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R. M. Sheppard, Jr.

Determination of LASA Detection and Location Ability Using Kurile Islands Events

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

DETERMINATION OF LASA DETECTION AND LOCATION ABILITY USING KURILE ISLANDS EVENTS

R. M. SHEPPARD, JR.

Group 64

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ABSTRACT

The Kurile Islands Ocean Bottom Seismographic Experiment of late 1966 provided a source of epicenters for small regional and local events in a seismic region. Epicenters obtained from ocean bottom seismometer data and from the U. S. Coast and Geodetic Survey were used to evaluate the Montana LASA epicenter location ability. Epicenters determined by a plane wave approximation method gave mislocation errors, relative to the CGS locations, that averaged about 60 km. The same events were mislocated an average of 80 km when the epicenters were determined by a closely spaced grid of beams. Although the beam epicenter locations were worse than those of the plane wave method, the beam location method was able to produce epicenters for magnitudes well below the threshold of the plane wave method.

The events in this experiment represent a sufficiently large population on which beam detection thresholds can be evaluated. The detection thresholds that were obtained confirm earlier predictions based on extrapolation from a single sensor. The detection results indicate that a 90% cumulative detection on a LASA beam will occur at about magnitudes 3.85 and 4.15 for a seismicity curve with a slope of 0.75 and 1.0, respectively.

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

I. INTRODUCTION

The aim of this study is to better determine both the Montana LASA teleseismic detection threshold and its epicenter location accuracy. Epicenter locations were determined by the use of the best plane wave approximation to the wave front and also by the technique of determining which of a cluster of closely-packed LASA beams gave maximum output (beamsplitting). A study of the comparative detection levels of a global network and the large array was also undertaken.

The Kurile Islands Ocean Bottom Experiment, conducted at the end of 1966, provided the opportunity of obtaining accurate locations for several small underwater explosions and the location of many small local and regional earthquakes in a seismically active area. The locations of the small local and regional events were obtained from a network of ocean bottom seismometers (OBS) while the epicenters for the larger events were obtained from the U. S. Coast and Geodetic Survey Preliminary Determination of Epicenter (PDE) listings. Additional epicenters were obtained from the LASA station bulletin.

The population of events obtained from these sources, principally the OBS network, provided the epicenters for many small events thus permitting an effective evaluation of the Montana LASA detection and location ability using beams. The smaller subset of epicenters that were reported by CGS provided a number of events suitable for determining the accuracy of epicenters obtained by the plane wave approximation technique. LASA plane wave epicenter accuracy was compared to the accuracy of epicenters obtained using beamsplitting.

II. DATA BASE

The epicenters of events in this study were obtained primarily from four major sources in order of preference: (1) The Coast and Geodetic Survey Preliminary Determination of Epicenter cards, (2) epicenters produced from the OBS network data by Texas Instruments, Inc., (3) epicenters produced from the OBS network data by Lincoln Laboratory, and (4) the LASA station bulletin. During the dates of interest, 23 October to 12 December 1966, the four sources published over 200 distinct epicenters that lie in the vicinity of the Kurile Islands. Although LASA was not recording digital data on a 24-hour basis, recordings were available for 69 events, approximately 35 percent of the published epicenters. A graphical presentation of the data base and the contribution of each of the four sources to the data base is shown in Fig. 1.

Each of the 21 events obtained from the Coast and Geodetic Survey was recorded by one or more of the seismometers in the OBS network.

The second major source of epicenters was the list published by Texas Instruments from data obtained from the OBS network.[1] A total of 13 events was obtained from this list, which includes 10 underwater explosions. (Although 17 of the 21 CGS-reported events had sufficient data from the network to obtain a hypocenter, no epicenter was published in Reference 1 when a CGS epicenter was available.)

When LASA digital data was available and yet no epicenter from sources 1, 2 or 4 was reported during the data period, arrival time data[1] obtained from the OBS network were examined and processed to obtain additional epicenters by methods given in the next Section.

A fourth source of epicenters was the LASA station bulletin. During this time period the locations published by LASA were considered to be the least accurate of the four sources because station correction data had not been fully implemented into the LASA epicenter location program.

III. LINCOLN LOCATIONS USING THE OBS NETWORK

Because the event locations obtained from CGS, Texas Instruments and the LASA station bulletin did not constitute a sufficiently large population, it was necessary to increase the data base by obtaining epicenters from the OBS network using less than the minimum data necessary for a hypocenter determination. If a surface focus is assumed, it is possible to obtain an epicenter using only two seismometers which both record a P arrival and only one recording of an S arrival. Although two epicenters result from this approach, it is possible to eliminate the ambiguity with a third station P reading or one could just eliminate the more unreasonable of the two epicenters. In the case when more than the minimum amount of data was available, combinations of two P arrivals and one S arrival were used. In this manner, several epicenters would be produced which would cluster about the true epicenter, provided the P and S arrivals were consistent for the event. Figure 2 is an example of the graphical output of this epicenter determination program. Additional details about this method are given in a previous report.[2] In Fig. 2 the three ocean bottom seismometers are located as stars and are identified by the number to the upper right of each symbol. The epicenters produced from the three P arrivals and three P-S intervals are shown as "x" and are located in the upper right section of the plot, off the coast of Kamchatka. The final epicenter was determined from the average of all individual epicenters.

An important factor in this technique is a knowledge of the P_n speed and of the function giving S-P time versus distance. A value of 8.0 km/sec for the P_n speed was considered to be reasonable for a region like the Kurile Islands. The determination of the S-P time function involved the use of the actual data.

Because of the accurate location of the underwater explosions in the Kurile Islands it should be possible to use the shot data to calibrate the region. However, when the S-P times were plotted, Fig. 3, the scatter was so great that it was not possible to obtain a good idea of the S-P interval as a function of distance. The next most accurate epicenters are those published by CGS. Using these events and the corresponding S-P time intervals recorded on the OBS network, it was possible to obtain fairly accurate values for the S-P interval. In Fig. 4 it is seen that the Jeffreys-Bullen (J-B) curve lies above nearly all of the measured data and is not a good fit for the Kurile Islands region. The other line through the data points is a graphic least squares fit that can be expressed as a linear function of distance. (In a previous study[2] of a similar nature using small local events from Honshu and Hokkaido, Japan, the function of the S-P interval had to be expressed as a quadratic in distance; however, the distances from epicenter to station were less than those involved in the Kurile Islands.)

