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# RAYLEIGH WAVE DETECTION AT THREE LP ARRAYS DURING THE ISM

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Rayleigh waves from each event in the ISM epicenter list were sought at the LASA, ALPA, and NORSAR long period arrays. The method utilized FKCOMB, a program which computes a three dimensional Fourier transform in frequency-wave number space for overlapping four minute windows. The Rayleigh wave from a listed event was declared detected if an energy peak greater than some minimum threshold appeared in the predicted time and azimuth windows, with

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This paper discusses the Rayleigh wave detection rates, missed signal rates, and false alarm rates measured at these three long period arrays during the International Seismic Month.

RAYLEIGH WAVE DETECTION AT THREE LP ARRAYS
DURING THE ISM

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# ABSTRACT

Rayleigh waves from each event in the ISM epicenter list were sought at the LASA, ALPA, and NORSAR long period arrays. The method utilized FKCOMB, a program which computes a three dimensional Fourier transform in frequency-wave number space for overlapping four minute windows. The Rayleigh wave from a listed event was declared detected if an energy peak greater than some minimum threshold appeared in the predicted time and azimuth windows, with an acceptable period and group velocity. False alarm rates were estimated by attempting to detect Rayleigh waves ostensibly coming from a fictitious epicenter list. The procedure is quantitative and can be automated on a digital computer.

This paper discusses the Rayleigh wave detection rates, missed signal rates, and false alarm rates measured at these three long period arrays during the International Seismic Month.

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## INTRODUCTION

There are several advantages to the use of frequency-wave number (f-k) analysis in detecting surface waves on long period arrays. Since frequency-wave number analysis is essentially beamforming in the frequency domain, many beams can be examined simultaneously. Thus the azimuth and velocity of the signal need not be assumed. One has only to look for the beam(s) with the power maximum(a). Moreover the computer forming the f-k spectra can detect and trace the time migration of a power peak through successive time windows (f-k analyses), and indicate the corresponding signal parameters in a few lines of printer output. The slow process of time-domain beamforming, plotting, and visual analysis can be avoided.

Smart (1971), (1972), developed a high speed algorithm for the computation of f-k spectra. Smart and Flinn (1971) made use of this algorithm in a frequency-wave number analysis program (FKCOMB) employing a Fisher detector and applied it to the real-time analysis of infrasonic array data. Mack (1971), (1972) applied this technique to long period seismic arrays for detecting Rayleigh waves. Since the short period threshold is expected to be lower than the long period threshold for arrays such as LASA and NORSAR, Mack estimated the thresholds of the long period arrays by using the LASA Daily Summary to compute expected arrival times and azimuth for Rayleigh waves from Kurile Island earthquakes.

In this paper we followed Mack's approach to measure the detection and missed signal rates for Rayleigh waves for ISM events with two additions. First, instead of seeking only power peaks from events listed on the ISM, we performed FKCOMB analysis of all four minute (256 second) time intervals during the ISM at all three long period arrays, LASA, ALPA, and NORSAR. Second, by seeking Rayleigh waves during the ISM from earthquakes on a false epicenter list (the C list from different month), we obtain an empirical measure of the false alarm rate.

## METHOD

We applied FKCOMB to all ISM data at tne three long period arrays. Because FKCOMB uses a fast Fourier transform algorithm requiring 2n samples per input channel, the time windows were all 256 seconds long. This time window is long compared to the transit time across the largest LP array (67 seconds for a 3 km/second wave to traverse LASA). Still the window is short enough so a small surface wave signal with little dispersion would not be lost in a overly long window. For long, dispersed surface wave trains several adjoining windows can be expected to exhibit the signal peak at different period from essentially the same azimuth.

For each time window the computer printout lists several power peaks throughout the F-K space indicating the size, azimuth, period, velocity, and signal-to-noise ratio of each. Table I lists the average number of detections per window, the average maximum and average minimum powers of these detections for each of the LP arrays during quiet times with no expected ISM events arrivals. NORSAR was subject to higher noise levels during much of the ISM due to North Atlantic storms. The average number of detections and power levels during these noisier intervals are also indicated on Table I.

