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EXTENDED ARRAY EVALUATION PROGRAM

Terence W. Harley

Texas Instruments, Incorporated

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EXTENDED ARRAY EVALUATION PROGRAM

FINAL REPORT

1 April 1971 to 31 March 1972

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13. ABSTRACT

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SECTION I
INTRODUCTION

This final report summarizes work performed on Contract F33657-71-C-0843, Extended Evaluation of ALPA, NORSAR and VLPE Data, which was conducted by Texas Instruments Incorporated at the Seismic Array Analysis Center (SAAC) in Alexandria, Virginia. The program consists of the following seven tasks:

- Continued evaluation of the Alaskan Long Period Array (ALPA)
- Evaluation of the long period Norwegian Seismic Array (NORSAR)
- Evaluation of the short period Norwegian Seismic Array
- Evaluation of the stations of the Very Long Period Experiment (VLPE) network
- Investigation of network capabilities and analysis techniques
- Adaptive processing studies
- Investigation of high-resolution frequency-wavenumber spectral estimation techniques

The software required to perform the evaluation was developed under a previous contract (Contract F33657-69-C-1063). Modifications made to that software during the present program have been documented and submitted to the VELA Seismological Center (VSC) during the course of the program.

Results obtained on the current program are presented in detail in the eight Special Technical Reports listed in Appendix A. This final report summarizes these results for each task in Sections II to VIII.

SECTION II

ALPA EVALUATION TASK

Results obtained in the ALPA evaluation task are detailed in Special Reports No. 4, which summarizes the overall evaluation effort, and No. 3, which discusses the effectiveness of various array processing techniques. Summaries of Special Reports No. 4 and No. 3 are presented below.

A. Special Report No. 4: Evaluation of the Detection and Discrimination Capabilities of the Alaskan Long Period Array.

This report presents the results of an evaluation of the full nineteen-site Alaskan Long Period Array (ALPA). It extends an analysis performed on a nine-site ALPA subarray, which has been reported earlier in Final Report for Long Period Array Processing Development (Harley, 1971). The evaluation focuses on determination of optimum techniques for the extraction of those long-period signals which may be useful in classifying events, and on the utility of classification parameters obtained at ALPA. Specific areas of investigation include:

- Signal Analysis
- Noise Analysis
- Analysis of Two Component Processing
- Matched Filter Performance
- Analysis of S-Wave Processing

- Seismic Event Detection Threshold
- Behavior of Seismic Discriminants

When applicable, results from the evaluation of the limited array are compared to the full array results.

Summarized below are the major results from each of the areas of evaluation:

1. Signal Analysis

   - Signal similarity across the full 19 element ALPA array is less than that across the limited nine element array studied earlier. Average signal correlation coefficient for the vertical component is 0.84 for the full array and 0.93 for the limited array.
   - Average beamsteer signal attenuation for the transverse component is approximately the same for both the full array as for a seven site hexagonal subarray, about 1.4 dB. For the vertical and radial components the full array beam causes about two dB attenuation, as opposed to about one dB for the small array beam.

2. Noise Analysis

   - The anomalous long-period noise problem observed at ALPA during 1970 has been substantially alleviated.
   - Between days 120 and 240 the site average RMS vertical ground motion amplitude in the 0.025 to 0.055 Hz band ranged from four to ten mμ. After day 240 most of the samples showed slightly higher noise levels but occassionally the site averages were substantially higher ranging as high as 26 mμ.

- Azimuths of strong directional noise sources rarely coincide with azimuths of areas of interest.
- The RMS value of beamsteered noise in the 0.025-0.055 Hz band ranges from 1.5 to 3.0 mμ.
- On the average the 19 site array will provide no more than 0.1 M_s units of increased signal detectability over the nine-site array.

3. Two-Component Beamforming

- SNNR (signal plus noise to noise ratio) gains of one to two dB in the bandpassed output beam may be expected from two component beamforming, but gains of more than three dB are observed on occasion.

4. Matched Filter Studies

- Overall SNNR improvements from master waveform matched filtering of the transverse, vertical, and radial components average 2.1 dB, 3.5 dB, and 2.7 dB, respectively.
- Instances of SNNR improvements of more than seven dB were observed. These gains might be exceeded in some instances if more nearly optimum master waveform lengths were used, and if, in certain regions, more than one master waveform matched filter were tried.
- Chirp filter improvements from the transverse, vertical, and radial components average 2.0 dB, 3.9 dB, and 3.0 dB, slightly better overall than master waveform improvements. Large gains (greater than five dB) were observed in the same percentage (17%) of cases for both forms of matched filter.

- Two component matched filtering appears generally to preserve the SNNR gains obtained from two component beamforming.

5. S-Wave Processing Results

- The S-wave detection probability appears to lie above an m_b of 5.5 for Central Asian events.*

- It appears that the S-wave is a good earthquake-explosion discriminant; however, since S waves are detected only for the largest earthquakes in areas of interest, the S wave discriminant appears to be of little practical value.

6. ALPA Earthquake Surface Wave Detection Capability

- The directly-determined 90% detection probability for surface wave occurs near m_b = 4.5 for Central Asian events and near m_b = 4.3 for events from the Kurile/ Kamchatka region.

7. Behavior of Standard Discriminants

- The M_s - m_b relationship determined from Love wave energy is a better discriminant than the same relationship determined from Rayleigh wave energy.

- AL and AR were not fully successful as discriminant methods and were clearly inferior to the M_s - m_b discriminants.

- No discrimination method achieved a complete separation of earthquakes and presumed explosions, although the Love wave M_s - m_b discriminant failed clearly in only one case.

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*Note in all references to detection probabilities in this report the false alarm rate is essentially zero.

The following areas will be emphasized in future analysis of ALPA:

- Continued monitoring of the ALPA noise field, and a detailed analysis of anomalous noise samples.
- Analysis of complicated signals in an attempt to understand multipath structure.
- Further investigation of the effects of master waveform matched filter length on performance, and more detailed study of the utility of multiple master waveforms for each region.
- Comparison of simple phase shift-and-sum two component processing with more sophisticated techniques such as two component multi-channel filtering.
- Region-by-region estimation of the ALPA detection threshold utilizing matched filtering regional differences.

In addition to these ALPA studies, ALPA evaluation results will be integrated with those obtained from the Norwegian Seismic Array, and the stations of the Very Long Period Experiment in order to obtain an estimate of the detection and discrimination capability of the existing long period network.

