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Shaking-Table Tests of the NGC-23 Wideband Velocity Seismometer System

L. F. Brady

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Albuquerque, New Mexico 87115

ABSTRACT

This report contains a compilation of data obtained from tests of 18 seismometer/amplifier systems conducted on the shaking-table facility at the Teledyne Geotech Laboratory in Garland, Texas. Included are descriptions of the seismometer and amplifier and of the systems test procedures; the test results are also presented. The seismometer systems are part of the Sandia Seismic Network in Nevada, Utah, and California.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SHAKING-TABLE TESTS OF THE NGC-23 WIDEBAND VELOCITY SEISMOMETER SYSTEM

Introduction

Sandia Laboratories operates a network of six seismological stations in Nevada, Utah, and California (see SC-DR-71 0414, July 1971). In 1966-1967, the instrument complement at these stations was expanded to include a wideband (0.1 to 20 Hz) velocity gage, the National Geophysical Company, Model 23 (NGC-23), system. Table I shows the seismometer systems by station locations and component. The manufacturer provided such specifications as seismometer signal coil resistance (R_c), the damping resistance required (R_d), the seismometer undamped natural frequency (F_n), and the signal coil generator constant (G). R_c, R_d, and F_n could be checked in the field rather easily. The generator constant (G) could not be checked in the field but was assumed equal to the manufacturer's specification.

TABLE I

Seismometer Systems

Seismometer Ser. No.	L-12 Ampl. Ser. No.	Component Assignment	Station Name	Geographic Location	
				Lat.	Long.
325	12	V	Tonopah	38° 04' 30"	117° 13' 21"
331	11	R*	Tonopah	38° 04' 30"	117° 13' 21"
330	18	T**	Tonopah	38° 04' 30"	117° 13' 21"
324	2	V	Leeds	37° 14' 35"	113° 22' 36"
336	3	R	Leeds	37° 14' 35"	113° 22' 36"
337	4	T	Leeds	37° 14' 35"	113° 22' 36"
329	10	V	Battle Mtn	40° 25' 53"	117° 13' 18"
338	6	R	Battle Mtn	40° 25' 53"	117° 13' 18"
335	5	T	Battle Mtn	40° 25' 53"	117° 13' 18"
327	13	V	Darwin	36° 16' 37"	117° 35' 37"
341	14	R	Darwin	36° 16' 37"	117° 35' 37"
332	8	T	Darwin	36° 16' 37"	117° 35' 37"
326	16	V	Nelson	35° 42' 44"	114° 50' 36"
334	7	R	Nelson	35° 42' 44"	114° 50' 36"
340	19	T	Nelson	35° 42' 44"	114° 50' 36"
328	9	V	Ely	39° 07' 54"	114° 53' 32"
339	15	R	Ely	39° 07' 54"	114° 53' 32"
333	17	T	Ely	39° 07' 54"	114° 53' 32"

---

*R = radial to NTS

**T = tangential (normal to NTS radial)

Tests of 18 seismometer/amplifier systems were performed during the summer of 1972 through the spring of 1973 on the shake-tables at the Teledyne Geotech Laboratory in Garland, Texas, to establish realistic system parameters, specifically for the generator constant (G) and the relative system sensitivity through the specified bandpass. Teledyne-Goetech had assumed responsibility for the NGC-23 system for the National Geophysical Company as the result of a merger. This report describes the NGC-23 system and the shaking-table test procedures and presents the results of those tests.

NGC-23 Seismometer System

The complete NGC-23 wideband velocity seismometer system consists of an NGC-23 seismometer (Figure 1) and an L-12A amplifier (Figure 2). The overall system specifications are as follows:

Peak particle velcocities	2×10^{2} cm/sec (max) 9×10^{-5}cm/sec (min)
Signal-to-noise ratio at minimum	
Particle velocity	4:1 (min)
Frequency range	0. 1 to 20 Hz (3-db points) (18-db/octave rolloff, both sides)
Calibration	Seismometer deflected by precisely known current, then switched to amplifier. Amplifier output pulse is monitored.
Calibration time	Seismometer deflection, 30 sec Calibration pulse, 30 sec

NGC-23 Seismometer

The NGC-73 seismometer specifications are as follows:

Weight	36 lbs (max)
Case length	9 inches (max)
Case diameter	8 inches (max)
Coil alignment	Visual sighting of coil to center
Natural frequency (F_n)	1. 25±0. 05 Hz
Coil resistance (R_c)	700 ohms (nominal)

Figure 1. NGC-23 Seismometer

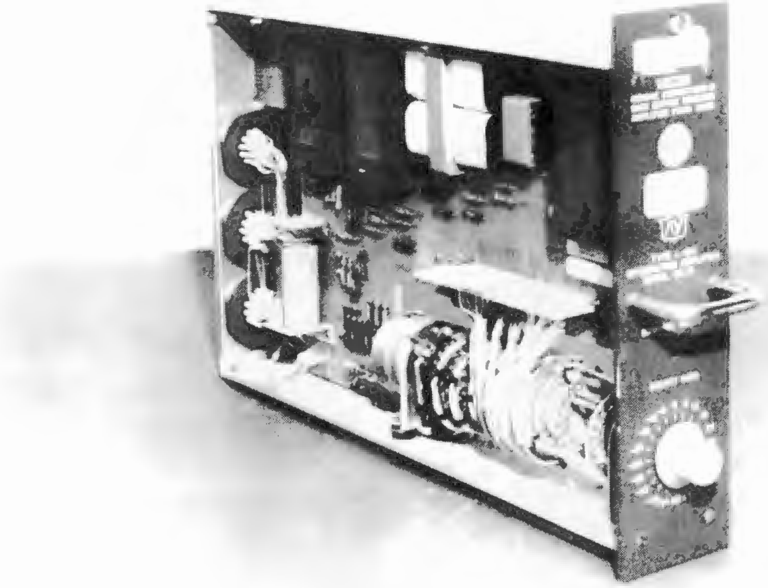


Figure 2. L-12A Amplifier

Generator Constant (G)	425 volts/meter/sec (min)
Linearity of G over full coil travel	±4%
Linearity of F_n over full coil travel	±4% (±0.05 Hz)
Peak-to-peak mass Displacement	3/8 inch (min)

L-12A Amplifier

The L-12A amplifier (Figure 2) is an all-solid-state amplifier with an integrating-type response that results in gain being a function of frequency. The amplifier has the following specifications:

Supply voltage	±10V to ±18V (±15V nominal)
Power required	2 watts peak
Amplifier gain	The maximum gain is such that the system sensitivity is 60 db above the seismometer generator constant within the system frequency range.
Attenuator	Approximately 114 db in 2:1 steps (6.02 db) from -54 to 60 db
Accuracy of gain settings	±5%
Output levels	4 levels separated by 4:1 (12.04 db)
Output impedence	Outputs 1 and 3 less than 0.1 ohm Outputs 2 and 4 - 750 ohms
Output levels	Outputs 1 and 3 saturate at ±10V Outputs 2 and 4 saturate at ±2.5V
Output noise	High-level channel (output 1) with maximum gain: 200 mv peak to peak
Thermal drift of output	1 mv/°C (max)

Calibration	Seismometer current network incorporated into amplifier chassis along with a relay to switch amplifier to calibrate mode.

System Check Capability

The L-12A seismic amplifier contains an integral relay for calibration purposes. Activation of the relay disconnects the seismometer from the amplifier and connects it to a network which deflects the coil with a precisely known current. Deactivating the relay reconnects the deflected seismometer to the amplifier. The resulting amplifier output transient may be used as a calibration method. The transient is a pulse with a single overshoot (see Figure 3). A wafer on the gain control switch automatically selects the proper deflection current so that a pulse peak voltage value greater than 1 volt from Output 1 is produced. The other outputs will have the same transient attenuated 4:1 from each other as noted previously. The deflection currents used for each gain setting are tabulated in Table II. The same calibration current is used for gain settings below -30 db because the seismometer output is not sufficient to maintain calibration pulse level. Higher deflection currents will cause the seismic mass to hit the stops.

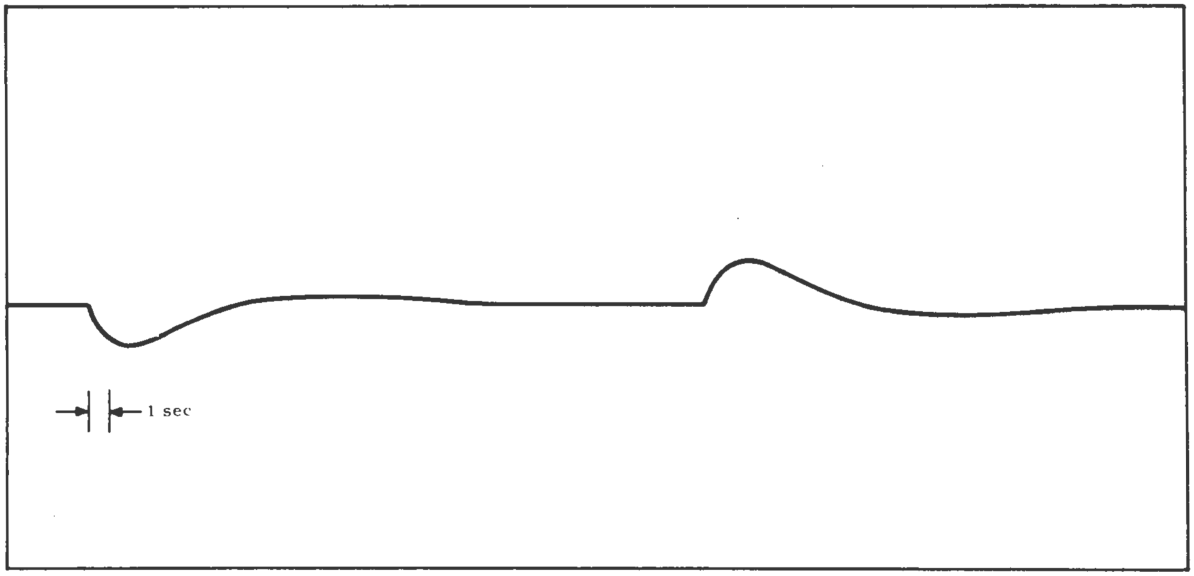


Figure 3. Transient Pulse

TABLE II

Deflection Currents

Amplifier Gain (db)	Deflection Current (μa)
60	0.002182
54	0.004364
48	0.008728
42	0.01746
36	0.03491
30	0.06982
24	0.1396
18	0.2793
12	0.5586
6	1.117
0	2.234
-6	4.469
-12	8.938
-18	17.88
-24	35.75
-30	71.50
-36	71.50
-42	71.50
-48	71.50
-54	71.50

NOTE: Because of the highly damped mode of seismometer operation and the integrating nature of the L-12A amplifier, no direct correlation between the amplitude of the calibration pulse and the earth motion measured can be obtained on the same gain setting. Once the system is set up, however, the height of the calibration pulse may be used to test for a change in any of the system parameters.

