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HEMP SIMULATION TESTS [redacted]

FINAL TEST REPORT, Sanitized Version

W. A. Bereuter
S. M. Dunivin

Revised 10 September 1992

Prepared for: Director
Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22310-3398
Contract No. DNA001-91-C-0093
CDRL Item No. 16

Prepared by: MISSION RESEARCH CORPORATION
4935 North 30th Street
Colorado Springs, CO 80919

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RDT&E RMSS CODE: B 4662 D RV RD 00128 3400 A AF

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13. ABSTRACT (Maximum 200 words)

This report documents the results of the HEMP simulation tests conducted at the [redacted] during May and June 1992. The following tests were performed: [redacted] communications antennas were illuminated with CW fields and the field-to-antenna coupling transfer functions were measured.

14. SUBJECT TERMS
HEMP, MIL-STD-188-125, Long Pulse, Intermediate Pulse, MHD-EMP

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PREFACE

This work was sponsored by the Defense Nuclear Agency under the Advanced FGBC4I EMP Testing (AFEMPT) program. The DNA project officer for this effort is MAJ Michael R. Rooney.

CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement

MULTIPLY → BY → TO GET
TO GET ← BY ← DIVIDE

angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm^2	4.184 000 X E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 X E +1	*giga becquerel (GBq)
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	$t_K = (t°f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 X E -3	meter^3 (m^3)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 X E +3	kilo pascal (kPa)
ktap	1.000 000 X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N-m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 X E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 X E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 X E -2	**Gray (Gy)
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shake	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0° C)	1.333 22 X E -1	kilo pascal (kPa)

* The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

** The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

This report documents the results from the tests conducted [redacted] 8 May to 17 June 1992.

The overall purpose of the test was to acquire test data to support the further development of MIL-STD-188-125 (Reference 1), and to demonstrate the test requirements in this standard in practice. The tests addressed the following objectives:

1. [redacted]
   - [redacted]
   - [redacted]
2. [redacted]
   - [redacted]
   - [redacted]
3. [redacted]
   - [redacted]

[redacted]

5. Measure the HEMP field coupling transfer functions to [redacted] communications antennas.

   - To define waveforms for injecting antenna lines, and thus verify the hardness of radio equipment against HEMP, measurements at typical antennas are necessary to ensure that the waveforms properly represent the induced threat transients.

   - Useful measurements at all antennas were acquired for this purpose.

DOD-STD-2169A specifies the HEMP field environments in terms of three time regimes: The early time (E1) field pulse, the intermediate time (E2) field pulse, and the late time (E3) field pulse.

All three environments induce current pulses on exposed electrical lines. MIL-STD-188-125 defines generic current pulses for each environment: The E1 field environment produces the Short Pulse, the E2 environment produces the Intermediate Pulse, and E3 produces the Long Pulse. [redacted] Unfortunately, the terminology of DOD-STD-2169A is now also widely used when referring to the coupled currents. For example, the Long Pulse is also known as "E3"; the corresponding pulser is called the "E3 pulser." This short-hand presumably does no harm as long as environments (in Volts/meter) and coupled currents (in Amps) are not confused.

The test [redacted] addressed all three HEMP time regimes:

[redacted]

The tests and measurements acquired for objectives 1, 2, and 3 are described in Section 2. The Intermediate Pulse test data (objective 4) are contained in Section 3.

Section 4 documents the antenna coupling measurements (objective 5). The conclusions and recommendations are summarized in Section 5. For detailed descriptions of the test activities see Reference 2.

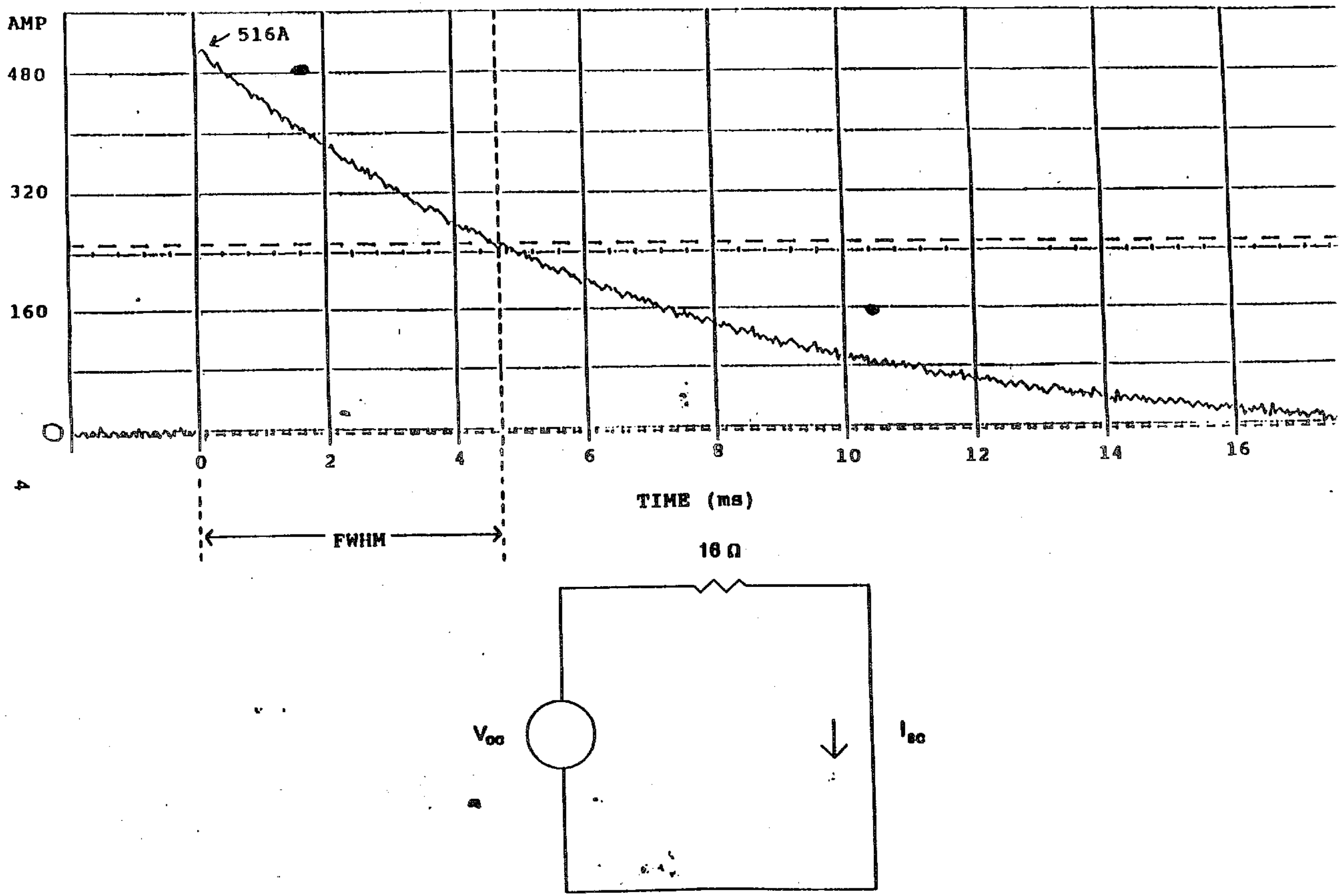
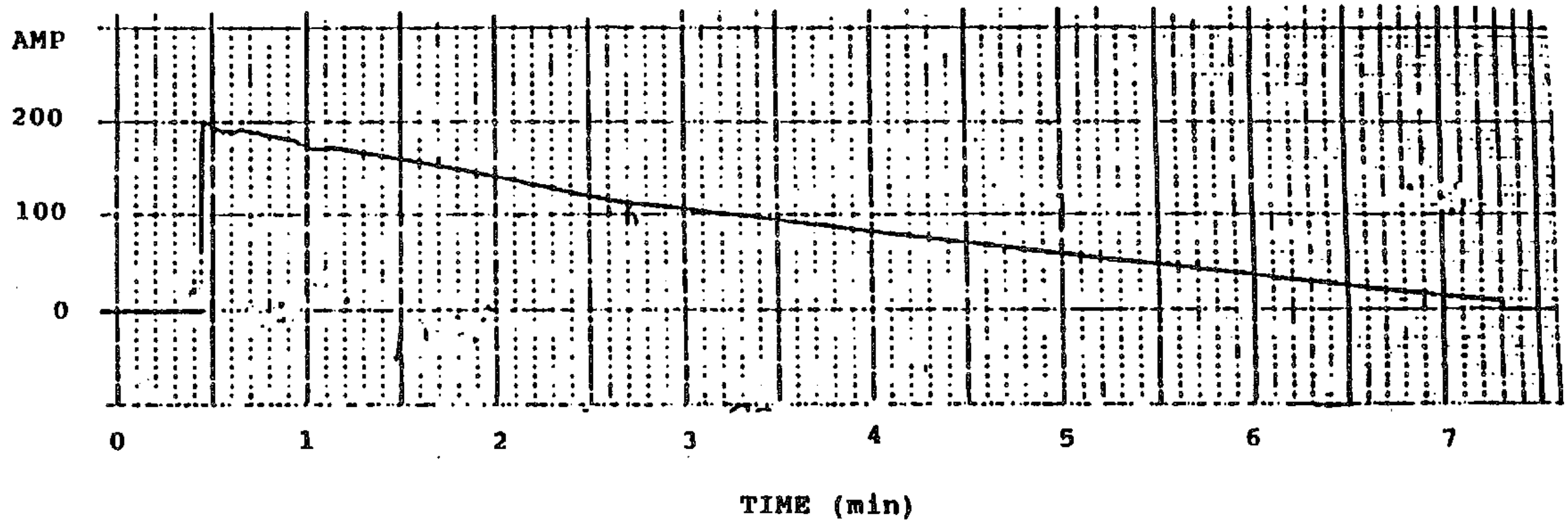


Figure 1-1. E2 pulser short circuit current.



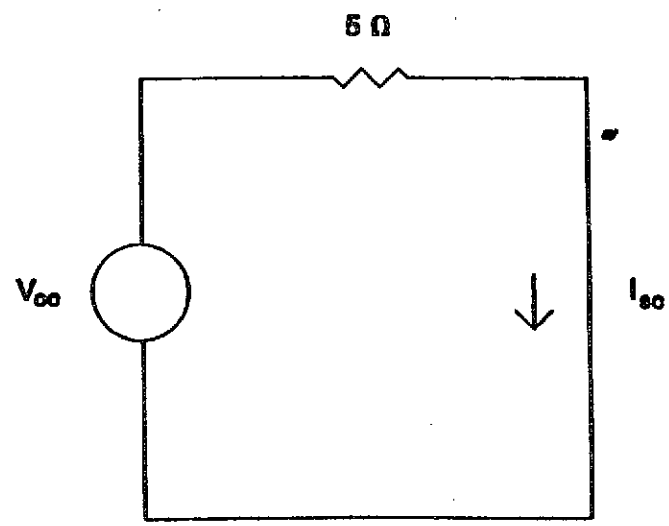


Figure 1-2. E3 pulser short circuit current.

SECTION 2

LONG PULSE CURRENT (E3) INJECTIONS

The current waveform induced by MHD-EMP is specified in MIL-STD-188-125 as a double exponential waveform (200 A peak, less than 0.5 seconds rise time, and at least 100 seconds full-width-at-half-max). The waveform provided by the E3 pulser (Reference 3) meets these requirements.

[redacted]

2.1 [redacted]

[redacted]. Injections were performed with the pulser output connected [redacted] The injected current was increased stepwise as a precaution as shown in Table 2-1 [redacted] The first column lists the pulser voltage for each shot. The second and third columns are the measured peak currents on the pulser output cable and on the return, respectively.

Since the return current is equal to the pulser output current, all coulombs are properly accounted for; i.e., Kirchhoff's circuit equations are satisfied. The last column is the estimated path resistance (R_{path}). It is in series with the pulser source impedance (5 ohms by design). R_{path} can be estimated from the peak pulser voltage V_P and the measured peak input or return current I_{meas} as follows:

$$R_{PATH} = \frac{V_P}{I_{meas}} - 5 \qquad (\Omega) \tag{2-1}$$

The calculated values in the last column of Table 2-1 indicate that the path resistance is less than 1 ohm [redacted]

The waveforms were recorded [redacted]. The transients were generally sampled every 1 ms. Thus, for a full E3 measurement, there are 360000 samples (9 Mbytes). Consequently, the full time history of the measurements cannot be plotted in a useful manner; instead, narrow time windows were selected in all following displays.

[redacted] Figure 2-3 is the same pulse, but with the time scale expanded. The ripples on the E3 pulse (evident on the blowup of the early time portion) [redacted]

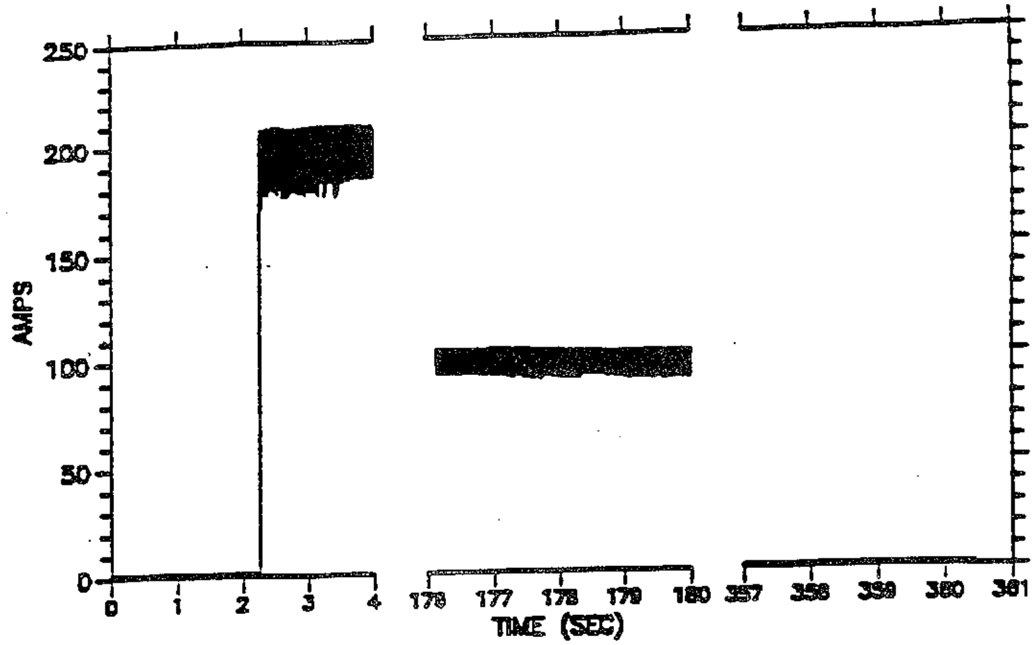


Figure 2-2. [redacted] current injected at [redacted] pulser voltage (file 3C000ABC).

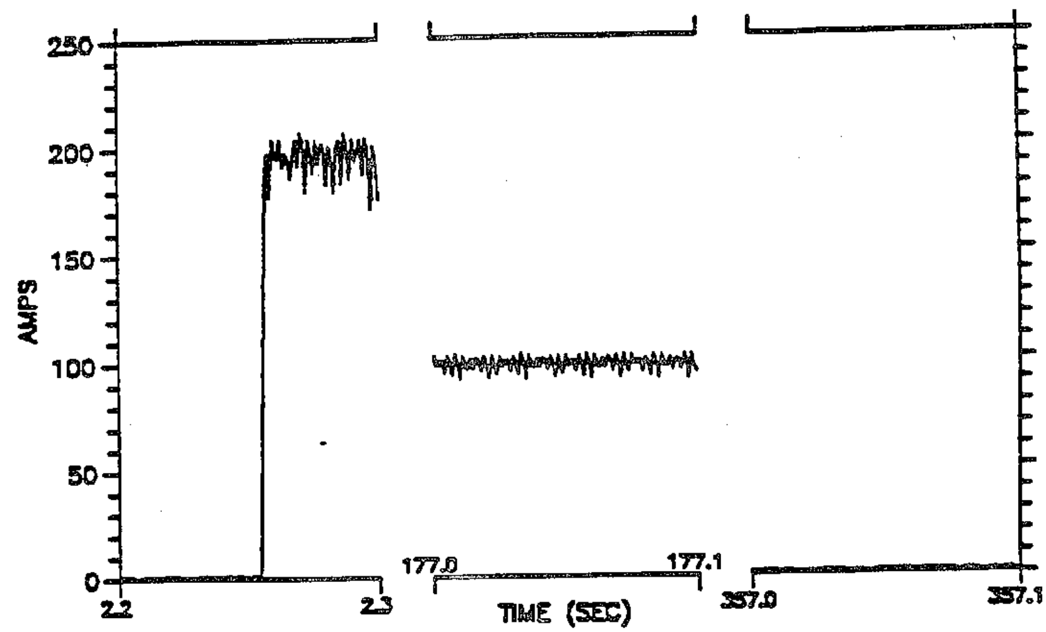


Figure 2-3. [redacted] current injected at [redacted] pulser voltage; expanded time scales (file 3C000ABC).

