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Technical Note 1966-36

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LASA On-Line Detection, Location and Signal-to-Noise Enhancement

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

LASA ON-LINE DETECTION, LOCATION AND SIGNAL-TO-NOISE ENHANCEMENT

E. J. KELLY

Group 64

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ABSTRACT

This report describes the results of carrying out a number of seismic signal handling operations in on-line digital equipment at the Large Aperture Seismic Array Data Center in Montana. An appraisal is 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.

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INTRODUCTION

In this report we shall describe and evaluate several techniques, manual and automatic, for the detection and location of seismic events. Some of these techniques work directly with single-sensor data while others, forms of predetection processing, combine single-sensor inputs to provide signal-to-noise enhancement for improved detection and/or location.

In Section A of the report we first describe the single-sensor detection capability of LASA, in an attempt to determine a threshold magnitude which can serve as a baseline with respect to which the detection thresholds can be computed when various predetection processing schemes are added. This threshold evaluation amounts to a site survey of the LASA location in Montana. The detection performance of an automatic detection system is described next in Section B, followed by a discussion of manual and automatic methods of epicenter determination in Section C.

In Section D we discuss a study of on-line techniques for improving the signal-to-noise ratio of seismic events, both at the subarray and full array level. We conclude by presenting in Section E estimates of detection and location threshold magnitudes obtained by taking threshold estimates made in Sections A and B of the report and modifying them downward by the amounts of processing gain given in Section D.

A. SINGLE SENSOR DETECTION THRESHOLD

The primary objective of our experimental work with LASA is to assess the ability of a large array to enhance the visibility of seismic signals, permitting detection and some forms of discrimination to be performed at lower magnitudes. The array location was chosen, in part, because it provided quiet locations for seismometers over the full aperture involved, so that good data would accumulate rapidly for system evaluation. However, it is of interest to know the character of the site itself, in terms of some threshold magnitude for reliable detection. This, in turn, is difficult to measure because one needs to know the location of events detected by a station in order to compute magnitude, and LASA is at least as sensitive as the stations comprising the network we used for comparison, namely the World-Wide System of the U. S. Coast and Geodetic Survey. Thus many of the events detected at LASA are not reported by C. and G. S., and, since these are mostly at our detection threshold, one cannot get a fair picture of the actual limits of detectability. However, several pieces of information are available which allow us to make some inferences about this limit.

First, we have some information on the strength and character of the background noise at LASA, by which we shall mean the usual, irreducible quiet background. This level is occasionally exceeded by local wind or electrical storms, ranching or road-building activity, and less often by a rise in the microseism level itself. A number in the range 3 to 6 millimicrons (mμ) appears to be typical for the total r.m.s. noise background, and this is primarily low-frequency microseismic noise. Storms can

increase this level by a factor of 10, but this appears to happen only a few days of the year. A typical spectral decomposition of the noise output of a single seismometer is shown in Fig. 1. The predominance of the microseisms at periods near five seconds over cultural noise at frequencies above 1 cps is clearly shown. We find from these spectra that the integral of the noise spectral density between the frequencies 0.6 and 2.0 cps is smaller than the total noise by amounts ranging from 12 to 15 db. The r.m.s. noise levels in this "signal band" range from 1.0 to 1.5 mμ. Many other measurements of the total r.m.s. noise output of a filter which effectively passes this signal band confirm this range of "in-band" noise levels, and for purposes of further discussion, we shall take 1.3 mμ as a typical number for the r.m.s. noise level in the signal band of a single seismometer. These measurements apply to the "deep-hole" instruments at 500 feet. Under quiet-background conditions, the noise level of the instruments at 200 feet is often no larger, but an average value for several comparisons is 1.6 mμ, or an increase of 1.5 db.

Second, to get some idea of the average signal level at LASA, we have compared actual levels with those at two nearby observatories, UBSO and BMSO, and we have compared magnitudes computed from LASA measurements with those of C. and G. S. We find that signal amplitudes on a given event vary greatly across LASA in a manner which varies from event to event (about 4 to 1 on the average event with occasional cases up to 6 to 1). Variations in amplitude of up to 2 to 1 are routinely observed across one subarray with occasional events varying over a 3 to 1 range. Studies are in

progress to find a predictable component of the relative levels as a function of epicenter. When combined with the station correction data discussed below, these data should provide useful clues to the crustal and upper mantle structure under the array. No one site within LASA stands out as having superior signal level for all events, although a few, including the central site, A0, which is used as a reference point, appear to be relatively weak in signal reception (by a few db).

We have measured a rough amplitude, averaged over the array, on some 200 teleseisms detected by the automatic detection system (see below), and compared the amplitudes for about half of them with the values measured at UBSO and BMSO, as reported by C. and G. S. These stations are well within 10 degrees of one another, hence the amplitudes were compared directly with no distance corrections (all the events are P-arrivals from sources at least 30 degrees distance). In Figs. 2 and 3 we have plotted UBSO and BMSO amplitude versus LASA amplitude for these events. The scatter is very great, and the results depend on the criteria used by the operators, but the data show clearly that LASA signal levels are relatively large. The comparison is probably more meaningful for weak events, where there are fewer cycles of signal to choose from, hence we compared stations for events recorded at LASA with amplitudes not exceeding 10 mμ. We find that half of these events have signal levels at LASA which are at least 2.2 times as great (0.35 mag.) as their levels at UBSO and that half have levels at LASA which are at least 3.5 times (0.55 mag.) their levels at BMSO.

An independent study of about 100 events reported by C. and G. S. showed that magnitudes computed from reported LASA amplitudes averaged 0.4 magnitude units higher at LASA than at UBSO, and 0.6 magnitude units higher at LASA than at BMSO. These two results are quite consistent. A separate comparison of some 300 events places LASA magnitudes higher than C. and G. S. magnitudes by about 0.2 magnitude units. These last measurements are accompanied by a scatter of at least ± 0.3 magnitude units.

Single sensor r.m.s. noise levels[1] at UBSO and BMSO in the signal band are about 0.3 mμ and 0.7 mμ, respectively. Thus signal-to-noise ratios are roughly comparable at UBSO and LASA, and appear to be at least 2 db higher at BMSO. The numbers on which this conclusion is based are shown for reference in Table I.

It has been shown[1] that a signal-to-r.m.s. noise ratio of about 2 db is required for reliable (say 75%) detection in a single trace for signals of the most easily-detectable type. For average signals, the number is more like 7 db. If signal levels are "normal" at UBSO, this corresponds to a range from m = 3.9 to m = 4.3, for minimum detectable (75%) signal magnitude at a distance of 60 degrees (and normal depth) at UBSO, and hence also at LASA.

This detection threshold has not been demonstrated by direct observation, since we have never monitored LASA data at high magnification for the purpose of detecting the weakest possible events. However, several comparisons with events reported by C. and G. S., and lying in the teleseismic distance range (roughly 40° to 90°) from

TABLE I

COMPARISON OF LASA, UBSO AND BMSO SINGLE SENSOR DATA

	Average Reported Magnitude Relative to U.S.C. & G.S.	Noise Level (Quiet Conditions) in Signal Band
LASA*	+0.2	1.3 mμ
UBSO	−0.2	0.7 mμ+
BMSO	−0.4	0.3 mμ+

* Level at deep hole sensors. The event detection and location programs operated from these sensors.

