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Group Report

1965-1

P. E. Green, Jr.

A Large Aperture Seismic Array

6 January 1965

Prepared for the Advanced Research Projects Agency
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Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts



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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

A LARGE APERTURE SEISMIC ARRAY

P. E. GREEN, JR.

Group 64

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ABSTRACT

The Large Aperture Seismic Array is an experimental system designed to provide improved capability for seismic discrimination of nuclear explosions and earthquakes. This improvement is to be brought about by suppression of reverberation and microseismic noise relative to the signal through the use of a larger number of sensors and a larger array aperture than previously employed in seismic arrays for this purpose. This report gives a brief sketch of the way in which the signal improvement is to be achieved, followed by a short physical description of the various parts of the entire array design as it is currently envisioned, including the choice of sensors, array geometry, signal telemetry, and signal processing.

Accepted for the Air Force
Stanley J. Wisniewski
Lt Colonel, USAF
Chief, Lincoln Laboratory Office

I. INTRODUCTION

One of the most useful new techniques introduced into seismology in recent years has been that of connecting together a number of sensors distributed in a horizontal plane so as to form an array. This has proved to be particularly useful in the monitoring of underground nuclear tests, since the events are of small magnitude and the criteria used to distinguish source type depend on freeing the weak signal as far as possible of both the additive microseismic noise and reverberation components.

The general way in which a horizontal array with linear processing of the outputs operates to perform such a separation is indicated most conveniently by a representation like that of Figure 1. Since the microseismic noise is very close to a gaussian random process,¹ it can be shown that linear processing operations are the ones that lead to the greatest suppression of noise relative to (undistorted) signal.^{2,3} Nonlinear operations will produce signal distortions and also the well-known weak-signal suppression effect for threshold conditions such as are apt to be encountered in the seismic source discrimination problem.

The array and its associated linear processor, shown in Fig. 1, can be described by a function $p(x, y, t)$ having an extent L_x , L_y , and T in the three variables, respectively. The Fourier transform of p gives the response pattern in three frequencies, one temporal (f) and the two components of spatial frequency, or wave number, (k_x and k_y). This coordinate system is shown in the right side of Fig. 1. The problem is to design array sensor locations and choice of filter functions (that is, p) to place a response peak at the locus in the f - \vec{k} space along which the signal is located while nulling out undesired components as much as possible. The available widths of the response peak along the three coordinates are roughly $1/T$, $1/L_x$, and $1/L_y$, respectively, as shown in the right side of Fig. 1. The level of peak response relative to the average sidelobe (expressed as an amplitude) is roughly proportional to N , the number of sensors.

The Large Aperture Seismic Array discussed here represents an experiment in increasing both L and N by roughly $1\ 1/2$ orders of magnitude over previous seismic arrays (L going from roughly 10 km to 200 km, and N from roughly 300 to 500). As far

as nuclear test detection is concerned, the array is to be used, not so much for detecting much smaller events than can presently be seen, but to improve the clarity of those that are observable.

The frequencies of initial interest in the LASA experiment lie in the range 0.2 to 5 cps. Since the body wave signals that are to be observed propagate undispersed (velocity independent of frequency), they can be represented in f - \vec{k} space as straight lines of slope equal to the horizontal phase velocity c_H and at the azimuth from which they approach, as shown at the left in Figure 2. P-waves from teleseisms ($\Delta > 30^\circ$) will lie within a cone described roughly by $12 \text{ km/sec} < c_H < \infty$ and S-waves will lie within $8 \text{ km/sec} < c_H < \infty$.

The undesired components can be briefly listed as follows:

a) Trapped Mode Microseismic Noise whose f - \vec{k} behavior for a single remote noise source at a particular azimuth is shown at the right of Fig. 2, and whose spectrum is schematized in Figure 3. At the high edge of the desired frequency band where wave number values k are like 1.6 c/km ($\lambda = 1/k = .6 \text{ km}$) are observed the noise is of local origin. Because of this and its rapid attenuation it may not propagate across an array of more than several km size in an organized fashion so as to be suppressible by array processing; however, it does attenuate rapidly with depth. The storm microseism component at the low frequency end propagates from distant sources at various azimuths and is therefore organized. The trapped modes lie at velocities below roughly nine-tenths of local shear velocity and thus occupy a region in f - \vec{k} that is separated from that of the body wave signal. For this reason it is very effectively dealt with by arrays such as the previous Vela arrays ($L = 3\text{-}10 \text{ km}$).⁴ The effectiveness of such velocity filtering disappears at the very lowest frequencies because the wavelength of the noise is so large. (A value of $\lambda = 16 \text{ km}$ at 0.2 cps is shown in Fig. 2.)

b) Undesired Teleseisms These range in size all the way from a steady background of small teleseisms overlapping in time ("mantle P-wave" microseismic noise) to large single events from unwanted epicentral regions. A small resolution cell (i. e. , a very large array) is required to resolve the signal from these interferences, and in addition, a large dynamic range of all the circuitry in the system is needed for seeing small teleseismic events in the presence of the large ones. Figure 4 shows a slice through $f-\vec{k}$ space at $f = 1.0$ cps laid out according to the geographical source of P-phase signals.⁵ The probable long-time average $f-\vec{k}$ character of mantle P-wave noise (consisting mostly of initial P-arrivals) can be deduced from the locations of seismic belts on such a plot.

c) Leaky Mode Noise of as yet undetermined strength, lying between trapped mode velocities and infinite velocity, is theoretically permitted.

d) Surface Wave Reverberation, or "signal generated noise",^{7,8} indicated in Figure 5. This is caused by generation of trapped mode energy when the P-wave signal is incident on some discontinuity. The properties in $f-\vec{k}$ of such a reflection are about the same as trapped mode noise from some specific azimuth or set of azimuths.

e) Body Wave Reverberation, Figure 6, which will occupy exactly the same locus in $f-\vec{k}$ as the signal (regardless of mode conversion back and forth between P and S) if the underlying discontinuities are parallel, but which will show slight differences for the more realistic case of not exactly parallel layering. In the latter case, small resolution cells in $f-\vec{k}$ may help for suppression, and in both cases deconvolution⁶ of the signal waveforms to undo the reverberation is very desirable.

II. GEOMETRY AND SITING

The question of how to arrange approximately 500 sensors over a region approximately 200 km on a side must be dealt with by examining the intensity and location in $f-\vec{k}$ space of the signal and the various sources of interference just listed. Only so much optimization of the array in the two spatial coordinates is practical since both trapped mode and teleseismic microseisms have slowly time-varying statistics. The best that can be done is to optimize geometry on the basis of gross long term statistics and do the rest of the optimization by changing the filter functions at frequent intervals.

During the initial planning stages of the LASA project it was proposed to make fairly detailed studies of both the microseismic noise distribution in $f-\vec{k}$ space as a function of position and time, and also signal coherence with distance at several proposed site areas in the U. S. These were areas that were known to be reasonably quiet, and were less than 90° from most of the U.S.S.R. and China. (It proved impossible to find a good U. S. location at teleseismic distances (> 2500 km) from the Nevada Test Site.)

It was soon concluded that time would not permit a complete survey of this type, and that anyhow most of the important differences between sites had to do with the absolute noise level, simplicity of crustal structure in the area, and logistic factors, rather than detailed noise statistics. Accordingly, the choice was narrowed down to one site, the area around Miles City, Montana.⁵ Noise and coherence studies for this area are proceeding in parallel with array development rather than preceding it.^{7, 11}

The geometry chosen for the Large Aperture Seismic Array is shown in Figure 7; the reasons for choosing such a geometry are best explained by referring to Fig. 8. The array consists of 21 subarrays each 7 km in diameter and having 25 sensors. Thus, each subarray is seen to be roughly equivalent to one of the earlier Vela arrays. A minimum element spacing of $1/4$ km was chosen to avoid spatial aliasing of trapped mode noise and reverberation into the wedge-shaped region of desired P-wave signals ($12 \text{ km/sec} < c_H < \infty$). A 7-km subarray radius is used so that the pattern response width at the low frequency end (0.2 cps) provides some suppression of the trapped modes.

