UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Preliminary Design Study
for a
National Digital Seismograph Network

by

Jon Peterson

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Open-File Report 81-1046

Albuquerque, New Mexico

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1.0 INTRODUCTION

Recently, the National Research Council published a report by the Panel on National, Regional, and Local Seismograph Networks of the Committee on Seismology in which the principal recommendation was for the establishment of a national digital seismograph network (NDSN). The Panel Report (Bolt, 1980) addresses both the need and the scientific requirements for the new national network. The purpose of this study has been to translate the scientific requirements into an instrumentation concept for the NDSN.

There are literally hundreds, perhaps thousands, of seismographs in operation within the United States. Each serves an important purpose, but most have limited objectives in time, in region, or in the types of data that are being recorded. The concept of a national network, funded and operated by the Federal Government, is based on broader objectives that include continuity in time, uniform coverage, standardization of data format and instruments, and widespread use of the data for a variety of research purposes. A national digital seismograph network will be an important data resource for many years to come; hence, its design is likely to be of interest to most seismologists.

Seismologists have traditionally been involved in the development and field operation of seismic systems and thus have been familiar with both the potential value and the limitations of the data. However, in recent years of increasing technological sophistication, the development of data systems has fallen more to system engineers, and this trend is likely to continue. One danger in this is that the engineers may misinterpret scientific objectives or subordinate them to purely technological considerations. Another risk is that the data users may misuse or misinterpret the data because they are not aware of the limitations of the data system. Perhaps the most important purpose of a design study such as this is to stimulate a dialogue between system engineers and potential data users.

The NDSN system concept presented in this report is intended to serve as a point of discussion -- a strawman, if you will. It is a feasible solution to what we perceive to be the objectives of the NDSN, but it is not a unique solution. Current technology offers a variety of choices in meeting design objectives. We have examined some but not all of these choices. Although our fundamental concept of the NDSN is based on current technology, we have anticipated developments in several fields where state-of-the-art is evolving rapidly, notably satellite communications and database management. If the installation of the NDSN is delayed 5 - 10 years, we anticipate that the methods proposed to record, communicate, and manage the data may change, but it is likely that the fundamental data requirements will be the same. Therefore, in this study we have concentrated more on the types of data that will be generated at the NDSN stations and less on specific hardware that might be used in the data system. When the NDSN is budgeted, a second, more hardware-oriented design study may be needed.

2. BACKGROUND AND OBJECTIVES

The Panel has recommended the establishment of a national digital seismograph network comprising 36 stations, of which 29 would be located in the contiguous United States (see Figure 2.1), 5 would be located in Alaska, 1 in Hawaii, and 1 in Puerto Rico. Each station will produce seismic data in three components over a wide range of frequencies and amplitudes. Some or all of the station data may be telemetered to regional or national centers for rapid processing and analysis. The Panel Report addresses many related topics, including local and regional networks, ocean-bottom seismographs, and a portable research array. This study, however, focuses entirely on the design of an NDSN data system and organization of the NDSN data.

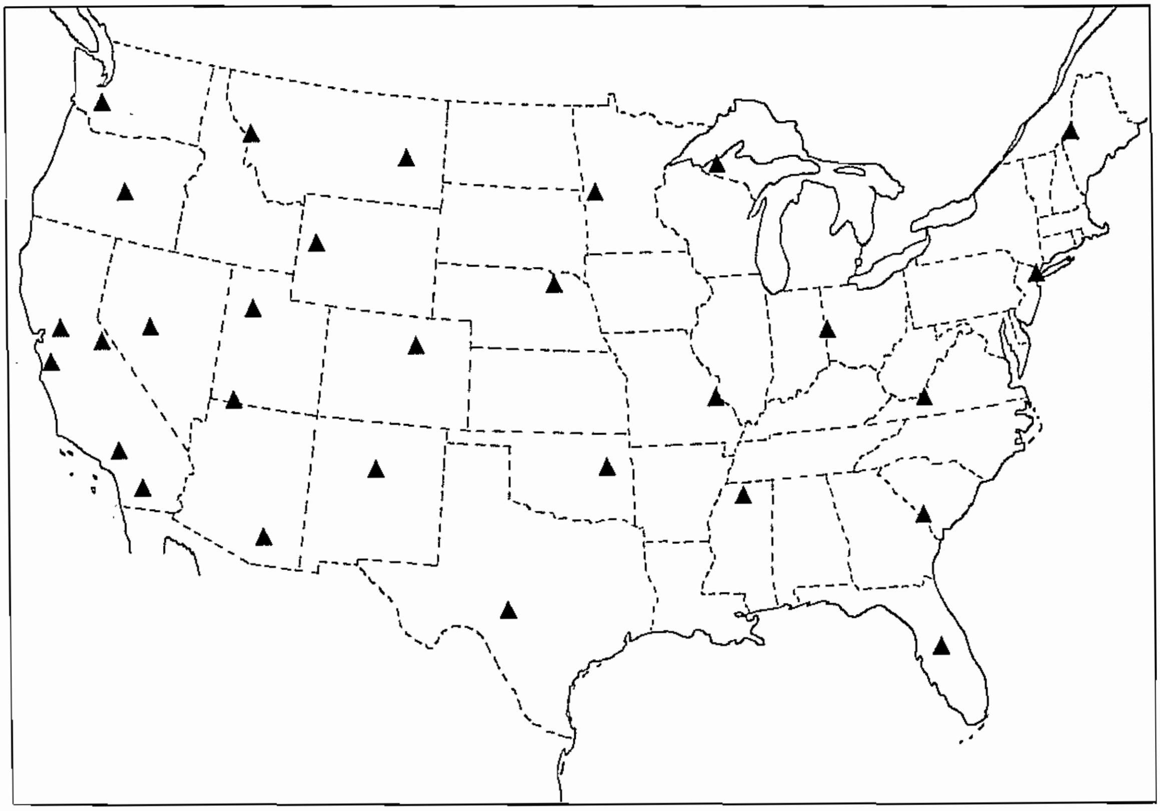


Figure 2.1--Proposed locations of NDSN stations in the contiguous United States. In addition, the Panel proposed that 5 stations be installed in Alaska, 1 in Hawaii, and 1 in Puerto Rico.

The U.S. Geological Survey (USGS) currently manages a global network of seismograph stations consisting of the World-Wide Standardized Seismograph Network (WWSSN) and the Global Digital Seismograph Network (GDSN). There are 27 WWSSN stations in the United States and these constitute what would be considered the existing national seismograph network. Nearly every seismologist is familiar with the WWSSN, so it serves as a good reference when discussing the requirements for a new national network. The WWSSN has been a most important source of seismic data, but the constraints imposed by analog recording limit the usefulness of the data for contemporary research. In analog recording, what you see is what you get. Digital waveforms are a much richer source of information, information that can be extracted by computer processing. This is the most compelling reason for replacing or augmenting the WWSSN by a network of digital seismographs. A dramatic improvement in the seismic database is certain to be followed by significant progress in the science.

One of the major objectives of the NDSN, as stated in the Panel Report, is to uniformly monitor and record earthquakes in the United States. The goal is to obtain high-quality standardized recordings at five or more stations of the seismic wave trains from any earthquake in the conterminous United States large enough to be felt, a magnitude threshold of about 3.0 to 3.5. The threshold for adequate recording is not so much limited by instrumentation as it is by network configuration and site characteristics. The network configuration proposed by the Panel was based on an optimum distribution of stations taking into account predicted noise levels and signal propagation losses. There is, however, one attribute of a data system that does enhance its short-period recording threshold -- the capability to be operated unattended. The WWSSN stations require daily maintenance and, as a result, many are located at noisy sites for convenient accessibility. The NDSN stations will be capable of functioning for extended periods without maintenance, permitting their installation at relatively isolated sites in order to avoid cultural noise.

A second major objective of the NDSN is to record ground motion over a wide range of frequencies. In the United States, short- and long-period seismic data have traditionally been recorded in separate bands to achieve better detection performance. The rejection of microseismic noise has also meant the loss of useful data in the mid-period band. There is sufficient resolution in digital recording to permit much wider recording bands; signals can be enhanced or rejected during post processing. An NDSN system should accommodate a spectral range from the short periods (.04-.1 seconds) associated with small local earthquakes to the long periods (100-300 seconds) associated with mantle waves. While it may not be possible to accomplish this on a single wideband channel, it is possible to design recording bands so that they will overlap without any loss of signal resolution. The need for very-long-period (1000 seconds and longer) sensing at the NDSN stations has not been as clearly defined, but in terms of recording capacity, the capability to record normal modes and earth tides can be provided without major impact on cost or complexity.

A third major objective of the NDSN is to accommodate signal amplitudes ranging from ambient background noise at a quiet site to those normally recorded on strong-motion seismographs. One of the major deficiencies of existing seismograph networks has been the lack of recording range. Apart from strong-motion seismographs, few instruments have been deliberately set to record large earthquakes, so much of the data from earthquakes of greatest interest have been consistently lost because of overdriven recorders. This problem is illustrated in Figures 2.2 and 2.3, which show expected signal amplitudes from two different size earthquakes as a function of distance, together with the recording range of the WWSSN seismographs. The magnifications of the WWSSN systems vary from station to station, so the recording range on a network basis is somewhat better than shown. However, all of the WWSSN stations in the United States are likely to be overdriven for an m_b 7.5 earthquake occurring within a distance of 40°. Gain-ranged digital recording provides the capability to accommodate a large range of signal amplitudes; 120 dB of range is common in digital systems. Nevertheless, it will be necessary in the NDSN system to use at least two sets of sensors operating at different sensitivities to cover the full range of possible signal amplitudes (about 200 dB).

The timeliness of data is not a critical factor in most research applications. However, the acquisition of real-time data is useful to the USGS National Earthquake Information Service (NEIS) in its day-to-day activities. Rapid analysis of telemetered data permits an immediate response to public inquiries and enables the USGS to provide timely information to other agencies concerning

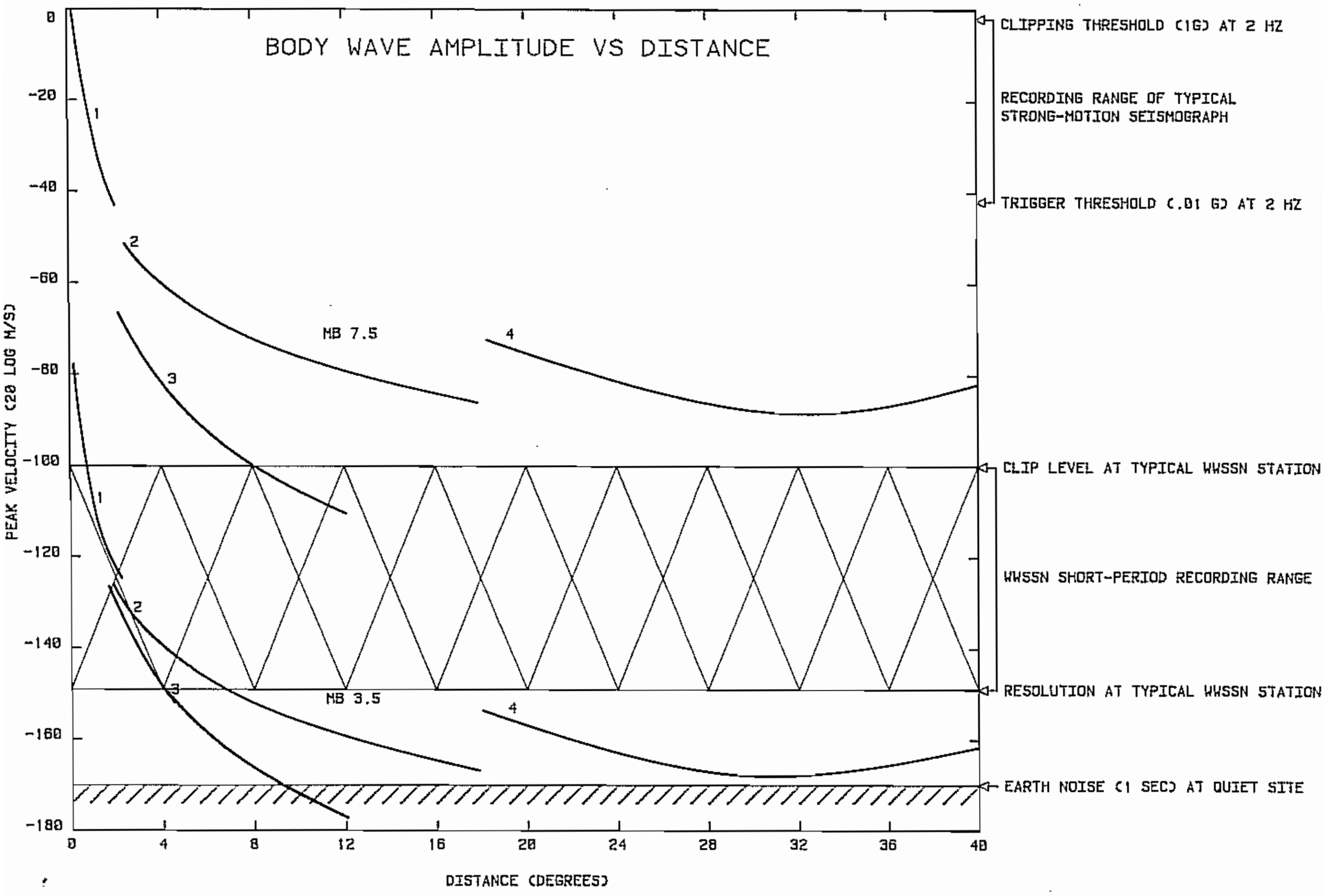


Figure 2.2--Expected body-wave amplitudes vs. distance for m_b 7.5 and m_b 3.5 earthquakes with the recording ranges of typical WWSSN and strong-motion seismographs. Curves labeled 1 were derived from the M_L magnitude formula. Curves labeled 2 and 3 were derived from Evernden's (1967) magnitude formulas for Eastern and Western United States, respectively. Curves labeled 4 were derived from the unified magnitude formula. In this and later figures it has been necessary to compare amplitudes scaled from seismograms (the basis for the magnitude relationships) with amplitudes derived from spectral estimates of background noise. The method used to convert noise power spectral density to peak velocity is as follows: computed power spectral density in units of $(m/s)^2$ per Hz is converted to root-mean-square (RMS) velocity per octave bandwidth, then the RMS value is multipled by 3 to obtain peak velocity per octave bandwidth, which are the units used in the figure for earth noise. Some authors (Fix, 1972 and Melton, 1976, for example) use 1/3 octave bandwidths and different RMS to peak scaling factors, but the 1 octave bandwidth and scaling factor of 3 appears to work relatively well based on a limited set of empirical observations.

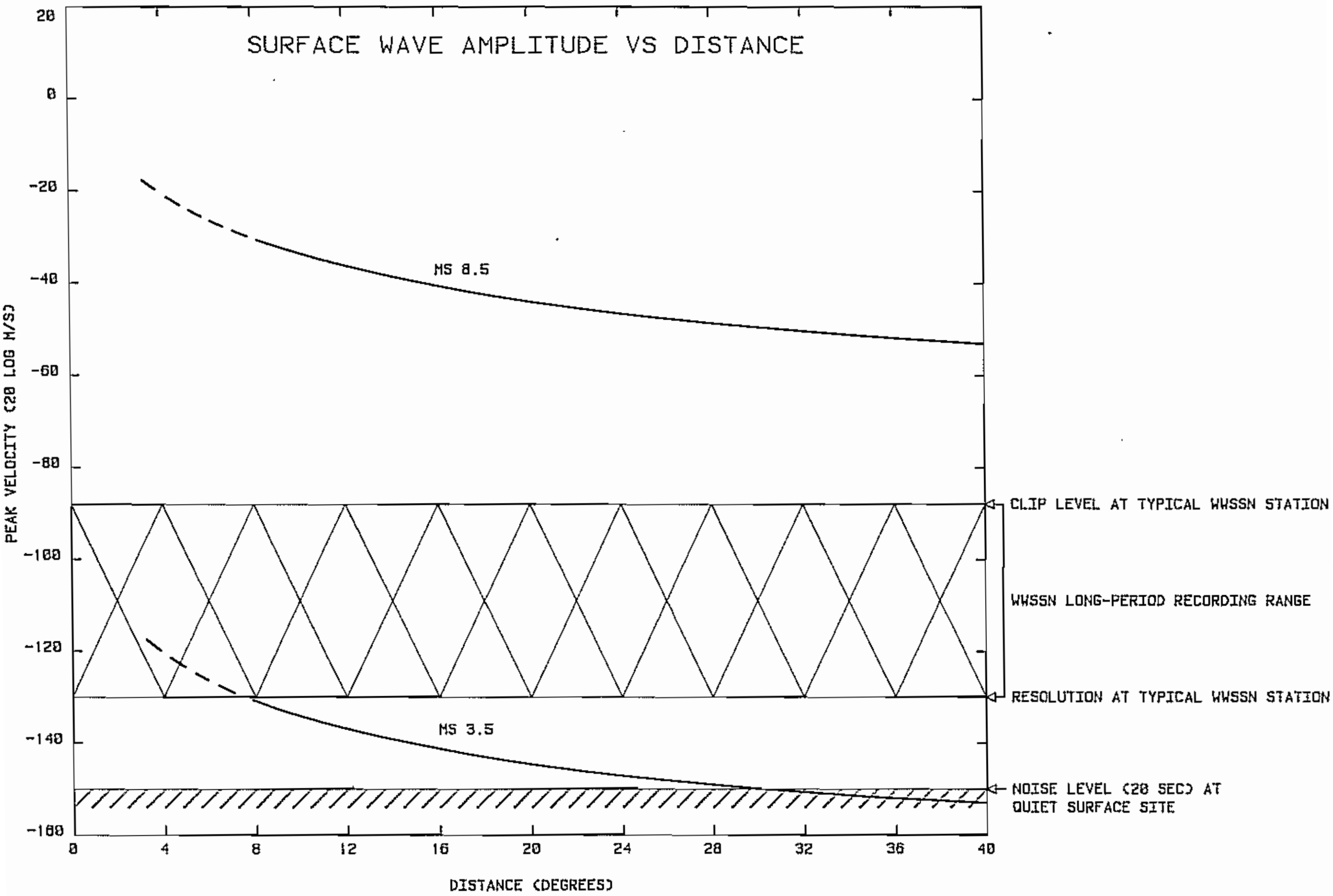


Figure 2.3--Expected surface wave amplitudes vs. distance for M_s 8.5 and M_s 3.5 earthquakes with typical WWSSN recording range. Curves were derived from the M_s magnitude formula.

destructive earthquakes. It may not be feasible to telemeter all of the NDSN data to the NEIS office in Colorado initially because of cost or bandwidth constraints. However, the NDSN data systems should be designed to permit full telemetry of the data, as well as full on-site recording and a mix of recording and telemetry options. Some stations may be configured differently than others with respect to recording and telemetry, and there are certain to be changes during the lifetime of the network.