\+ Data inferred from Reference 1.

LASA have been made. One such comparison reported earlier[2] showed that 80% of the events in this distance range reported by C. and G. S. were detected (manually) with high enough signal-to-noise ratio to permit the measurement of onset times of P across the array. However, comparisons with C. and G. S. cannot easily be used to determine detection threshold, since the number of events, reported by them, of magnitude at least m, when plotted versus m, breaks very gradually away from the corresponding curves of natural seismicity as will be seen shortly in connection with Fig. 5.

Our conclusion is that the 75% detection threshold on a single sensor is at a magnitude of 4.1, still treating UBSO magnitudes as correct, or 4.3 at the C. and G. S. level.

B. THRESHOLD OF AUTOMATIC DETECTION

The automatic detection system, or TSD (teleseism detector) now operating at LASA detects essentially all the events reported by C. and G. S. This system, described earlier,[3] consists of eight automatic event detectors, monitoring the central seismometer from each site in the E and F rings. Four or more reports within a 20-second interval are reported as a teleseism. The times of the individual reports in this interval, together with those of any new reports in the subsequent 20-second interval are noted for source location purposes in the event sourcing program (ESP), described below.

In one period, roughly four months in duration, 212 teleseisms at distances from 40° to 90° from LASA were reported by C. and G. S. during the times when the TSD was operating. The TSD reported 195, or 92%, of these events. Twenty of these 195 events were too weak to permit the determination of epicenters by manual time-picking from the raw data. During the same period, the TSD reported many more events, including 39 for which we were able to determine epicenters (which placed them in the distance range in question). The false alarm rate of the system, in its present configuration, is about 2-3 events per day of continuous operation. The TSD is at least as good as a human observer watching the same eight traces, and probably better. When the TSD reports an event, it also reports the number stations (at least four) which detected it. A breakdown of detection performance according to the number of channels reporting is shown in Fig. 4. We plot here the probability of at least

n reports as a function of C. and G. S. magnitude for n = 5, 6, 7, and 8. Over half of the events with magnitude 4.6 or greater were detected on all eight channels.

As mentioned above, the average amplitude and period at LASA were determined for the 200-odd events reported by the TSD during the period studied. These data were converted to earthquake magnitude, and cumulative numbers of detected events were plotted versus this LASA magnitude in the upper curve of Fig. 5. The curve of detections versus LASA magnitude breaks cleanly with the projected straight-line seismicity curve. This is expected, since it really represents detection performance in terms of signal-to-noise ratio at LASA (assuming constant noise level). At higher LASA magnitudes (above about 5.3) the curve appears statistically unreliable because of an insufficient length of observation period. According to this curve, detection performance is reliable (75% probability) above an apparent magnitude of about 4.6. Assuming an event at 60° distance and a dominant period of 0.8 seconds (all typical numbers), this corresponds to a signal level of about 4.0 mμ, or a signal-to-noise ratio of 8 db above the quiet in-band background noise level. If the "scale factor" of 0.4 magnitude units between LASA and UBSO holds, then this level corresponds to 4.2 at UBSO, and to some extent corroborates our estimate of 4.1 for the single-sensor threshold, based on signal and noise levels. There were 70 additional TSD reports on which we cannot read times well enough for epicenter determination. We feel certain that many of the 70 are in fact real events. A realistic 75% threshold for automatic detection is at a LASA magnitude of 4.5, or about 4.3 at the C. and G. S. level.

Figure 5 also contains cumulative plots of the 212 events reported by C. and G. S. and the 195 events seen by both C. and G. S. and the TSD during this same period. These numbers are to be compared with the 234 that were not only detected by the TSD but located so that magnitudes could be assigned.

In future work we plan to determine the relative level of signals at LASA as a function of distance and bearing. Tentative results already indicate a bearing dependence and a sufficiently rapid drop in sensitivity between 80° and 90° that the inclusion of this distance interval in our previous detection studies may noticeably prejudice the results.

We conclude that the detection threshold for automatic detection (using eight channels) is at most 4.4 (LASA) and probably lower. At the C. and G. S. level, this is 4.1 to 4.2.

C. SOURCE LOCATION

In order to determine an epicenter from times of arrival across an array, or to form a beam by delaying and summing individual seismometer outputs, it is necessary to have fairly accurate knowledge of the station corrections (anomalies in arrival time) for each subarray. As described elsewhere,[4] we have been collecting data since the installation of LASA, measuring arrival times at the E and F ring sites, relative to the reference site, A0. The differences between these times and those implied by the C. and G. S. hypocenter and origin time provide the raw data for our station correction analysis. In Fig. 6, we show data for subarray F4, in the form of station error versus bearing to epicenter. Distance dependence is shown by the use of four symbols for different ranges. All events were of magnitude 5 or greater. The curve is a least-squares best-fitting Fourier series up to terms in 2β (β is bearing). A single curve fitting all distances out to the core shadow distance (about 103 degrees) appears to be adequate for our purposes. Corrections for PKP arrivals, other phases, and their relation to crustal structure will be discussed elsewhere. The present versions of these curves for the E and F ring sites are included in our programs for the computation of epicenters.

A station bulletin is now being issued daily from the LASA Data Center in Billings. It covers events up to two days old. Detection is aided by the TSD system mentioned above, but amplitude, period and arrival time measurements are done manually. In order to find rough epicenters quickly by table lookup, we have selected 12 distinct

triangles of LASA subarrays, and precomputed epicenters for various relative time readings at each of these. Times are incremented by 0.1 seconds, and a range of minus to plus 10 seconds is included, which covers all but the nearest events. These epicenter books are based on normal-depth travel times, but station corrections are included. Normally, four or more triangles are used and the resulting epicenters are averaged. Speed and bearing are also reported in the bulletin.

It is our intention to automate the production of this bulletin. The principle impediment at present is the measurement of relative arrival times. As mentioned before, the present TSD system records the arrival times at each of the four or more stations whose reports gave rise to the event detection. These times are instants when signal energy crossed a threshold based on past history. If the event is sharp and well-correlated across the array, these times are nearly good enough for source location. However, on the average, due to slow rise times and noise they may be in error (relative to manual time picks) by as much as ± 0.5 seconds. These automatic times are nevertheless useful for preliminary sorting of events by rough location, which has been accomplished by the Epicenter Sourcing Program (ESP) in the following way. Instead of using the times to find a position directly, we pick one of a series of test epicenters and test the correlation of the measured times with the theoretical ones (including station corrections) from this epicenter. This is done by computing all the pairwise differences for the measured times and comparing with the corresponding differences for the theoretical times. If a measured difference is within a preassigned error of the corresponding theoretical difference, this pair is said to correlate. The

number of such correlations is the "score" for this event, and it is computed on-line by the ESP program. In the present version, the preassigned error is ± 1 second. If all eight stations report an event, a perfect score would be 28. For seven stations, 21, and so on. The time of detection by the TSD, the eight (or less) individual time picks, and the ESP score for four fixed epicentral positions are computed on-line and output on punched paper tape. This tape is sent by teletype to Lincoln Laboratory daily.

