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MULTIPLE SEISMIC EVENTS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Visual records from all available sources for eight nuclear shots of a multiple nature have been obtained and converted to digital form. Identification logic employing Cepstrum analysis has been established and the application of this logic to real data is presently under investigation. Preliminary results with Cepstrum analysis appear encouraging. Identification logic including the use of P-wave radiation patterns and/or cross correlation with signals of known origin are being considered. Preliminary results indicate

20. ABSTRACT. (cont'd)

that for distance ranges of 100 km to 1000 km the P-wave radiation pattern may provide a viable means of identification. M_L and m_b magnitude relationships were developed for shots and earthquakes. Triggering of microearthquakes by tidal forces were also investigated.

Technical Report Summary

The purpose of this project is to investigate seismic means of discriminating multiple point sources from natural earthquakes at distances less than 1000 kilometers with special emphasis on the use of unmanned seismic observatories. This would include both theoretical and analytical studies. Based on the discriminants developed, the density or distribution of the unmanned observatories will be determined for various detection and identification thresholds.

The procedure used during the first six months of this investigation was twofold in nature - one was a collection of data dealing with multiple point sources and earthquakes from the same source region and the other was the development of computer programs to analyze the data as it became available and to obtain results from theoretical models.

Seismograms were obtained from a number of sources for eight sets of multiple point source events and for one earthquake that occurred at the Nevada Test Site. We are attempting to obtain additional data for these events because a good azimuthal distribution of recordings is necessary to determine the radiation patterns. We are still in the process of digitizing and analyzing these recordings. Our preliminary studies show that Cepstrum analysis techniques appear promising. For one double event (low yield), the smaller shot (approximately 1/3 the yield of the larger event) which was fired in alluvium was detected in the P wave coda of the

larger shot which was fired in tuff. The events were approximately 4.3 km apart and were fired simultaneously. A detailed evaluation of this technique will be made following the analysis of all available data.

The magnitude relationship of explosive sources and earthquakes are an important factor that has to be taken into consideration when discussing these events. There has been little published on the M_L and m_b relationship for small or low yield events and of course this type source is not a good generator of long period surface waves that the M_s magnitudes are based on. Hence a study was conducted to determine the relationship between the types of body wave magnitudes that are in use and the local magnitude (M_L) vs body wave magnitude (m_b) for both shots and earthquakes. Three empirical equations were developed that allow magnitude comparisons:

Shots

$$m_b \text{ (NOAA)} = .72\ m_b \text{ (Evernden)} + 1.72$$

$$m_b \text{ (NOAA)} = .96\ M_L + .36$$

Earthquakes

$$m_b \text{ (NOAA)} = 3.73 - .16\ M_L + .08\ M_L^2$$

Shots and earthquakes were found to have on the average about the same relationship between an M_L or m_b range of 4.2 to 4.8. At magnitudes above $M_L = 4.8$ shots appear to have larger m_b magnitudes while at magnitudes below $M_L = 4.2$ earthquakes appear to have larger m_b magnitudes. There was, however, considerable scatter in the earthquake data. We plan to investigate further the magnitude relationships since they may be influenced by multiple source events.

Of potential interest to the development of evasion concepts is the possible triggering of microearthquakes (and conceivably larger earthquakes) by tidal forces. Microearthquake data were obtained in 1969 during a program sponsored by AFOSR/ARPA in connection with the JORUM event. A large number of small high frequency microearthquakes were recorded at that time which showed a definite periodicity. These data were studied further under the sponsorship of this grant to determine the relationship of this periodicity. Cross correlation functions and cross spectral densities were computed for the frequency of occurrence of these events and the vertical component of the earth tidal acceleration. A strong correlation was found with the principal lunar diurnal component. The maximum positive correlation occurred at 4 hours ahead of the peak earth tide acceleration and a 6 hour lag was found for the maximum negative correlation with the earth tide minimum. However, when a comparison was made between the rate of change (derivative) of the vertical component of the tidal acceleration and the number of earthquakes per hour, an almost one to one comparison was found.

Studies of the P wave radiation pattern expected from multiple detonations, in the distance range of 100 km to 1000 km, have been initiated. A FORTRAN program for the numerical evaluation of the radiation pattern (both phase and amplitude) for two point sources has been written and is operating. This will be compared to measured radiation patterns to determine the station distribution and density necessary to employ the radiation pattern as a discriminant. In addition to radiation patterns, studies of the cross correlation of nuclear event data with natural and unknown data have been started. The objective of this is to show that the cross correlation of single event data with multiple event data is significantly different from the cross correlation of single event data with natural data. A discriminant of this nature would require a low degree of station coverage and, hence, it would be the most desirable in this respect. Spectral analysis studies are underway but have not gone beyond the program writing stage.

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April 15, 1974

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1400 Wilson Boulevard
Arlington, Virginia 22204

Subject: First Semiannual Technical Report for Period Covering 1 June 1973 through 31 December 1973.

Dear Sir:

This report is a summary of research dealing with multiple seismic events and first zone discriminants. The research is divided into the following categories and will be discussed individually.

Introduction

This grant is for an investigation into the design of discriminants to detect and identify multiple seismic sources from natural sources recorded at distances less than 1000 km utilizing urmanned observatories. The research includes both theoretical and analytical studies.

A major effort was made during the first six months to collect seismic data available on multiple events and earthquakes from the same source region recorded at first zone distances. Data were obtained from the World Wide Standard Seismic Network, the LRSM stations, the USGS (formerly NOAA) Branch of Seismic Engineering at Las Vegas, the University of California Lawrence Livermore Laboratory, and Sandia Corporation. These data are in the process of being digitized and analyzed. The analyses will include the determination of the spectral content, surface wave generation ratios, radiation patterns, record complexity, corner frequency, seismic moment and stress drop using extensions of the Brune or Archambeau earthquake models. The potential of geometrically dependent time delays within the arrivals of body wave phases, resulting from physical separation of the event, are being investigated through the use of Cepstrum analysis. Where feasible, known characteristics of seismic signatures in areas such as the Asian region will be included in the first zone discriminants.

Technical Reports, Publications and Presentations

The following report was prepared and presented at the Sixty-ninth Annual Meeting of the Seismological Society of America on 31 March 1974 at Las Vegas, Nevada:

"Earth Strain Measurements and Strain Release in Nevada and Adjacent Areas".

The above report was sponsored in part by this grant and by a grant from the Atomic Energy Commission.

Data Collection and Digitization

Initially, major effort was devoted to obtaining a complete data base for analysis. Visual records for eight nuclear events and one earthquake were obtained, to the extent they were available, from the WWSSN system, the University of California Lawrence Livermore Laboratory, the USGS Branch of Seismic Engineering (formerly NOAA Special Projects Group), the Sandia Laboratories and LRSM System. While a significant number of these records fall at distances in excess of 1000 km, attempts will be made to remove the effects of excess distance.

The majority of the visual records have been converted to digital form. While equal increment digitization was not possible, an interpolation program was written and used for conversion of the unequally spaced points to equally spaced data. The equally spaced data is then plotted at the original scale and visually compared to the analogue record.

Magnitude Relationship - Low and Intermediate Yield Shots and Earthquakes

Considerable research has been conducted over the past fifteen years that deals with the magnitude relationship between shots and earthquakes. Most of this has been directed at events recorded at teleseismic distances and for the larger yield events. The investigation being conducted under this program is concerned mainly with the smaller yields recorded at first zone distances. The shot vs earthquake magnitude relationship for the latter is not as well understood. Hence a study was initiated to determine these factors and the significance that they may have on the basic goals of this program. Preliminary results are discussed in the remainder of this section.

