MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

SEISMIC DISCRIMINATION

SEMIANNUAL TECHNICAL SUMMARY REPORT
TO THE
ADVANCED RESEARCH PROJECTS AGENCY

1 JULY – 31 DECEMBER 1965

ISSUED 15 MARCH 1966

ABSTRACT

The experimental Large Aperture Seismic Array (LASA) in Montana was put into operation and has been used for routine monitoring and data recording. Most of the physical elements of the system are working more reliably than had been anticipated (Sec. I). Research and experimentation with various array processing techniques are under way using LASA data (Sec. II). Results on automatic event detection and location are discussed in Sec. III. Both these sets of investigations are approaching the point at which the LASA capabilities can be established, the signal processing hardware design can be finalized, and a design of a possible global network of LASA's can be worked out, should it be needed.

The large array is a signal improvement system whose outputs are to be used for nuclear test monitoring and research on the solid earth. Early results are reported in Secs. IV and V, respectively.

Two miscellaneous studies of seismic instrumentation are reported: a survey of electromagnetic means of measuring long-baseline earth strains (Sec. VI), and a comparative critique of the noise performance of several methods of amplifying near DC signals (Sec. VII). Section VIII is a cumulative list of our publications in this program.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

INTRODUCTION

This is the fourth Semiannual Technical Summary Report on Lincoln Laboratory's work for the Advanced Research Projects Agency on the seismic discrimination problem (Vela Uniform).

During this reporting period, the experimental Large Aperture Seismic Array (LASA) in Montana was put into operation and has been used for an extensive program of routine monitoring and data recording. As described in Sec. I, most of the physical elements of the system are working more reliably than had been anticipated, considering the size of the system, the speed with which it was built, and the inaccessibility of some portions of it.

An extensive program of research and experimentation with various array processing techniques is under way using LASA data. The current results are described in Sec. II. Off-line SNR gains of 30 db (1.5 mag.) are typically obtainable. These gains appear to be more a consequence of the use of large numbers of sensors and complex processing, and less a consequence of the large aperture. Predetection processing gain for on-line detection and location of very weak teleseisms has not been completely evaluated, but is certain to be smaller than the 30-db off-line figure.

Our results on automatic event detection and location, which figure importantly in modern seismic array systems, are discussed in Sec. III. Both the array processing and automatic event screening investigations should soon reach the point at which the various capabilities of the experimental LASA can be well established, the signal-processing hardware design can be finalized, and a design of a possible global network of LASA's can be worked out, should it be needed.

The large array is not an end in itself but a signal improvement system whose outputs are useful for both nuclear test monitoring and for research on the solid earth. We are now beginning to use LASA data for both these purposes. Early results are reported in Secs. IV and V, respectively.

Two miscellaneous studies of seismic instrumentation are reported: a survey of electromagnetic means of measuring long-baseline earth strains (Sec. VI), and a comparative critique of the noise performance of several methods of amplifying near DC signals (Sec. VII).

A cumulative list of our publications in this program forms Sec. VIII.

P. E. Green, Jr.

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SEISMIC DISCRIMINATION

I. LARGE APERTURE SEISMIC ARRAY SYSTEM

A. INTRODUCTION

In the first half of this reporting period, installation and checkout of the LASA hardware were completed.

During the second half, following the official dedication ceremonies, the system has been in constant operation and has recorded a large number of events – both natural and underground explosions.

This period of operation has been used to shake down both the hardware and the operational procedures, as well as to exercise the maintenance facilities and refine them before the bad weather places its heavy demands on both equipment and personnel.

In this Introduction, a few of the highlights will be mentioned; the details will be covered in subsequent paragraphs.

The most important conclusion from this period of operation is that the over-all system design is fundamentally sound. The LASA works in the way that was intended, the performance of the hardware can be monitored satisfactorily, and the field equipment can be maintained effectively.

Nearly all the items of hardware in the system have performed well – to the point of exceeding expectations, considering the minimum time available for design, construction, and testing

The system has been operating continuously for some time, with recordings being made for two shifts of each day of the working week, the third shift being used for maintenance and testing.

To facilitate this operation, a small number of additional personnel have been added to the complement. Of particular note is the addition of the first of two resident computer programmers and of a permanent contract site manager.

The latter appointment marks the end of the transition phase of hardware installation and system checkout, and the beginning of the ensuing phase of continuous operation and event recording. To this phase will ultimately be added an enlargement of on-line processing capability when enough is learned from the presently intended complement of two general-purpose computers and one special-purpose computer so that suitable additional computer equipment can be made available.

R.V. Wood, Jr.
R.G. Enticknap

B. SUBARRAY ELECTRONICS

The subarray electronics module (SEM) was described in some detail in the previous Semiannual Technical Summary Report.*

Twenty-five SEM's have been completed and are in use operationally or as spares. These units have proven in service to be operationally satisfactory. They have fulfilled their purpose and have proven highly reliable, requiring a minimum of field maintenance.

The system of remote monitoring from the Data Center has worked well in practice and a number of modifications to the SEM have been made to improve and enlarge this capability. Additional modifications have been made to provide for additions, such as the planned installation of long-period seismometers.

A detailed manual covering the SEM equipment, particularly aimed at the needs of operation and maintenance, is in the final stages of preparation.

Weather-sensing equipment and electronics to telemeter the data to the LASA Data Center at Billings has been installed at subarray A0 and is now working satisfactorily.

J.P. Densler R.M. Martinson
R.A. Guillette I. Wigdor

C. COMMUNICATIONS

The communication system, also described in the 30 June 1965 Semiannual Technical Summary Report, has been in continuous operation for this reporting period.

Results have been excellent, both in terms of performance and reliability.

Detailed studies of error rate and error distribution have not been made. However, the incidence of errors is sufficiently small to have an imperceptible effect on over-all system performance, compared particularly to computer and tape errors; consequently, any examination has been a matter of low priority.

A few small problems have shown up and been corrected. One such problem in the modem was that loss of sync sometimes occurred following a temporary circuit interruption. This was determined to be due to an overload condition in one of the circuits. A new plug-in card has been provided which eliminates the trouble.

Some unreliability in ringing both to and from certain of the remote sites was experienced. This was traced to improper calling signal level settings. These have been set correctly and the trouble eliminated. Checking these levels and a check of proper ringing action has been included in the Telco periodic maintenance routine.

A full complement of spares for the Western Electric equipment is not yet available. This is apparently due to the fact that the equipment is of a new type and production capacity is overloaded.

The situation is not a critical one and would only become so in the unlikely event of a large number of simultaneous failures.

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* Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (30 June 1965), DDC 467395.

The equipment has proved reliable in service, and repair appears well within the capability of the local telephone company.

A stock of spare poles and wire has been provided by the Mid-Rivers Company in Miles City, in case severe winter conditions necessitate replacements.

R.G. Enticknap

D. DATA CENTER ELECTRONICS

1. Data Display Units

In addition to the two 8-channel digital-to-analog data display units used primarily for maintenance, two 24-channel analog output units have been provided. These are used to drive Develocorders and AFTAC-provided analog magnetic tape units. At present, two Develocorders and two tape units are installed. It is anticipated that a number of additional Develocorders will be provided in the near future, to provide permanent records of the present short-period seismometers and the long-period instruments when they are installed. In addition, processed outputs from the computers will be available in analog form. To satisfy this growing need, an additional 24-channel unit is to be provided.

E.W. Richards

2. System Timing

A second complete timing generator has been constructed and will be installed in January 1966. This will be a spare for the existing unit and will serve to operate the LASA system in the event of a failure in this vital unit. Both units will be in continuous operation and are so arranged that the system can be driven from either generator by a simple cable changeover.

The performance of the present timing system has been most satisfactory and the clock stability is such that drift, as checked against WWV, is 1 or 2 msec per week.

E.P. Edelson

3. Computers

Since the previous report (30 June 1965), two items have been added: the special-purpose Texas Instrument Multichannel Filter (MCF), and the PDP-7 Outputter.

Because of pressures of other work, the MCF has not yet been thoroughly exercised; therefore, it is too early to comment on its performance and reliability. Its signal enhancement capability is touched on in Sec. II-B.

The PDP-7 computer has worked well enough and often enough to obtain good recordings of a sufficient number of representative events to support a research program.

One PDP-7 computer and two tape units were delivered to the site on schedule in June 1965. A second PDP-7, with two tape drives and other peripheral equipment, was delivered to the Laboratory in September. As a result of experience at both Billings and Lincoln, the manufacturer is engaged in a series of modifications and tests with the third PDP-7 and two tape units at his plant.

The PDP-7 Outputter, as modified by Lincoln personnel, has proved immensely useful. In addition to providing outputs of processed data, such as the beams formed in the PDP-7 (see Sec. II-B), it facilitates on-the-spot checks of data both prior to and after recording. As a result, a number of computer faults, not previously detected, were found and corrected.

When the results of these tests are available, it is expected that the two modified units will be shipped to the LASA Data Center at Billings to replace the present units.

Disposition of the third computer will await the results of these tests.

J.R. Brown

E. ON-LINE PROCESSING

The on-line processing accomplishes the following seven tasks. First, all data are read into core memory; that is, once every sampling interval (50 msec) each seismometer waveform is digitized, multiplexed and transmitted to the core memory. This is done by a block transfer, i.e., one computer cycle is stolen when each digitized sample is assembled at the computer and stored directly in the main memory.

Second, all these data are written onto magnetic tape. When two samples of data are taken (100 msec), enough data are generated to write a reasonably sized record (about 7 inches) and, again, this is written into tape via a block transfer. At present, these data are accumulating at a very rapid rate, one 2500-foot reel every 6 minutes. This means that some method of deciding which data are to be saved is imperative in order to avoid being swamped by reels of tape. The next several points are directed to this end.

Third, 10 predetection processed outputs are formed, pointed to 10 preset positions in the world. Five of these are formed in the PDP-7 using the delay-and-sum method (beam forming) on essentially the entire array. The other five are formed in the MCF using the filter-and-sum method. All these have a SNR improvement which allows detection of weaker events in the areas where they are pointed.

Fourth, eight independent event detectors are connected to any eight waveforms, either widely separated sensors, beam outputs, or MCF outputs. The event detectors output the GMT time whenever an event occurs in their input waveforms.

Fifth, the event detector outputs from the widely separated sensors are put into a vote-taking program which determines whether the event was a teleseism or a false alarm. On this basis, a decision to save or reuse the tapes is made.

Sixth, the computer telemeters calibrate commands to the sensors, and analyzes their responses and decides which sensors are bad and which are good. When all the sensors are tested, the computer types out their status so that maintenance teams can be dispatched to repair the faulty instruments.

Finally, the computer provides D/A conversion of any 31 channels (either input waveforms or beam outputs) for on-site chart recording and transmission to remote places for human checking.

P.L. Fleck
F.E. Heart (Group 62)

F. BUILDINGS AND SERVICES

The Miles City building modifications were completed early in this reporting period and provided two office areas and a semi-clean room for electronic maintenance.

Battery-driven power-supply systems for the vaults are still not available because of difficulties with the inverters. The SEM and modem equipment is working off prime power which has proved highly reliable. Sites supplied with power by McCone Electric are all supplied via a single substation (see Fig. 1). Because of the undesirability of a multiple outage in the event of a major failure in this system, various additional feed points are under investigation. A particularly attractive proposal is to provide an alternative feed to these sites from the south via Tongue River Electric facilites.

Specific proposals are expected in early 1966.

S.B. Barnard
R.G. Enticknap

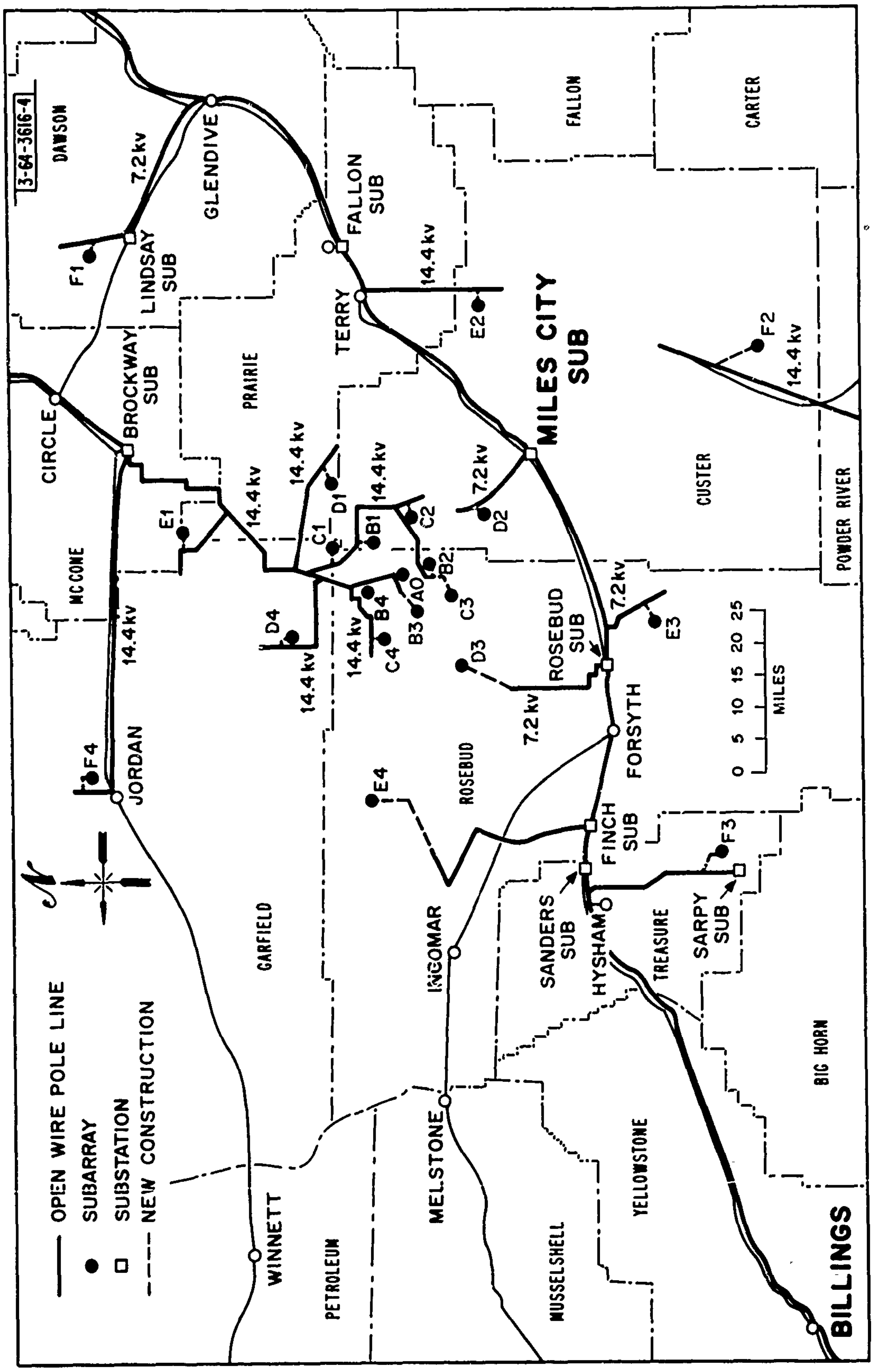


Fig. 1. Power distribution for experimental LASA in Montana.

II. ARRAY PROCESSING

A. LASA OFF-LINE SIGNAL-TO-NOISE IMPROVEMENT RESULTS

Digital array data from LASA have been processed with the purpose of establishing optimum compromises between signal-to-noise ratio (SNR) improvement and complexity or cost of doing the processing. A knowledge of these compromises is necessary for both the design of on-site processing hardware for LASA and the evaluation of the capabilities of the entire system. The aperture and the number of sensors used in LASA are much larger than those previously employed in a seismic array, so that previous results are of only modest assistance in seeking the desired compromises. Among the factors considered which affect the SNR gain are the number of sensors used, array aperture, the frequency with which the noise correlation matrix must be measured, the length of the noise measurement interval, the number of filter points, sensitivity to random differences in seismometer gain and phase, and the inclusion of frequency prefiltering.

The particular types of linear array processing that were considered were delay-and-sum (DS), weighted delay-and-sum (WDS), and filter-and-sum (FS). In DS processing, a simple steering delay is applied to each sensor output before summing; in WDS, the steering delay plus an amplitude coefficient is applied to each; and in FS, a convolutional filter (with NFP time samples) is applied to each. The steering delay in this last case can be considered a part of the filter function. WDS is seen to be the special case of FS for NFP = 1. In our studies, the processor parameters used in both WDS and FS were designed from a sample of noise preceding the signal. The particular form of FS used is the maximum-likelihood procedure described previously.*

Two families of experiments were carried out using these procedures: those using unfiltered seismometer traces, and those using traces that had been sharply bandpass filtered to maximize P-phased detectability. The results are summarized in Figs. 2 and 3, respectively. The frequency function of the prefilter used for most of the experiments of Fig. 3 is given in Fig. 4. The aim of the unfiltered trace experiments was to determine the gain against noise that could be made by off-line processing of LASA tapes, where computing complexity is not a basic limitation, while distortion of signal waveform features must be avoided. The prefiltered trace experiments, on the other hand, were aimed at modeling various predetection processing procedures that might be implemented on-line at a LASA site. In this case, computing complexity is a basic limitation while signal waveform distortion is largely irrelevant, since the processing feeds into machine-detection and location programs. The DS, WDS, and FS processing methods do not introduce any signal frequency distortion of their own, since the N frequency functions sum to unity at all frequencies; thus, the over-all passband characteristic of the processing is flat in the unfiltered experiments and is given by Fig. 4 in the prefiltered trace experiments. The prefiltered trace off-line processing work discussed in this section is supplemented by on-site experiments described in Sec. II-B.

