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PROPAGATION AND EXCITATION OF Lg, Sn, AND P-Pn WAVES FROM EASTERN UNITED STATES EARTHQUAKES BY REGRESSION ANALYSIS OF RSTN DATA

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SEISMIC ATTENUATION STUDIES AT U.K. ARRAYS

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Propagation and Excitation of L_g , S_n , and $P-P_n$ Waves from Eastern United States Earthquakes by Regression Analysis of RSTN Data					
1.) By applying regression analysis to amplitudes of the regional phases P_n, S_n and L_g in various frequency ranges we have derived the attenuation rates, extrapolated source spectra, and relative site responses for these phases in Eastern North America using RSTN data. Observed regional phase amplitudes are modeled with three parameters according to the regression model: (19. Continued)					
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$$\log A_{ij}(f_k) - \log G(\Delta_{ij}) = E_j(f_k) + \log S_i(f_k) - 0.4343 (\gamma(f_k) \Delta_{ij})$$

where i is the site index, j is the event index, and Δ_{ij} is the event-station distance in degrees. A , the amplitude, and G , the dispersion/geometrical-spreading factor, are known or assumed quantities for the phase. Model parameters to be estimated are $E(f_k)$, the source strength, $S(f_k)$, the station bias, and $\gamma(f_k)$, the anelastic attenuation coefficient.

Resulting estimates for $Q(f) = \pi f \gamma U$, where U is group velocity for the specified phase are:

$$\begin{aligned} Q_{Pn}(f) &= 640 f^{0.50} \\ Q_{Sn}(f) &= 825 f^{0.80} \\ Q_{Lg}(f) &= 1000 f^{0.35} \end{aligned}$$

assuming a combined dispersion and geometrical spreading factor of $\sim \Delta^{-5/6}$, appropriate to the amplitude decay of an Airy phase. Since the combined dispersion/geometrical spreading factor can be traded off against $Q(f)$ and the level of the source excitation, a computer program that relates Q to various spreading factors is also given in this report. Since $Q(f)$ apparently increases with frequency more rapidly for Pn and Sn than it does for Lg , path attenuation produces a seismogram in which Lg appears as a low frequency signal, while Pn and Sn appear as high frequency signals. This effect, which becomes more pronounced with increasing distance, is a path attenuation effect and is apparently not due to source excitation.

The estimated source excitation levels for all three phases exhibit high-frequency falloff rates between f^{-2} and f^{-3} and have approximately the same shape. The average day and night noise levels of the RSTN stations were also measured as part of this study. The seismic noise displacement amplitude falls off roughly as f^{-2} over the frequency band from 1 to 20 Hz. A diurnal variation in the noise levels is observed at all of the RSTN sites, with the daytime noise averaging from 1.5 to 3 times higher than the nighttime noise.

The final part of this study involved estimation of regional phase detection thresholds at the RSTN stations. We find for distances less than 16° , that Lg has the lowest detection threshold, followed by Sn , Pg , and Pn . The frequency at which each phase has its minimum threshold decreases rapidly with distance, most dramatically for Lg . At 3° , all four phases have their lowest thresholds in the 4-8 Hz range; this shifts to 1-4 Hz by 16° . These results are consistent with the observations of the behavior of regional phases from the bandpass-filtered seismograms. Minimum 50% detection thresholds for Lg range from magnitude 1.9 at 3° to magnitude 3 at 16° . The standard deviation of these estimates is 0.3 to 0.4 m.u., and the addition of 2 m.u. is required to bring the detection thresholds to the 98% level.

Seismic Attenuation Studies at U.K. Arrays

The productivity of any future U.S. researchers using Blacknest data and of the Blacknest staff themselves will be significantly enhanced if the interactive graphics capability of the Sun workstation were used for the analysis of seismic array data. It was therefore decided that the objective of this task would be to devise data base display and analysis software that could be used on the Sun workstation at Blacknest. In particular, software would be installed that would make the Blacknest data accessible by programs already written to handle data archived at the Center for Seismic Studies in Arlington, Virginia. This would make the U.K. data readily available to future U.S. researchers, and it would lay the necessary groundwork for any international data exchange experiment that, unlike the GSETT, would involve the exchange of waveforms as well as of parameter data. Also, the Blacknest staff would be instructed in the use of the new software, so that they could add to it and, over a period of

(19. Continued)

time, adapt their data analysis from the batch mode processing on the mainframe computer to interactive processing on the Sun workstation.

Although the software development project involved performing a variety of tasks such as writing and maintaining utility programs and copying selected software from the Center, there were two programs that were developed which are the most important for researchers who wish to process U.K. seismic array data on the Sun workstation. The first of these programs is RDBNST, which de-archives the array data that are stored in a dozen different formats in the Blacknest tape library and converts them to the ".w" format used at the Center. RDBNST is much more "user friendly" than its predecessor, and this is a necessary feature for the program to be used by Blacknest personnel who are inexperienced with UNIX and who are unfamiliar with the Center's data base structure. When coupled with the seismogram display capabilities that were developed for the Sun, the RDBNST program should make it easy for the staff at Blacknest to satisfy requests from the U.S. for data from specific events. This was tested successfully when data were provided to the Center for 2 specific spans of 2 hours duration, for each one of the 4 U.K. seismic arrays, in response to a request from DARPA.

New software was also written for the purpose of examining seismic array data such as those which are archived at Blacknest. In order that this software be easily modified by Blacknest staff, most of the code was written in FORTRAN 77. The new program is based on the "SunCore" graphics system rather than on "SunWindows", unlike other currently available waveform analysis packages. This program that was developed at Blacknest for displaying and making measurements on multi-channel data is known as the Interactive Display of Array Seismograms (IDAS) program. It has been ported from the Sun workstation at Blacknest to workstations at the Center, so researchers there can examine the U.K. array data also. Copies of IDAS have been provided to other contractors in the U.S., namely Science Applications International, ENSCO, and Science Horizons. Copies have also been sent to the Australian National University and to the Ruhr - Universitat Bochum Institut fur Geophysik in Germany. Documentation of the program has furthermore been provided to other international participants in the GSETT. IDAS has been used for the analysis of data not only from the 4 arrays operated by the U.K. but also for the analysis of data recorded at NORESS and at Grafenberg.

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SUMMARY

Propagation and Excitation of L_g , S_n , and $P-P_n$ Waves from Eastern United States Earthquakes by Regression Analysis of RSTN Data

By applying regression analysis to amplitudes of the regional phases P_n , S_n and L_g in various frequency ranges we have derived the attenuation rates, extrapolated source spectra, and relative site responses for these phases in Eastern North America using RSTN data. Observed regional phase amplitudes are modeled with three parameters according to the regression model:

$$\log A_{ij}(f_k) - \log G(\Delta_{ij}) = E_j(f_k) + \log S_i(f_k) - 0.4343 (\gamma(f_k) \Delta_{ij})$$

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PROPAGATION AND EXCITATION OF Lg, Sn, AND P-Pn
WAVES FROM EASTERN UNITED STATES EARTHQUAKES
BY REGRESSION ANALYSIS OF RSTN DATA

by

John H. Goncz, William C. Dean, Zoltan A. Der,

Alison C. Lees, Keith L. McLaughlin,

Thomas W. McElfresh, and Margaret E. Marshall

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SUMMARY

By applying regression analysis to amplitudes of the regional phases P_n , S_n and L_g in various frequency ranges we have derived the attenuation rates and extrapolated source spectra for these phases in Eastern North America using RSTN data, mostly from earthquakes. Vertical component seismograms extending in time from before the P arrival to after the L_g arrival were band-pass filtered and the maximum zero-to-peak signal amplitudes within predicted P_n , S_n and L_g arrival time windows were picked. The nine band-pass filters utilized had center frequencies f_k that span the frequency range from 0.4 Hz to 20 Hz evenly on the log-frequency scale. The outputs of these filters were used to determine the Q factors of the regional phases analyzed as functions of frequency.

Observed regional phase amplitudes are modeled with three parameters according to the regression model:

$$\log A_{ij}(f_k) - \log G(\Delta_{ij}) = E_j(f_k) + \log S_i(f_k) - 0.4343 (\gamma(f_k) \Delta_{ij})$$

where i is the site index, j is the event index and Δ_{ij} is the event-station distance in degrees. The left hand side contains known or assumed quantities; A is the amplitude and G is the dispersion/geometrical-spreading factor appropriate for the phase. For arrivals for which this factor is not well known we assumed various plausible factors to limit the values of γ and $Q(f) = \frac{\pi f}{\gamma U}$ as well as the estimates of the source strength defined below. Model parameters to be estimated are on the right hand side of the equation; $E(f_k)$ is the source strength, $S(f_k)$ is the station bias and $\gamma(f_k)$ is the anelastic attenuation coefficient.

For an event to be used in the regression analyses we required that there must be at least two sites that receive the same signal phase for a given event. The RSTN network is well suited for this kind of analysis because during its operational life it has provided a data set that

contains a broad range in source sizes ($m_b = 1.7$ to 6.2) and a broad range in epicentral distances ($\Delta = 0.6$ to 33 deg). Together, these broad ranges in the independent variables tend to reduce the uncertainties of the estimated model parameters.

Earthquake magnitudes do not appear in the regression analysis because source strengths were estimated at each frequency $E(f_k)$ independently. These $E(f_k)$'s can be regressed upon network magnitudes and the resulting straight line relations used to construct source excitation spectra from magnitudes 2 to 6.

Approximate expressions for $Q(f) = \pi f \gamma U$, where U is group velocity for the specified phase are:

$$Q_{Pn}(f) = 640 f^{0.50}$$

$$Q_{Sn}(f) = 825 f^{0.80}$$

$$Q_{Lg}(f) = 1000 f^{0.35}$$

All these were obtained for a combined dispersion and geometrical spreading factor of $\sim \Delta^{-5/6}$, appropriate to the amplitude decay of an Airy phase. Since the combined dispersion/geometrical spreading factor can be traded off against $Q(f)$, and our data cannot resolve this nonuniqueness, a simple computer program that relates Q to various spreading factors is also given in this report assuming various group velocities and fitted in specified epicentral distance ranges. The reader can compare, using this program, various values of Q reported in the literature which were obtained by using various spreading factors.

The estimated source excitation levels for all three phases exhibit high-frequency falloff rates between f^{-2} and f^{-3} and have approximately the same shape. Generally, in the 200-1200 km distance range, the Lg amplitude spectral level is roughly one order of magnitude larger than the Pn and Sn amplitude spectra for the same event at 1 Hz.

Because, apparently, $Q(f)$ increases with frequency more rapidly for Pn and Sn than it does for Lg , path attenuation produces a seismogram in which Lg appears as a low frequency signal, while Pn and Sn appear as high frequency signals. This effect, which becomes more pronounced with increasing distance, is a path attenuation effect and is apparently not due to source excitation.

The average day and night noise levels of the RSTN stations were also measured as part of this study. The seismic noise displacement amplitude falls off roughly as f^{-2} over the frequency band from 1 to 20 Hz. A diurnal variation in the noise levels is observed at all of the RSTN sites, with the daytime noise averaging 1.5 times higher than the nighttime noise at RSSD, the quietest site, and up to 3 times higher for some frequencies at RSCP and RSON. The site with the largest seasonal variation is RSNT which is quietest in the winter when the Great Slave Lake is frozen. The RSTN noise levels are comparable to the noise levels measured in Fennoscandia and are very similar to results from other studies of the same stations.

The final part of this study involved estimation of regional phase detection thresholds at the RSTN stations. We find for distances less than 16° , that Lg has the lowest detection threshold, followed by Sn , Pg , and Pn . The results for Pg are marginal because Pg is not often a prominent arrival on our mostly eastern North America paths. The frequency at which each phase has its minimum threshold decreases rapidly with distance, most dramatically for Lg . At 3° , all four phases have their lowest thresholds in the 4-8 Hz range; this shifts to 1-4 Hz by 16° . These results are consistent with the observations of the behavior of regional phases from the bandpass-filtered seismograms. Minimum 50% detection thresholds for Lg range from magnitude 1.9 at 3° to magnitude 3 at 16° . The standard deviation of these estimates is 0.3 to 0.4 m.u., and the addition of 2 m.u. is required to bring the detection thresholds to the 98% level.

INTRODUCTION

Understanding the propagation and excitation characteristics of regional seismic arrivals (P_n , P_g , S_n and L_g) is of importance for detection, discrimination, and yield estimation of nuclear explosions, and this knowledge is especially important for the siting of stations to be used to monitor a Comprehensive Test Ban Treaty (CTBT) or a Threshold Test Ban Treaty (TTBT). This study focuses on two aspects of these problems, attenuation of regional phases and detection thresholds for regional phases. These investigations are done using regional arrivals recorded at the RSTN stations from events in eastern and central North America.

The importance of research along these lines is stressed in a recent review paper by Evernden *et al* (1986) which discusses the implications of regional propagation characteristics of various crustal phases with regards to detectability and discrimination capability for decoupled nuclear explosions by a hypothetical internal network in the USSR. As pointed out by Evernden *et al*, in order to have confidence in our capabilities to detect and discriminate regional events, as would be required by a CTBT, it is important to have a better understanding of the frequency dependence of attenuation, local site noise structures, the characteristics and physics of high frequency signal propagation, and the source characteristics of small explosions and earthquakes.

One goal of this study is to determine the frequency-dependent attenuation characteristics of various seismic phases (P_n , P_g , S_n and L_g) from local and regional events. Simultaneously, we utilize the data to estimate the source excitation spectra of the regional phases P_n , P_g , S_n and L_g from earthquakes as functions of frequency. Throughout this study we utilized RSTN data exclusively. In order to use RSTN sites for the measurement of the propagation characteristics of regional events and to evaluate the RSTN sites with regards to detection capability, we apply a statistical regression model of the signal amplitudes measured which contains rela-

tively few parameters to be estimated. Since we can only measure the signals at the output (the seismogram), the model includes the attenuation properties of the earth as well as the spectral characteristics of the sources and sites. The result is a measure of the apparent spatial attenuation; we do not distinguish between anelastic and scattering attenuation. Station bias is estimated only for the RSTN sites relative to each other, not compared to some other seismic network. Thus these station terms are constrained to sum to zero at each frequency for the RSTN network.

There have been a number of studies of the attenuation properties of regional phases, particularly *Lg*, in various regions of the world (e.g. Nuttli 1973 in Eastern US; Mitchell 1975 in North America; Bollinger 1979 in Southeastern US; Nuttli 1980 in Iran; Nicolas *et al* 1982 in France; Hasegawa 1985 in Eastern Canada; Gupta and Burnetti 1980 in Eurasian shield regions, Campillo *et al* 1985 in France, Chun *et al* 1987 in Canada). In most of these studies the attenuation effects have been estimated by *a priori* assuming the authors' preferred forms of the geometrical spreading-dispersion effect and fitting $Q(f)$. The model appropriate to the anelastic attenuation contribution to the amplitude-distance relation is an exponential decay of the individual frequency components with distance. Most studies which use time domain amplitudes model the combined dispersion and geometrical spreading with terms which go approximately as the $-5/6$ or -1 power of distance for *Lg* (see Ewing *et al* 1957, Nuttli 1973) depending whether the Airy phase or other parts of the dispersed wave trains are assumed to be measured. It is less certain what exponential geometrical-dispersion spreading decay factors are the most appropriate to *Pn*, *Pg*, and *Sn* since the physics of the propagation of these phases is not yet understood. The geometrical spreading factor (composed of cylindrical spreading and dispersion) cannot be determined uniquely by regression analyses of data since the Δ^{-n} and $\exp(-fT/Q(f))$ functions trade off against each other. Although the mathematical forms of these factors are different they cannot be separated by regression analyses because of the great

scatter in all regional amplitude data sets. Moreover, we often have to fit the data in limited distance ranges.

In any case, by assuming a geometrical spreading factor and fitting a $Q(f)$ we essentially obtain an empirical fit to the observed amplitude-distance function, and extrapolating the amplitudes backwards to the source we obtain an estimate of the source spectrum regardless of what geometrical spreading factor was assumed. The various choices for the geometrical spreading factor make a significant difference mostly in the ratios of the absolute amplitudes of the various phases very near to the source. It appears that since $Q(f)$ dominates the spectra at high frequencies the choice of geometrical spreading factors, as long as they are reasonable, is not critical.

Another plausible approach to choosing the most appropriate geometrical spreading factor is to run synthetic seismograms for the most likely models of the local crustal structure (Bouchon 1982, Campillo *et al* 1984) with an infinite Q and to measure the decay rate of the phase amplitudes and regard these as due only to geometrical spreading. By fitting a function of the form Δ^{-n} to these one can then attribute the residual amplitude decay in the observed data to the exponential attenuation factor. Using this approach Campillo *et al* (1984) predicted, for a crustal model of France, that the geometrical spreading effect for P_g should be $\Delta^{-1.5}$. This would imply that for P , the Q should be infinite or very large near 1-2 Hz for a similar crustal structure assumed for the eastern North America, since the observed amplitude decay is also $\Delta^{-1.5}$ (Warren *et al* 1978) as evidenced by the Early Rise data.

Unfortunately, when this approach is used, it not possible to verify that the crustal models chosen represent the structure of the region studied well enough for such analyses. Moreover, many published synthetic seismograms are quite different from the observed ones. We were unable to find in the literature synthetic seismograms with prominent, high frequency S_n

phases similar to those seen in actual seismograms and shown later in this report. Moreover, most techniques for computing synthetic seismograms tend to deteriorate in accuracy with increasing frequency, and there have been no satisfactory means devised yet to model the significant scattered energy in the seismograms present at high frequencies. In addition, the geometrical spreading factor may also be frequency dependent since the low and high frequency energy in the various phases may not be controlled by the same waveguide.

Unlike the network used by Campillo *et al* (1985), the RSTN sites are few in number and fairly distant from each other (10 to 16 degrees separate the neighboring RSTN stations). Hence in this study the distance variation must come from many sources in different locations recorded at a few stations. This implies that we are forced to assume that all of the sources and all of the paths have the same properties within our chosen area of study in order to keep the number of unknowns in our regression analyses reasonable. Thus, our results give statistically averaged propagation and detection characteristics over eastern North America, not exact predictions for any given event over any specified path. This way we shall obtain a fairly representative average picture of the propagation characteristics of regional phases over stable regions.

The second main goal of this study is to estimate the detection magnitude thresholds at the RSTN network of regional phases propagating primarily through eastern North America (ENA). We estimate 50% detection thresholds for P_n , P_g , S_n , and L_g for a suite of frequencies from 1-16 Hz at various distances by measuring relative amplitude levels of noise and each of the seismic phases. For regional distances of 3 to 16°, smaller events are best detected at the higher frequencies.

The basic plan of this report is as follows: the first part discusses the propagation attenuation model used for the regressions. Then we present estimates of $Q(f)$ for various regional

phases, followed by estimates of the source spectra and scaling laws for each. In the following section we review and compare results of other studies in both stable and tectonic environments with ours. This is followed by the analyses of background noise at each RSTN station. Following this we present estimates of the detection thresholds for each regional arrival as functions of frequency and distance. Our results are again compared to those of other studies. The emphasis in this study is on the Lg phase since it usually has the maximum amplitude of the regional phases and is anticipated to have the lowest detection thresholds at many frequencies.

PROPAGATION-ATTENUATION MODEL

The time domain amplitude decay for dispersed surface waves is given by Ewing *et al* (1957) and Nuttli (1973) as

$$A = A_0 \Delta^{-1/3} (\sin \Delta)^{-1/2} e^{-\gamma \Delta}, \quad (1)$$

where Δ is the epicentral distance, measured in degrees, and γ is the coefficient of anelastic attenuation. For regional distances, the combined dispersion (for an Airy phase) and geometrical spreading, $\Delta^{-1/3}$ and $(\sin \Delta)^{-1/2}$, respectively, is $\sim \Delta^{-5/6}$ for small Δ .

The parameter γ is related to the quality factor Q by

$$\gamma = \frac{\pi f}{U Q(f)}, \quad (2)$$

where U is the group velocity and f is the frequency of the wave, equal to the reciprocal of its period.

If we consider a given phase from an earthquake source, the output amplitude of the seismic signal recorded at a seismometer Δ degrees from the source can be written as

$$A_{ij}(f) = E_j(f) S_i(f) \Delta_{ij}^{-1/3} (\sin \Delta_{ij})^{-1/2} e^{-\gamma \Delta_{ij}} \quad (3)$$

where A_{ij} is the amplitude received at the i th station from the j th event in a set of seismograms,

E_j is the event effect of the j th event, essentially a measure of the event magnitude, and S_i is the station bias of the i th RSTN site relative to the average of all RSTN sites.

Equation (3), describing a regression model of the regional signal propagation, is written for a single frequency, but it also holds for a narrow band of frequencies in the seismic signal passband. Thus, we can solve the problem for the relevant parameters at any frequency in the signal passband and so derive estimates of the spectra of the source effect E , the station effect S , and Q .

We are also assuming that the radiation pattern of all events is, on the average, azimuthally isotropic. This may be justified on the basis of synthetic simulation studies for the phase Lg (Alexander and Von Seggern, 1983, personal communication) that indicated that the total radiation pattern for Lg was close to isotropic for a wide variety of source mechanisms. It appears that since Lg arrivals are made up of many modes, even if the radiation pattern for individual modes is strongly directional, the superposition of many such modes must be much less asymmetric. However, we must note that a recent study by Kim *et al* (1985) asserts that visible asymmetries exist in the radiation pattern of a Swedish earthquake. In any case, when estimating attenuation rates from many earthquakes such asymmetries will simply increase the "noise level" of the least squares fitting procedure without affecting the results as long as the radiation patterns in the events used are sufficiently different.

It is not clear what form the combined geometrical spreading and dispersion should take for regional arrivals other than Lg . Since these may also be thought of as made up of numerous normal modes (Harvey 1981) we may try the same forms as used for Lg . Alternatively, we may adopt the values measured from synthetic seismograms of these phases computed by assuming no losses in anelastic attenuation (Harvey 1981, Bouchon 1982, Kennett and Clarke 1983a,b). As we shall see later, quite different spreading factors may yield similar

Q estimates at high frequencies where attenuation is the dominant factor in determining the wave amplitudes.

Finally, we assume that there is no variation in signal with variation in source depth. All the events in this study are shallow, less than 30 km deep and most are less than 20 km deep. Certainly the very deep events which might be poor generators of L_g (Noponen and Burnett 1980) are missing.

Some of these assumptions can be modified or removed by adding complexity to the model. Such would be the case if different Q values were assigned to different geographic areas and the Q for each source to receiver path adjusted to allow for the distance traversed through each of these areas. For this report however, only the simpler model defined by the above assumptions is used.

By taking logarithms of the terms in equation (1) of our model we get

$$\log_{10} A_{ij} = \log_{10} E_j + \log_{10} S_i - \frac{1}{3} \log_{10} \Delta_{ij} - \frac{1}{2} \log_{10} (\sin \Delta_{ij}) - 0.4343 \gamma \Delta_{ij} + \epsilon_{ij} . \quad (4)$$

The logarithms are to the base 10 so the event effect and station effect terms are proportional to the normal magnitude scales (for m_b , M_s , etc) used in seismology. The ϵ_{ij} is an error term.

Rewriting Equation (4) putting all the known terms on the right hand side and keeping all the terms to be estimated on the left, we have

$$\log_{10} E_j + \log_{10} S_i - 0.4343 \gamma \Delta_{ij} = \log_{10} A_{ij} + \left(\frac{1}{3}\right) \log_{10} (\Delta_{ij}) + \left(\frac{1}{2}\right) \log_{10} (\sin \Delta_{ij}) . \quad (5)$$

The matrix form of this equation becomes

$$G m = d \quad (6)$$

where d is the data vector which includes the L_g amplitude measurements along with the Airy phase dispersion and geometric spreading terms, $1/3 \log \Delta$ and $1/2 \log \sin \Delta$, respectively, and

where m is the model, a vector of the event effects (E), the station effects (S), and the γ term we are trying to estimate. G is the coefficient matrix, mostly of 1's and 0's describing the presence or absence of each model vector term for the particular station-event pair representing a single equation. The least squares solution of (6) is:

$$m = (G^T G)^{-1} G^T d . \quad (7)$$

DATA ANALYSIS

Selection of Events

Lists of events were compiled from several earthquake bulletins for this study, including the PDE lists from the USGS National Earthquake Information Network (NEIS), the Central Mississippi Valley Earthquake Bulletin (St. Louis University), the Seismic Network of Utah (University of Utah), the Southeastern US Seismic Network (Virginia Polytechnic Institute), the Northeastern US Seismic Network (Weston Observatory, Boston University), the Lamont-Doherty Network (Columbia University), and the Tennessee Earthquake Information Center (Memphis State University). Most of the local networks recorded events of small magnitude, too small to be seen at more than one RSTN site. Consequently, the predominant number of events are from the PDE lists of NEIS.

Figure 1 shows the geographical distribution of the epicenters and the RSTN stations. Figure 2 shows the paths from the epicenters to the RSTN sites for the L_g detections at 1 Hz. The complete list of events used in this study is given in Table 1.

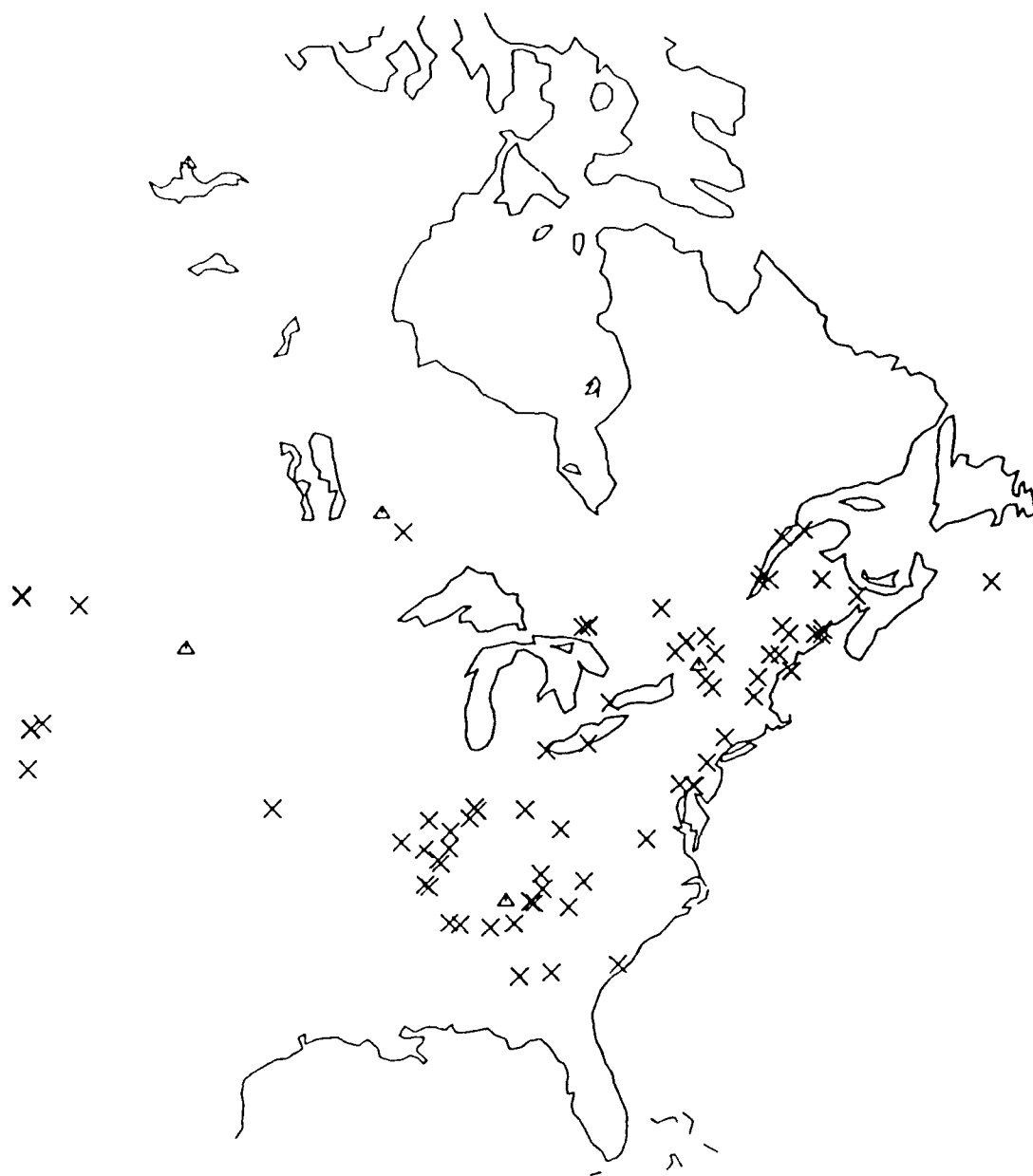


Figure 1. Geographical distribution of RSTN stations (triangles) and epicenters (crosses) used in this study.

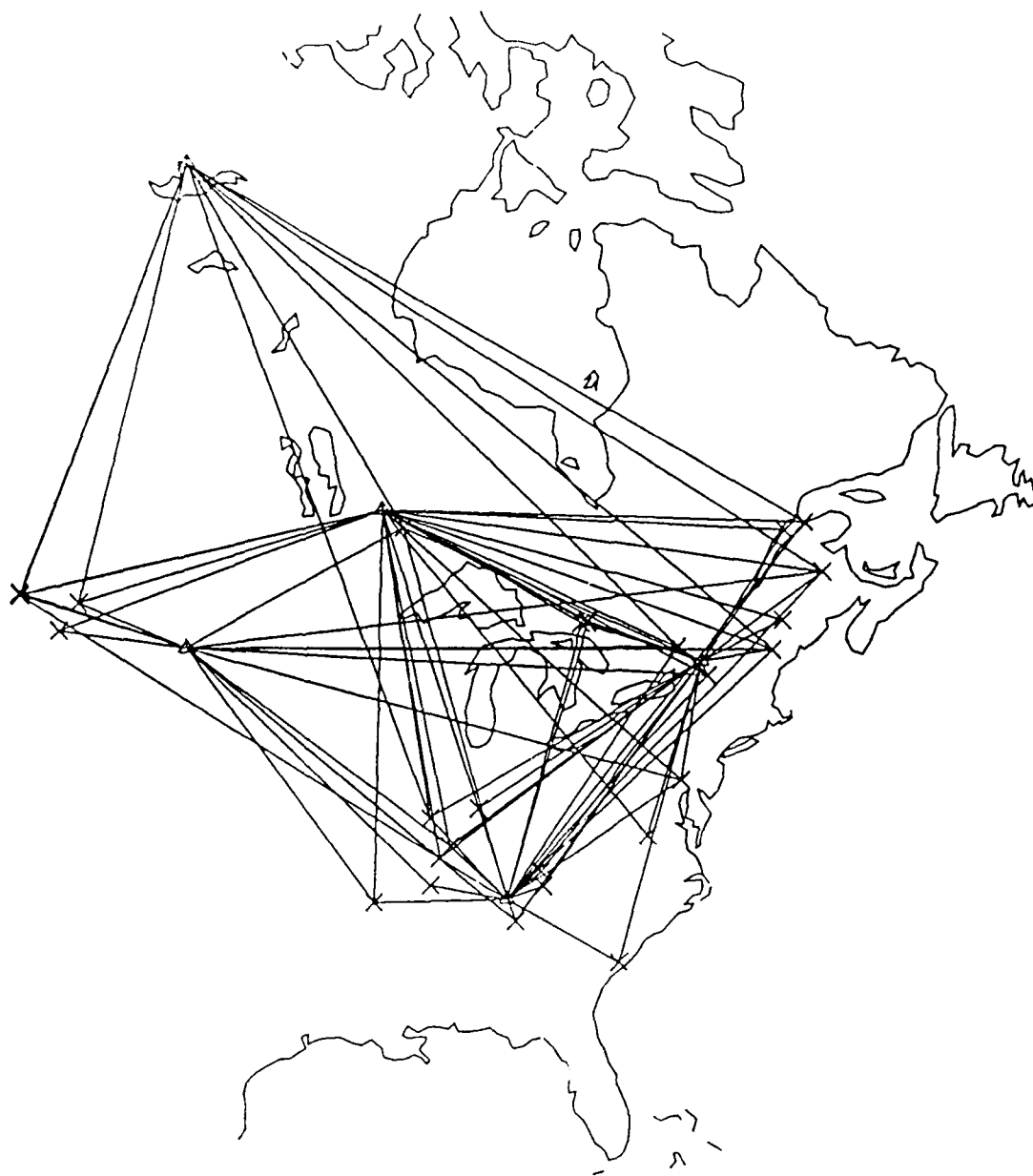


Figure 2. Epicenter-to-station paths used for studying L_g at 1 Hz. The path coverage is representative of that used for each of the regional phases for each frequency band.

