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Seismic Discrimination

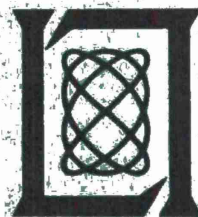
31 December 1966

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Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts



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SEISMIC DISCRIMINATION

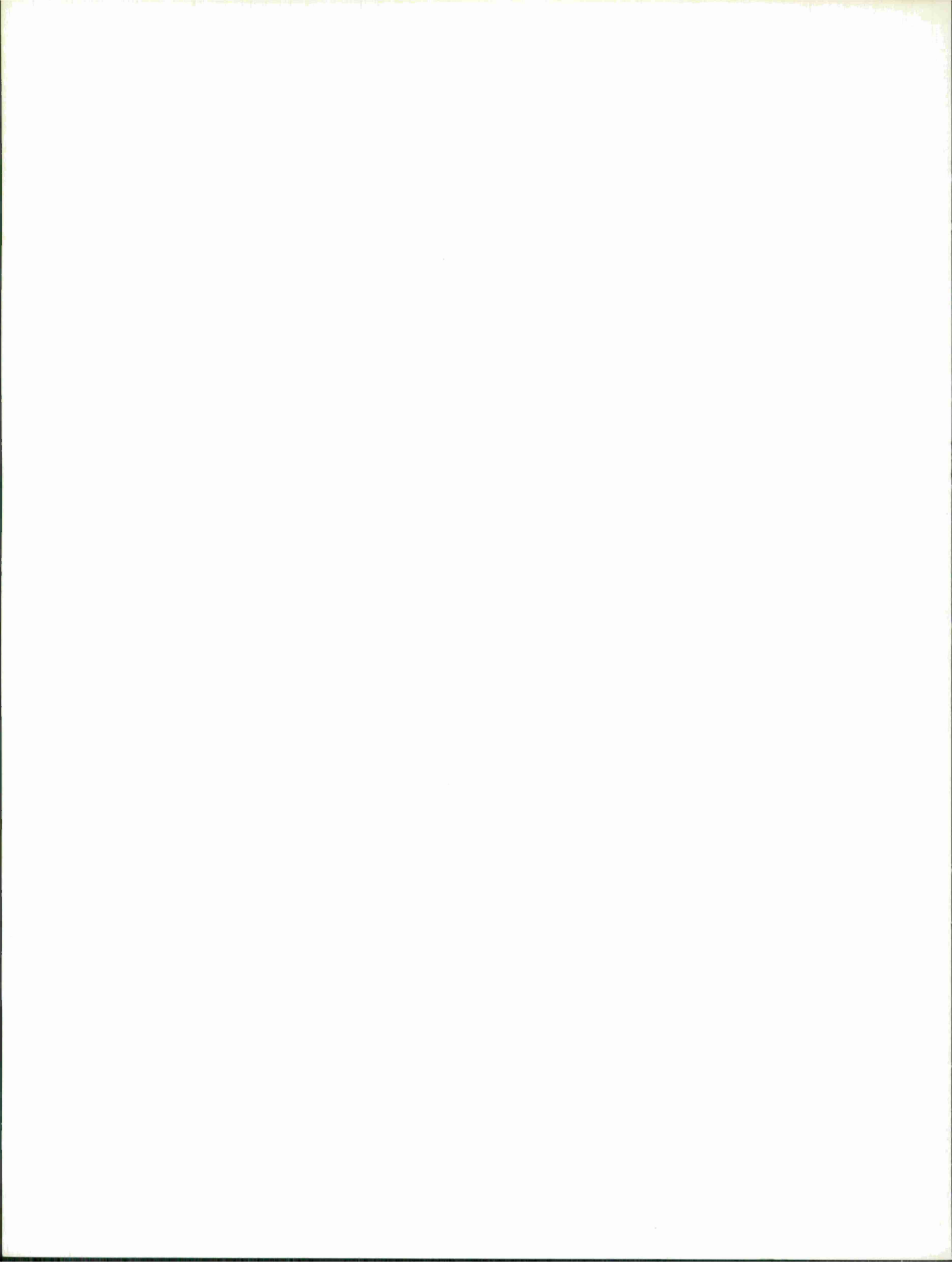
SEMIANNUAL TECHNICAL SUMMARY REPORT
TO THE
ADVANCED RESEARCH PROJECTS AGENCY

1 JULY - 31 DECEMBER 1966

ISSUED 25 JANUARY 1967

LEXINGTON

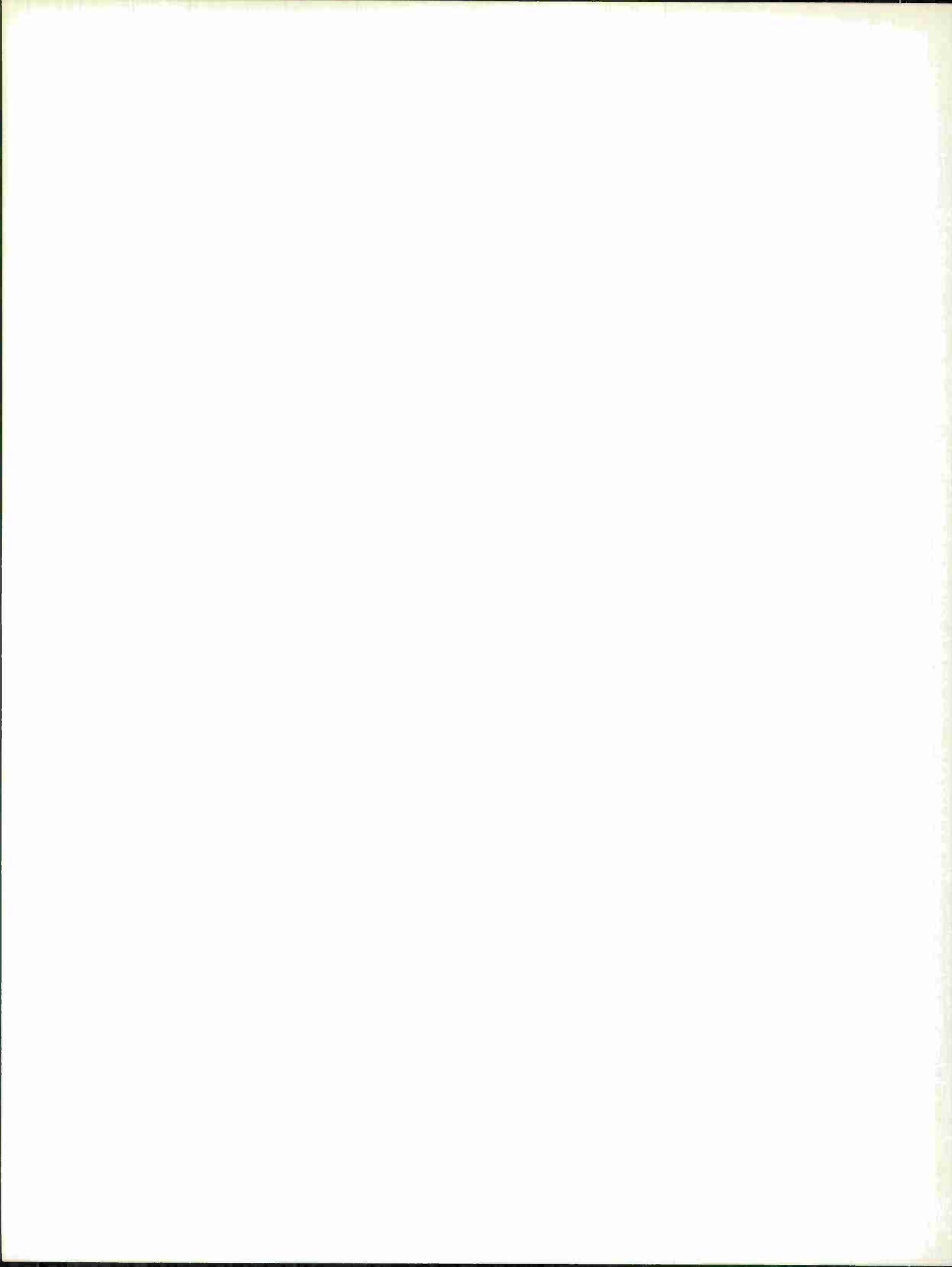
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ABSTRACT

Studies have continued of the ability of a single Large Aperture Seismic Array (LASA) station to detect and roughly locate teleseismic events and to generate outputs derived from various long- and short-period seismogram parameters, particularly those related to exact epicenter location and source discrimination. The behavior of networks that exchange such data and that consist of both small and large array stations has begun to receive attention. Computer-controlled automatic monitoring and maintenance of large seismometer arrays are discussed.

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



INTRODUCTION

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

Beginning in this reporting period, we have attempted to shift the main focus of our work away from the Large Aperture Seismic Array (LASA) as an end in itself toward consideration of the seismic surveillance problem as a whole and the role that networks of arrays of various kinds might play in this function.

Studies of networks (Sec. I) are presently limited to mathematical simulations and to studies of LASA data as sample outputs from a station to a net of stations. The particularly interesting outputs are various waveform discriminants, which are treated in Sec. II.

The on-site detection and location that take place autonomously at a single large array station are described in Sec. III. These detections and locations, performed at one such station, can be used to initiate off-line array processing functions at this and other stations. Section IV describes recent results in the off-line processing area, both with short- and long-period array structures.

The current program on techniques of automatic maintenance and monitoring of all physical elements of large arrays, along with recent additions and improvements made to the Montana LASA, is described in Sec. V.

P. E. Green

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SEISMIC DISCRIMINATION

I. SEISMIC SURVEILLANCE NETWORKS

A. LARGE ARRAYS IN SEISMIC SURVEILLANCE NETWORKS

During this reporting period, some thought was given to the role that one or more large arrays such as the LASA in Montana might play as components of networks to detect, locate and identify seismic events. Previous experience with the single Montana LASA was used to define the outputs that large and small array stations can contribute to a joint network. The operation of the network had to be inferred, partly through the use of simulation of the type described in Sec. B below.

H. W. Briscoe
P. E. Green
E. J. Kelly

B. SYSTEM SIMULATION OF EPICENTER LOCATION

A system simulation program has been written to permit comparison of various world-wide networks from the point of view of their ability to provide accurate epicenters. A set of station coordinates and noise levels is assigned, and it is assumed that epicenters are determined from reported arrival times by a least-squares procedure. This procedure weights each station report inversely with the variance, σ^2 , of the error in its time-picking (i.e., a maximum-likelihood estimate for Gaussian errors). This variance, in turn, is determined from the formula

$$\sigma = a(A/n)^{-1} + b$$

where (A/n) is the voltage signal-to-noise ratio at the station, and a and b are constants. If $A/n < \frac{1}{2}$, or if the station is beyond 100° from the epicenter, no detection is assumed. We have used the values $a = 1.0$ and $b = 0.1$ (in seconds) so that time-accuracy standard deviations range from 0.1 to just over 2.0 sec. So far, we have treated the source depth as known. All travel time irregularities, including regional source biases and observing station corrections, are assumed known because they are fixed nonfluctuating and presumably measurable properties of the earth.

A linearized error analysis of this estimation procedure, due originally to M. J. Levin, is used to obtain the parameters of the error ellipses for the resulting epicenters. Because station corrections are assumed known, the estimates are unbiased. Although this feature is unrealistic, the intent is to compare various networks on the basis of the random component of their errors of epicenter determination. For each epicenter on the preassigned grid, the program determines the event magnitude required so that the order of the ellipse, of 95-percent confidence, is an assigned number (we have used 500 km^2). The required magnitude is automatically infinite if fewer than three stations detect the event.

Large arrays can be represented in such a study in various ways. For one, the array can be credited with a certain signal-to-noise enhancement factor, γ , which is modeled by assigning

Section I

the array a noise level smaller by the factor γ than that of a conventional station. Another way is to enter the array in the network as N separate stations, where N is the number of subarrays in the large array. This automatically reduces σ^2 for the array by the factor N , which is a reasonable way of modeling performance. In the first method, γ is taken to be $N^{1/2}$. Results will be published in a separate report.

E. J. Kelly
R. J. Kolker

II. IDENTIFICATION

A. VISUAL IDENTIFICATION OF DEPTH PHASES

In an experiment reported earlier,* Briscoe and Sheppard found that the "depth phases" pP and sP can be identified with high reliability at an individual LASA station. Two factors other than SNR gain appeared to contribute (1) space diversity whereby the P-waveforms in various subarrays show slight differences, particularly in the coda, but have the depth phase in common, and (2) the array's directivity, the array aperture being large enough so that the depth phase shows the same time lag after P from subarray to subarray, unlike other phases, interfering teleseisms or reverberation.