After determining the function in this manner (Fig. 4) the list of P and S arrivals on the OBS network was scanned for readings that seemed to be consistent and for which there was no epicenter published by Texas Instruments. After processing, 26 events were added to the data base. There were only two events for which it was not possible to resolve the ambiguous epicenter. In this case, each epicenter was processed as a separate event.

To obtain some knowledge of the accuracy of the epicenters located by this technique, epicenters produced by CGS were relocated using only OBS network data. The shifts in distance and in direction of the relocated epicenters are plotted in Fig. 5.

IV. LASA EPICENTER LOCATION BY PLANE WAVE APPROXIMATION

The method of epicenter location currently in use in preparing the station bulletin at the LASA Data Center is to fit a plane wave to the arrival times of the P waves to obtain horizontal phase velocity and azimuth and thus the epicenter. The epicenter accuracy of this method depends on the quality of the time picks and can be quite sensitive to reading errors or station time anomalies.[3] To insure that reading errors were held to a minimum, time picks for this study were made by using a side-by-side display to visually crosscorrelate the waveform across the array, using filtered signals when necessary. To reduce station time anomalies to a minimum, the station correction data obtained from Teledyne, Inc. was used.[4] Because the station corrections for the inner subarrays, such as the B, C or D rings, are rather large and fluctuate widely with the azimuth to the epicenter the time picks were made on the E and F rings only. For small events, all obtainable time readings were used regardless of the subarray.

The computer program "LOCATE" that is currently employed for preparing the station bulletin at the LASA Data Center was used to compute the plane wave approximation epicenters. The actual uncorrected time picks are first used to compute an apparent horizontal phase velocity and azimuth of the passing wave front. Using these two parameters the program is able to obtain a station time correction for each subarray from a prestored table. If pP was seen, the program will compute an approximate depth and set up the proper travel time table and horizontal phase velocity table.

The station-corrected readings are then used to compute a more accurate velocity and azimuth. At this stage of the calculations one line of information is output on a teletype to inform the analyst of the RMS error of the plane wave fit, the number of stations used in the calculation and the residual to the plane wave at the worst station. If the plane wave fit and the residual are acceptable, the program will print out all relevant epicenter information. However, if the plane wave fit is poor or one station exhibits an unusually large residual to the plane wave fit the analyst can delete the bad station and rerun the event by typing the appropriate key on the teletype. The typical event can be located in about one second of computer time.

The population of events that were identified by CGS were used to determine the accuracy of the plane wave approximation method. The procedure was to first plot the 21 subarray straight sum channels and then make the time picks on the E and F rings. Three events in the population were either too small to permit time picks on the minimum required three subarrays or to give time picks of sufficient accuracy to obtain a reasonable epicenter. The magnitude of the mislocation error (assuming the CGS location to be exactly correct) and the direction of the error relative to the CGS epicenter are plotted in Fig. 6. The magnitude of this location discrepancy as a function of LASA magnitude is shown in Fig. 7. There does not seem to be any strong bias in the location discrepancy, indicating that the station corrections have removed most of the regional anomalies for this area. Most of the location discrepancies are less than 100 km with the average at about 65 km or less.

The plane wave epicenter location accuracy of the Montana LASA is greatly affected by station anomalies or station time corrections. At the time the events in this study occurred, late in 1966, not much was known of the values of the LASA station time anomalies. Since then, however, the station anomalies have been learned and studied in great detail and their effect on epicenter accuracy has been removed. The mislocation of the station bulletin epicenters for 16 CGS reported events is shown in Fig. 8. The least mislocation error is about 130 km while the average mislocation is about 240 km. If these same events were relocated using the current version of the program "LOCATE" now in use at the Montana LASA, the average mislocation error would only be about 60 km, as shown in Fig. 6.

V. LASA EPICENTER LOCATION WITH BEAMS

The 200 km aperture of the Montana LASA permits the effective application of the process of velocity filtering and beamsplitting. This is the process in which the outputs of seismometers within the array are added to form a LASA beam, after having been time shifted to insure that the seismic signal is in phase. The seismometer outputs can be time shifted for any phase such as P, PcP, or pP and once the outputs have been properly added an enhancement of the signal can be expected. However, to insure proper phasing of the P wave signal it is necessary to apply the time station correction at each subarray. The actual values of the LASA time station corrections can be as large as 0.8 seconds relative to the array center and therefore can seriously affect proper phasing of the seismic signal.

Epicenter location by means of velocity filtering and beamsplitting can be achieved by steering several hundred beams at the region where the event is suspected to originate, after applying subarray station corrections. The output power of each beam is then measured over the received seismic signal and the beam that produces the highest power can be considered to be the closest beam to the actual epicenter. Since beamforming will enhance the S/N over a single sensor it would be expected that this process of epicenter location would produce more accurate locations at smaller magnitudes than the plane wave method. To determine the accuracy of the beamsplitting technique, each event in the CGS population was processed by this method.

The beamsplitting program used in this study forms 400 beams around the event epicenter, each beam separated by 0.5 degrees in latitude and longitude. The output of each beam was then filtered using a synchronous filter of center frequency equal to $\sqrt{2}$ Hz with a bandwidth of 0.5 Hz. The power measurements were made over the first five seconds of the seismic signal on each of the 400 beams. The numerical values of the signal power were contoured, then the power measurements were smoothed or averaged to produce a second contour plot somewhat simpler in structure than the first contour plot. Examples of unsmoothed and smoothed contour plots for the same event are shown in Figs. 9 and 10. In some cases the smoothing process would shift the beam of peak power to an adjacent beam position. The smoothing process was used because in several cases a beam near the actual peak of the contour pattern would have enough noise in the signal to produce a power measurement that was slightly higher than the true beam pattern peak. It was found that a smoothing process tended to shift the pattern peak to the geometric center of the contours. The epicenters achieved after the smoothing process were accepted as the final epicenters determined by beamforming.

