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Semiannual Technical Summary

Seismic Discrimination

30 June 1966

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Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts



ESRL

June 1966

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

SEISMIC DISCRIMINATION

SEMIANNUAL TECHNICAL SUMMARY REPORT

TO THE

ADVANCED RESEARCH PROJECTS AGENCY

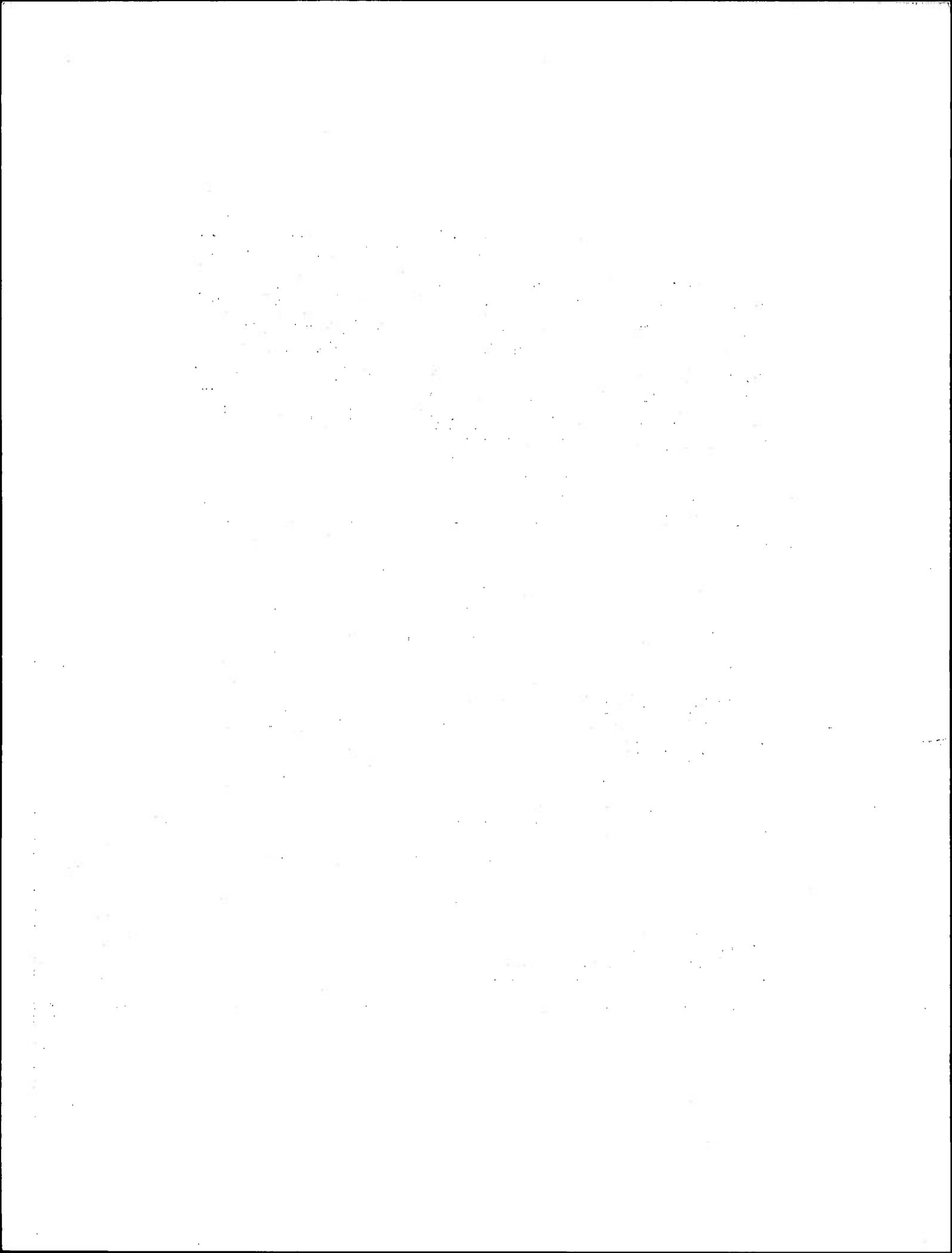
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ABSTRACT

The capabilities of the experimental Large Aperture Seismic Array (LASA) to detect, reprocess, and identify teleseismic signals have been evaluated. The detailed results are summarized, and current performance of the physical elements of the system is discussed. Exploratory work on the following topics is described: a different method of measuring P-complexity, a novel scheme for wide-band seismometer calibration, processing of signals from a set of three-component seismometers, and a computer simulation of the LASA seismometer channel.

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



INTRODUCTION

This is the fifth 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, we continued to study the engineering performance of the experimental Large Aperture Seismic Array (LASA) in Montana and have concluded that any troubles are due to component failures. Therefore, it is felt that in any future such installation, no redesign of the system will be necessary, although improved methods of automatic fault monitoring will be required (Sec. I).

An analysis was made of data from the experimental LASA for the purpose of establishing its various capabilities (Secs. II, III, IV, V-A). It was found that above magnitude 3.5, 50 percent of all events lying from 30 to 90 degrees from the station are detected using the present on-line beam processing having a 12-db SNR gain. Off-line procedures with gains up to 27 db are achievable with the present LASA. The effect of SNR improvement, expressed as an equivalent shift in seismic magnitude of the received signal, was found to be about the same as that given by the SNR gain for some waveform features, but greater than that for others.

A study was made of P-complexity using a new computation procedure intended to take advantage of coda differences between subarrays (Sec. V-B).

Section VI describes a new technique for testing the calibration of both amplitude and phase of a seismometer across its entire operating band using a single input signal, a pseudo-random square wave.

An analog processing system for three-component single-sensor data has been built and used to accumulate data on the particle motion of a number of teleseisms (Sec. VII).

In order to deduce the effect of changing any of a number of parameters in the LASA seismometer and its associated signal transmission circuitry, a mathematical model embodying these elements has been set up on the computer (Sec. VIII).

P. E. Green, Jr.

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SEISMIC DISCRIMINATION

I. LARGE APERTURE SEISMIC ARRAY SYSTEM

A. INTRODUCTION

The activities during this reporting period have been concentrated on operating the LASA to provide the basis for an evaluation of system capabilities.

The Montana LASA was conceived as an experimental tool to demonstrate the general performance to be obtained by the sophisticated processing of seismic signals. The system now in existence was not designed for continuous, interruption-free service. It was felt that the additional cost and installation time were not justified by the minimal advantage that would accrue to the research program envisioned. Naturally, good engineering practice dictated a system design such that, with a few recognized exceptions, single failures cannot cause the entire array to be inoperative.

Operation in the high-rate recording mode for 10 hours per day has been maintained since the beginning of the year. Addition of the second PDP-7 at the Data Center permits substantial off-line processing activity, and provides standby capability for the on-line system. In addition to the high-rate recording period, use of the low-rate data recording mode (Slow Mode) has been instituted, currently for 10 hours per day. This 6-month operating period has also served to shake down the LASA hardware and system operating procedures and to illuminate the areas needing further attention.

Of particular note, during the latter part of this reporting period, is the acceptance by Lincoln Laboratory of the overall system responsibility for control and maintenance of LASA. A supporting contract has been negotiated with the contractor, the Philco Corporation, for assistance in operating and maintaining the Montana LASA. This new arrangement, in addition to the obvious improvement, efficiency and economies accruing from the consolidation of effort, provides for an expansion of professional level support, both at the LASA Data Center and at the Maintenance Depot. A breakdown of personnel shows 7 professional staff, 31 technical support personnel and 6 managerial and administrative personnel.

The complement is not typical of that which might be involved in an operational situation, but is heavily influenced by the experimental nature of the Montana LASA, particularly by the planned program of system upgrading.

B. SUBARRAY EQUIPMENT

1. General

In general, all components of a LASA subarray are "single thread," including the individual communications links. The sole exception is the provision of automatic standby power, which is discussed in Sec. 2 below. The microwave communications links, where several subarrays are concentrated, are all provided with diversity channels and, in some cases, spare channels as well. All have at least 12 hours of standby power.

2. CTV Standby Power

A standby power-supply system for the LASA subarray has now been designed. Two prototype models are currently undergoing bench and field tests. The new system utilizes the present batteries and charger, although some major modifications are required in the latter. A completely new inverter is being provided, in addition to necessary control circuitry lacking in the earlier system. Assuming that the test results are satisfactory, all subarrays will be equipped with this standby power system. In view of this, and because of certain pole-line right-of-way difficulties, the proposal to provide alternate routing for prime power to some of the subarrays, which was discussed in the last Semiannual Technical Summary Report,* has been abandoned.

3. Well-Head Vault Electronics

The record to date suggests very strongly that the well-head vault equipment has been the weakest link in the LASA system. The troubles are of two distinct types. Statistically, the majority of failures were due to the effects of lightning. Of a total of some 991 outright failures, some 927 are attributable to this cause, all occurring early in the summer of 1965. Since the 1965 lightning season, a number of modifications in this part of the system were made and others are currently in progress. Indications are that these modifications will produce substantial improvements. However, this is an area in which controlled experiments are impossible, and reliable statistics will be available only after several years of field experience.

The second principal cause of unreliability is the gain instability of the RA-5 well-head amplifiers. Failure rate is quite low (a total of 7 failures have been recorded) and each failure has been due to a breakdown of a different component.

It has been established by laboratory measurement, as well as by field experience, that the gain of the RA-5 is unacceptably temperature sensitive. Large variations in gain occur over the temperature range normally experienced in the well-head vaults in Montana. These gain changes, of course, reduce the dynamic range of the signal collecting system and, in addition, cause series difficulties with the signal processing. Also, there are other weaknesses in the well-head vault installation, such as undue sensitivity to power supply ripple and noise pickup, which limit the present usefulness of the system.

A redesign of this well-head amplifier has been completed and tested in the Laboratory. Twenty-five amplifiers are now to be modified and will undergo extensive testing, both on the bench and in the field. Assuming successful test results, we will extend the modification to the entire LASA.

A major modification has been made in the well-head power distribution and subarray lightning protection at subarrays B1 and F3. These were the first two sites to be installed and they differ from the other 19 in that the underground cables are of lighter gauge wire and contain insufficient wire pairs to permit all necessary functions without multiplexing. As now modified, power to the well-heads comes from a separate, AC-operated power supply instead of directly

*Semiannual Technical Summary Report to the Advanced Research Projects Agency on Seismic Discrimination, Lincoln Laboratory, M.I.T. (31 December 1965), DDC 630559.

from the 24-volt battery. This permits the provision of lightning protection for both sides of the DC power line running from the subarray CTV to each well-head vault. The new modification provides for the injection of calibration signals into the RA-5 input terminals by reversing the polarity of the well-head power feed. The AC-operated power supply also greatly reduces the 60-cycle interference previously generated by the charger-battery combination.