There have been numerous underground nuclear tests that have been conducted in Nevada since 1957. Most of these have m_b magnitudes below 5.5. Some of these tests are listed in the NOAA publications on earthquake epicenters. Other shots have magnitudes listed in various reports such as the LRSM shot reports, the former C&GS shot reports and in publications in journal articles (e.g., Evernden, 1967; Romney, 1959 and 1967; Basham, 1970). Some are also contained in Rodean's text on Nuclear Explosion Seismology. A composite list of these NTS shots with their body wave or local magnitudes was compiled from these sources and additional magnitudes were determined for as many shots as there were data available.

In utilizing these magnitude data it is necessary to reconcile the difference in body wave magnitudes that different groups or individuals have used.

Shown in Figure 1 is the relationship between two basic groups - the one includes body wave magnitudes listed by the National Earthquake Information Service (formerly of NOAA, now USGS) and the LRSM/C&GS shot reports. The second group consists of those magnitudes that are equivalent to Evernden's m_b' corrected for measurements at regional distances. A linear relationship between the two groups can be seen and is given by:

$$m_b \text{ (NOAA)} = .72\ m_b' \text{ (Evernden)} + 1.72$$

Some shot data have reported only M_L magnitudes. In an effort to determine the M_L vs m_b relationship a search was made of the NOAA data tape for all shots that had both NOAA (USGS) m_b and Pasadena or Berkeley M_L magnitudes. Shown in Figure 2 is the relationship of M_L vs m_b for 57 nuclear detonations reported by NOAA (USGS) and the Berkeley net. Richter's M_L vs m_b curve for earthquakes obviously does not fit the nuclear data. A linear least square expression for the best fit is:

$$m_b \text{ (NOAA)} = .96\ M_L + .36.$$

Also shown in this figure is the expression derived by Bayer and Wuollet (1973) for data that they obtained at the Nevada Test Site using Wood-Anderson seismographs that were set up especially to determine the M_L vs m_b relationship for the lower yield events. Hence, two different data sets were used. Their expression

$$m_b \text{ (NOAA)} = 1.01\ M_L + .170$$

agrees quite well with the results we obtained using the Berkeley data.

The original Richter relationship for m_b vs M_L for earthquakes does not fit the earthquake data for this area very well over the range 2.5 to 5 as shown in Figure 3. Shown in this figure is a plot of NOAA (USGS) m_b vs Pasadena M_L for earthquakes in Southern California and Nevada that are listed in the NOAA earthquake data file for 1961-1972. A least square fit of these data shows a second degree approximation that fits the data better than Richter's equation but still shows considerable scatter. This fit is given by:

$$m_b \text{ (NOAA)} = 3.73 - .16\ M_L + .08\ M_L^2.$$

Figures 2 and 3 show fair agreement for m_b vs M_L for both types of events over an M_L or m_b magnitude range of about 4.2 to 4.8. Above $M_L = 4.8$ shots appear to have larger m_b magnitudes than earthquakes. Below $M_L = 4.2$ for the data available, earthquakes generally show larger m_b magnitudes than shots. There is, as noted above, considerable scatter in the earthquake data. On the other hand, the scatter for the shot data is small, especially when considering no attempt

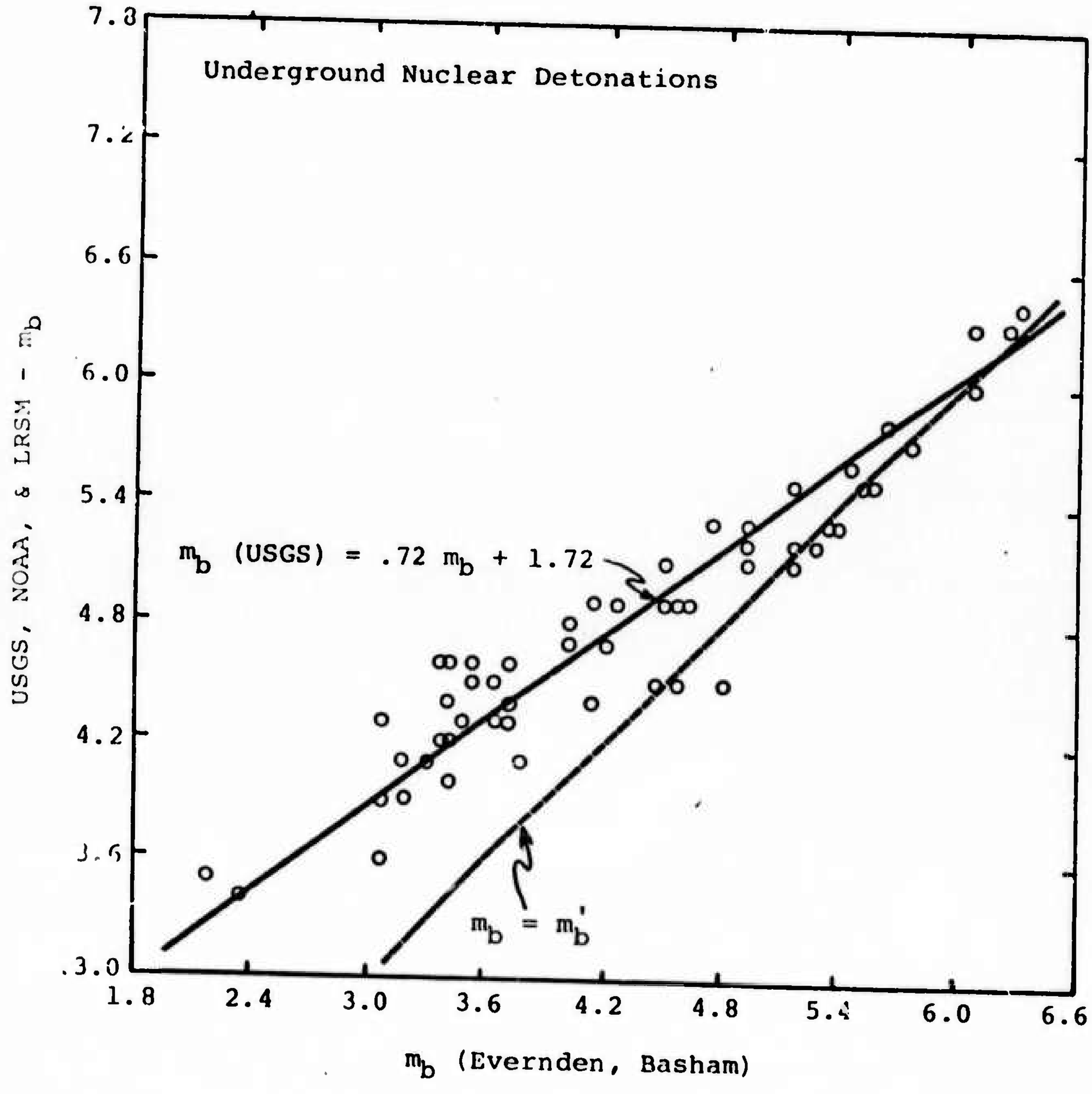

Figure 1. Relationship between body wave magnitudes used by NOAA (m_b) and Evernden (m_b').