B. Special Report No. 3: Array Processing of Alaskan Long Period Data.

The purpose of this study was to evaluate the performance of multi-channel filter (MCF) processors on ALPA data, and to compare their performance with that of the much simpler beamsteer processor. The types of MCF processors tested included two different frequency-domain optimal filters, a time-domain optimal filter, and a time-domain adaptive filter. In addition, the effectiveness of the weighted beamsteer technique was investigated. The work was performed using the vertical component of the nine-site subarray which was available during 1970 and early 1971.

Two approaches to the design of MCF's in the frequency domain were considered. It was found that the use of noise crosspower spectral matrices estimated by smoothing conjugate products over adjacent frequencies of a long transform was superior to the use of matrices estimated by smoothing conjugate products over many short transforms at the same frequency. The results summarized below are based on the use of the former technique.

Some variability in noise suppression was observed when the optimal MCF's were applied to the design noise (the noise gate on which the required noise crosspower densities were estimated). One of the frequency-domain designs suppressed this noise by about five dB more than the beamsteer processor. In the practical case, however, when the filters were applied to off-design noise (a later data gate containing the presumed signal), the performance dropped and none of the optimal MCF's was materially superior to the beamsteer.

To overcome this performance loss in processing off-design data, several MCF's were designed from crosspower densities estimated on the data gate which contained the signal. When this was done the resultant MCF tended to degrade the signal, and the output signal-to-noise ratio was not any better than that obtainable with beamsteer processing.

There was some evidence that the adaptive time-domain filter can achieve somewhat better results. In one case, the adaptive filter suppressed the noise by 6 dB more than the beamsteer.

The relatively simple weighted beamsteer processor was also considered. In most cases this type of processor achieves results very similar to the beamsteer, but on occasion it provides an additional four dB of noise suppression.

SECTION III

NORSAR LONG PERIOD EVALUATION TASK

Results obtained on the NORSAR long period evaluation task are detailed in Special Report No. 5 (Preliminary Evaluation of the Norwegian Long Period Array); a summary of this report is presented below.

A. Special Report No. 5: Preliminary Evaluation of the Norwegian Long Period Array.

This report presents the results of a preliminary evaluation of the long-period Norwegian Seismic Array (NORSAR) using seismic data recorded during the time period 1 May 1971 through approximately the end of December 1971. The evaluation of NORSAR has three overall objectives:

- Determine the best method of enhancing the signal-to-noise ratio of Eurasian events.
- Determine the array detection capability for Eurasian events.
- Evaluate the performance of various discriminants at NORSAR for Eurasian events.

These objectives were accomplished by using analysis procedures similar to those used to evaluate ALPA (Harley, 1971). Six separate studies were undertaken:

- Noise analysis.
- Signal analysis.
- Array processing effectiveness.
- Matched filtering performance.
- Detection threshold estimation.
- Behavior of standard discriminants.

The long-period NORSAR is an array of 22 seismometer sites spread over an area approximately 100 km in diameter and located north of Oslo, Norway. Each site contains three seismometers (25-second period) aligned in vertical, north-south, and east-west directions.

The results presented in the following are based on the analysis of events located in or near the Sino-Soviet area. The only exception was a United States underground nuclear explosion (CANNIKIN). Consideration only of these areas essentially restricted the data to events lying east of NORSAR. The performance of NORSAR for westerly events may be somewhat different; however, an estimate of that performance may be inferred from results of the noise analysis.

Transmission of NORSAR long-period data is accomplished by a communications system called the Trans-Atlantic Link (TAL). Received NORSAR data are multiplexed with LASA and ALPA data and then recorded on magnetic tape. Data become available at SAAC during the first quarter of 1971, however, because of various difficulties with both the transmission hardware and software, data quality prior to April 30, 1971 was not satisfactory for analysis. Thus, results presented are based on data recorded after that date.

Events for analysis were selected on the basis of location, magnitude, and depth. Source information was primarily from the NOAA-ERL "PDE" lists and the SAAC (LASA) bulletins. During the last quarter, the NDPC (NORSAR) bulletin became available and was also used. The criteria for selecting events for analysis were:

- Epicenter in or near the Sino-Soviet area.
- Magnitude (m_b) between 4.0 and 6.0.
- Depths less than 70 km.
- No interfering events.

During the eight month period beginning 1 May 1971, 251 events were considered for analysis. Edit attempts were made on 152 of these.

Of the 152 edited events, 112 were suitable for processing. The events selected but not edited are eliminated primarily because of excessive data dropouts during events. This was a fairly serious problem during the summer of 1971 but by fall had reduced in severity to a minor one. The dropouts were caused either by NORSAR being down or, as was usually the cause, by transmission failure. The duration of data loss was from one second to ten seconds and occasionally went for several minutes. There was one eight-day period (about days 180-188) when no data was received due to a TAL problem. Since this fall, NORSAR has become fully operational and the data loss rate from dropouts is small. Other causes for eliminating edited events included:

- Unreported interfering event.
- Unremovable spikes or transients in the data.
- Mislocation (as determined from particle motion and/or misrotation effects).

In addition to signals, noise data was specially edited for separate analysis. The procedure was to obtain as long an interval as possible without known events occuring. Noise edits were obtained at approximately 10 day intervals.

The following results are noted. The results are based on data which were obtained from the interval of 1 May 1971 to the end of 1971 and using an average of 15 to 16 sites out of the 22 total sites. Events were restricted almost exclusively to those occurring in or near the Sino-Soviet area.

The data for NORSAR as received at SAAC have generally been excellent since September 1971. Previous to that time, particularly during early summer, there was considerable difficulty in obtaining good data consistently. At any given time, usually 20 to 21 sites are operating. The difference between this number and the average number of 16 sites processed arises from the sites dropped because of particular problems such as spikes and transients.

Although much free-period and mass-position test information was recieved, no full frequency and phase response data were obtained. This prevented the drawing of conclusions in some areas such as the travel-time anomalies of signal waveforms mentioned below. However, results from noise analysis and array processing did imply good equalization.