4. Sensors

The reliability of the LASA sensors has been consistent with expectations for instruments of this type. That is to say, the instrument is basically simple and is reasonably well constructed. In some 11 months of operation, there have been 16 failures out of the total of 525 in use. Of these failures, 6 were due to sticky mass; the others were due to a variety of different causes and do not appear to be statistically significant. It is interesting to note that of the sticking mass failures, 1 occurred shortly after installation, but the other 5 all occurred during the winter cold months.

At this time, the knowledge of sensor behavior is limited to that which is measurable by a single frequency calibration waveform and to that which can be inferred from processing results. In an attempt to correct this deficiency, a broad-band calibration system has been developed and is undergoing tests. This system includes the hardware for generating and injecting a noise-like signal into the seismometer calibration circuits at selected subarrays and the software necessary to calculate and display the sensor circuit transfer function at the LASA Data Center. Current results indicate that the installation of this calibration system will provide a major improvement in our understanding of the sensor system behavior.

Also undergoing tests at subarray D2 is a 3-axis seismometer, the Teledyne, Inc., Model TD-202. At the same subarray, we are testing two Geotech Shallow-Hole Seismometers and complementary amplifiers.

A measurement is under way which attempts to determine the seismic noise contributed by the action of wind on pole lines within the subarrays. Poles have been instrumented with 3-axis instruments and comparisons are being made of the outputs of these instruments, with measurements from subarray seismometers at varying distances from the pole lines.

It is clear that the efforts cannot be regarded as covering all the problems connected with the design and installation of sensors for large seismic arrays. There remain a number of areas still to be investigated; for example, magnetic pickup of power-line-induced noise and cable crosstalk. So far, these areas have been considered of less importance than those presently observed. However, they must be looked at in the near future, since the knowledge will be essential in formulating recommendations for future systems.

5. Long-Period Seismometers

Installation of the LASA long-period seismometers is proceeding under an Air Force Technical Applications Center (AFTAC)/Geotech Corporation contract. This work is being closely followed by Lincoln Laboratory engineers as well as by the on-site personnel. The objectives here are a long-period installation which is compatible with the rest of the LASA system, and a trained team of on-site technicians capable of assuming the long-period maintenance and operation at the end of the installation phase.

6. Subarray Electronics Module (SEM)

Of the five units which comprise the SEM, only one (the multiplexer and analog/digital converter) was not designed and constructed at the Laboratory. On the basis of previous experience, circuits and components in these Laboratory designs were developed to maximize the reliability of the unit.

This conservative approach has paid dividends. All units have been in continuous operation since their installation approximately 1 year ago and, to date, a total of 20 failures has been reported. During the shakedown period, some component deficiencies appeared. These were corrected and, subsequently, the troubles have been distributed by cause in a way which indicates that only isolated and infrequent component failures are to be expected in the future.

Changes planned for the SEM's in the immediate future involve the design and substitution of a new Control Section. This will provide for additional telemetry command signals plus a new wide-band calibration signal generator. No special problems in reliability are to be expected with this change since no new circuits or components are involved.

7. Communications

The LASA communication system employs a number of relatively new techniques and components. The wide-band data modems, while not developed specifically for LASA, were the first of their type to see commercial service. The frequency multiplexing of bidirectional wide-band data and voice on a single pair of open wires was entirely novel. All of the facilities, both open-wire and microwave, while not new in technique, were constructed specifically for LASA, and on a very short time scale. Experience with data transmission systems of any kind was a novelty to all of the several independent telephone companies involved in the LASA effort and, of course, the particular system employed was new to the Bell System.

In spite of the above, the service provided has been very good. As might be anticipated, there were a number of initial problems. For example, at first a design defect in the data modem caused it to lose synch after momentary circuit interruptions; this has been corrected by a circuit change. Some difficulties were experienced with unreliable calling on the voice channel; this has been cured by proper level setting of the ringing signals and by appropriate preventive maintenance. A number of "people troubles" were encountered; training programs and experience have eliminated most of these.

Lightning caused some operating problems during the summer of 1965. A major cause of difficulty has been eliminated by replacing all carbon block protectors with gas tubes. However, it is to be expected that there will continue to be a small incidence of communication failure due to physical damage to poles and lines by lightning. A few failures have occurred due to windstorm damage to the open wires. However, the incidence has been only 3 or 4 cases and, while impossible to prove, these failures may have occurred at points where the lines were nicked or improperly installed during the construction phase. Two failures have occurred in the microwave system; neither were due to fundamental engineering design weaknesses, but were attributable to faulty components.

Arrangements are in effect with all telephone organizations in the LASA area to the effect that service charges are rebated for all service interruptions in excess of 2 hours' duration.

Complete records are available of all such occurrences. There have been no cases where complete failure has occurred on all sites. At this time, complete records of short interruptions, particularly those that occur outside normal working hours, are not available because the system providing for automatic monitoring of communication circuit status is not yet operational. Error rates on all circuits were checked during the installation phase and have subsequently been checked when the occasion arose. No distribution statistics are available at this time. A simple, nonrecording monitor alarm indicates that the design goal of not more than 1 error per 10^6 bits is surpassed by considerable margin.

The original design of the data communication system included a transmission rate margin to permit the addition of error-correction equipment. The performance has been sufficiently good so that the task of gathering the statistics of rates and distributions of errors, necessary before an error-control system could be designed, has been relegated to a low priority. It is expected that collection of such data will be started by the end of calendar year 1966, but it is not anticipated that any error control system will be necessary or economically justified.

C. DATA CENTER EQUIPMENT

1. PLINS/Timing

The PLINS (Phone Line Input System) provides the interface between the telephone modem equipment and the computer (parallel transfer) and digital-to-analog converters (serial transfer). The PLINS also provides the telephone input interface for telemetry commands from the computer or maintenance console. Physically, it consists of a single rack of micrologic circuitry. Since installation in July 1965, only 1 failure has been recorded (in May 1966).

The LASA Data Center timing system provides the stable master oscillator and the derived timing clock pulses, synchronized to WWV and distributed individual components in the Data Center, plus timing distribution and synchronization for the subarray digital sampling operation and the clock to provide day-of-the-year and time-of-day (TOD) for the computer and analog recording consoles. In addition to the master clock, there is a separate Vela Time Code generator for the Develocorders which derives its timing from the master clock. The original timing system was installed in July 1965 without a TOD clock; this was added in September 1965. Since January 1966, 1 failure has been recorded due to a broken wire. Prior to January, several broken wires or connectors had been repaired. In May 1966, a backup timing system was installed to insure that the site would not be disabled by a timing system failure.

2. Digital Processing

The digital processing and recording system for the experimental LASA includes two PDP-7 general-purpose computers and one special-purpose multichannel filter processor (MCF) manufactured by Texas Instruments, Inc. Digital recording is performed using four digital tape transports shared by the two PDP-7 computers.

In discussing the reliability of digital processing equipment, several forms of failure must be considered, each having different effects on system operation. The first class of failure is a transient aberration in function or hardware. In the case of the general-purpose computer,

Section I

this normally results almost immediately in the computer control operating an illegal instruction and causing the processor to trap to a particular memory location normally containing a halt operation. Thus, the computer (and therefore the recording or processing) is stopped until the program can be reloaded and restarted. The restarting operation presently involves the manual entry of all current nonstandard operating parameters and ordinarily requires only a few minutes but may take as long as 20 minutes. This period could be reduced to about 1 minute by providing an automatic restart capability from an additional magnetic tape unit or other bulk storage. The same symptoms may, of course, be the result of a programming error, and it is often difficult to separate program and equipment failures during the early operation of a new program which may still not be completely debugged. Since the restart operation is not particularly complex, these transient failures do not add much to unscheduled downtime, but they are an important factor in determining mean time between failures. Transient errors in the special-purpose processor (MCF) result in spurious data outputs of up to 2 seconds, and are normally undetected unless they become so frequent that they result in visibly unusable output data.

A second class of failure to be considered is an electronic component failure in the processor. The cause of this type of failure must be found and corrected before the computer can be operated. Such a failure in the general-purpose computer does not result in excessive downtime for the LASA system because the second computer provides a backup facility that can be put into operation in about 30 minutes. Experience indicates that most of the unscheduled downtime on the LASA Data Center processors results from these processor component failures.

A third class of failure is a digital tape unit malfunction. The immediate effect of a tape unit failure is similar to that of a transient processor failure, since another tape unit can be quickly connected to replace the inoperative unit. Frequently, however, a tape unit failure is the culmination of a period of undetected marginal operation which may result in a number of tapes on which the data are inaccessible or recoverable only with great difficulty.

During a typical month of operation at the LASA Data Center, the mean time between failure for a single PDP-7 was 9 hours, 42 minutes. The total unscheduled downtime on this machine was 30 hours.

The MCF has proved to be a difficult machine to troubleshoot because of the complexity of the operations it performs. The MCF was installed in October 1965. Two of the 5 output channels were unusable until January 1966 because of transient errors apparently caused by an intermittent weld joint on a micrologic circuit board. Since January, the mean time between transient errors has been about 1 minute so that useful automatic processing of the output of the machine has been impossible. Most of the present transients seem to be associated with the memory section of the machine. In the future, we expect that troubleshooting this machine will be aided by a planned program to use the PDP-7 to detect and analyze MCF failures.

3. Analog Processing

The analog equipment in the LASA Data Center presently consists of 72 digital-to-analog (D/A) converters each, plus a variety of analog chart and film recording devices used for maintenance and data verification. The first 24 D/A channels were installed during the summer of 1965 to drive the maintenance console; the second 24 were installed in December 1965; and the

third set of 24 was completed in May 1966. Now under construction is a fourth set of 24 D/A channels, to provide conversion to an accuracy of 14 bits for use with the long-period seismometer data. A structure has been designed and constructed to house the ten Data Center Develocorder units. This assembly stacks the recorders in 2 tiers and provides a platform to permit analysts to work in front of the upper-level instruments. Installation of this equipment began in late June.

To complement this expanded analog recording capability, a patching unit is under construction at the Laboratory. In addition to permitting a versatile patching of the several instruments, summing amplifiers and filters are provided together with a calibration capability at several levels, i.e., instrument, analog channel and overall system.

Most of the failures in the analog section have been associated with the recording devices themselves and have not been in the electronics. Within the D/A electronics racks, there have been 3 or 4 failures due to bad connectors and 2 failures involving the micrologic circuits since December 1965.

4. Automatic Monitoring and Fault Diagnosis

The concept of centralized monitoring and control has proven in practice to be ideally suited to the LASA system, even though the monitoring facilities presently in existence fall short of those required. In the initial implementation of the LASA system, a sensor monitoring program was provided in the computer, and the maintenance supervisor was provided with facilities for simultaneous display of a number of sensor outputs in analog form, and for the remote initiation of diagnostic functions in the subarrays. Originally, this monitoring was automatic and consisted of a series of tests made on each sensor at $\frac{1}{2}$ -hour intervals. This mode of operation was later changed to allow performance of the series of tests only on command of the maintenance supervisor.

