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Texas Instruments, Incorporated

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PRELIMINARY NETWORK EVALUATION STUDIES

SPECIAL REPORT NO. 8
EXTENDED ARRAY EVALUATION PROGRAM

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Area Code 703, 836-3882 Ext. 300

TEXAS INSTRUMENTS INCORPORATED
Services Group
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Evaluation of a network of such stations to decrease problems in detection, unmixing of signals, and evaluating source radiation pattern effects is discussed. Preliminary data for beamsteering continental and world-wide long period array networks is inconclusive as yet because of a limited multiple station observation base.

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INTRODUCTION

This report describes investigations of the network aspects of the Very Long Period Experiment (VLPE) stations, with the purpose of developing a basis for identification of both the strong and potentially weak parts of such a network for the detection and identification of long-period signals from explosions and earthquakes. The evaluation emphasizes theoretical characteristics of a network, primarily because of the experimental value of the seismograph systems and a consequent limitation of joint multiple station signal observations. Sufficient real data are given to demonstrate the theoretical cases, however, and later data observations can be expected to refine the estimated capabilities, but not change the characteristics expressed here to any great extent.

Section II of this report provides the theoretical basis for estimation of signal detection capability at the VLPE stations and the observational data supporting the estimate. The single station capability is then merged into a theoretical network capability model. The network model, which may include contributions from the long period arrays, ALPA, NORSAR, and LASA, is then used to calculate estimates of the world-wide surface wave detection capability of networks of stations selected from the current and projected station list. Both 20 and 40 second Rayleigh wave detection estimates are presented.

SECTION II

PRELIMINARY ESTIMATES OF NETWORK DETECTION CAPABILITIES USING ALPA, NORSAR, LASA, AND THE VLPE STATIONS

A. SINGLE CHANNEL DETECTION MODEL

1. Basic Model

If x is a numerical valued random phenomena obeying a normal probability law with parameters (μ, σ) representing the mean (μ) and standard deviation (σ) of the distribution, then the probability that the random value x will be less than or equal to X is given by (Parzen 1967):

$$P\left[x \leq X\right] = \frac{1}{\sqrt{2\pi}\,\sigma} \int_{-\infty}^{X} e^{-1/2\left(\frac{x-\mu}{\sigma}\right)^2} dx \qquad (1)$$

We will apply this well-known model to estimate the probability of long-period signal detection at the VLPE stations. Note that the probability that a randomly selected value will be less than or equal to the mean of the distribution is given by the relationship above for $X = \mu$, with a probability of 0.5, and the probability that it will be greater is 1.0 - 0.5 = 0.5, since the function is continuous $\{-\infty + \infty\}$. The point of interest to the detection problem for this distribution is that, given an estimate of the distribution of signal and noise amplitudes, a standard method is available for estimating the probability characteristics of detection. Such a method may be applied if seismic parameters can be described which satisfy the basic model requirements.

2. Seismic Parameters for the Detection Model

The probability field for signal detection, in simple form, describes the probability that the signal amplitude (A_S) from a seismic event will exceed the noise amplitude (A_N) so that a "useful" or unbiased measurement of the signal may be obtained in order to estimate the source magnitude. Both signal and noise amplitudes are known to vary, and it is assumed that both are lognormal variables. We also assume that the signal and noise are independent variables.

Given two independent variables X_1 and X_2 with normal distributions $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, respectively, a random variable describing the distribution of the difference between the two may be defined which suits the requirements for determining the probability that a random signal amplitude will exceed a random noise amplitude. Letting X_1 be the distribution of the logarithms of signal amplitude $N(\mu_s, \sigma_s^2)$ and X_2 the distribution of the logarithms of noise amplitude $N(\mu_n, \sigma_n^2)$. define a function Y :

$$Y = X_2 - X_1 \tag{2}$$

According to distribution theory (Hogg and Craig, 1968), the new random variable Y is also normally distributed $N(\mu_n - \mu_s, \ \sigma_n^2 + \sigma_s^2)$. The probability that Y is less than or equal to zero (i.e., that the signal amplitude is greater than or equal to the noise amplitude calculated from the basic model in equation(1) is:

$$P\left[Y \le 0\right] = \frac{1}{\sqrt{2\pi}\sigma_Y} \int_{-\infty}^{0} e^{-1/2\left(\frac{Y-\mu_Y}{\sigma_Y}\right)^2} dY \tag{3}$$

$$= P\left[X_2 \le X_1\right]$$

$$\sigma_Y = (\sigma_s^2 + \sigma_n^2)^{1/2}$$

$$Y = X_2 - X_1 \tag{4}$$

3. Estimation of μ_s and σ_s

We commonly observe that the estimate of surface wave magnitude (M_s) made at several stations shows considerable difference because of radiation pattern at the source or path dependent signal attenuation effects. The reported magnitude is usually an average of the observations, and an estimate of the variance of the M_s observation may be calculated. The M_s value here is, therefore, assumed here to be a normally distributed random variable for our purposes, with a mean value of M_s and a standard deviation of σ_M. We may then calculate the value of the logarithm of the signal amplitude, log A_s, given the magnitude of the event and the distance to the observing station.

Assuming a simple magnitude model for surface wave observations near 20 seconds:

$$M_s = \log A/T + 1.12 + \log \Delta \qquad (\pm\ \sigma_M) \qquad (5)$$

where
- M_s = surface wave magnitude
- A = peak-to-peak ground displacement in millimicrons
- T = wave period in seconds for A measurement
- Δ = epicentral distance between source and recording station in degrees of central arc
- σ_M = standard deviation of magnitude data based upon M_s estimated from several stations for the same source event

If Δ is expressed in kilometers, T = 20 seconds, and the expected value of A equal to A_s, the magnitude becomes:

$$M_s = \log A_s - 2.23 + \log \Delta_{kms} \qquad (6)$$

Then, for an event with a given M_s value, the amplitude of signal expected as some distance Δ(kilometers) is:

$$\log A_s = M_s + 2.23 - \log \Delta \qquad (7)$$

Assuming that all variations in the magnitude estimate are in the log A_s term (i.e., T is a constant 20 seconds and distance is a constant for a given observation), then variation in the logarithmic term represents radiation and path effects.

The standard deviation of the logarithms of amplitudes therefore equals the magnitude standard deviation, or $\sigma_s = \sigma_M$, and

$$\mu_s \; (\pm \; \sigma_s) = M_s + 2.23 - \log \Delta \tag{8}$$

4. Estimation of μ_n and σ_n.

Estimates of the seismic noise amplitude as viewed through the seismograph passband may be calculated from direct measurement of amplitude on visual recordings providing proper corrections for system amplification have been taken in order to determine true ground motion. For this preliminary estimate of VLPE noise, the Power Spectral Density (PSD) measurement of seismic noise has been obtained from a number of selected noise samples of about one-hour length (actually 3584 seconds length) in time windows free from known seismic signals as an alternate method. The RMS noise (over a given frequency band) is obtained from the PSD and the peak-to-peak amplitude is estimated by multiplying the RMS values by some constant for an estimate of A_n, the amplitude of noise.

VLPE digital recording systems have been calibrated to provide a measure of the number of computer counts (C) output from the system for a given input of ground motion in millimicrons (I), at several frequencies within the passband of interest. The PSD provides a smoothed estimate of the density in computer counts ($C^2/\Delta f$) over a narrow frequency band (Δf) centered at $n\Delta f$ steps ($n = 0, 1, 2, \ldots, m$), with the final value m equal to the Nyquist frequency of the data sample. For the noise estimate here, the bands ranging from about 20 to 30 seconds and 20 to 40 seconds are used. The RMS noise level is simply the square root of the sum of the PSD (corrected for frequency response) over the frequency band of interest ($n_1\Delta f$ to $n_2\Delta f$):

$$I_{RMS} = \left[\Delta f \sum_{n_1 \Delta f}^{n_2 \Delta f} PSD\,(n\Delta f) \right]^{1/2} \qquad (9)$$

Noise amplitudes in the 20 to 30 second period range are presumed here to represent the amplitude of noise which will interfere with visual signal detection at about 20 second wave period in seismograms unprocessed except for the seismograph passband. The broader band of 20-40 seconds is used to estimate interfering noise for waves of about 40 second period since the relatively few cycles of about 40 second period in a typically dispersed signal wave train may be more difficult to discern under both higher and lower frequency noise conditions. Arguments can certainly be made that other passbands would be more representative, but these bands are representative of those which interfere with visual analysis procedures, and the levels are representative of those which are expected to interfere with signal detection.

Estimates of seismic noise characteristics were obtained from seven VLPE sites for the vertical instrument channel by converting the PSD measurements to RMS ground motion (corrected for system frequency response) and averaging the result for the 20 - 30 second and 20 - 40 second period bands. Distribution of the samples, which are approximately one hour in length and free from known signals, is shown in Figure II-1 as the number of samples taken by Julian day (1971). Table II-1 gives the average of observed values at each station, with data for the Australian location estimated on the basis of only four observations because of digital recording difficulties.

