiener filter to optimize the signal estimates will be considered.

Development of the interactive discrimination package for the PDP-15 is proceeding according to schedule, with a demonstration planned for the end of the next quarter. The discrimination tasks performed will be variable frequency magnitude measurements (VFM) and the derivation of possible discriminants based on the cepstrum analysis of signals. Most of the automatic processing subroutines and a general display subroutine have been completed. The special purpose interactive subroutines are currently being written and checked-out.

For the higher mode study, a comparison of narrowband filtering and maximum entropy spectral analysis has indicated that the former provides the most straightforward method for calculating higher mode amplitudes. With the acquisition of more data, energy attenuation coefficients will be calculated for the continental United States, and source depths of presumed explosions will be estimated using multimode surface waves.

SECTION II
ARRAY AND NETWORK EVALUATION

A. ILPA AND SRO EVALUATION

1. Current Status

During the last quarter, the necessary software modifications were made on the Very Long Period Experiment (VLPE) edit program to permit editing of Seismic Research Observatory (SRO) data in a format compatible with the succeeding programs in the VLPE package. This edit program has been tested on the data available to us - one test tape containing data from 28-29 August 1974 as recorded at Albuquerque and one test tape containing 5 hours of data from 29 November 1975 as recorded at Albuquerque. (One other test tape was received but could not be read by the IBM 360/44 computer.) We are currently using this test data to formulate an optimum processing scheme to maximize the amount of data handled.

Since we expect to have SRO data in-house before ILPA data, our program modification effort has been directed toward the SRO edit problem. Work on program modification to permit processing of ILPA data has been initiated in the last week with an investigation of the changes to be made in the array edit program. Modifications will also have to be made in the beamforming program. Finally, we have also begun examining the software modifications necessary to place ILPA data in a subset format and in the transmission of ILPA data to the mass storage center.

2. Future Plans

Once the SRO data begins arriving, analysis of short-period data on the PDP-15 and long-period data on the IBM 360/44 will commence.

Due to the present uncertainty of how much data will be received, it is currently planned to process all known events without regard to epicenter location. Should the quantity of data received later prove to make this approach unworkable, we will restrict event processing to specific regions of interest.

Program modifications will be made in the array edit and beamforming programs to permit processing of ILPA data. Processing will commence as soon as ILPA data is received.

Work on the long-period network evaluation will be delayed until the final quarter of the contract, when the necessary ILPA data will be available.

B. AUTOMATIC SIGNAL DETECTOR EVALUATION

1. Current Status

Evaluation using the November 1974 KSRS data was completed for 149 events with a 0.8-second integration gate and a 10/per hour false alarm rate. Warm-up period was 6 minutes and prefiltering was accomplsihed with a single-sensor optimum detection filter. Results were obtained for the Fisher detector, the conventional power detector (for array beams), and single-channel power detector (usually sensor 1 was used).

Table II-1 tabulates the Gaussian parameters for the detection probability functions from a maximum likelihood estimate method (Ringdal, 1974). Both 120 and 30-second signal detection windows were studied. The top portion of Table II-1 shows the results without taking into account the false alarm probability using maximum likelihood estimates, while the lower portion of the table shows the results with the false alarm probability. In this table, the 'old bandpass' was taken from the previous results (Black and Lane, 1975).

Comparison of the detection performance for various prefilters was also made using the algorithm without constant false alarm rate consideration. With a six minute warm-up period, processing was accomplished for