A 25-element star-shaped subarray pattern that had previously been studied⁵ was selected and 21 such subarrays were arranged in a tapered geometry consisting of squares within squares. Thus the total number of sensors is 525. The tapered geometry of the overall array causes the main lobe to be only slightly broader than would be the case with a more even distribution (the half-power beamwidth is shown in Figure 4). The square-within-square arrangement results from placing points along the arms of four logarithmic spirals emerging from the center; this "log-periodic" character makes it possible to keep the main lobe width (expressed in angle rather than wave number) constant over a wide range of frequency (see Fig. 8). The concentration of subarrays near the center also has logistical advantages, and also may turn out to reduce degradation in array performance should signal coherence versus distance in the Miles City area decrease faster than anticipated.

Siting and land procurement^{7,9} have taken into account the location of probable sources of noise (such as highways, well-drilling, dams, etc.), and have also proceeded with the hope of keeping sensor height differentials within ± 100 ft ($\lambda/6$ for 5 cps and 2 km/sec) within each subarray.

III. SUBARRAY CHARACTERISTICS

Since, for discrimination purposes, the most important part of a teleseismic signal is the compressional energy of the first minute or so, it was proposed to install short-period vertical sensors only, but to leave enough spare telemetry capacity for later installation of some wide-band, long-period, or horizontal instruments, as experience might dictate. It was also realized that if the overall array proved as successful as hoped in suppressing noise at the low-frequency end, an extension of sensor response well below the initial design figure of 0.2 cps might be important.

A combination of a Hall Sears HS-10-1 short-period vertical instrument feeding a Texas Instruments RA-5 solid-state parametric preamplifier was found to be a reasonable choice.⁹ The sensors are placed at the bottom of 200-ft. holes and their outputs ultimately terminate in a subarray terminal vault at each subarray center.^{7,10}

The preamplifier for each sensor is placed in a small vault at the surface near the top of each borehole instead of down-hole to facilitate later small readjustments of frequency response by varying the impedance seen by the seismometer transducer. Most of the holes are cased so as to simplify retrieval of the sensors, but several sensors are being tried in uncased holes in the first two subarrays to see if it is economically feasible either to dig them out (e.g. hydraulically) or to consider them expendable and plant new ones when the old ones fail.

The small vault at the top of each seismometer hole contains the RA-5 low-noise amplifier and lightning protection circuitry. The spoked geometry of each subarray allows the multiconductor armored cables running to the subarray terminal vault from the seismometer vaults in one "spoke" to be laid in a common bundle. Each bundle is plowed in to a depth of three feet, and they all terminate inside the ten-by-twelve foot underground subarray terminal vault. (Units originally designed as fallout shelters were found to be quite appropriate for this function.) There are three conductor pairs from each seismometer vault to the subarray terminal, of which (in the initial setup) one is being used to carry the signal output, a second to carry individual calibration signals out from the subarray terminal, and the third is being reserved for remotely supplied power. If it turns out to be practical, additional signals from the sensor to the subarray terminal vault could be handled by feeding a common calibration signal to all four sensors on a spoke and perhaps likewise for the power.

One objective in the design of the system has been to reduce the need for personnel to operate it to a bare minimum. This point of view, plus the fact that the most convenient and dependable telemetry from the subarray terminals to the array terminal uses the open wire telephone line with its copious bandwidth of 50-100 kilocycles, both argue that preprocessing of signals in the subarray terminal is not very desirable, at least in the initial tests of the LASA concept. Therefore, operations on the signals in the subarray are limited to conditioning them for telemetry to the array center.¹¹ The principle problems are

1) The large dynamic range required for processing weak signals in the presence of strong ones, and for filtering in the computer to bring out low-frequency components well down on the sensor response curve, and

2) The necessity for automatically indicating at the computer the presence of spurious phone line noise.

For both these reasons f.m. telemetry, which has proved completely adequate when the records were to be examined by eye, did not appear nearly so suitable for LASA as digital telemetry. The dynamic range in the system is presumably limited by the RA-5 amplifier, which when properly adjusted has about 80 db dynamic range. Hence, an 84 db dynamic range is employed by using 14-bit samples of the sensor outputs (with a fifteenth parity check bit added). With the expectation that the highest teleseismic signal frequencies of interest lie around 4-5 cps, a sampling rate of 20 per second was chosen.⁸

Thus, the electronic equipment in each subarray terminal includes, in order, a set of lightning protection circuits for the 25 sensor inputs, 32 balance-to-unbalance terminating amplifiers (for the 25 inputs plus spares), 32 5.0 cps low-pass filters to suppress aliasing in the digitization, and a 32-channel multiplexer and digitizer which produces (as presently planned) a single 9.6 kilobit per second bit stream of which 7.5 kilobits per second ($25 \times 20 \times 15$) represent the 25 sensor outputs.

IV. TELEMETRY^{8, 11}

The only other sizable piece of equipment in the subarray terminal is the modem unit (modulator-demodulator) which modulates the bit stream onto a carrier for telephone line transmission. In the experimental model for the first two subarrays, this is commercially available equipment, but in the final model, Western Electric 303A10 units are being leased with maintenance from the Telephone Company. These Western Electric units are designed to operate at 19.2 kilobits per second, exactly twice the subarray output bit rate. At the start this extra capacity will probably not be used. If

experience proves it necessary, error-correcting coding equipment will be installed and will utilize some or all of the excess.

As shown in Figure 9, the point at which all 525 sensor outputs are collected is the array terminal near Billings, Montana, where recording and processing equipment is to be placed. The location of existing or planned Telephone Company microwave carrier circuits (shown by double lines) is such that six of the 21 subarray outputs can feed directly into these carrier circuits by frequency multiplexing at nearby repeater terminals. The other subarray output signals will be frequency multiplexed at an unmanned site near the center of the array where a commercially available microwave link (heavy line) will send the composite signal to the Telephone Company repeater site just west of Miles City. Two-way voice communication is provided between each subarray terminal and the array terminal. Billings was chosen for the array terminal location rather than Miles City or the array center for reasons of logistical convenience, since there will be large amounts of experimentation with the LASA outputs. Maintenance of the subarray equipment will be done by maintenance crews who will be directed to specific trouble spots on the basis of signals received at the array terminal. Recordings of sensor outputs made at the array terminal are probably not needed for this work, provided the maintenance crews have suitable mobile monitoring and recording equipment to make observations on site.

At the array terminal, twenty-one Western Electric 303A10 modems will produce the twenty-one 9.6 kilobit per second digital outputs. These signals will pass through a timing and interface unit before being fed to the signal processing equipment described in the next section. This timing and interface unit provides the sync signals for transmission back to the modems at each subarray so as to establish sampling timing throughout the array. In addition, time of day is generated for inclusion on the data recordings.

V. SIGNAL RECORDING AND PROCESSING^{8, 11}

At first glance, the processing problem for an array of 525 sensors 200 km across appears very forbidding. If one envisions a processor that accepts all 525 inputs

and produces for simultaneous display each output signal from resolvably different regions of the U.S.S.R., China, and one or two other areas, the number of such output channels is 30-50 (see Fig. 4), and the processor has the form indicated in Figure 10. However, it is unnecessary to build such a processor to work on-line in real time because, first of all, the output display is not needed in real time, and secondly the fraction of the time that events in these interesting target areas occur is fairly small, probably no more than ten per day.

Therefore, the processing procedure outlined roughly in Figure 11 is to be used; it provides processing on-line, but slowed down and delayed from real time. In this scheme, the outputs obtained from four or five widely spaced parts of the array are used in a "network processing" scheme to perform an immediate epicenter location¹² on each event observable on these four or five outputs. The outputs might be straight sums of the innermost sensors in the outermost subarrays, or they might be very efficiently processed signals gotten from applying, say, Wiener filtering to each subarray as has been done before at various Vela array observatories⁴; this will depend on the desired detection level. Epicenters are to be located automatically from these outputs by a threshold procedure on each line to tell when an event has occurred, followed by cross correlation to determine relative arrival times, followed by a least-squares fit of observed times to get the epicenter by determining azimuth and horizontal phase velocity.¹¹ If and only if the desired determination has sufficient internal consistency and indicates an epicenter in the interesting part of the earth, a permanent recording is made of all 525 sensor outputs for the duration of interesting portions of the signal plus several minutes of noise preceding it. The noise record is needed for optimizing the filter responses in the processing to which the recording is subjected.