5. Interfering Noise and Signal-to-Noise Ratio

If the RMS amplitude is considered as a measure of the square root of the mean squared amplitude of an equivalent steady state sinusoidal signal at the frequency of interest with amplitude A, frequency W, and initial phase ϕ, then instantaneous amplitude at time t :

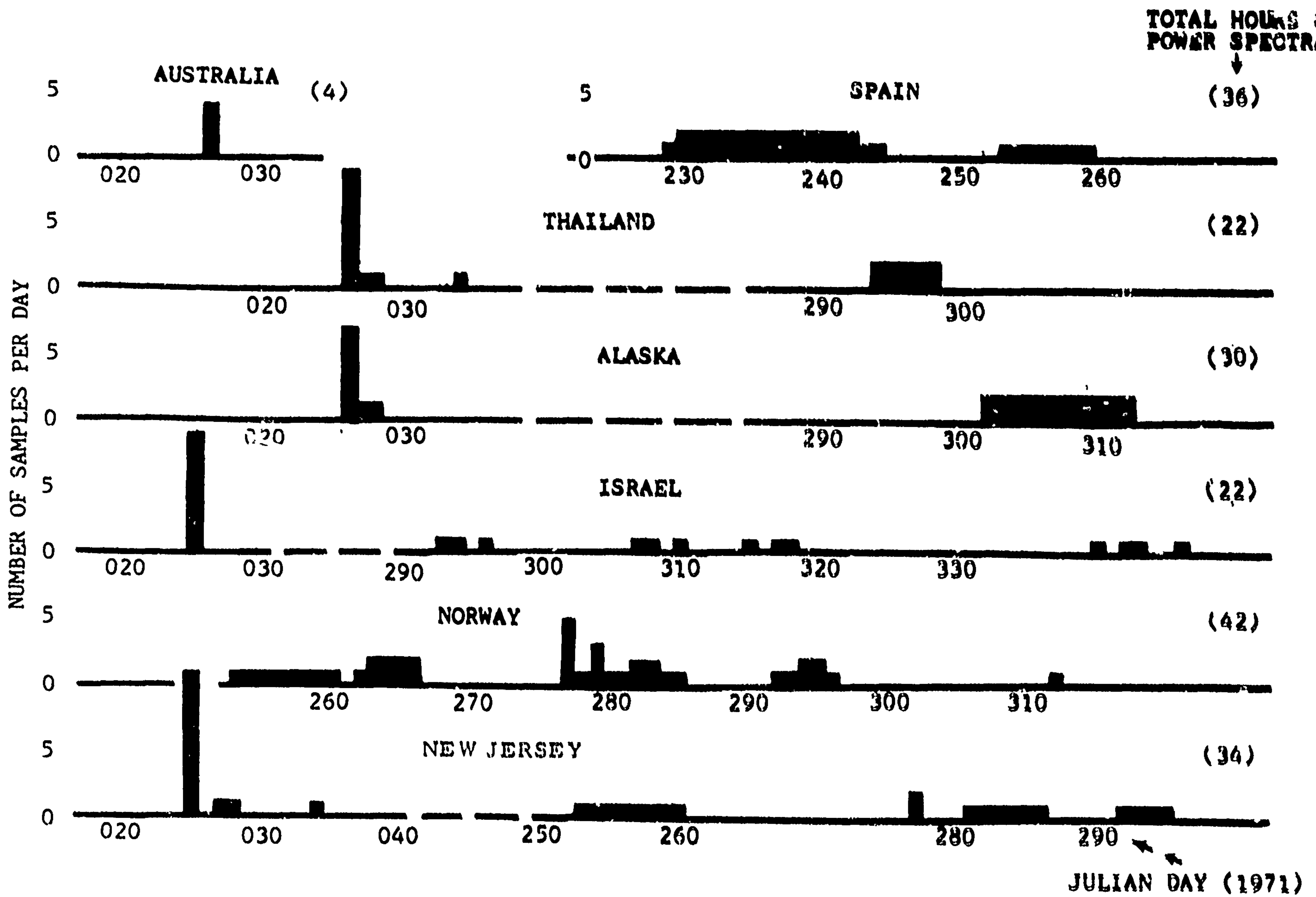

FIGURE II-1

ONE-HOUR NOISE SAMPLING AT VLPE SITES FOR NOISE LEVEL ESTIMATE

TABLE II-1

MEAN SEISMIC NOISE ($m\mu_{RMS}$) FOR 20 - 30 SECOND AND 20 - 40 SECOND BANDS, AND STANDARD DEVIATION OF NOISE IN THESE BANDS FOR SEVEN VLPE SITES

Station	Noise $m\mu_{RMS}$ 20-30 Seconds	σ_n (equivalent in magnitude) 20-30 Seconds
Australia	(12.1)	(.28)
Thailand	12.6	.19
Alaska	13.9	.27
Spain	7.6	.46
Israel	3.8	.31
Norway	6.7	.17
New Jersey	19.6	.27
	$m\mu_{RMS}$ 20-40 Seconds	σ_n (equivalent in magnitude) 20-40 Seconds
Australia	(15.0)	(.28)
Thailand	12.8	.22
Alaska	18.1	.29
Spain	8.0	.42
Israel	4.3	.33
Norway	7.4	.16
New Jersey	27.6	.25

$$A(t) = A \sin(Wt - \phi) \tag{10}$$

and RMS amplitude over n cycles, $T = \frac{2\pi}{W}$:

$$A_{RMS} = \left[\frac{1}{nT} \int_0^T A^2 \sin^2(Wt - \phi)\, dt \right]^{1/2} \tag{11}$$

$$= .707\, A \qquad \text{(zero-to-peak, RMS)}$$

and, for peak amplitude of the signal:

$$A(o\text{-}p) = 1.414\, A_{RMS} \tag{12}$$

$$A(p\text{-}p) = 2.828\, A_{RMS} \approx A_n \tag{13}$$

Given a signal with amplitude $A_s = A_{RMS} \times 2.828$ at the same frequency, it should be possible to show a signal was present at least one-half of the time if this amplitude equaled the noise amplitude (simply due to changes in amplitude and phasing caused by interference of the two). This level of signal-to-noise does not give an adequate opportunity for measurement of an unbiased signal, so some greater ratio of signal-to-noise is necessary. An arbitrary figure of something greater than about 3.0 x $noise_{RMS}$ should improve the measurement accuracy significantly, especially considering that steady state signals and noise are not the ordinary conditions for detection.

Measurement of the maximum peak-to-peak noise amplitude and RMS noise estimate at the same wave period for 1200 second long-period noise samples given by Harley (1971) indicated that a factor of 5 - 6 times $noise_{RMS}$ represented the maximum peak-to-peak measurement in the noise sample. A factor of 4.5 (13 dB) was used in that study to estimate improvement in detection of chirp filtering. A similar study by Laster (1970) showed that little or no influence of noise was noted in chirp filtered data when used to estimate magnitude if the zero-to-peak maximum signal amplitudes in the 20 second period range were 2 - 4 times the $noise_{RMS}$ estimate. Even when zero-to-peak signal-to-$noise_{RMS}$ ratios were 1 - 2, noise contamination in the signal resulted in changes of the magnitude estimate on the order of only 0.1 M_s units.

The implications in these results lead to the conclusion that a factor of about 6 x $noise_{RMS}$ for detecting a "useful" peak-to-peak signal is a reasonable estimate of the factor for use in the theoretical model of single station detection. Proof of the estimate must wait for additional observational data, which itself will provide a better estimate of the long-term influences of non-seismic factors as well as regional and local seismic characteristics of importance to the estimate.

This factor of 6 is assumed here to represent both a conversion of the RMS noise amplitude to "interfering noise amplitude" for signal detection as well as a "signal to noise ratio" factor. Considerable argument about the proper factor for use has been presented in discussions by others concerned with the purpose and use of the results. The factor should be doubled according to these arguments, i.e., a factor of 12 x RMS for the same level of confidence in detection. This appears somewhat overly conservative in character according to the paragraph above. The net result of using the 12 x RMS estimate is to elevate the estimates of capability presented here by 0.3 M_s units. It is important to remember that the 6 x RMS (or 12 x RMS) represents the .50 probable detectable peak-to-peak signal amplitude in the method of estimating detection capability, and higher or lower signal amplitudes will have greater or lesser probability of detection, respectively.

6. Summary

Seismic parameters for estimation of the single station detection capability using the normal distribution function are:

$$\mu_s \pm \sigma_s = M_s + 2.23 - \log \Delta, \quad \sigma_s = \sigma_M \tag{14}$$

$$\mu_n \pm \sigma_n = \log (6 \times I_{RMS}) \pm \sigma_n \tag{15}$$

For single station detection, using a log normal distribution:

$$P\left[A_s \geq A_n\right] = P\left[A_s - A_n \geq 0\right]$$

$$= P\left[Y \geq 0\right] \quad (16)$$

$$= \frac{1}{\sqrt{2\pi}\sigma_Y} \int_{-\infty}^{0} e^{-1/2\left(\frac{Y-\mu_Y}{\sigma_Y}\right)^2} dY \quad (17)$$

where

$$Y \text{ is } N(\mu_s - \mu_n, \sigma_s^2 + \sigma_n^2)$$

and

$$\sigma_Y = (\sigma_s^2 + \sigma_n^2)^{1/2}$$

B. NETWORK DETECTION MODEL

1. Basic Model

The fundamental network model used in this study was developed under contracts AF33657-12447 and F33657-C-0941, and has been modified for the special case of VLPE data where the method of estimating the noise parameter is consistent with the signal estimation process.

If we state that $A_1, A_2, \ldots, A_M$ are the observations in an M-station network, with probabilities that signal will exceed noise by a factor of f noted as $P(A_1), P(A_2), \ldots, P(A_M)$ respectively, then the probability that some number of stations m, P(m), will detect may be calculated. Following Parzen (1967):

Let

$$S_0 = 1$$

$$S_1 = \sum_{k_1}^{M} P(A_k) = P(A_1) + P(A_2) +, \ldots, P(A_M)$$

$$S_2 = \sum_{k_1}^{M} \sum_{k_2}^{M} P(A_{k_1} A_{k_2}) = P(A_1 A_2) + P(A_1 A_3) + \ldots \qquad (18)$$

$$= P(A_1)\, P(A_2) + P(A_1)\, P(A_3) + \ldots$$

(i. e., all non repeating 2 station products)

.

.

.

$$S_r = \sum_{k_1}^{M} \sum_{k_2}^{M}, \ldots \sum_{k_r}^{M} P(A_{k_1} A_{k_2}, \ldots, A_{k_r})$$

(i. e., all non repeating r station products)

.

.