As experience was gained and as the demands on the on-line computer operation grew, the monitor program was retired. Since that time, sensors have been manually monitored twice daily. Diagnostic routines continue to be exercised as necessary, also under manual control. Within the past few months, a simple alarm monitor has been installed to provide for each of the Data Center input channels an indication of such things as loss of synch, parity errors and the status of certain telemetry functions. These facilities have been acceptable for the installation and debugging phases of the LASA experiment. It is abundantly clear that they are no longer adequate.

Therefore, design is under way on a comprehensive system of automatic and continuous monitoring of sensor, subarray and communication system performance and status. The outputs of these monitoring functions will be used to influence the on-line data recording, event detection and beam forming functions. They will also generate printed records of statistical data and initiate diagnostic routines, either automatically or under manual control, when the necessity is indicated.

The physical implementation of these monitoring and diagnostic functions will be by separate digital computer equipment installed in the LASA Data Center. The existing computer capacity is not sufficient to carry this additional burden. In addition, the ongoing research program in processing as well as in the monitoring/diagnostic areas requires a flexibility that can best be provided by separate computers.

Section I

D. BUILDINGS AND SERVICES

A tape and film library facility has been constructed in the LASA Data Center. In addition to facilities for storage, a dry process film copier is available, together with normal film display consoles. A new outside vestibule has been provided to obtain more operations room space in the Center, particularly to permit the installation of the expanded analog recording equipment. The existing and planned facilities for the Data Center utilize all the present space, and any sizable additions would necessitate a major building addition or relocation of the Center.

E. CONCLUSIONS

As the preceding discussion of component reliability shows, with the exception of certain computer problems there is little that is surprising in the performance of the elements of the LASA Data Center. A perusal of the daily status reports shows that the system is operational for a majority of the time. If one eliminates from the statistics cases where a sensor is reported having high or low gain, it is evident that the entire array is operational most of the time; occasionally, a subarray is out, but seldom is the entire array out. Considering the complete LASA system, the major source of trouble has been the digital computers and, in particular, the magnetic tape units. In the last 3 months, some 2126 hours of computer operating time were logged and some 236 hours of scheduled maintenance time were expended. Some 25 hours per month of unscheduled downtime were reported.

The nature of the system is such that its overall effectiveness is not seriously impaired by the loss of a number of sensors, or by a subarray or so, provided that these losses are known at their times of occurrence so that this can be taken into account in the signal processing. The overall system reliability has been quite satisfactory for an experimental system. The factors affecting overall reliability are believed to be all known and appear to be largely concerned with components. No fundamental system design limitations are apparent and, consequently, there would be no changes in the basic design if a new system were to be designed at this time.

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II. LASA CAPABILITIES EVALUATION

We have made an appraisal of the operational capabilities of the Large Aperture Seismic Array and have presented our results in several reports.¹⁻⁴

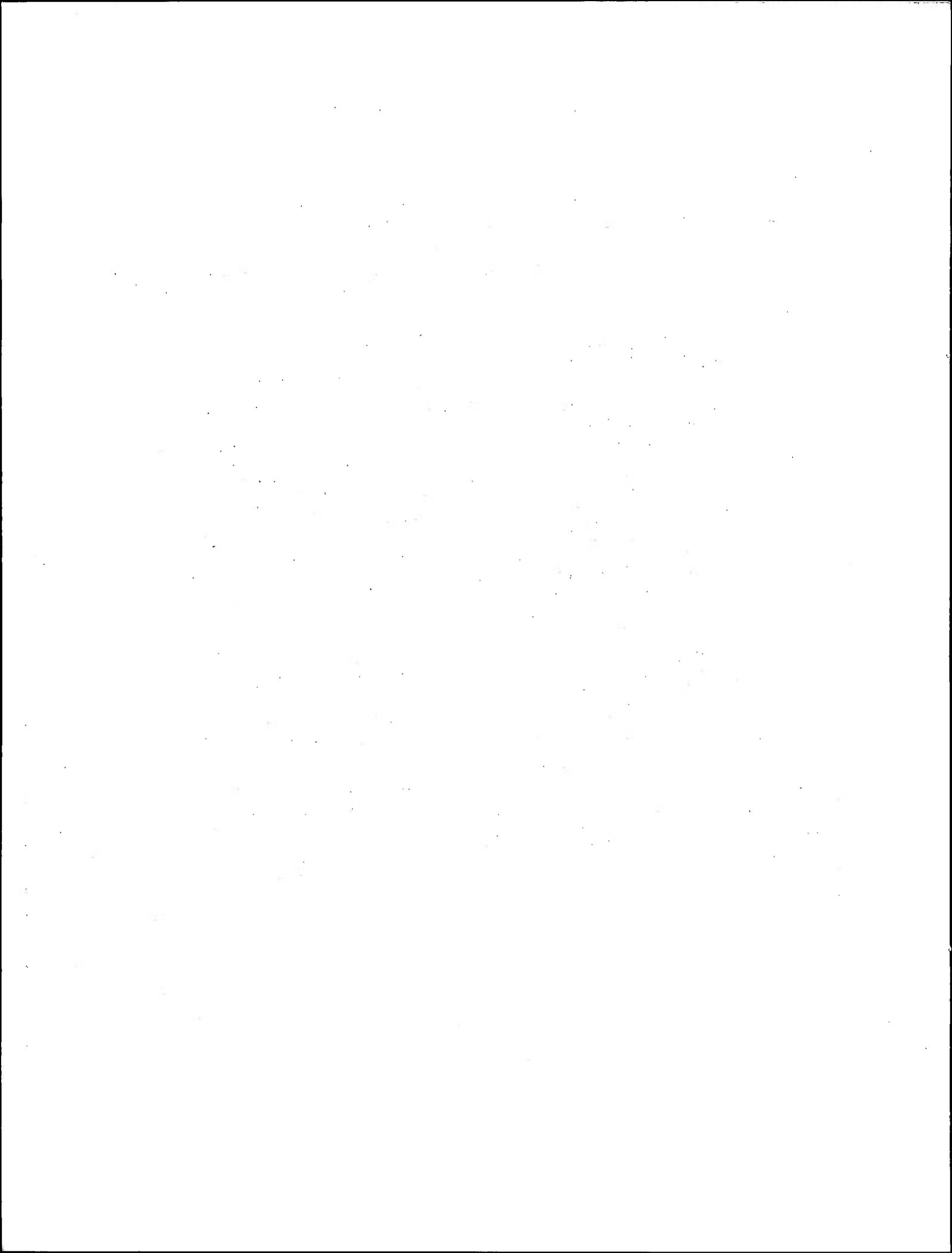
Several conclusions can be drawn about the usefulness of arrays of the LASA type for nuclear test surveillance. By such arrays we mean any that include (a) a sufficient number (200 to 500) of adequately separated sensors to produce a large signal-to-noise gain, (b) sufficient aperture (roughly 200 km) for rough location, (c) means for automatic detection and approximate location operations, and (d) provisions for making wide-band large dynamic range recordings for off-line analysis.

- (1) It is clear that arrays of the LASA type are most useful in the magnitude range in which the noise otherwise interferes with reliable identification using classical stations. For example, LASAs probably are of minimal assistance in the location of an event, or the observation of its first motion, if the waveform onset is already quite clear on single traces, say above magnitude $4\frac{3}{4}$.
- (2) For purposes of test-ban monitoring, observations at smaller magnitudes may be required, however. For a LASA of the type built in Montana, events down to a magnitude of $3\frac{1}{2}$ can be detected and recorded. Off-line analysis can then be carried out on the recorded data to improve signal-to-noise by 1 to $1\frac{1}{2}$ magnitude units relative to a typical single seismometer trace, or $\frac{3}{4}$ to $1\frac{1}{4}$ magnitude units relative to typical small arrays having no off-line processing capability.
- (3) The effect of off-line processing on the readability of identification characteristics cannot be inferred from the signal-to-noise gain figures alone. We have found that the diversity inherent in having 21 separately located subarrays introduces additional reliability for certain types of observation, so the effect is somewhat better than that expected from signal-to-noise considerations alone.
- (4) The ability of a LASA to null out strong interfering teleseisms should provide greatly increased continuity of surveillance during periods of strong teleseismic activity.

Thus, a great many events which are either undetectable or barely detectable in a network of classical stations can not only be detected but well located and identified with a LASA network. One LASA obviously has negligible capability to perform precise location and identification, but a modest net of two or three such stations should have considerable capability.

These conclusions are for body wave signals; data for surface wave phases will not be available until the long-period seismometers are operating and the data obtained from them are processed.

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III. ARRAY PROCESSING

Most of our work on array processing during this reporting period has been described in a recent Technical Note³ from which we quote here by way of summary.

"The spurious precursor introduced by one form of signal processing, and shown to be caused primarily by the signal amplitude scatter within a subarray, can be effectively reduced by using amplitude equalization. These corrections have to be inserted for various bearings and epicentral distances. The signal amplitude scatter within a subarray, and between subarrays, is thus found not to degrade seriously the performance of the signal processing." In fact, the scatter of amplitudes between subarrays (up to 9:1), which is significantly larger than that within a subarray (up to 2.5:1), is a definite asset, since some small number of subarrays, the particular ones depending upon the event epicenter, have significantly better SNR than the average. This can be of considerable value for small events.

"It was found that the effectiveness of the processing depends not only on the array spatial filtering ability, but on differences in absolute level of the noises in the various sensors. Long-period array data from the extended TFO array were processed and showed roughly \sqrt{N} improvement.

"Our experience in processing a number of events is illustrated by a discussion of the results obtained on two particularly weak events with the maximum-likelihood filter. The apparent magnitude of one event (as averaged over the LASA) was 3.5, and that of the other was 4.0. It was found that the processing was capable of extracting both events from the background noise to the extent that they could be identified as earthquakes and not nuclear explosions. An experiment in suppressing large events that obscure simultaneous smaller events from other source regions is reported."

On the basis of these results, several recommendations concerning off-line and on-line processing methods and array geometry can be given.

"It has been determined that prefiltering of data before designing and applying filter-and-sum (FS) or weighted delay-and-sum (WDS) processors has a considerable effect upon the gain of the processors as a function of frequency. If truly wideband signals or signals in the band 0.1 to 0.5 cps are of interest, then unfiltered FS processing is to be recommended. If some minor distortion is allowed but first motion is to be preserved, then a notch prefilter, designed to reject low frequency microseisms, can be used. Prefiltering with a 0.6 to 2.0 cps bandpass filter is recommended if first motion can be distorted and only more gross characteristics of the waveform, such as complexity, are under consideration.

"If we include the case when data are not prefiltered, then it has been shown that increasing the subarray size from 7 km to about 15 to 20 km, and spreading seismometers uniformly over the aperture, does not reduce the SNR gains achievable. In fact, for prefiltered data SNR gains almost comparable to those for FS applied to a 7 km subarray can be obtained using DS or WDS processing. The FS gains for prefiltered data and the larger aperture are as good or better than those for prefiltered 7 km subarrays. This result would argue in favor of a larger size subarray with the 25 sensors spread uniformly over the aperture. The uniform spacing (minimum separation greater than 2 km) is recommended since closer spacing would require the

Section III

application of FS processing to achieve significant SNR gains. The fraction of events requiring FS processing should be smaller for the larger subarrays than for the 7 km subarrays.