A still more detailed sketch of how this is to be carried out is presented in Figure 12. Two time phases for this work are to be distinguished. In Phase II, the system just discussed is to be realized in such a way that substantially all the processing, as well as the recording, is to be done at the array terminal at Billings. Since an evaluation of the LASA concept will be needed sooner than all this can be accomplished, an

earlier Phase I is planned, wherein only the detection, location, and recording operations are done at Billings, and the recordings made are of several tens of small teleseisms which can be processed at Lincoln Laboratory to establish the observed performance obtainable from LASA with each of several processing schemes. The objective of trying several processing schemes is to establish trade-offs between processing complexity and processing gain. (For example, delay-and-add combining of 21 straight sums would be very easy to do but would most likely be greatly inferior to delay-and-add combining of either Wiener processed^{2,4} or maximum-likelihood-processed outputs^{3,11} and the last two in turn would presumably be more efficient but more trouble if they were required to track the changing noise statistics.)

The arrangement of Figure 12 satisfies the objectives of both Phase I and II. Computers C1, C2, and C3 are identical, small, general-purpose machines. In Phase I, C1 reformats the 21 bit streams for continuous recording on one of a set of four magnetic tape units. It also detects (but does not necessarily try to locate) events, and upon observing one prepares a suitable output tape. This 525-sensor tape is either shipped to Lincoln for processing or is telemetered in slowed-down time. For Phase II, the total capacity of C1 and C2 (and possibly the test computer C3 at Lincoln) is used for recording and event detection as before, but also for event location and screening according to location. Whatever capacity remains is to be used for efficient subarray processing of the sensors of the four or five subarrays used for location. Since the subarray processing operation uses a great amount of machine capacity, special-purpose subarray processors may be needed ultimately if the magnitude level of events that can be screened according to location is to be reduced to anything near the magnitude level of events that can be clearly seen in the final processed output.

The processing procedure just outlined provides for fully efficient off-line processing of all sensor outputs but only for part of the time, namely those time intervals during which it has been determined that an event has taken place in a region of interest. Means will also be provided for achieving some partial array capability all of the time. This is to be done by around-the-clock recording of 21 subarray sums (or outputs of

subarray processors if they exist). Subarray sums are formed in a resistor network at each subarray terminal and are telemetered on a spare channel to the array terminal where they are recorded. Optionally they will also be telemetered on a voice grade phone line to other users. Dubs of the complete 525-sensor recordings of events may also be made available to other users.

VI. EXPECTED PERFORMANCE

At this time it is difficult to assess quantitatively the reduction in reverberation components likely to be produced by the large array. One encouraging development is that the few studies that have been made of coherence over distances of up to several hundred km show that the coherence is highest for the first few P-wave cycles, thus suggesting that P-wave codas will be suppressed.

In the case of microseismic noise, a lower bound on expected improvement can be given. Previous experience⁴ with arrays roughly equivalent to LASA subarrays has consistently demonstrated signal-to-noise improvements that are never poorer than that which would be obtained were all the sensor noises statistically independent. In many cases the improvement is significantly larger than this amount, which (when expressed in terms of an energy ratio) is equal simply to the number of sensors. Thus, for example the observed improvement of a 19-element array over a single element is at least 13 db or 0.65 seismic magnitude unit. An array of twenty one 25-element subarrays would be expected to give a further improvement of 14 more db or 0.7 magnitude unit.

Improvements in signal quality of this order will be quite significant for remote monitoring of underground nuclear tests. The Large Aperture Array should be of considerable value for this purpose and should also provide a unique capability for advanced research in seismology.

ACKNOWLEDGEMENT

I have attempted to summarize the entire LASA system in a Lincoln Laboratory report although its conception and implementation are a shared effort between several organizations. In particular, Dr. Robert A. Frosch and Mr. Harry Sonnemann of ARPA have been prime movers behind this effort, and Dr. Carl F. Romney and Major Robert A. Meek of the Vela Seismological Center (AFTAC) have directed most of the field implementation. Within the Laboratory, the following individuals have made particularly strong contributions to the project to date: H. W. Briscoe, R. G. Enticknap, F. E. Heart, J. L. Holsinger, R. Price, C. A. Wagner, and R. V. Wood.

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SEISMOMETER ARRAY

FILTERING ABILITY OF ARRAY

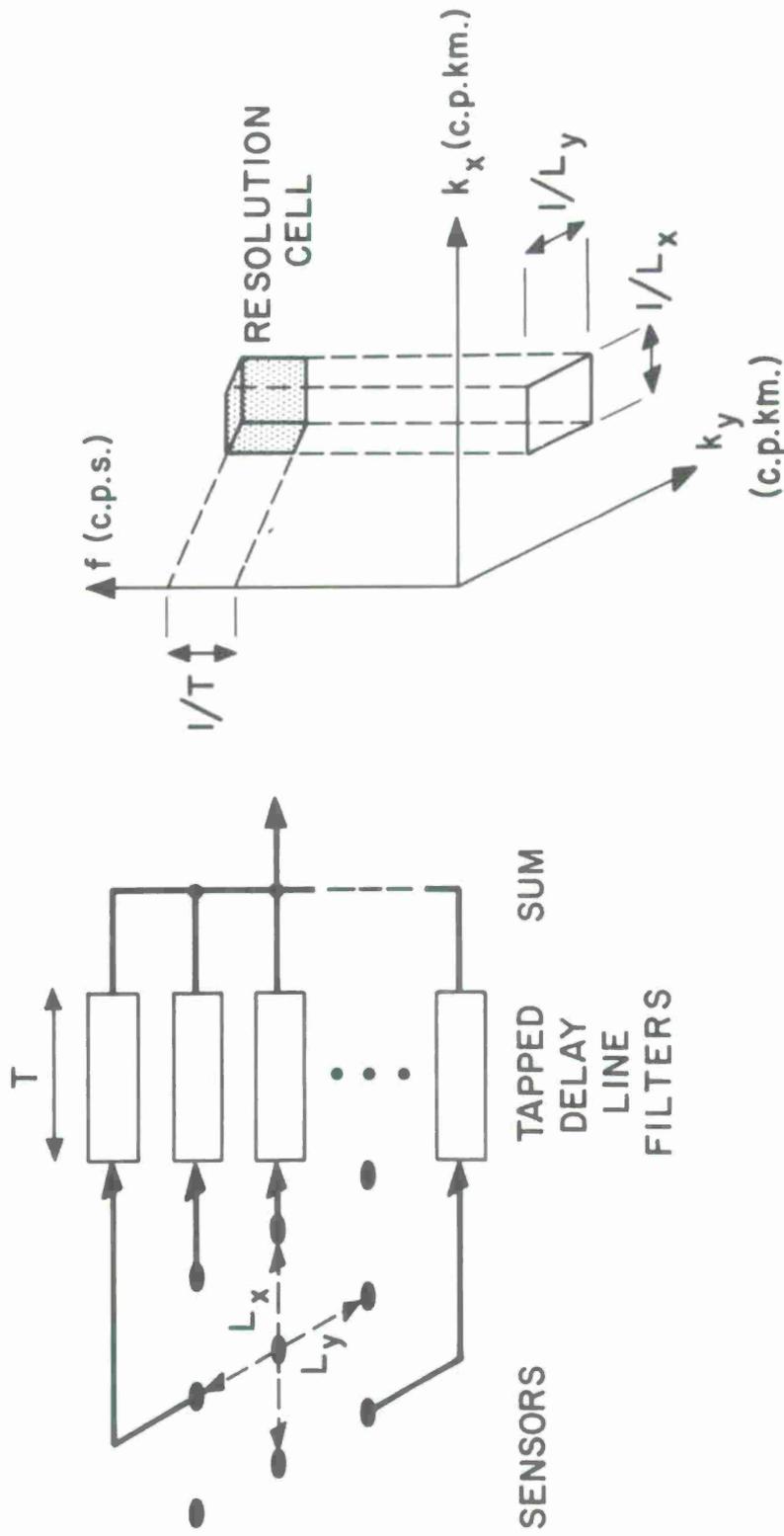
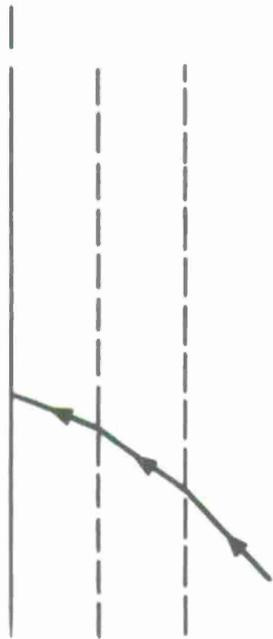
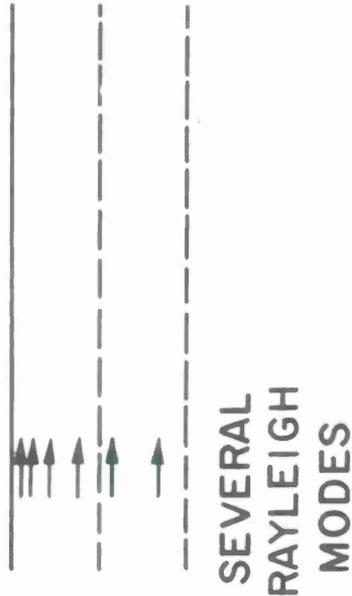


Fig. 1. Filtering of spatial and temporal frequency with an array.



