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Semiannual Technical Summary

Seismic Discrimination

31 December 1969

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

SEISMIC DISCRIMINATION

SEMIANNUAL TECHNICAL SUMMARY REPORT
TO THE
ADVANCED RESEARCH PROJECTS AGENCY

1 JULY - 31 DECEMBER 1969

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ABSTRACT

During the reporting period short-period data from several sites have been used to study the nature of the spectra from presumed explosions, to test a potential new discriminant, and to study depth phases. Surface- and body-wave magnitude data have been obtained and used to study regionalization phenomena. Preliminary studies of ultra-long-period data have been undertaken. Modifications of continental array processing methods have been completed and signal equalization studies initiated. Upgrading of software and hardware facilities has continued.

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

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SUMMARY

This is the twelfth Semiannual Summary of Lincoln Laboratory's work for the Advanced Research Projects Agency on the seismic discrimination problem (Vela Uniform).

The Laboratory has continued its studies of short-period data and discriminants. Emphasis has been upon the simultaneous utilization of data from several scattered sites. Cepstral analysis methods have been applied to four Soviet presumed underground explosions as recorded at Norway, LASA, and three United Kingdom array sites. Reflections from the earth's surface above the shot points may have been detected. The same data have been used to detect changes as a function of yield in short-period spectra which are consistent with those predicted by theory for explosions (Sec. I-A). LRSM data from stations in North America have been used for a preliminary test of a discriminant based on body-wave magnitude, period, and the minimum complexity observed for the set of stations utilized (Sec. I-B). A limited study of depth determination using possible depth phases at LASA and NORSAR has been completed. Utilization of two or more stations reduces the probability of erroneously locating an explosion at depth based on apparent depth phases (Sec. I-C).

Investigation of discrimination based upon surface- and body-wave magnitude ($M_s - m_b$) has continued with emphasis upon the regional effects due to both receiver and source locations. A study of western United States events using LRSM data verifies that presumed explosions and earthquakes tend to be separated by $M_s - m_b$ but that the two populations are close together (Sec. I-D). Additional $M_s - m_b$ data for Asia have been measured at Norway and compared to similar LASA data. A tentative interpretation of Kurile Islands data in terms of a downthrusting lithosphere has been undertaken and preliminary analysis indicates this will be useful for regionalization studies (Sec. I-F).

Some studies of explosion characteristics at ultra-long periods have been undertaken. Frequency-wavenumber analyses of data from NTS shots recorded at LASA have been computed in the frequency range from 0.01 to 0.05 Hz. Significant coherent signals were not detected at about 0.02 Hz but were detected at lower frequencies (Sec. I-G). Spectra have also been obtained for teleseismic explosions detected by ultra-long-period instruments operated by the M.I.T. Earth and Planetary Sciences Department at Harvard, Massachusetts (Sec. I-H).

Array processing research has included studies of continental-sized arrays and data equalization for array processing. Continental array beamforming has been modified to compensate for variations in signal power in time and at different sites (Sec. II-A). Equalization filters for LASA have been investigated as a preliminary to studies of deconvolution filters which might be used to improve secondary phase detection (Sec. II-B).

Previously developed tools have been applied to problems of geophysical interest. The potential value of LASA and array methods for studies of core phases has been indicated (Sec. III-A). The high-resolution frequency-wavenumber method has been applied to micro-barograph data (Sec. III-B).

Sections III-C and III-D describe changes in our PDP-7 computer facility in Cambridge and support software for it as well as for the M.I.T. Information Processing System IBM 360 computers.

R. T. Lacoss

GLOSSARY

EDR	Earthquake Data Report
F-K	Frequency-Wavenumber
IPC	Information Processing Center
LAMA	Large Aperture Microbarograph Array
LASA	Large Aperture Seismic Array
LRSM	Long Range Seismic Measurement
NTS	Nevada Test Site
OONY	Oslo Norway
SATS	Semiannual Technical Summary
UKAEA	United Kingdom Atomic Energy Authority
USCGS	United States Coast and Geodetic Survey
VESPA	Velocity Spectral Analysis

SEISMIC DISCRIMINATION

I. SEISMIC IDENTIFICATION RESEARCH

A. SHORT-PERIOD SEISMIC SPECTRUM OF EXPLOSIONS

A study has been made of the short-period P-wave spectra recorded at five arrays from four presumed Soviet nuclear tests. The purpose of the study is to determine if certain information regarding the explosive source parameters can be obtained from short-period spectra. Specifically, a modulation of the spectrum due to surface reflections near the source and a shift in spectral content with yield have been sought.

The data have been taken from LASA; the United Kingdom arrays at Yellowknife, Canada, Warramunga, Australia, and Gauribidanur, India; and an array at the LRSM station OONY at Lillehammer near Oslo, Norway. The global location of these arrays and great circle paths to the source region are shown in Fig. 1-1. The United Kingdom data were kindly supplied in digital form by the UKAEA Data Analysis Center for Seismology at Blacknest, England. It was reformatted at Lincoln Laboratory in order to make it compatible with established analysis procedures. The LRSM data was digitized at Lincoln Laboratory. The data analysis console, described in a previous SATS,¹ was used as the primary analysis tool.

It is hoped that the use of array beams in these spectral source studies has minimized recording site crustal effects and enhanced spectral features due to the sources. Of course, this assumes the crust will vary beneath the array and be averaged out in the beam. Under this assumption, the greater attenuation of recording site effects is anticipated as the maximum array dimension increases. The maximum dimensions of LASA, the United Kingdom arrays, and the Oslo array are roughly 200 km, 25 km, and 5 km, respectively. The array beams were formed by aligning the first discernible motion using the data analysis console. A 10-sec data time window was used for all the spectra computed. The four presumed explosions were located by LASA to lie in eastern Kazakh within a circle of 2.5° radius and were assigned body-wave magnitudes of 5.3, 5.4, 5.6, and 6.4 by LASA. The USCGS located the three latter events to lie within a circle of 0.5° radius and assigned body wave magnitudes of 5.3, 5.3 and 5.7. Here, the events will be referred to by their LASA magnitudes.

Cepstral analysis² was performed on the spectrum of each event as recorded at each of the array sites. The log spectrum was computed, a second order trend removed, a taper to zero at 0.0 and 3.0 Hz applied, and the spectrum of the log spectrum (cepstrum) computed. Under the assumption of a plane wave elastic reflection (pP) at the surface above the source, the delay (τ) of this reflection is calculable from the cepstrum. The delay is related to depth of burial and other parameters by $\tau = 2h/(\alpha \cos i)$ where h is the depth of burial, α the compressional wave velocity in the overburden, and i the angle of incidence at the receiver. At the epicentral distances considered here, $\cos i$ varies only from about 0.88 to 0.96. Table 1 lists the values of τ to the nearest 0.1 sec which were inferred from maxima in the computed cepstra. In cases where two distinct maxima were observed, two values for τ are listed.

TABLE I DELAYS INFERRED FROM MAXIMA IN COMPUTED CEPSTRA Delay τ (sec)					
LASA m_b	Norway	Australia	India	Canada	LASA
5.3	No data	0.4	0.6	0.4	0.5
5.4	0.6	0.5	0.4, 0.8	0.7	0.4, 0.9
5.6	0.6	0.4	No data	0.7	0.5
6.1	0.5	0.4, 0.9	0.5	0.6	0.5

The cepstral results do not appear to be definitive. Although the values obtained are reasonable, the variation between sites is greater than can be accounted for by the variation of the angle of incidence. Also, assuming the overburden velocity to be unchanged, an increase of τ with magnitude might be expected, since increased magnitude usually means increased depth, but is not evident from these data. Finally, at Norway, Australia, and LASA the values of τ seem to remain rather constant, indicating a possible array site effect, while at Canada and India such constancy is not observed. This work is continuing and will include analysis of earthquakes as well as presumed explosions.

Possible shifts in the spectral content of presumed explosions as a function of yield have been investigated by using the ratios of short-period spectra for different events recorded at each array. Displacement spectra, based on Haskell's³ analytical approximation to experimental curves for reduced displacement potentials of contained underground explosions, were used as a basis for comparison. Haskell's displacement spectra for granite at various yields are shown in Fig. I-2. Note that there is considerable change in the shape of the short-period spectrum as a function of yield.

In Fig. I-3 the log spectral ratios $\log A(f)_{6.1}/A(f)_{5.4}$ and $\log A(f)_{5.6}/A(f)_{5.4}$ computed for LASA and Australia are plotted over the bands 0.6 to 2.0 Hz. Here $A(f)$ is the spectrum of the seismometer output which is roughly proportional to ground velocity in this frequency band. The subscripts indicate the LASA magnitude of the event. By taking spectral ratios at a fixed recording site of events from similar locations, cancellation of the spectral effects of the seismometer and the earth transmission should take place, leaving only those due to variation of the source spectrum. The solid straight line is a least squares fit to the observations. The dashed line represents the spectral ratio based on Haskell's expressions for granite and the magnitude yield relation $m_b = 3.7 + \log(\text{kilotons})$. The change in slope of the fitted line with increasing magnitude differential is apparent. Table II summarizes the spectral ratio data for all of the array sites. The slope of the line fitted to the observed spectral ratios is given for each array and values derived from Haskell's expressions are given for comparison. At each array (where

TABLE II SLOPE OF LEAST SQUARES FIT TO RATIO OF SPECTRA						
LASA m_b Ratio	Norway	Australia	India	Canada	LASA	Haskell Theoretical Slope
5.6/5.4	0.006	-0.201	No data	+0.011	+0.023	-0.083
6.1/5.4	-0.229	-0.398	-0.280	-0.119	-0.310	-0.367

data is available) the slope of the fitted line decreases with increasing magnitude differential. This is taken as a good indication of the existence of source-related information in the short-period spectrum at teleseismic distances.

J. Filson

B. DISCRIMINATION USING WORLDWIDE OBSERVATIONS OF PERIOD, COMPLEXITY AND BODY-WAVE MAGNITUDE

It has been found, using LASA data, that valuable discriminants can be based on the use of the spectral ratio and the relation between surface-wave and body-wave magnitude, $M_s - m_b$. However, these discriminants are not useful at LASA below a certain magnitude threshold. It is not clear that the spectral ratio defined for LASA data will provide effective discrimination results when obtained at other stations. This statement is based on preliminary data from NORSAR. It is possible to use the $M_s - m_b$ discriminant effectively at other stations. However, the utility of this discriminant is limited by the difficulty in detecting the Rayleigh surface wave due to the poor signal-to-noise ratio on the long-period instruments, as compared to that on the short-period sensors. Thus, in attempting to lower the identification threshold by using worldwide observations, it is desirable to utilize discriminants other than those mentioned previously.

One effective way of lowering the identification level is to use discriminants based solely on the gross characteristics of the P-wave, due to the high signal-to-noise ratio on the short-period seismometers. A preliminary investigation of such a discriminant will now be described. The quantity P is defined as

$$P = C_{\text{MIN}} (\bar{T} - 0.5)^2$$

where C_{MIN} is the minimum complexity observed across a network, the complexity at the j^{th} station is defined as

$$\frac{\int_2^{35} |D_j(t)| dt}{\int_0^2 |D_j(t)| dt},$$

$D_j(t)$ is the P-wave data at the j^{th} station, t is the time in seconds, the onset time of the P-wave corresponds to zero time, $\bar{T}$ is the average of the dominant periods observed across the network and the dominant period is the period associated with the largest peak-to-peak excursion of the

P-wave amplitude in the first few cycles following the onset time. The actual discrimination is performed by plotting P vs $\bar{m}_b$, where $\bar{m}_b$ is the average of the body-wave magnitudes observed across the network and is defined in the usual way for teleseismic events.