A large amount of noise data was processed and several results can be given with confidence:

- There are definite seasonal changes in the spectral shape, average power level, and directionality of the ambient noise field at NORSAR. Summer noise is generally easterly with microseismic energy at 16-18 seconds, and 8-10 seconds. Winter noise arrives primarily from the northwest quadrant with average power levels increasing by a factor of 2 or 3. In the winter, the 8-10 second energy increases and some 4-5 second energy appears.
- There was one clear-cut correlation of high noise level with weather (day 348). It is probable that with more detailed analysis, the increased winter noise levels could be correlated with weather in the north Atlantic.
- All sites seem to be well equalized based on average noise levels at each site.
- Multichannel squared coherence is generally greater than 0.7 between 0.03 Hz to 0.15 Hz. This suggests that MCF processing has some potential for additional array gain.

The number of events processed to ascertain signal characteristics was relatively small. However, the results show definite patterns. Major results are:

- Waveform similarity between sites shows only small changes across the array along the path of propagation. Much larger changes are observed along the wavefronts normal to the propagation path.
- Small but consistent travel-time anomalies have been observed at a few sites. These seem to be independent of event azimuth hence

are probably caused by instrumental effects. Their cause could not be investigated because of lack of phase response calibrations.

- Wavefront arrival azimuth is generally the great circle path. Events from Turkey, however, show a more southerly shift in arrival angle by about five to eight degrees.
- All signal spectrum measurements were on the raw spectrum uncorrected for instrument response. On the uncorrected spectra, the -6 dB power points were generally between 0.025 Hz to 0.060 Hz. Turkey events and very large Central Russian events may extend the upper -6 dB level to 0.075 Hz.
- The ratio of radial to vertical Rayleigh wave amplitudes was about 0.68. This is smaller than the ratio of 0.8 at ALPA.

The array processing performance results are based on only twelve noise samples. This is because the intent was to obtain MCF's as reliable as possible which in turn required long-duration noise samples. The results for these samples are:

- Signal degradation due to beamsteer processing was about 0.7 dB for LRV and LQT modes and 1.0 dB for the LRR mode.
- Out of the MCF design gate both BS and MCF processors achieved about $\sqrt{N}$ array gain most of the time. Within the design interval MCF's always were better than $\sqrt{N}$. Array gains were larger when using wider bandwidths both inside and outside of the design gate.
- The extra array gain achieved by the MCF over the BS processor in the design gate averaged 5.1 dB wideband and 3.7 dB in the passband of 0.025 - 0.055 Hz. Outside of this gate, these extra gains were to 3.0 dB and 1.9 dB respectively. The enhanced performance of the MCF was particularly sensitive to the upper frequency limit of the passband. With a lower limit of 0.02 Hz, the MCF improvement for upper limits of 0.059 Hz, 0.055 Hz, and 0.051 Hz were

4.3 dB, 3.6 dB, and 3.0 dB respectively in the design gate. For the same bands outside of the design gate, the improvements were respectively, 2.7 dB, 1.7 dB, and 1.2 dB. The lower band limit had little effect on gain.

- Because of the amount of data required for reliable MCF design, it is probably not practicable to design MCF's routinely to optimize array gain for any particular event. However, the seasonal trends in noise level and directionality indicate that an MCF processing occasionally will be useful, particularly in the winter (when up to 6 dB additional noise rejection was achieved).

Matched filtering performances of master events and chirp filters were measured for a large number of events. Major results are:

- Master event and chirp filter improvements are highly variable from event-to-event and region-to-region. The chirp filters tended to give more stable, but slightly lower gains than the master event filters.
- Master event filters averaged 0.5 to 1.0 dB more gain than chirp filters. Signal-plus-noise-to-noise ratio improvements decreased with decreasing bandwidth. The improvements for 0.020-0.059 Hz and 0.025 to 0.051 Hz respectively were:

LRV:	3.7 and 3.2 dB
LRR:	3.8 and 3.2 dB
LQT:	2.9 and 1.9 dB

- Chirp filter performance was not particularly bandwidth sensitive. The corresponding numbers for the chirp filters for the passbands above were:

LRV:	2.7 and 2.7 dB
LRR:	2.7 and 2.8 dB
LQT:	2.4 and 1.9 dB

- There was no obvious correlation between improvement and master-test event separation. Source mechanism and relative fault orientation should be more important in predicting signal-plus-noise-to-noise ratio improvement.
- Some regions tend to larger improvements with wider bandwidths while for other regions, narrow bandwidths give better results.
- Master events for a few regions gave poor results even thouth their waveforms appeared to differ relatively little from the test events.
- More sophisticated chirp filters may provide enhanced performance without significantly increased algorithm complexity.

The incremental detection threshold of NORSAR, using 15 to 16 sites, was measured directly from event detection histories and indirectly using implied magnitudes based on ambient noise levels. The results show that:

- The direct estimate indicates the 90% detection level at an $m_b = 4.6$ and the 50% level at $m_b = 4.2$. These estimates are not reliable since they are based on only a few non-detections in an event ensemble whose mean m_b is around 4.8.
- The indirect measurement of detection threshold gave unrealistically low detection thresholds (90% at $m_b = 3.8$, 50% at $m_b = 3.3$). It is felt that failure to account for the signal variance causes this low bias.
- The best estimates of detection threshold will have to come from a larger event ensemble.
- There is no significant variation in detection behavior between the three different passbands used.

The behavior of three standard discriminants, M_s-m_b, AR-m_b, and AL-m_b was observed for a number of Sino-Soviet events. All three discriminants showed good separation between earthquakes and presumed explosions. Both AL-m_b and AR-m_b gave better separation than M_s-m_b with AL-m_b giving the best results.

General plans for future tasks in the NORSAR evaluation are directed to answering questions which arose during this preliminary evaluation, enlarging the event ensemble, particularly at smaller magnitudes, and obtaining data covering a full calendar year so that seasonal effects can be examined.

In particular, noise analysis will be continued, and weather maps will be obtained for additional work correlating surface weather with the ambient noise field.

Future signal analysis will investigate the amount and effect of multipath energy at NORSAR. Some work should be done to explain or categorize the signal characteristics on a regional basis. This would be useful, in conjunction with matched filtering studies, in constructing models for "best" master events and chirps for given areas.

Future array processing analysis will investigate MCF performance using long or combined noise samples on an extended basis. If investigation of the noise field reveals stable directional noise on a seasonal interval, the performance of modeled wavenumber filters will be tested.