The two graphs show the results of processing various numbers of traces N, and give as the ordinate the ratio of output SNR to the average of the SNR's of the N inputs. Beyond N = 25 (the

* Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (31 December 1964), pp. 21-23, DDC 455743.

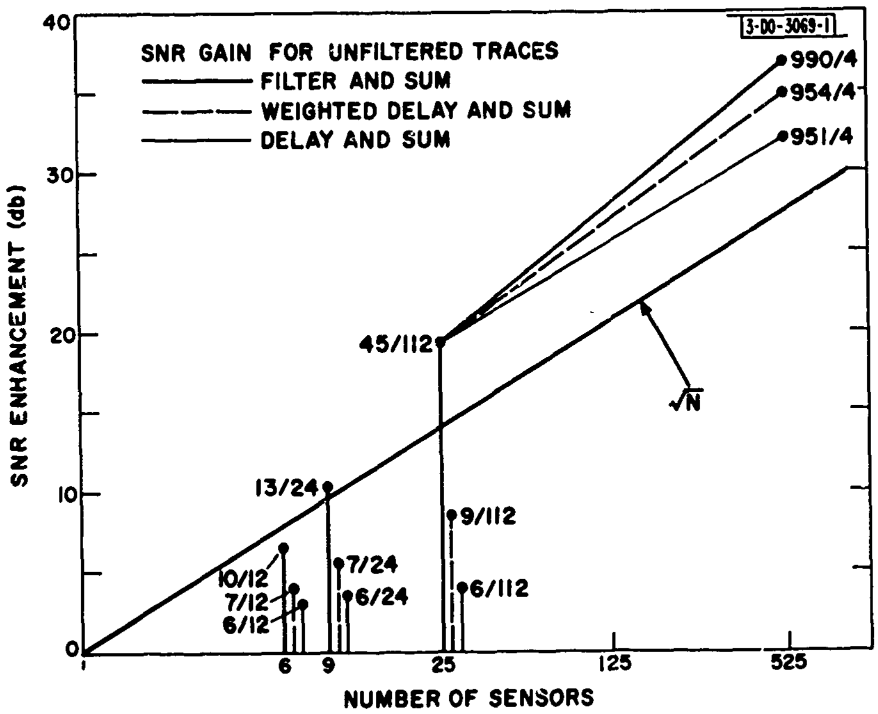


Fig. 2. SNR improvement on unfiltered traces vs number of sensors for maximum-likelihood (FS), weighted delay-and-sum (WDS), and delay-and-sum (DS) processing.

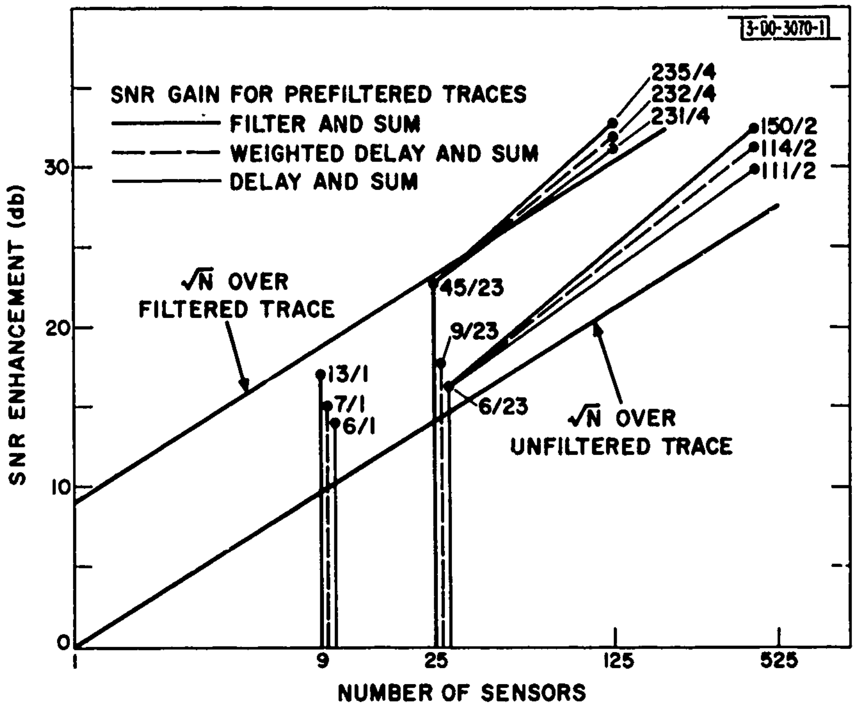


Fig. 3. SNR improvement on prefiltered traces vs number of sensors for maximum-likelihood (FS), weighted delay-and-sum (WDS), and delay-and-sum (DS) processing.

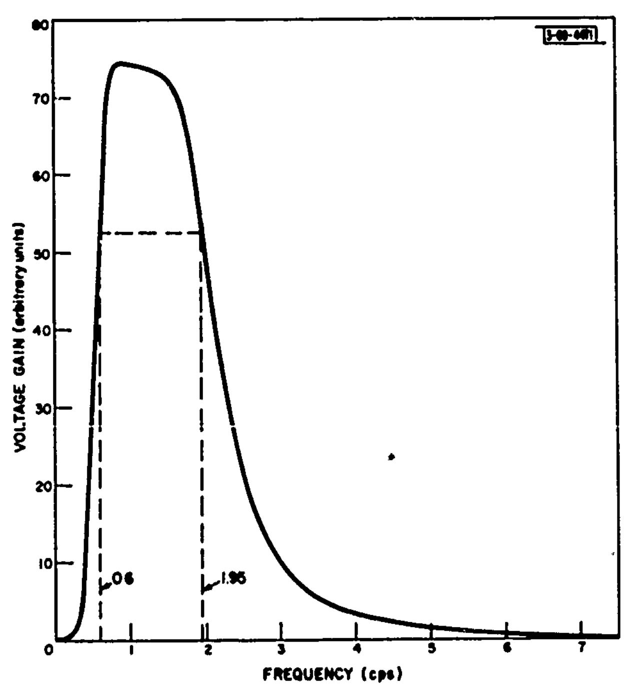


Fig. 4. Steady-state frequency response of recursive prefilter used to obtain data of Fig. 3.

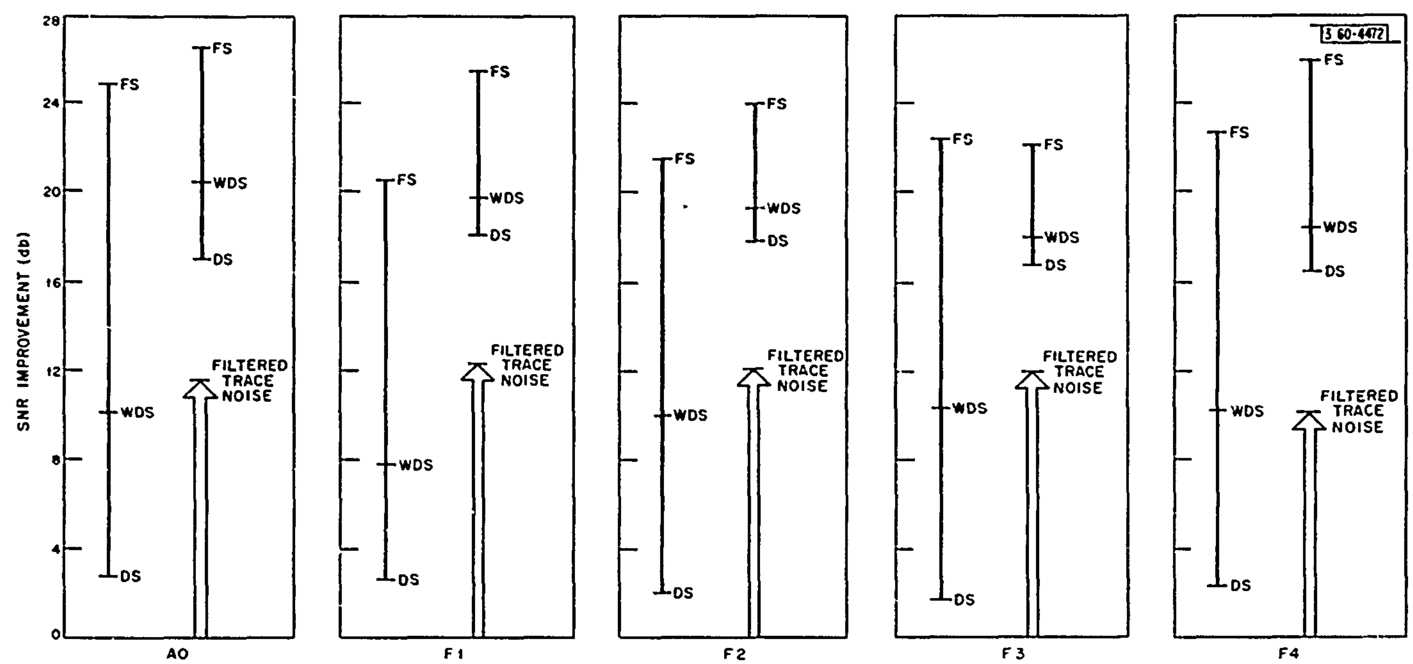


Fig. 5. Comparison of processing on filtered and unfiltered traces for five subarrays. Event of 11 November 1965. NFP = 21. For each subarray, figures on left indicate processing gain for unfiltered traces; figures on right indicate processing gain due to filtering of traces followed by processing.

number of sensors in one LASA subarray), the traces were combined in two steps. For example, in each figure the upper right-hand point was obtained by FS processing of each of several sets of 25 sensors followed by an FS combination of the outputs Only a total of five subarrays (A0, F1, F2, F3, and F4) was used for the filtered-trace experiments, since it was considered unlikely that on-line processors for more than five subarrays would be economically feasible.

In our experiments, subarray outputs were aligned by eye for the final processing steps; in practice, when the SNR of an individual subarray output is too small for this to be done, station corrections (Sec II-I) will have to be used instead.

Figure 2 shows an available average SNR gain of up to 36 db (1.8 magnitude units) for 525 sensors unfiltered. The ordinate values in Fig. 3 are total SNR gains due to prefiltering and then processing. Since prefiltering alone produces typically a 9.0-db SNR gain, the figure shows processing gains of up to 33 – 9 = 24 db (1.2 magnitude units) for 125 prefiltered traces. Figure 5 shows, subarray by subarray, the results of prefiltering followed by DS, WDS, and FS on a particular event.

One important conclusion to be drawn from Figs. 2 and 3 is that the FS is greatly superior to WDS and DS for unfiltered traces, whereas they are much more nearly competitive when the traces have been filtered. This is simply a confirmation of the fact that seismic noise statistics vary strongly with frequency. In the rest of this section, practical problems in achieving the various SNR gain figures should become apparent.

There are two small figures given beside each SNR gain number in Figs. 2 and 3. The right-hand figure is the number of separate runs that were made with the stated N and the stated processing scheme to get the plotted value (e.g., 5 events were averaged to get the 36-db point in Fig. 2). The left-hand figure is the number of minutes of 7094 time required, which is observed to be quite large in some cases. A number of efforts are in progress to reduce the processing time. Two of the most promising are described in Secs. II-D and II-E.

Other efforts were made to determine if there are some simple ways of achieving the gain which can be obtained by processing the entire array. Toward this end, the FS outputs of four subarrays forming a ring around subarray A0 were combined with the results shown in Table I.

TABLE I

SNR IMPROVEMENT FOR 11 NOVEMBER 1965 RAT ISLAND EVENT

Ring	Average Subarray FS Gain	Total DS	Total WDS	Total FS
B	23.2	29.1	29.6	30.0
C	23.0	28.4	28.6	28.8
D	22.1	27.9	28.2	28.6
E	21.6	27.6	27.8	28.5
F	21.8	28.3	29.3	30.3
Entire array	22.5	35.2	35.9	37.9

It was also hoped that this experiment would shed some light on the question of SNR gain vs aperture, since there are five different ring radii available. It is seen from Table I that, by processing just one of the five rings of LASA, each of which consists of four subarrays, it was possible on this particular event to come within about 8 db of the over-all 38-db FS gain obtainable with LASA more or less independent of aperture. It these results are typical, then the usefulness of the large LASA aperture seems to be more of a matter of epicenter location (Sec. III) and reverberation suppression (Sec. IV) than SNR gain.

Approximately 1 hour of 7094 computer time is required per 25-element subarray. About 20 min. are needed to measure the correlation matrix of a 3-min. noise sample, 20 min. are required to synthesize twenty-five 21-point filters, and 15 min. for processing 25 input traces which are 9-min. long. In all cases, 5-min. setup time is required. Thus, to process all 21 sites in the entire array for a given event requires about 22 hours of 7094 computer time. It is possible to process only a ring of subarrays, such as the F-ring, in about 4 hours. Thus, the total computer time may be cut from 22 to 4 hours, but at the expense of about 8-db gain in SNR.

It is readily apparent that frequent noise recomputation and filter design is undesirable so that data on noise stationarity is important. The best operational test of noise stationarity was considered to be to process the event of a given day and time with maximum-likelihood filter functions designed from noise on a different day and time to see how much the SNR gain dropped because the filters were synthesized on the wrong noise. The sensitivity to this effect, on the basis of the very limited data obtained to date, is modestly discouraging. An average drop of about 8 db occurred for 3 subarrays for the 21 November 1965 event, processed with filters designed ten days earlier. Figures of 4 to 6 db within 10 to 14 days had been observed earlier for N = 9 for one event at TFO and for two events at the Montana LASA.

The duration of the correlation matrix measurement step in the processing is proportional to the noise measurement interval, called the "fitting interval." This step is the most time consuming, so it is important to know how short a fitting interval can be used. The results obtained in studying this question on an 11 September 1965 Solomon Islands event at subarray B1 are depicted in Fig. 6. The 2-min. filter yields a high gain in its fitting interval, but the gain drops sharply outside the fitting interval. The 3-min. filter gives a somewhat lower gain in its fitting interval, but the gain does not drop much outside of its fitting interval. The 8-min. filter gives a rather uniform gain both inside and outside its fitting interval. These results indicate that 3 min. represents a good compromise to use in the design of the filter. The figure also gives information on stationarity of the type described in the preceding paragraph, but on a time scale of minutes rather than days.

The SNR gain figures given in Figs. 2 and 3 are based on output noise levels observed in the fitting interval. It is probably prudent to subtract about 3 db from the unfiltered FS decibel figures for N = 25 to 525 in the likely practical situation in which the fitting interval ends 1 to 2 min. before the signal phase of interest.

The duration of the impulse response of each filter in the filter-and-sum processor is the product of two quantities: NIP, the number of 0.05-sec digital sampling intervals between adjacent filter sample points; and NFP, the number of filter sample points. If NIP is made too small, the impulse response duration for a given NFP is insufficient to give the desired frequency resolution, and the long-period noise suppression will be poor; whereas, if NIP is too large, frequency aliasing introduces noise into the output. Experiments with NIP equal to 1, 2, 5, 10, with NFP fixed at 21 showed that, for 25 sensors, NIP = 2 gives the best compromise.

Figure 7 shows the effect of the number of filter points NFP on SNR gain for processing of unfiltered traces using NIP = 2, for a 27 August 1965 Japan event, site C1. Along the lower curve, the filters are physically realizable, i.e., the sum of their impulse responses is zero for all values of delay except the first one at which the sum is unity, so that the filter operates on the basis of only past samples of the noise. Along the top curve, the filters are symmetrical, i.e., the sum of the impulse responses is zero except at the center sample point at which they sum to unity, so that the symmetric filter operates on the basis of the future as well as the past values of the noise. They are thus said to be "physically unrealizable." The other curves represent filters whose buildup point is intermediate to that of the realizable filter and the symmetric filter. The results clearly indicate the superiority of the symmetric filter in yielding a high SNR gain over the asymmetric filters. It is also seen that additional gain is available by increasing the number of filter points beyond 41. However, this entails a further increase in the amount of 7094 computer time required. Thus, the best compromise was thought to be 21 filter points, and this figure was used in all the processing of the various events reported here. One hazard of using unrealizable filters is the possibility of unwanted precursors in the output trace. This is discussed in Sec. IV, in connection with observations of first motion.

One final encouraging result that deserves mention is that observed differences of up to ±15 percent in signal amplitude and ±12° in phase across a subarray do not lead to any appreciable loss in the FS output and they rarely cause precursor problems. This leads to the conclusion that the FS processing is not too sensitive to the assumption that the signal be identical across the subarray.

J. Capon
R. J. Greenfield
R. J. Kolker

B. LASA ON-SITE WEAK SIGNAL DETECTABILITY

A preliminary study has been made of the performance of the five on-line beams and the Texas Instruments multichannel filter (MCF). The beams are formed by steering and adding the 21 straight sums formed within each subarray. Rough station corrections are included for the eight most distant stations. The MCF filters, designed by Texas Instruments, Inc., are based on theoretical, isotropic noise and a wide-band signal with perfect coherence and high SNR. For the period of this study, the processor was steered due south for a speed of 18 km/sec.