We wish to utilize a signal detection method which is quantitative so that a detection is not subject to analyst judgement. After reviewing the average noise detections from FKCOMB and the signal parameters of a few large ISM events, we chose a five-dimensional detection window. Thus a detection is declared if the expected signal has a F-statistic above a minimum size and lies within specified tolerance on azimuth, velocity, period, and arrival time. Table II lists the limits on the two detection windows used. The upper window for signals with F-statistics equal to or greater than 20, or 17 on LASA, allowed azimuth variations of ± 10° from a great circle path prediction. This fairly wide tolerance allows for location errors in epicenter and for refracted arrival paths from most seismic regions. For small signals, with F-statistics greater than 10 but less than 20, or 17 on LASA, the azimuth tolerance was ± 4° to reduce the chances of detecting false alarms.

TABLE I

Number and Size of FKCOMB Detections in Background Noise at the Three LP Arrays

| | LASA | ALPA | NORSAR |
|---|---|---|---|
| Average number of detections per window (FKCOMB) | 5.5 | 5.6 | 5.9 |
| F-Statistics | | | |
| Average maximum during quiet times | 18.6 | 43.8 | 26.9 |
| Average minimum during quiet times | 4.1 | 6.9 | 6.5 |
| Average maximum during noisy times | 71.7 | 55.3 | 71.4 |
| Average minimum during noisy times | 9.2 | 13.4 | 25.3 |

The signal size parameter was the F-statistic from a Fisher detection algorithm rather than signal-to-noise ratio. In FKCOMB the signal-to-noise ratio computed as:

$$S/N = \frac{P(f,\underline{k})}{Av(f) - P(f,\underline{k})}$$

where $P(f,\underline{k})$ is a power maximum in f-k space. The denominator is an estimate of the array noise power for that frequency (f) and beam (k). The noise power estimate is equivalent to subtracting the best signal estimate (delayed beam) from each trace and averaging the noise power residues over the array. The F-statistic is computed from the signal-to-noise ratio by:

$$F = (S/N) \cdot (n - 1)$$

where n is the number of array channels (Shumway, 1971).

TABLE II

5 - Dimensional Detection Windows

UPPER WINDOW

| | |
|---|---|
| Minimum F-statistic | 17 on LASA; 20 on ALPA and NORSAR |
| Azimuth | Predicted azimuth $\pm$ 10° |
| Velocity | 3.0 to 4.0 km/second |
| Period | 16 to 31 seconds |
| Arrival Time | Predicted arrival for 25 second-period. Must arrive in the predicted window, the first previous window, or either of the two following windows. Early arrival must have period 25 seconds. When a signal is detected in more than one window, the detection with maximum power was selected. |

LOWER WINDOW

| | |
|---|---|
| F-statistic | 10 to 16 on LASA; 10 to 19 on ALPA and NORSAR |
| Azimutn | Predicted azimuth $\pm$ 4° |
| Period, Velocity Arrival Time | (Same as Upper Window) |

## RESULTS

The number of detections and missed signals at each of the three LP arrays are shown on Figure 1 compared with the 950-event epicenter list for the ISM. A major category for each of the three arrays is data not available (66% for NORSAR). Although some of the missing data was not recorded (7.5% at LASA, 6.5% at ALPA, 8.5% at NORSAR), most of the data loss resulted from incompatibilities between the program, FKCOMB, and the operating system on the IBM 360/91 at UCLA where the processing was done. A considerable portion of this data may be recoverable. Just how much and the reasons for these problems are beyond the scope of this report. Suffice to say that the actual data set for measuring the detection threshold of the LP arrays is smaller (192) than the 950 events reported in the ISM epicenter list.