SIGNAL

NOISE

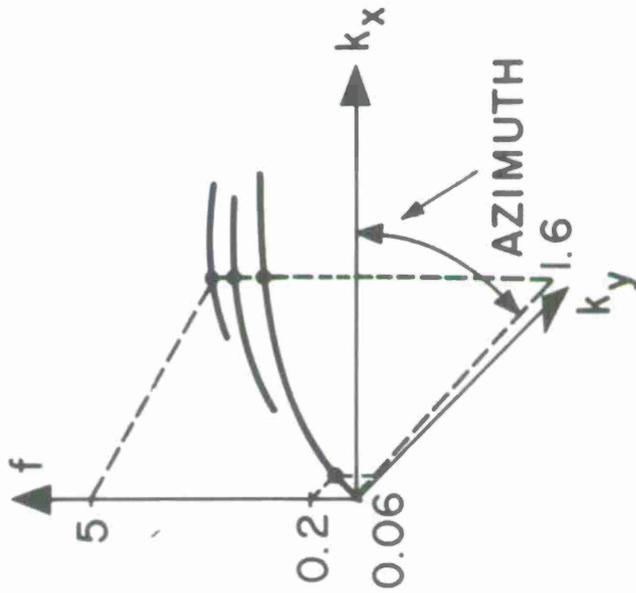
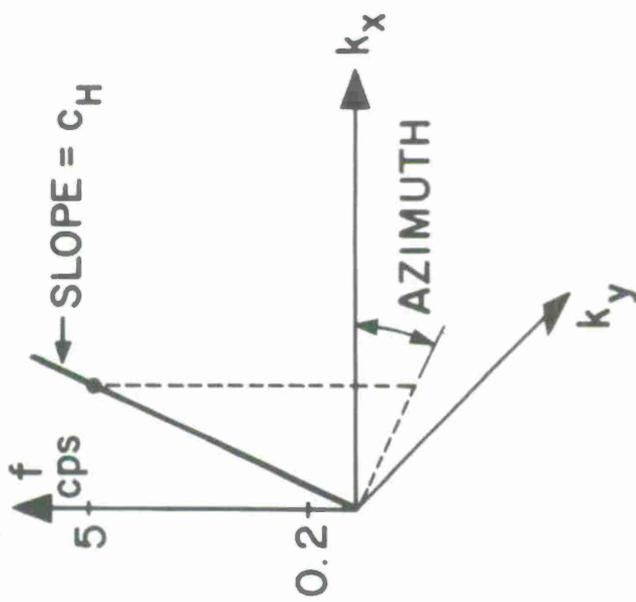


Fig. 2. Signal and trapped mode noise in the earth (top) and in f - \vec{k} space (bottom).

MICROSEISMIC NOISE

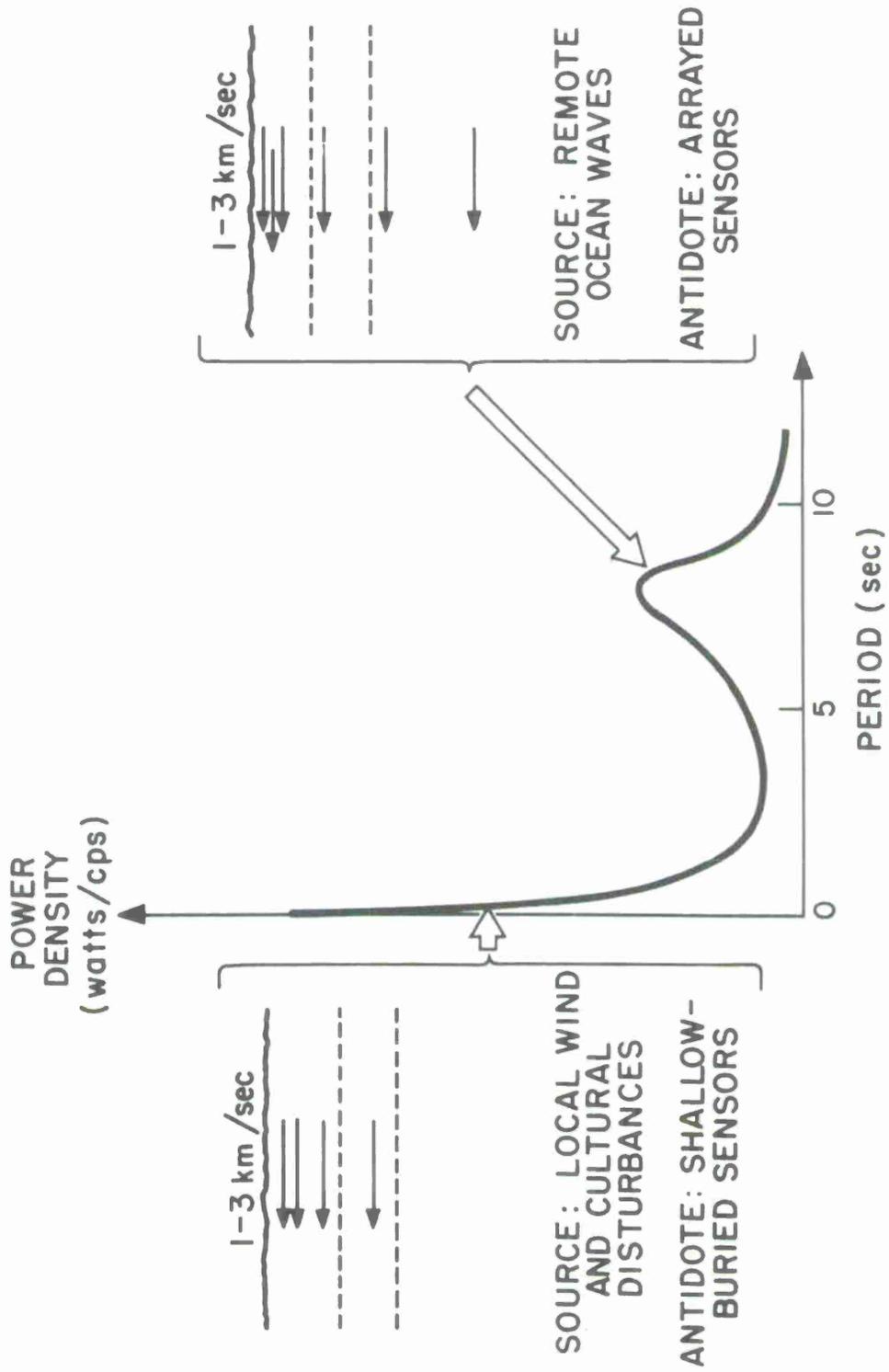


Fig. 3. Trapped mode microseismic noise spectrum.