"The use of FS processing on-line in a large subarray certainly seems unjustified in view of the great cost of installing the necessary computing equipment. However, the 3 to 4 db advantage of FS still makes it desirable as an off-line processing method, where the computing equipment is readily available, and it is desired to obtain as much gain as possible to identify weak events.

"In summary, the subarray aperture should be increased to 15 to 20 km and on-line processing should consist of prefiltering, either bandpass or notch, followed by DS. Further SNR gains can be achieved off-line by using appropriate prefiltering followed by FS, WDS, or even DS, depending upon the availability of computing equipment. Special situations such as the almost simultaneous arrival of two teleseisms should also be handled off-line using techniques which are suitable for the purpose."

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

IV. AUTOMATIC EVENT DETECTION AND LOCATION

A. CURRENT LASA DATA CENTER OPERATION

A report² has been prepared describing the status of on-line operations at Billings. As Fig. 1 shows, these include predetection SNR enhancement, automatic detection, and automatic location. The abstract of the report follows.

This report describes the results of carrying out a number of seismic signal handling operations in on-line digital equipment at the LASA Data Center in Montana. An appraisal was made of the threshold detection capability of a single LASA sensor by comparison with two well-calibrated stations nearby, UBSO and BMSO. It was found that signals average slightly higher at LASA than at these other stations. When the detection threshold of one LASA sensor is corrected for the predetection processing gain being achieved by current LASA beamformer programs, a LASA detection threshold for event detection by surveillance is established. This number is at a C. and G. S. magnitude of 3.7 for 75% detection or 3.5 for 50% detection by a single LASA for events 30 to 90 degrees away. Some further improvement is possible by more careful on-line beam processing. A combination of automatic event detection and location programs working from individual subarrays is described. This program has been used on single seismometer outputs, giving a 75% threshold for detection and location at a C. and G. S. magnitude around 4.2. Methods for lowering this by various predetection processing schemes are compared.

E. J. Kelly

B. LASA STATION BULLETIN

As Fig. 1 indicates, one of the Data Center functions is the generation of a station bulletin. At present, such a bulletin is being prepared manually each day and is distributed by teletype and mail to a number of seismological research groups. It gives the following data on events detected without predetection processing: approximate location (± 4 degrees rms), amplitude averaged over LASA, dominant period, magnitude, and sign of first motion. Modifications are being made to include other parameters.

Work is also in progress on a computer program that will compute the station bulletin quantities automatically.

H. W. Briscoe
P. L. Fleck

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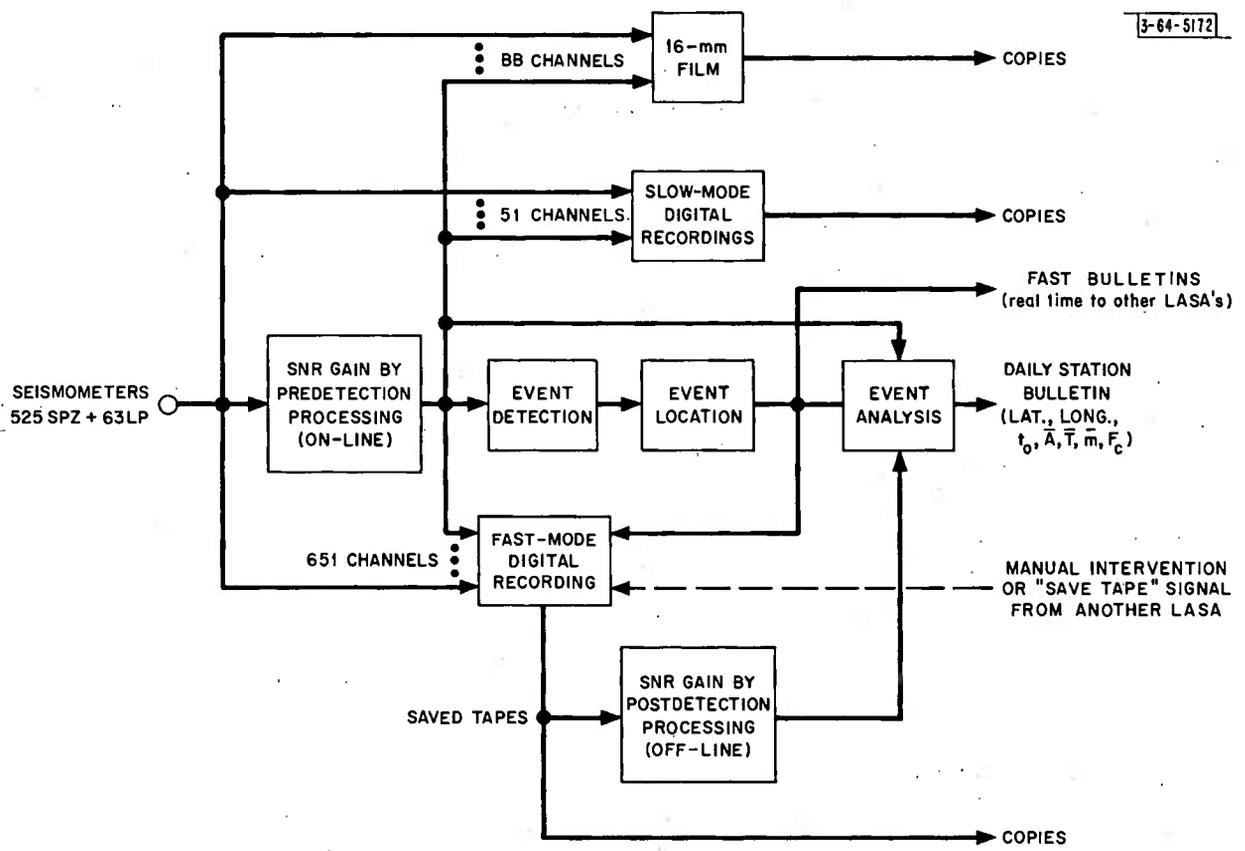


Fig. 1. Signal flow into and out of LASA Data Center.

V. SOURCE IDENTIFICATION

A. IMPROVEMENT DUE TO LASA SIGNAL PROCESSING

Several studies have been performed to investigate the ability of a LASA or a network of LASAs to aid in discriminating between explosions and natural earthquakes from observations of the seismic waves they generate. The identification capability of a network of LASAs cannot be determined from experiments using just one LASA, since most identification criteria involve the comparison of observations from several stations.

The major effort has been an attempt to relate an increase in the ability to observe the pP phase, first motion, and complexity of an event to the well-documented ability of LASA to improve signal-to-noise ratio. The results indicate that the improvement in ability to see first motion varies directly with SNR enhancement, but that the ability to identify pP is apparently improved more than the SNR gain would indicate, probably because of the ability of a large array to measure velocity directly. We observed that complexity observations were much more reliable on the processed data, principally because of noise suppression, but also, in the case of simple waveforms, because of a slight reduction in reverberation. However, it proved difficult to define a quantitative measure of improvement. We observed that complexity can vary widely between different subarrays and, of course, combining subarrays tends to smooth out the variations.

Two experiments designed to take advantage of the high SNR gains available at the lower frequency end of the short-period band (0.1 to 1.0 cps) are in progress. One experiment, an attempt to observe S-wave energy on small events, has been hampered by an unexpected and, as yet, unexplained high level of signal distortion. The other study, designed to investigate the pattern of P-wave spectra in the 0.1 to 1.0 cps region by using sonograms,⁵ has indicated that the energy in this band may be lower for explosions than for earthquakes, but it is too early in the study to state quantitative results.

These studies are all described in some detail in a recent report.⁴

H. W. Briscoe
R. J. Greenfield
R. M. Sheppard

B. COMPLEXITY STUDY

An investigation was carried out to measure the complexity of teleseismic signals arriving at the LASA. It was hoped that because of the wide separation of the outside (F-ring) subarrays, a form of processing could be developed which would include in the complexity measurement the part of the coda that was common to two subarrays while rejecting local crustal reverberations which should differ from one F-ring subarray to another. To do this, a form of processing was developed which multiplies together the envelopes of the bandpassed delayed sums of two subarrays to give a trace from which the complexity is computed. This parameter is termed the co-complexity; if a single subarray envelope is used for the product trace, the parameter is termed the auto-complexity.

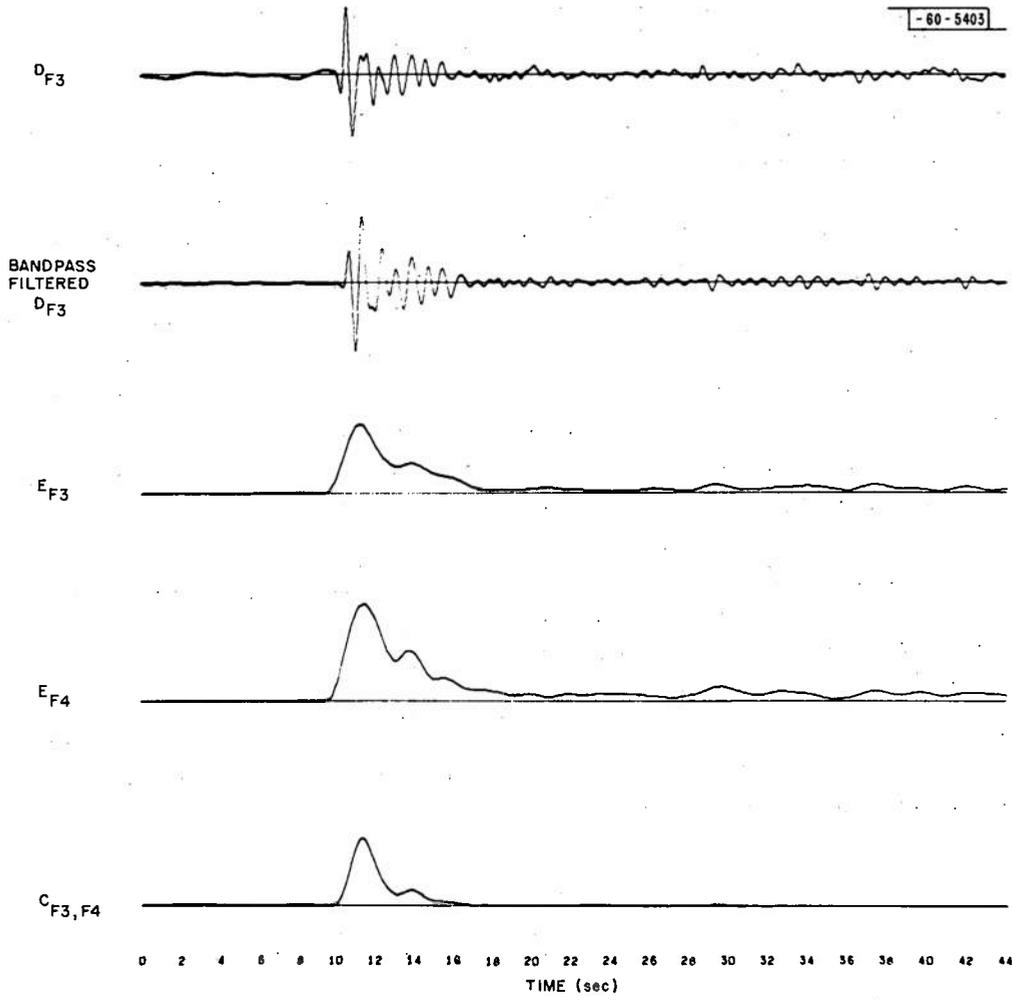


Fig. 2. Typical traces in co-complexity computation (11/21/65 E. Kazakhstan event).

