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# National Seismic Stations Transducers and Filters

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January 13, 1981

 Lawrence  
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Laboratory



**Test Ban Treaty Verification Program**

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Manuscript date: January 13, 1981



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# National Seismic Stations Transducers and Filters

## ABSTRACT

The National Seismic Stations (NSS) instruments are being developed for seismic monitoring of regional and teleseismic events. They consist of two 3-component, broadband, borehole seismometers: the KS-36000 and the S-700, which is the backup for the KS-36000. Output is divided into frequency bands to reduce data loss due to saturation.

Complete block diagrams of the KS-36000 and S-700 NSS seismometers and filters are presented. Both open-loop and closed-loop steady-state amplitude and phase curves are given. Without band-pass filters (but with shaping filters) the KS-36000 has a flat (i.e., between the -3dB points) velocity sensitivity from 0.03 to 23 Hz. With its shaping filters, the S-700 is flat from 0.2 to 40 Hz. The structure of the three band-pass filters (LP, MP, and SP) is superimposed on these velocity sensitivities. Passbands of the resulting overall velocity sensitivity for the KS-36000 are as follows: LP band = 0.03-0.05 Hz, MP band = 0.02-1.3 Hz, and SP band = 1-10 Hz. Step-function responses and phase and group delays are given for each of the bands. The MP-band step response is oscillatory, due to its sharp, high-frequency cutoff, but an MP-band filter with a less abrupt cutoff eliminates the oscillation.

To generate typical NSS output seismograms, velocity inputs from three representative seismic events were used: an underground nuclear test ( $\Delta \approx 3.6$  km), a regional earthquake ( $\Delta \approx 20$  km), a local earthquake ( $\Delta \approx 1.8$  km), and a teleseismic earthquake ( $\Delta \approx 25$  km). The velocity inputs for these events were obtained from the ENEI data set of the DSS1 around the Nevada Test Site (NTS). The seismogram's resulting in the three bands were satisfactory, although the low-frequency end of the three MP bands was increased in frequency to 0.08 Hz.

The S-700 with an open-loop resonant frequency of 23 Hz, was chosen to exceed the specification at 1 Hz. We therefore recommend that the S-700 be run as a long-period conventional short period seismometer, such as the Mars Pro model 1-4.

## CHAPTER 1: INTRODUCTION

National Seismic Stations (NSS) instruments are being developed for seismic monitoring of regional and teleseismic events. These instruments consist of two 3-component, broadband, borehole seismometers: the KS-36000 and the S-700, which is the backup for the KS-36000. Output is divided into frequency bands to reduce data loss due to saturation.

NSS instruments intended to monitor regional and teleseismic events have a low-frequency response that is flat (i.e., between the -3dB points) from 0.03 to 23 Hz. The low-frequency response is flat because the KS-36000 and S-700 are designed to respond to regional and teleseismic events, which are characterized by low frequencies. The KS-36000 is also designed to respond to local events, through the use of a low-cut filter with a corner frequency of 0.05 Hz, and to high-frequency teleseismic events. The broadband output of the KS-36000 is fed into the NTSF digital signal processor. The outputs of NSS seismometers are broken up into separate frequency bands to reduce data loss due to saturation.

in boreholes to reduce seismic noise. Three components are used because they greatly increase the ability to identify particular wave types.

This report presents the steady-state sinusoidal and dynamic responses of both NSS seismometers. The block diagram of each instrument and filter is given, and corresponding analytic transfer functions are contained in the Appendices.

Both open- and closed-loop frequency responses are plotted for the two transducers. Overall (including filters) velocity sensitivity\* (VS) curves together with phase and group delays are also presented.

The dynamic response of each seismometer and filter combination is shown; both by its response to a

step function in velocity and its response to seismic inputs. Representative seismic inputs are velocitygrams of local, regional, and teleseismic events as recorded by the LLNL digital seismic network.

Data for these computations were taken from the August 11, 1979 and February 27, 1980 informal reports of H. B. Durham (Sandia): "NSS-Model II, Seismic Data System Response Functions." Transfer functions for the S-700 were taken from the latter report and those for the KS-36000 from the former; therefore the responses for the KS-36000 are slightly, but not significantly, different from the current version.

## CHAPTER 2: THE KS-36000

### OVERALL BLOCK DIAGRAM

The overall block diagram for the KS-36000 is shown in Fig. 1. The transducer itself is block  $H_1$ , which is further broken down into its internal feed

\* The term VS refers to a seismometer's magnitude of sensitivity to ground motion, expressed in velocity.

back loop. Transfer functions for  $H_1$ ,  $H_3$ ,  $H_B$ , and  $K_1$  are given in Appendix A.  $H_1$  is followed by the Long Period/Mid Period (LP/MP) shaping filter,  $H_{S1}$ , and the Short Period (SP) shaping filter  $H_{S2}$ . Transfer functions for  $H_{S1}$  and  $H_{S2}$  are also given in Appendix A. The two shaping filters feed into the

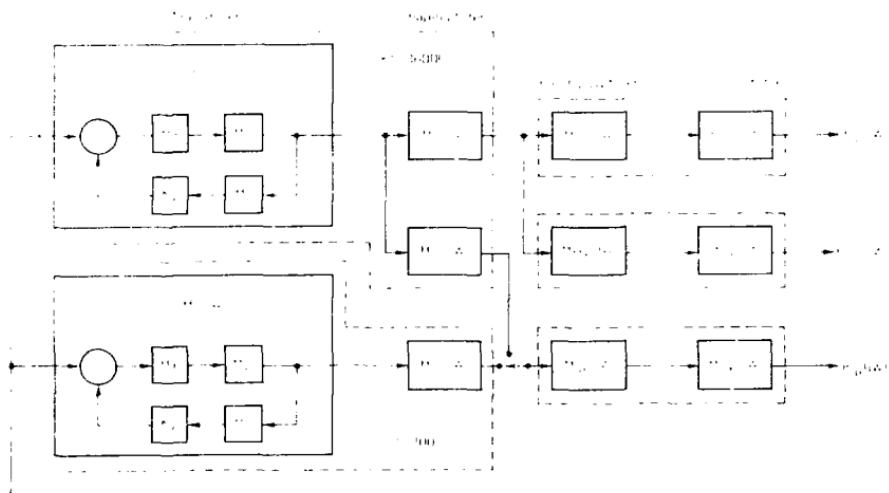


FIG. 1. Overall block diagram for NSS seismographs showing feedback loops for the transducers, shaping filters, band-pass filters, and common filters.

three major band-pass filters  $H_{LP}$ ,  $H_{MP}$ , and  $H_{SP}$  which, in turn, are followed by the three common filters,  $H_{CF}$ . Transfer functions for the band-pass and common filters are listed in Appendix B.