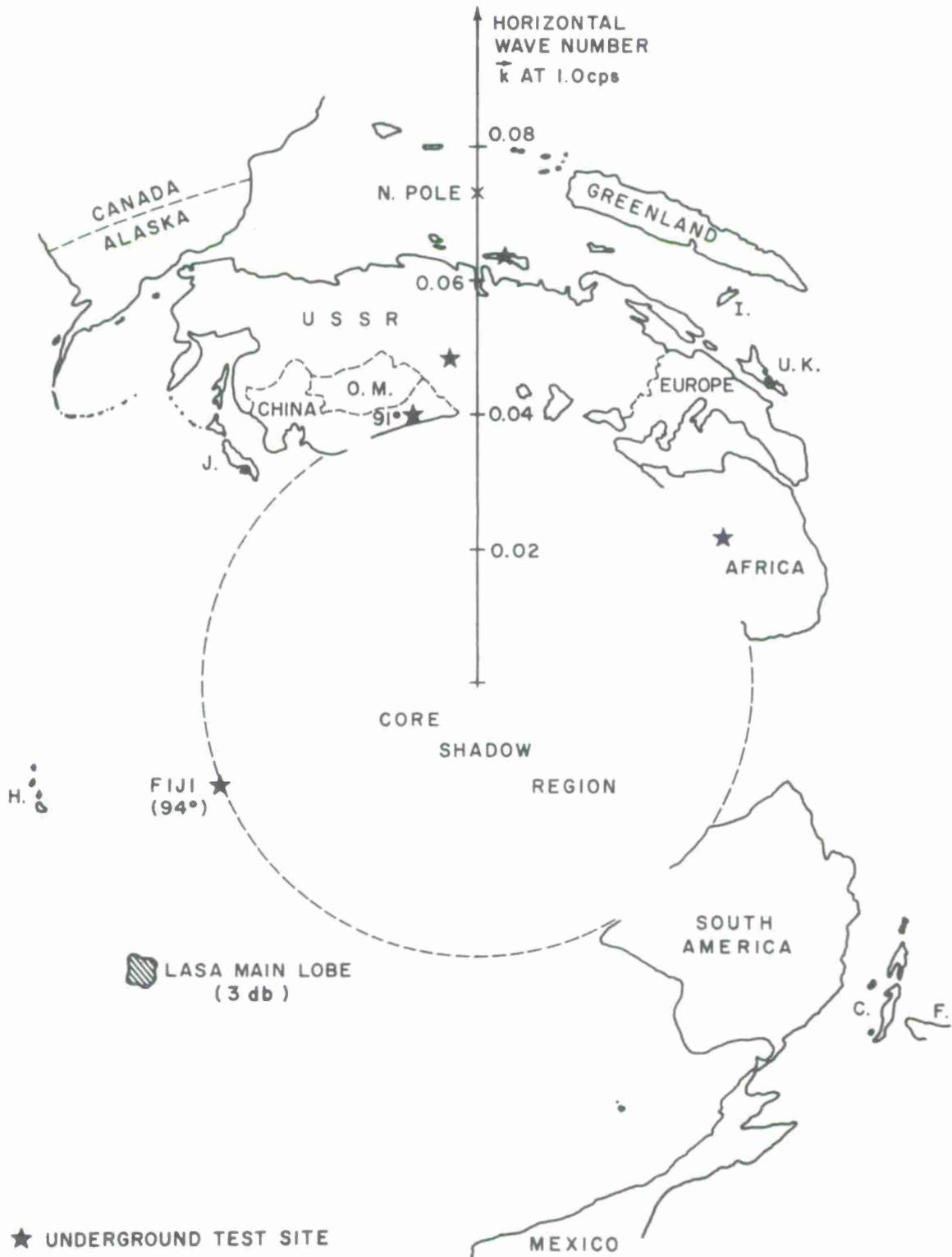


Fig. 4. The earth as seen from the center of the LASA (Distances of 30° - 90°).

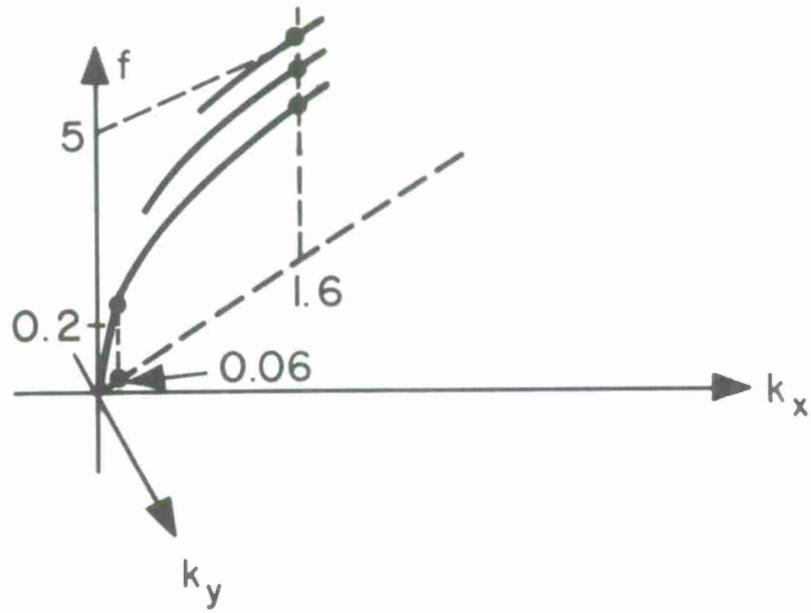
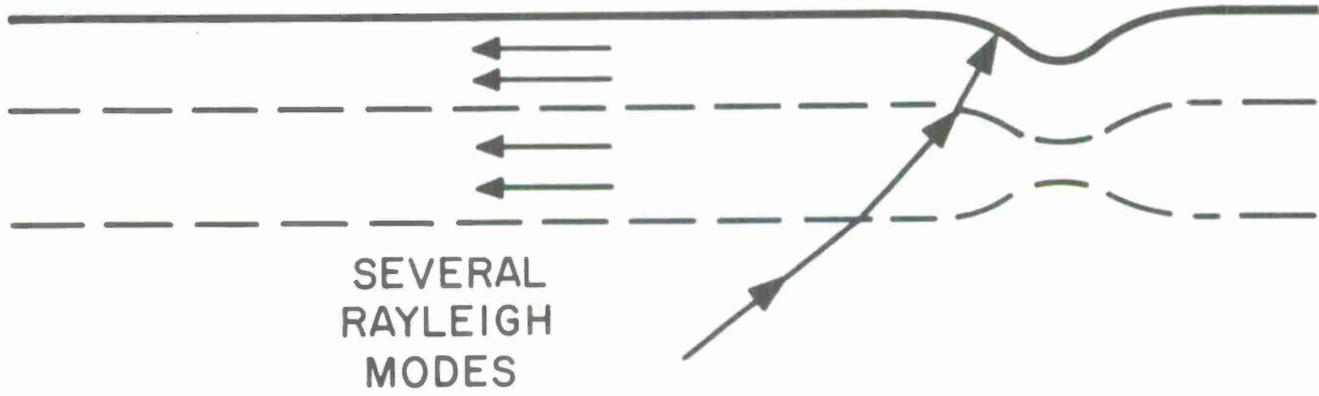
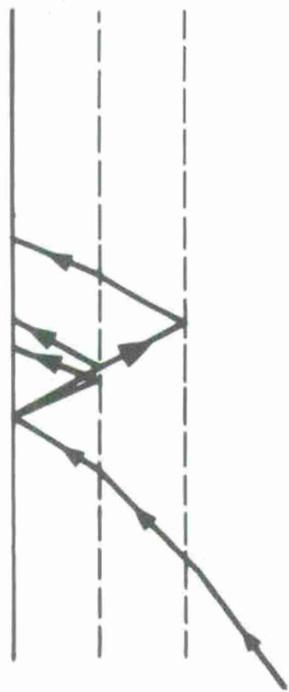
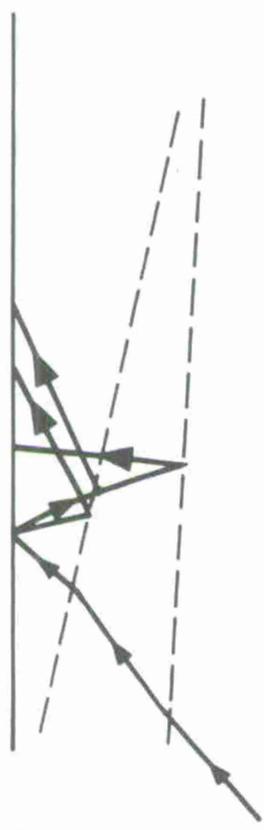


Fig. 5. Surface wave reverberation.