We have analyzed the ESP scores for some hundred events (over 400 scores) for which all eight stations reported an event. The scores are viewed as functions of the distance Δ_s from the actual epicenter to the test epicenter. Perfect scores are theoretically possible out to 7 to 8 degrees, because of the one-second error permitted in the time differences. However, even for epicenters close to the test epicenter, much lower scores are often observed because of the rough nature of the time picks. In Fig. 7, we show a scatter diagram of scores versus distance from test point out to 40°. No score above seven was observed for distances beyond 40°; in fact, the scores drop rapidly to three or less. We find a natural break at about 20°; no score above 11 was observed beyond 20°, and very few (5% of the total) scores below 11 for distances within 20°. It should be recalled that one bad time pick out of eight will reduce the score to 21, two bad picks will reduce it to 15. Thus, if the world were covered with a mesh of test epicenters 25-30 degrees apart, then with high probability each event reported on all eight channels would be assigned unambiguously to the vicinity of one of these points.

We feel that the present TSD is sufficiently reliable to allow the decision to save recordings to rest with it. If only events from a given area are of interest, the ESP is probably reliable enough to reject automatically events from outside this region. A new technique is now being developed which promises to provide more accurate time picks (by using zero crossings) and which will compute amplitude, period, position, and magnitude automatically. A key feature of this technique is a display of tentative time picks which allows an operator to approve of disapprove them in much less time than it would take him to measure them. This technique is expected to provide a nearly automatic station bulletin.

D. ON-LINE SIGNAL-TO-NOISE ENHANCEMENT

The on-line techniques to be discussed here are only those that have already been tried on-line. They include straight summation and multichannel filtering at the subarray level, and delay-and-sum beamforming at the array level. (More complex schemes that can be implemented off-line are discussed in a companion report by Capon, et al[5].) The on-line array beams are actually formed from the straight sums of each of the 21 subarrays. All the measurements are made with a prefilter passing the signal band from 0.6 to 2.0 cps. The results of the discussion that now follows are summarized in Table II which refers to 500-foot seismometer conditions. (For convenience, numbers quoted in Table II are underlined in the following text.)

To analyze the signal-to-noise improvement in a processed trace, we have determined separately the amount of noise reduction and the signal loss. The processed output is normalized in such a way that there would be no signal loss for perfectly coherent signals. For example, consider a beam output, y(t), formed by delayed summation of N inputs $x_i(t)$:

$$y(t) = \frac{1}{N} \sum_{i=1}^{N} x_i(t - \tau_1) ,$$

where τ_i are the steering delays. We shall assume that these delays are correct, and that the signal component of $x_i(t - \tau_i)$ is just $A_i f(t)$. In other words, the signals are perfectly coherent, being all proportional to the waveform f(t), but have different

TABLE II

GAIN IN MAGNITUDE UNITS RELATIVE TO A SINGLE SENSOR AT 500 FEET

(1.0 mag. unit = 20 db.)

	Noise*	Signal	Signal/Noise*
ARRAY PROCESSING			
Off-Line Beam (Array)	+ 0.90	− 0.15	+ 0.75
On-Line Beam (Array)	+ 0.90	− 0.30	+ 0.60
SUBARRAY PROCESSING			
Straight Sums	+ 0.22	− 0.08	+ 0.15
Delay and Sum	+ 0.22	− 0.00	+ 0.22
Maximum Likelihood On-Line**	+ 0.3	− 0.10	+ 0.20
Maximum Likelihood Off-Line	+ 0.50	− 0.05	+ 0.45

* Noise in the Signal Band (0.6 − 2.0 cps)

** Noise sample six weeks old

amplitudes, A_i. Then the signal component of the beam output is also proportional to f(t), with amplitude B, equal to

$$\frac{1}{N} \sum_{i=1}^{N} A_i = \overline{A} ,$$

the average of the A_i. This is the ideal case, with no signal loss. In practice we measure the output amplitude, B, and the individual amplitudes, A_i, and compute the signal loss from the ratio $B/\overline{A}$, expressed in db.

Suppose also that the noise component of $x_i(t)$ is stationary (for the few minutes of observation), and has variance (mean square value) σ_i^2. If σ^2 is the variance of the output noise, then we determine the noise reduction from the ratio of σ^2 to the average value

$$\frac{1}{N} \sum_{i=1}^{N} \sigma_i^2 .$$

If the individual noise traces are uncorrelated, then it is easy to show that the expected noise reduction is a factor of N in power. We measure σ^2 and the individual σ_i^2 by means of a computer program which literally averages the square of the sample value from the digital recording over an interval of time, usually several minutes. A check on the stability of our estimates of noise power implies that most of them are significant to about 0.5 db. The signal amplitudes are determined manually with about the same accuracy.

We begin with subarray processing techniques, and take the average level of signals and noise at the seismometers buried at 200 feet as our norm. Since our detection threshold data, given in Sections A and B, referred to the use of the 500-foot sensors, we will then adjust our numbers to this level. Noise levels (quiet conditions) averaged 1.5 db lower at the deep hole (500 feet) sites for a set of events studied in detail, but signal levels were also lower, by 1.0 db on the average. The average improvement in signal-to-noise ratio in the deep holes was therefore 0.5 db. We do not have sufficient data during periods of wind noise to assess the improvement in the deep holes during these times.

In one set of five events, the straight sums of traces from one subarray had an average noise reduction of 5.9 db, but this figure is quite variable, depending on the velocity structure of the noise. (For one event, the straight-sum noise reduction varied from 2.6 db to 8.3 db across the array.) It should be noted that a straight sum of 25 inputs would be expected to achieve 14 db of noise reduction if the inputs contained independent noise. The signal loss of the sums averaged 2.7 db for this set of events, but some of the loss is due to steering. The straight sum is, in effect, steered for infinite horizontal phase velocity, while the events studied had velocities from 12 to 22 km/sec. For the five events, the signal loss over and above the steering loss (1.6 db) (evaluated from the ideal pattern of the straight sum) averaged 1.1 db. This last estimate is probably high, since the ideal pattern is only a rough guide for the combination of wide-band signals of unequal amplitude. Other data on steered sums of subarray

elements show a negligible signal loss. Our overall average signal-to-noise improvement referred to a 500-foot trace for the straight sums is

$$[5.9 \text{ (ave 200-foot noise reduction)} - 1.5 \text{ (correction to 500 feet)}] - [2.7 \text{ (signal loss)} - 1.0 \text{ (correction to 500 feet)}] = \underline{4.4} - \underline{1.7} = \underline{2.7} \text{ db}$$

The range of variation in our sample was from 0.9 db to 6.5 db.