These six outputs have been recorded at Billings on film since 2 December 1965, and this film was sent to Lincoln Laboratory for analysis. Until 28 December, the five beams were characterized by the parameters:

Source Area	Speed (km/sec)	Bearing (deg)
Kamchatka	15.8	317.7
Tonga	24.2	240.2
North Atlantic Ocean	12.7	104.5
Novaya Zemlya	15.9	006.0
Kazakhstan	22.0	357.3

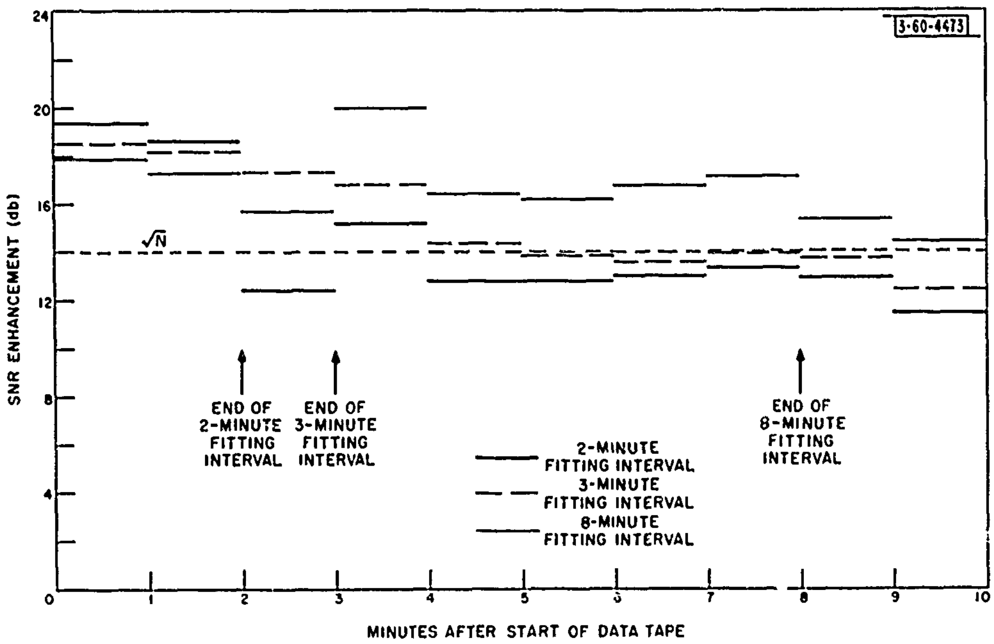


Fig. 6. Effect of length of fitting interval on noise suppression obtained with maximum-likelihood filtering. Event of 11 September 1965, subarray B1, NIP = 2, NFP = 21. Noise suppression is measured over 1-min. intervals. No prefiltering of traces was used.

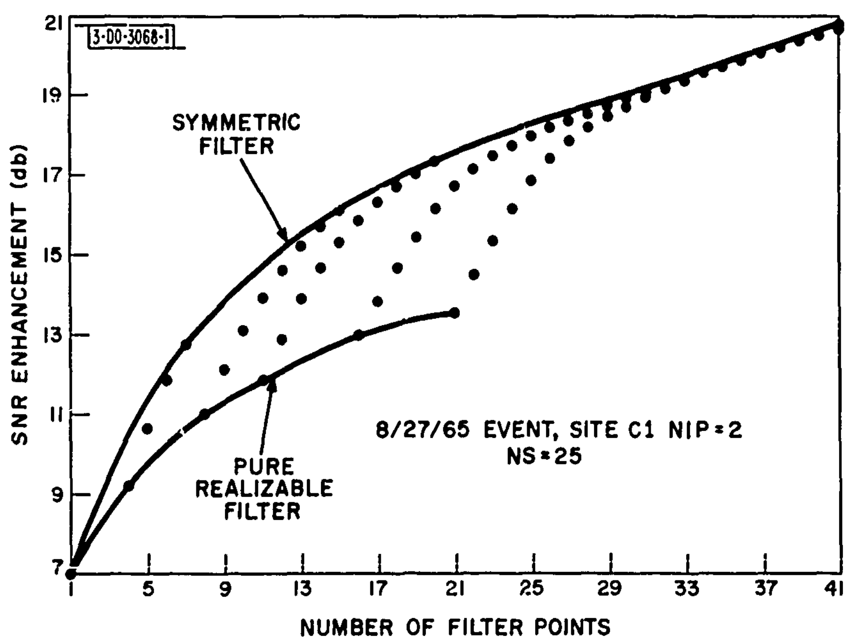


Fig. 7. Effect of filter length and filter asymmetry on maximum-likelihood SNR gains. Upper curve indicates filters symmetrical about the time origin (unrealizable). Lower curve represents filters whose earliest nonzero value is at the time origin (pure realizable).

After this date, a new set of beams was formed, steered to Rat Island, Kazakhstan, Fiji, Southern Peru, and Honshu, Japan. These new beams include improved station corrections.

Following the large Alaskan earthquake of 22 December (about 1941 Z), a special beam was formed using arrival times measured on the earthquake. This beam was being recorded within a few hours of the event and remained on-line for 5 days. The object of this "panic beam" exercise is to observe small events (aftershocks) in the beam to speed up the otherwise slow accumulation of events in the main lobes of the beams. However, this earthquake, although of apparent magnitude no less than 6.0, does not seem to have spawned many aftershocks. This panic beam procedure is available on short notice and will be used again to observe aftershock sequences.

The study of over 100 events occurring during December 1965 has yielded eight which occurred sufficiently near to the beam centers to exhibit better than 10-db signal-to-total-noise improvement in the beam over a single trace, including one in the Kazakhstan beam (see Fig. 8).

It has not been possible with this limited number of events (nearly all of which lack detailed identification as yet) to see the near side-lobe structure of the beams. It is well known that distant side lobes (and "side nulls") are badly smeared by the wide-band character of the signals. This effect is made quite obvious in the time domain by the particular appearance that large events have on the "wrong" beams. Often, the duration of the major portion of the P-wave is a good deal less than the time of propagation across the array. In this case, the signals do not have a chance to add either constructively or destructively, in the wrong beams, to produce the peaks and wells characteristic of beam patterns computed for sinusoidal signals. The typical result is roughly equal amplitudes in all of the wrong beams. This can be seen in Fig. 8.

The period during which the special "panic beam" was formed was scanned for small events. In this period, none occurred which was visible in a beam but invisible in all single traces.

The MCF output is displayed on the Develocorder with the gain set so that the noise level on the processor output is approximately equal to the noise level of each of the five single seismometers displayed below it. Although no events were observed at the center of the acceptance region, the effective beam is wide enough to result in significant SNR gains for several observed events. Figure 9 shows the effect on an event near the center of the acceptance region for which the MCF trace showed a SNR gain of approximately 2.5 in amplitude. (In this example, the processor was using raw traces other than those of the A or B ring sites illustrated in the last five traces, so that the SNR gain is not apparent from the figure.)

E. J. Kelly
H. W. Briscoe

Direct evaluation of the effect of both the on-line beams and the MCF processor in lowering the detection threshold of the LASA is continuing along these lines. Meanwhile, to supplement this, there is the indirect evidence we have obtained by (1) comparing the single-sensor detection threshold magnitude at LASA with that of another site whose performance is well known, and then (2) correcting this downward by the SNR gain demonstrated off-line (Sec. II-A) of the particular processing scheme that is used on-site.

A comparison based on several hundred events indicates that LASA has about the same single-trace detection threshold as the Tonto Forest Seismological Observatory (TFO). Since the average noise levels are higher at LASA this implies that the signal levels are higher too, on the average. TFO Helicorder traces were scanned visually to pick rough times, at a high

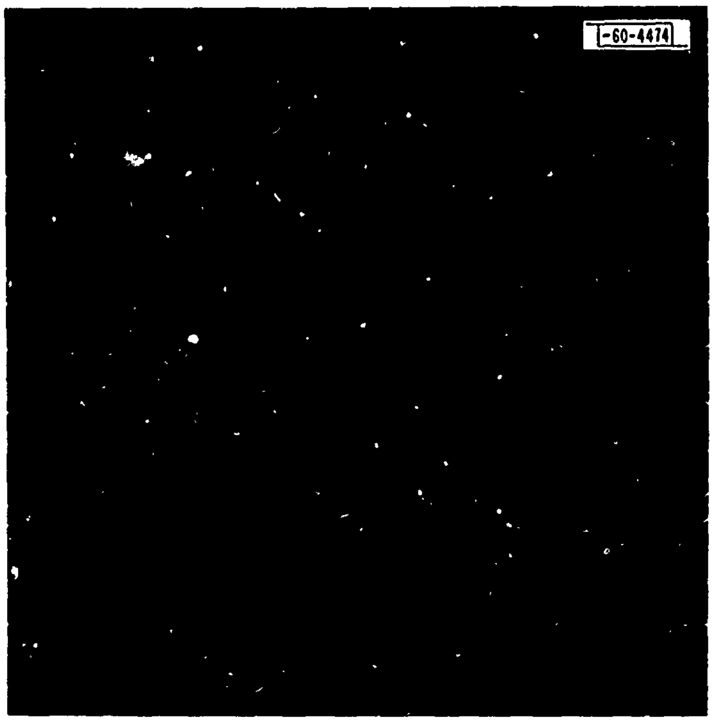


Fig. 8. Kazakhstan event of 24 December 1965 as seen in beamformer output. Top five traces are beam outputs listed in text; sixth trace is output of MCF (pointed south); last five traces are selected single se' ometer outputs.

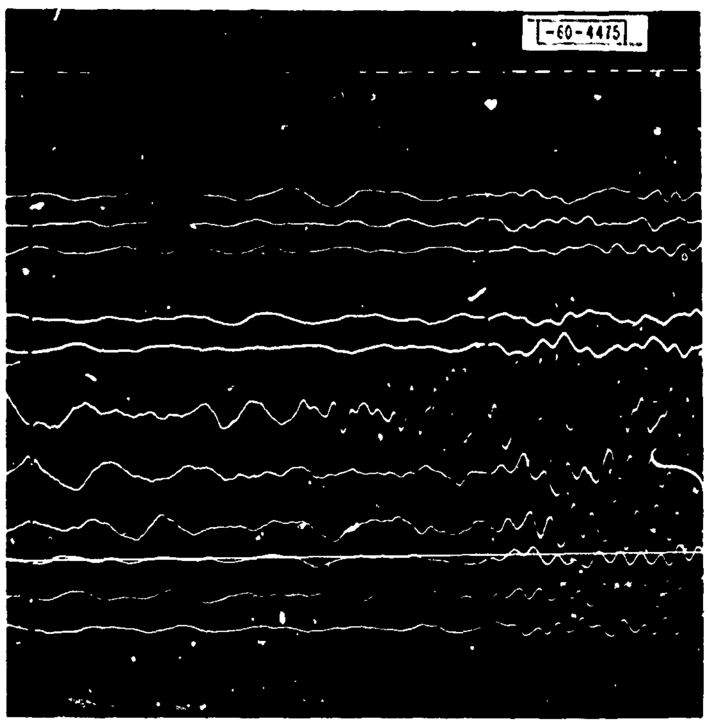


Fig. 9. Easter Island event of 4 December 1965 as seen in MCF output (sixth trace from top). Trace identification is same as in Fig. 8.

false-alarm rate, and these times were examined on Develocorder film records. Results are shown in Fig. 10 as a scatter diagram of several hundred events, giving the reported (U.S. Coast and Geodetic Survey) magnitude vs epicenter distance, and whether the events were detected by us (dots), found only after prompting by USC&GS (triangles), or were completely undetectable (circles). A simple empirical curve was evolved representing a detection threshold. This threshold is constant at about m = 4.4 for distances of 40° to 80°. A similar diagram was prepared from the LASA data reaching Lincoln Laboratory by telephone line for a two-month period beginning in late April 1965 (Fig. 10). These data consisted of one trace from site B1 and one trace from site F3, usually the deep central seismometer A0, recorded only on film. All events reported by USC&GS for this time period were sought on the film recordings and hits (either station showing the signal) and misses recorded. These results, all prompted by USC&GS reports, are also shown as a scatter diagram of magnitude vs distance (Fig. 11). Performance of the 500-ft sensors is shown separately from the 200-ft sensors. The improvement due to deep burial was not striking in this small data sample. The empirical broken line curves obtained for the two locations (TFO and LASA) do not differ significantly from one another.

E. J. Kelly
R. M. Sheppard
J. Fairborn

C. BEAM PATTERN STUDIES

The seismograms obtained from an array of seismometers can be combined by filter-and-sum processing (or any special case of it) to yield a single trace. Such processing schemes are best described by their gain characteristics in the three-dimensional space of frequency and two components of wave number which is Fourier conjugate to a space with a single time dimension and the two spatial dimensions giving seismometer locations.[1,2] Computer programs have been written to expedite the study of these gain characteristics. An existing program for computing straight sum directivity patterns in a two-dimensional wave number space, with or without unequal amplitude weights, has been modified and improved. This program uses a line printer to generate a contour map of the gain characteristics which determine the directivity of the array and associated signal-processing scheme. A second program has been written which can be used to obtain gain characteristics of processing schemes which have frequency-dependent as well as wave-number-dependent gains. For each of any number of frequencies, the gain is evaluated along rays which are perpendicular to the frequency axis of frequency-wave-number space and which intersect the frequency axis at the given frequency. The value of gains along these rays can be printed out or can be plotted by a Stromberg Carlson 4020 plotter.

Two different studies have been undertaken using these programs as tools. It has been possible to compare different potential configurations for LASA's by comparing their gain characteristics in wave-number space when straight-sum processing of data is used. The other study involves the gain characteristics associated with different filter-and-sum signal-processing schemes[3] applied to the same array. In the first study, the geometry of the array has been changed; in the second study, only the processing method is subject to change.

The first of these two studies has been completed, and a report has been prepared[4] which compares the quality of the straight-sum gain characteristics of the experimental LASA with

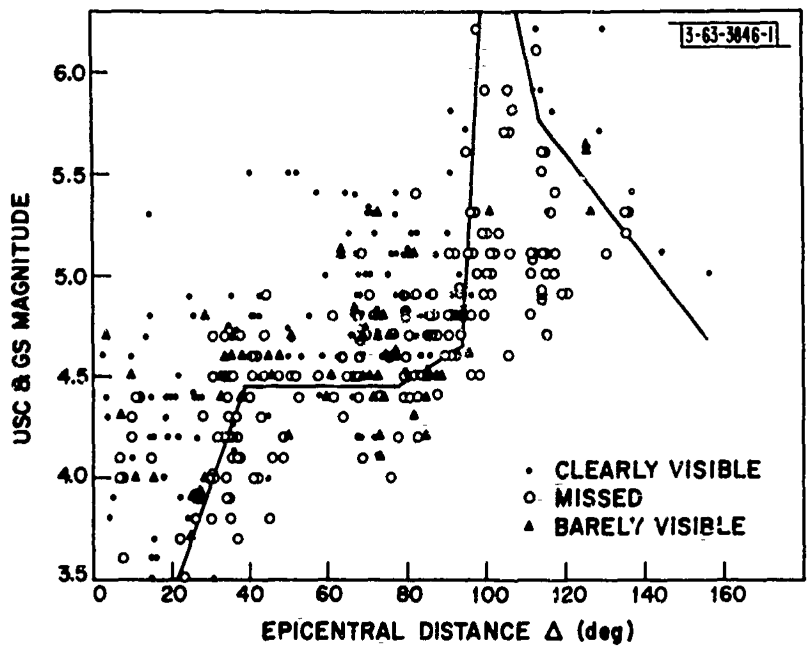


Fig. 10. TFO single-sensor detectability study (375 events). Solid line indicates roughly the threshold magnitude for 75-percent detection probability.

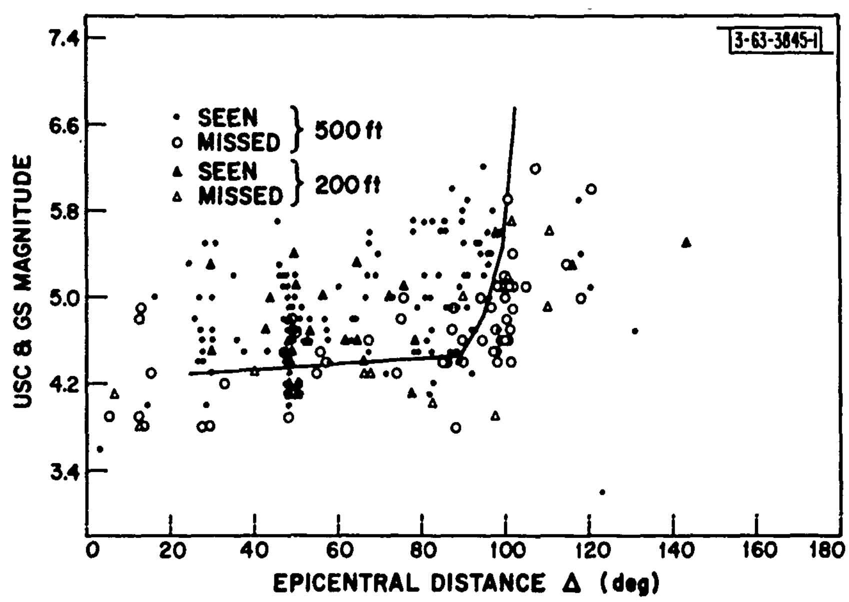


Fig. 11. LASA (B1) single-sensor detectability study (224 events). Solid line indicates roughly the threshold magnitude for 75-percent detection probability.

those of many other possible configurations. One of the results of this study will be described here. Figures 12(a) and (b) show the subarray locations for the LASA in Montana and for a superior alternative geometry which would require the same number of subarrays. Figures 13(a) and (b) show the gain evaluated along an azimuthal ray in wave-number space for each of the geometries. The rays are not both exactly in the same direction, but in directions chosen to show the most undesirable gain characteristics of the configurations. The patterns shown assume that each subarray has an infinitely broad main beam. Actual subarrays tend to attenuate all but the closest side lobes of the pattern for the experimental LASA.