TABLE 1

Earthquakes Used in RSTN High Frequency Study

DATE (yr/doy)	ORIGTIME (GMT)	LAT (degN)	LON (degW)	DEPTH (km)	ml (mb)	EVENT (name)
1983010	04:03:18.3	39.67	-110.65	7.9	2.4	3U010a
1983012	02:49:41.1	39.28	-84.60	0.0	1.9	3M012a
1983012	17:46:22.9	39.33	-111.10	1.3	2.0	3U012a
1983013	23:49:16.9	39.28	-111.15	5.0	2.2	3U013a
1983017	19:35:51.0	49.11	-66.98	18.0	4.1	3B017
1983017	19:35:51.0	49.11	-66.98	18.0	4.5	3P017
1983019	02:30:41.6	35.28	-92.16	4.0	3.9	3S019
1983019	10:40:35.5	39.32	-111.12	9.2	2.1	3U019a
1983021	01:34:58.8	39.31	-111.19	9.4	2.3	3U021a
1983022	07:46:57.9	41.87	-81.19	5.0	2.7	3P022
1983022	11:44:49.1	39.95	-111.95	4.0	2.8	3P022a
1983023	07:46:59.3	41.86	-81.16	0.0	3.0	3M023a
1983026	14:07:44.8	32.73	-83.38	5.0	3.5	3P026
1983026	14:07:44.8	32.73	-83.38	5.0	3.5	3V026b
1983027	22:09:35.0	36.05	-83.62	15.0	2.6	3P027
1983027	23:37:11.8	37.78	-110.67	7.0	3.3	3U027a
1983036	13:08:19.0	34.73	-88.31	3.0	3.2	3S036
1983037	20:25:15.5	44.57	-110.64	5.0	4.7	3P037
1983039	10:54:54.9	43.3	-111.19	7.0	4.4	3P039
1983040	16:10:23.5	38.60	-97.75	0.0	1.7	3K040a
1983042	15:46:56.0	48.99	-68.30	18.0	3.6	3B042
1983050	05:45:45.1	40.65	-74.77	6.0	2.5	3P050
1983054	08:09:14.2	37.08	-88.87	20.0	3.0	3P054
1983054	08:51:27.0	36.19	-89.60	9.0	3.6	3P054a
1983057	19:59:35.4	41.55	-73.66	7.0	2.9	3P057
1983072	13:03:11.6	43.70	-71.33	2.0	2.9	3P072
1983073	20:41:40.0	44.85	-57.00	18.0	4.0	3P073
1983083	14:27:20.4	42.96	-71.71	1.0	2.9	3P083
1983084	02:47:11.1	35.34	-82.46	9.0	3.2	3P084
1983102	20:13:05.0	43.69	-69.41	18.0	2.7	3P102
1983133	17:26:02.0	47.00	-66.60	5.0	3.6	3P133
1983133	23:40:57.0	47.00	-66.60	5.0	4.1	3P133a
1983135	05:16:21.6	38.77	-89.57	9.0	4.3	3P135
1983136	02:01:57.0	47.70	-69.93	10.0	4.0	3P136
1983147	23:03:35.1	45.54	-69.46	10.0	3.2	3P147
1983149	05:45:49.8	44.50	-70.41	2.0	3.9	3P149
1983153	06:30:23.0	47.45	-70.22	10.0	3.4	3P153
1983155	05:00:23.0	47.46	-69.65	10.0	3.0	3P155
1983161	04:22:39.0	47.00	-66.60	5.0	3.3	3P161
1983162	13:47:58.0	47.00	-66.60	5.0	3.4	3P162
1983180	02:06:14.1	43.73	-69.46	16.0	2.4	3P180
1983189	19:29:05.9	35.54	-84.15	11.0	3.3	3P189
1983224	14:08:47.6	44.97	-67.68	12.0	3.6	3P224
1983224	14:08:47.6	44.97	-67.68	12.0	3.6	3B224
1983229	14:03:15.0	38.47	-82.77	12.0	3.5	3P229
1983240	10:44:03.9	34.66	-87.77	7.0	2.6	3P240
1983240	22:45:06.5	36.70	-83.84	5.0	3.1	3P240a
1983277	17:18:40.0	43.44	-79.79	2.0	3.1	3P277

1983280	10:18:46.1	43.94	-74.26	13.0	5.1	3P280
1983280	10:39:38.5	43.95	-74.26	8.0	3.5	3P280a
1983280	10:59:03.8	43.95	-74.26	8.0	2.9	3P280b
1983284	04:10:55.0	45.21	-75.77	15.0	4.2	3P284
1983285	02:17:06.3	43.95	-74.26	8.0	2.8	3P285
1983289	03:00:47.0	45.62	-75.05	11.0	3.1	3P289
1983301	14:06:06.6	44.06	-113.86	10.0	6.2	3P301
1983301	19:51:24.4	44.07	-113.91	7.0	5.4	3P301a
1983303	01:24:51.2	44.08	-113.97	13.0	4.3	3P303
1983303	17:02:53.3	44.44	-69.88	10.0	2.9	3B303
1983305	10:16:52.0	45.68	-73.90	18.0	3.5	3P305
1983310	09:02:19.8	32.94	-80.16	10.0	3.1	3P310b
1983310	09:04:14.6	32.93	-80.15	11.0	2.2	3P310a
1983310	21:04:44.8	44.15	-113.97	12.0	4.3	3P310
1983321	19:55:06.5	39.83	-75.66	5.0	2.2	3P321
1983338	10:48:33.7	45.19	-69.14	1.0	3.4	3P338
1983342	12:23:05.3	45.08	-67.21	10.0	3.2	3P342
1983346	05:15:09.5	39.83	-75.66	5.0	2.0	3P346
1983362	12:24:21.0	47.01	-76.33	18.0	3.4	3P362
1983365	06:31:12.1	32.60	-84.90	5.0	2.6	3P365
1983365	17:17:27.2	32.57	-84.92	5.0	2.6	3P365a
1984012	02:48:15.7	37.59	-89.75	2.0	3.0	4P012
1984014	09:08:34.5	45.05	-67.18	8.0	3.4	4P014
1984014	09:09:33.1	45.05	-67.18	8.0	3.6	4P014a
1984014	20:14:31.2	41.65	-83.43	5.0	2.5	4P014b
1984017	19:04:46.0	45.56	-75.12	19.0	3.1	4P017
1984019	05:26:09.2	44.88	-67.34	11.0	3.8	4P019
1984019	23:03:34.0	39.79	-75.52	5.0	2.4	4P019a
1984042	11:26:41.0	50.23	-92.24	18.0	3.9	4P042
1984044	22:42:45.3	37.21	-89.02	2.0	3.3	4P044
1984045	20:54:31.0	36.12	-83.73	8.0	3.7	4P045
1984045	22:56:10.4	37.21	-89.00	2.0	3.6	4P045a
1984055	03:17:14.0	47.00	-66.60	5.0	3.7	4P055
1984108	04:44:43.8	38.38	-88.44	20.0	3.4	4P108
1984110	04:54:58.3	39.92	-76.32	5.0	3.0	4P110
1984114	01:36:00.1	39.92	-76.36	5.0	4.1	4P114
1984164	18:26:48.2	38.92	-87.46	3.0	3.4	4P164
1984172	14:12:27.0	46.58	-80.80	1.0	3.4	4P172
1984172	16:10:22.0	46.63	-80.78	1.0	3.5	4P172a
1984172	16:18:17.0	46.53	-80.80	1.0	3.3	4P172b
1984178	15:15:19.9	36.10	-89.39	12.0	3.3	4P178
1984181	07:58:29.3	37.70	-88.47	2.0	4.1	4P181
1984188	17:24:52.0	46.53	-81.17	1.0	4.0	4P188
1984210	23:39:27.3	39.22	-87.07	10.0	4.0	4P210
1984212	07:33:46.5	37.83	-90.92	7.0	3.0	4P212
1984222	02:42:35.2	34.56	-86.31	5.0	3.0	4P222
1984230	18:05:46.8	37.87	-78.32	8.0	4.2	4P230
1984233	10:58:16.6	44.91	-73.48	12.0	3.2	4P233
1984242	06:50:56.4	39.37	-87.22	10.0	3.2	4P242
1984243	16:26:28.5	35.56	-84.34	14.0	3.2	4P243
1984243	16:41:52.2	35.61	-84.37	15.0	2.4	4P243a
1984267	08:56:31.0	46.00	-64.80	18.0	3.9	4P267
1984283	11:54:26.2	34.72	-85.16	5.0	4.0	4P283
1984296	18:58:41.9	36.36	-81.67	8.0	3.1	4P296
1984297	06:26:21.5	43.59	-73.94	1.0	3.2	4P297

In this study we used a naming convention for events to facilitate searching and editing event files and analysis results. Since the RSTN data did not become available until 1982 and after, the event name includes the last number of the year, a letter indicating which bulletin listed the event, and the three digits indicating the day of the year. Thus event 4P150 was an event on day 150 of 1984 listed by the NEIS PDE bulletin. A second event on this same day is referred to as 4P150a; a third event would be 4P150b, and so on. The bulletin codes are listed in Table 2.

TABLE 2

Bulletin Codes for Event Names

Letter Code	Bulletin
B	Northeastern US Seismic Network Bulletin, Boston College, Weston Observatory
D	Lamont-Doherty Network Bulletin, Columbia University National Earthquake Information Service
K	Kansas-Nebraska Regional Network Bulletin, University of Kansas
M	Ohio-Indiana Regional Network Bulletin, University of Michigan
P	Preliminary Determination of Epicenters, National Earthquake Information Service, US Dept. of Interior, Geologic Survey
S	Central Mississippi Valley Earthquake Bulletin, St. Louis University
T	Tennessee Earthquake Information Center Bulletin, Memphis State University
U	Utah Seismic Network Bulletin, University of Utah
V	Southeastern US Seismic Network Bulletin, Virginia Polytechnic Institute & State University

Signal and Noise Spectra

The amplitude versus frequency data needed for the regression analysis can be obtained from either spectra or from bandpass filtered time domain data. Typical Lg spectra and accompanying noise spectra sampled prior to the onset of the Pn phase are shown in the Figure 3 for an event at the five RSTN stations. The spectral windows were 25.6 seconds long and were tapered with a Parzen time window. The spectra have been corrected for instrument

displacement response and smoothed with a 16 point running average. The signal spectra are plotted with pluses (+) and noise spectra plotted with zeros (o). The best S/N ratio of L_g for this event is typically at around 2-4 Hz, and the S/N ratio decreases considerably below 1 Hz due to low frequency microseismic noise.

Narrow Band Filtering

While spectra such as those shown in Figure 3 can be used to obtain the amplitude versus frequency data, we have chosen to use bandpass filtered seismograms instead. The approach used is essentially identical to that of Mechler *et al* (1980), and it has the advantage of giving a clear picture of the behavior of the regional arrivals in both the frequency and time domains. The relative amplitudes of the various arrivals vary from band to band, some are not apparent in some frequency bands, and the decrease in amplitudes with distance also varies with frequency.

The entire regional seismogram for an event at an RSTN site includes some noise before the initial P plus the P_n , P_g , S_n and L_g phases. This trace is used as the input to each of nine Butterworth band-pass filters. The center frequencies of these filters were equally spaced on the log(frequency) scale and they all had a 24 db/octave falloff at the flanks. The choice for this filtering method was based on the requirement that all filter outputs would exhibit relatively low ringing, so that the codas of the phases could be recognized. Had we chosen bandpass filters equally spaced on the frequency scale the phases would have run into each other at high frequencies because of the long ringing time of the filters. The frequency ratio corresponding to the spacing of the filter center frequencies was 1.54:1.

The outputs of the nine narrow passband filters were rectified and smoothed using a running average of 20 points applied twice (which amounts to a triangular weighting (smoothing) function over 1 second duration) to produce an envelope tracing of the filtered seismogram.

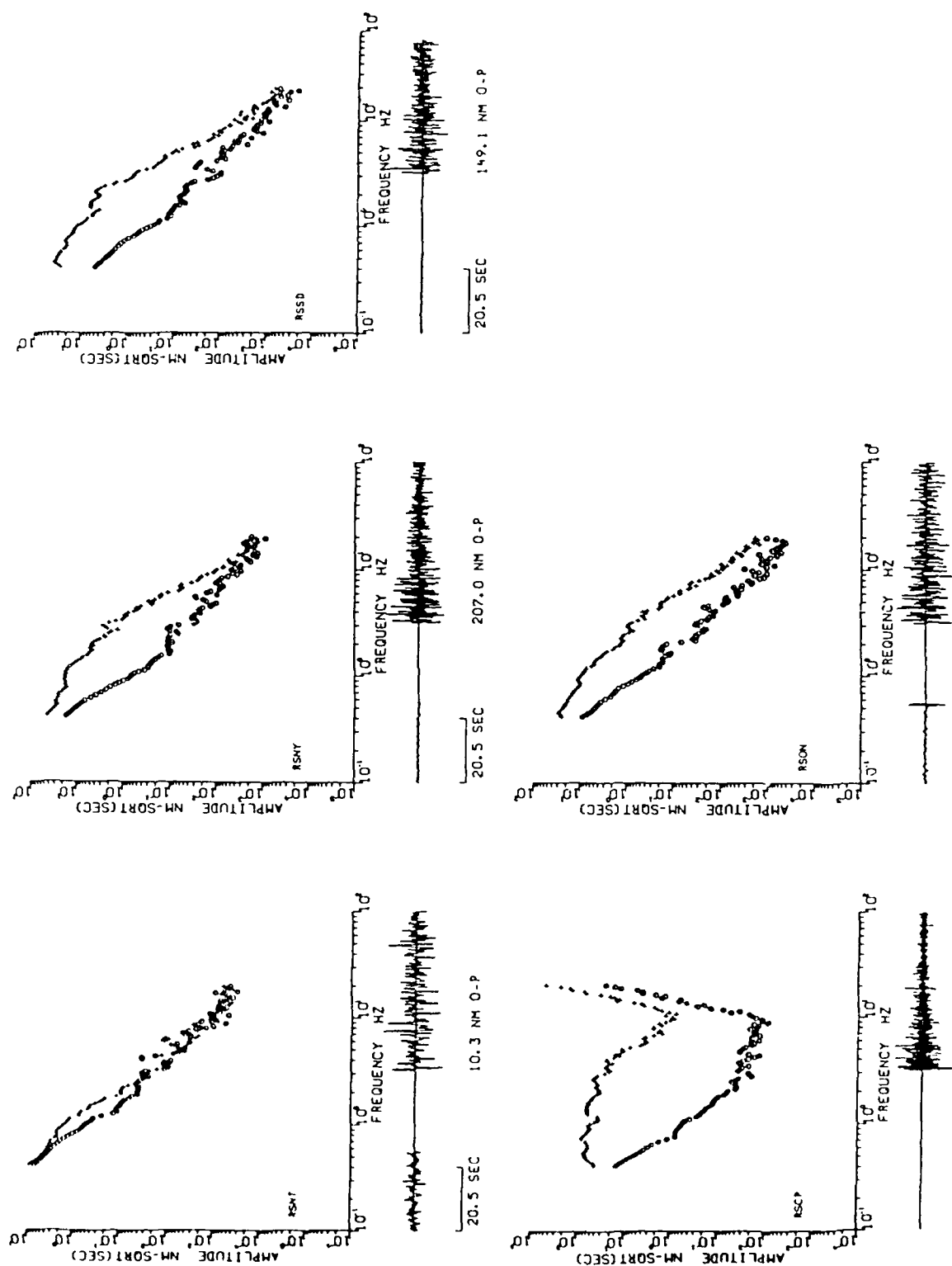


Figure 3. Examples of L_g signal (crossed) and noise (open circles) spectra at the five RSTN stations for an m_b 4.3 earthquake, event 3P135. Below each pair of spectra are the original noise (left) and signal (right) traces, plotted on the same scale. The noise window is from before the P arrival.

Finally, the signal amplitude for a particular phase such as Lg is the maximum amplitude of the filtered envelope trace in the expected arrival time window for the phase. The frequency assigned to that reading is determined by counting the average number of zero crossings per second for all of the filtered seismograms (prior to rectifying) in the data set (over 100 earthquakes) through that narrow bandpass filter. In all cases, the frequency is below the center of the filter passband since both the signal and the noise displacement spectra decay with increasing frequency and the dominant frequency of the band-pass filtered signal usually is not quite the same as the central frequency of the band-pass filter although in most cases they are not too different from it. These measured frequencies were used in the regression analysis.

Examples of the envelope seismograms are shown in Figures 4a-4e. In each case, the top trace is the envelope of the unfiltered data. The following nine traces are the outputs of the nine passband filters from lowest to highest frequency.

Figures 4a to 4d show seismograms associated with shield type propagation. At low frequencies Lg dominates, but as the frequency increases Pn becomes prominent (Figure 4a). At larger distances, Lg disappears as the frequency increases, and Pn and Sn dominate. Seismograms of similar nature have also been observed in eastern Canada (Shin 1985, Shin and Herrmann 1987) and at NORESS over paths of "shield" type (Kvaerna and Ringdal 1986).

Figure 4e shows typical features for events located in the tectonically active western part of North America as recorded at RSSD. In contrast to the previous examples, such events show a clear Pg phase and an Lg that is seen to high frequencies. No Sn is visible. The Pn phase sometimes emerges at high frequencies with low amplitudes although it is not visible at low frequencies.

Most of the features of our results are similar to those obtained by Mechler *et al* (1980). Mechler *et al* studied regional wave propagation across France using bandpass filtered seismo-

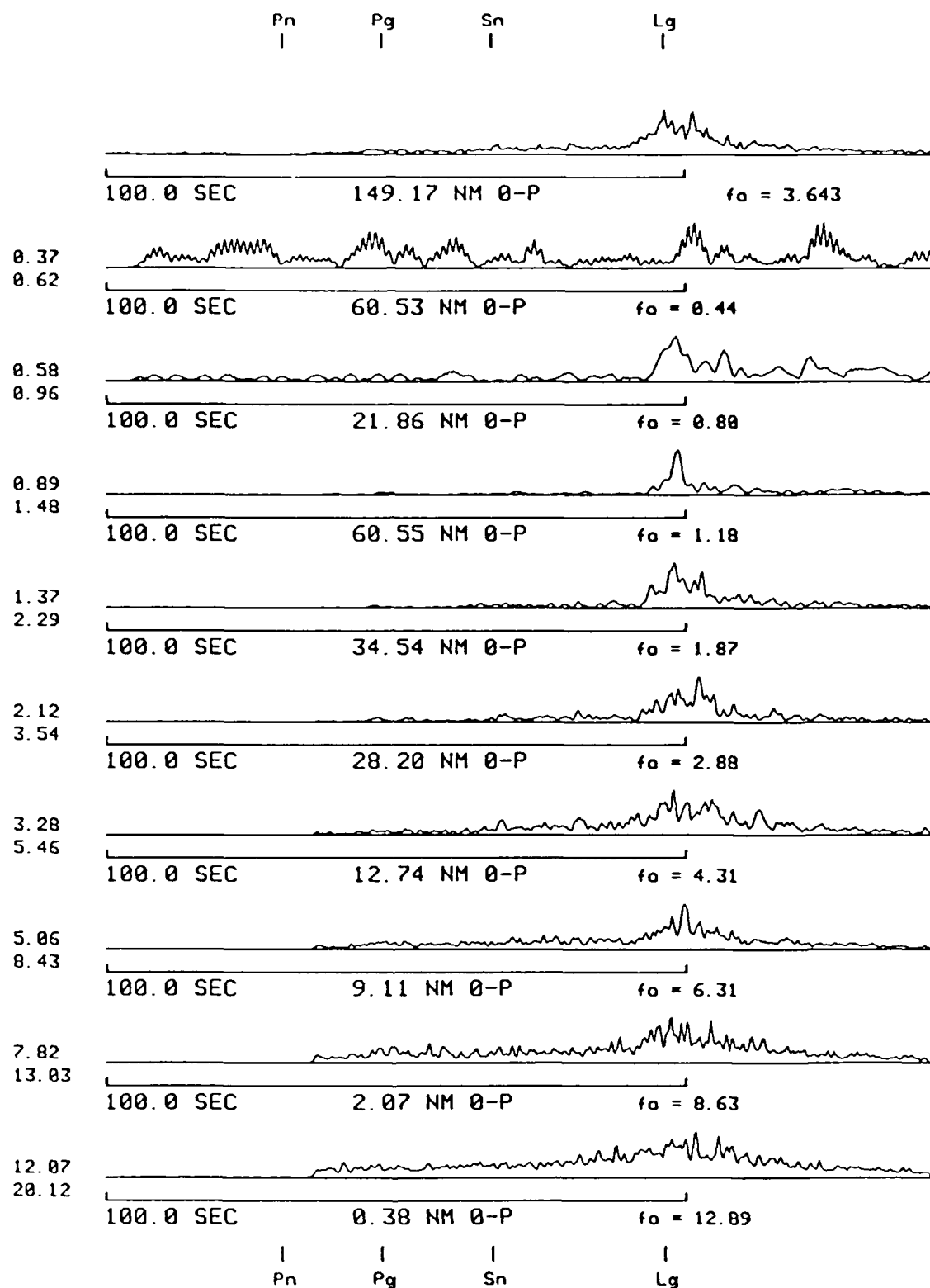


Figure 4a. Broadband envelope seismograms (top) followed by narrow band envelope seismograms. The corners of the frequency band are to the left of each seismogram. The maximum amplitude and the average frequency (from counting zero-crossings prior to rectification) are below each trace. Estimates of arrival times of the regional phases P_n , P_g , S_n , and L_g are marked above and below each suite of traces. Seismograms for an m_b 3.2 earthquake, event 3P147, recorded at RSNY at the epicentral distance of 3.7 degrees. Only P_n and L_g phases are discernible.

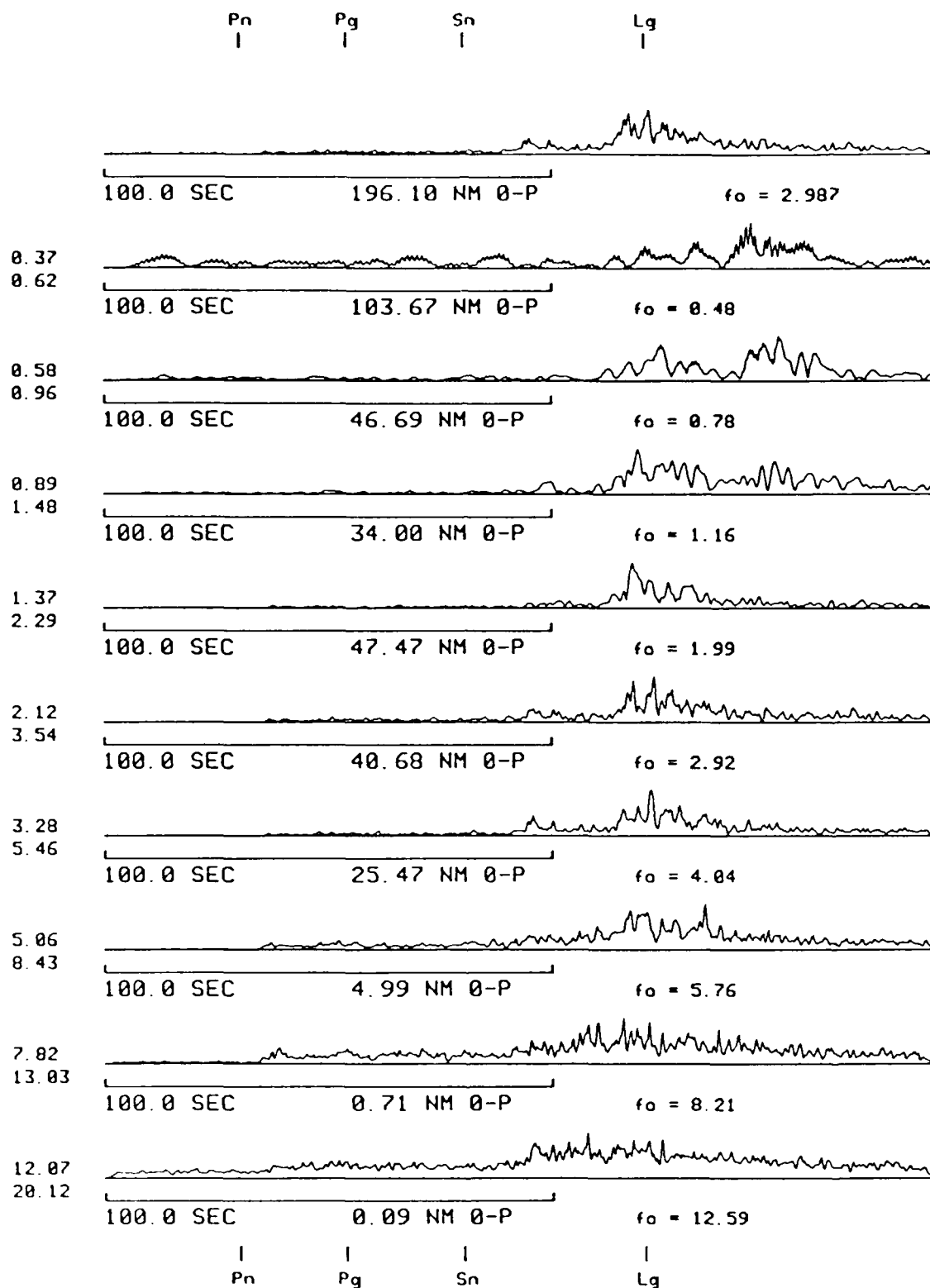


Figure 4b. Like Figure 4a except seismograms for an m_b 4.0 earthquake, event 4P188, recorded at RSNY at the epicentral distance of 5.1 degrees. The phases Pn , Pg , Sn and Lg are discernible. Lg is the largest phase at low frequencies. The Sn phase becomes dominant at the highest frequencies, while Lg disappears into the coda of Sn .

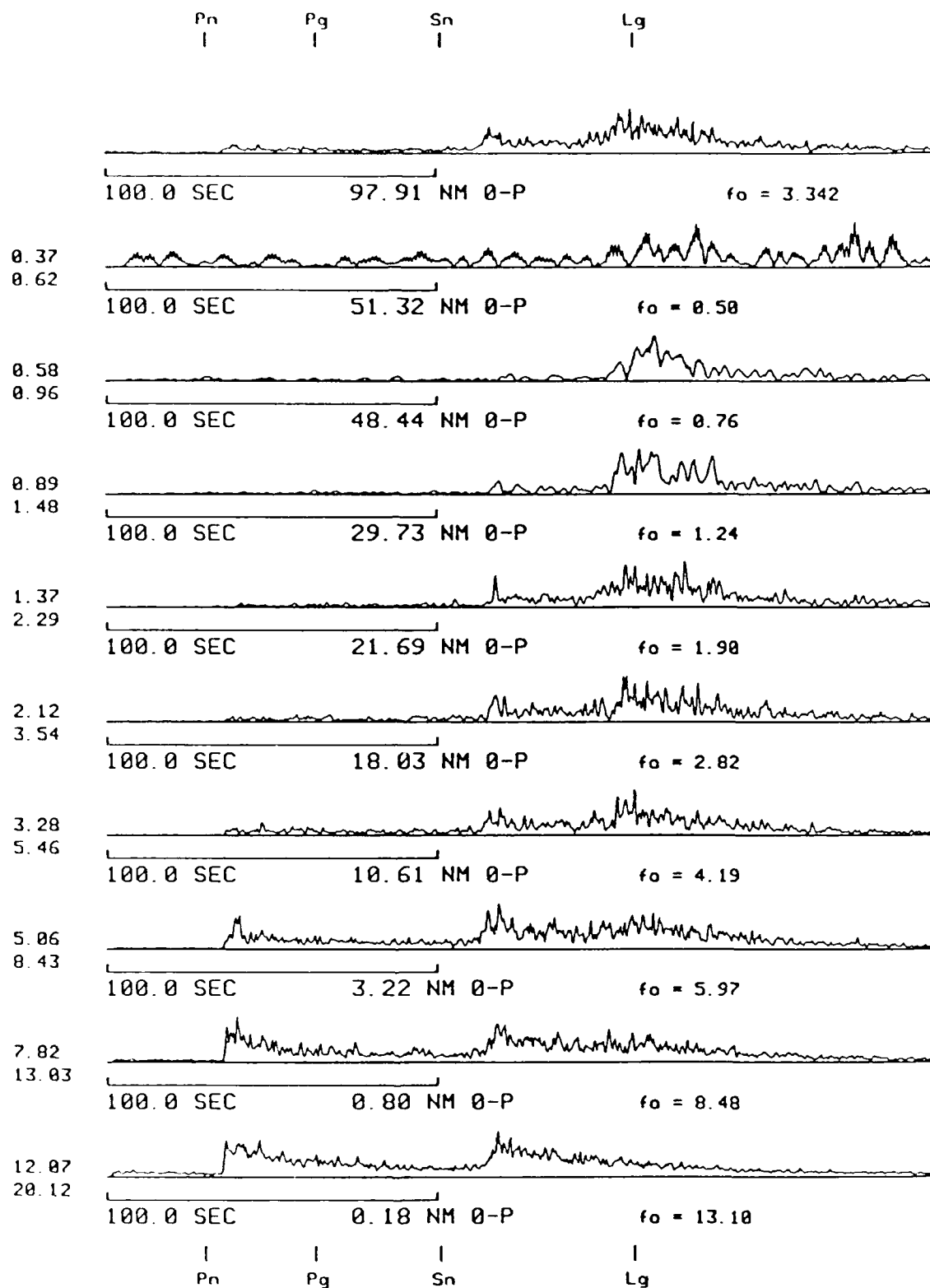


Figure 4c. Like Figure 4a except seismograms for an m_b 4.1 earthquake, event 4P230, recorded at RSNY at the epicentral distance of 6.9 degrees. As in Figure 4b, Lg dominates at low frequencies, while Pn is very small in comparison. At the highest frequencies Pn and Sn dominate with much higher S/N ratios than at lower frequencies.

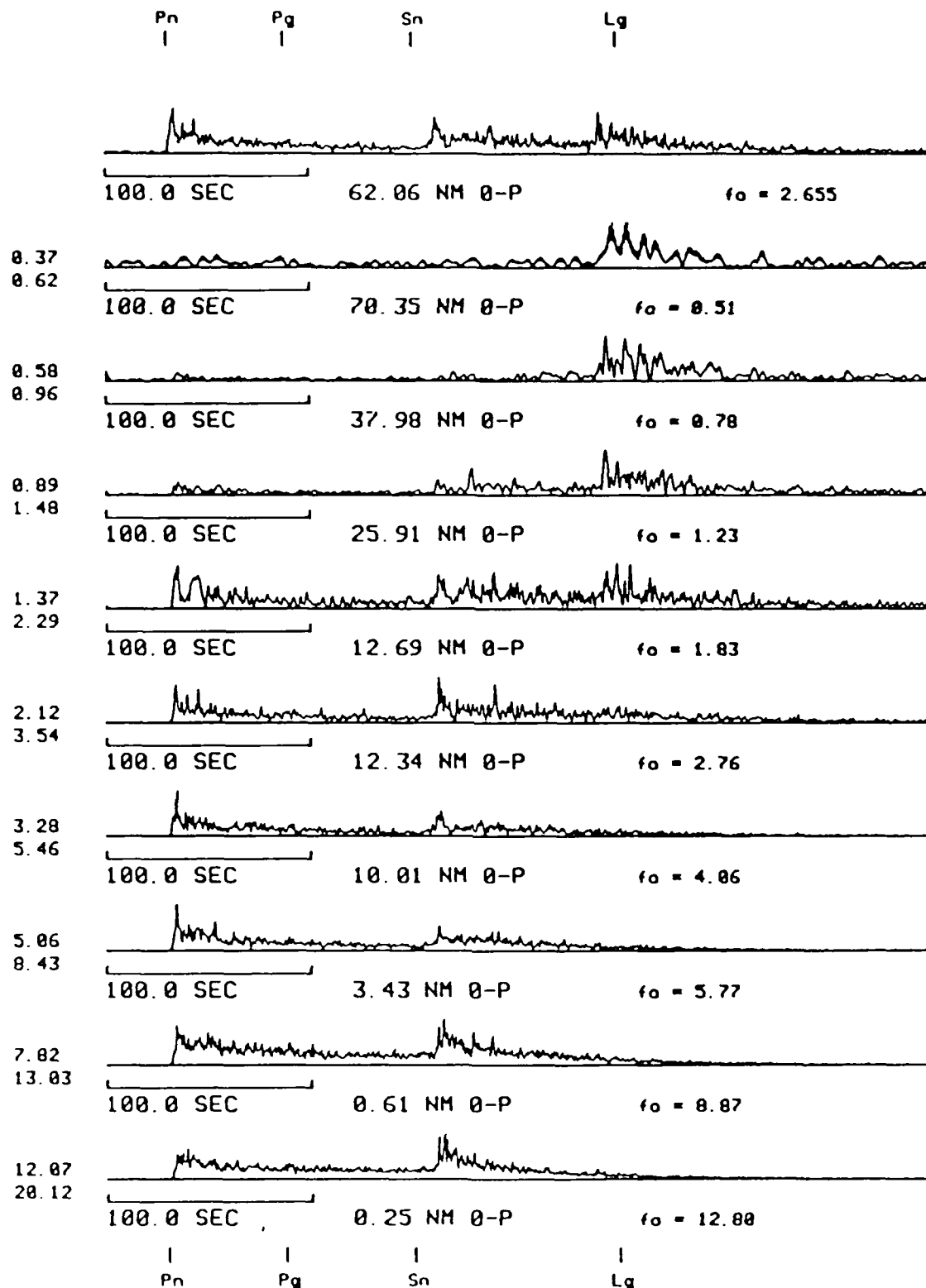


Figure 4d. Like Figure 4a except seismograms for an m_b 4.3 magnitude earthquake, event 3P135, recorded at RSON at the epicentral distance of 12.4 degrees. The relative behavior of the three phases P_n , S_n and L_g is similar to that in Figures 4b and 4c.

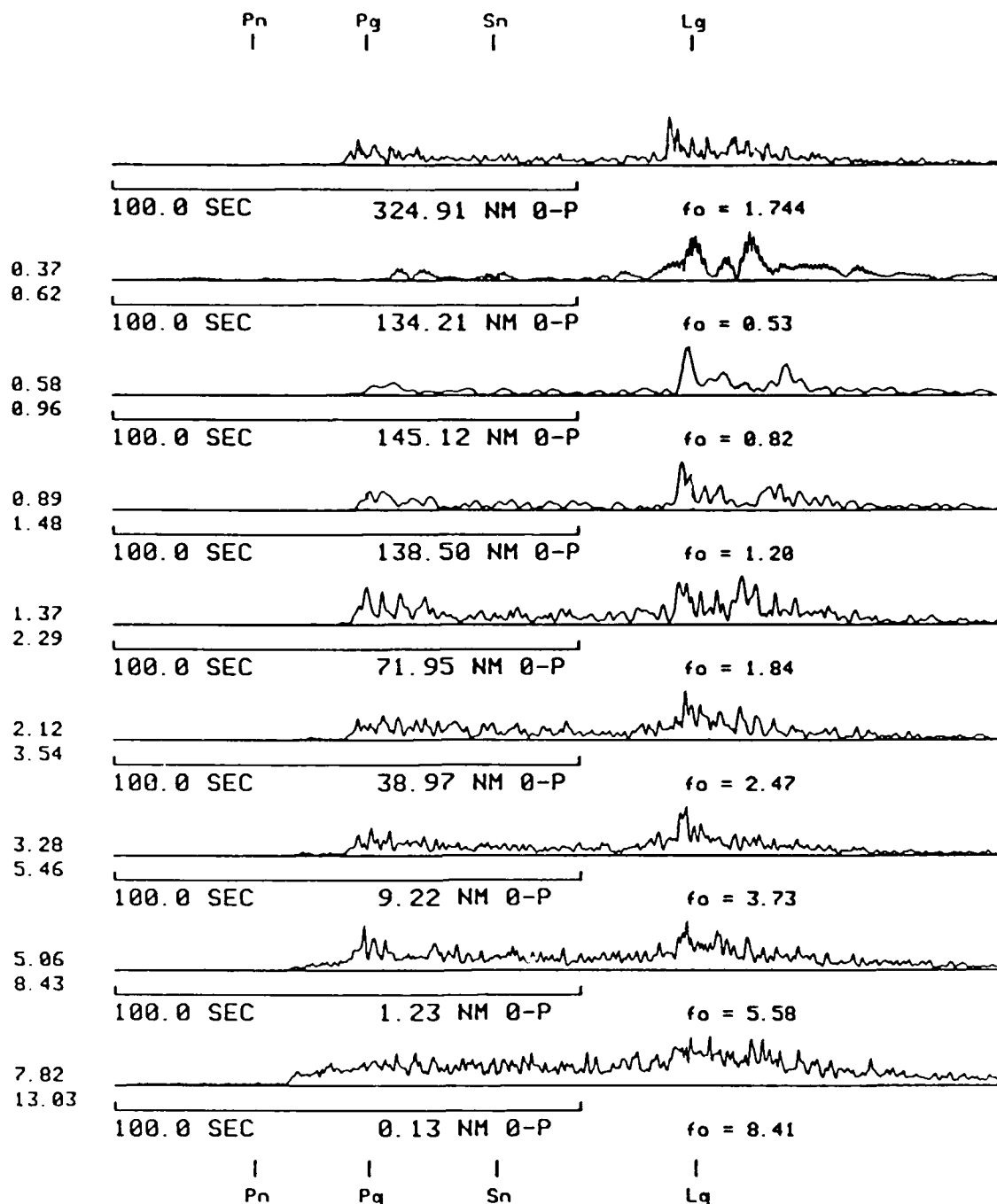


Figure 4e. Like Figure 4a except seismograms for an m_b 4.4 magnitude earthquake, 3P039, recorded at RSSD at the epicentral distance of 5.3 degrees. The relative behavior of Pn , Sn and Lg is quite dissimilar to the previous examples, Sn is not visible, Lg persists to quite high frequencies, and there is a prominent Pg phase besides the small Pn . The highest S/N is at lower frequencies. The path crossed some tectonically active regions in the western United States.

grams and found that P_n and S_n have their maximum energy at higher frequencies than do P_g and L_g . The main difference between the results of Mechler *et al* and this study is that in our data the P_g arrivals are less pronounced and are often absent. This is probably due to the different nature of the propagation paths in the two studies. Most of our paths are in the shield-like eastern North America and show little or no P_g while our paths from events in the tectonically active regions of the western North America tend to show a clear P_g , and more L_g and less P_n and S_n than the eastern paths. Mechler *et al*'s paths are across France which has more recently been more active tectonically than has eastern North America. The difference in the relative amounts of P_n and P_g observed on different propagation paths may be due to the different crustal and upper mantle velocity structures.