Beam epicenters were determined on the same population of events that were used to determine the plane wave epicenter accuracy. The magnitude and direction of beam epicenter location discrepancy relative to the CGS epicenter is shown in Fig. 11. The magnitude of the discrepancy is plotted as a function of LASA beam magnitude in Fig. 12. The symmetrical distribution of points in Fig. 11 seems to indicate that the time station corrections were effective in removing most of the regional bias for the Kurile Islands area.

It is disturbing to note, however, that the magnitude of the location discrepancy is much greater than expected and in nearly every case seems to be greater than the location discrepancy produced by the plane wave technique. Two reasons may account for the larger errors produced by the beam epicenters. The coarseness of the grid of 400 beams will only permit an epicenter determination accuracy that is in increments of 0.5 degrees of latitude and longitude. If interpolation between beams had been attempted, the epicenter errors may have been reduced to values near those obtained from the plane wave technique. A second factor, the time station correction, may play an important role in reducing the epicenter error. The time station corrections were originally obtained to reduce travel time errors across LASA and thereby serve to correctly align the first break or first peak of the seismic signal. The time station correction that is necessary to maximize the beam power over intervals as long as five seconds may have values significantly different from those actually used. Other factors such as the filter, the integration interval of the signal and the use of a noisy sensor will affect the accuracy of the epicenters determined from beamforming. The effects of these latter factors have not been studied in great detail but some processing results give an indication that sensor noise can seriously effect epicenter accuracy while long integration intervals tend to reduce the contour gradients and therefore reduce the relief across the contour plot.

VI. LASA DETECTION AND LOCATION ABILITY

Some idea of the location ability of LASA can be obtained from a closer look at the event population used in this experiment (Figs. 13a and b). An examination of the subset of events identified by CGS (Fig. 13a) indicates that of the 21 events in this subset 17 of them could have been located by Texas Instruments from OBS data, 15 of these 17 events were also located by LASA on the station bulletin. LASA located three events from the CGS subset that were not locatable from OBS data. Only one event in the CGS subset was not locatable by LASA using teleseismic data or by Texas Instruments using OBS data.

The Texas Instruments subset of the event population (Fig. 13b) contains 30 events that had sufficient data recorded on the OBS network to yield a hypocenter determination. Of these 30 events, CGS reported 17 epicenters while the LASA station bulletin listed 19. Fifteen events in this subset were located by both CGS and the LASA station bulletin. Nine events in this subset were not located by either CGS or the LASA station bulletin.

If the data in the entire population is considered. (Fig. 13c) the Montana LASA was able to detect and locate 54 events (78% of the population), while CGS reported epicenters for only 21 events (30% of the population). There are 14 events that were not seen at LASA nor reported by CGS.

The 69 events in the data base, compiled from the four sources described earlier, are either known to have occurred or are strongly suspected to have occurred in the Kurile Islands area. This population may not be representative of the seismicity of the Kurile Islands area because it was selected on the basis of available LASA digital data. However, the population does represent a large number of events on which epicenter location by beamforming has been attempted. The beam detection thresholds that are obtained from this population can be used to support or contradict earlier estimates of the beam detection threshold.

Figure 14 is a "recurrence curve," that is, a plot of the total number of events detected of magnitude equal to or greater than a given magnitude plotted as a function of magnitude. If the regional seismicity curve has a slope of 1.0, a 90% cumulative detection occurs at a body-wave magnitude of about 4.15. If a slope of 0.75 is used, the 90% cumulative detection threshold is about 3.85. Assuming a 0.30 magnitude differential between fixed and cumulative detection probabilities,[6] this means that 90% of all events actually at magnitudes 4.45 or 4.15 will be detected and located using the 1.0 or 0.75 slope, respectively.

In an earlier attempt to obtain an idea of the beam detection threshold[5] the performance of a single sensor was used as a basis to predict the detection threshold of a LASA beam. This earlier projection predicted a 50 to 75 percent cumulative detectability at a CGS magnitude of 3.5 and 3.7, respectively. This was for a seismicity curve with a unity slope. For this population (Fig. 14) the corresponding detection thresholds would be at LASA magnitudes of 3.4 and 3.6. This would seem to confirm the earlier projected thresholds.

VII. CONCLUSIONS

The Kurile Islands Ocean Bottom Experiment of late 1966 provided an opportunity to effectively evaluate the LASA epicenter location errors produced by two epicenter location techniques, plane wave approximation and beamforming. To obtain a sufficient population of events for evaluation, epicenters were obtained from the CGS Preliminary Determination of Epicenter cards, Texas Instruments' evaluation of ocean bottom seismometer data, the LASA station bulletin and epicenters produced by Lincoln Laboratory from OBS data.

In the process of producing epicenters from OBS data, it was necessary to determine values of the S-P interval for local and near regional epicenters in the Kurile Islands area. The S-P intervals from the accurately located underwater shots gave such large amounts of scatter that it was impossible to determine the interval accurately. The reasonably accurate locations of events obtained from the PDE cards were then used to obtain S-P values. These S-P values differed from the expected J-B values by several seconds.

A subset of the data base, the PDE epicenters, was used to determine the accuracy of epicenter locations produced by using the plane wave approximation method. The use of time station corrections removed the regional anomalies and produced epicenter mislocation errors averaging about 60 km. These same events when located in 1966, at a time when little was known about the time station correction, had given an average mislocation error of 240 km.

The beamsplit epicenter error was determined on the same population used above. In almost every case the beam epicenter mislocation error was greater than the plane wave error with the average beam mislocation error at about 80 km. This increase in epicenter error may be due to the coarseness of the grid of beams and to the time station correction. The beam centers were separated by 0. 5 degrees of latitude and longitude and since no interpolation was made between beams the epicenter was determined in increments of 0. 5 degrees. The time station corrections were originally determined to align only the first break or first peak of the seismic signal and are not necessarily the same corrections necessary to maximize the energy over several seconds of signal.

Since computer time necessary for epicenter determination by beamforming is approximately 900 times greater than that needed for epicenter location by the plane wave method, there is no advantage to the beamforming epicenter method for larger events. However, beamforming is able to yield more accurate epicenters at much smaller magnitudes than is the plane wave method and herein lies an advantage to beamforming.