Because of the susceptibility of false alarms at a single array, the LP network detection threshold is better measured by insisting on Rayleigh wave detection at two or more of the three arrays. Figure 2 shows the LP network performance for all ISM events for which data was available and processable at all three arrays. Of these 192 events NORSAR and ALPA each detected 50% and LASA 40%. There were 45 events (23%) detected by all three arrays, and 83 events (43%) detected on at least two of the three arrays. The number of events detected at each array at the secondary threshold (with an F-statistic between 10 and 19) is small (less than 10% for ALPA and NORSAR and less than 12% at LASA). Moreover every event detected on two or more arrays had at least one of the signals in the upper threshold.

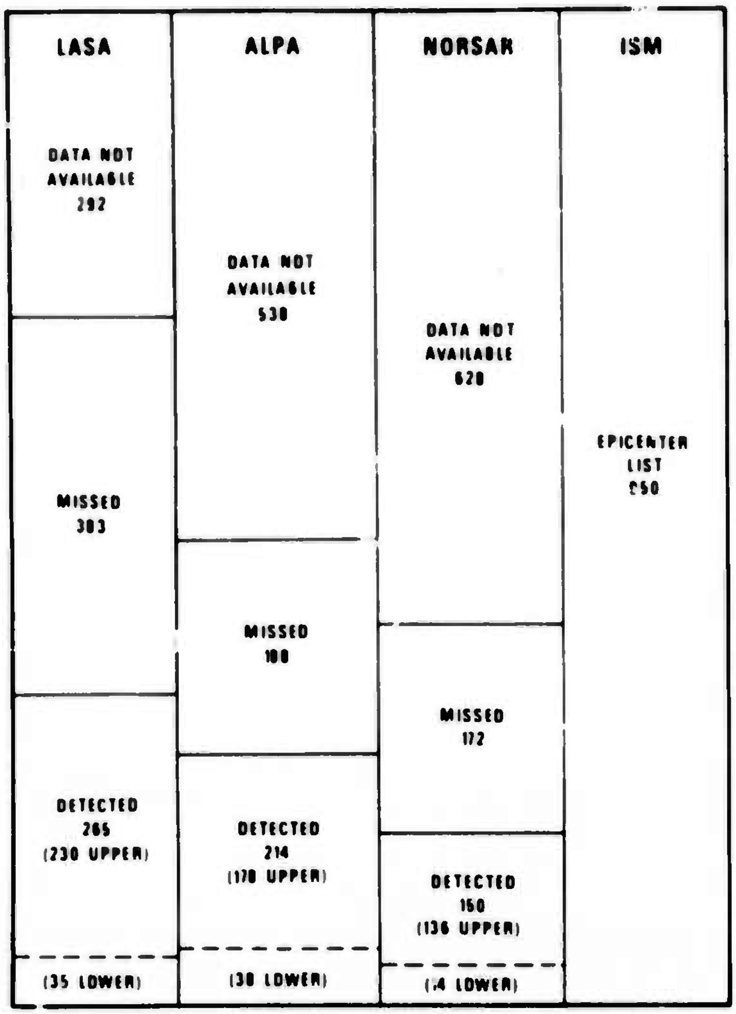


Figure 1. Detections, missed signals, and data available at the 3 LP arrays during the ISM.