PARALLEL
LAYERING



NON-PARALLEL
LAYERING

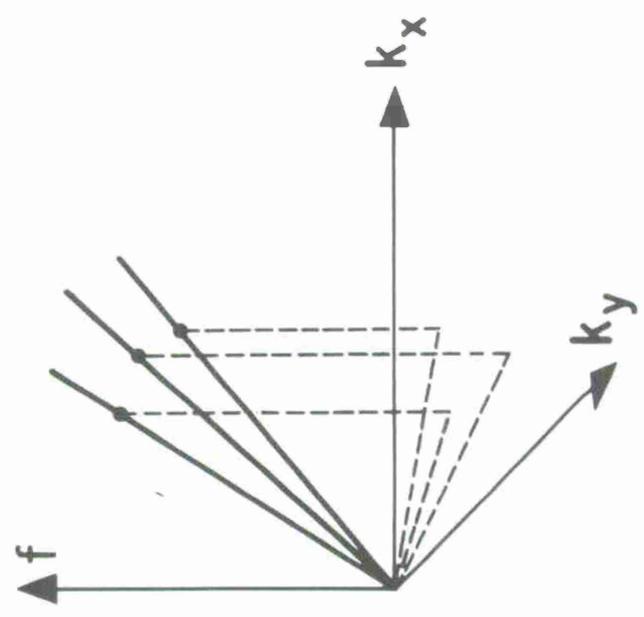
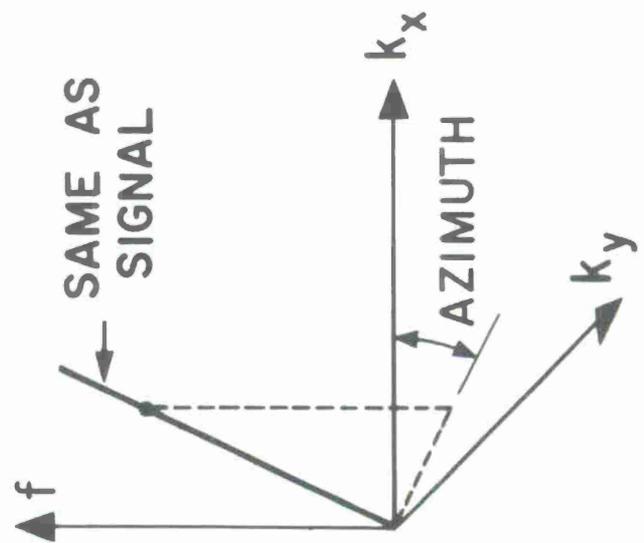


Fig. 6. Body wave reverberation.

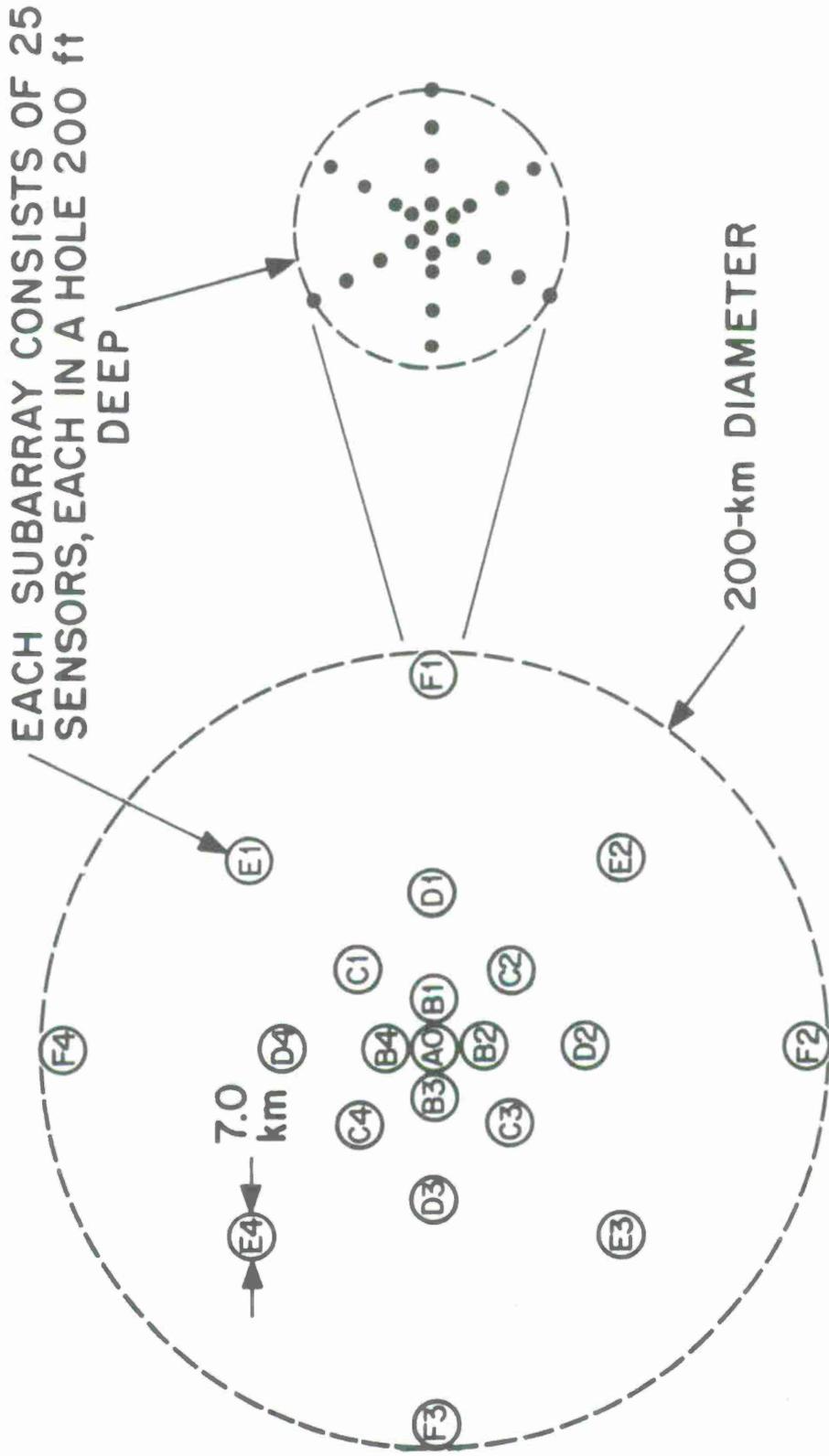


Fig. 7. Large Aperture Array geometry.

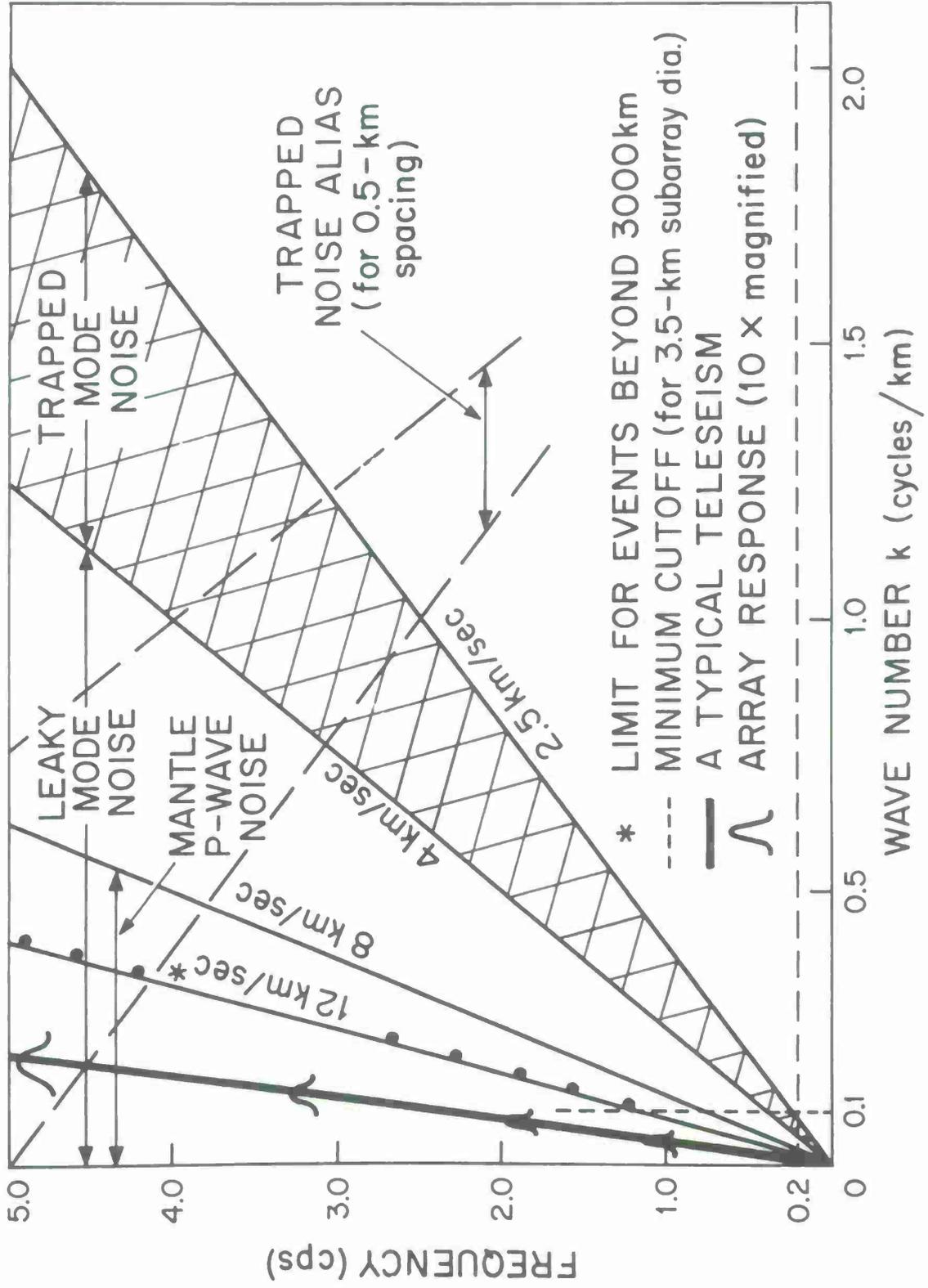


Fig. 8. Signal and noise in f-k space.