3. SELECTION OF NDSN RECORDING BANDS

3.1 General

The selection of recording bands is the first and most important step in meeting the design objectives of the NDSN. The fundamental data characteristics of the system are defined by the seismometer and filter transfer functions, sampling rates, and the format of the digital data word. Some of these parameters are interdependent. There are other practical considerations as well; for example, it is best to choose instrument specifications that can be met using off-the-shelf technology if possible.

Three separate sensor subsystems are proposed for the NDSN: short period (SP), broad band (BB), and acceleration (AC). The amplitude response characteristics of these three recording bands are shown in Figure 3.1. Specific reasons for choosing these recording bands are addressed below. In general, they were chosen because they meet the basic data requirements of the NDSN. The composite operating range of the three subsystems will be through a spectral band from less than .01 Hz to 25 Hz and through amplitudes from earth background noise to 1 g of acceleration.

The short-period subsystem will produce high-resolution short-period data that will be used principally for event detection and location. The broad-band subsystem has two intended purposes: to produce wideband body-wave data and to produce surface-wave data in lieu of a conventional long-period seismograph. The SP and BB recording bands overlap so that data recorded in the two bands can be combined during analysis to provide even greater bandwidth if needed. The acceleration subsystem will be used to record signals from those infrequent but important earthquakes that overdrive the SP and BB susbsystems. The amplitude range over which the three subsystems will operate is illustrated in Figures 3.2 and 3.3.

3.2 Sampling Rates and Data Word Format

The sampling rate fixes the high-frequency cutoff of the recording band and it is chosen so that the Nyquist frequency will accommodate the highest frequency of interest. In seismology, the highest frequency of interest is

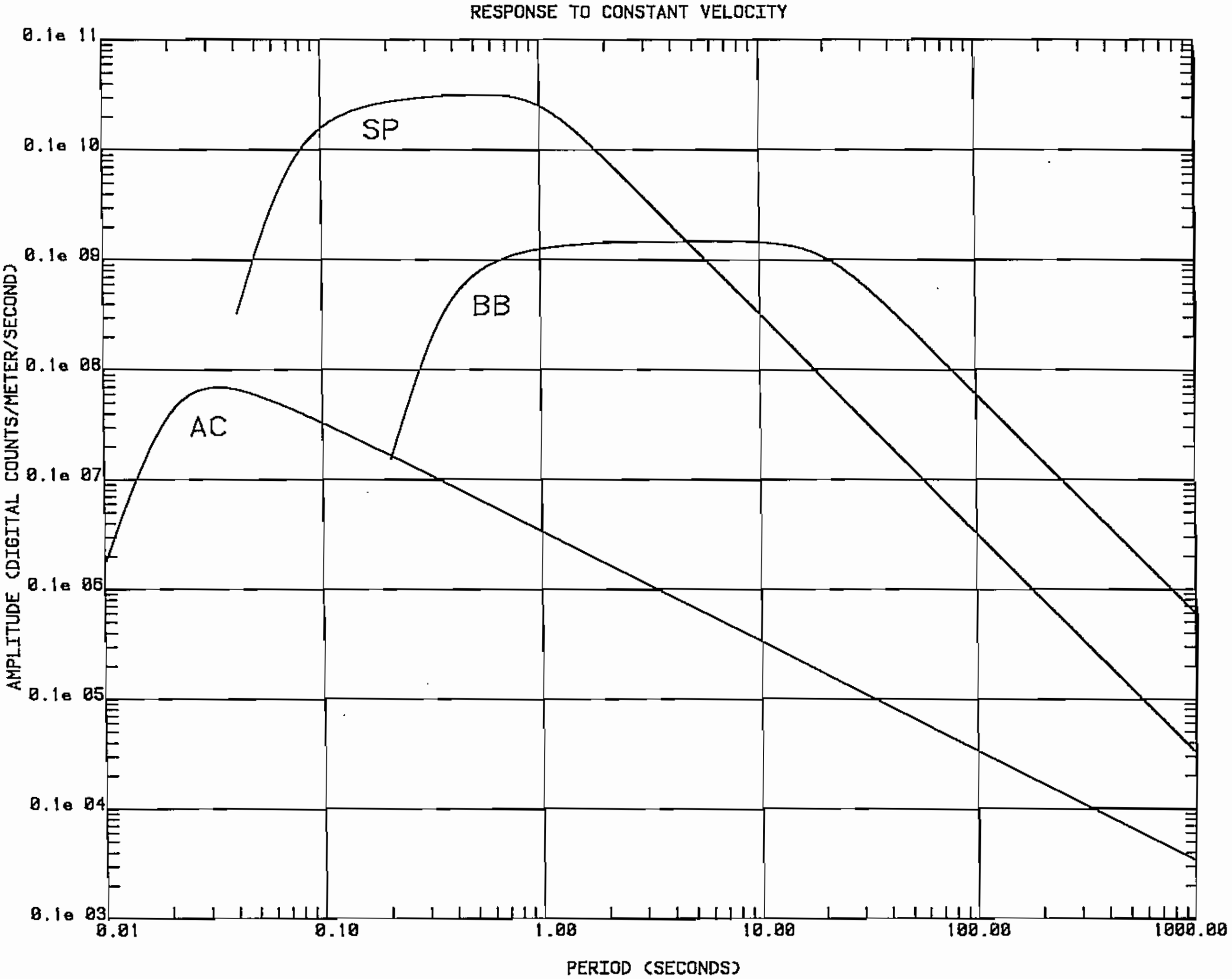


Figure 3.1--Amplitude response curves for the three recording bands proposed for the NDSN -- short period (SP), broad band (BB), and acceleration (AC).

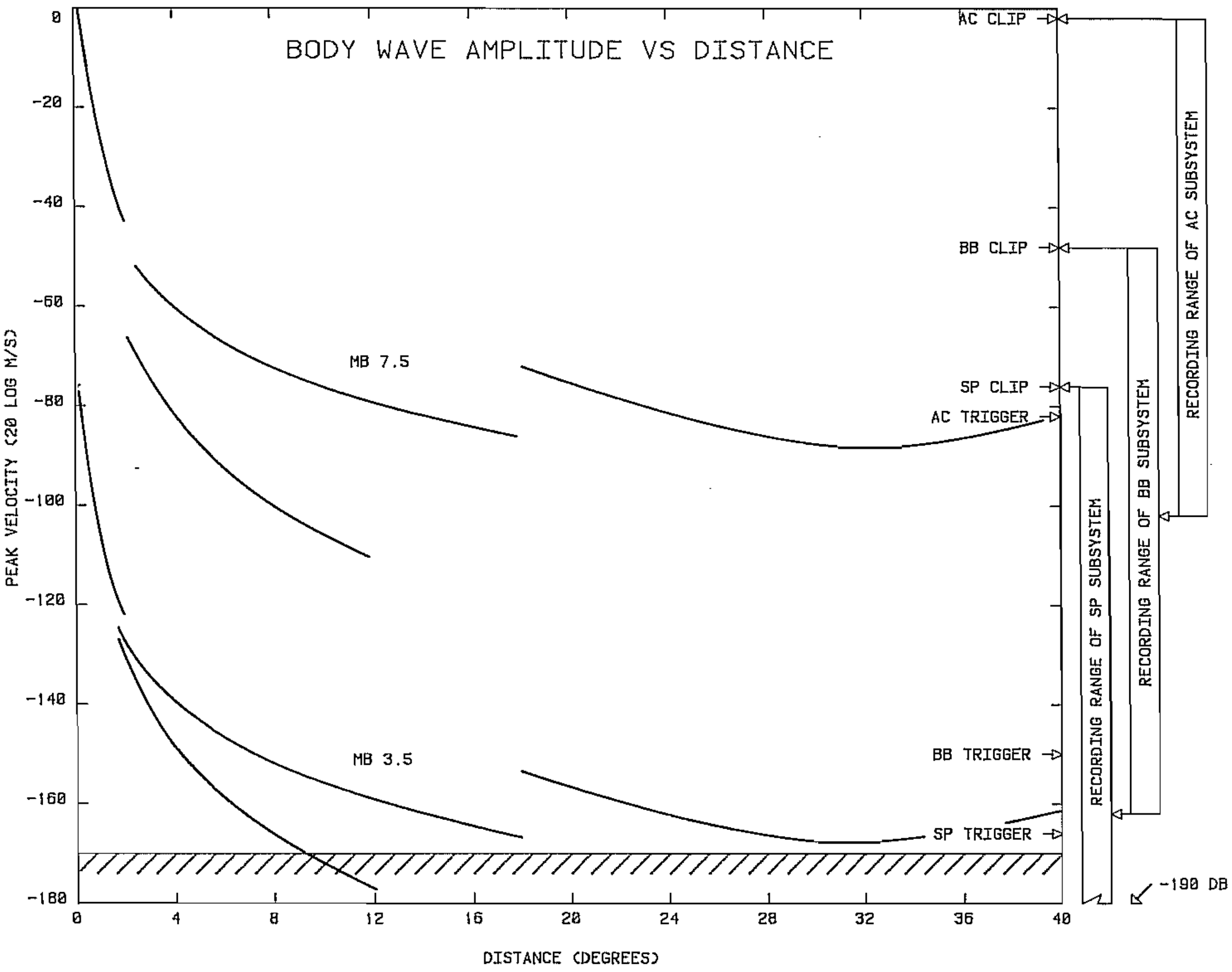


Figure 3.2--Proposed operating ranges of the three NDSN recording bands compared with predicted body wave signal amplitudes. See Figure 2.2 for an explanation of the curves. The maximum distance of 40°, centered on California, will encompass all of the proposed NDSN sites.

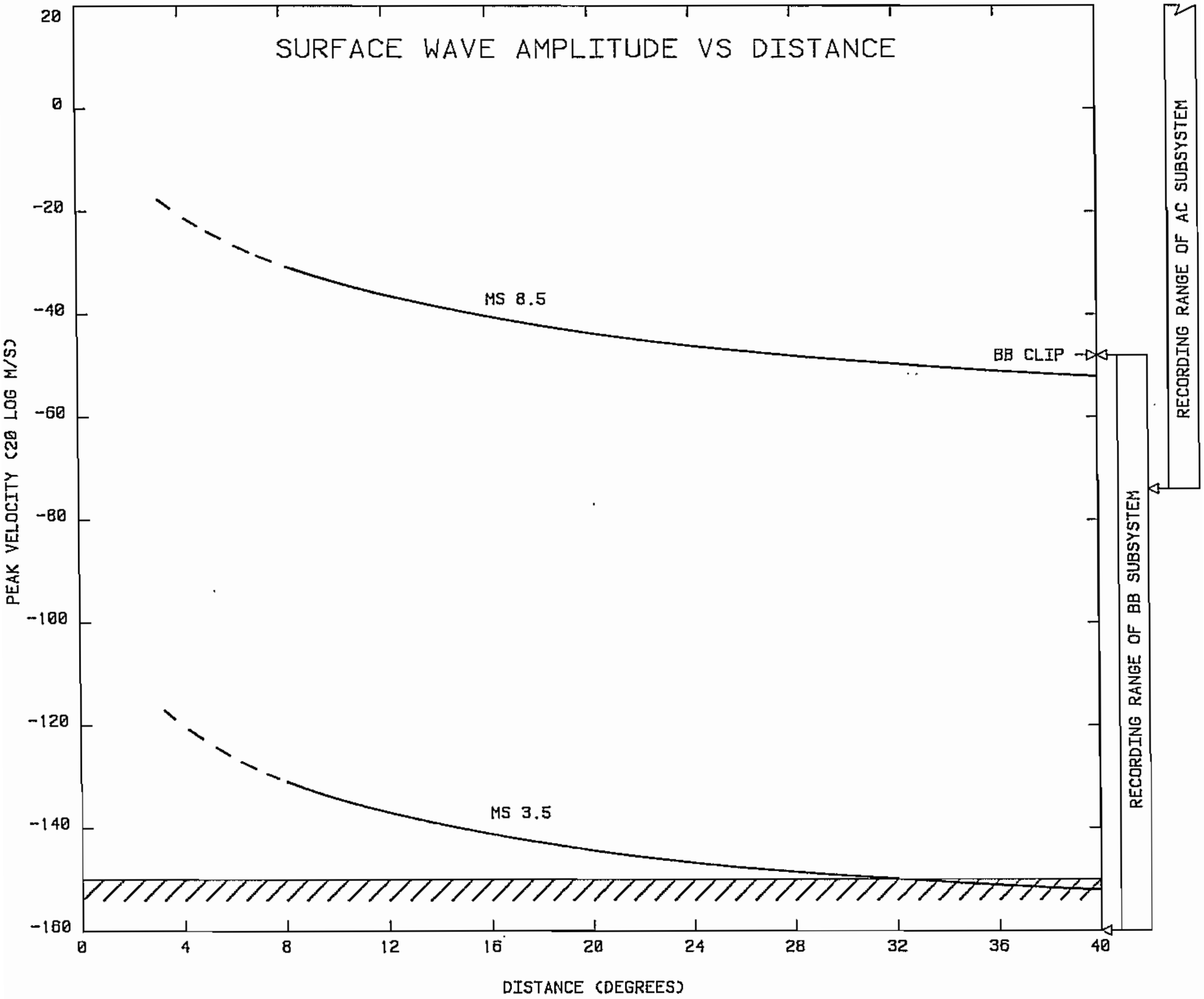


Figure 3.3--Proposed operating ranges of the BB and AC subsystems compared with predicted surface-wave signal amplitudes.

debatable. Given a choice, the sampling rate would be set high enough to preclude debate. However, there is a practical limit to the amount of data that can be transmitted or recorded on site. Sampling rates of 200, 50, and 10 samples per second have been chosen for the AC, SP, and BB recording bands respectively. These sampling rates establish Nyquist frequencies of 100, 25, and 5 Hz respectively, the cut-off points shown in Figure 3.1. The sampling rates selected in this study need not be the only choices available. The NDSN system should be designed with higher optional sampling rates so that it will be possible later to take advantage of higher density recording or the availability of higher transmission rates.

There are compromises involved in the selection of a data word format as well. Here, the tradeoff is between resolution and recording range. For a 16-bit data word, which is assumed for the NDSN, maximum achievable resolution is 90 dB and the peak recording range in this case would also be 90 dB. With a combination of gain ranging and a floating-point data word, recording range can be increased at the expense of resolution. In the Seismic Research Observatory (SRO), for example, there is 66 dB of resolution and a total of 126 dB of recording range.

Resolution is important in the study of signals that are buried in noise or masked by larger signals. However, there is a limit to the amount of resolution that is useful. This limit is imposed by system nonlinearities. A nonlinear system generates intermodulation distortion products that appear as spurious signals if they are capable of being resolved. The average distortion level in the SRO seismometers, which are very linear devices, was found to be -73 dB, the worst case being -64 dB (Peterson and others, 1980). If the NDSN seismometers do not have better linearity, it does not appear useful to provide more than 72 dB of resolution. (This is probably a safe assumption, but it should be verified in tests.)