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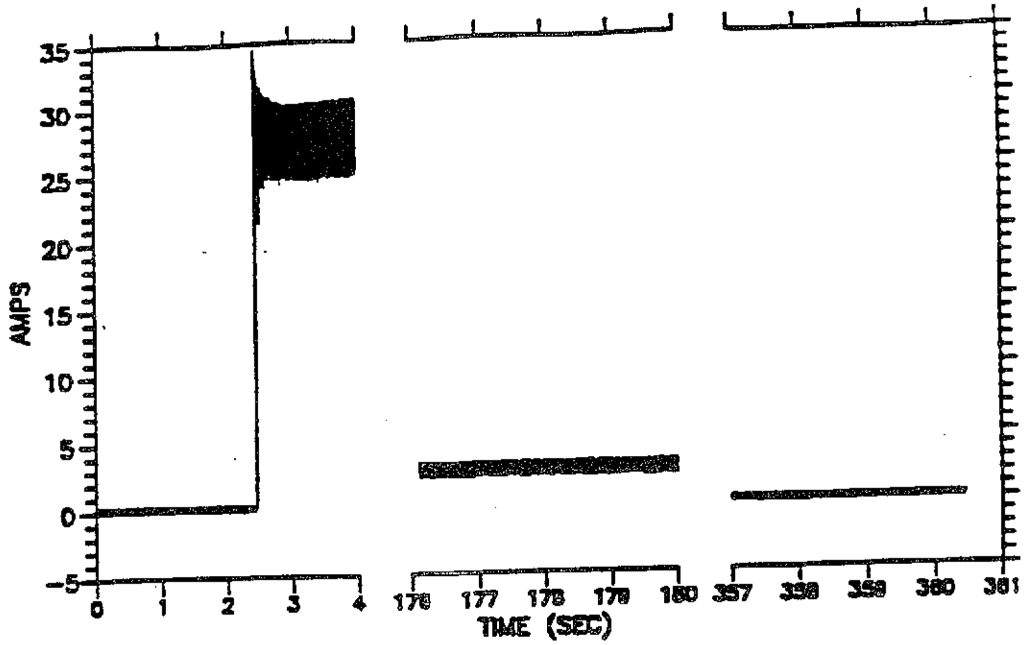

Figure 2-10. [redacted] current injected at [redacted]pulser voltage (file G17900AC).

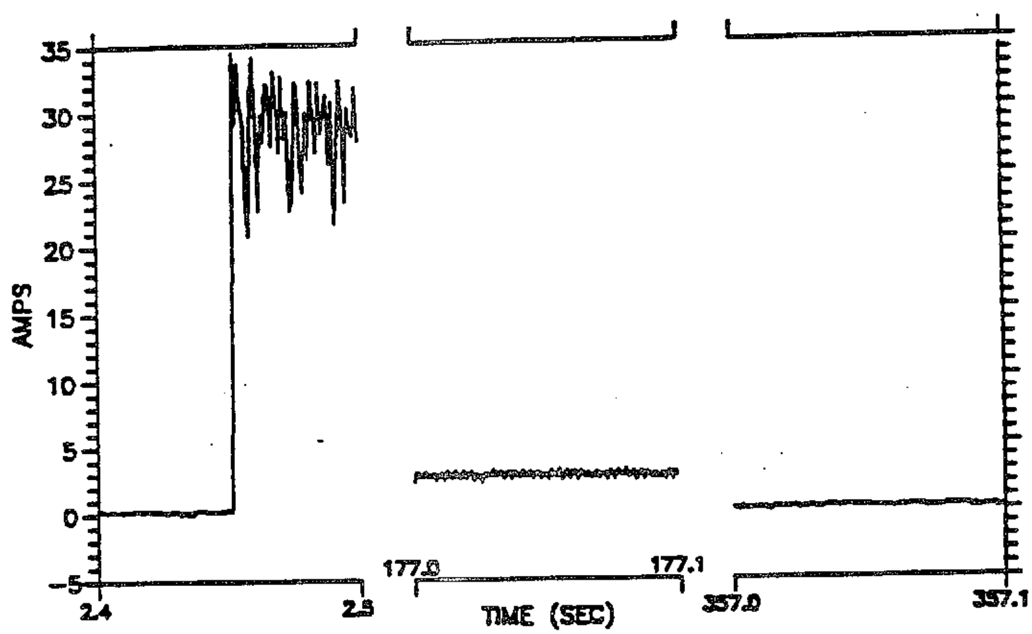

Figure 2-11. [redacted] current injected at [redacted] pulser voltage, expanded time scale (file G17900AC).

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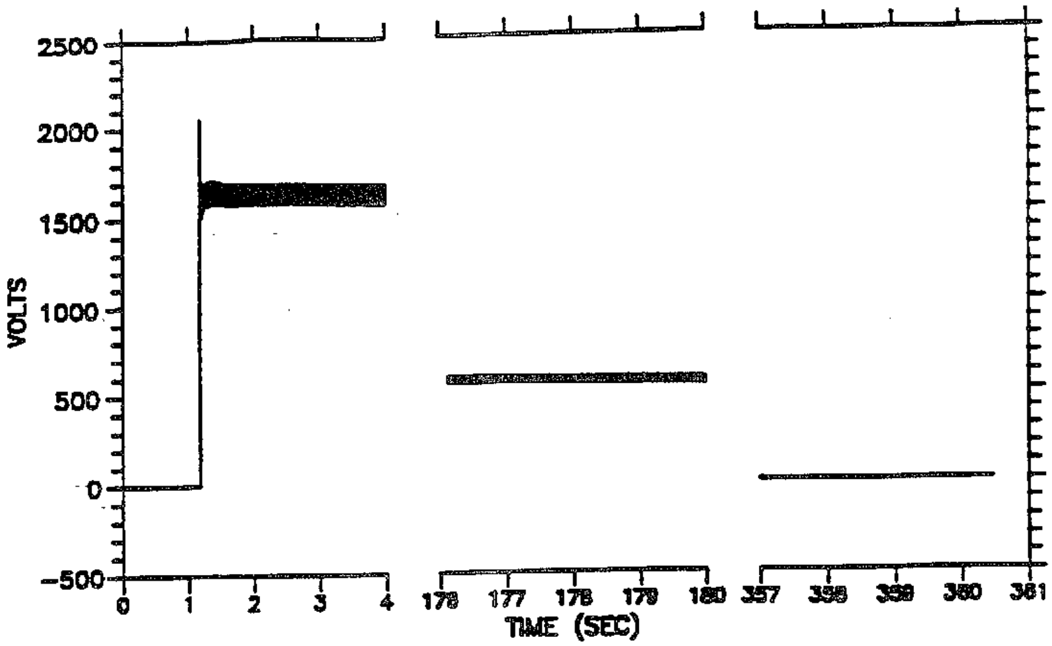

Figure 2-13. E3 common mode injection, [redacted] (file 3C0024AV).

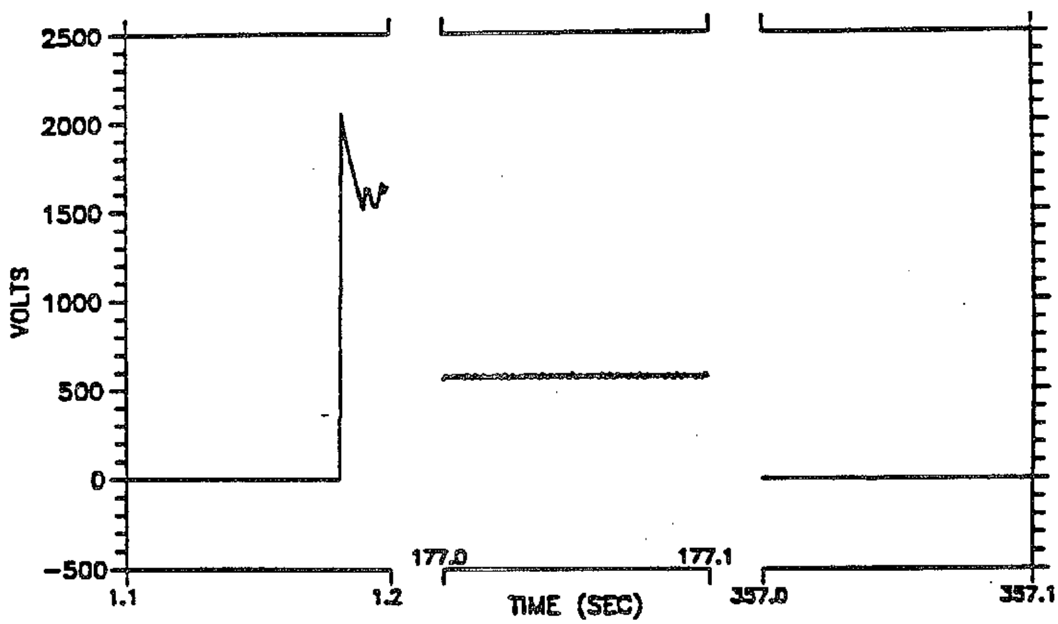

Figure 2-14. E3 common mode injection [redacted] expanded time scale (file 3C0024AV).

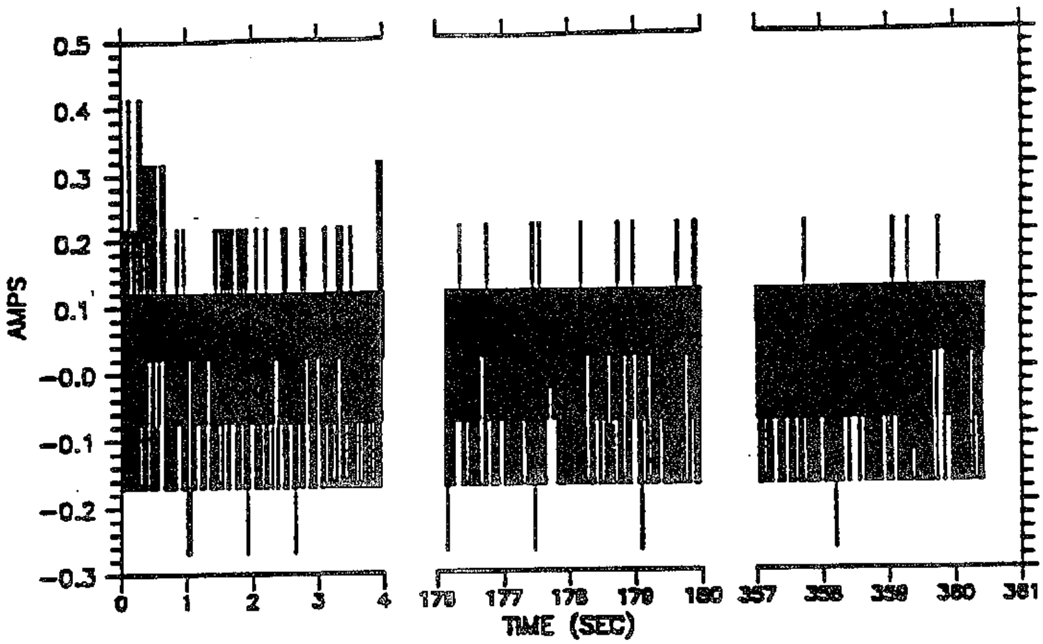

Figure 2-15. [redacted] (file 3C0024AC).

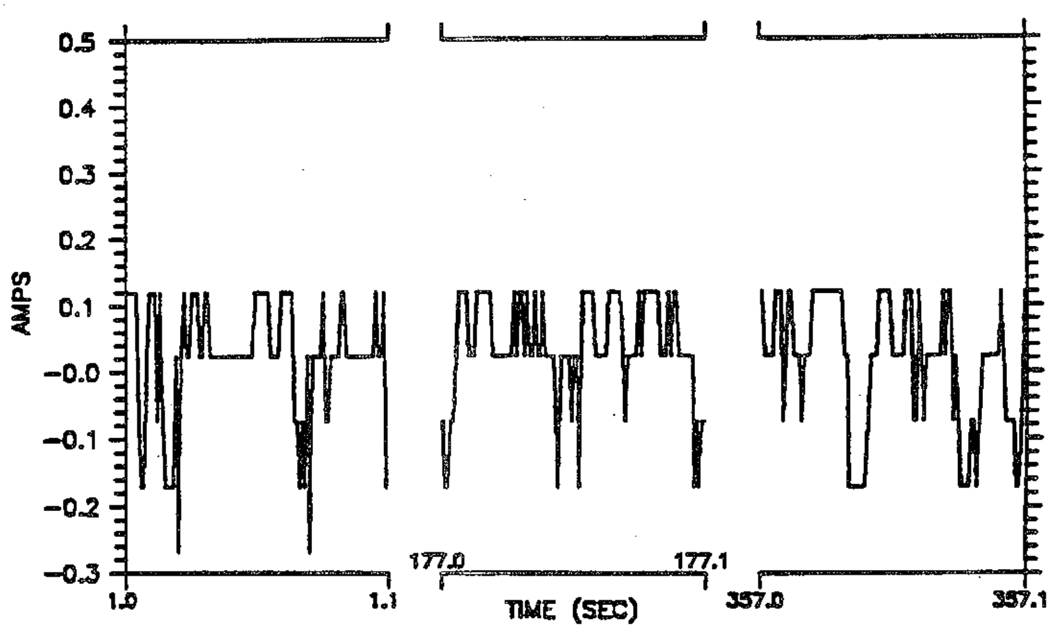

Figure 2-16. [redacted] (file 3C0024AC).

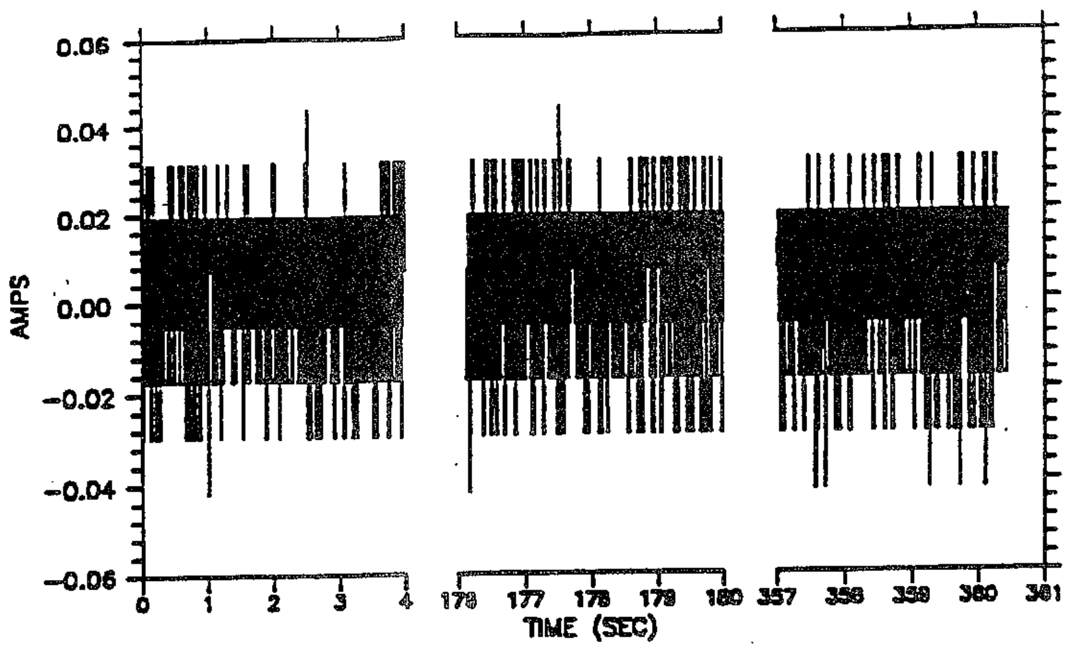

Figure 2-17. E3 common mode injection[redacted]file 3C0025AC).