.

$$S_M = P(A_1 A_2, \ldots, A_M) \qquad (19)$$

(S_r is the summation of probabilities over all possible $\binom{M}{r}$ combinations,

$$\left[\binom{M}{r} = \frac{M!}{r!\,(M-r)!}, \quad r = 1, 2, \ldots, M) \right]$$

The probability that exactly m stations will detect, P(m) , is defined by:

$$P(m) = \sum_{r=m}^{M} (-1)^{r-m} \binom{r}{m} S_r \qquad (20)$$

$$= S_m - \binom{m+1}{m} S_{m+1} + \binom{m+2}{m} S_{m+2} -, \ldots,$$

$$\pm \binom{M}{m} S_M \qquad (21)$$

and the probability that at least m will detect, $P(\geq m)$, is

$$P(\geq m) = P(m) + P(m+1) + P(m+2) + \ldots + P(m+n = M) \quad (22)$$

$$= \sum_{r=m}^{M} (-1)^{r-m} \binom{r-1}{m-1} S_r \quad (23)$$

2. **Derived and Estimated Input Parameters**

Equivalent ground motion for PSD ($6 \times I_{RMS}$) and $\sigma_{sn} = (\sigma_s^2 + \sigma_n^2)^{1/2}$ is given for the VLPE stations in Table II-2, with $6 \times I_{RMS}$ equaling the 0.50 detection probability. An estimate for two additional VLPE sites is also provided, as is an estimate for array processed capability (time phased and sum) for ALPA, NORSAR, and LASA, where approximately $\sqrt{n}$ improvement over single instrument is assumed.

3. **Theoretical Network Capability**

If it is required that a signal amplitude from some event location exceed the noise observed (or estimated) at the stations, and further that this will occur at some minimum number of stations, a probability of detection by the network may be calculated. Given the estimated noise, shown in Table II-2, and a signal amplitude decay with distance (equation 14), then the individual station probabilities that signal exceeds noise are calculated (equation 17). These individual probabilities for some given event magnitude and location are then calculated (equation 18) and the network probability of signal detection by at least m of M stations is computed (equation 22).

4. 20-Second Rayleigh Waves

The calculations above were completed for several station networks made up of VLPE and Long Period Array installations using a hypothetical grid of epicenters as sources. The results indicate that it is highly likely (.90 probable or greater) that two or more stations in a network comprised of the seven VLPE stations listed in the upper part of Table II-2 will detect a 20-second Rayleigh wave in most of Eurasia if the source magnitude is equivalent

TABLE II-2

STATION LOCATIONS, ESTIMATED AMPLITUDE ($m\mu$, p-p) OF INTERFERING SEISMIC NOISE (EQUALING 6 x $noise_{RMS}$) AND COMBINED STANDARD DEVIATION OF THE LOGARITHMS OF SIGNAL AND NOISE AMPLITUDE

Station	Latitude	Longitude	20-30 Seconds		20-40 Seconds	
			6 x Noise RMS	$\sigma_{s,n}$	6 x Noise RMS	$\sigma_{s,n}$
Australia	20.1S	146.3E	72.6	.41	90.0	.42
Thailand	18.8N	99.0E	75.6	.35	76.8	.35
Alaska	64.9N	148.0W	83.4	.40	108.6	.42
Spain	39.9N	4.0W	45.6	.47	48.0	.52
Israel	29.3N	34.5E	22.8	.43	25.8	.44
Norway	60.8N	10.8E	40.2	.35	44.4	.34
New Jersey	41.1N	74.6W	117.6	.40	165.6	.39
	Estimated Station Parameters					
ALPA	65.0N	148.0W	25.0	.50	25.0	.50
NORSAR	61.0N	11.0E	25.0	.50	25.0	.50
LASA	47.0N	106.0W	25.0	.50	25.0	.50
Hawaii	20.0N	155.0W	150.0	.50	150.0	.50
Japan	36.0N	138.0E	100.0	.50	100.0	.50

to at least an $M_s = 3.3$ shallow focus continental earthquake. In the Kamchatka-Kurile region (eastern USSR), an $M_s = 3.4$ source magnitude is required, and in western Eurasia the lowest magnitude detectable under these criteria is about $M_s = 3.0$. Capability for two station detection is about $M_s = 3.2$ in central Russia for this network, and about $M_s = 3.2$ in most of China.

If the VLPE stations in Norway and Alaska are deleted from the network and the Long Period Arrays in Norway, Montana, and Alaska are included, 20-second Rayleigh wave detection in Eurasia is improved by about 0.2 magnitude units overall. The Kamchatka-Kurile region shows slightly greater improvement to a two-station capability of $M_s = 3.1$. Inclusion of relatively low quality stations in Hawaii and Japan reduce the detectable magnitudes 0.1 M_s units in the Kamchatka-Kurile region and in eastern China, resulting in "threshold" magnitudes of about 3.0 for highly probable two-station Rayleigh wave detection.

Conversion of M_s to equivalents in body wave magnitude (m_b) of these values is difficult since some questions have been presented about the relationship between the two at low magnitudes. If the well known Gutenberg relationship $M_s = 1.59\ m_b - 3.97$ is used, capability for the seven-station network is about $m_b = 4.5 - 4.6$, and for the 10 station network of about $m_b = 4.3 - 4.4$. The Gutenberg relationship is usually accepted to be valid above $m_b = 4.5 - 5.0$, so these figures must be considered only tentative.

5. 40-Second Rayleigh Waves

Examination of the VLPE data indicates that surface wave amplitude attenuation for a given path is not the same for all wave periods. In terms of signal detectability, it is especially important to note that the attenuation of 40 second Rayleigh waves is greater than that of 20 second waves on the whole, and the effectiveness of a noise "window" at the longer periods is therefore influenced. Estimates of source magnitude are also affected, but insufficient information has been published to estimate this factor very well.

Tryggvason (1965) showed data indicating the effective amplitude attenuation (vertical component of Rayleigh motion) as a function of wave period and distance from 14 WWSSN stations recording a nuclear explosion on Novaya Zemlya in 1962. The attenuation factor given by Tryggvason is in terms of Q^{-1}, where Q is the effective intrinsic attenuation factor for seismic waves Tsai and Aki (1970) show additional data in the 20- to 40-second period range which essentially agreed with Tryggvason's result.

The point of interest in both studies for application here is that the attenuation of 40 second waves is, for average world paths, apparently greater than that for 20 second waves. The interpretation of this situation is that 40 second waves penetrate into the "low velocity zone" of the earth's mantle where relatively low Q exists, and 40 second amplitudes are reduced at a greater rate with distance than the 20 second amplitudes.

If we assume simple geometrical spreading and absorption models for the 20 and 40 second waves, an estimate of the relative attenuation influence on magnitude determinations is straightforward:

$$A_{20}^{r} = A_{20}^{o} r^{n} e^{-\frac{\pi f r}{Q_{20} V}} \tag{24}$$

where A_{20}^{r} is the amplitude of 20 second surface waves r kilometers from the source

A_{20}^{o} is the amplitude of 20 second surface waves at the source

r^{n} is a geometrical spreading in kilometers

f is surface wave frequency ($= T^{-1}$ T= wave period)

V is surface wave group velocity

Q_{20} is the effective intrinsic seismic wave attenuation factor for 20 second waves and for 40 second waves with appropriate subscript changes:

$$A_{40}^{r} = A_{40}^{o} r^{n} e^{-\frac{\pi f r}{Q_{40} V}} \qquad (25)$$

The ratio of 40 second amplitudes to 20 second amplitudes observed at a single station, letting $K = \frac{\pi f r}{Q_T V}$ is:

$$\frac{A_{40}^{r}}{A_{20}^{r}} = e^{-(K_{40} - K_{20}) r} \qquad (26)$$

assuming that the amplitude for both periods is the same at the source, that the geometrical term for both periods is the same, and that radiation patterns are independent of period.

Figure II-2 gives Tryggvason's results for the explosion observations in terms of K vs. wave period. Scaling from the figure, K at 40 seconds is about $160 \times 10^{-6} km^{-1}$, and for 20 second waves about $80 \times 10^{-6} km^{-1}$. The amplitude ratio computed from the relationship may be used to estimate the amplitude expected at 40 seconds given a 20 second measurement, and the magnitude difference expected from the amplitude difference is obtained easily from standard magnitude curves. Equating M_{s40} to M_{s20} estimate through the predicted amplitude difference $(r = \Delta)$:

$$M_{s40} = \log A_{40} - 2.53 + \log \Delta + .35 \times 10^{-4} \Delta \qquad (27)$$

The difference in magnitudes expected between 20 and 40 second waves due to difference in amplitude attenuation is shown as a function of distance for six of the VLPE sites in Figures II-3(a) and II-3(b). Data on the figures include the M_{s40} and M_{s20} calculated from observed amplitudes at a wave period of about 20 and 40 seconds. Sources include only shallow focus earthquakes (33 kms or less from PDE reports) occuring in Eurasia primarily, and