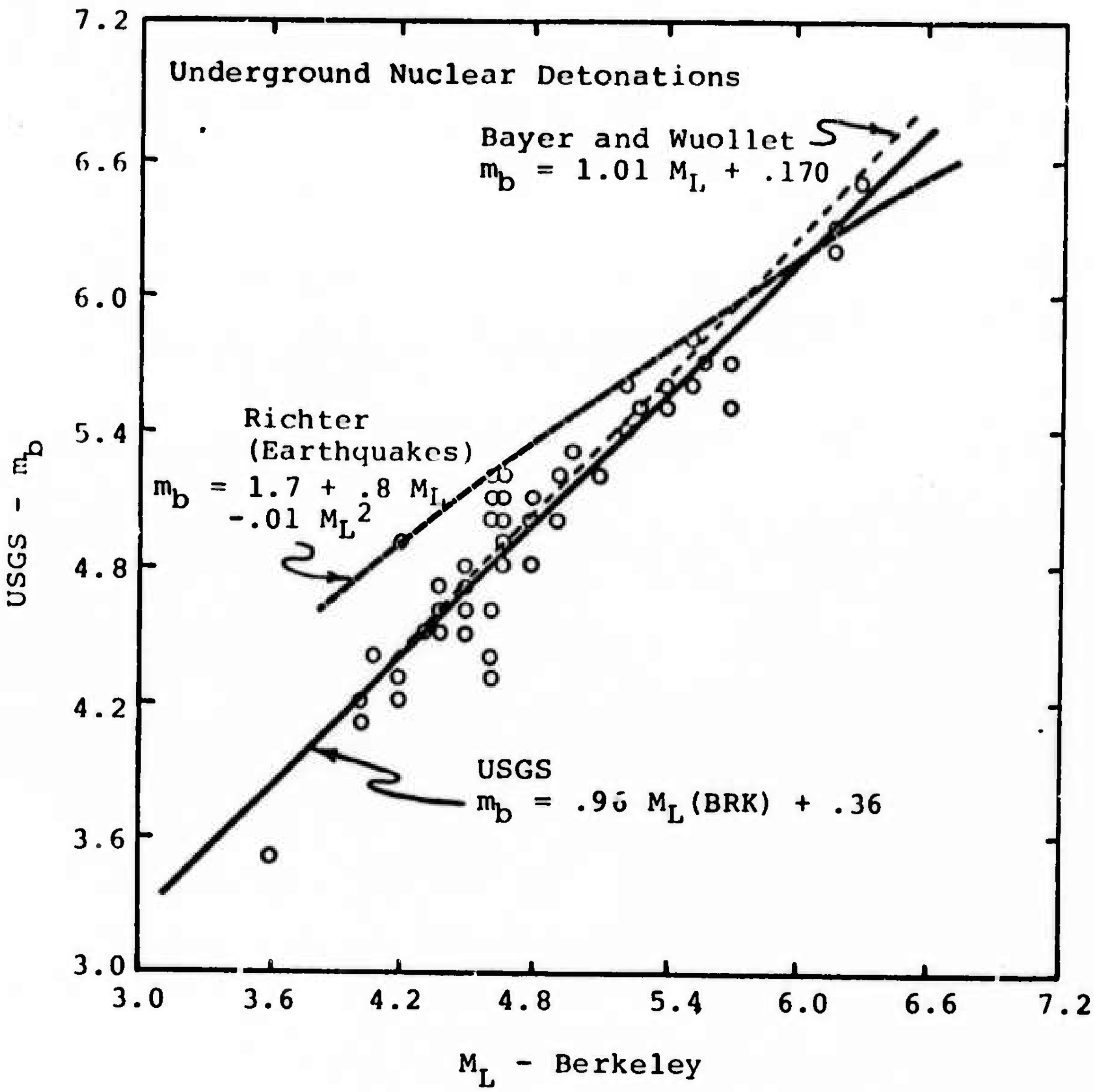

Figure 2. Relationship between body wave magnitudes and local magnitudes for underground nuclear detonations fired at the Nevada Test Site.

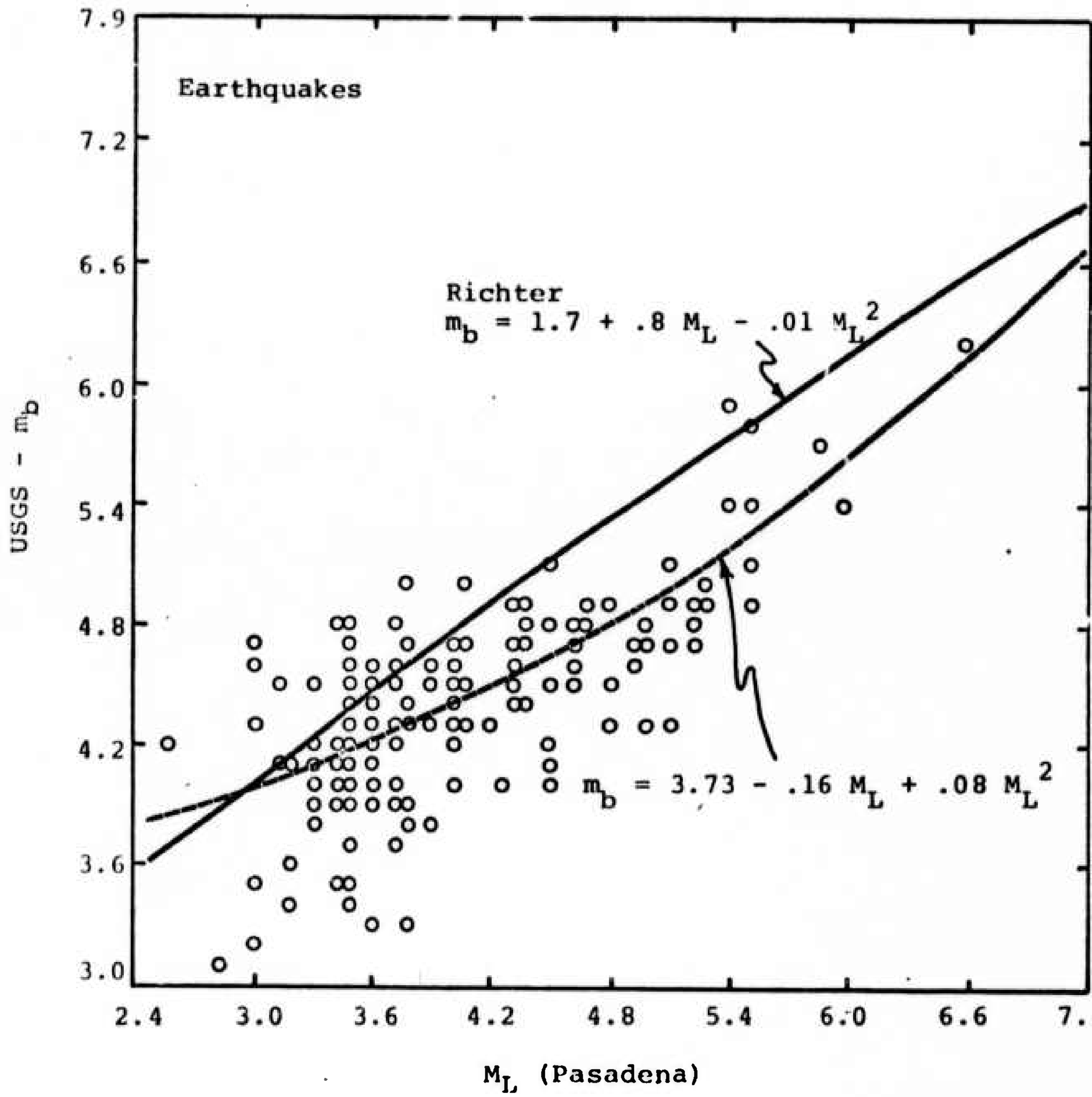

Figure 3. Relationship between body wave magnitudes and local magnitudes for earthquakes located in Southern California and Nevada.

was made to subdivide the data on the basis of the geologic rock type of the source area. The earthquake data are also from a much larger source region while the shot data are almost all from the Nevada Test Site area.