The study of alternative geometries for LASA's included the development of a sensitivity function which measures the sensitivity of patterns to perturbations of subarray locations. A program has been written to evaluate sensitivity for certain restricted perturbations. The output of such a program has been used to indicate which perturbations might yield an improved pattern.

The study of array patterns also led to the conclusion that the operation of an array could be improved by increasing the diameter of subarrays from 7 km up to from 10 to 15 km. Such an increase of subarray size would require the modification of the very regular geometry which has been used for the subarrays of the experimental LASA.

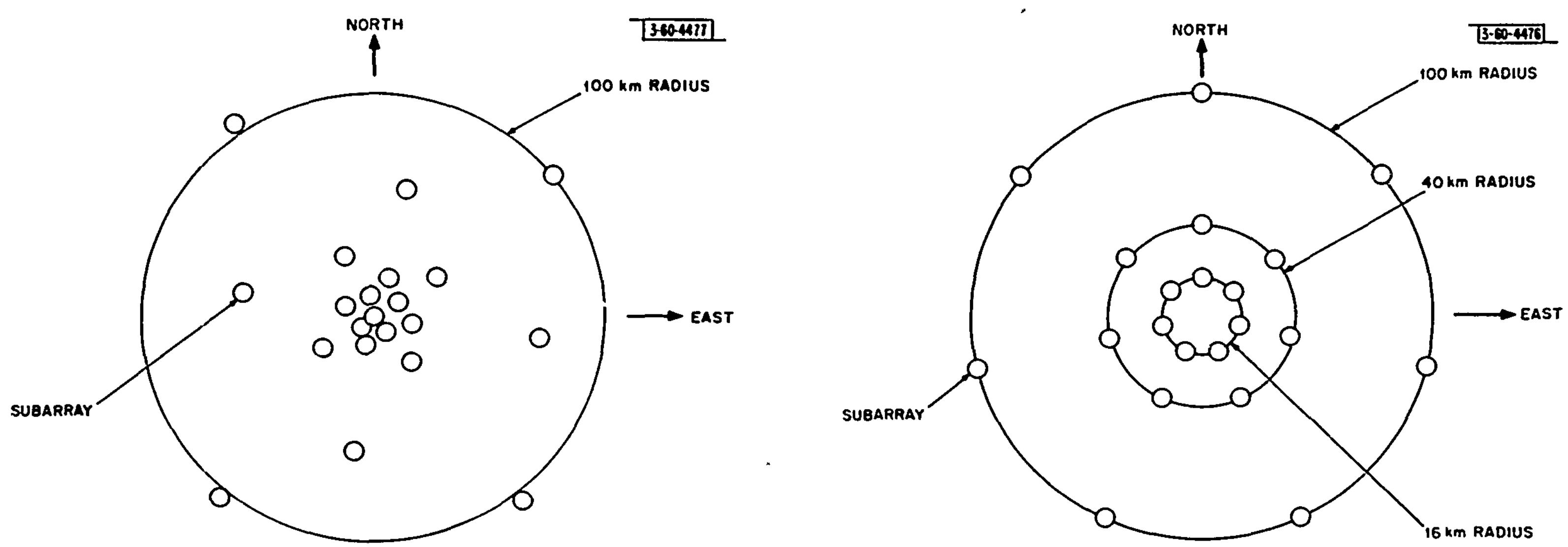
An investigation of the frequency wave-number gain characteristics of a variety of signal-processing schemes applied to outputs from a single array has been undertaken. Thus far, only delayed-sum and weighted-delayed-sum processing of the data from one of the experimental LASA subarrays has been considered. These simple processing schemes are frequency independent and thus can be completely characterized in a two-dimensional wave-number space. Tentative results indicate that signal processing which has been designed to optimally extract a signal from a noise field tends to modify the straight-sum gain characteristics in such a way that the gain is reduced in the regions of wave-number space which contain the most noise power (see Figs. 21 through 23). The optimal processing scheme may have large gains in regions where the noise power is small. Such studies will be continued in conjunction with power spectral estimation in frequency wave-number space and with the design of signal-processing schemes in both the frequency and time domains.

R. T. Lacoss

Theoretical studies of beam patterns have just been discussed. Here, we present results of studying beam resolution obtained by delayed sum processing of actual data using seismometer arrays having apertures much larger than the 7-km-diameter LASA subarrays.

In this work, the direction from which the event arrives is known. By aiming in this azimuthal direction, the value of horizontal phase velocity V was varied to observe the arrival of different phases and to find approximately the 3-db beam diameter.

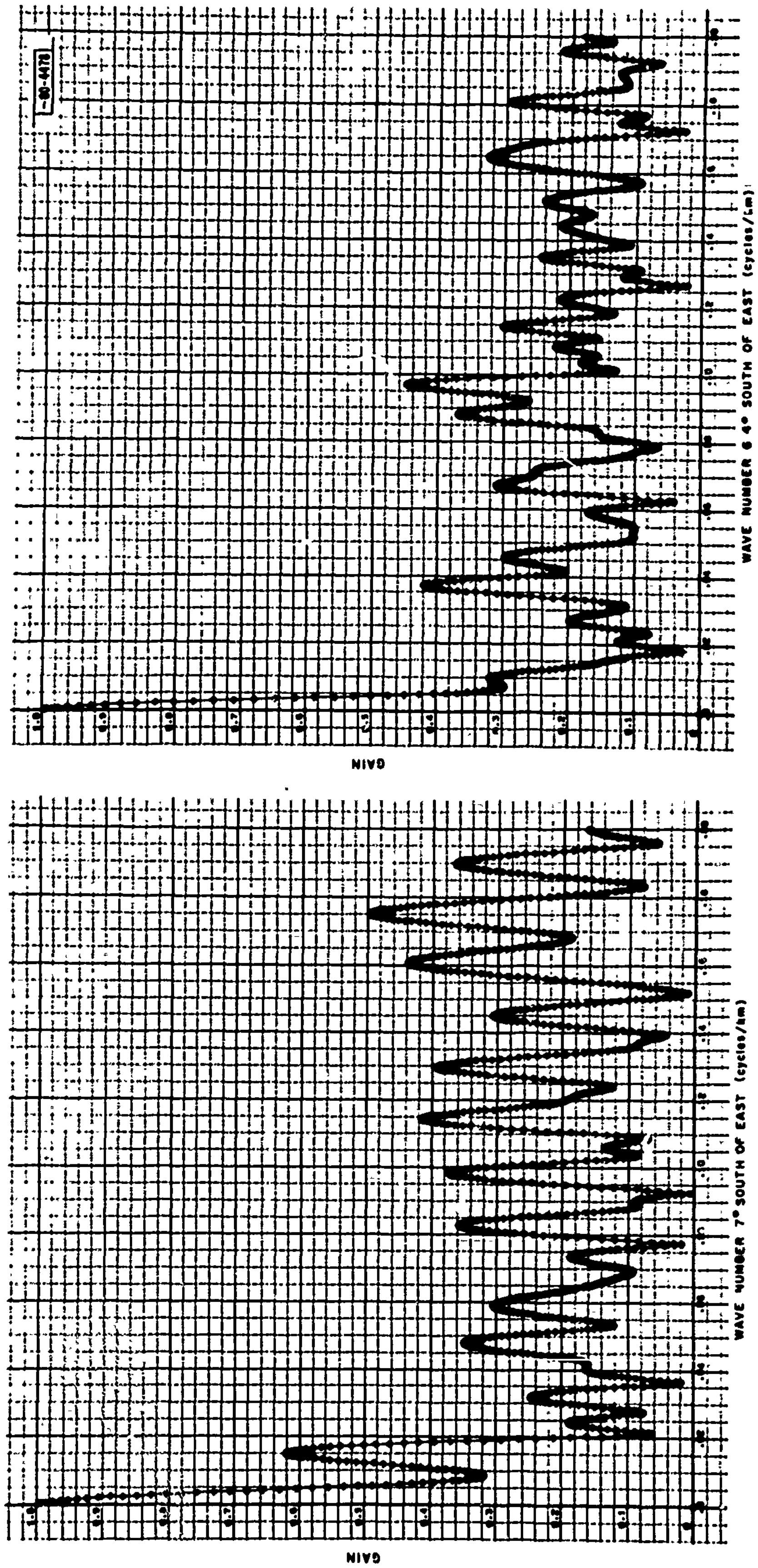
We show in Fig. 14 the output traces obtained by delayed summation of the 29 October 1965 Longshot arrivals. The array used consisted of 17 seismometers taken from the LASA subarrays C4, B4, A0, C3, and C2. The total length D of the array projected in the direction of the event was 32 km. The amplitude of the first arrival P wave was largest on the traces for V = 13.0 and 13.8 km/sec. (The arrival velocity observed for P using the whole LASA array was V = 14.2 km/sec.) The beam passed velocities from 11 to 17 km/sec with less than 3-db



(a) Experimental LASA.

(b) Alternative geometry.

Fig. 12. Subarray locations for experimental LASA and for a possible alternative geometry.



(a) Pattern for experimental LASA.

(b) Pattern for alternative geometry.

Fig. 13. Gain characteristics generated by arrays of 21 points shown in Fig. 12.

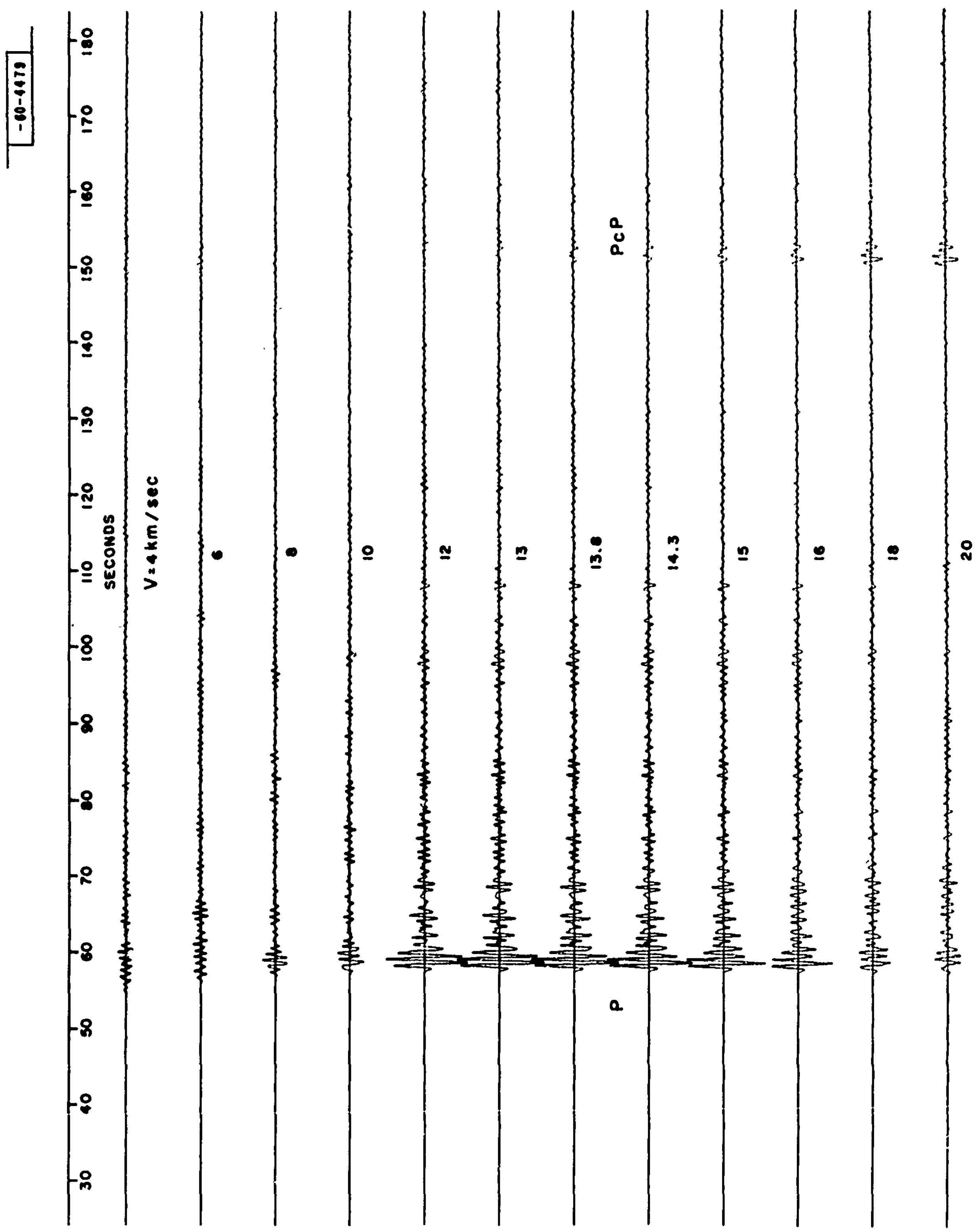


Fig. 14. Effect of different assumed pha.e velocity on P-wave amplitude for 32-km linear array. Longshot event of 29 October 1965.

attenuation. If k is the wave number defined as

$$k = \frac{f}{v} \text{ cycles/km}$$

and we take the dominant frequency (1 cps) of the first arrival for the frequency f, then the beam (defined in terms of 3-db points) passed signals for which $0.09 \geqslant k \geqslant 0.06$ cycle/km.

Using the same array, delayed sum processing was done at velocities surrounding the PcP velocity (31.7 km/sec). The PcP signal was passed with less than 3-db attenuation for 17 km/sec $\leqslant V \leqslant \infty$; then corresponds to $0.06 \geqslant k \geqslant 0$. Theoretical computations for the 32-km array give a beam diameter in k of 0.04 cycle/km. The P-phase and coda in the output of the beam steered at 32 km/sec were reduced by approximately 14 db from the individual trace values.

Two other events were processed by delayed summing. The results for these events, as well as for Longshot, are given in Table II. For a uniform linear array of length D, the 3-db aperture K_s to a sinusoidal wave is given theoretically by the condition

$$K_3 \cdot D = 1 \quad .$$

It is seen from the last column of Table II that, with the exception of the Longshot beam aimed for PcP, the observed beams displayed approximately the aperture predicted.

Delayed sum processing of the 11 November 1965 Rat Island event showed that a phase which arrived 14 sec after P had the same velocity as P. This supports the identification of this phase as pP. In addition, the delayed sum processing brought out PcP, which was not visible on the raw-data traces.

R. J. Greenfield

D. MAXIMUM-LIKELIHOOD FILTER SYNTHESIS IN FREQUENCY DOMAIN

The time domain synthesis of the maximum-likelihood multidimensional filter, which is used for array processing, requires approximately 40 min. of 7094 computer time for a 25-element subarray. This computing time is divided equally between two Fortran II computer programs, CORRA and WTST. The purpose of CORRA is to measure the correlation matrix of the noise, and WTST synthesizes the filter by means of a recursive matrix inversion technique. The computer time required by CORRA is approximately

$$L \times (NS)^2 \times (NFP) \times (\mu + \alpha) \text{ sec}$$

where L is the number of data points to be used in the correlation matrix estimation, NS is the number of seismometers, NFP is the number of filter points, and μ and α are the multiply and addition times, respectively. If L is equal to 1800, corresponding to 3 min. of noise, 20 data points per second, and every other data point skipped, and if NS is 25 and NFP is 21, then the 7094 computing time required is about 20 min. The computer time required by WTST is approximately

$$2.5(NFP)^2 (NS)^3 (\mu + \alpha) \text{ sec}$$

and, for 21 filter points and 25 channels, is about 20 min. for the 7094.

