SCIENCE SERVICES DIVISION

TEXAS INSTRUMENTS
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LARGE ARRAY SIGNAL AND NOISE ANALYSIS

Quarterly Report No. 2

3 September through 2 December 1966

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P. O. Box 5621
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AFTAC Project No. VT/6707

19 December 1966

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SCIENCE SERVICES DIVISION

19 December 1966

Headquarters
United States Air Force
AFTAC/VSC
Washington, D. C. 20333

Attention: Captain Carroll F. Lam

Subject: Second Quarterly Report Covering Period September 3 through December 2, 1966

Identification: AFTAC Project No. VT/6707
Project Title: Large Array Signal and Noise Analysis
ARPA Order No. 599
Name of Contractor: Texas Instruments Incorporated
Date of Contract: 16 May 1966
Amount of Contract: $593,673
Contract Number: AF 33(657)-16678
Contract Expiration Date: 15 May 1967
Program Manager: Frank H. Binder
Area Code 214
FL 7-5411, Ext. 443

WORK PROGRESS:

Below is set forth the progress against milestones and an indication of the direction of effort in the future against the milestones.

Formation of Library of Short-Period Noise and Signals

As of December 3, 19 tapes of a total of 32 short-period reels have been received and put into the TIAC system after being reformatted by the Seismic Data Laboratory.

This data is of good quality and about 95 percent usable. The unusable data mostly is the result of dead traces or spikes which were on the original

LASA digital tapes. Six of the 38 LASA field tapes requested for Project 57060-05 have been copied and shipped by SDL and are now being processed. One tape is unusable, due to clipping.

Formation of Library of Long-Period Noise and Signals

As of December 3, no usable long-period has become available. It is anticipated that a library of about 25 long-period tapes will be necessary.

A program has been written to convert the slow mode LASA tapes (long-period data) to the TIAC format. The program has been checked out using a poor quality slow mode tape. The cost to reformat one slow mode tape (about 80 minutes of data) is about $60.

Pilot Study of Subarray Processing

Intensive processing on one noise sample has been carried out to try to understand the subarray noise field. The goal is to implement a subarray processor whose output will be, insofar as is possible, velocity limited ($v > 10$-12 km/sec) over a broad band. Some of the principal results are discussed in more detail below.

The noise sample was an 8 minute noise sample recorded 4:26:12.8 to 4:34:12.7 GCT, March 25, 1966. Subarray B4 was dead at that time. This noise sample will be referred to as N1 throughout this report.

Results to date indicate that a multichannel filter system design from theoretical signal and noise models will be quite satisfactory. Pre-equalization of the seismometer outputs appears to be necessary.

Multichannel Filtering Results

A multichannel filter system was designed from theoretical correlations generated from a signal model of $11 \text{ km/sec} < v < \infty$ (disc) and noise model $2 \text{ km/sec} < v < 6 \text{ km/sec}$ (annulus) with two percent white noise. The filters were 3.5 seconds (35 pts) long. The filters were designed to operate on ring-stacked data.

Using the relative large LASA subarrays, this system had a very satisfactory wavenumber response between 0.2 and 2.0 cps. It would pass the "signals" ($v > 11$ km/sec) and severely attenuate the "noise" 2 km/sec $< v < 6$ km/sec throughout this frequency range.

N1 (all subarrays except B-4) were processed through the above multichannel filter system. Between 0 and $1\frac{1}{4}$ cps the noise rejection compared to a single seismometer was fairly variable. Subarrays B1 and C2 are at roughly opposite ends of the noise rejection "spectrum" obtained. They were, therefore, chosen for more intensive study.

After trace equalization on the basis of noise power in a fairly narrow band the low frequency noise rejection is the same at both subarrays.

The MCF system gave about 6 db noise rejection in the region of the microseism peak at both subarrays.

This suggests that: prequalization is necessary and at least 75 percent of the low frequency (about 1/3 cps) energy is low velocity.

The possibility of doing equalization on narrow or broad band noise power will be checked out more extensively. If this procedure appears reasonable, it will be implemented on all LASA noise.

The spatial organization of the noise will be discussed in more detail in the section dealing with wavenumber analysis.

Wavenumber Analysis of Subarray Noise

Wavenumber spectra for N1 were obtained using the B1 and C2 subarrays. These spectra were calculated using only seismometers on the 1, 3, 4, 5, 6, and 8 rings for a total of 19 sensors. A computer program limitation forced the use of the partial array data.