Since the event population was selected on the basis of available digital LASA recordings, it should not be considered typical of the seismicity of the Kurile Islands region. When the events are plotted as the cumulative sum of detected events above a given magnitude (Fig. 14) it is possible to obtain a value for the detection threshold. For this earthquake population recorded at the Montana LASA the 90% cumulative detection threshold is approximately 3.85 and 4.15 for a seismicity curve with a slope of 0.75 and 1.00, respectively. Since the 90% incremental detection threshold is 0.30 magnitude units greater than the cumulative detection threshold, this population would give LASA a 90% incremental threshold at 4.15 and 4.45. These numbers roughly confirm projections of LASA beam detection thresholds made several years ago on the basis of single-sensor data.

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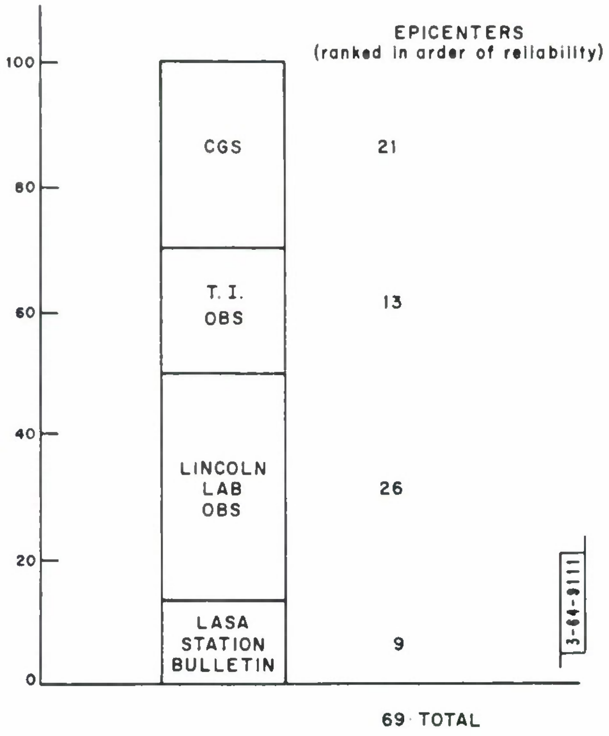

Fig. 1. Data base.

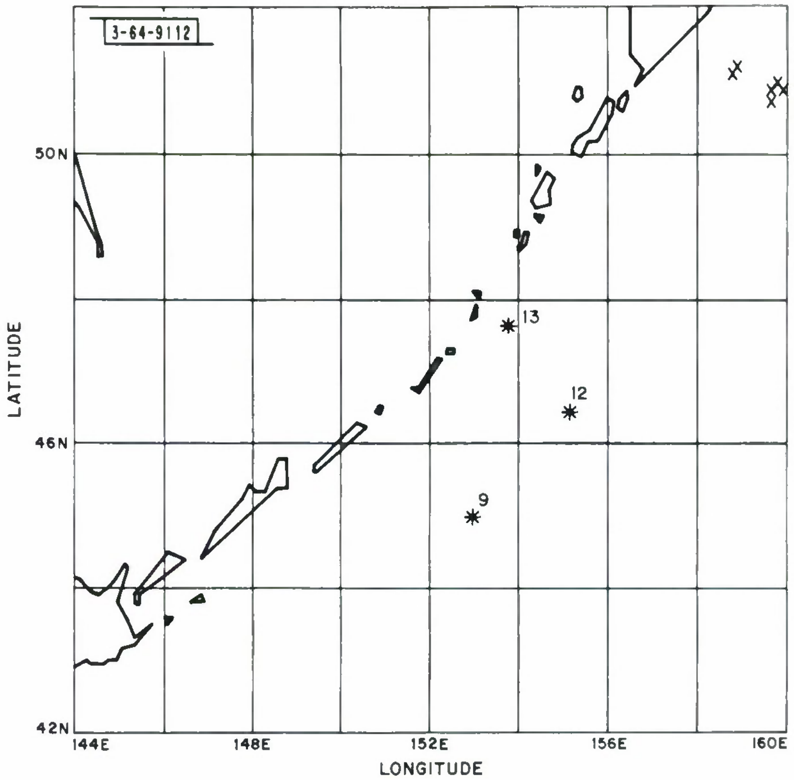

Fig. 2. Computer generated map showing an event epicenter location.

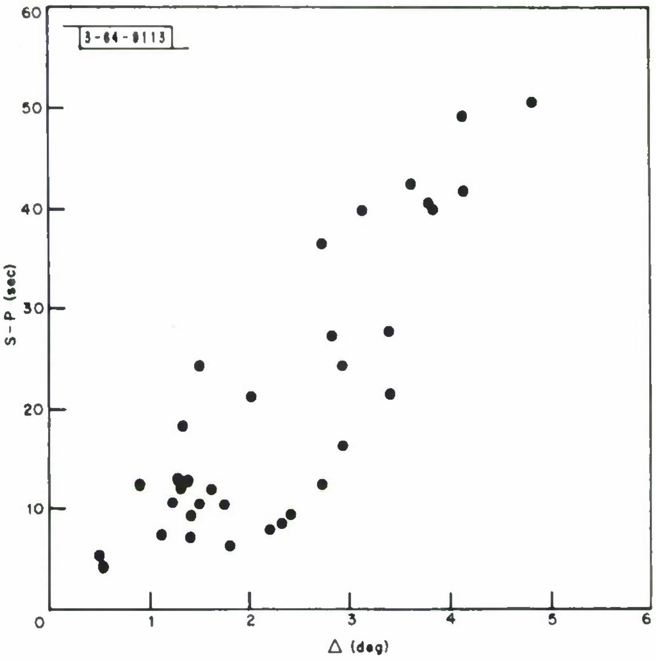

Fig. 3. S-P intervals for underwater shots.