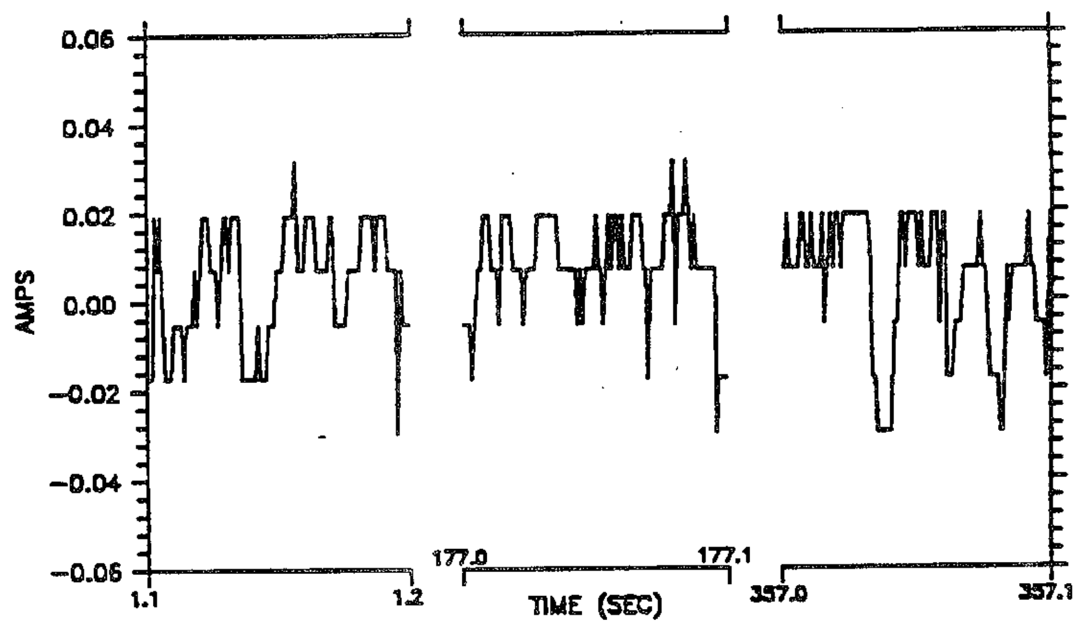

Figure 2-18. E3 common mode injection,[redacted]expanded time scale (file 3C0025AC).

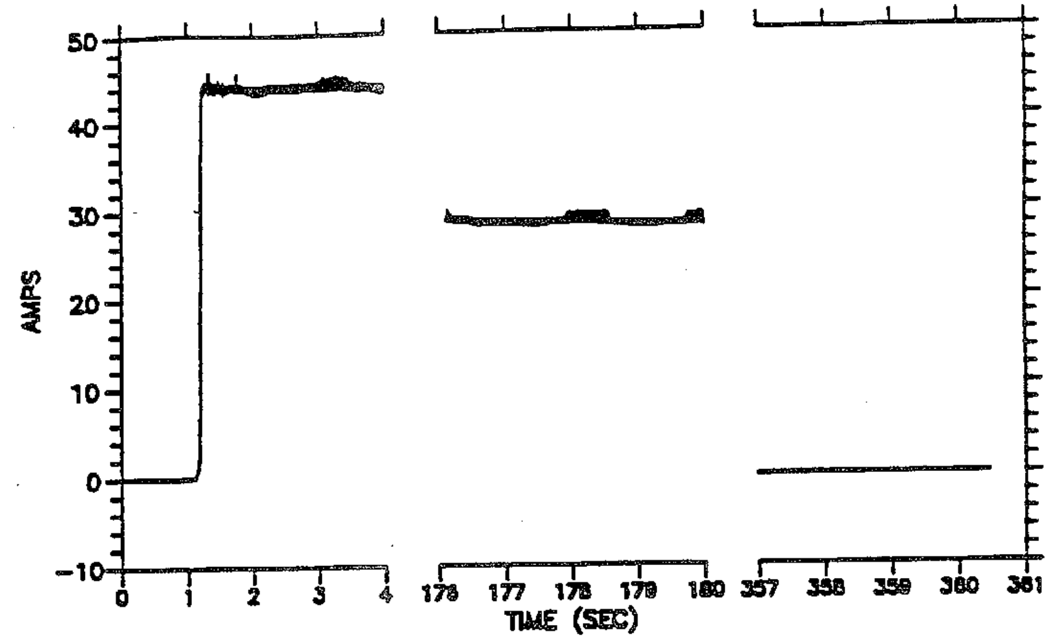

Figure 2-20. E3 wire-to-ground injection, input current (file 3A0021AC).

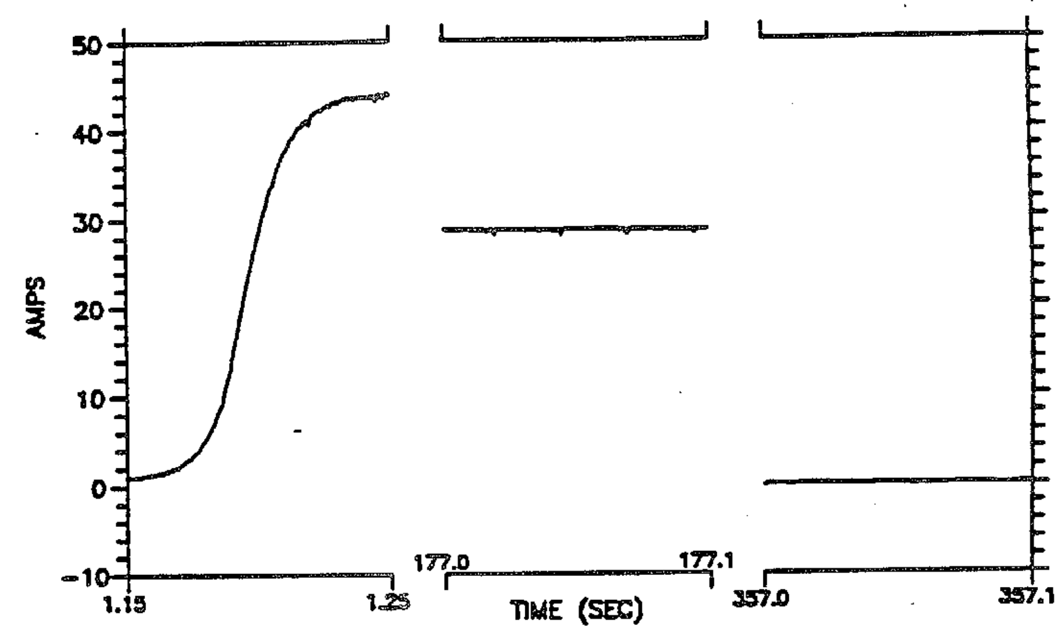

Figure 2-21. E3 wire-to-ground injection, input current expanded time scale (file 3A0021AC).

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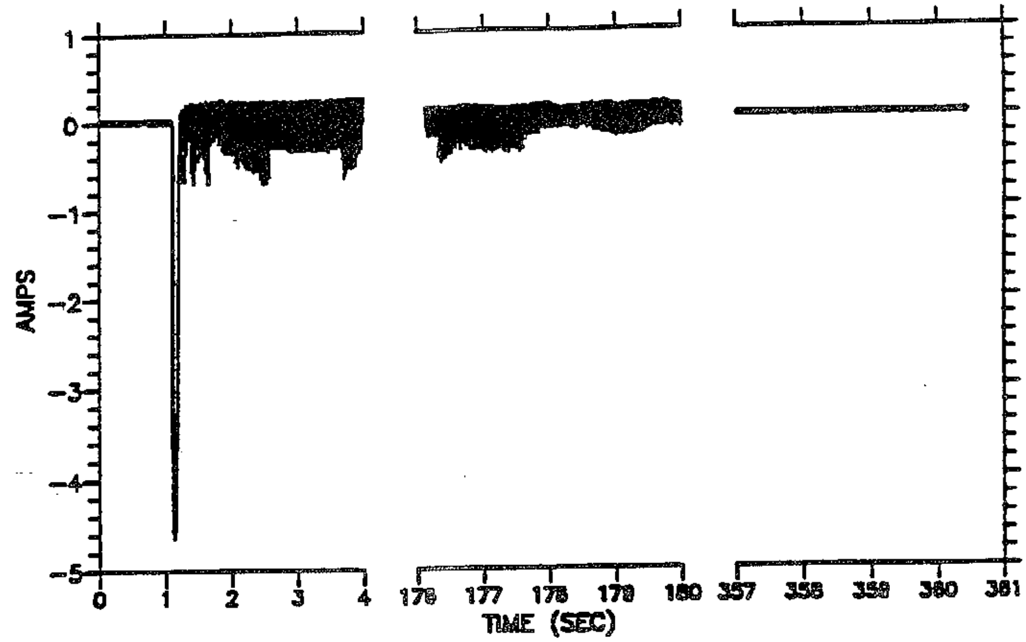


Figure 2-22. E3 wire-to-ground injection, [redacted] (file 3A0025BC).

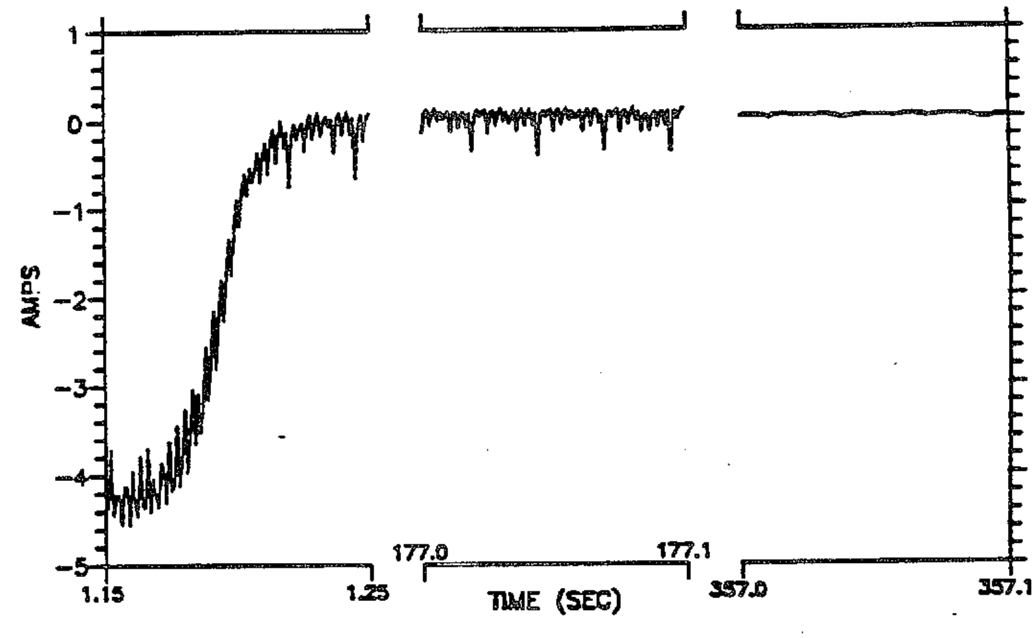


Figure 2-23. E3 wire-to-ground injection, [redacted] expanded time scale (file 3A0025BC).

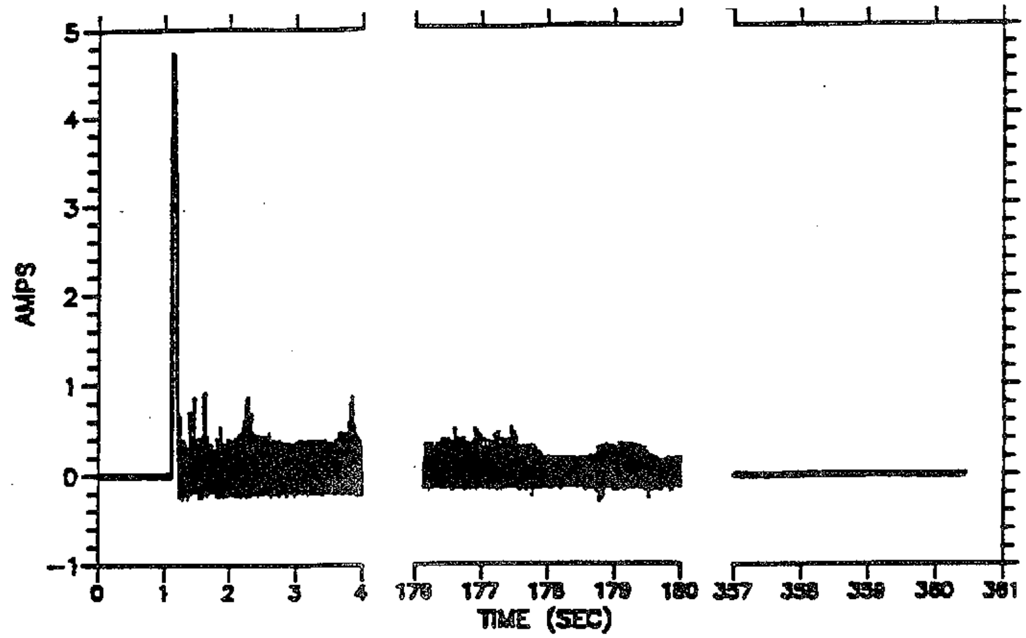


Figure 2-24. E3 wire-to-ground injection, [redacted] file 3A0026BC).

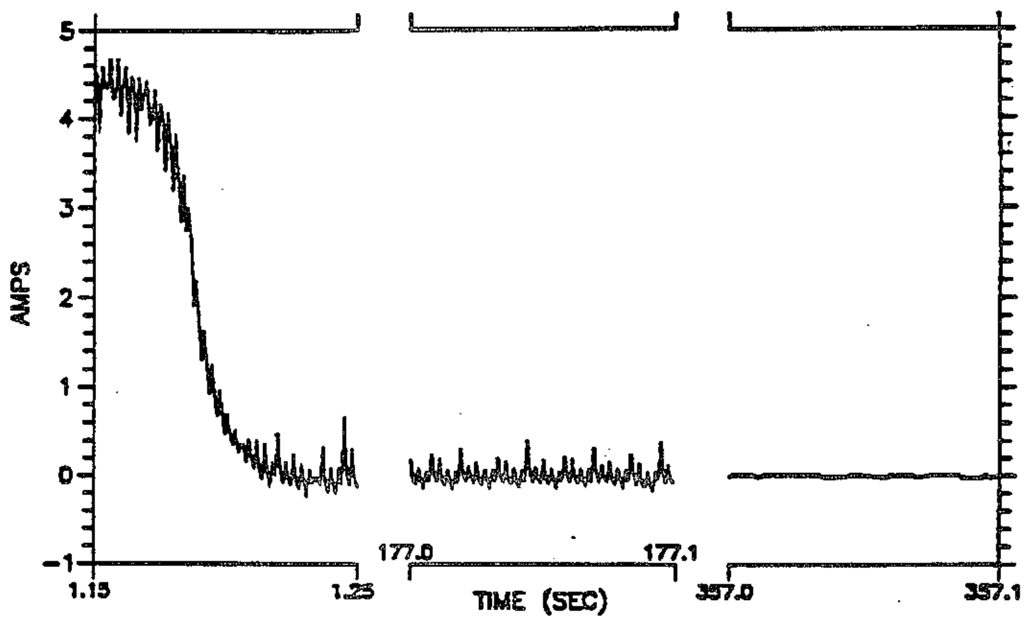


Figure 2-25. E3 wire-to-ground injection, [redacted] expanded time scale (file 3A0026BC).

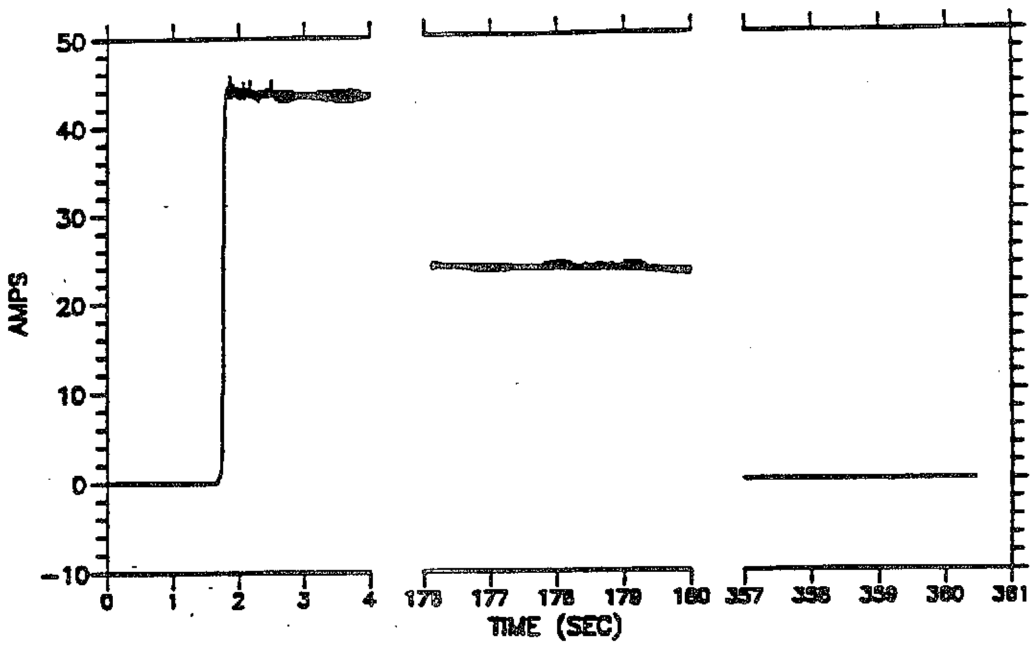


Figure 2-26. E3 wire-to-ground injection, input current (file 3A0021CC).