Triggering of Microearthquakes by Tidal Forces

Many authors have investigated possible earthquake triggering by earth tides (Tamrazan, 1967, 1968; Dix, 1969; Mauk and Kienle, 1973). The term trigger refers to "that which initiates an event." To this date on a global basis no definite correlation has been shown to exist between earth tides and earthquakes.

Allen (1936) pointed out that in attempts to cross correlate earthquakes and earth tides, authors have concerned themselves with a region of too great an areal extent. Carrying this idea further, cross correlation between earth tides and earthquakes would be best attempted when earthquake activity is abundant and confined in area. In a region of limited areal extent, the earth tides will be in phase and will potentially effect all the events at the same time. Aftershock sequences or microearthquakes confined in area would be best suited for this type of cross correlation study.

Under sponsorship of an earlier ARPA/AFOSR contract through the University of Michigan, continuous seismic recordings were made at three stations in central Nevada over a five week time period (Willis, 1970). This time period was centered around the JORUM event which was fired at the Nevada Test Site in September 1969. During the last few days of recording at one of these sites (Groom Mine) the recording equipment was moved into an abandoned mine shaft. As a result, considerably higher record gains were possible. During a time period from 2 October 1969 to 6 October 1969, 255 distinct high frequency microearthquakes were recorded. In a manner basically similar to that of Ryall, VanWormer and Jones (1968) an hourly count of these microearthquakes was cross correlated with the theoretical vertical tidal acceleration calculated at that location.

Figure 4 is a plot of the cross correlation function. The maximum positive correlation occurs at +4 hours lag and the maximum negative correlation exists at -6 hours lag. This means the microearthquake activity peak leads the theoretical earth tidal peak by four hours or lags behind an earth tidal minimum by six hours.

Since most microearthquakes are considered to have their origin below the surface affected by the daily heating and cooling cycle, it was felt that temperature triggering was not a likely cause of the microearthquakes.

Figure 5 shows the cross spectral density plot for the microearthquake activity and theoretical earth vertical component tidal accelerations. The pronounced peak at 25 hours also serves to eliminate temperature as a possible cause for the microearthquakes. At the time increment of digitization

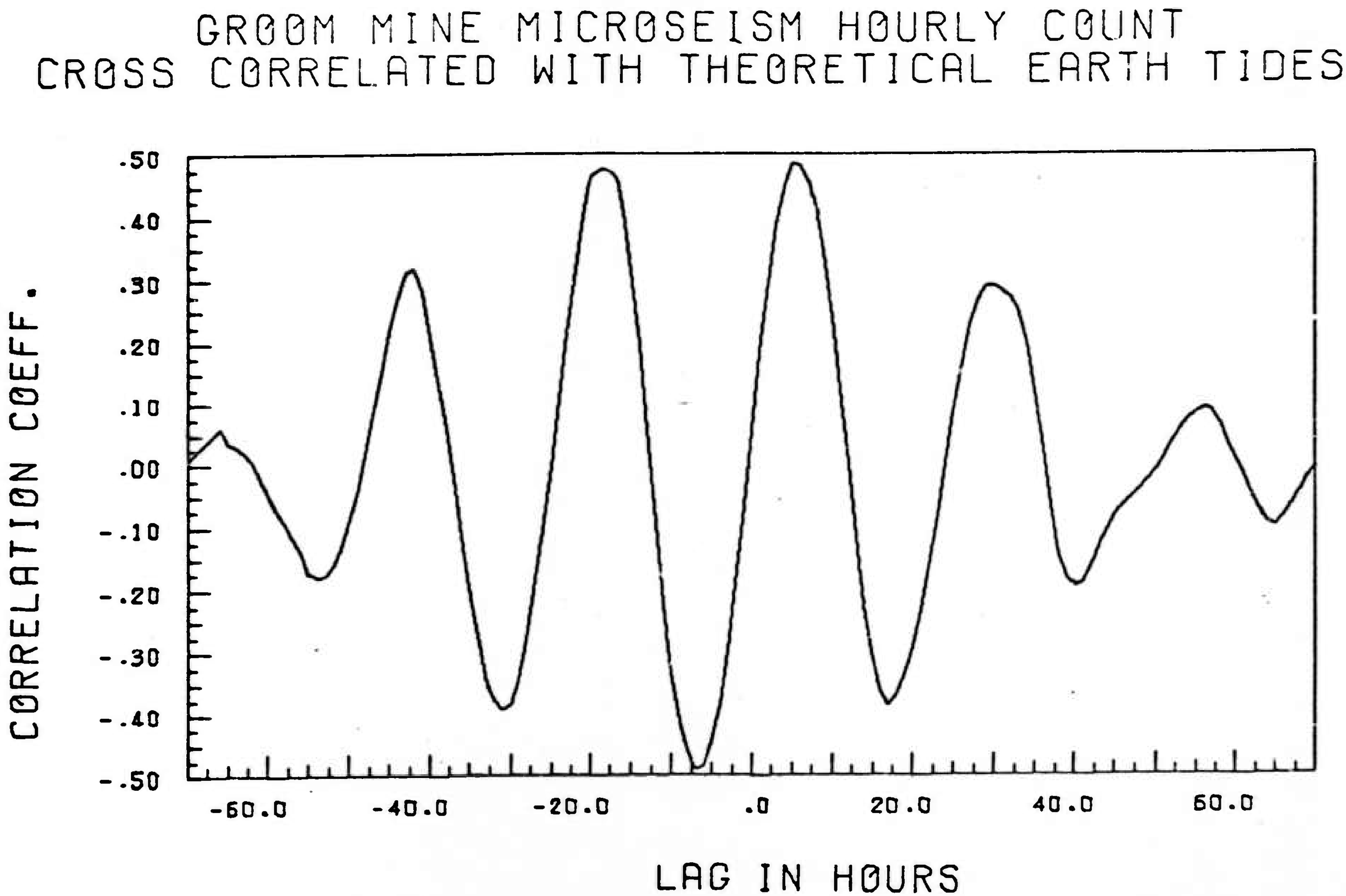

Figure 4. Cross correlation function of the Groom Mine microearthquake activity (number per hour) and the vertical component of the earth tidal acceleration.