Test Procedures

The shaking-table tests were performed primarily to redetermine (1) the seismometer generator constant (G) and (2) the relative response characteristics of the seismometer/amplifier system (the seismometers and amplifiers are used as matched sets in the seismic network). The seismometers and amplifiers were removed from the seismic stations as complete sets (three seismometers with three amplifiers) and shipped via air express to the Teledyne Geotech Laboratory. Prior to removal from the seismic station and again upon receipt by Teledyne Geotech, the parameters mentioned in the introduction were checked to correlate measurement methods between Sandia and Teledyne Geotech and also to check for shipping damage. Some damage was found during the checking at Teledyne Geotech. These instances are mentioned in the following section.

Seismometer Mechanical Inspection

Upon receipt by Teledyne Geotech, the seismometers, amplifiers, and test panels (housing for three amplifiers) were inspected externally for signs of damage incurred during shipping. The seismometers were then further inspected in the Teledyne Geotech "clean room" facility by removing the external case, checking for damage to the signal coil suspension system (delta rods, see Figure 4), and removing any foreign particles, particularly in the air gap between the signal coil and magnet assembly. Table III lists by seismometer serial number the results of the mechanical inspection, cleaning, repairs, and reassembly.

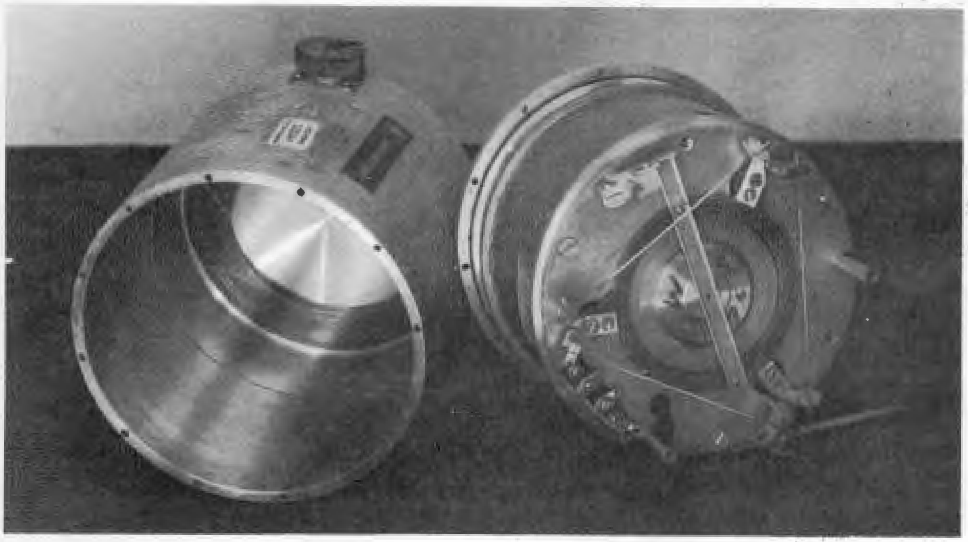


Figure 4. NGC-23 Horizontal Seismometer

TABLE III

Free Period with Mass Centered

Seismometer Serial No.	As Received (Hz)	After Disassembly and Cleaning (Hz)	Comments
325	1.26	1.26	
331	1.30	1.28	Bent delta rod
330	1.27	1.25	
327	1.27	1.27	
341	1.27	1.26	
332	1.25	1.25	
328	1.30	1.29	
339	1.24	1.24	
333	1.26	1.26	
326	1.24	1.24	Broken ground wire
334	1.25	1.25	
340	1.21	1.23	
324		1.22	
336		1.26	
337		1.27	
329		1.26	Replaced delta rods*
335	1.27	1.25	
338	1.15	1.27	Installed stiffer delta rods

---

*This instrument was not operative when received by Teledyne Geotech and, in their opinion had been dropped in transit. A shorted capacitor (C-2) in amplifier Serial No. 15 and an erratic op-amp in Serial No. 17 were also corrected during the preliminary inspection checks.

Shake-Table Calibration

The primary instrumentation for calibrating the shake table is an interferometer consisting of two optical flats and a helium monochromatic light source. The principle of operation is shown in Figure 5. When the optical flats are viewed from above, a series of light and dark lines can be seen. The dark bands are caused by the light rays reflected from the lower prism interfering with the rays transmitted through the upper prism. The distance between the lower and upper optical flat at each dark band is an integral number of half wavelengths of the light used. As the table moves, the lifting pointer will increase or decrease the angle between the flats and will cause the fringes to move. The shake-table displacement can be measured at low frequencies by counting the number of fringes that pass the tip of the lifting point and by multiplying this number by the half wavelength of the light used. The results of this method of calibrating the shake-table monitors can be directly compared with the National Bureau of Standards reference if the wavelength of the light source is known.

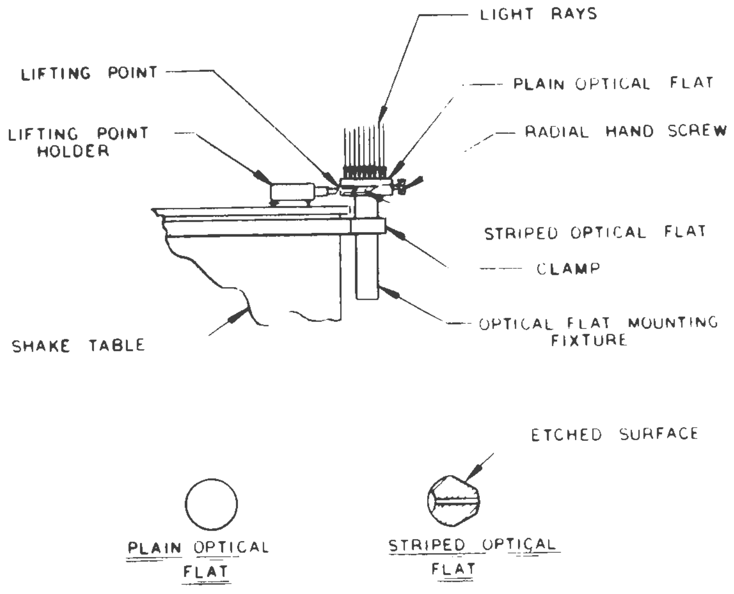


Figure 5. Vertical Table Calibration Via Interferometer

A DoAll Model 2M helium light source with a half wavelength of 11.6×10^{-6} inch (0.294×10^{-6} M) is used in calibrating the shake table. Because of the seismic noise, it is usually difficult to measure the displacement closer than about 0.5 micron with the interferometer.

A Wayne Kerr electronic micrometer is used in conjunction with the interferometer method to increase the calibration resolution by a factor of 10. This instrument filters most of the high-frequency seismic noise. The calibration of the electronic micrometer is checked by comparing its measurements with those made with the interferometer.

The vertical table is first calibrated with both devices. Then the Wayne Kerr electronic micrometer is transferred to the horizontal table to calibrate that system.

The shake-table system was calibrated as described in the previous paragraph on October 23, 1972. The results are given in Table IV.

TABLE IV

Calibration Results

Wyane Kerr Micrometer Readout (inch)	Horizontal Shake Table Readout (inch)	Vertical Shake Table Readout (inch)	Interferometer Readout (bands)	Interferometer Readout (inch)
0.000197		0.0002	17	0.0001972
0.000990	0.000985			

System Parameter Determination

The open-circuit generator constant (G) and the damping factor (λ) at the specified external damping resistance (DRX) were determined for each seismometer. These results are listed in Table V. These measurements were made with the L-12A amplifier set to "0" db and its damping (input resistance) set to the value specified on the nameplate of the seismometer at which it terminates.