The wavenumber spectra were obtained by expanding the array data in correlation space at various frequencies and then taking a two-dimensional Fourier transform. Some normalization and frequency smoothing were incorporated.

In general, the wavenumber spectra obtained at the two arrays are quite similar. They show only high velocity noise ($v > 8$ km/sec) below 0.5 cps. Above .7 cps there is apparently some low velocity noise showing up.

These results do not agree with the noise rejection obtained from multichannel filtering subarrays B1 and C2.

The wavenumber spectra and MCF results together suggest a noise field which includes a high velocity power density peak and a fairly uniformly distributed, lower power density, trapped mode annulus.

The wavenumber spectra obtained may not show the low velocity because of the spectral window involved in the spectral estimate. We will make further attempts at wavenumber analysis using high resolution techniques and a different spectral window.

<u>Noise Predictability Within Subarrays</u>

Weiner filters were designed to predict the center seismometer from the other 24 using N1 at subarrays B1 and C2. The data had been whitened and the outlying seismometers had been stacked on a ring basis. This results in a 7-channel prediction problem. The filters were 35 points (3.5 seconds) long.

The noise at the center seismometer is highly predictable at both subarrays. The predictability is maximum at the microseism peak (0.3 cps) and is still about 65 percent predictable at 1 cps. The noise is essentially unpredictable above 2 cps.

The predictability of the noise at a LASA subarray is roughly comparable to that obtained at TFO and WMO. The noise predictability at CPO is markedly superior.

The prediction filters were also applied to an 8 minute noise sample immediately following the noise used in the filter design. The results are quite similar to that obtained for the design noise except near the microseism peak (below $\frac{1}{2}$ cps) where the prediction filters are very ineffective on this new noise sample.

This suggests that the spatial organization of the low frequency noise has changed. The sensitivity of the prediction filters to changes in the noise field is not known.

Noise Rejection Obtained by Straight Summation (Subarray Level)

For N1 a straight summation output was obtained for each subarray and the output noise power was computed. Ratios of the summation to seismometer 21 noise spectra were obtained. In general, out to about 1.0 cps the summation gave 0 to 3 db rejection, between 1.0 and 2.0 cps the rejection increased rapidly to about 14 db ($\sqrt{N}$), where it remained to 4.5 cps. These results imply the noise above 2.0 cps was essentially random.

Space Variability of LASA Noise

For N1 the seis 21 and summation outputs were taken for each subarray and decorvolved (using the same filter for all outputs). The data were then bandpass filtered into three frequency bands (0 to .7 cps, .7 to 1.4 cps, 1.4 to 2.1 cps) and the average power in each frequency band was computed using the entire 8 minute record. A comparison of the average power levels at each subarray showed that the seismometer 21 levels varied by about 8 db in all three frequency bands. The summation levels were somewhat more stable in the two lower frequency bands (about 4 db maximum variation) and did not necessarily follow the single seismometer variations from subarray to subarray. The 1.4 to 2.1 cps summation levels varied about 8 db, and followed the single seismometer variation at about a 12 db lower level.

Comparison of Noise Levels on 500 and 200 Foot Seismometers

For N1 the ratio of the 500 foot seismometer (10) power spectrum to one of the 200 foot seismometers (21) power spectrum was computed for all subarrays except B-4 (which was dead). The average spectral ratio was then computed, and showed that between 0 and 1.0 cps the two seismometers had about the same power, between 1.0 and 2.5 cps the ratio decreases about linearly to -4 db, and between 2.5 and 4.5 cps the ratio was about constant at -4 db. Thus, to get an accurate measure of the noise rejection obtained by any processing scheme, some seismometer other than seismometer 10 should be used. In our analysis, seismometer 21 has been used.

Comparison of LASA and TFO Noise Levels

The power density spectrum for seismometer 21 of subarray C2 (which was representative of the "average" noise level at LASA) was scaled in absolute units of db relative to 1 $m\mu^2$/cps at one cps. (All filter responses except that of the seismometer were removed.) The spectrum was then compared with that for TFO seismometer Z-63 on December 21, 1963. For the 1/4 to $1\frac{1}{2}$ cps range (where the LASA and TFO seismometer responses were essentially the same), the LASA spectrum was higher over the whole band, by amounts ranging from about 0 db at 1/2 cps to 6 db at 1 cps. It should be noted, however, that the variations over LASA were about ±5 db (for example, Seis 21 of subarray E-4 was about 5 db lower than the C-2 Seis 21). Thus the comparison should be considered as one of average power density levels.