It has been pointed out[5] that it is possible to design the maximum-likelihood filter in the frequency domain with the advantage of having to use much less computer time. However, the

TABLE II

COMPARISON OF OBSERVED AND CALCULATED MAIN LOBE BEAM WIDTH

Event Location	Date (1965)	Phase	Array Length D (km/sec)	3-db Beam Width in Velocity (km/sec)	3-db Beam Width in k (K_3) (km^{-1})	$K_3 \cdot D$
Amchitka (Longshot)	29 October	P	32	$11 < V < 17$	$0.09 > k > 0.059$	1.0
Amchitka (Longshot)	29 October	PcP	32	$17 < V < \infty$	$0.059 > k > 0$	1.9
Kazakhstan	21 November	P	178	$23.5 < V < 25.5$	$0.049 > k > 0.043$	1.1
Rat Island	11 November	P	32	$11 < V < 18$	$0.091 > k > 0.005$	1.2
Rat Island	11 November	PcP	32	$18 < V < 50$	$0.055 > k > 0.02$	1.1

filter designed in the frequency domain is only asymptotically optimum, that is, its performance approaches that of the time domain filter only as NFP becomes large. In order to design the frequency domain filter, the spectral matrix must be estimated at (NFP + 1)/2 frequencies uniformly spaced across the frequency band of interest. If a direct method of spectral estimation is used, i.e., a method in which the data are transformed into the frequency domain and then used to estimate the spectrum directly, then the computing time is

$$L \times NS \times (NS + NFP)(\mu + \alpha) \text{ sec} \quad .$$

For the given values of L, NFP, and NS, this time is smaller than that required by CORRA by a factor of 11.4. The time required to synthesize the frequency domain filter is

$$NFP \times (NS)^3 (\mu + \alpha) \text{ sec}$$

which for 21 filter points is less than the time required by WTST by a factor of 52.5. In practice, these large savings are not actually achievable because of the requirement of reading and rewinding magnetic tapes which is common to both the time and frequency domain methods. However, it may be possible to achieve a great deal of the predicted saving in computing time, and it may be that the loss in performance of this scheme relative to the time domain synthesis scheme will be small. In order to explore this possibility, a computer program is being written in Fortran IV, for both the 7094 and 360, to synthesize the maximum-likelihood filter in the frequency domain.

J. Capon
R. J. Kolker

E. ITERATIVE DESIGN OF ARRAY PROCESSORS

Stochastic approximation methods are statistical techniques which have evolved from a 1951 paper by Robbins and Monro.[6] These methods, which generally concern themselves with the iterative solution of a variety of linear or nonlinear regression problems, have been adapted to the design of optimum filters.[7] Related but not strictly convergent iterative procedures have also been described[8] which can be useful even when true stochastic approximation techniques might be of little value. All of these iterative methods can be considered as deterministic iterative methods to which stochastic perturbations have been applied.

We have undertaken a study to determine if some stochastic approximation method might be found for the iterative design of seismic array processors. Such methods could be of great value for both on-line and off-line processing of data by reduction of the computer time and memory required for the design of the processors. The possibility suggests itself of on-line adaptive design of array processors to monitor regions of the earth which might be of particular interest.

Initial effort is being directed toward real-time design of optimum weighted delay-and-sum (WDS) processors. The variance of the noise resulting from WDS processing of data from an array is a quadratic form in the weights. The matrix of the quadratic form is the covariance matrix of the vector valued seismometer output noise process. The design of optimum weights is simply the determination of the weights, subject to the constraint that they add to unity, which will minimize the initially unknown quadratic regression function.

Methods which are currently being used[9] to design array processors require that all of the noise observations be used to obtain a best estimate of the covariance matrix. Then, using that estimate, a deterministic minimization is undertaken to determine weights to apply to each seismogram. The estimation of the covariance matrix and the solution of the deterministic minimization problem consume a considerable amount of computer time (see Secs. II-A and II-D). Storage of the estimate of the covariance matrix can require several hundred, or even thousands, of memory locations in the computer.

The iterative techniques currently under consideration avoid the time-consuming estimation of covariance matrices and solution of deterministic minimization problems. No covariance matrices are to be directly estimated. The computer memory requirements are much smaller than those for the direct method just described. The iterative methods are to use only crude estimates of the gradient of the noise variance of a processed trace with respect to the weights applied to seismograms. These estimates are then to be used to generate a new estimate of the best weights to use. One of several possible iterative schemes is

$$\omega_j(n+1) = \omega_j(n) - \frac{C}{n} \sum_{\ell=0}^{M-1} \left\{ \left[\sum_{k=1}^{N} \omega_k(n)\, x_k(nM+\ell) \right] \times \left[x_j(nM+\ell) - \frac{1}{N} \sum_{k=1}^{N} x_k(nM+\ell) \right] \right\}$$

where $\omega_j(n)$ is the n^{th} estimate of the best weight to apply to the j^{th} seismogram, $x_j(n)$ is the value at time n of the j^{th} seismogram, N is the number of seismograms, and C and M are constants. The seismograms are assumed to be time shifted as if delay-and-sum processing were to be applied.

Two different experimental runs have been completed using 3 min. of data from a subarray and using an iterative scheme of the form given above. The parameter values were updated every 25 data samples. For both runs, the SNR gain after one pass through 3 min. of data was within 3 db of the optimum WDS figure; after the fourth pass, it was within 2 db. Studies are continuing, particularly on stability and convergence rates.

R. T. Lacoss

F. RELATIONSHIP OF DIFFERENT PROCESSING PROCEDURES

A brief report has been prepared[10] summarizing, by illustrative examples (using 2 seismometers and 3 filter points per seismometer), the relationship between several different types of filter-and-sum array processing schemes. Among these are Levin's "minimum variance unbiased" version of the maximum-likelihood estimation,[11] a modification of this in which the amplitude weights are equipartitioned between seismometers in a certain way to avoid "supergain" problems, the prediction error processor,[12] and "annihilation filtering." The prediction error processor predicts the noise in a particular sensor at some future time (from the noises in all sensors) and then subtracts the prediction from the actual noise present at that time. The annihilation processor constrains the individual filtered noises to have equal power, while the noise in the sum has minimum power.

J. F. Claerbout

G. ISOLATION OF SPECIFIC SEISMIC PHASES

The ability of an array to suppress signal components at one vector velocity in favor of another at a different velocity is important, not only for studying specific seismic phases but also for observing a small event in the presence of a large one – for example, a nuclear test during a large earthquake.

Records from the 17-seismometer 32-km aperture array formed from LASA sensors (described in Sec. IV) were used for maximum-likelihood processing of data from the Longshot explosion of 29 October 1965. In the first case, the processing attempted to suppress the P arrival (velocity = 14.2 km/sec) while passing the PcP arrival (velocity = 31.7 km/sec). The fitting interval used to compute the cross correlations which are used to design the filter began 1 min. before the first arrival and was 2 min. long. In Fig. 15, the results of the processing are shown. The P phase and its coda were suppressed by approximately 21 db from their raw trace value.

A second case was run to suppress the P (velocity = 14.2 km/sec) arrival while passing array signals which arrived with the theoretical PP velocity of 10.5 km/sec. The same cross correlation interval as above was used. The processing reduced the P coda amplitude by approximately 14 db, even though the P and PP velocities were not greatly different. However, no PP was observed in the processed trace.

The S arrival is not often recorded on short period vertical instruments. However, it was felt that an effort should be made to find S on both earthquake and explosion records. Data from Longshot, from an earthquake on 11 November 1965 from nearby Rat Island, and from a 21 November 1965 Kazakhstan event were all processed by maximum-likelihood processing for the time period covering S arrivals. The Longshot data were taken from the 17-seismometer 32-km array already described, while the Rat Island and Kazakhstan events were processed using the 25 seismometers of subarray B1. For these events, the noise power was reduced by approximately 14, 23, and 14 db, respectively; however, no S waves were visible in the processed traces.

R. J. Greenfield

H. 3-COMPONENT ARRAY PROCESSING

A modification of the "maximum-likelihood" filter and sum-processing program was prepared which uses an array of 3-component instruments to estimate the compressional waveform from a known source location. The program was run on data from a set of eight 3-component short-period seismometers (total of 24 channels) at TFO, and the results compared with a maximum-likelihood estimate of the vertical waveform using 21 TFO seismometers observing the same event. The over-all aperture of the 3-component and the vertical arrays was the same. The processed traces are shown in Fig. 16. The noise reduction on the vertical array was 3.5 db better than on the 3-component array, although the 3-component array had three more channels to work with. The 3-component run showed a SNR gain 2.8 db greater than processing a 9-seismometer vertical array. Thus, the preliminary results indicate that the inclusion of polarization information (3-component sampling) results in a small improvement in noise rejection over the use of velocity and frequency data only for the same number of points in space, and that the additional data channels are better used to sample more points in space for better frequency-velocity filtering.

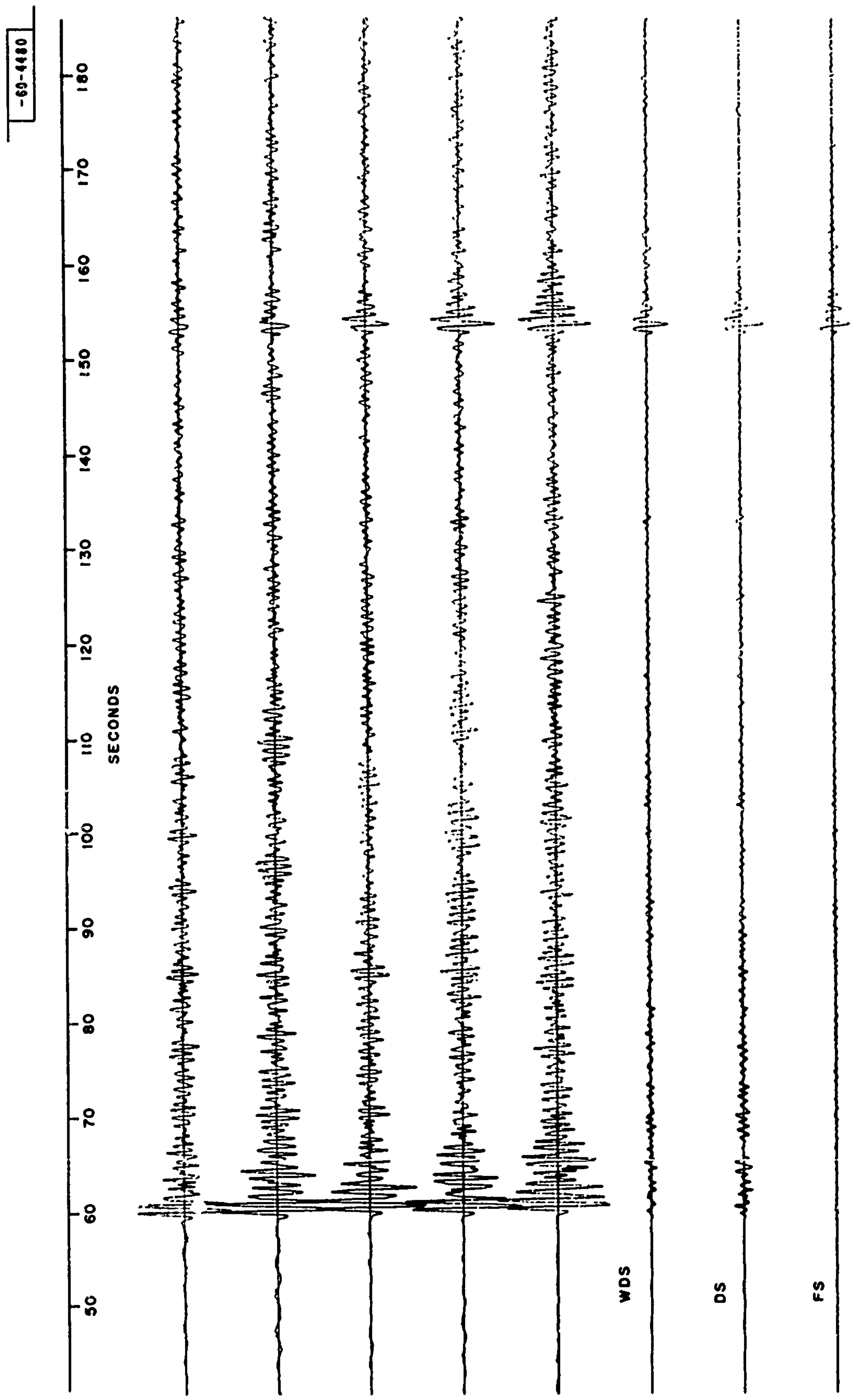


Fig. 15. Effect of one LASA subarray in accentuating the PcP phase of the Longshot signal while suppressing the P phase, which has a different phase velocity.

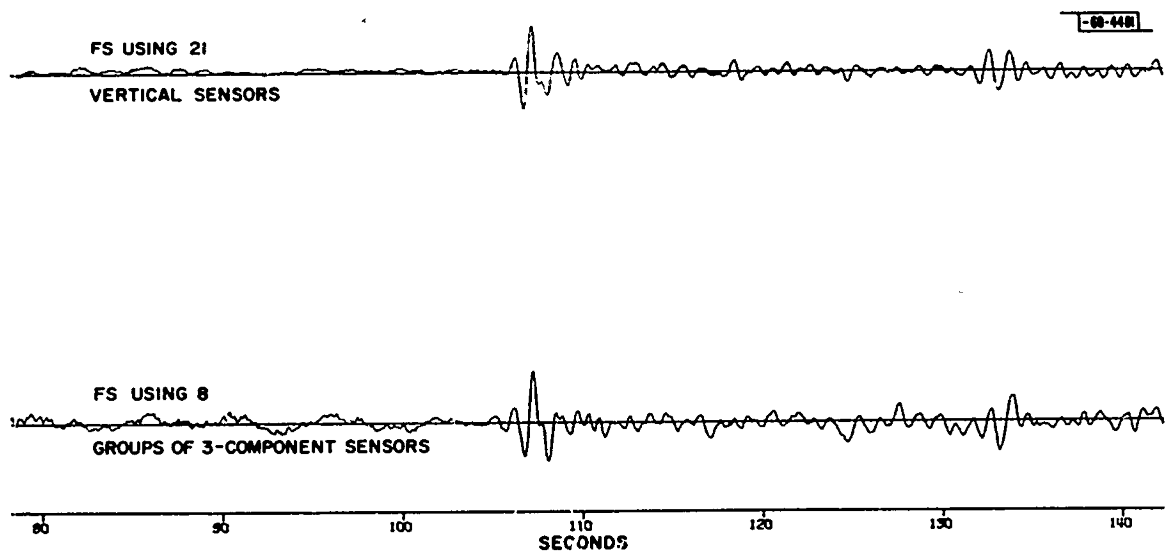


Fig. 16. A comparison of the noise-suppressing capabilities of an array of eight 3-component sensors with an array, having equal aperture, composed of roughly three times the number of vertical sensors. TFO data, 11 November 1964, Peru event.

These results are only preliminary, and additional experiments with 3-component arrays are needed to (1) confirm these results, (2) investigate the use of 3-component arrays for long period data, and (3) investigate the use of 3-component arrays for analysis of phases other than P (e.g., S phases).

H. W. Briscoe
R. J. Kolker

I. STATION CORRECTIONS

During this reporting period, we have shifted our attention from the extended TFO array to LASA in Montana, and have begun to repeat the same experimental work which provided the TFO station corrections described in the last Semiannual Technical Summary Report.[13] Ten data channels from LASA are currently being received at Lincoln using the FM analog telephone-line telemetry equipment formerly used at TFO. These channels are the "10" (500-foot hole) seismometers from each of the subarrays F1, F2, F3, F4, E1, E2, E3, E4, and A0, together with the direct sum from A0. Film recording is almost continuous in time, and all events are manually detected and timed. The relative arrival times at each subarray are recorded and later compared with those implied by the USC&GS epicenters. Rough epicenters are also obtained immediately from the station times by means of tables listing source positions vs arrival times for each of several LASA tripartite arrays. These epicenters are used as aids to screening of events for possible inclusion in our library of digital recordings.

To date, we have data from about fifty earthquakes and tests, and consistent patterns of station corrections are beginning to emerge. Although the geological structure underlying the Montana array is probably simpler than that in northeastern Arizona, we are finding bearing-dependent station corrections for Montana of the same order of magnitude as those found at TFO. Since these corrections often exceed 0.5 sec, they will have to be accurately determined in order to obtain optimum performance from the array.

We are also recording station amplitudes for the larger events in the hope of finding some systematic dependence of relative amplitude on source location. When the data on station corrections, both in time and amplitude, are sufficient, an attempt will be made to deduce structural features from them.

E. J. Kelly
R. M. Sheppard

REFERENCES

1. J.P. Burg, "Three-dimensional Filtering with an Array of Seismometer," Geophysics XXIX, No. 5, 693 (1964).
2. E.J. Kelly, Jr., "The Representation of Seismic Waves in Frequency-Wave Number Space," Group Report 1964-15, Lincoln Laboratory, M.I.T. (6 March 1964), DDC 433611, H-569.
3. Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (30 June 1964), DDC 443444.
4. R.T. Lacoss, "Geometry and Patterns of Large Aperture Seismic Arrays," Technical Note 1965-64, Lincoln Laboratory, M.I.T. (31 December 1965).
5. J. Capon and R.J. Greenfield, "Asymptotically Optimum Multidimensional Filtering for Sampled-Data Processing of Seismic Arrays," Technical Note 1965-57, Lincoln Laboratory, M.I.T. (17 December 1965), DDC 626180, H-690.
6. H. Robbins and S. Monro, "A Stochastic Approximation Method," Ann. Math. Stat. 22, 400 (1951).
7. D. Sakrison, "Iterative Design of Optimum Filters for Non-Mean-Square-Error Performance Criteria," Trans. IRE, PGIT IT-9, 161 (1963).
8. H. Kushner, "A Simple Iterative Procedure for the Identification of the Unknown Parameters of a Linear Time Varying Discrete System," Trans. ASME, J. Basic Eng. 85, 227 (1963).
9. Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (31 December 1964), pp. 21-23, DDC 455743.
10. J.F. Claerbout, "A Summary, by Illustrations, of Least Square Filters with Constraints," Technical Note 1966-1, Lincoln Laboratory, M.I.T. (in preparation).
11. Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (31 December 1964), Sec. IV-A, DDC 455743.
12. J.F. Claerbout, "Detection of P-Waves from Weak Sources at Great Distances," Geophys. 29, No. 2, 197 (1964).
13. Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (30 June 1965), DDC 467395.