The open-circuit generator constant (G) and equivalent earth motion were calculated from the following formula:

$$G = \frac{E}{2\pi fd} ,$$

where:

E = volts out p-p open circuit

f = frequency in Hz

d = displacement in meters

G = volts/meter/second

The damping factor was found by comparing the open circuit and damped sensitivities* of the seismometer with the following formula:

TABLE V

Test Results

Seismometer Type	Serial No.	Manufacturer's Spec F_n (Hz)	R_c (ohms)	R_d (ohms)	G (v/m/sec)	Ampl Gain at 0 db	Test Data F_n	G* (v/m/sec)	λ* (ratio: 1)	Ampl Gain at 0 db (db)	Comments
NGC-23V	325	1.27	699	3468	473	-0.20	1.27	516	10.2	-0.39	
NGC-23H	331	1.28	704	3709	487	-0.20	1.26	531	10.8	-0.49	
NGC-23H	330	1.22	694	3680	463	-0.20	1.22	522	10.4	-0.28	
NGC-23V	324	1.22	699	3495	475	-0.20	1.22	494	10.0	-0.36	
NGC-23H	336	1.25	707	3471	479	-0.20	1.26	518	11.5	-0.79	
NGC-23H	337	1.26	704	3468	469	-0.20	1.26	505	10.6	-0.58	
NGC-23V	329	1.23	687	3279	451	-0.20	1.23	465	11.5	-0.79	
NGC-23H	338	1.23	707	3743	486	-0.20	1.23	465	11.8	-0.76	
NGC-23H	335	1.27	700	3010	450	-0.20	1.27	439	11.4	-1.05	
NGC-23V	327	1.27	713	2943	463	-0.20	1.27	489	9.8	-0.99	
NGC-23H	341	1.26	707	3427	468	-0.20	1.26	505	10.3	-0.28	
NGC-23H	332	1.25	700	3353	483	-0.20	1.25	509	10.8	-0.58	
NGC-23V	326	1.26	708	2986	459	-0.20	1.24	494	11.5	-0.74	
NGC-23H	334	1.27	696	3418	484	-0.20	1.25	522	10.6	-0.63	
NGC-23H	340	1.23	703	3171	463	-0.20	1.23	518	10.7	-0.77	
NGC-23V	328	1.23	713	2894	456	-0.20	1.29	506	10.6	-0.94	
NGC-23H	339	1.24	712	3424	478	-0.20	1.24	527	10.4	-0.56	
NGC-23H	333	1.26	698	3013	456	-0.20	1.26	506	11.0	-0.97	

---

*At specified R_d

$$F = \frac{f}{f_n}\left\{\frac{1}{\sqrt{\left[1-\left(\frac{f_n}{f}\right)^2\right]^2 + 2\lambda\left(\frac{f_n}{f}\right)^2\Big]^2}}\right\}$$

where

F = normalized transfer factor

f_n = natural frequency in Hz

f = frequency where measurements were taken in Hz

λ = damping factor

*Damped sensitivity is calculated as follows:

$$\left(\frac{\text{DRX + coil res}}{\text{DRX}}\right) \times \left(\begin{matrix}\text{Measured volts out p-p}\\ \text{across DRX}\end{matrix}\right) = \text{damped output}$$

The curve shown in Figure 6, which was plotted for F versus λ at $f/f_n = 10$ for convenience, was used in the actual determination of damping factor.

The relation below was used for determining λ from the curve:

$$\frac{\text{Volts out p-p open ckt}}{10} = \frac{\text{damped output}}{F}$$

or

$$F = \frac{\text{10X damped output}}{\text{Volts out p-p open ckt}}$$

The relative output of the seismometer plus amplifier system was plotted versus driving frequency. These checks were made in the frequency spectrum of 0.1 to 40 Hz. Plots of the results for the 18 systems are given in the appendix.

Figures 7, 8, and 9 are schematic representations of the various equipment setups used in checking parameters.

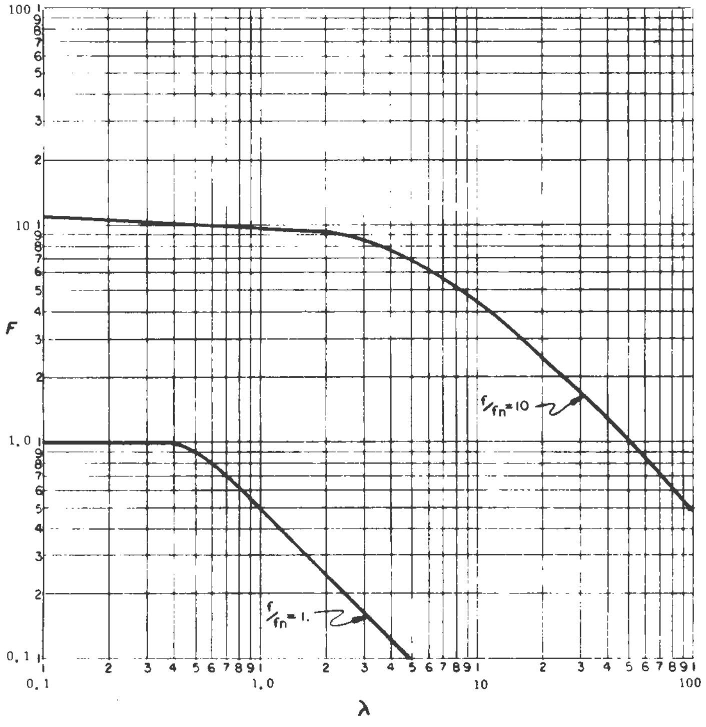


Figure 6. Graph of Normalized Transfer Factor vs. Damping Ratio

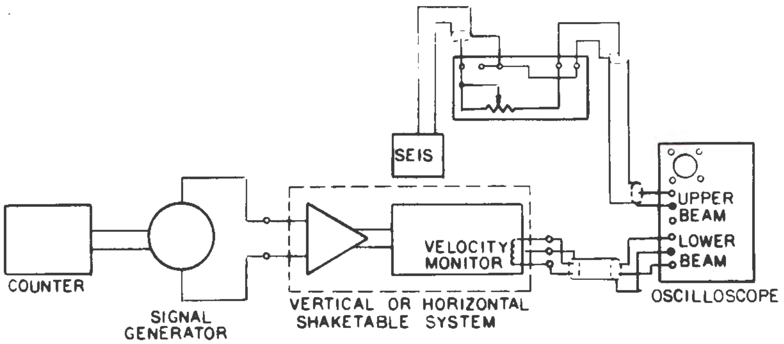


Figure 7. Schematic: Test Array to Determine "G"

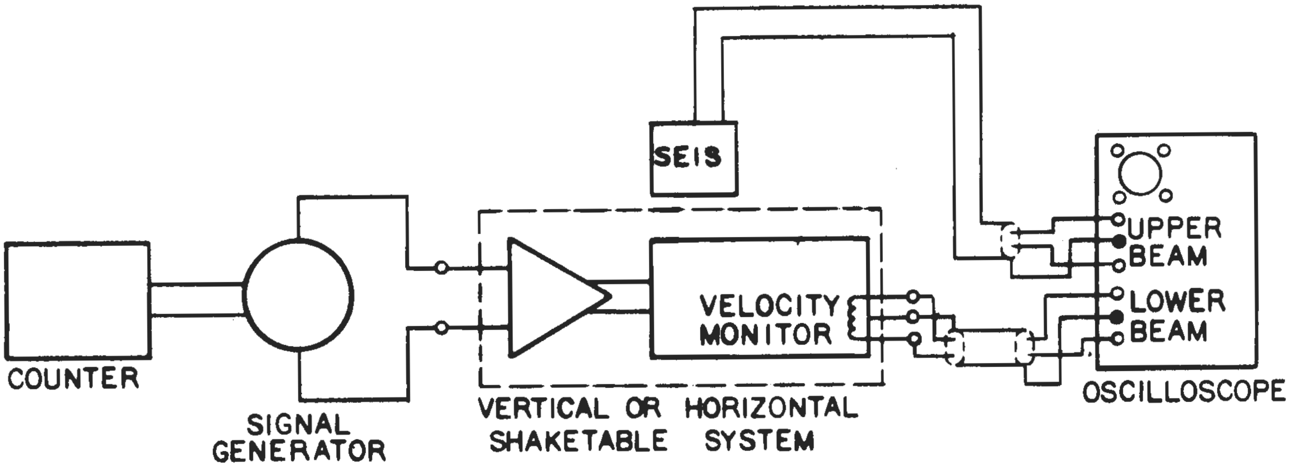


Figure 8. Schematic: Test Array to Measure Damping

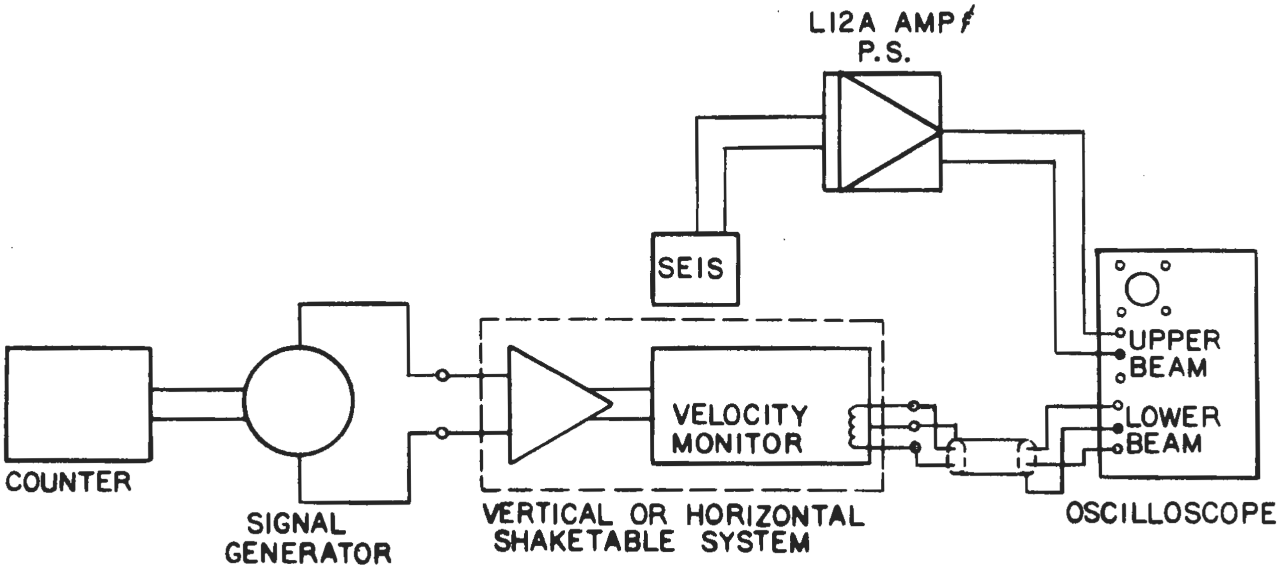


Figure 9. Schematic: Test Array to Measure System Response

L-12A Amplifier Gain

A check on the L-12A amplifier gain was not a requirement placed on Teledyne Geotech. However, certain measurements made in the process of determining other parameters made it possible to calculate the gain at least at the 0-db setting. The amplifier gain is defined as the system sensitivity above the seismometer generator constant within the system frequency range. The seismometer output (open-circuit p-p) was measured in the process of calculating G. The seismometer was then connected to the L-12A amplifier (the amplifier input resistance was set to the correct seismometer external damping resistance value) and the system output measured at the L-12A output terminals. The gain can be determined as follows:

$$\text{Amplifier gain}_{\text{db}} = \log_{10}\left(\frac{E_{\text{out p-p L-12A ampl}}}{E_{\text{out seismometer p-p open ckt}}}\right) .$$

The specified gain of the L-12A amplifier at 0 db is -0.20 db. The gains calculated based on test measurements were generally less than -0.28 db. The results are listed in Table V.

