**UNCLASSIFIED**

<table>
<thead>
<tr>
<th>AD NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD822532</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIMITATION CHANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>TO:</td>
</tr>
<tr>
<td>Approved for public release; distribution is unlimited.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FROM:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 06 OCT 1967. Other requests shall be referred to Air Force Technical Applications Center, Washington, DC 20333.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AUTHORITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFTAC USAF ltr 25 Jan 1972</td>
</tr>
</tbody>
</table>

**THIS PAGE IS UNCLASSIFIED**
STATEMENT 12: UNCLASSIFIED

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of U.S. Technical Applications Center, Attn: VSC, Wash., D.C. 20333.
ADVANCED ARRAY RESEARCH
Quarterly Report No. 3
15 June 1967 through 14 September 1967

George Hair, Program Manager
Area Code 214, 238-3473

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P.O. Box 5621
Dallas, Texas 75222

Contract No. F33657-67-C-0708-P001
Beginning 15 December 1966
Ending 14 December 1967

Prepared for
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

Sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
ARPA Order No. 624
AFTAC Project No. VT/7701
6 October 1967
This document is subject to special export controls, and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Chief, AFTAC.
Air Force Technical Applications Center
VELA Seismological Center
Headquarters, USAF
300 N. Washington Street
Alexandria, Virginia 22314

Attention: Captain Carroll F. Lam

Subject: Quarterly Report No. 3 for period 15 June 1967 through 14 September 1967

Identification: AFTAC Project No: VELA T/7701
Project Title: Advanced Array Research
ARPA Order No.: 624
ARPA Program Code No.: 7F10
Name of Contractor: Texas Instruments Incorporated
Contract Number: F33657-67-C-0708-P001
Effective Date of Contract: 15 December 1966
Amount of Contract: $625,500
Contract Expiration Date: 14 December 1967
Project Manager: George Hair
Area Code 214
238-3473

WORK PROGRESS

Progress during the third quarter is presented in this report by principal tasks. Areas of current investigation and plans for the fourth quarter are also presented.
Task A

Using an ensemble of seismic array network data to be furnished by AFTAC, investigate bodywave noise on a coherent worldwide basis. Investigate interarray equalization problems. Study methods of combining the subarray output for network signal extraction. Investigate the capabilities of a worldwide network for resolving events closely spaced in time and space.

Using data from the CPO array, several procedures for computing f-k spectra have been compared in order to choose an optimum technique for the study of bodywave noise at the station level. Conventional and high-resolution techniques were compared using conventional correlation-transform techniques and also using the direct transform (Cooley-Tukey) method. Consistent results were obtained for all cases. The direct transform, high-resolution procedure was determined optimum from the standpoint of spatial definition and computation time.

Further comparisons were made to explore normalization procedures, optimum signal-to-noise ratio and the extent of variation in spectral estimate due to the choice of reference sensor. In terms of spatial stability and relative insensitivity to both reference sensor choice and signal-to-noise ratio, f-k spectra computed from unsmoothed direct transforms proved superior to those computed from smoothed transforms. An additional advantage is the applicability of a computational shortcut significantly reducing required computation time. With this method, an f-k spectrum may be computed representing the average of the individual spectra computed for each reference sensor in approximately the time formerly required to obtain each individual spectra. A description of this method will be included in Special Report No. 6, now being prepared.

Using high-resolution f-k spectra, a study of the bodywave noise observed at the station level has been proceeding. All array stations were examined using two noise samples chosen for analysis from meteorological data indicating large storm centers. Ten frequencies were examined from 0.2 Hz to 2.0 Hz in 0.2 Hz increments. Unsmoothed direct transforms were computed over a 410-sec data gate, and high-resolution f-k spectra were computed from these transforms. The results of this analysis will be reported in Special Report No. 6. This report will also summarize station array characteristics, such as location, configuration and straight sum responses. A description of the two noise samples used will be included along with available meteorological data.

A technique for obtaining worldwide f-k spectra, using network station outputs as components of a worldwide array, has been programmed and is being evaluated using synthetic data. The procedure is essentially a beam-steer in the frequency domain and is designed for detection of bodywave energy. The procedure will be used subsequently for extraction of high-velocity noise and signals at the network level. A special report will be prepared describing the technique and the results of the evaluation.

The comparison of techniques for removal of low-velocity energy at the station level is proceeding. Conventional disk model MCF's, both from measured and theoretical designs, straight-sum and beam-steer outputs, and maximum-likelihood adaptive procedures are being compared. Initial results indicate that the maximum-likelihood adaptive procedure will probably not be satisfactory for medium-to-high velocity noise extraction. Disk-model adaptive procedures would be preferable but are not routinely operational at this time.
An initial study has been made of signal similarity across
the network. Earthquake data was utilized due to an unanticipated delay
in receipt of explosion recordings. Correlation coefficients have been
computed and analyzed to determine which station appears most represen-
tative of the network, i.e., to which station the network should be equalized.