TABLE II-1

GAUSSIAN PARAMETERS OF DETECTION PROBABILITY FUNCTION FROM A MAXIMUM LIKELIHOOD ESTIMATE

Detection Parameters - Without False Alarm Probability				
Filter/ Detection Window	Detection Parameter	Fisher Detector	Conventional Detector	Single Sensor
Optimum/ 120 sec	m_b 50	4.67 ± 0.10	4.54 ± 0.09	4.62 ± 0.09
	m_b 90	5.70 ± 0.24	5.56 ± 0.23	5.65 ± 0.24
	Sigma	0.80 ± 0.15	0.80 ± 0.15	0.80 ± 0.15
Optimum/ 30 sec	m_b 50	5.02 ± 0.12	4.85 ± 0.08	5.10 ± 0.14
	m_b 90	6.00 ± 0.26	5.54 ± 0.16	6.13 ± 0.30
	Sigma	0.76 ± 0.13	0.54 ± 0.08	0.80 ± 0.15
Old Bandpass/ 30 sec	m_b 50	5.11 ± 0.14	5.04 ± 0.11	-
	m_b 90	6.14 ± 0.31	5.91 ± 0.24	-
	Sigma	0.80 ± 0.15	0.68 ± 0.12	-

Detection Parameters - With False Alarm Probability				
Filter/ Detection Window	Detection Parameter	Fisher Detector	Conventional Detector	Single Sensor
Optimum/ 120 sec	m_b 50	4.75 ± 0.10	4.64 ± 0.09	4.72 ± 0.10
	m_b 90	5.79 ± 0.25	5.59 ± 0.21	5.75 ± 0.25
	Sigma	0.80 ± 0.15	0.74 ± 0.13	0.80 ± 0.15
Optimum/ 30 sec	m_b 50	5.18 ± 0.12	4.90 ± 0.08	5.21 ± 0.14
	m_b 90	5.99 ± 0.25	5.53 ± 0.15	6.19 ± 0.31
	Sigma	0.70 ± 0.12	0.49 ± 0.07	0.76 ± 0.14
Old Bandpass/ 30 sec	m_b 50	5.21 ± 0.15	5.09 ± 0.11	-
	m_b 90	6.24 ± 0.33	5.86 ± 0.21	-
	Sigma	0.80 ± 0.16	0.59 ± 0.10	-

twelve events using four different prefilters. Results are summarized in Table II-2, where a detection was claimed when the maximum detector output fell in the computed 2-minute signal window with a correct nearest azimuth. The results seemed to suggest that the array-beam optimum detection filter might be the best among the prefilters tested, on the basis of the very limited number of events. Further work is being conducted.

2. Future Plans

While awaiting new KSRS data, the study is being conducted with a 12-minute warm-up period using the same data.

TABLE II-2

COMPARISON OF FISHER AND CONVENTIONAL DETECTORS FOR FOUR PREFILTERS

Prefilter Used	Integration Rate (second)	Number of Events Detected (Out of 12)	
		Fisher	Conventional
Old Bandpass Filter	0.8	7	5
	1.6	7	5
	3.2	7	5
	6.4	7	5
Single-Sensor Optimum Detection Filter	0.8	7	7
	1.6	8	6
	3.2	8	7
	6.4	8	6
Array-Beam Optimum Detection Filter	0.8	9	8
	1.6	8	8
	3.2	7	8
	6.4	7	7
Noise-Whitening Filter	0.8	4	5
	1.6	5	6
	3.2	5	6
	6.4	7	7

SECTION III

SIGNAL DETECTION METHODS

A. NETWORK CAPABILITY

1. Current Status

NETWORTH is a program which evaluates network location and detection capability. In NET2 three improvements have been added to the original NETWORTH, to make the results more meaningful in evaluating real networks. The signal-to-noise ratio required for detection has been made a station variable, since networks in general are composed of stations of varying capabilities. Compensation for error in expected signal amplitude variations due to crustal inhomogeneities has been included using signal amplitude correction terms for given station/epicenter combinations. The effect of station reliability (down-time) upon network capability has also been included.

A study is now being performed to evaluate the effect of certain physical parameters upon network capability. The parameters being tested include the signal-to-noise ratio required for detection, station reliability, signal variance, the number of stations in the network, the geographical distribution of the network, and the contribution to network capability due to each station. The objective of the study is to determine which parameters have greater impact upon network capability. A quantitative evaluation of the effect each parameter has upon the network capability forms a rational basis to compare proposed network changes. For example, we wish to determine if more stations are as useful as having fewer stations with greater reliability or lower signal-to-noise ratio required for detection. From this study, we hope to set quantitative guidelines.