Matched filter studies will be used in an effort to obtain a better estimate of SNR gains for different regions. Possibly, given sufficient data, models of optimum filters can be constructed.

The detection threshold estimate of NORSAR will be refined by obtaining considerably more event data at smaller magnitudes. This effort will comprise the majority of the work on the extended NORSAR evaluation program.

SECTION IV

NORSAR SHORT PERIOD EVALUATION TASK

Results obtained on the NORSAR short period evaluation task are detailed in Special Report No. 6 (Preliminary Evaluation of the Norwegian Short Period Array); a summary of this report is presented below.

A. Special Report No. 6: Preliminary Evaluation of the Norwegian Short Period Array.

This report presents the results of a preliminary evaluation of the Short-Period (SP) Norwegian Seismic Array (NORSAR), using seismic data recorded during 1970, 1971, and 1972. The overall objectives of the NORSAR SP evaluation are:

- Determine the best processing methods for enhancing the signal-to-noise ratio of Eurasian events
- Determine the array detection capability for Eurasian events
- Evaluate the performance of short-period discriminants at NORSAR
- In conjunction with the long-period NORSAR data, determine the detection and discrimination capability of NORSAR for Eurasian events.

Substantial progress has been made toward achieving the first three objectives; future analysis will be directed toward improving the preliminary results presented in this report and meeting the fourth objective.

Five analysis tasks were undertaken in order to meet the first three objectives stated above:

- Noise analysis
- Signal analysis
- Array processing effectiveness
- Preliminary detection threshold estimation
- Behavior of SP discriminants

The NORSAR SP array, centered about 100 km due north of Oslo, Norway, consists of 132 short-period seismometers and has an aperture of about 100 km. The sensors are grouped into 22 six-element subarrays; each subarray has a center sensor and a five-sensor ring and is about 7 km in diameter. In this report subarray 1 refers to subarray 01A, subarrays 2 through 8 to subarrays 01B through 07B, and subarrays 9 through 22 to subarrays 01C through 14C. Within a subarray, sensors 0 through 4 refer to sensors in the surrounding ring, starting with the first sensor east of a north (0^{o}) azimuth, and proceeding clockwise around the ring. Sensor 5 refers to the central sensor of a subarray. Thus, sensor 0 of subarray 1 is sensor 01A01 in the official nomenclature, and sensor 5 of subarray 22 is sensor 14C00.

The results presented are based primarily on analysis of events located on the Eurasian continent. A total of 102 events have been analyzed.

Geographically, the events are concentrated principally in the Northwestern Pacific (from Kamchatka to Taiwan) and in south central Asia (north and west of the Himalayan system). There are five events from the Ural Mountain region, three from continental North America, two from as far west in Europe as Greece, two from the Arctic Ocean and one from the Aleutian Islands. Ninety percent of the events are either shallow (≤ 100 km) focus or have unknown depths. Twelve events are signals from known test areas, including six from Eastern Kazakh, one from Novaya Zemlya, two from the Ural Mountains, one from the Aleutian Islands and two from Nevada.

For 72 of the signals an associated 320-second noise sample taken just prior to the signal was edited and processed, these samples were used to obtain the noise analysis results.

Data quality was excellent; about one-half of the time all 132 sensors were operational. In most of the other cases one subarray (six sensors) was dead; the worst data loss was 19 sensors. With the exception of one event, there were essentially no spikes in the data. We do not have individual seismometer response curves; however, based on results of the signal and noise analysis, it appears that the seismometers are reasonably well equalized across the array.

Conclusions about the performance of the short period NORSAR array, based on analysis of just over 100 signals (primarily from Eurasia) and 72 noise samples, are given below.

Conclusions from the noise analysis are based on 72 samples and can be stated with good confidence. Major results are:

- The noise spectral shape is very simple. The peak occurs at 3 to 6 seconds and the spectra decrease rapidly at shorter periods. The spectral shape does not change significantly either across the array or with time.
- Noise levels are very similar across the array. Maximum single sensor variations typically are ± 6 dB, and most sensors are within ± 3 dB of the average single sensor level. Variation among

subarray beam noise levels in the region of significant power (0 to 2.0 Hz) is $\pm$ 2 dB.

- Wideband noise levels show a definite seasonal dependence; winter-time levels are about a factor of 2 higher. The increased winter-time level results because the 3 to 6 second microseismic peak is stronger in the winter. Application of the "standard" bandpass filter, which rolls off sharply at high frequencies, reduces the difference between summertime and wintertime noise levels.

- RMS levels on the "standard"-filtered adjusted-delay array beam range from 0.04 to 0.17 mμ, and typically are 0.12 mμ. This is about a factor of two higher than LASA detection-filtered beam noise levels.

- Multiple coherence levels within a subarray are low except at the 3 to 6 second microseismic peak. Inter-subarray multiple coherencies are low over the entire 0 to 5.0 Hz band.

Major conclusions from the signal analysis are:

- Except for a few close-in, high-frequency events signal similarity is good within a subarray. Among subarrays, however, similarity is quite variable.

- Amplitude variations across the array typically are 4:1. Some regions (e.g., Kazakh) show variations as high as 10:1.

- Eurasian signals usually have a substantial amount of high frequency energy (out to about 2 Hz). Spectral shapes are quite variable, but the close-in events ($\Delta < 30^{\circ}$) generally have more high-frequency content. The limited ensemble of Western hemisphere events processed show substantially less high frequency energy than the Eurasian events.

- Time-delay anomalies (deviation from plane wave propagation along the great circle path) are not significant for subarray beamforming, except perhaps for a few close-in events. Anomalies are significant, however, among subarrays and corrections are essential for array beamforming. Consistent subarray delay anomalies could be obtained for all regions except those within 30° epicentral distance of NORSAR.

- NORSAR m_b's averaged about 0.2 units less than PDE (and LASA) m_b's. This discrepancy can be explained as signal loss in array beamforming, and thus it appears that NORSAR m_b's, if corrected for signal loss, are about the same as PDE m_b's. The PDE-NORSAR m_b differences do appear to be larger at low magnitudes; this is presently not understood.

Major conclusions from the array processing performance study are:

- $\sqrt{N}$ noise rejection is achieved over the entire 0 to 5 Hz band for both subarray and array beamforming. Thus noise rejection totals about 21 dB (8 for subarray and 13 for array beamforming).