The frequency dependences of the attenuation and of the excitation of the various crustal arrivals will have to be explained eventually with some appropriate models of the crustal waveguide. Given the fact that most theoretical algorithms for doing theoretical simulations of regional arrivals become less efficient and are expensive to run as frequency increases while the valid data extend to very high frequencies, this poses a major challenge to theoreticians. Moreover, it seems certain that the amplitude decay of crustal phases is mostly caused by scattering and not anelastic attenuation, which requires the development of theoretical models of scattering appropriate to the crust and uppermost mantle. The examples above demonstrate that there is quite a variety in the appearances of the seismograms for various paths and that the regional phases P_n , P_g , S_n and L_g appear and disappear in the various frequency bands depending on the nature of the propagation paths. Thus in any scheme devised for an automatic recognition of the regional phases one needs a knowledge base that incorporates all the regionally varying characteristics of regional arrivals (Kennett and Mykkeltveit 1984; Kennett *et al* 1985; Mykkeltveit and Kvaerna 1986).

Signal Selection

As stated previously, the signal amplitudes used in the regression analyses are the peak values of the filtered envelope traces in the expected arrival time window of the particular phase. These values are read by the computer from the envelope traces themselves rather than read by an analyst from the plotted waveforms. Obvious noise readings were deleted manually later in a quality control phase. This way, not all traces are read for all frequencies for all RSTN sites for each event.

In order to avoid the use of marginal and noisy data we decided that to be included in our data set, an *Lg* signal must be detectable at any site on the unfiltered, raw seismogram. Although this limits the data sets mostly to larger signals, we also eliminate many marginal events with poor S/N ratios while retaining a sufficient number of events for reliable analyses of the data. In estimating thresholds of detection from such a set of larger events we had to determine the sizes of events that would have a S/N ratio of unity (50% threshold) by extrapolating the data to smaller events.

For each raw, unfiltered seismogram where an *Lg* was detected, we scanned the narrow passband envelope traces to determine, by eye, in which of the frequency passbands the *Lg* phase was seen. Only these signal amplitudes at these frequencies were entered into the regression analysis.

The net result of this selection process is that 227 station-event pairs of *Lg* signals were included in the analysis. Table 3 shows the distribution of event magnitudes included in this study for which at least one RSTN site detected an *Lg* phase.

TABLE 3			
DISTRIBUTION OF EVENT MAGNITUDES USED IN L_g ANALYSES			
magnitude	number	magnitude	number
$(m_b \text{ or } m_l)$	no.	$(m_b \text{ or } m_l)$	no.
1.7	1	3.4	8
1.9	1	3.5	6
2.0	2	3.6	7
2.1	1	3.7	2
2.2	3	3.8	1
2.3	1	3.9	4
2.4	4	4.0	5
2.5	2	4.1	4
2.6	4	4.2	2
2.7	2	4.3	3
2.8	2	4.4	1
2.9	5	4.5	1
3.0	7	5.1	1
3.1	6	5.4	1
3.2	8	6.2	1
3.3	6	...	.

RESULTS

In this section, we discuss the results of the joint regression analyses performed for attenuation, source, and receiver terms. First, Q , source spectra, and station terms are presented for L_g , and then the results for P_n and S_n . Our results are compared with those from other studies for both shield and tectonic regions. We also present average noise spectra at the five RSTN stations for both day and night conditions.

Q vs. Frequency for L_g

The results of the regression of 227 L_g signal measurements from 114 earthquakes recorded at the five RSTN sites are shown in Table 4. The Table shows the predominant frequency of each of the nine narrow passband filters as measured by the rate of zero crossings together with the regression estimate of γ and its standard deviation. The combined geometri-

cal spreading and dispersion was taken at $\Delta^{-5/6}$ per Equation (1). Q is determined immediately from the estimate of γ using Equation (2).

TABLE 4							
FREQUENCY VERSUS ATTENUATION FOR L_g							
Freq Band No.	Dominant Frequency (Hz)	Number of Signals	γ (deg ⁻¹)	$\hat{s}(\gamma)$ (deg ⁻¹)	Q	$\hat{s}(Q)$	RMS of Amplitude Residuals
1	0.5	48	0.062	0.019	774	235	0.16
2	0.7	69	0.079	0.010	939	117	0.13
3	1.1	121	0.104	0.010	1103	101	0.17
4	1.8	121	0.162	0.009	1109	62	0.16
5	2.8	95	0.174	0.018	1585	163	0.23
6	4.1	65	0.278	0.018	1482	98	0.17
7	5.9	32	0.292	0.040	2025	278	0.25
8	9.1	18	0.442	0.054	2055	252	0.10
9	13.7	18	0.500	0.123	2730	670	0.23

Figure 5 shows a log-log plot of γ versus frequency. Figure 6 shows a similar plot for Q versus frequency on a log-log scale. The straight-line fit to this estimate of Q is

$$Q = 1000f^{0.35} \quad (8)$$

It has been suggested that at frequencies above 7 or 10 Hz in the Appalachians and eastern Canada, L_g experiences significant contamination from S_n coda (Shin 1985, Chun *et al* 1987, Shin and Herrmann 1987). This is suggested by the way that L_g disappears into the S_n coda at higher frequencies on bandpassed seismograms such as those for eastern North America events in Figures 4a to 4c. To reduce the chances for such errors, we have also computed Q_{L_g} only using frequencies up to 5.9 Hz and 9.1 Hz, respectively. In both cases, the Q_{L_g} agrees with Equation (8). This is probably because at each frequency only L_g observations that had been confirmed by an analyst examining the bandpass filtered seismograms were included in the analysis. Thus, many fewer L_g observations were used at the higher frequencies than at frequencies around 1-3 Hz where L_g dominates (see column 3 of Table 4).

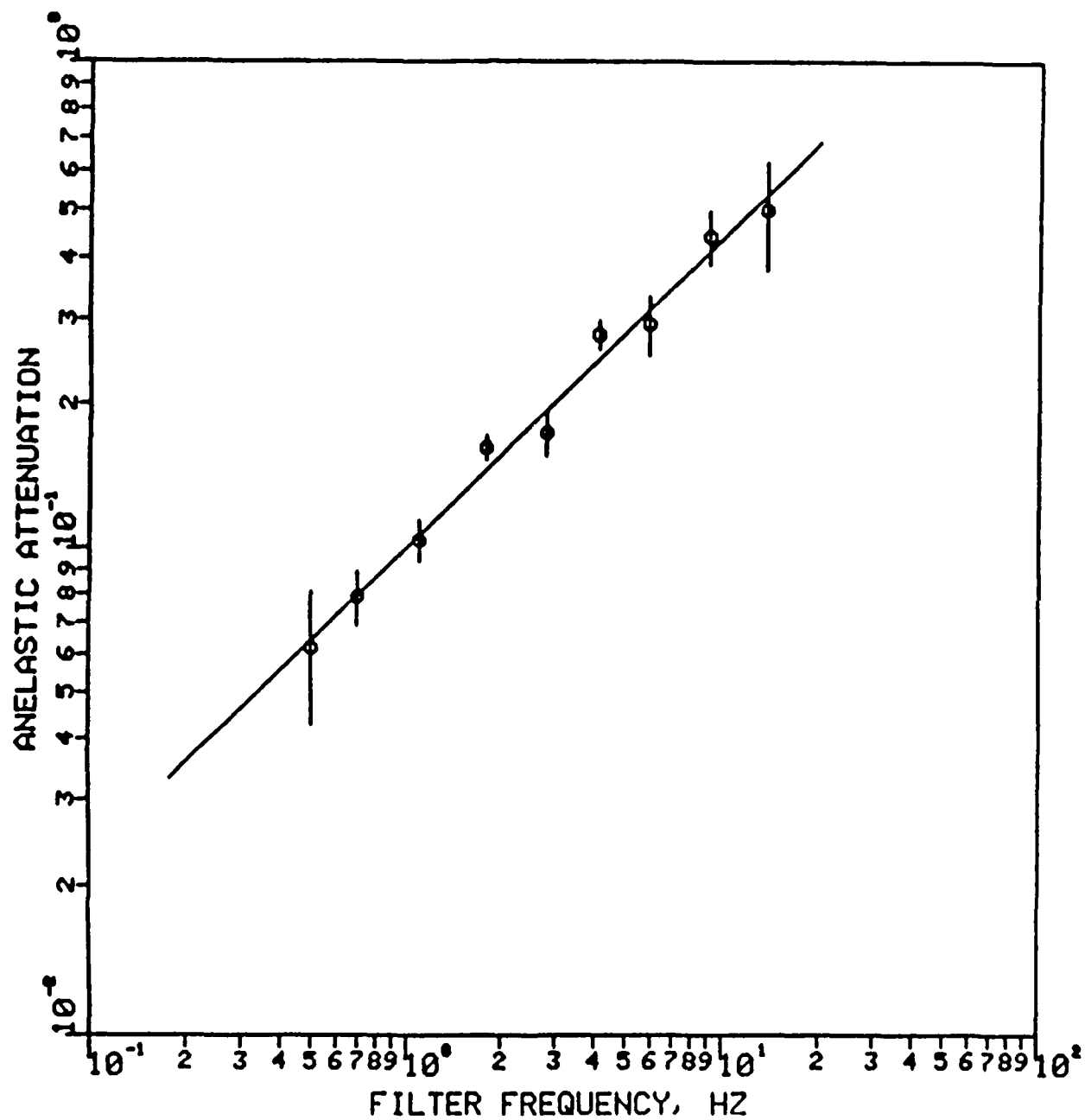


Figure 5. Log-log plot of L_g attenuation coefficient γ versus frequency. The estimated standard deviation is indicated by bars.

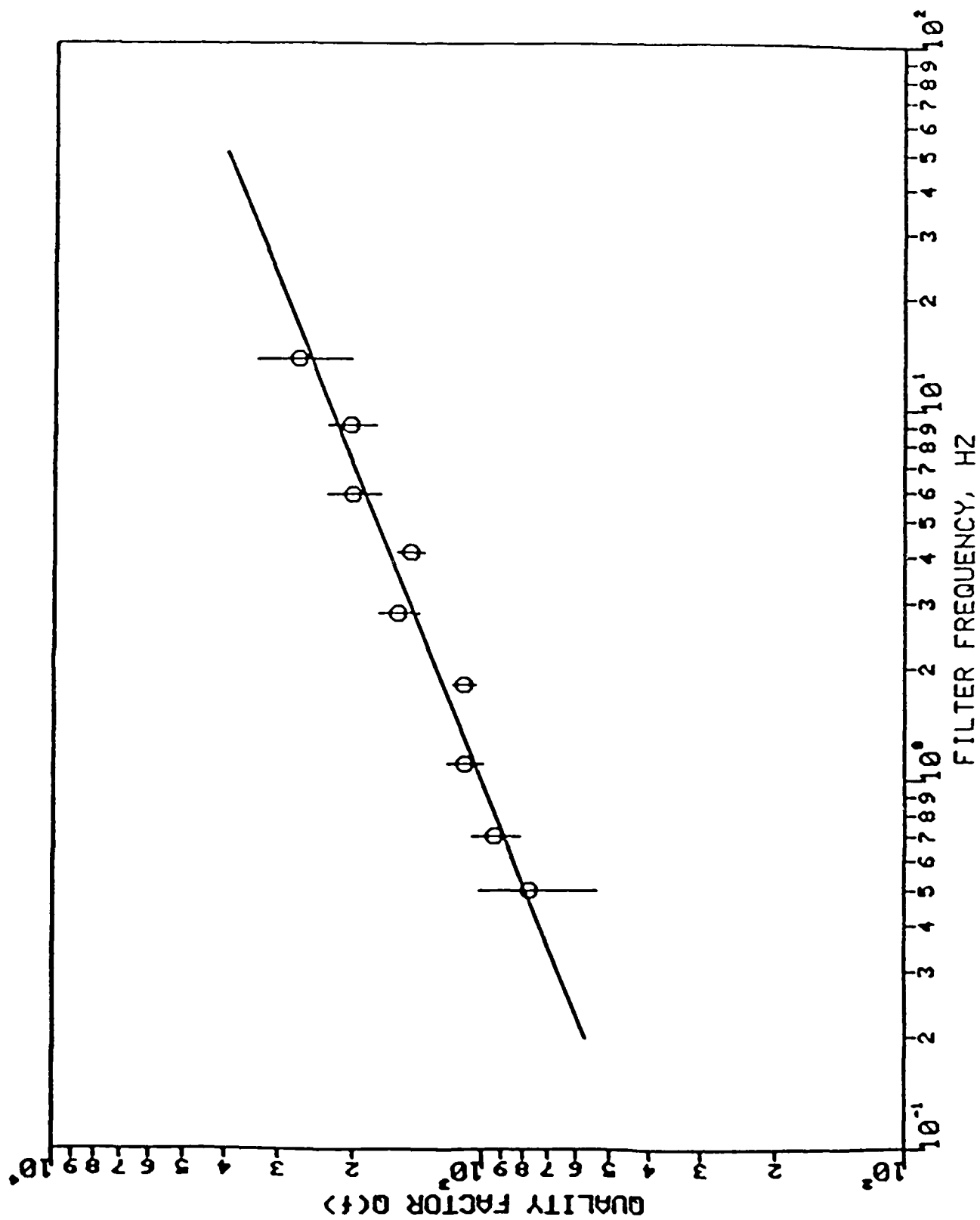


Figure 6. Log-log plot of Q versus frequency for L_R . The bars indicate one standard deviation of the Q estimates.

Station Effects

In the regression analysis the station bias to *Lg* signals for RSTN sites is measured relative to each other. This means that the sum of all RSTN station bias measures is unity at all frequencies. The bias as a function of frequency for all five RSTN's is shown in Figure 7. Since the RSCP site cuts off sharply for frequencies beyond 8 Hz, no attempt was made to include its bias with those from the other sites beyond 8 Hz. We had no data from RSNT above 3.5 Hz.

The station effect (y-axis) is a logarithmic measure like the magnitude scale. RSSD is the site with the largest negative bias, especially at the higher frequencies. The other sites are near zero or with positive bias to compensate for RSSD. The bias for all RSTN sites at frequencies less than 3 Hz is slight. These results are not inconsistent with the site terms found by Gupta and McLaughlin (1987b). Gupta and McLaughlin find that the RSSD site term has a downward trend at frequencies above 3 Hz, while the RSON and RSNY site terms are flatter than the RSSD site term. We do not expect too many similarities between our results and those of Gupta and McLaughlin because Gupta and McLaughlin's data set included many more stations than ours, and the site terms are not absolute but are relative to each other. The lower high frequency amplitudes at RSSD might be because some *Lg* arrivals with low high frequency content were included in our data. These probably come from mixed tectonic-stable paths covering part of western North America. Gupta and McLaughlin (1987a) have also found from a similar study which included many LRSM stations that large site amplitudes correlate well with soft site geology while small site amplitudes correlate well with hard rock site geology.

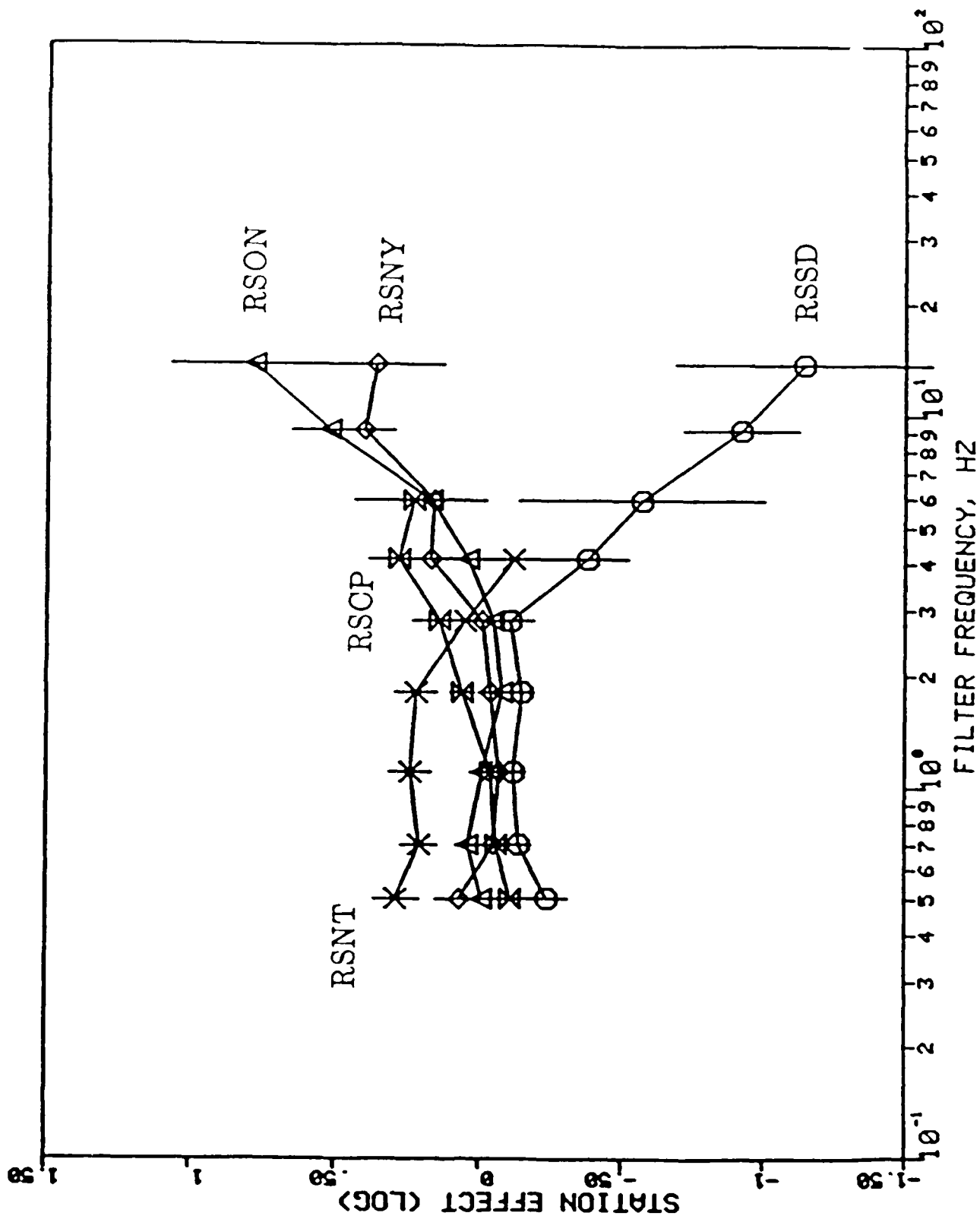


Figure 7. Station effect versus frequency for L_g for the five RSTN stations.

Source Spectra for Lg

The regression analysis yields an event effect which is a measure of the *Lg* excitation and the size of the event. Figure 8 shows the *Lg* event effect estimates versus network magnitude with a linear least squares fit for each of the nine frequency bands. We use local magnitude when it is available and substitute m_b for the other events. The numbers on the Figure correspond to the frequency band from which the data was obtained; i.e. 3 is for the third frequency band which has a dominant frequency of 1.1 Hz (see first two columns of Table 4). We can read this set of curves at a particular magnitude to produce a spectral estimate of the event effect for eastern US earthquakes of that magnitude. By repeating this process for a suite of magnitudes we can generate a family of source spectral responses as shown on Figure 9. These source spectral responses represent *average* source functions for events in the eastern and central US at a distance of 11.39° from the source ($\Delta^{-1/3} = (\sin \Delta)^{-1/2}$).

The source spectra estimated from *Lg* signals show ill-defined corner frequencies for the lower magnitudes ($m_b = 2, 3, \& 4$) which shift to lower frequencies with increasing magnitude as most proposed scaling laws predict. The frequency coverage (0.5 to 13.7 Hz) is not low enough to show the corner frequency for the larger magnitudes. There is not enough data available for the larger magnitudes around m_b 5 and 6 for the details of these two curves to be significant. The decay of the source spectral estimates above the corner frequency appears to be f^{-2} to f^{-3} at the high frequency end of the spectra.

Q vs Frequency for Pn and Sn

We have followed the approach used above to estimate the attenuation and source excitation characteristics for both *P-Pn* and *Sn* signals. We lump the *Pn* and *P* waves together in this analysis. Since we are mostly interested in the detectability of phases at various distances we need not make any distinction between the two types of arrivals. It seems likely, though,

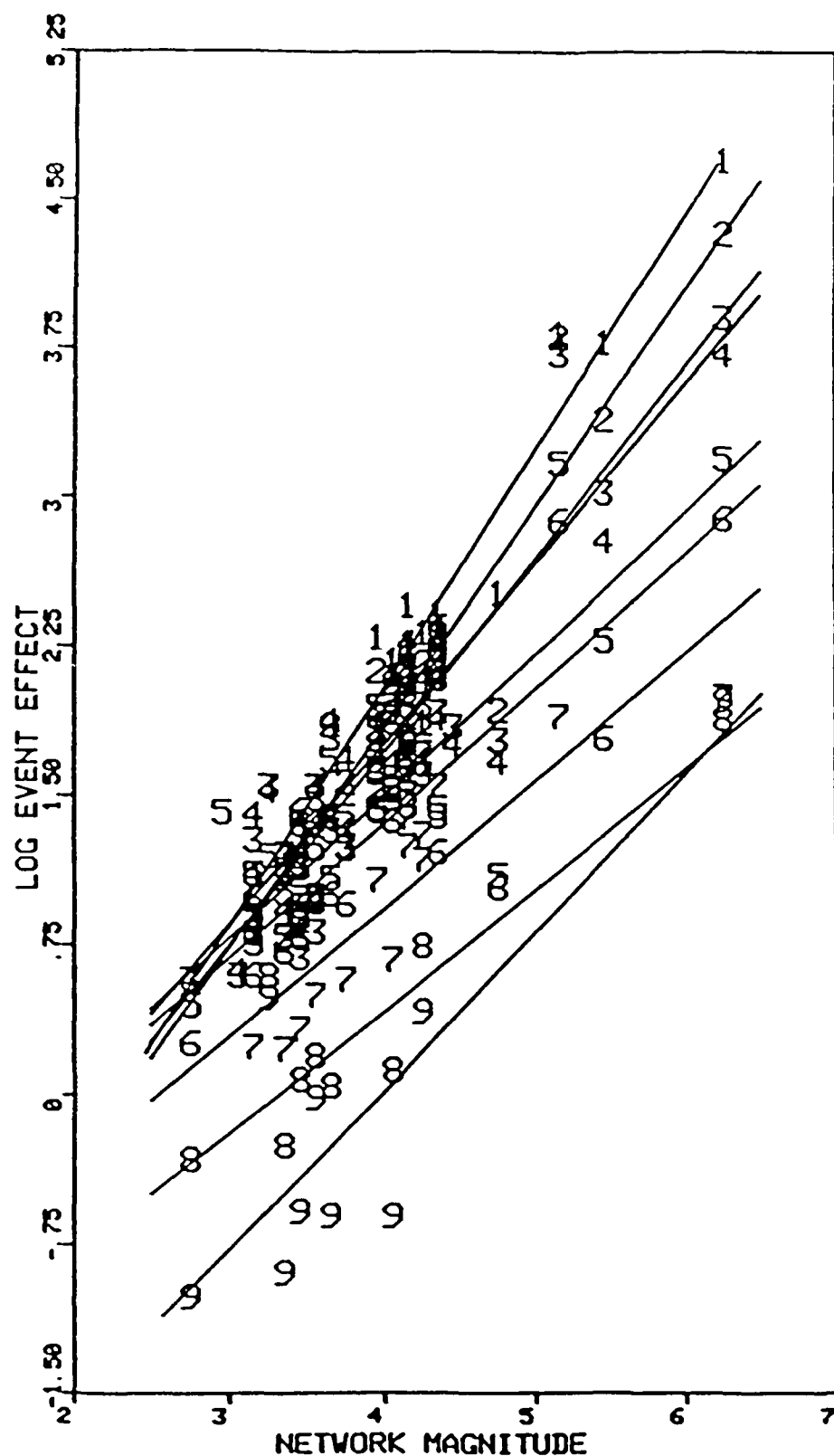


Figure 8. Regressions of L_g event effect versus magnitude for each of the various frequency bands. The numbers 1, 2, ..., 9 correspond to the number of each frequency band (column 1 of Table 4); the corresponding frequencies are in column 2 of Table 4.

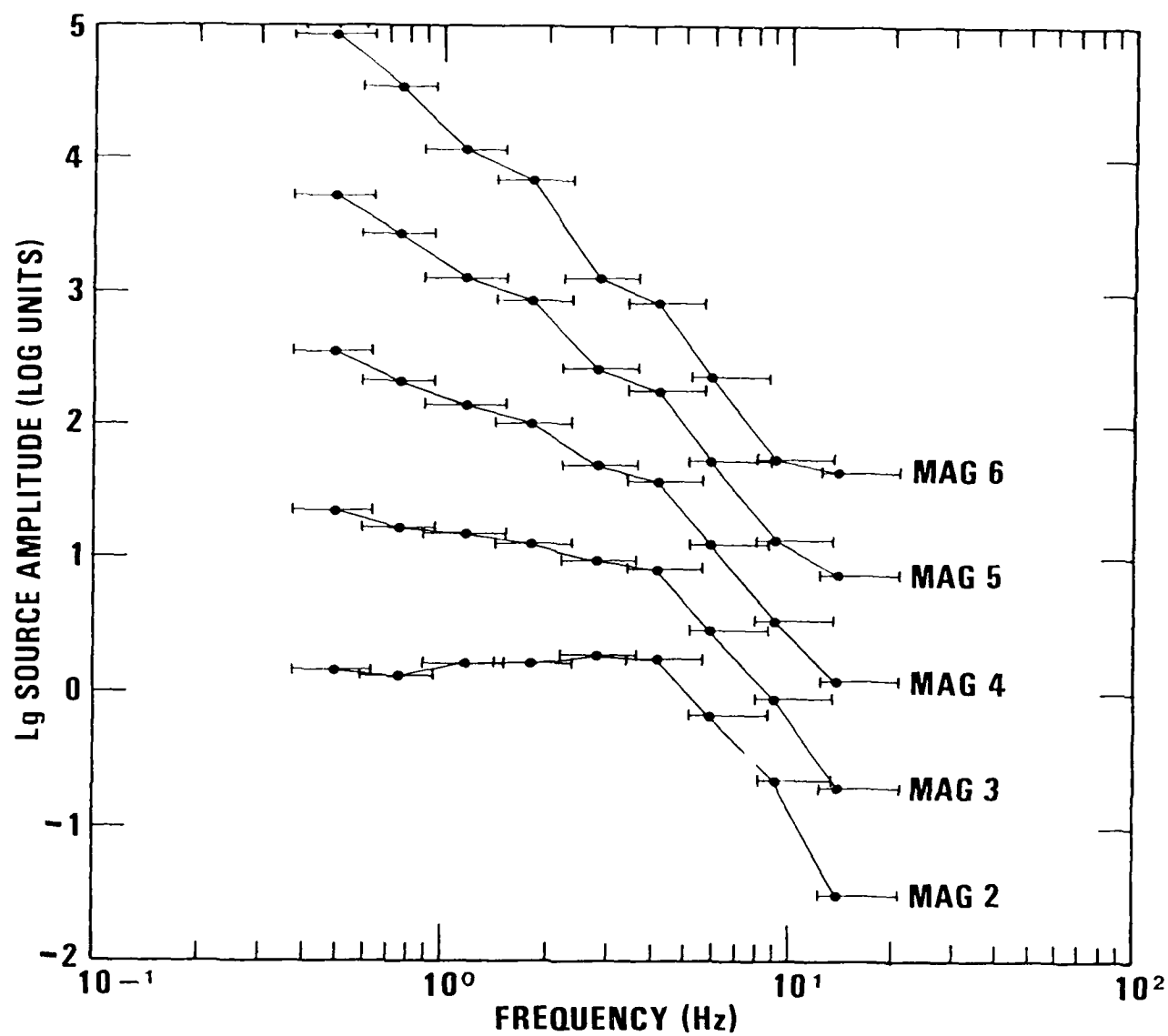


Figure 9. Average L_g source spectra for Canadian and eastern US earthquakes estimated from the event effects of the regression analysis in Figure 8.

that what we observe at very high frequencies is Pn , while at lower frequencies and large distance direct P , traveling through the upper mantle, may dominate. The frequency dependencies of Q for the P phases may thus be artifacts due to the changing nature of the arrivals with frequency. Again, this makes no difference as far as detectability studies are concerned.

We have used the same events as those used in the Lg study. Again only short period vertical seismograms were processed. Since both Sn and Pn signals normally are smaller than the Lg signals, fewer of the seismograms in this database provided Sn and Pn detections than was the case with Lg . Consequently, there are fewer station-event pairs in the Pn and Sn analyses than there are in the Lg analysis.

There were 64 signal measurements from 31 earthquakes for Sn and 62 signal measurements from 27 earthquakes for Pn . Table 5 shows the regression results for Pn with the geometrical spreading factor inversely proportional to distance.

TABLE 5							
FREQUENCY VERSUS ATTENUATION FOR Pn with $1/\Delta$							
Freq Band No.	Dominant Frequency (Hz)	Number of Signals	γ (deg ⁻¹)	$\hat{s}(\gamma)$ (deg ⁻¹)	Q	$\hat{s}(Q)$	RMS of Amplitude Residuals
1	0.5	‡	‡	‡	‡	‡	‡
2	0.7	‡	‡	‡	‡	‡	‡
3	1.1	23	0.068	0.038	738	418	0.14
4	1.8	38	0.078	0.026	1007	341	0.17
5	2.8	46	0.102	0.023	1187	267	0.17
6	4.1	52	0.133	0.025	1351	250	0.17
7	5.9	45	0.155	0.033	1665	357	0.18
8	9.1	28	0.189	0.067	2109	743	0.14
9	13.7	‡	‡	‡	‡	‡	‡

‡ insufficient data

Table 6 shows the regression results for Sn . For Sn the combined geometrical spreading and dispersion factor was inversely proportional to distance to the 5/6 power, just as was the case for Lg .

TABLE 6							
FREQUENCY VERSUS ATTENUATION FOR S_n							
Freq Band No.	Dominant Frequency (Hz)	Number of Signals	γ (deg ⁻¹)	$\hat{s}(\gamma)$ (deg ⁻¹)	Q	$\hat{s}(Q)$	RMS of Amplitude Residuals
1	0.5	‡	‡	‡	‡	‡	‡
2	0.7	14	0.039	0.076	1488	2928	0.10
3	1.1	25	0.086	0.015	1032	178	0.05
4	1.8	45	0.105	0.019	1332	237	0.10
5	2.8	48	0.123	0.017	1744	247	0.10
6	4.1	41	0.149	0.024	2139	348	0.12
7	5.9	42	0.161	0.029	2862	507	0.13
8	9.1	31	0.13	0.049	5435	2031	0.19
9	13.7	‡	‡	‡	‡	‡	‡

‡ insufficient data

Figure 10 gives these results for Q versus frequency with the same geometrical spreading factor, $\Delta^{-5/6}$, for P_n and S_n as the one used for L_g . The least squares fit for Q versus frequency for the different phases are:

$$\text{for } L_g, Q(f) = 1000f^{0.35}$$

$$\text{for } S_n, Q(f) = 825f^{0.80}$$

$$\text{for } P_n, Q(f) = 640f^{0.50}$$

The various formulas shown for different geometrical spreading-dispersion relationships all give about the same amplitude decrease rates with distance in the 200-1200 km distance range where most of the data were fitted. Since the $\Delta^{-5/6}$ geometrical spreading-dispersion factor may not be appropriate to S_n and P_n , in Table 7 we list the $Q(f)$ formulas for some other candidate exponential distance factors:

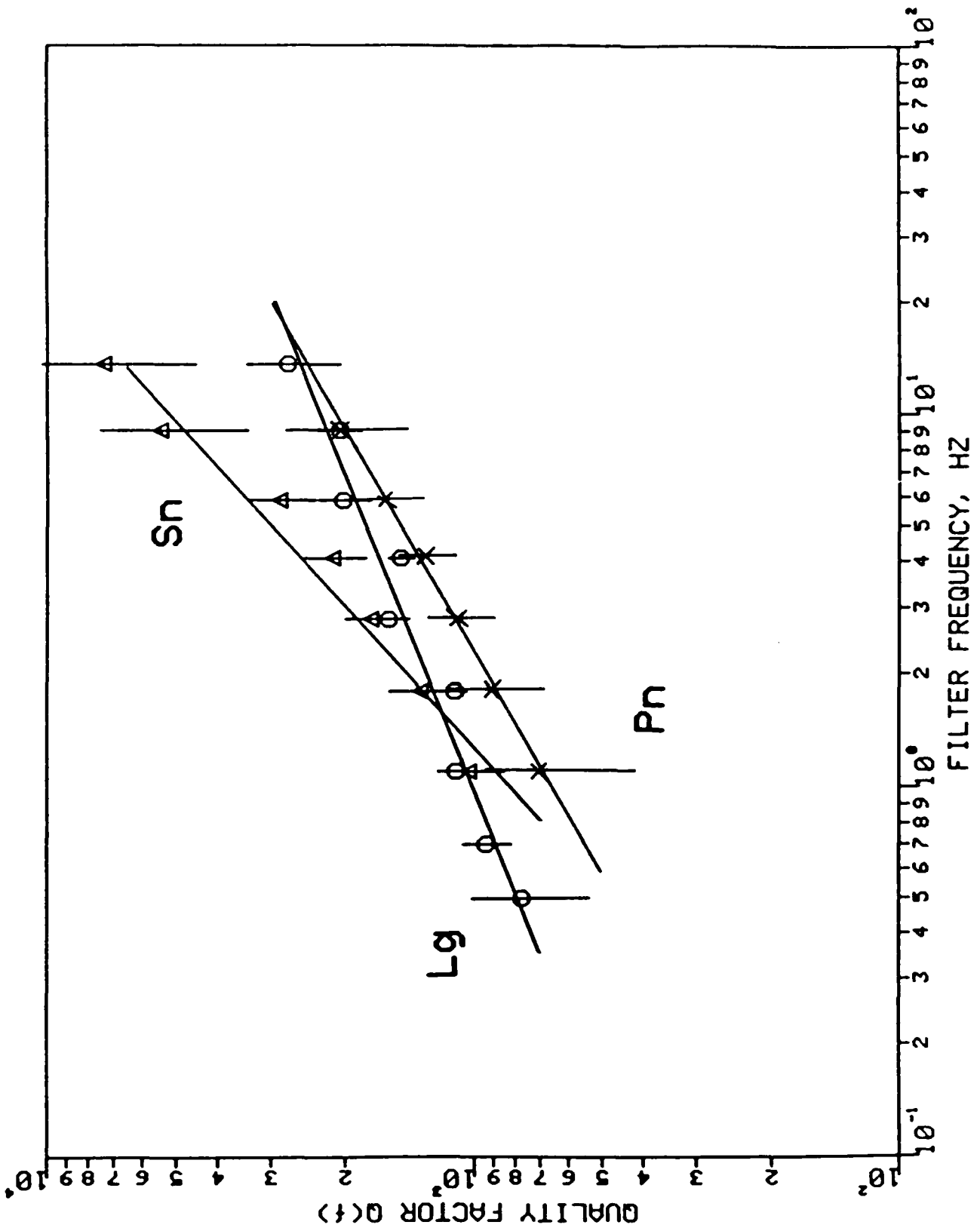


Figure 10. Q versus frequency for P_n , S_n , and L_g . A combined geometrical spreading and dispersion term of $\Delta^{-5/6}$ was assumed for all phases.