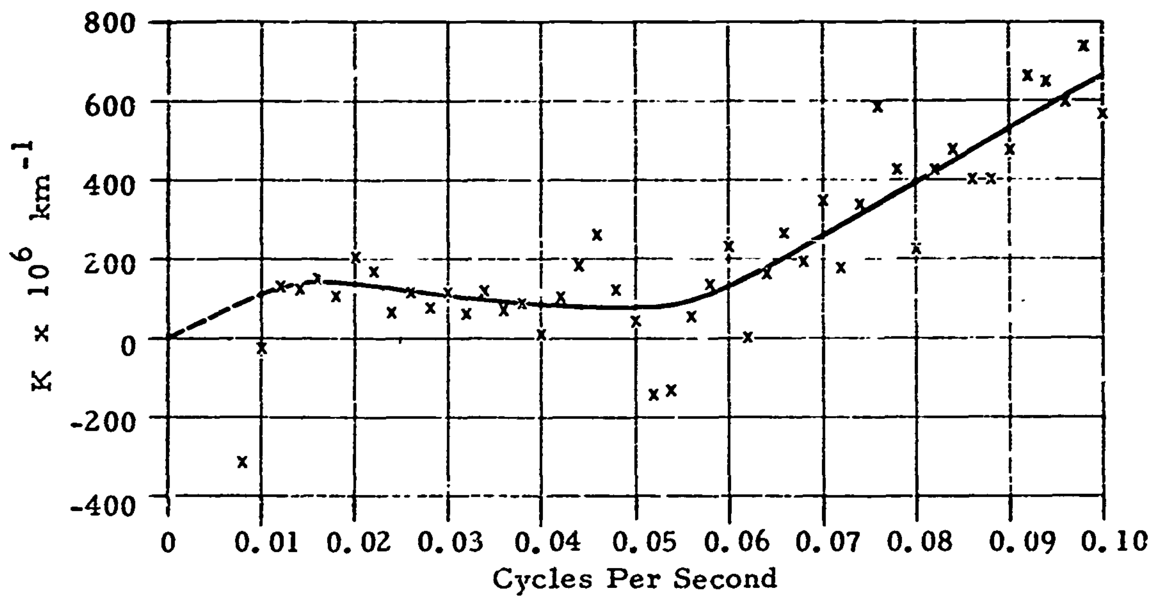

FIGURE II-2

COMPUTED COEFFICIENT OF ENERGY DISSIPATION

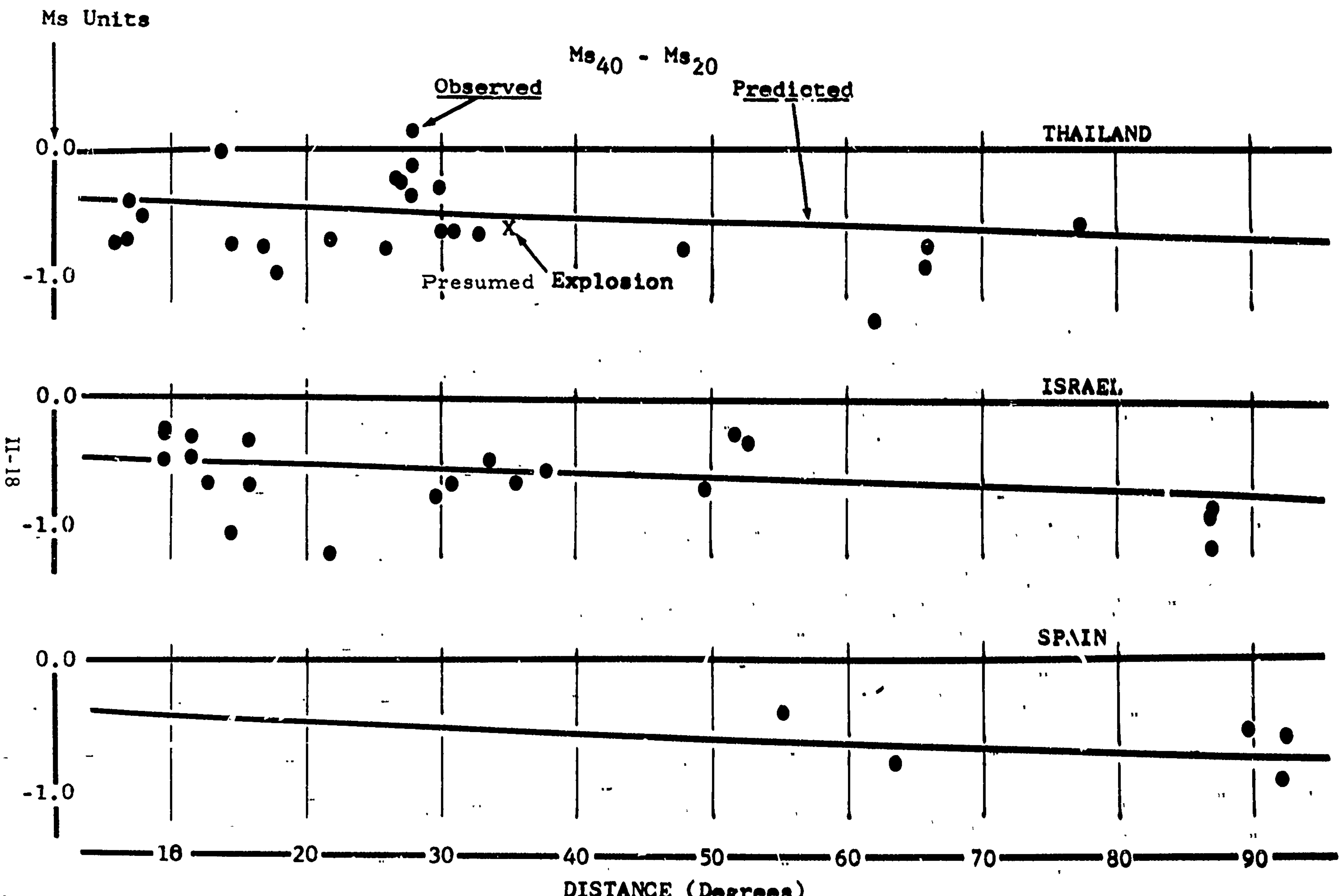

FIGURE II-3(a)
DIFFERENCE IN MAGNITUDE EXPECTED BETWEEN 20 AND 40 SECOND WAVES DUE TO DIFFERENCE IN AMPLITUDE ATTENUATION

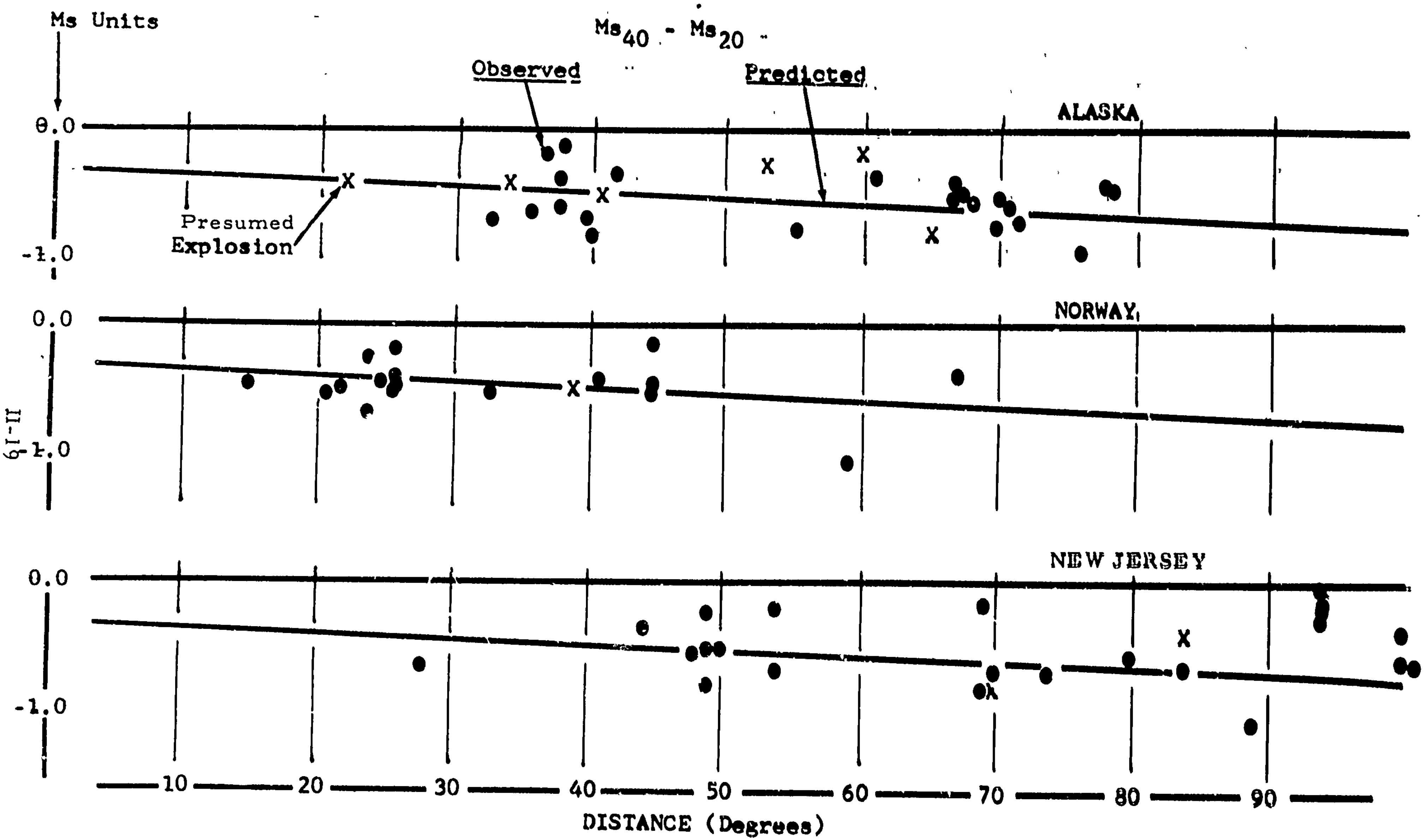

FIGURE II- 3 (b)
DIFFERENCE IN MAGNITUDE EXPECTED BETWEEN 20 AND 40 SECOND WAVES DUE TO DIFFERENCE IN AMPLITUDE ATTENUATION

several known or presumed explosions (including one in Nevada and one in the Aleutian Islands).

While the amount of data available is limited, these results indicate that use of the attenuation difference could be a valuable tool for estimating source magnitude from the different wave periods. Given more accurate hypocenter information, some of the scatter in magnitude difference can be reduced (deep events tend to result in about equal magnitude estimates from either wave period), and improved estimates of signal detectability or source influence may be possible. The M_{s40} and M_{s20} difference reported by many authors may be biased by the distance dependence clearly indicated in all VLPE data shown here, and some correction for this factor must be taken into account to evaluate the meaning of such a difference.

In addition to increasing the amount of data for purposes of improving an estimate of the relative attenuation for many wave paths, some regionalization of effective attenuation will no doubt be necessary. Paths which show about the same relative attenuation for several events, but which do not necessarily agree with the predicted relationship, were noted within the data given in the figures. An evaluation of these regions is needed, both for fuller understanding of the attenuation processes and for delineating their effect upon detection capability and source mechanism description.