Equalization Problems

Intra Array

Two new tools will be used to approach the seismometer equalization studies. A third method, which is quick and easy, will probably be used on the bulk of the data.

One method equalizes the power spectra of a large signal on a given trace to the power spectra of the target trace using a minimum phase filter. The resulting time traces will be similar only if they differ by a minimum phase filter.

It is reasonable to assume that the differences due to local coupling and recording systems can be represented as a minimum phase filter. These processes are stable and passive (with the exception of the amplifier).

The method of equalizing the power spectra uses a new technique which avoids undesirable end effects when using a short time gate. The filter obtained from this technique is constrained to be minimum phase.

This technique will be carefully evaluated and the results reported upon in the final report. The technique of equalization was developed under company research funds and will remain proprietary.

The second technique will involve using the program written to maximize the coherence between two groups of sensors. This program is discussed in more detail under the Mantle P-Wave Study section.

This technique will again use large signals which are assumed to be the same everywhere except for local coupling effects and recording differences. It can be shown that if the sensors all have had their output filtered with a different linear filter the weights (at a fixed frequency) which maximize the group coherence are the inverses of the filters.

The possible effectiveness of this technique is unknown. The results will be detailed in the final report.

The third method which appears to be adequate for multichannel processing is to equalize the noise power on all sensor outputs within each subarray. This method is being tried out on a pilot study and, if successful, will be used on all LASA data.

Inter-Subarray

The purpose of this study is to evaluate the usefulness of equalizing the subarray signal outputs, and to study the feasibility of developing average equalization filters for particular epicentral regions. This will be accomplished by comparing large array processor outputs for equalized and unequalized data, and by comparing the effectiveness of average and individual equalization filters. Filters for up to 40 events that will be developed under another subtask of this contract will be used in the analysis.

Study of Signal Similarity

The object of this analysis is to examine variations in signal waveform both within a subarray and across the LASA. The variations will be analyzed as a function of subarray location, event location, and frequency contact. The methods that will be used are:

(1) Computation of a correlation coefficient (ρ) between pairs of traces where:

$$\rho = \frac{\sigma gh\ (max)}{\sqrt{\sigma gg\ \sigma hh}}$$

and σgh (max) is the maximum cross-correlation value σgg, σhh are the zero-lag autocorrelation values

(2) Computation of short-gate power spectra, using a technique which is not affected by truncation (which is usually a serious problem for short-gate spectral analysis)

The necessary software is available and a pilot program is presently under way to determine exactly how to process the data so as to extract the most meaningful information (including a study of how to empirically relate variations in signal waveform to degredation of the signal resulting from processing). It is anticipated that the pilot program will be completed by mid-January, 1967.

About 25 to 30 short-period events will then be processed on a production basis and results will be interpreted on the bases outlined above. Long-period events will be processed on the same basis as it becomes available. The results will be incorporated into the final report.

<u>A Study and Application of Signal Dissection Techniques</u>

The usual Wiener MCF design is based on the assumption that the data being filtered is signal plus noise. It is desirable to examine the extent to which better signal processing can be done when the times of signal arrival are known.

The problem of optimum signal extraction, when the first part of the data is noise and the time aligned signals are present in the last part of the data, can best be separated into two problems for computational purposes. First, the noise in the signal can be estimated from the pure noise and subtracted from the observed signal plus noise. Second, optimum signal extraction filters can be designed to apply to the signal plus noise error.

A series of programs are being written to evaluate the signal extraction procedure outlined above. These include as follows:

1. Starting with the Levinson MCF forward and backward filters, iterate to filters which will do multichannel prediction M points ahead.

2. Determine the variance-covariance matrix N' of the prediction error.

3. Determination of the signal extraction filters χ which satisfy the general system of equations

$$(S + N')\chi = S^*,$$

where the only difference between this equation and the usual Wiener equation is that N' is not Toeplitz in form and a general matrix inversion will replace the Levinson iteration. The matrix S' is the variance-covariance matrix for the signal model.

4. Application of the filters -- first to predict the noise ahead and subtract the predicted noise from the observed signal plus noise. Second to filter the signal plus noise error with the filters χ to get the optimum signal.

The results of this nontime stationary processing will be compared with the usual MCF approach both by theoretical mean square error comparisons and with actual data.