The results of applying this discriminant to ten earthquakes and eight presumed underground nuclear explosions, all from the Central Asian region, using film data recorded at LRSM stations in North America, are shown in Fig. 1-4. An average of about six stations was used for each observation point. These preliminary results are encouraging since there is no overlap between the two populations. However, it is desirable to perform the experiment using more events, and, in particular, events with body-wave magnitudes in the 3.5 to 4.5 range. It is important to note that the discriminant based on P vs $\bar{m}_b$ may be measured visually by an operator using film data and does not necessarily require elaborate digital or analog signal processing equipment. This may be an advantage if only film records from a network of stations are available. However, computer compatible recordings would significantly reduce the labor required for complexity measurements and would probably increase accuracy and consistency.

J. Capon
L. Lande

C. LASA-NORSAR DEPTH PHASE STUDY

If it can be shown that an event has occurred at a depth greater than a few kilometers, such an event can be identified as an earthquake. The major difficulty with this method is the possibility of erroneously locating an explosion at a depth greater than a few kilometers. This problem was graphically demonstrated in a recent report⁴ where a presumed explosion clearly showed an arrival at LASA which could have been interpreted as pP or sP and would have located the event deep in the crust. The usual suggestion is that such problems can be circumvented by requiring corroborating apparent depth phases at several other receiver sites. We have now completed a limited study to evaluate this suggestion using only LASA and NORSAR data.

A total of 41 earthquakes and six presumed explosions have been found with usable short-period NORSAR data; LASA beams had previously⁴ been formed and possible depth phases identified. These events were all from eastern Europe and Asia. Beams were formed using the eleven available sensors at NORSAR and an analyst identified possible depth phases on those beams. The presumed explosion which showed a possible depth phase at LASA was not in this population. However, a different presumed explosion showed a possible depth phase at NORSAR which was not corroborated at LASA.

Table III is a summary of depths implied by depth phase picks for the 37 earthquakes for which either site showed a provisional depth phase. The depth shown is that which follows from assuming that the phase was pP. If the phase were sP, the depth would be reduced by a factor of roughly 2/3. A zero entry indicates no depth phase was picked by the analyst. Events in the table have been identified as showing good, fair, or poor agreement between the LASA and NORSAR depths. Good or fair agreement was obtained for 54 percent of the events. Comparison with USCGS events indicate that some events with poor agreement probably had a correct depth phase picked at one or both sites.

TABLE III								
DEPTH DATA FOR USCGS AND LASA-NORSAR BASED UPON POSSIBLE pP PICKS								
Events with Good LASA-NORSAR Agreement			Events with Fair LASA-NORSAR Agreement			Events with Poor LASA-NORSAR Agreement		
LASA	NORSAR	USCGS	LASA	NORSAR	USCGS	LASA	NORSAR	USCGS
150	160	155	34	40	50	0	90	-
580	580	582	30	55	33R	15	90	-
450	470	463	23	30		140	40	161
510	510	511	15	20		0	8	-
20	25	21	55	30		0	15	-
120	110	118	30	50		150	15	134
15	15	33R	50	33		0	15	20
170	170	160	17	11		110	0	113
30	25	-				0	80	16
20	17	-				20	100	33R
46	44	-				33	10	50
45	50	-				115	15	10
						50	0	-
						75	0	94
						0	21	33R
						70	20	33R
						0	160	-

Extrapolating to a system using many sites, it appears that 50 percent or more of the earthquakes might be identified by depth phases without erroneously locating any explosions at depth. This could be very significant since many earthquakes identified in this way might be troublesome events for other criteria. An experiment using many sites and many events is required.

R. T. Lacoss
L. Lande

D. DISCRIMINATION OF NORTH AMERICAN EVENTS USING BODY- AND SURFACE-WAVE MAGNITUDES

A valuable discriminant for distinguishing between earthquakes and underground nuclear explosions is based on the relation between the surface-wave magnitude M_s and the body-wave magnitude m_b . It has been found^{4,5} that, above a body-wave magnitude of about 4.9 and for presumed Soviet explosions, there is near-perfect separation between the two populations using the

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discriminant even if data from only a single site (LASA) is utilized. However, recently it has been proposed by Liebermann and Pomeroy⁶ that this discriminant will not provide a perfect separation between the two populations, particularly in the body-wave magnitude range $m_b < 4$.

In order to investigate this problem, measurements of M_s and m_b were made on 24 earthquakes and nine presumed underground nuclear explosions in North America, using film data recorded at LRSM stations in North America. The average value $\bar{M}_s$ of the surface-wave magnitudes observed across the network was used, as well as the average body-wave magnitude $\bar{m}_b$.⁷ The value of m_b at each station was computed according to the procedure suggested by Evernden⁷ for near-regional distances in the United States. An average of about 5 LRSM stations, varying in distance from about 2° to 40° from the epicenter of the event, were used for each measurement of $\bar{M}_s$ and $\bar{m}_b$. The results of the measurement are shown in Fig. I-5, along with the Gutenberg-Richter relationship, $M_s = 1.59 m_b - 3.97$. It is observed from Fig. I-5 that there is not a perfect separation between the two populations. The open circle which lies above the Gutenberg-Richter line corresponds to the Gasbuggy explosion. The two populations appear to be very close together, particularly at the lower body-wave magnitudes. They are much closer together than similar populations for central Asia.⁵ This result is in reasonably good agreement with that given by Liebermann and Pomeroy.⁶ It is possible that the two populations may be close together due to the triggering of earthquakes in the vicinity of the Nevada Test Site by the underground nuclear explosions. Unfortunately, our data does not include any very low magnitude explosions.

J. Capon
L. Lande

E. DISCRIMINATION USING BODY- AND SURFACE-WAVE MAGNITUDES MEASURED AT NORSAR

M_s and m_b measurements have been made at NORSAR for 33 shallow (depth ≤ 50 km) earthquakes and four presumed underground nuclear explosions occurring outside the western United States and Mexico. These are shown in Fig. I-6. The M_s value is the average of the M_s value determined at each of the three temporary long-period sites established in Norway by Lincoln Laboratory. Previously-published data⁸ used M_s measured at only one site, consisted of many fewer events, and did not include NORSAR m_b values.

Unfortunately, the $M_s - m_b$ values could only be determined exactly for two of the four presumed explosions examined. The individual outputs of the NORSAR short-period vertical instruments were clipped for the presumed explosion which is plotted at $m_b = 6.0$. We would estimate the true value of m_b for this event as 6.2. The surface waves from one of the three other presumed explosions could not be positively identified above the noise. Only an upper bound on M_s could be determined for this event and the event is shown with an arrow pointing down to indicate this fact.

We now have sufficient data from the Kurile Islands and central Asia to undertake a preliminary comparison of the NORSAR data with similar data obtained at LASA.⁵ The NORSAR data are presented in Figs. I-7(a) and I-7(b). The solid straight line is the Gutenberg-Richter relationship between M_s and m_b . The NORSAR Kurile Islands data cluster about $m_b = 6$ and the central Asia earthquake data are clustered about $m_b = 5$. A comparison with LASA data suggests some hypotheses which might be substantiated using considerably more data with a wider variation

in m_b recorded at both sites. First, for the Kurile Islands events in the vicinity of $m_b = 6$, the LASA M_s values lie below the Gutenberg-Richter line, while the NORSAR values lie nearly on it. The situation is changed in central Asia. For this region, the NORSAR values still tend to lie on the Gutenberg-Richter line but the LASA values tend to be above the line. This shift at NORSAR brings the earthquake population and explosions population closer together.

The reasons for the apparent average differences between NORSAR and LASA $M_s - m_b$ data are not entirely clear at this time. However, one factor has been investigated using USCGS and NORSAR data for the 11 Kurile Islands earthquakes. The mean of m_b (NORSAR) - m_b (USCGS) for the 11 events is 0.44. The structure under the Kurile Islands has been portrayed as a low attenuation lithospheric plate thrusting downward into a relatively high attenuation upper mantle. The seismic activity occurs along the upper edge and in any graben features. A plausible explanation for the higher m_b values at NORSAR is that the body-wave propagates through the upper few hundred kilometers of the mantle in the low attenuation lithosphere rather than the surrounding high attenuation upper mantle.

Figure I-7(c) shows the NORSAR M_s vs the USCGS m_b for the Kurile events. Comparison with Fig. I-7(a) makes the shift in m_b values obvious. The m_b values do not cluster at $m_b = 6.0$ but range over the interval 5.0 to 6.0. The scatter also seems to be significantly reduced. Much of the scatter in Fig. I-7(a) may be due to large variations in body-wave attenuation resulting from small changes in epicenter. This is possible since small epicenter shifts can significantly affect the amount of P-wave travel in the low attenuation lithosphere. The USCGS m_b is not as sensitive to this since it is an average over several stations at different azimuths. All of this seems to indicate that for a small complex region, such as the Kuriles, the difficulty is using $M_s - m_b$ from a single station as a discriminant may result more from scatter in m_b values than in M_s values.

To ascertain the extent to which the scatter of the NORSAR central Asia events is due to a single station determination of m_b , we used the multistation USCGS m_b for these events. Figure I-7(d) shows the result. Scatter is reduced and the separation between earthquakes and presumed explosions somewhat enhanced. However, the m_b values for USCGS still cluster about $m_b = 5.0$ as the NORSAR values did. Since the central Asia region encompasses a much larger area than the Kurile Islands, the $M_s - m_b$ relation for earthquakes is not as well defined and scatter is not reduced as significantly. These results agree with those previously⁴ obtained for a similar experiment using LASA data.

R. W. Ward (M. I. T. Earth
and Planetary Sciences Department)

F. SURFACE- AND BODY-WAVE MAGNITUDE OBSERVATIONS REPORTED TO USCGS

A study is under way to determine the regional effects on magnitude obtained from surface waves and body waves for earthquakes. To avoid the problems associated with obtaining a large data base, such as acquiring seismograms and reading them, the data on surface-wave and body-wave magnitudes published by the USCGS in their Earthquake Data Report publications are being used. For about a year, the USCGS has been publishing surface-wave magnitudes associated with approximately five percent of their published epicenters. Over the period of one year, it was possible to obtain surface-wave magnitudes on over 400 events and well over a thousand individual

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station surface-wave magnitudes. These data have been reduced to punched cards and presently represent our initial data base. Periodic updating will occur and enlarge the data base to an expected several thousand readings.

A preliminary analysis of data for epicenters in the Japan region has produced some results. When the individual surface-wave magnitudes M_s are plotted versus the USCGS body-wave magnitudes m_b , it can be seen that stations in Europe have higher M_s values for the same event than stations in North America. This effect is in substantial agreement with the results obtained by R. Ward from Kurile Islands earthquakes recorded at NORSAR and LASA and discussed in Sec. I-E of this report. In addition to our being able to obtain a knowledge of source and receiver regional variations, we expect that it will be possible to determine station magnitude corrections for M_s and m_b .

R. M. Sheppard

G. LONG- AND ULTRA-LONG-PERIOD CHARACTERISTICS OF NTS EVENTS RECORDED AT LASA

The distance from NTS to Montana LASA is in the range 12° to 15° . This is considerably less than teleseismic distance and so very little interest has previously been shown in NTS events recorded at LASA. However, the application of array processing techniques to surface waves generated by nuclear explosions at this relatively short distance may indicate discriminants which could be applied on a global scale. Furthermore, the detection of waves with periods up to 100 secs may be possible by beamforming.