As a check on the results of this experiment, it was decided to compare the record in correctly picking depth phases achieved by the Montana array, the five Vela observatory stations individually and collectively, and, if possible, a hypothetical network that included overseas single-sensor stations. (Each Vela observatory is roughly equivalent to a LASA subarray.) For this purpose we picked an interval of time (1 August through 15 September 1966), and a geographical region (the area within 600 km of the boundaries of the Sino-Soviet Bloc area and within 90° of LASA), and analyzed the 64 events so reported by the USCGS ("Preliminary Determination of Epicenters") from world-wide observations, and the 81 so reported in the LASA station bulletins. During this period the LASA station bulletins were prepared from film records of nine subarray outputs and no beams so that the station's performance in picking depth phases was well below that simulated in the experiment reported earlier. Figure 1 shows the results of the analysis. Of the 64 events reported by CGS, the number detected by each observatory is given as the overall height of a corresponding bar, while the number detected by at least one observatory in a hypothetical network of five small arrays was 59 as shown by the next bar. LASA detected and located 43 of the 64 events, but also detected and located (in the prescribed region) 38 events not reported by CGS; this total of 81 is indicated by the bar at the right.

The CGS-tabulated station reports on the 64 events were examined to see how often each observatory station and the Montana LASA reported a phase within 60 sec after P. These pP -P times reported were then checked against the CGS-reported depths. If they lay more than 5 sec outside the CGS one-sigma tolerance range on depth computed from P-times or deduced from depth phases, the reports were called false; otherwise, they were considered to be valid depth phase identifications (or PcP if the time was within 5 sec of theoretical PcP time). The number of valid identifications and false reports for the various stations are shown in the figure as shading within the vertical bars.†

*H. W. Briscoe and R. M. Sheppard, "A Study of the Capability of a LASA to Aid the Identification of a Seismic Source," Technical Note 1966-38, Lincoln Laboratory, M.I.T. (11 July 1966), DDC 437440, H-731.

† In the case of the five-array network, a false report was counted only if all five stations reported falsely. In the case of LASA it was assumed that the 38 events on which no CGS report was obtained subdivided into false and valid reports in the same ratio as with the 49 that CGS did report. This ratio was verified in an independent study of 249 CGS-reported (world-wide) events on which LASA or one or more observatories reported a phase within 60 sec after P. LASA correctly reported 157 depth phases or PcP 's with 18 false alarms; the five-array net correctly reported 125 depth phases or PcP 's with 28 false alarms.

Section II

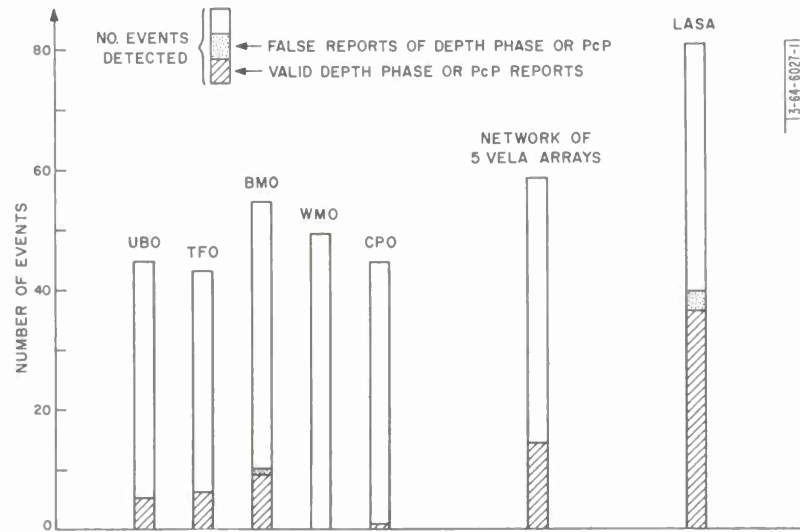


Fig. 1. Depth phase reporting of LASA vs a 5-station network in the United States (1 August - 15 September 1966; distance $\leq 90^\circ$, Bloc countries + 6°).

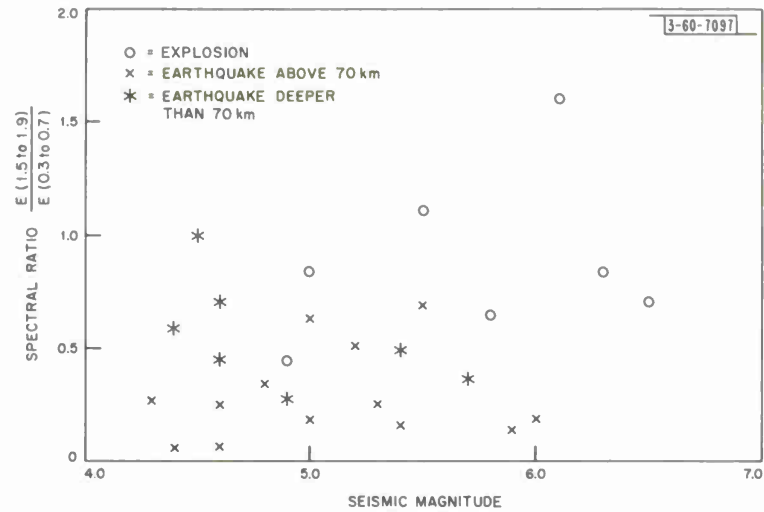


Fig. 2. Spectral ratio of seismic events.

Examination of CGS reports of observations of these same events from single sensor seismological stations around the world revealed that no one such station was nearly so effective in either detection or identification of depth phases as just one of the Vela observatories. The single-sensor stations had relatively high false alarm rates on depth phase reporting, so the difference cannot be ascribed to insensitivity of record analysis at the station. It seems clear that the greater effectiveness of the Vela arrays is due to the SNR gain inherent in the multiple traces plus the small amount of space diversity available within their 3- to 10-km apertures.

Figure 1 shows that, even using only nine subarray outputs displayed side by side and no directive beams, the single LASA made over twice as many valid depth phase or PcP identifications as the five-station network. This has implications in organizing systems of stations and deciding whether they should interchange merely station bulletins (lists of event times) or waveform outputs. Presumably, the large disparity in depth phase performance shown in Fig. 1 would not exist if output traces from the five observatories had been transmitted to a common point and displayed side by side for analysis. This would involve problems in compensating for propagation delays which are not severe for real-time work with the 200-km LASA aperture, but which would become formidable for a five-array net if many epicenter regions were to be examined. The data of Fig. 1 corroborate in a qualitative way the encouraging picture of the depth phase identifying ability of a single LASA given by the earlier results.

P. E. Green

B. RATIOS OF SPECTRAL DENSITIES

The possible use of spectral differences between explosive and natural events as a means of identifying the nature of a seismic source has been suggested and investigated by several people. Near-zone measurements have shown that explosions generate seismic signals rich in high-frequency energy (about 1.5 Hz), but most of this energy is filtered out in propagation to teleseismic distances. Most investigations of the short-period P-energy have been limited by low SNR except for a very narrow band around 1 Hz.

Since one of the potential advantages of a large array is to provide a good SNR on signal energy over a wider bandwidth than that available from a smaller station, a study is in progress to investigate whether the wider bandwidth will help detect spectral differences between explosive and natural sources. The initial procedure has been to use beamforming (delay-and-sum) processing to improve the SNR on a signal and then to compute the ratio of the energy in a band from 0.3 to 0.7 Hz to the energy in the band from 1.5 to 1.9 Hz. This ratio should be higher for earthquakes than for explosions. A set of 27 events including explosions from four underground test sites was processed using this procedure. Results of this preliminary experiment, which are shown in Fig. 2, tend to show some separation of the two source types. One exception is apparent in this figure. A presumably explosive event of LASA magnitude 4.9 has a ratio of 0.44. This was found to be the result of an unusually high level of low-frequency noise after processing so that the low-frequency window was actually looking at noise, not signal. The delay-and-sum processing was not effective in this case, partly because data from several subarrays contained transients due to phone-line trouble and calibrations being performed during the time the event arrived, so they could not be used in the beamforming process. More elaborate processing

Section II

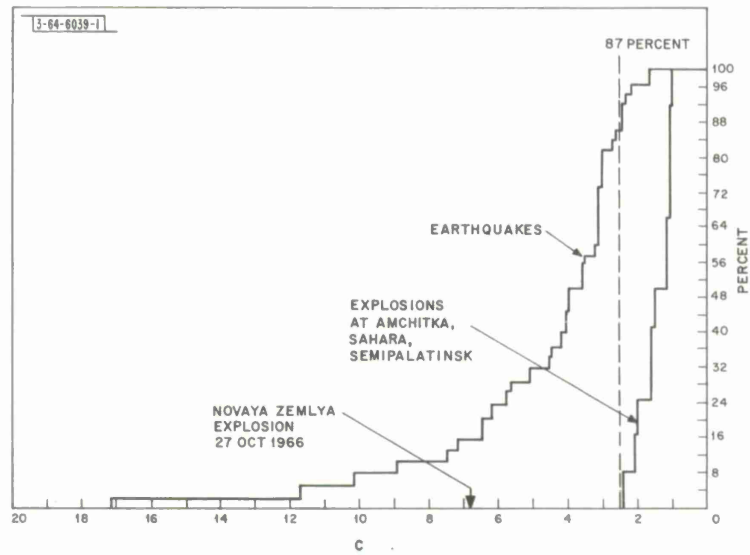


Fig.3. Percent of earthquakes with complexity $\geq C$.

techniques are being investigated to provide better signal-to-noise level, particularly when only part of the array is operating normally.

The small sample used in this preliminary experiment was chosen as a pilot population, and a much larger sample including all events from the experiment described in Sec. III-D will be processed when the procedure has been evaluated and debugged.

H. W. Briscoe

C. COMPLEXITY MEASUREMENTS

The automatic station bulletin program (discussed in Sec. III-A) computes, among other things, the complexity of each detected P-arrival at each subarray, and averages those complexities which correspond to subarray output channels used in the determination of epicenter. As used here, the complexity of a waveform $f(t)$, is defined by

$$C = \frac{\int_5^{30} |f(t)| dt}{\int_0^5 |f(t)| dt}$$

where $t = 0$ represents the time of automatic detection (t in seconds). For a single event, the measured complexities are observed to vary widely across the array, and it was thought that the average value might be a more reliable discriminant than single trace values. Another approach to averaging over the array was described in Sec. V-B of the last Semiannual Technical Summary Report.*

The automatic bulletin program, using a notch prefilter to minimize microseismic noise, was run on 38 earthquakes and 12 explosions in our data library. The earthquakes were all P-arrivals (i.e., distance not greater than 100°) and included none whose reported depth exceeded 200 km, on the grounds that deeper events, while often simple in waveform, would be recognized as deep from P-arrival times alone. The explosions were from three source points. The results are shown in Fig. 3, a plot of percentages of the two populations whose complexities exceeded the value of the abscissa. None of the explosions in this group had a complexity greater than 2.5, while 87 percent of the earthquakes were more complex than this. Three of the explosions had complexities in excess of 1.6, and these were the three weakest explosion records in the group (the largest amplitude was $11 \text{ m}\mu$). Noise alone has a complexity of about 6, and weak signals nearly always have higher complexities than they would have had at high signal-to-noise ratios. All of the earthquakes in our population had complexities in excess of 1.6, hence the power of complexity as a discriminant could perhaps be significantly improved by computing complexities only on array-processed traces of high SNR. A test of this notion is in progress.

The explosion complexities also showed a relatively small variation across the array. For each explosion we computed the standard deviation of the 21 measured complexities, and found that the average value (for all 12 explosions) was 0.4, just 27 percent of the average complexity of 1.5. The earthquakes showed a much higher variability.

*Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (30 June 1966), DDC 637308.

Section II

The recent (27 October 1966) event in Novaya Zemlya showed strongly anomalous behavior for a presumed explosion (similar to former events from that region). Its complexity, averaged over the array, was 6.8, with a standard deviation of 41 percent of that value. No explanation for this is available, and complexity thresholds may ultimately have to be dependent upon epicenter.