Significant equalization problems are observed, and a theo-
retical investigation of different methods to minimize the mean-square-
error on a network basis is underway. Specifically, a method that does
not require the choice of a target or reference station is being examined.

Processing of a second event, Kurile 2, under the worldwide
signal extraction study is nearing completion. For this study, various pro-
cessing techniques are examined in order to determine the optimum technique
to enhance teleseismic signals at the network level. Techniques examined
include simple beam-steer, weighted beam-steer, and the beam-steer of
Levinson equalized data. Both unprocessed and bandpassed data are used.

Different types of weighting, including signal-to-noise ratios,
signal ratios and noise ratios, have been analyzed in the weighted beam-steer
technique. Results of this study indicate that the optimum technique is a com-
bination of signal-to-noise ratio weightings and Levinson equalization of
bandpassed data. However, due to the additional processing costs of the
technique, several additional tests will be performed to determine if the
use of Levinson equalization filters is warranted. Levinson filters studied
thus far have been designed for and applied to the same event; on-line pro-
cessing will require the development of a set of filters for each signal area
of interest. The use of filters designed from an ensemble of events will be
evaluated when additional events have been processed and analyzed.

The phase-extraction study has been limited by the lack of
available events containing good depth phases. However, the second event
processed for the signal extraction study does contain several later arriving
phases. The two analyzed events will be studied using P-30 correlation, square-and-integration of P-30 correlations, and a time shift of the P-30 correlations using time shifts based upon pP-P time differences to enhance depth phases.

A special report on the signal extraction and phase extraction studies is being prepared for publication during the coming quarter.

**Task B**

Continue investigations of multi-element system studies to determine possible new combinations of sensors for noise reduction. Study methods of specifying, for given noise fields, the optimum multisensor system for noise reduction with the desired result a set of guidelines for array design. These guidelines should include, but not be limited to, the type of sensors required and, for an array, the size and geometry, subject to the constraints of practicability.

1. **Program for Computing Theoretical Crosspower Spectra and/or Crosscorrelation Functions**

The following is a resume of the work done toward developing the crosspower/crosscorrelation matrix program and the reason for this work.

The need for this program arises in two areas of our work. In attempting to assess the potential value of arrays which employ new geometries and/or various types of instruments, it is often desirable

---

to begin with a theoretical study of processors for the arrays. To do this, it is necessary to specify representative signal and noise fields and then to obtain the resultant crosspowers between various elements of the array. This type of analysis has been done for horizontal-vertical seismometer arrays and for vertical arrays. It is possible that additional vertical array work of this nature may be warranted.

The second need arises in designing filters. In designing filters for application to data from an existing array, it is necessary to obtain the signal and noise crosscorrelation matrices. While use of measured noise is customary for this purpose, it is generally difficult to obtain signal records of sufficient quality and duration to provide an adequate statistical representation of the signal. The best solution is often to generate the signal statistics theoretically.

The program now being developed would be a substantial improvement over previous programs which provide this type of information. Programs currently available handle separate parts of the overall problem. By properly employing a series of these programs, it is possible to obtain the desired result. In practice, however, as a result of the complexity of this approach and unfamiliarity with the programs, the goal is either achieved at undue expense or an inferior result is accepted. The new program would treat the entire problem and in such a way as to make it readily accessible to potential users.

Programs now available are not adequate for all situations. For example, theoretical work on horizontal seismometers necessitated writing a new program. The approach was such that the program does not output the crosspower matrices for such arrays and thus, we do not currently have this capability. New situations of immediate interest can be treated by the new program and, more importantly, the new program will be readily extendable to other configurations as they arise.
The first case considered during the development of this program was the relatively simple case involving a surface array of vertical seismometers and the solid disk $f-k$ space model. Mathematical representation of the solid disk $f-k$ is as follows:

$$P(f, k, \theta) = \frac{v^2}{\pi f^2}$$

for $0 \leq k \leq \frac{f}{v}$, $0 \leq \theta \leq 2\pi$

In this case, where $v$ is the minimum apparent velocity for the model, it is not necessary to consider the crustal structure of the medium. In effect, whatever the crustal structure, excitation will be assumed such that the resultant vertical motion at the surface is described by this $f-k$ space model. It is a simple matter to compute the resulting crosspower spectra. Flexibility is achieved by combining two such models to form an annulus and by tilting the model to simulate anisotropic propagation.