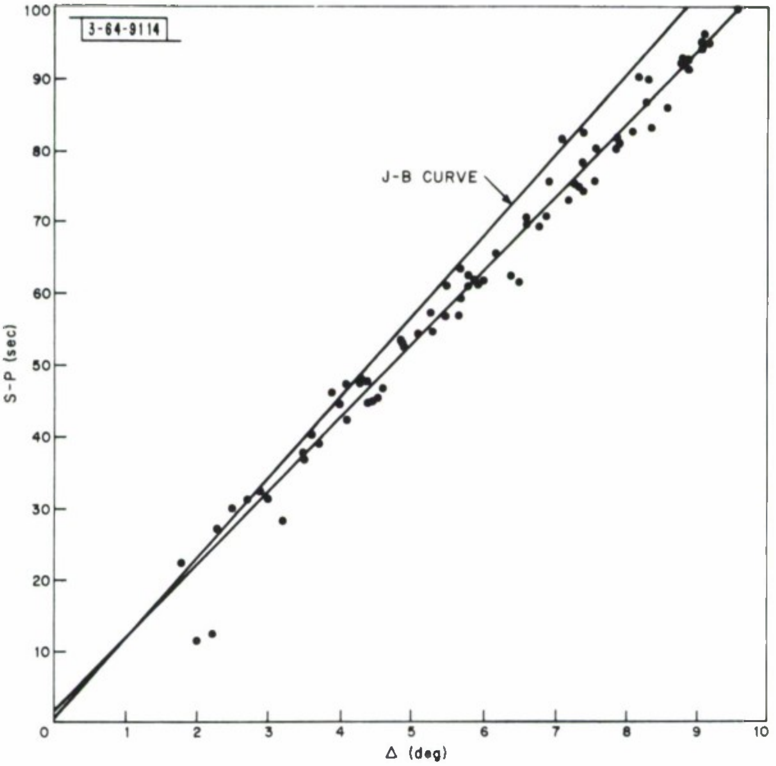

Fig. 4. S-P intervals obtained from CGS epicenters.

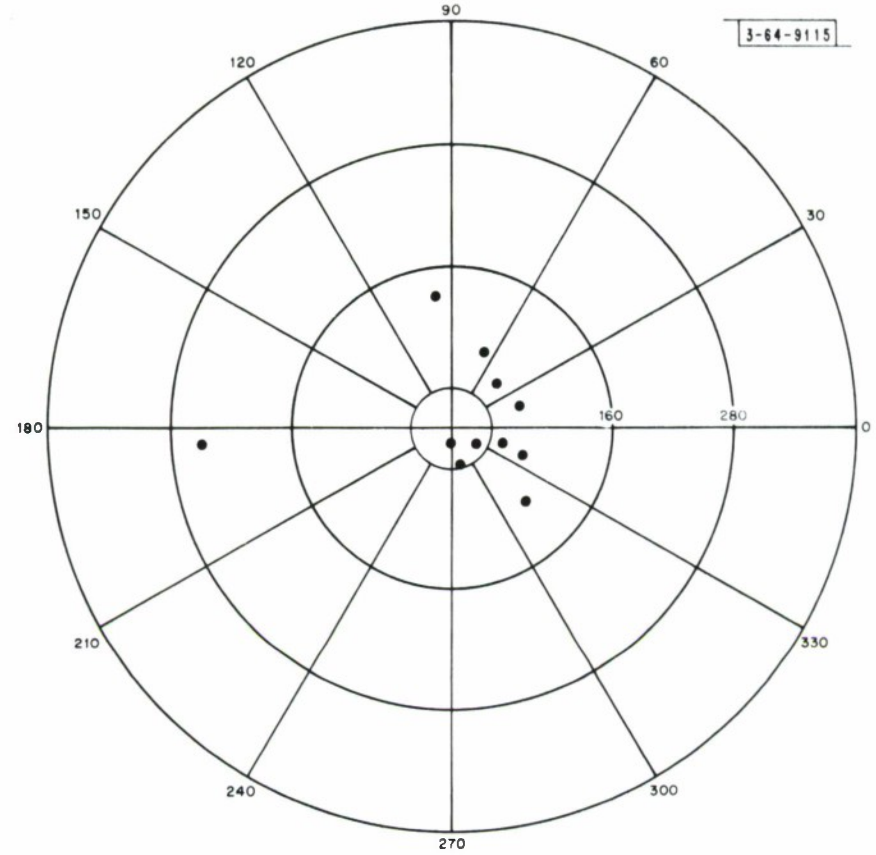

Fig. 5. Lincoln Laboratory OBS epicenter error relative to CGS epicenters.

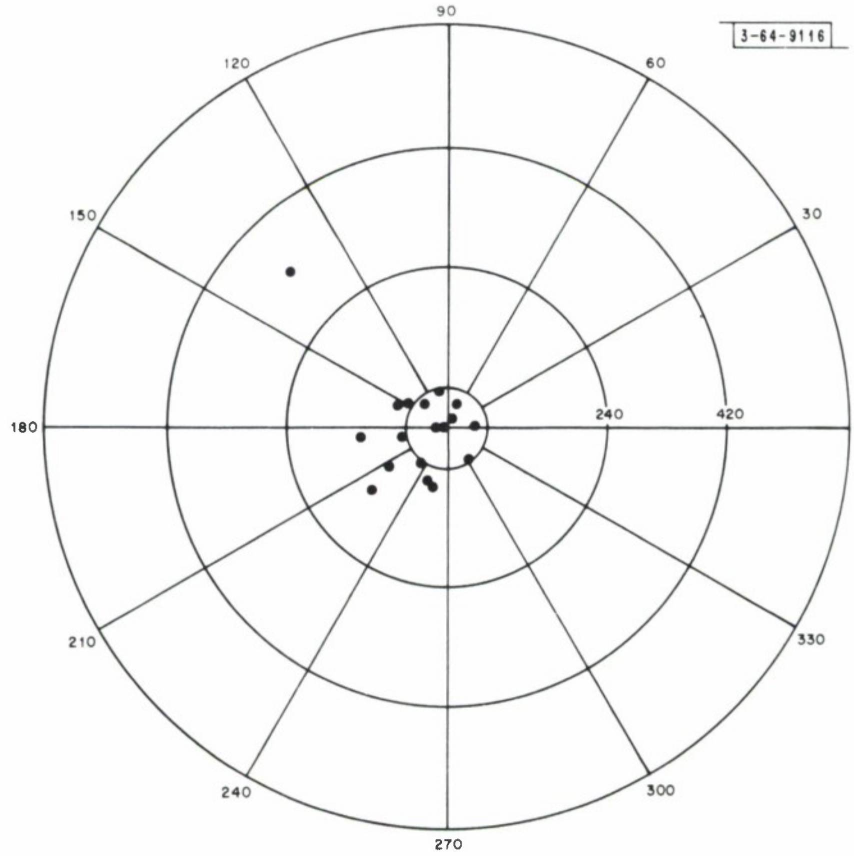

Fig. 6. Plane wave epicenter errors relative to CGS epicenters.