E. J. Kelly

D. RECTILINEAR MOTION STUDIES

The three-component processor described in Sec. VII of the last Semiannual Technical Summary Report has been operated with on-line signals telemetered from a set of short-period seismometers at TFO in Arizona. The processor is basically an off-line device in that its parameters (gains, filter center frequencies and bandwidths) ought to be adjusted and optimized for each event under study. However, due to personnel limitations we have used only unattended real-time film monitoring of the Arizona data with parameters set to form the best compromise over the range of events which might occur.

One expects the processor to enhance an analyst's ability to discover and identify later phases of an event, including pP, out of the large amount of delayed return energy arriving after the first P. The processor offers an advantage over operations performed on exclusively vertical waveforms in that it is sensitive both to the degree of rectilinearity of the earth particle motion and to the azimuthal angle of arrival. (Experience has shown that during an extended coda of, for instance, 20-sec duration, 75 percent of the time can be eliminated as possible pP. The remaining 5 sec are typically split up among several discrete peaks which the processor output suggests are possible phases.) It is a difficult problem to measure quantitatively the amount of improvement in phase-picking the processor really affords. This is because the processor is not a threshold device (such as an event detector) and because, as an analyst's aid, its output should be used in conjunction with other analytical techniques (such as beam outputs steered at different velocities) to narrow down the range of possibilities in making actual phase picks.

Nevertheless, an attempt was made to see what kind of phase-picking was possible using the output of the present processor configuration as the primary indicator. We studied all available events reported by the CGS during the period 1 August through 15 October 1966 in the region within 6° of the Sino-Soviet Bloc boundaries. A number of events were not available on film; others were available, but of too large or small an amplitude to be of use to the processor with the gain settings then in effect; and a few were obscured by severe man-made noise at the site. No events were omitted from consideration because of poor waveform or difficulty in reading later phases where the initial P-phase was visible.

From the 24 usable events so obtained (including 18 in the Kurile-Kamchatka region), an attempt was made on each event to pick the single cleanest depth phase candidate (except once when none seemed likely) using the filmed processor output. Two general principles were followed: (1) a depth phase should present a processor output very similar in appearance to that obtained from P itself; (2) a depth phase should have one of the largest subsequent amplitudes at the proper azimuth. These two criteria for phase-picking occasionally conflicted. In such cases, it was usually arbitrary which criterion was actually applied. The time of the phase candidate so selected was then compared with possible times predicted for pP, sP, or PcP from

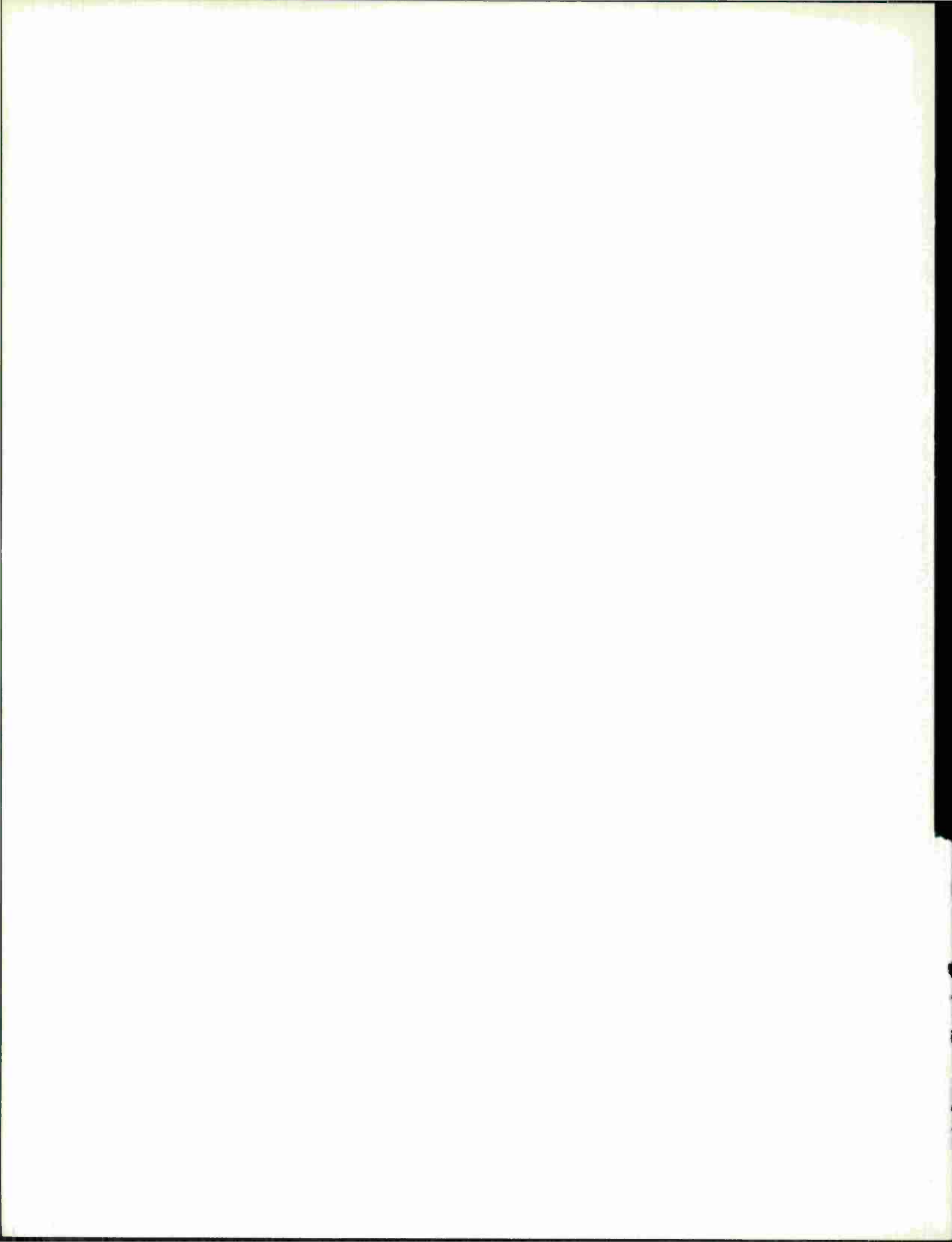
	Bloc	Kurile-Kamchatka
No. of three-component film records available	37	29
No. of usable three-component records	24	18
No. of which apparent depth phase selected	23	17
No. of PcP's	1	1
No. of false alarms	5	3
No. of pP or sP	17	13
No. of usable three-component events on which TFO reported	24	18
No. of TFO-reported depth phases	5	5
No. of PcP's	0	0
No. of false alarms	0	0
No. of pP or sP	5	5

the CGS location and depth determinations on this event. If the selected candidate lay within the tolerance range for pP or sP (plus or minus an additional 5 sec to allow for timing errors in reading the records), the phase pick was considered successful. Valid PcP picks are listed separately. (These are the same criteria used in the experiment described in Sec. II-A.)

Table I compares our TFO three-component readings with the reports to CGS from TFO vertical outputs alone. (Comparable data on all five observatory arrays and the LASA are contained in Fig. 1.) It is seen that a very high score is achieved by the three-component processor, accompanied, however, by a high false-alarm rate of about one to every four valid picks. This is to be contrasted with the five-station Vela array network and LASA, which achieved a comparable fraction of successful picks but no more than two false alarms out of a set of 64 events. In comparison with TFO alone, the processor gives a much higher rate of valid picks (three times as many) but, again, a much higher false alarm rate. Although it cannot be shown in Table I, which is based on a single pick from each event, the processor frequently disclosed several good phase candidates and it frequently occurred that the second and/or third candidates turned out to be valid whether or not the first candidate itself was or was not a valid phase.

An improved three-component processor having outputs normalized by the envelope of the vertical seismogram will be employed in further studies.

C. A. Wagner
E. Gehrels



III. LASA DETECTION AND LOCATION

A. LASA DAILY STATION BULLETIN

The format and procedures for generating the LASA station bulletin have been modified several times during this period. In August the format was modified to one which could be interpreted automatically and was easier to understand. During the last quarter, an automatic bulletin generation program was used and its reliability analyzed to suggest areas where it could be improved. In November additional off-line programs to aid in generation of the bulletin were put into routine use and the format for some of the parameters was modified.

Studies of the amplitude scatter at various subarrays in the array are summarized in Table II. The large scatter between subarrays compared to that within a subarray has led to the conclusion that the magnitude estimate for an event obtained by averaging over all of LASA has a significantly smaller scatter than that from a single small array station. As a result, one of the changes in bulletin format in November was to report an average magnitude to the nearest 0.1 magnitude unit instead of using a single subarray and reporting to 0.5 magnitude unit.

	Ratio of Standard Deviation to Mean		Ratio of Strongest to Weakest Sensor	
	Typical Event (percent)	Worst-Case Event (percent)	Typical Event	Worst-Case Event
Subarray (16 sensors in F4)	15	30	1.8:1	2.6:1
Array (center sensors from each of 16 subarrays)	40	80	4:1	9:1

A preliminary evaluation based on one month of data indicates that the routine use of the off-line programs designed to aid the preparation of the bulletin (including the initial automatic bulletin program described in Sec. B below) has improved the threshold for event reporting in the bulletin by 0.2 to 0.3 magnitude unit compared to bulletin preparation without machine aid. During normal operating conditions, magnetic tape recordings of array data are not available for 24 hours a day, 7 days a week, so the improved threshold will only be realized part time.

The performance of the bulletin during August and September is summarized in Table III.

The total improvement over the last 6 months in the overall event reporting ability of the LASA station can be deduced from Fig. 4, which indicates at the present time a 4.1 magnitude

TABLE III	
LASA STATION BULLETIN ERRORS	
(Based on the 58 Events Detected and Located by Both LASA and CGS as Lying $\leq 90^\circ$ from LASA and Within 6° of Sino-Soviet Bloc; 1 August - 15 September 1966)	
Magnitude (LASA - CGS)	Mean: +0.09 Standard deviation: 0.31
Epicenter location	Standard deviation: 3.4° (370 km)
Origin time	Standard deviation: 21.8 sec

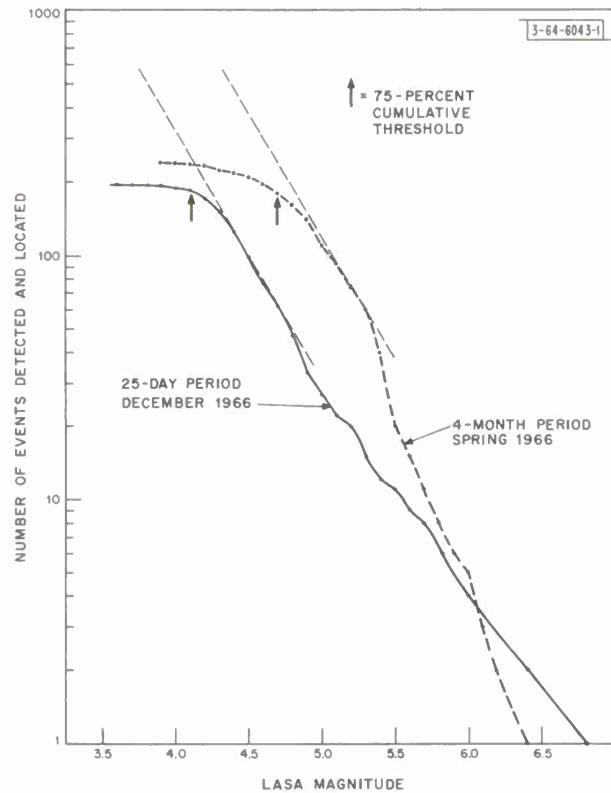


Fig. 4. Number of events detected and located at and above a given magnitude vs that magnitude.

threshold above which 75 percent of all events 40° to 90° from the LASA are detected and located. The dotted curve shows results obtained in the spring of 1966* using visual operations only, before the initiation of the daily bulletin.

So far, the bulletin has been prepared using subarray outputs separately, that is, without combining them into beams as in Secs. III-C and -D. Very recently, we have started adding beam-detected and located events.

H. W. Briscoe

B. AUTOMATIC STATION BULLETIN

A Fast Automatic STATION BULLETIN (FASTABUL) program has been written which automatically computes and tabulates:

- (1) The amplitude of the first arrival,
- (2) The period of the first arrival,
- (3) The complexity of the seismic waveform,
- (4) The direction of first motion,
- (5) The horizontal phase velocity, and
- (6) The azimuth of the best-fitting plane wave across the whole array.