Results

The test results and comparative parameters are listed by seismometer serial number in Table V. The measurements and calculations show that (1) the seismometer damping factors ranged from 9.8:1 to 11.8:1 with the specified external damping resistor; (2) with two exceptions the seismometer generator constant (G) was higher than specified on the instrument nameplate by as much as 12.7 percent, and the mean was +8.5 percent; and (3) the L-12A amplifier gain at 0 db was less in every case than the -0.2 db specified, varying from -0.28 to -1.05 db.

Conclusions

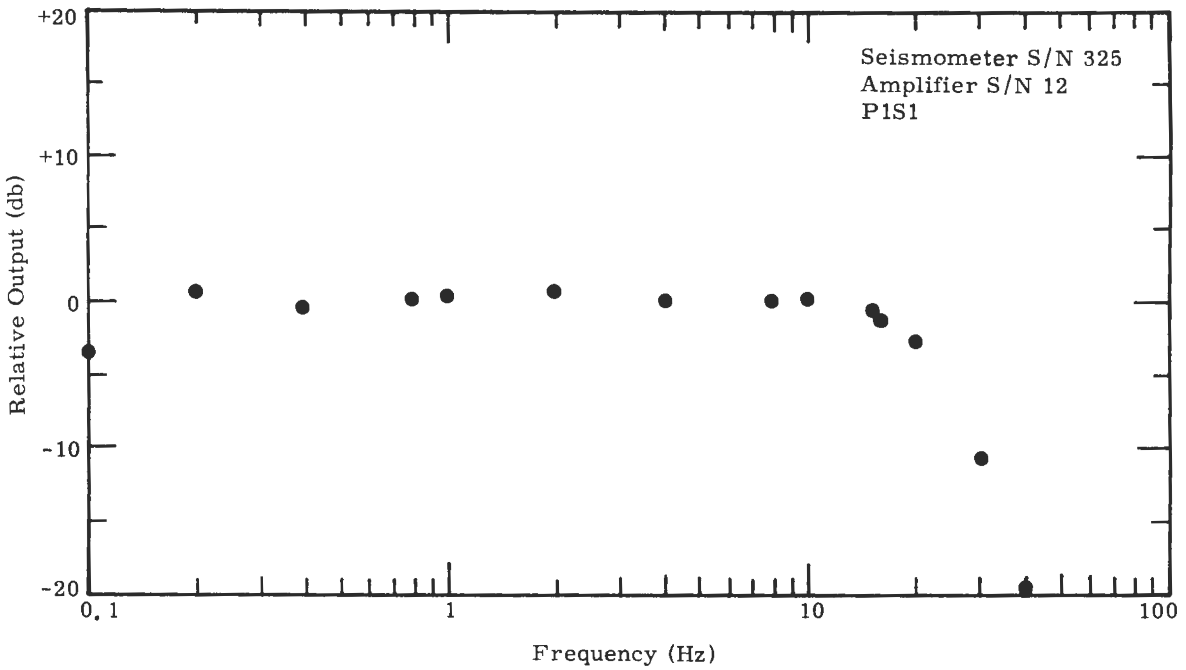
Understanding and confidence in the data from a seismic network stems from a large data base collected over a long period of time (years). Conversely, confidence in transducer and signal conditioning system parameters which cannot be readily checked in the field diminishes with time. Therefore, where it is feasible to do so, it can be very valuable to redetermine seismic system characteristics by removing transducers (or whole systems as the case may be) to a facility such as the laboratory of Teledyne Geotech for testing under controlled conditions. In the instance described in this report, the tests were particularly timely and valuable because the original equipment manufacturer was no longer available and because the tests enabled the new "supplier" to use this period to familiarize themselves with the system and to supply Sandia with current data on the system parameters. The data obtained should be useful when future repairs or testing are required. No decision has been made at this time to use the changes in system parameters to actually modify previously recorded data.

Acknowledgements

The assistance and cooperation of two persons contributed greatly to the satisfactory completion of this project: Mr. A. Brandon McNeill, who acted as project engineer for Teledyne Geotech and contributed greatly to the substance of this report, and "Doc" Hall, Marketing, Teledyne Geotech, who coordinated the shipping and testing in such a manner as to enable the minimum "down" time for the Sandia Seismic Network.