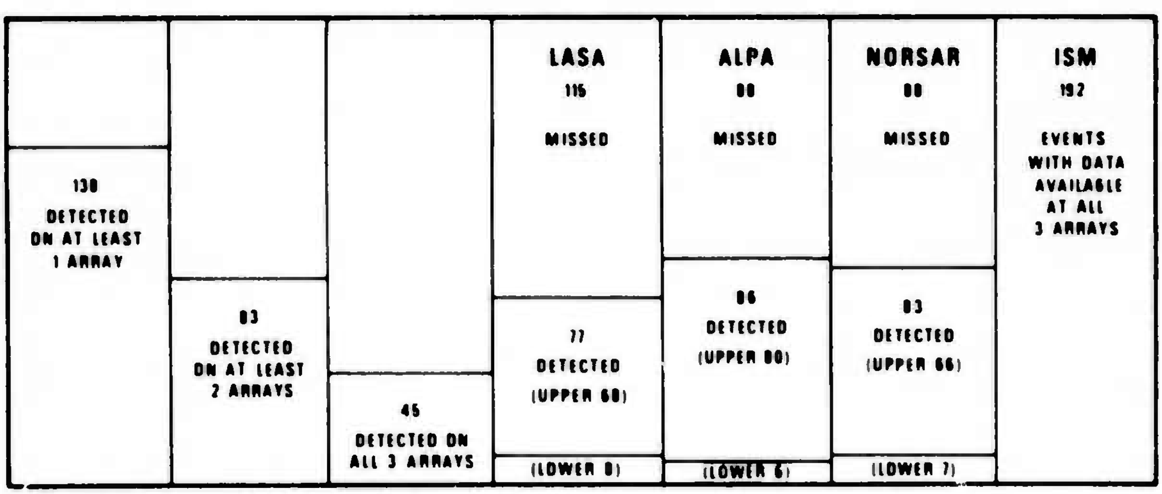


Figure 2. LP array and network detections for ISM events with data available at all 3 arrays.

Detection rates by two or more of the three arrays as a function event size (average $m_b$ reported on the ISM epicenter list) is shown in Figures 3 through 6. Figure 3 shows the number detected and the number missed in ranges of 0.5 $m_b$ for all depths. We have again cut the sample form 192 events to 162 events by eliminating those events for which the ISM did not report a short period magnitude.

Figure 4 shows the number detected and the number missed versus $m_b$ for events with ISM-listed depths of less than 100km. There were 72% of these shallow events detected with magnitudes ($m_b$) from 4.5 to 4.9. More than half of those in the $m_b$ range of 4.0 to 4.4 were missed.

Figure 5 shows the number detected and the number missed for events with ISM-listed depths equal to or greater than 100 km. Less than 25% of these were detected in the $m_b$ range of 4.0 to 4.4.

Figure 6 shows a similar plot for ISM events for which no depth has been specified. The erratic behavior of both detections and missed signals as functions of $m_b$ implies that this group is probably a mixture of deep and shallow events.

Figures 7, 8, and 9 show the $M_s$ versus $m_b$ plots for detections at each of the three LP arrays for ISM events with listed depths. Although events at the higher $m_b$ range (mb from 4.5 to 6.0) show generally larger $M_s$ values for the shallow earthquakes versus the deep earthquakes on the LASA and NORSAR plots, there is considerable overlap. At the lower $m_b$ ranges (less than $m_b$ = 4.5) and for all ranges on ALPA there seems to be little distinction between $M_s$ values for the deep and the shallow events.

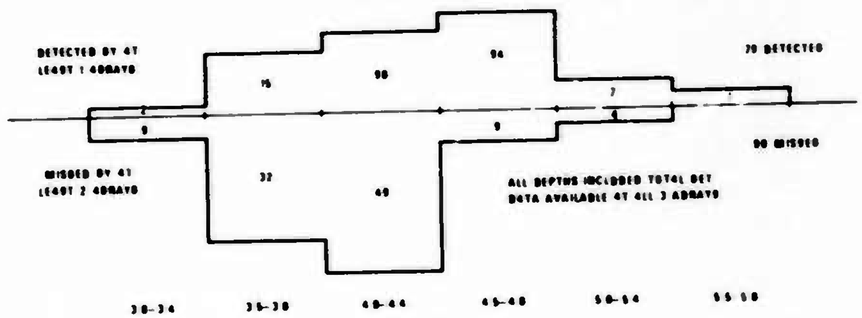

Figure 3. Detection of ISM events by at least 2 of 3 LP arrays vs $m_b$.