## TRANSDUCER CHARACTERISTICS

The open-loop frequency-response curve,  $H_T H_A H_V K_F$ , is given in Fig. 2. The peak at approximately 0.2 Hz is due to the resonance of the lightly damped ( $\xi = 0.01417$ ) spring-mass system of the seismometer itself. The closed-loop acceleration response which is flat out to 23 Hz (-3dB) with a corner frequency at approximately 30 Hz is shown in Fig. 3.

## SHAPING FILTERS

Figures 4 and 5 show the frequency response of the two shaping filters,  $H_{S1}$  and  $H_{S2}$ . The purpose of  $H_{S1}$  is to cause the VS curve of  $H_1$  to fall off as  $\sim f^3$  at frequencies below 0.01 Hz. (Without  $H_{S1}$ , it would fall off as  $f$ .) The resulting overall VS curve for the transducer ( $H_1 H_{S1}$ ) is shown in Fig. 6. It rises with a +3 slope (corresponding to  $f^3$ ) below its low-frequency corner at 0.0105 Hz (= 1.95 sec). It is then flat out to approximately 20 Hz where it falls off with a -4 slope. The frequency response of LP and MP bands will be superimposed on this curve to obtain the overall VS curves for the KS-36000.

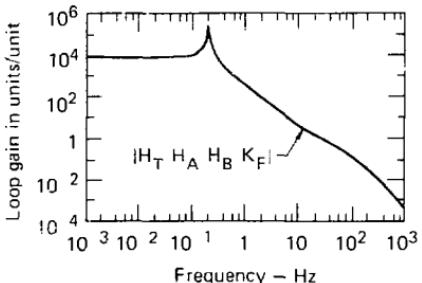


FIG. 2. KS-36000 open-loop frequency-response curve peaks at approximately 0.2 Hz due to mechanical resonance of the pendulum.

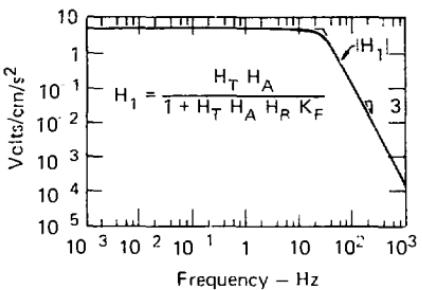


FIG. 3. KS-36000 closed loop acceleration response is flat to 23 Hz.

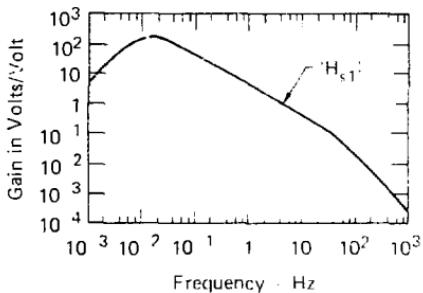


FIG. 4. Shaping filter,  $H_{S1}$ , frequency response.

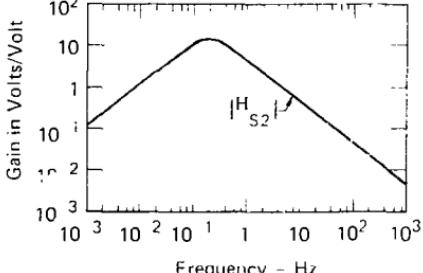


FIG. 5. Shaping filter,  $H_{S2}$ , frequency response.

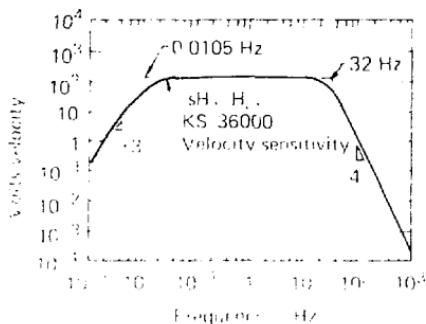


FIG. 6. KS-36000 velocity sensitivity without band filters for EP and MP bands.

The overall response of the KS-36000 to a 1-Hz sine wave is shown in Fig. 6. The overall velocity sensitivity of the KS-36000 for the EP and MP bands is plotted in Fig. 7. Since the overall velocity response of the KS-36000 is the product of the individual velocity sensitivities of the three band filters, the overall response is the product of the 30-Hz SP pass

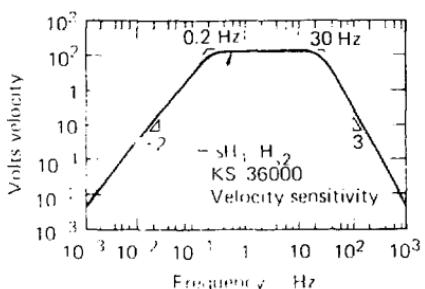


FIG. 7. KS-36000 velocity sensitivity without band filters for SP band.

and of the filter that will be imposed on this response to obtain the overall SP AS.

In summary, the two important curves represented in Figs. 6 and 7 which characterize the VS of the KS-36000

## CHAPTER 3: THE S-700

The overall response of the S-700 seismometer is shown in Fig. 8. The overall response of the S-700 is the product of the  $H_{SP}$ ,  $H_{MP}$ ,  $H_{EP}$ ,  $H_{sH}$ , and  $H_{H2}$  filters. The overall response of the S-700 is the same form as that for the KS-36000. The overall response  $H_{SP}H_{MP}H_{EP}H_{sH}H_{H2}$  for the S-700 is given in Appendix A. The response of the S-700 to a 1-Hz sine wave is shown in Fig. 9. Note that the overall response of the S-700 to a 1-Hz sine wave is the same as that obtained with the KS-36000 because the  $sH$ ,  $H_2$ , and  $H_{sH}$  filters have a high-pass section. The overall response of the S-700 is approximately

50 Hz. The peak of shape of the velocity response of the S-700 is corrected by the addition of the shaping filter  $H_{sH}$  shown in Fig. 9. The resultant overall AS for the S-700 for a 1-Hz sine wave is approximately 0.2 to 40 Hz. Whether or not the S-700 response will generate useful data above 0.2 Hz will very much depend on the magnitude of the electronic noise in that region. The characteristics of the SP filter will be compared with this response to develop the overall AS for the S-700 as seen through the SP filter. The overall EP or MP is used for the S-700.

## CHAPTER 4: BAND-PASS FILTER CHARACTERISTICS

As can be shown in the NSS block diagram, only parts of the KS-36000 and the S-700 are shaped by passing them through the three band-pass filters EP, MP and SP. Before describing these filters in detail it is worthwhile to review some general characteristics of filter types used in the NSS.

### PROPERTIES OF BAND-PASS FILTERS

Filters discussed in this section are all of the band-pass type. They are described in terms of some

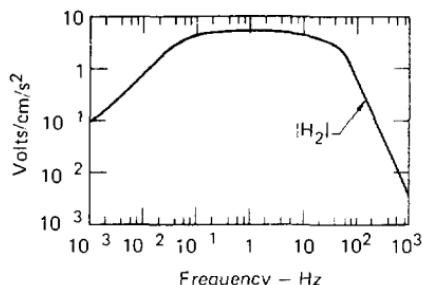


FIG. 8. S-700 closed-loop acceleration response.