APPENDIX

DATA OBTAINED FROM TESTS OF EIGHTEEN SEISMOMETER/AMPLIFIER SYSTEMS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Amplifier S/N 12
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+20
+10
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-10
-20
Relative Output (db)
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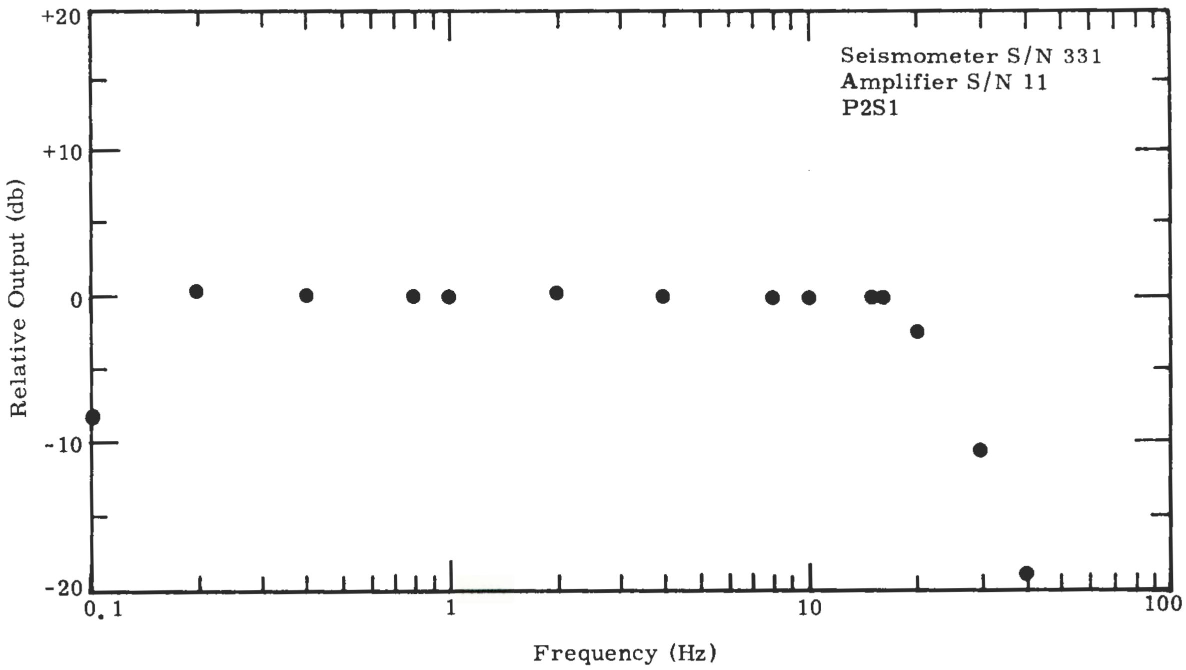
1
10
100
Frequency (Hz)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Amplifier S/N 11
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+10
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-10
-20
Relative Output (db)
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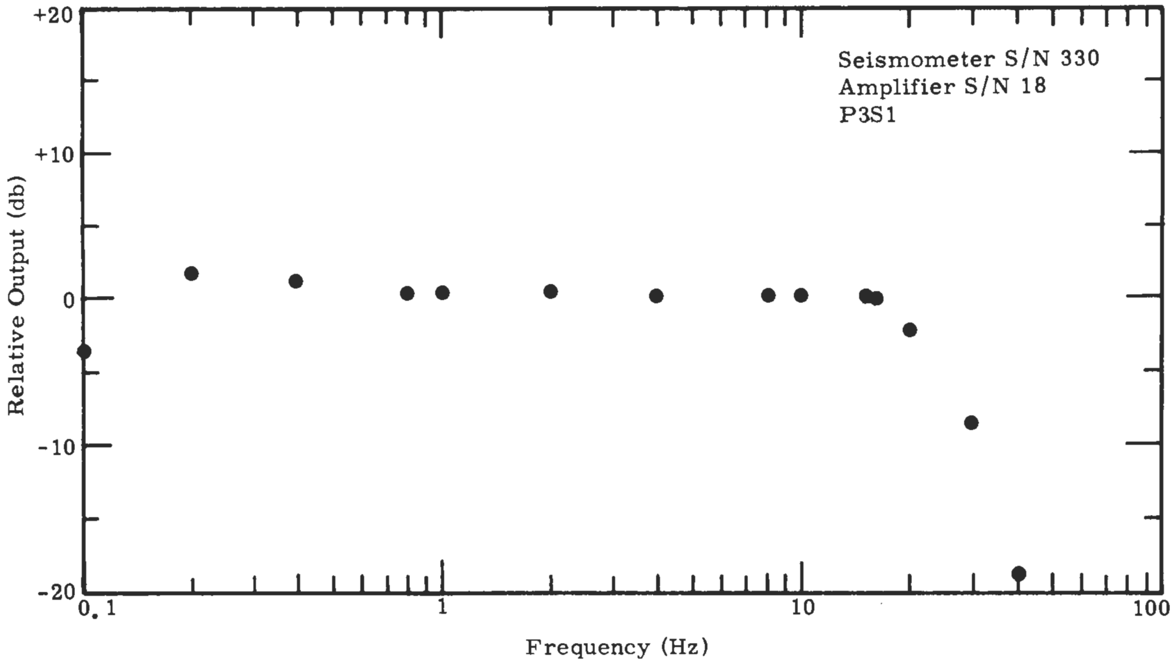
1
10
100
Frequency (Hz)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Amplifier S/N 18
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-10
-20
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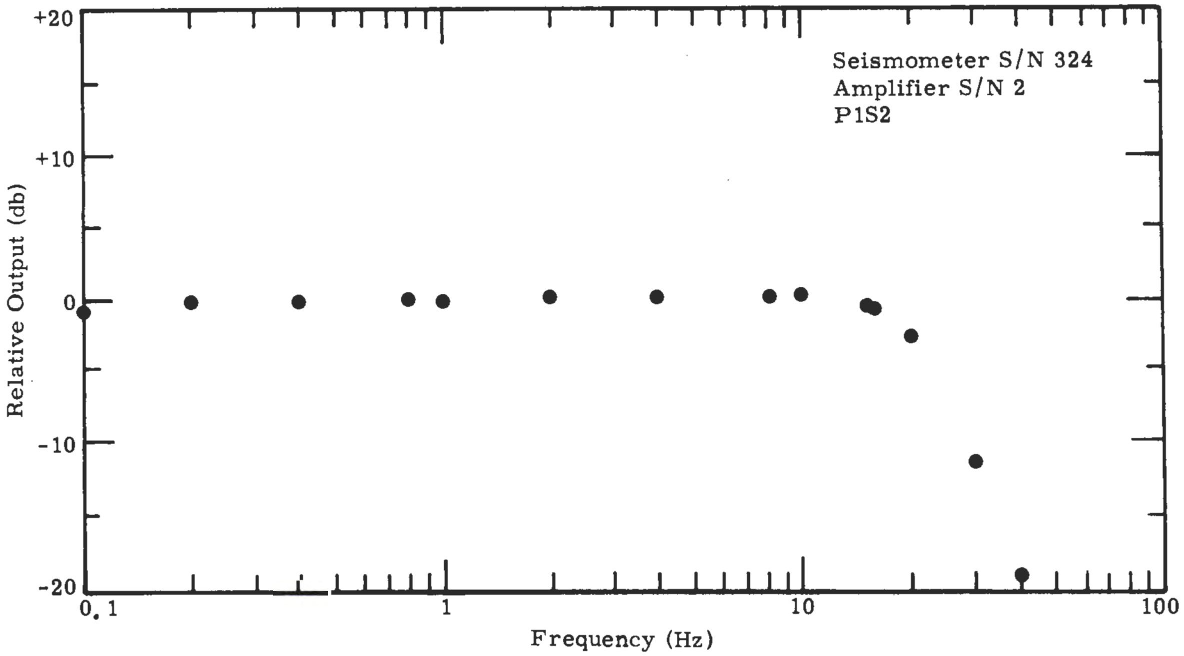
10
100
Frequency (Hz)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+10
0
-10
-20
Relative Output (db)
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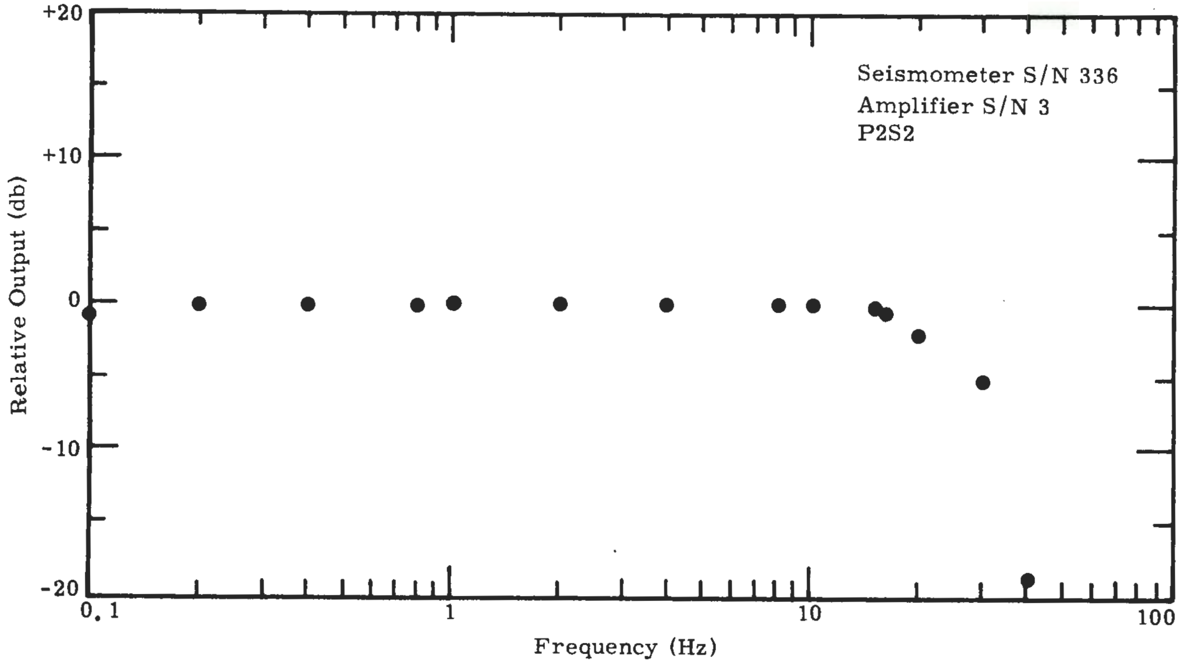
1
10
100
Frequency (Hz)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Relative Output (db)
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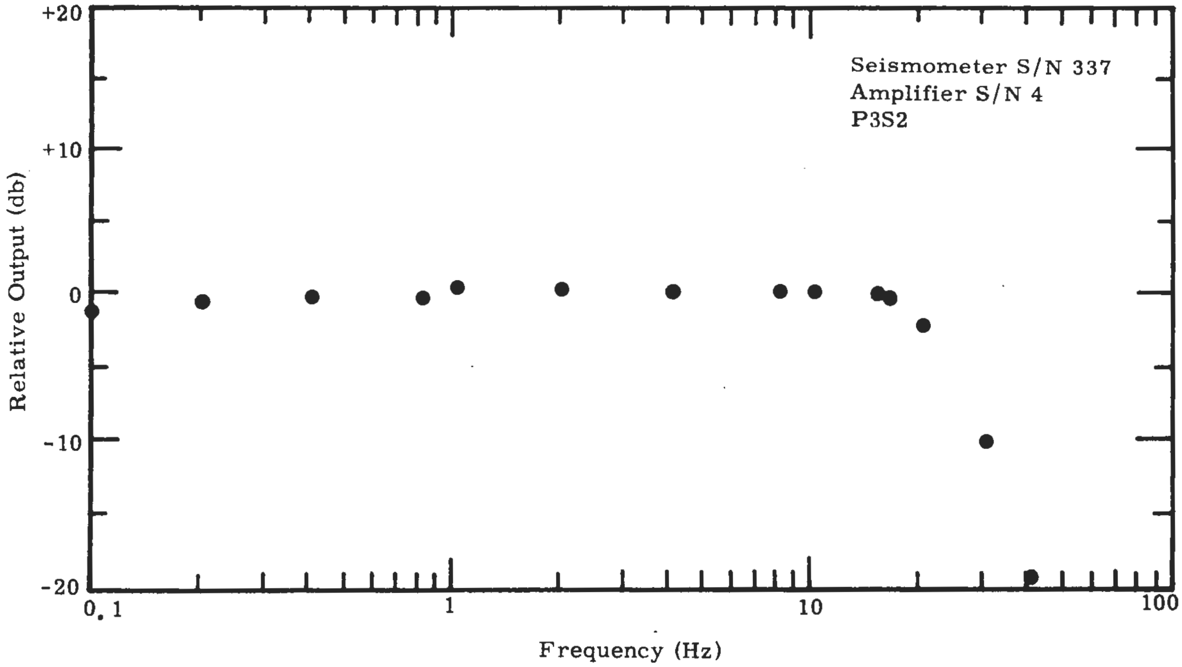
10
100
Frequency (Hz)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-10
-20
Relative Output (db)
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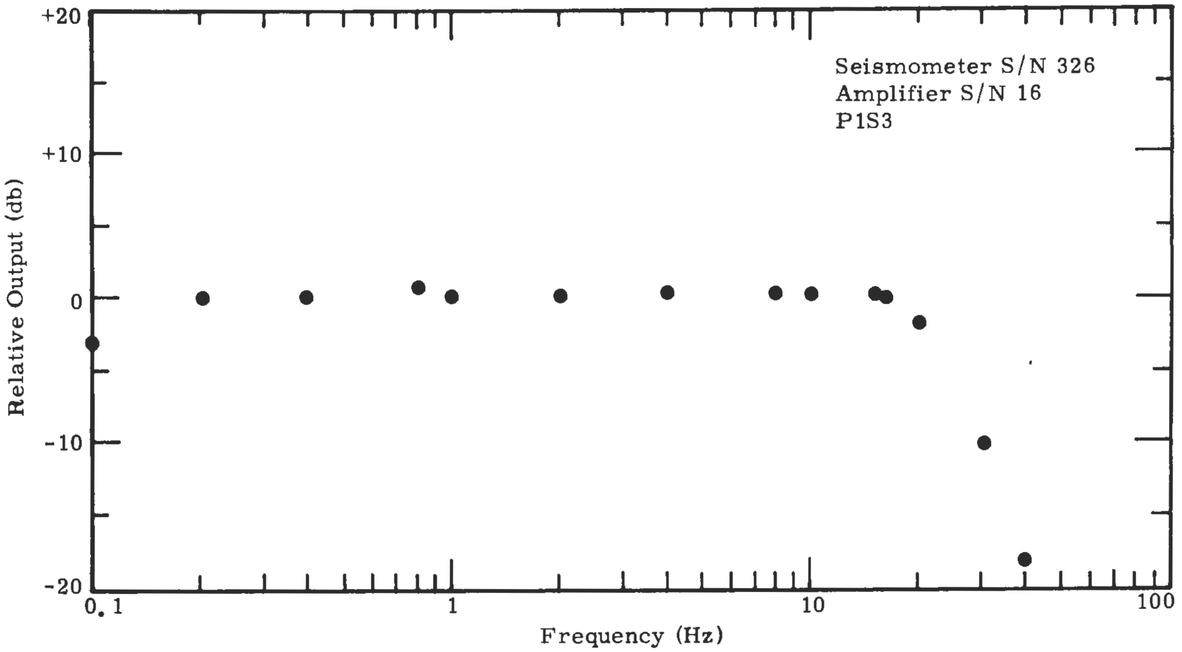
10
100
Frequency (Hz)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10
100
Frequency (Hz)
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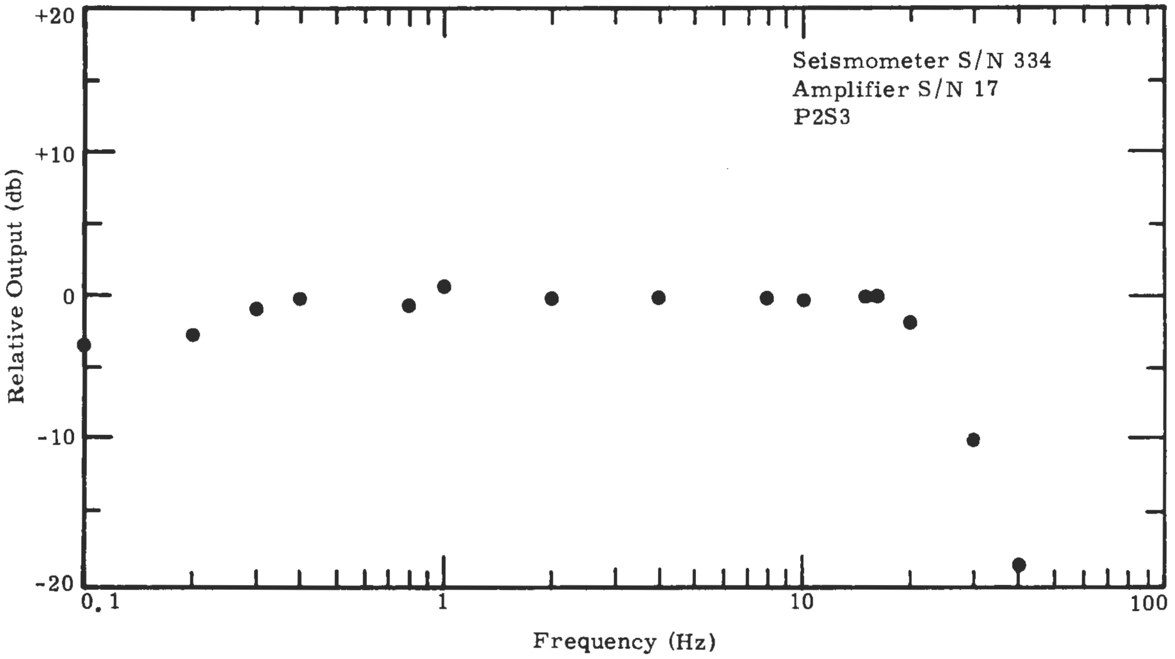
Amplifier S/N 16
P1S3