TABLE 7				
Q for Different Assumed Geometrical Spreading + Dispersion Values				
Phase	Assumed Geometrical Spreading + Dispersion			
	$\Delta^{-1/2}$	$\Delta^{-5/6}$	Δ^{-1}	$\Delta^{-1.5}$
P_n	$480 f^{0.60}$	$640 f^{0.50}$	$770 f^{0.45}$	$1840 f^{0.10}$
S_n	$610 f^{0.85}$	$825 f^{0.80}$	$1000 f^{0.75}$	$2660 f^{0.10}$
L_g		$1000 f^{0.35}$		

If the reader wishes to compare these results with those appropriate to some other spreading-dispersion factor, in Table 8 we give a listing of a computer program that can be used to relate $Q(f)$ values obtained by two different Δ^{-n} factors as fitted in various distance ranges. Later in this report we shall compare findings of various researchers with regards to $Q(f)$ for the various crustal arrivals by the use of this program. The fact that we have used $\Delta^{-5/6}$ as a standard of comparison does not mean that we believe that this factor is the right one for all crustal arrivals.

TABLE 8

FORTRAN77 Program *newq*

```

program newq

c   This program allows an examination of the range of plausible tradeoffs
c   between Q and the combined geometrical spreading/dispersion expressed as  $\Delta^{-n}$ 
c
c   Given the Q, Q1, at some frequency, f, for a given distance range,
c   imin to imax (in km), assuming an exponent of distance, n1, for the
c   combined geometrical spreading and dispersion,
c   calculates the Q, Q2, at f, for a different exponent of distance, n2,
c   assuming the model below:
c
c   given Q1, n1, n2, U, and f, finds Q2 for a given distance range
c
c    $A \sim A_0 \Delta^{-n} e^{-\gamma \Delta}$ , where  $\gamma = \frac{\pi f}{UQ}$ 

real n1,n2
real ds(30),x(30),y(30)
character*80 dum

data pi/3.14159265/

c   'ENTER EXPONENTS n1 AND n2:'
read(5,*) dum
read(5,*) n1,n2
c   'ENTER Q1:'

```

```

      read(5,*) dum
      read(5,*) q1
c    'ENTER GROUP VELOCITY:'
      read(5,*) dum
      read(5,*) u
c    'ENTER FREQUENCY (Hz):'
      read(5,*) dum
      read(5,*) freq
c    'ENTER MIN AND MAX DISTANCES (km), AND DISTANCE SIZE STEP:'
c    "distance size step" must be an integral multiple of the difference between
c    the min & max distances
      read(5,*) dum
      read(5,*) imin,imax,istep
      ndist=((imax-imin)/istep)+1

      gamma1=pi*freq/w/q1

c    Linearize the equation  $\Delta^{-\alpha_1} e^{-\gamma_1 \Delta} = \Delta^{-\alpha_2} e^{-\gamma_2 \Delta}$ ,
c    by taking the log of both sides.
c
c    Then do a least squares fit of the linearized equation over the given distance range,
c    constraining the midpoint of the new fit to equal the midpoint of the old fit.
c    (This constraint is necessary since there is a third term, the source, being
c    traded off in addition to the Q and geometrical spreading/dispersion terms.)
c
      do 20 i=1,ndist
        ds(i)=float(imin)+float((i-1)*istep)
        x(i)=ds(i)
        y(i)=(n1-n2)*log(ds(i))
20  continue
      xa=0.0
      ya=0.0
      pts=float(ndist)
      do 30 i=1,ndist
        xa=xa+x(i)
        ya=ya+y(i)
30  continue
      aa=0.0
      bb=0.0
      xa=xa/pts
      ya=ya/pts
      do 40 i=1,ndist
        aa=aa+(x(i)-xa)*(y(i)-ya)
        bb=bb+(x(i)-xa)**2.
40  continue
      b=aa/bb
      a=ya*b*xa
      gamma2=gamma1+b
      q2=pi*freq/w/gamma2
      print *,freq,q2

c    After repeating this procedure for a suite of frequencies, one can calculate Q(f) from
c    the resulting table of Q versus f

      end

```

A constraint on which model for the attenuation of P_n is the most applicable is provided by the Early Rise data described by Warren *et al* (1978). They succeeded to fit the amplitude

decay of Pn phases with a $\Delta^{-1.5}$ near 1 Hz in the distance range of 50-1200 km. This would favor models of very high Q coupled with a geometrical spreading factor near $\Delta^{-1.5}$. For all of the phases analyzed Q increases with frequency. However, for none of them does Q increase with frequency to the first power which it must to give the same propagation efficiency at high frequencies (20 to 40 Hz) as at 1 Hz. From these data it does appear that $Q(f)$ for Sn is significantly higher than that for Pn at all frequencies.

Source Spectra for Pn and Sn

The estimates of the source excitation functions for Pn and Sn are derived in the same way as those for Lg . Figures 11 and 12 show the source spectral estimates for Pn (Δ^{-1}), and Sn respectively. The source spectra for Pn have the same shape regardless of the geometrical spreading factor assumed since that factor is only a function of distance, not of frequency. Incidentally, we have found no significant differences in the shapes of source spectral estimates when we used geometrical spreading factors other than $\Delta^{-5/6}$, only their absolute levels were different.

The Pn and Sn amplitude spectra have generally the same shape as the Lg spectra, though the Pn and Sn amplitude spectral levels are roughly one order of magnitude less than the Lg amplitude spectral levels for an event of the same magnitude. Like the Lg source spectra, the Pn and Sn source spectra have ill defined corner frequencies, partially because these source spectra are averages over many events with possibly varying stress drops. The high frequency fall-off rates for Sn are $\sim f^{-2}$ to f^{-3} . For Pn , the fall-off rates appear lower (though we probably do not have enough frequencies in our data to properly resolve the corner frequencies of the smaller magnitude events).

We see no evidence for significantly different fall-off rates between P and S phases such as suggested by Evernden *et al* (1986) who found a P high frequency fall-off of f^{-3} and a S

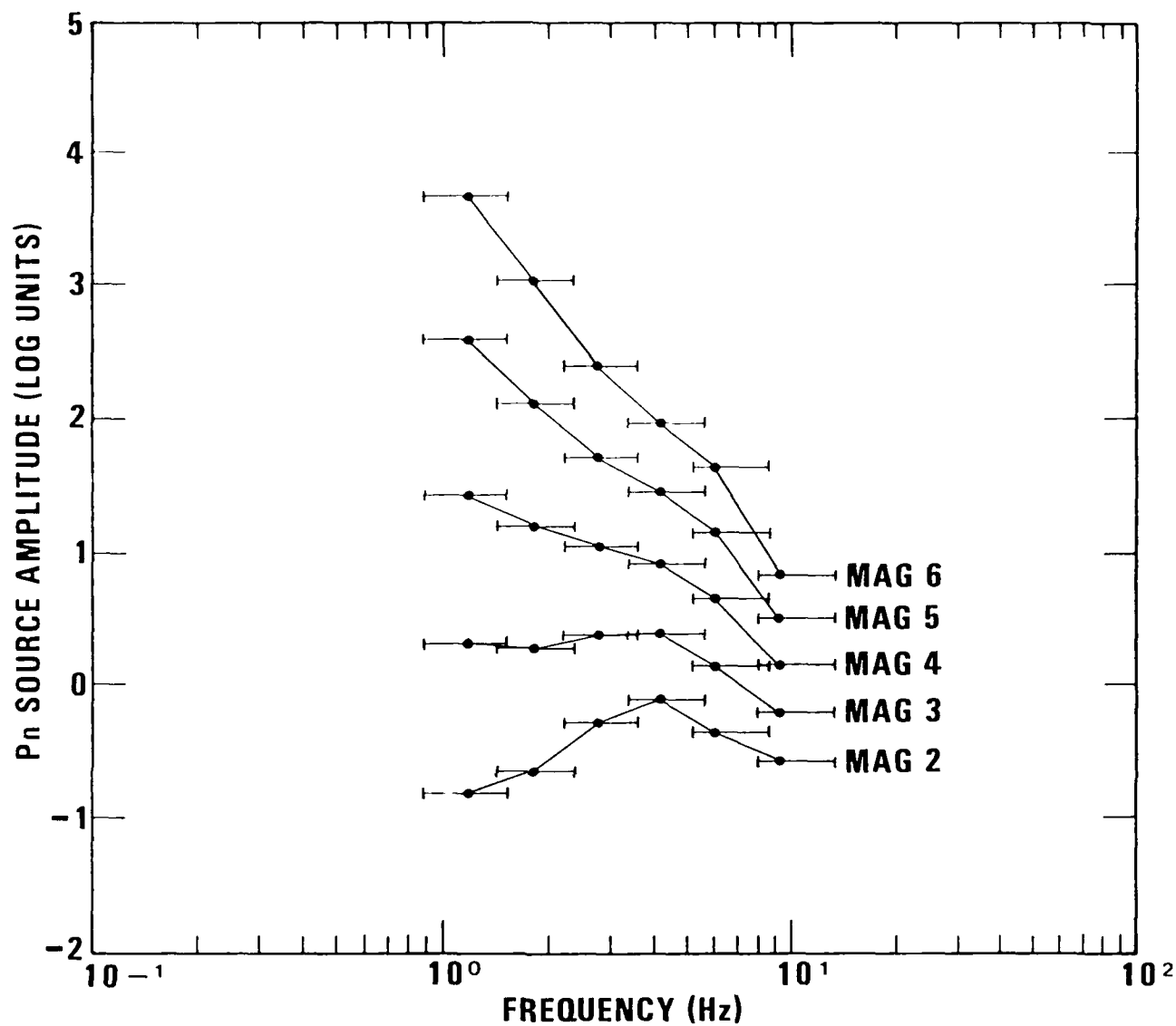


Figure 11. Source excitation functions estimated from P_n signals assuming combined geometrical spreading and dispersion of Δ^{-1} .

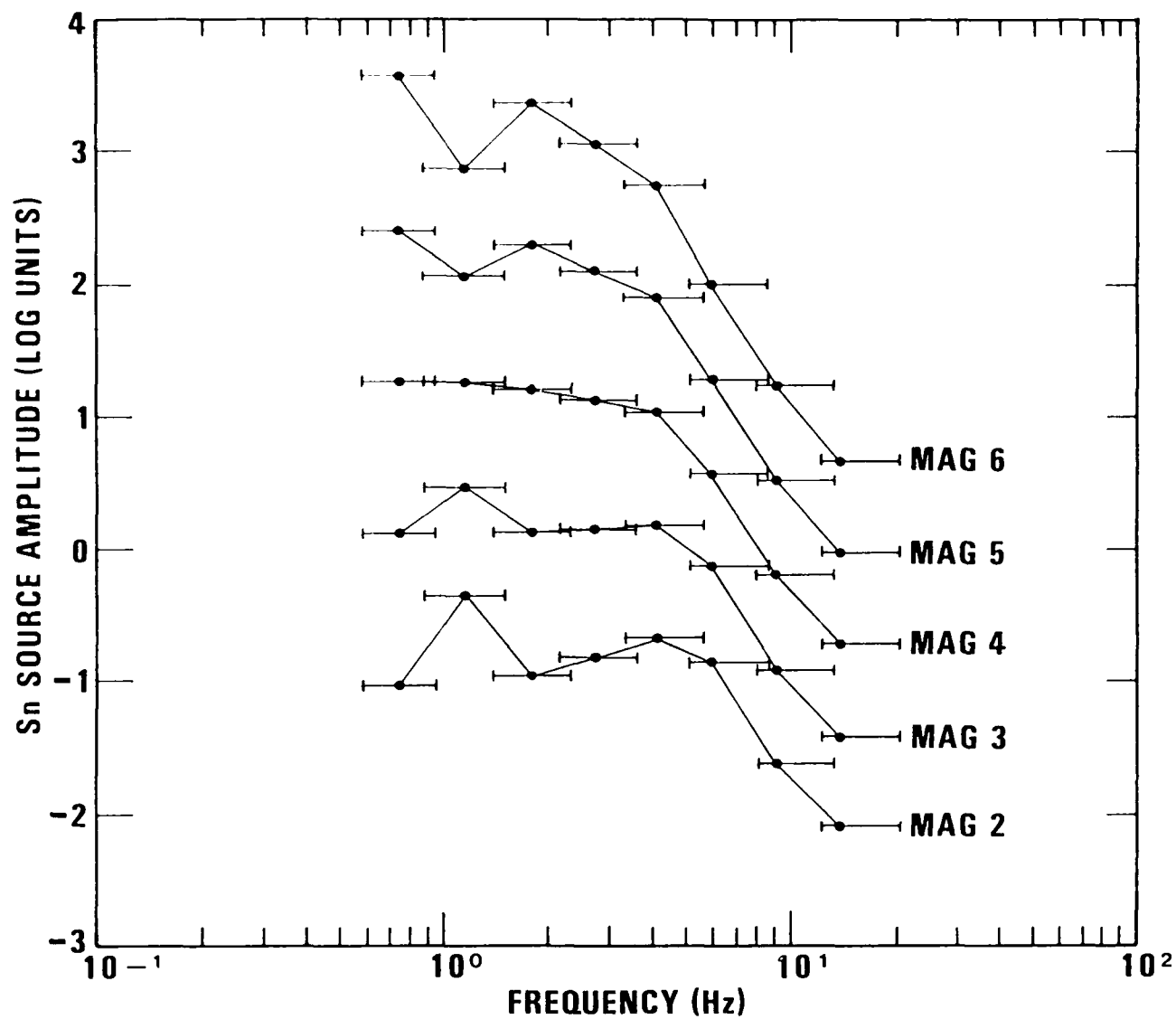


Figure 12. Source excitation functions estimated from S_n signals.

high frequency fall-off of f^{-2} for a regionally recorded event in New York. To test this further, we computed ratios between Pn and Sn spectra for the same event, corrected for Q and instrument, recorded at regional distances at RSTN stations. Though we do not generally have enough good signal-to-noise above the corner frequency to make any strong statements, these ratios show no evidence that P has a faster fall-off rate than S above the corner frequency.

Comparisons with Other Studies

The seismological literature is replete with formulas derived for the quality factors of regionals crustal arrivals, especially for Lg . Some of these are constant Q estimates, such as those of Evernden *et al* (1986) who did not want to be involved with details of frequency dependence. Nevertheless these authors also stated some limits to the frequency dependence of Q for short-period crustal P and S waves. A large number of the Q for regional arrivals given in the literature are frequency dependent. Some were derived by inverting multimode surface wave data (Mitchell 1981). Other set of numbers comes from coda Q studies (Singh and Herrmann 1983). Finally, a smaller set of results comes from the independent estimation of $Q(f)$ from multistation data for each individual crustal phase (Campillo *et al* 1985, Mechler *et al* 1980, Chun *et al* 1987). Some results come from different geographical regions. Comparing these results gives us an idea of the reliability of the methods and the extent of worldwide regional variability of $Q(f)$ for each phase as well.

The results of previous studies are summarized in Table 9 for tectonically stable "shield" areas and in Table 10 for regions with other tectonic regimes. The synopsis in Table 9 shows that Q_{Lg} has been well studied in shield areas and that the results by various workers, including this report, are roughly comparable. Our results for $P-Pn$ and Sn are, on the other hand, relatively new. Comparison of the shield results to those from other areas show that the $Q(f)$ are lower overall, but some results, especially those of Mechler *et al* (1980) for France are

remarkably similar *in form* in that the $Q(f)$ for Sn increases the most rapidly with frequency of all the regional arrivals, while that for Lg is the least frequency dependent. By exercising the computer program in Table 8 the reader can easily compare the various formulas for $Q(f)$ using various Δ^{-n} . It should be noted that $\Delta^{-5/6}$ is appropriate for the time domain Lg Airy phase spreading factor, but that spectra of Lg for constant group velocity windows have a geometrical spreading factor of $(\sin\Delta)^{-1/2}$ (Shin 1985).

TABLE 9

Summary of Q Results from Studies for Shield Regions

Pn

Author	Q(f)	Geometrical Spreading + Dispersion	f (Hz)	Region	Method Distance Range
This report	$480f^{0.6}$ $640f^{0.5}$ $770f^{0.44}$ $1840f^{0.1}$	$\Delta^{-1/2}$ $\Delta^{-5/6}$ Δ^{-1} $\Delta^{-1.5}$	1-9 " " "	Central & ENA	time domain max amps Δ ~500-3000 km
Warren <i>et al</i> (1978)	∞	$\Delta^{-1.5}$	~1	NENA,SENA	time domain max amps Δ ~50-1700 km
Evernden <i>et al</i> (1986)	9000	Δ^{-2}	5-50	NENA	theoretical modeling of spectral shape Δ to at least 1000 km

Sn

Author	Q(f)	Geometrical Spreading + Dispersion	f (Hz)	Region	Method Distance Range
This report	$610f^{0.85}$ $825f^{0.8}$ $1000f^{0.75}$ $2660f^{0.5}$	$\Delta^{-1/2}$ $\Delta^{-5/6}$ Δ^{-1} $\Delta^{-1.5}$	0.7-9 " " "	Central & ENA	time domain max amps Δ ~500-3000 km
Evernden <i>et al</i> (1986)	4000	Δ^{-2}	5-50	NENA	theoretical modeling of spectral shape Δ to at least 1000 km

Lg

Author	Q(f)	Geometrical Spreading + Dispersion	f (Hz)	Region	Method Distance Range
This report	$1000 f^{0.35}$	$\Delta^{-5/6}$	0.5-13	Central & ENA	time domain max amps $\Delta=500-3000$ km
Street (1976)	900	$\Delta^{-5/6}$	1	US & Canada E of Rockies	time domain amplitudes $\Delta=200-4500$ km
Horner <i>et al</i> (1978)	1500	$\Delta^{-5/6}$	1	Canadian shield	time domain amplitudes $\Delta=300-7000$ km
Mitchell (1981)	$\sim 900 f^{0.2}$		0.25-1	ENA	theoretical modeling of spectral shape $\Delta=500-2000$ km
Nutli (1981)	$800 f^{0.5}$ $1500 f^{0.2}$		-1-5 "	ENA CUS	$\Delta \leq 1000$ km
Dwyer <i>et al</i> (1983)	$1280 f^{0.4}$	$\Delta^{-5/6}$	1-10	Central US	time domain max amps from bandpass filtered data $\Delta=200-2000$ km
Singh & Herrmann (1983)	$900 f^{0.35}$	$\Delta^{-5/6}$	0.5-3.5	NENA	Lg coda $\Delta=300-800$ km
	$1000 f^{0.1}$	"	"	S. Appalachians	"
	$1200 f^{0.2}$	"	"	Central US	"
	$900 f^{0.25}$	"	"	Central Central US	"
Pulli (1984)	$660 f^{0.4}$		0.75-10	NENA	Lg coda amps $\Delta=50-600$ km
Hasegawa (1985)	$900 f^{0.2}$	$\Delta^{-1/2}$	0.6-20	Canadian shield	spectra of ground acceleration $\Delta=70-900$ km
Shin (1985)	$(500 \pm 50) f^{(0.6-0.7)}$	$\Delta^{-5/6}$	1-10	Eastern Canada	time domain max amps
	$(500 \pm 50) f^{(0.6-0.7)}$	$\Delta^{-1/2}$	1-10	Eastern Canada	freq domain amp spectra $\Delta=100-1000$ km
Chun <i>et al</i> (1987)	$1100 f^{0.19}$	$\Delta^{-1/2}$	0.6-10	Eastern Canada	spectral ratios $\Delta=53-210$ km
Gupta & McLaughlin (1987a)	$800 f^{0.32}$	$\Delta^{-5/6}$	0.5-7	CUS & ENA	amplitudes from PSRV $\Delta < 1100$ km
	400	"	1	CUS	
	1100	"	"	EENA	
	1400	"	"	Appalachians	

TABLE 10

Summary of Q Results from Studies for Non-Shield Regions

Pn

Author	Q(f)	Geometrical Spreading + Dispersion	f (Hz)	Region	Method Distance Range
Mechler <i>et al</i> (1980)	$810 f^{0.1}$	$\Delta^{-5/6}$	2-8	France	time domain max amps from bandpass filtered data $\Delta=350-1100$ km
Evernden <i>et al</i> (1986)	~1000-2000		5-50	tectonic regions	theoretical modeling of spectral shape Δ to at least 1000 km

Pg

Author	Q(f)	Geometrical Spreading + Dispersion	f (Hz)	Region	Method Distance Range
Mechler <i>et al</i> (1980)	$200 f^{0.64}$	$\Delta^{-5/6}$	0.5-8	France	time domain max amps from bandpass filtered data $\Delta=350-1100$ km

Sn

Author	Q(f)	Geometrical Spreading + Dispersion	f (Hz)	Region	Method Distance Range
Mechler <i>et al</i> (1980)	$490 f^{0.73}$	$\Delta^{-5/6}$	1-8	France	time domain max amps from bandpass filtered data $\Delta=350-1100$ km

Lg

Author	$Q(f)$	Geometrical Spreading + Dispersion	f (Hz)	Region	Method Distance Range
Mechler <i>et al</i> (1980)	$400 f^{0.44}$	$\Delta^{-5/6}$	0.5-8	France	time domain max amps from bandpass filtered data $\Delta=350-1100$ km
Nuttli (1981)	$200 f^{0.7}$		-1-5	S. Calif.	$\Delta \leq 1000$ km
Campillo <i>et al</i> (1985)	$290 f^{0.52}$	$\Delta^{-5/6}$	0.5-10	France	time domain max amps & theoretical modeling $\Delta=150-2000$ km
Chavez & Priestly (1986)	$206 f^{0.68}$	$\Delta^{-1/2}$	0.3-10	US Great Basin explosion	frequency domain amplitudes $\Delta=200-500$ km
	$214(\pm 50) f^{0.54 \pm 0.09}$	"	0.3-5	US Great Basin earthquakes	"

Noise Spectra at RSTN Stations

Noise spectral estimates are important in estimating the detection thresholds of different sites. We have calculated noise spectral estimates for the five RSTN sites corrected for instrument response from a suite of noise samples recorded on the short period vertical instruments. The noise samples were chosen just prior to the onset of signals from 57 of the 114 earthquakes used in our regression analysis. The suite represents a random sampling occurring at all times of day and night and during all seasons of the year.

Figures 13 through 22 show the day time and night time log-averaged noise spectra for each of the five RSTN sites along with curves at ± 1 standard deviation, σ , from the mean. For each data set, the mean and the standard deviation were computed separately at each frequency to produce the mean spectra shown in the figures. The RSCP noise spectra are only valid to around 8 Hz since RSCP has a sharp high frequency cutoff filter which takes effect at 8 Hz. Beyond that frequency, the spectra exhibit only roundoff errors in the digitizer, not true ground

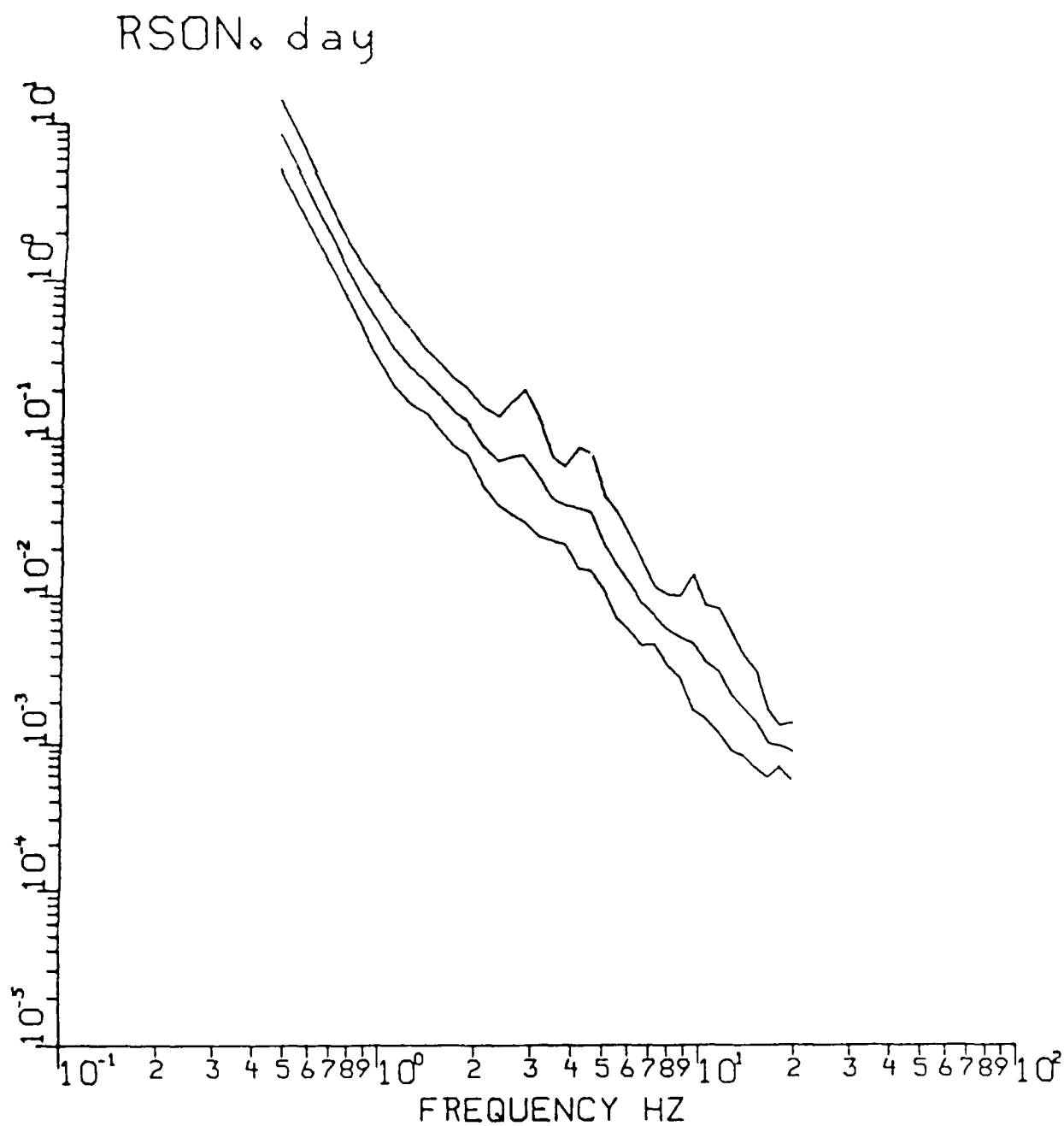


Figure 13. Average daytime noise spectra at RSON. Mean and one standard deviation limits indicated.

RSON. night

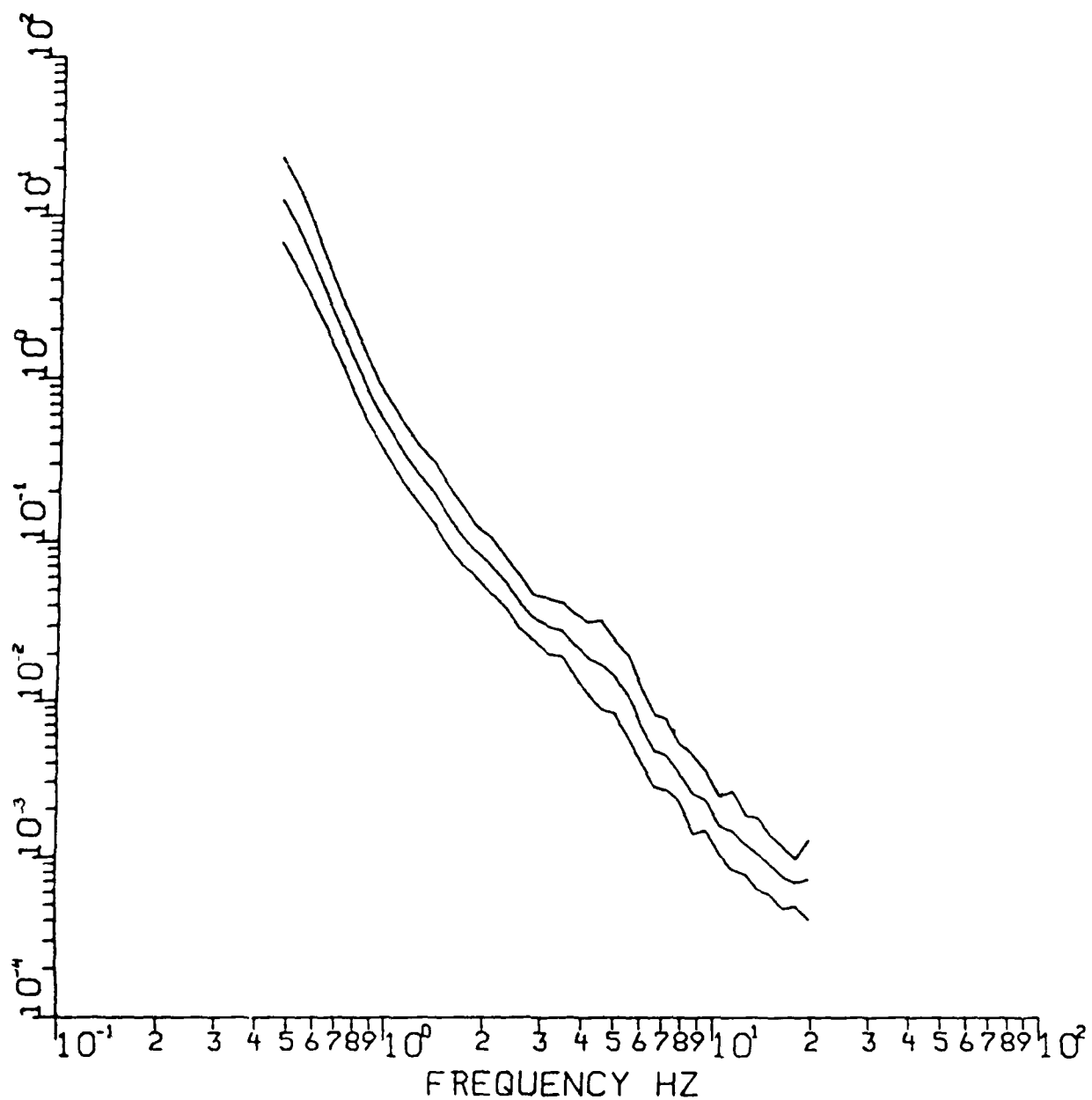


Figure 14. Average nighttime noise spectra at RSON. Mean and one standard deviation limits indicated.

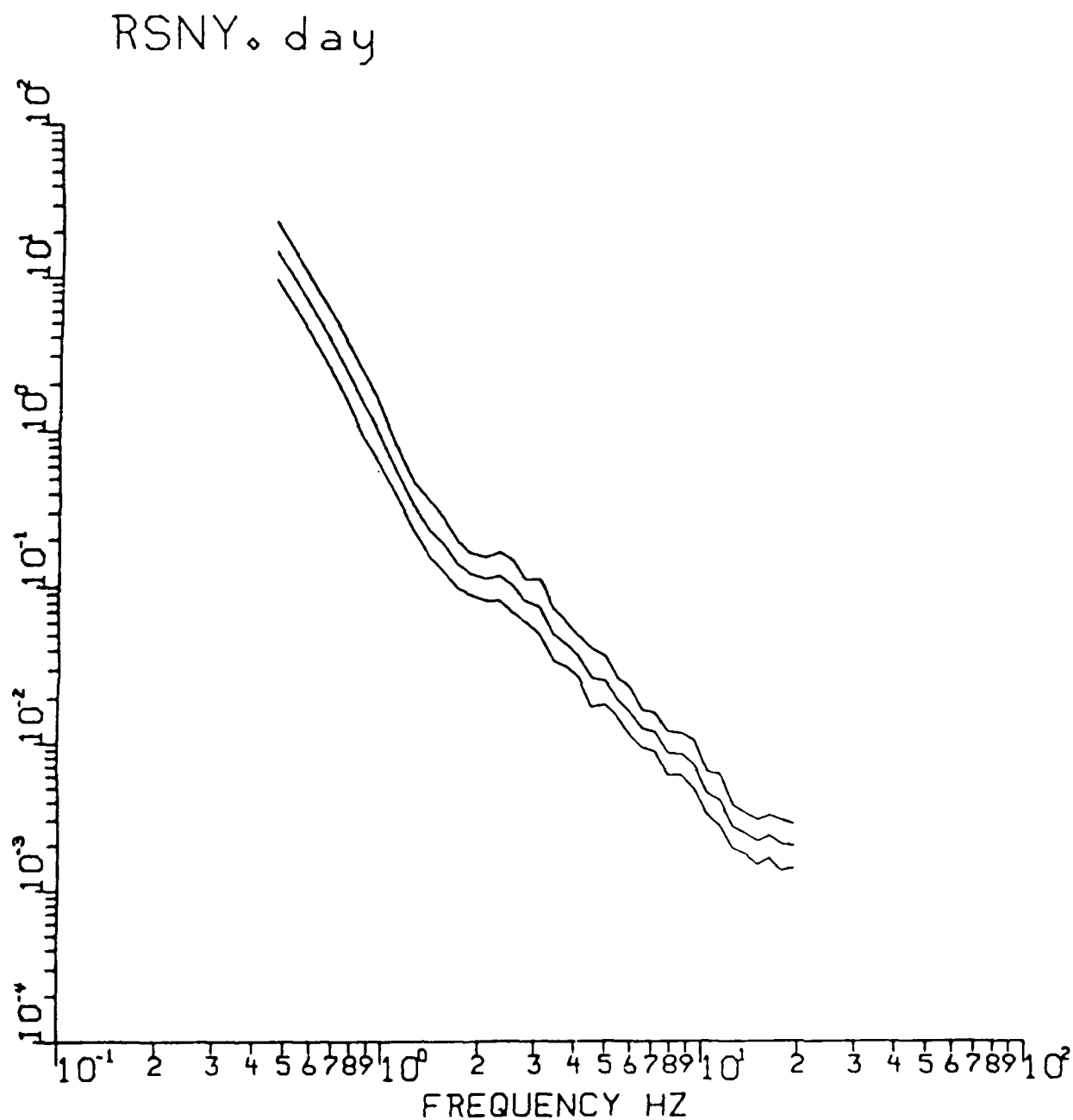


Figure 15. Average daytime noise spectra at RSNY. Mean and one standard deviation limits indicated.