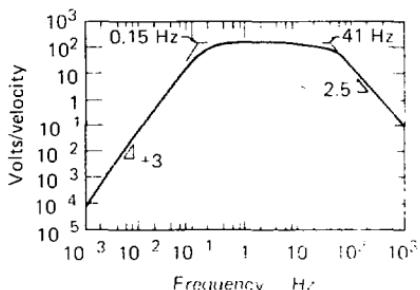


FIG. 11. Overall velocity sensitivity for S-700.

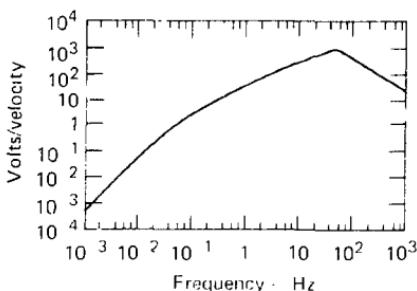


FIG. 9. S-700 closed-loop velocity response.

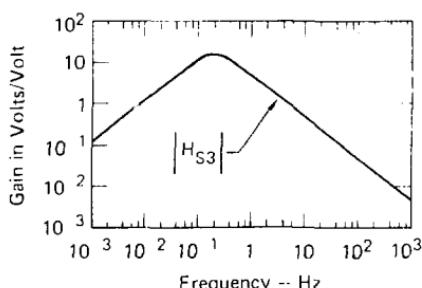


FIG. 10. Shaping filter,  $H_{S3}$  for S-700.

combination of their transfer function, frequency and phase response, and step-function response.

Some general properties of such pass filters are as follows:

1. The sharper the filter corner, the greater the tendency for ringing in its step-function response.

2. In general, for broad band-pass filters the rise time of the step-function response is determined by the high-frequency corner and the decay by the low-frequency corner.

3. The more the phase response departs from the unity (i.e., the curve departs from a linear relationship), the more phase distortion or dispersion results.

4. In general, the steeper the filter corner, the higher the Q; the greater the corner, the faster the filter to ring.

## TYPES OF CLASSICAL ANALOG FILTERS

Three types of analog filters most often used as seismic filters are as follows:

1. Simple filters. All poles and zeros lie on the negative real axis of the s plane, with  $\omega_c < \pi/2$ . A critically damped or overdamped filter of this type could be considered to be a second-order<sup>2</sup> s-plane filter.

2. Butterworth filters. All poles lie on a semicircle in the left half of the s plane. The amplitude spectrum is very flat and has no relatively sharp corner.

<sup>2</sup>The order of the filter is the number of poles in the system describing the filter.

TABLE I. Summary of simple, Butterworth, and Bessel filter characteristics.

|                                      | Simple filter                              | Butterworth filter      | Bessel filter                     |
|--------------------------------------|--|-------------------------|-----------------------------------|
| Shape of spectral amplitude response | Moderately flat, moderately rounded corner | Very flat, sharp corner | Very sloping, very rounded corner |
| Overshoot in step response           | None                                       | Moderate                | Very little                       |
| Phase distortion                     | Moderate                                   | Quite a bit             | Least                             |

3. Bessel filters. These filters tend to approximate a linear phase response and thus exhibit minimum phase distortion or dispersion. The amplitude spectrum is quite sloped with a very rounded corner.

Based on the above descriptions, the simple filter can be regarded as midway between the Butterworth and the Bessel filter.

A fourth type of filter, the Chebyshev, is not used in present-day seismic instruments because its amplitude spectrum is not smooth and its step response has a large overshoot.

Table I shows that none of the filters exhibits all three desirable qualities at once: rectangular passband, low overshoot in step response, and linear phase. From the viewpoint of selectively rejecting noise in one band and passing signal in another, near-rectangular passband (Butterworth filter) is desirable. But with regard to deconvolving seismic data (freedom from overshoot and dispersion), it is important. It is also desirable to minimize the number of poles to reduce the phase distortion. These tradeoffs will be referred to again when discussing the details of the NSS receiver system.

## CHAPTER 5: NSS BAND-PASS FILTERS

### BAND FILTERS

To lessen the chances of saturation of the electronics during large seismic events, it is desirable to split up the KS-30000 and S-700 output into bands. For example, if there were only one band (a so-called broadband system), the large amplitude surface waves generated by a major, remote earth quake could cause saturation of the electronics and loss of all signals during the period of the saturation. By breaking the output into bands, presumably only the LP band would experience electronic saturation, although mechanical or electrical saturation of the transducer would spoil the data in all three bands.

### SANDIA FILTERS

Amplitude spectra of LP, MP, and SP filters proposed by Durham et al. (Sandia top cut) are shown

in Fig. 12, and their characteristics are given in Appendix B.

The LP band filter (SFP) is essentially the same as that in the SRO. It consists of a 2nd-order,

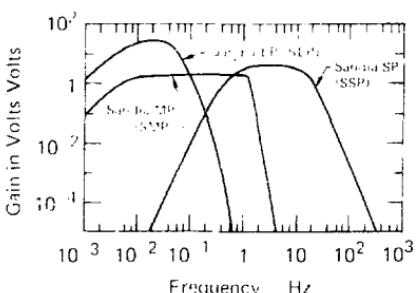


FIG. 12. Sandia LP, MP, and SP band filter amplitude spectra.

simple high-pass section at 0.005 Hz followed by a series of low-pass sections which result in a 12th-order rolloff (slope of -12). The result is the narrow LP band shown in Fig. 12, which is centered on 0.02 Hz ( $\approx$  1.50 sec).

The MP band is a broad, flat band running from approximately 0.02 to 1.3 Hz bracketing the microseism band. It begins at low frequencies with the same 2nd-order, simple high-pass section at 0.005 Hz as the LP filter. This is followed by a sharply breaking 10th-order Butterworth low-pass filter at 4.3 Hz. This is followed by two simple low-pass sections at 10 and 100 Hz. Since the high-pass section is 2nd order and the low-pass sections are 10th order above 10 Hz, the result is the so-called "inverted" curve labeled SMP in Fig. 12.

The SP band is flat from approximately 1 to 6 Hz. It consists of a 2nd-order, simple high-pass section, a 4th-order, inverted curve, 10th-order Butterworth low-pass filter at 4.3 Hz, and a 10th-order high-frequency section. The result is a nearly symmetric SP transfer function. The filter associated with the symmetric SP transfer function at 4 Hz is also called an SSP, Fig. 12.

A short summary of NSS system losses from the transfer functions of the LP, MP, and SP filters is given in Table II. The total system filter loss (the ratio of output power to input power) is the product of the individual filter losses.