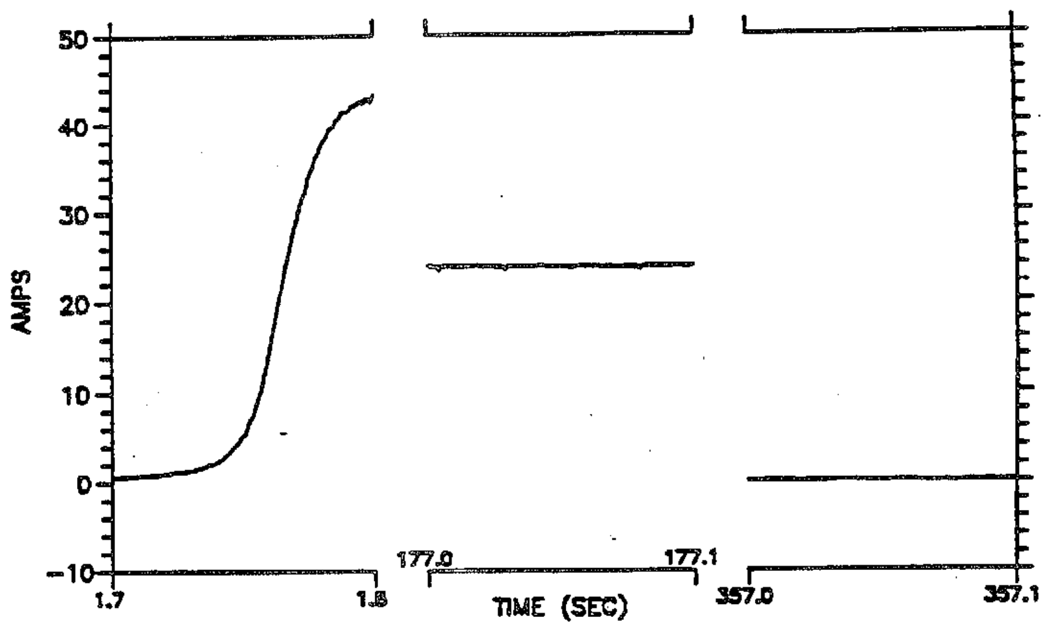


Figure 2-27. E3 wire-to-ground injection, input current expanded time scale (file 3A0021CC).

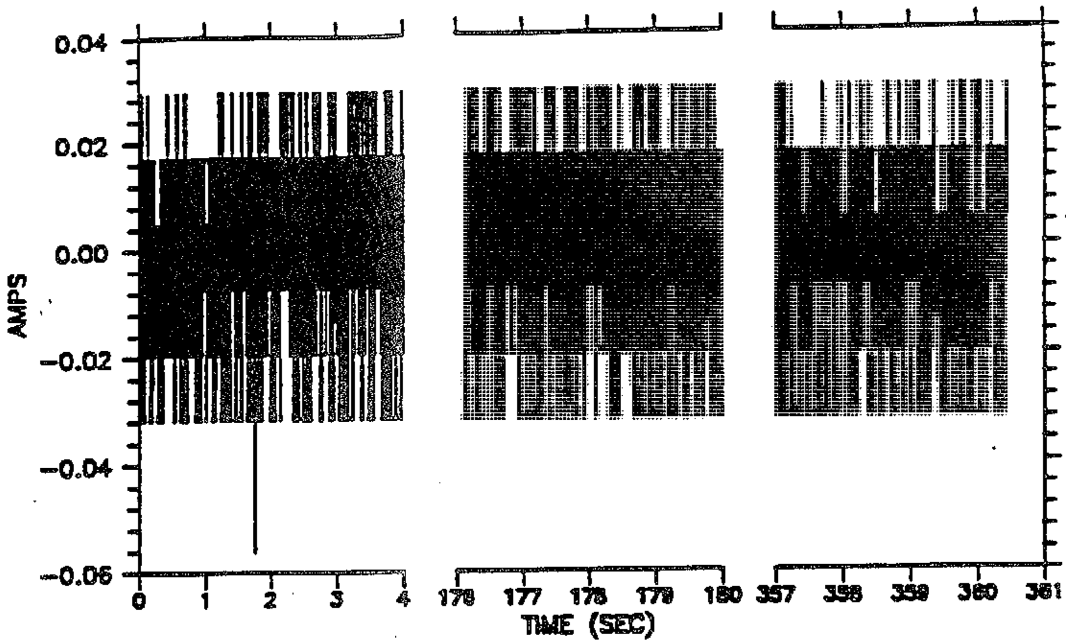


Figure 2-28. E3 wire-to-ground injection[redacted]file 3A0027BC).

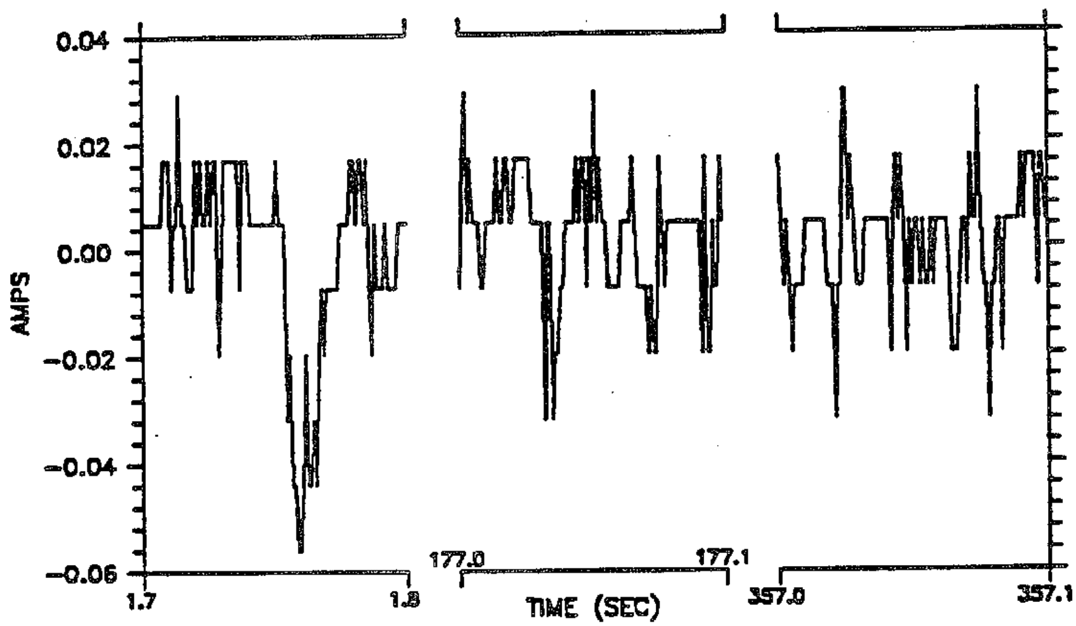


Figure 2-29. E3 wire-to-ground injection, [redacted] expanded time scale (file 3A0027BC).

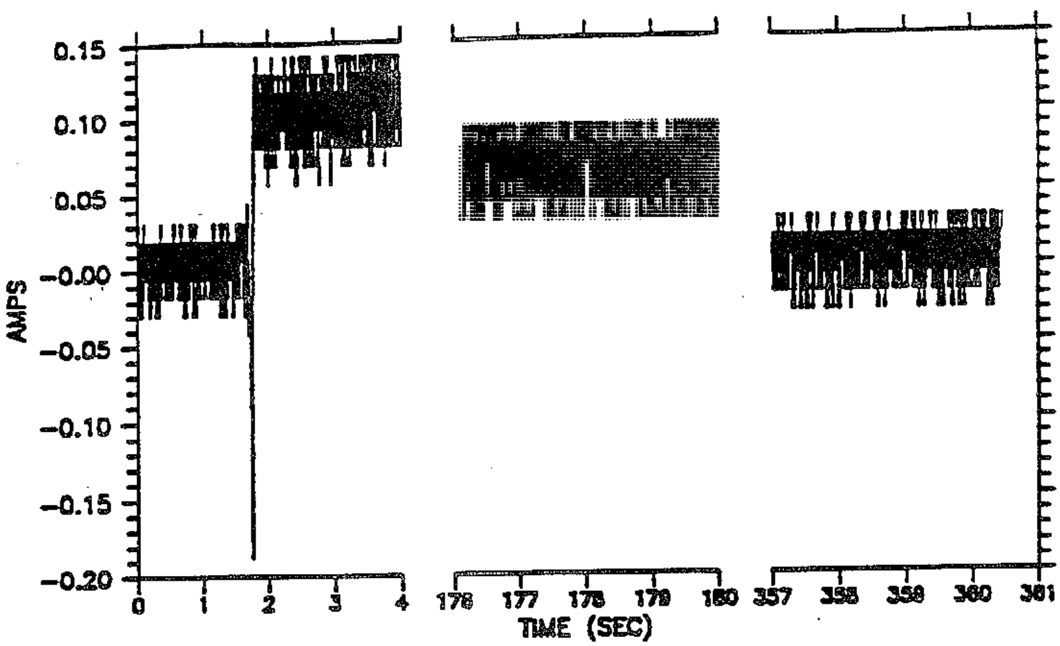


Figure 2-30. E3 wire-to-ground injection,[redacted]file 3A0028BC).

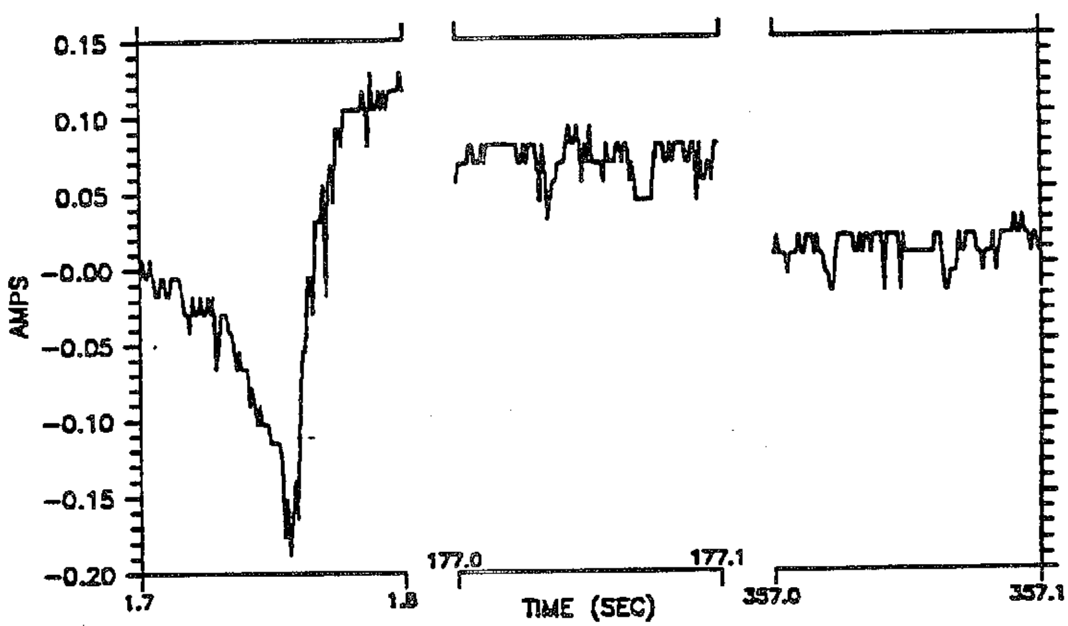


Figure 2-31. E3 wire-to-ground injection[redacted]expanded time scale (file 3A0028BC).

Pages 27-34 removed in their entirety,

[redacted]

The E2 pulser meets the requirements of MIL-STD-188-125 for the Intermediate Pulse (500 A peak, less than 1 μs rise time, and more than 0.5 ms full-width-at-half-max). [redacted]

3.1 [redacted]

Pages [redacted] 37-38 removed in their entirety

[redacted]

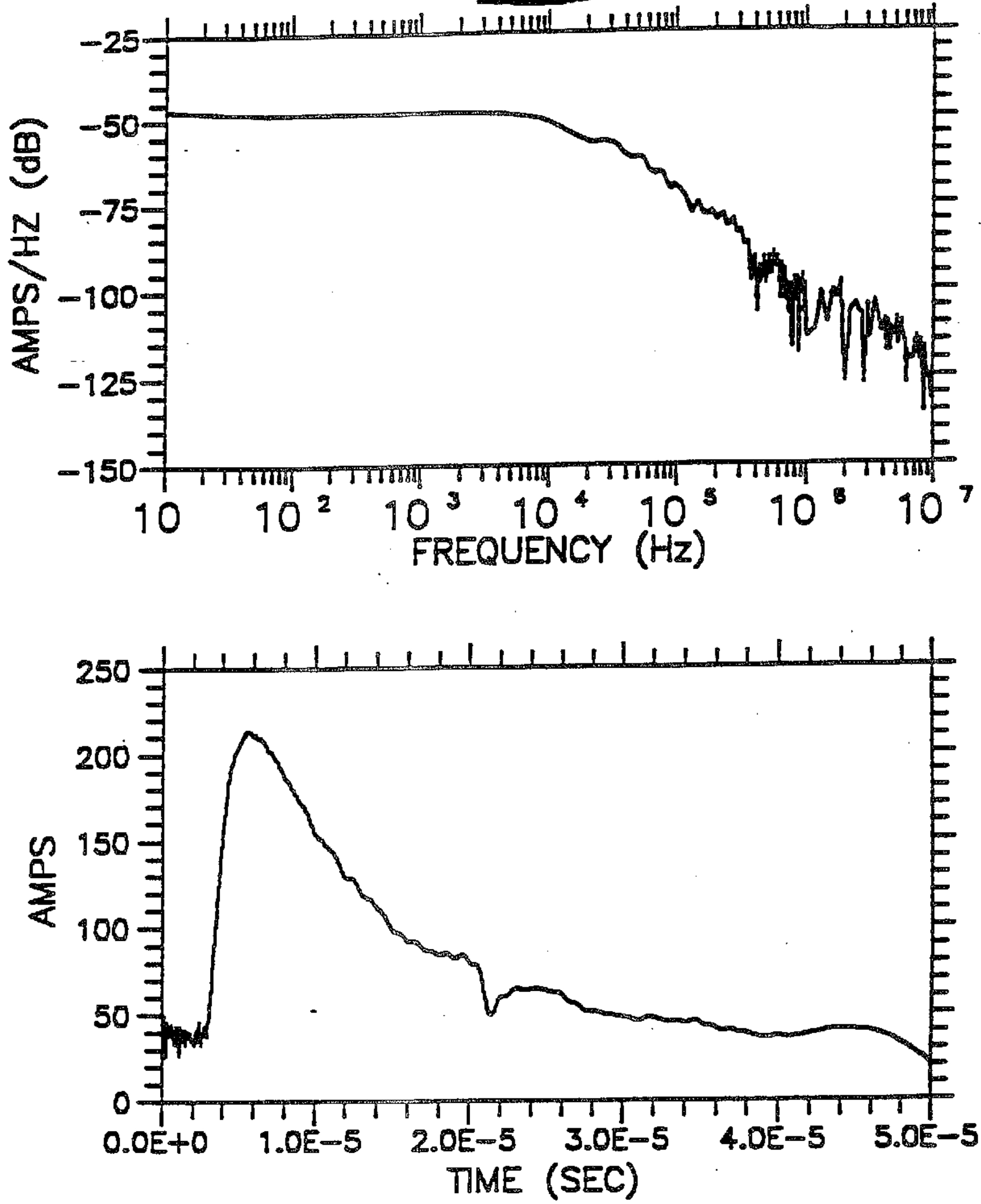


Figure 3-2. [redacted]

[redacted]