From these last two quantities, the station bulletin also computes:

- (7) The distance of the epicenter from LASA,
- (8) The latitude of the epicenter,
- (9) The longitude of the epicenter,
- (10) The arrival time of the first motion at LASA, and
- (11) The origin time.

From items (1), (2), and (7) it computes:

- (12) The magnitude of the event.

The basic problems in an automatic station bulletin are to have the computer recognize a P (or PKP) first arrival from the background noise and to measure accurately these arrival times at each subarray. This program goes through a series of operations on the seismic waveforms and picks arrival times, culls these arrival times and discards the ones that disagree with a plane wave propagating across the array, and computes the station bulletin parameters. It also plots the seismograms and marks on them the times it has picked. Under normal conditions it does rather well, but sometimes, as when the signal is extremely weak or when two teleseisms arrive together, it does poorly. In these cases, a human operator can look over the time picks and perhaps make a wiser choice of channels for the computer to use to recompute the station bulletin parameters. This is called the "semiautomatic mode" of operation.

The input waveforms to this program can be the twenty-one "10" seismometer outputs, or 21 maximum-likelihood processed traces where each trace is a combination of the entire output from each subarray, or waveforms from any type of S/N improvement scheme. Therefore, the minimum magnitude for which this automatic station bulletin will work depends on the type of preprocessing used on the input waveforms. If only one waveform is input to the program (for example, a beam made up from the entire array), the location of the source is determined

* E. J. Kelly, "LASA On-Line Detection, Location and Signal-to-Noise Enhancement," Technical Note 1966-36, Lincoln Laboratory, M.I.T. (1 July 1966), DDC 636144, H-727.

Section III

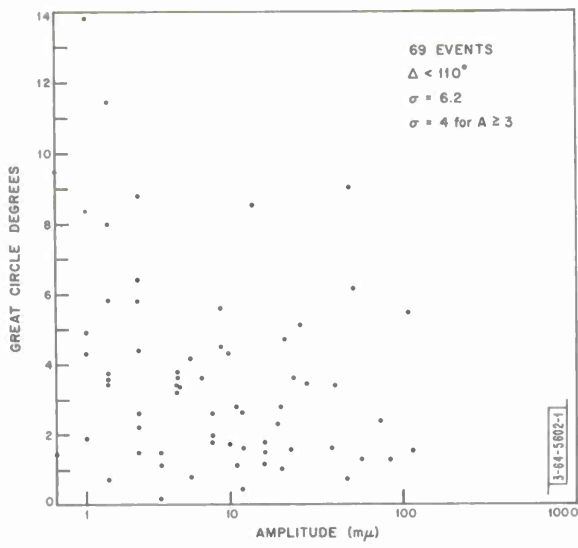


Fig. 5. Error in location (automatic station bulletin).

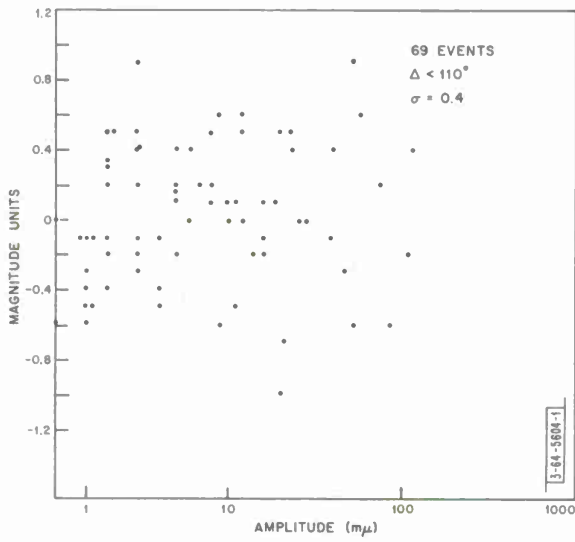


Fig. 6. Error in magnitude.

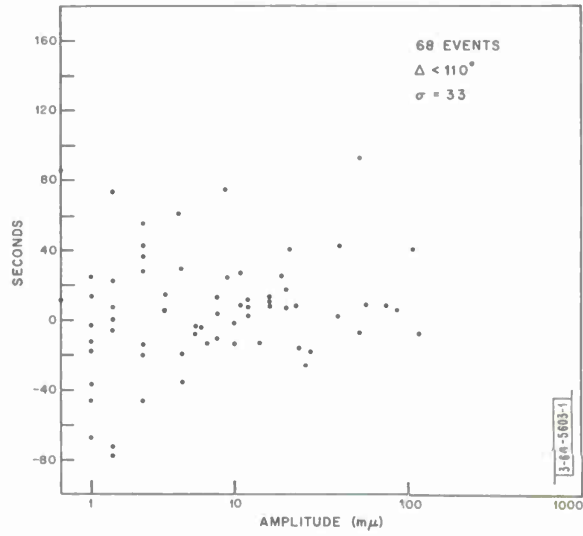


Fig. 7. Error in origin time.

by where the beam is pointed, so the program need only calculate complexity, magnitude, first motion, and origin time.

The exact method by which the automatic station bulletin parameters are computed is described in detail in a recent report.*

This program was tested in the fully automatic mode using 70 events, which are all the events in our library from 1 October 1965 to 13 January 1966 that have been identified with CGS events and for which, therefore, we know the location, magnitude, and origin time. This should represent a typical population of events. The events which were not saved in our library were later arriving phases of strong events.

The results of the test for all the events with epicenters less than 110° from LASA (P phase only) are shown in Figs. 5, 6, and 7. The error is plotted as a function of LASA amplitude because, as the signal becomes stronger, the automatic identification becomes better. The overall mean-square error using fully automatic location, averaged over events of all sizes, was 6.2 great circle degrees. The mean-square error for all the events which were received with an amplitude greater than $2 \text{ m}\mu$ was 4° . These can be reduced somewhat by employing the semi-automatic mode, but there is a limit of about 2.5° due to the limited aperture of the LASA array itself (200 km) and inherent timing errors which include our present imperfect knowledge of the station corrections. These timing errors become much more restrictive for the PKP phases. The errors due to the travel time curves seem small compared to these timing errors, even though a depth of 33 km is assumed throughout. The overall mean-square difference between the CGS and LASA magnitudes is 0.4, but this is not too surprising since the CGS reports are averaging stations with world-wide coverage and which have large deviations themselves. The overall mean-square error in determining the origin time is 33 sec.

It is difficult to put a lower bound on the magnitude for which this automatic station bulletin will work. If the signal is received with an amplitude greater than $5 \text{ m}\mu$, the automatic picks are made about as well as a human can make them.

Recently, the FASTABUL program has been modified to preprocess the individual waveforms which are input to the program. The preprocessing used here means passing the data through a four-pole four-zero filter which forms two notches in the frequency domain at 0.2 and 0.3 Hz. The filter has very little phase shift at frequencies higher than these so that long-period microseisms are attenuated without significantly distorting the teleseism waveforms. This new program (NOTCHSTABUL) has been tested using the same 70 events mentioned above. Although the results were not reduced in the same manner, it appears that, qualitatively, the prefiltering improves the performance by reducing the overall mean-square error.

P. L. Fleck

C. OBSERVATIONS IN HONSHU AREA

The difficulty of obtaining a direct verification of the detection capability of LASA, when some form of predetection processing (such as beamforming) is employed, owing to the lack

* P. L. Fleck, "FASTABUL (A Fast Automatic STATION BULLETIN Program)," Technical Note 1967-3, Lincoln Laboratory, M.I.T. (6 January 1967).

Section III

of independent reporting of the requisite weak events, has frequently been pointed out. In order to obtain reports of weak events in time to permit the saving of tape recordings in Montana, we focused our on-line beams on Japan and made arrangements with the Earthquake Research Institute of the University of Tokyo, who kindly allowed one of our people (J. Fairborn, a graduate student in the M.I.T. Geophysics Department) to work there for a time with direct access to their data. The data itself consisted of Helicorder-type recordings from a tripartite of stations surrounding Tokyo. These stations are equipped with short-period instruments (peak response at 20 Hz), designed for the detection of local events. The times and amplitudes of the P and S arrivals for a 5-week period in midsummer were recorded, and the event times teletyped to this Laboratory. As a result, tape recordings of about 150 events were obtained, more than half of which are from the Matsushiro area.

The great majority of these events were within 10° of Tokyo, and we developed a simple plane-earth method for finding the epicenters from the arrival times and S-P intervals. The time-difference between the arrivals at two stations implies (using an empirical P_n -speed of 7.5 km/sec) that the epicenter is on a certain hyperbola, and the S-P interval for one of these stations fixes a distance, yielding two possible epicenters. The empirical relation

$$D = (7.86 + 0.04\tau) \tau \quad ,$$

where τ is the S-P interval in seconds, was used to obtain the distance D in kilometers. If a third station arrival was recorded, the ambiguity between the two epicenters can be resolved. In most cases, more than one S-P interval was recorded and often all three arrival times were measured. The consistency of the epicenters obtained from such redundant data was fair, and we estimate that our epicenters are accurate to ± 15 km for most of the events.

The next step is the off-line formation of beams steered for the computed epicenters which, if the epicenters themselves are to be believed, will establish the detection threshold for beamforming in the optimum case where the events occur exactly in the beam. In parallel with this, a grid of 14 beams covering Honshu were formed off-line on all recordings. These beams are 4° apart in each direction, and should give us some idea of how future beamsplitting techniques will work out. The experiment is also a severe test of our station corrections for this area, and should provide an absolute calibration of beam pointing of considerable precision.

Although signal amplitudes at the tripartite stations were recorded, we do not have sufficient confidence in our knowledge of the effective magnification of the instruments or the precise nature of the first arrivals to be able to determine (teleseismic) body wave magnitudes. Hence, amplitudes at LASA are being measured on those events detected, and a cumulative curve of number of detections vs apparent magnitudes is being constructed.

The on-line beams were formed using rough and incomplete station corrections, and their performance, as read from film recordings, was not impressive. However, the beams formed off-line have used station corrections for the entire array for the Honshu area,* and they have shown the full S/N enhancement factor (\sqrt{N}) that has been found with beams using hand-picked times.

* "Travel-Time Anomalies at LASA," Report No. LL-1, Earth Sciences, A Teledyne Company, Alexandria, Virginia (2 November 1966).

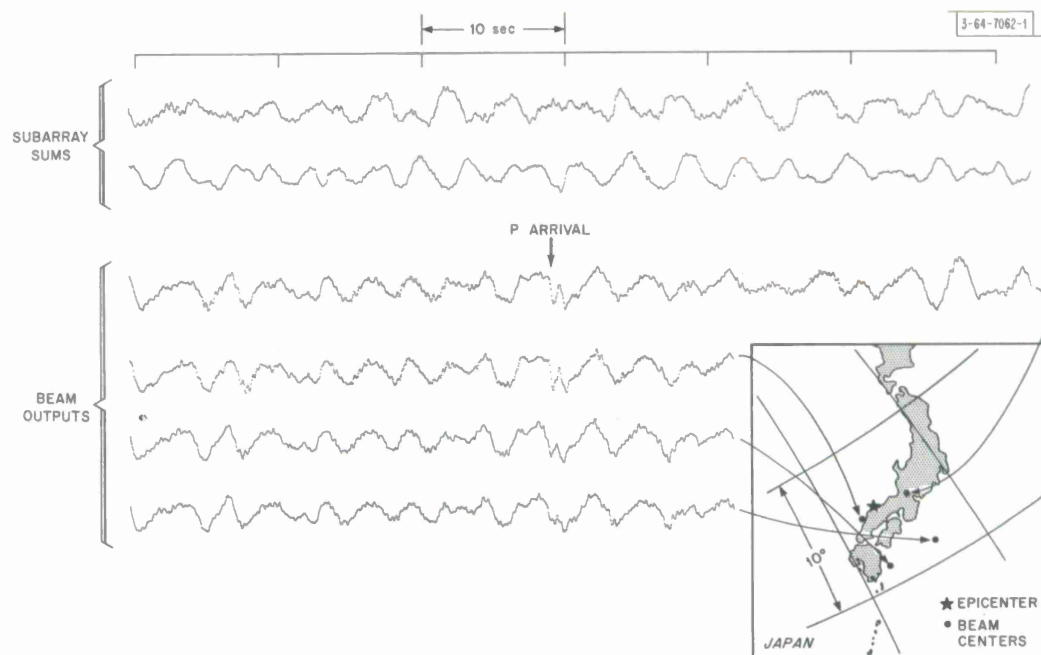


Fig. 8. Several beam outputs on an event of LASA magnitude 3.7.