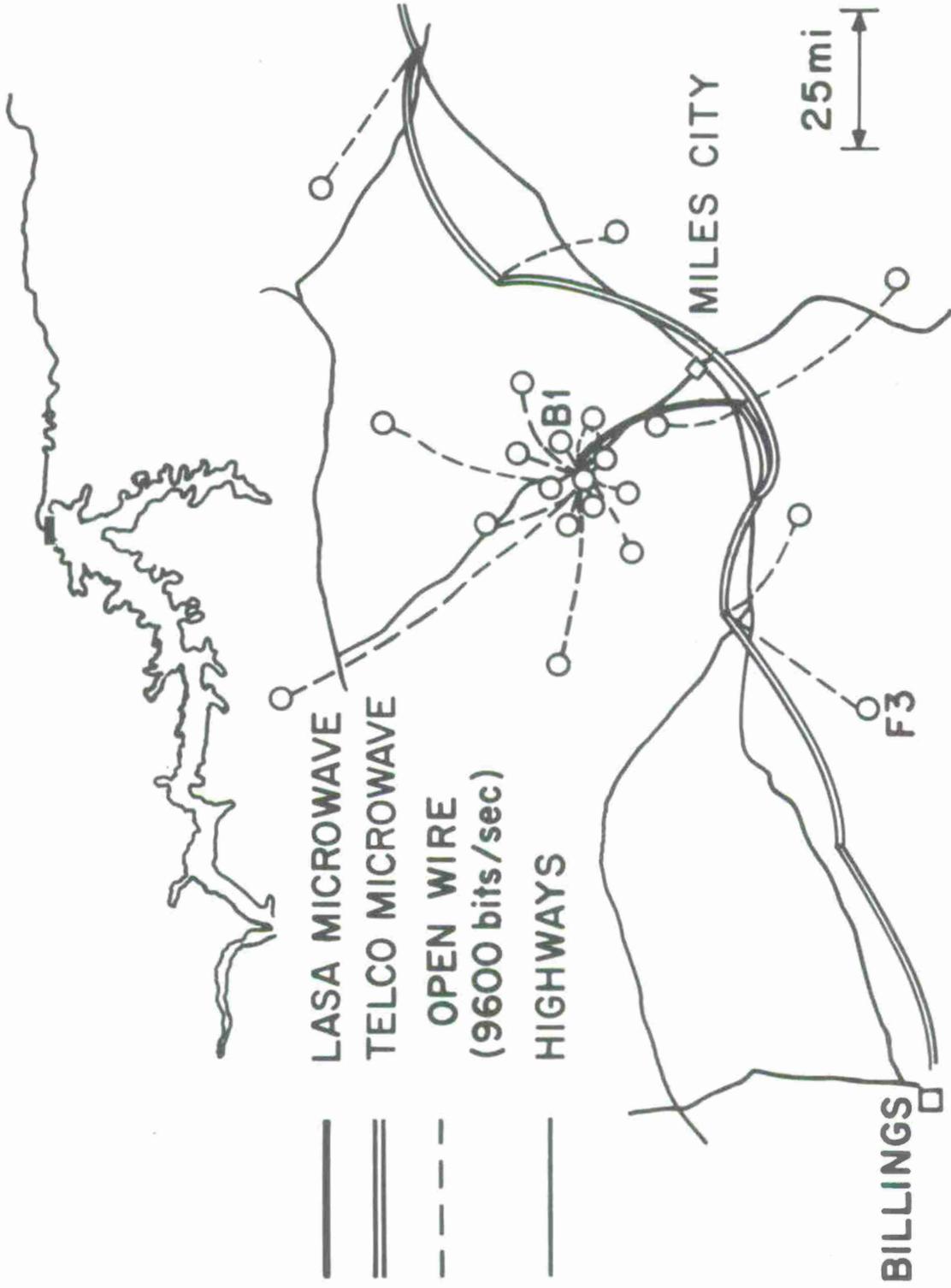


Fig. 9. LASA telemetry.