Obtaining crosspower spectra for arrays involving vertical and horizontal seismometers using the mode for vertical motion was the next step attempted. In this case, it was necessary to consider the crustal structure since this determines the relationship between horizontal and vertical motion. The most simple structure is the infinite half space. Even in this simple case, the model given above was not tractable. It was replaced, therefore, by the following models, one for isotropic and the other for directional propagation.

$$P_I(f, k, \theta) = \frac{1}{2\pi k} \delta(k - \frac{f}{v})$$

for $0 < \theta < 2\pi$

$$P_D(f, k, \theta) = \frac{1}{k} \delta(k - \frac{f}{v}) \delta(\theta - \theta_1)$$
In these models, the symbol $\delta$ represents the delta function. This is not a serious limitation, since any continuous model can be simulated as closely as possible by combining groups of such models with appropriate values of $v$ and $\theta$. A more serious objection is the fact that the case involving horizontal-vertical seismometer arrays requires slightly different treatment than does the case involving all vertical seismometer arrays. This difficulty would be compounded as further extensions, such as multilayer crustal structures, vertical arrays and dispersive propagation, are contemplated. By starting from a special case and attempting to go to the general case, the unity of the problem was being obscured, making it obvious that a new approach was needed.

The key to this problem is to treat the multilayer crustal structure immediately. By employing the Haskell matrix formation, it is a straightforward matter to obtain $f-k$ space transfer functions between any combinations of vertical and horizontal seismometers at different depths. Moreover, these relationships are of the same basic form for both bodywave and dispersive propagation. These transfer functions and the second two $f-k$ space models given above are all that is required to calculate the desired crosspower spectra. Love waves require a slight modification due to the absence of vertical motion, but the same general treatment can be applied.

Use of this approach provides the unified theory necessary for implementation of the program. The remaining task is to actually do the programming.

We believe that the program can be completed to treat arrays of vertical and horizontal inertial seismometers within the duration of the present contract. This will require about three man-months and seven hours of computer time.
2. Analysis of the WMO Noise Sample

Three noise samples recorded at WMO in 1962 have been analyzed using $k$-line wavenumber spectra. The most interesting result of this study is the identification of broadband Rayleigh-wave energy (0.2 to 1.0 Hz) coming from the northeast. The broadband character of this energy indicates a source relatively close to the array. Two small lakes located northeast of the array appear to be likely sources. It was also possible to obtain some information about the 2 Hz noise characteristics of this site. This 2 Hz energy was found to be propagating in one of three directions. Choice of one of these three directions is prevented by the aliasing properties of the array configuration. Velocities associated with each of the three possible directions are all close to 3 km/sec. The high degree of repeatability between the three samples indicated that, subject to this ambiguity, the source direction is known rather precisely. Details of this analysis are presented in Special Report No. 2.*

3. Data Recording at the WMO Horizontal Seismometer Array

Data are currently being digitally recorded from the array of horizontal seismometers at WMO. These data will be used to experimentally study the proposition that teleseismic signal enhancement can be accomplished by using the horizontal seismometer outputs to predict the surface wave noise on a central vertical seismometer. The data will be processed using both conventional MCF design and adaptive filter design techniques. Data from the shallow-buried array of vertical seismometers is also being recorded for possible use in

interpreting the results. In addition, the strain seismometer outputs are being recorded for possible future use. Because of the nature of the array, a possible additional benefit of this recording effort may be resolution of the ambiguity in the direction of propagation of the 2 Hz noise.

**Tasks C and D**

Theoretically investigate methods of implementing continuously adaptive systems for application to time-varying noise fields and postdetection processing. Any system that can be simulated off-line should be evaluated using suitably characteristic data. Investigate the effects and methods of reducing locally generated noise. The effects of such non-plane wave fields on multichannel filter design should be evaluated.

Work during the third quarter consisted of

- Prediction error processing of additional data samples
- Development of an adaptive filtering program for signal extractions based on a theoretical signal model
- Implementation of a second maximum-likelihood algorithm

At the beginning of the third quarter, adaptive prediction error filtering had been completed on four data samples. These were short-period vertical data from surface arrays. In order to establish a broader base for study of adaptive techniques, adaptive prediction error filtering was undertaken on eight additional data samples. These samples included data from an array of long-period 3-component instruments, deep-well vertical array
data, and ring stacked short-period vertical data, as well as the usual short-period vertical surface array data. All data samples except the vertical array data were processed both before and after prewhitening. Plots of mean-square-error vs $k_s$ (the rate of convergence parameter) mean-square-error vs time, power spectra, and false alarm probability are used in comparing the adaptive results with Wiener results from the same data. The most apparent observations from the results are

- Adaptive filter outputs approach Wiener results as $k_s$ approaches zero for both whitened and nonwhitened data
- Mean-square-error increases rapidly with increasing $k_s$ in every case for whitened data, while for nonwhitened data mean-square-error decreases slightly with increasing $k_s$ for some of the data samples

A computer program for adaptive signal extraction based on a theoretical signal model was completed during the third quarter. Checkout on this program is in progress. Tests on the running time of this program indicate that this type of processing will be economically competitive with Wiener signal extraction if the number of channels is less than ten and the number of filter points less than twenty-five.