Frequency-wavenumber (F-K) spectra⁹ have been calculated for the vertical components of the NTS events ZAZA, LANPHER and SLED, recorded at Montana LASA. The advantage of F-K spectra is that the full capabilities of the array to detect coherent propagating waves are utilized. Figure I-8 shows the high resolution F-K spectrum for ZAZA at a frequency of 0.05 Hz. This corresponds to the peak energy in the power spectrum of the event. High resolution F-K spectra were calculated for several frequencies down to 0.01 Hz and it appears that measurable coherent energy persists out to very low frequencies. Figure I-9 shows the F-K spectrum at a frequency of 0.15 Hz. Tentatively, it appears that coherent energy from the events was detectable even at 0.01 Hz. At such a low frequency the resolution of LASA is poor and so no great significance can be attached to the precise values of azimuth and phase velocity obtained at low frequencies when compared with the same quantities measured at higher frequencies. An apparent loss of coherent signal is encountered in the region of 0.02 Hz. Figure I-10 shows the high resolution F-K spectrum at 0.02 Hz and there is certainly no discernible coherent energy.

A plot of average power versus frequency is shown in Fig. I-11 for ZAZA. The average power is the power spectrum averaged over the individual sensors of LASA and has contributions from both coherent and incoherent disturbances. The values are normalized to the power at a frequency of 0.05 Hz. A dip in average power is evident at frequencies around 0.02 Hz. The lower curve in the same figure is a measure of the ratio of the coherent power to total power as determined by F-K analysis and a distinct drop in this value is seen at frequencies around 0.021 Hz, corresponding to the notch in the average power spectrum. Figure I-12 shows the same measurements for the event SLED and a very similar pattern emerges.

The above results suggest that the LASA long-period system may be used to study waves with frequencies down to 0.01 Hz, using frequency domain beamforming and F-K spectra.

H. Mack (M. I. T. Earth
and Planetary Sciences Department)

H. LONG- AND ULTRA-LONG-PERIOD SIGNALS RECORDED FROM EXPLOSIONS AT TELESEISMIC DISTANCES

The M. I. T. mercury tube tiltmeter has been operating for about one year at the Agassiz Station, Harvard, Massachusetts. A companion Geotech vertical Press-Ewing has been operating for about nine months. During this time, four U. S. underground tests have been recorded on the tiltmeter, including one from Amchitka Island. The vertical component has recorded two additional U. S. tests, including one from Colorado, and a Russian test from Novaya Zemlya. All three components have been bandpass filtered (10- to 80-second periods) to enhance long-period surface waves, so body waves from small events are not recorded. Detection thresholds, therefore, are based on recording surface waves. At 35° , we estimate that the tiltmeter will record Rayleigh waves from underground explosions greater than 500 kt, whereas the vertical component is sensitive enough to record events down to 40 kt. For earthquakes at about the same distance, the vertical component has recorded surface waves from a Santa Rosa, California aftershock with $M_s = 3.4$, more than one magnitude unit less than the minimum recorded on the tiltmeter.

In their study of long-period discrimination, Molnar, et al.¹⁰ defined amplitude ratios for Rayleigh and Love as $A_R = A_{19-22}/A_{40-60}$ and $A_L = A_{17-25}/A_{40-60}$ respectively, where A_{19-22} is the maximum amplitude of the Rayleigh wave at period 19 to 22 sec, and so on. They found that $A_R = 6$ completely separated explosions from earthquakes, but that no separation could be found for A_L . These results, and the lack of sensitivity of the tiltmeter compared to the vertical long-period seismometer, suggest that the tiltmeter will be of minimal use for discrimination at present. The long-period vertical, however, seems capable of providing a single station teleseismic discriminant, especially if installed at a quiet site. For example, the instrument used by Molnar, et al. was installed deep in a mine with careful temperature and pressure control at Ogdensburg, New Jersey, and has recorded events at 30° to 40° of M_s as low as 2.7, better than half an order of magnitude below the smallest recorded at Harvard. In general, more testing of discriminants utilizing ultra-long-period waves remains to be done.

J. Derr (M. I. T. Earth
and Planetary Sciences Department)

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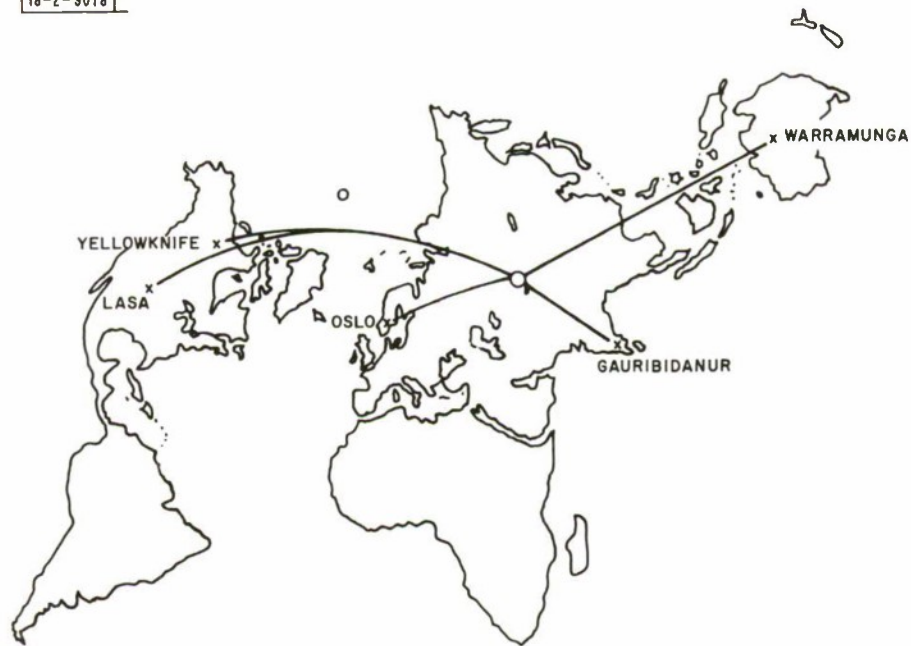


Fig. 1-1. Global location of arrays from which short-period data was obtained.

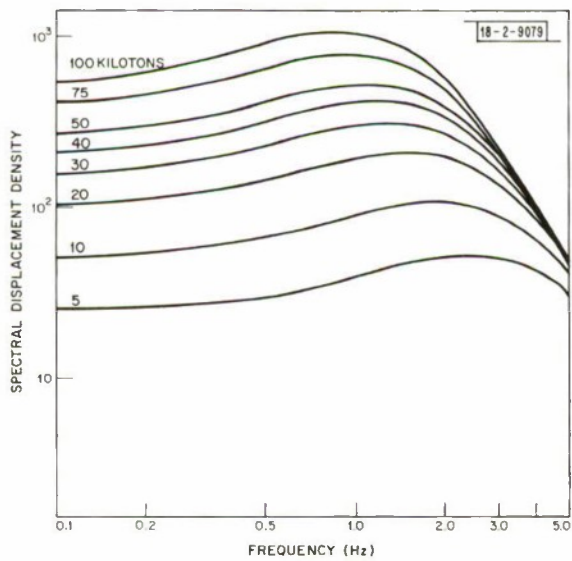


Fig. 1-2. Displacement spectra based on Haskell's analytic approximation for various yields in granite.

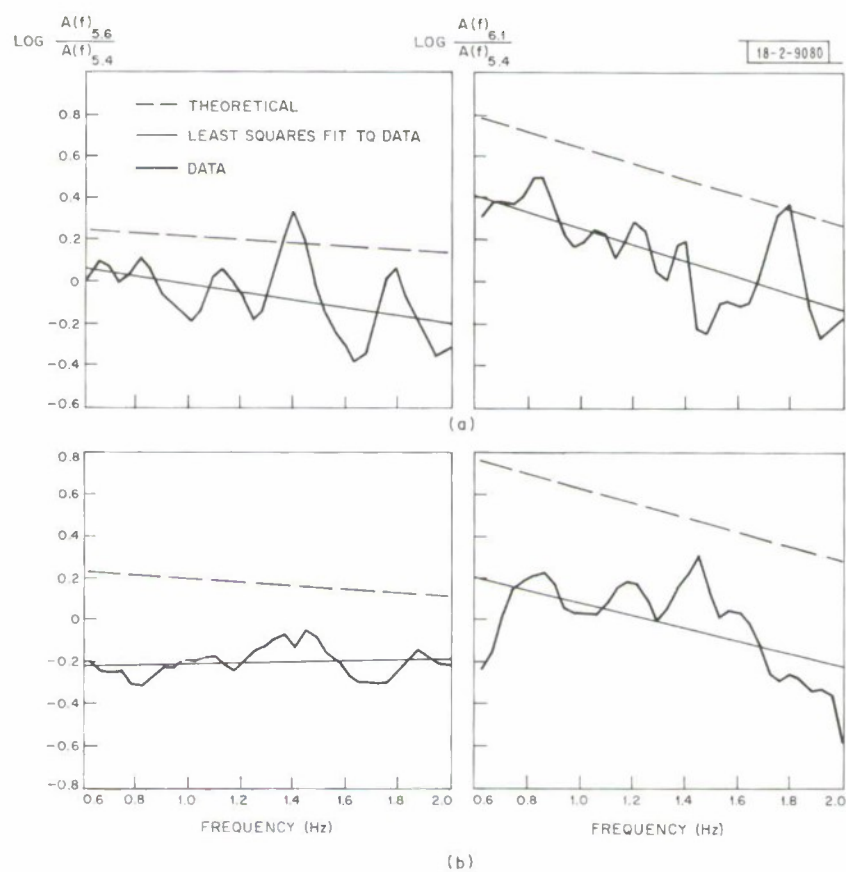


Fig. I-3. Log ratios of presumed explosion spectra of (a) Australia and (b) LASA. Solid straight lines are fitted to data; dashed lines are computed from Hoskell's approximation.

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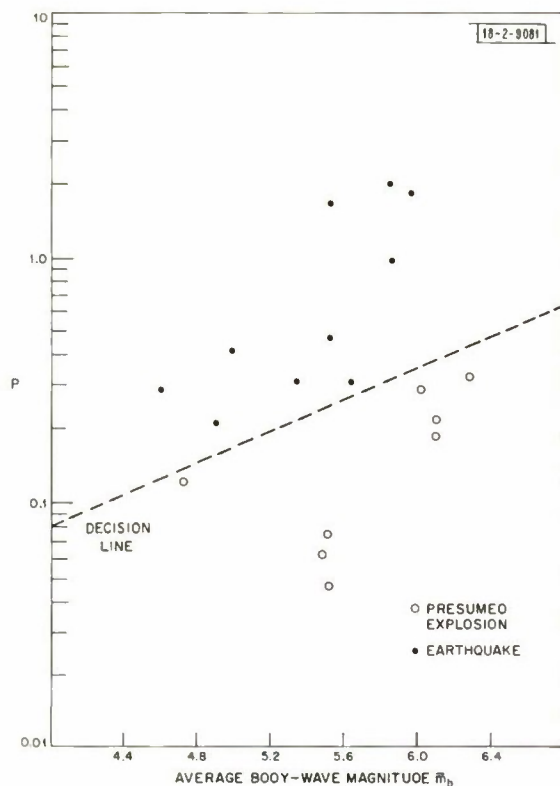


Fig. I-4. Discrimination based on worldwide observations of period, complexity, and body-wave magnitude.