Twelve bits of the 16-bit word will be needed to provide a resolution of 72 dB. One of the remaining bits will be used for sign, and the other three bits will be used to specify one of eight gain steps. If the gain is incremented in 6 DB steps from 1 to 128, there will be 42 dB of gain ranging and a total digital recording range of 114 dB. The gain could be stepped in larger increments, but the value in doing this is marginal as the signal conditioning equipment can not be expected to have a dynamic range much in excess of 120 dB. The use of overlapping bands (in amplitude) in the NDSN system will make a larger recording range unnecessary in any event.

For the data word format just specified, the maximum digital count will be 524,288, zero to peak. If the analog-to-digital converter (ADC) is set for 10 volts full scale, the least-significant bit (LSB) will be equivalent to 2.44 millivolts at minimum gain and 19.1 microvolts at maximum gain.

3.3 Selection of Low-Pass Filters

Low-pass filters will be needed in each of the recording bands as part of the signal conditioning to prevent, or at least reduce, the aliasing of signals above the Nyquist frequency into the recording band. Some general observations concerning the filter choices may be appropriate at this point.

As an illustration we will use a short-period seismometer operated at a period of 1 second with a damping ratio of 0.6 and sampled at an interval of .02 seconds. Then the Nyquist period is .04 seconds. The transfer characteristics of this seismometer, when operated together with a 2-pole Butterworth filter with a corner period of .08 seconds, are illustrated in Figure 3.4. The response functions were computed with respect to earth velocity. This particular seismometer/filter combination would be useful for analog recording. However, it could not be used for digital recording at the specified sampling rate because the short-period attenuation is not steep enough to prevent a significant amount of aliased signal from appearing in the recorded data.

The amount of attenuation needed at the Nyquist frequency is debatable, possibly even site dependent. If the signal power were constant with frequency, it would be necessary to provide attenuation equal to the resolving power of the system (72 dB in this case) to prevent aliasing. However, the seismic signal power is not independent of frequency; earthquake spectra and noise spectra both fall off as frequency increases. In fact, aliasing has not proven to be a serious problem in the SRO short-period band, even though there is only about 30 dB of attenuation at the Nyquist frequency. A reasonable compromise for the NDSN system appears to be an attenuation of about 40 dB at the Nyquist frequencies.

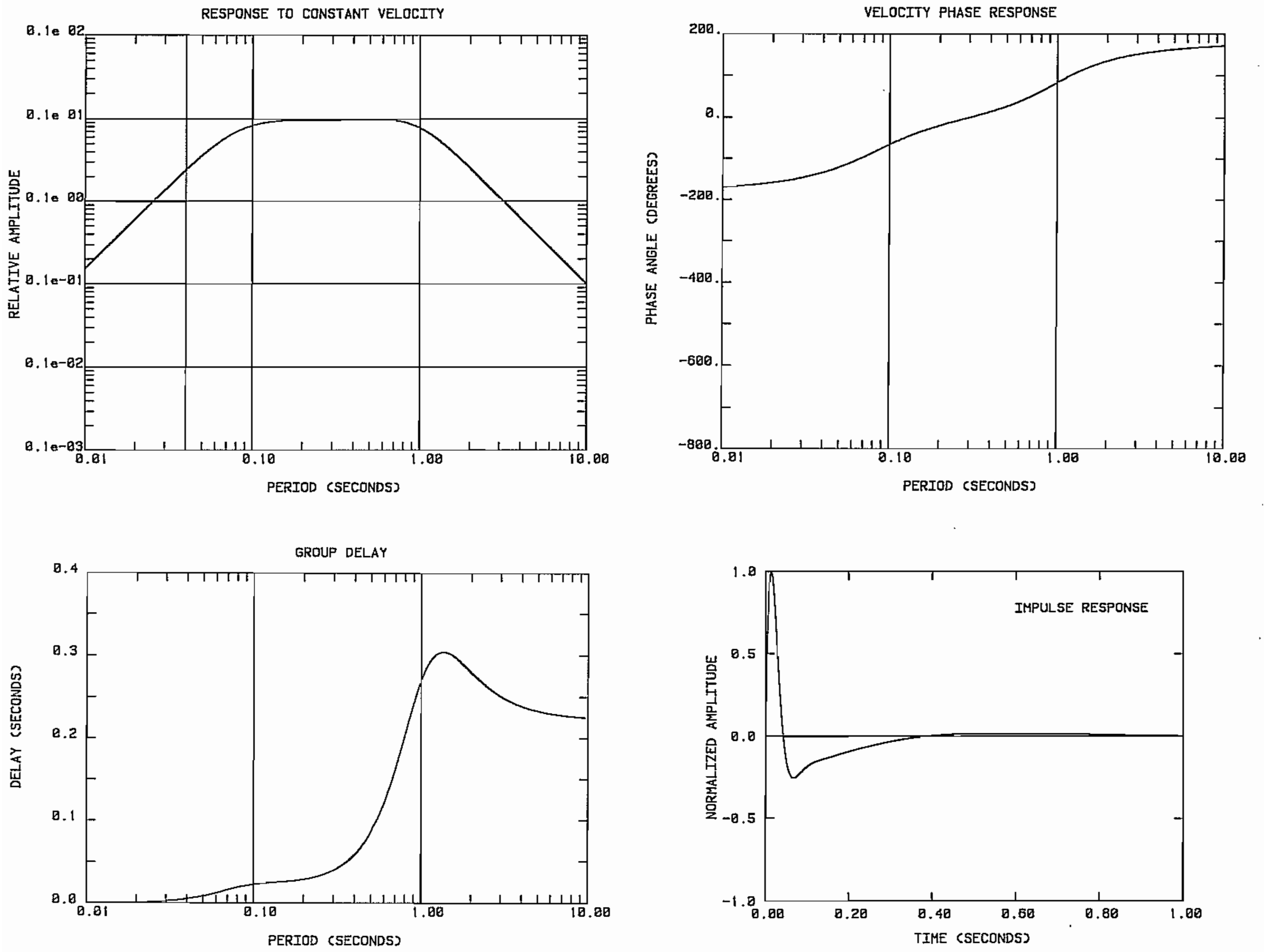


Figure 3.4--Response functions for the combination of a 1-second seismometer and a 2-pole Butterworth filter with a corner period at .08 seconds.

Low-pass filters distort the amplitude and phase of the recorded signal; some introduce spurious signals (ringing) as well. Any filter response, so long as it is predictable, can be removed during post processing. Nevertheless, it is probably best to minimize distortion, as unprocessed analog represenations of digital waveforms are commonly used for time and amplitude measurements.

Common families of low-pass filters include the Chebyshev, Butterworth, and Bessel. Figure 3.5 illustrates the characteristics of a combination of a 1-second seismometer and a 7-pole Chebyshev filter with a corner period at .056 seconds. This particular filter provides 40 dB of attenuation at the Nyquist period and a flat amplitude response. However, it has a very non-linear phase response which produces a strong peak in the group delay, and there is pronounced ringing in the impulse response. Figure 3.6 illustrates the characteristics of a 7-pole Butterworth filter with a corner period at .08 seconds. The Butterworth filter is commonly used for anti-aliasing. The Bessel filter (see Figure 3.7) with the same corner period has a somewhat poorer amplitude response than the Butterworth filter, but it has the smoothest delay function and no ringing. Seven-pole filters have been used for illustration because they provide about 40 dB of attenuation in a single octave. The same attenuation at the Nyquist period could be achieved using, say, a 4-pole Butterworth filter with a corner period at .13 seconds. However, neither the amplitude or phase characteristics of the 4-pole filter (see Figure 3.8) are quite as good as those of the 7-pole Bessel filter.

For the purposes of this study, the Bessel filter will be chosen to provide low-pass filtering. However, there are a variety of customized hybrid filters that could be used and it would be useful to investigate the possibility of broad-band phase equalization for the NDSN.

3.4 Broad-Band Subsystem

The broad-band subsystem will be expected to produce signals over a wide band of frequencies and a wide range of amplitudes. The data will be used for the analysis of both body waves and surface waves. For both purposes it is most appropriate to construct a response that is proportional to earth velocity (as opposed to earth acceleration). This will insure that body wave signals

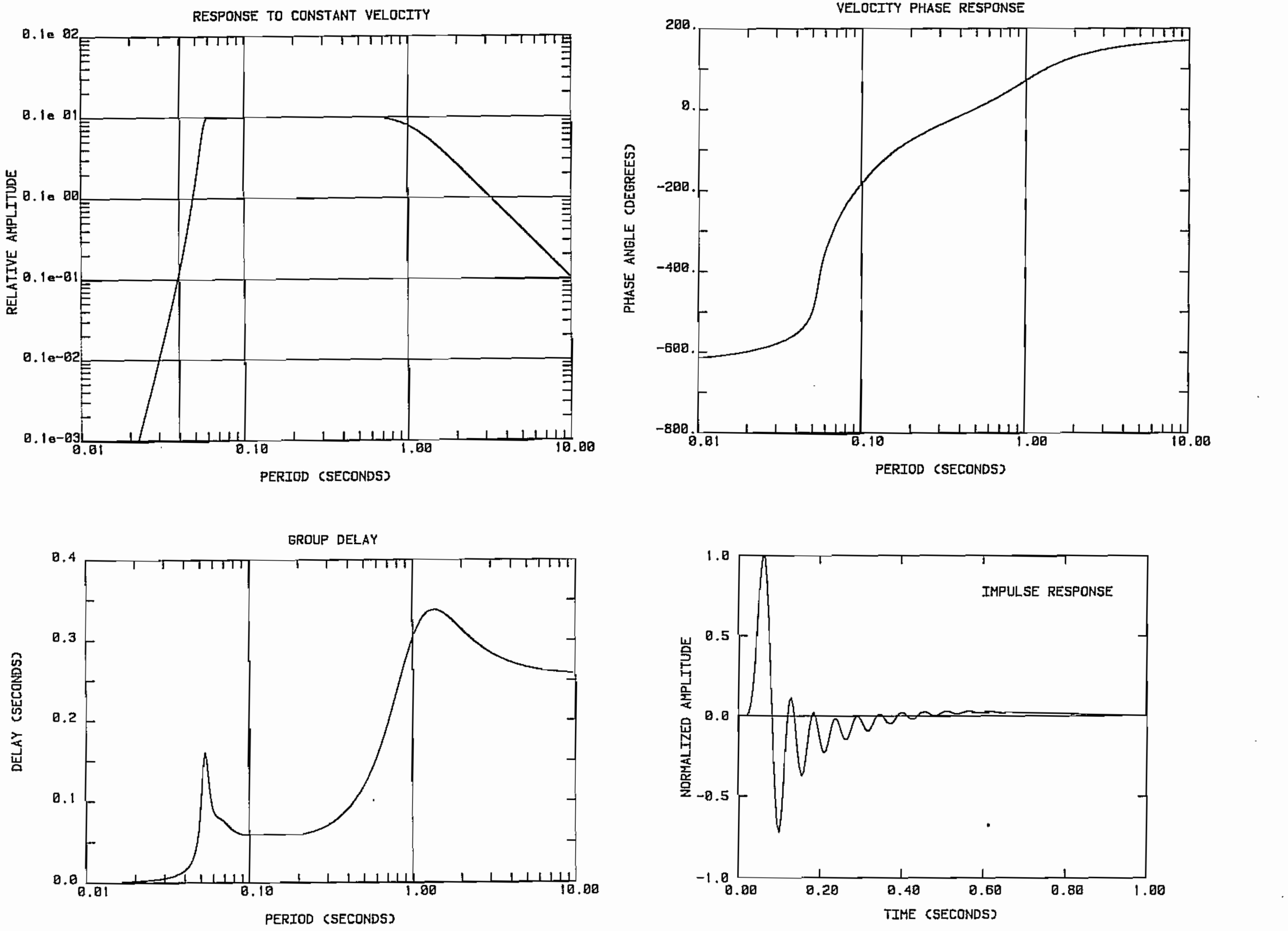


Figure 3.5--Response functions for the combination of a 1-second seismometer and a 7-pole Chebyshev filter with a corner period at .056 seconds.

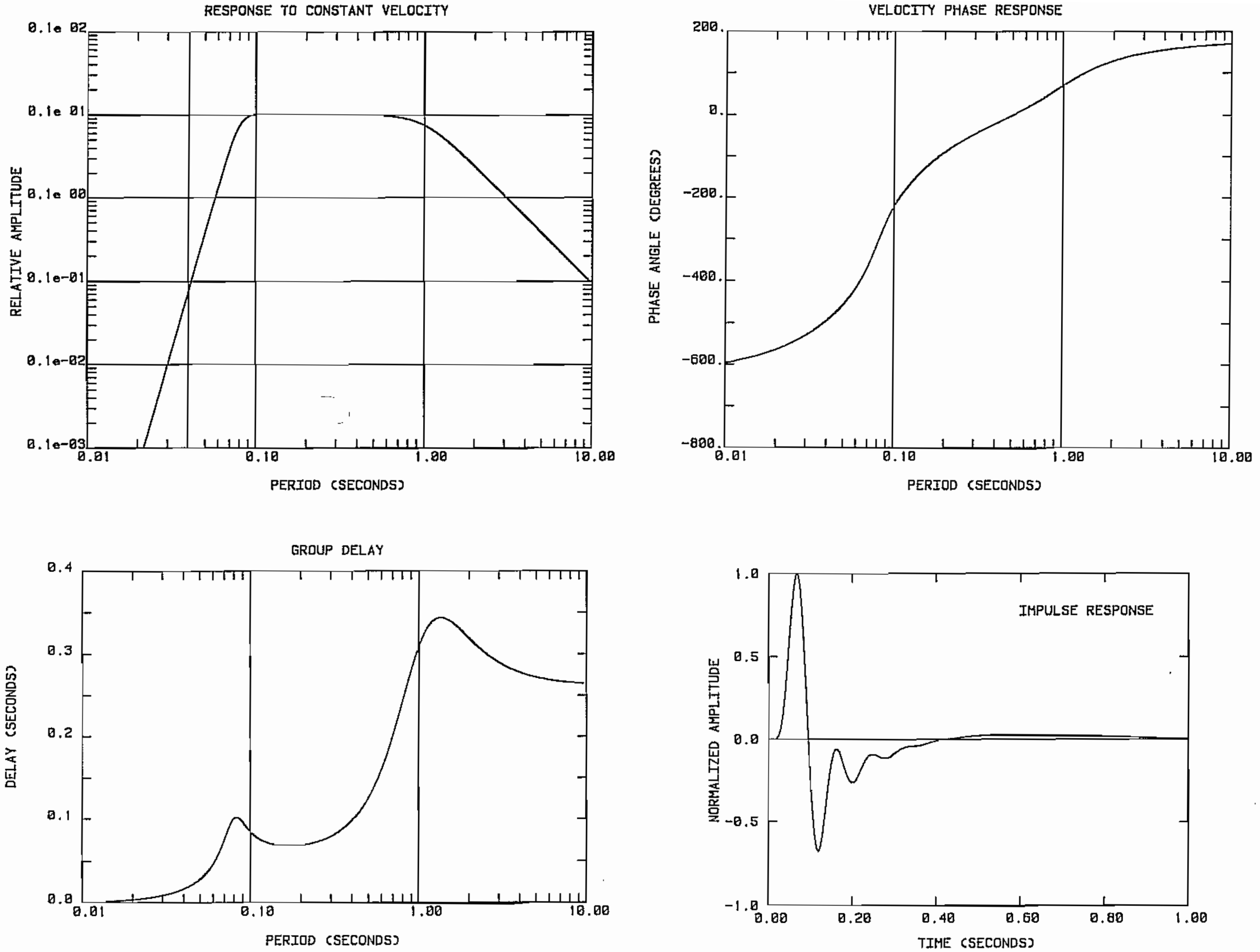


Figure 3.6--Response functions for the combination of a 1-second seismometer and a 7-pole Butterworth filter with a corner period at .08 seconds.