- Signal degradation for subarray beamforming typically is 1 dB; but for some close-in high-frequency signals, loss appears to be about 3 or 4 dB.

- Signal degradation for array beamforming is quite variable, but generally appears to be only about 2 to 4 dB. On some events, however, degradation appears to be as high as 11 dB. It should be pointed out that it is quite difficult to estimate array beamforming signal degradation, especially when it is large, because of the dissimilarity of subarray waveforms.

- Net signal-to-noise ratio (SNR) gain typically is 15 to 18 dB. For the problem close-in events gains drop as low as about 10 dB. For these events the reference subarray beam often has a higher SNR than the array beam. (Usually the array beam SNR is about 1 to 5 dB higher than the reference subarray beam SNR).
- Diversity stack beamforming provides 0 to 2.5 dB, and typically 1 dB, better SNR improvement than the adjusted-delay beam.
- For detection of Eurasian events, a bandpass filter with corner frequencies at about 1.2 and 2.8 Hz and a very sharp rolloff at low frequencies appears to be about optimum. The relatively high bandpass is desirable because event SNR's generally peak at about 1.5 Hz. This filter may not be best for Western hemisphere events which appear to have somewhat lower signal spectral content.

A preliminary estimate of the NORSAR detection threshold for Eurasian events gives a 90% incremental value of $m_b \sim 4.3$. Much more data are required to obtain a reliable estimate, however.

Standard short-period discriminants were calculated for all detected events, and the conclusions are:

- Discriminants based on event complexity (P30 mean square, autocorrelation mean square, and envelope difference) do not appear to be very effective in separating shallow earthquakes or earthquakes of unknown depth from presumed explosions for Eurasian events.

- Discriminants based on spectral energy distribution (dominant period and spectral ratio) appear to work reasonably effectively, although complete separation between Eurasian earthquakes and presumed explosions was not achieved. Surprisingly, the very simple dominant period measurement gave the best results. The spectral ratio of energy in the bands 0.3 to 0.8 Hz and 1.4 to 1.8 Hz was clearly inferior to the ratio of energy in the bands 0.55 to 1.5 Hz and 1.5 to 5.0 Hz. This fact is not surprising, since the first two bands were based on events processed using LASA data.
- The short period discriminant values for Eurasian events are significantly different that those obtained for a limited ensemble of Western hemisphere earthquakes and presumed explosions. This observation points out that the effectiveness of short-period discriminants depends on the source and station location.

Future NORSAR short-period evaluation efforts will concentrate on increasing the Eurasian event ensemble, emphasizing low-magnitude events, in order to improve estimates of the array detection capability. Close-in events will be analyzed in detail in an attempt to find techniques for improving array SNR gain.

SECTION V

VLPE STATION EVALUATION TASK

Results obtained on the VLPE station evaluation task are detailed in Special Report No. 7 (Preliminary Evaluation of Single Stations of the Very Long Period Experiment Network); a summary of this report is presented below:

A. Special Report No. 7; Preliminary Evaluation of Single Stations of the Very Long Period Experiment Network.

The Very Long Period Experiment represents an effort to install a small network of high-gain, high-quality seismometers and associated instrumentation at various locations throughout the world. The instrumentation has been described previously by Pomeroy et al (1969). To date instruments have been installed in Australia, Thailand, Alaska, Spain, Israel, Norway, and New Jersey. Detailed studies of the data from the station at Ogdensburg, New Jersey, were presented by Savino et al (1971). Also Savino presented preliminary results from all seven of the network stations at the MIT Seismic Discrimination meeting in January 1972, at Cambridge, Massachusetts. His results were obtained primarily from analysis of the photographic records at each station, while results of this study were obtained from the digital recordings.

In this report the seven individual stations are evaluated separately; the stations are evaluated as a network in Special Report No. 8 (Texas Instruments Incorporated, 1972) on this contract.

Because the amount of digital data processed thus far has been relatively small and somewhat scattered in time, results presented represent only a preliminary evaluation of the seven stations. The evaluation includes analysis of the individual station RMS noise levels, noise spectral content, station surface wave detection capability, and behavior of the M_s-m_b discriminant. Also, calibration analysis is presented for the Thailand station. One important aspect of the Very Long Period Experiment has been a comparison of the station detection and classification capability at 20 and 40 seconds. Therefore, we have undertaken a detailed study of the surface wave magnitude, M_s, computed at 20 and 40 seconds, and preliminary results of this study also are presented.

Attempts were made to analyze essentially all of the available data through November, 1971 at all stations except Ogdensburg. However, a substantial amount of the data at each station had to be eliminated due to the following problems:

- On a large number of occasions (nearly all of the Australian data) tape formatting problems in the digital systems prevented reading of the field tapes. Formatting problems included illegal sample rate, illegal number of channels present, and bad timing words in the header records. Also another type of error is the absence of the channel one sync flag in the first channel one sample point in each record.
- Several field tapes had short inter-record gaps which caused the tape drives to mis-position between records and hence caused problems in reading the header records (especially the Spain tapes).
- Some tapes had spurious end-of-file marks in the middle of the tapes, while other tapes were not terminated with an end-of-file mark.
- On several occasions, the field tapes had bad data due to various hardware problems (PTA's at Israel and the digital system at Thailand).

A total of 252 events were processed; however, multiple-station data were available for only a very limited number of these. Essentially all of these events were either in or on the edges of the Sino-Soviet area, and most of the events were either shallow (less than 60 km) or had unreported depth.

The events analyzed came from a reference list which was a combination of PDE and LASA bulletin data. The LASA bulletin data was included because PDE coverage below $m_b = 4.5$ in the Sino-Soviet area is sparse. The LASA bulletin, while not offering complete coverage, does provide event data to $m_b = 4.0$ and below for some regions (e.g., The Kurile Islands). However, use of the LASA bulletin does provide some problems in that occasional deep events may be included in the event ensemble.

Eight percent of the 276 good events could not be analyzed due to the presence of large interfering events. (It should be noted that numerous other events were not edited when PDE or LASA bulletin data showed that large interfering events would coincide with the event arrival at the station or stations of interest.) However, it is possible that most of the 20 interfered events would not have been masked at all seven of the stations. It is hoped that the interfering event problem can be analyzed further in the future when the entire network becomes operational.