+20
+10
0
-10
-20
Relative Output (db)
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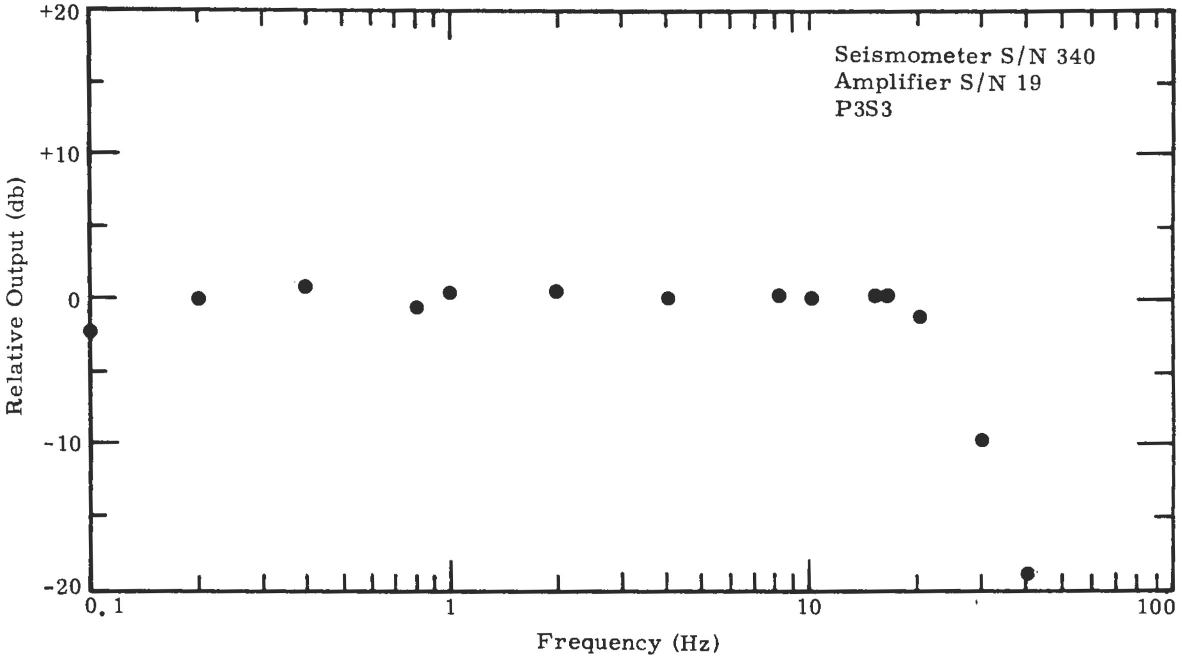
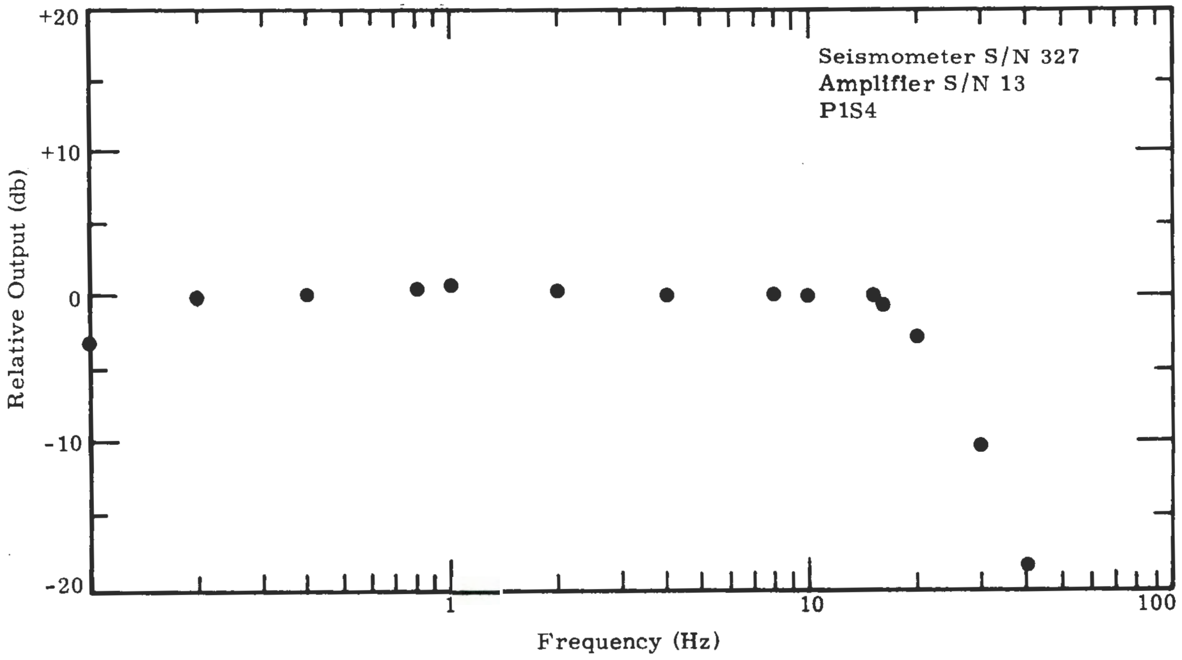
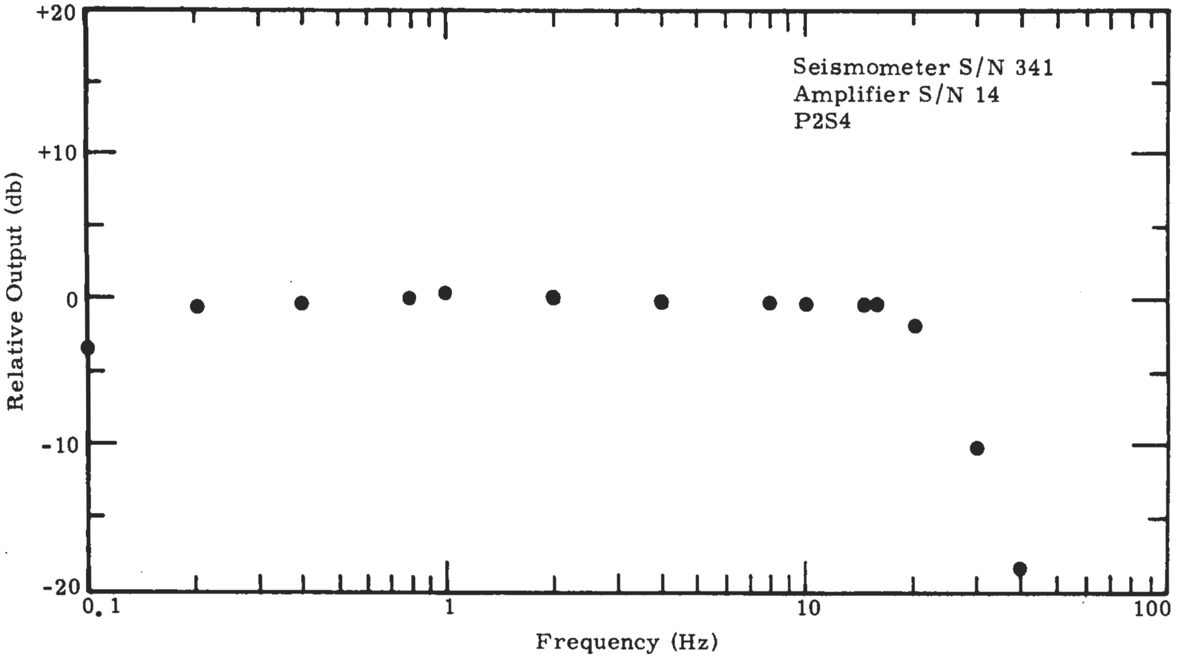
1
10
100
Frequency (Hz)
Seismometer S/N 334
Amplifier S/N 17
P2S3