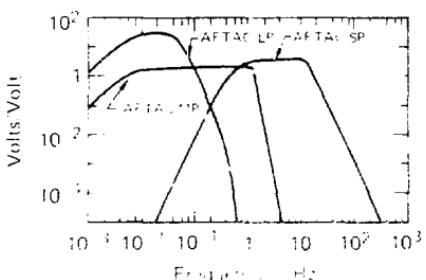


FIG. 13. AFTAC LP, MP, and SP band filter amplitude spectra.

dropping of the SP curve at 60 Hz is due to practical parasitic effects in the power supply rather than to the system.

## AFTAC FILTERS

AFTAC uses proposed bandpass filters which are shown in Fig. 13. The main difference between AFTAC filters and those proposed by Sandia is that the AFTAC filters have SP bands up to 400 Hz. Because the proposed system is a stepped filter, the total number of filters is 12, while the AFTAC system has 10 filters. The proposed system has a much higher passband gain than the AFTAC system, however.

## CHAPTER 6: NSS OVERALL RESPONSES INCLUDING TRANSDUCERS AND BAND-PASS FILTERS

In the previous section the details of the proposed bandpass filters were described. In this section the overall system responses will be presented, including the transducers. For example, the KS-36000 AS transfer LP and MP transfer functions (Fig. 8, SH-Hs) are multiplied by the LP and MP band transfer functions shown in Fig. 12 (scaled filters for read-in over an AS). The SP AS, SH-Hs, of Fig. 7 is multiplied by the SP transfer function, also shown in Fig. 12. This overall AS relates the velocity response into the transducer or to coils out of the common filter, H<sub>pp</sub>, which is the last filter in each of the band-pass filters.

Although each of the band filters has an absolute gain associated with it, this discussion is not

concerned with the absolute gains of the various filters. The overall system response is concerned with the relative gains of the various filters. However, the overall system response is dependent upon the absolute gains of the filters.

## PROPERTIES OF THE KS-36000 WITH SANDIA FILTERS

### Velocity Sensitivity

The amplitude spectra of the resulting overall KS-36000 and sandia system transfer function for ASs is shown in Fig. 14 for the proposed Sandia filters. The resulting curves are similar to those of

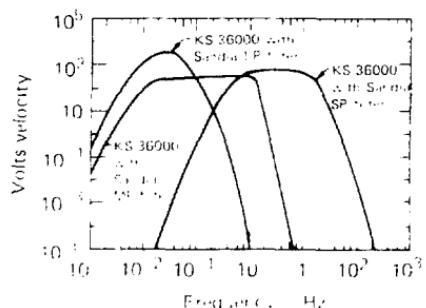


FIG. 14. Velocity sensitivity with filters: Sandia LP, Sandia MP, and Sandia SP.

Fig. 14, the filters are except for the regions of very low and high frequencies where the KS-36000 VS degrades to some point. In those regions, the response is steeper by the KS-36000 response alone.

The three 1/3 octave 3dB points for this overall system are:

- LP Band 0.004-0.8 Hz
- MP Band 0.02-3 Hz
- SP Band 0.1-10 Hz

### Phase Response (b)

The phase response accompanying the VS is shown in Fig. 15 for the three Sandia filters. The phase response of the SSP was begun arbitrarily at -10 degrees for low frequencies, and the other two phase responses were plotted accordingly. It should be noted that there is a bump at the MP curve near 1 Hz. This is due to the sharp, high-frequency corner of the MP filter. Although it is difficult to envision on semi-log plots, the closer the phase response is to linear in frequency, the less distortion of signals passed.

### Group Delays

Group Delay  $\tau_g$  is the delay which would be experienced by a wave packet. It is calculated from the phase delay,  $\phi(\omega)$ , by the relation

$$\tau_g = \frac{d\phi(\omega)}{d\omega} = \frac{1}{2\pi} \frac{d\phi(\omega)}{dt} \quad (1)$$

It is useful to examine group delay since minima would result in large amplitude waves known as Anti phases, which distort the seismogram. Of course, onset times are also retarded by the group delay associated with the particular period of arrival.

Group delays of the KS-36000 with Sandia filters are shown in Fig. 16. The delays are large at low frequencies and approach zero at very high frequencies. Since the slopes of phase delay curves increase in proceeding through the SP, MP, and LP bands, group delays proceed in the same order with the largest delay issued from the LP filter. Since it is relatively clear in the magnitude slope of the phase-delay curve where near the corner frequency of a filter, minimum seen in Fig. 16 can be associated with a particular corner frequency, and the size of the group delay is proportional to the number of poles.

### Step Responses

Step function responses of KS-36000 in four of its Sandia LP, MP, and SP filters are shown in Fig. 17. The plots are in seconds. Note that these responses are not filters, but rather show that SP reduces and LP increases the step response. The response to the filter of the three curves is the oscillations in the MP response. This scaling of the curves is such a dramatic change in the 1/3 octave 3dB Butterworth response of the KS-36000 that the step function is scaled down to be consistent with the order of magnitude of the MP step response which was 144 degrees for the 0.02-3 Hz. This scaling does not correct for the actual system performance.

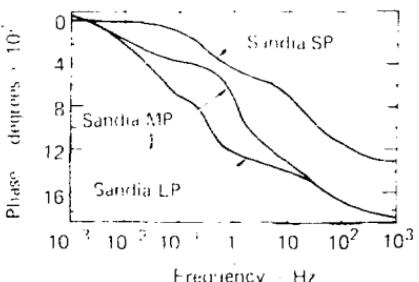


FIG. 15. Phase response of KS-36000 with Sandia filters.

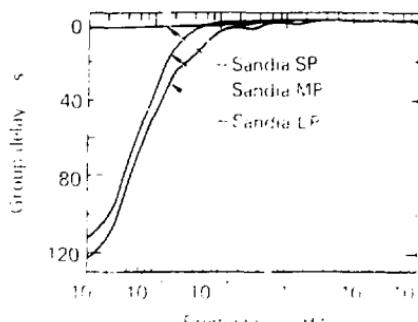


FIG. 16. Group delay of KS-36600 with Sandia filters.

## PROPERTIES OF THE KS-36000 WITH ALUMINUM FILTERS

### Velocity Sensitivity Curves

SP. and T. of ALL LAW in  
order now to Bass, but used the S.  
of the best men, 4 frontier Bards,  
which made it a strong support.

### Step-function Response

The first two sections of the *SP* document are reproduced below.

### Phase and Group Delay

The resulting SP picture is clearly sharper than with the Sordi filter in the red  $\sim 700$ – $1400$  nm wavelength region. The phases of the amplitude oscillations for the K8-30000 with AEI filters are given in Appendix I, Figs. C1 and C2.