III. AUTOMATIC EVENT DETECTION AND LOCATION

A. DIGITAL EVENT DETECTORS

Eight event detectors similar to that described in the last Semiannual Technical Summary Report* are now operating on-line in Billings. They are connected to the center seismometers in subarrays E1, E2, E3, E4, F1, F2, F3, and F4. The program looks for several detectors triggering within a short time (approximately 20 sec) of one another, which is what happens when a real teleseism with horizontal phase velocity of 10 km/sec or larger propagates across the array. When this occurs, the program types a "save tape" message to the operator and rings a bell. The report times of each detector are also printed out. Use of coincidence detection permits individual channels to be operated at high sensitivity, while keeping the over-all false-alarm rate at a low level.

P. L. Fleck

B. ANALOG EVENT DETECTORS

An experimental analog event detector "breadboard" has been built to assist in scanning telemetered seismic data for events, and to serve as a flexible tool for studying the event detector problem. In past months, information gleaned from either the analog or digital event detectors has proved useful to the design of the other.

The equipment itself centers about special narrow-band filters whose three parameters (gain, absolute bandwidth, and center frequency) are each adjustable, independent of the other two. Bandwidth is changed by factors of two in steps from 2 to $\frac{1}{8}$ cps. Gain and center frequency are each continuously adjustable.

In the basic event detector configuration which has been used in recent months (Fig. 17), the seismic signal is monitored by two narrow-band filters of identical bandwidth (usually 0.25 or 0.5 cps). Filter A is tuned to the optimum event detecting frequency (1.0 to 1.5 cps), and filter B is tuned somewhat above it (1.75 to 3.0 cps). Detector-integrators provide running estimates ($\bar{A}$ and $\bar{B}$) of the magnitude of the detected filter outputs averaged by a lossy integrator with a 1000-sec time constant. In "normalized-gain" operation, the filter outputs are each divided by this estimate and then full-wave rectified, using an RC averager with 2-sec time constant (for removing AC ripple) to produce the normalized "instantaneous" magnitude, A and B. The detector output $B/\bar{B}$ is then subtracted from $A/\bar{A}$ and passed to an adjustable threshold device which triggers when $(A/\bar{A}) - (B/\bar{B})$ exceeds a preset positive value. In the "fixed-gain" mode, $\bar{A} = \bar{B} =$ unity.

The normalized-gain event detector logic described above should have a good ability to adapt to normal slow changes in the background noise level and yield a relatively constant level of false alarms caused by background noise. However, this configuration was found to have two inherent liabilities. First, the sensitivity to events of a given magnitude and spectrum shape is varied as a result of changes in the magnitude and spectrum shape of the noise. Second, even with the long time constants employed in obtaining the $\bar{A}$ and $\bar{B}$ estimates, many events are

*Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (30 June 1965), DDC 467395.

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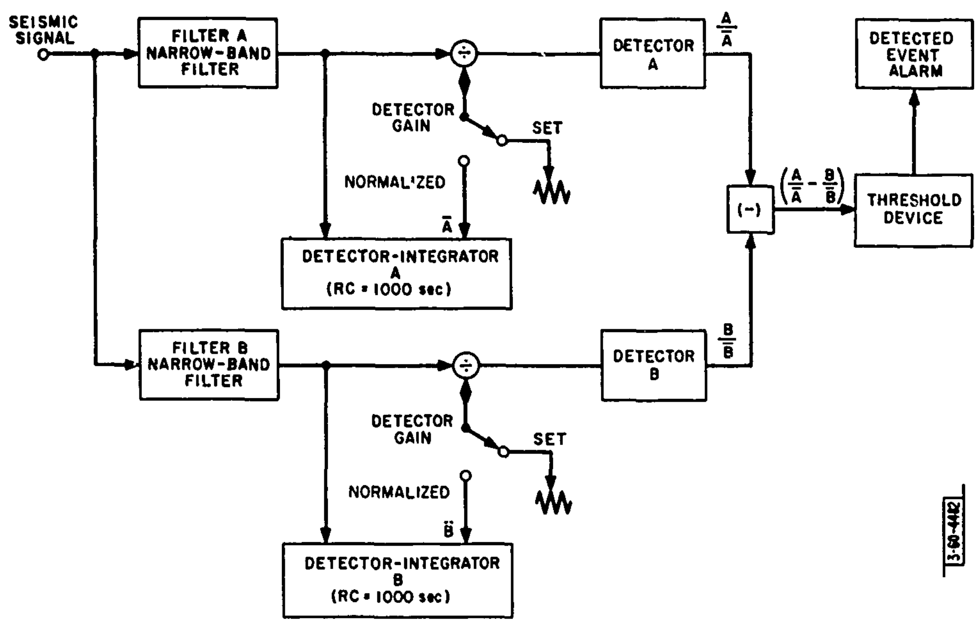

Fig. 17. Two-filter analog event detector diagram.

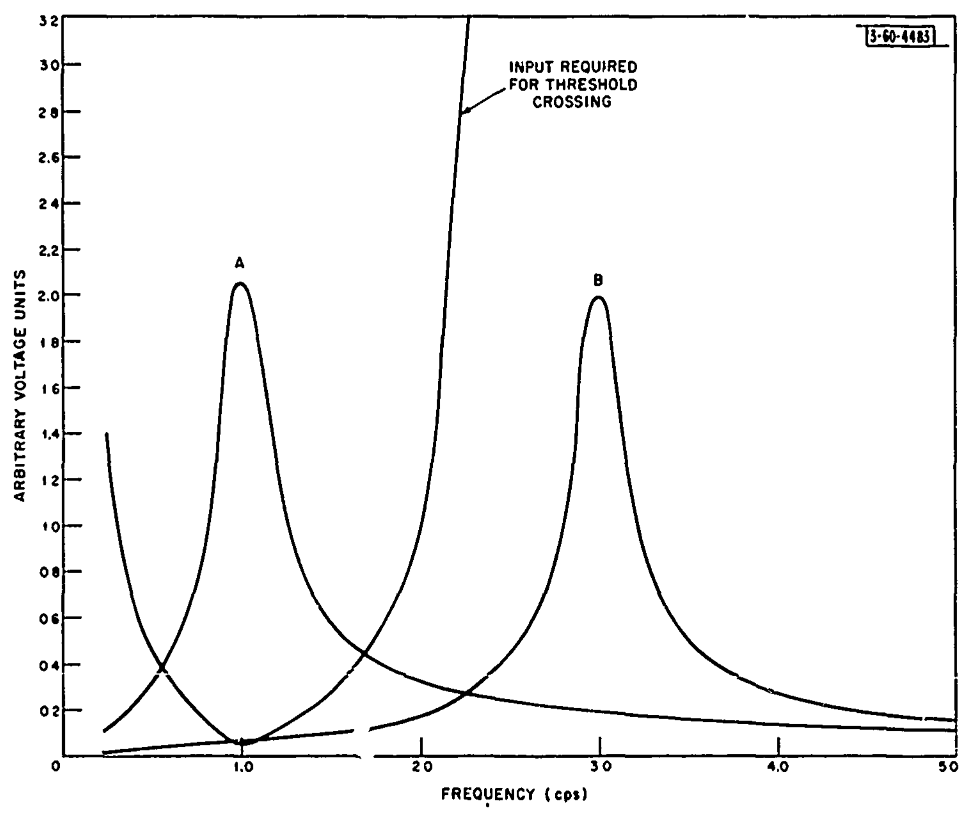

Fig. 18. Response of analog event detector filters and plot of sensitivity for a sine wave input.

themselves high enough above the background to add appreciably to, and therefore distort, the $\bar{A}$ and $\bar{B}$ estimates. This second, and operationally serious problem, can presumably be solved by intervening to block event signals from reaching the $\bar{A}$ and $\bar{B}$ detector-integrators while placing the integrator sections on "hold" until the event is passed.

Using the "fixed-gain" mode of operation, the detector has been operated with the A and B filters at several sets of bandwidths and center frequencies. Figure 18 shows the response of filters A and B with a particular setting, namely 0.25-cps bandwidths and center frequencies of 1.0 and 3.0 cps, respectively. A curve of input sine wave voltage required to trigger as an "event" is also shown on the same coordinates. In making changes in filter settings, the filter bandwidths are kept identical to provide as nearly similar responses as possible to transient phenomena.

C.A. Wagner

C. EVENT DETECTOR PERFORMANCE

The performance of the on-line LASA detection system has been quite satisfactory. By demanding nearly coincident reports from a majority of the eight detectors, it has been possible to operate at a sensitivity which is easily equal to that of an operator watching the same eight channels and superior to the performance of an operator watching two of these channels, as was our practice with the data telemetered to Lincoln Laboratory. The only misses (of events detected manually) have been due to flaws in the logic. For example, the detection system was made insensitive for 2 min. following each reported event, and occasionally a false alarm would place the dead period over a weak event. The reports of the event detector are automatically punched on paper tape and sent to Lincoln Laboratory by teletype, where they provide a substantial aid in finding events on our records.

If all eight channels are carrying normal seismic noise, the system false-alarm rate is quite low (of the order of a few per day). However, a steadily noisy channel has the effect of reducing the effective threshold, hence increasing the false-alarm rate (without reducing the sensitivity). In operation, some simple monitor on individual channels would be desirable.

The relative times at which the individual detectors report have been surprisingly good. On impulsive waveforms, they are usually within 0.1 sec of the manual times, hence could be used directly in a source location program. For more emergent arrivals, the time of automatic detection sometimes slips a half cycle or even a full cycle. On very emergent near-earthquakes, the times make no sense at all. It is possible that certain events of no interest could be rejected automatically on the basis of these times. For example, the variance of the report times is a rough measure of speed, and could be used to reject near events (large variance) and some data errors (coincident errors, hence very small variance). In any case, if some more-accurate means of automatic picking of start time can be devised, it need only search a data interval of the order of 2 sec preceding the time of detection.

The analog detector described above shows promise of rejecting local events by means of their frequency content. It has shown itself to be capable of rejecting better than half of the many locals observed on the TFO data, and those locals which trigger the detector usually do so with their later, lower-frequency arrivals. Certain types of impulsive noise are also rejected. The detector appears to be quite capable of matching the performance of an operator on a single trace, with a reasonable false-alarm rate (a few per day).

E. J. Kelly

IV. SEISMIC SOURCE IDENTIFICATION

The ability to make 525-channel LASA recordings, which has existed at the LASA Data Center in Billings, Montana since September 1965, has provided us with a library of some 96 events so far. Based on unclassified information (e.g., in the public press) plus our own epicenter determinations, five of these appear to be nuclear explosions. We are thus in a position to begin investigating systematically the blast-earthquake discrimination problem, using the LASA. Some of the various proposed criteria for discrimination (or more accurately, for classifying events as either earthquakes or unidentified events) are direction of first motion, depth of focus, complexity, aftershock patterns, energy ratios (e.g., P/S, LR/LQ), and spectral shape. To be fully effective, the first three of these all require observations at a number of globally separated stations, and yet it should be possible for us to make some appraisal of the effectiveness of a hypothetical network of LASA's by examining data derived from the experimental one in Montana. Such an effort has just been started and we have several fragmentary results to report.

We can give only two results on first motion. First, on one known explosion a rarefactional first motion was apparent from examination of raw traces, whereas, after maximum-likelihood processing, compressional first motion was seen on most of the subarray outputs. Specifically, upon processing, the fraction of traces with rarefactional first motion went from 40 to 20 percent, with compressional from 10 to 70 percent, and with unclear first motion from 50 to 10 percent. Second, it is known that misleading half-cycle precursors can sometimes be introduced in the maximum-likelihood output trace because of violation of the assumed condition of signal identity across the subarray, for example, due to large differences in seismometer gains and/or time misalignments. We are finding such precursor only very rarely; in 37 subarray outputs from known blasts, only 11 had such a sign-reversed precursor. The largest one seen was 20 db down from the largest half cycle. In practice, as long as determination of first motion is based on outputs from more than one subarray, this should constitute no problem.

It was thought that the amount of complexity in a signal could be seen more easily if a form of processing were used which smoothed the individual oscillations of the data to give a plot of the signal envelope. This is done for example in the "correlogram" type of display introduced by the UKAEA group.* Just what form of smoothing is best has not yet been thoroughly investigated, but one possibility which we have tried seems satisfactory, if not optimum, and allows comparison with correlogram waveforms. The envelope plots are formed from a single signal by first rectifying it, then passing the rectified signal through a low-pass filter whose output then follows the envelope of the rectified signal. In making these envelope plots, we have used a filter with a time constant of 2 sec; this represents a reasonable compromise between over-smoothing and allowing too much ripple in the envelope.

To compare the complexity of signals before and after array processing, both individual seismometer and processed traces from an event are shown in Fig. 19. The first of each pair of traces is the unsmoothed trace, while the second is the envelope plot. Two individual

*E. W. Carpenter, "Teleseismic Methods for the Detection, Identification and Location of Underground Explosions," VESIAC Report 4410-67-X, University of Michigan (April 1964).

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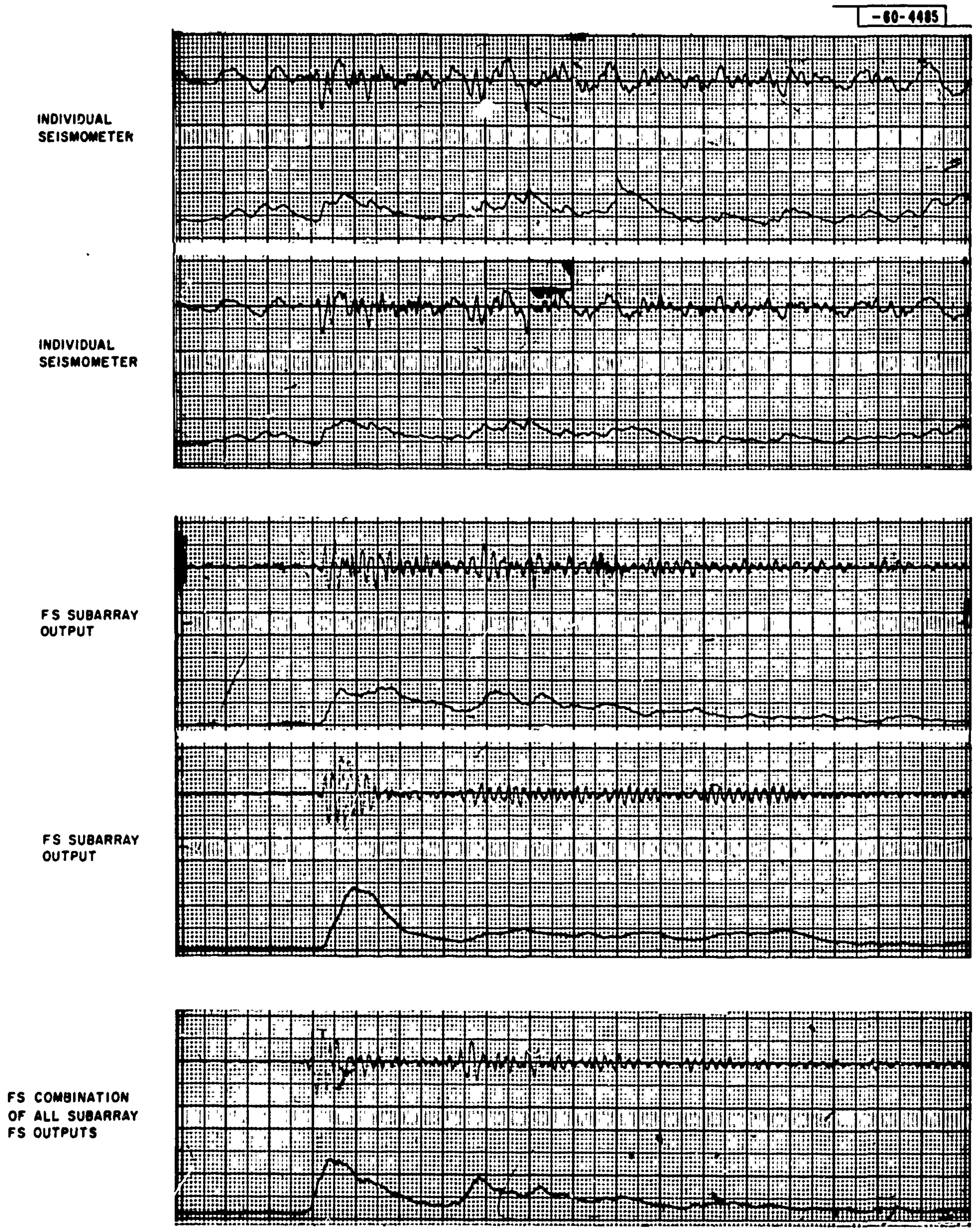

Fig. 19. Seismograms and envelope plots for the 11 November 1965 Rat Island event.

seismometer outputs, two subarray maximum-likelihood outputs, and the outputs of the maximum-likelihood processing of the subarray maximum-likelihood traces have been plotted.