The method of computing complexity described here is similar to the "correlogram" method used by the British AWRE group, but differs in that the envelopes are formed before multiplying the two traces together rather than after, and in that the trace analogous to the correlogram has the dimensions of (amplitude)² rather than amplitude.

Specifically, the co-complexity ψ_{ij} is computed by the following steps which are illustrated in the waveforms of Fig. 2.

- (1) Align all seismograms to have a common arrival time t_a .
- (2) Compute the bandpass filtered delayed sum $D(t)$ for each of the two subarrays. (A 0.6- to 2.0-cps Butterworth filter was used.)
- (3) Compute an envelope function for each subarray as

$$E(t) \equiv \left[\int_{-a}^a \Lambda(\tau) D^2(t + \tau) d\tau - \overline{N^2} \right]^{1/2}$$

where

$$\Lambda(\tau) \equiv \frac{1}{a} \left(1 - \frac{|\tau|}{a} \right)$$

is a triangular time window, and $\overline{N^2}$ is the expected value of the noise power for the subarray bandpass filtered delayed sum.

- (4) Compute a trace analogous to the correlogram.

$$C_{ij}(t) \equiv E_i(t) E_j(t)$$

where E_i and E_j are the envelopes for the subarrays i and j . Notice that $C_{ij}(t)$ is large only when the envelopes of both subarrays are large.

- (5) Compute the complexity ψ_{ij} as

$$\psi_{ij} \equiv \frac{\int_{t_a+5 \text{ sec}}^{t_a+35 \text{ sec}} C_{ij}(t) dt}{\int_{t_a-1.0 \text{ sec}}^{t_a+5 \text{ sec}} C_{ij}(t) dt}$$

This form of processing was applied to the 12 events listed in Table I. It was hoped that the co-complexity computed using two subarrays might be reduced by the elimination of local reverberation, and that the co-complexity of explosions might be reduced to a greater degree than that of earthquakes. However, it was found that, generally, the co-complexity computed using two subarrays was about the same as the geometric mean of the two individual auto-complexities. For example, on event 5 the co-complexity divided by the geometric mean, $(\psi_{ij} / \sqrt{\psi_{ii} \psi_{jj}})$, varied only from 0.86 to 0.96 for different pairs of subarrays. It therefore seems unnecessary to compute the co-complexities. However, since the results obtained on individual complexities indicate that the complexity computed from one subarray may be misleading, individual complexities should be computed using several subarrays.

Figure 3 shows the results of auto-complexity measurements of the 12 events listed in Table I using F-ring subarrays. Several observations may be made from this figure:

- (1) There is often considerable difference in the complexity of a given event as seen at different subarrays.

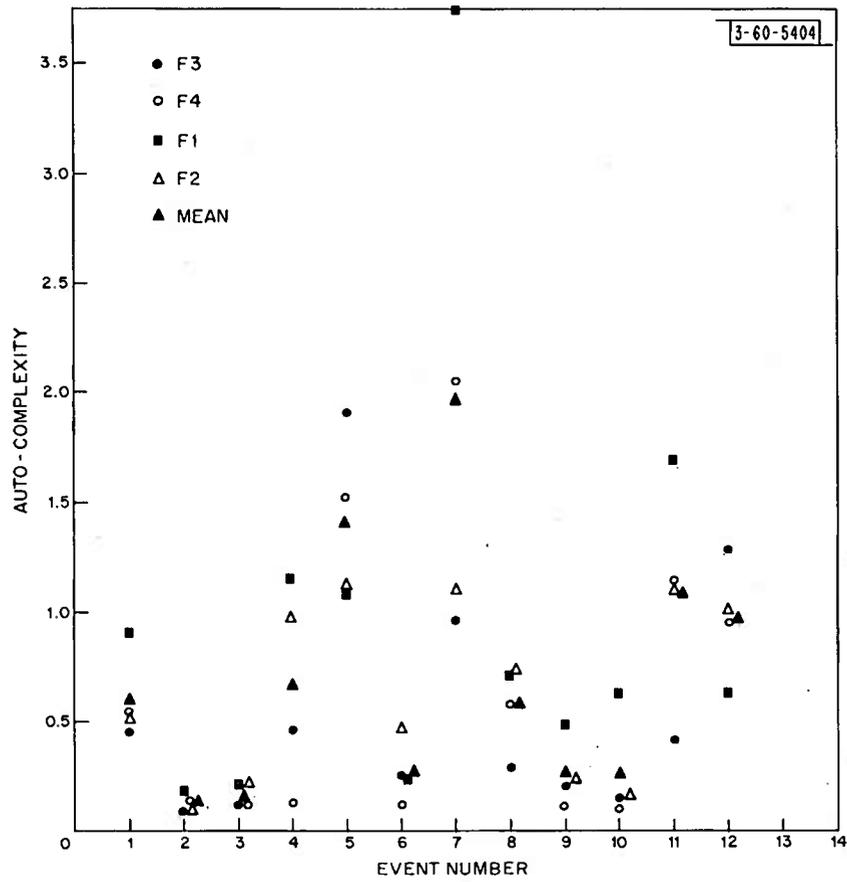


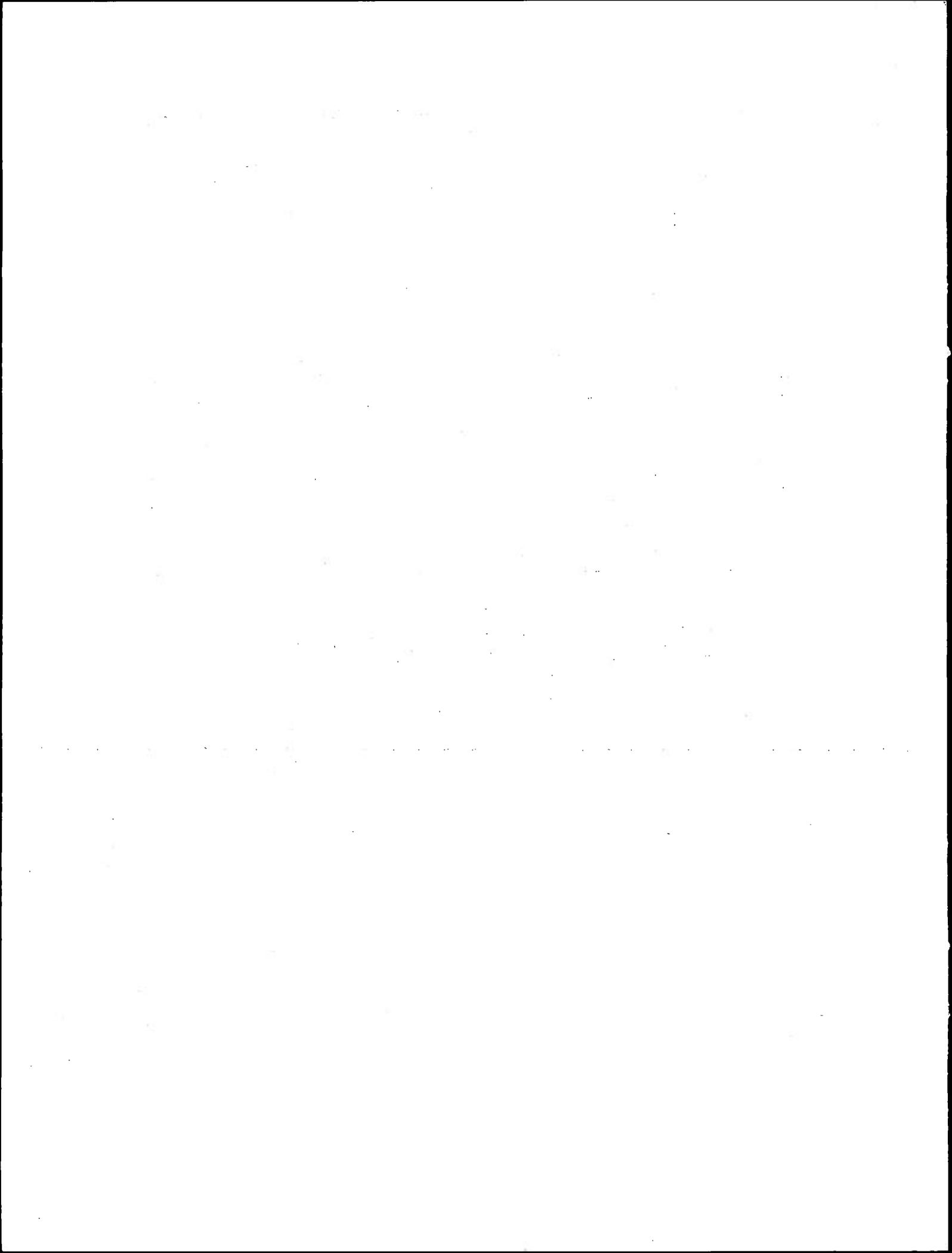
Fig. 3. Complexity measurements of 12 events at four LASA subarrays.

TABLE I
EVENTS USED IN COMPLEXITY STUDY

Event Na.	Location	Date	Depth	Distance from LASA (deg)	LASA Amplitude (μ)
1	Amchitka Is.	10/29/65	0	47	256
2	S. Algeria	12/1/65	0		29
3	E. Kazakhstan	11/21/65	0	84	56
4	Hanshu	11/6/65	73	81	22
5	Kamchatka	1/7/66	92	57	15
6	Marianas Is.	11/20/65	33-R	87	17
7	Kurile Is.	11/24/65	33	66	14
8	Easter Is.	11/24/65	33	74	10
9	Kurile Is.	11/5/65	unknown	62	16
10	Argentina	12/11/65	unknown	90	13
11	N. Atlantic	11/9/65	33-R	52	4
12	Peru	12/10/65	131	41	7

- (2) Subarray F4 has the most complex signal for 7 of the 12 events, and the signal is almost as complex as the most complex subarray output for 2 other events. This suggests that the complexity is quite dependent on the local geologic structure, and that this structure is complex under subarray F4.
- (3) Although the three explosions are not highly complex, some earthquakes appear to be at least as simple as any of the explosions (e.g., events 9 and 10).