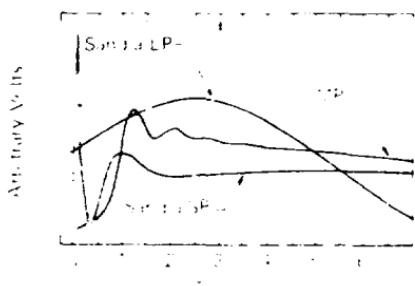


FIG. 17 Step responses of KS-36000 with Sandia filter

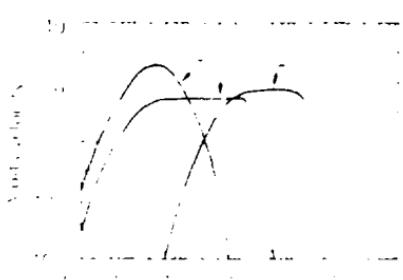


FIG. 18. Velocity sensitivity with filters: MELAC, LP, MELAC-MP, and MELAC-SP.

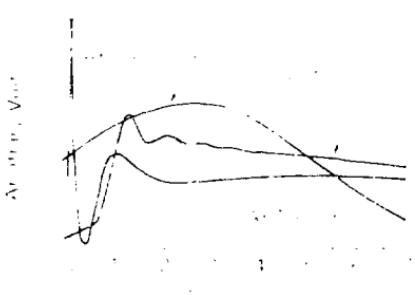


FIG. 19. Step responses of KS-36000 with AE-LAC filters.

## CHAPTER 7: THE MP-BAND FILTER

As was stated previously, the upper corner of the Sandia MP-band filter is abrupt. It consists of a 10th-order Butterworth filter at 1.3 Hz. This results in the oscillatory step response for the MP band shown in Figs. 17 and 18. Because this is undesirable, it is worthwhile considering two other low-pass filters for the high-frequency corner of the MP band. One is a 4th-order Butterworth also centered at 1.3 Hz. The other is a 4th-order Bessel with the same corner frequency. The corresponding AS curves for the three filters are shown in Fig. 20. Note that the Bessel is the more rounded curve. Corresponding phase and group delays appear in Figs. 21 and 22. The group delay plots show why

an expanded scale. The minima in group delay for the 10th-order Butterworth is considerably greater than that for the 4th-order Butterworth. There is almost no minimum associated with the Bessel filter because of its nearly linear phase response (which is difficult to see in Fig. 21 because the horizontal axis is logarithmic).

Figure 23 compares the step-function responses of the three filters. The three different degrees of overshoot are in the order expected for each of the filter types. From this figure it is clear that the Bessel filter outperforms the Butterworth because of its improved transient behavior.

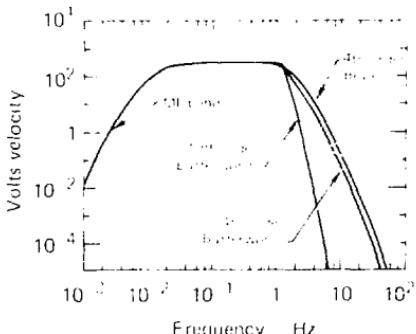


FIG. 20. Frequency response comparison of three MP band low pass filters.

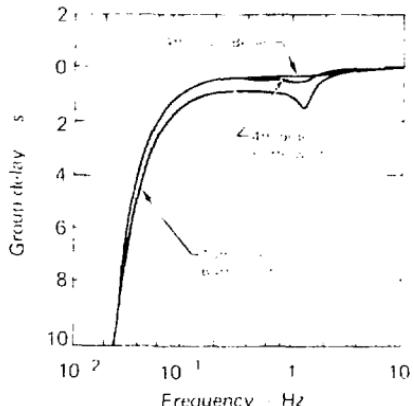


FIG. 22. Group delay comparison of three MP band low pass filters.

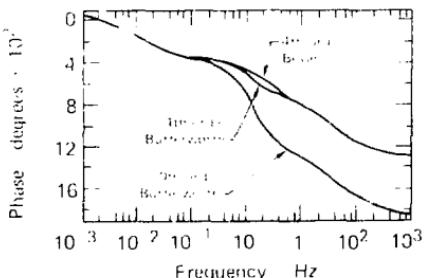


FIG. 21. Phase delay comparison of three MP band low pass filters.

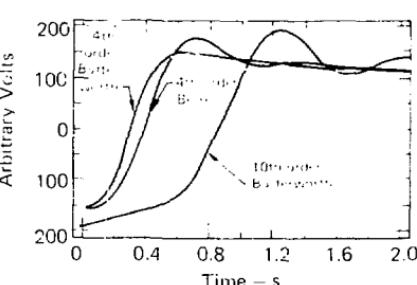


FIG. 23. Step response comparison of three MP band low pass filters.

## CHAPTER 8: THE KS-36000 RESPONSE TO VARIOUS REAL SEISMIC SOURCES

To develop a understanding of the significant differences in passbands, four actual seismic inputs are used as a database to calculate outputs of the three NSS passbands. The four events are an very head ground velocity event (event 1) from two of the four DSS stations, 11 and 12, and the NIS. These events are characterized as VS response of the system (Fig. 10) which is Fig. 24. Therefore, it is to be expected that the other two ground motion events will also have similar characteristics.



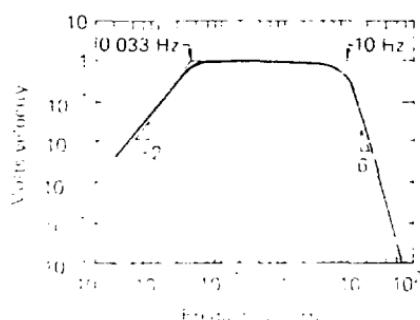
1994-1995: 133 cases.

#### EVENTS UNDERGROUND NUCLEAR SHOT ( $A \approx 3.6 \times 10^5$ )

The second derivative of the 1.88 sec. response curve shows a small peak at 1.88 sec. This corresponds to the time constant of the EP and the SPM. The SPM and EP are therefore in series. The SPM is in parallel with the detector. The time constant of the SPM and EP is 1.88 sec. The spectrum of the SPM and EP is shown in Figure 10. It is seen that the two curves are identical. No appreciable difference between the EP and the SPM is expected for the 1.88 sec. response. A very slight, several seconds decay in the time constant of the SPM is observed. This can be attributed to the detector noise or background.

#### EVENT (ii): REGIONAL EARTHQUAKE ( $\Delta \approx 20^\circ$ )

The entropy of Fig. 26 is in the entire range of temperatures has distinct phases, and



#### Fig. 24. DSE normalized velocity sensitivity.

## EVENTS IN LOCAL EARTHQUAKE ZONES

**EVENT (i.e., LARGE  
EARTHQUAKE)  $\approx 123^\circ$**

The 1880 census shows that the effect of the Civil War was to increase the number of slaves in the state. The census of 1890 shows that the number of slaves had decreased, but the freedmen had increased.