RSNY. night

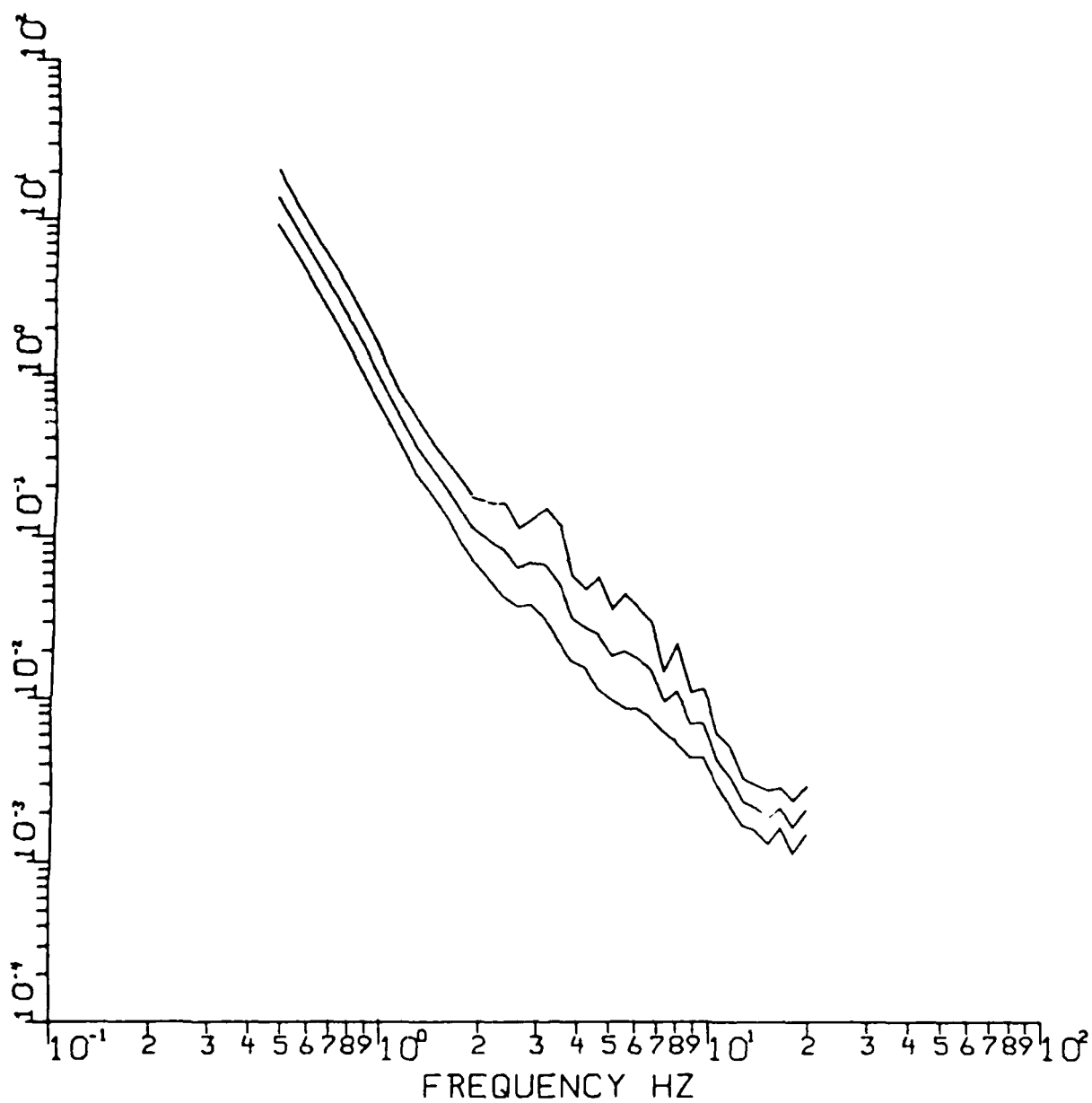


Figure 16. Average nighttime noise spectra at RSNY. Mean and one standard deviation limits indicated.

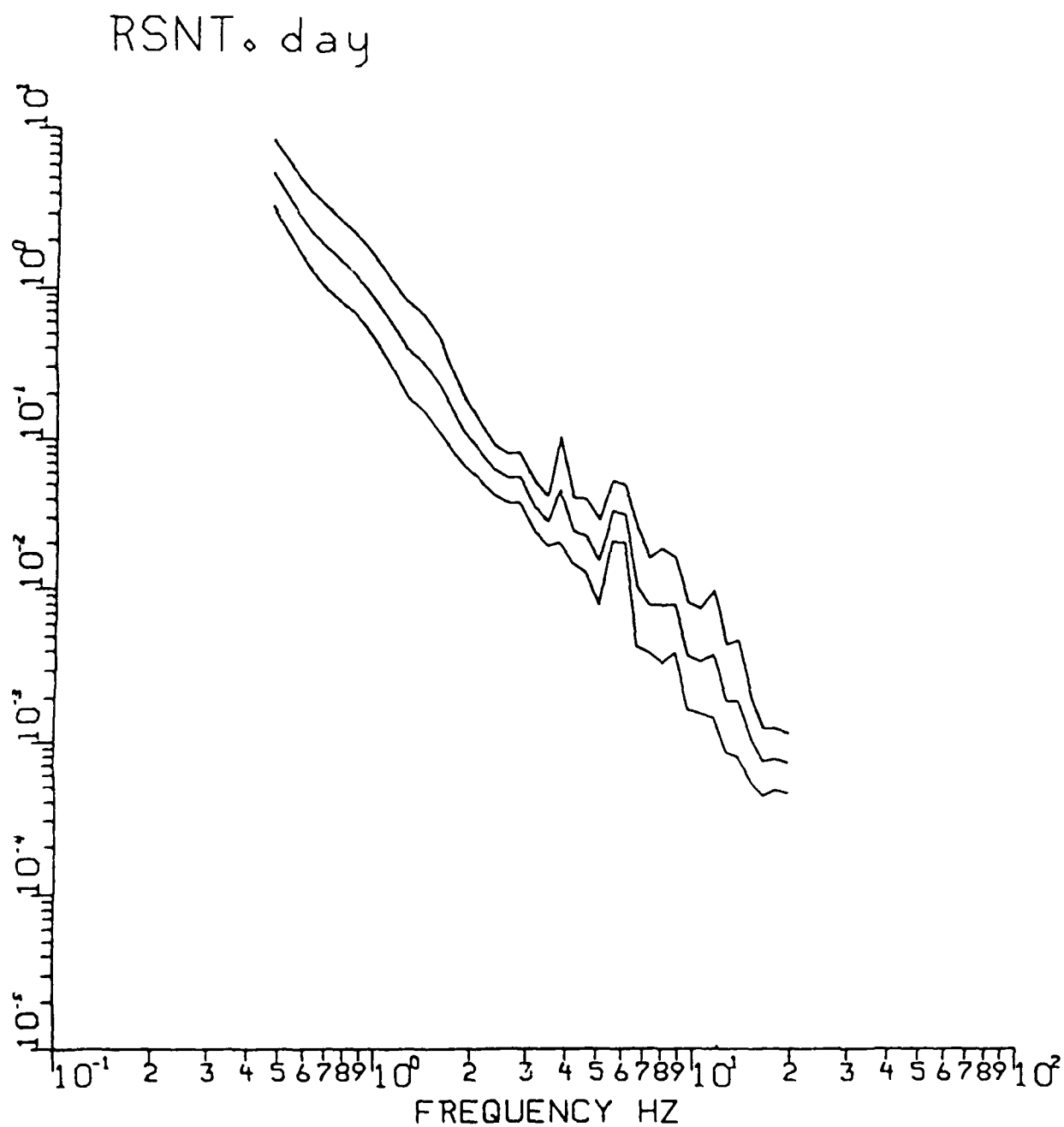


Figure 17. Average daytime noise spectra at RSNT. Mean and one standard deviation limits indicated.

RSNT. night

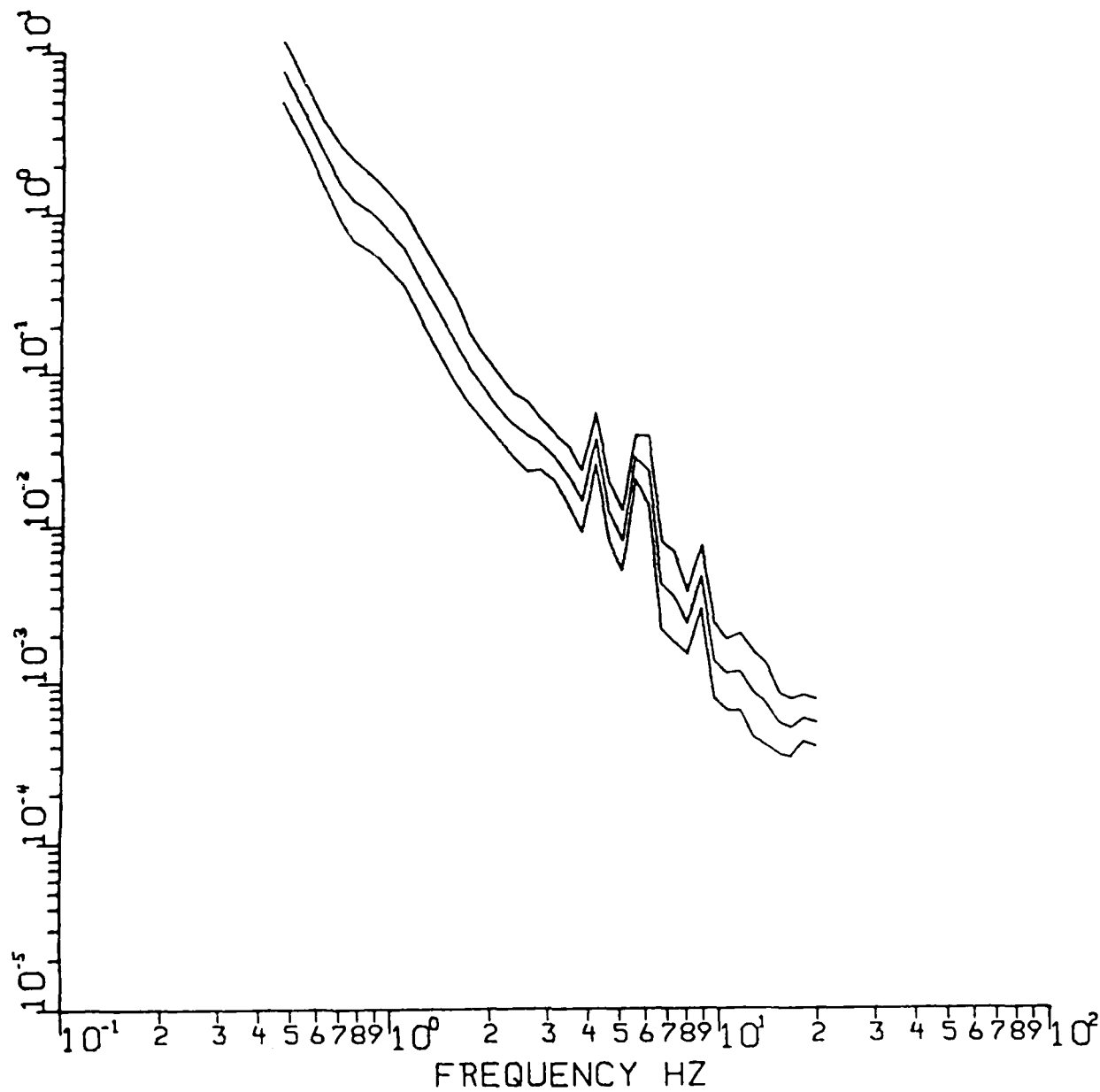


Figure 18. Average nighttime noise spectra at RSNT. Mean and one standard deviation limits indicated.

RSSD. day

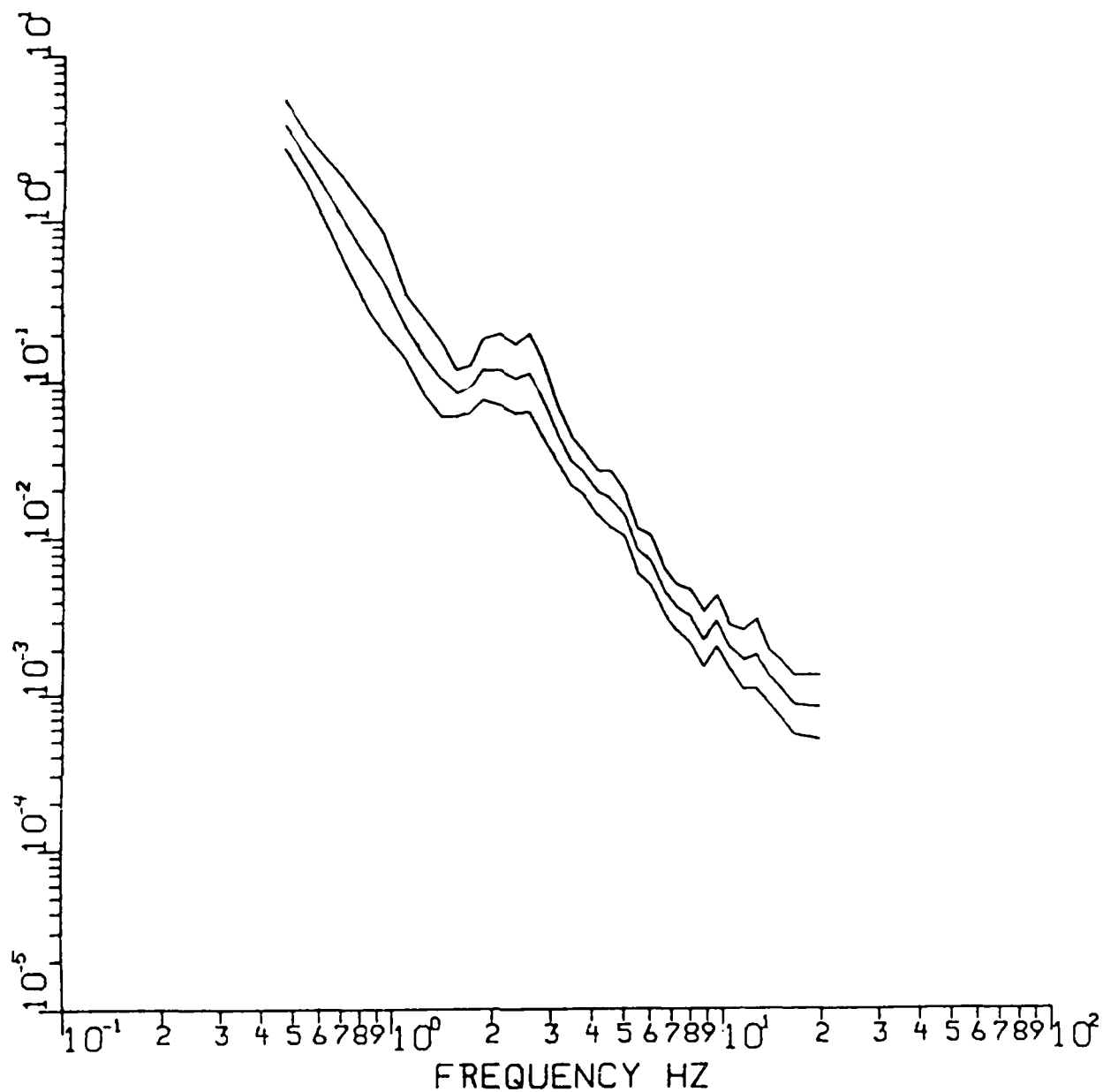


Figure 19. Average daytime noise spectra at RSSD. Mean and one standard deviation limits indicated.

RSSD. night

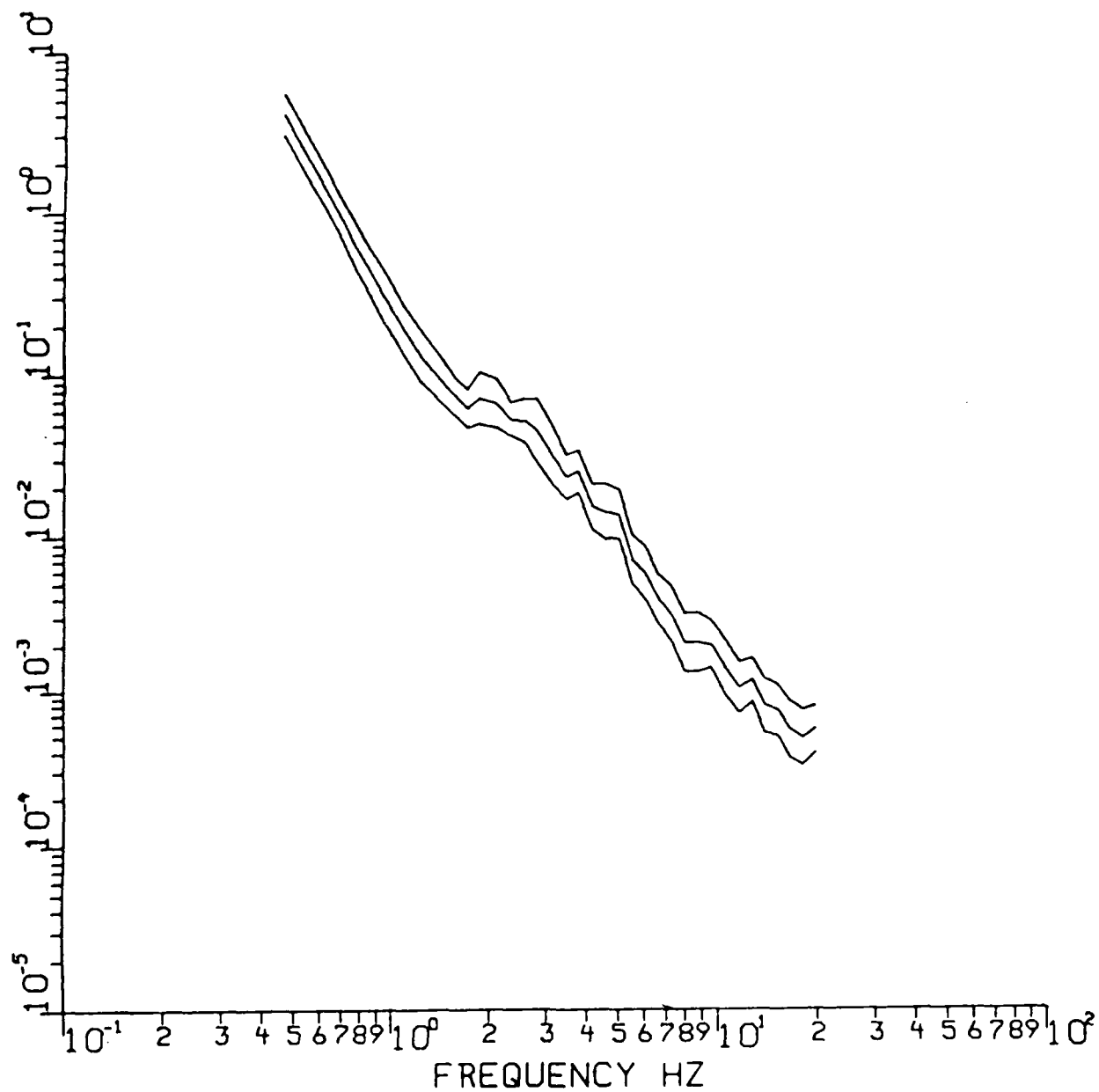


Figure 20. Average nighttime noise spectra at RSSD. Mean and one standard deviation limits indicated.

RSCP. day

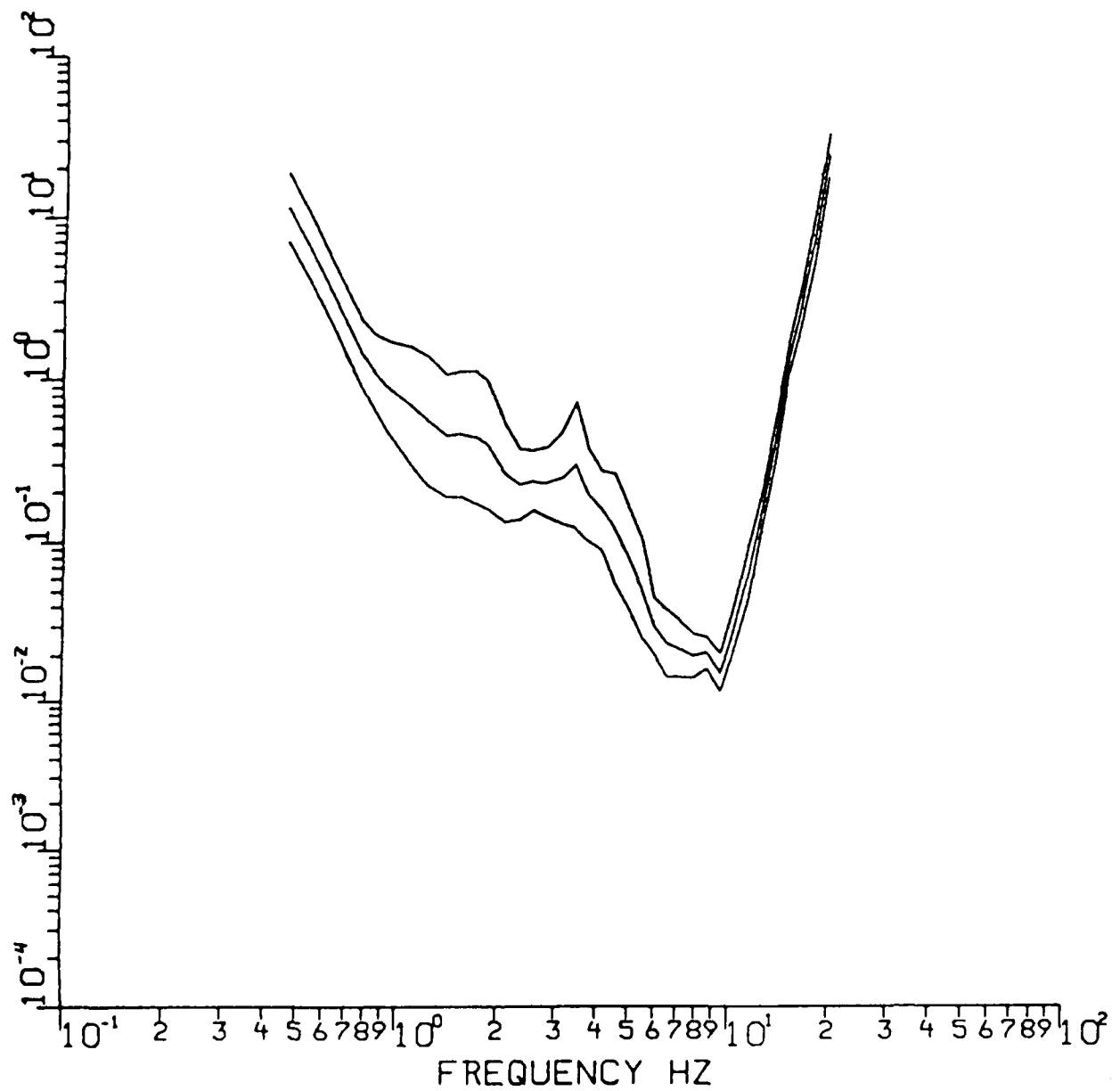


Figure 21. Average daytime noise spectra at RSCP. Mean and one standard deviation limits indicated.

RSCP. night

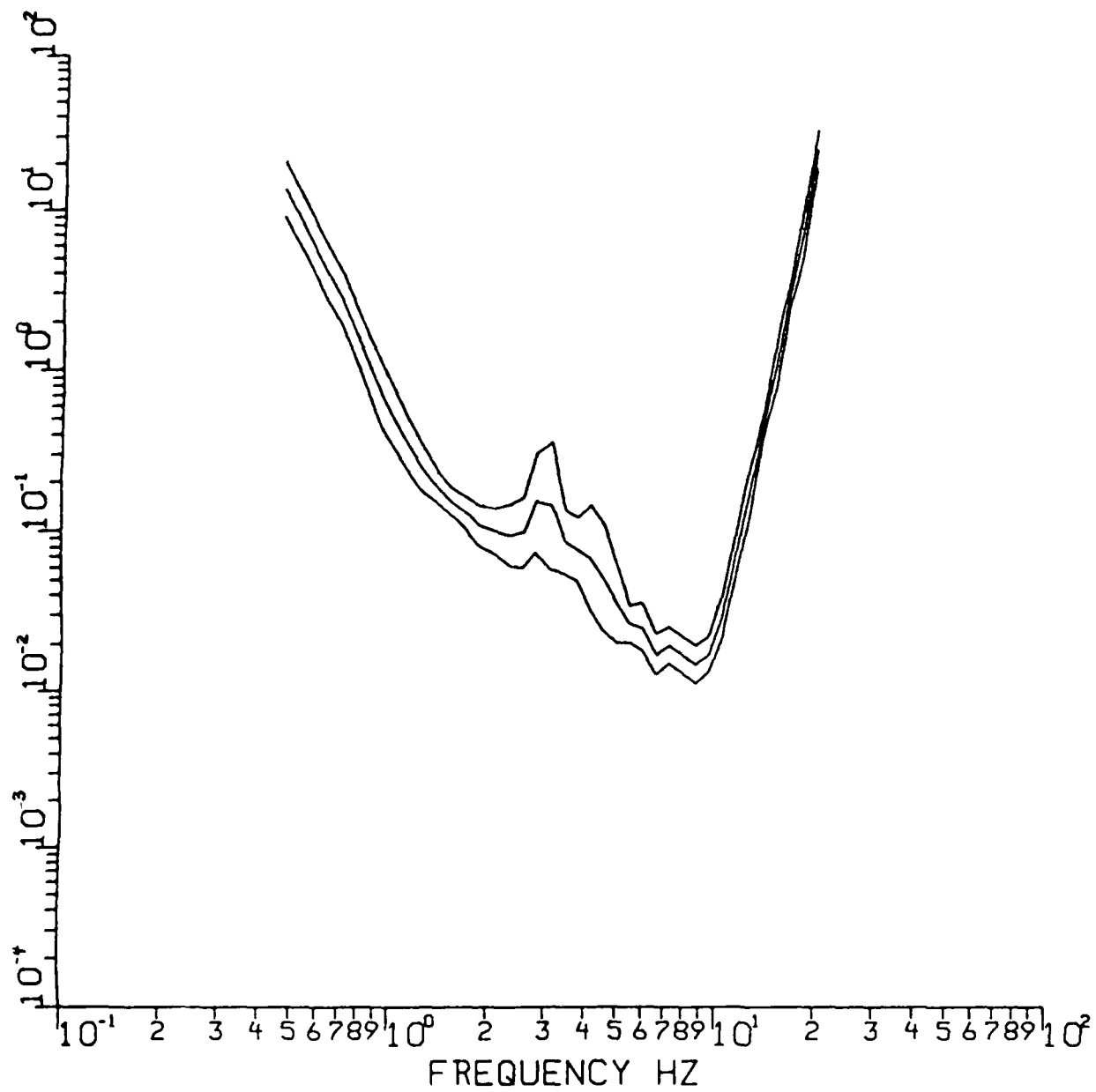


Figure 22. Average nighttime noise spectra at RSCP. Mean and one standard deviation limits indicated.

motion. Consequently, when the instrument correction is applied, this A-to-D roundoff error, which is in fact a flat spectrum, increases with frequency at the inverse of the filter falloff rate.

For comparison, the noise spectral level was also calculated from the peak readings of the envelope time traces. For RSSD, the spectral estimate which most closely approximates the one calculated from peak readings of the envelope time traces is the upper bound estimate. Table 11 shows the log-average noise level and the normalized standard deviation of the noise estimate at five frequencies (1, 2, 4, 8 and 18 Hertz) for each of the RSTN sites.

TABLE 11										
Noise Displacement Amplitude at the RSTN Stations in nm/√Hz										
Freq	1 Hz		2 Hz		4 Hz		8 Hz		18 Hz	
Station	$\bar{m}$	σ_n	$\bar{m}$	σ_n	$\bar{m}$	σ_n	$\bar{m}$	σ_n	$\bar{m}$	σ_n
RSSD	0.27	67%	0.093	65%	0.021	43%	0.0025	52%	0.00064	61%
RSON	0.48	60	0.098	62	0.029	100	0.0046	76	0.00084	50
RSNT	0.76	79	0.087	63	0.038	95	0.0045	151	0.00067	54
RSNY	0.80	49	0.108	44	0.036	56	0.0096	74	0.00192	44
RSCP	0.66	102	0.227	151	0.118	95	0.0186	33		

A diurnal variation in the noise levels is observed at all of the RSTN sites, with the day-time noise averaging 1.5 times higher than the nighttime noise at RSSD and up to 3 time higher at some frequencies at RSCP and RSON. The site with the largest seasonal variation is RSNT which is quietest in the winter when the Great Slave Lake is frozen. For frequencies above 2 or 3 Hz, the noise amplitude spectra fall off as $f^{-2.2}$ to $f^{-2.6}$. RSSD is the quietest station while RSNY and RSCP are the noisiest. These results, including the general details of the spectral peaks and nulls, agree very closely with spectral noise estimates made for the RSTN stations by LLNL (Rodgers *et al* 1987). The noise levels at the RSTN stations are similar to the noise levels in southeastern Norway (Bungum *et al* 1985), and are not quite as low as the quiet noise levels at Lajitas.

DETECTION THRESHOLDS FOR REGIONAL SIGNALS

One of the most important reasons for this study is to determine the detection thresholds for the various crustal arrivals as functions of epicentral distance and frequency. The results are of prime importance for predicting the performance of any CTBT monitoring network installed in or around the USSR.

The detection thresholds for all regional phases were estimated following the approach used by Blandford *et al* (1983). We have plotted the quantity of $m_b - \log(A/N)$ for each frequency band against distance for each phase, where A is the signal envelope amplitude and N is the preceding noise envelope amplitude measured off the bandpass filtered outputs. This quantity is an estimate of the magnitude at which the signal amplitude equals that of the noise, which may be assumed to be the 50% detection threshold. Due to the spectral differences associated with source scaling this approach tends to give conservative (too high) threshold estimates.

These 50% thresholds, of course, cannot be applied in practice since the associated numbers of false alarms would be unacceptably high (Israelson 1986a,b). In order to achieve, say, 84% detection efficiency we must raise the 50% detection thresholds by one standard deviation of the $m_b - \log_{10}(S/N)$ population. Our data set has typically 0.3-0.4 m.u. standard deviations and this is the amount by which the thresholds shown below must be increased to achieve 84% efficiency. 98% detection thresholds require the increase of an additional standard deviation.

Figures 23 to 26 show our 50% detection threshold estimates for Pn , Pg , Sn , and Lg , respectively, as functions of frequency for various epicentral distance ranges. As expected, the Lg detection thresholds are the lowest at low frequencies but approach those of the Sn at high frequencies and small distances. This is understandable since at small distances Lg is very

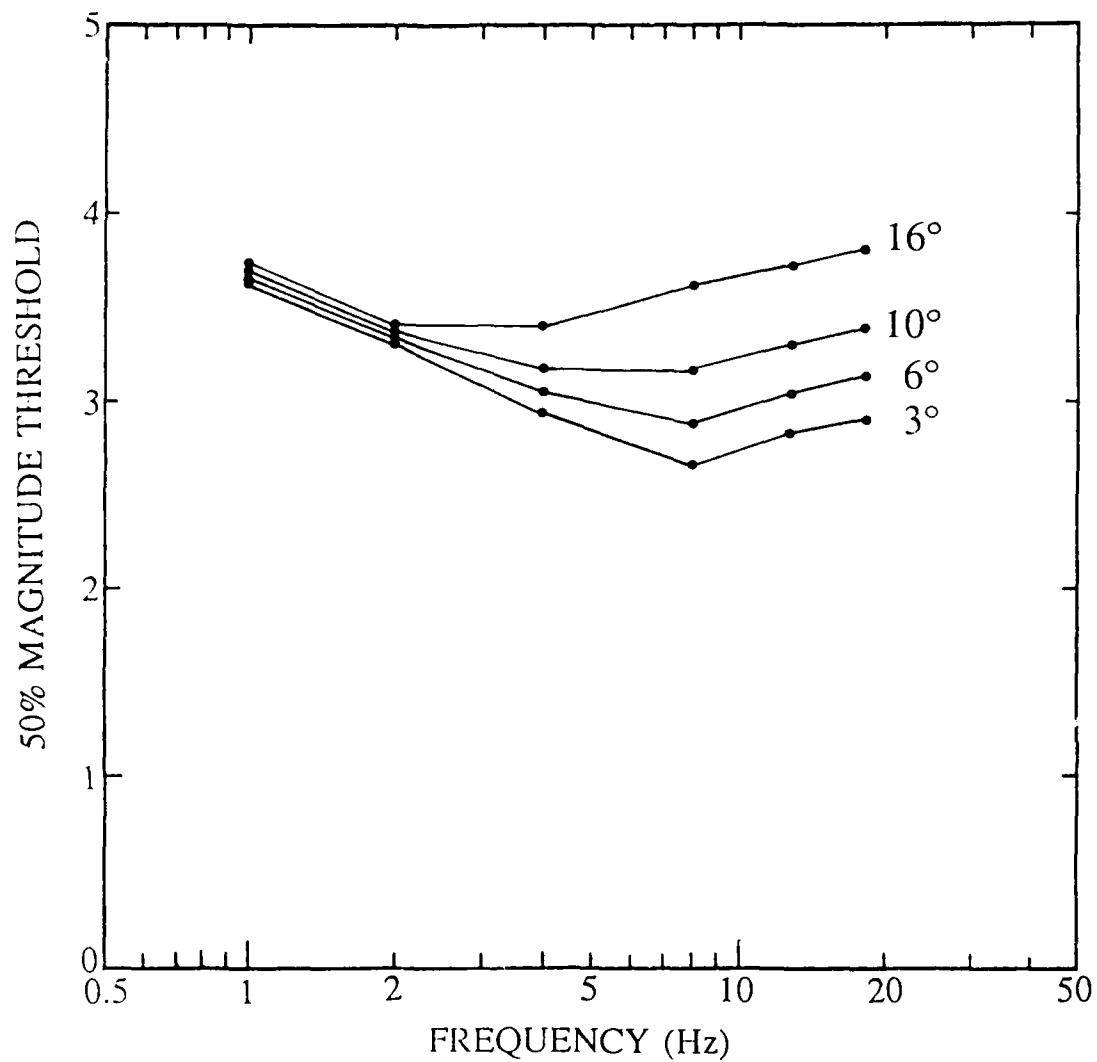


Figure 23. Average RSTN 50% detection threshold curves as a function of frequency for P_n for distances from 3 to 16°.