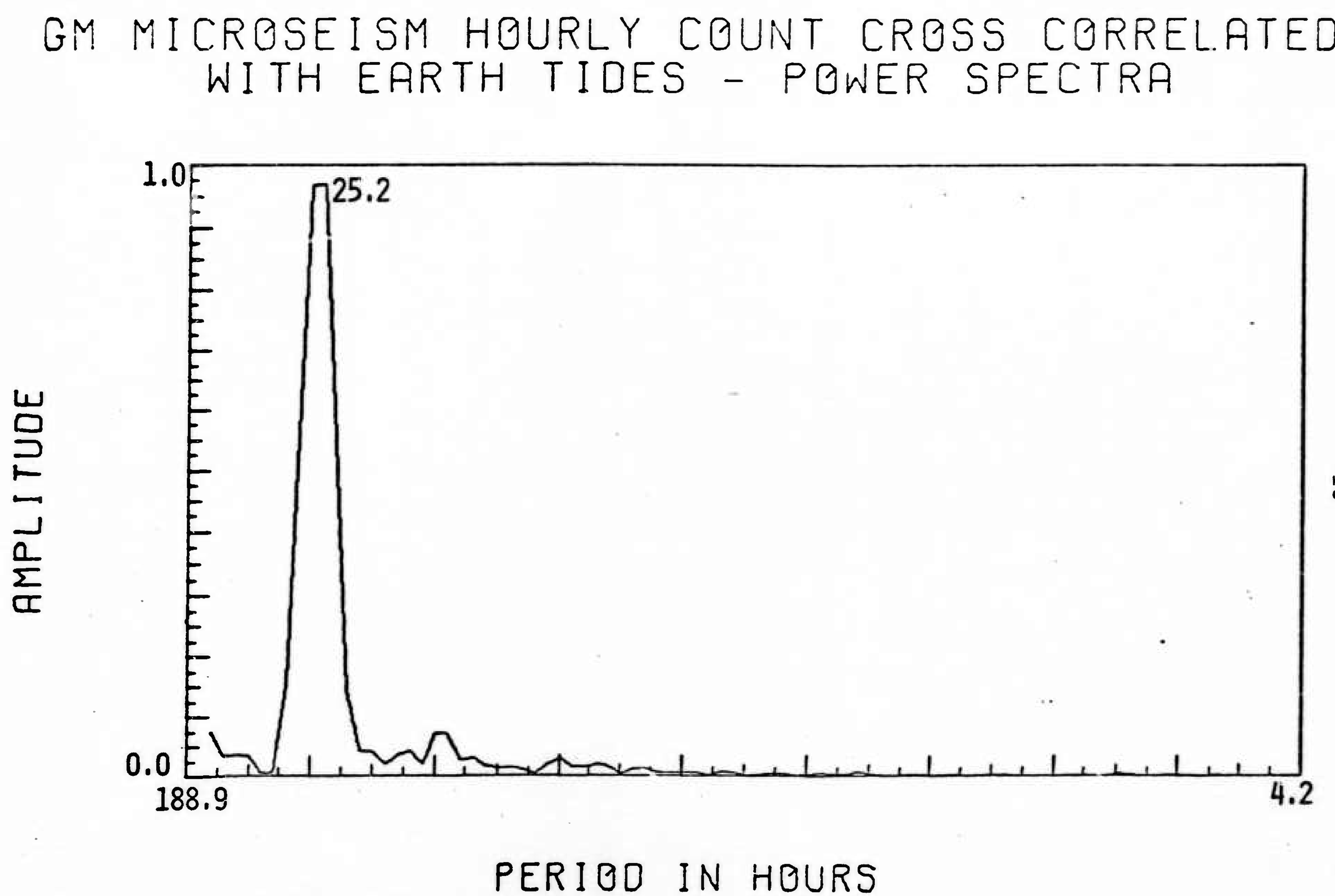

Figure 5. Cross spectral density plot of the microearthquake activity at Groom Mine with the vertical component of the earth tidal acceleration.

used for this data, the peak value may be ±0.75 hours from the time peaks shown. The O_1 (principal lunar diurnal component) tidal component with a period of 25.81 hours falls within this range.

To further investigate the phase relationship between tidal acceleration and microearthquake activity, a plot of the rate of change of the vertical component of the tidal acceleration and the number of microearthquakes as a function of time over the 72 hour time window is shown in Figure 6. The dashed line is the derivative of tidal acceleration while the solid line corresponds to the number of earthquakes in a one hour time window. The correlation can be seen to be very good. To our knowledge this is the first documented correlation of this type to be reported.

This phenomenon could be useful in the development of evasion concepts.

Cepstrum Analysis for the Detection of Multiple Events

A potential method for the discrimination of multiple detonations is to identify the multipole nature of the arriving waveform. Cepstrum analysis (Bogert, Healy and Tukey, 1963) provides a theoretical basis for the identification of a second arrival within the waveform of the initial arrival. Under suitable conditions, the identification of a second arrival could be used to imply the existence of a dipolar type source. In a similar manner it is also possible

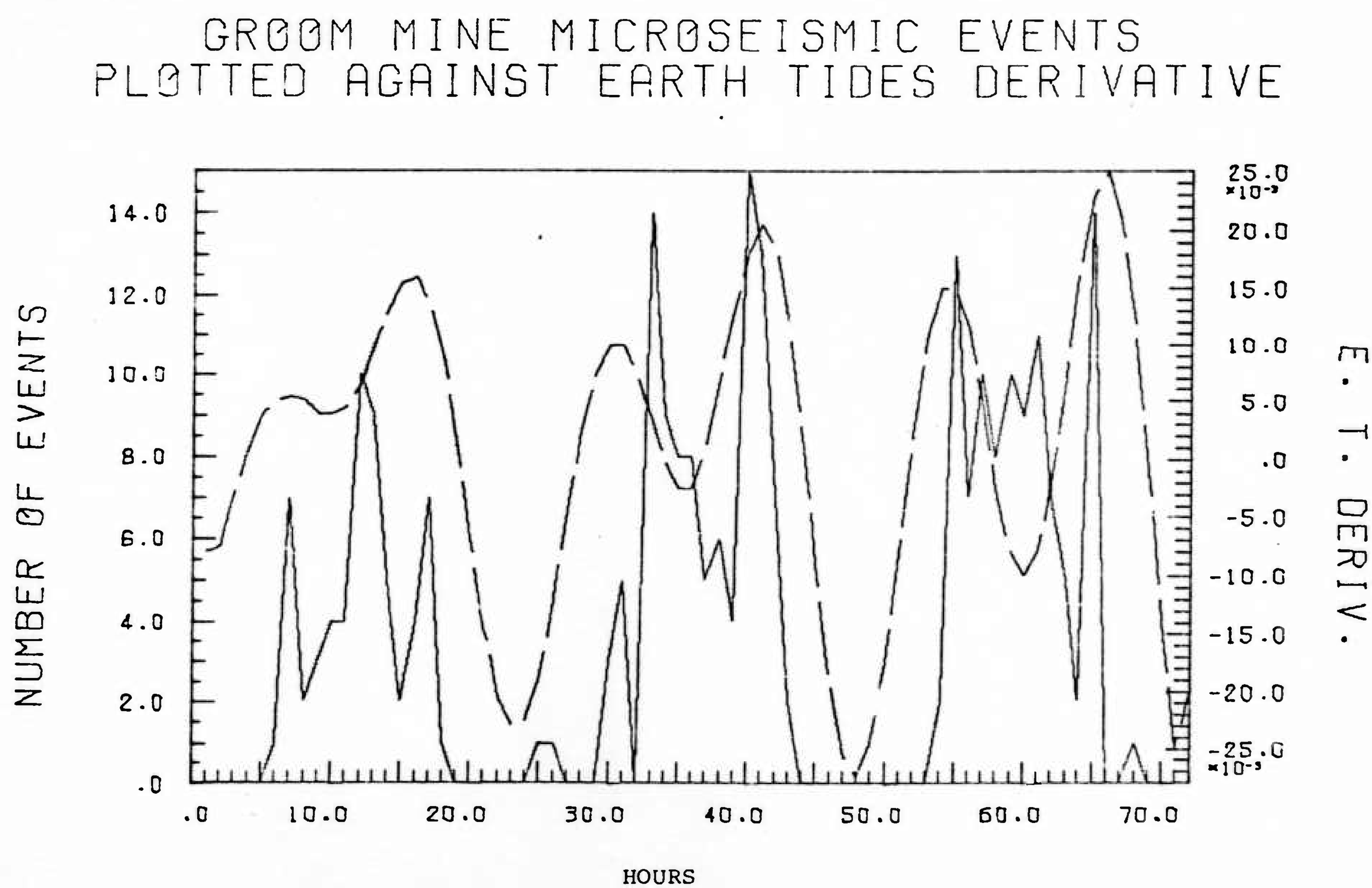

Figure 6. Groom Mine microearthquake activity (number of events per hour) vs the derivative of the earth tidal acceleration (dashed curve).

that the analysis could be extended to multiple detonations of order higher than two.