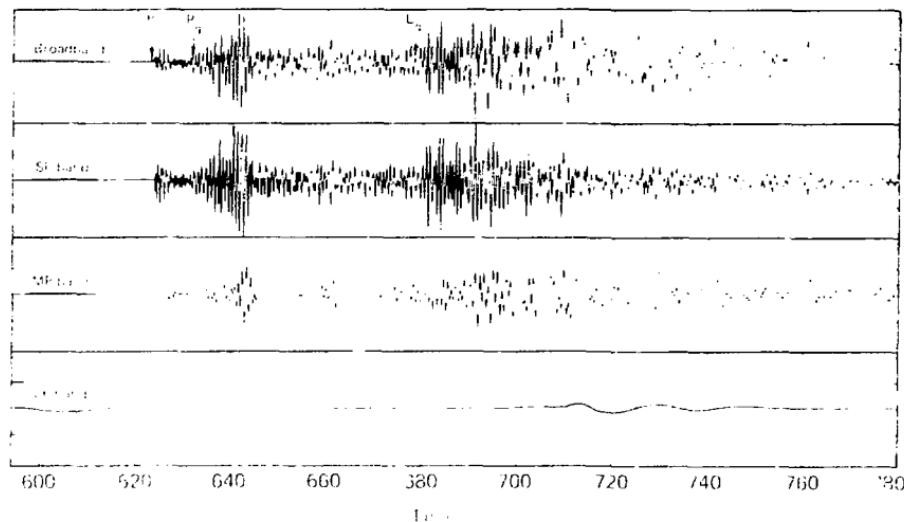


FIG. 25. Event (i): underground nuclear shot (1.5 kT).

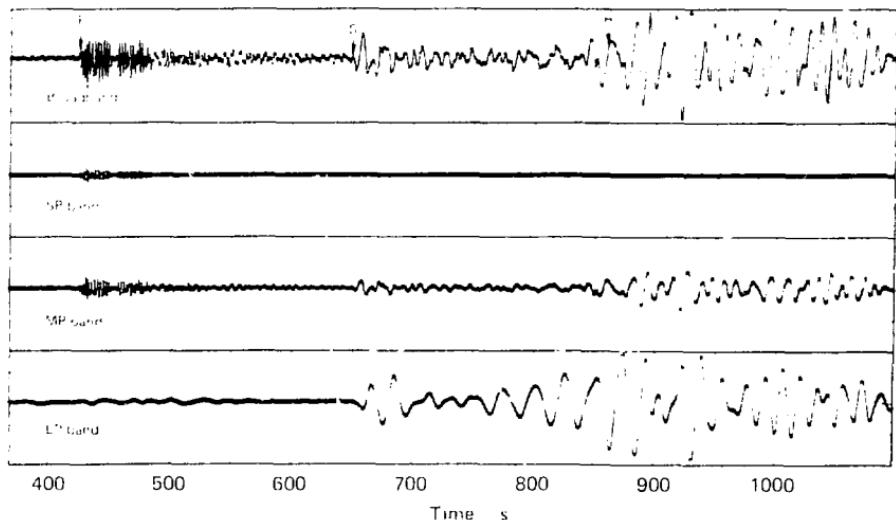


FIG. 26. Event (ii): regional earthquake ( $\Delta \approx 20^\circ$ ).

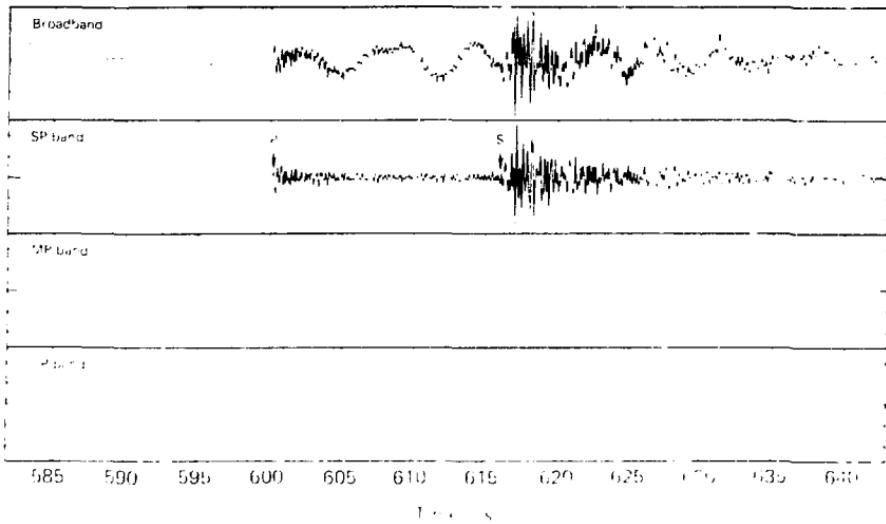


FIG. 27. Event (iii): local earthquake ( $\angle \approx 15^\circ$ )

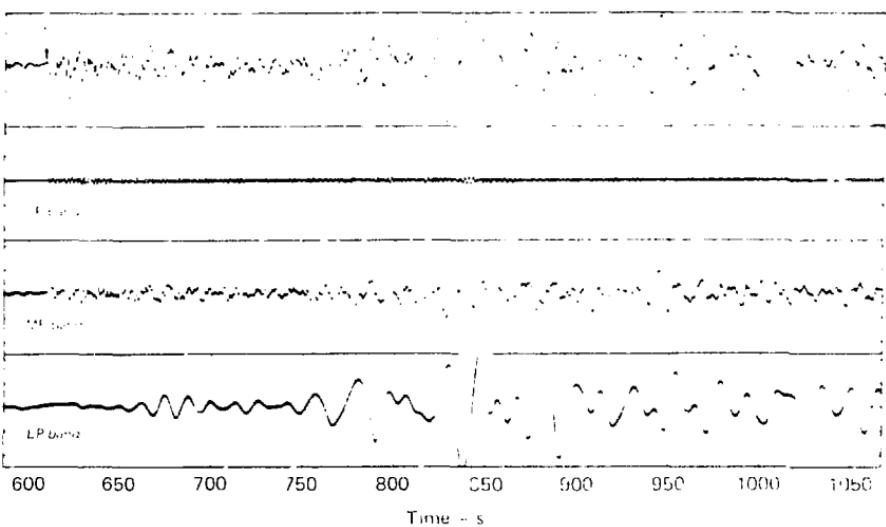


FIG. 28. Event (iv): large teleseism ( $\angle \approx 123^\circ$ )

Figure 26. A comparison of the performance of the MP-based filters to the EKF and the extended Kalman filter (x). The MP-based filters are shown in the upper row, and the EKF and the extended Kalman filter are shown in the lower row. The figure shows the results for the first 400 time steps. Because of the large number of plots, they are arranged in two rows. The top row contains plots for the first 200 time steps, and the bottom row contains plots for the remaining 200 time steps.