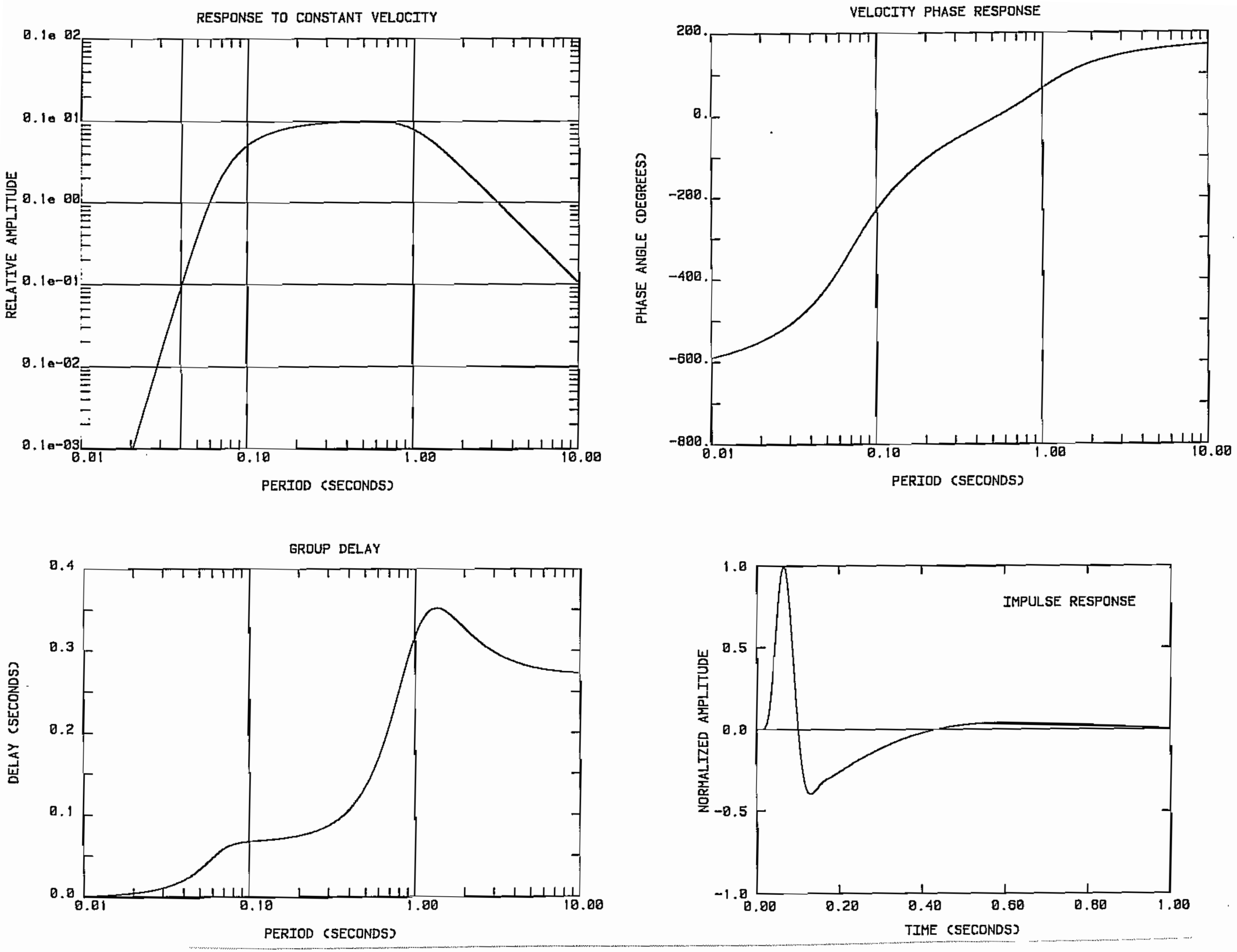


Figure 3.7—Response functions for the combination of a 1-second seismometer and a 7-pole Bessel filter with a corner period at .08 seconds.

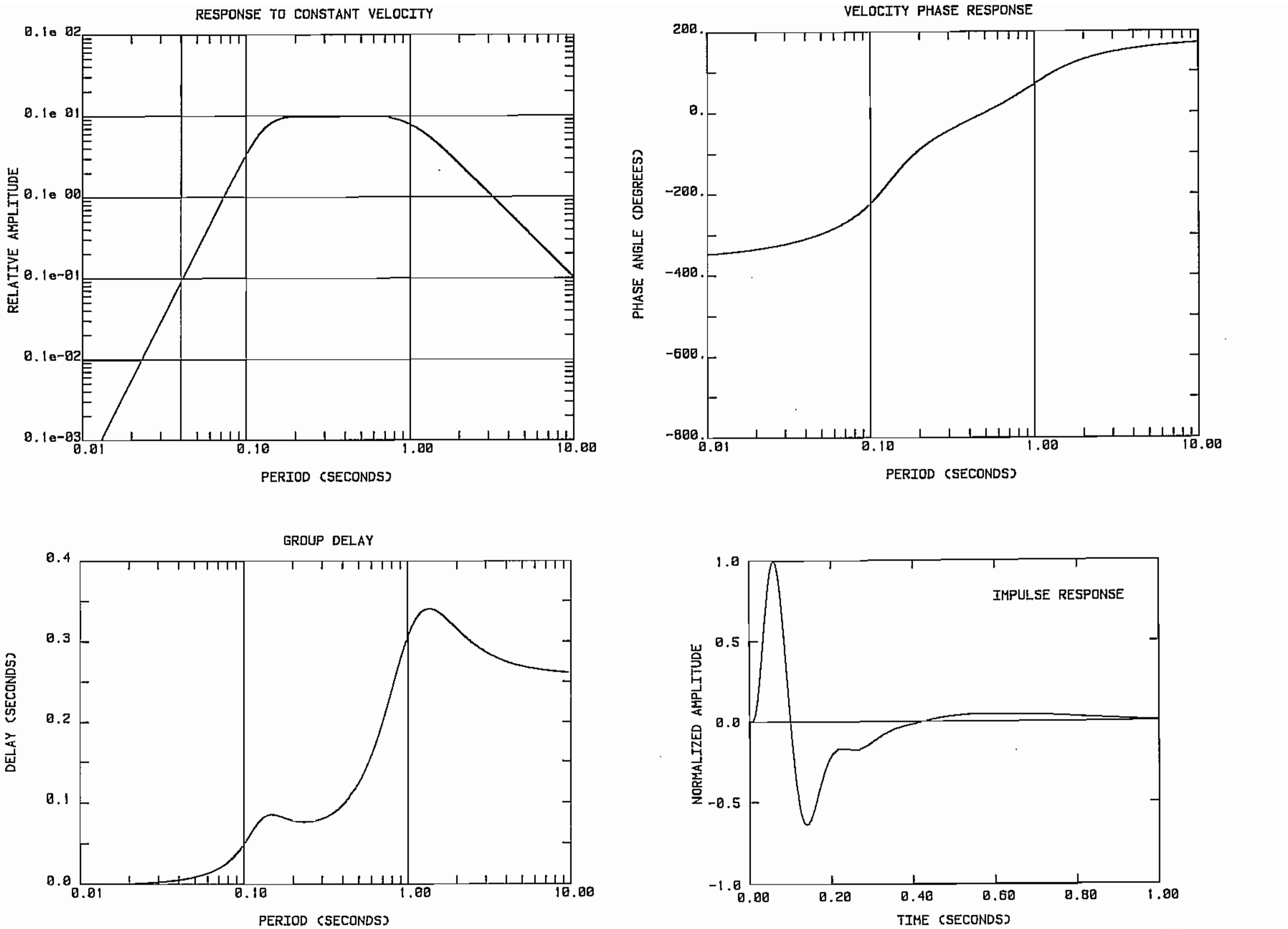


Figure 3.8--Response functions for the combination of a 1-second seismometer and a 4-pole Butterworth filter with a corner period at .13 seconds.

will contain useful long-period energy and there will be less attenuation of long-period surface waves with respect to the earth noise peak at 6 to 8 seconds period.

The broad-band velocity response can be constructed using a long-period seismometer with a velocity transducer in combination with a low-pass filter. Since the sampling interval of 0.1 seconds has been proposed for this subsystem, it will be necessary to use a low-pass filter that provides 40 dB of attenuation at the Nyquist period of 0.2 seconds. The combination of a 20-second seismometer with a .707 damping ratio and a 7-pole Bessel filter with a corner period at 0.7 seconds produces the transfer characteristics shown in Figure 3.9. Note that the response functions are plotted with respect to displacement rather than velocity, a more typical representation that permits comparison with other types of seismograph systems. The proposed broad-band transfer function poles and zeros are listed in Table 3.1.

A signal from a moderately large earthquake recorded on an intermediate-period channel of the digital WWSSN is shown in Figure 3.10. The signal is similar to what would be recorded by an NDSN BB channel as the responses of the two systems are similar, the principal difference being that the WWSSN long-period seismometers are operated at a period of 15 seconds rather than 20 seconds. In Figure 3.11, the P-wave power spectral density (PSD) of the illustrated signal, corrected for instrument response, is compared to the predicted PSD (in volts) at the output of the NDSN BB subsystem. The comparison shows that body waves recorded on the BB channel will be a close approximation in spectral content of actual ground motion for an earthquake of this magnitude and distance.

In a broad-band seismograph, earth noise in the 6 - 8 seconds period band can limit the resolution of small signals. The earth noise curves shown in Figure 3.12 are composite curves derived from SRO and ASRO data. None of the NDSN sites would be expected to be as quiet in the short-period band as the composite low-noise curve and only NDSN stations located in the Aleutians would be expected to be as noisy as the composite high-noise curve. The predicted outputs of the broad-band subsystem for the two levels of earth noise are shown in Figure 3.13. At the noisiest sites, it may not be possible to resolve earth noise in the long-period band; however, the detection of small

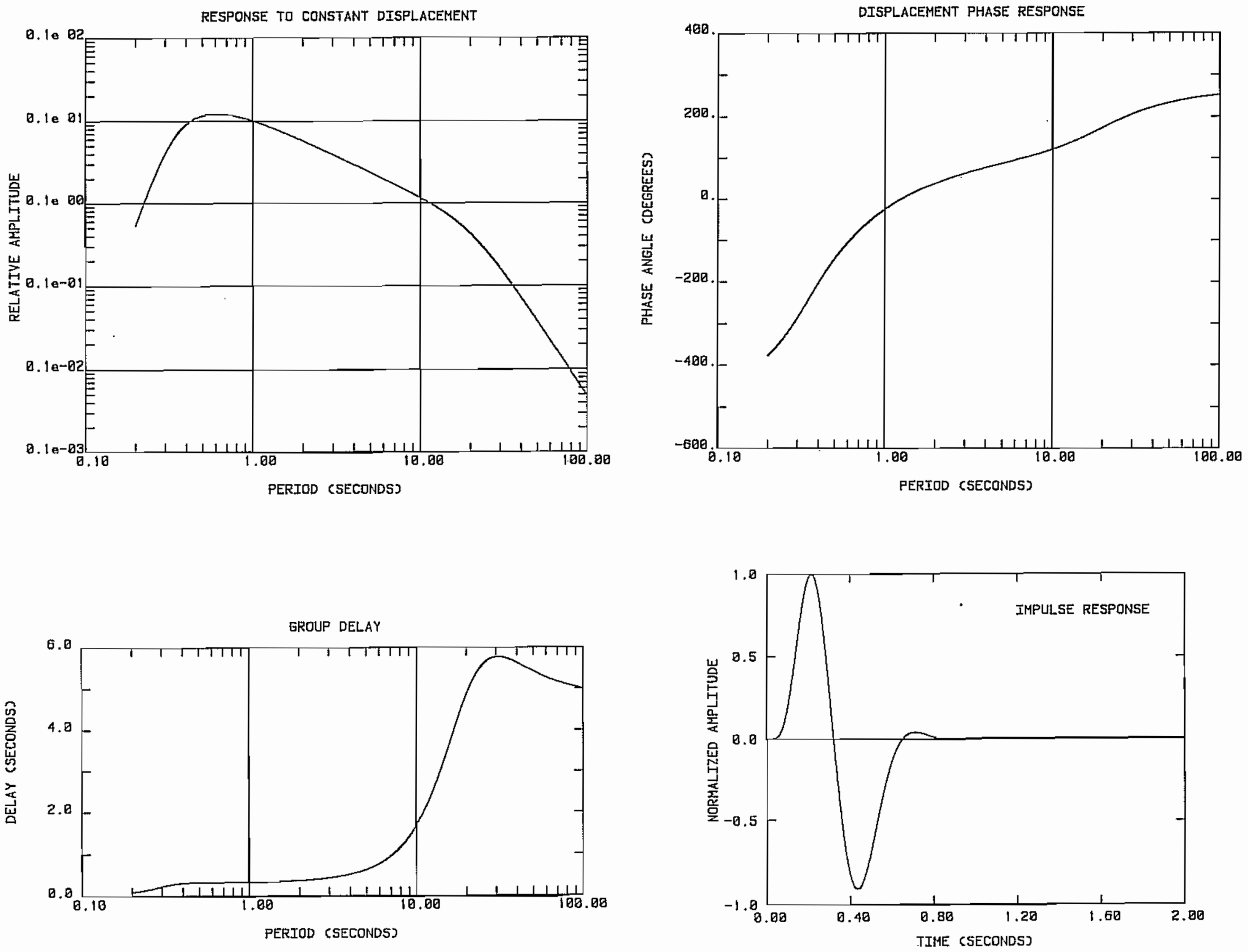


Figure 3.9--Predicted response functions for the proposed NDSN broad-band subsystem.

BB SUBSYSTEM
(displacement input)

Poles:

$s= -.2221 \pm .2221j$
$s= -14.49 \pm 5.300j$
$s= -12.40 \pm 10.71j$
$s= -8.180 \pm 16.51j$
$s= -15.14$

Zeros:

s^3

SP SUBSYSTEM
(displacement input)

Poles:

$s= -4.021 \pm 4.828j$
$s= -72.39 \pm 26.46j$
$s= -61.92 \pm 53.51j$
$s= -40.86 \pm 82.47j$
$s= -75.64$

Zeros:

s^3

AC SUBSYSTEM
(acceleration input)

Poles:

$s= -201.1 \pm 241.4j$
$s= -248.6 \pm 129.2j$
$s= -172.4 \pm 264.8j$
$s= -270.4$

Table 3.1--Polynomial roots of proposed NDSN transfer functions.

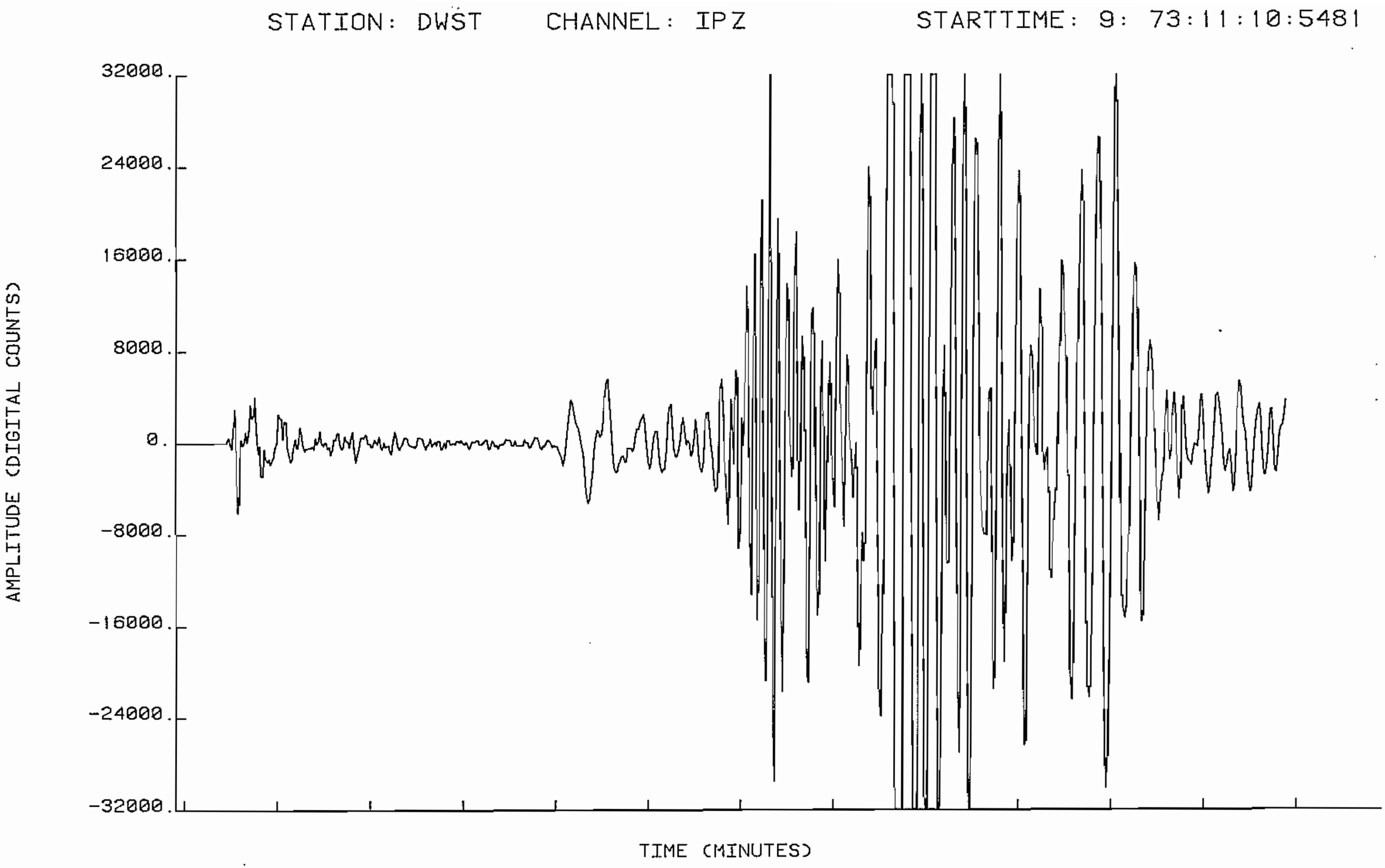
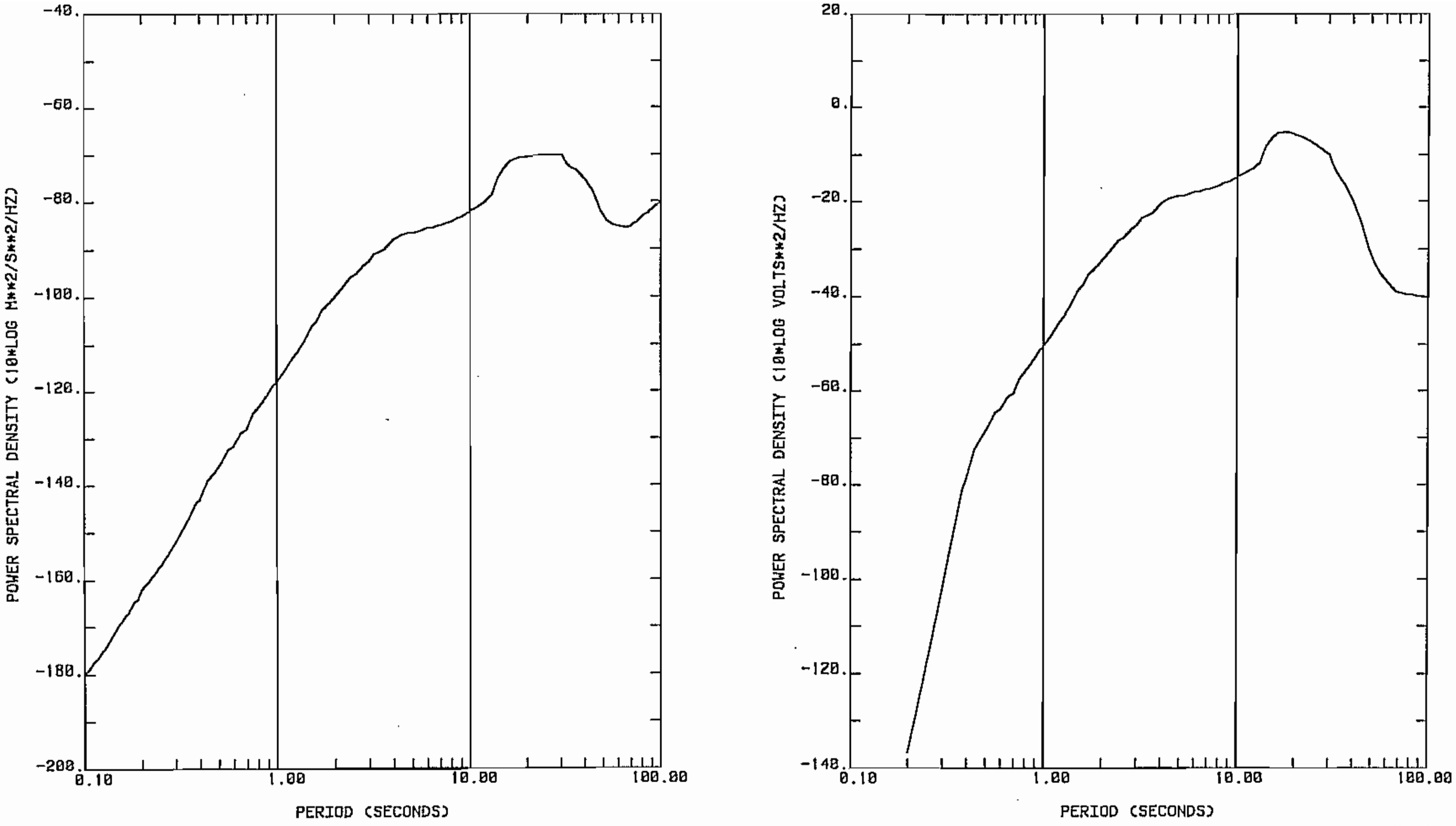