A network with the corresponding noise figures was furnished by the Air Force. Most of the processing has been completed and results are being tabulated and plotted.

2. Future Plans

Use of NET2 to evaluate KSRS and SRO data when the data becomes available, probably late in 1976.

B. ADAPTIVE BEAMFORMING DETECTOR

1. Current Status

Work on adaptive beamforming detector (ABF) for the quarter included: (a) the ABF signal-to-noise improvements over the time-shift-and-sum (i.e., beamsteer) method for strong events and weak events, (b) false alarm rates, and (c) spectral analysis for the ABF and beamsteer outputs. In addition, an attempt to detect secondary P-waves and to use them for discrimination was also made.

Seven strong events were processed with three prefilters, which were applied to single-channel input data before beamforming. The ABF high convergence rate (0.5) improvements were 5.2 - 9.5 dB for the unfiltered data, 9.3 - 12.4 dB for the low frequency band (0.5-1.1 Hz) filter, and 1.8 - 6.3 dB for the KSRS optimum detection filter. (Note that the low-frequency band filter was mistaken as 'unfiltered' in Quarterly Report No. 1. The time-domain convolution filter was designed for long-period data and is in the ABF system. A default will result in the filter if input prefilter is not specified.) For weak events, the optimum detection filter yielded the best performance among the filters tested. The Gaussian parameters (average and standard deviation) for false alarm probability function were computed for the processed (hour-long) noise samples, using the conventional power detection algorithm. Prefilters applied to noise samples were delta function

(i.e., unfiltered input), single-sensor optimum detection, array-beam optimum detection, low-frequency band, and whitening filters.

Power density spectra were computed for one event from Novaya Zemlya (m_b = 6.7) and two noise samples. Figure III-1 illustrates the power-density spectra for the ABF and beamsteer outputs (composed of single-channel unfiltered data). For this case, the peak-to-peak amplitudes on the beamsteer and the ABF beams were the same. Substantial later arrivals, presumably coda waves, were suppressed on the ABF output. Figure III-2 shows the noise beam spectra (with a 0° look azimuth and a 15.1 km/sec velocity) for a noise sample. In this figure, significant noise reduction relative to beamsteering was in the 0.0 - 1.0 Hz band, where noise was well-correlated. The ABF noise power suppression relative to the beamsteering was 7.14 dB for this case.

2. Future Plans

In the near future, weak event processing will be continued and spectral computation will be repeated with different ABF lengths. A systematic study will be attempted to detect pP, PcP, and PP phases of P-waves. The results will be used for precise determination of source depths.