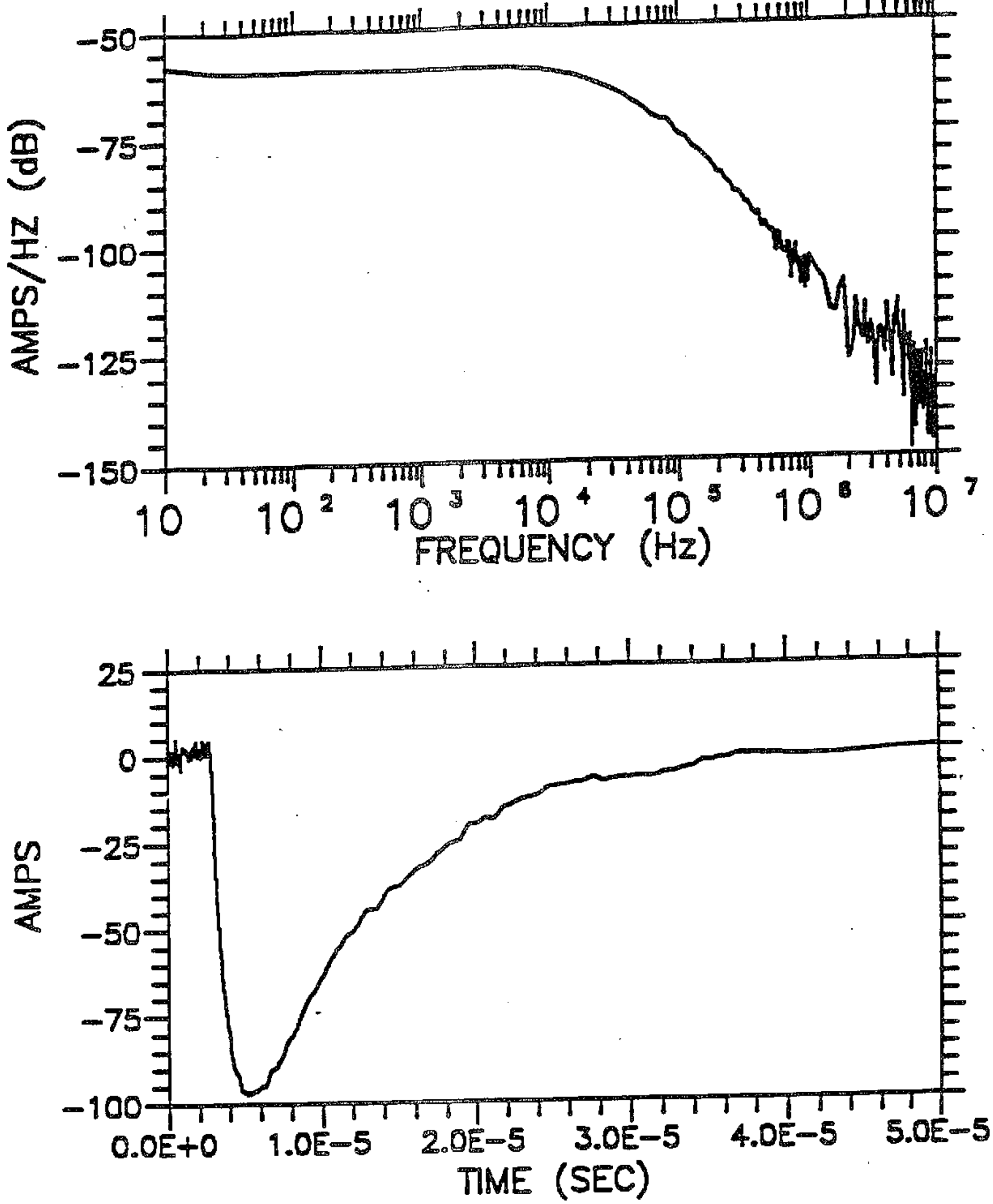


Figure 3-3. [redacted]).

[redacted]

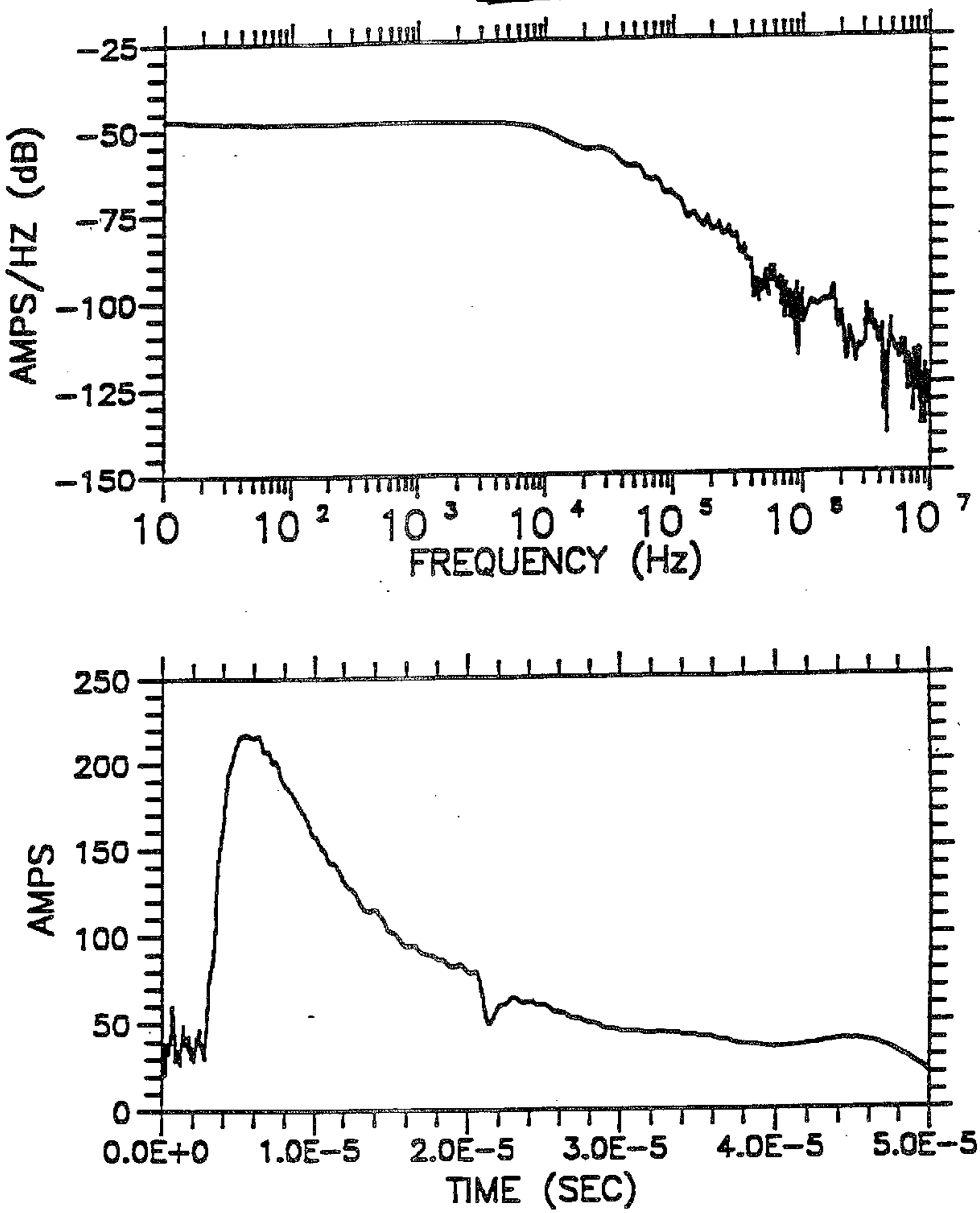


Figure 3-4. [redacted].

[redacted]

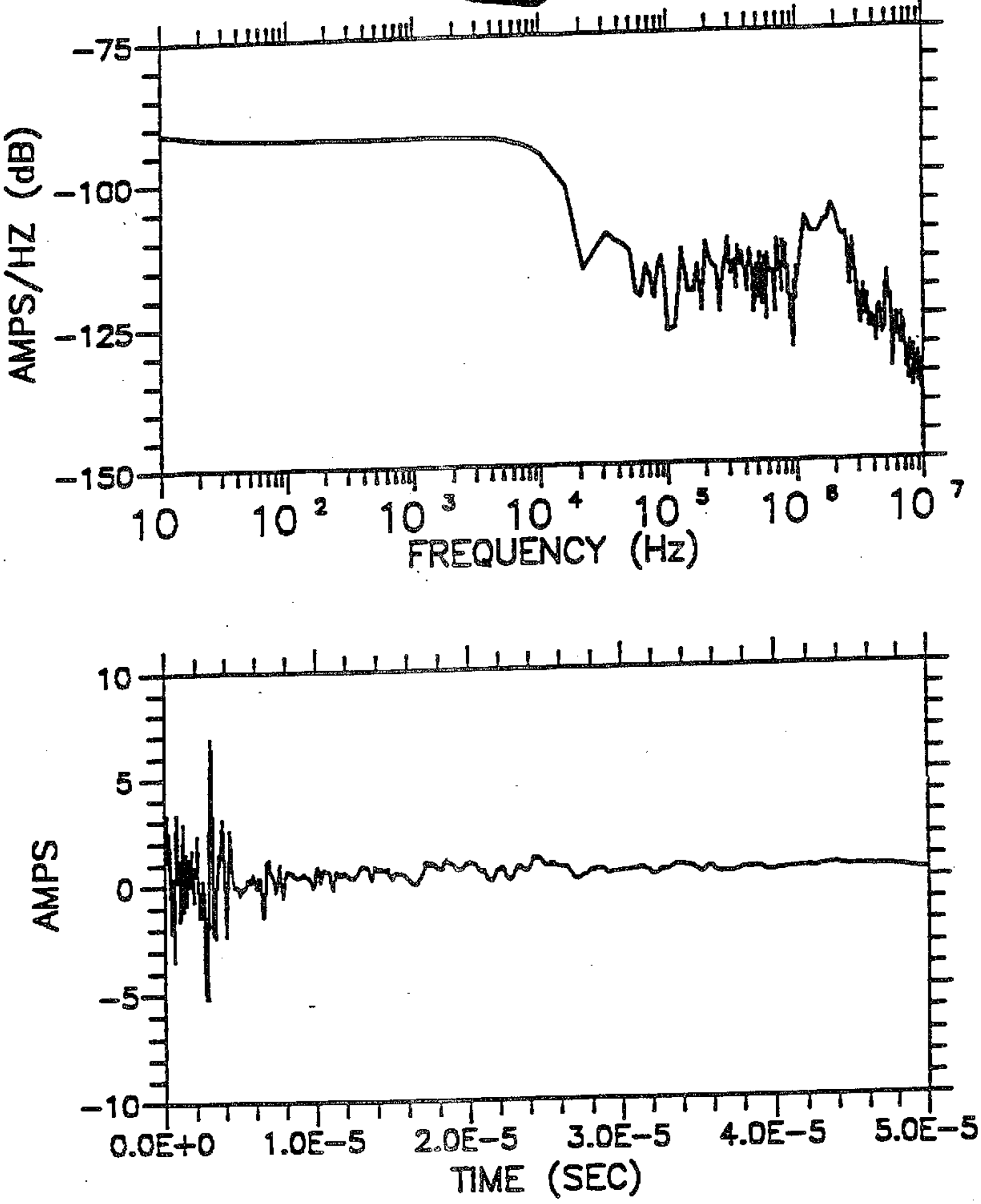


Figure 3-5. [redacted]

[redacted]

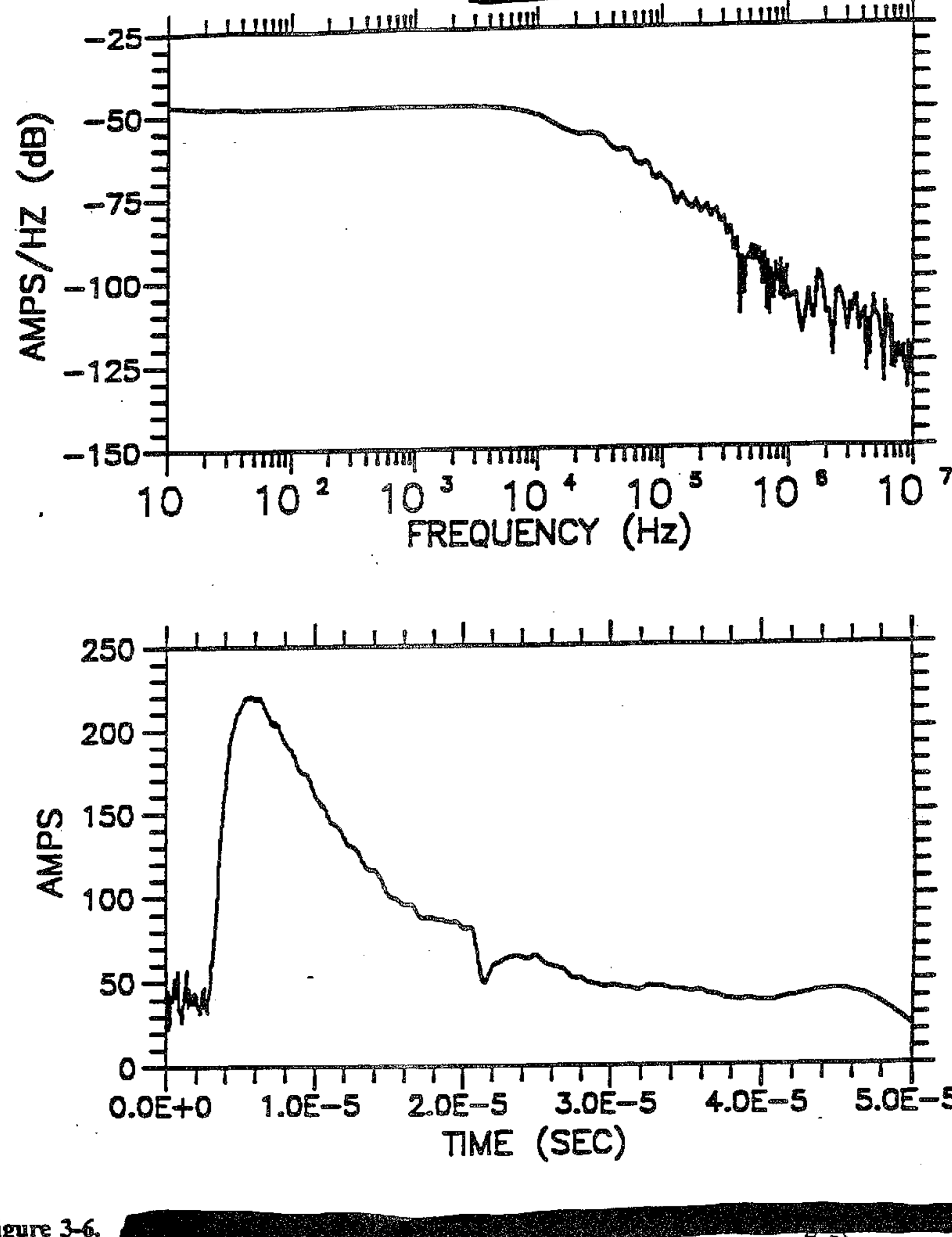
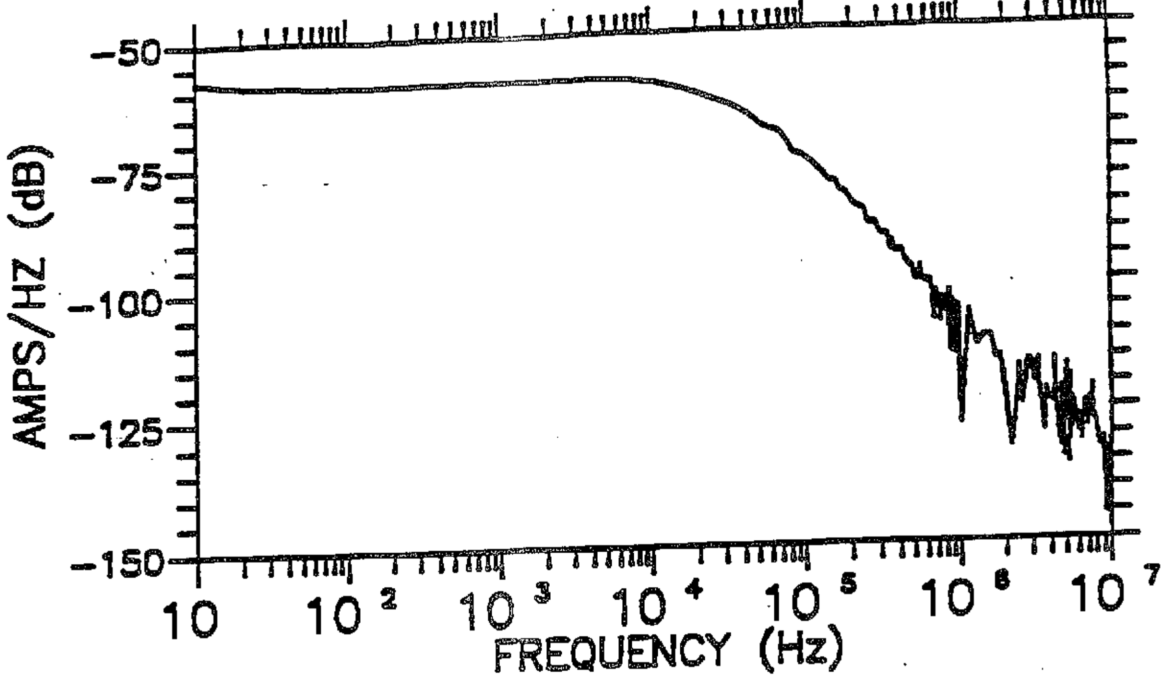
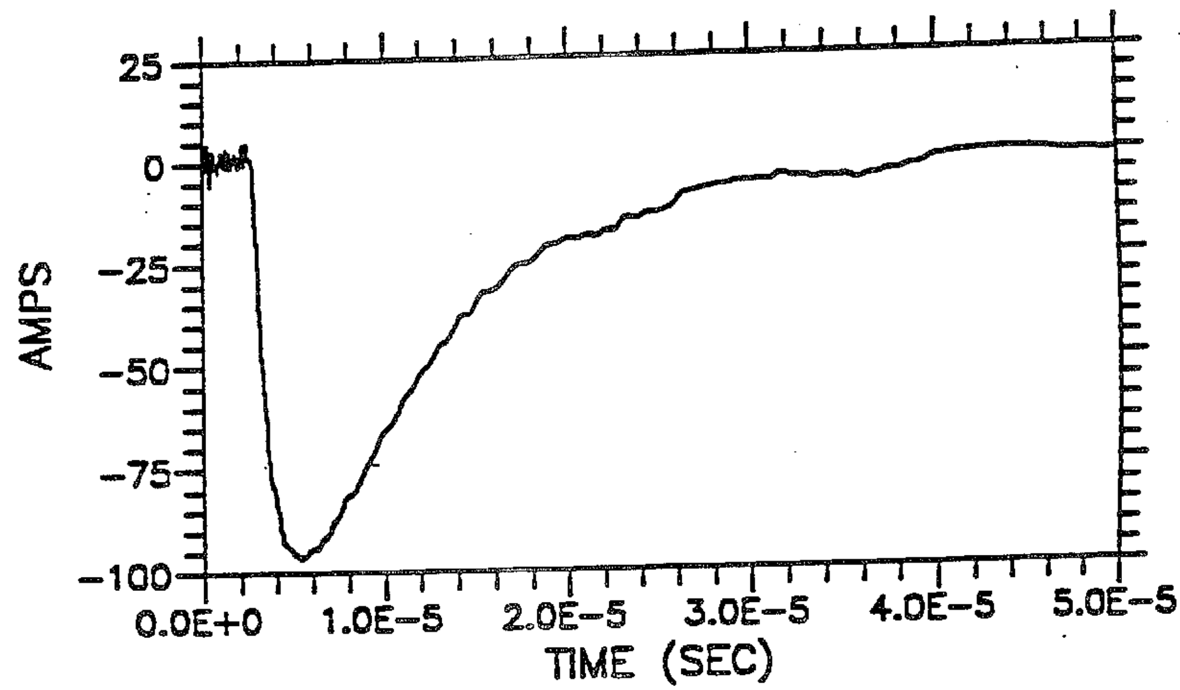