Using the same grid of theoretical epicenters as was used for the 20-second Rayleigh wave detection estimate results in a slightly lower detection threshold at 40 seconds when the epicenters are near the greatest den[illegible] of station positions. A rather rapid loss of this extra capability with distance [illegible] because of the additional attenuation. Most of eastern Eurasia (Europe) is [illegible]ed by highly probable (.90), 2 or more station detection for events of magnitudes $M_s = 2.8 - 2.9$ or greater using the basic 7-station network. The addition of the 3 large arrays depresses the threshold here by 0.1 - 0.2 M_s units. Along the USSR - China border, the basic network has calculated capability of $M_s = 3.1-3.2$

The addition of arrays again adds 0.1 - 0.2 M_s units to this capability, lowering the threshold to M_s = 3.0 - 3.1.

Capability for detection of 40 second Rayleigh waves for sources in the Kamchatka-Kurile region shows the effects of attenuation strongly, with the basic network having capability of M_s = 3.3 - 3.4 and addition of arrays dropping the threshold to about M_s = 3.0. Approximately the same levels are observed in central and southern China. Contribution to reducing this threshold by Hawaiian and Japanese stations is only a local effect and not a strong contribution to the 40-second detection in a network sense.

It is important to remember that these values are for surface wave magnitudes computed at 40 seconds. If the noise levels and variances, signal amplitudes, and decay rates (with distance) were the same at 20 and 40 seconds then these values would be 0.3 units lower than the equivalent 20-second values. The values of both are about the same with the 0.3 units offset in the 40-second estimate because higher decay rates and slightly higher noise levels were used. The estimates suggest that detection at 40 seconds may be slightly lower than detection at 20 seconds, but a large observational data base will be required to make a quantitative comparison.

SECTION III

NETWORK PROCESSING BY BEAMFORMING AND ALSO STACKING MATCHED FILTER OUTPUTS

A. GENERAL

The objectives of "time delay and sum" procedures applied to the VLPE data include taking advantage of the opportunity to add in-phase unprocessed or processed signals while also adding randomly phased noise. Theoretically the result should improve the signal-to-noise ratio by a factor of $\sqrt{n}$, where n is the number of inputs to the summation, and thereby improve overall capability to detect signals of interest for further analysis. In a practical sense, it should also be assumed that the signal amplitude expected at widely spaced single sensors will have some reasonable amplitude in comparison to the noise.

Long period signals which can be treated in this way include the long-period body phases P and S, and surface wave signals processed in some way so that in-phase characteristics could be obtained for useful summation of the result. Each of these phases has certain limitations in both physical characteristics and possible uses for discrimination between earthquake and explosion source types. Therefore their use will be of interest as supporting evidence to other criteria or in the rare situation where these signals are the only data available or when all other criteria fail.

B. LONG PERIOD BODY PHASES

Detection of long-period P and S has several factors appropriate to the discrimination problem. One of these factors is that the difference in energy expected between the long-period phases and higher frequency (short-period) body waves should be on the order of that indicated by the "standard discriminant" of $M_s : m_b$. In other words, an $M_{b(p)} : m_b$ or $M_{b(s)} : m_b$ might be developed. The utility of such discriminants becomes most important when the surface wave is not detectable. As another example, while demonstrations of significant shear energy does not exclude the possibility of tectonic shear energy release in the vicinity of an explosion, a total lack of shear energy might suggest a very small effective source volume of "explosion-like" source mechanism.

Signal detection capability for short-period P-waves is generally better than that for the long-period body phases. For this reason, hypocenter parameters are available which provide a reference for reasonably accurate estimation of relative time delays for the long-period body phases within a world-wide or continental-dimensioned network of recording stations. Some loss in the theoretical $\sqrt{n}$ improvement can be expected due to possible radiation patterns and selective travelpath effects (such as frequency dependent energy absorption), but if some library of information for regions of interest can be accumulated, the effect of such factors can be minimized.

When more multiple station digital data become available, multiple observations of long-period P and S will permit an evaluation of the beam-forming potentials for the VLPE network with the following goals:

- Demonstrate $\sqrt{m}$ improvement or lack of improvement
- Establish single and multiple station signal detection limit for the long-period body phases
- Demonstrate possible discriminants where the standard $M_s:m_b$ discriminant cannot be obtained.
- Accumulate long-period body wave characteristics for regionalization of source and path effects.

An example of the beam-forming approach is shown below for a three-station beam. The polarity radiation problem for P probably does not enter in this example, but future plans include an evaluation of the possibility of improving P detectability and minimizing the polarity effect by forming a Z x R beam prior to time delay and summation. Z x R denotes a point-by-point multiplication of simultaneous vertical and radial data to enhance in-phase components, such as P motion, at the expense of the out of phase vertical-horizonal motions in a plane radial to the source. The approach is not useful for S since the particle motion of S becomes very complex after the first observed cycle or half-cycle in most cases.

In this preliminary test of the LXTRAN beamforming program using VLPE data, a presumed explosion at 49.7 N, 78.2E, $m_b = 5.8$ was selected from the limited multiple station observations available. This selection was made in order to eliminate the problem of signal polarity which might be a problem with an earthquake source. Delay times were computed from J-B traveltimes contained within the program, then applied to the data traces from Thailand and Alaska. The third station, New Jersey, was used as a reference trace. All other data are delayed to match the P arrival times with the expected P at New Jersey, and the summation trace time reference is the same as the New Jersey traces. Results are shown in Figure III-1.

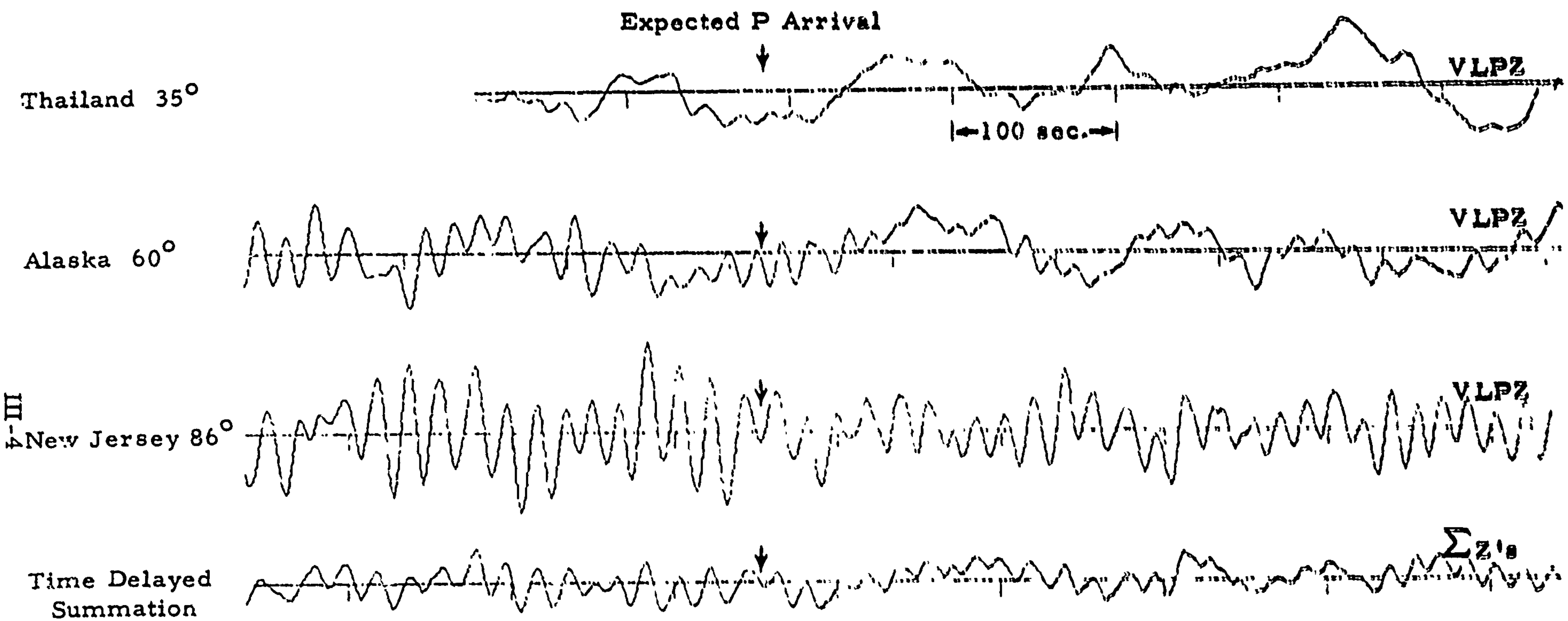

FIGURE III-1

UNSUCCESSFUL LONG-PERIOD P BEAM FROM VLP EXPERIMENT STATIONS. EVENT IS A PRESUMED EXPLOSION IN EASTERN KAZAKH AT 49.7N, 78.2E, ON 03/22/71 04:32:58Z, m_b (C&GS) = 5.8. RAYLEIGH WAVE WAS OBSERVED AT THAILAND AND ALASKA

Beamforming was unsuccessful in extracting the P wave, which is not considered too surprising in view of the total absence of visual P motion on any of the traces and the very few stations available for the beam. The amplitude of P from the suspected explosion is very low, probably less than 1/10 the amplitude of Rayleigh observed at the Thailand and Alaska stations, suggesting that the P summation will be useful for discrimination primarily in an extreme case of interference of the higher amplitude Rayleigh motion.

C. TIME DELAYS AND STACKED MATCHED FILTER OUTPUTS

The dispersive character of surface waves and the difference in dispersion for different travel paths make direct "delay - and - sum" techniques impractical for these propagation modes. For this reason, delay and sum would have to be performed on matched filter outputs which ideally compress the surface wave signal into a single pulse-like signal.