The multichannel filter (MCF) processor, built for Lincoln Laboratory by Texas Instruments, Inc. and described elsewhere, has been used to study the behavior of maximum-likelihood processing on 0.6 – 2.0 cps prefiltered traces with fixed beams and multichannel filters based on old samples of noise (i.e., a non-adaptive on-line mode of operation). Our data to date are incomplete, but typical numbers appear to be 7-8 db of noise reduction for filters designed on noise six weeks old (compared to 10-12 db for off-line maximum-likelihood processing on the noise immediately preceding the event). Signal losses of the order of 2-4 db have been observed on-line (compared to 1-3 db for many more events off-line). Therefore, we have

$$[7.5 \text{ (ave. 200 foot noise reduction)} - 1.5 \text{ (correction to 500 feet)}] - [3.0 \text{ (signal loss)} - 1.0 \text{ (correction to 500 feet)}] = \underline{6.0} - \underline{2.0} = \underline{4.0}$$

for on-line, and

$$[11.5 \text{ (ave. 200 foot noise reduction)} - 1.5 \text{ (correction to 500 feet)}] - [2.0 \text{ (signal loss)} - 1.0 \text{ (correction to 500 feet)}] = \underline{10.0} - \underline{1.0} = \underline{9.0}$$

for off-line (six weeks old). Further details on maximum-likelihood processing will be found in the report by Capon, et al.[5]

The computer in Billings forms five beams, on-line, using theoretical arrival times for the B, C, and D rings, and station-corrected times for the E and F rings.* One beam is steered to Eastern Kazakhstan, and the other four to seismically active areas. The performance of these beams was studied for 12 events which occurred near the center of one beam, and a set of five events, one quite close to the aiming point of each beam, was studied in more detail, off-line, by measuring the actual arrival times and forming new beams with the exact delays necessary for trace alignment. These five events were all clearly recorded at LASA. The noise reduction, relative to the average of the noise levels on the straight sums making up the beam, is always within 1 db of 13.0 db. This number is consistent with a model of uncorrelated noise components (in the signal band) in the outputs of the subarray straight sums (namely 13.2 db for 21 terms). Experiments with partial arrays obtained by deleting the rings of subarrays, one at a time, from the outside in, confirm that noise reduction is within 1 db of the factor of N (in power) which holds with uncorrelated noise. Signal loss of the off-line beams using hand-picked times averaged 1.3 db for our five events, which speaks rather well for the coherence of these signals across the array. The on-line

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* Another form of "trace combining," simpler than beamforming, is the choice of the best individual subarray. The best trace was different for each of our five beam-centered events, and the average improvement in signal level over the average was 4.8 db. The noise levels were actually slightly smaller than average on the best trace, hence 5 db is a fair number for the signal-to-noise enhancement obtainable by selection. These numbers apply to the direct sum outputs, and show that beams must be accurately steered to produce results significantly superior to trace selection. It should be mentioned that no one site exhibits nearly this much improvement over the average for all events observed.

beams for these same events had an average loss of 4.4 db, although the steering parameters for the beams and corresponding events never differed by more than 1.5% in speed and 1.7 degrees in bearing. The difference is mainly due to the lack of station corrections for the interior sites (and imperfect corrections for the others). The r.m.s. time difference, σ, between the hand-picked time delays and those used in the beams did not exceed 0.2 seconds, and a plot of signal loss versus σ is roughly consistent with the parabola: Loss = $1.3 + 150\,\sigma^2$ (db). Averaged over 12 events, rainging out to 10% errors in speed and bearing, the on-line signal loss was 5.5 db.

We can now combine our figures for straight-sum and beam gain to find the performance of the beams relative to a single sensor. The noise reduction on a beam is 13.0 + 5.9 or about 19 db, relative to the average noise level of 200-foot seismometers. Referred to a 500-foot instrument, this becomes 17.5 db. The signal loss is 1.3 + 2.7 or 4.0 db for hand-picked times, and 4.4 + 2.7 = 7.1 db for the beams presently in operation (with no station corrections out to the D ring). These numbers become 3 db and 6 db referred to the 500-foot condition. These two numbers apply to events near the center of the beam. To work with a reasonable number of beams in an operational context, one might expect two or three db more signal loss to occur due to off-axis steering.

Incidentally, for each of the five events in one of the beams, we averaged the signal level in each of the four other beams. Averaged over the five events, the out-of-beam signals were reduced by 16.2 db, or 3 db more than the noise reduction. This

does not represent a systematic study of side-lobe levels, but nevertheless it is a reassuring number.

E. THRESHOLDS WITH PREDETECTION PROCESSING

From this data one may conclude that the single-sensor 75% detection threshold of 4.3 (C. and G. S. level) for detection can be reduced to about 3.5 – 3.6 by the use of carefully-formed beams for predetection processing. The 75% threshold of present beamformers is 3.7, and the 50% figure is 3.5. The application of multichannel filtering to the subarrays used for automatic event detection could reduce that threshold from 4.1 down to 3.7 – 3.9, depending on the speed with which the noise sample is updated.

Neither of these levels has been verified by direct observation, although event detectors have been coupled to on-line beam outputs for several months. The problem is chiefly the one of finding corroborative evidence of the existence of an event so weak as to be barely visible on a single processed trace. One is forced to try an arrangement whereby LASA is steered to an area well covered by local stations, such as Japan. The events in question would appear as local or regional events in this network, and unambiguous association is quite difficult. Even if the association can be made, the teleseismic magnitude is difficult to determine from the local magnitude. Nevertheless such an experiment ought to be worthwhile.

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3. Ibid., Section II

4. M.I.T., Lincoln Laboratory, "Seismic Discrimination," Semiannual Technical Summary, 31 December 1965, pg. 30.

5. J. Capon, R. J. Greenfield, R. T. Lacoss, "Off-Line Signal Processing Results for the Large Aperture Seismic Array," M.I.T., Lincoln Laboratory Technical Note 1966-37, July 1966.