In Special Report No. 1* it was shown that maximum-likelihood filtering could be reduced to a problem of predicting one channel of the data from the other channels minus the channel to be predicted. During the past quarter an additional maximum-likelihood algorithm has been programed

---

where the mean across channels is predicted from the set of channels formed by subtracting the mean from each channel. To date, two samples have been processed by both of these maximum-likelihood algorithms for the purpose of comparing the methods. Results indicate that in terms of mean-square-error the two processes are similar. However, the frequency content of the output traces appears to be different for each type of filtering. Investigation into the reasons for this difference is planned for the coming quarter.

**Task E**

Continue studies of the instrumental equalization problem. Apply any new techniques available for studying instrumental equalization and evaluate the effectiveness of such techniques.

1. Statistical Misdesign Study

Special Report No. 3* contains the derivation and probability curves for the statistical design parameters $\alpha$ and $\beta$ under the Gaussian assumption. ($\alpha$ is the ratio of the true mean-square-error of the measured filter to the mean-square-error, and $\beta$ is the ratio of the measured mean-square-error of the measured filter to the minimum mean-square-error.) These curves should be used in all future experimental planning. Special Report No. 5** contains generalization of the scalar $\alpha$ and $\beta$ quantities into $\alpha$ and $\beta$ matrices. This latter work, although directed toward practical problems, has no apparent application at present. Special Report No. 5 does contain a possibly more enlightening discussion of the derivation of $\alpha$ and $\beta$ than contained in Report No. 3.

---


2. Long-Noise Sample Study

Preparations for analyzing a very long-noise sample from LASA are being discontinued because of lack of sufficient funds to perform the work adequately.

Obtaining a suitable LASA long-noise sample does not appear to be a major problem. DAC playouts, supplied to us by SDL, of LASA subarray data recorded on 5 December 1966 and 12 December 1966 indicate that at any time one can expect to find several subarrays which are fully operating with a minimum of locally generated noise. By ignoring weak teleseisms, which would contribute almost no energy to the total recording, 10 hour and longer noise periods are readily uncovered. There are some recording error problems, such as channel dropouts in the multiplexing and zeroing of data, but these errors seem amendable to automatic detection and correction.

A primary analysis technique currently being used to study LASA noise is the measurement of group coherence. The application of this analysis technique to the TFO long-noise sample and the design and interpretation of group coherence multichannel filters in terms of equalization problems will constitute the primary effort under Task E during the next quarter.
FINANCIAL STATUS

The financial status of the project as of 31 August 1967 is summarized on the Cost Planning and Appraisal Chart submitted under separate cover.

No significant total variance from the original cost estimate is anticipated.

Very truly yours,

TEXAS INSTRUMENT INCORPORATED

George Hair
Program Manager
ADVANCED ARRAY RESEARCH, QUARTERLY REPORT NO. 3

Hair, George D.

6 October 1967

F33657-67-C-0708-P001

VIELA T/7701

This document is subject to special export controls and each transmittal to
foreign governments or foreign nationals may be made only with prior approval
of Chief, AFTAC.

ARPA Order No. 624
ARPA Program Code No. 7F10

Advanced Research Projects Agency
Department of Defense
The Pentagon, Washington, D.C. 20301

Progress during the third quarter, present effort and plans for future
work in the areas of network studies, multisensor arrays, continuously
adaptive filtering, near-array noise sources, and intra-array equalization
studies are presented.
### UNCLASSIFIED

**Security Classification**

**KEY WORDS**

<table>
<thead>
<tr>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROLE</td>
<td>WT</td>
<td>ROLE</td>
</tr>
</tbody>
</table>

- Bodywave noise
- High-resolution techniques
- Continuously adaptive systems
- Network signal extraction
- Phase extraction
- Crosspower/crosscorrelation matrix program
- Instrument equalization

### INSTRUCTIONS

1. **ORIGINATING ACTIVITY.** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. **GROUP:** Automatic downgrading is specified in DOD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** Make appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8a. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b. & 8c. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. **ORIGINATOR’S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

   1. "Qualified requesters may obtain copies of this report directly from DDC.

   2. "Foreign announcement and dissemination of this report by DDC is not authorized.

   3. "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ."

   4. "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ."

   5. "All distribution of this report is controlled. Qualified DDC users shall request through ."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

13. **ABSTRACT:** Enter a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

   It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

   There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indicator of technical context. The assignment of links, rules, and weights is optional.

---

**UNCLASSIFIED Security Classification**