Two major matched filter techniques are being investigated: (1) the Master Event method, where surface wave signals from high signal-to-noise ratio recordings are used as a filter to emphasize low-level signals from the same source region, and (2), Chirp Filters, which attempt to provide an inverse of the surface wave dispersion characteristic of some particular travel path. Both techniques should provide a strong filter output when the filter "waveform" matches the signal waveform, and this output may be correct enough to attempt the delay and sum technique. Close match of signal and filter characteristics is necessary to obtain the compactness needed. A large library of filters is necessary because of the strong differences of surface wave dispersion among the possible world travel paths.

Figures III-2 and III-3 demonstrate the difficulties related to beamsteer in the case of Matched Filter stacking. The time delayed summation of signals recorded at ALPA and NORSAR from an event in eastern Russia (53.4N, 120.3E) were filtered with a master waveform and chirp filters. The results show that the compact signal needed is not formed very satisfactorily and if the beams were stacked according to a 25 second Rayleigh (LR) velocity of 3.5 km/sec or Love wave (LQ) velocity of about 3.8 km/sec for the same period (noted by an arrow on the figures), not too much information would be obtained. The development of more accurate chirps or selection of Master waveforms which more closely model the signals are obviously needed in this instance, again indicating the need for a library of waveforms.

D. INTERFERING EVENTS

The interfering (or mixed) event problem is significant on long period surveillance; Table III-1 (Mack, 1971) shows the percentage of events interfered with at LASA over a 50-day period. Generally the percentage of mixed events is about 15% at a single station, and is dependent on magnitude (the problem is more severe for smaller events).

The availability of multi-station data should reduce the severity of the problem somewhat, because the distribution of individual stations increases the probability that the desired event will be "clearly" recorded at some station in the network. However, we wish to obtain measureable signals from as many locations as possible so that maximum information about the signal source is available. Techniques for separating these mixed signals are being investigated for specific problem conditions, since the ability to separate improves the overall network aspects of detection and discrimination capability.

In some instances it is possible to separate mixed events at arrays. It has been established that if the two events have on the order of 30° or more azimuthal separation, array processing techniques can be used to extract the desired event from the overlapping event. The best capability is no more than one magnitude unit (i.e., an $M_s = 4.0$ event could be recovered from an $M_s = 5.0$ event).

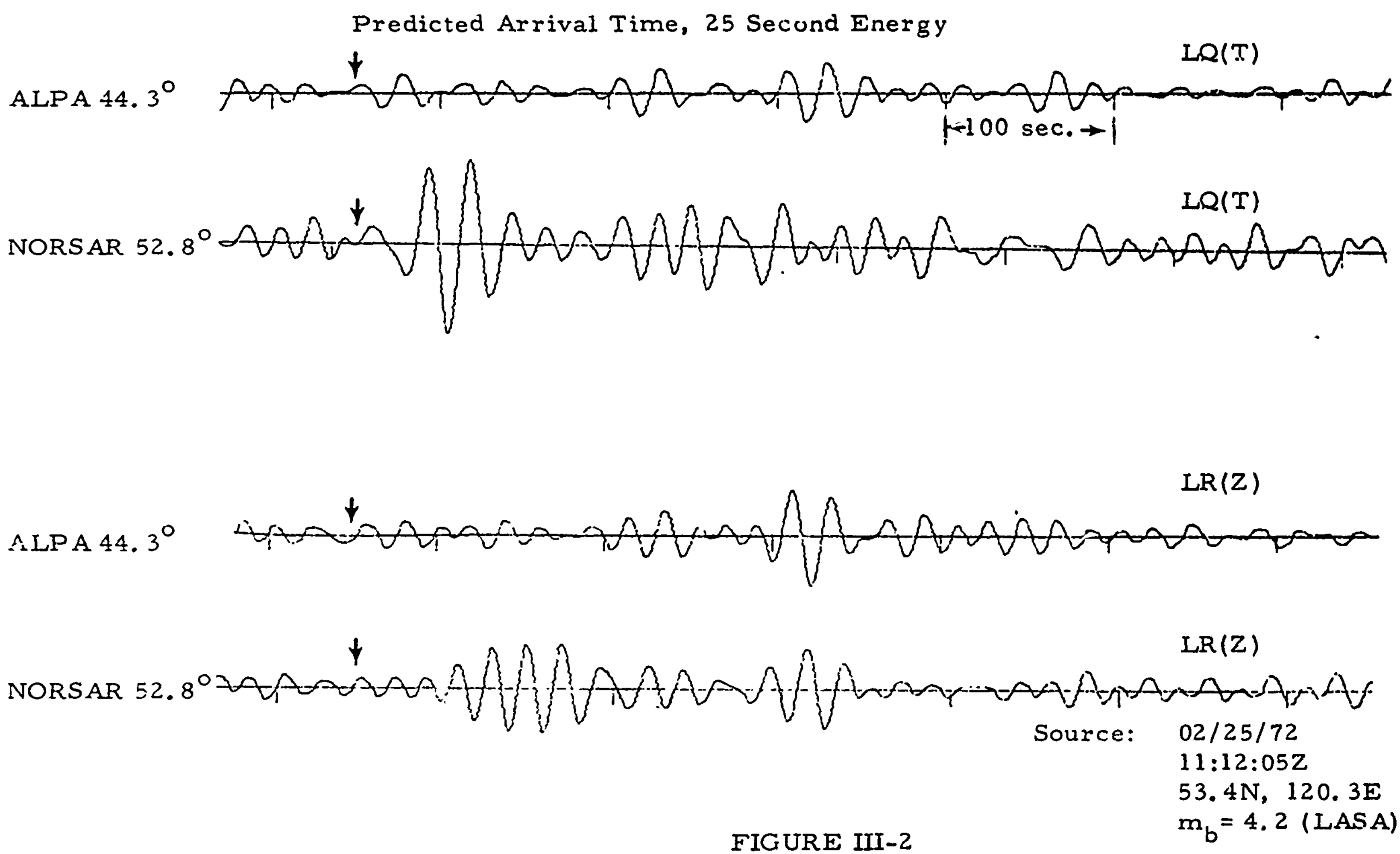

FIGURE III-2

DEMONSTRATION OF CHIRP FILTER OUTPUTS AND POTENTIAL FOR STACKING FILTER OUTPUTS (POOR)

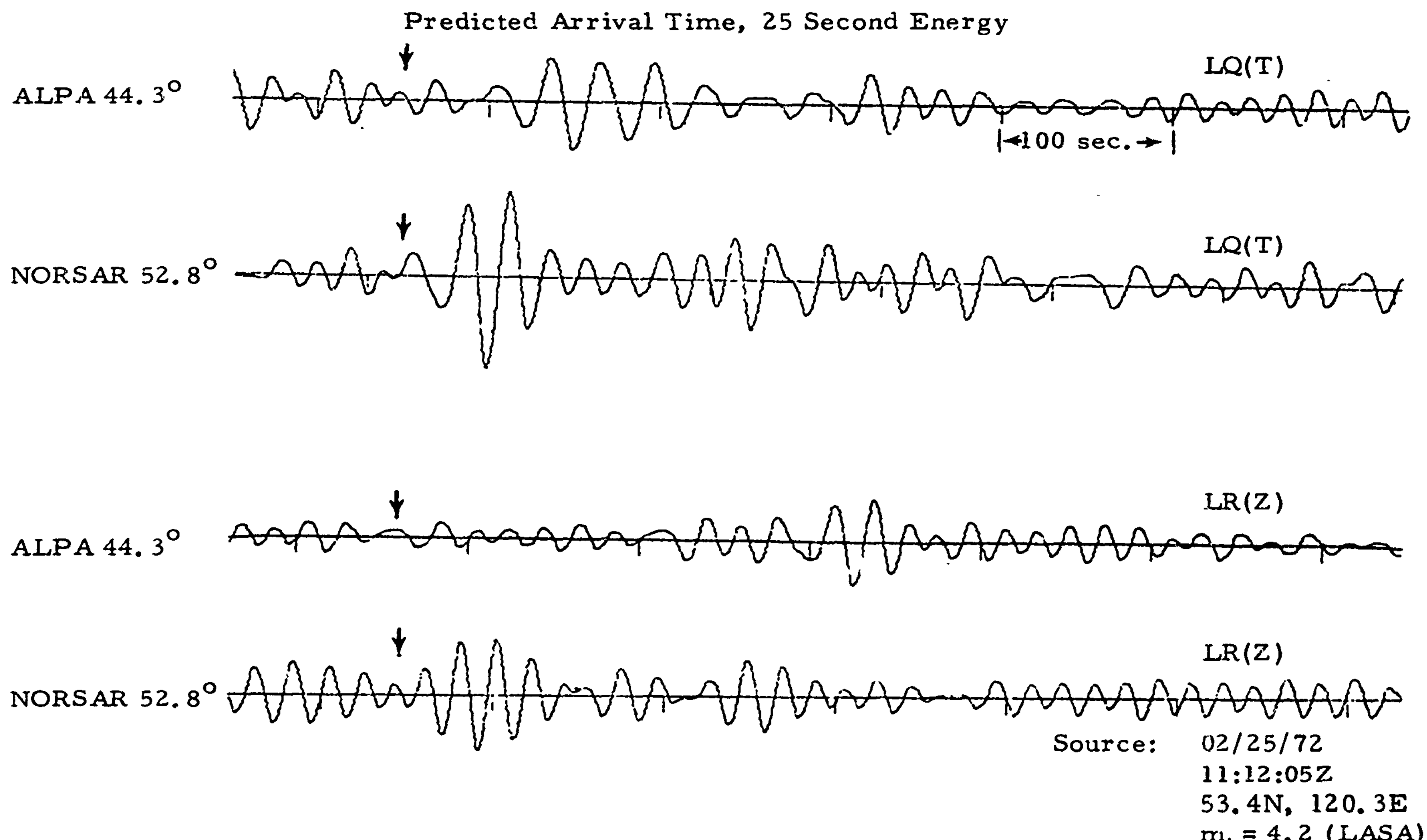

FIGURE III-3

DEMONSTRATION OF MASTER EVENT FILTER AND POTENTIAL FOR STACKING MATCHED FILTER OUTPUTS (POOR)

TABLE III-1

PERCENTAGE OF MIXED* EVENTS AT LASA (MACK, 1971)

	Magnitude m_b				
LASA	≤ 3.9	4.0 - 4.4	4.5 - 4.9	5.0 - 5.5	> 5.5
Number of Events	357	239	105	52	27
% Mixed	19.9	17.2	19.1	11.6	7.4

* A mixed event is the recording of multiple signal arrivals from different sources on the seismograms which cannot be interpreted with enough resolution to provide useful information from the recorded data.