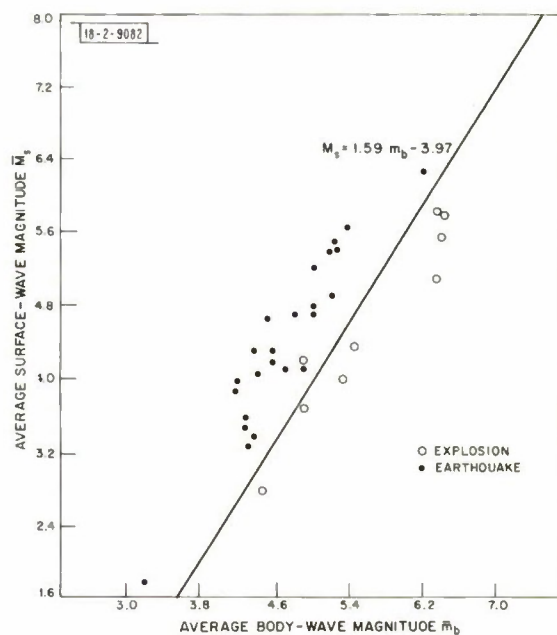


Fig. I-5. Surface-wave vs body-wave magnitude for North American events using LRSM data.

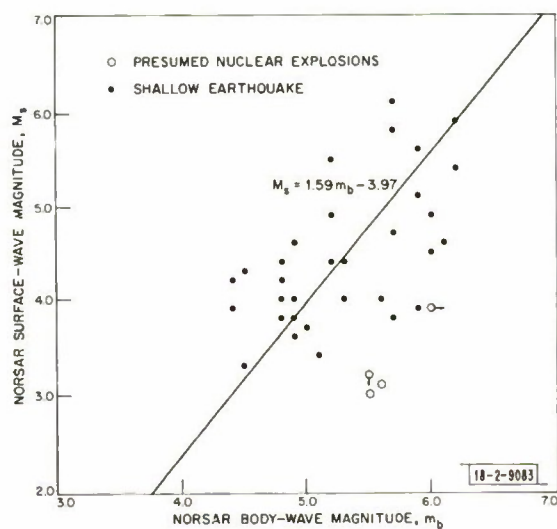


Fig. I-6. Surface-wave vs body-wave magnitude using NORSAR data. All events are outside western United States and Mexico.

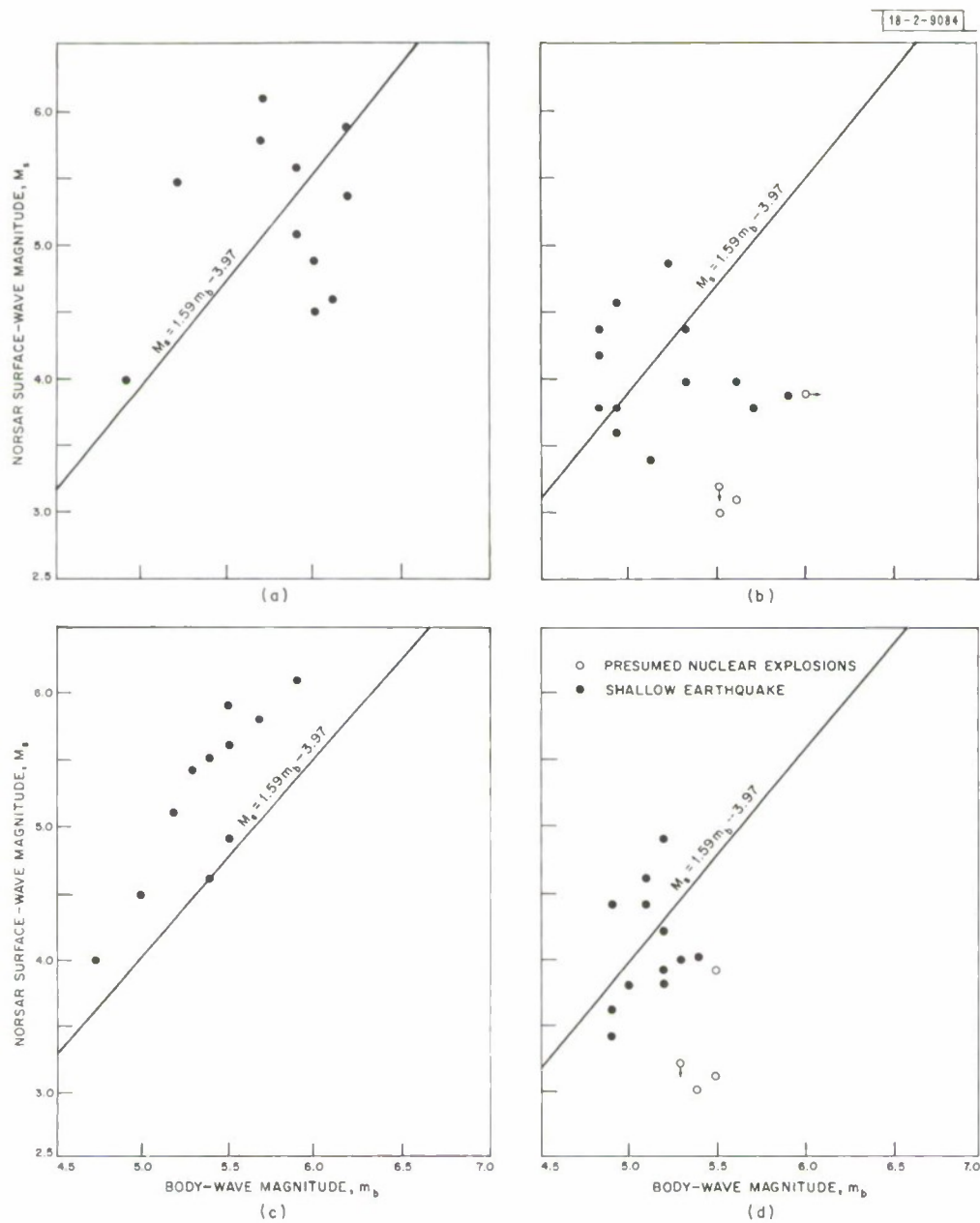


Fig. 1-7. NORSAR surface-wave magnitude vs body-wave magnitude.

- Kurile Islands events with NORSAR body-wave magnitude.
- Central Asia events with NORSAR body-wave magnitude.
- Kurile Islands events with USCGS body-wave magnitude.
- Central Asia events with USCGS body-wave magnitude.

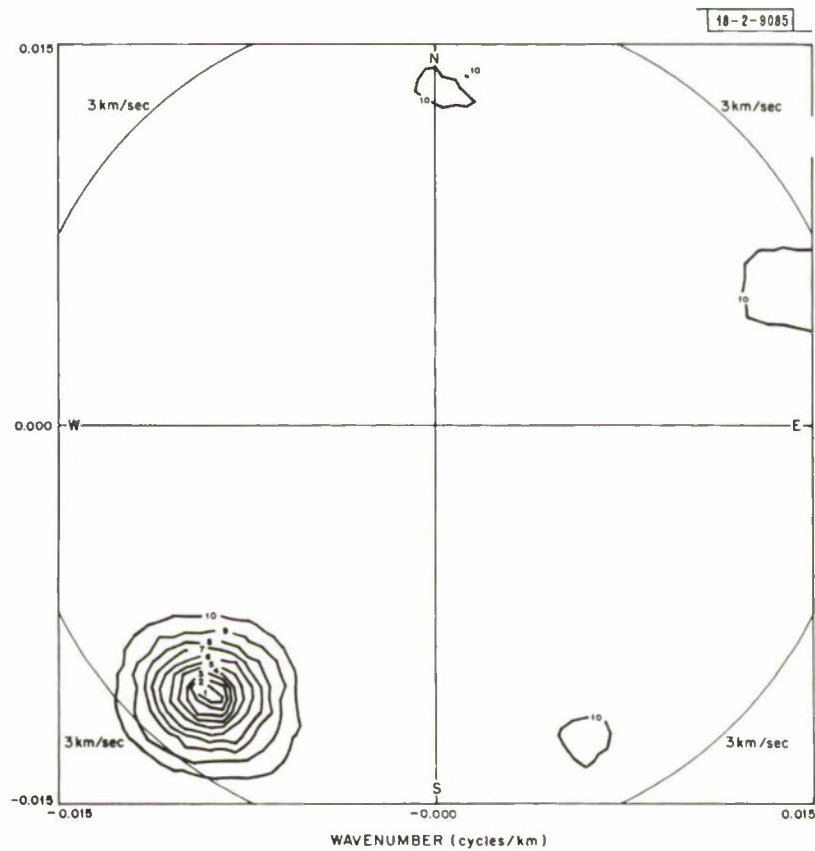


Fig. I-8. High resolution wavenumber spectrum of vertical component at LASA for NTS event ZAZA at 0.05 Hz. Contours are in dB.

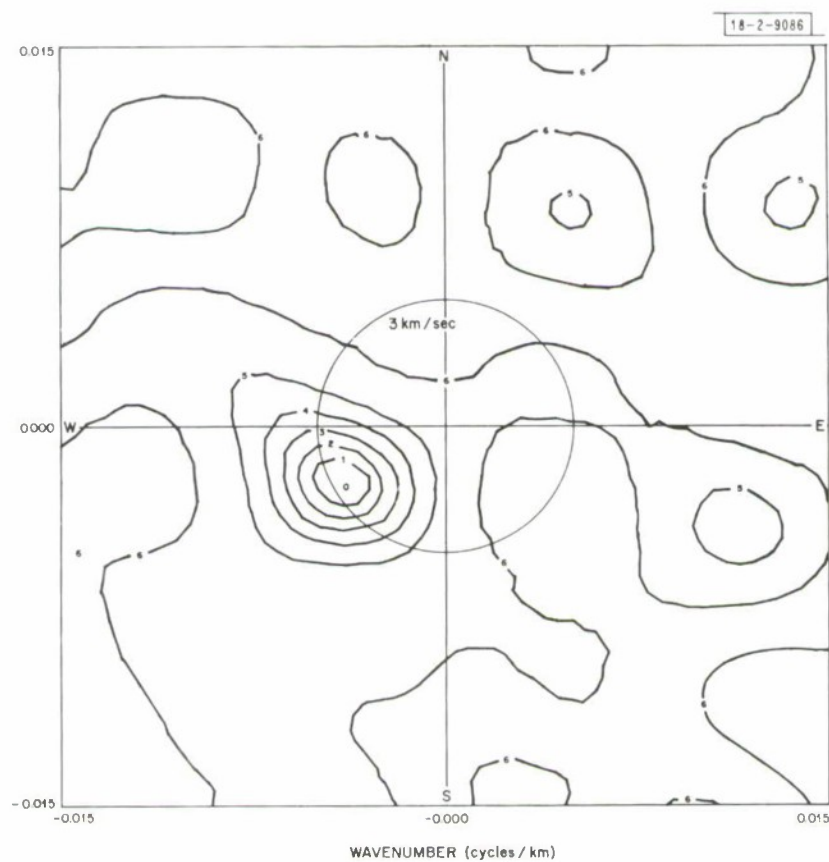


Fig. I-9. High resolution wavenumber spectrum of vertical component at LASA for NTS event ZAZA at 0.015 Hz. Contours are in dB.