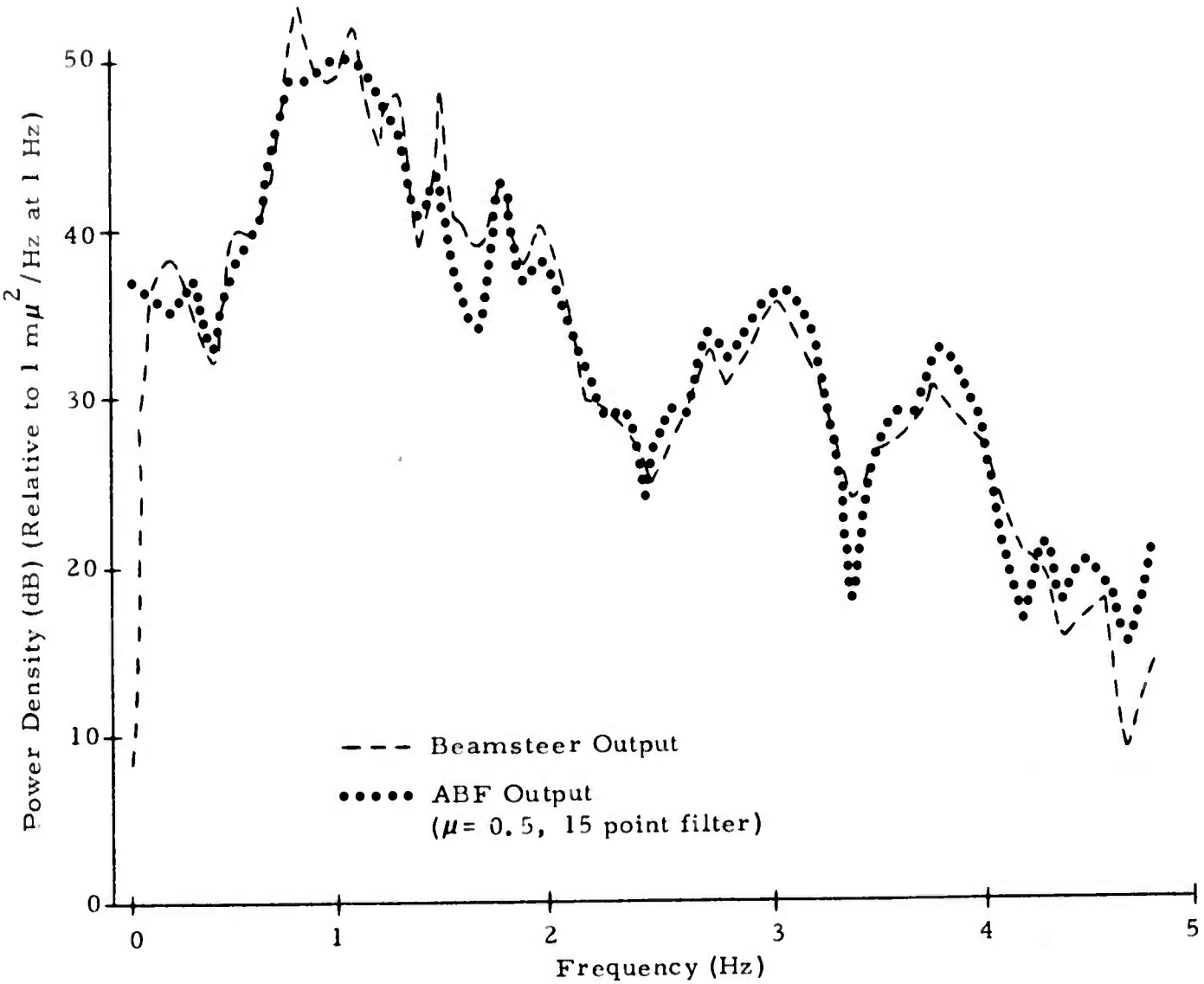


FIGURE III-1

POWER-DENSITY SPECTRA FOR THE EVENT FROM NOVAYA ZEMLYA, DAY 306 1974 (m_b = 6.7)