## CONCLUSIONS REGARDING THIS BAND STRUCTURE

— 8 —

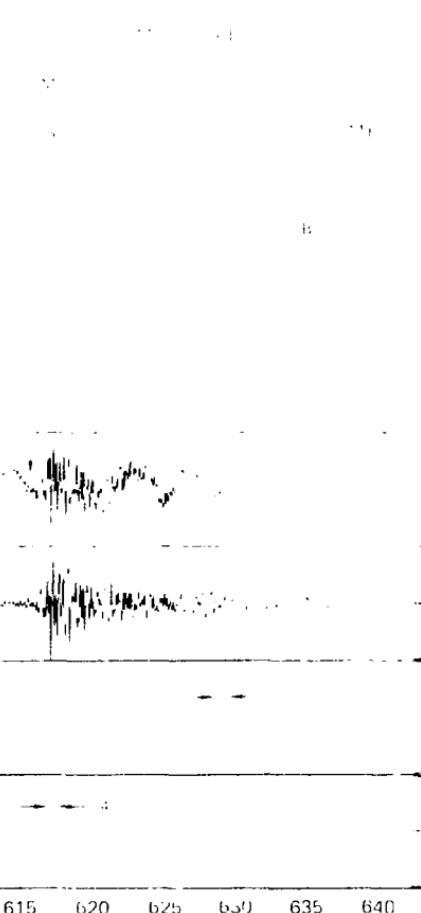


FIG. 29. Effect of two MP filters on a local earthquake.

## CHAPTER 9: THE S-700 SYSTEM

## S-700 RESPONSE TO REAL INPLIS

The KS 7000 VSP and the KS 6000 VSP are the latest additions to the KS series. Both are designed to meet the needs of the modern Heliocentric surveyor. The KS 6000 VSP is a fast, accurate, and reliable instrument.

The expected value of the  $S_{T(0)}$  component is zero, since the  $S_{T(0)}$  component is a linear function of the  $S_{T(0)}$  component of the



5700 RESOLUTION AND NOISE

CHAPTER 10: GENERAL COMMENTS

## GENERAL CONFIGURATION OF THE KS-36000

The first two rows of the table give the values of  $H_{\text{eff}}$  and  $H_{\text{ex}}$  for the  $\text{H}_2$  molecule, and the last two rows give the corresponding values for the  $\text{D}_2$  molecule.

## BAND STRUCTURE

The present analysis of the structure of the NMR-  
NMR patterns is a continuation of studies with the ex-  
ception of the high frequency content on the MR.

111-5700

## **ACKNOWLEDGMENT**

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## APPENDIX A: SEISMOMETER TRANSFER FUNCTIONS

### TRANSFER FUNCTIONS FOR THE KS-36000 SEISMOMETER

$$H_{\text{low}} = \frac{H_{\text{low}} + H_{\text{low}'}^*}{m + H_{\text{low}} + H_{\text{low}'}} = K_{\text{low}} \left( \frac{\omega}{\omega_{\text{low}}} \right)$$

$$H_{\text{low}'} = \frac{1}{m + H_{\text{low}} + H_{\text{low}'}} \left( \frac{\omega_{\text{low}'}}{\omega} \right)$$

$\omega_{\text{low}} = 0.01$

$\omega_{\text{low}'} = 0.001$

$$H_{\text{mid}} = \frac{1}{m + H_{\text{mid}} + H_{\text{mid}'}} \left( \frac{\omega_{\text{mid}'}}{\omega} \right)$$

$$H_{\text{mid}'} = \frac{1}{m + H_{\text{mid}} + H_{\text{mid}'}} \left[ \frac{1 - \frac{\omega_{\text{mid}}}{\omega}}{1 + \frac{\omega_{\text{mid}}}{\omega}} \right] \left( \frac{\omega_{\text{mid}'}}{\omega} \right)$$

$$K_{\text{mid}} = \frac{1}{m + H_{\text{mid}} + H_{\text{mid}'}} \left( \frac{\omega_{\text{mid}}}{\omega} \right)$$

### TRANSFER FUNCTIONS FOR THE KS-36000 LP AND MP SHAPING FILTERS

$$H_{\text{LP}} = H_{\text{LP},1} + H_{\text{LP},2} \left( \frac{\omega}{\omega_{\text{LP}}} \right)$$

$$\omega_{\text{LP},1} = \frac{\text{Cutoff}_1 + 308.4 \text{s}}{\text{Cutoff}_1 - 308.4 \text{s}} \left( \frac{\omega}{\omega_{\text{LP}}} \right)$$

$\omega_{\text{LP},2} = 0.001$

$$\text{Cutoff}_1 = \frac{1.00}{\cot(\pi/\text{period})} \left( \frac{\omega}{\omega_{\text{LP}}} \right)$$

$$\omega_{\text{LP},2} = \frac{0.324 \cdot 88 \text{s}}{1.2 \cdot 0.91 \text{s} + 112.6 \text{s}} \left( \frac{\omega}{\omega_{\text{LP}}} \right)$$

## TRANSFER FUNCTIONS FOR THE KS-36000 AND S-700 SP SHAPING FILTERS

$$H_{K_1}(s) = \frac{+18.61s}{s + 268s + 0.673s^2} \left( \frac{\text{volts}}{\text{volts}} \right)$$

$$H_{K_2}(s) = \frac{+36.74s}{s + 268s + 0.673s^2} \left( \frac{\text{volts}}{\text{volts}} \right)$$

## TRANSFER FUNCTIONS FOR THE S-700 SEISMOMETER

$$H_{S-700}(s) = \frac{H_{K_1} H_{K_2} s^2}{H_{K_1} + H_{K_2} + H_{B_1} + K_1} \left( \frac{\text{volts}}{\text{volts sec}} \right)$$

$$H_{S-700}(s) = \frac{s^2 + 1.0 \times 10^4}{s^2 + 2.68s + 0.673} \left( \frac{\text{volts}}{\text{volts sec}} \right)$$

$\Delta t = 5\text{ sec}$

$$\omega_c = 100\pi = 314 \quad \omega_n = 268 \quad \zeta = 0.673$$

$$H_{S-700}(s) = \frac{s^2 + 1.0 \times 10^4}{s^2 + 2.68s + 0.673s^2} \left[ \frac{\text{volts}}{\text{volts sec}} \right]$$

$$H_{B_1}(s) = \frac{9 \times 10^{-4}s}{s + 1.8 \times 10^{-3}s + 1} \left( \frac{\text{dynes}}{\text{volts}} \right)$$

$$H_{K_1}(s) = 18.61 \times 10^{-4} \left( \frac{\text{volts}}{\text{dynes}} \right)$$

## APPENDIX B: FILTER TRANSFER FUNCTIONS

### SHORT PERIOD FILTER TRANSFER FUNCTIONS

$$H_{\text{SP}}(s) = G_{\text{SP}} = H_{\text{P}}(s) + H_{\text{I}}(s) + H_{\text{D}}(s) + H_{\text{PS}}(s) \left( \frac{\lambda_{\text{SP}} s}{\omega_{\text{SP}}} \right)$$

a)  $G_{\text{SP}} = 1$

b)  $H_{\text{P}}(s) = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{\omega_{\text{SP}}} \end{bmatrix}$

c)  $H_{\text{I}}(s) = \frac{1}{\tau_{\text{SP}}} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} = \frac{1}{\tau_{\text{SP}}} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} e^{-\frac{s}{\tau_{\text{SP}}}}$

d)  $H_{\text{D}}(s) = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{\tau_{\text{SP}}} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0.025 \end{bmatrix} e^{-\frac{s}{\tau_{\text{SP}}}}$