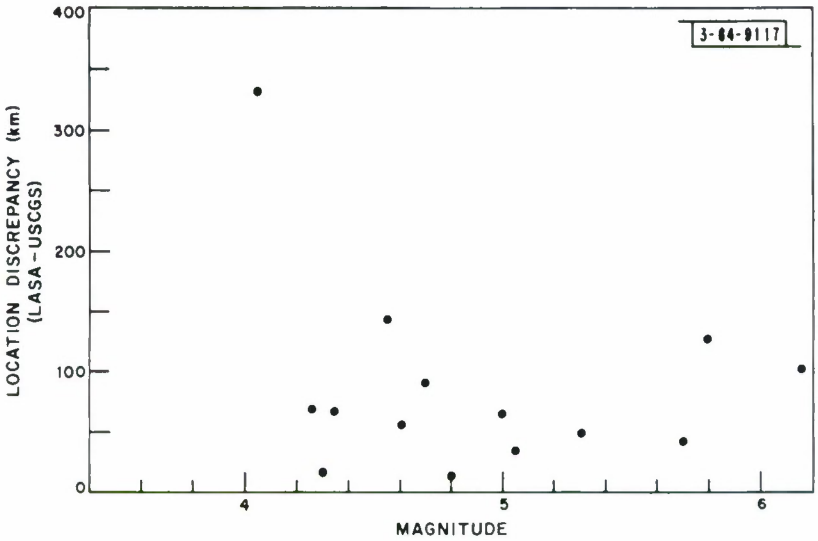

Fig. 7. Plane wave epicenter errors as a function of LASA magnitude.

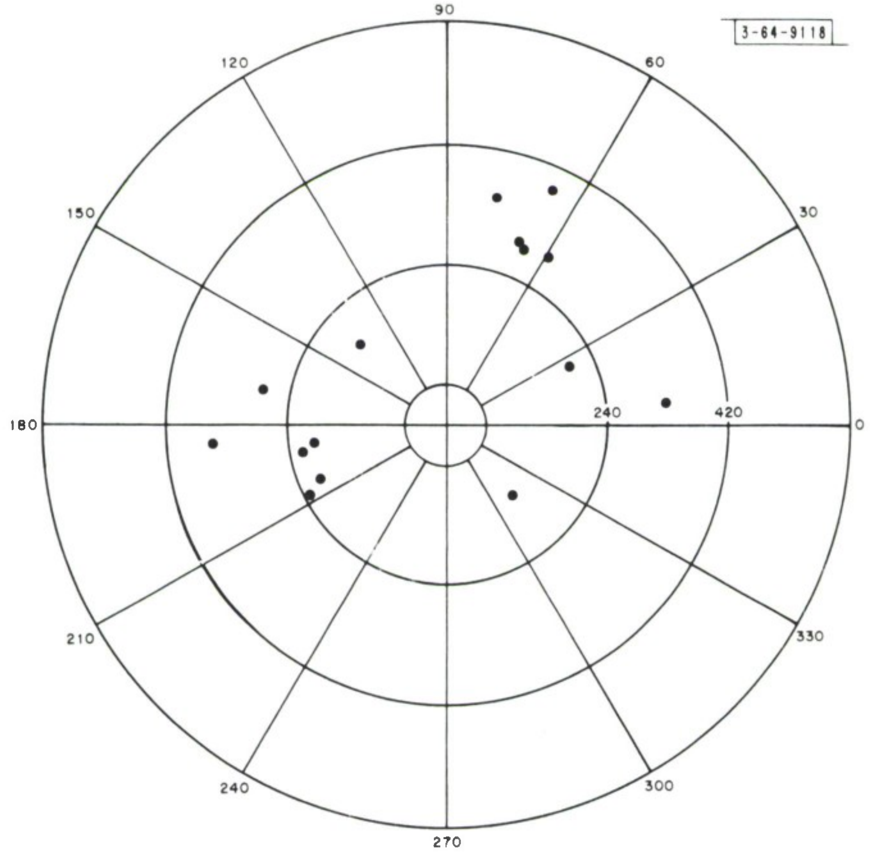

Fig. 8. LASA station bulletin epicenter location errors in 1966 relative to CGS epicenters.

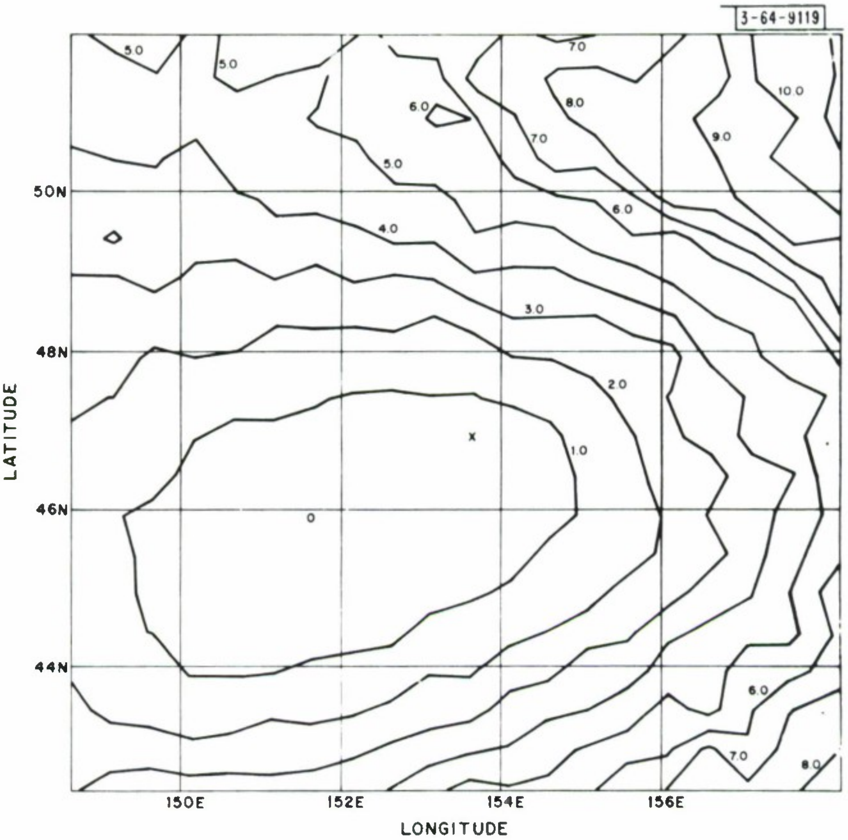

Fig. 9. Unsmoothed beam pattern.