Figure 3.10--Wideband signal recorded on a digital WWSSN intermediate-period channel from an M_s 7.6 earthquake at 18° distance. The surface waves would not overdrive the NDSN BB subsystem.



(a)

(b)

Figure 3.11--Smoothed power spectral density for the P wave shown in Figure 3.10 (a) computed from the signal and corrected for instrument response and (b) predicted for the output of the NDSN broad-band subsystem using the BB transfer function.

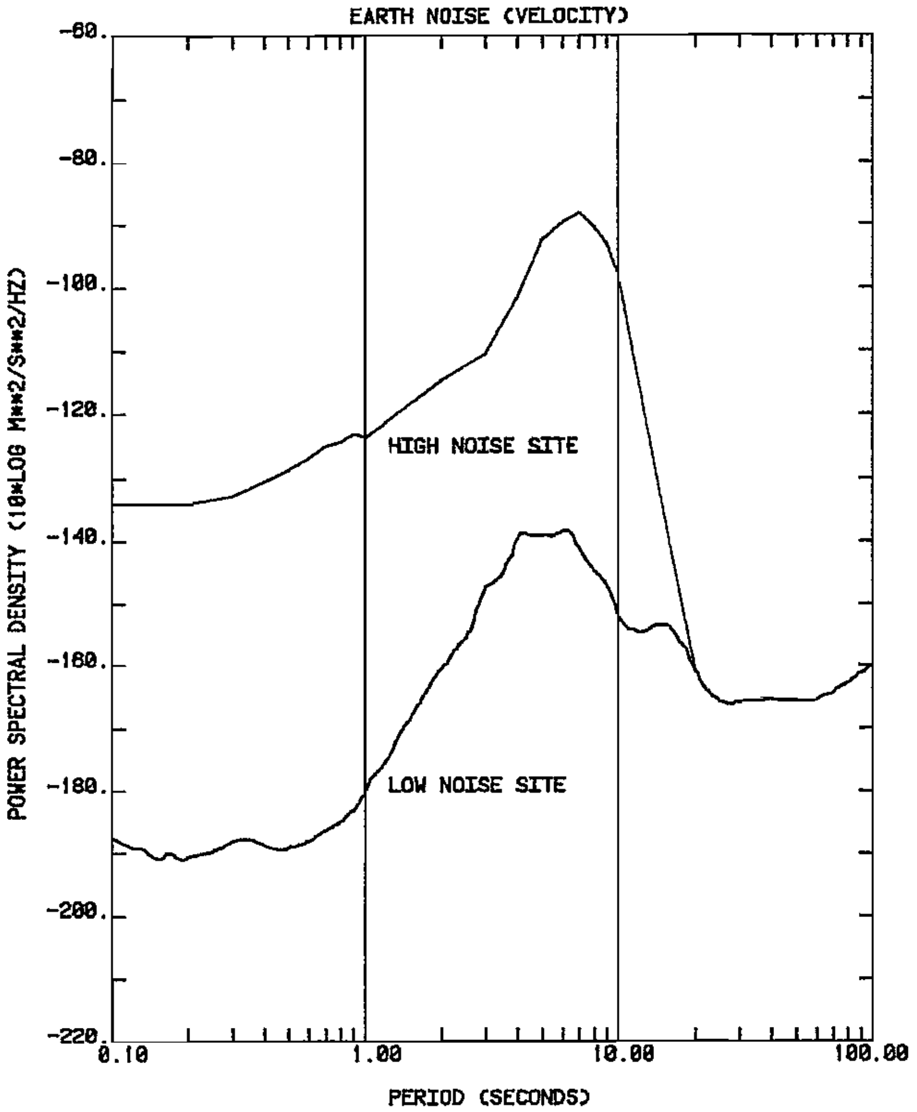


Figure 3.12--Composite background noise curves for quiet and noisy sites. Data for the low-noise curve were derived from SRO and ASRO stations (Peterson, 1980). Data for the high-noise curve were derived from SRO stations and other sources.

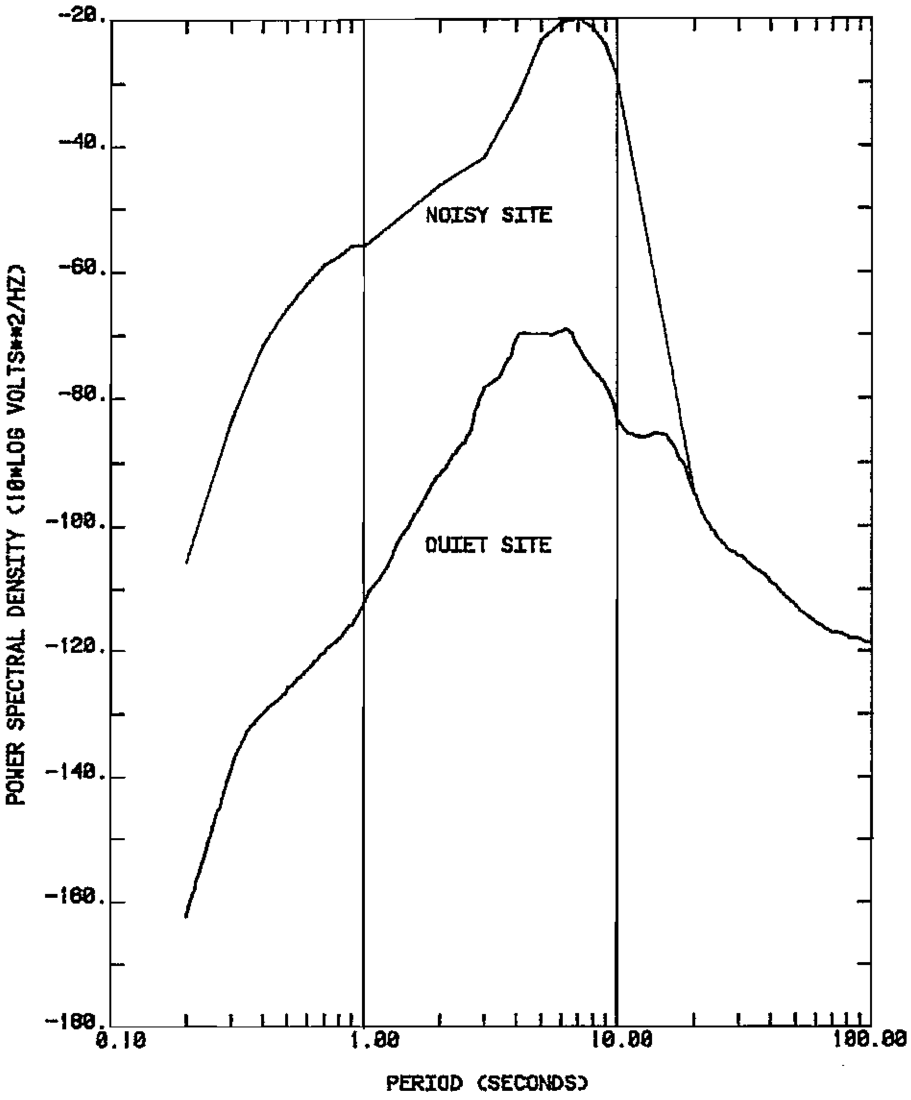


Figure 3.13--Predicted spectral outputs of the NDSN broad-band subsystem for background noise at quiet and noisy sites.

surface waves has not been assumed to be an important objective of the NDSN. If it were, it would be necessary to consider using borehole seismometers.

The transduction constant (sensitivity) of a seismograph establishes its absolute operating range with respect to earth motion. For the NDSN broad-band subsystem, a transduction constant of 2400 volt-seconds/meter (measured at the input to the ADC) appears to be a reasonable choice for a quiet site. This will set the least-significant bit about 10 dB below the background noise level. With this sensitivity, the operating range of the BB subsystem at a period of 1 second is illustrated in Figure 3.14. The scale (in dB) is referenced to clipping threshold (assumed to be 10 volts peak). Predicted background levels were derived from Figure 3.13. RMS voltages were computed from the PSD curves over the band from 0.2 to 100 seconds, then multiplied by 1.414 to obtain an average zero-to-peak value. The predicted signal levels from earthquake sources at 2° and 20° are shown to illustrate the operating range of the seismograph as a function of magnitude. The operating range of the broad-band subsystem at a period of 15 seconds is illustrated in Figure 3.15 together with predicted amplitudes of surface waves from earthquakes at 20°.

Although any long-period seismometer with a velocity output could be used to produce the broad-band signals, there are reasons for being careful in the choice. Most vertical-component long-period seismometers have relatively massive springs that tend to resonate when excited by local earthquakes. The resonances not only introduce spurious signals at the resonant frequency, they cause the spring to contract, which introduces a large transient signal in the long-period band. Conventional long-period seismometers are also very sensitive to environmental changes and, while they generally have a large amplitude range, the linearity of the mechanical suspension over this range is questionable. Where dynamic range and linearity are important, as they are in the case of the NDSN, force-balance sensors have an advantage in that the dynamic range and linearity are determined by the behavior of the electronics in the feedback circuit rather than the mechanical suspension. One disadvantage of force-balance sensors is their relatively poor performance at short periods. The fundamental signal is derived from a displacement transducer and displacement signals are very weak at high frequencies. In spite of

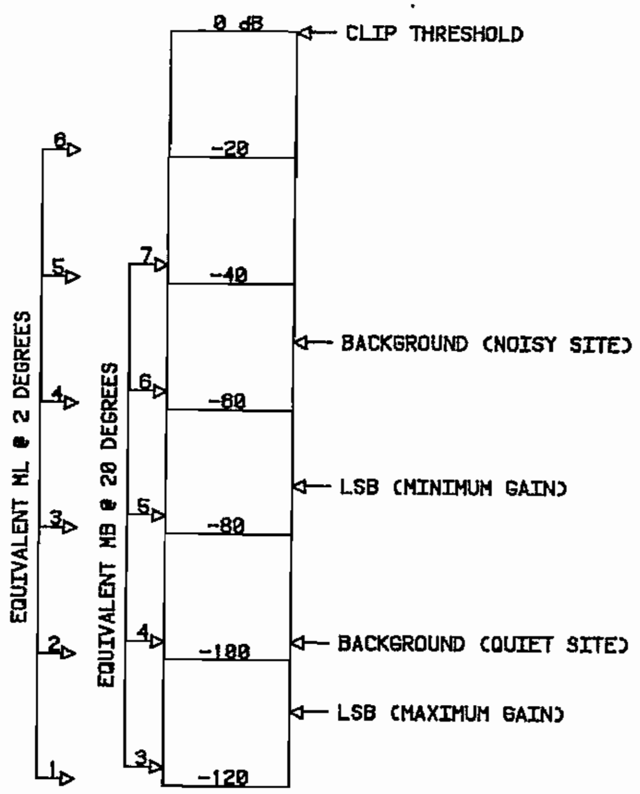


Figure 3.14--Predicted operating range of the broad-band subsystem for earthquake body waves.

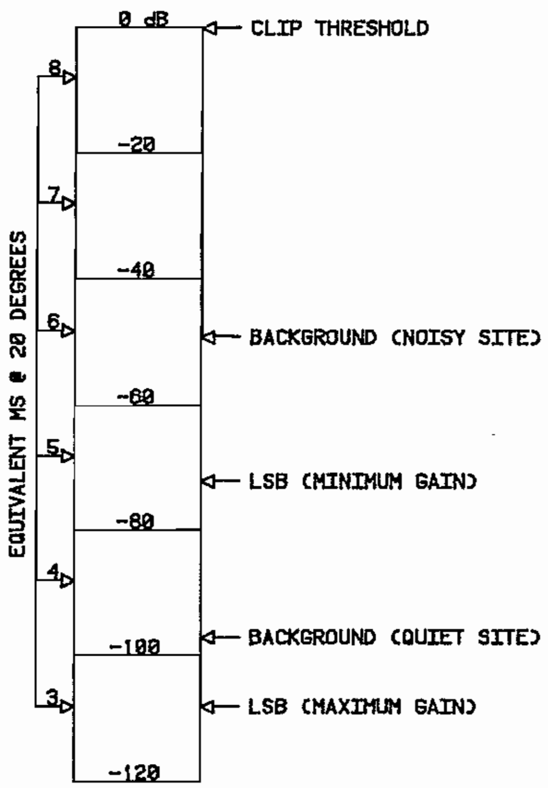


Figure 3.15--Predicted operating range of the broad-band subsystem for earthquake surface waves.

this disadvantage, a force-balance sensor is clearly the best choice for the NDSN broad-band subsystem.

The feedback-controlled wideband seismometer described by Wielandt (1975) is available commercially and should be considered for the NDSN system. The Wielandt seismometer produces a velocity output that is equivalent to the output of a 20-second seismometer at periods above 0.2 seconds. In addition, it provides a displacement output that might be used for recording very-long-period signals. According to published specifications, the Wielandt seismometers have a dynamic range of at least 140 dB, an apparent transduction constant of 2400 volt-seconds/meter, and no parasitic resonances below 70 Hz. Seidl (1980) has been able to simulate the SRO vertical-component long-period data using signals from the Wielandt seismometers operated at the Grafenburg array. This would indicate that good long-period data can be obtained from these instruments, at least during wind-free periods. The high frequency limit for these instruments is expected to be about 5 Hz.

3.5 Short-Period Subsystem

The purpose of the NDSN short-period recording band is to provide good P, S, and Lg signal detection capability in the frequency band from 0.1 to 25 Hz. The SP data are expected to be used for determination of phase parameters (time, amplitude, and period) and for spectral analysis of local and regional events.