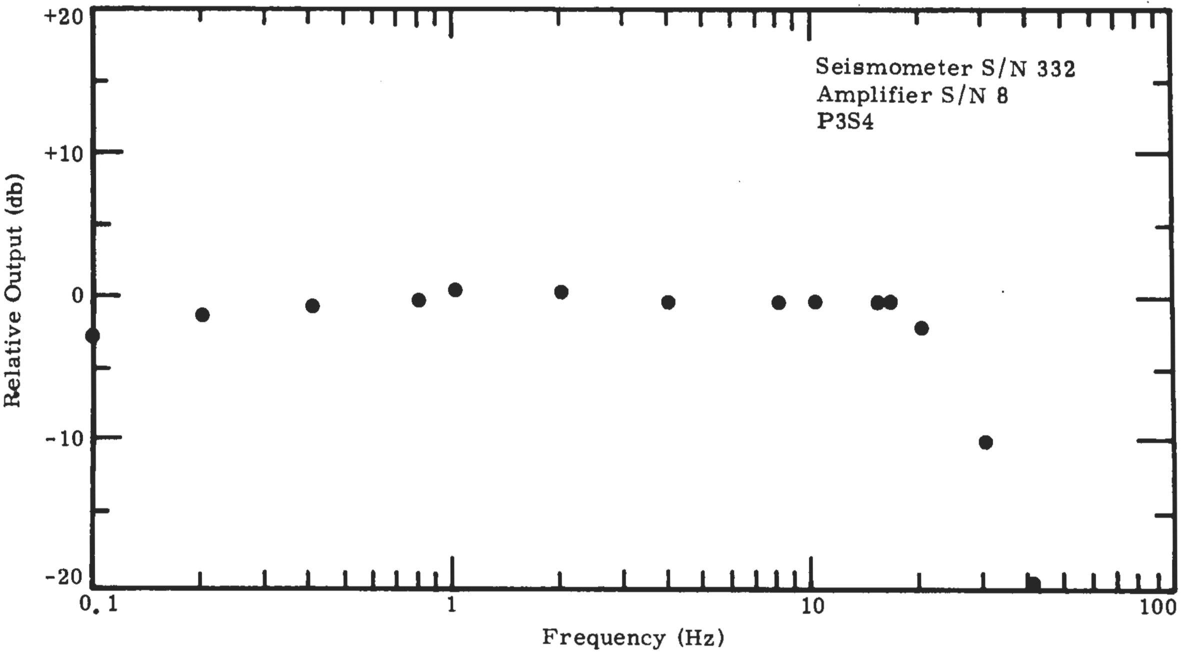


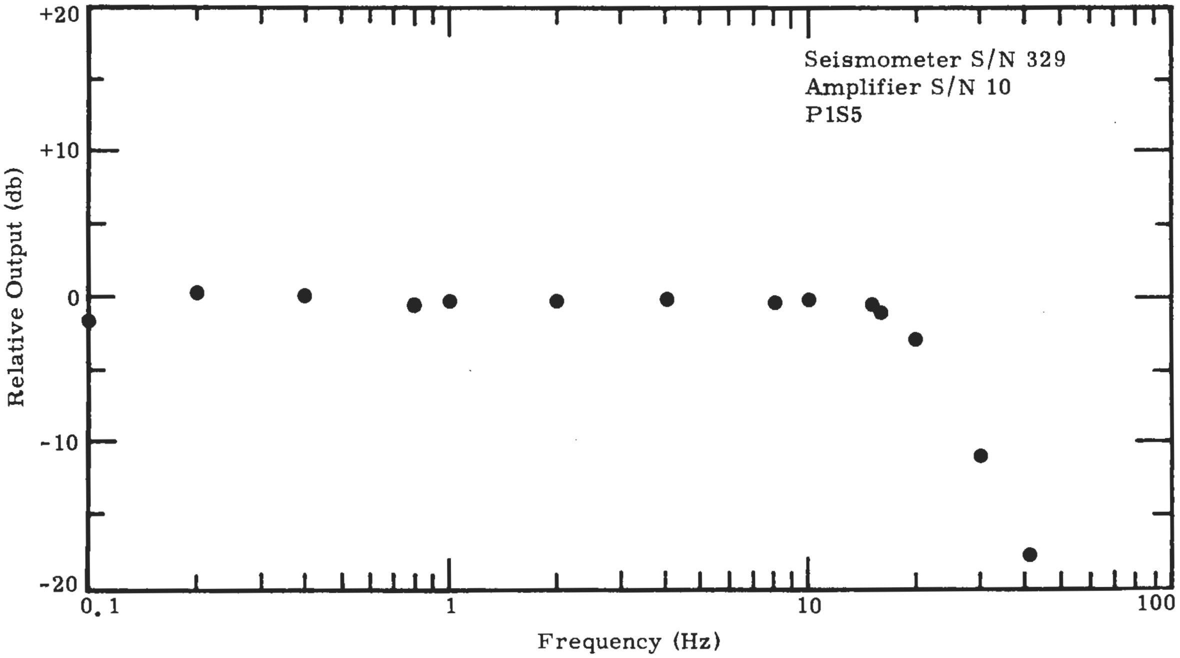
Seismometer S/N 340
Amplifier S/N 19
P3S3
+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)



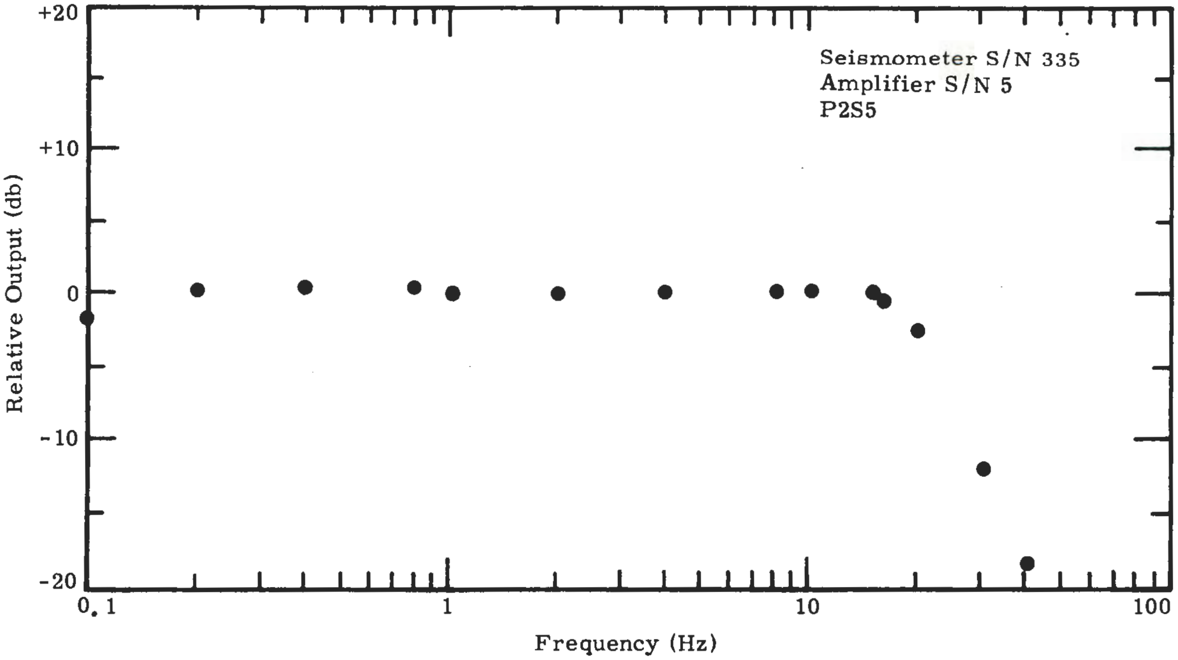
Seismometer S/N 327
Amplifier S/N 13
P1S4
+20
+10
0
-10
-20
Relative Output (db)
1
10
100
Frequency (Hz)


+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)
Seismometer S/N 341
Amplifier S/N 14
P2S4