TABLE IV KURILES UNDERWATER TEST EXPLOSIONS		
	5 Ton	1 Ton
Total number	10	7
Data gap on beams	3	3
Visually detected	5	1
Possible detection	1	1
Not detected	1	2

Section III

Reasonable agreement has been found between the epicenters determined directly from the ERI data and those inferred from the grid of beams. Based on the 10 to 15 events of marginal visibility we have so far found, we would place the 50-percent probability of detection threshold for beams at about magnitude 3.5 (fixed level, not cumulative probability).

In Fig. 8 we show an example of the Japan data, an event of apparent magnitude 3.7. The upper two traces are straight subarray sums, unfiltered, and the next four are beams, also unfiltered, steered at points near the epicenter (determined from ERI data) as indicated in the figure. These beams are steered sums of the 21 straight-sum subarray outputs. We are also studying the performance of beams made up of seven sensors from each of the 21 subarrays, each sensor appropriately delayed, and using various sets of station corrections.

E. J. Kelly
R. M. Sheppard

D. KURILE OBSERVATIONS

During November and December 1966, as part of another Vela Uniform program, a network of ocean-bottom seismometers was placed off the Kurile Islands and a series of 17 high-explosive shots were fired within the network. In order to take advantage of the local coverage of small magnitude events provided by this network, all five beams available in the on-line LASA processing facility were steered to the Kurile region and an attempt was made to operate the site 24 hours a day. Data tapes were saved for all events detected and located within 5° of the Sino-Soviet region from 1 November to 20 December, and for all events detected but not located from 15 November to 20 December. Events using the beams were detected by visual scanning of film records of the beam data. Although all of the data has not been assembled or analyzed, preliminary tabulation of the first month of data shows 44 located Sino-Soviet events (within 5° of the Sino-Soviet region) between 1 November and 6 December, and 67 events detected but not located between 15 November and 6 December. Off-line processing of several days' unlocated events at Lincoln Laboratory indicate that approximately 20 percent of the currently unlocated events will be located in the Sino-Soviet region.

The results of visual detection of the 17 high-explosive shots from film records are shown in Table IV. The film records were unfiltered or filtered with a wide-band filter. This presentation of the data was thus not designed to optimize detection. The best recorded shot (3 December at 22:49 GMT) had a period of 0.8 sec and a LASA magnitude of approximately 4.4.

H. W. Briscoe

IV. ARRAY PROCESSING

A. STUDIES OF OPTIMUM SUBARRAY GEOMETRIES AND PROCESSING

1. Implications from Beamforming

In an earlier report,* some results were described which showed that in the 0.6- to 2.0-Hz P-wave spectral range, an increase of minimum inter-element spacing from 0.5 to 3 km resulted in a significant increase in SNR gain using delay-and-sum (DS) processing (beamforming). The gains achieved were roughly the same as those available from maximum-likelihood (FS) processing. These results argue in favor of redesigning the present 25-element LASA subarrays to have an aperture of around 20 km with roughly 3-km spacing (see Sec.V-C). A LASA composed of such subarrays would develop a large fraction of its total available SNR gain by on-line beamforming.

In order to determine an optimum configuration for the design of future LASA subarrays, a number of beamforming experiments were carried out, using LASA data, which essentially continue the earlier experiments. The LASA data were prefiltered with the special 0.6- to 2.0-Hz Butterworth filter of Fig. 9, and various arrangements of seismometers were considered. The results are presented in Table V.

It is seen from the noise reduction figures that if the sensors are spaced about 6 km apart, the noise is essentially random in the 0.6- to 2.0-Hz frequency range. At this spacing, the noise reduction is 13.2 db, which is close to the 14 db that would be obtained if the noise were incoherent. This noise reduction is consistent with the noise coherency measurements discussed in the next section. As a practical matter, it is inconvenient to have 6-km spacing between sensors, so that 3-km spacing seems more reasonable. If 25 sensors are spread over a 22-km aperture with 3-km spacing, an average SNR gain of about 11 db is achieved. If this minimum spacing is maintained but more sensors are added in the desire to increase the gain, then the aperture of the subarray must be increased. However, as this is done, the signals tend to be less coherent so that the loss in gain due to signal reduction increases.

The highest average SNR gain was obtained with 58 sensors spread over 40 km. However, the loss relative to \sqrt{N} is 4.7 db, which compared unfavorably with the 3.0-db loss when 25 sensors were spread over 22 km. Thus, the results indicate that the most reasonable choice for the design of a future LASA subarray is to have 25 sensors with a minimum 3-km spacing between sensors and with an aperture of approximately 20 km.

2. Coherency Measurements on Noise

The manner in which the coherency of seismic noise decreases with distance provides an indication of how much gain can be obtained by delayed sum processing. This relationship will be developed in a forthcoming report.

The main signal energy in the LASA short-period seismometer is at frequencies between 0.6 and 2.0 Hz. Values of $|C_{ij}(f)|$ were computed at five frequencies in this range to determine

* J. Capon, R. J. Greenfield and R. T. Lacoss, "Off-Line Signal Processing Results for the Large Aperture Seismic Array," Technical Note 1966-37, Lincoln Laboratory, M.I.T. (11 July 1966), DDC 637016, H-730.

Section IV

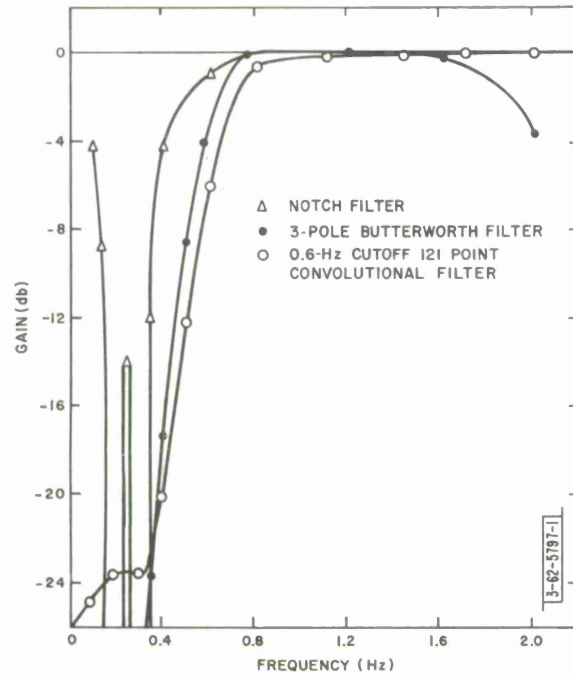


Fig. 9. Gain characteristics of various filters.

TABLE V
RESULTS OF BEAMFORMING EXPERIMENTS

Aperture (km)	Minimum Spacing (km)	Number of Sensors = N	Number of Runs	Noise Reduction* (db)		Average Noise Reduction* (db)	Signal Reduction† (db)		Average Signal Reduction† (db)	Average SNR Gain (db)	\sqrt{N} (db)
				Min	Max		Min	Max			
7	0.5	25	30	4.0	6.5	6.1	0	0.2	0.1	6.0	14
22	3	25	5	10.0	12.0	11.5	0.2	0.7	0.5	11.0	14
40	6	25	7	10.9	15.4	13.2	0.4	2.5	1.5	11.7	14
40	3	58	20	11.6	16.1	14.5	0.6	4.2	1.6	12.9	17.6
65	3	91	6	14.3	16.5	15.3	1.2	6.1	3.1	12.2	19.6

* Measured with respect to average sensor noise power.
† Measured with respect to average sensor signal amplitude.

Section IV

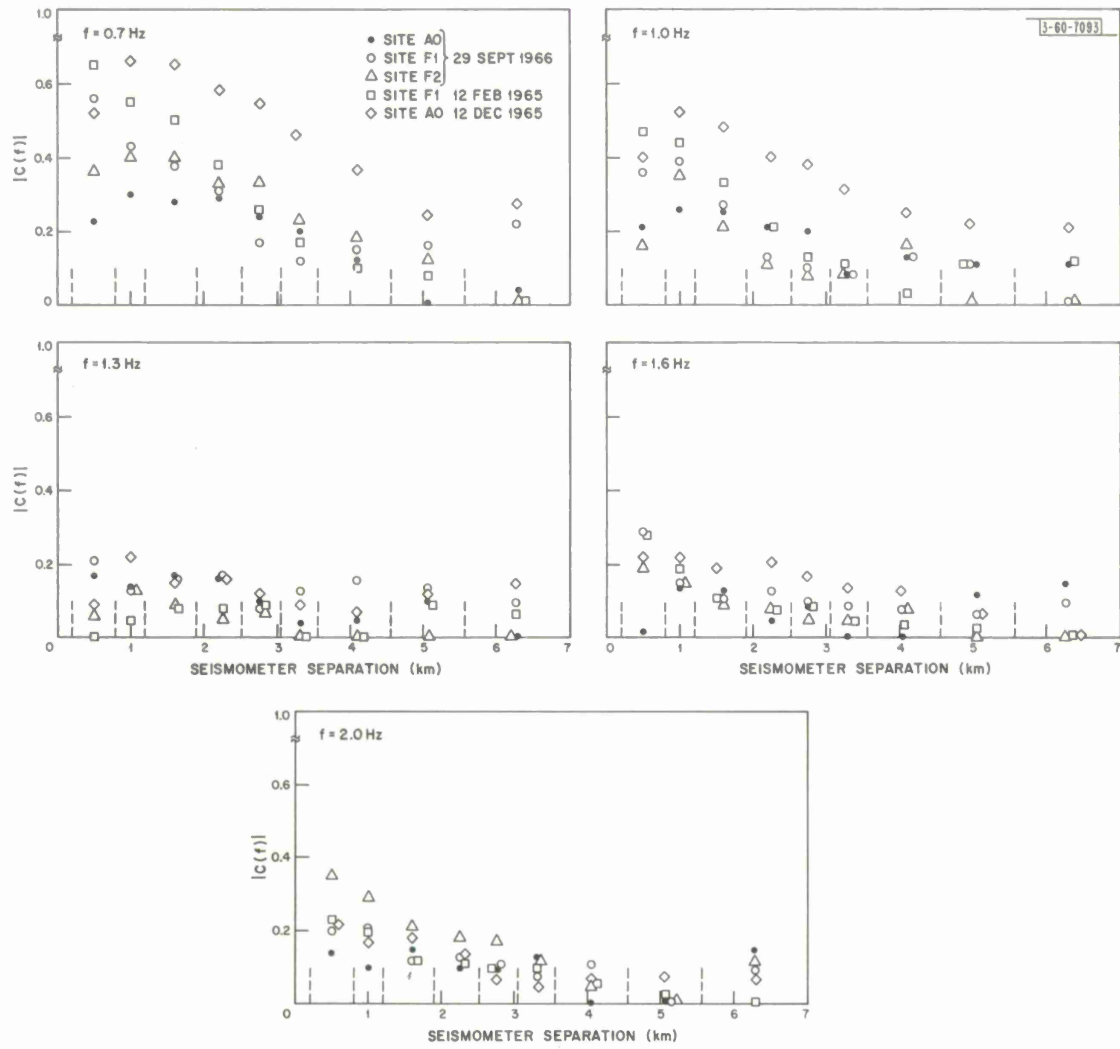


Fig. 10. Noise coherency vs seismometer separation.

how $|C_{ij}(f)|$ varies as a function of seismometer separation. The value of $|C_{ij}(f)|$ for each pair of seismometers in a LASA subarray was computed from the definition

$$|C_{ij}(f)| = \frac{|f_{ij}(f)|}{\sqrt{f_{ii}(f) f_{jj}(f)}}$$

where

$f \equiv$ frequency

$C_{ij}(f) \equiv \frac{f_{ij}(f)}{f_{ii}(f)}$ \equiv complex coherency for i and j^{th} seismometers

$f_{ij}(f) \equiv$ cross power spectra for i and j^{th} seismometers.

The estimation of $f_{ij}(f)$ was made using the direct segment method.* The data block length used was 10 sec which gives a spectral resolution of 0.1 Hz. The length of data used for estimation varied from 410 to 700 sec or from 41 to 70 data blocks.