The combination of a 1-second seismometer and a 7-pole Bessel filter with a corner period at .08 seconds will produce the transfer characteristics illustrated in Figure 3.16. Note again that the response functions are shown with respect to earth displacement. Poles and zeros of the proposed transfer function are listed in Table 3.1.

The predicted spectral outputs of the SP subsystem (in volts) for the two levels of earth noise (from Figure 3.12) are shown in Figure 3.17. The proposed SP transfer function is a reasonably good prewhitener of earth noise. With the resolution available, there does not appear to be any justification for using a higher frequency sensor or a high-pass filter to provide more attenuation of the microseisms.

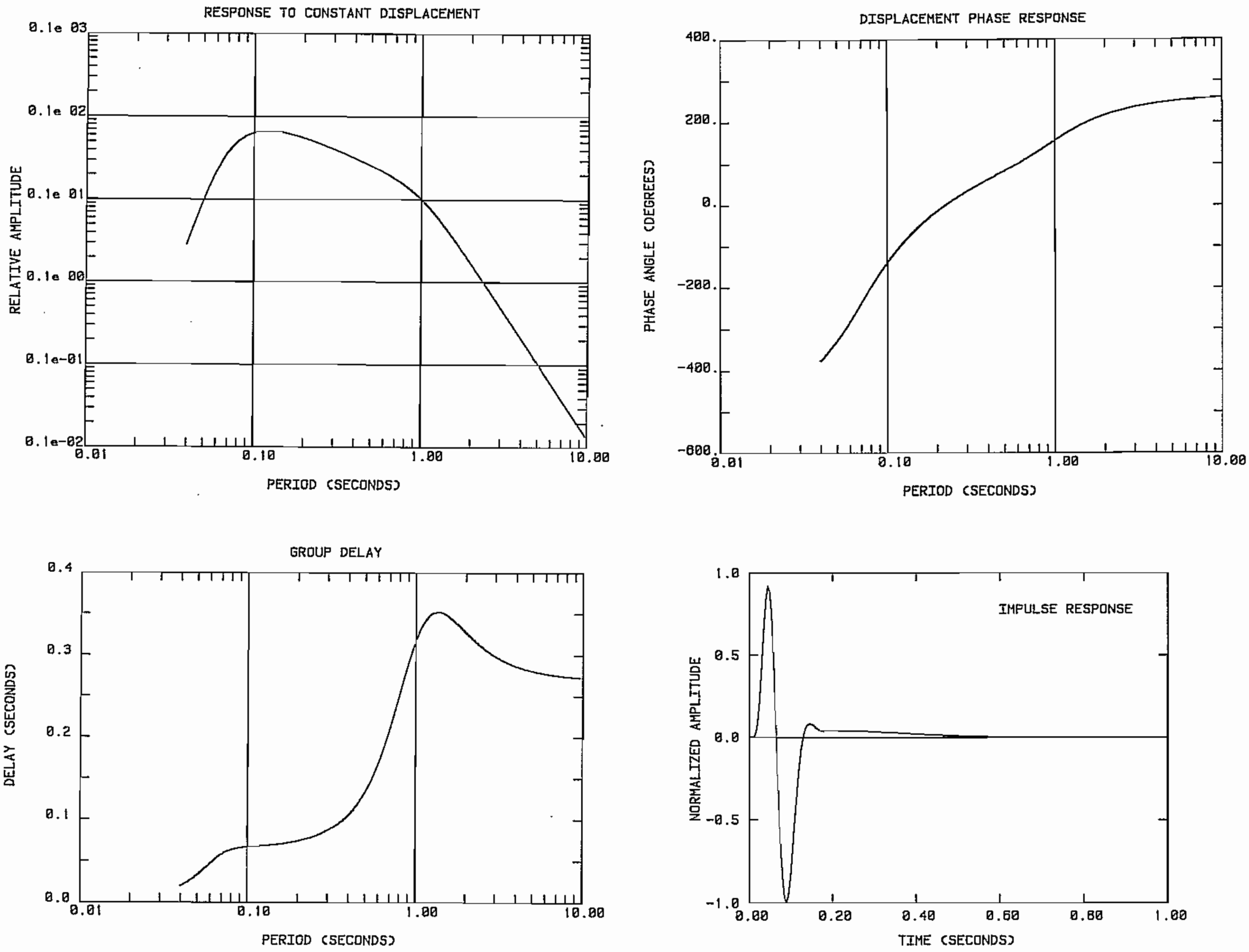


Figure 3.16--Predicted response functions for the proposed NDSN SP subsystem.

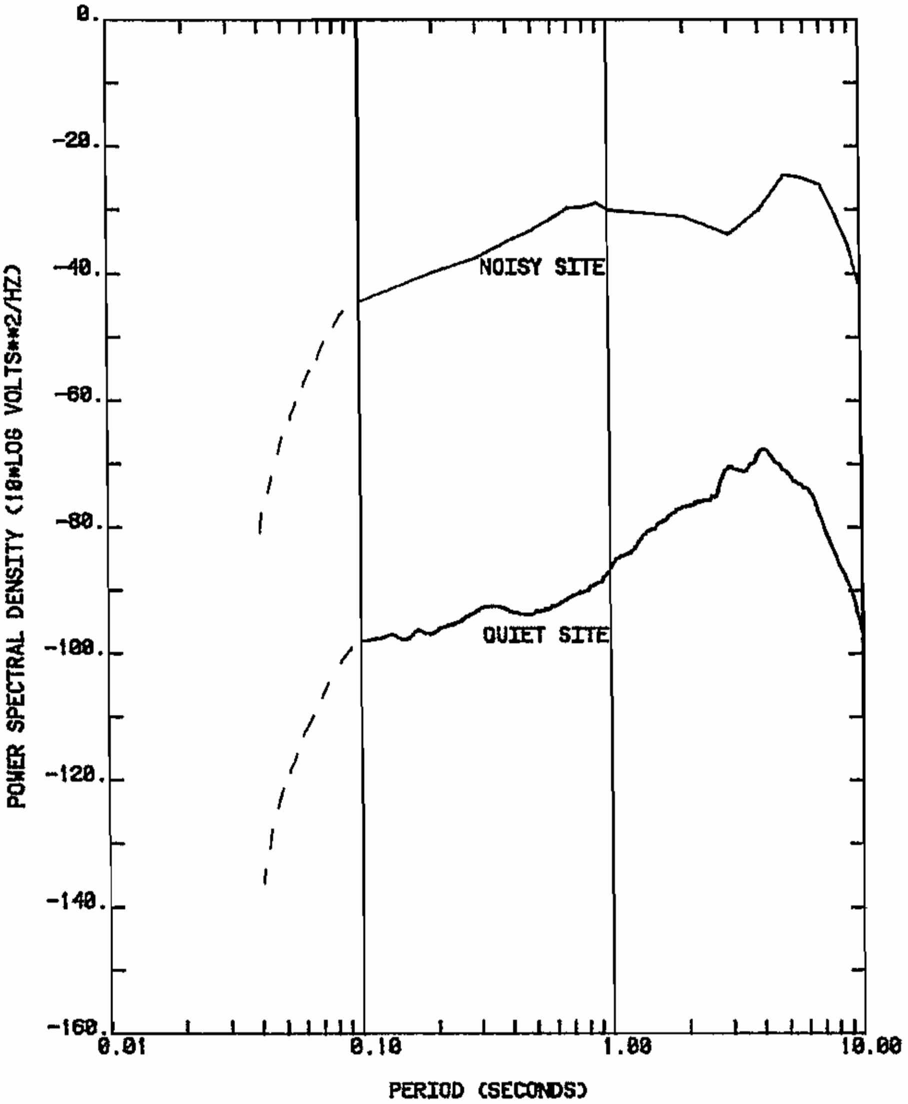


Figure 3.17--Predicted spectral outputs of the NDSN short-period subsystem for background noise at quiet and noisy sites. Lines are dashed where data were not available; they track the low-pass filter response.

The predicted operating range of the SP subsystem is shown in Figure 3.18. The scale was set for a transduction constant of 60,000 volt-seconds/meter. This is a good choice for a quiet site, but some attenuation of the sensitivity will be needed at the noisy sites.

Conventional short-period seismometers and amplifiers that will satisfy the requirements of the NDSN system are readily available from commercial sources.

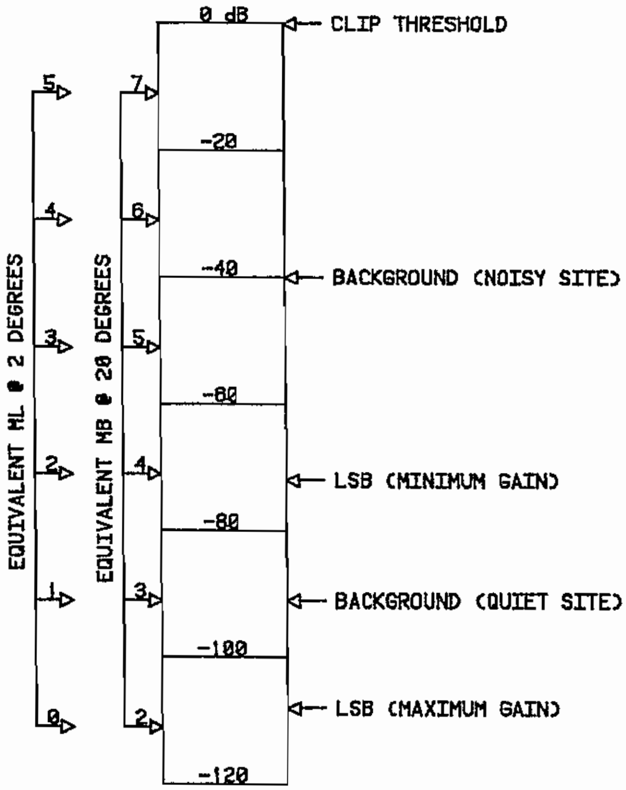


Figure 3.18--Predicted operating range of the short-period subsystem for short-period signals.

3.6 Acceleration Subsystem

The purpose of the acceleration subsystem is to record the signals that overdrive the short-period and broad-band subsystems. The operating range will extend to 1 g of acceleration.

The signal detection threshold of strong-motion accelerometers is limited by instrument noise rather than earth noise at most sites. Noise tests were made on two types of commercially available accelerometers to determine if the noise levels were lower than the clipping threshold of the short-period and broad-band subsystems. The results of one of these tests is shown in Figure 3.19. The noise level of the accelerometer is compared to earth noise levels from Figure 3.12 (converted to units of acceleration). This particular accelerometer, a Kinemetrics Model FBA with 25 volts per g sensitivity,

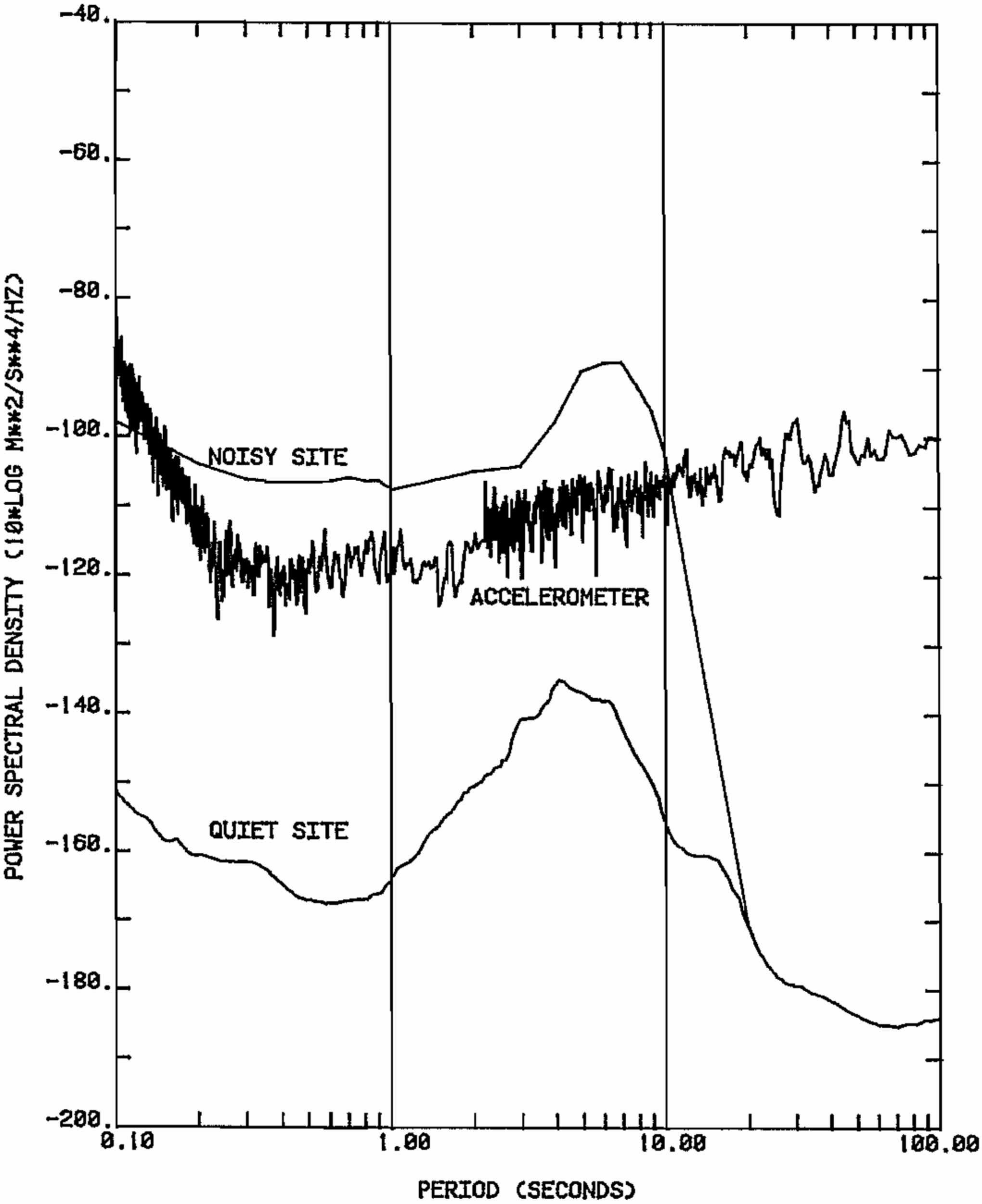


Figure 3.19--Computed noise power spectral density estimate for a vertical-component FBA accelerometer; two separate segments were patched at 2.2 seconds period. Noise spectra are referred to the input, that is, corrected for instrument response. Earth noise curves are shown for comparison. The increase in accelerometer noise at periods shorter than 0.4 seconds is due to amplifier and ADC noise, not the test accelerometer.

was the noisiest of the group in the long-period band. Even in this case, however, the RMS noise level is below the expected clipping threshold of the broad-band subsystem, so any of the tested accelerometers could be used. The

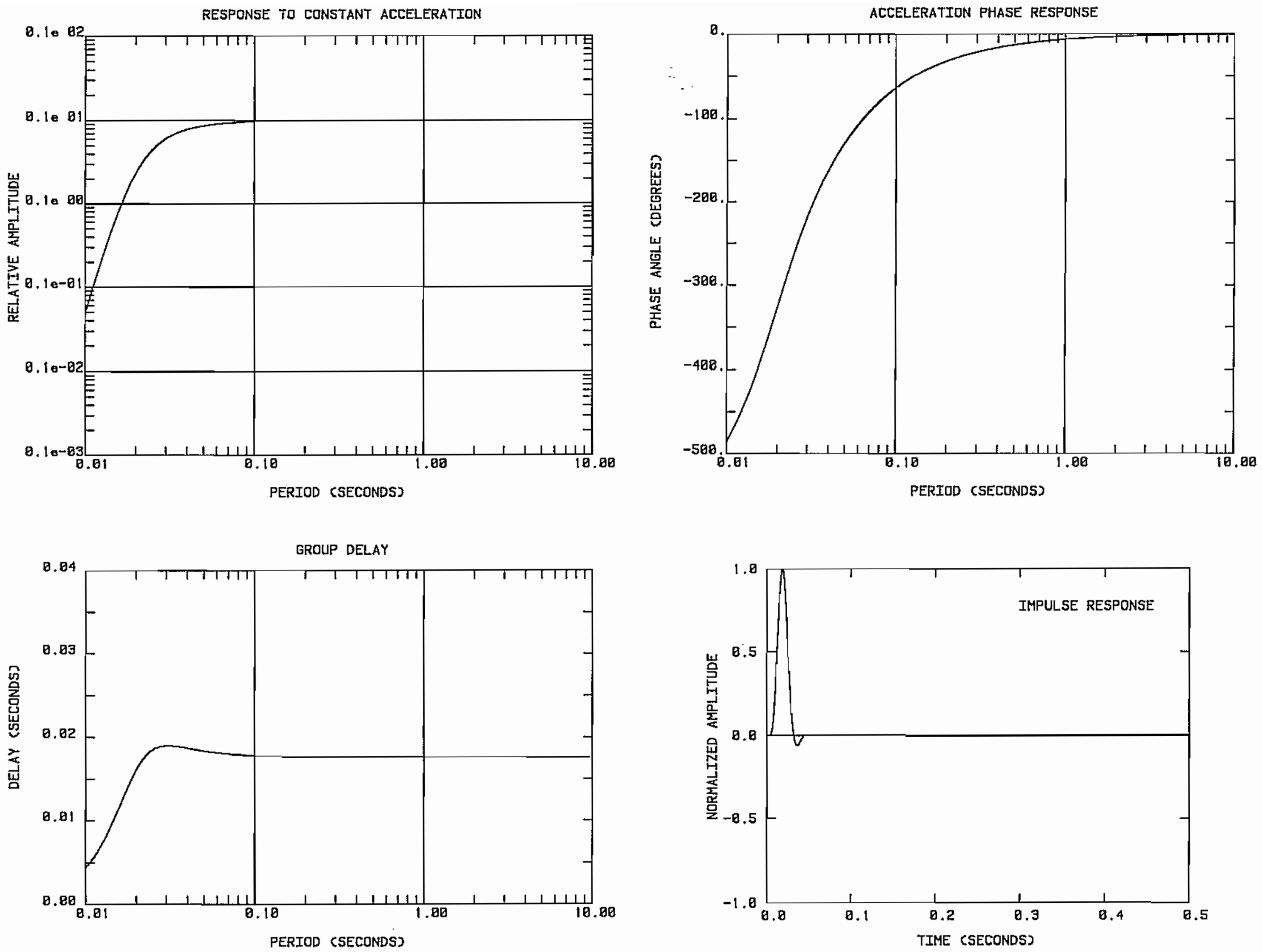


Figure 3.20--Predicted response functions for the proposed NDSN acceleration subsystem.

second type of accelerometer tested was a Sundstrand Q-Flex. These were quieter than the FBAs when operated in the horizontal mode, but we were unable to offset the 1 g bias without introducing unacceptable noise when operating in the vertical mode.