Cepstrum analysis has yielded successful detection of second arrivals in a number of cases (Flinn et al, 1973; Cohen, 1970). It does not appear, however, that the method has been shown to be insensitive to fake alarms resulting from interfering second arrivals expected from a natural event or single detonation. The most serious interfering second arrivals in the 500 km to 1000 km distance range would appear to be the "slap-down" signal, which may result from an underground explosion, and reflected, refracted or converted arrivals occurring with either explosions or natural events. The dependence of delay in the second arrival, on azimuth and on distance from the epicenter, appears to provide a means for distinguishing second arrivals of a slap-down, reflected, refracted or converted nature, from second arrivals of double event nature. The qualitative relationship of second arrival delay to azimuth and distance, for the various second arrivals, is shown in Figure 7.

To utilize the results implicit in Figure 7 will clearly require a fair degree of station coverage. Prior to considerations of required coverage, however, it is our intent to establish the reliability of the curves in Figure 7 using real data. At this point we have written a FORTRAN program for numerical evaluation of the Cepstrum method and applied the program in a limited number of cases.

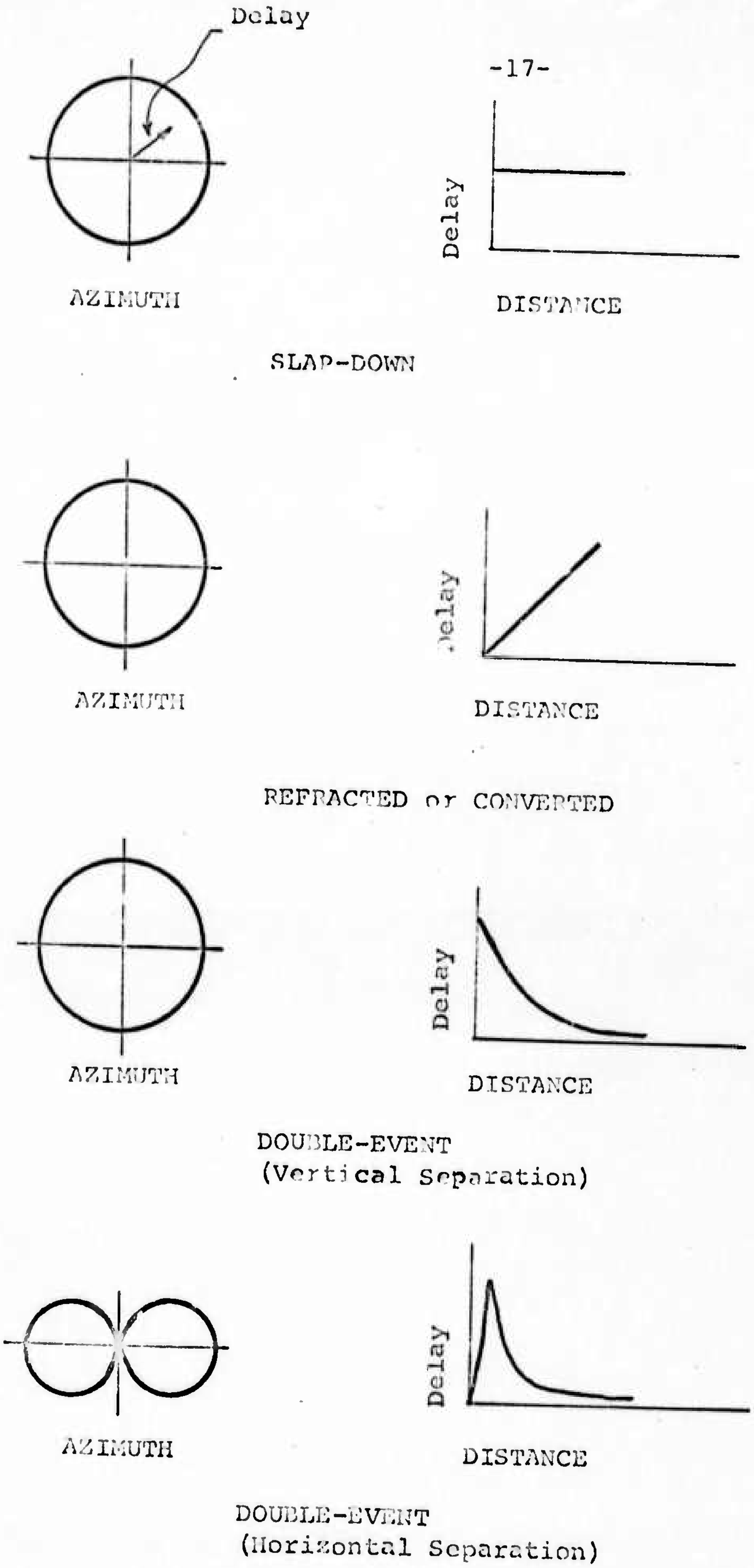

Figure 7. The qualitative delay in the second arrival as a function of azimuth and distance for various sources of the second arrival.

Typical single-station results for a nuclear shot of low to intermediate yield is shown in Figure 8. The strong peak at a delay time of 1.54 seconds suggests the arrival of a second phase (second event) at this time. This is highly encouraging since the shot considered here was a double event separated by approximately 4.4 km along a N25°E line. The receiving station was located along a N10°E line, yielding a projected source separation of 4.3 km. If an average near-surface P velocity of 3 km/sec is assumed, the 1.54 sec delay indicates a separation of approximately 4.6 km.

Major effort is now being devoted to the detection of second arrivals as a function of azimuth and distance for this and other events. In addition, the second arrivals associated with natural events will be examined.

Amplitude Studies

The high dependence of radiated energy on azimuth for most natural events, as compared to the uniform radiation pattern expected from nuclear events, provides a potential means for discrimination of the two. Multiple shots can be employed to create an azimuth dependent radiation pattern which could display the characteristics of a natural radiation pattern. The extent to which this is possible is dependent upon the geometry of the events and the period range of interest. The theoretical P-wave radiation pattern for two point sources separated by 1 km in a flat homogeneous