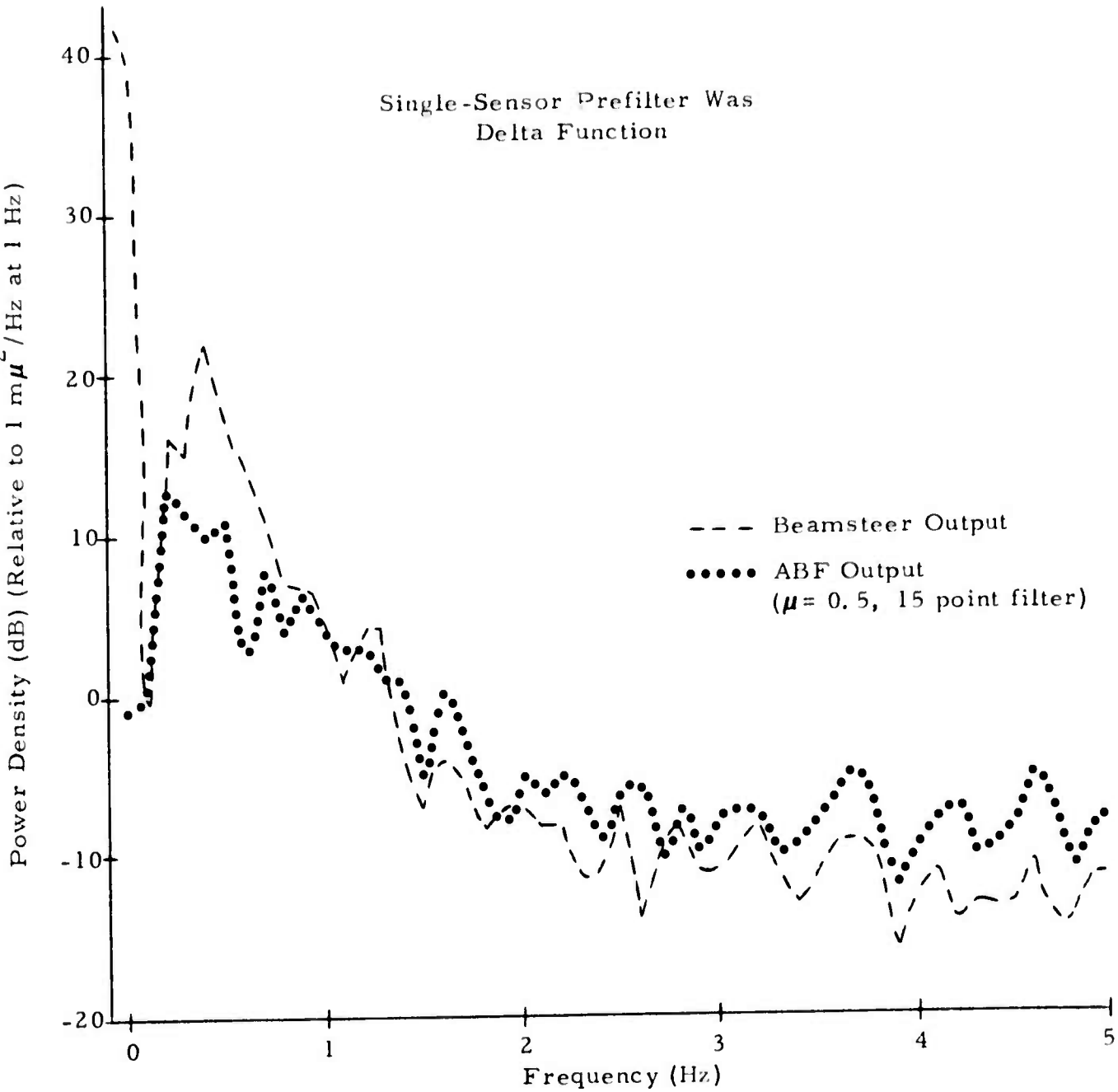


FIGURE III-2

NOISE BEAM SPECTRA FOR DAY 325 1974 SAMPLE
(05.05.00 to 05.18.39)

SECTION IV

SIGNAL ESTIMATION TECHNIQUES

A. CASCADING STUDIES

1. Current Status

Software development for the computer program framework of the cascading study is nearly complete. The program allows the analyst to bury a signal in noise at a known signal-to-noise ratio, and to apply three component adaptive filtering, optimum Wiener filtering, and matched filtering in any order. The signal-to-noise ratio of the processed signal is available at each step.

2. Future Plans

Real signals will be processed with the program described above at various signal-to-noise ratios. The net signal-to-noise ratio gain will be plotted as a function of input SNR for each processing order, and the most effective order determined. That order which yields the lowest detection threshold will also be determined, as it may be different from that which gives the best gain for larger signals.