Preliminary evaluation of the seven stations of the Very Long Period Experiment network has led to the following conclusions:

1. The vertical noise spectra generally are about flat and low level between 20 and 40 seconds, however they do increase rapidly at periods larger than 40 seconds at some stations. The horizontal noise spectra generally begin to increase at periods shorter than 40 seconds.

2. The vertical RMS noise levels in the 20 to 40 second band are generally around 5 $m\mu$, the horizontal levels are more variable but generally higher than the vertical levels.

3. Our data base is not yet large enough to make definitive estimates of the stations' detection thresholds. However, some preliminary statements can be made:

- Generally, the stations' detection thresholds for shallow focus earthquakes appear to be in the range 4.0 to 4.5 m_b for 30° epicentral distance and 4.5 to 5.0 m_b for 60° to 80°.

- Israel and Norway appear to be somewhat more sensitive than the other stations. Thailand is not particularly noisy, but recorded surface waves seem to be lower amplitude than at other stations.
- The detection capability at 20 seconds appears to be somewhat better than that at 40 seconds; the difference may not be as large as the 0.3 M_s units indicated by our data if careful bandpass filtering is done at each station.

4. The M_s - m_b plots for the seven stations analyzed are typical of those observed at other stations. Separation between earthquakes and events from known test areas is generally good, except for a few earthquakes at each station which have M_s - m_b values somewhat below the bulk of the earthquake population.

5. The relative amount of 40 and 20 second energy does not appear to depend on event magnitude for events with $3 \leq M_s \leq 6$.

6. Based on results from a large number of earthquakes and a small number of presumed explosions, it appears that no increase in average separation between earthquakes and presumed explosions will be obtained by using $M_s(40):m_b$ instead of $M_s(20):m_b$.

SECTION VI
NETWORK EVALUATION TASK

Results obtained in the network evaluation task are defined in Special Report No. 8 (Preliminary Network Evaluation Studies); a summary of this report is presented below.

A. Special Report No. 8: Preliminary Network Evaluation Studies

This report describes investigations of the network aspects of the Very Long Period Experiment (VLPE) stations, with the purpose of developing a basis for identification of both the strong and potentially weak parts of such a network for the detection and identification of long-period signals from explosions and earthquakes. The evaluation emphasizes theoretical characteristics of a station network at this point in time, primarily because of the experimental nature of the seismograph systems and a consequent limitation of joint multiple station signal observations.

This report provides a theoretical basis for estimation of signal detection capability at the VLPE stations and the observational data supporting the estimate. The single station capability is then merged into a theoretical network capability model. The network model, which may include contributions from the long period arrays, ALPA, NORSAR, and LASA, is then used to calculate estimates of the world-wide surface wave detection capability of networks of stations selected from the current and projected station list. Both 20 and 40 second Rayleigh wave detection estimates are presented.

Preliminary data indicate that the VLPE network has the theoretical capability for detection of shallow focus continental earthquakes in

Eurasia at about $M_s = 3.1$ or less when all stations are in operational status and the network includes the large arrays. The theoretical basis of the estimate requires that a systematic evaluation of actual signal detections be reserved as the final demonstration of capability.

Because of limited observational data, a true picture of the network contribution to mixed event and radiation pattern problems cannot be clearly demonstrated at this time. Beamforming for long period P and S signal detection may have utility in special cases, but these are not likely to contribute to identification of sources as routine discriminants. The power of Tsai's method at the single station, when fully evaluated, may contribute to the network aspect very significantly in terms of mixed events. Utility of matched filter stacks for overall depression of the detection threshold will be marginal until a suitable library of filters can be developed. This factor influences the ability of a limited number of stations to observe the radiation patterns with enough resolution to describe the problem in any detail.

SECTION VII

ADAPTIVE PROCESSING TASK

Results obtained on the adaptive processing task are detailed in Special Report No. 1, which describes theoretical algorithm analysis. In addition a study of implementation and operation of an on-line adaptive processor is currently in progress and will be reported in the near future.

A. Special Report No. 1: Adaptive Convergence Studies

The rate of convergence of an adaptive filter algorithm to a neighborhood of the optimum filter is approximated in terms of the eigenvalues corresponding to the principal components of some matrix closely associated with the noise matrix (Brennan, 1971). For the frequency-domain maximum-likelihood adaptive algorithm, the adaptive update equation is:

$$A^{t+1} = \left[I - 2\mu \left(I - \frac{VV^H}{V^H V} \right) X^t (X^H)^t \right] A^t ,$$

where X^t is the input data vector at the t^{th} iteration, V^H is the beamsteer filter, A is the conjugate transpose of the adaptive filter vector at the $(t+1)^{th}$ and t^{th} iterations, respectively, and μ is a real scalar quantity controlling the adaptation rate. The superscript H denotes conjugate transpose. The output of the adaptive filter at the t^{th} iteration is $(A^H)^t X^t$. If we substitute $\Phi = E(XX^H)$ for $X^t(X^H)^t$ in the update equation for this particular algorithm, the time constant τ_p is approximately

$$\frac{1}{2\mu\lambda_p}$$

for energy lying on the p^{th} orthonormalized eigenvector of the matrix

$$\left(I - \frac{VV^H}{V^H V}\right) \Phi \left(I - \frac{VV^H}{V^H V}\right)$$

where $\mu << 1/\lambda_p$. Here λ_p is the p^{th} eigenvalue of that matrix. τ_p is the time constant for the p^{th} principal component in the sense that the portion of the excess filter output RMS

$$\sqrt{A^H \Phi A - (A^H \Phi A)_{minimum}}$$

associated with the p^{th} principal component of the matrix

$$\left(I - \frac{VV^H}{V^H V}\right) \Phi \left(I - \frac{VV^H}{V^H V}\right)$$

is reduced by a factor $e = 2.71828$ in approximately $1/2\mu\lambda_p)$ iterations. Similarly, the amplitude

$$\left| a_p - (a_p)_{optimum} \right|$$

of the difference between the adaptive filter and the optimum maximum-likelihood filter along the p^{th} principal component is likewise reduced by a factor e in the same period of time. It is assumed that substitution of Φ for $X^t(X^t)^H$ does not change the answer much.*

Stability of the adaptive algorithm requires that

$$\mu < 1/\lambda_{max}$$

so that the time constant for weak components may be very great and cannot be chosen sufficiently large for practical effectiveness against very weak components. The purpose of the present study is to investigate the ability of modified adaptive algorithms to increase the convergence rate on weak noise components.