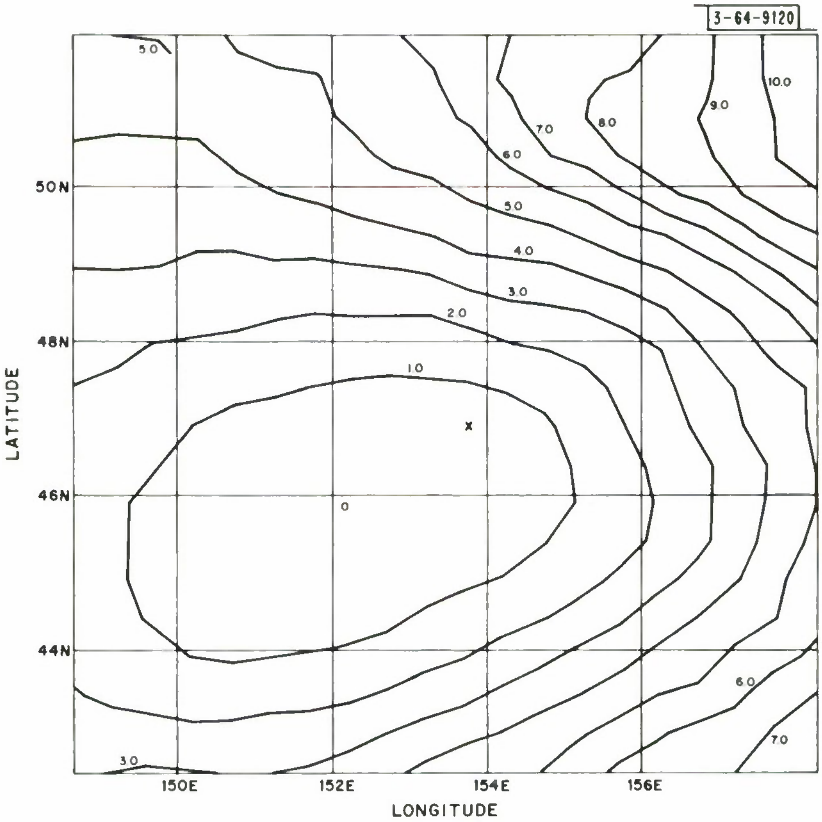

Fig. 10. Smoothed beam pattern.

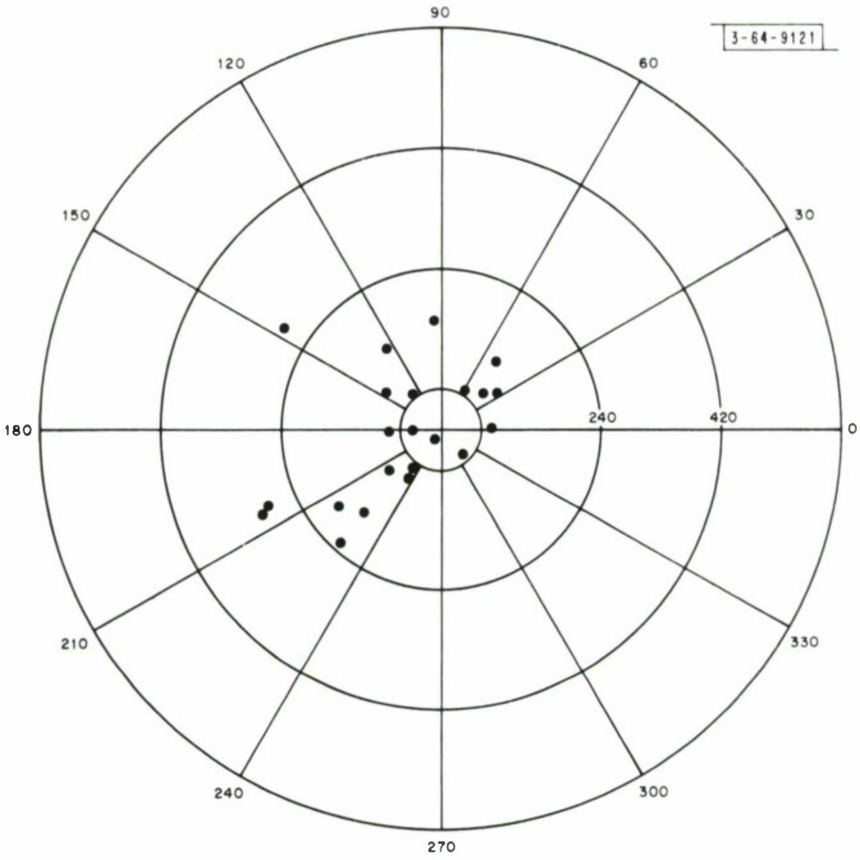

Fig. 11. Beam epicenter location errors relative to CGS epicenters.