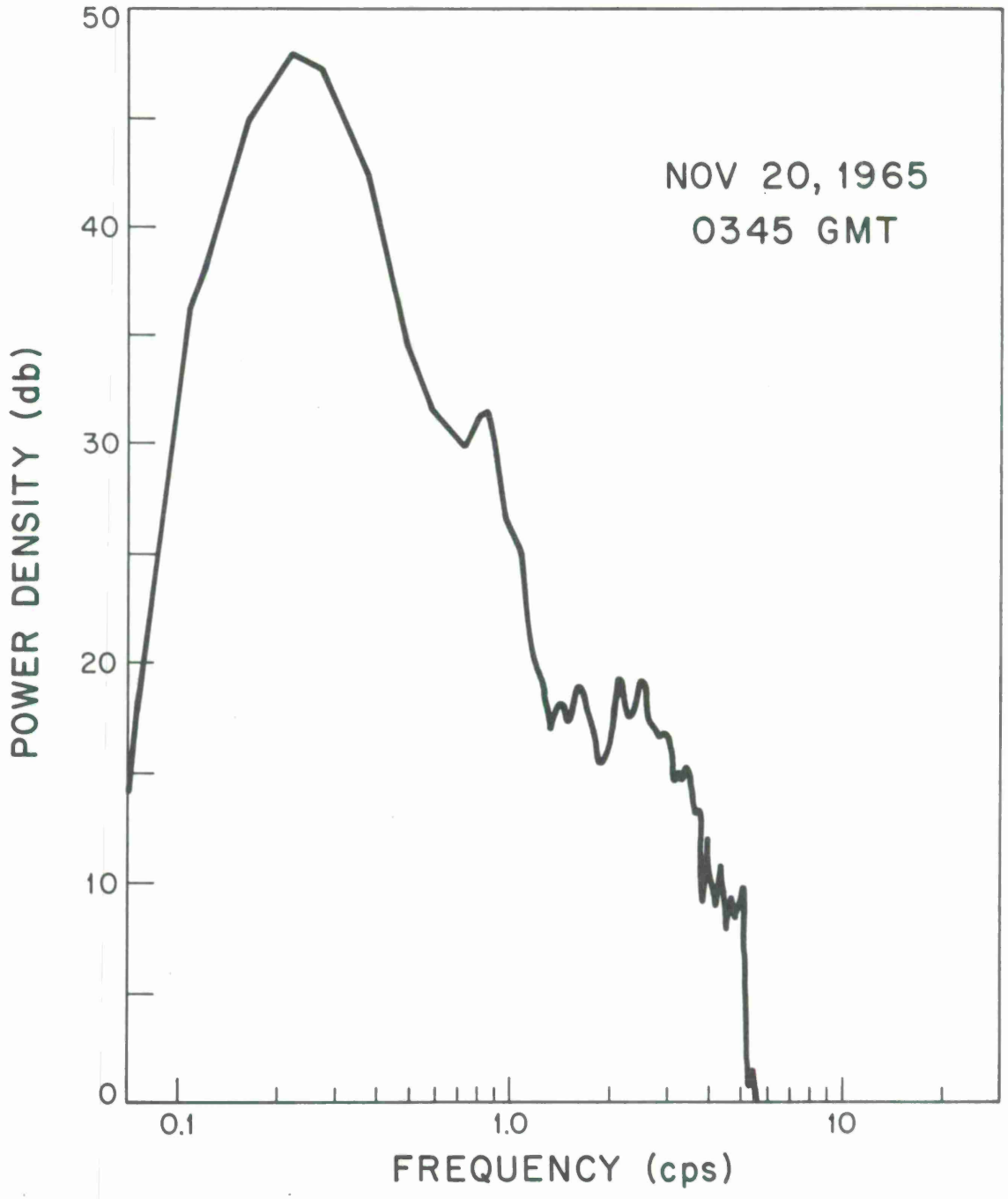

Figure 1. Typical input trace noise power density. November 20, 1966, 0345 GMT.

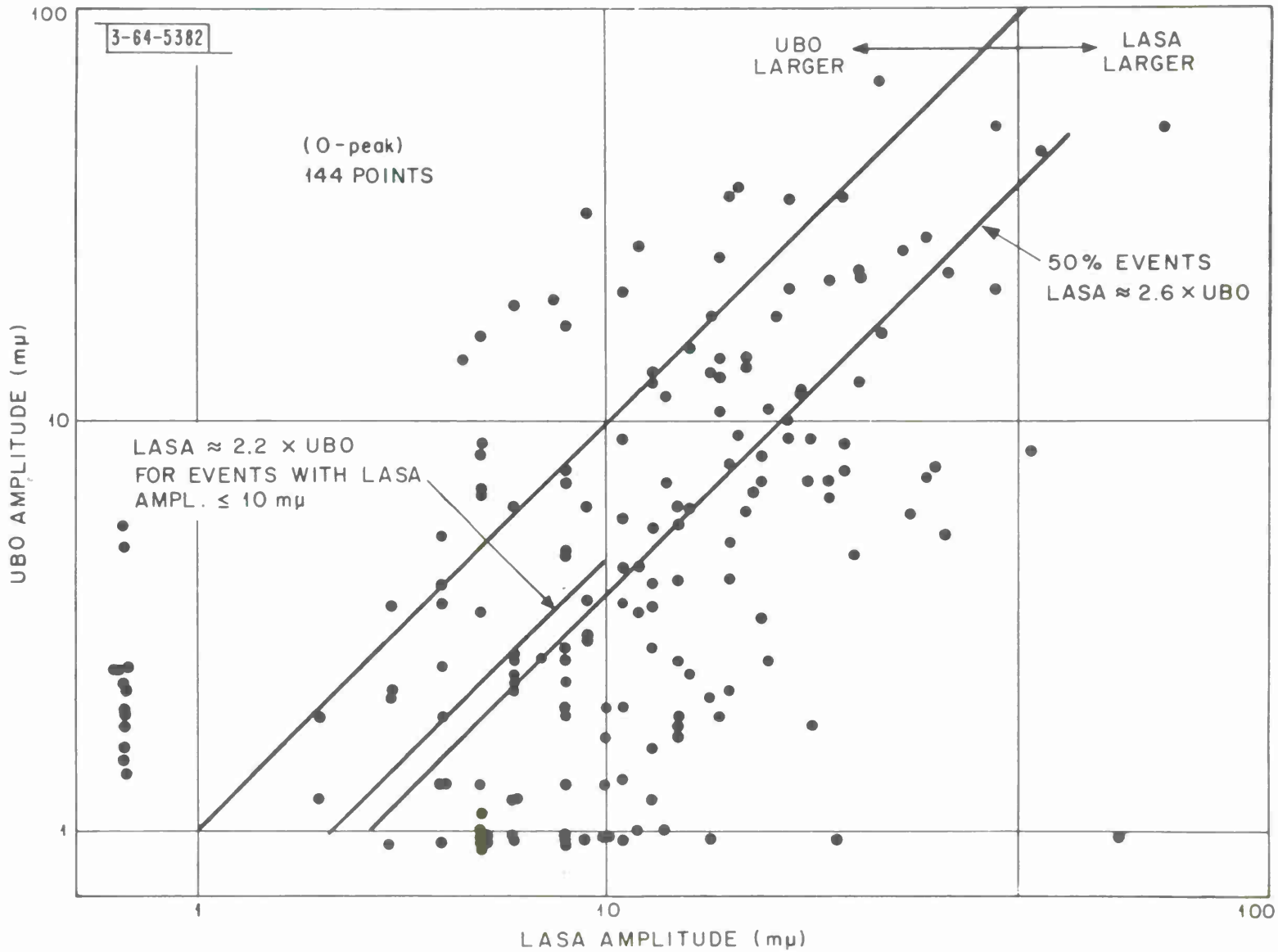

Figure 2. Zero to peak amplitudes observed at the Uinta Basin Seismological Observatory (Vernal, Utah) vs. amplitudes averaged over LASA on 100 events.