Both the observation of depth phases (for example, pP following P) and the use of the complexity criterion require that reverberation introduced into the code of a given primary phase be reduced as much as possible. The large aperture of LASA seems to be of considerable effect in this respect, although this is more apparent on the output traces themselves than on the envelope plots derived from them.

Some results on the identification of depth phases by determination of their horizontal phase velocity is described in Sec. II-G, as is the attempt to isolate S phases.

R. J. Greenfield E. Gehrels
J. Capon C. A. Wagner

V. SEISMOLOGY RESEARCH

A. FREQUENCY-WAVE-NUMBER SPECTRA OF MICROSEISMIC NOISE

It is intended to make a series of studies of the spectral density of seismic noise (in frequency-wave-number space) using various configurations of LASA sensors. One program has been written and used which computes the spectral density from the space-time correlation function, along the lines described in the December 1964 Semiannual Technical Summary Report.* The correlation functions for the elements of a single subarray are automatically available as an intermediate step in the maximum-likelihood processing scheme. Some spectra have been computed in this way, but the small size of the subarray provides only very coarse wave-number resolution.

For a given value of wave-number, it is possible to obtain estimates of noise power integrated over frequency. Figure 20 is a contour plot of estimated noise in wave-number space as seen by a LASA subarray steered for a particular event. The plot is in decibels with respect to the power level observed at the origin of wave-number space. Because of the small aperture of a subarray, most of the noise appears to be smoothly clustered about the origin.

The same noise sample which was used to obtain estimates of wave-number spectral density was used to design, in the time domain, a best "weighted delay-and-sum" (WDS) processing scheme for a teleseismic event which occurred after the noise sample. This processing scheme differs from the simple delay-and-sum scheme in that it applies an amplitude weight to each seismometer in such a way that the main lobe still points to the signal while the sidelobes and nulls are oriented to minimize noise output power. That this is actually happening can be seen from Figs. 20 through 22. Figure 21 shows the gain characteristic in wave-number space of the weighted delay-and-sum processing scheme. Figure 22 is the gain characteristic, or pattern, of a delay-and-sum processing scheme. The central dots on Figs. 20 and 21 identify the location of the major part of observed noise and a beam which has had its width reduced in order to reject that noise while passing a signal which is in the center of the beam. Other dots indicate the correspondence between regions of relatively high noise and of relatively low gain of the WDS processor. Secondary peaks of the gain characteristic are very high, but only in regions where the noise power is low.

Several digital recordings containing event-free periods of normal and high-level microseismic noise are now available in our library, and we plan to analyze these using special arrays of sensors. We expect to obtain a frequency resolution of about 0.1 cps and a wave-number resolution of about 0.05 cycle/km, which should permit separation of surface wave modes.

R. T. Lacoss
E. J. Kelly

B. CALCULATION OF CRUSTAL EFFECTS ON LASA SIGNALS

The crustal layering at the source region and under the recording station greatly affect the shape, size, and duration of the observed body waves. The extent of variation of the pulse shapes

* Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (31 December 1964), DDC 455743.

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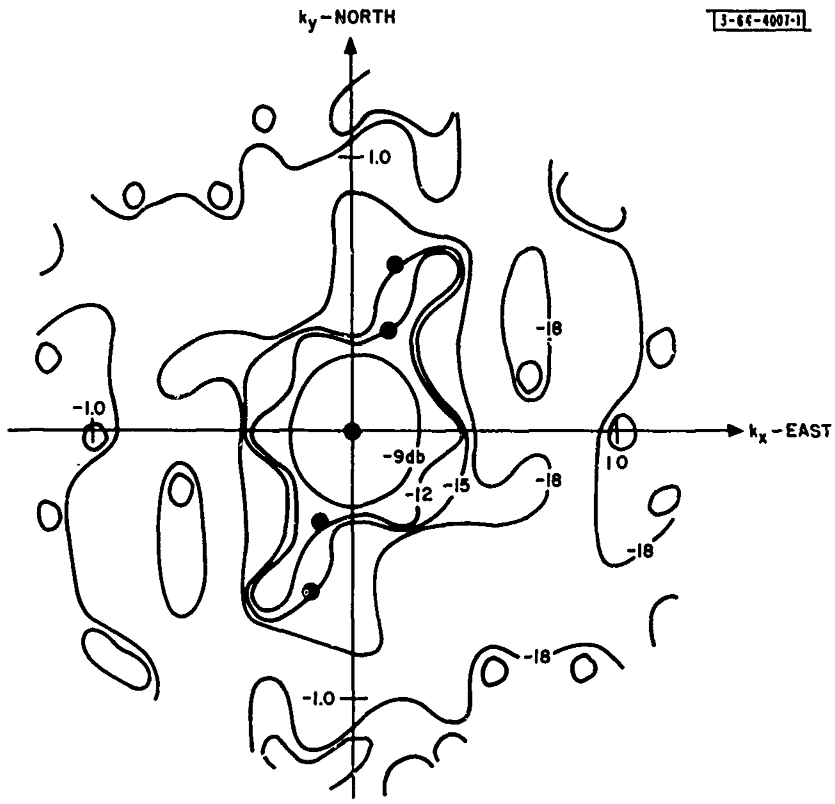

Fig. 20. Estimate of noise spectral density, totaled over all frequencies, as a function of horizontal wave number. 27 August 1965, subarray C4.

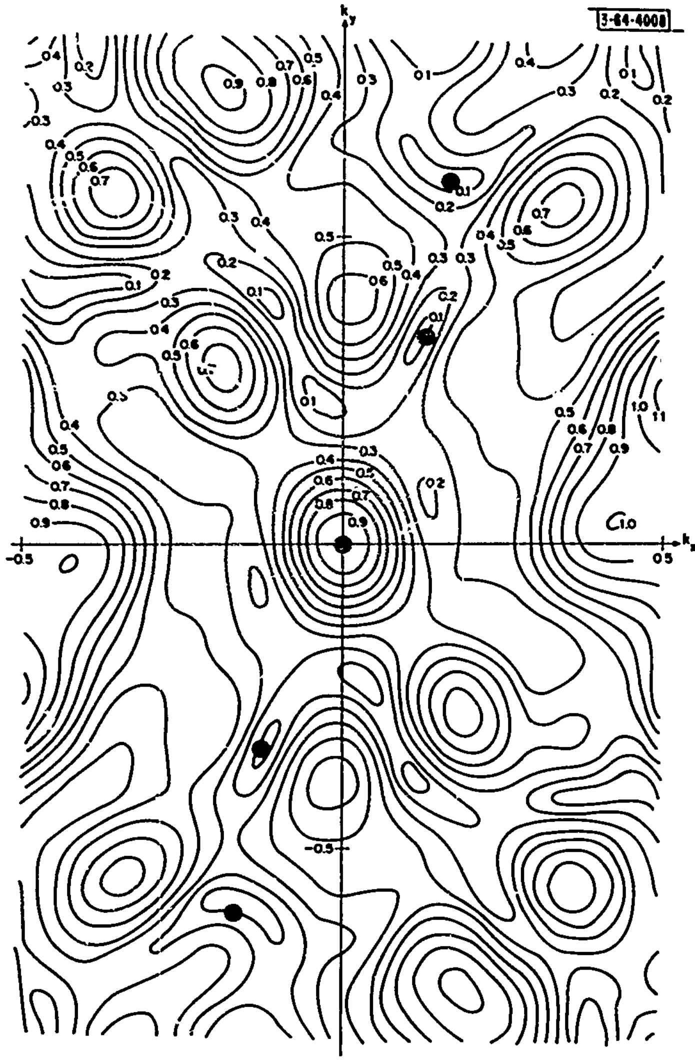

Fig. 21. Weighted delay-and-sum directivity pattern of subarray C4 when the weights are designed from the sample of noise used for Fig. 21.

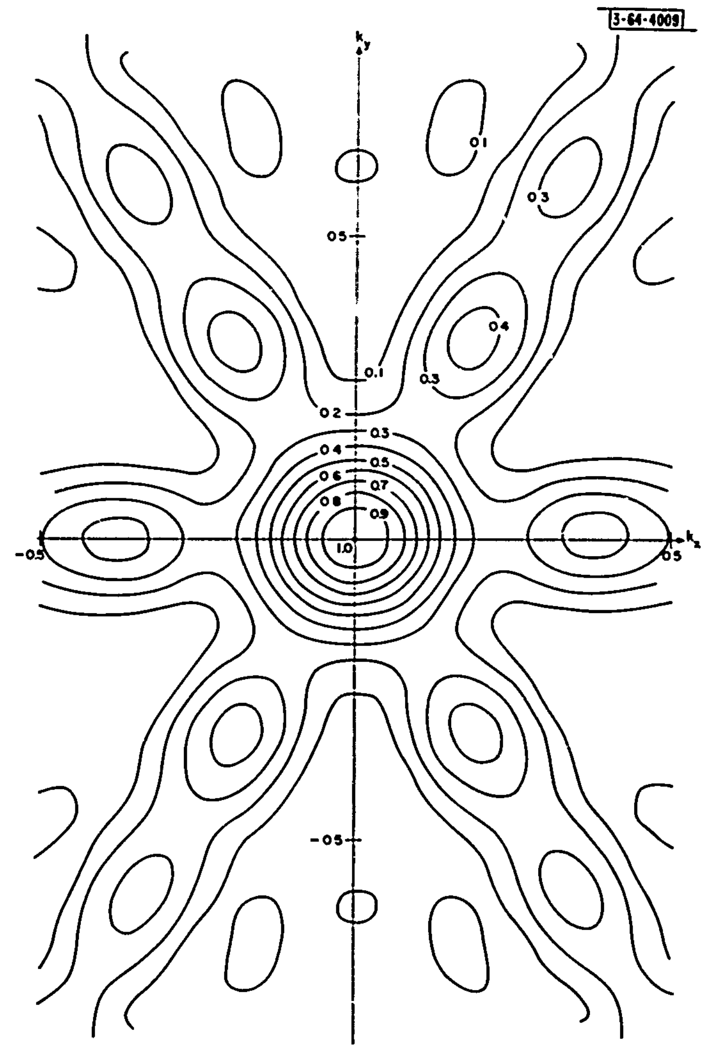

Fig. 22. Delay-and-sum directivity pattern of subarray C4. (Power as a function of horizontal wave number.)

due to the location of the station was demonstrated by Gutenberg.[1] More recently, the crustal response problem was formulated[2] and was calculated numerically.[3,4] Ben-Menahem, et al.,[5] corrected for the phase response of the crust in studying the source mechanism of the deep focus earthquakes using long period P-waves. They could not use the short periods (i.e., shorter than 10 sec) because the amplitude and phase responses were very strongly dependent on the structure.

The gross features of the earth's crust under the LASA site are known at least along one N-S profile.[6,7] Using this information, we can compute the extent of the signal distortion under LASA.

Let us assume that the crust is horizontally layered and that the mantle below the M-discontinuity is homogeneous. A plane wave that is incident at the base of the crust will be reflected, refracted, and converted (P to S, or S to P conversions) at each interface. Hence, the surface recording of this pulse will have a longer duration than that of the incident pulse.

The computation of the crustal response can be formulated in the frequency domain using a matrix formulation.[2] The impulse response of the crustal filter must then be obtained by Fourier synthesis using the computed amplitude and phase response. The necessity for frequency domain computation arises because of the frequency dependent reflection and transmission coefficients in the case of oblique incidence.

In computing the amplitude and phase responses of the crustal filter for the LASA site, we used a modified version of S. W. Smith's program. The transformation to time domain (i.e., Fourier synthesis) was achieved using a method suggested by Aki.[8] The seismogram x(t) is given by

$$x(t) = 2 \sum_i A_i(\omega_i)\,\Delta\omega_i \,\frac{\sin\left\{\frac{\Delta\omega_i}{2}(t - t_i)\right\}}{\frac{\Delta\omega_i}{2}(t - t_i)}\,\cos(\omega_i t - \omega_i \tau_i) \tag{1}$$

where $\tau_i = \varphi_i(\omega_i)/\omega_i$, $t_i = \tau_i + \omega_i(\partial\tau/\partial\omega)_i$, A_i = amplitude, φ_i = phase, and $\Delta\omega$ = frequency sampling interval. The advantage of this method is that it is faster than the conventional Fourier synthesis technique.

A N-S refraction profile traverses the LASA site.[6,7] Other profiles in the area indicate that the deep structure is fairly uniform with mildly dipping interfaces. However, there is not much detailed information on the seismic velocities and thickness of the sedimentary layers. Indications are that the sedimentary structure may vary considerably from one location to another at the LASA site.

The first site structure we used in computing the response is designated as Model I. Model II is a perturbation of Model I, where the top sedimentary layer is replaced by two layers with the same total thickness and average parameters. The parameters are tabulated in Table III.

The crustal response curves are computed for two reasons: (1) to determine the dependence on the angle of incidence of the waves, and (2) to determine the effects of small crustal perturbations. Figure 23 shows the P-wave incident at the base of the crust. The pulse is synthesized from amplitude and phase response of a short period seismograph, and the precursor as well as the oscillations are due to the synthesis. In Fig. 24, the effect of the crust (Model I) is

TABLE III ELASTIC PARAMETERS FOR CRUST UNDER LASA			
Model 1			
Layer Thickness h (km)	P Velocity α (km/sec)	S Velocity β (km/sec)	Density ρ (gm/cc)
1.0	2.0	1.1	2.1
2.0	3.7	2.1	2.4
17.0	6.1	3.6	2.8
17.0	7.0	4.0	3.0
16.0	7.6	4.4	3.2
∞	8.1	4.6	3.4
Model 2			
0.5	1.8	1.0	1.9
0.5	2.8	1.6	2.2
2.0	3.7	2.1	2.4
Remainder of layers as in Model I, above			

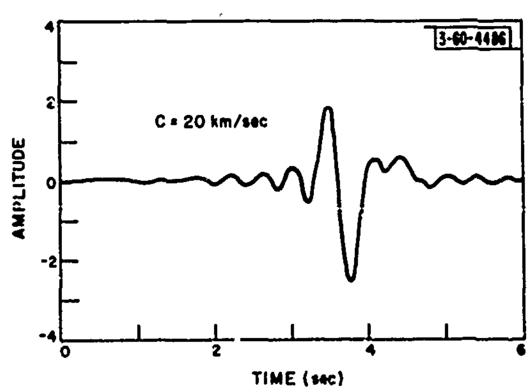

Fig. 23. Theoretical P-wave pulse incident at base of crust with an apparent surface velocity of 20 km/sec.

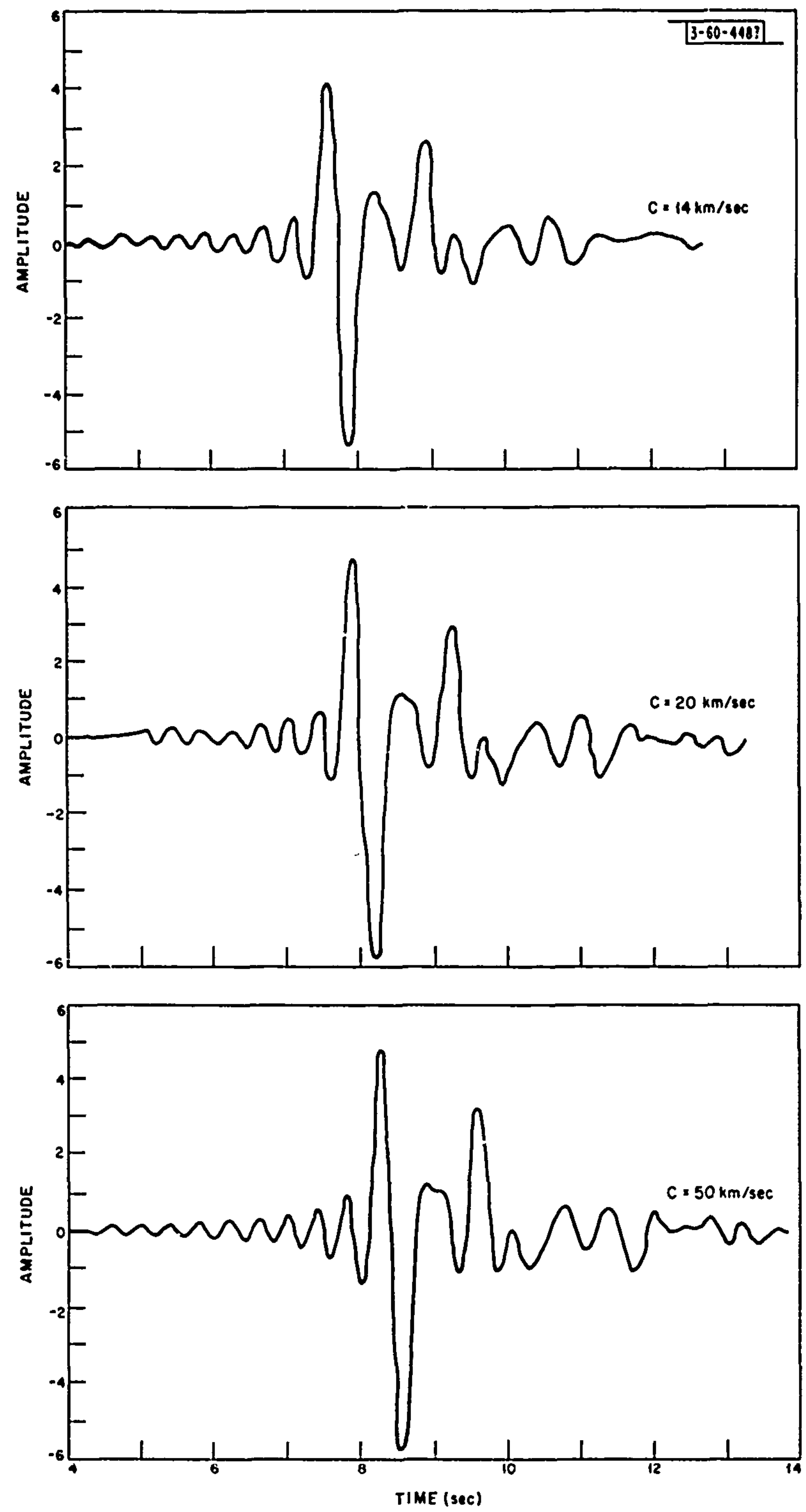

Fig. 24. Vertical component of surface motion for three different angles of incidence for crustal Model I.

demonstrated for three different angles of incidence corresponding to surface phase velocities of 14, 20, and 50 km/sec. The incident waves are the same in each case [Fig. 23] and the motions shown are the vertical components at the surface. These waveforms are quite similar, indicating that the variation with the angle of incidence (hence, the epicentral distance) is very small for teleseismic distances between 30° and 95°.