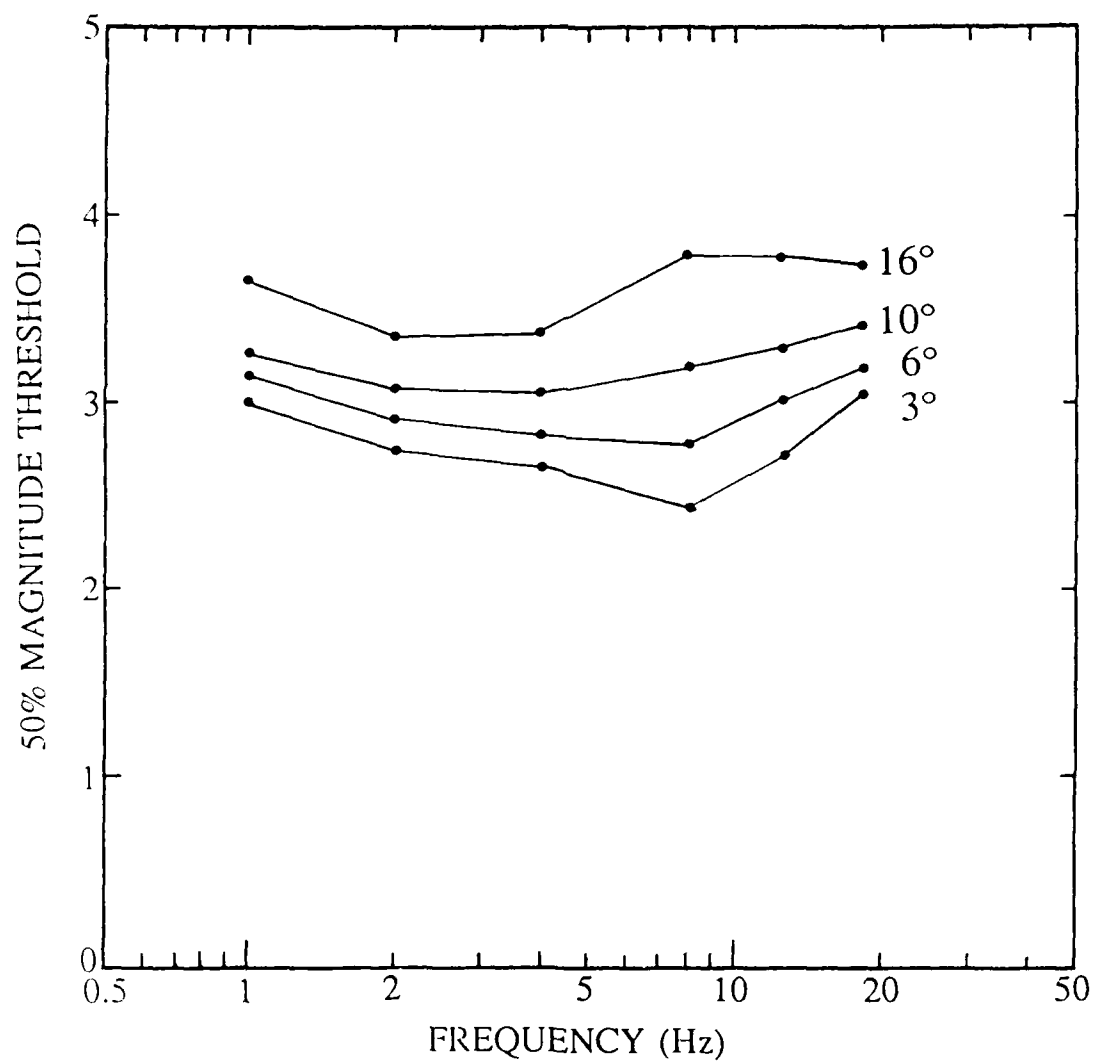


Figure 24. Average RSTN 50% detection threshold curves as a function of frequency for P_g for distances from 3 to 16°.

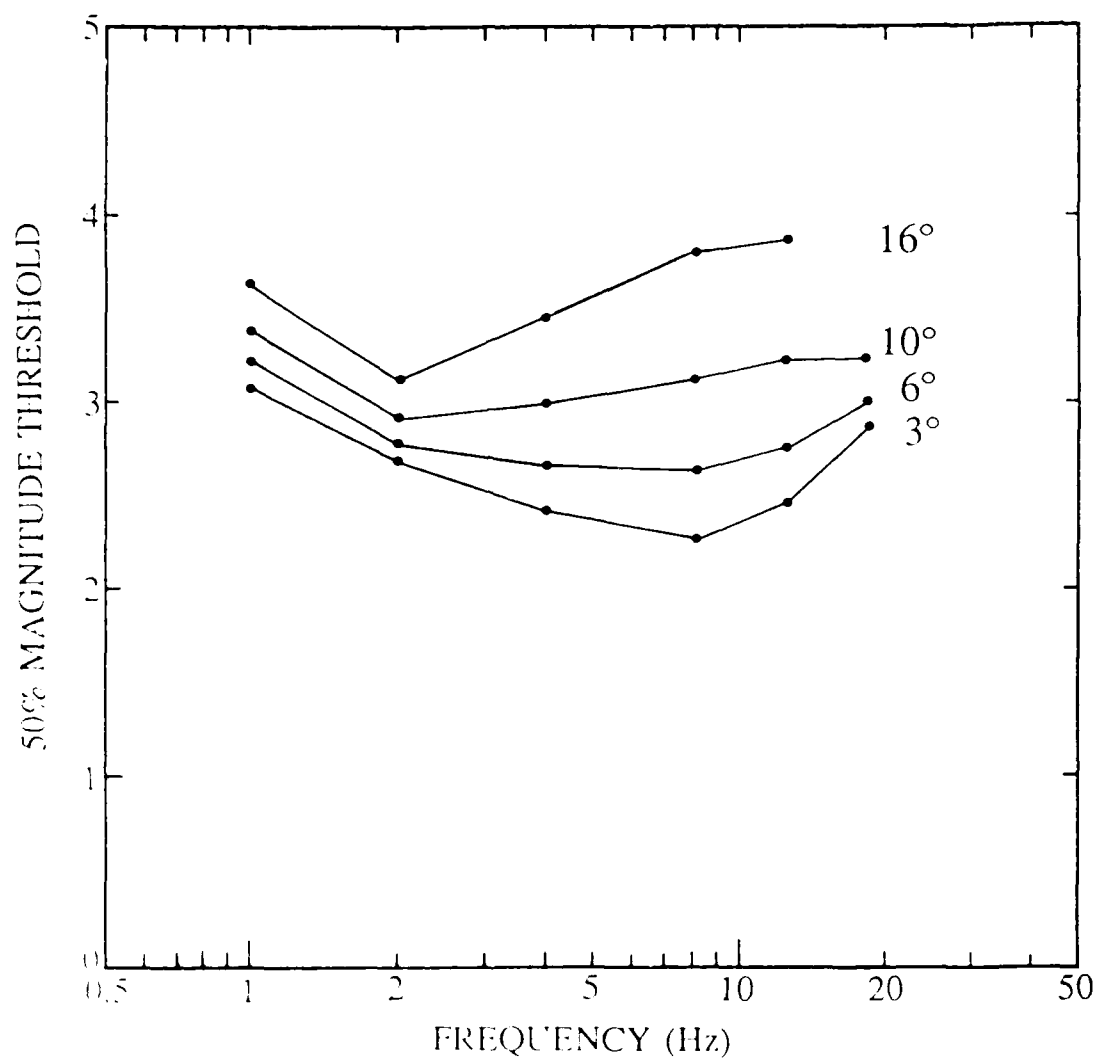


Figure 25. Average RSTN 50% detection threshold curves as a function of frequency for S_n for distances from 3 to 16°.

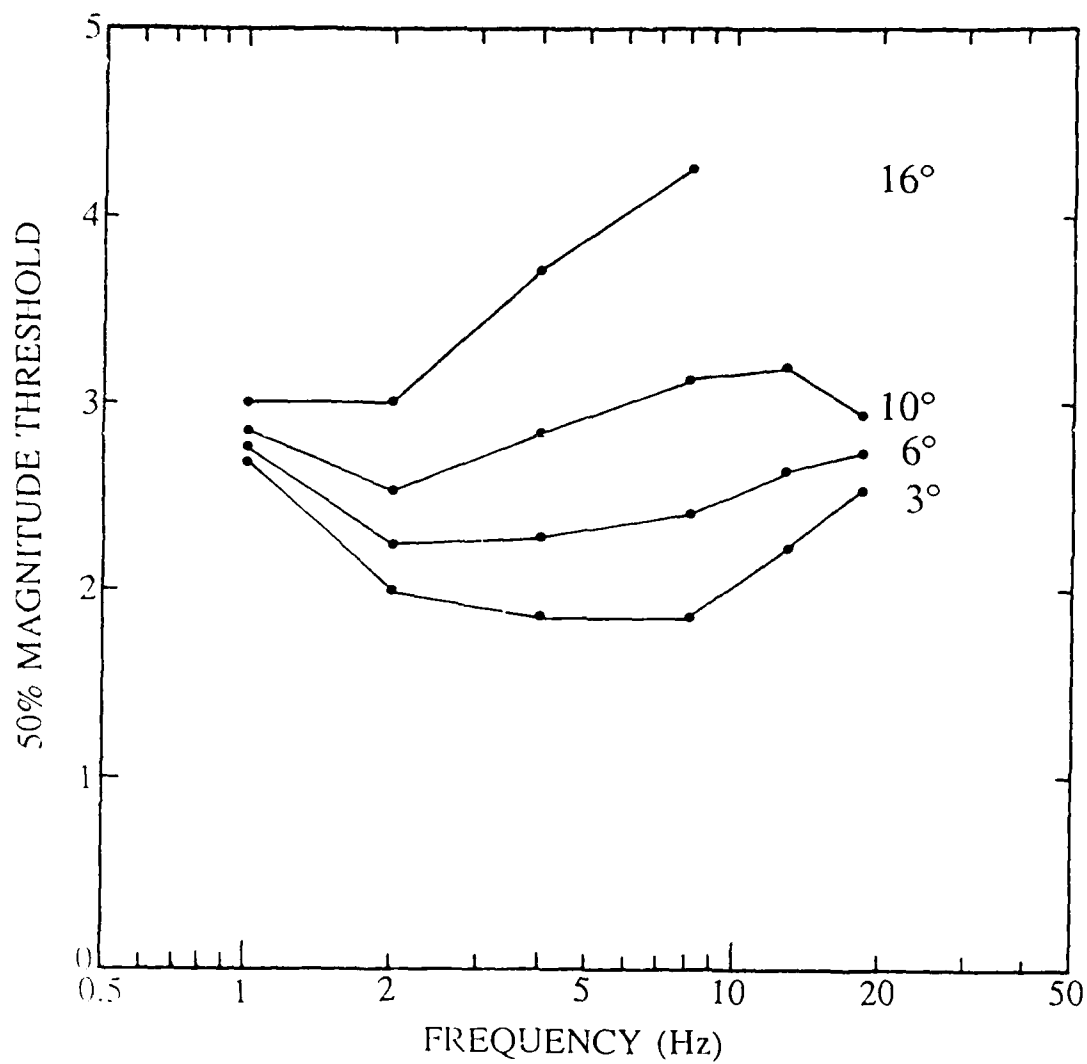


Figure 26a. Average RSTN 50% detection threshold curves as a function of frequency for L_g for distances from 3 to 16°. Curves for averages of threshold estimates.

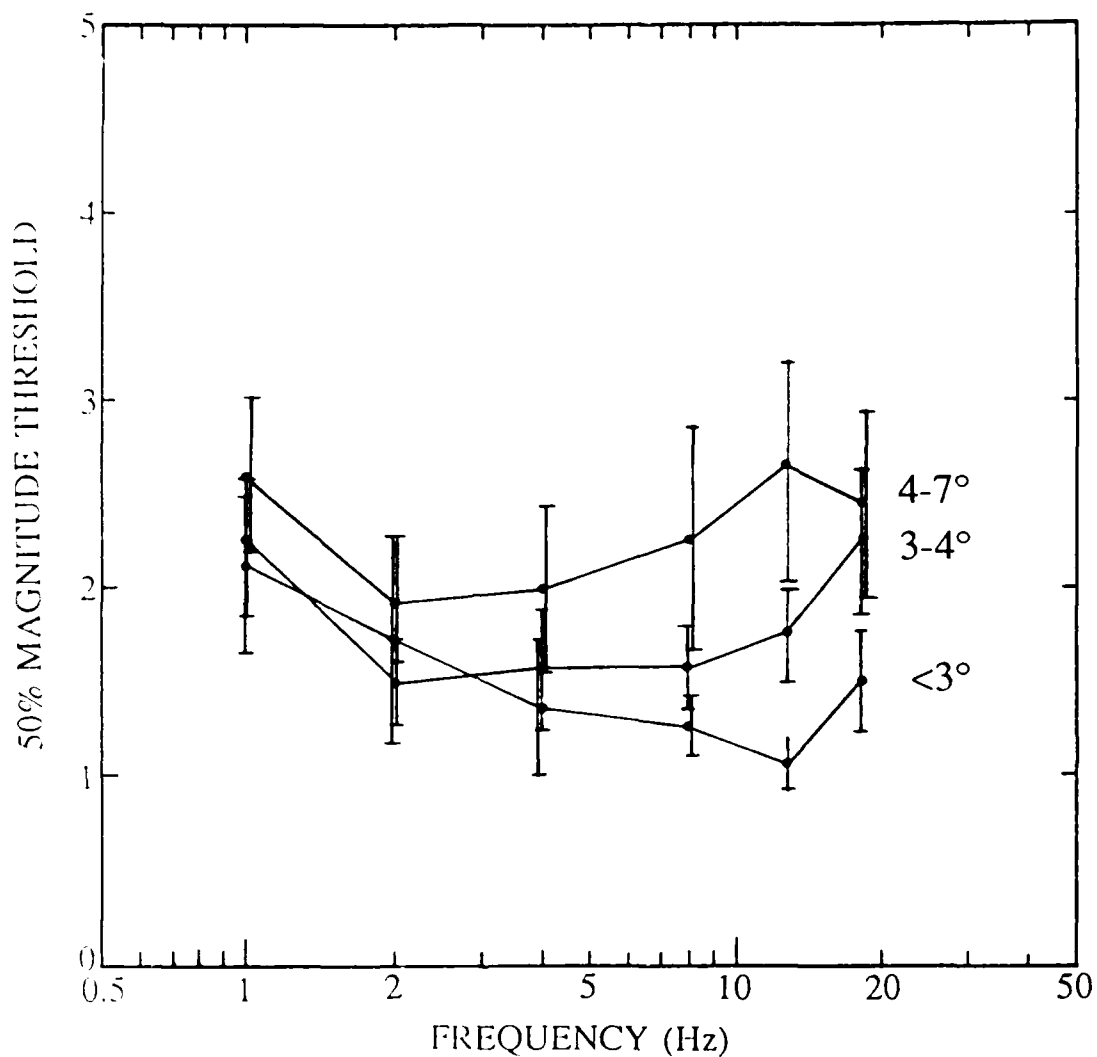


Figure 26b. Average RSTN 50% detection threshold curves as a function of frequency for Lg for distances from <3 to 4° . Curves for maximum likelihood threshold estimates. At the higher frequencies, there appears to be some separation between thresholds for events at distances of $<3^\circ$ and $3-4^\circ$. Even with the large error bars, it is clear that the minimum threshold shifts to higher frequencies for shorter distances.

close and sometimes indistinguishable from *Sn*. At high frequencies and large distances the *Lg* thresholds are higher than those of the *Pn* and *Sn* because *Lg* contains little high frequency energy and most of the high frequency energy observed is probably in the coda of *Sn*. At small distances and high frequencies the *Pn* and *Sn* thresholds are very close because the two phases have similar amplitudes, at lower frequencies the *Sn* thresholds are lower than for *Pn*. Because *Pg* is seen infrequently along paths contained entirely in the tectonically stable parts of North America, our thresholds for this phase probably have larger errors than those for the other phases. In agreement with the predictions of Evernden et al (1986), the lowest absolute values of detection thresholds are associated with the high frequency *Pn* and *Sn-Lg* phases at distances less than 8°.

Comparing the thresholds estimated for individual stations to those for the whole RSTN network reveals some differences. The detection capability of RSCP is somewhat lower than that of the "average" RSTN station. RSNY and RSON have about the same thresholds as the RSTN average station.

We have also looked at the same quantities for the individual RSTN stations RSCP, RSNY and RSSD. Two stations RSON and RSNT did not cover enough events over a large enough range of distances to sketch out the detection thresholds similarly to the others. The estimates agree generally with the results by Blandford et al (1983) and the predictions of Evernden *et al* (1986) that very small events can be detected the most efficiently at high frequencies in tectonically stable regions. The examples of envelope seismograms further illustrate this point.

Our results are also in general agreement with the detection thresholds estimated by LLNL (Heusinkveld 1986). At regional distances, both studies agree that *Lg* is the best detector from among the regional phases in the 1-3 Hz band. *Sn* is the next best detector, and then

Pn. At higher frequencies and larger distances ($>15^\circ$), *Pn* is a better detector than is *Lg*. Generally, for a given distance, at the 50% detection threshold level, our results predict detection of slightly lower m_b s than do LLNL's results. The two studies agree fairly closely with respect to *Lg* detectability. The differences in the results between the two studies may be due to a number of factors. About a third of LLNL's data set consisted of events occurring in the WNA while our data set contains mostly events in the ENA and CNA; due to the greater attenuation of the WNA crust and mantle relative to the ENA, this would bias our detection thresholds to be lower than LLNL's. Because we are concentrating on ENA events, our data set doesn't include data from RSNT. Our data set is somewhat biased in that it was culled initially to only include events with an *Lg* observable on the raw unfiltered trace. Thus, our thresholds are extrapolated from the signal to noise ratios of larger events following Blandford *et al* (1983). In this study we have used more and narrower bandpasses than were used in the LLNL study; for marginal cases this may allow a detection in some narrow frequency band while a detection would not be made on a trace filtered with a wider frequency band.

The detection thresholds for regional phases at RSTN stations can also be estimated from the previously obtained estimates of attenuation, source, and noise spectra. The family of source spectral estimates, modified by the geometrical spreading and dispersion factor, the instrument response, and the expected attenuation as a function of frequency, estimates the expected signal spectra at any given distance from the epicenter. By combining the expected signal spectra for a phase and the noise spectra for the RSTN sites, the signal-to-noise ratio for the given phase can be estimated at each frequency for each RSTN site at the given distance. In this way we can estimate the detection thresholds for regional signals at any given distance and also determine over what frequency band the given signal will be seen. These detection threshold estimates are 50% detection threshold estimates because we are again estimating the magnitude at which the signal amplitude equals that of the noise.

Figure 27 shows the expected *Lg* spectra for the family of eastern US earthquakes ($m_b = 2, 3, 4, \dots$) at a distance of 5 degrees from RSSD. The mean noise spectra at RSSD is also drawn to scale on this plot. These curves show that an event of magnitude 2.0 could be detected at RSSD over the frequency band of 2 to 12 Hz. Figure 28 shows envelope time traces for a 2.5 magnitude event at 6.3 degrees from RSCP where the *Lg* phase is easily seen in the middle frequencies but not at the low frequencies.

Another example is shown on Figures 29 and 30. Here the distance is 12.6 degrees. The same average RSSD noise spectra is plotted on the expected signal spectra. From the spectral plot we would expect to be able to detect a magnitude 3 event over the middle frequency range (1.1 to 4.1 Hz). The time series plots for a magnitude 3 event at 12.6 degrees from RSSD show no signal on the first filtered trace (0.5 Hz), some evidence of the *Lg* on the next three traces (0.7 through 1.8 Hz) and none at higher frequencies.

A third example at 20 degrees shows that a magnitude 3.5 event might be detectable over the 2nd, 3rd and 4th frequency bands (Figure 31). The accompanying time trace plot (Figure 32) shows that a magnitude 3.5 event 19.7 degrees from RSSD shows some evidence of the *Lg* phase on the 2nd, 3rd and 4th filtered envelopes.

Finally, the expected *Lg* spectra at 30 degrees shows that RSSD can not detect a magnitude 4 or smaller event at that distance (Figure 33).

The results in Figures 29, 31, and 33 are consistent with the thresholds determined above from relative signal and noise amplitude levels and those determined by LLNL (Heusinkveld 1986). The *Lg* threshold for 5° in Figure 27 is up to a magnitude unit lower at some frequencies than the previously determined thresholds and the LLNL thresholds. Our source estimate at 5° may not be as good as at the larger distances because 5° is near one end of the distance range used in the combined inversions for source, site, and attenuation, and thus extrapolations

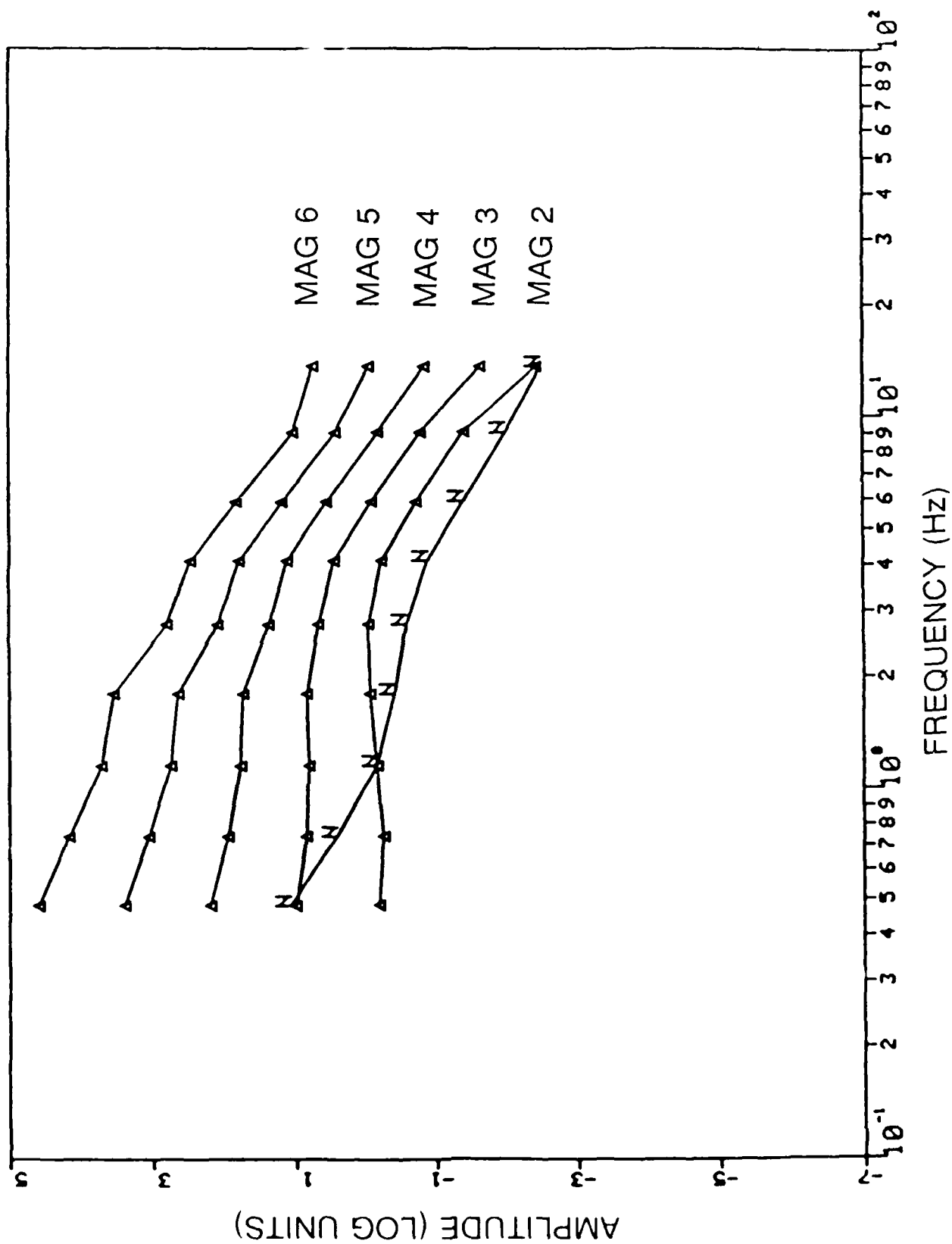


Figure 27. Expected L_g signal amplitude at RSSD from eastern US earthquakes 5 degrees distant. Triangles represent the predicted maximum peak to peak signal amplitude for a suite of magnitudes while N's represent the noise rms amplitude.

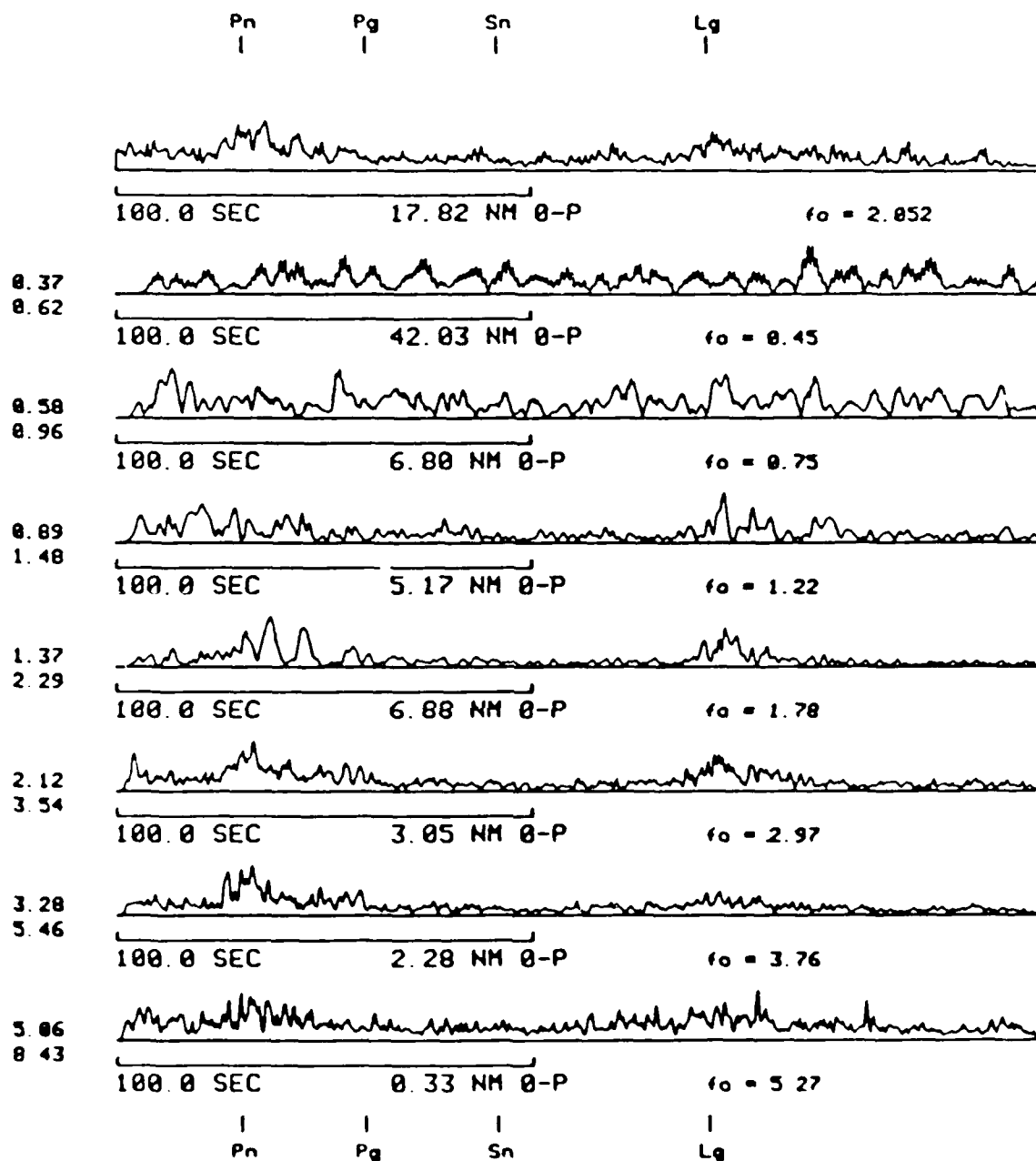


Figure 28. Envelope seismograms at RSCP from an m_b 2.5 earthquake, event 4P014b, 6.3 degrees distant

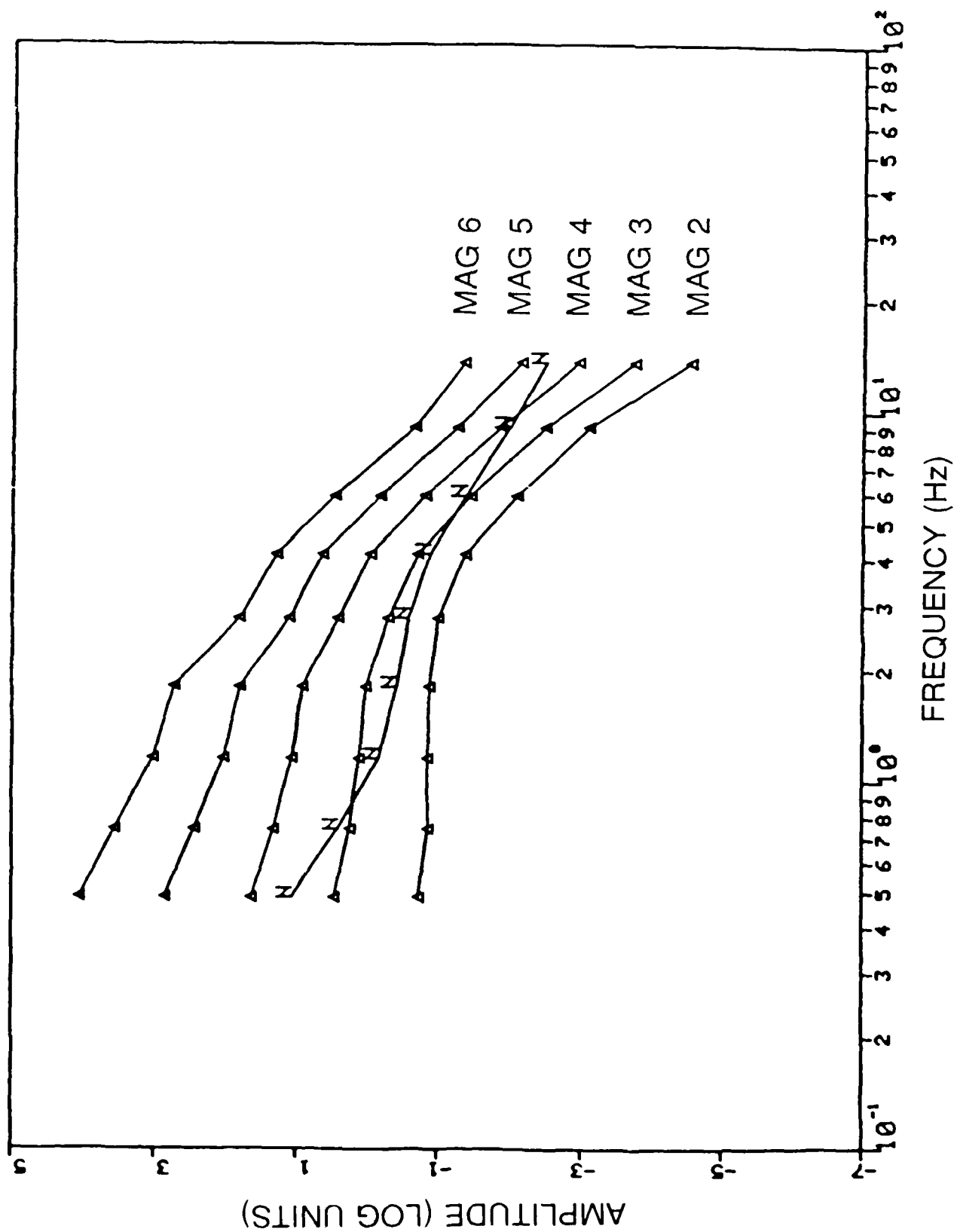


Figure 29. Same as Figure 27 for earthquakes 12.6 degrees distant.

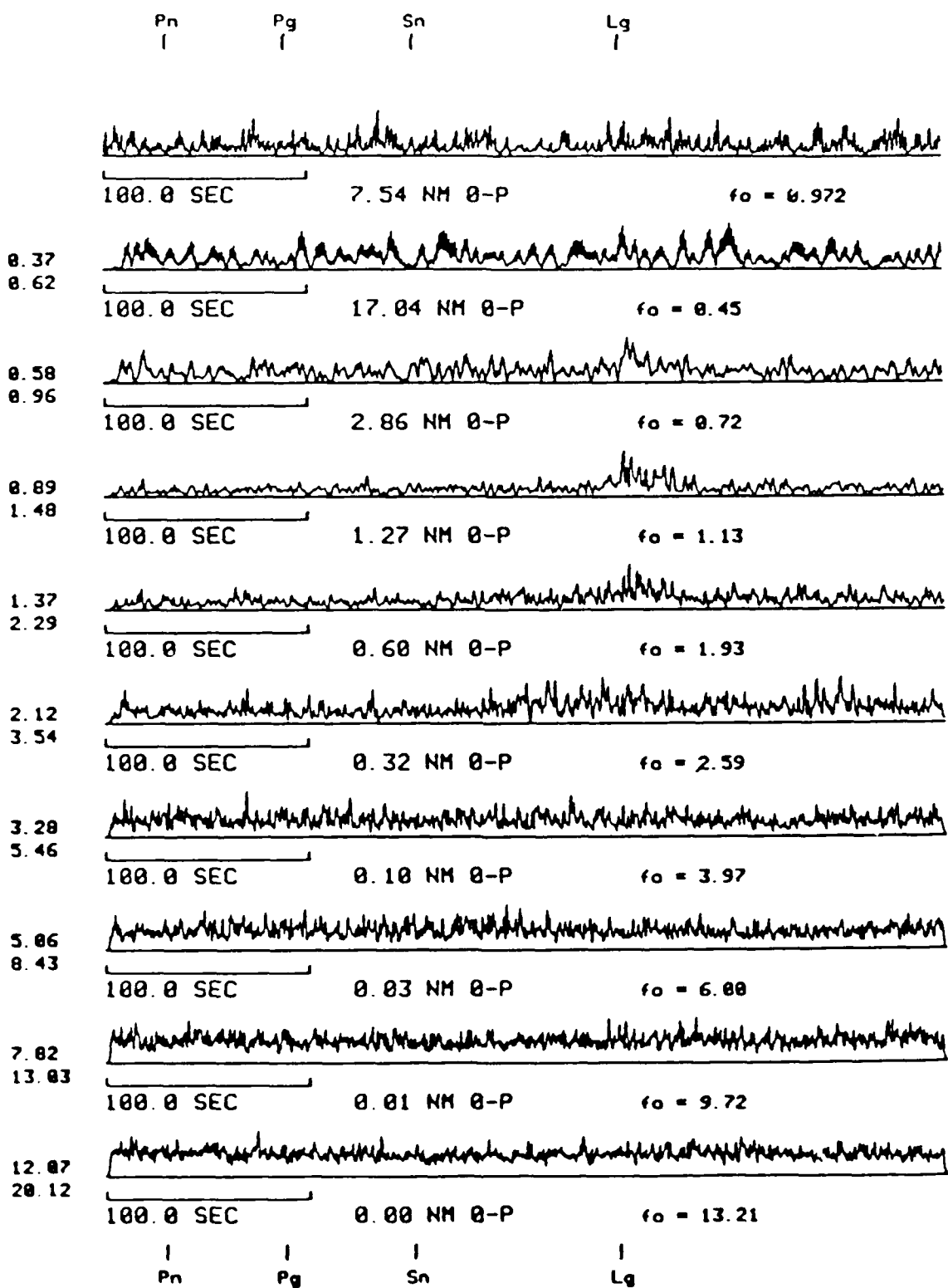


Figure 30. Envelope seismograms at RSSD from an m_b 3.0 earthquake, 4P012, 12.6 degrees distant.