A trial transfer function for the AC subsystem was derived by combining an FBA-type accelerometer (f_s=50 Hz, λ=.64) and a 5-pole Bessel filter with a corner period at .02 seconds. The transfer characteristics of this combination are illustrated in Figure 3.20. Poles of the transfer function are listed in Table 3.1. Assuming a transduction constant of 10 volts per g, the operating range of the AC subsystem would be as shown in Figure 3.21. The triggering threshold for event recording will be set to the equivalent of an M_L 5.0 to 5.5 earthquake at 2^o. When triggered, the AC subsystem will be recorded long enough to insure that surface waves are recorded.

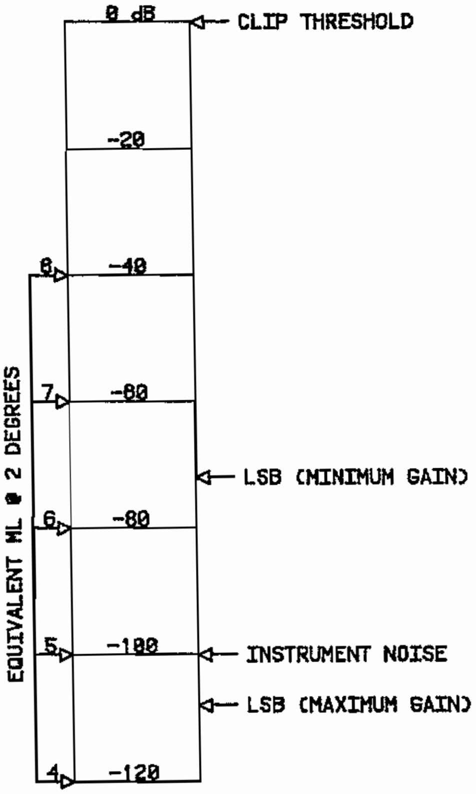


Figure 3.21--Predicted operating range of the acceleration subsystem in the short-period band. Magnitudes were computed at a period of 0.5 sec.

4. NDSN DATA RECORDING AND TRANSMISSION

4.1 General

The key word in selecting transmission and recording modes for the NDSN is flexibility. There are many options available, but what seems appropriate today may not be the best choice several years from now. This is an area of technology that is advancing rapidly and we would not want to exclude the possibility of innovative changes in the future.

Ideally, all of the data produced by the NDSN stations would be telemetered to a national center, not just because the real-time data are useful, but because of the efficiency with which the data could be processed, stored, and distributed. Full-scale telemetry of the NDSN data via satellite should be established as a goal for the NDSN, but there are other options that could be implemented at less cost in the near term. These include on-site recording or a mix of on-site recording and telemetry of selected data via landline.

4.2 On-Site Recording

One of the design assumptions has been that the NDSN stations must function without the need for frequent servicing. Ideally, it should not be necessary to service a station more frequently than once a month. This will permit the stations to be located at relatively remote sites and it eliminates the need for a host operator; that is, the stations could be serviced from a central facility. However, long service intervals will make it necessary to record most of the data in an event-only mode. Each station will generate in excess of 30 megabytes of continuous SP and BB data each day. Even with high-density recording, only 1 or 2 days of continuous data could be stored on a single tape.

Event recording has been used successfully in the global seismograph network for the past eight years. In recent years, there have been improvements in event detection techniques to the point where the probability of missing events that an analyst would detect visually has become very small. The NDSN event detector will operate on data from the short-period subsystem. All detected events will trigger recording of the three short-period channels, and the recording will continue until the signal level decreases to some preset value based on the amplitude of the background prior to the event. Broad-band data recording will be triggered when the short-period signal level exceeds a preset threshold. The threshold will be adjustable, perhaps from 0 to 40 dB above the ambient short-period background signal level. Once triggered, the broad-band data will be recorded until the signal level has decreased below some adjustable threshold and remained there for at least 15 minutes. This will insure a continuous record even though the signal level decreases to ambient background between phases. The recording of acceleration data will be triggered when the broad-band signal levels exceed a preset threshold (also adjustable) and will continue recording until the signal level has remained below a preset threshold for at least 15 minutes. As presently conceived, the NDSN system will not trigger on surface waves, although surface wave signals will reset the turn-off delay used with broad-band and acceleration recording. Continuous data from each component will be cycled through buffers. The length of these buffers will be selected to insure that at least 20 seconds of pre-event data are recorded with the triggering onset. However, the buffer lengths will not insure that undetected P phases are recorded if the triggering occurs on the S phase.

An estimate of the amount of digital data that will be recorded at each station each day is summarized in Table 4.1. The estimated percentage of short-period recording time (5%) is based on relatively comprehensive statistics derived from the recording history of the SRO and ASRO stations. Over a recent 26 month interval, the average short-period recording time at 14 stations was 4%. The lowest time was 1.2% at Narrogin, Australia, and the highest recording time was 8.7% at Kabul, Afghanistan. Most NDSN stations would be expected to fall within this range. The estimated recording time of broad-band data is less certain. The triggering threshold is higher than for the SP channels, but the recording duration per event will also be higher. The duration of acceleration recording at most stations will be negligible on an average basis but significant on the 5 to 10 days each year when recording might be expected to trigger. On the average, the total triggered recording is estimated to amount to about 2.2×10^6 bytes per day. A recording system should be designed with

Component	Samples/Second	Bits/Second	Estimated Recording Time	Bits/Day	Bytes/Day
SPZ	50	800	5%	3.46×10^6	4.32×10^5
SPN	50	800	5%	3.46×10^6	4.32×10^5
SPE	50	800	5%	3.46×10^6	4.32×10^5
BBZ	10	160	15%	2.07×10^6	2.59×10^5
BBN	10	160	15%	2.07×10^6	2.59×10^5
BBE	10	160	15%	2.07×10^6	2.59×10^5
ACZ	200	3200	.1%	2.76×10^5	3.46×10^4
ACN	200	3200	.1%	2.76×10^5	3.46×10^4
ACE	200	3200	.1%	2.76×10^5	3.46×10^4
			Totals	1.74×10^7	2.18×10^6

Table 4.1--Estimated daily triggered data recorded at NDSN station.

sufficient excess capacity to accommodate the increased recording due to the rare but important major earthquakes, such as the Alaskan earthquake of 1964.

In addition to the triggered recording, there will be periodic calibration and noise data recorded and possibly some continuous data as well. Weekly calibration of each component, together with 15 minutes of continuous data preceding or following the calibration, will generate 5.4 x 10^4 bytes of data on an average daily basis. Very-long-period data may be recorded at some stations. With three components recording and a sampling interval of 10 seconds, this will amount to 5.2 x 10^4 bytes per day.

Assuming current technology, the most practical recording medium appears to be high-density tape. High capacity cartridge drives are available in which each cartridge will store up to 32,768 2048-byte records. (The cartridge actually records in 1024-byte sized blocks, but for our purposes it is more convenient and efficient to organize the data into 2048-byte sized records.) Fourteen bytes in each record will be used to record time and other information, leaving 2034 bytes for data. On the average, there will be 1060 records of event and calibration data recorded each day, 1086 records if VLP data are recorded. Then the storage capacity of each tape will be between 30 and 31 days. Three tape drives at a station would provide 60 days of recording with a 50% excess capacity.

4.3 Landline Data Transmission

There are several options with respect to the telemetry of selected data via landline circuits. Conventional voice-grade landlines can be used if the data rate is reduced to 2400 bits per second (BPS). This bandwidth will permit the transmission of sufficient data for rapid earthquake reporting. For example, it would be possible to transmit 1 channel of vertical-component short-period data together with 3 channels of broad-band data. The broad-band data could be filtered at the receiving terminal to produce conventional short-period (limited to 5 Hz) signals, 15-30 second surface wave signals, and 100-300 second mantle wave signals. It would be possible to transmit all three components of short-period data plus the broad-band data if the short-period signals are first decimated to 25 samples per second at the station.

If full-time data transmission is not possible because of circuit costs, an alternative is to store selected data in a buffer at the station, then interrogate the station periodically using a dial-up circuit. If all of the detected events were stored in a buffer, and assuming the average event load per day, it would take about 2 hours each day to interrogate each station. If only vertical-component short-period and broad-band events were stored in the buffer, the interrogation time would be about 40 minutes per station each day.

Transmission of site-processed data could be considered as an alternative to the transmission of waveform data. James Murdock (pers. commun., 1981) has developed an algorithm that not only detects events but provides the arrival time, sense of first motion, maximum amplitude, and average period of the first several cycles. Site-processed data would be stored in a buffer in ASCII format to be recovered periodically via a dial-up circuit. The GOES satellite could be used in lieu of a telephone circuit. One channel on the satellite would be more than sufficient to interrogate the entire network.

4.4 Satellite Data Transmission

Satellite transmission is an attractive method of data telemetry for the NDSN, although moderately expensive from the standpoint of initial equipment capitalization. A remote satellite terminal has been developed for use with the National Seismic Station (NSS) being developed by Sandia Laboratories for the Department of Energy. The remote terminal was designed for use with the Intelsat communication satellites but can be used with domestic satellites as well. The transmission rate is 9600 BPS, although in the NSS system dual transmission and forward error-correction encoding limit the effective data rate to 2400 BPS. A 96 BPS reverse link is used to transmit commands from a network control center to the individual stations. A five-station Regional Seismic Test Network will be installed using NSS systems and this will be a valuable demonstration of satellite communication links for transmitting seismic data.

Motorola manufactures the terminals used in the NSS system and is now marketing a less expensive version called the Modet/3. This terminal consists of a 3-meter antenna assembly, a microwave subsystem, and a modulator/demodulator. Available data transmission rates range from 4.8 to 56 KBPS. Forward error-correction encoding is provided. A transmission rate of 9600 BPS would permit the transmission of all NDSN station data plus an increase in sampling rates. For example, it should be possible to double both the SP and BB sampling rates. The cost of a remote terminal, without the reverse channel, is estimated to be $30,000. The reverse channel adds considerably to the cost of the remote terminal. If a command link is needed, it may be more cost effective to employ a dial-up landline circuit. A receiving terminal, which includes a 5-meter dish antenna, is estimated to cost $450,000. This does not include the cost of on-line computer facilities that will be needed for processing and recording the incoming data streams. Satellite circuit lease costs for a 36-station network are estimated to be $100,000 per year.

Even if satellite communications are not used initially in the NDSN, the stations should be designed to accommodate satellite communications in the future. When economical mass store devices come on line in the next 5-10 years, it will be possible to store all of the network data (not just events) on line and the only practical way of moving the data from the stations to the mass store will be via satellite.

4.5 Recommendations

Each NDSN station should be designed so that any of the options discussed could be implemented simply by adding the appropriate equipment module. A single formatter can handle as many as four tape drives. Three of these could be used for recording event or continuous data; the fourth would be used for storage of calibration, diagnostic, and operating programs and, if necessary, for storage of interrogatable data. A communications module should be furnished as part of the basic data system that will provide a programmable mix of serial data at 2400, 4800, or 9600 BPS. Modems, transmitters, and other hardware needed for data telemetry would be furnished as each station is configured or reconfigured for a particular mode of transmission. Each station will be equipped with a 2400 BPS dial-up modem as part of the original equipment. Whether or not this is used for transmitting waveform or site-processed data, it will be used for day-to-day control of station operation.

5. NDSN SYSTEM CONCEPT

5.1 General

A detailed examination of NDSN system design options will become an appropriate task when there has been a management commitment to the development of an NDSN. Technology is evolving so rapidly, particularly in microprocessor-based design, that a detailed system design based on current technology is likely to be obsolete in a year or two. On the other hand, the functional requirements of the system are not as likely to change. A general concept of the NDSN system based on the functional requirements will be useful as a model for developing more detailed component and interface specifications in the future. It is also useful when formulating plans for the installation and operation of the network.

5.2 System Configuration

A block diagram illustrating the major implied components of an NDSN system is shown in Figure 5.1. The seismic subsystems will each contain three seismometer components, amplifiers, and filters. These will interface with the multiplexer and gain-ranging amplifiers of the analog-to-digital converter. The ADC will sample signals from all components continuously at rates that will be programmable.

The station processor will clock and control all of the real-time functions of the station; it will provide buffering for the continuous data streams, perform event detection and signal processing, initiate calibration sequences, format data for recording, select tape drives, route data for transmission, and perform routine diagnostic and status checks. It will be desirable to be able to change the operating software remotely. This will require that the program be stored in random access memory or in electrically-erasable programmable read-only memory.

A calibration module will generate transient and steady-state sinusoidal signals for calibrating the sensors. The calibration program will be contained in read-only memory and be activated by remote command or automatically by the

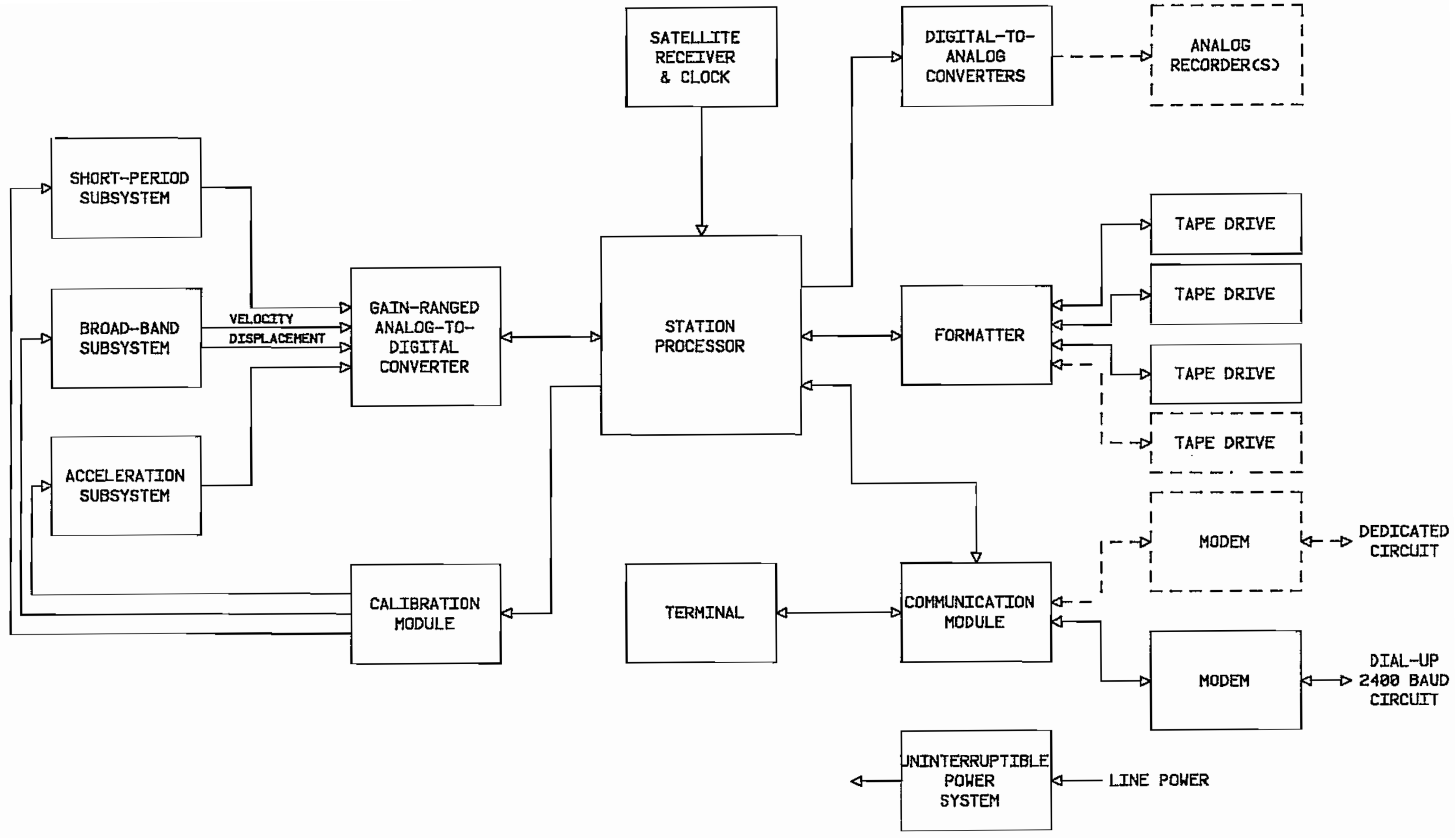


Figure 5.1—Block diagram showing major components of the NDSN system.

station processor at programmable intervals, perhaps once each week. Calibration will be inhibited if event recording is in progress. The short-period and broad-band seismometers will have calibration coils; it may be necessary to design a mechanical calibration device, such as a tilt table, to calibrate the accelerometers.