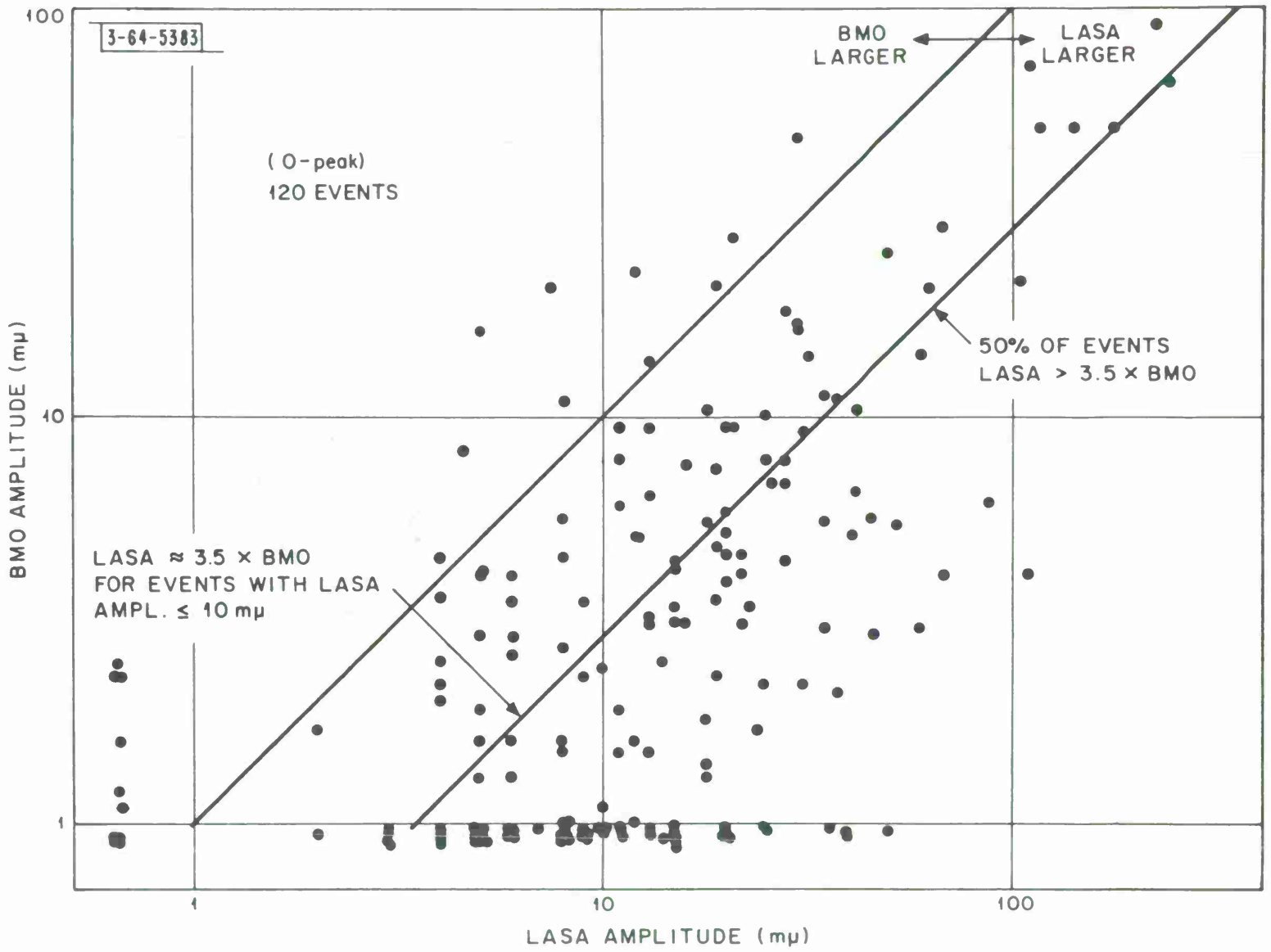

Figure 3. Zero-to-peak amplitudes observed at Blue Mountain Seismological Observatory (Baker, Oregon) vs. amplitudes averaged over LASA on 100 events.