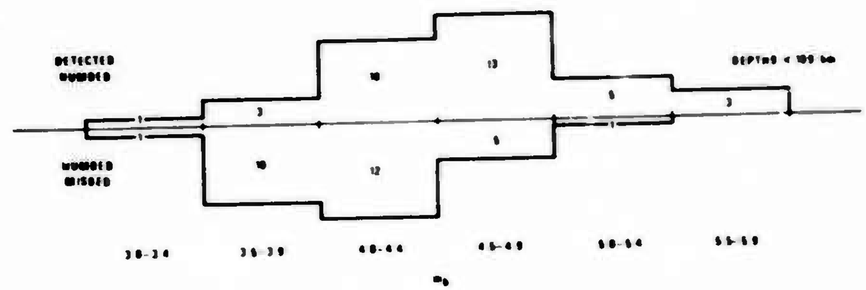

Figure 4. Detection of shallow ISM events by at least 2 of 3 LP arrays vs $m_b$.

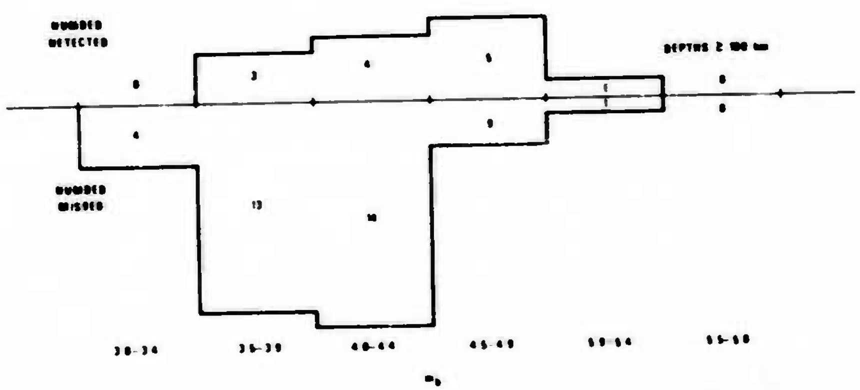

Figure 5. Detection of ISM events, depths $\geq$ 100 km by at least 2 of 3 LP arrays vs $m_b$.

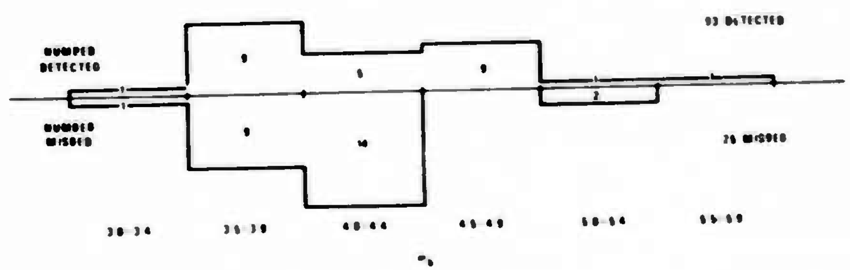

Figure 6. Detection of ISM events with no listed depth by at least 2 of 3 LP arrays vs $m_b$.