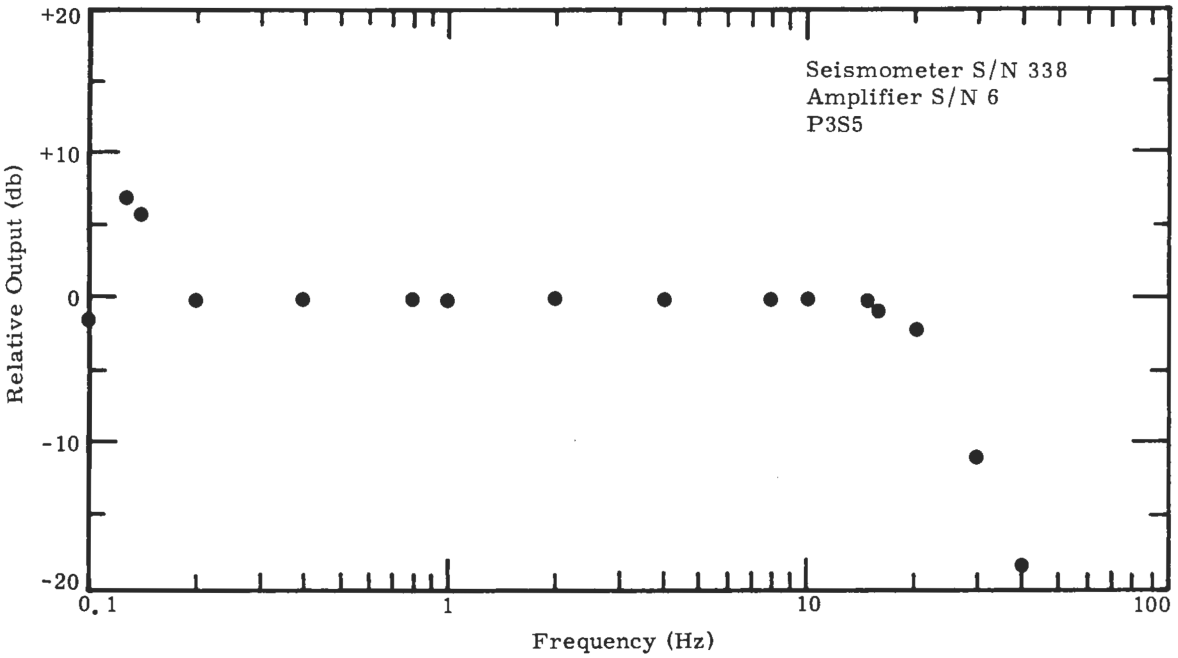

+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)
Seismometer S/N 332
Amplifier S/N 8
P3S4

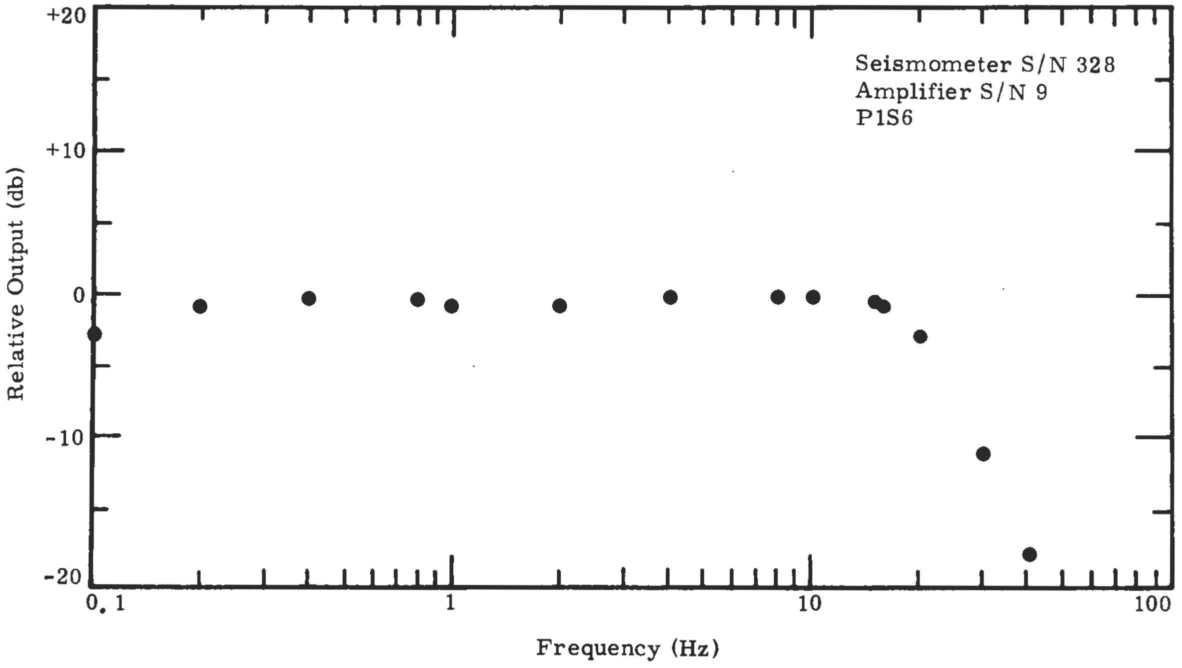


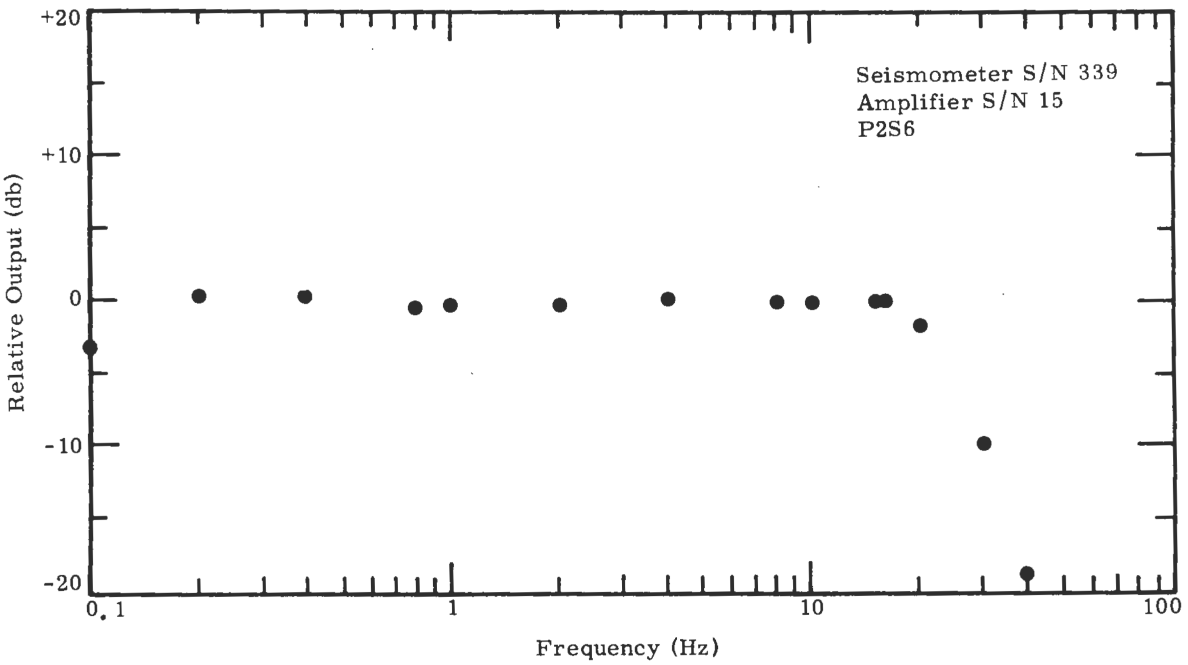
+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)
Seismometer S/N 329
Amplifier S/N 10
P1S5

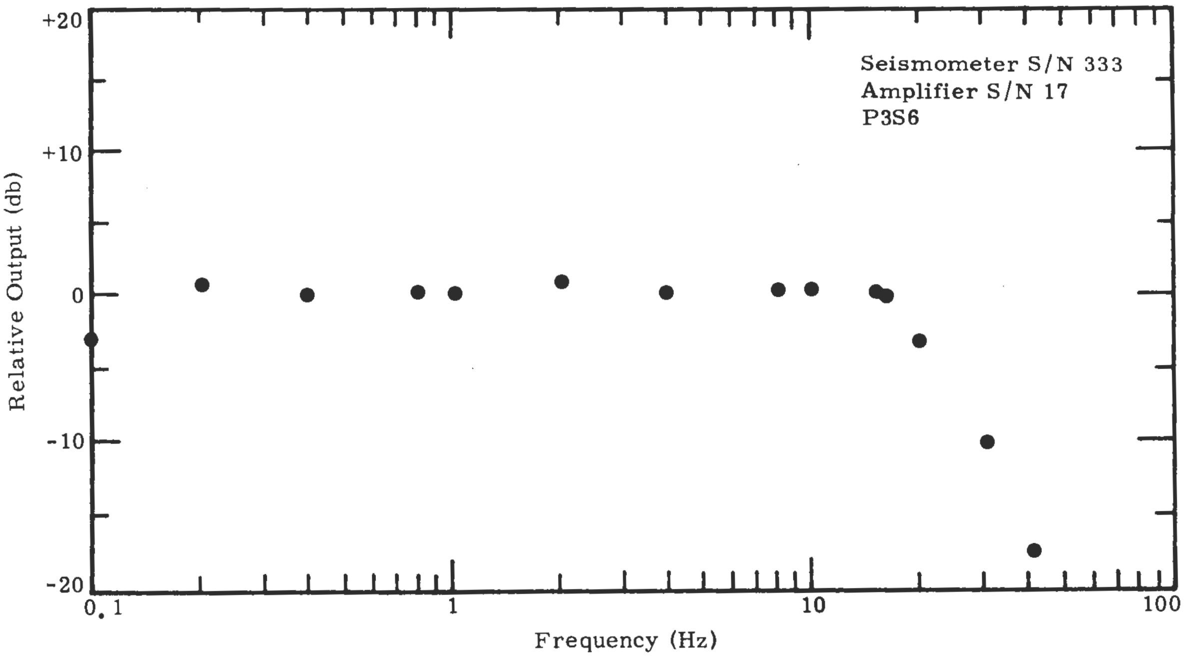


+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)
Seismometer S/N 335
Amplifier S/N 5
P2S5


Seismometer S/N 338
Amplifier S/N 6
P3S5
+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)


Seismometer S/N 328
Amplifier S/N 9
P1S6
+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)


+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)
Seismometer S/N 339
Amplifier S/N 15
P2S6


+20
+10
0
-10
-20
Relative Output (db)
0.1
1
10
100
Frequency (Hz)
Seismometer S/N 333
Amplifier S/N 17
P3S6

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