Primary timing for the station will be derived from satellite time transmissions. There are several commercially available receivers with clocks that receive and decode timing signals, one that operates with the GOES satellite and one that operates with the TRANSIT satellite. The TRANSIT satellite provides global coverage, but the GOES satellite should be in range of all the NDSN sites.

The station will be equipped with digital-to-analog converters so that any channel of data can be monitored in analog format during installation and maintenance. Some of the NDSN stations might be manned or located adjacent to manned observatories, and in this case continuous recording of analog data may be desirable.

Any data recorded on site will be placed on high-density tape cartridges. The number of tape drives (up to four) will depend on the recording mode. As one tape fills, the station processor will switch recording to another. Automatic switching will also take place if there is a hardware failure in one of the drives. One drive may be used to store interrogatable data, status information and alternate operating programs.

The communications module will provide the ports for communicating with the station processor and for transmitting data. Each station will be equipped with a dial-up modem, except in unusual cases where telephone communications are not possible. Some stations may be equipped with modems for continuous data transmission as well, and it is hoped that ultimately all stations will be equipped with a remote satellite terminal. The selection of data for transmission will be programmable from the receiving terminal. The terminal shown in the block diagram will be used to communicate with the station processor during installation and service visits.

The NDSN stations will require line power. A self-contained power source would add significantly to station costs and it would severely limit flexibility in system design. An uninterruptible power system with excess capacity will be installed at each site. Batteries will power the station for at least 12 hours in the event of line power failure.

5.3 NDSN Station Facilities

The NDSN stations are intended to be permanent observatories; therefore, it is important that the facilities for housing the station equipment be designed and constructed with care. Both the quality of the data and the reliability of the station are enhanced by properly designed facilities.

Although expensive to construct, a subsurface vault for the instruments is the most desirable approach to facility design. A subsurface vault provides an excellent operating environment for the instruments and it provides good security, which is needed for stations that are unattended. The vault need not be large, perhaps 10 square meters. The seismometers will be placed on a thermally-insulated pier and completely covered by styrofoam sheets. The broad-band seismometers require the most environmental protection. Normally, a Wielandt seismometer is covered with a Mu metal case, an aluminium cover, and finally by an evacuated glass bell. The electronics cabinet will be placed in the entryway, which will be vented to dissipate heat. The power subsystem will be placed in a separate surface enclosure vented by a thermostatically controlled fan. Power and communication cables will be buried from the vault to the power substation, which will be located at least 100 meters from the vault. The subsurface vault should be covered by at least 1 meter of soil.

5.4 Operation and Maintenance

Some of the stations will be serviced directly from the USGS Albuquerque Seismological Laboratory; others may be serviced by cooperating organizations on a regional basis. The servicing headquarters will be in communication with the stations via the dial-up circuits. Periodically, perhaps daily, the stations will be interrogated. Any malfunctions that the station processor had detected during routine status checks (power failure, component failures, etc.) will be reported. During interrogation it will be possible to check the status of other parameters -- temperature in the vault and power subsystem enclosure, mass position of the broad-band seismometers, number of records written on the tape, and critical voltage levels. The person monitoring station functions should be able to sample any seismic subsystem to check data quality, change the operating program (sampling rates, transmission modes), initiate calibration sequences, and run diagnostic programs. The scheduling of service visits, principally for tape collection, will be based on information recovered from the station during interrogation.

6. NDSN DATA MANAGEMENT

6.1 General

Data management planning and development must parallel the development of the NDSN. The success of the program depends to a large extent on the efficient organization, storage, and dissemination of the data after they have been collected from the stations. The distributed data should be timely, standardized in format, and easily accessed. They should also be inexpensive; it makes little sense to invest millions of dollars in the collection of data only to restrict their use by the research community through excessive charges. The major costs of organizing and distributing the data to organizations and individuals should be included in the network operating budget.

There has been steady progress in seismic data management technology during the past decade, particularly in the area of real-time, on-line applications. Dean (1981) provides a history and evaluation of developments in this field, which has been supported principally by the Vela Uniform program. Real-time processing of the NDSN data will be especially important to the USGS because of its responsibility for reporting and cataloging earthquake parameters. However, it is not a subject of this study. A more appropriate concern of this study is the organization and distribution of NDSN data for off-line research.

The management of data in both on-line and off-line applications is especially dependent on data storage technology, a technology that is expected to improve significantly during the next decade. If the NDSN is installed within the next 5 years, it is likely that magnetic tape will still be the principal data storage medium and storage will be off line. In the short term, plans will have to be developed for a tape-based data management system. On the other hand, the advent of optical disk storage is certain to make mass on-line storage of data both technically and economically feasible within the lifetime of the NDSN, so it is appropriate to anticipate the procedures that will be used when this technology becomes available.

6.2 Tape-Based Data Management

If the NDSN were to be installed in the near future, the procedures used to organize, store, and distribute the NDSN data would be modeled on the procedures used for the GDSN data. While somewhat cumbersome because of the volume of tape that must be handled, the GDSN data management system has, in fact, worked very well. A diagram of proposed NDSN data flow is shown in Figure 6.1. Station tapes will be collected by the Albuquerque Seismological Laboratory and run through an automated review process. Data will be read into disk files capable of storing 30 to 40 days of network data on line. If satellite communications are used to transmit continuous data, the signals will be event detected at the receiver, then entered into the disk. Network-day tapes will be compiled from the waveform data on file. They will also contain all of the information needed by an analyst to process and interpret the data (station

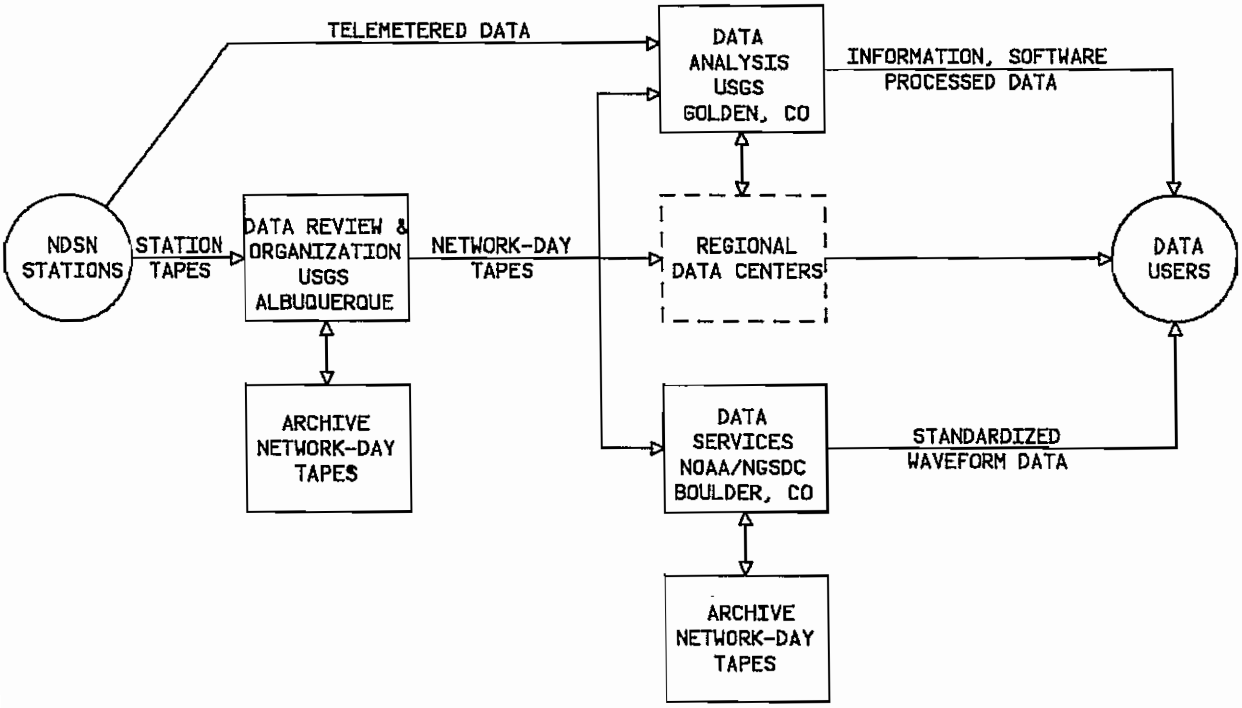


Figure 6.1--Data flow in a tape-based data management system.

coordinates, transfer functions, timing corrections). Hoffman (1980) has published a description of the GDSN network-day tape format, which will serve as a pattern. The network-day tapes will be the raw end product of the NDSN; they will be used for both storage and distribution of the data.

Full sets of network-day tapes will be furnished routinely to the USGS in Golden, Colorado, to the NOAA data center in Boulder, Colorado, and to any regional data centers that may be established. Copies of the network-day tapes also will be provided by the Albuquerque Seismological Laboratory to any organization or individual that furnishes magnetic tape.

The USGS data analysis group in Golden will provide data users with information, software, and processed data. It will also furnish facilities and assistance to visiting scientists. The NOAA data center will fill special requests for data derived from the day tapes -- event tapes, plots, and other customized data sets.

At least two regional data centers should be established, one on the east coast and one on the west coast, and equipped with sufficient computer facilities to display and plot the digital data and perform a moderate level of computational processing. The regional data centers, which would be operated by scientific institutions, will be furnished with full sets of NDSN and GDSN data and will be expected to provide data, facilities, and assistance to visiting workers.

6.3 Mass-Store-Based Data Management

According to industry literature, optical disk technology is advancing rapidly. Single disks with a capacity of 10^{11} bits of digital data should be available within 5 years. Data storage systems with a capacity of 10^{14} to 10^{15} bits are likely within the decade. A storage capacity of 10^{14} bits would accommodate 25 years of NDSN data (all data, not just events). Clearly, this will have a dramatic impact on seismic data management, with changes in both the methods of acquiring station data and in data management procedures.

The flow of data in a mass-store based data management system might appear as shown in Figure 6.2. It now becomes feasible to collect and store all of the SP and BB data, and even increase the sampling rates if this is desirable.

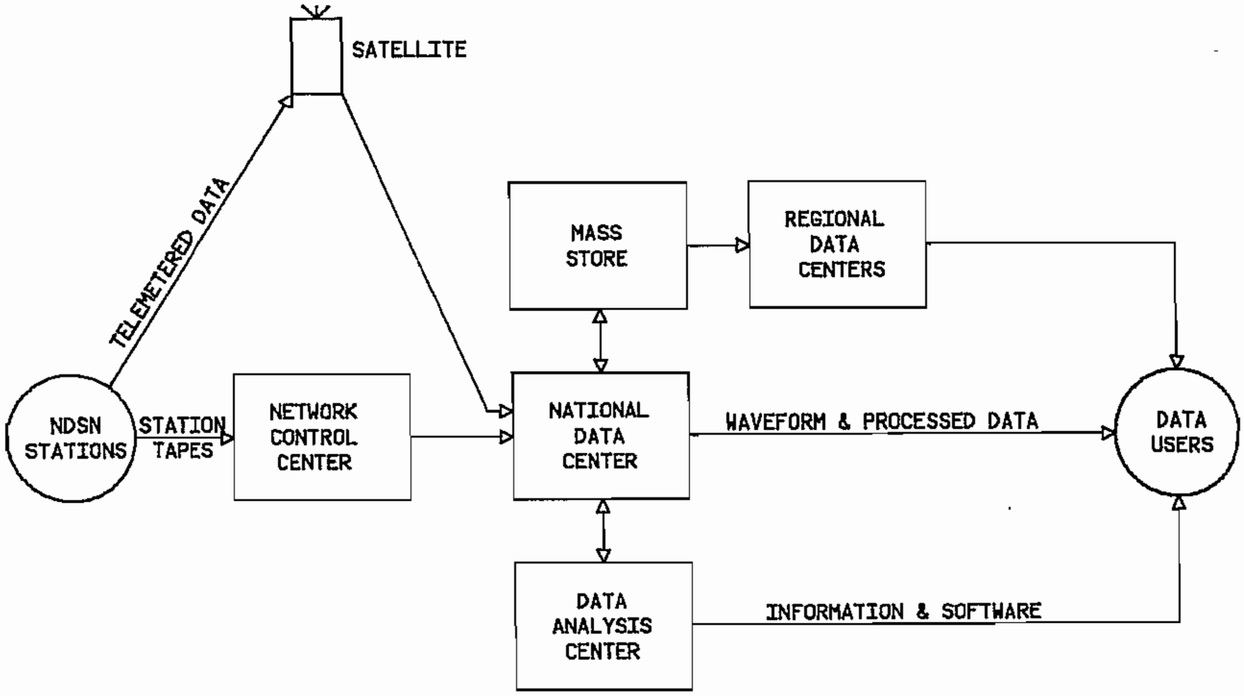


Figure 6.2—Data flow in a mass-store-based data management system.

Satellite links will be used for data transmission. All of the network data will be analyzed in real time and placed unedited into the mass store together with event parameters. Data and catalog information in the mass store will be accessed directly by the regional data centers via dedicated landline or satellite communication links. Independent data users could access the mass store through the national data center using dial-up communication links. The data centers will furnish tapes, plots, and other special data sets to users that cannot access the database directly.

Although a data management system based on a mass store could not be implemented economically today, it appears close enough to warrant examination. For example, it may be possible to store on line in a national data center all of the NDSN and GDSN data, as well as digitized data from most of the regional and local networks operated within the United States. A data management plan should be developed in a separate study together with plans for on-line processing of the data. System development is best left to private manufacturers as they appear to be pursuing it aggressively. The development of software will not be a trivial task, but it is likely that database management systems (comprising host computers, storage and retrieval, and operating software) will be developed by private industry since there is certain to be a demand for turn-key systems.

7. NDSN COST ESTIMATES

We estimate the cost of installing a 36-station NDSN to be $10,351,000 (see Table 7.1). The estimate is based on an interim system concept that assumes on-site recording and tape-based data management. The estimated annual cost of operating this network is $1,350,000 (see Table 7.2). This does not include the cost of dedicated landline or satellite telemetry links. The installation and operational estimates are not based on an exhaustive cost study and some items are subject to considerable uncertainty. Nevertheless, they are considered accurate enough to serve as a basis for preliminary budget planning.

The estimated cost to upgrade the NDSN to a fully telemetered network is $1,800,000 -- $1,080,000 for remote terminals, $450,000 for a receiver, and $270,000 for computer processing and recording equipment. Increased annual operating cost would be about $100,000, although some of this would be offset by a reduction in station maintenance.

The projected cost of a mass-store-based data management system is far less certain because the technology is evolving. A database management system (host computer, optical disk storage, and software) might cost about $1,200,000 when it becomes available.

Field System Development		
Design Study	100,000	
Prototype Development	250,000	
Installation	80,000	
Test & Evaluation	50,000	
Documentation	20,000	
		$ 500,000
Network Installation		
Site Survey & Land Acquisition	6,000	
Site Preparation	80,000	
Field Systems	125,000	
Installation	5,000	
	216,000 per station	
x 36 stations		7,776,000
Data Processing Facilities		
Albuquerque	525,000	
Boulder	250,000	
Golden	250,000	
Regional Data Centers (2)	500,000	
		1,525,000
Network Control Center		
Depot Supplies	400,000	
Space	150,000	
		550,000
	Total	$ 10,351,000

Table 7.1--Estimated cost of installing a 36-station network.

Station Maintenance		
Contract Maintenance	220,000	
Travel	85,000	
Supplies & Repair	150,000	
Communication	75,000	
Land Lease	50,000	
		$ 580,000
Data Management		
Albuquerque	220,000	
Boulder	100,000	
Golden	100,000	
Regional Centers (2)	150,000	
		570,000
Program Management		200,000
	Total	$ 1,350,000

Table 7.2--Estimated annual cost of operating a 36-station network.

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