### COMMON FILTER TRANSFER FUNCTION

$$H_{\text{C}}(s) = \frac{1}{\tau_{\text{C}}} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} e^{-\frac{s}{\tau_{\text{C}}}} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

### MID PERIOD FILTER TRANSFER FUNCTIONS

$$H_{\text{MP}}(s) = G = H_{\text{C}} + H_{\text{P}} + H_{\text{I}} + H_{\text{D}} + H_{\text{P}} - H_{\text{I}} + H_{\text{PS}} + H_{\text{DS}} \left( \frac{\lambda_{\text{MP}} s}{\omega_{\text{MP}}} \right)$$

a)  $H_{\text{PS}} = \frac{0}{s + 0.2438s + 0.0499s^2}$

b)  $H_{\text{DS}} = \frac{0}{s + 0.8182s + 0.0499s^2}$

$$d) \quad H_E(s) = \frac{1.0}{1.0 + 0.1734s + 0.01499s^2}$$

$$d) \quad H_D(s) = \frac{1.0}{1.0 + 0.1112s + 0.01499s^2}$$

$$e) \quad H_{D1}(s) = \frac{1.0}{1.0 + 0.13830s + 0.01499s^2}$$

$$e) \quad H_F(s) = \begin{bmatrix} -31.83s \\ 1.0 + 31.83s \end{bmatrix}$$

$$23) \quad H_{LP}(s) = \frac{1.0}{1.0 + 0.192s + 0.01 + 0.892 \times 10^{-3}s^2}$$

$$f) \quad G_{LP}$$

## LONG PERIOD FILTER TRANSFER FUNCTIONS

$$H_{LP}(s) = G_{LP} \cdot H_A(s) \cdot H_E(s) \cdot H_D(s) \cdot H_{D1}(s) \cdot H_F(s) \left( \frac{\text{volt}}{\text{volt}} \right)$$

$$H_A(s) = \begin{bmatrix} -31.83s \\ 1.0 + 4.886s + 0.17s^2 \end{bmatrix}$$

$$6) \quad H_E(s) = \frac{1.0}{1.0 + 0.9460s + 0.2918s^2}$$

$$c) \quad H_D(s) = \frac{1.0}{1.0 + 0.6926s + 0.2308s^2}$$

$$4) \quad H_{D1}(s) = \frac{1.0}{1.0 + 0.28388s + 0.2398s^2}$$

$$e) \quad H_F(s) = \begin{bmatrix} -31.83s \\ 1.0 + 31.83s \end{bmatrix}$$

$$6) \quad H_F(s) = \frac{1.0}{1.0 + 0.1592s} + \frac{1.0}{1.0 + 1.892 \times 10^{-3}s}$$

$$g) \quad G_{LP} = 32.0$$

## APPENDIX C: PHASE AND GROUP DELAY WITH AFTAC FILTERS

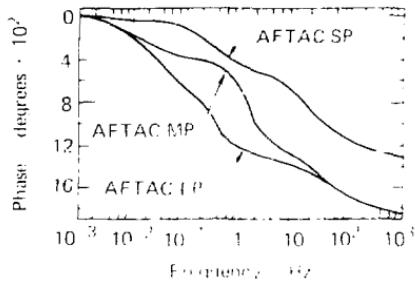


FIG. C1. Phase delay - KS-36000 with AFTAC filters.

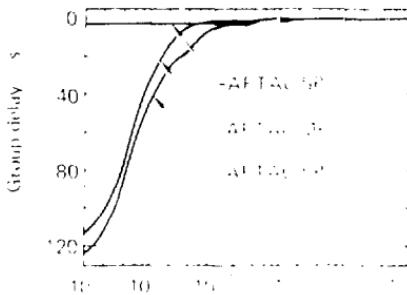


FIG. C2. Group delay - KS-36000 with AFTAC filters.

## APPENDIX D: EVENT AMPLITUDE SPECTRA

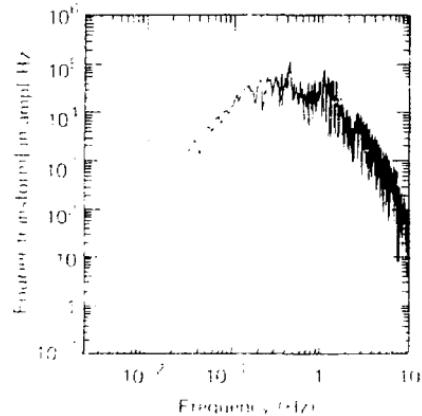


FIG. D1. Event (i): underground nuclear shot amplitude spectrum.

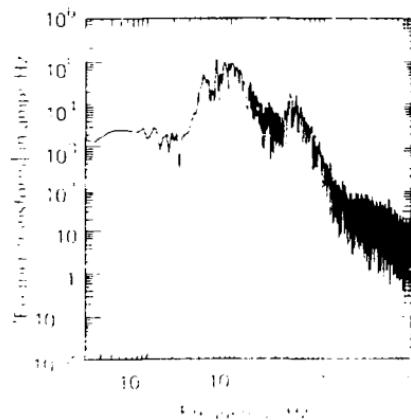


FIG. D2. Event in regional earthquake amplitude spectrum.

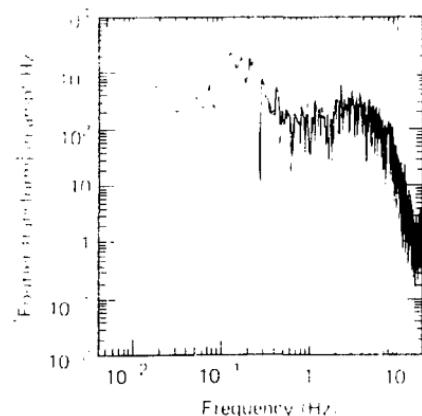


FIG. D3. Event (iii): local earthquake amplitude spectrum.

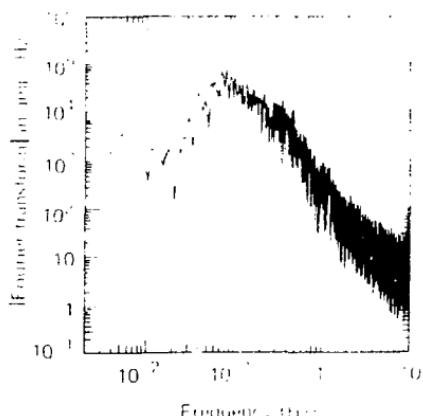


FIG. D4. Event (iv): large teleseism amplitude spectrum.