B. THE THREE COMPONENT ADAPTIVE PROCESSOR

1. Current Status

During the last quarter the evaluation of the Love wave upgrade version of the three component adaptive processor was completed and the first draft of the report was written. The following statements summarize the findings of this evaluation:

- The most effective form of the new Love wave processor combines rotation of the Love wave frequency components about the vertical axis to the radial azimuth with a limit on the permissible Love wave arrival azimuth.
- At zero dB true signal-to-noise ratio, we can expect about 6 dB gain for Love waves from the new processor when applied to single site data.
- No significant gain can be expected from the new processor when applied to beamsteered data.
- Application of the new Love wave processor on single-site data lowered the 50 percent Love wave detection threshold by 0.3 to 0.4 m_b units.

2. Future Plans

Editorial corrections and revisions will be made on the report.

C. DISPERSION RELATION FILTER

1. Current Status

The dispersion relation filter has been implemented in its basic form. In preliminary tests, it is found to be capable of reproducing linear chirp waveforms, and of timing their onsets within 4 seconds under noise-free conditions. The filter is being evaluated under various noise conditions. A Wiener filter design to optimize the signal estimates is under consideration. Noise spectral analysis and further signal spectral analysis are in progress. A major problem is the generation of false signal estimates, i.e., the filter generates partial chirp waveforms from pure noise. Part of this quarter's time has been spent on software conversion for dual DOS/TS44 operation in order to realize a reasonable software output.

2. Future Plans

The stationarity and the procedure for finding the expected value of the noise spectrum will be investigated. Based on these findings the Wiener filter will be implemented. The false estimate problem will be examined further. Further filter evaluation will be performed by burying synthetic waveforms and high-SNR signals in noise and checking the filter output error. The filter then will be applied to the weaker Sinkiang event signals. The filter design and evaluation will be recorded in a technical report.

SECTION V
DISCRIMINATION

A. PDP-15 DISCRIMINATION PACKAGE

1. Current Status

A data base of NORSAR recorded earthquakes and presumed explosions was visually analyzed for quality control by means of edit matrix plots of all sensors. For the purpose of performing the third quarter demonstration, several high S/N single sensor records were selected to demonstrate interactive processing on several presumed explosions and shallow earthquakes.

The discrimination tasks performed will be variable frequency magnitude measurements (VFM) and the derivation of possible discriminants based on Cepstrum analysis of signals. The discrimination based on VFM implies that explosions of a given time domain magnitude are of incrementally higher magnitude at the higher frequencies and of incrementally lower magnitude at lower frequencies. The object is to maximize the spread between high and low frequency magnitude measurements. Noise limits how high or how low the frequencies can be taken. Discriminants based on cepstrum analysis will be (1) reflection coefficient of the apparent echo, (2) the correlation coefficient between the apparent echo and signal, and (3) the F statistic of the signal and echo model derived from cepstrum analysis.

Block diagrams of special purpose interactive subroutines designed to perform the discrimination tasks have been finalized. Most of the automatic processing subroutines and a general display subroutine have also been completed. The special purpose interactive subroutines are currently

being written and checked out. The general purpose command language used to control the interactive processing has been previously developed and documented as the 'Interactive Seismic Processing System' (ISPS). The special purpose processor under control of ISPS, described above, will be designated as 'Short Period Earthquake/Explosion Discriminator' (SPEED), shown in Figure V-1.