*This would be the case if successive data vectors were independent. In the dependent data vector case at hand, one might expect this to be true for μ very small.

For the purpose of simplicity, the modified algorithms in the frequency domain will be discussed. Let there be a sequence of data vectors X^t at a specific frequency. These vectors are to be processed adaptively so as to preserve a signal $S = cV/(V^H V)$, where c is a complex scalar quantity and V is the conjugate transpose of the beamsteer filter V^H. One way to formulate this algorithm is

$$o_1^t = V^H X^t - (F_1^H)^t X^t ,$$

where o_1^t is the output of the first loop at time t, and $(F_1^H)^t$ is an adaptive filter applied to X^t to predict the complex-valued scalar quantity $V^H X^t$. If the constraint $(F_1^H)^t V = 0$ is imposed for all t, then it follows for the input $X^t = S = cV/(V^H V)$ that the output is

$$o_1^t = \frac{c\left[V^H V - (F_1^H)^t V\right]}{V^H V}$$

$$= \frac{cV^H V}{V^H V}$$

$$= c$$

so that the combined filter $V^H - F_1^H$ has a unit response to the signal. It is possible to consider a second loop or filter

$$o_2^t = o_1^t - (F_2^H)^t X^t$$

or in general

$$o_k^t = o_{k-1}^t - (F_k^H)^t X^t$$

where the signal is still preserved if the constraints

$$(F_k^H)^t V = 0$$

are required. If the filters are to operate independently, the optional additional constraints

$$(F_j^H)^t F_k^t = 0 \qquad (j \neq k)$$

need to be specified. The algorithm with only the constraint to preserve the signal will be termed the single-constraint mode algorithm, whereas for the algorithm with the additional constraints, the terminology multiple-constraint mode will be used. Heuristically, the second loop allows the filters F_k^H to concentrate on the smaller components of the noise because F_1^H has reduced the largest noise component.

B. Study of On-Line Adaptive Processing Results Using Alaskan Long Period Array Data

The adaptive processing task of the Extended Array Evaluation Program has as its objectives:

- To gain experience in operating a real-time adaptive signal estimation processor based on the time-domain maximum-likelihood algorithm
- To perform theoretical studies relating to the convergence of the algorithm and to analyze the output of the adaptive processor in an attempt to upgrade its performance

This work deals solely with the problems associated with operating the real-time adaptive processor on ALPA data. A modified version of the TI interim ALPA system is used to implement the adaptive-filtering algorithm. A theoretical study of the effect of floating means upon filter performance has been made.

The adaptive-filter output y(t) at time t is formed by applying a convolution filter to each channel and summing the outputs of all channels:

$$y(t) = \sum_{i=1}^{M} \sum_{j=-N}^{N} a_i(j)x_i(t-j)$$

where $a_i(j)$ is the filter weight for the i-th channel at a lag of j sample points, $x_i(t-j)$ is the value of the channel i at time t-j, M is the number of channels, and 2N+1 is the total length of the filter in points. Prior to forming the filter output, each channel is time-shifted to time-align energy arriving from the desired steer direction.

The adaptive filter weights are updated by the following algorithm:

$$\overset{\text{NEW}}{a_i(j)} = \overset{\text{OLD}}{a_i(j)} + \lambda(t)y(t)\left[\bar{x}(t-j) - x_i(t-j)\right]$$

where

$$\bar{x}(t-j) = \frac{1}{M} \sum_{i=1}^{M} x_i(t-j)$$

and $\lambda(t)$ is the convergence parameter at time t. This update algorithm incorporates the maximum-likelihood constraints.

The convergence parameter $\lambda(t)$ is calculated by the formula:

$$\lambda(t) = \frac{2K_s}{(2N+1) \sum_{i=1}^{M} P_i(t)}$$

where K_s is an input parameter, M is an input parameter, and $P_i(t)$ is a moving power average for the i-th channel. $P_i(t)$ is computed by the formula:

$$P_i(t) = (1-\mu) \left[\bar{x}(t) - x_i(t)\right]^2 + \mu P_i(t-1) \qquad t \geq 1$$

where μ is an input parameter. $P_i(0)$ is zero, and several values of $P_i(t)$ are computed before the filter is allowed to vary.

Floating DC levels in the data channels transmitted from ALPA caused considerable difficulty in implementing an adaptive filtering system until their effect was studied theoretically and effective remedial action taken. Two steps were taken:

- The data traces were run through a filter having a response exactly equal to zero at DC.
- The adaptive filtering program was examined to uncover DC bias introduced by the computations. Bias compensation was incorporated into the program and intermediate results were rounded instead of truncated wherever possible.

One of the problems considered in this study is the effect on filter performance of varying the convergence rate. Somewhat related to this is the problem of freezing the filters when a signal is encountered. If this is not done, differences between the signal model and the true signal might allow the filters to adapt on and consequently suppress the true signal. Also the filters will tend to make the noise look like -s(t) to minimize the output under the constraint of undistorted signal if the filter is allowed to adapt through the signal. In connection with this the effect of noise suppression of freezing the filters is under study. Noise suppression will be evaluated both for strongly directional noise fields and for more isotropic or random noise. Suppression of off-azimuth signals is also under consideration.

Problem definition and software preparation were completed under the present contract. Processing and analysis of results are currently in progress. These results will be reported in a special report under contract F33657-72-C-0725.

SECTION VIII

HIGH RESOLUTION FREQUENCY-WAVENUMBER SPECTRUM TASK

Results obtained in the task to evaluate various high resolution frequency-wavenumber spectral estimation tasks are detailed in Special Report No. 2 (Resolution and Stability of Wavenumber Spectral Estimates) and in a technical memorandum submitted to the Vela Seismological Center. Summaries of these two documents are presented below.

A. Special Report No. 2: Resolution and Stability of Wavenumber Spectral Estimates.

The goal of this research is to investigate the relative resolution and stability of conventional and new methods of array processing or spectral estimation. Resolution as intended here will mean the directivity of the processing technique or the ability to differentiate two signals from almost the same direction. Also, we will investigate resolution from the point of view of the technique's ability to detect weak signals, i.e., the relative noise threshold of the techniques. These questions will be studied with true covariance matrices corresponding to a fixed number of plane wave signals plus noise. Stability is investigated by generating random column vectors V_i, $i=1, \ldots N$ from the covariance matrix and applying the techniques to the conventional estimate $\Omega = N^{-1} \Sigma_i V_i V_i^H$ of the covariance matrix, where H denotes conjugate transpose.