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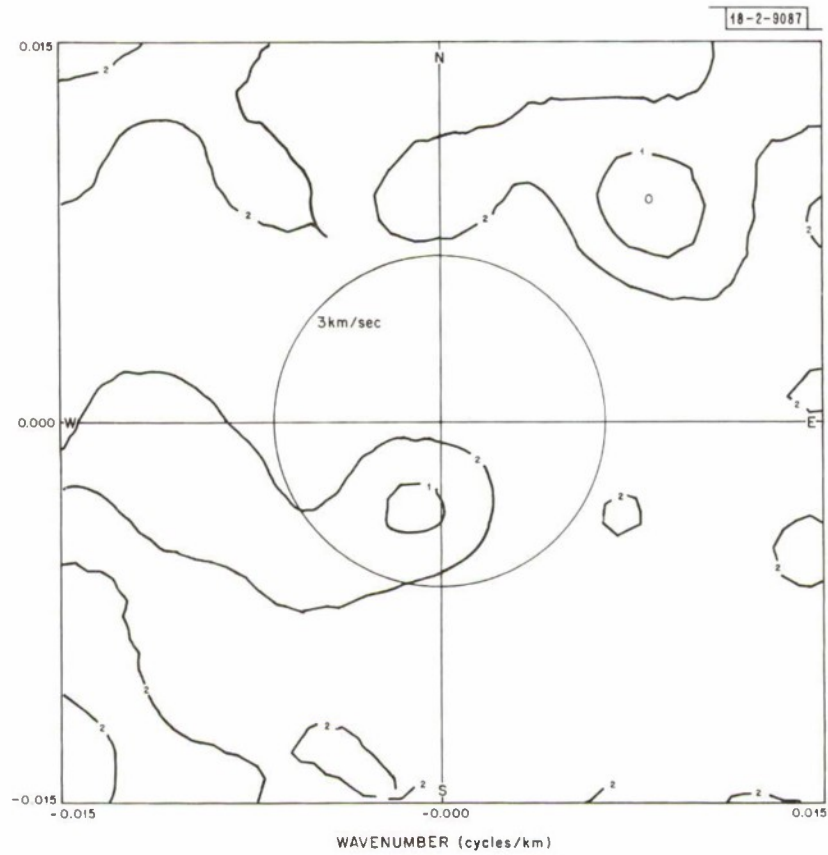


Fig. I-10. High resolution wavenumber spectro of vertical component of LASA for NTS event ZAZA at 0.02 Hz. Contours ore in dB.

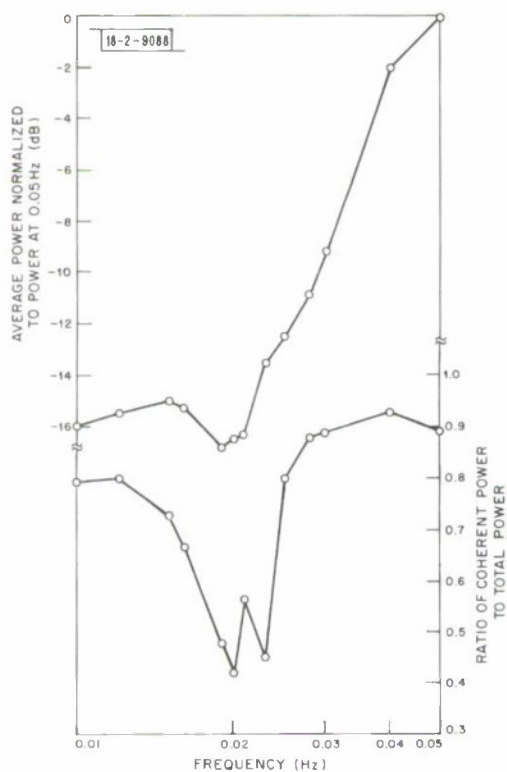


Fig. I-11. Average power spectrum and coherency measure for NTS event ZAZA recorded by the LASA LP system.

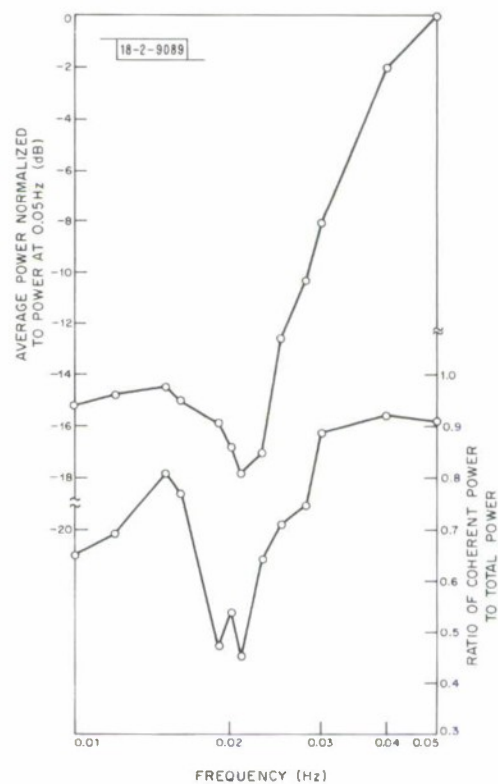


Fig. I-12. Average power spectrum and coherency measure for NTS event SLED recorded by the LASA LP system.

II. SIGNAL PROCESSING RESEARCH

A. CONTINENTAL APERTURE SEISMIC ARRAYS

A description of the continental aperture seismic array computer program has been given previously.¹¹ It will be recalled that the purpose of this program is to determine the depth of an event by recognizing the arrival of the pP phase, making use of P-pP differences in velocity, and to determine the P-wave source structure of the event by essentially steering many beams in the vicinity of the event. The data consist of the digitized and merged records from LASA and LRSM sites located in North America. The results obtained for processing the 27 October 1966 Novaya Zemlya event with this program were presented previously.¹¹

Several experiments have been performed recently to determine the validity of the results obtained using the computer program. These results will now be described. One of the experiments dealt with the effect of power level changes as a function of time, for the seismic data. In this experiment an exponentially damped sinusoid, whose frequency was 1 Hz, was generated at a number of stations. The stations used were the same as those employed previously¹¹ in processing the 27 October 1966 Novaya Zemlya event. The waveforms at all of the stations were made to be identical, indicating that the data were being generated by a stationary source located at a fixed point on the earth which was taken to be the epicenter for the previously-mentioned event. Thus, when the beamforming process is performed over successive two-second intervals of data, the location of the peak of the output beam power should remain stationary at the assumed epicenter.

However, it was found that the location of this peak did not remain stationary, but shifted by a considerable amount. This shift of position was due to power level inequalities along the waveform. In other words, it is possible that, when two-second segments of the waveform at each sensor are shifted using time delays corresponding to a source location other than the epicenter, the decrease in beam power output due to the misalignment of the traces is more than compensated for by the increase in power level in each of the waveforms. This effect, due to power level variations, is undesirable and should be removed, since otherwise there would be very little credence placed in the source structure computation.

In order to remove this effect, compensation for power level variations was employed in the beamforming process. This was accomplished by measuring beam power output as

$$P_i = \sum_{k=1}^M \left(\sum_{j=1}^N W_{j,i} D_{j,k+t_{ji}} \right)^2$$

where

$$W_{j,i}^2 = \sum_{k=1}^M D_{j,k+t_{ji}}^2$$

and $D_{j,k}$ is the data in the j^{th} sensor at the k^{th} time sample, t_{ji} is the time delay required in the j^{th} sensor for the i^{th} source location, N is the number of sensors and M is the number of data samples contained within the integration time of two seconds, which for 20 samples per second

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would be equal to 40. In the previous beamforming operation where no power compensation was used, the preceding formula applies with $W_{j,i} = 1$. In essence, this new beamforming operation is measuring the coherence of the delayed waveforms and is relatively immune to power level variations. When this new beamforming operation was applied to the artificially generated data mentioned previously, the location of the peak power output remained stationary as was desired.

Another experiment was performed to test the validity of the P-wave source structure computation using the new beamforming operation which compensates for power level variations. In this experiment four source locations were assumed at the points X, A, B, C, as shown in Fig. II-1. The point X corresponded to the location of the epicenter for the 27 October 1966 Novaya Zemlya event. A pulse is assumed to propagate from a given source location (point X, A, B, or C), to each sensor in the array, which is the same as that discussed previously, with a travel time determined by the time required for a compressional wave to propagate from point X to the given source location plus the time required for a P-wave to travel from the given source location to the sensor. This latter time is determined from travel time tables by using the distance from the given source location to the sensor. The time required for a compressional wave to propagate from point X to a given source location is equal to the distance between these points, in km, divided by 6 km/sec. The amplitudes of the pulses from X, A, B, C were assumed to be 1, $\sqrt{2}/2$, $1/2$, $\sqrt{2}/4$, respectively, corresponding to successive 3-dB increments in power level. This sequence of four pulses at each sensor was applied to a bandpass filter, 0.50 to 1.70 Hz, to make the data look somewhat like actual observed seismic data.

The results of the source structure computation are shown in Fig. II-1, which shows contours of $-10 \log(P_i/P_{\max})$, where $P_{\max}$ is the maximum value of P_i . The level of the contours varies from 0 to 3 dB in increments of 1 dB. The dotted contour surrounding the epicenter, marked X, in Fig. II-1 indicates the locus of points of possible sources of scattered P-waves. The results shown in Fig. II-1 indicate that the location of the peak power output shifts by an amount which is in reasonably close agreement with the known shift in location of the source of the P-waves. That is, the location of the zero in Fig. II-1 shifts successively from point X to A, to B, and then to C. Thus, a reasonably accurate computation of source structure has been obtained.

A more stringent test of the method was performed by assuming a shift of source location in two opposite directions simultaneously, instead of a shift in a single direction as was done previously. In this case, the shift in the location of the peak output power was unable to follow the shift in location of the source. Thus, it would appear that the source structure computation is useful only in those situations where the source location is moving in a single direction. The new beamforming operation has been applied to several events, including both earthquakes and presumed underground nuclear explosions. The results will be reported on soon in a Technical Note.

J. Capon

B. SHORT-PERIOD DATA EQUALIZATION AND DECONVOLUTION

Measurements are being made of large magnitude, short-period teleseismic P events to estimate the variation in crustal filtering recorded at the different subarray sites of LASA. For each event crustal equalization filters have been computed to convert a chosen reference trace

into various subarray traces. By repeating the calculations for other events from the same epicentral location, a similar set of equalization filters should be obtained. This assumes that each teleseismic event has a uniform wave shape over the wave front incident at the base of the crust and that the recorded signal variations over the aperture of LASA are caused predominantly by variations in crustal structure under LASA. This appears to be true from the data studied which is discussed below.