Figure 3-6. [redacted].

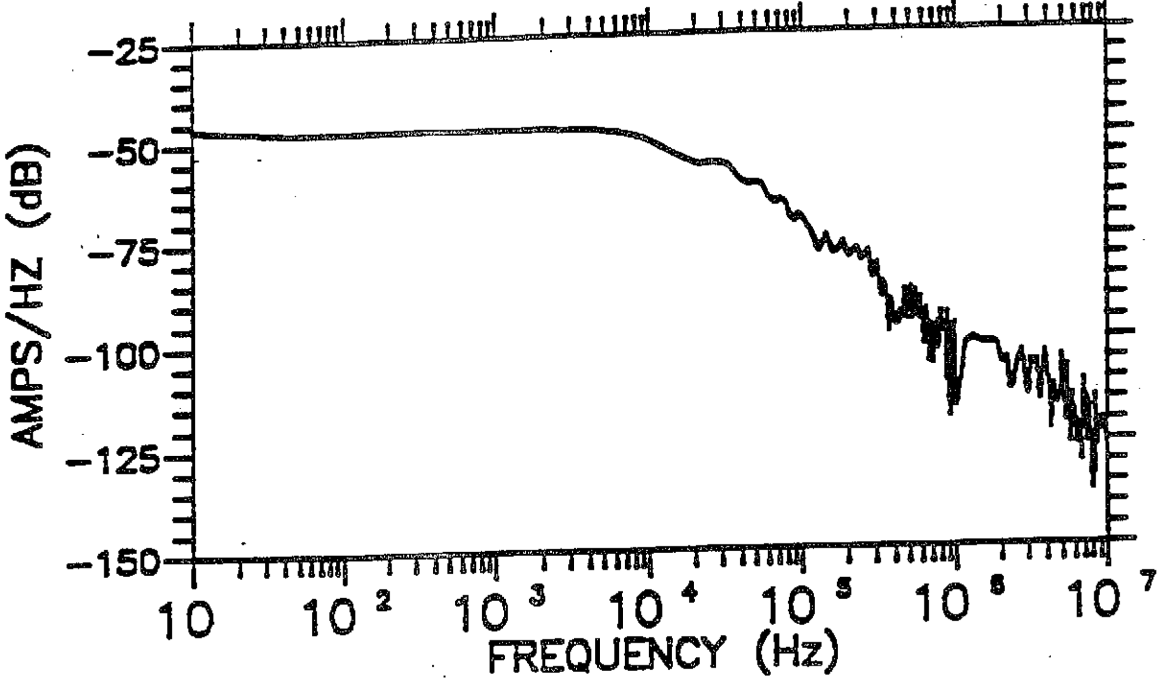
[redacted]





[redacted]

[redacted]



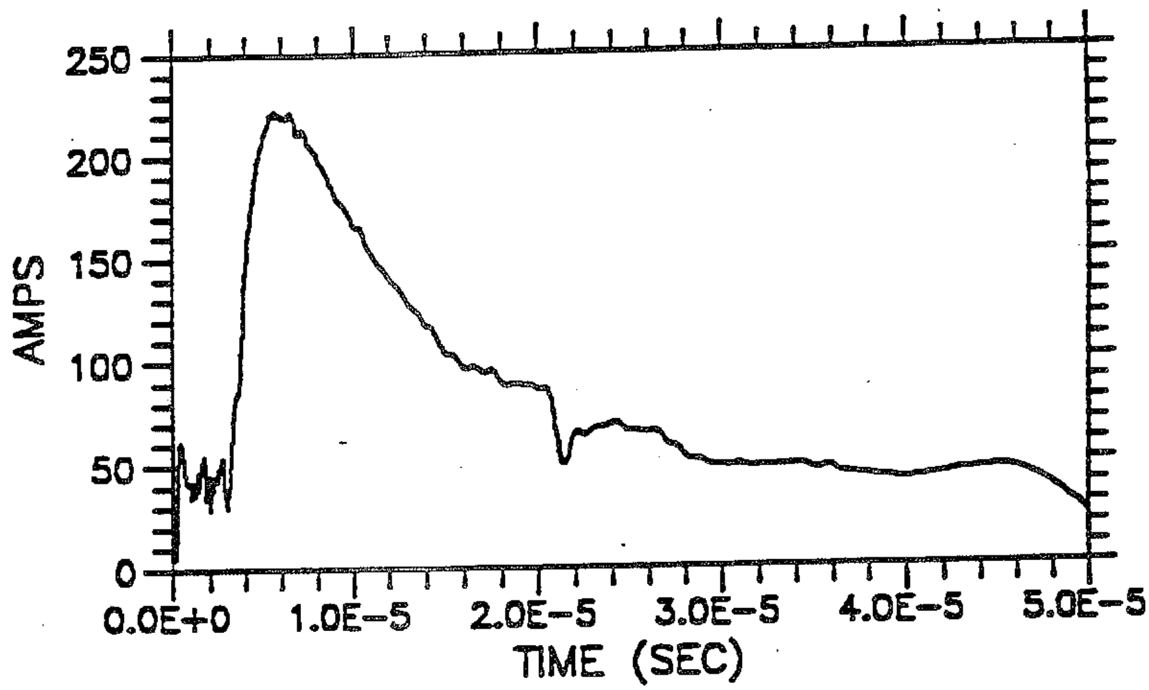


Figure 3-8. [redacted].

[redacted]

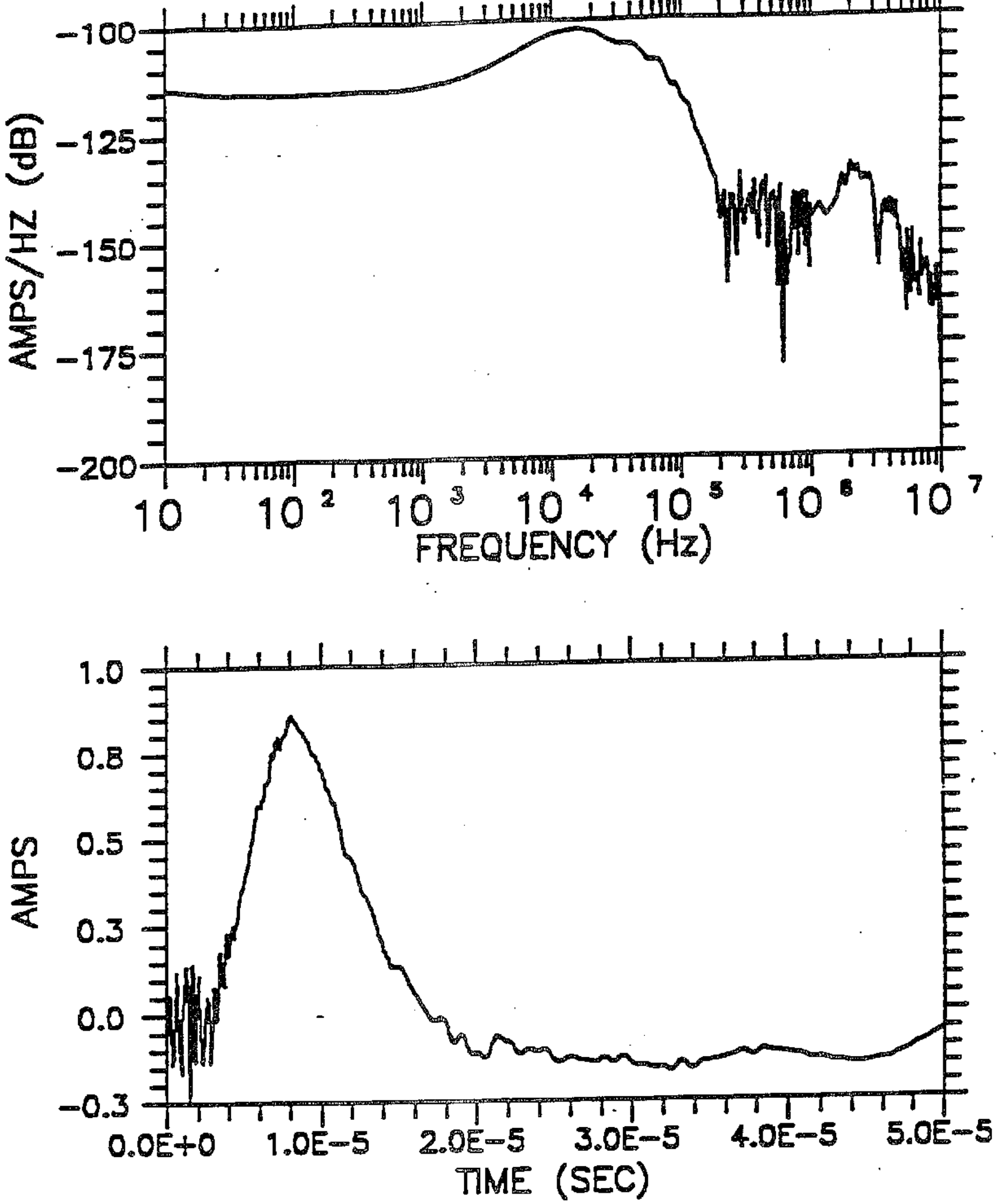


Figure 3-9. [redacted]

[redacted]

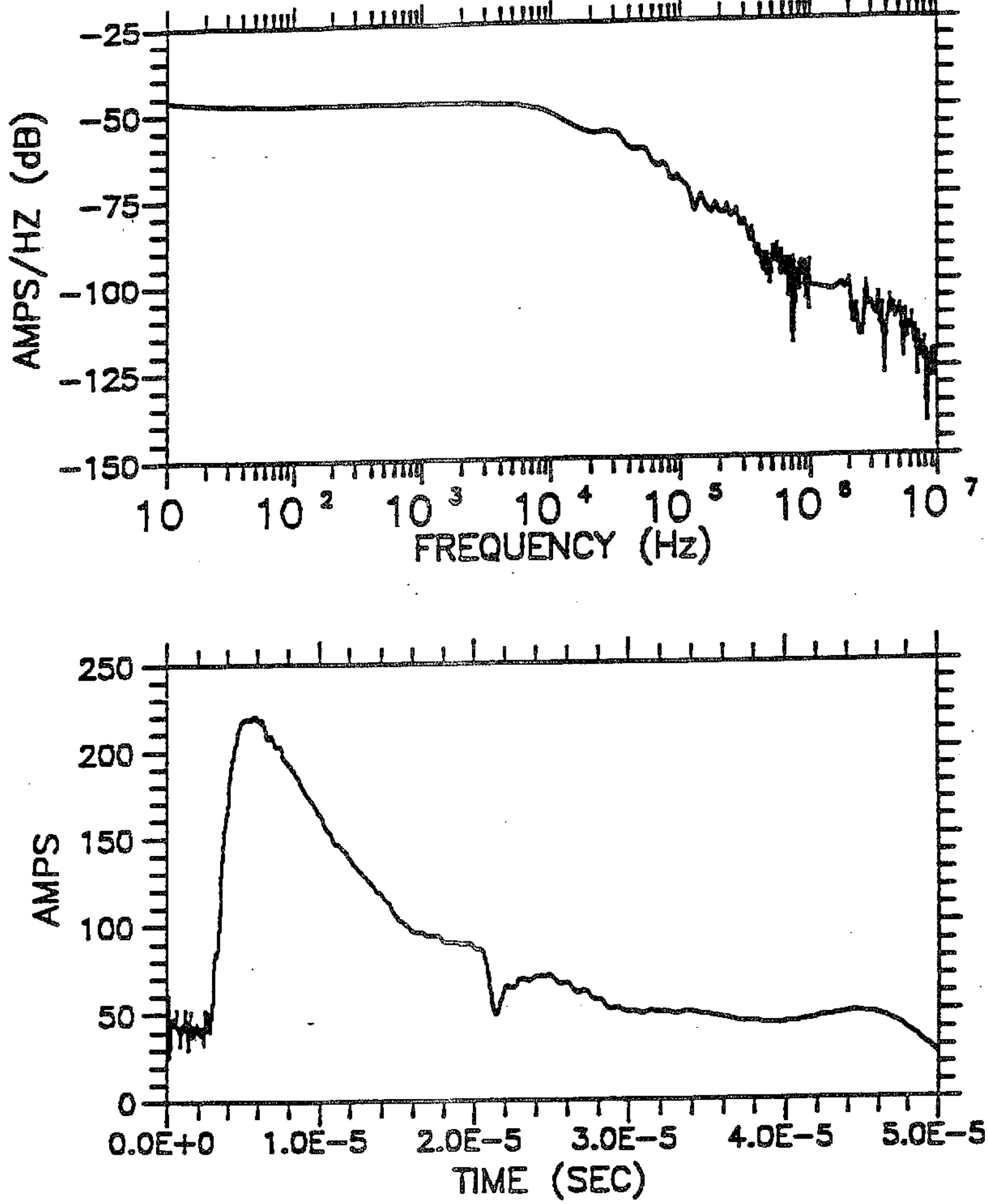


Figure 3-10. [redacted]