In a subarray, the distance between seismometers varies from 0.5 to 7 km. This range of separations was divided into nine subranges, and an average was formed for each subrange using all separation pairs in the subrange. The average for the k^{th} subrange is denoted by $\bar{C}_k(f)$. The measurements of $C_{ij}(f)$ are biased, since a finite length of record was used for the spectral estimation. The bias is especially large for values of $C_{ij}(f)$ near zero. A correction for the bias was made to $\bar{C}_k(f)$ using tables given by Amos and Koopmans;† the number of degrees of freedom for the measurements, called n by Amos and Koopmans, is equal to the number of data blocks used in the estimation. The corrected values of $\bar{C}_k(f)$ are denoted by $\tilde{C}_k(f)$. In Fig. 10, $\tilde{C}_k(f)$ is plotted vs the separation distance covered by the subrange. The results show that the noise is more coherent at the lower part of the signal frequency band. At 0.7 and 1.0 Hz, $\tilde{C}_k(f)$ is generally below 0.2 for separations greater than 3 km.

3. Convolutional Filter for Short-Period Data

A linear-phase high-pass convolutional digital filter may be used to remove, with almost no distortion, microseismic noise while passing a teleseismic signal. An input signal $X(t_i)$ is filtered by the following formula to give the output trace $Y(t_i)$:

$$Y(t_i) = X(t_i - t_0) - \sum_{k=0}^{2L} X(t_i - kt_s) \cdot \Lambda(kt_s) \cdot R(kt_s)$$

where

$t_s \equiv$ sampling rate

$L \equiv \frac{t_0}{t_s} =$ half the length of the filter

* J. Capon, R. J. Greenfield and R. J. Kolker, "A Frequency-Domain Synthesis Procedure for Multidimensional Maximum-Likelihood Processing of Seismic Arrays," Technical Note 1966-29, Lincoln Laboratory, M.I.T. (6 May 1966), DDC 634233, H-724.

† D. E. Amos and L. H. Koopmans, "Tables of the Distribution of the Coefficient of Coherence for Stationary Bivariate Gaussian Processes," Monograph SCR-483, Sandia Corporation (March 1963).

Section IV

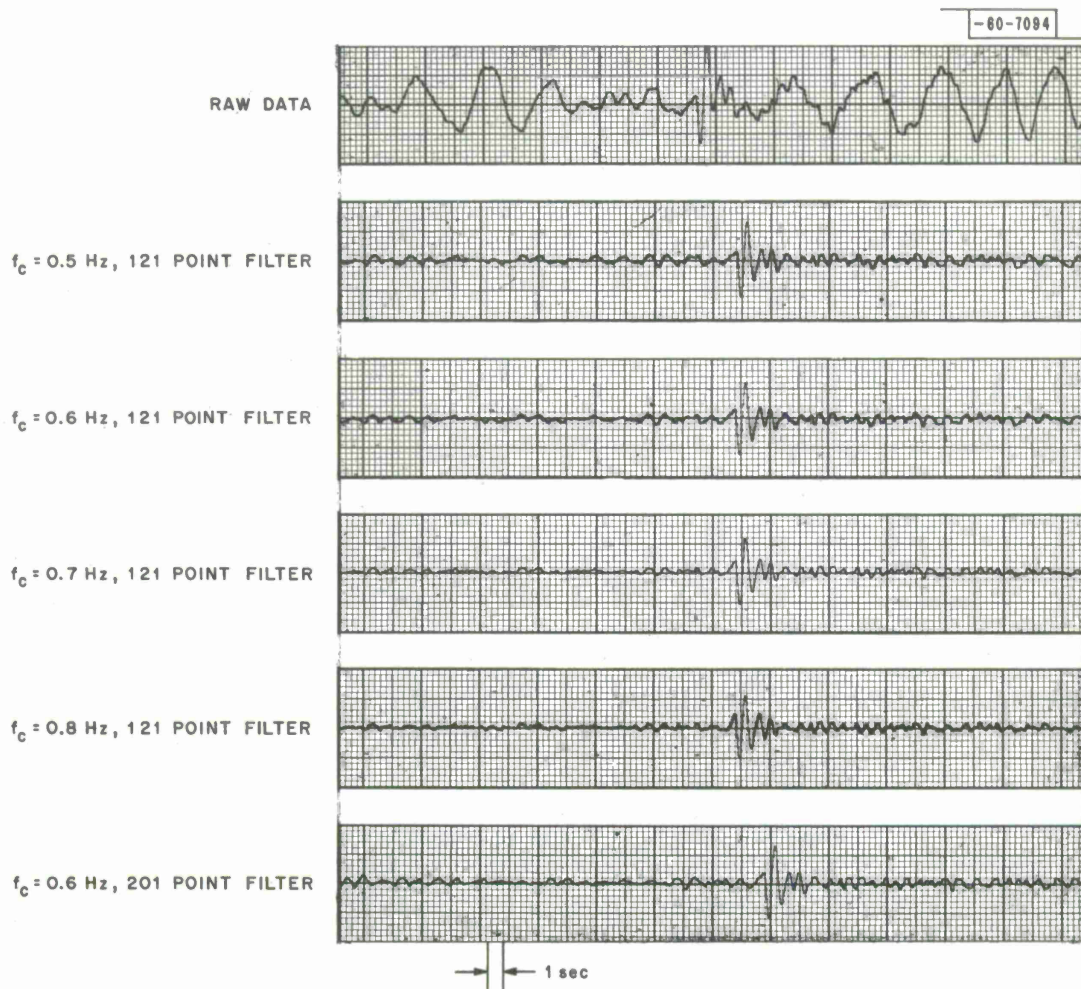


Fig. 11. Example of convolutional filter of Fig. 9 applied to record of 20 November 1965 Marianas event.

$$R(kt_s) \equiv \sin \frac{[2\pi f_c (kt_s - t_o)]}{\pi(kt_s - t_o)}$$

$$\Lambda(kt_s) \equiv 1 - \frac{|kt_o - t_o|}{t_o}$$

$$f_c \equiv \text{low-frequency cutoff} \quad .$$

The frequency-domain response of this filter for a particular choice of parameters, as well as the response of two other filters used in LASA data processing, is shown in Fig. 9. In Fig. 11, the results of applying the convolutional filter to seismic data show how little this filter distorts a teleseismic signal.

B. LONG-PERIOD RESULTS

Preliminary processing of data from the 21 three-component long-period seismometers in LASA has been completed. (The nominal transfer characteristic of the seismometers is shown in Fig. 18, Sec.V.) Delay-and-sum, optimum one-point filters (WDS) and maximum-likelihood filters (FS) have been applied to each of the three components of the LP data from LASA. The processors were adjusted to pass either S or P waves from teleseismic events.

We have reached the following tentative conclusions based upon preliminary results: (1) Sophisticated linear array processors can be applied in order to enhance signals on long-period seismograms with no measurable signal degradation on the output trace. (2) Voltage SNR gains in the signal band at least as large as \sqrt{N} can be achieved on all three components using LP data, where N is the number of seismometers. (3) The LP noise can become more organized causing SNR gain of delayed sum processing to be reduced a few db below \sqrt{N} , but not adversely affecting the SNR gain of optimal processors. (4) Experiments with two events from the same region over a week apart have indicated that filters which are designed using one of these events can be used to achieve 20- to 25-db signal rejection when applied to the other. This ability to see through events will be of great value when dealing with LP data because of the long duration of surface wave trains.

Table VI shows typical SNR improvements obtained for a few events. The three forms of processing were applied to three strong events to determine SNR gain when the processor is designed to pass either P or S phases undistorted. The range of observed gains, due to normal statistical fluctuations as well as variations in background noise, is shown in the Table. The range for delayed summing to enhance surface waves included other events in addition to the three mentioned above. Figure 12 shows the waveforms obtained on the three orthogonal sets of seismometers in processing one event to enhance S relative to noise. Figure 13 shows the results of processing which made an initially invisible LP P-phase quite visible on the processed traces. Figure 14 shows the power spectral density of a typical vertical seismogram and a typical curve of SNR gain vs frequency for maximum-likelihood processing. Curves for horizontal components are similar.

An experiment was performed to determine if filters which are designed to suppress a long-period interfering teleseism on one particular day can be used to suppress a teleseism from the

TABLE VI
LONG-PERIOD SIGNAL-TO-NOISE GAINS (db)
(N = 19, \sqrt{N} = 13 db)

	Component	Type of Processing		
		DS	WDS	FS
P-phase	Z	8-11	12-14	13-16
	X	8-13	11-14	12-16
	Y	7-13	11-14	13-15
S-phase	Z	8-11	12-14	13-16
	X	8-13	11-14	12-16
	Y	7-13	11-14	13-15
Surface-wave phase	Z	6-11	Not measured	
	X	10-12	Not measured	
	Y	9-11	Not measured	

same region on another day. The filter coefficients for FS and WDS were obtained by placing a 21 November 1966 teleseism from the Kurile Islands region in the fitting interval, which is used to design the filters. Thus, these filters were designed to suppress this teleseism and to pass S waves from another event. The filters were then applied to a 12 November 1966 teleseism from the Kurile Islands, and the overall suppression obtained by FS was about 23 db, although the suppression at times rose to as high as 31 db.

Program limitations in the frequency-domain maximum-likelihood program did not allow us to apply WDS and FS processing to detect surface waves using the full LASA aperture. However, delayed sum processing has been used to assist in the analysis of long-period surface waves arriving at an array. On 20 November 1966, there was a series of three small earthquakes off the Northern California coast and a small earthquake ($m_b \cong 4.5$) near Rat Island. A beam steered toward the California events passed these surface waves while rejecting the Rat Island surface waves by 10 db. When the beam was steered toward Rat Island, the Northern California off-shore event surface waves were attenuated by 8 db. The processing thus allowed identification of the Rat Island surface waves. This could not be done from the raw traces. The beams, as well as several raw traces, are shown in Fig. 15. The WDS and FS suppression of surface waves, described above, holds promise as an even more powerful tool than delayed summing for the identification of one surface-wave source in the presence of another.

J. Capon
R. J. Greenfield
R. T. Lacoss

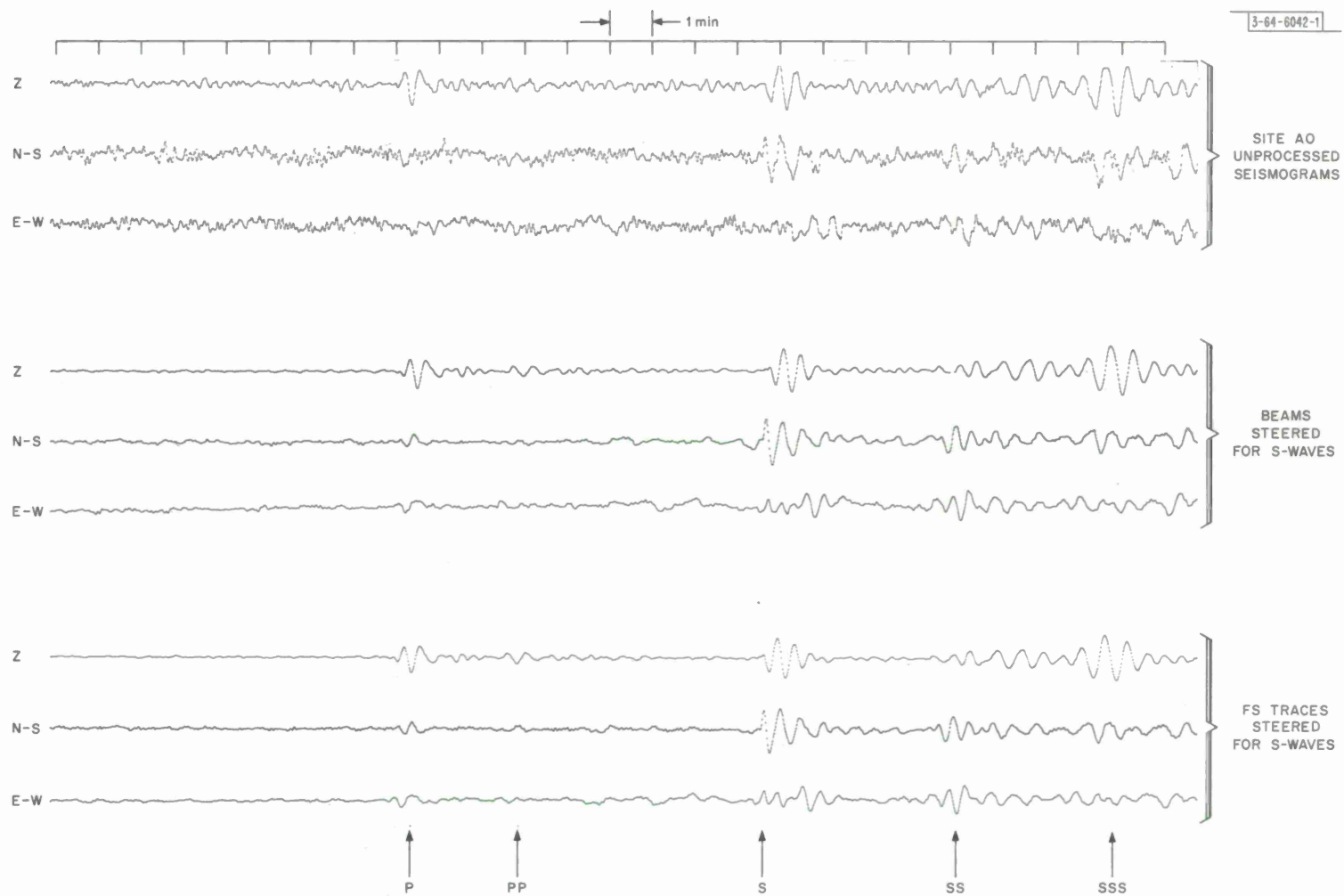


Fig. 12. Three-component LP-processed traces for the 21 November 1966 Kurile Islands event (SP P-magnitude = 6.0, LP Rayleigh magnitude = 4.5).