Eight Aleutian events of magnitude 5.4 or greater were selected for the initial study of crustal filtering. These events are listed in Table II-1 in order of increasing epicentral distance from LASA. Events 1 and 2 are from the Fox Islands; Events 3 through 6 are closely located

Event	Date	Arrival Time	Distance	Back Azimuth	Phase Velocity	Magnitude
1	12/4/65	2:19:39 GMT	39.6°	299.7°	13.39 km/sec	5.7
2	1/14/68	12:48:34	42.9°	303.1°	13.66	5.6
3	6/22/67	15:44:49	45.3°	304.1°	13.94	6.3
4	2/25/68	18:16:30	45.5°	302.4°	13.96	5.6
5	12/19/67	14:48:52	46.0°	303.9°	14.03	5.5
6	9/16/67	8:40:06	46.9°	303.7°	14.14	5.8
7	9/13/67	18:50:10	51.2°	308.9°	14.71	5.6
8	2/9/68	15:42:10	52.2°	311.5°	14.85	5.4

in the Andreanof Islands; and Events 7 and 8 are from the Near Islands. The clearest variations of crustal filtering in this set of events are seen on the subarray traces for Event 3 which are shown in Fig. II-2. The variations of amplitude and time duration of the P-wave shown here are similar to variations observed for the other events in this group.

In order to calculate equalization filters for the subarrays of LASA, each recorded event is assumed to have the form

$$e_i(t) = c_i(t) * s(t)$$

where $s(t)$ is the incident teleseismic plane wave source at the base of the crust under LASA, $c_i(t)$ is the crustal transfer function for subarray site i , and $*$ denotes convolution. The crustal transfer function may depend upon azimuth and distance of the event. An equalization filter for converting $e_1(t)$ to $e_2(t)$ for an event is given in the frequency domain by

$$F_{12}(\omega) = E_2(\omega)/E_1(\omega)/C_1(\omega)$$

where ω is frequency and $[E_i(\omega), C_i(\omega)]$ are Fourier transforms of $[e_i(t), c_i(t)]$. Note that the equalization filter is independent of the source waveform if the source location is fixed.

Equalization filters were computed for all subarray sites for each of the eight events. The reference trace used was the sum of the B4 and A0 traces. This trace generally had a simple

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form and was used for this reason as a reference trace. The reference traces for the eight events are shown in Fig. II-3, plotted against the epicentral distance of each event from LASA.

The equalization filters were computed in the time domain by a least-squares technique. Two examples of the filter computation are shown in Figs. II-4(a) and (b). In (a) a filter is calculated to shape five seconds of the input trace of Event 3 into 10 seconds of a ringing P-wave recorded at site B1. This equalization filter is applied to the complete input trace and the result compared with the complete desired output trace. It is of interest that the equalization filter equalizes the pP phases as well as the P phases on the two traces. This is another consistency check on the data since the pP and P phases traverse almost identical paths to the seismometers in LASA. In Fig. II-4(b) a more complex source is apparent on the input trace of Event 4. The equalization procedure again equalizes later portions of the traces not used to design the filter.

Finally, it is useful to examine the similarities of equalization filters for different events. Figure II-5 shows equalization filters designed to shape the A0 plus B4 reference trace to three ringing subarray sites, i.e., (a) B1, (b) C2, and (c) D1. The vertical scale for the filters equals 1 between the pips. There are several interesting features of these filters to notice. A strong multiple spike appears on all three filters for the closely-spaced events at $\Delta \sim 46^\circ$. The equalization filters for C2 have at least two reliable multiple spikes for these events even though the input traces shown in Fig. II-3 are quite different in shape. Events 7 and 8, which are only 5° away from Events 3 through 6 seem to lose the multiple spikes. This verifies the extreme sensitivity of the crustal response to azimuth and phase velocity changes as noted by Mack¹² and Larner¹³ for nonuniform crustal structures.

Results of this preliminary work show that crustal equalization filters can be designed for teleseismic events from localized regions. A possibility now being investigated is the deconvolution of all subarray traces back to a short duration signal. This inverse equalization filtering may be useful for short-period detection of pP phases buried in P-wave codas. In the light of the strong crustal filtering variations shown above, it is clear that short-period data can be used for discrimination only with the understanding that the discriminant may be site-dependent.

C. W. Frasier

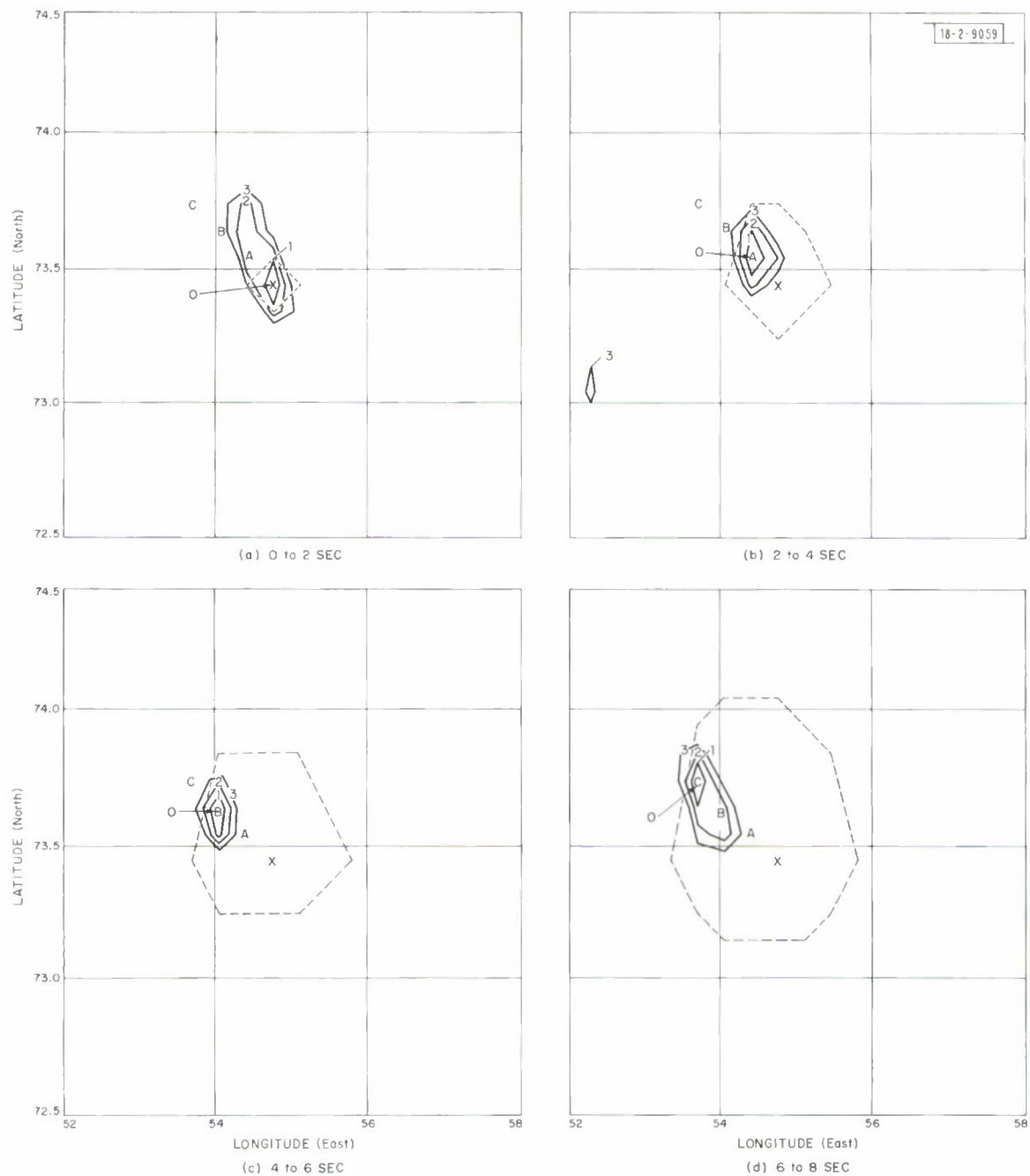


Fig. 11-1. P-wave source structure result for artificially-generated seismic data.

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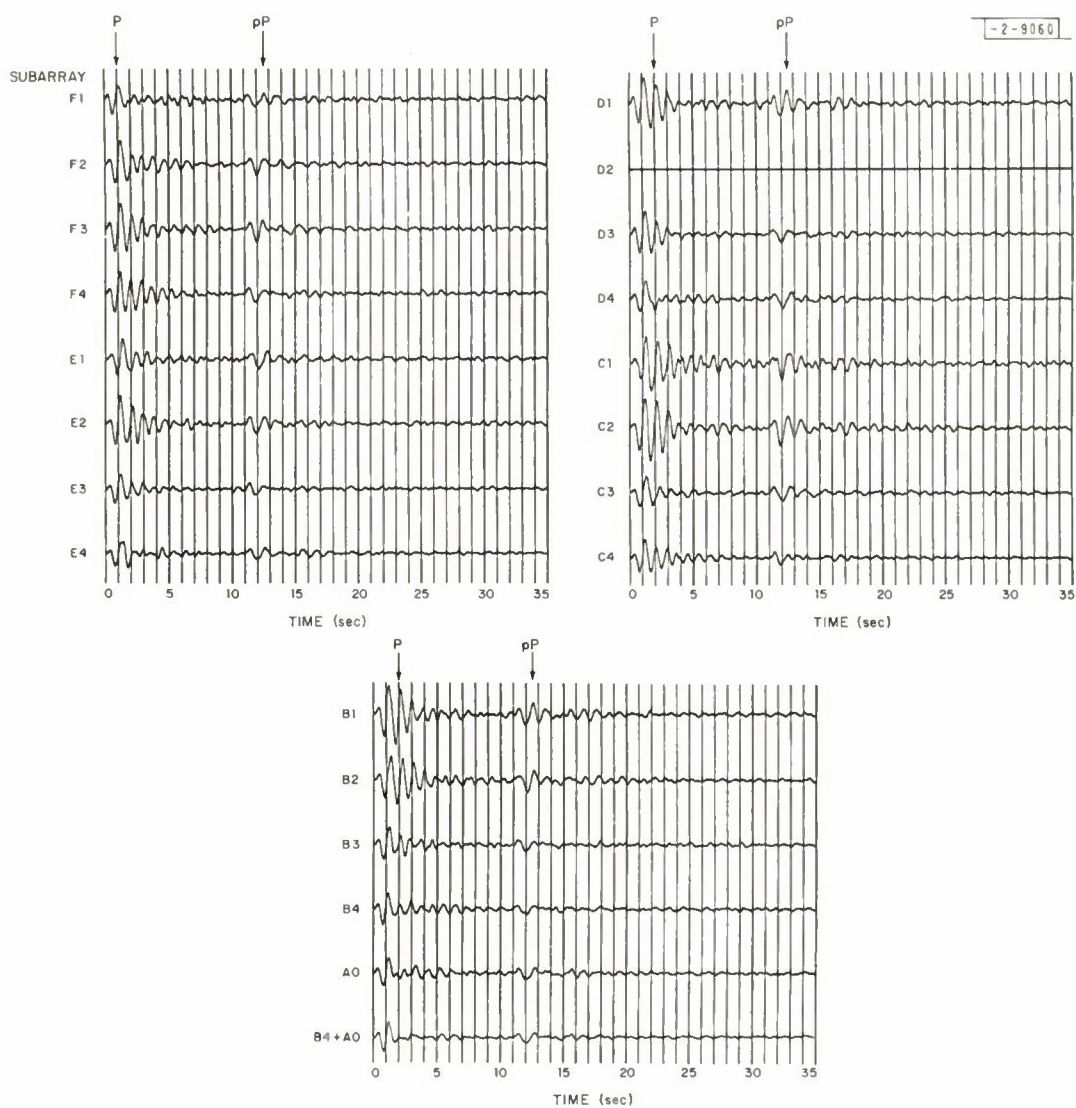


Fig. II-2. Summed subarray traces at LASA for Event 3, a magnitude 6.3 P-wave from the Andreanof Islands.