For mixed events having about the same azimuth, array processing cannot be used. However, the complex cepstrum technique (Linville, 1971) can be used for this case. This technique also could be applied to a single station when the mixed events have different azimuths.

The capability of the complex cepstrum technique to separate mixed events has not been fully tested. Figure III-4 shows results for a test case for two events from essentially the same epicenter (on the mid-Atlantic ridge) recorded at Ogdensburg. The first event is about one-half the amplitude of the second (overlapping) event; the complex cepstrum separates these two events very well.

To test the resolution of the technique, the estimate of first event was scaled down by a factor of two and four, and added back to the second event with the original time separation (108 seconds). Note that the first event now is one-fourth (0.6 M_s units) and one-eighth (0.9 M_s units) the size of the second (overlapping) event. Figures III-5 and III-6 show that separation is achieved by applying the complex cepstrum technique in both cases. Note that when the first event is one-eighth the size of the second event, it is difficult to see it in the mixed waveform, and impossible to get an accurate M_s estimate.

In this case the complex cepstrum technique recovered the desired event when it was 0.9 M_s units smaller than the overlapping event; this is essentially as good as the array processing capability. It should be noted that the example used, while constituting real data, probably represents close to the best case for this technique because the two events were simple (i.e., no multipathing) and had essentially the same spectrum. For more complicated cases the performance probability would not be as good, but still should offer some capability to separate mixed events. The technique has excellent potential because:

- It provided separation capability for mixed events having similar epicenters and, in fact, probably works best for this situation. Note that array processing is ineffective here.
- It can be applied at a single station.

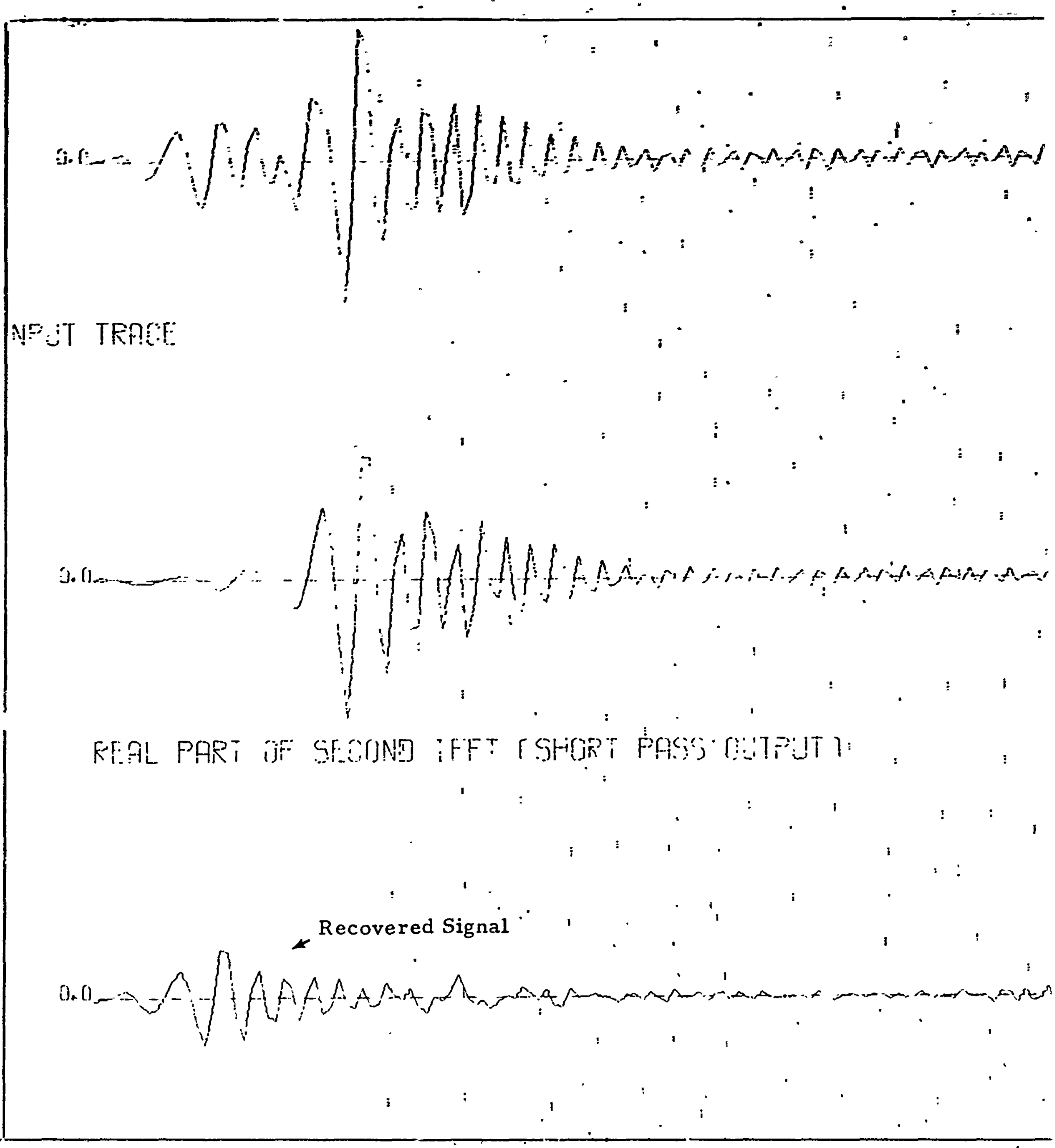

FIGURE III-4

RECOVERY OF A LOW LEVEL SIGNAL FROM A MIXED EVENT WITH SIGNAL-TO-SIGNAL RATIO OF ABOUT 2:1 (MAXIMUM AMPLITUDE) BY THE COMPLEX CEPSTRUM TECHNIQUE APPLIED TO SINGLE STATION DATA. MID-ATLANTIC RIDGE EVENTS RECORDED ON THE OGDENSBURG VLPE SEISMOGRAPH

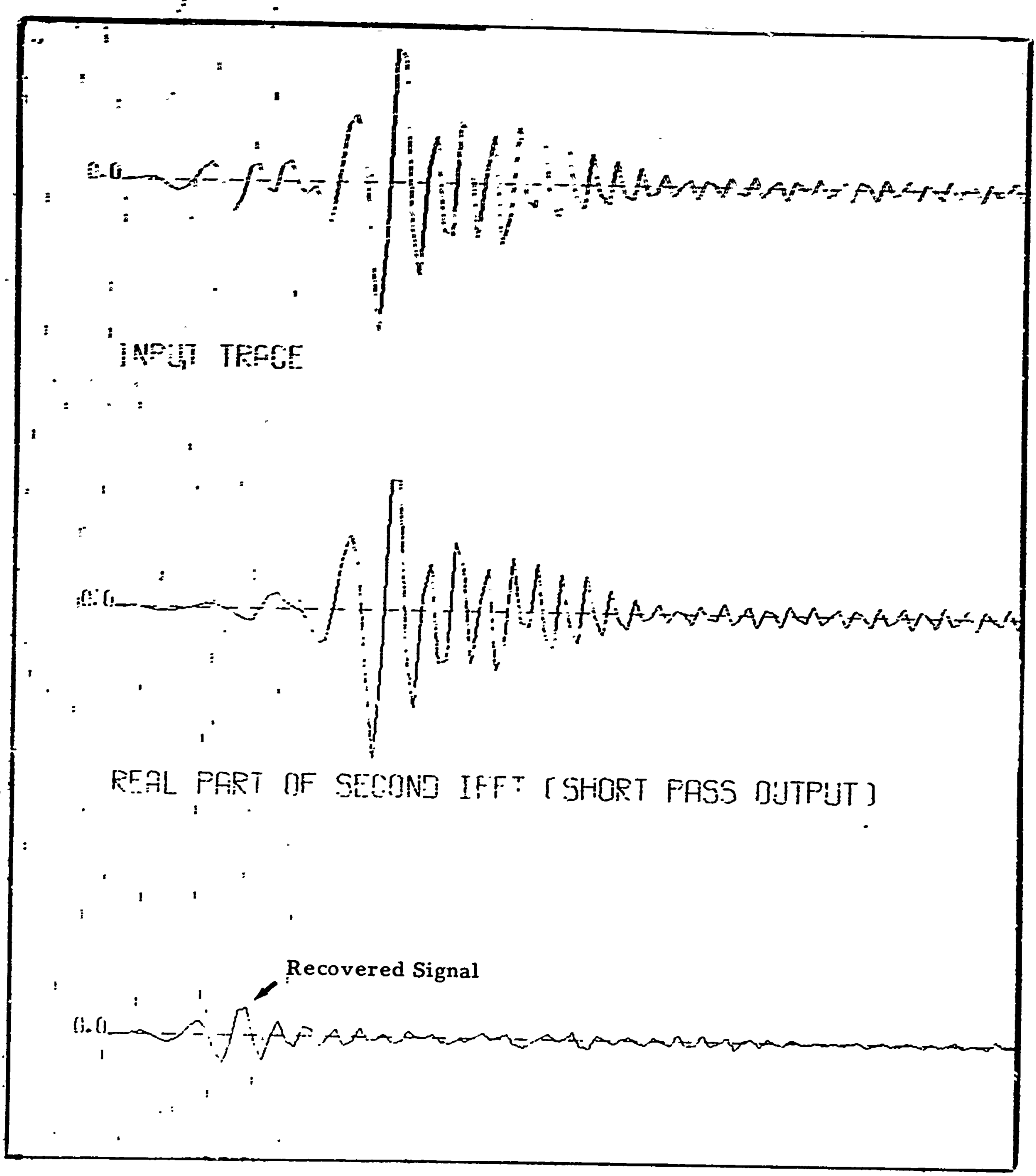

FIGURE III-5

RECOVERY OF A LOW LEVEL SIGNAL FROM A MIXED EVENT WITH SIGNAL-TO-SIGNAL RATIO OF ABOUT 4:1 (MAXIMUM AMPLITUDE) BY THE COMPLEX CEPSTRUM TECHNIQUE APPLIED TO SINGLE STATION DATA. MID-ATLANTIC RIDGE EVENTS RECORDED ON THE OGDENSBURG VLPE SEISMOGRAPH