This technique offers possible improvement only in the first part of the signal. Hopefully it will give an improved estimate of the initial part of the P-wave arrival. The same technique may also be useful in cleaning up a later arriving phase.

The procedures and results will be covered in detail in the final report.

Resolution of Events

The object of this study is to determine how effectively LASA can separate two events which occurred close together and which overlapped in time.

To determine the best resolution that would be possible (for a given wavenumber separation), the subarray outputs for two large events separated by about .005 km^{-1} at 1 cps will be chosen and their correlation statistics will be computed. The events will then be stacked (with the appropriate time-tie) and the stacked-event correlation statistics will be computed. Signal extraction filters will be designed for both events and applied to the stacked traces. The outputs will be compared to the original traces to determine how well the two events were resolved. The process will be repeated for different ratios of signal one to signal two power.

In a practical case the events actually will overlap in time and so the individual event correlation statistics (column vector in the signal extraction problem) will not be available. In this case we must assume that the location of the two events can be provided, and that the moveout anomalies for LASA are known. Then the column vector can be obtained by assuming a power spectrum for the signal and introducing the appropriate phase shifts (note that this approach also assumes that the signal is perfectly coherent across the array - studies of signal similarity will provide a measure of the validity of this assumption). Signal extraction filters will be designed for both events (i.e., the same ones that were used above) and applied to the stacked traces. The resolution obtained will be compared to that obtained in the "ideal" case.

At present, signals are not available for this study. However, they are expected in the near future, and work will be begun immediately upon their becoming available. Several pairs of events, having different separations in wavenumber space, will be processed.

Study of Mantle P-Wave Noise at the Large Array

The questions to be answered under this milestone as we see it now are:

1) The spatial coherence of the mantle P-wave noise

2) The spatial organization of this noise

3) The time variations in the P-wave noise

4) Does the mantle P-wave noise contain any discreet wavelets, and if so, how can these be characterized

The overall goal is a better understanding of the high velocity noise field.

Some initial analysis with poorly velocity limited data indicates that only part of the large array can be used as a tool to study the high velocity noise. Most of the studies will probably be limited to subarrays inside or on the "D" ring of subarrays. In general, processing is not sufficiently advanced to give any useful preliminary answers at this time.

To date most of the effort has been directed toward accumulating the necessary computational tools and deciding upon methods of approaching the P-wave noise problems. Pursuant to these goals, several new programs have been or are being written.

A program has been written and checked out which will compute multiple coherences very efficiently. This information is equivalent to multichannel prediction error. These data can be obtained very efficiently as a function of frequency and as a function of increasing sensors. This program was developed under this contract and the procedures will be described in detail in the final report.

A program which develops filters which will maximize the coherence between two groups of sensors has been written but is not yet checked out. The filters designed will give information about the wavenumber spectra of the most coherent noise. The procedure is an iterative one which will pick out the next set of filters which maximize this "group coherence" subject to the constraint that this output be uncorrelated with the previous output. Thus in some sense it will be hunting the second most coherent energy.

The value and uses of this program have yet to be explored. It may also be useful in seismometer equalization and it may be a good way to process signals.

This program is being developed under this contract and the procedures will be reported in detail in the final report.

A program which calculates a moving power spectra and looks for anomalously high power in a given frequency band has been written and checked out. The purpose of the program is to detect discreet wavelets by looking for spectral characteristics which are sufficiently deviant from the expected values of a Gaussian stationary process. Results to date are inconclusive.

This program was developed under this contract and will be covered in detail in the final report.

A procedure has been developed by Mr. John Burg of Texas Instruments which will give exceptionally high resolution spectra from a line array. This technique has been checked out at TFO and appears to give excellent results. This technique will be used extensively on data from subarray arms at the LASA.

This program has been developed under company funded research and only the final results and interpretation will be presented.

A program which calculates conventional wavenumber spectra in a much more efficient manner has been written and is being checked out. This program uses the Cooley Tukey algorithm to get a very rapid estimate of the cross power matrix. The procedure is then the conventional one of expanding in correlation space and taking a two-dimensional Fourier transform.

The usefulness of this program is its efficiency. It will allow computation of a large number of conventilnal wavenumber spectra at much reduced costs.

The exact plans for processing and evaluating the mantle P-wave noise depend on intermediate results and will not be detailed in this quarterly report.

In general, the analysis tools will be the above programs. Conventional analysis such as power spectra and spectral ratios will also be used extensively. The Fisher Analysis of Variance technique will be used in trying to identify discreet arrivals in the ambient noise.