Fig. II-3. Aleutian Islands events used to study the crustal filtering of P-waves at LASA. Each trace is the sum of subarray sites B4 and A0.

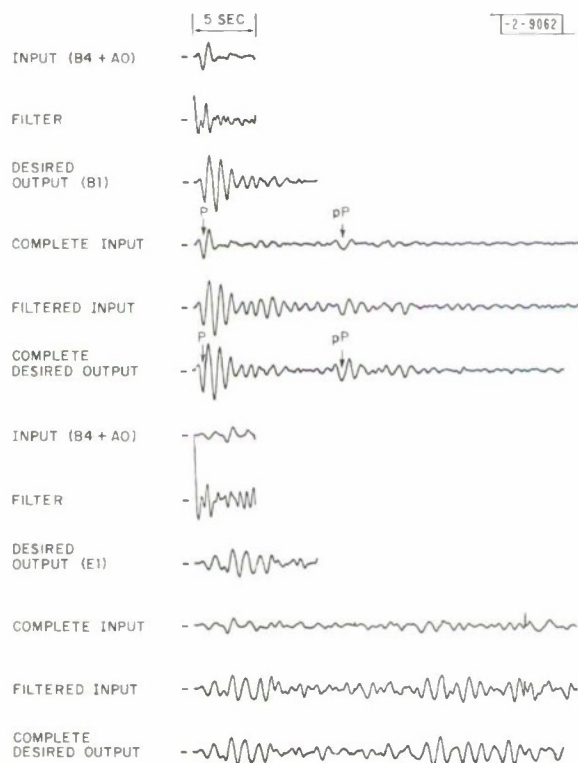
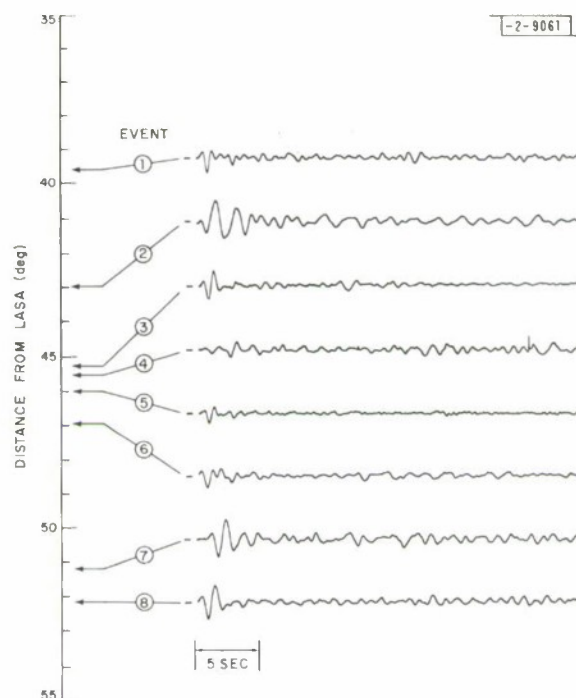


Fig. II-4. Examples of equalization procedure for LASA subarray sites for two Aleutian P events; in each case 5 sec of the (B4 + A0) trace sum is used as the input for the filter calculation. (a) Event 3, equalization to B1 subarray. (b) Event 4, equalization to E1 subarray.

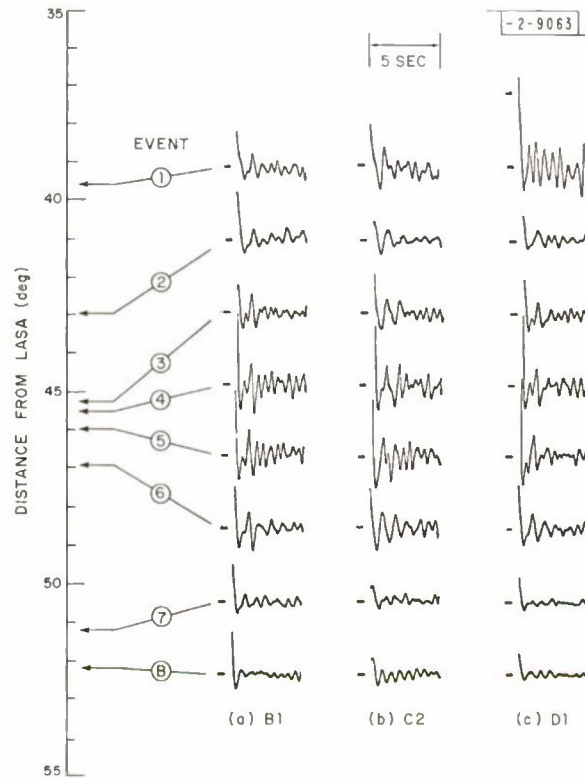


Fig. II-5. Examples of equalization filter impulse responses. In each case the input is the B4 + A0 subarray sums of Fig. II-2. Desired output subarrays are (a) B1, (b) C2, and (c) D1.

III. MISCELLANEOUS PROJECTS

A. VESPA AS A GEOPHYSICAL TOOL

A study has been made to determine if the program VESPA (Velocity Spectral Analysis) will be of use in measuring ray parameters at LASA of phases whose relative arrival times cannot be measured accurately by eye because of single trace amplitudes that are too weak or near other arrivals. VESPA is described in the June 1968 and December 1968 SATS.^{14,15} It steers the array to the appropriate azimuth and forms 61 beams with slowness from 0.0 to 12.0 sec/deg in increments of 0.2 sec/deg. The powers of each of the beams are computed over 1-sec intervals and these powers are contoured as a function of time and slowness. Using the subarray outputs of the D, E, and F rings of LASA, the scheme has been applied to the P arrivals from 17 earthquakes within the distance range of 140° to 170°. From events within this range multiple arrivals are observed due to the earth's core and its internal structure.

As an example, Fig. III-1 shows a contour plot of power vs slowness and time (hereafter called a vespagram) for an earthquake of October 25, 1967. The USCGS EDR parameters for this event are: origin time 15h 09m 35.3s, location 50.15°S and 114.27°E, and normal depth (restricted to 33 km). With respect to the LASA centerpoint the event is at a distance of 153.1° and an azimuth of 247.7°. The beam formed using the D, E, and F subarray sums delayed arbitrarily for a slowness of 2.8 sec/deg is shown beneath the vespagram in Fig. III-1. Three distinct arrivals are apparent and numbered on the beam trace. The vespagram computed from this data and contoured in 2-dB increments down from the peak power shows three peaks associated with these arrivals, each at a different slowness. The time intervals between peaks 1 and 2, and 1 and 3 are about 7 and 20 sec, respectively. The core phase travel time tables of Bolt¹⁶ give arrival times for three phases at 153°. The earliest and latest of these are based on observations, the intermediate phase is a smooth extrapolation of observations at lesser distances and is based on a theoretical model. At 153° the time intervals between the first and second and first and third phases of Bolt's tables are 4.8 and 18.1 sec. At 154° these intervals are 6.0 and 21.0 sec. Slowness values computed from Bolt's tables at 153° are 1.25, 2.2, and 4.25 sec/deg. For the event shown in Fig. III-1, values of 1.4, 2.6, and 4.25 sec/deg were measured on a vespagram. In Fig. III-1 the contouring interval is greater than that normally used in order to make the display clearer in reproduction.

The vespagrams of 16 additional events were "read" in a similar manner. The measured slownesses are plotted (open circles) against measured travel time in Fig. III-2 in order to convey as much information as possible concerning the relevancy of the measurements. USCGS data was used for origin times and locations; all of the depths were either restricted to or computed to be less than 33 km. Peaks in the velocity spectrum were timed. These usually ranged from 1 to 4 sec following the onset of the group of contours indicating the arrivals. Curves computed from Bolt's tables are drawn on Fig. III-2 as a standard against which to compare the data. The letters refer to branches given in his tables. The curves are dashed where his tables indicate extrapolations.

It must be stressed that the plotted points of Fig. III-2 represent a rough test of an analysis scheme rather than a refined set of observations. The plotted observations follow the established

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curve of PKP₂ well at larger slownesses. At smaller slownesses, along the PKIKP branch, the analysis appears to trend toward a greater value for $|d/dT(dT/d\Delta)|$ than indicated by the established observations.

In conclusion, the technique appears promising as a geophysical tool. However, the assignment of error ranges and, in the present case, station corrections at the higher velocities remain as problems.

J. Filson

B. ANALYSIS OF MICROBAROGRAPH DATA FROM ATMOSPHERIC EXPLOSIONS

The French thermonuclear device, exploded on 24 August 1968 in the South Pacific, was recorded by the Large Aperture Microbarograph Array (LAMA) situated in Montana. High-resolution frequency-wavenumber techniques⁹ have been applied to the recordings and some examples are given in Figs. III-3(a) and III-3(b). The two frequencies represented correspond to maxima in the frequency spectrum of the received signal.¹⁷ The phase velocity of the 0.006-Hz wave is seen to be slightly over 0.3 km/sec. This agrees with the accepted value for acoustic propagation in the lower atmosphere. The velocity for the 0.01-Hz wave is apparently somewhat higher.

H. Mack (M.I.T. Earth
and Planetary Sciences Department)

C. PDP-7 DATA PROCESSING FACILITIES DEVELOPMENT

The following hardware items have been added to our computer system:

- (1) The Beta hard copy printer has been delivered and installed so that it can be shared by the two computers. In a few seconds this device can generate 8-1/2- x 11-inch copies of any data which has been displayed on our computer-driven D.E.C. 340 scopes.
- (2) The 40.8-kilobaud data link between the M.I.T. Information Processing Center (IPC) and one of the PDP-7's has been installed and preliminary closed loop tests that exercise the PDP-7 interface, phone line and the two modems show satisfactory performance. The IBM 360/40 at the IPC is being modified to accept data in our format and should soon be ready for remote job entry of large data files.
- (3) A shaft encoder and knob box have been constructed and installed on computer 2, along with a 32-channel multiplexer and A/D converter. As a result, both computers can use the Data Analysis Console at the same time to analyze different data.
- (4) The design modifications for the 3:1 speedup for the D.E.C. 340 display have been completed. It was found to reduce the flicker by at least a factor of three, and can be increased to five at the expense of decreasing the point plotting accuracy slightly.

The following items of software have been completed or are in progress:

- (5) The New Data Analysis Console has been designed and several sub-programs have been coded. The drum has been returned to the factory for replacement of the spinner and flying head assembly to correct a manufacturing error. Consequently, final checkout and debugging is deferred until the drum is back in operation.
- (6) The software for the data link to the 360 is complete so that, when the IBM 360 hardware is ready, we will be able to send jobs to the 360 on a time-shared basis with the New Data Analysis Console.

- (7) A program has been written that makes hard copy prints, via the Beta device and PDP-7 computer, from magnetic tapes made by the IBM 360 in Stromberg-Carlson 4020 format for plotting by the latter device. This program has been included in the package called "Routine Processing" as described in the previous SATS.¹⁸
- (8) The FORTRAN compiler tape backup system has been completed and is now usable. The final system will be put on the drum and should be easier to use and faster. The IBM G level FORTRAN syntax checker is just being started by the subcontractor. The compiler has been documented by us and is published as Chapter IV in the PDP-7 Software Handbook. Several FORTRAN user packages are currently being programmed in machine language to give our system capabilities similar to software routines in the IBM 360 system. These include Stromberg-Carlson-type plotting routines and Input/Output routines to read and write LASA format data tapes. This will enable many of the FORTRAN programs which are currently being run on the IBM 360 to be run on our system. This should encourage the scientist-type programmers to use our system instead of the IBM 360 because they will be able to read data tapes and create displays without having any machine language experience. This has the added advantage of instantaneous output which should result in more efficient utilization of human resources.