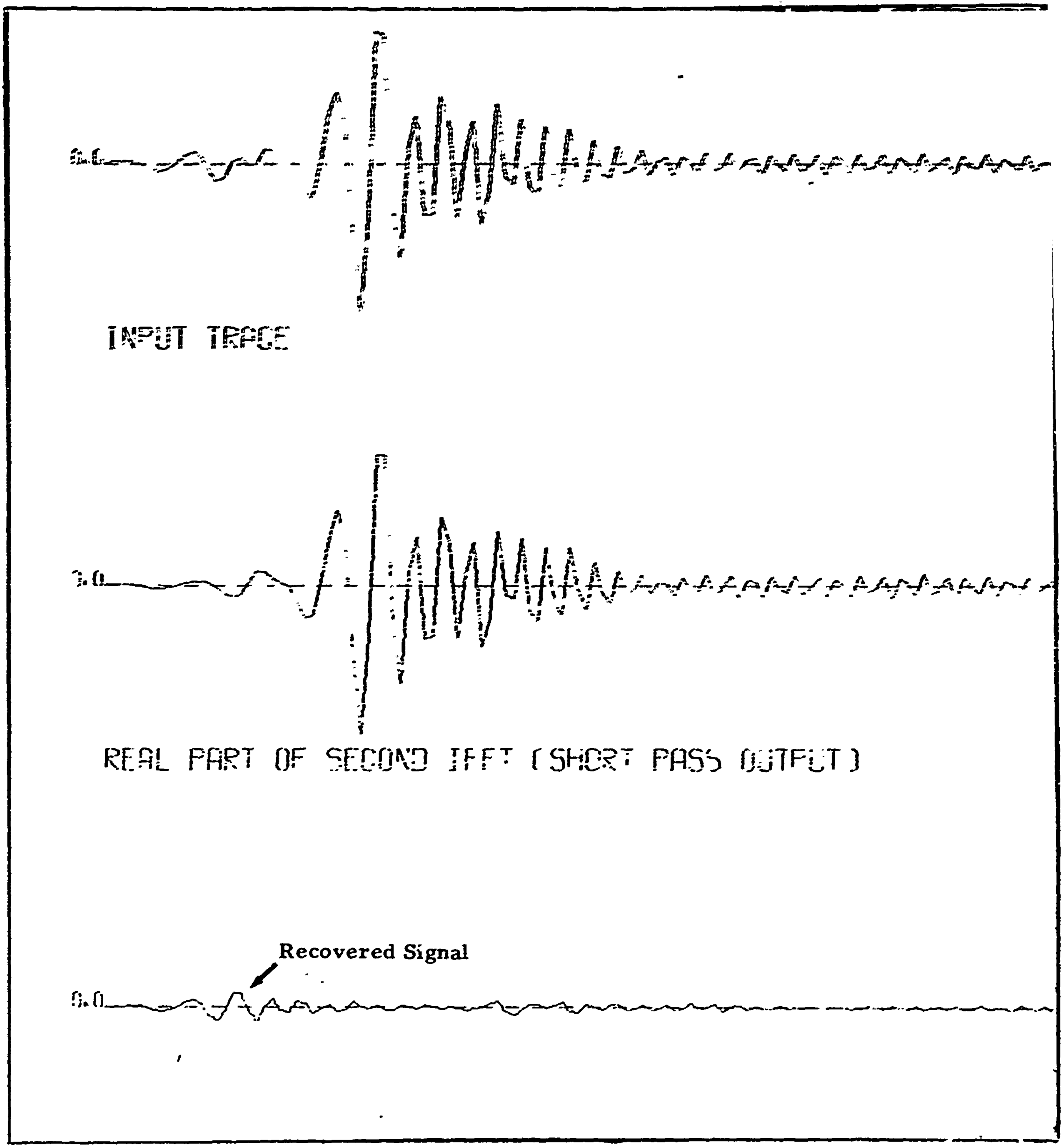

FIGURE III-6

RECOVERY OF A LOW LEVEL SIGNAL FROM A MIXED EVENT WITH SIGNAL-TO-SIGNAL RATIO OF ABOUT 8:1 (MAXIMUM AMPLITUDE) BY THE COMPLEX CEPSTRUM TECHNIQUE APPLIED TO SINGLE STATION DATA. MID-ATLANTIC RIDGE EVENTS RECORDED ON THE OGDENSBURG VLPE SEISMOGRAPH

Multi-station digital data have not been available in sufficient quantity to allow us to quantize the reduction in the number of mixed events provided by the VLPE network. We plan to investigate this in the future by following the steps outlined below:

- Select a continuous time period of one to two months in duration (a period when the VLPE network has many stations operational).
- Obtain a comprehensive event list (Note that the list currently being generated by Lincoln Laboratories for the February-March time period would be suitable).
- For each event and each station, tabulate the percentage of mixed events. In our application we would limit the desired events to those from the Sino-Soviet area.
- Combine the station data to produce additional listings of percentage mixed at all stations, all but one station, and all but two stations.
- Compare the single station and network "mixing levels" as a function of magnitude.

The result of this study will be to provide a quantitative estimate of how much the network reduces the mixed event problem, the severity of the problem remaining, the critical stations in the network (these should be determined by their related location with respect to areas of high seismicity and the Sino-Soviet area), and the improvement achieved (if any) by increasing the number of stations.

Included in the tabulation of mixed events described earlier will be a measurement of the amplitude of the interfering event during the expected arrival time of the desired event. The expected amplitude of the desired event will be obtained (either from M_s measurements at stations where the desired event is clearly recorded or by converting event m_b values to M_s) and the amplitude ratio ΔA will be calculated:

$$\Delta A = A_I / A_D$$

where: A_I is the amplitude of the interfering event

A_D is the estimate of the amplitude of the desired event.

The quantity ΔA provides an estimate of the relative size of the two events. Then, using typical values for array processing and/or complex cepstrum gains, the reduction in the percentage of mixed events which could be achieved will be estimated. The residual percentages of events mixed at all, all but one, and all but two stations provide estimates of the size of the "unresolvable" mixed event problem.

A special case that the above analysis may not account for is the very large earthquake, which can generate large amplitude surface waves lasting several hours. Events will be recorded during this time period and many will not be recovered, even when processing gains are taken into account. The mixed event problem in this case can be quantized as follows:

- Measure coda amplitude decay rates for several large earthquakes ($M_s \geq 6.0$) at several stations and obtain an average decay rate. Both network and station averages will be obtained.
- Determine the time window when the events sought will be unrecoverable at all stations, taking processing gains into account. The time window will be magnitude (M_s) dependent.
- From seismicity data, estimate the number of events in a given magnitude range which would occur during the time period.
- Again, from seismicity data, estimate the number of events with $M_s \geq 6.0$ per year.

This will provide an estimate of the number of unrecoverable events per year due to very large earthquakes. Depending on the data base selected in the analysis discussed previously, this number may have to be added to that obtained in that study.

Another special case is the major aftershock sequence associated with a large earthquake in the earthquake swarm. Both sequences typically involve several days time, during which a very large percentage of desired events will be mixed. Because of the complexity of these sequences a detailed study of the mixed event problem would be difficult, however, the following simple approach should define the "worst case" situation.

- Determine the time in the sequence when the events are no longer "continuous" (i.e., the time separation between events exceeds event duration - about 30 minutes to one hour, depending on the event size).
- From the magnitudes of the aftershocks preceding this time, estimate the minimum recoverable magnitude, taking processing into account. Note that this magnitude probably would be time dependent and, in the case of the aftershock sequence, the first several hours would have to be excluded because the main shock would dominate.
- Again, from seismicity data, estimate the number of mixed events expected during the time period and the number of swarms and aftershock sequences per year.

This procedure would provide a rough estimate of the number of mixed events/year due to aftershock sequences in swarms. Again, depending on the original data base this number may have to be added to previous values to obtain a complete estimate of the mixed event problem.

We plan to look at these special cases during the coming year also.

SECTION IV

CONCLUSIONS

The VLPE network has the theoretical capability for detection of shallow focus continental earthquakes in Eurasia at $M_s = 2.9 - 3.0$ when in operational status and in combination with the large arrays. The theoretical values of the estimate requires that a systematic evaluation of actual signal detections be reserved as the final demonstration of capability. The preliminary empirical data show that no serious error in estimation is likely, but some refinement will very likely be possible. This is particularly true in the case of 40 second surface waves, which are attenuated at a different rate than the 20 second signals.

Because of limited observational data, a true picture of the network contribution to mixed event and radiation pattern problems cannot be clearly demonstrated at this time. Beamforming for long period P and S signal detection may have utility in special cases, but, these are not likely to contribute to identification of sources as routine discriminants. The power of the complex cepstrum method at the single station, when fully evaluated, may contribute to the network aspect very significantly in terms of mixed events. The approach discussed for description of a set of mixed event parameters in Section III can provide an important measure of the potential for this approach. Utility of matched filter stacks for overall reduction of the detection threshold will be marginal until a suitable library of filters can be developed. This factor influences the ability of a limited number of stations to observe the radiation patterns with enough resolution to describe the problem in any detail.

SECTION V

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