Study of Long-Period Noise at the Montana LASA

No long-period data has yet been received. When received the data will be processed to determine multichannel coherence, spatial organization space, and time stationarity.

The techniques will be the same used in the Mantle P-Wave Study. Long-period noise studies can begin as soon as the data is available.

Comparison of Maximum Likelihood Filtering and Weiner Filtering for Specific Events

The maximum likelihood filters used in the study by Flinn, Harterberger and McCowan of SDL will be used in this study.

The plan is to obtain the filters on punched cards and evaluate their performance as compared to an appropriate Weiner filtering scheme. To date the filters have not been received.

The initial processing will be oriented to understanding the Max. Like. filters. Wavenumber responses, noise rejection as a function of frequency, etc., will be computed for these filters.

After the characteristics of the maximum likelihood filters are well understood some subarray and large array Weiner filters will be designed. The performance of the two types of processing will be examined, compared, and explained insofar as is possible.

Work can start on this milestone as soon as filters are received.

Report on Subarray Filtering Results

This will be a portion of the final report. The method of presenting the data will not be considered until all the data have been processed and analyzed.

FINANCIAL STATUS:

The financial status of the contract through October 31, 1966, is summarized on the enclosed Cost Planning and Appraisal Chart.

Very truly yours,

TEXAS INSTRUMENTS INCORPORATED

Frank H. Binder

Frank H. Binder
Program Manager

FHB:pr
Encl.

COST PLANNING & APPRAISAL CHART TI-10311

PROJECT NUMBER	CONTRACT NUMBER	PROGRAM DESCRIPTION
VT 6707	AF 33(657)-16678	Large Array Signal And Noise

COLUMN CODE:
1. Monthly budget direct costs as projected in negot'ated price.
2. Monthly actual direct cost
3. Cumulative budgeted direct dollars
4. Cumulative actual direct dollars
5. Variance budgeted vs. actual to date
6. New estimate of total direct costs to complete
7. Original estimate of total direct costs
8. Current estimate of direct costs

COST DATA

DIRECT COSTS

TASK/ITEM IDENTIFICATION	BUDGET EXPENSE MONTH: Oct. 1966 Budget (1)	Actual (2)	EXPENDITURES TO DATE Budget (3)	Actual (4)	BUDGET VAR. + OVER − UNDER (5)	NEW ESTIMATE TO COMPLETE (6)	TOTAL ESTIM... ORIGINAL ESTIMATE (7)
Contract not broken	25000	22169	90185	86271	-3914	293142	379413
down by Tasks as Cost							
Records cut across							
the Tasks							
SUB TOTAL	25000	22169	90185	86271	-3914	293142	379413

INDIRECT COSTS

TASK/ITEM IDENTIFICATION	MONTH Oct. 1966	TO DATE	NEW ESTIMATE TO COMPLETE	TOTAL ESTIMATED INDIRECT COSTS ORIG. EST.	CURRENT EST.	VAR. (+) OVER (−) UNDER	CODE
	10521	31473	128818	160291	160291		
SUB TOTAL	10521	31473	128818	160291	160291	0	
G & A	1121	3016	16953	19969	19969		
FEE	2058	7362	26638	34000	34000		
TOTAL ESTIMATED COST AND FEE	35869	128121	465552	593673	593673		

CRIPTION

Array Signal And Noise Analysis

DATE 12-6-66

d vs. actual to date
total direct costs to complete
of total direct costs
of direct costs

9. Variance budget vs. new estimate
10. See instructions

SYMBOL CODE: Start event (scheduled); Complete event (scheduled); Anticipated slippage; Actual slippage; ▲ Milestone

NEW ESTIMATE TO COMPLETE	TOTAL ESTIMATED DIRECT EXPENDITURES			% COMPL. TOWARD TECHNICAL OBJECTIVE
	ORIGINAL ESTIMATE	CURRENT ESTIMATE	VARIANCE + OVER — UNDER	
6	7	8	9	10
293142	379413	379413		20
293142	379413	379413	0	20

SCHEDULE DATA

TIME: ☐ WEEKS ☐ MONTHS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26

RECT COSTS

VAR. (+) OVER (—) UNDER	CODE	ANALYSIS OF SIGNIFICANT PROJECT VARIANCES & PROBLEMS (COST - SCHEDULE - PERFORMANCE)
0		

B