R. J. Greenfield



VI. LASA SENSOR CALIBRATION EXPERIMENTS

By mid-1965, it was clear that conventional single-frequency calibration of the individual sensors in LASA was inadequate for monitoring sensor performance in a large array. A technique was needed whereby information on a given sensor's response over its entire operating frequency range could be obtained. In addition, this information should be available on short notice and capable of frequent and convenient updating on demand by the LASA Data Center. Several multiple-frequency techniques, capable of being initiated and controlled from the Data Center, were considered, but it was concluded that all were too complex and unwieldy in operation for serious consideration.

The present experimental broadband calibration system was arrived at by considering the basic requirements for a satisfactory calibration procedure. One wishes to be able to inject energy into the seismometer calibration circuit at any or all operating frequencies. It would be desirable to inject this energy at all the frequencies simultaneously, since this would reduce the time required to calibrate the sensor. In addition, because of the requirements of the LASA lightning protection circuits and the need to maximize calibration energy (and hence calibration signal-to-noise ratio) during the process, one would like a calibration waveform having a peak-to-average ratio close to unity.

Investigation showed that a pseudo-random binary digital sequence would satisfactorily meet the above constraints. For this application, the output of a generator driven by such a sequence may be a two-level signal in which the times of transitions from one level to another are pseudo-random but quantized to integral multiples of the generator clock pulse. As an illustration, the sequence of binary states 01100111010 would produce in the sequence generator output the time sequence shown in Fig. 4.

Without presenting the mathematical justification, the following are the relevant characteristics of the class of pseudo-random binary sequences and of the sequence generator output signal considered here.

- (a) The sequence time duration (period) is $2^n - 1$ clock intervals where n is a positive integer.
- (b) In the frequency domain, the spectrum of the generator output is a line spectrum, contained in a $\sin X/X$ envelope, with line spacing equal to the reciprocal of the sequence period and with the first zero of the envelope occurring at the reciprocal of the clock period.

In our experimental sequence generator, the two levels between which the generator output varies are ± 10 volts. The clock interval is 0.1 sec and n is six, giving a sequence period of 63 clock intervals or 6.3 sec. Hence, the spectrum lines appear at 0.159-cps intervals, starting at 0.159 cps.

Figure 5 shows the analog waveform from a typical sensor, corresponding in time to one period of the 63-state sequence generator. Figures 6 and 7 show the amplitude and phase components of the sensor transfer function, obtained by performing a Fourier analysis of the waveform of Fig. 5 and comparing the results of this analysis, frequency by frequency, with the data from a similar analysis of the calibration signal injected in the sensor calibration circuit.

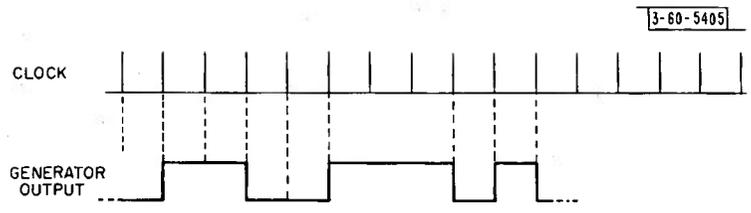


Fig. 4. Pseudo-random sequence generator waveforms.

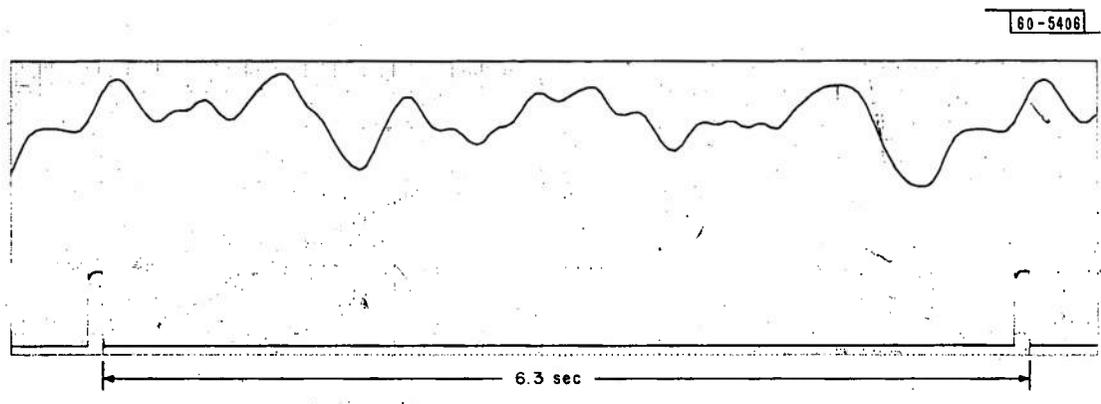


Fig. 5. Typical seismometer output when input is of type shown in Fig. 4.

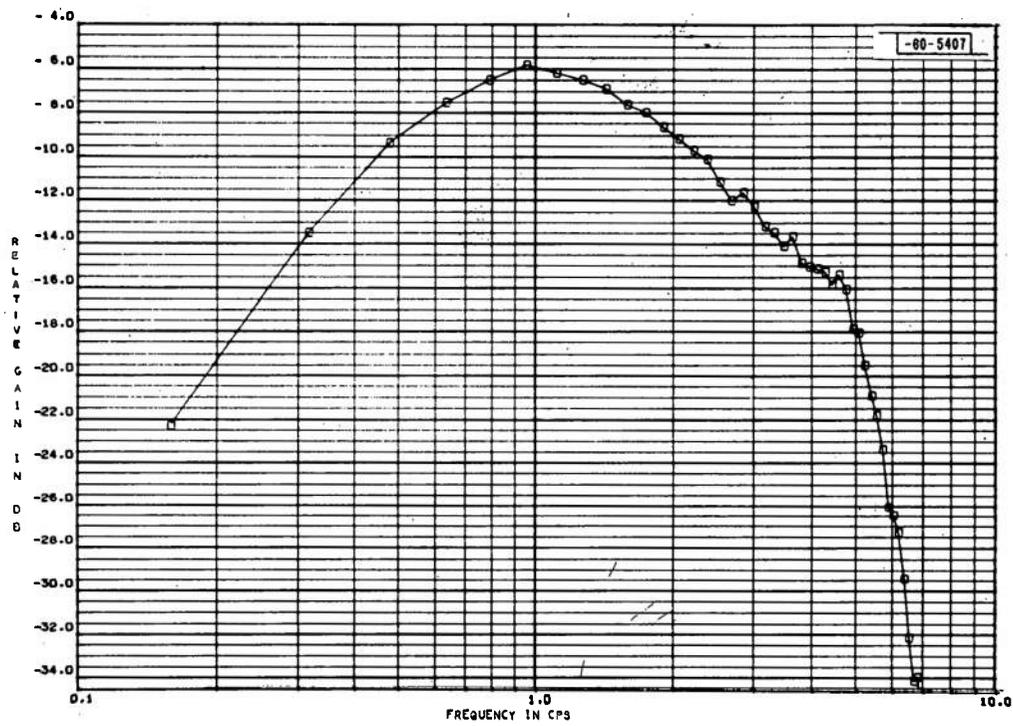


Fig. 6. Typical seismometer amplitude response.

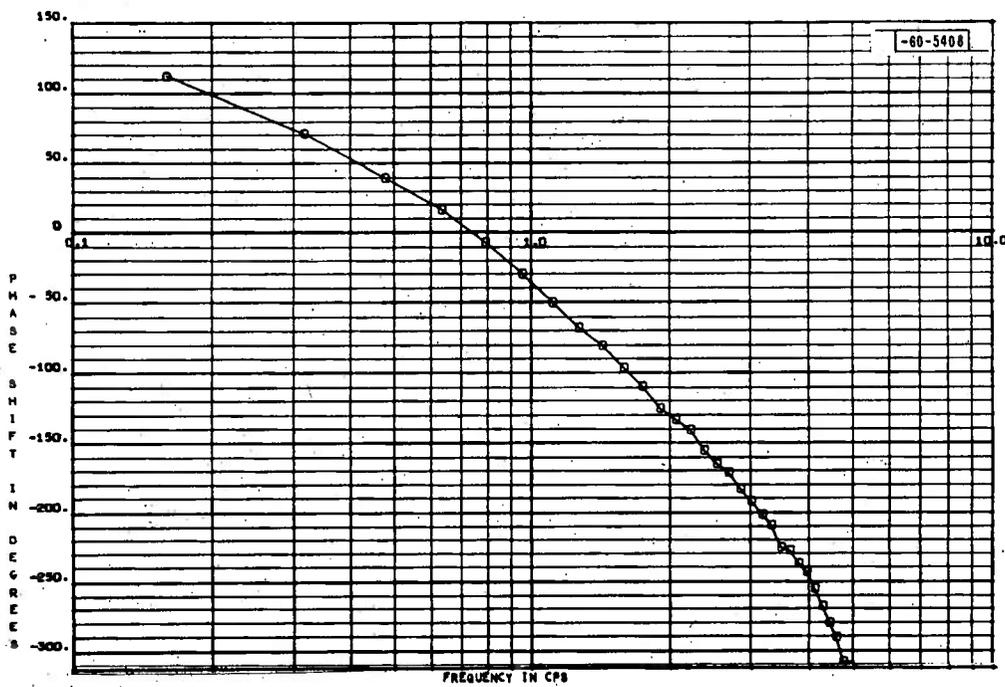


Fig. 7. Typical seismometer phase response.

Section VI

A problem in any sensor calibration procedure is the unavoidable presence of seismic noise during calibration. If one may assume that such noise will be incoherent with respect to the 6.3-sec sequence period, one can considerably improve the calibration signal-to-noise ratio and hence the calibration accuracy by digitally integrating the data samples over a sequence period, for a number of periods, before performing the spectrum analysis. Our experiments show that this digital integration does indeed improve the performance. Data now being collected will indicate the optimum number of periods over which the integration should be performed. Future experiments, using sequences with longer periods, will check on the relationships among sequence periods, extent of digital integration, and calibration accuracy.

R. V. Wood, Jr.
R. A. Guillette

VII. ANALOG THREE-COMPONENT PROCESSOR

An analog three-component processor has been built and is being used to gain experience on the general character and usefulness of three-component seismic data. Work in this area was suggested by the REMODE filtering used by the Vela Seismic Data Laboratory.⁶ An equipment block diagram is shown in Fig. 8 and includes some of the means of displaying and recording the immediate and filtered outputs of the processor. All three seismometer outputs are filtered through identical bandpass filters tuned to enhance the arriving teleseism. The two filtered horizontal signals are then each multiplied by the filtered vertical signal in two specially developed multipliers having the wide dynamic range (>60 db) needed for this processing. When the N-S and E-W multiplier outputs are presented to the vertical and horizontal plates of an oscilloscope, respectively, they generate a form of azimuthal plane vector diagram. The spot rests in the center of the screen, and as a rectilinear P-wave arrives, the spot moves out from the center and back (on one side only) at twice the event frequency, forming a straight line whose angle with respect to "north" on the screen is the azimuthal angle of arrival of the event.