[redacted]

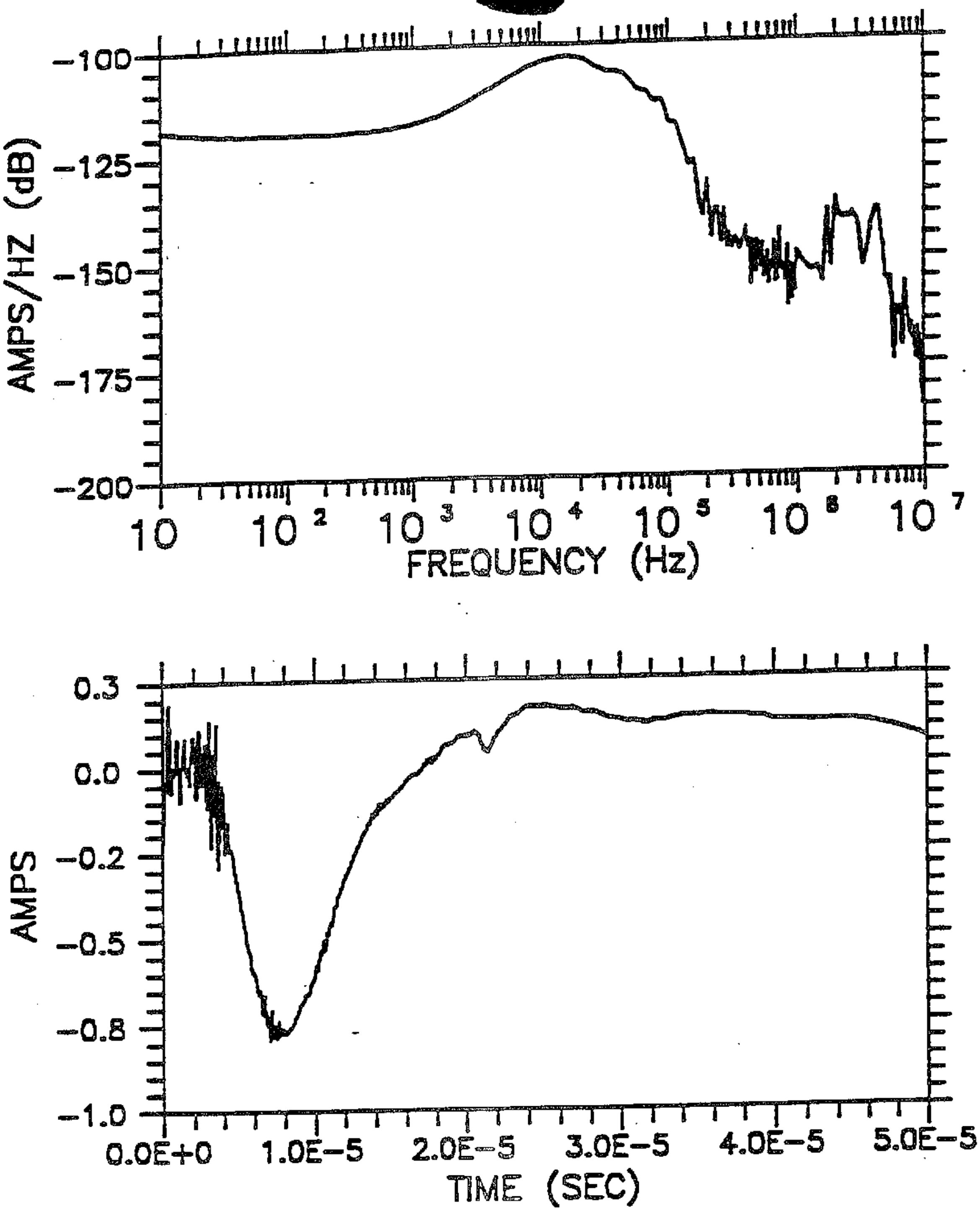


Figure 3-11. [redacted].

[redacted]

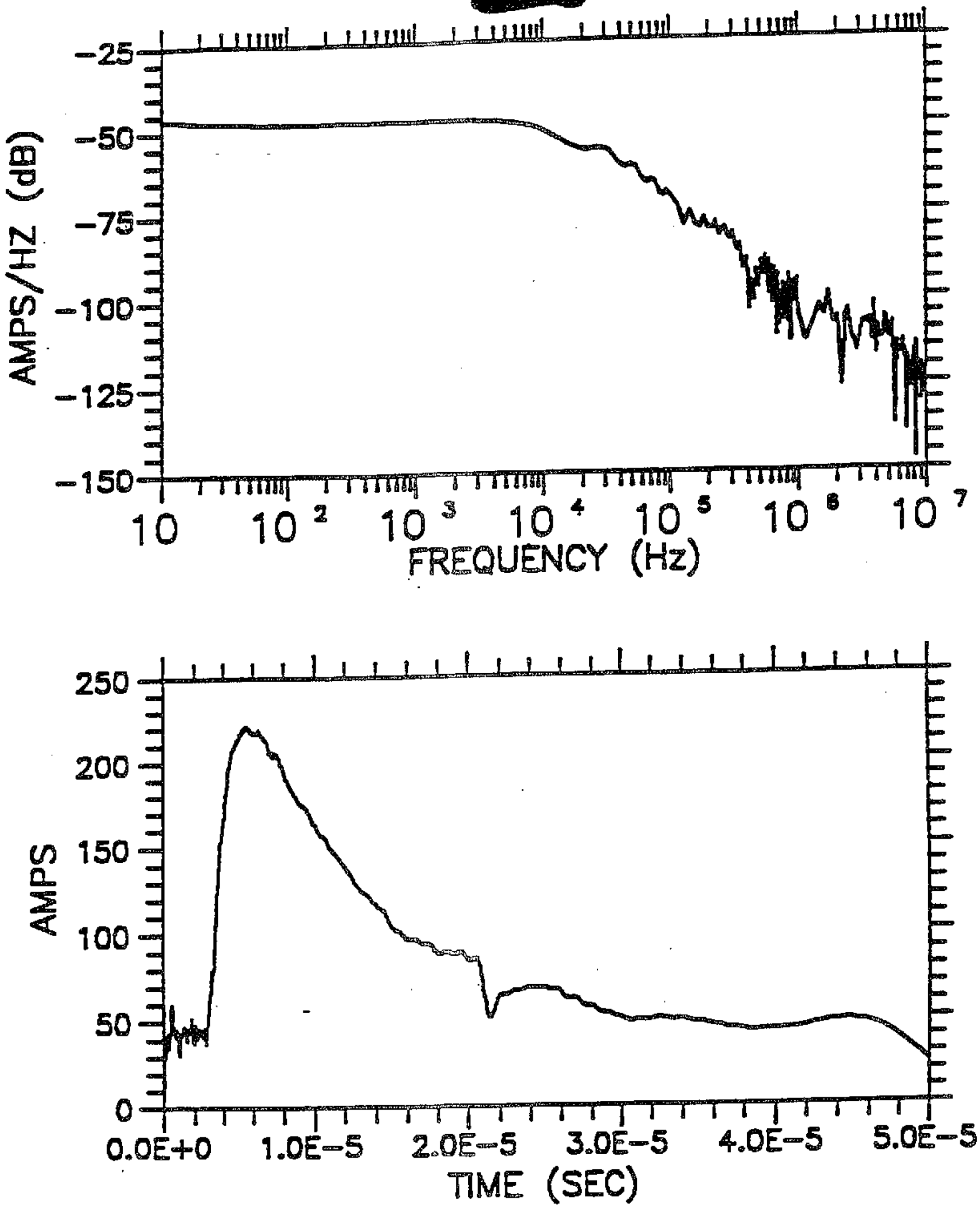


Figure 3-12. [redacted].

[redacted]

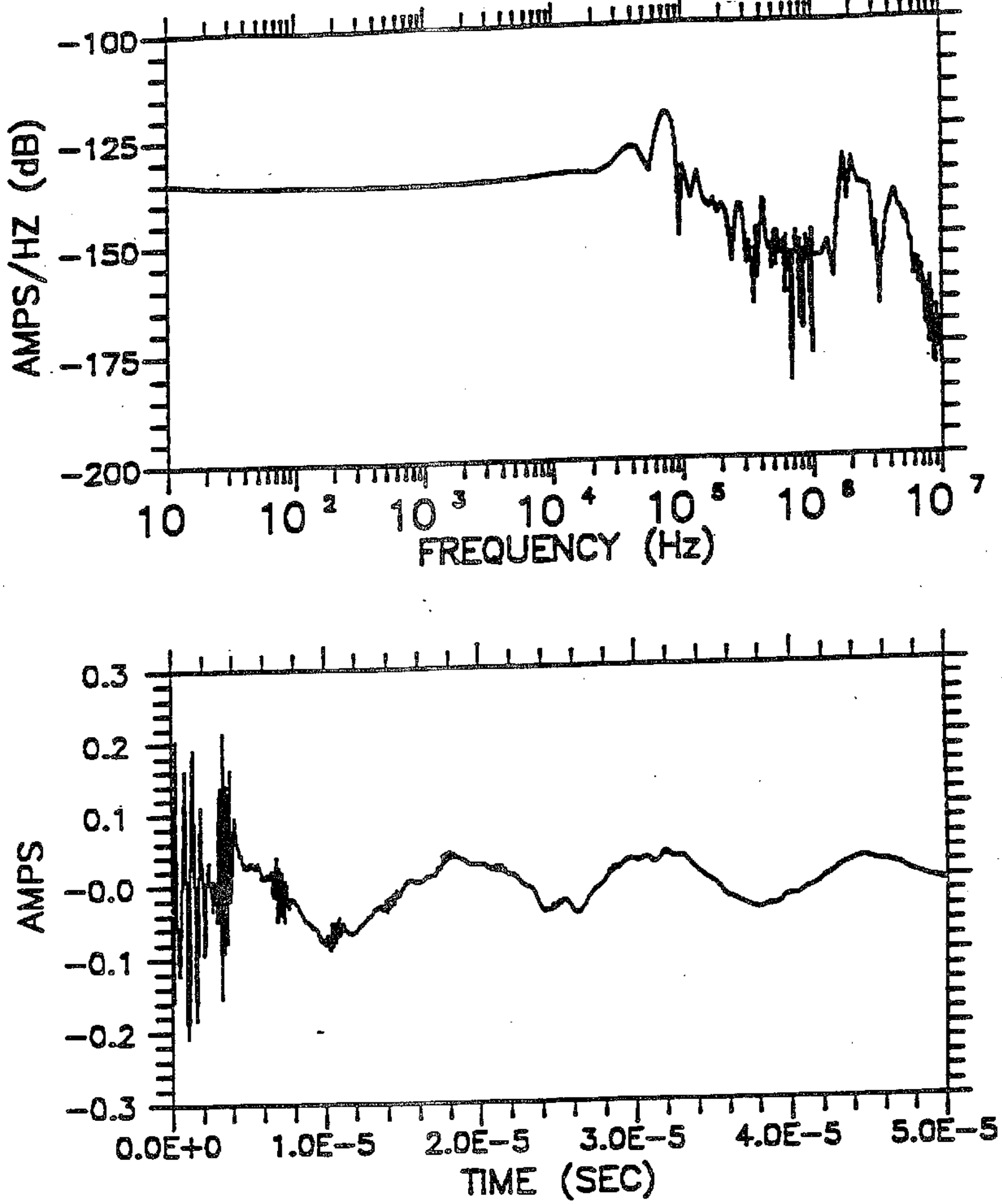


Figure 3-13. [redacted].

[redacted]

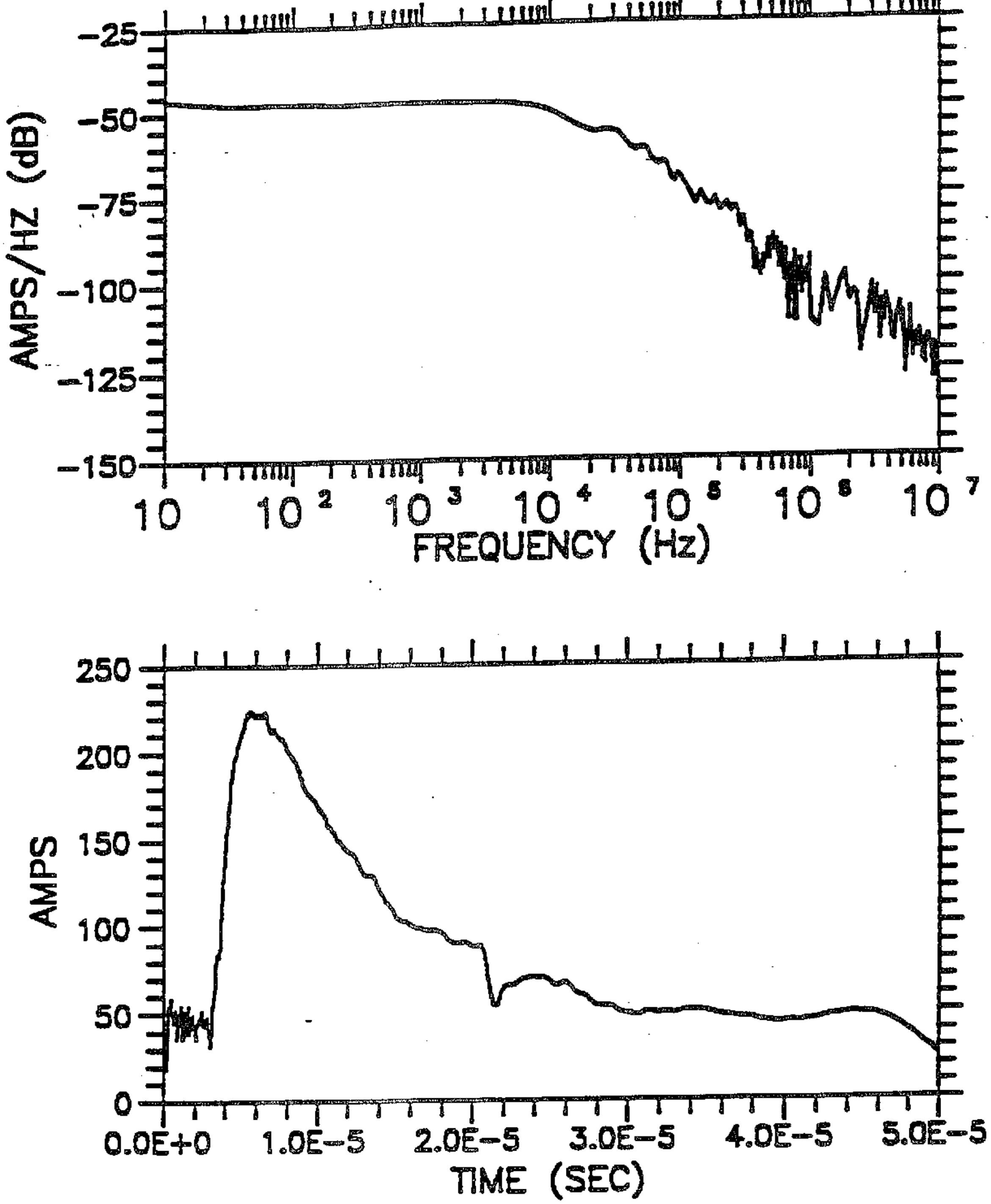


Figure 3-14. [redacted]).