Section IV

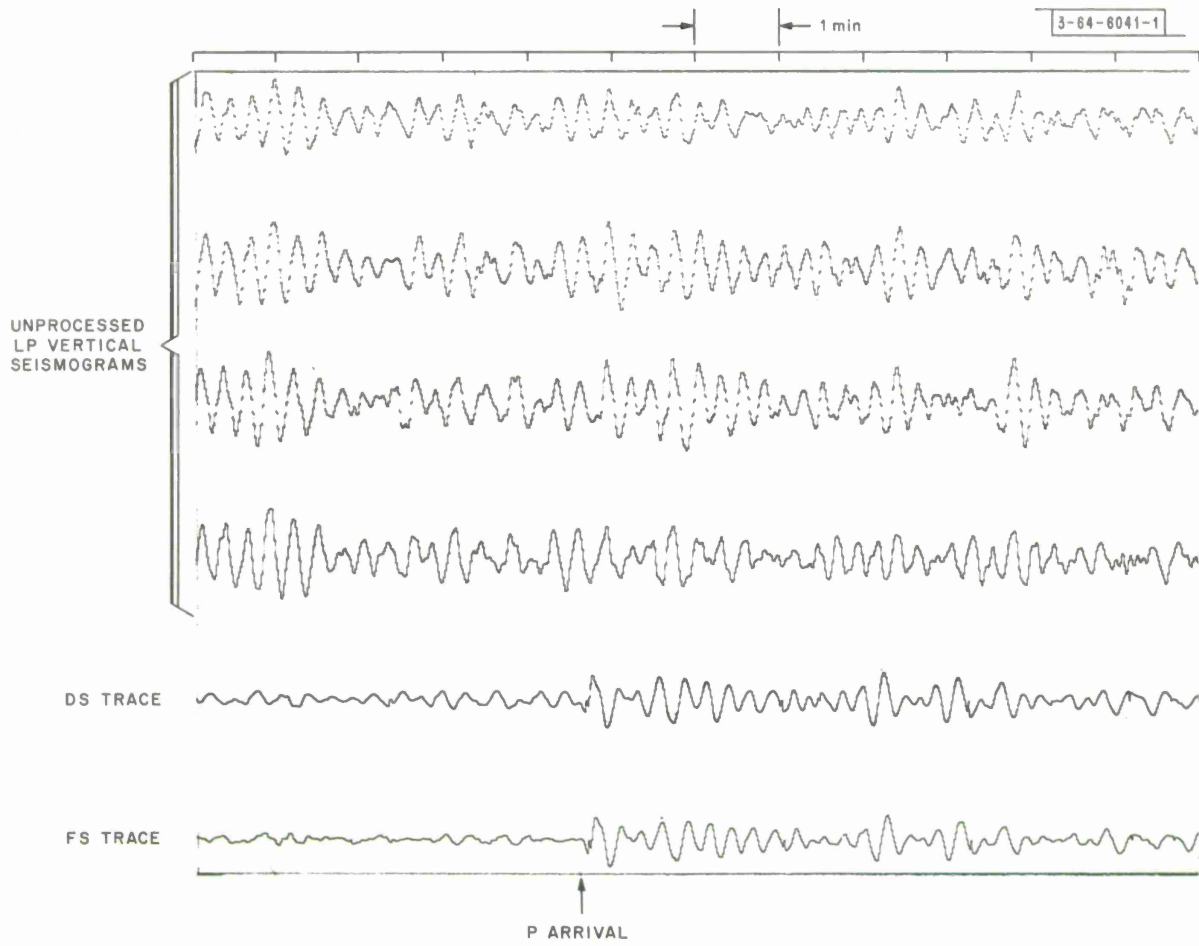


Fig. 13. Results of processing the 12 November 1966 Kurile Islands event to uncover hidden LP P-wave (SP P-magnitude = 5.1, LP Rayleigh magnitude = 5.3).

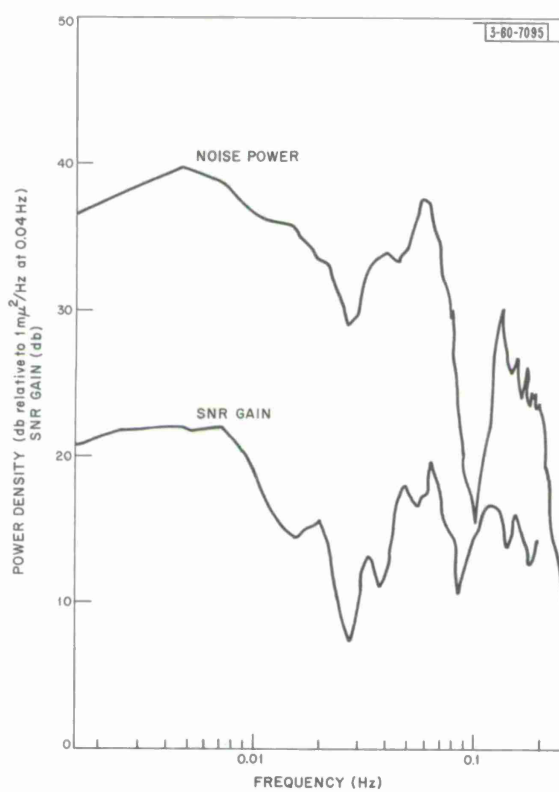
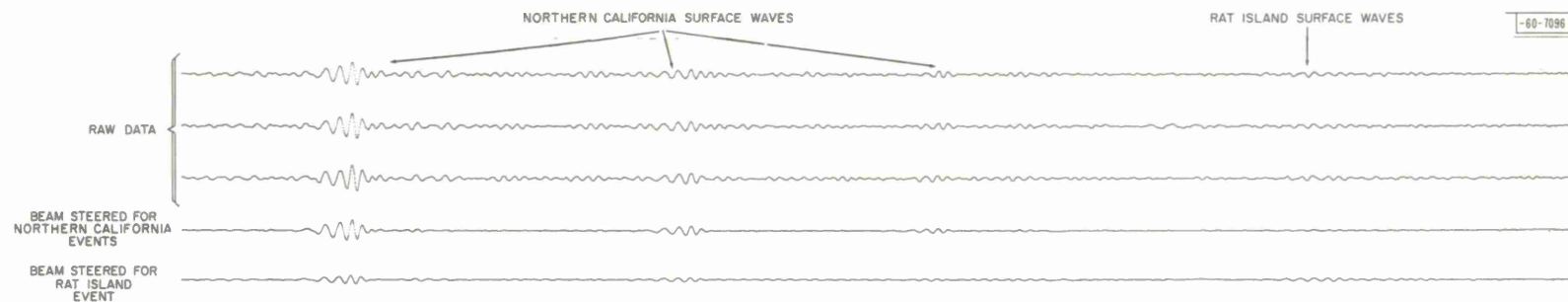


Fig. 14. Typical SNR gain vs frequency and typical input power spectrum for vertical long-period array (21 November 1966 Kurile Islands event).



30

Fig. 15. Beams formed with long-period vertical seismometers (20 November 1966 events).

V. MONTANA LASA SYSTEM

A. AUTOMATIC MONITORING AND FAULT DIAGNOSIS

In the previous Semiannual Technical Summary Report (30 June 1966), the background leading to this series of experiments was discussed. A brief description of the initial goals and the means of achieving them were included. System details were not available, since design had been under way for only a few months.

At present, system design is complete and hardware installation is expected to be complete within a month. The hardware consists of an SDS-930 general-purpose digital computer coupled to the LASA signal collection system and to the PDP-7 computer by means of a Lincoln-designed interface (MINS). The peripheral equipments initially associated with the SDS-930 are largely commercial products. They include three magnetic tape drives, a high-speed line printer, a card reader, a paper-tape reader/punch, a keyboard/printer and an X-Y plotter. This hardware is currently being installed at the LASA Data Center at Billings. The intent in pursuing this system design has been to provide as much flexibility as is economically feasible, so that a series of experiments can be performed in quick succession. Figure 16 shows the monitoring system structure in block diagram form. The system will perform two distinct functions:

- (1) Monitor Function – Checks continuously and automatically on the performance status of each part of the Montana LASA, reporting to the PDP-7 computer and to the maintenance supervisor when performance of a part is subnormal.
- (2) Diagnostic Function – Enables the maintenance supervisor to efficiently couple with the Montana LASA system for purposes of making diagnostic tests and measurements on system elements whose performance has been questioned by the monitor function.

The initial set of computer programs to perform these functions is organized as an executive program controlling the operations of the real-time monitor program plus the diagnostic programs. Figure 17 shows the timing in the 50-msec data cycle.

The executive program performs all input and output operations, monitors and services all interrupts, calls in and executes all diagnostic programs, and in general supervises the operation of the entire programming system. Included are a loader, an octal dump routine, initialization routines, a recovery routine to handle power failure, a routine to send telemetry commands, and miscellaneous subroutines of a utility nature.

The function of the monitor is to determine how well the Montana LASA hardware system is performing. It will detect and identify deficiencies and/or malfunctions in the system and alert the operator and/or the PDP-7 to the particular condition. The monitor will perform the following functions:

- (1) For each sensor, compute the absolute average of sensor data over some period of time (minutes) and determine if the average exceeds some previously determined threshold value. The threshold for each subarray will be determined from the average of the 25-sensor averages.
- (2) For each data circuit, count the number of sync word errors and determine whether the allowable error rate has been exceeded over some unit time.
- (3) For each data circuit, count the number of parity errors and determine whether the allowable error rate has been exceeded over some unit time.

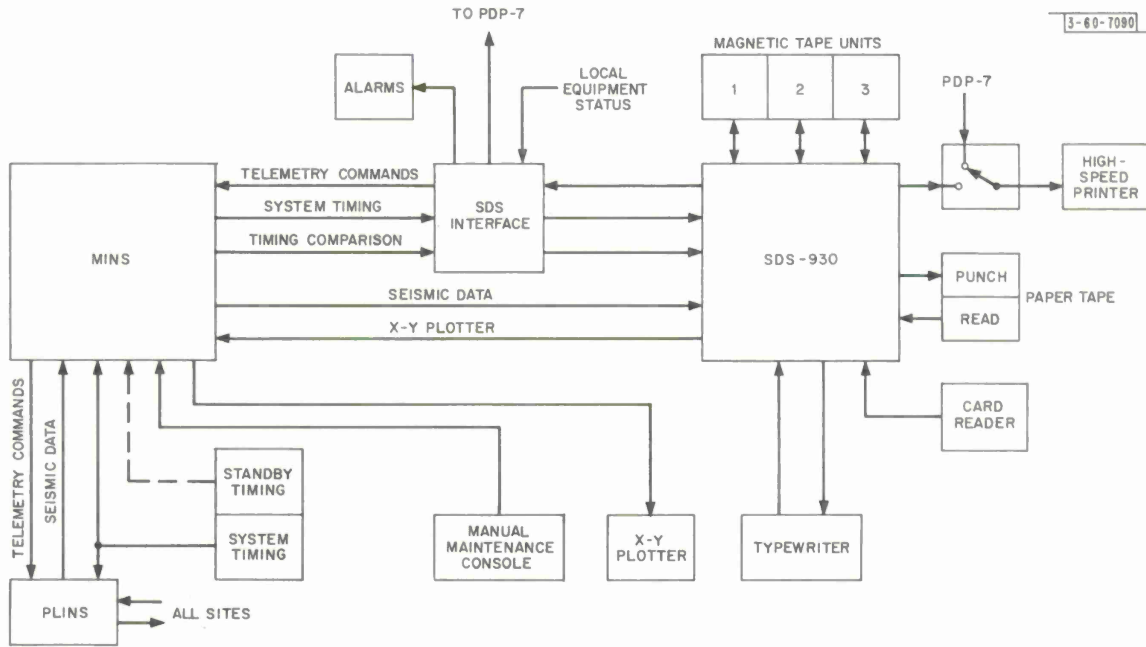


Fig. 16. Automatic monitoring and fault diagnosis system.