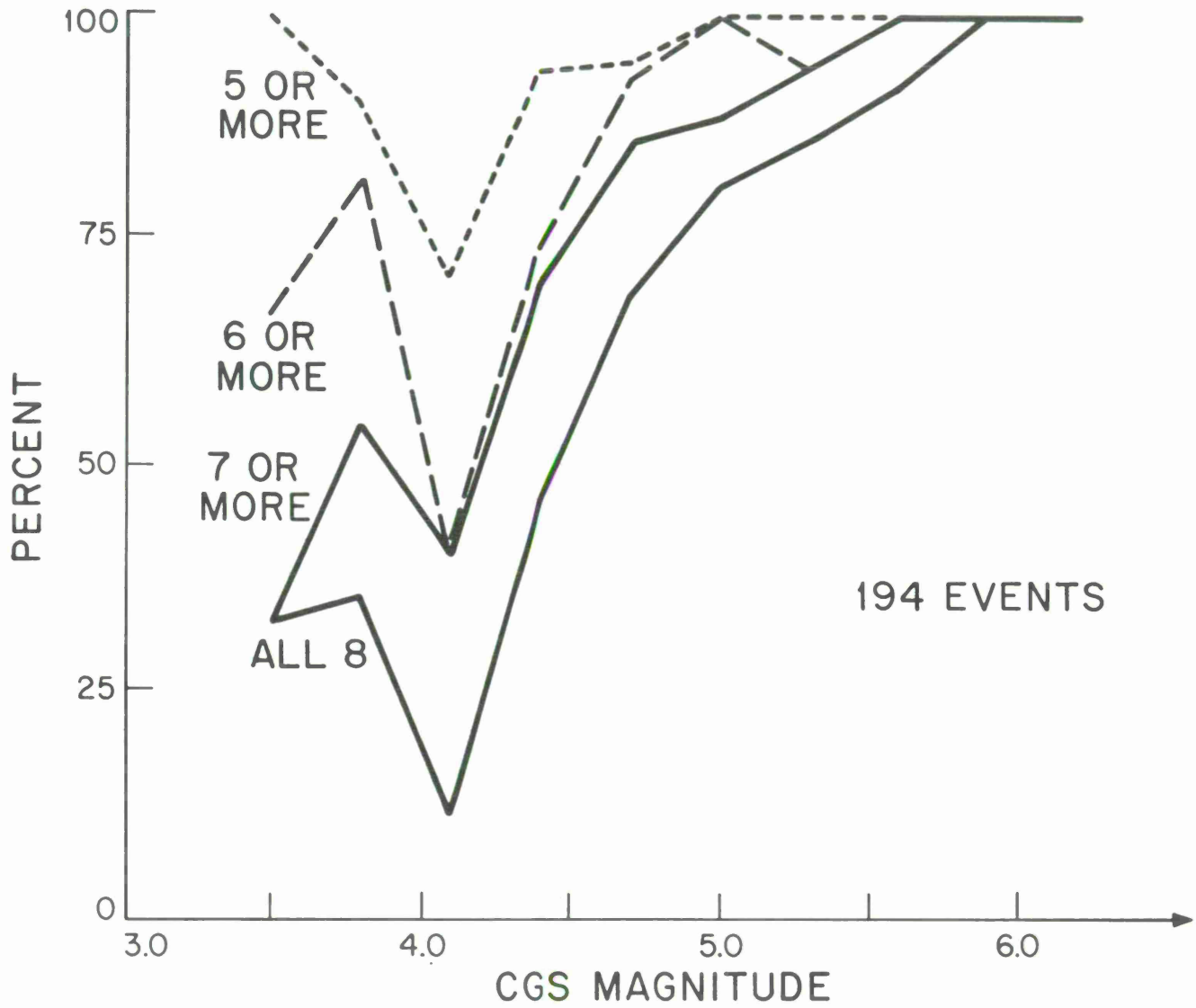

Figure 4. Performance of the teleseism detector (TSD) program on 194 events. Plots show fraction of detectors reporting vs. C. and G. S. magnitude.

C64-307

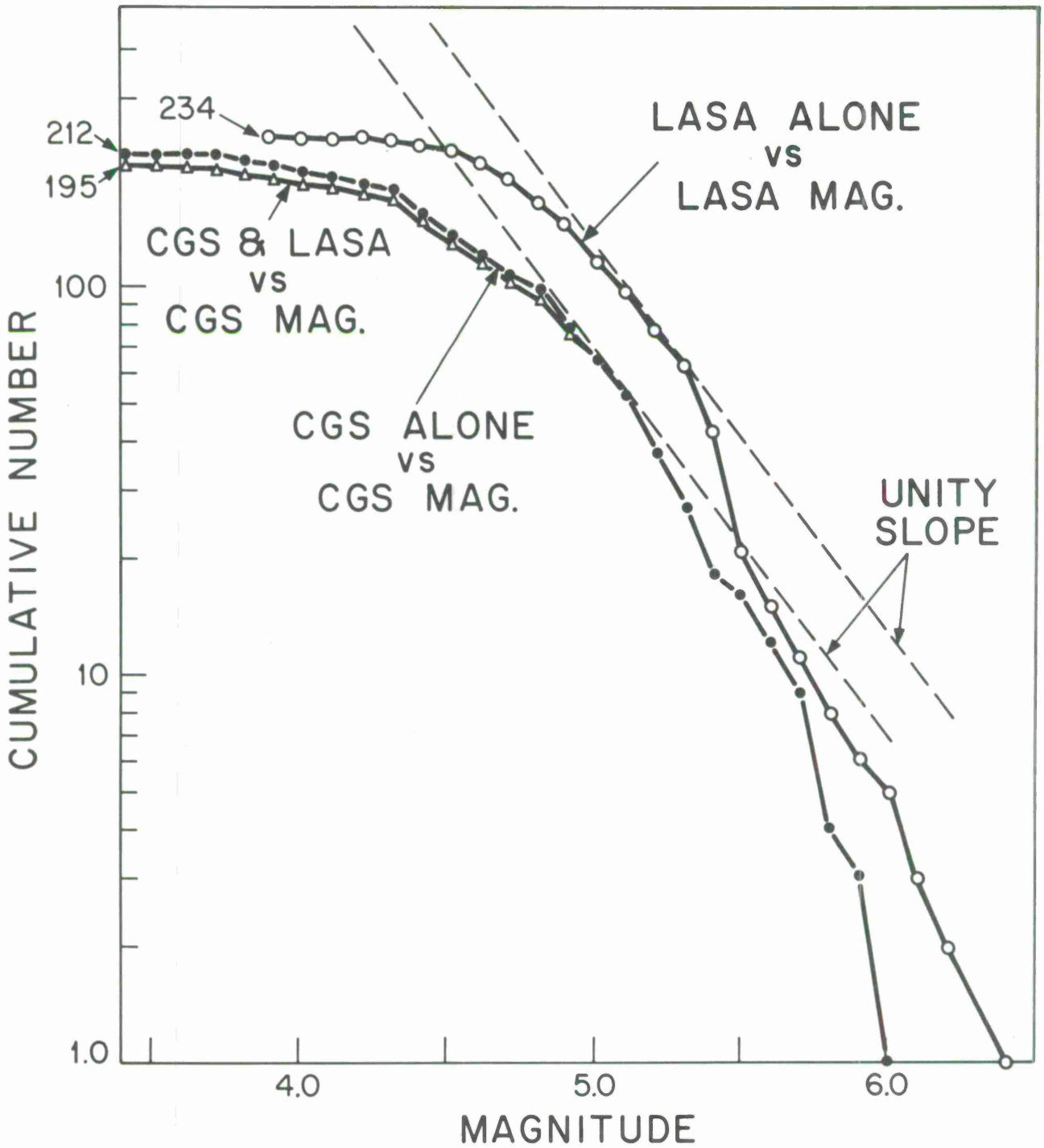

Figure 5. Cumulative plots for number of events reported above a given magnitude vs. that magnitude. The top curve gives LASA Teleseism Detector (TSD) data. The other two curves show C. and G. S. reported events (dots) and events reported by both C. and G. S. and the LASA TSD (triangles).