A more recordable processor output is formed as follows: The average value of each multiplier output is proportional to the product of the input amplitudes multiplied by the cosine of the phase difference. For rectilinear particle motion, the phase angle is zero, and thus the average labeled "N-S processor output" is proportional to the product of Z and N-S amplitudes, and similarly for the "E-W processor output."

These outputs are of considerably lower frequency than the raw seismometer traces and can therefore be recorded and identified, with no loss of information, on a single Develocorder trace. This is done by passing the two filter outputs and a reference ground into a three-position switch (a "triplexer") which cycles through its three inputs spending noticeably different dwell times on each. The "triplexed" waveform is then fed to a single galvanometer of a Develocorder. A sample of how the recorded processor output appears is given in Fig. 9 which shows an event arriving from the southeast. Note that this record allows the departure from rectilinearity in the P-coda to be readily seen in the form of a shift in the ratio of E-W and N-S traces. Film recordings of this type have been made for the last four months on three-component signals telemetered from TFO in Arizona.

C. A. Wagner

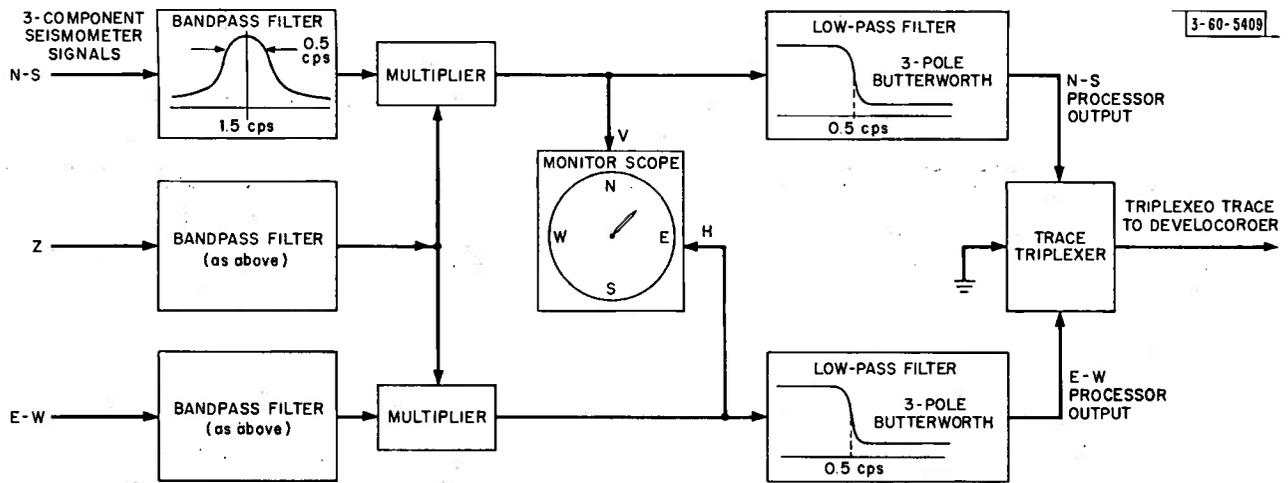


Fig. 8. Three-component processor.

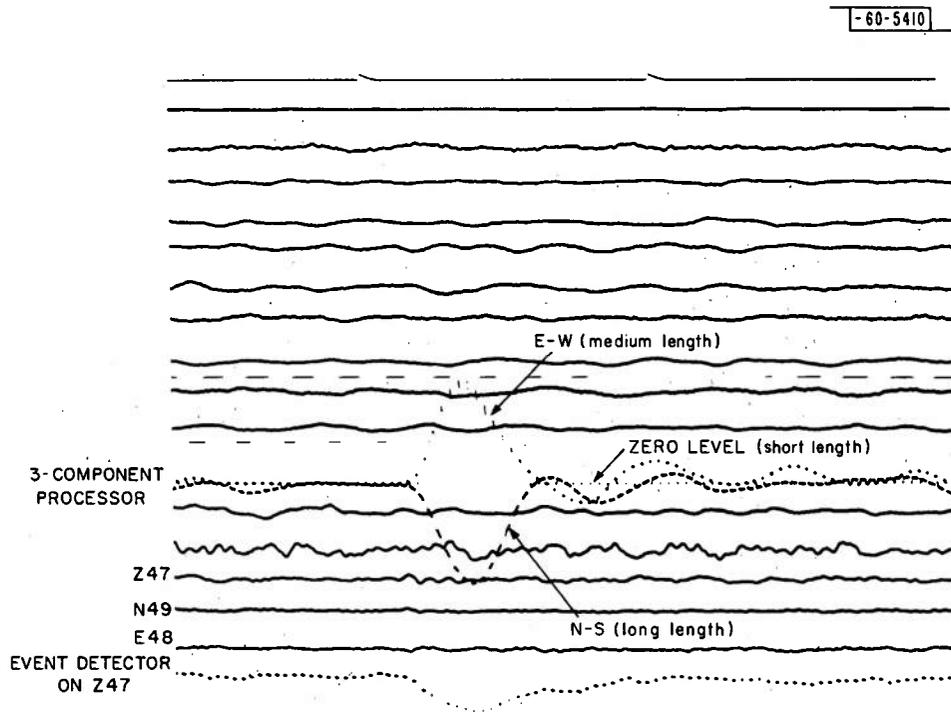


Fig. 9. Recorded three-component processor output.

VIII. LASA SENSOR CHANNEL MATHEMATICAL MODEL

As part of the effort to control the LASA signal collecting system effectively, it is first necessary to understand how the system behaves. The digital portions of the system are well understood; however, because the behaviors of the various analog portions are more difficult to understand, it is necessary to have a model which can be used to study the effect of component changes on the system output. An important consideration which dictates the final form of the model is the fact that the common signal collection point, located at the LASA Data Center, is the only place where all the outputs of the various sensor channels can be conveniently monitored. Finally, a model of appropriate form can be used as a control against which empirical measurements can be compared. From these comparisons, an understanding of component behavior in terms of the system output can be developed.

The analog portion of each channel in the LASA system consists of an HS-10-1/ARPA geophone, whose output coil is connected to a Texas Instruments Model RA-5 solid state, high-gain amplifier. The outputs of these filters are connected to the rest of the information collecting system by means of analog-to-digital converters.

The model which was produced is capable of representing the frequency domain amplitude and phase response of the analog channel just described. The transfer function thus represented computes the ratio of the output voltage of the 5-cps low-pass filter to a constant current input to the electromagnetic calibrator on the HS-10-1 geophone.

These computations were carried out by means of a Fortran IV computer program whose data inputs consisted of the various component values in the analog channel. An important feature of the analytical model computer program is that the input parameters are the values of the actual components in the system. For example, the seismometer damping resistance is an input to the program rather than the total coefficient of damping. Another important feature is that once a computation of amplitude and phase is completed for a particular set of parameters, a set of numbers representing percentages of change in these parameters can be read in and another computation can be performed. By comparing the amplitude and phase data from the new computation with the previous values for the control case, a set of differences is computed. These sets of results can be compared with similar sets of measured data, and the magnitudes of the various component changes effectively evaluated.

The results of these computations are available in both printed and graphical form from the computer program. The graphs which are produced show the reference case and the perturbed case plotted on the same grid. The computed differences are plotted on a separate grid and show essentially the same information but with greater detail. As an example of a typical set of calculations, the curves shown in Figs. 10 through 13 are presented, exactly as displayed from the computer. The solid curves in Figs. 10 and 11 show a reference case with all parameters set to their proper values. The dotted curves on the same grid show the effect on system behavior of decreasing the value of the external damping resistor on the seismometer by 20 percent. The curves plotted in Figs. 12 and 13 show the differences only. In all cases where amplitude ratios are plotted, the units are in db. Where a change in system response due to a change in filter parameters is being investigated, additional curves showing data for the filter characteristic alone can be produced.

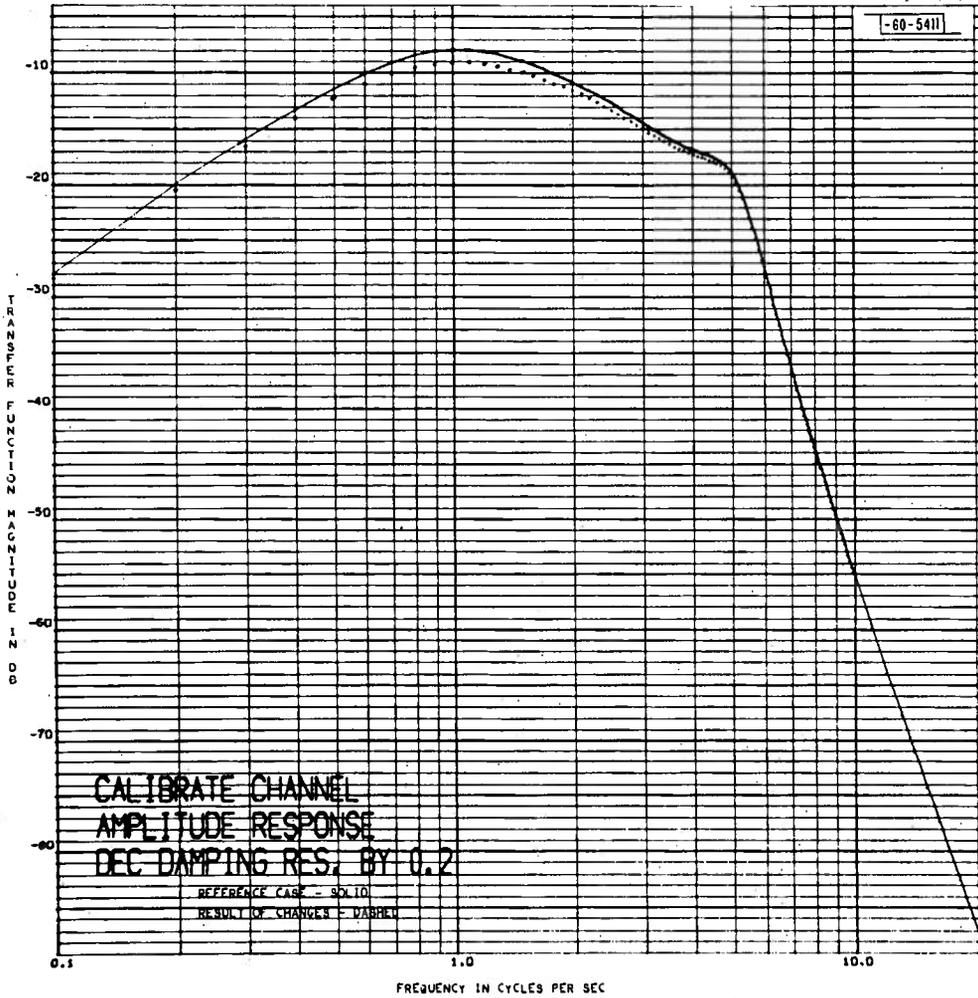


Fig. 10. Amplitude response of model sensor channel. Dotted curve shows effect of 20-percent change in damping resistance.