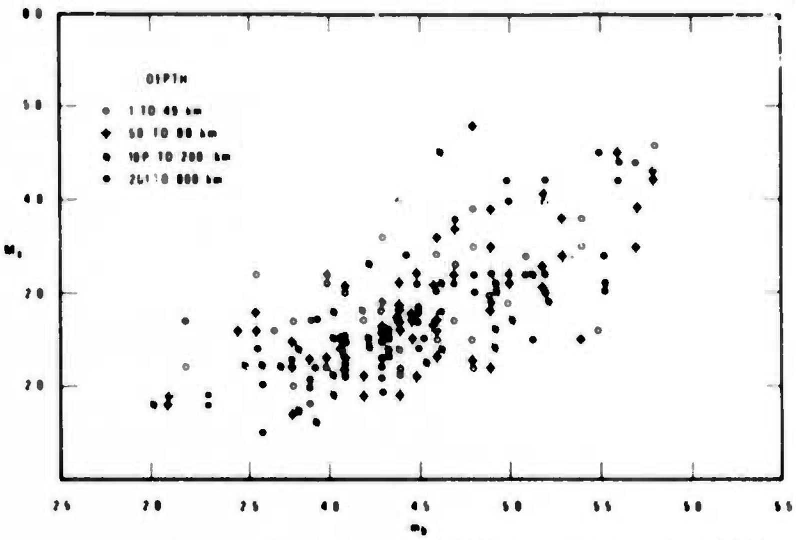

Figure 7. Rayleigh wave detections($M_s$ vs $m_b$) LASA ISM events.

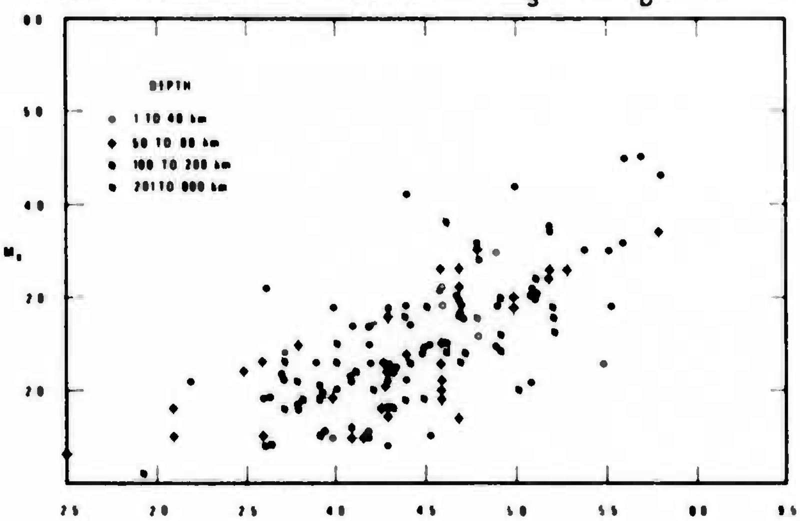

Figure 8. Rayleigh wave detections($M_s$ vs $m_b$) ALPA ISM events.

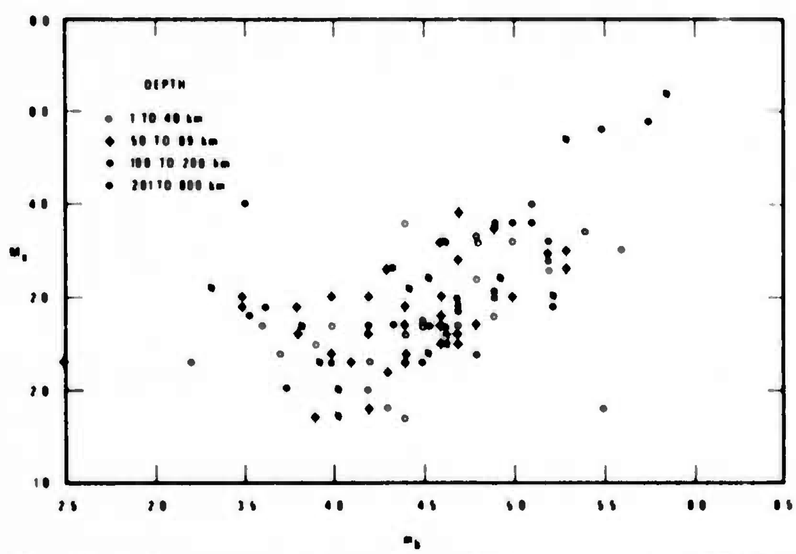

Figure 9. Rayleigh wave detections($M_s$ vs $m_b$) NORSAR ISM events.