Two simplifications of the general problem have been made so that the computations become reasonable. First, we will conduct the analysis at a given frequency so that the matrix dimension is C by C where C is the number of sensors. Second, computation for the maximum entropy spectrum is greatly simplified by using a line array of equally spaced sensors, i.e., we avoid iterative methods for spectral estimation.

The techniques to be considered are conventional beamsteer BS, maximum-likelihood (unbiased minimum mean square error) ML, maximum entropy (K-line or Burg technique), and principal components or eigenvalue analysis.

The method of principal components differs somewhat in philosophy from the other techniques, and it is not directly a method for spectral estimation or array processing. Justification for its inclusion lies in its complete invariance to random noise and the tendency to isolate plane wave signals on eigenvectors ordered by signal strength. The procedure is to compute the eigenvectors and then compute the eigenvector response function (or eigenspectra), which is the absolute square value of the dot product of the eigenvector and a "look direction" exponential vector. The direction at the maximum of the successive eigenspectra will be shown empirically to correspond to the directions of the plane wave signals specified in the covariance matrix. Mathematically $\Omega Z = \lambda Z$ must be satisfied, where Z, and λ are an eigenvector and eigenvalue of Ω, respectively. Thus $(\Omega + \beta I) Z = (\lambda + \beta) Z$ for any constant β, so that the eigenvectors of Ω are also the eigenvectors of $\Omega + \beta I$ and the technique is therefore expected to be insensitive to random noise.

There has been considerable previous theoretical treatment in the use of principal components but very little actual application of the technique to array processing. The classical multivariate statistics approach is treated by Anderson (1958) and the interpretation of these results in terms of multiple stationary time series is discussed by N. R. Goodman (1967). The actual stimulation for our consideration of principal components in the present effort came from a paper by N. L. Owsley (1971) where he suggested that plane wave signals tend to be isolated on individual eigenvectors and ordered according to strength.

Four wavenumber spectral estimation techniques, beamsteer (BS), maximum likelihood (ML), maximum entropy (MK) and eigenspectral analysis (EG) have been compared in terms of resolution and stability using synthetic covariance matrices generated for a linear array. In addition, the EG technique, which has not been applied previously in seismology was used on real seismic data and compared with a high-resolution technique applied to the same data. Major conclusions are given below:

1. For the synthetic data the EG technique recovered weak signals best; in certain cases it was capable of recovering signals 50 dB below the largest signal in the covariance matrix. The ML and MK techniques could recover signals 30 dB below the largest signal. The better performance by the EG technique resulted because it is insensitive to random noise.

2. The MK technique showed the best capability to resolve two signals having similar azimuths. For the synthetic example used, the MK technique could resolve two signals 6° apart, but could not resolve two signals 2° apart. The ML and EG techniques could resolve signals 9° but not 6° apart; the BS technique could not resolve signals 9° apart.

3. The stability of all estimates appeared to be good. The BS was the most stable, the EG (at least in the vicinity of the signal directions) seemed to have the next best stability, and the ML and MK techniques appeared to be similar.

4. Application of the EG technique to real seismic data gave interpretable results consistent with a high-resolution analysis of the same data. In fact, the EG technique seemed to give better resolution of the propagating noise components.

5. The EG technique appears to be a very valuable tool for array analysis; its insensitivity to random noise is a very important property because

real seismic data usually has a significant random noise component which can limit the ML and MK techniques. Possible applications of this technique include separation of overlapping events and array detection.

B. Technical Memorandum: Results of Attempts to Compare Four Frequency-Wavenumber Spectrum Analysis Techniques Using Real Data.

The intent of this small study was to compare the beamsteer (BS), maximum likelihood (ML), Markov-Field (MF) and Maximum Entropy (ME) frequency-wavenumber spectrum analysis techniques using two samples of real seismic noise; one from ALPA and one from TFO. Unfortunately, problems were encountered in obtaining the prediction error filter used in both the MF and ME techniques and so the four techniques could not be compared. Lack of time prevented us from isolating the problem; it is thought to be program-related (perhaps a precision problem).

SECTION IX
REFERENCES

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APPENDIX A

LIST OF REPORTS ON CONTRACT F33657-71-C-0843

A. QUARTERLIES

1. Quarterly Report No. 1, covering the period 1 April 1971 to 30 June 1971, 15 July 1971.

2. Quarterly Report No. 2, covering the period 1 July 1971 to 30 September 1971, 15 October 1971.

3. Quarterly Report No. 3, covering the period 1 October 1971 to 31 December 1971, 15 January 1972.

B. SPECIALS

1. Adaptive Convergence Studies, by A. H. Booker and Chung-yen Ong, 30 April 1972.

2. Resolution and Stability of Wavenumber Spectral Estimates, by A. H. Booker and Chung-yen Ong, 30 April 1972.

3. Array Processing at Alaskan Long Period Data, by Leo N. Heiting and Chung-yen Ong, 30 April 1972.

4. Evaluation of Detection and Discrimination Capability of the Alaskan Long Period Array, by Leo N. Heiting, Gary D. McNeely and Allan C. Strauss, 30 April 1972.

5. Preliminary Evaluation at the Norwegian Long Period Array, by William H. Swindell, John S. Eyres and Phillip R. Laun, 30 April 1972.

6. Preliminary Evaluation of the Norwegian Short Period Array, by Thomas E. Barnard and Richard L. Whitelaw, 30 April 1972.

7. Preliminary Evaluation of Single Stations of the Long Period Experiment Network, by Stephen A. Benno, 17 April 1972.

8. Preliminary Network Evaluation Studies, 30 April 1972.

C. TECHNICAL MEMORANDUM

Results of Attempts to Compare Four Frequency-Wavenumber Spectrum Analysis Techniques Using Real Data.

D. PAPERS PRESENTED

1. Preliminary Evaluation of the NORSAR Short Period and Long Period Arrays, presented by Terence W. Harley, NORSAR Technical Conference, 23 November 1971.

2. Evaluation of the ALPA and NORSAR Long Period Arrays, presented by Terence W. Harley, MIT Discrimination Conference, 11 January 1972.