The effects of crustal variation are shown in Fig. 25. The two waveforms, corresponding to Models I and II, are quite dissimilar, although all the input parameters except the top sedimentary layers are the same. Comparing these, we observe that the second prominent peak arriving 1.2 sec later than the first motion in Model I is due to the reflection of the wave in the sedimentary layer. In the case of Model II, this disappears because of the more gradual velocity transition toward the surface. This strong effect of the near-surface sedimentary layer on the recorded waves creates a need for matching or compensation between the elements of the array.

We conclude that the modification of the seismic pulses by the crustal layering under the recording station has two effects on the problem of seismic discrimination. First, since the incident pulse is made more "complex" by the reverberation, it becomes more difficult to detect the source characteristics of the seismic disturbance. Among the characteristics that may be vital for the discrimination are the pulse duration and the identification of the pP phase of very shallow events.

The second problem arises because of the variations in the crustal response from one station to another. In an ideal array, the signals would be identical, except for time delays, at all channels. In the absence of such uniformity, it may be desirable to compensate to a reference station using a set of filters. The synthesis of such compensation filters requires the crustal response at each station.

At LASA, there are observable variations between the recordings of some subarrays and especially of those of distant subarrays. The near-surface structure is not known under each subarray to compute the crustal response at each site and to correlate these with the recordings. Until a detailed crustal structure (including the near-surface sedimentary layer) of each area is available, computation of compensation filters can be done using the recorded earthquake signals. To avoid the near-source reverberations, it would be best to use the recordings from a deep shock. Since the responses do not seem to vary strongly with distance, it is sufficient to compute one filter for each subarray for all teleseismic events. Also, if the filtering is done following the subarray processing, all of LASA requires only twenty filtering operations.

M. Nafi Toksöz

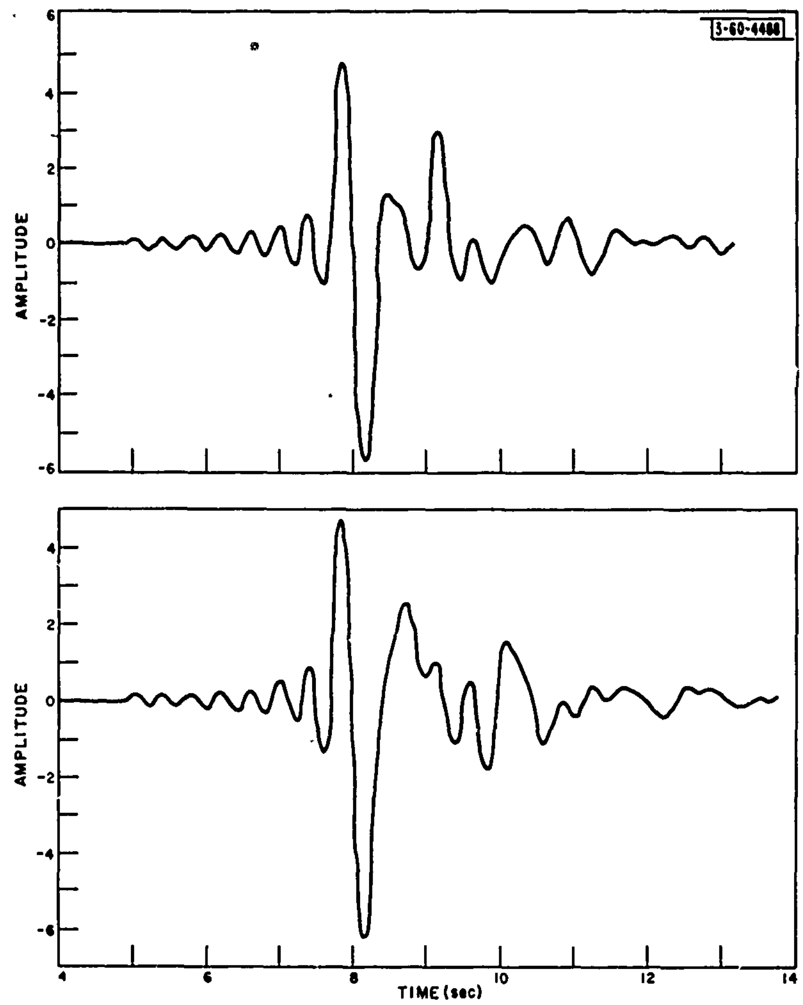

Fig. 25. Surface motion (vertical component) due to same P-wave incident at base of crustal Models I and II.

REFERENCES

1. B. Gutenberg, "Effects of Ground on Earthquake Motion," BSSA 47, 221 (1957).
2. N. A. Haskell, "Crustal Reflection of Plane P and SV Waves," J. Geophys. Res. 67, 4751 (1962).
3. R. A. Phinney, "Structure of the Earth's Crust from Spectral Behavior of Long-Period Body Waves," J. Geophys. Res. 69, 2997 (1964).
4. W. J. Hannon, "An Application of the Haskell-Thomson Matrix Method to the Synthesis of the Surface Motion due to Dilatational Waves," BSSA 54, 2067 (1964).
5. A. Ben-Menahem, S. W. Smith and T. Teng, "A Procedure for Source Studies from Spectrums of Long-Period Seismic Body Waves," BSSA 55, 203 (1965).
6. L. C. Pakiser and J. S. Steinhart, "Explosion Seismology in the Western Hemisphere," Research in Geophysics, Vol. 2, H. Odishaw (Ed.) (M. I. T. Press, Cambridge, 1964), pp. 123-147.
7. J. S. Steinhart and R. P. Meyer, "Explosions Studies of Continental Structure," Carnegie Institute Washington Publications, No. 622, 409 (1961).
8. K. Aki, "Study of Earthquake Mechanism by a Method of Phase Equalization Applied to Rayleigh and Love Waves," J. Geophys. Res. 65, 729 (1960).

VI. STRAIN MEASUREMENT FEASIBILITY STUDY

The measurement of earth strains by interferometer techniques may be of use in attacking the earthquake prediction problem. These methods have been studied, and the results reported in a Technical Note.[1] Here we briefly state the problem and summarize the conclusions.

In earthquake regions, the earth develops secular strains increasing at a rate, typically, of 10^{-6} per year. Superimposed on these are periodic tidal strains of 10^{-8}. It is hoped that by accurately measuring strains to this order of magnitude or smaller, additional effects will be observed just prior to an earthquake. The suggestion has been made to instrument heavily certain fault zones to find criteria that would permit the anticipation of earthquakes.[2]

To date, earth strain has been most reliably measured by comparing the length of a section of rock against a length standard such as a quartz tube. Despite the high degree of perfection of the method,[3] it suffers from the variability in the length of the standard over long periods and the fact that it is not possible to measure strains over lengths exceeding several hundred feet. The short baseline method is therefore subject strongly to local variations that may represent pure noise in the sense that they have no relation to the fault development.

The interferometer can provide the accuracies required over distances of 1 to 10 km, using the frequency or the wavelength of electromagnetic radiation as the primary standard. Two approaches were found to be the most promising: the modulated light beam principle, as incorporated in the commercial Geodimeter; and the direct optical interferometer using the laser. In both, atmospheric refraction is the principal limitation, but for different reasons. (It is possible to avoid the atmospheric refraction if one is willing to go to the expense of an underground, hermetically sealed light tube.)

The atmospheric refraction depends upon the temperature, pressure, and somewhat on the water-vapor content. It is necessary to calibrate out this variation in refractive index. This can probably be most reliably accomplished by taking advantage of the 3-percent difference in the atmospheric refraction at the two ends of the visible spectrum. This, however, increases by a factor of 30 the burden on the instrumental accuracies. This places an over-all limit of 10^{-7} or 10^{-8} for a modulated light beam system, taking advantage of the gigacycle modulating frequencies available with solid state techniques. (The commercial instruments strive for much less accuracy, using modulation frequencies between 10 and 30 Mcps.)

The laser interferometer can achieve considerably higher inherent accuracies (10^{-9}), but requires a coherent light wave front. If atmospheric turbulence should be sufficient to break up the uniform wave front into a completely random distribution, the system fails completely. Still, the great inherent advantage of the direct interferometer makes it worthwhile to study its possibilities further.

E. Gehrels

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REFERENCES

1. E. Gehreis, "A Review of Long-Range Earth Strain Measurement Techniques for Providing Earthquake Warning," Technical Note 1965-62, Lincoln Laboratory, M.I.T. (13 December 1965), DDC 625817, H-689.
2. Ad Hoc Panel on Earthquake Prediction, F. Press, Chairman, "Earthquake Prediction – A Proposal for a Ten Year Program of Research" (May 1965).
3. H. Benioff, "Fused-Quartz Extensometer for Secular, Tidal, and Seismic Strains," Bull. Geolog. Soc. Am. 70, 1019 (August 1959).

VII. STUDY OF NOISE AND LOW-FREQUENCY AMPLIFIERS

Technical Note 1965-52* covers a study of noise and low-frequency amplifiers. The abstract of this report follows.

This paper is a study of low-noise amplification in the near direct current frequency range. The paper is a survey of the problem and no "ultimate amplifier" is presented in conclusion. The purpose of this paper is to analyze the problem and to present conclusions as to best class of amplifiers to use in this frequency range.

Two classes of amplifiers are considered. The "chopper" amplifier and the semiconductor diode parametric amplifier. It is concluded that the semiconductor diode parametric amplifier is inherently the lower noise device of the two. There are no intrinsic noise sources in this amplifier and noise arises mainly from parasitic effects which theoretically can be made arbitrarily small. The use of this type of amplifier at low frequencies marks a new and successful application of a device usually associated with microwave frequencies.

The first section of the paper is a critique of the various figures of merit used in specifying noise performance. The significance and proper use of the noise figure is discussed.

The section on the "chopper" amplifier includes analysis involving both the junction transistor and the field effect transistor. The conclusions are that the best overall performance of the chopper amplifier results when the junction transistor is used with a low impedance source.

M. Adler

* M. Adler, "Noise and Low-Frequency Amplifiers," Technical Note 1965-52, Lincoln Laboratory, M.I.T. (21 December 1965), H-695.

VIII. CUMULATIVE LIST OF PUBLICATIONS

Reports

N. M. Abramson, "Further Considerations in the Use of Large Seismometer Arrays," Group Report 64G-6, Lincoln Laboratory, M.I.T. (14 November 1963), DDC 424594, H-550.

M. Adler, "Noise and Low-Frequency Amplifiers," Technical Note 1965-52, Lincoln Laboratory, M.I.T. (21 December 1965), H-695.

J. Capon and R. J. Greenfield, "Asymptotically Optimum Multidimensional Filtering for Sampled-Data Processing of Seismic Arrays," Technical Note 1965-57, Lincoln Laboratory, M.I.T. (17 December 1965), DDC 626180, H-690.

E. Gehrels, "A Review of Long-Range Earth Strain Measurement Techniques for Providing Earthquake Warning," Technical Note 1965-62, Lincoln Laboratory, M.I.T. (13 December 1965), DDC 625817, H-689.

P. E. Green, Jr., "A Large Aperture Seismic Array," Group Report 1965-1, Lincoln Laboratory, M.I.T. (6 January 1965), DDC 609851, H-628.

E. J. Kelly, Jr., "The Representation of Seismic Waves in Frequency-Wave Number Space," Group Report 1964-15, Lincoln Laboratory, M.I.T. (6 March 1964), DDC 433611, H-569.

____________, "Limited Network Processing of Seismic Signals," Group Report 1964-44, Lincoln Laboratory, M.I.T. (4 September 1964), DDC 447220, H-604.

____________, "A Comparison of Seismic Array Processing Schemes," Technical Note 1965-21, Lincoln Laboratory, M.I.T. (14 June 1965), DDC 618017, H-656.

E. J. Kelly and M. J. Levin, "Signal Parameter Estimation for Seismometer Arrays," Technical Report 339, Lincoln Laboratory, M.I.T. (8 January 1964), DDC 435489, H-643.

R. T. Lacoss, "Geometry and Patterns for Large Aperture Seismic Arrays," Technical Note 1965-64, Lincoln Laboratory, M.I.T. (31 December 1965).

M. J. Levin, "Bounds on the Inverse of a Positive Definite Symmetric Matrix," Group Report 1964-67, Lincoln Laboratory, M.I.T. (20 November 1964), DDC 452772, H-622.

__________, "A Method for Power Spectrum Parameter Estimation," Group Report 1965-8, Lincoln Laboratory, M.I.T. (10 February 1965), DDC 612796, H-633.

R. Price, "Statistical Synthesis of a pP-Wave Enhancer," Technical Note 1965-22, Lincoln Laboratory, M.I.T. (14 June 1965), DDC 617951, H-655.

________, "An Approach to Estimation in Seismic Equalization," Technical Note 1965-24, Lincoln Laboratory, M.I.T. (28 June 1965), DDC 619020, H-663.

J. S. Richters, "The Application of Analysis of Variance to the Seismic Discrimination Problem," Group Report 1964-60, Lincoln Laboratory, M.I.T. (3 November 1964), DDC 451871, H-618.

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Journal Articles

H. W. Briscoe and P. L. Fleck, "Data Recording and Processing for the Experimental Large Aperture Seismic Array," IEEE Proceedings (December 1965).

R. A. Frosch and P. E. Green, Jr., "The Concept of a Large Aperture Seismic Array," Proc. Roy. Soc. A 290, No. 1422 (March 1966).

P. E. Green, Jr., R. A. Frosch and C. F. Romney, "Principles of an Experimental Large Aperture Seismic Array (LASA)," IEEE Proceedings (December 1965).

P. E. Green, Jr., E. J. Kelly, Jr. and M. J. Levin, "A Comparison of Seismic Array Processing Methods," Second I. U. G. G. Meeting, Rehovot, Israel, 13-23 June 1965. Geophysical Jour. of Roy. Astron. Soc. (in preparation).

M. J. Levin, "Least-Squares Array Processing for Signals of Unknown Form," Radio Electron. Eng. 29, 213 (1965), DDC 618772.

R. V. Wood, Jr., R. G. Enticknap, C.-S. Lin and R. M. Martinson, "Large Aperture Seismic Array Signal Handling System," IEEE Proceedings (December 1965).

DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Lincoln Laboratory, M.I.T.	Unclassified
	2b. GROUP None

3. REPORT TITLE

Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Semiannual Technical Summary Report 1 July to 31 December 1965

5. AUTHOR(S) *(Last name, first name, initial)*

Green, Paul E., Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
31 December 1965	64	41

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
AF 19(628)-5167	Semiannual Technical Summary (31 December 1965)
b. PROJECT NO. ARPA Order 512	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
c.	
d.	ESD-TDR-65-597

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Advanced Research Projects Agency, Department of Defense

13. ABSTRACT

The experimental Large Aperture Seismic Array (LASA) in Montana was put into operation and has been used for routine monitoring and data recording. Most of the physical elements of the system are working more reliably than had been anticipated (Sec. I). Research and experimentation with various array processing techniques are under way using LASA data (Sec. II). Results on automatic event detection and location are discussed in Sec. III. Both these sets of investigations are approaching the point at which the LASA capabilities can be established, the signal processing hardware design can be finalized, and a design of a possible global network of LASA's can be worked out, should it be needed.

The large array is a signal improvement system whose outputs are to be used for nuclear test monitoring and research on the solid earth. Early results are reported in Secs. IV and V, respectively.

Two miscellaneous studies of seismic instrumentation are reported: a survey of electromagnetic means of measuring long-baseline earth strains (Sec. VI), and a comparative critique of the noise performance of several methods of amplifying near DC signals (Sec. VII). Section VIII is a cumulative list of our publications in this program.

14. KEY WORDS

seismic array
seismometer
seismology