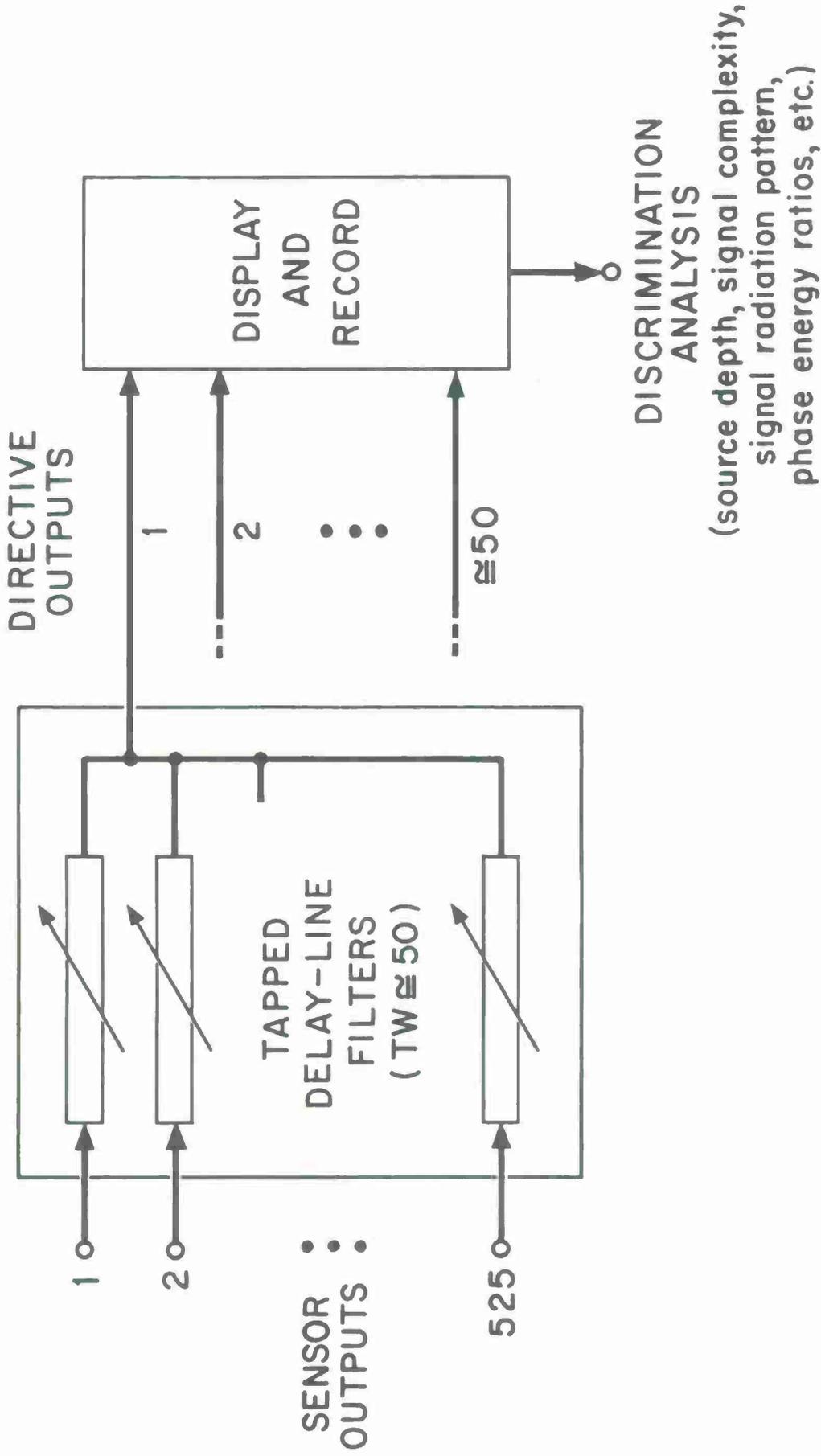


Fig. 10. Basic LASA signal processing

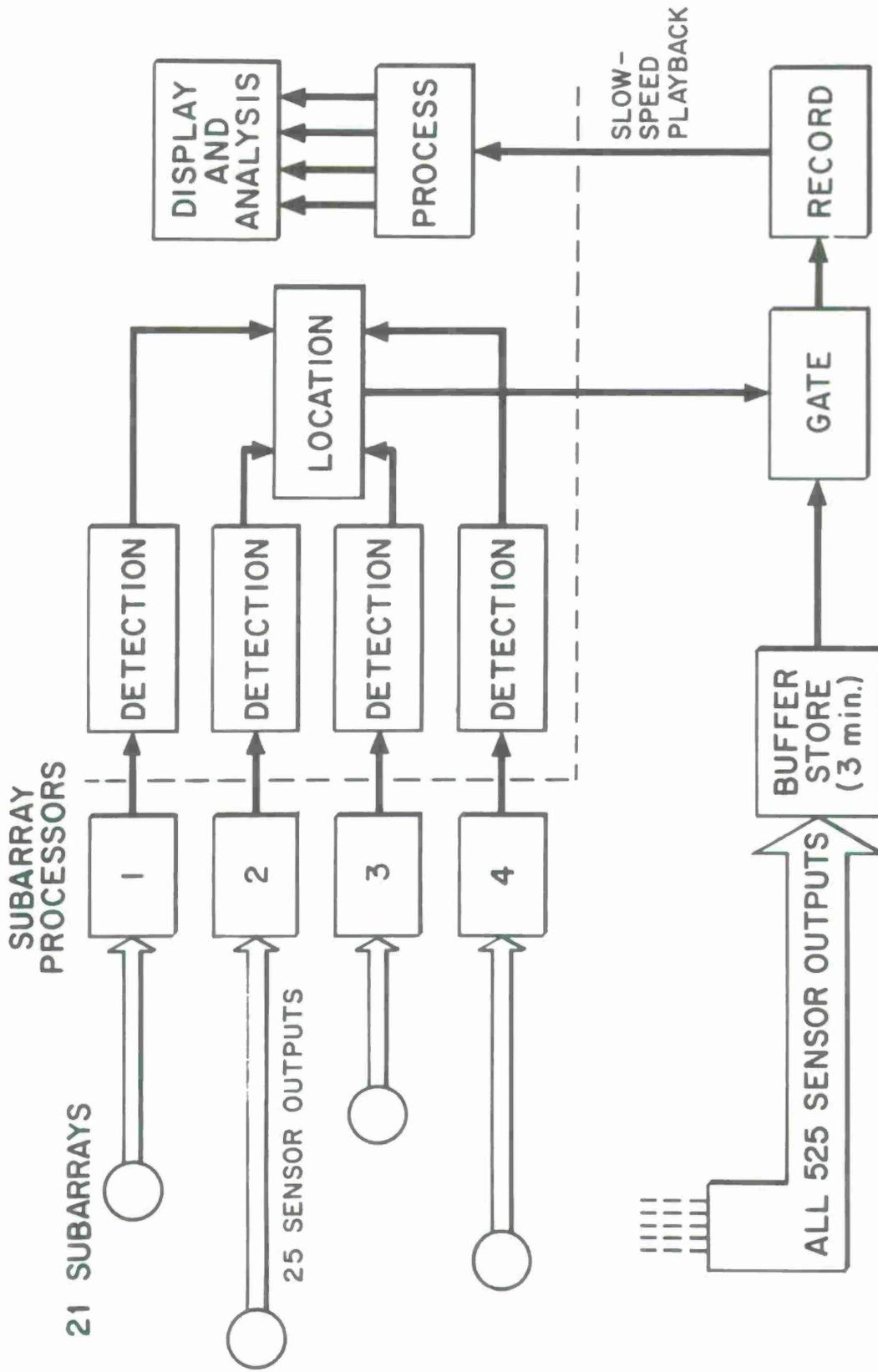


Fig. 11. Functional breakdown of LASA signal processing.

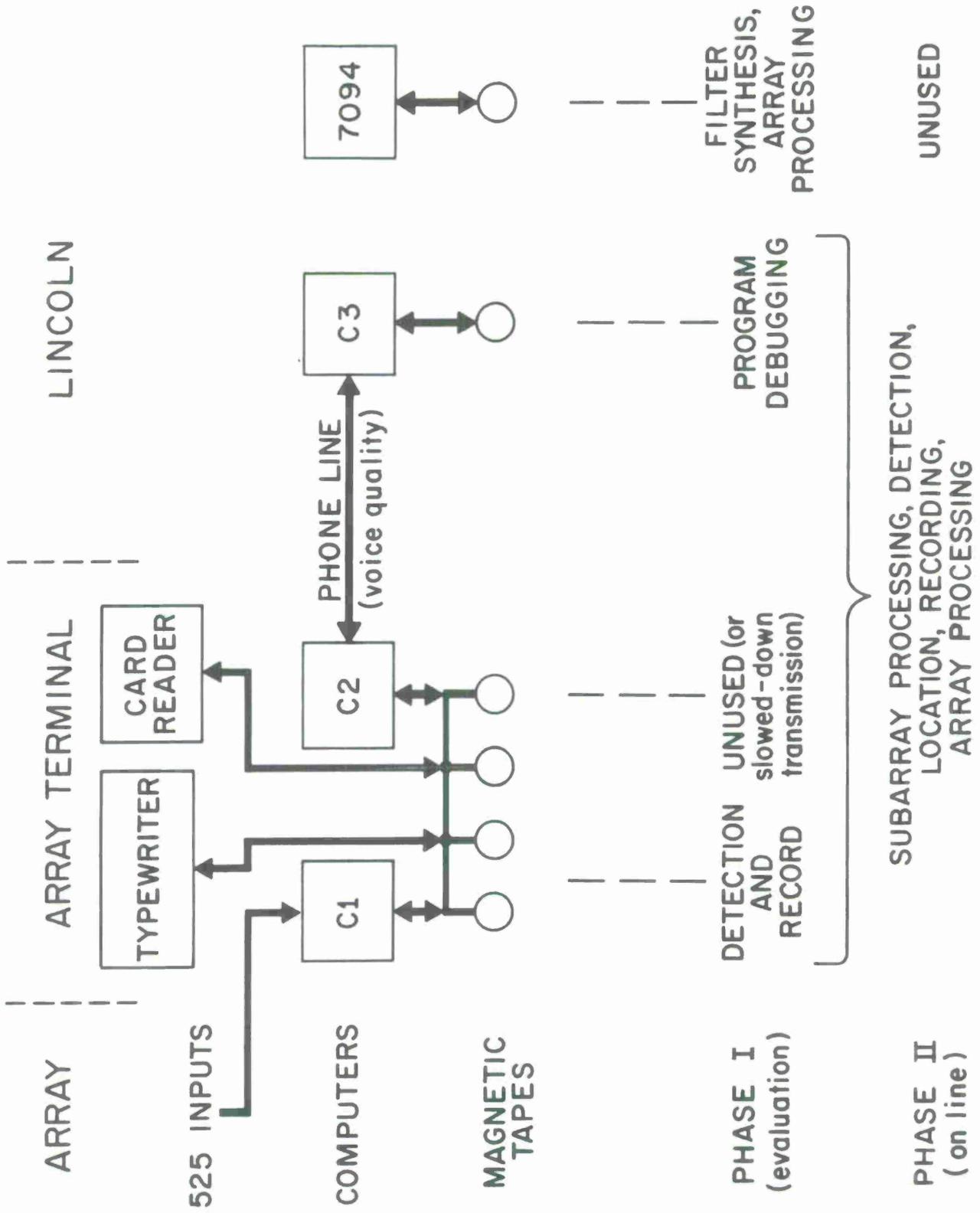


Fig. 12. L.A.S.A. signal processing broken down by machine.