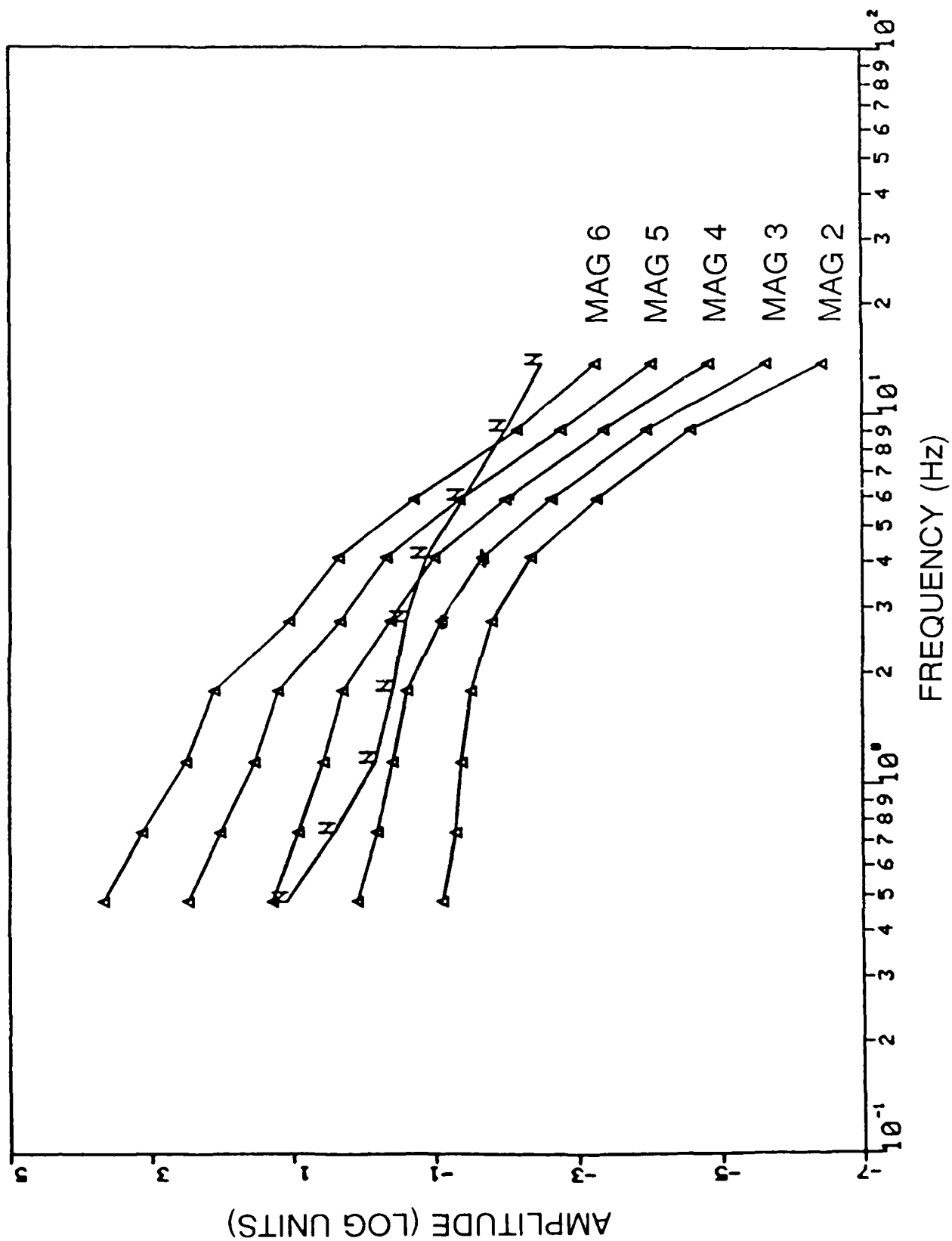


Figure 31. Same as Figure 27 for earthquakes 20 degrees distant.

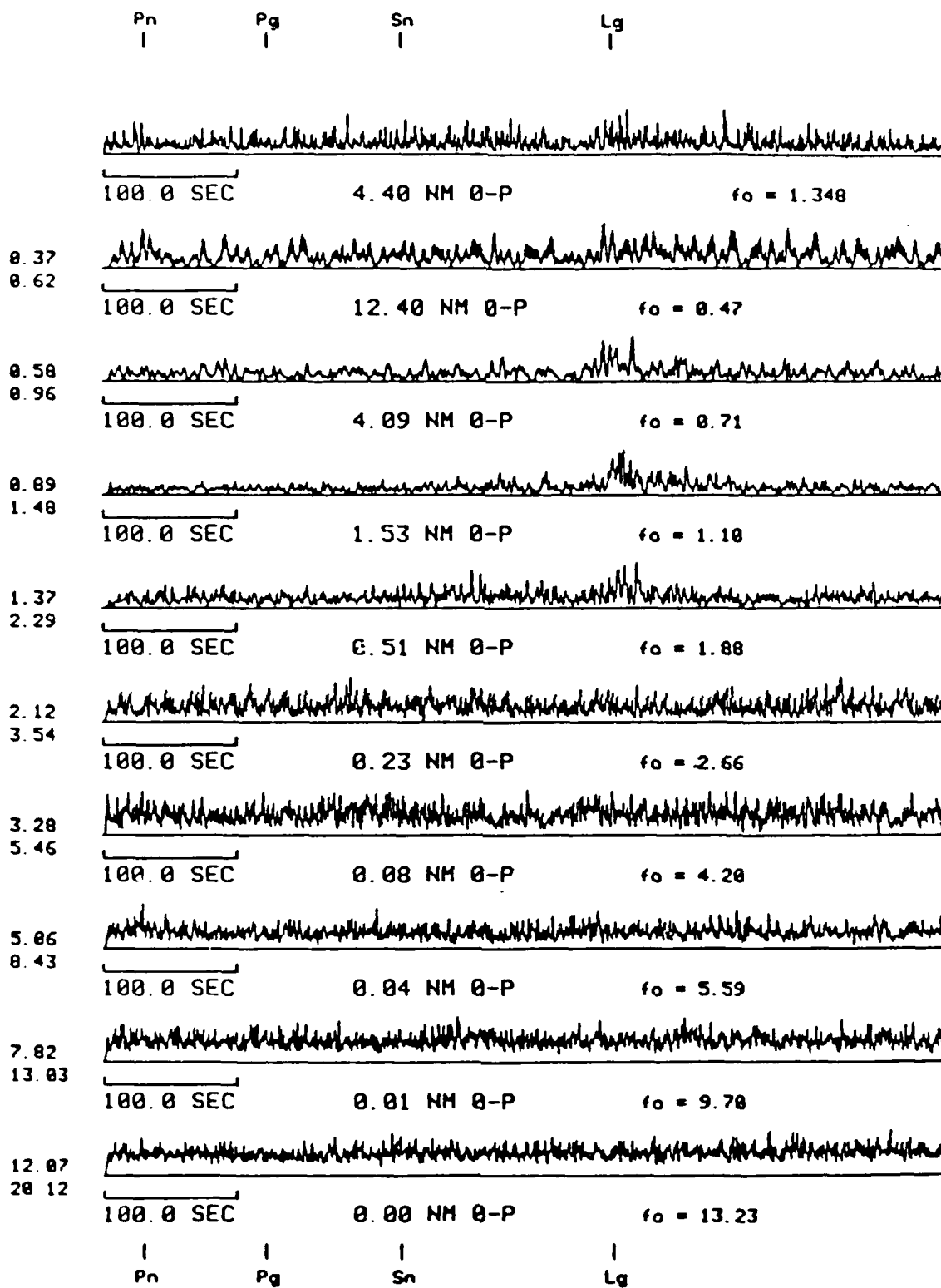


Figure 32. Envelope seismograms at RSSD from an m_b 3.5 earthquake, event 3V026b, 19.7 degrees distant.

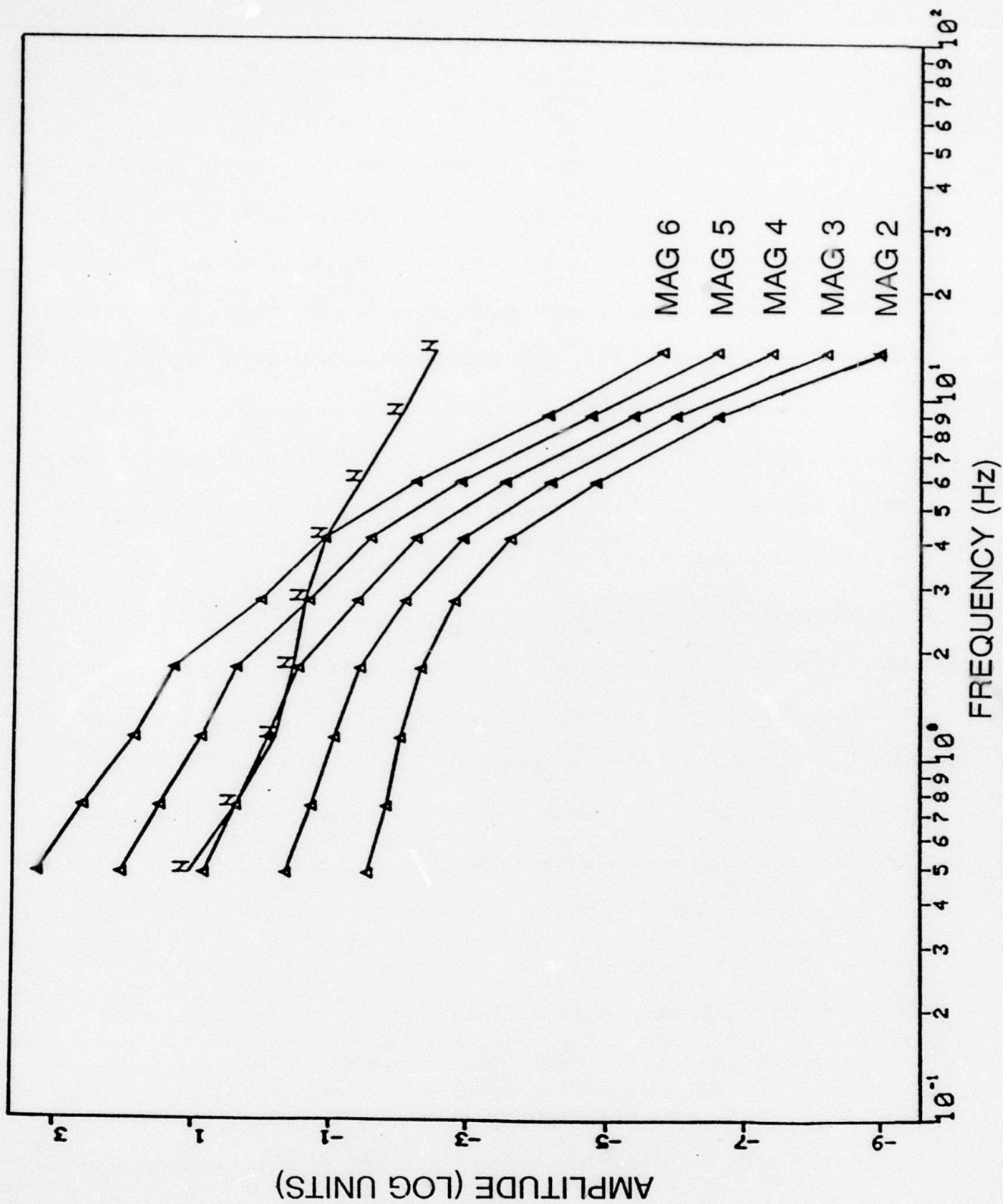


Figure 33. Same as Figure 27 for earthquakes 30 degrees distant.

may give additional inaccuracies.

CONCLUSIONS

This study provides results of apparent attenuation and detection threshold estimates for the regional phases P_n , P_g , S_n , and L_g recorded at RSTN stations from events in Eastern North America (ENA). Knowledge of attenuation and its frequency dependence is important in yield estimation and the attenuation of regional phases is quite different than that of the more often studied teleseismic direct phases. Detection thresholds for regions with wave propagation characteristics similar to those in the Soviet Union are important with regards to designing a seismic monitoring network should a CTBT or TTBT be signed. ENA is a good place for such a study since most of ENA is relatively shield-like in character, similar to many of the major Soviet nuclear test sites.

For the attenuation part of the study, rectified seismograms that had been bandpass filtered by a suite of filters were used to provide measurements of the amplitudes of the different regional phases as a function of frequency for each event. The bandpass filtered traces were used instead of taking the spectral amplitudes because they provide a complete time and frequency picture of the behavior of each phase. For paths which propagate in ENA, L_g is the most prominent phase at lower frequencies to about 10 Hz, after which P_n and S_n are the most prominent phases. Often P_g is not observed at all. For paths that are predominantly in western North America (WNA), P_g and L_g are the dominant phases at all frequencies, and P_n and S_n are very weak arrivals if seen at all. Similar regional wave propagation characteristics have been for waves traveling across France (i.e. Mechler *et al* 1980) which is also a region that has undergone recent tectonic activity. The difference in propagation characteristics between ENA and WNA is probably due to the very different crustal structures in the two

regions. However, a better understanding of regional crustal structures and of the physics of the propagation of regional phases is needed to explain these results. Some attempts have been made at modeling regional phases: P_n and S_n have been modeled as whispering gallery phases (Menke and Richards 1980) or, for oceanic P_n and S_n , as leaky modes (Sereno and Orcutt 1987), while P_g and L_g have been modeled as the sum of many modes trapped in the upper crust (Harvey 1981, Bouchon 1982, Campillo *et al* 1984, 1985). All of these modes of wave propagation are particularly sensitive to the details of the crustal and lithospheric velocity structure and the differences in crustal structure between shield and tectonic regions may explain why different regional phases propagate more efficiently in different regions.

Through a regression analysis, $Q(f)$ was determined for P_n , S_n , and L_g (since most of the paths were in ENA, not enough data was available to estimate a Q for P_g). The Q measurements are of apparent attenuation which include both intrinsic and scattering contributions to the attenuation. The results are presented below, assuming a geometrical spreading factor of $(\sin \Delta)^{-1/2}$ and a dispersion term of $\Delta^{-1/3}$, suitable for an Airy phase. These terms are correct for time domain analysis of L_g , though it is not clear what the correct geometrical spreading term should be for P_n and S_n . $Q(f)$ for these phases assuming different geometrical spreading terms was presented in Table 7.

Phase	Q	Frequency Range (Hz)
P_n	$640 f^{0.5}$	1.0-9
S_n	$825 f^{0.8}$	0.7-9
L_g	$1000 f^{0.35}$	0.5-13

Q_{S_n} has the strongest frequency dependence, and Q_{L_g} the weakest. Q_{S_n} is greater than Q_{P_n} for all frequencies in this study and greater than Q_{L_g} for frequencies above 2 Hz. Even if other reasonable values of the combined geometrical spreading and dispersion coefficient are used,

$Q_{Sn} > Q_{Pn}$ for all frequencies above about 2 Hz. These frequency dependent Q values imply that the Sn to Pn amplitude ratio will increase with frequency, and this is what is observed, for example see Figures 4b and 4c.

These results are similar in trend to those of Mechler *et al* (1980) (Figure 34), though higher in absolute Q 's since this study contains mostly shield paths while Mechler *et al*'s paths are across central (and more recently tectonic) France. Both studies cover roughly the 1 to 10 Hz frequency band and find that Q_{Sn} has the strongest frequency dependence, and that Sn has the highest Q values. Mechler *et al* find that the frequency dependence of Q_{Pg} is very similar to that of Q_{Sn} , although the absolute Q s are lower for Pg . Both studies also find the same frequency dependence for Q_{Lg} , though we find a significantly higher frequency dependence for Q_{Pn} than do Mechler *et al*. This may be because Pn propagates much more efficiently across shield regions than tectonic regions, at least in North America (see Figure 4).

Butler *et al* (1987) and Sereno and Orcutt (1987), studying oceanic Pn and Sn (or Po and So) also find $Q_{Sn} > Q_{Pn}$. Butler *et al* suggest that either there is a significant amount of bulk attenuation in the lithosphere or that oceanic P propagates as a leaky mode while the oceanic S is more effectively trapped in the lithosphere.

The curves for Q_{Pn} and Q_{Sn} along with those for Q_P and Q_S from Evernden *et al* (1986) are plotted in Figure 35. The Q_{Sn} curve crosses the Evernden *et al* Q_S curve around 7 Hz, while, if extrapolated, the Q_{Pn} curve would cross the Evernden *et al* Q_P curve around 200 Hz. In estimating Q_P and Q_S , Evernden *et al* used the relation $Q_P/Q_S = 2.25$, which is generally consistent with observations of mantle Q values. However, the physics of wave propagation must be very different in the crust than in the mantle, at least in the 1 to 10 Hz range, since $Q_{Pn}/Q_{Sn} < 1$, and decreases with increasing frequency.

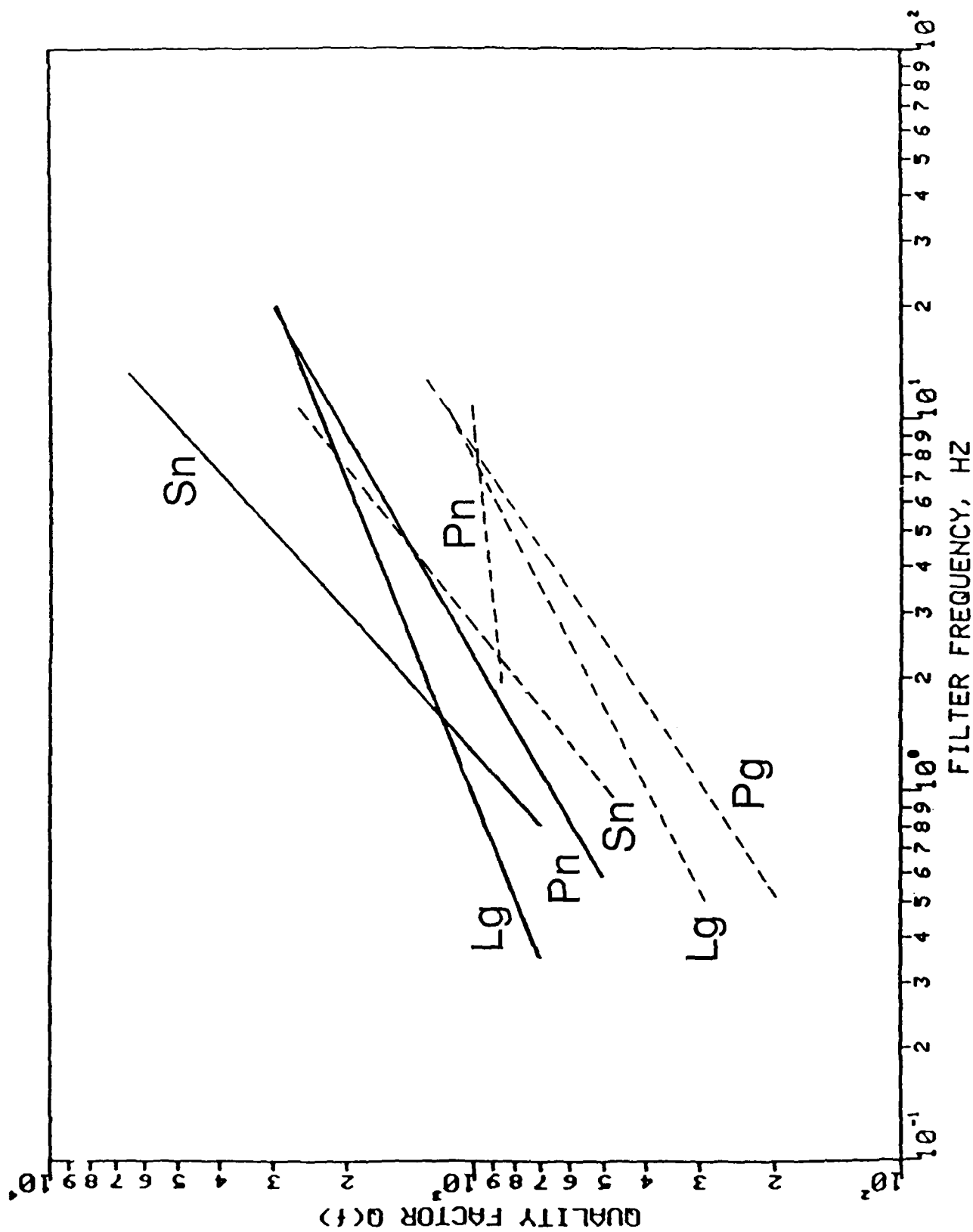


Figure 34. Q versus frequency for regional phases from this study (solid lines) and Mechler *et al.* (1980) (dashed lines).

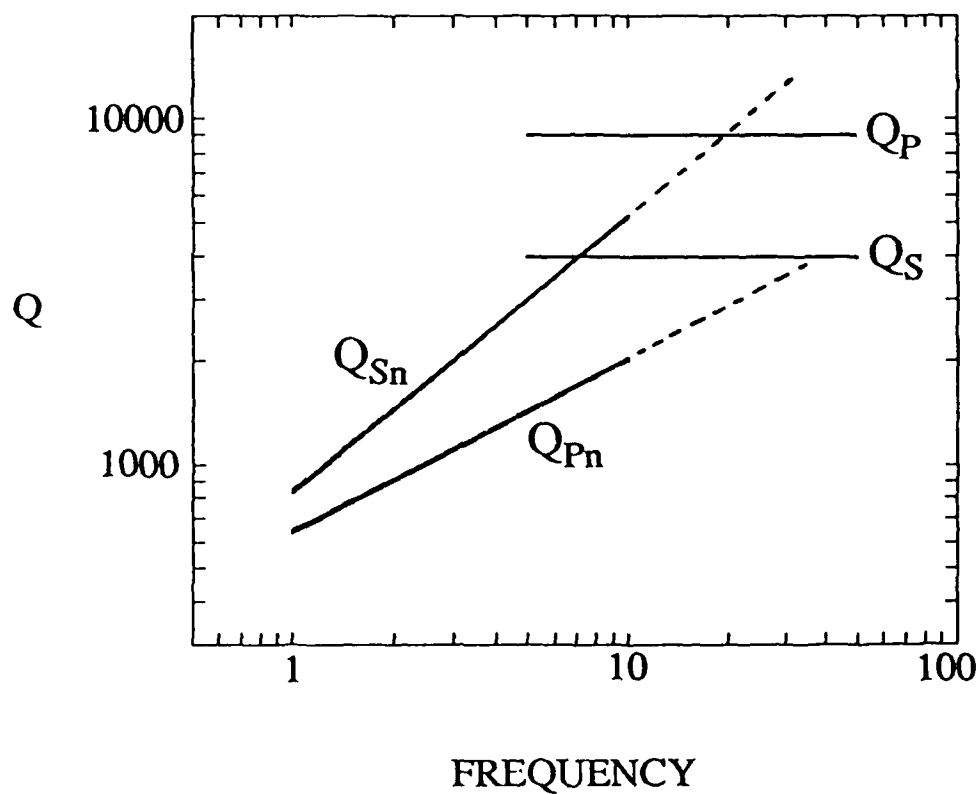


Figure 35. $Q(f)$ for P and S from Evernden *et al* (1986) and Pn and Sn from this study (labeled Q_P , Q_S , Q_{Pn} , and Q_{Sn} , respectively). The dotted lines are extrapolations of our results beyond the frequency range from which data was used.

One obvious mechanism to explain the Q differences between P and S is bulk attenuation in the crust and lithosphere (Butler *et al* 1987, Sereno and Orcutt 1987). However, a number of hypotheses about the mode of regional wave propagation have also been put forth which are consistent with the observations of $Q_{Pn}/Q_{Sn} < 1$, $Q_{Pg}/Q_{Lg} < 1$ (tectonic France), and $Q_{Pd}/Q_{So} < 1$ at high frequencies, above 1-2 Hz. The general idea is that regional phases tend to propagate as modes or rays trapped in the crust or lithosphere. Although both P and S have post-critical reflections in the medium which has trapped them, at each reflection the P transmits some S and thus dissipates as a "leaky" phase or by tunneling while this mechanism is not available to S (Haskell 1966, Pomeroy and Chen 1980, Menke and Richards 1983, Butler *et al* 1987, Sereno and Orcutt 1987).

However, the most important observation for threshold estimation is the total amplitude attenuation due to the effects of both Q and the combined geometrical spreading-dispersion. As we mentioned above, there appears to be a strong tradeoff between the apparent frequency dependences of Q and the assumed geometrical spreading-dispersion rates for the various phases since the amplitude goes as

$$A \sim A_0 \Delta^{-n} e^{-\gamma \Delta}, \quad \text{where } \gamma = \frac{\pi f}{UQ} \quad \text{and } Q = Q_0 f^{-\xi}.$$

If one assumes a low value for the exponent of the distance ($-n$) then the Q will be strongly frequency dependent. The exponent of frequency (ξ) will decrease if we attribute a higher portion of the amplitude decrease to geometrical spreading-dispersion effects and the frequency dependence will be less strong. It is near impossible to differentiate the various models because of the scatter in amplitude data.

In Figure 35, it is clear that $Q_{Pn}(f)$ and $Q_{Sn}(f)$ as found in this report are very different from $Q_P(f)$ and $Q_S(f)$ as estimated by Evernden *et al* (1986). Much of the difference is due to the fact, however, that the combined geometrical spreading/dispersion terms used in the two

studies are $\Delta^{-5/6}$ and Δ^{-2} , respectively. Figures 36 and 37 show the relative attenuation predicted at several frequencies for Pn and Sn , respectively, by Evernden et al (1986) (labeled EAC on the Figures) for combined geometrical spreading and dispersion of Δ^{-2} (solid line) and by this study for $\Delta^{-5/6}$, $\Delta^{-1.5}$, and $\Delta^{-1.75}$ (dashed lines). The difference between the dashed lines is a measure of the variations due to the application of the program in Table 8 and for a suite of frequencies and subsequent fitting of $Q(f)=e^{-\gamma\Delta}$ to the data. The curves are all normalized to unit amplitude at a distance of 500 km. Generally, there is a surprisingly good agreement in the amplitude decay predicted by the different formulations. For Pn at low frequency, Evernden et al predict a slightly steeper slope than this study, and at high frequency and larger distance, they overpredict the amplitude by more than a factor of two relative to the results of this study. For Sn , Evernden et al (1986) predict a steeper slope than does this study at all frequencies, and they significantly overestimate the total attenuation at larger distances.

It is also important that the total attenuation due to anelastic absorption and the combined geometrical spreading-dispersion be consistent with the observed fall-off of amplitude with distance for regional phases. For ~ 1 Hz Pn propagating in shield regions, Warren et al (1978) found total attenuation around $\Delta^{-1.5}$ for the eastern United States and Der et al (1982) found $\Delta^{-1.3}$ for the shield region of southern Africa. For Sn around 1 Hz, Der et al found $\Delta^{-1.9}$ for southern Africa. For Lg around 1 Hz in the eastern United States, Nuttli (1973) found $\Delta^{-0.9}$ for $0.5 \leq \Delta \leq 4^\circ$ and $\Delta^{-1.66}$ for $4 \leq \Delta \leq 30^\circ$. From Figures 36, 37, and 38, our attenuation models at 1 Hz, assuming a combined geometrical spreading-dispersion of $\Delta^{-5/6}$, give total attenuation at 1 Hz of Δ^{-1} to $\Delta^{-1.5}$ for Pn , Δ^{-1} to $\Delta^{-1.5}$ for Sn , and Δ^{-1} to Δ^{-2} for Lg . These are in general agreement with the observations quoted above, and as discussed in the introduction, not enough is known about the physics to be sure exactly what the geometrical spreading term should be for Pn and Sn . The total attenuation fall-offs of Δ^{-2} used by Evernden et al (1986) for P and S seem a little high, though their models were developed for frequencies

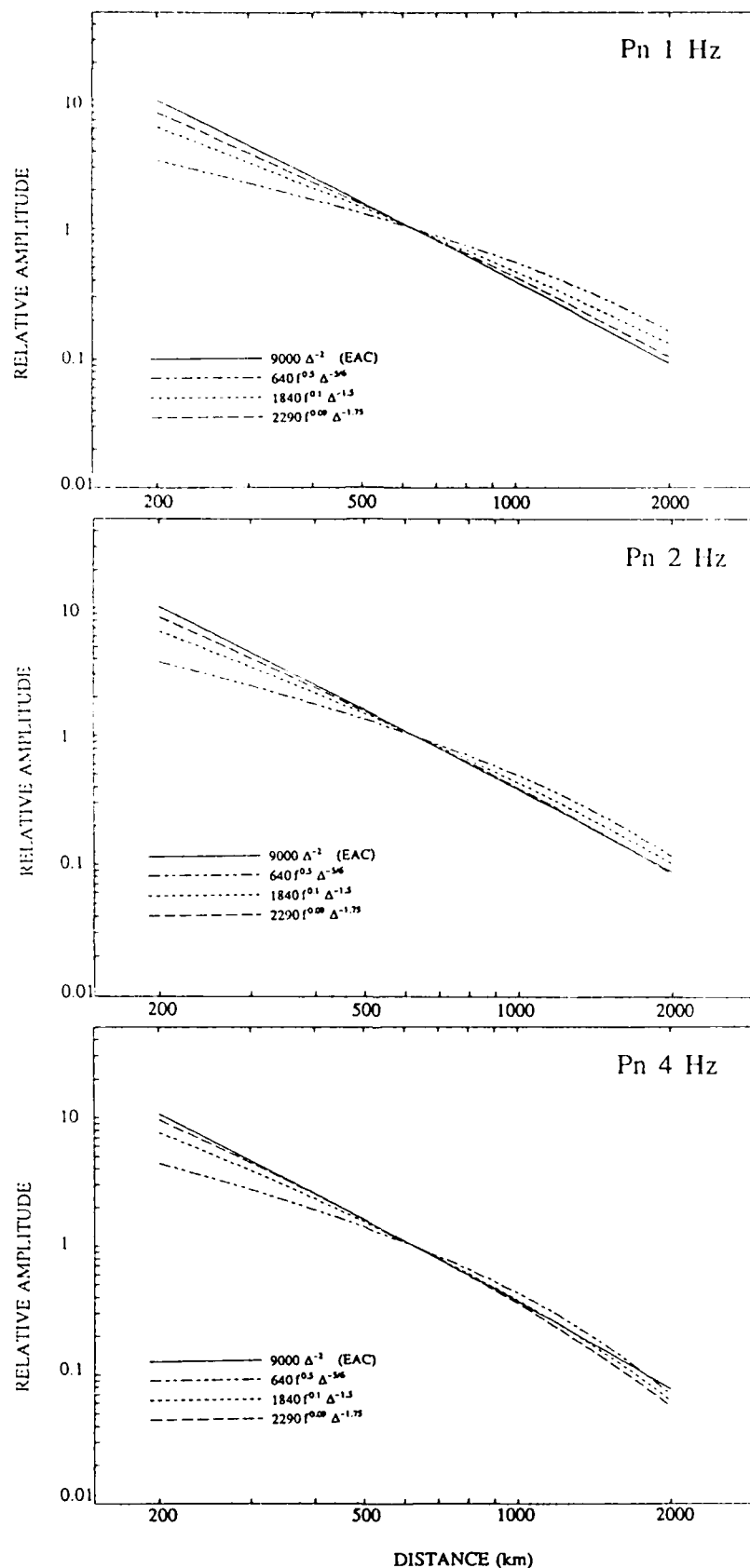


Figure 36. Relative amplitude versus distance for *Pn* at frequencies of 1, 2, 4, 8, and 16 Hz for several $Q(f)$ models and their corresponding combined geometrical spreading/dispersion terms (Δ^{-n}). The solid line corresponds to the model of Evernden et al (1986) and the dashed lines correspond to the models developed in this report (see Table 9). The curves are all normalized to unit amplitude at a distance of 500 km.

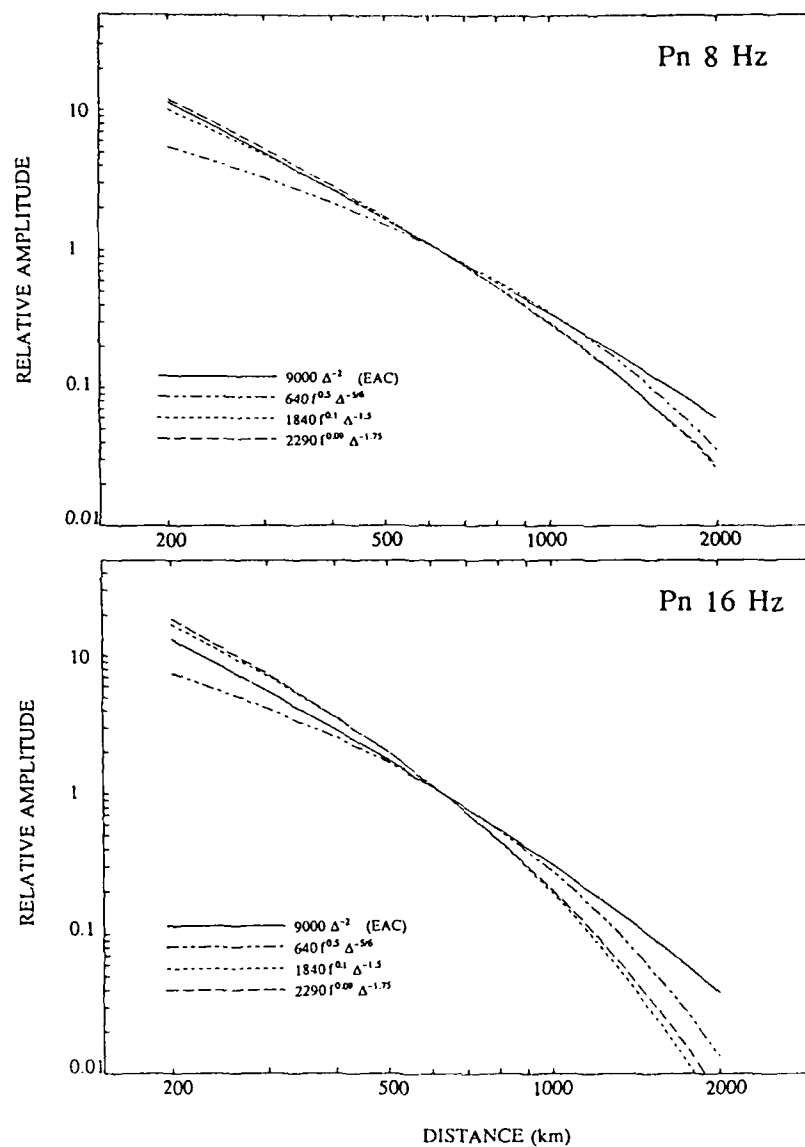


Figure 36 (continued).