2. Future Plans

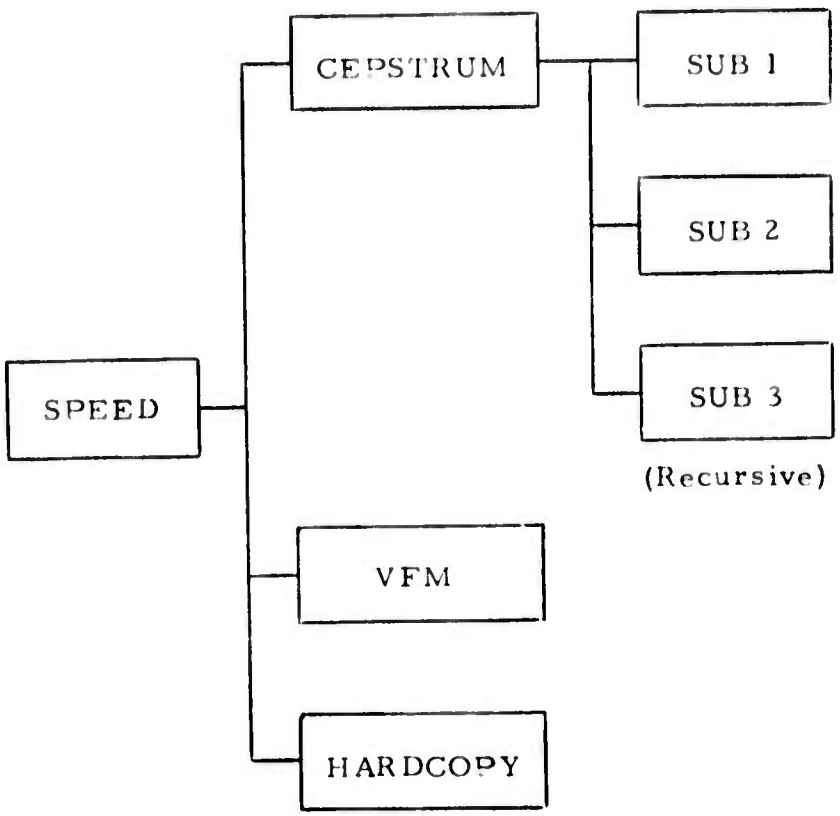
The development of SPEED will continue until the third quarter demonstration. After that, a final data base will be prepared by conditioning the array data to provide de-reverberated estimates of earthquakes and explosions by means of Generalized Linear Filtering. These events will be processed interactively to produce tables of discriminants derived from VFM and Cepstrum analysis. These discriminants will be analyzed statistically to determine the discrimination capability of information derived from the SPEED system.

B. HIGHER MODE STUDIES

1. Current Status

A comparison of narrowband filtering and maximum entropy spectral analysis has indicated that the former provides the most straightforward method of calculating higher mode amplitudes. Accordingly, it will be used for the remainder of this study.

Spectral amplitudes for a western United States explosion were calculated for the fundamental and first higher mode Love waves at the four stations for which data were available. As three of these stations were in a line with the event epicenter, energy attenuation coefficients could be calculated for both modes. These coefficients were an order of magnitude larger than those found in other studies. Time of arrival measurements of the



SUP 1 - Conditions Data
Exponential taper
Shoft time pass filter

SUB 2 - Separate Signal and Echo
Compute echo time delay
Reflection coefficient
Correlation coefficient between signal and echo

SUB 3 - Reconstruct Signal
F-statistic of signal and echo model
Pick next phase to be analyzed, and store on disk for next cepstrum analysis.

FIGURE V-1

SHORT-PERIOD EARTHQUAKE/EXPLOSION DISCRIMINATOR

various modes as a function of period suggested that the propagation path could best be fit by the Hamilton-Healy sedimentary model. The use of this model is consistent with the high values of attenuation found above.

Using the earth response of this model, and the first higher mode Love wave spectrum observed at two non-colinear stations, the source depth was found to be 60 km. Using these higher mode spectral values together with the observed fundamental mode Rayleigh wave spectra, the source depth was found to be 16 km.

These results are only tentative at this date, and perhaps the only conclusion to be drawn from them is that the study of higher mode surface waves is a complicated one.

2. Future Plans

The energy attenuation coefficient will be recalculated using more data as they become available. Source depths of explosions will be found using both Love and Rayleigh waves, and the most effective combination of modes for depth determination will be found.

SECTION VI
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