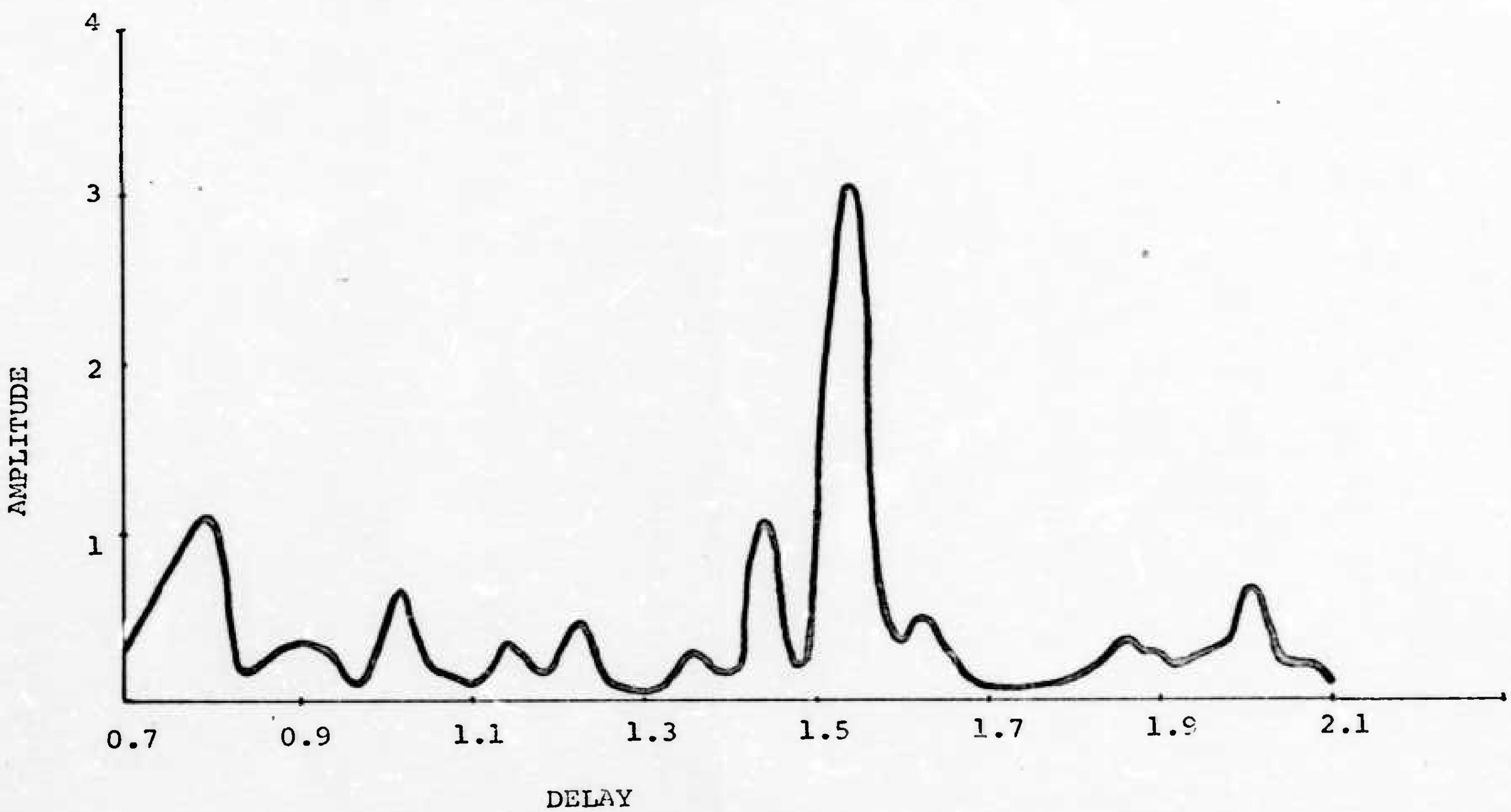

Figure 8. A typical example of the Cepstrum resulting from a multiple shot of low to intermediate yield.

earth with a P-velocity of [illegible] km/sec and observed at 100 km is shown in Figures 9, 10 and 11 for periods of 1, 3 and 5 seconds, respectively. The rapid convergence of the radiation pattern to a uniform pattern for longer periods is obvious. For the parameters used in generating these figures the radiation pattern at periods greater than 3 seconds could be used to distinguish most earthquakes from dipolar shots and that the radiation pattern at periods less than 3 seconds could be employed to distinguish multiple shots from single detonations. The unusually high P-wave velocity was employed since the effect of multiple sources on the radiation pattern will increase as the velocity decreases.

It is our intent to compare theoretical results of the above nature to the measured radiation pattern for a number of nuclear events. The expected differences, primarily due to the effects of geology, will be used to establish empirical rules for the use of observed radiation pattern as a discriminant. In addition, the results will be used in addressing the question of required station coverage.

Within certain distances the simple cross correlation, at a number of azimuths, of a waveform known to be of seismic or nuclear origin with a waveform of unknown origin may prove an effective discriminant. This approach is appealing in that the station coverage would be a minimum and the process lends itself to unmanned observatories. It would require, however, that the natural seismicity within an area was

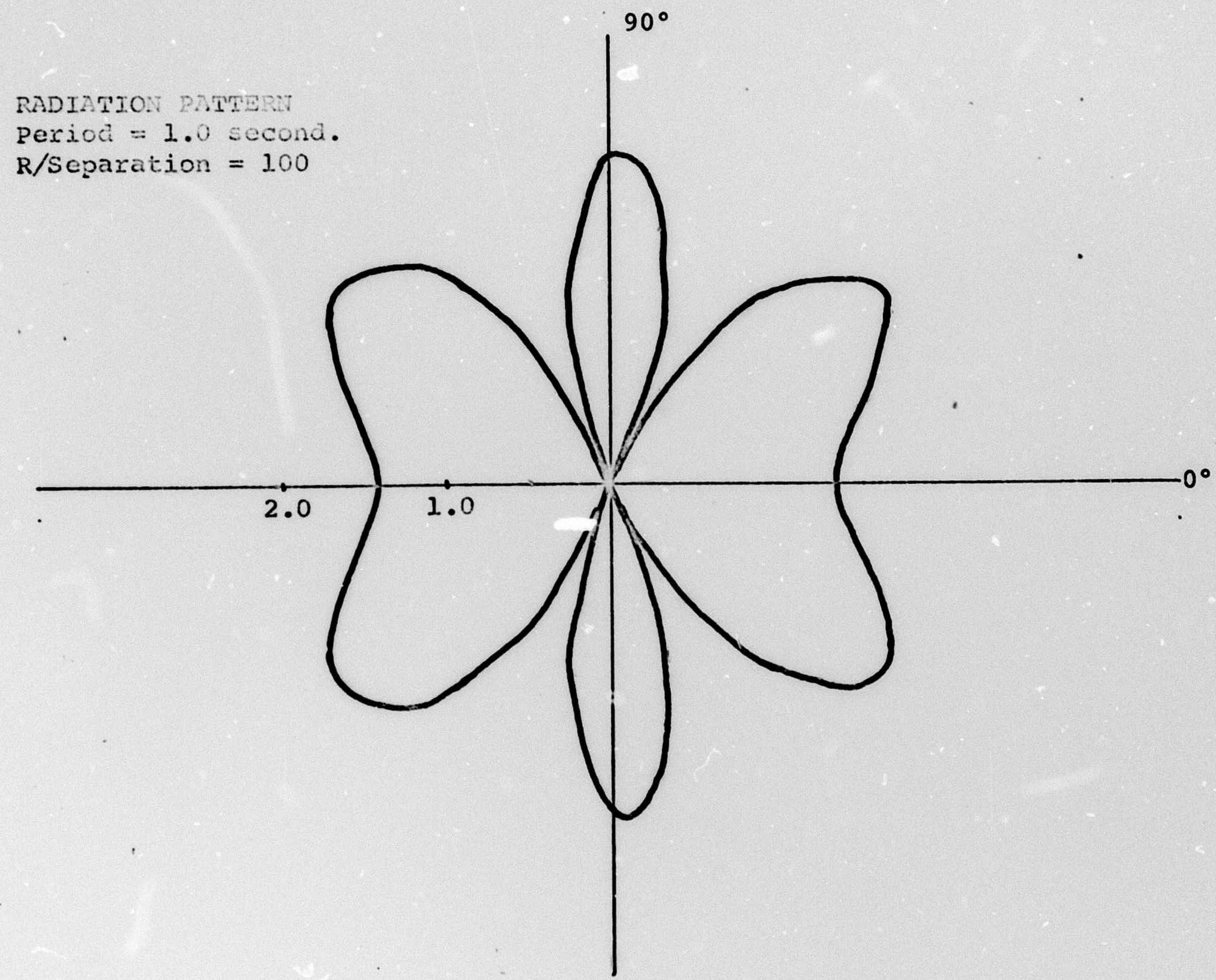

Figure 9. The radiation pattern at a period of 1 second for events of equal magnitude. R/Separation is the ratio of observation distance to source separation. The line of the sources is the 0° azimuth line.