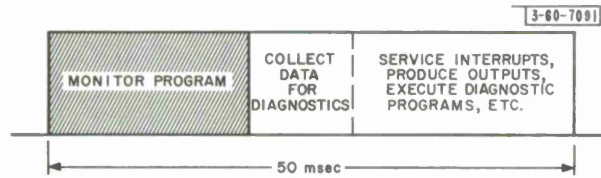


Fig. 17. Basic data cycle.

- (4) Maintain subarray/sensor status for transmission to the PDP-7 when a change in status occurs or when requested by the operator.
- (5) Periodically sense a series of input lines to check the on/off status of the Data Center equipment, and a non-comparison of the two Data Center clocks.
- (6) Monitor the 24 telemetry channels for alarm conditions.

The output of the monitor will take several forms. Statistical data in the form of the absolute average of sensor data and data circuit sync and parity errors will be output to the paper-tape punch every two hours. Weather information obtained from site A0 will also be output to the paper-tape punch periodically. All communications between the program and the operator will be reproduced on the paper tape for later off-line printing.

Error conditions, system malfunctions and deficiencies, etc., detected in (1) through (6) above, will be logged on the console typewriter. All such printouts will be accompanied by an audible alarm.

Several diagnostic programs are being written. The programs will reside on the system master tape and will be available to the operator on request via the console typewriter. These programs will provide the operator with a means of taking a closer look at any part of the system he wishes to investigate. The diagnostic function will be performed in two modes - manual and automatic. The automatic mode will be set when the system is loaded and can be reset by the type-in "AUTO" at any time. In this mode, a "resident" diagnostic will be in core and the monitor can perform certain diagnostic functions automatically. The operator places the diagnostic function in the manual mode by calling in any other diagnostic from the system master. The diagnostic functions presently being considered are those which:

- (1) Print out selected data compiled by the monitor, including sensor averages and sync and parity error counts.
- (2) Plot sensor data on the X-Y plotter.
- (3) Transmit and/or receive various known words.
- (4) Exercise the test SEM at Miles City (site 22) to verify that new, modified, or repaired components are functioning properly.
- (5) Obtain a read-out of the conditions which caused an alarm indication in the telemetry channel.
- (6) Compute and output the DC offset of the multiplexer at each site.
- (7) Perform a Fourier analysis of the 1-Hz sine wave test signal.
- (8) Perform a Fourier analysis of the random sequence generator test signal to obtain the transfer function of a selected sensor (broadband calibration).

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J. H. Helfrich R. V. Wood, Jr.

B. LONG-PERIOD SEISMOMETERS

Installation of the Montana LASA long-period seismometers was completed by Geotech Division, Teledyne Industries, and formally accepted by the Air Force Technical Applications Center (AFTAC) at the end of October 1966. At that time Lincoln Laboratory took over responsibility for the long-period system.

Section V

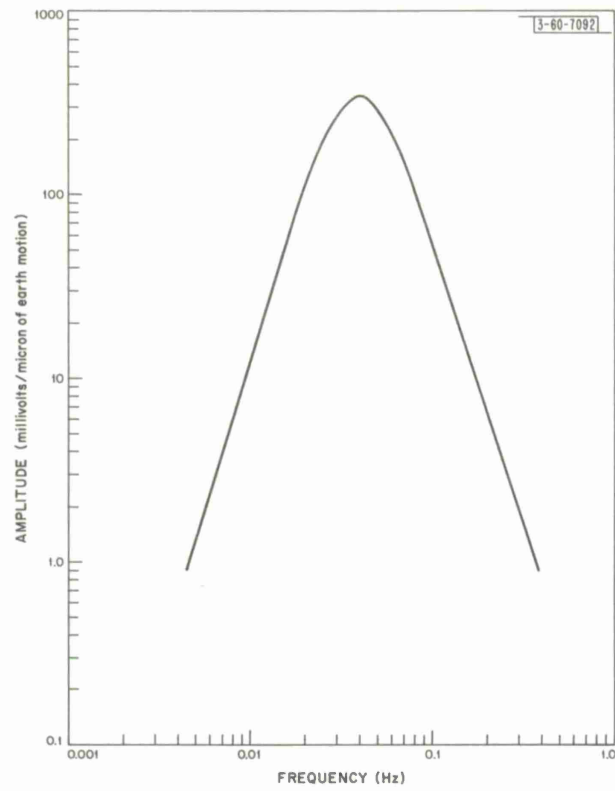


Fig. 18. Long-period system transfer function (25-sec filter).

Detailed observations of long-period data have been conducted only for a month or two, so that relatively little information on component performance is available. The intent is to operate the long-period system for several more months with no changes in parameters, so as to provide a better basis for performance judgments. With this in mind, the 25-sec filters were installed in all 63 long-period channels during October 1966 and are still in place. The nominal system amplitude response for this configuration is shown in Fig. 18. Wideband filters, which will extend the response toward 1.0 Hz, are under development by Texas Instruments and will probably be installed in the spring.

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R. V. Wood, Jr.

C. SYSTEM UPGRADING

1. Well-Head Vault Electronics Package

As part of a continuing program of demonstrating on one subarray techniques for upgrading component performance in the entire LASA, a completely revised well-head electronics package has been installed in subarray E3. Field measurements had indicated that major sources of cross-talk and coupling between signal lines, calibration lines, and 60-Hz ground currents were inherent in the original well-head vault electronics and cabling. The new installation consists of two separate sealed containers. One box contains all cable interconnections, plus lightning protection circuits. Normally, entry to this junction box after installation will not be necessary. Another box, coupled to the cable junction box by connectors, contains the electronics and will be replaced as a unit in the field in the event of failure. This new electronics box, as installed at E3, includes the RA-5 redesign to reduce gain sensitivity to temperature. An important feature of the new well-head vault system is that gain adjustment is now performed at the central terminal vault for all sensor channels.

J. H. Helfrich
C. B. Swanton

2. Extension of Subarray E3

Results of subarray signal processing reported in Sec. IV-A indicated the possibility that signals from a subarray of about 20-km aperture could be processed on line with a signal-to-noise improvement considerably closer to that obtainable from off-line maximum-likelihood processing than is the case for the 7-km subarray. This has important implications for future LASA design. To verify these results, and to test engineering feasibility of large subarrays, it was decided to modify subarray E3 to give a 19-km aperture, with 25 sensors and a minimum sensor spacing of 3 km. This modification was satisfactorily completed by the contractor in Montana in early December, within two weeks of the time predicted when the work started in early September.

R. V. Wood, Jr.

3. Subarray SEM Control/Output Modifications

For six or eight months, it has been clear that major changes in the SEM telemetry command section were required to adequately meet changing needs. Specifically, a major source of errors in the digitized data arriving at Billings was found to be the improper response of the SEM telemetry receiver to noise on the Billings-to-subarray channels. Also, the capacity of

Section V

the telemetry command channel had been reached, and could not readily be expanded without re-design. The eventual control of the long-period seismometer system from Billings will require a substantial number of new telemetry messages.

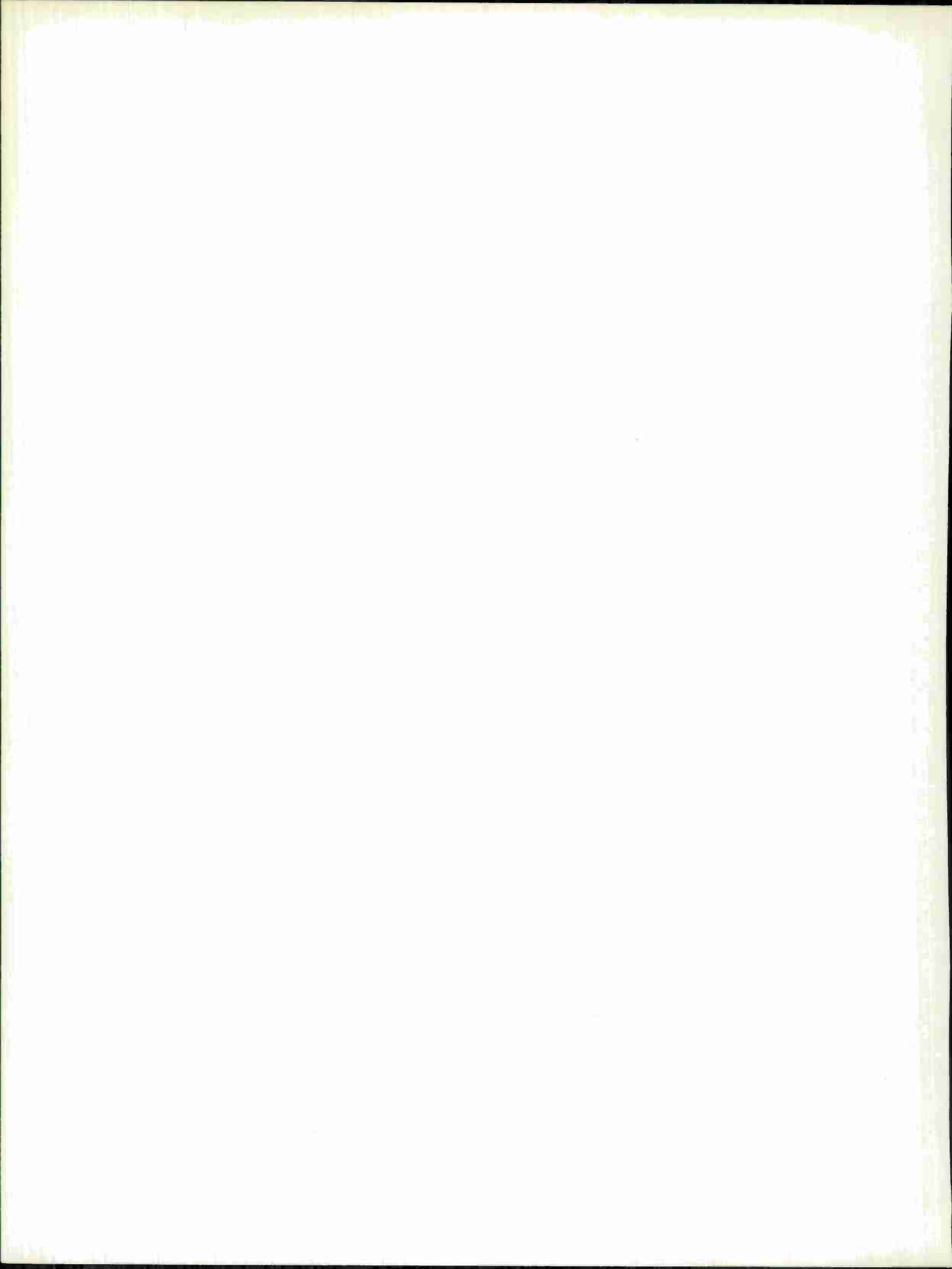
It was decided that the above needs could best be met by designing and building a completely new SEM control drawer, and extensively modifying the output drawer. The modification provides a telemetry command receiver which has protection against errors due to input noise. It also provides the capability for 63 distinct telemetry commands, about three times the previous capability. All the hardware for this modification has been completed and tested, and installation is currently under way.

J. P. Densler

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13. ABSTRACT <p>Studies have continued of the ability of a single Large Aperture Seismic Array (LASA) station to detect and roughly locate teleseismic events and to generate outputs derived from various long- and short-period seismogram parameters, particularly those related to exact epicenter location and source discrimination. The behavior of networks that exchange such data and that consist of both small and large array stations has begun to receive attention. Computer-controlled automatic monitoring and maintenance of large seismometer arrays are discussed.</p>			
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