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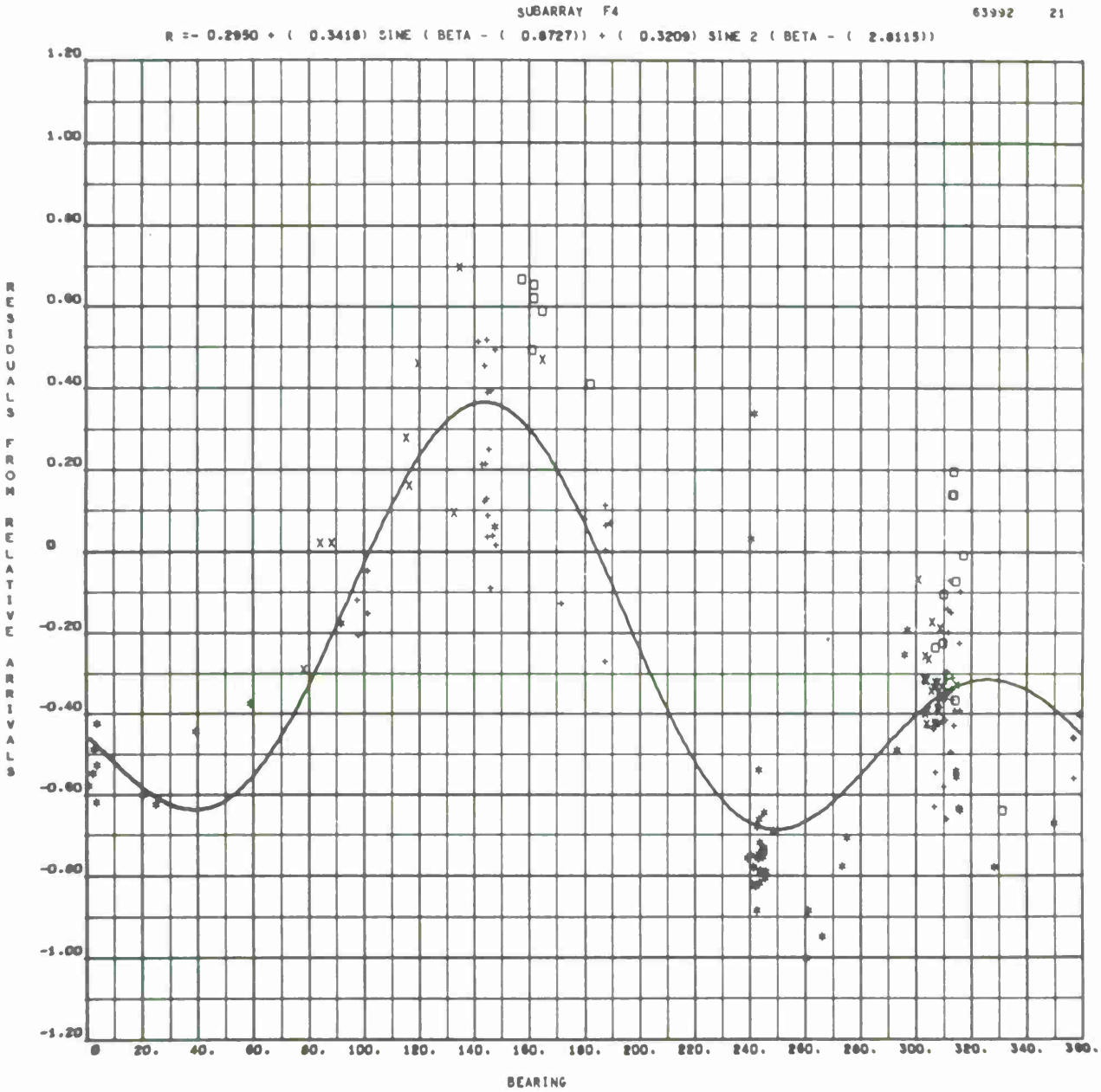

Figure 6. Station corrections for the pair F4-A0, plotted versus bearing for four intervals of distance. The distance intervals are identified by the symbols as follows:

□ : $0 \leq \Delta \leq 35^{\circ}$

X : $35^{\circ} \leq \Delta \leq 55^{\circ}$

\+ : $55^{\circ} \leq \Delta \leq 85^{\circ}$

* : $85^{\circ} \leq \Delta \leq 105^{\circ}$

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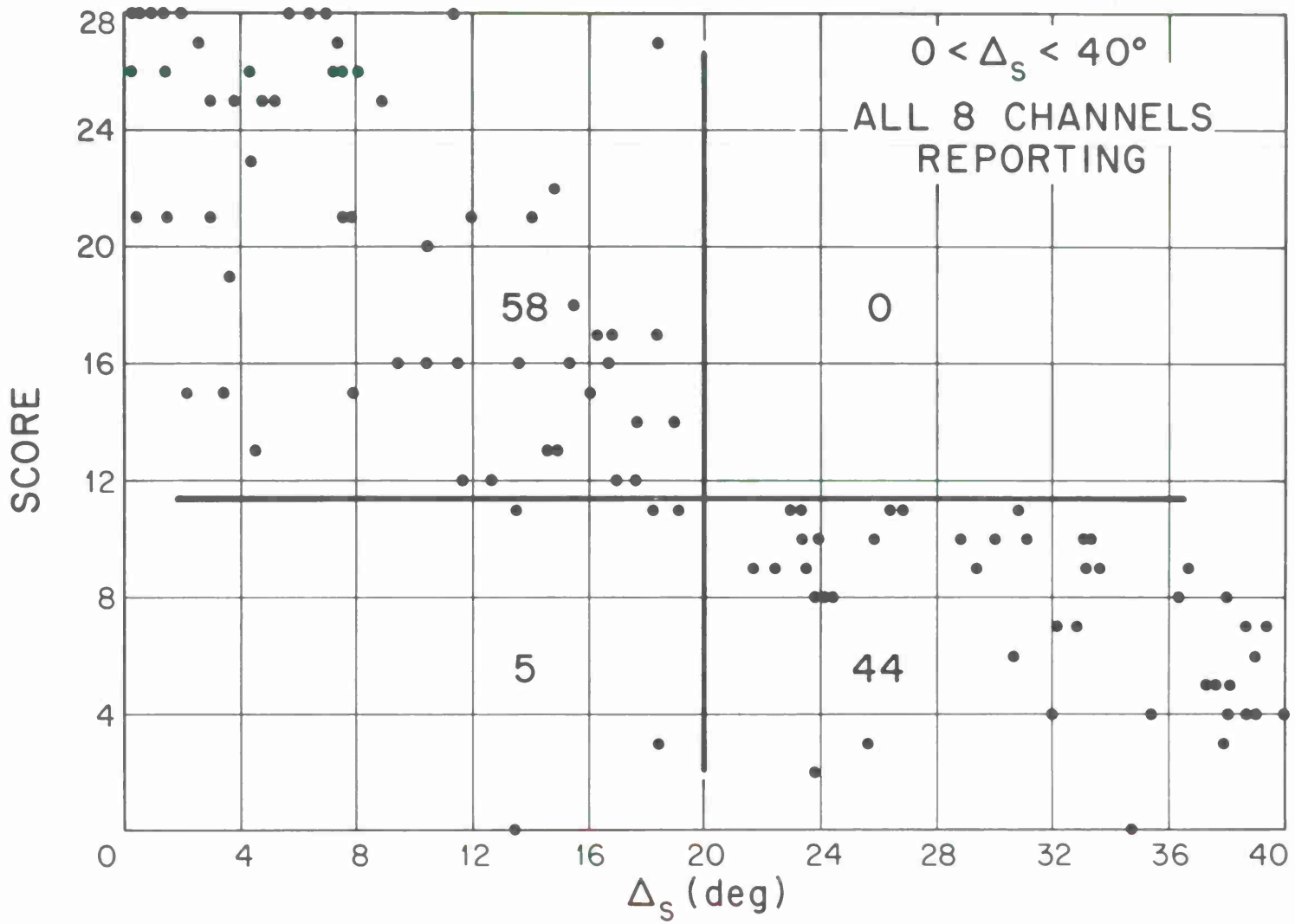

Figure 7. Behavior of the Epicenter Sourcing Program (ESP) in the form of score vs. Δ_s the separation of actual epicenter and ESP test epicenter. Data shown are only those for which all eight event detectors responded.

C64-306

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13. ABSTRACT

This report describes the results of carrying out a number of seismic signal handling operations in on-line digital equipment at the Large Aperture Seismic Array Data Center in Montana. An appraisal is 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.

14. KEY WORDS

seismic array
seismology
seismometers
Vela-Uniform