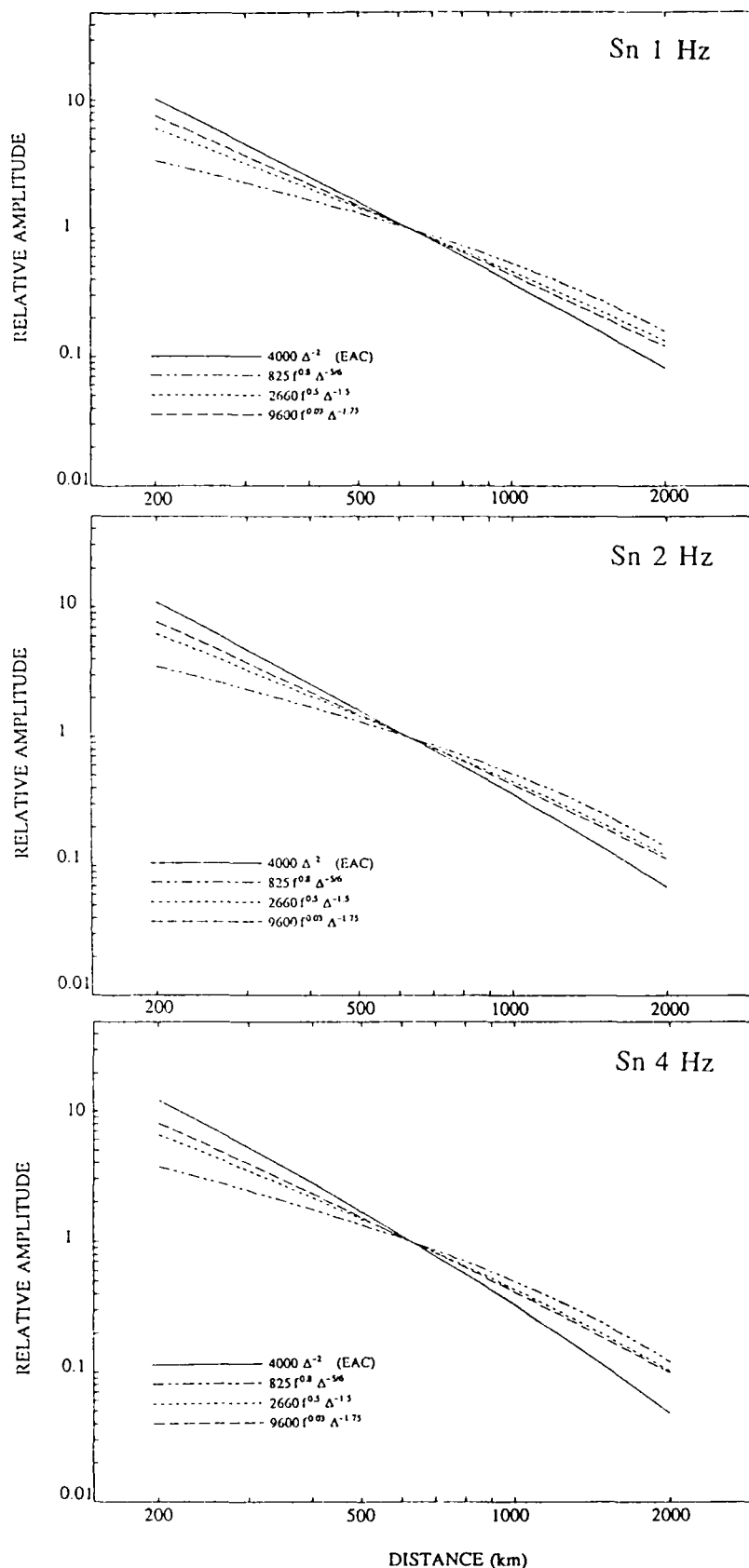


Figure 37. Relative amplitude versus distance for S_n at frequencies of 1, 2, 4, 8, and 16 Hz for several $Q(f)$ models and their corresponding combined geometrical spreading/dispersion terms (Δ^{-n}). The solid line corresponds to the model of Evernden et al (1986) and the dashed lines correspond to the models developed in this report (see Table 9). The curves are all normalized to unit amplitude at a distance of 500 km.

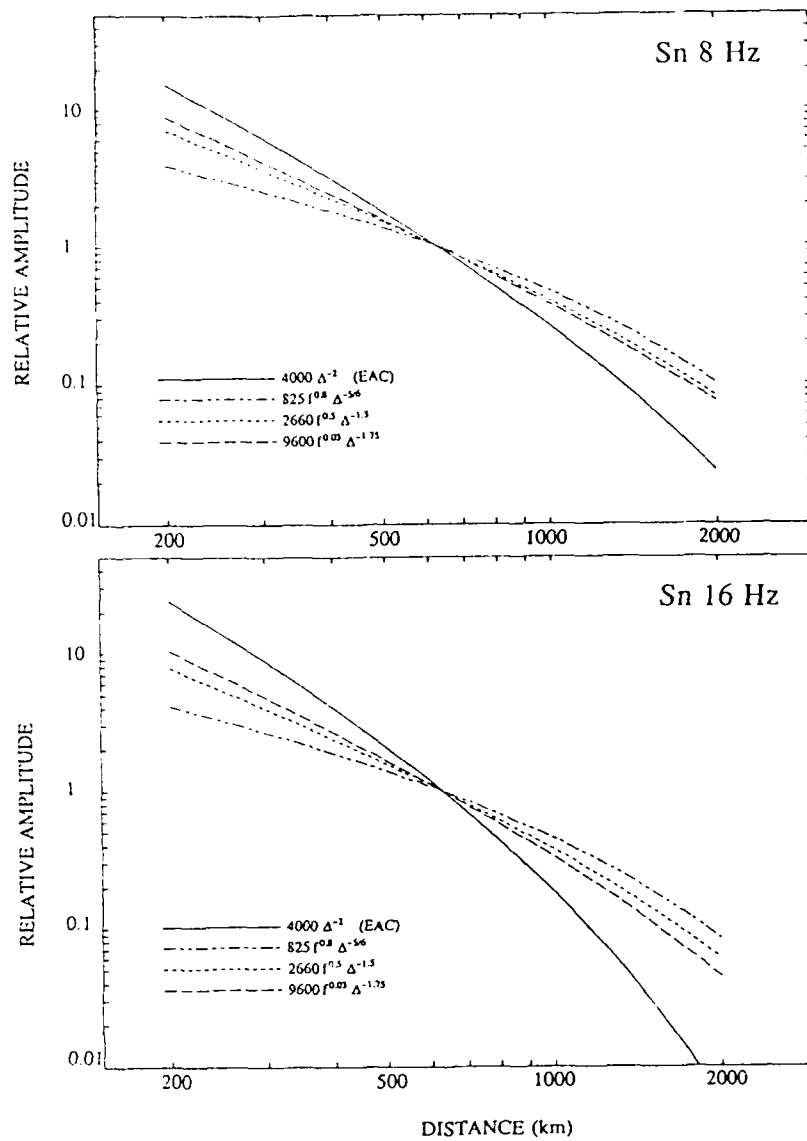


Figure 37 (continued).

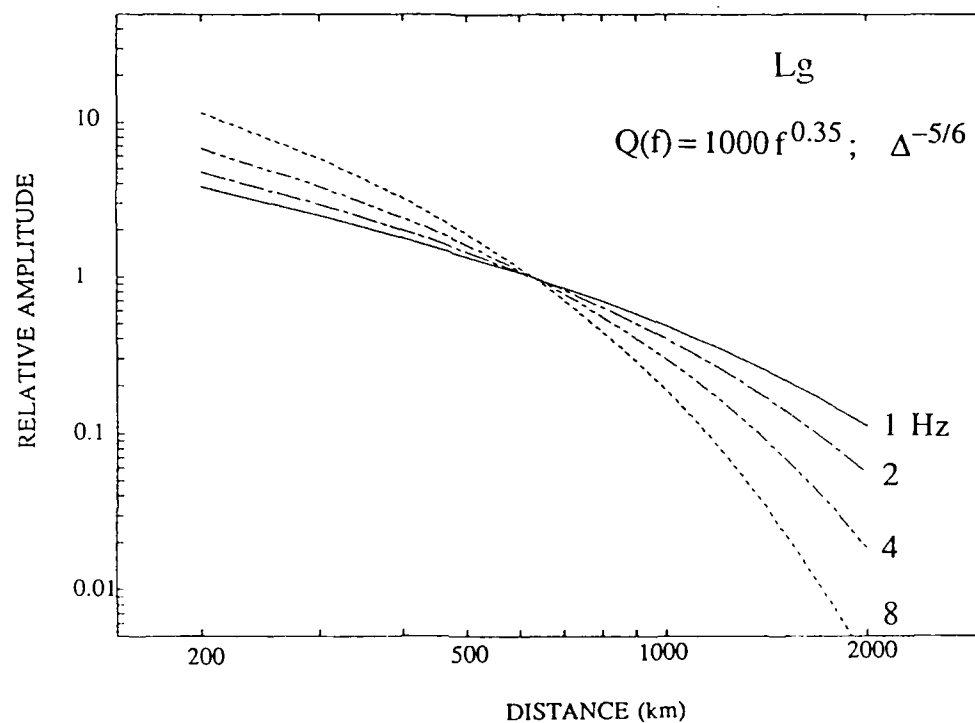


Figure 38. Relative amplitude versus distance for Lg at frequencies of 1, 2, 4, and 8 Hz for the $Q(f)$ model developed in this report and a combined geometrical spreading/dispersion term of $\Delta^{-5/6}$.

above 5 Hz.

The regression analysis also results in estimates of the source spectra and the relative site terms. The source spectra show ill-defined corner frequencies which shift to lower frequencies with increasing magnitude as most proposed scaling laws predict. Part of the lack of resolution of the corner frequencies is because the source spectra are averages of the source spectra for many events in ENA and central North America (CNA). The decay of the source spectral estimates above the corner frequency goes as f^{-2} to f^{-3} for all three phases. Thus, we found no evidence to support the hypothesis that the P and S wave amplitude spectra fall off at different rates. It seems premature to conclude that P waves from explosions and earthquakes can be discriminated reliably on the basis of spectral content. Although we believe that explosion P wave spectra fall off as the square of frequency, after correcting for attenuation effects, earthquake P waves may fall off at various rates. Therefore the discrimination of numerous, small detected events may still be a major problem in monitoring.

The relative site terms (the sum of which is constrained to be 0 at each frequency) are relatively flat for frequencies up to 3 Hz. Above about 5 Hz, RSCP and RSNT are not included in the calculations because of a low pass filter and minimal data, respectively. Of the remaining site terms, RSON and RSNY increase positively with frequency, offset by a decrease with frequency by the RSSD site term.

Noise spectra for the four RSTN sites out to 20 Hz show that the system noise for these RSTN's is less than the seismic background at least to 20 Hz. The response of RSCP prior to April 1985 had a filter which cutoff sharply at 8 Hz so that the RSCP output exhibited nothing but A-to-D round off (i.e. system) noise above that frequency. After day 102 in 1985 the seismometer at RSCP matched the other four. Since then RSCP could also reproduce the earth noise background to 20 Hz without system noise distortion. In addition, our noise spectra

matched those measured by Sandia and other groups for the RSTN stations.

The seismic noise displacement amplitude (in nm/sqrt Hz) falls off inversely as the square of frequency from 1 Hz to 20 Hz, the Nyquist frequency limit for the RSTN's. We estimated the diurnal variation at all of the RSTN sites however; the daytime noise averaging 1.5 times higher than the nighttime noise at RSSD, the quietest site, and up to 3 times higher, day over night, at RSCP and RSON. The site with the largest seasonal variation is RSTN, which is quietest in winter when the Great Slave Lake is frozen. The statements in Evernden *et al* (1986) concerning the low seasonal variation and the falloff rates of noise spectra with increasing frequency are supported by our findings.

The final part of this study involved estimation of regional phase detection thresholds at the RSTN stations. We find for distances less than 16° Lg has the lowest detection threshold, followed by Sn , Pg , and Pn . The results for Pg are marginal because Pg is not often a prominent arrival on our mostly eastern US paths. The frequency at which each phase has its minimum threshold decreases rapidly with distance, most dramatically for Lg . At 3° , all four phases have their lowest thresholds in the 4-8 Hz range; this shifts to 1-4 Hz by 16° . These results are consistent with the observations of the behavior of regional phases from the bandpassed filtered seismograms. Minimum 50% detection thresholds for Lg range from magnitude 1.9 at 3° to magnitude 3 at 16° . The standard deviation of these estimates is 0.3 to 0.4 m.u., and the addition of 2 m.u. is required to bring the detection thresholds to the 98% level.

REFERENCES

- Blandford, R.R., Goncz, J., Baumstark, R. and K.L. McLaughlin (1983). Evaluation of the RSTN network and further improvement to automatic association, *TGAL-TR-83-5*, Teledyne-Geotech, Alexandria, VA.
- Bollinger, G.A. (1979). Attenuation of the Lg phase and the determination of m_b in the southeastern United States, *Bull. Seism. Soc. Am.*, 71, 959-971.
- Bouchon, M. (1982). The complete synthesis of seismic crustal phases at regional distances. *J. Geophys. Res.*, 87, 1735-1741.
- Bungum, H., S. Mykkeltveit, and T. Kvaerna (1985). Seismic noise in Fennoscandia, with emphasis on high frequencies, *Bull. Seism. Soc. Am.*, 75, 1489-1513.
- Butler, R., C.S. McCreery, L.N. Frazer, and D.A. Walker (1987). High-frequency seismic attenuation of oceanic P and S waves in the western Pacific, *J. Geophys. Res.*, 92, 1383-1396.
- Campillo, M., M. Bouchon, and B. Massinon (1984). Theoretical study of the excitation, spectral characteristics, and geometrical attenuation of regional seismic phases, *Bull. Seism. Soc. Am.*, 74, 79-90.
- Campillo, M., J. Plantet, M. Bouchon (1985). Frequency dependent attenuation in the crust beneath central France from Lg waves: data analysis and numerical modeling. *Bull. Seism. Soc. Am.*, 75, 1395-1411.
- Chavez, D.E. and K.F. Priestly (1986). Measurement of frequency dependent Lg attenuation in the Great Basin, *Geophys. Res. Let.*, 13, 551-554.
- Chun, K-Y, West, G.F., Kokoski, R.J. and C. Samson (1987). A novel technique for measuring Lg attenuation - results from eastern Canada between 1-10 Hz, *Bull. Seism. Soc. Am.*, 77, 398-419.
- Der, Z.A., A. O'Donnell, T.W. McElfresh, R. Jutila, J.A. Burnetti, M. Marshall, M. Silk, and E. Gordon (1982). A study of seismic wave propagation at regional distances in five areas of the world, *VSC-TR-82-14*, Teledyne Geotech, Alexandria, Virginia.
- Dwyer, J.J., R.B. Herrmann, and O.W. Nuttli (1983). Spatial attenuation of the Lg wave in the central United States. *Bull. Seism. Soc. Am.* 73, 781-796.
- Evernden, J.F. (1967). Magnitude determination at regional and near-regional distances in the United States. *Bull. Seism. Soc. Am.* 57, 591-639.
- Evernden, J.F., C. Archambeau, E. Cranswick (1986). An evaluation of seismic decoupling and underground nuclear test monitoring using high frequency seismic data. *Reviews of Geophysics*, 24, 143-215.
- Ewing, W.M., W. S. Jardetzky, F. Press (1957). Elastic waves in layered media. McGraw-Hill Book Co., NY/Tor/Lon, pg 358.

- Gupta, I.N. and J.A. Burnetti (1980). Amplitude-distance relationships for regional phases in shield regions, *SDAC-TR-80-7a*, Teledyne-Geotech, Alexandria, VA.
- Gupta, I.N. and K.L. McLaughlin (1987a). Attenuation of ground motion in the eastern United States, *Bull. Seism. Soc. Am.*, 77, 366-383.
- Gupta, I.N. and K.L. McLaughlin (1987b). Regional crustal frequency dependent Q and site effects estimated from LRSN and RSTN data, Draft Paper for EPRI Workshop on Earthquake Ground-Motion Estimation in Eastern North America, March 31 to April 2 1987.
- Harvey, D.J. (1981). Seismogram synthesis using normal mode superposition, the locked mode approximation, *Geophys. J. Roy. astr. Soc.*, 66., 37-70.
- Hasegawa, H.S. (1985). Attenuation of Lg waves in the Canadian shield, *Bull. Seism. Soc. Am.*, 75, 1569-1582.
- Haskell, N.A. (1966). The leakage attenuation of continental crustal P waves, *J. Geophys. Res.*, 71, 3955-3967.
- Heusinkveld, M., editor (1986). Seismic monitoring research program, annual report, *UCID-20628-86*, Lawrence Livermore National Laboratory, Livermore, California.
- Horner, R.B., A.E. Stevens, H.S. Hasegawa, and G. LeBlanc (1978). Focal parameters of the July 12, 1975, Maniwaki, Quebec, earthquake - an example of intraplate seismicity in eastern Canada, *Bull. Seism. Soc. Am.*, 68, 619-640.
- Israelson, H. (1986a). Detection of underground explosions by the GSETT seismological station network. In Technical Report C86-05 (quarterly), Center for Seismic Studies, Science Applications Inc., Arlington, VA.
- Israelson, H. (1986b). Noise levels and detection thresholds of RSTN stations during GSETT. In "Regional Seismic Test Network Research Symposium Proceedings" Sandia Report SAND85-1243, Sandia National Laboratories, Albuquerque NM.
- Kennett, B.L.N. and T.J. Clarke (1983a). Rapid calculation of surface wave dispersion, *Geophys. J. Roy. astr. Soc.*, 72, 619-632.
- Kennett, B.L.N. and T.J. Clarke (1983b). Seismic waves in a stratified half space - IV: P-SV wave decoupling and surface wave dispersion, *Geophys. J. Roy. astr. Soc.*, 72, 633-646.
- Kennett, B.L.N. and S. Mykkeltveit (1984). Guided wave propagation in laterally varying media - II. Lg waves in north-western Europe, *Geophys. J. Roy. astr. Soc.*, 79, 257-267.
- Kennett, B.L.N., S. Gregersen, S. Mykkeltveit, and R. Newmark (1985). Mapping of crustal heterogeneity in the North Sea basin via the propagation of Lg-waves, *Geophys. J. Roy. astr. Soc.*, 83, 299-306.
- Kim, W-Y, Kulhanek, O., van Eck, T. and R. Wahlstrom (1985) The Solberg, Sweden, earthquake of September 29, 1983. Seismological Department, Uppsala University, Uppsala, Sweden.

- Kvaerna, T. and F. Ringdal (1986). Stability of various f-k estimation techniques, in Semiannual Technical Summary, NORSAR Scientific Report no. 1-86/87, L.B. Loughran ed.
- Mechler, P., Nicolas, M. and A. Chaouch (1980). Seismic crustal and subcrustal phase propagation, Final report for the AFOSR, Laboratoire de Geophysique Appliquee, Universite Pierre et Marie Curie, Paris, France.
- Menke, W.H. and P.G. Richards (1980). Crust-mantle whispering gallery phases: a deterministic model of teleseismic P_n wave propagation, *J. Geophys. Res.*, 85, 5416-5422.
- Mitchell, B.J. (1975). Regional Rayleigh wave attenuation in North America. *J. Geophys. Res.* 80, 4904-4916.
- Mitchell, B.J. (1981). Regional variations and frequency dependence of Q_β in the crust of the North America, *Bull. Seism. Soc. Am.*, 71, 1531-1538.
- Mykkeltveit, S. and T. Kvaerna (1986). Propagation characteristics of regional phases and NORESS real time processing performance, Proceedings of the DARPA/AFGL Seismic Research Symposium, 6-8 May 1986, US Air Force Academy, Colorado Springs, CO, pp. 117-124.
- Nicolas, M., B. Massinon, P. Mechler, M. Bouchon (1982). Attenuation of regional phases in western Europe. *Bull. Seism. Soc. Am.*, 72, 2089-2106.
- Noponen, I. and J. Burnetti (1980). Alaskan regional data analysis, In "Studies of Seismic Wave Characteristics at Regional Distances" AL-80-1, Teledyne-Geotech, Alexandria, VA 22314.
- Nuttli, O.W. (1973). Seismic wave attenuation and magnitude relations for eastern North America, *J. Geophys. Res.* 78, 876-885.
- Nuttli, O.W. (1980). The excitation and attenuation of seismic crustal phases in Iran. *Bull. Seism. Soc. Am.*, 70, 469-485.
- Nuttli, O.W. (1981). Similarities and differences between western and eastern United States earthquakes, and their consequences for earthquake engineering, in *Earthquakes and Earthquake Engineering: the eastern United States*, J.E. Beavers, Editor, Ann Arbor Science Publishers, Ann Arbor, Michigan, 25-51.
- Pomeroy, P.W. and T.C. Chen (1980). Regional seismic wave propagation, 03-80-3, Final Technical Report, Rondout Associates, Inc., Stone Ridge, N.Y.
- Pulli, J. (1984). Attenuation of coda waves in New England, *Bull. Seism. Soc. Am.*, 74, 1149-1166.
- Rodgers, P.W., S.R. Taylor, and K.K. Nakanishi (1987). System and site noise in the regional seismic test network from 0.1 to 20 Hz, *Bull. Seism. Soc. Am.*, 77, 663-678.
- Sereno, T.J. and J.A. Orcutt (1987). Synthetic P_n and S_n phases and the frequency dependence of Q of oceanic lithosphere, *J. Geophys. Res.*, 92, 3541-3566.

- Shin, T.-C. (1985). *Lg* and coda wave studies of eastern Canada, *Ph.D. Dissertation*, Saint Louis University, Saint Louis, Missouri, 185 pp.
- Shin, T.-C. and R.B. Herrmann (1987). *Lg* attenuation and source studies using 1982 Miramichi data, *Bull. Seism. Soc. Am.*, 77, 384-397.
- Singh, S. and R.B. Herrmann (1983). Regionalization of crustal coda *Q* in the continental United States, *J. Geophys. Res.*, 88, 527-538.
- Street, R.L. (1976). Scaling northeastern United States / southeastern Canadian earthquakes by their *Lg* waves, *Bull. Seism. Soc. Am.*, 66, 1525-1537.
- Warren, D.H., Healy, J.H., Hoffman, J.C., Kempe, R., Rauula, S. and D.J. Stuart (1978), Project Early Rise: travel times and amplitudes. United States Geological Survey, Open File Report #1024.

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SEISMIC ATTENUATION STUDIES AT U.K. ARRAYS

by

D. Wilmer Rivers

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SUMMARY

Work on this task was performed while the principal investigator was a Visiting Scientist at the Blacknest seismological facility of the United Kingdom Atomic Weapons Research Establishment (AWRE) in Aldermaston, England. The data archive at Blacknest is an important one for seismic research, particularly for research in the seismic monitoring of nuclear explosions, since it consists of a lengthy historical database of events recorded at an invariantly configured network which was designed especially for monitoring purposes. With attention in the seismic community once more being directed towards the use of arrays for signal processing, it is important that this data resource be made readily available to investigators who can use it in a wide range of research projects. Unfortunately, it has been awkward to carry out data retrieval and analysis at Blacknest on account of the hardware and software involved. The database management tasks are all performed on a PDP11/34 computer, using jobs which are written in undocumented assembly language code. These jobs require occasional revision (obviously, a difficult assignment on account of their coding), and the computer and its peripheral devices suffer frequent malfunction due to their age. The analysis of the data is performed using a powerful mainframe computer at the main site of AWRE, but this must be done in a batch mode using punched cards for programs and alphanumeric input. In addition to the limitation of receiving output only twice a day from the batch jobs, the researcher must cope with the problem of dealing with the enormous programs [physically, they consist of multiple trays of cards] which have been developed, over a period of years, for handling the seismic array data. These programs are poorly documented, and they are written in FORTRAN IV using constructions (*e.g.*, a host of "computed GOTO" statements) which make the logic difficult to follow and to modify. The principal program for analyzing Blacknest data, a massive example of awkwardly written and poorly documented code called BAPPL, presents

more of an obstacle than a pathway for research. Without the support of a staff of analysts and/or programmers, a scientist will thus find it difficult to retrieve and process the volume of data which is typically used in a research project. In light of the potential value to research of the Blacknest data base, a more effective procedure needs to be devised for the data to be retrieved and processed (in at least a preliminary investigation) so that they can be made available to seismologists working at Blacknest and to those in the US. Under this contract we have explored means by which the data can be made available more easily, using the Sun-2 workstation at Blacknest.

It was decided that the productivity both of any future U.S. researchers using Blacknest data and of the Blacknest staff themselves would be significantly enhanced if the interactive graphics capability of the Sun workstation were used for the analysis of seismic array data. The Sun had been installed at Blacknest in the autumn of 1984 for use in the Group of Scientific Experts Technical Test (GSETT). Unfortunately, the staff at Blacknest (which has become small in recent years) does not possess the necessary expertise in the UNIX operating system, the SunCore graphics language, the SunWindows window management system, nor in data base management systems to utilize the Sun as an alternative to the existing batch data processing. It was therefore decided that the principal investigator would work on devising data base display and analysis software that could be used on the Sun workstation at Blacknest. In particular, software would be installed that would make the Blacknest data accessible by programs already written to handle data archived at the Center for Seismic Studies in Arlington, Virginia. This would make the U.K. data readily available to future U.S. researchers, and it would lay the necessary groundwork for any international data exchange experiment that, unlike the GSETT, would involve the exchange of waveforms as well as of parameter data. Also, the principal investigator would instruct the Blacknest staff in the use of the new software, so that they could add to it and, over a period of time, adapt their data analysis from

the batch mode processing on the mainframe computer to interactive processing on the Sun workstation. This plan of action was approved by administrators at both Blacknest and DARPA as being beneficial to research in the U.S. and in the U.K., and especially as being needed for the exchange of data and software between Blacknest and the Center for Seismic Studies. With the approval of both the sponsor and the host, this task thus evolved from one of performing a particular research project at Blacknest (involving using BAPPL to generate a suite of spectra) to one of performing a general software development project there, which would be useful for other research projects (including the computation of spectra).

Although the software development project involved performing a variety of tasks such as writing and maintaining utility programs and copying selected software from the Center, there were two programs that were developed which are the most important for researchers who wish to process U.K. seismic array data on the Sun workstation. The first of these programs is RDBNST, which de-archives the array data that are stored in a dozen different formats in the Blacknest tape library and converts them to the ".w" format used at the Center. The original version of this program was written by M. Tiberio at the Center prior to this contract, but many new features were added to it, and it was extensively re-written for use at Blacknest. The new version is much more "user friendly", and this is a necessary feature for the program to be used by Blacknest personnel who are inexperienced with UNIX and who are unfamiliar with the Center's data base structure. When coupled with the seismogram display capabilities that were developed for the Sun, the RDBNST program should make it easy for the staff at Blacknest to satisfy requests from the U.S. for data from specific events. This was tested successfully when data were provided to the Center for 2 specific spans of 2 hours duration, for each one of the 4 U.K. seismic arrays, in response to a request from DARPA.

The only seismogram display program that existed on the Sun at Blacknest was the Graphical Parameter Measurement (GPM) program that had been developed at the Center for use during the GSETT. The GPM program permits measurements to be made on individual waveforms, so only one trace at a time is displayed on the graphics screen. Although this procedure is suitable for examining RSTN data, it is less than ideal for examining data from a seismic array, where the output of many data channels ought to be displayed simultaneously. Another problem with using GPM is that the code, like that of the large Blacknest data processing jobs, contains at best scanty documentation, so it is difficult to modify to do anything other than the specific set of operations which it was designed to perform. This problem is particularly acute since GPM is 9200 lines long and is written in C, a language with which the staff at Blacknest is unfamiliar. All of the graphics displays and interactions use the "SunWindows" system, a complicated C-language software package for managing windows and for manipulating pixels on the bit-mapped screen, and the use of this system further adds to the difficulty of modifying GPM. It was therefore decided not to attempt to introduce modifications to this program but instead to write new software particularly for the purpose of examining seismic array data such as those which are archived at Blacknest. In order that this software be easily modified by Blacknest staff, most of the code was written in FORTRAN 77. On the Sun, old FORTRAN IV library routines copied off the AWRE mainframe can be recompiled and used along with the new FORTRAN 77 code, so the programs that were written under this contract will continue to be developed by the Blacknest staff by the addition of their own code (both old routines and new ones). Although it was necessary to write some routines in C, they can easily be loaded along with the FORTRAN routines. The C routines can be called from the FORTRAN code in such a way that the FORTRAN programmer does not need to understand how they operate, so the inclusion of these routines does not present a hindrance to the staff at Blacknest.

In addition to writing new FORTRAN code to be used as an alternative to GPM, the principal investigator installed on the Sun at Blacknest the extensive "SPEX" and "DISPLAY" software packages written by J. Wang at S-Cubed and by J. Carter at Rondout Associates, respectively. Both of these packages are written in C and use SunWindows graphics, however, so they are not so suitable for modification by programmers at Blacknest as are the new programs that were written in FORTRAN. Seminars were given to the Blacknest staff in the use of these programs for analyzing seismic data and in the use of the Center's data base management programs.

In addition to being written in FORTRAN rather than in C, another major difference between the code that was developed under this contract and the GPM, SPEX, and DISPLAY packages is that our program is based on the "SunCore" graphics system rather than on "SunWindows" (although it does make some use of "SunWindows", again in such a way that programmers at Blacknest need not be concerned with it). The "SunCore" graphics system operates at a higher level than does the "SunWindows" system, so it is much easier to program. (The difference between the two systems is in some ways similar to the difference between FORTRAN and assembly language, since "SunCore" actually operates by making repeated calls to the primitive drawing functions of "SunWindows".) Another advantage of using "SunCore" is that it is an implementation of the ACM Core graphics standard. Since this standard is widely used throughout the computing industry, it should (at least in theory) be considerably easier to transfer our software to another type of computer (such as a VAX) than it would be to transfer GPM, which is so strongly tied to the particular functions used for drawing on the Sun's bit-mapped screen. Of course, a price must be paid in terms of performance for using a graphics system which operates at a high level close to the programmer rather than at a lower level close to the operating system. Nevertheless, we have found that the code which we have developed so far operates satisfactorily fast for its intended purpose to

permit U.K. array data to be retrieved and displayed. The speed could be improved further with the addition of a floating-point accelerator board to the hardware configuration, and it would certainly be enhanced if the code were transferred from the Sun-2 to a Sun-3 workstation equipped with a floating-point accelerator, so we do not feel that much has been sacrificed by our decision to use the higher level graphics.

The program that was developed at Blacknest for displaying and making measurements on multi-channel data is known as the Interactive Display of Array Seismograms (IDAS) program. It has been ported from the Sun workstation at Blacknest to workstations at the Center, so researchers there can examine the U.K. array data also. Copies of IDAS have been provided to other contractors in the U.S., namely Science Applications International, ENSCO, and Science Horizons. Copies have also been sent to the Australian National University and to the Ruhr - Universitat Bochum Institut fur Geophysik in Germany. Documentation of the program has furthermore been provided to other international participants in the GSETT. IDAS has been used for the analysis of data not only from the 4 arrays operated by the U.K. but also for the analysis of data recorded at NORESS and at Grafenberg. There follows an excerpt from the documentation that was distributed with the program code.

OVERVIEW OF THE IDAS PROGRAM

The Interactive Display of Array Seismograms [IDAS] program permits a user of the Sun-2 or Sun-3 workstation to display on the screen simultaneously the same time window in the records of every data channel of a seismic array. This display of the entire array's seismograms permits the analyst to make a visual inspection of the data, identifying those data channels which will be most useful for further analysis and those which should be deleted from the waveform processing, and it allows him to see how the waveforms vary across the array and to make comparisons among the vertical and horizontal channels and among the short-, intermediate-, and long-period channels. When the analyst has identified those channels which are suitable for the purpose, he can then use IDAS to combine them into a sum-and-delay beam, which will be displayed on the screen along with the individual data channels.

The analyst can choose a single channel (including the newly-formed "beam" channel) from out of the display for a more detailed examination. The screen will be cleared, and the chosen seismogram will be re-drawn on a larger scale. The analyst can next select a shorter segment (shorter in time and/or amplitude) from out of this waveform to expand still further in a new plot on the screen known as the "analysis window". The operator can choose the size, shape, and location on the screen of the "analysis window" (so long as it is confined to that region of the screen which lies beneath the plot of the entire seismogram). He can then perform certain manipulations on the graph of the waveform segment which appears in this window, using the Sun workstation's "mouse" input device to control the movement of cursors on the screen. These waveform manipulations include de-spiking, measuring the amplitude and period of individual peaks, and picking the signal arrival time (which will be transmitted back to the main grid on which all the waveforms are displayed simultaneously, where markers are then drawn indicating both the predicted and picked arrival times on every waveform). The

results of all operations are saved in an ASCII output file.

The operator can next proceed to display a number of graphs related to spectral processing of those time intervals on this waveform which were marked as the "signal" and "noise" windows. (The position of these windows will have moved if the operator chose to make a pick of the signal arrival time that was different from the predicted signal arrival time.) He can display graphs of the tapered waveform segments within the signal and/or noise windows (as they enter into the Fourier transform routine and as they would be reconstructed by inverting the transform), of the displacement or power spectra for both the signal and noise, of the signal phase spectrum, and of the seismograph's amplitude and phase response (for this particular data channel) which are removed from the signal and noise spectra. As was the case for the "analysis window", the operator has control over the size, shape, and location of each of these plots; in particular, he can overlay them. Finally, the operator can choose whether to add the signal and noise spectra to a stack (for the short-period vertical data channels only), thereby building up a frequency-domain counterpart to the time-domain sum-and-delay beam which was created earlier. He can then return to the initial display of all the channels together and select another one on which to repeat this detailed analysis.

Input to IDAS consists of the digital waveforms for every data channel of the seismic array, each in its own ".w" waveform file with a common ".wfdisc" seismogram header file, in conformance with the database structure used at the Center for Seismic Studies. Hypocentral information about the particular event under study, which is used by the program to make the predictions about signal arrival time, azimuth, and slowness, is specified by the operator along with information about how long he wishes the signal and noise windows to be and where he wishes them to be placed with respect to the signal arrival. This information can be typed in at the keyboard or read in from an ASCII file which the analyst has edited in advance. All

other interaction between the analyst and the program is performed using the mouse, except for a few possible interactions in which the analyst will respond to queries from the program by typing responses at the keyboard. Most of the interaction performed by the operator consists of choosing items from "menus" of possible actions that the program can perform next; these menus appear in a corner of the screen (usually in response to the operator's requesting them, although some appear automatically when a new phase of the analysis, such as the spectral processing, is begun), and the operator picks the "menu item" to be performed next by moving the mouse in such a way as to place a cursor on top of the selected item. The operator will also move the mouse, and hence move cursors on the screen, in order to select which waveform to display by itself, to choose a segment of that waveform to display in the "analysis window", to position the analysis window and the various spectral graphs on the screen, to pick the signal arrival time, and to make period and amplitude measurements.

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