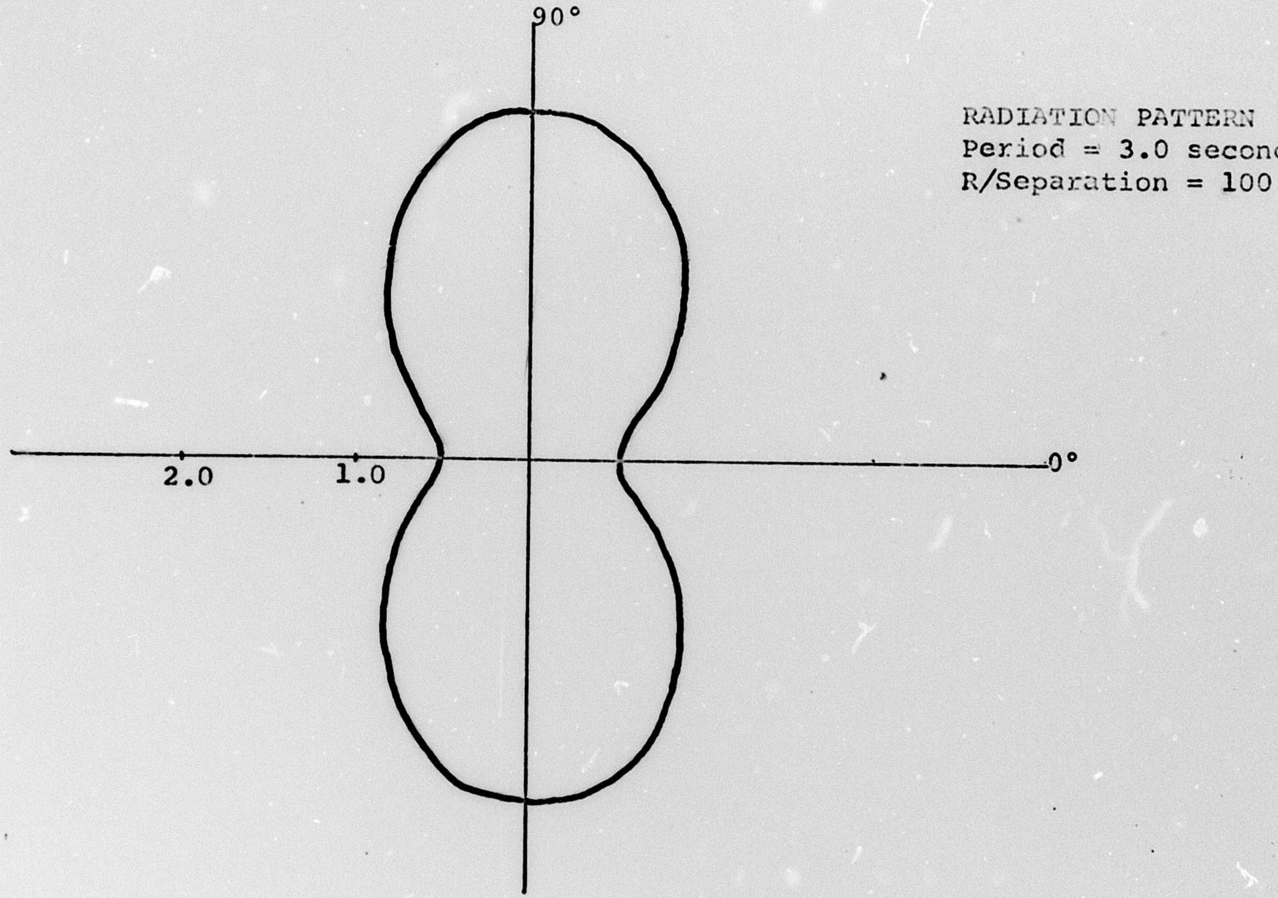

Figure 10. The radiation pattern at a period of 3 seconds for events of equal magnitude. R/Separation is the ratio of observation distance to source separation. The line of the sources is the 0° azimuth line.

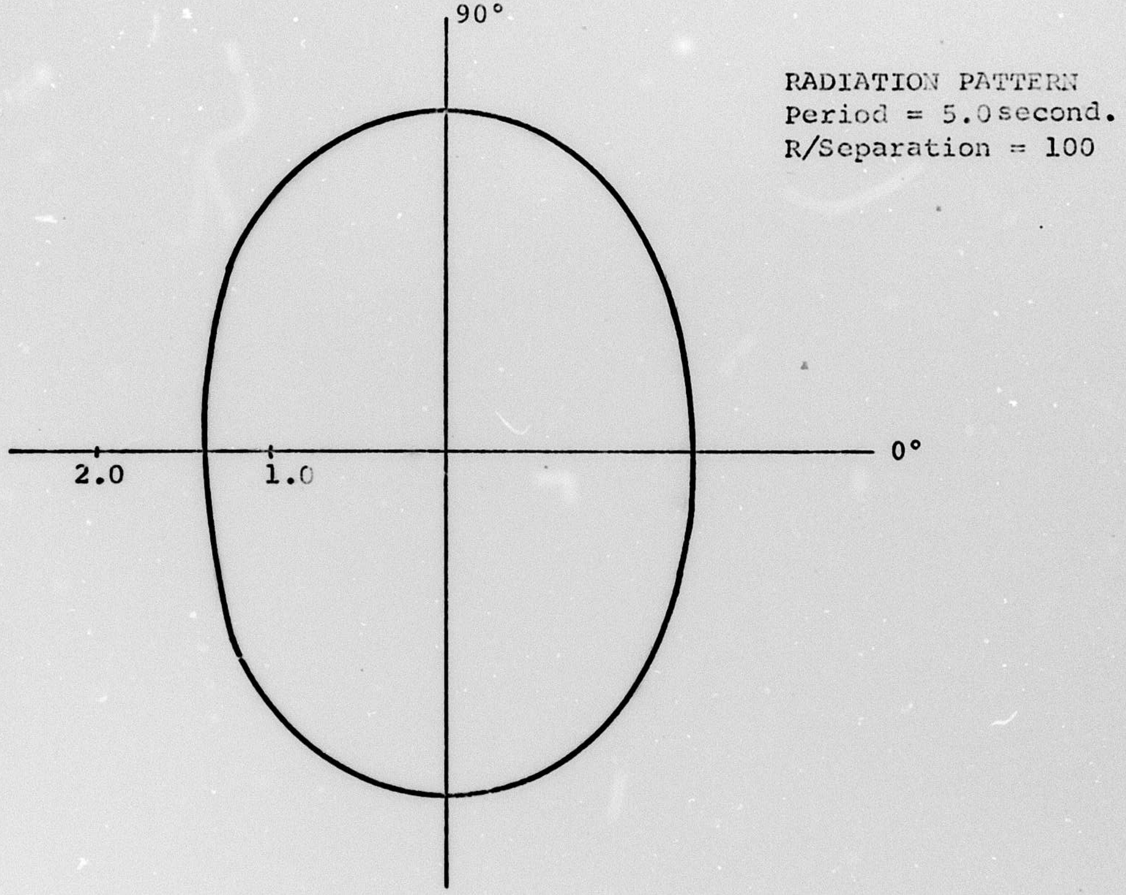

Figure 11. The radiation pattern at a period of 5 seconds for events of equal magnitude. R/Separation is the ratio of observation distance to source separation. The line of the sources is the 0° azimuth line.

characterized by a limited set fault type. The utility of this approach to discrimination is presently under investigation. The Massachusetts Mountain Earthquake of 1971 will be used as the known event for comparison with the previously mentioned nuclear events. The necessary programs are written and working and preliminary results will shortly be available.

Very truly yours,

Dr. R. W. Taylor
Co-Principal Investigator

Dr. D. E. Willis
Co-Principal Investigator

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