P. Fleck

D. SEISMOLOGICAL SUBROUTINE LIBRARY

A library has been established that consists entirely of subroutines useful for general seismological calculations. Because the setup and structure of this library is very similar to a computer operating system library it will allow the programmers rapid and easy access to a variety of subroutines required in seismological problems. The structure of most of the subroutines is rather flexible and at the same time permits them to be relatively free of input and output operations. Because of the variety of subroutines that are available, a great amount of programmer time can be saved by the use of these self-contained and tested subroutines.

Included in the variety of subroutines that are available in the seismological subroutine library are the basic routines to compute distance, azimuth, travel time of body waves, magnitude, depth of the hypocenter based on pP, elevation station correction, ellipticity corrections, Montana LASA time station corrections and the name of the geographic region at any given latitude and longitude. Other subroutines are useful with data from large arrays. These routines will allow the programmer to obtain azimuth, horizontal phase velocity and distance to the epicenter based on a least-squares fit of a plane wave to the observed arrival times. The plane wave delays across an array can also be obtained from any velocity and azimuth. Another basic routine will convert an array of station positions of latitude and longitude into positions in an xy plane. A general fast Fourier transform routine is also available for the purpose of obtaining spectra.

There are several routines available to aid the programmer with plotting and interpretation of data. One of the most useful routines will develop contour maps of data sampled in xy coordinates or in polar coordinates. The program generates a tape which can be plotted on the Stromberg-Carlson 4020 plotter or by the Beta attached to the PDP-7 system. As a further aid to interpreting the contour plot, there is a routine that will plot the two-dimensional array as a three-dimensional figure. Other subroutines will allow the programmer to plot waveforms, long-period or short-period, and specify any time scale desired. Several other routines are

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available that perform basic functions, such as reading or writing data tapes recorded at several large arrays or plotting data on the printer for a quick look at functions or data.

Because of the variety of programs in the library and their use in basic seismological problems, it is hoped that the programmer can be relieved of the effort required to write his own basic routines. The library is permanently mounted in the M.I.T. Information Processing Center operating system and is usable by programmers utilizing the IBM 360 at the IPC.

R. M. Sheppard

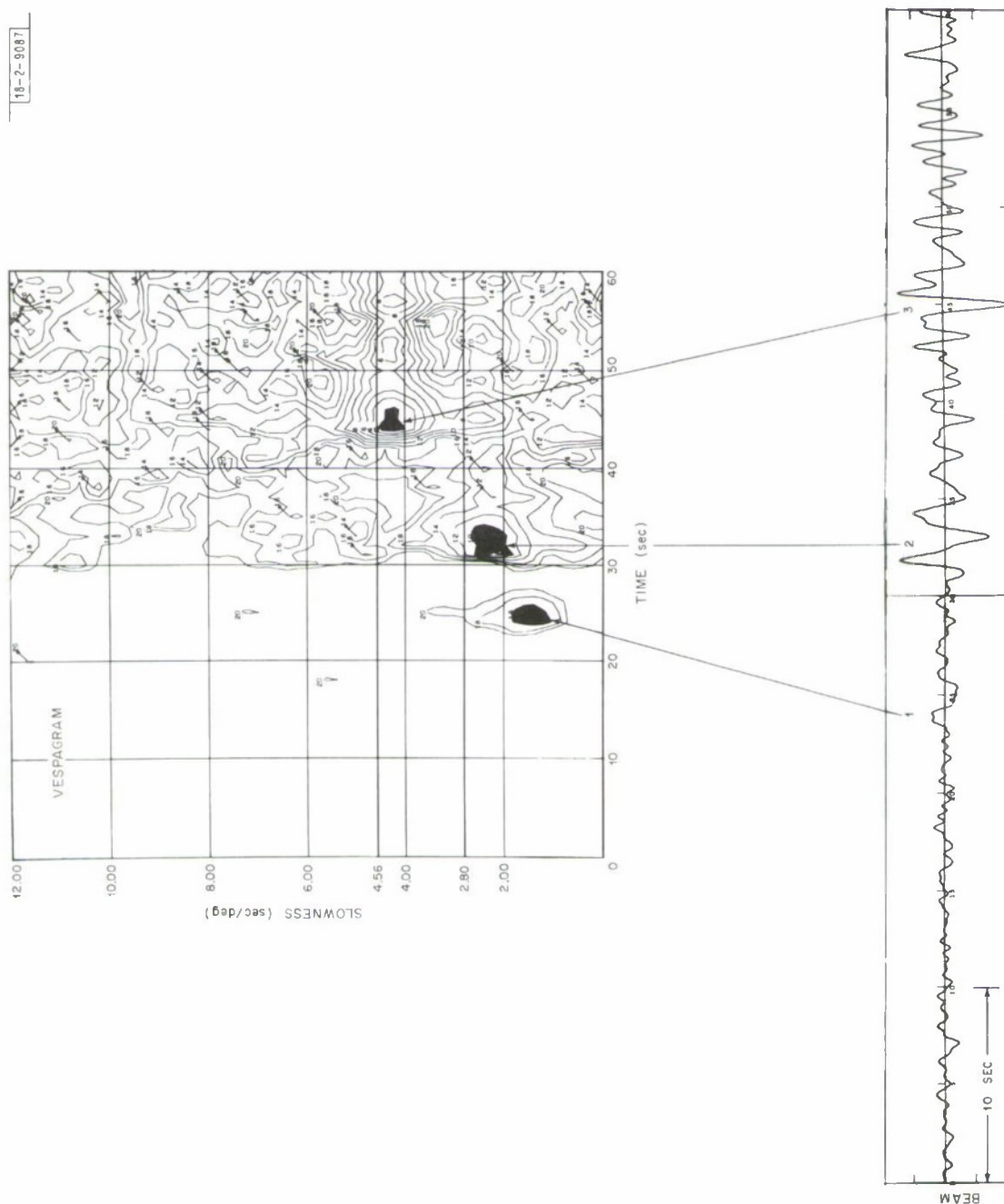


Fig. III-1. Beam formed using the D, E, and F ring subarray sums delayed at 2.8 sec/deg and the vespagram computed from the same data for the event of 25 October 1967.

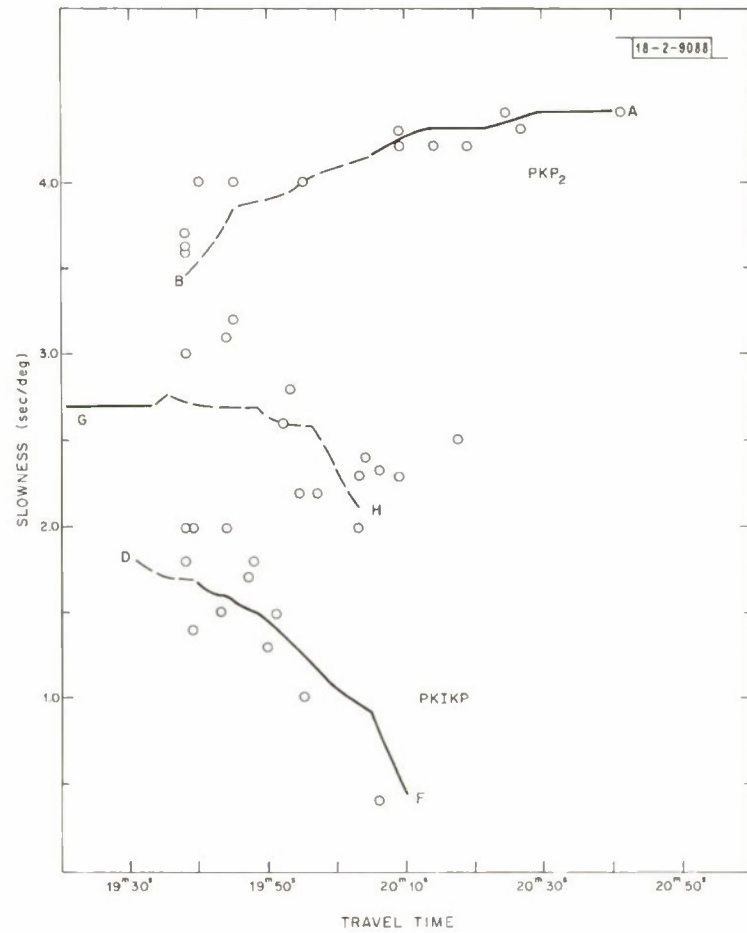


Fig. III-2. Slowness versus travel times read from vespagrams of core phases of LASA from 17 events at $140^\circ < \Delta < 170^\circ$.

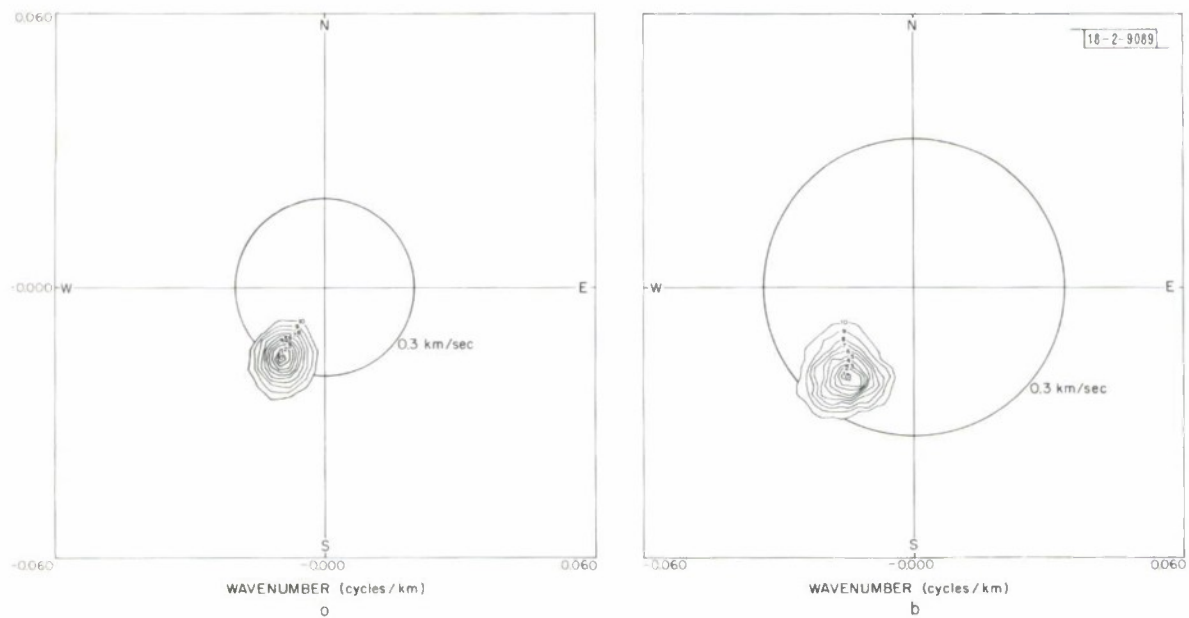


Fig. III-3. High resolution wavenumber spectrum of acoustic waves generated by French device on 24 August 1968 and recorded at the LAMA. (a) 0.006 Hz. (b) 0.01 Hz.

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