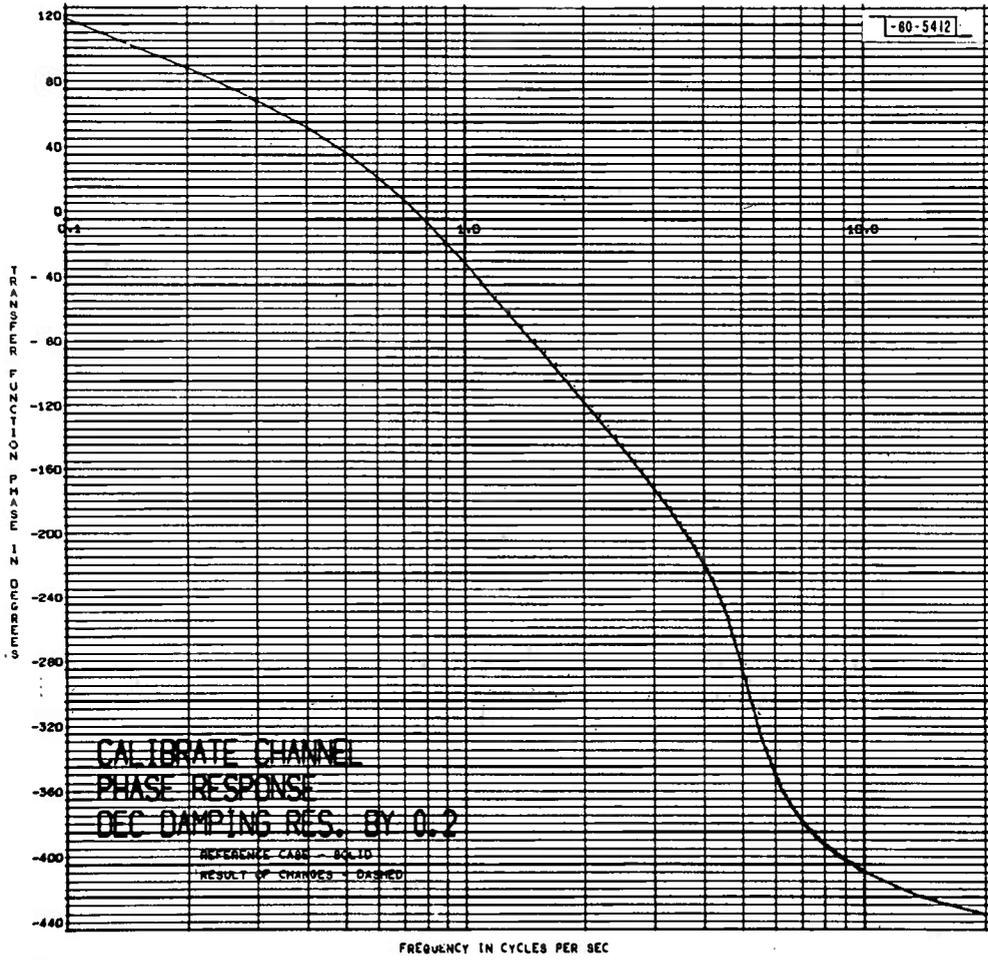


Fig. 11. Phase response of madel sensor channel. Dotted curve shows effect of 20-percent change in damping resistance.

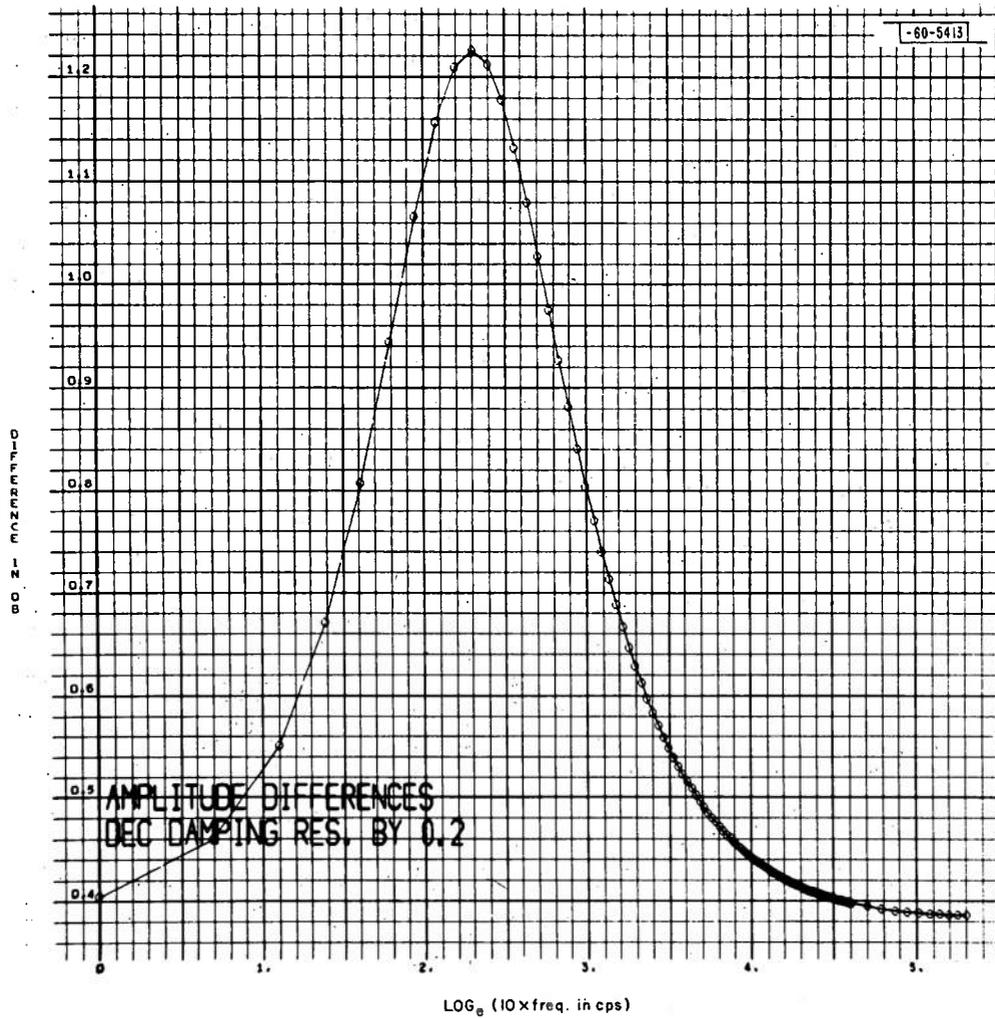


Fig. 12. Amplitude differences due to 20-percent damping resistance change.

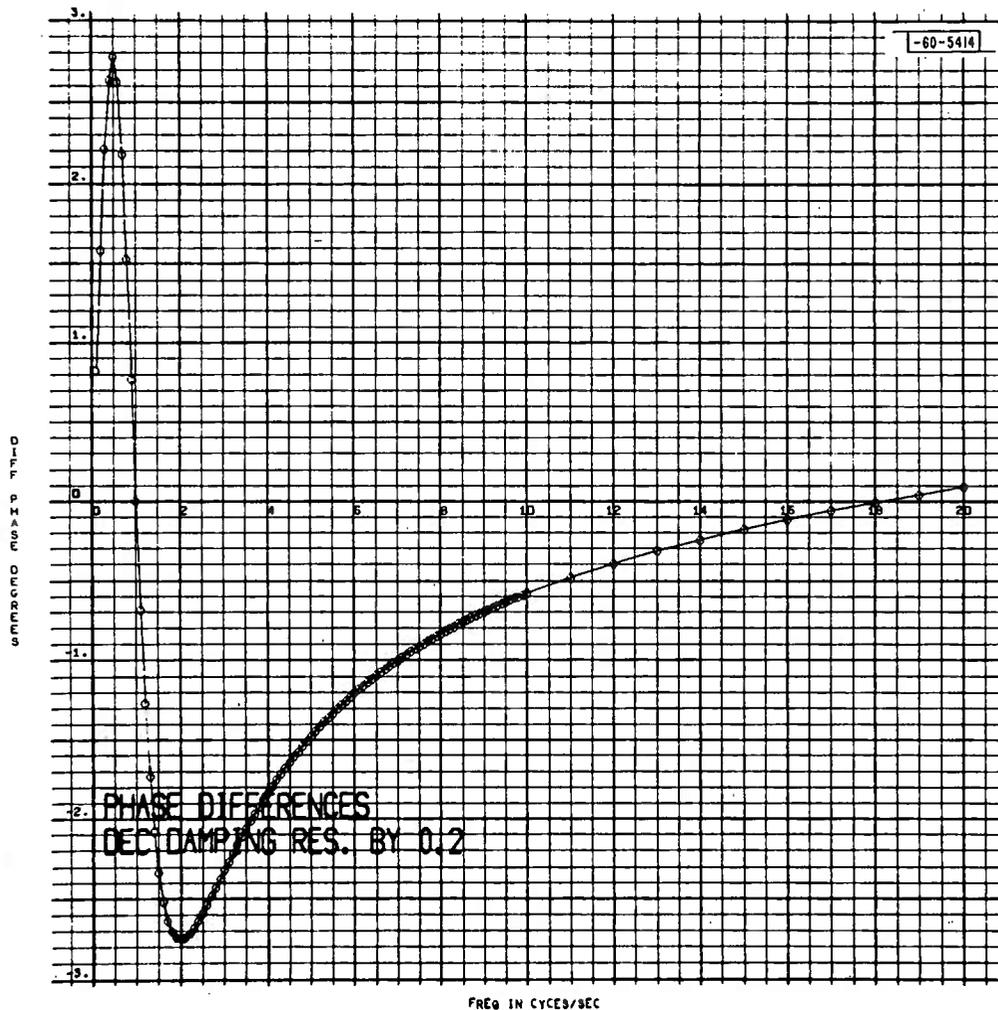


Fig. 13. Phase differences due to 20-percent damping resistance change.

Section VIII

The example of a sample perturbation given here is only one of fifteen possibilities. There are eight parameters in the seismometer, three in the high-gain amplifier circuit, and four in the filter circuit of which any one or combination can be varied to observe the effect on the total response.

R. A. Guillette

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13. ABSTRACT The capabilities of the experimental Large Aperture Seismic Array (LASA) to detect, reprocess, and identify teleseismic signals have been evaluated. The detailed results are summarized, and current performance of the physical elements of the system is discussed. Exploratory work on the following topics is described: a different method of measuring P-complexity, a novel scheme for wide-band seismometer calibration, processing of signals from a set of three-component seismometers, and a computer simulation of the LASA seismometer channel.		
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