## FALSE ALARMS

To measure false alarm rates we chose an epicenter list published by NOAA from 20 May through 18 June 1972, and attempted to find Rayleigh waves from each of these events on the FKCOMB output from the ISM. Again we followed the same detection rules for both upper and lower thresholds as we did for the ISM events. When the false epicenter list showed a large detection (F-statistic greater than 30) we checked the ISM epicenter list for a coincidence, i.e. an event occurring which would be expected to yield a surface wave from the same azimuth arriving at the same time. We found and eliminated 3 such coincidental events.

Table III shows the results of this false alarm test. Again this experiment was limited by the data available at the three arrays. At the three arrays we detected between 19% and 25% false alarms of which 9% to 10% were at the lower threshold. In considering the three arrays as a network we found only 37 events on our false list of 199 with data available at all three arrays. Of these 37 there were none detected at all three arrays, but there were 5 (14%) detected at two of three arrays. One was definitely a false alarm being detected above the upper threshold on two arrays. Three detections were above the upper threshold on one array and below the upper threshold on the other array. One detection was below the upper threshold on both arrays. Thus, for this sample, insisting that all detections be in the upper threshold at two or more LP arrays would eliminate all but one of the five false alarms.

TABLE III

False Epicenter List: NOAA Epicenters from 20 May 1972 through 18 June 1972 applied to ISM Data.

False Detections

| | LASA | ALPA | NORSAR |
|---|---|---|---|
| Total number of events | 313 | 313 | 313 |
| Data available at each array | 199 | 127 | 86 |
| Detections at each array | 45 | 32 | 16 |
| upper threshold | 26 | 21 | 9 |
| lower threshold | 19 | 11 | 7 |
| Average F-statistic for detections | 28.5 | 32.9 | 33.8 |

| | |
|---|---|
| Data available at all 3 arrays | 37 events |
| Number of detections at all 3 arrays | 0 |
| Number of detections at 2 of 3 arrays | 5 |
| upper threshold on both | 1 |
| lower threshold on one, upper on one | 3 |
| lower threshold on both | 1 |

## CONCLUSIONS

1. We find the 5-dimensional window in time, azimuth, velocity, period and signal size an effective way to analyze the output of FKCOMB. Moreover the limits on these variables for signal acceptance are easy to quantify the readily programmable on a digital computer.

2. Most detections acceptable through this 5-dimensional window are large signals (F-statistic greater than 20). Only 6% at ALPA to 12% at LASA of the detections are recorded in the lower threshold.

3. For long period network detection (at least 2 of 3 LP arrays detecting the signal) 3 out of 4 ISM events with $m_b$'s from 4.5 to 4.9 at all depths are detected. Only 1 out of 3 events in the $m_b$ 4.0 to 4.4 range are detected.

4. For events listed as shallow (less than 100 km deep) by the ISM epicenter list 3 out of 4 events in the range $m_b$ 4.5 to 4.9 are detected and slightly less than 50% in the range $m_b$ 4.0 to 4.4 are detected by the LP network (2 out of 3 LP arrays).

5. For events listed as deep (greater than 100 km) by the ISM epicenter list, 62% are detected in the range $m_b$ 4.5 to 4.9 and 1 out of 3 are detected in the range $m_b$ 4.0 to 4.4 by the LP network (2 out of 3 LP arrays).

6. At all 3 LP arrays the $M_s/m_b$ plots for these events detected do not show appreciably higher $M_s$ values for shallow events (less than 100 km) over the deep events. This same result is true even when the shallow/deep separation is 50 km rather than 100 km.

7. More than half of the false alarms at any of the 3 LP arrays occur above the upper threshold in the 5-dimensional window. No raising of this detection threshold would appreciably cut the false alarm rate without drastically reducing the true-signal detection rate at each array.

8. The combination of requiring 2 of 3 arrays for a detection and all detections in the upper threshold would reduce the false alarm rate from 5 in 37 to 1 in 37 and decrease the true detection rate from 83 in 192 (43%) to 71 in 192 (37%).

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