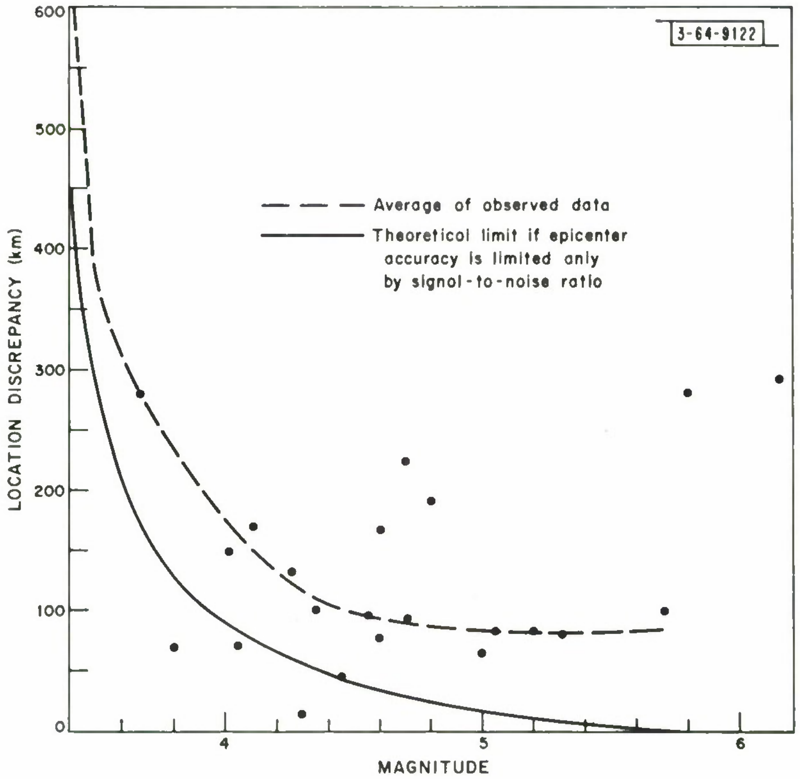

Fig. 12. Beam location errors as a function of LASA magnitude.

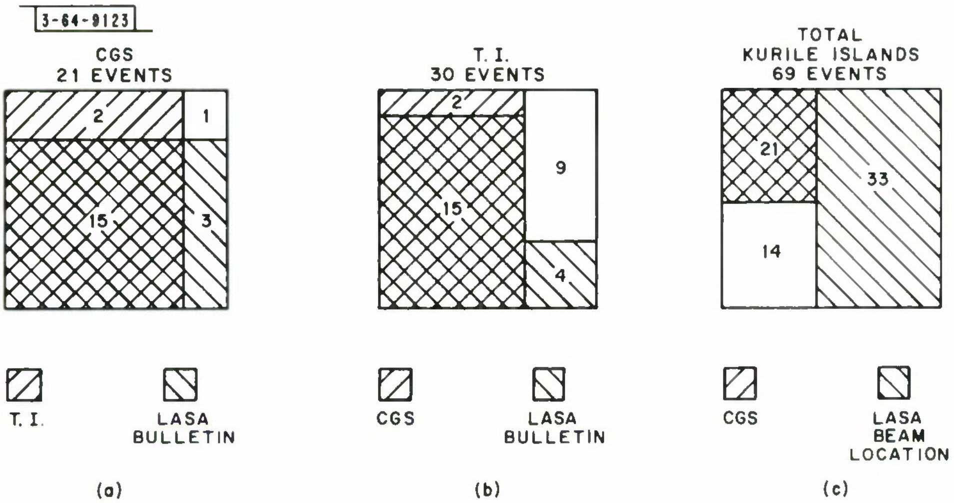

Fig. 13. Relative location ability.

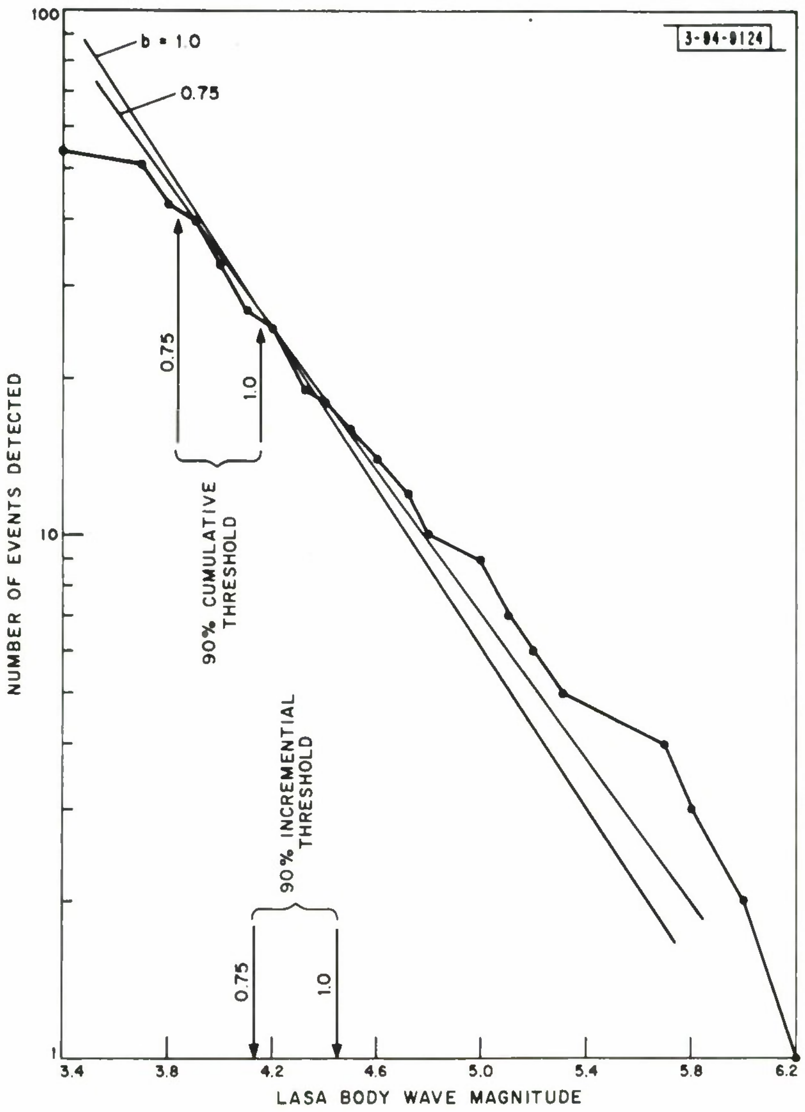

Fig. 14. LASA recurrence curve for the data base.

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13. ABSTRACT

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14. KEY WORDS

LASA
Kurile Islands
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