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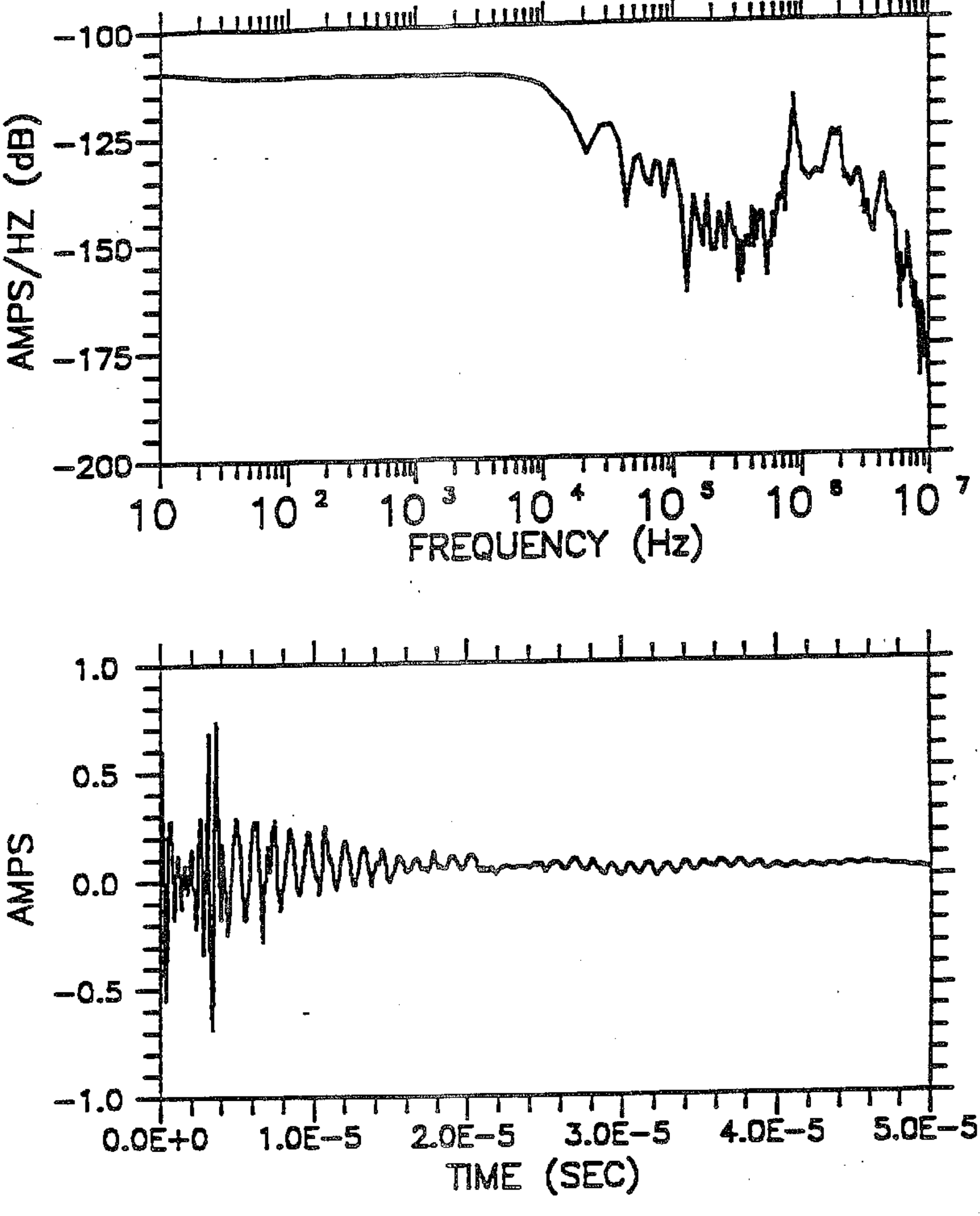

Figure 3-15. [redacted]

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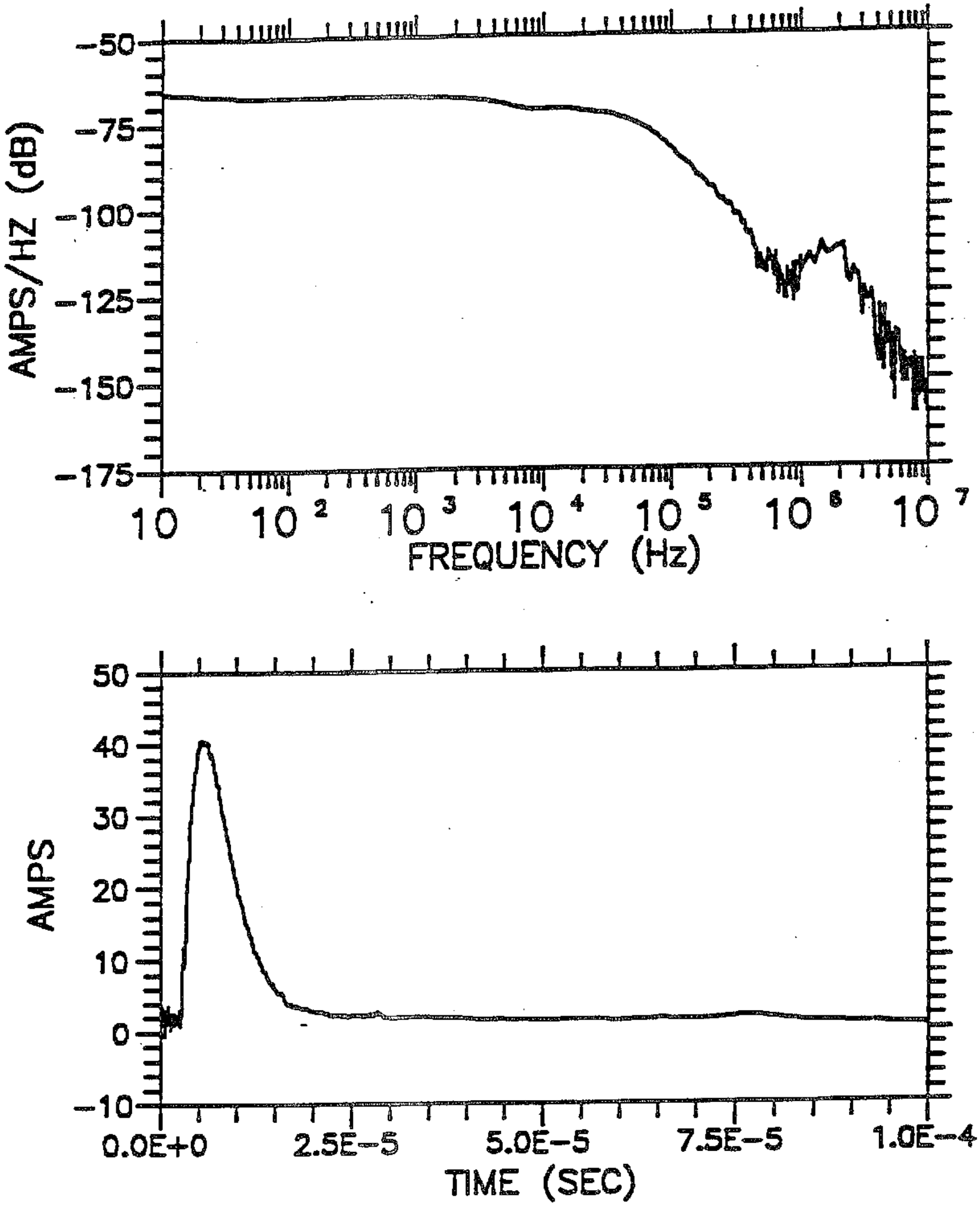

Figure 3-17[redacted]).

[redacted]

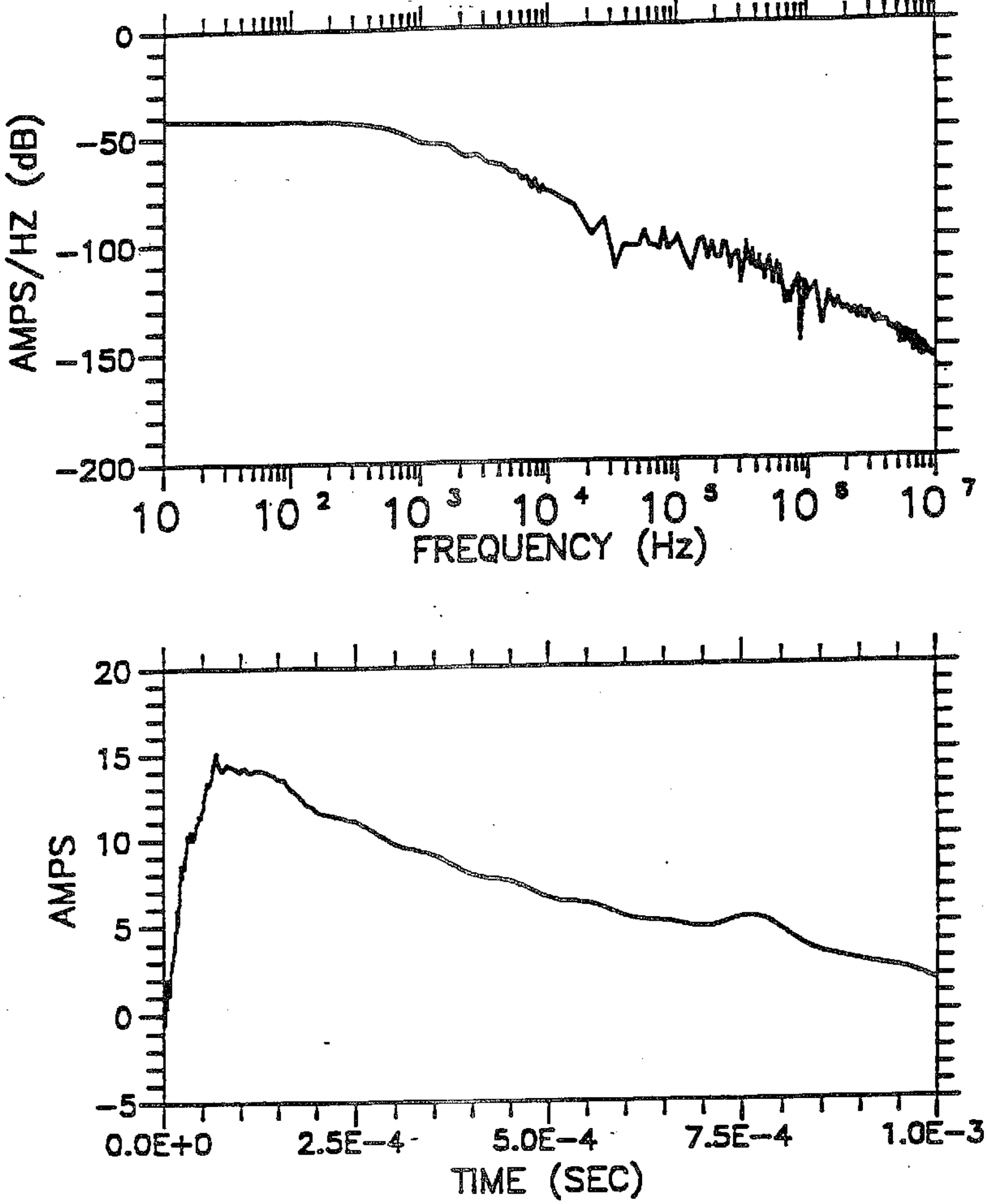

Figure 3-18. [redacted]

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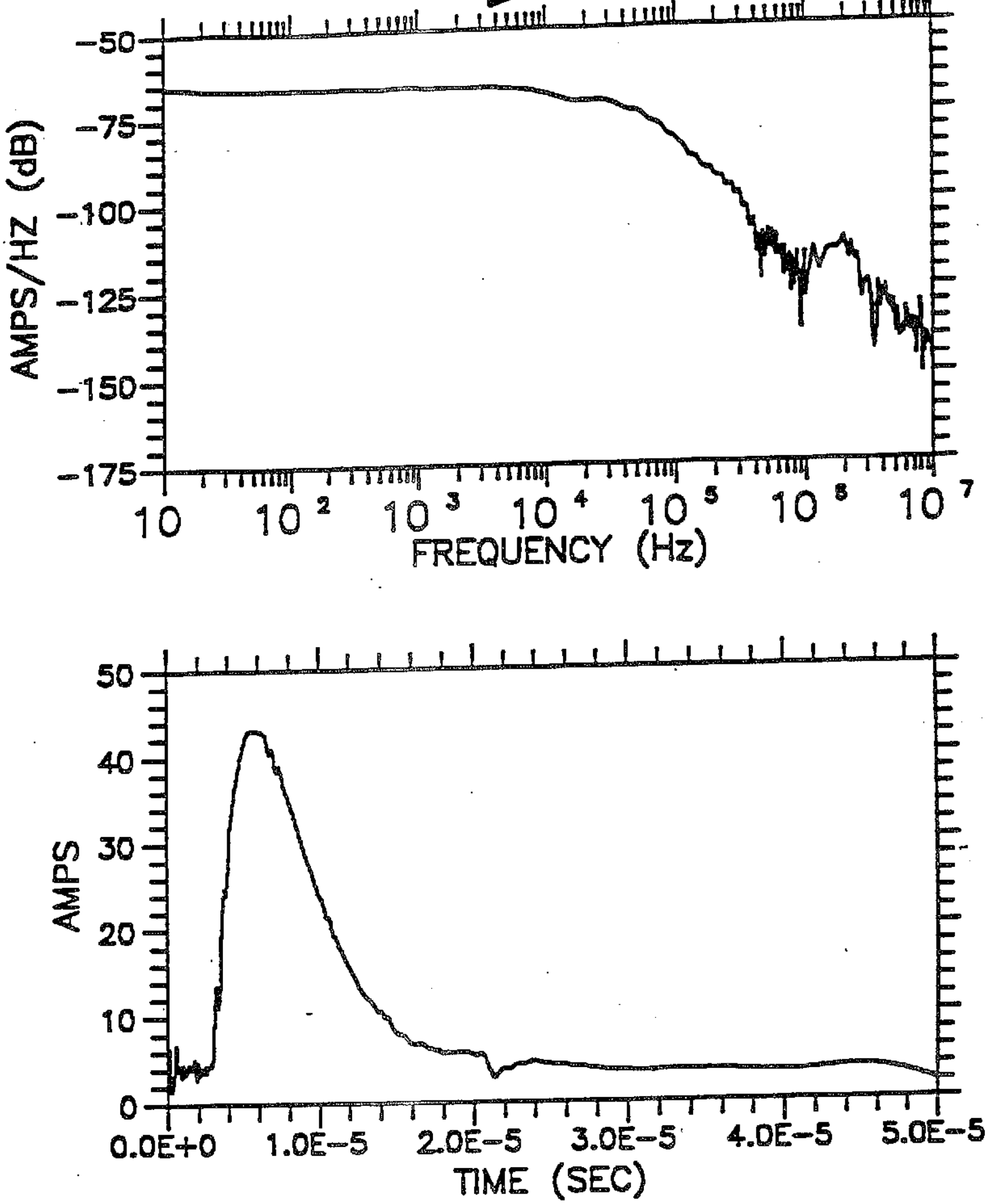

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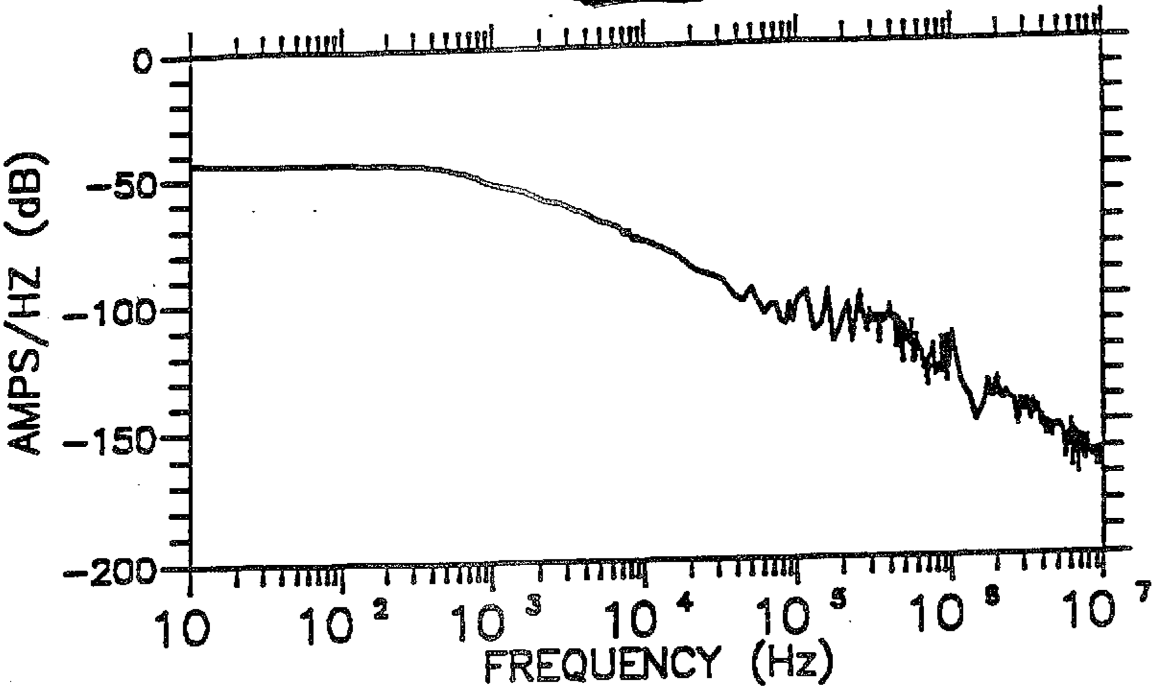

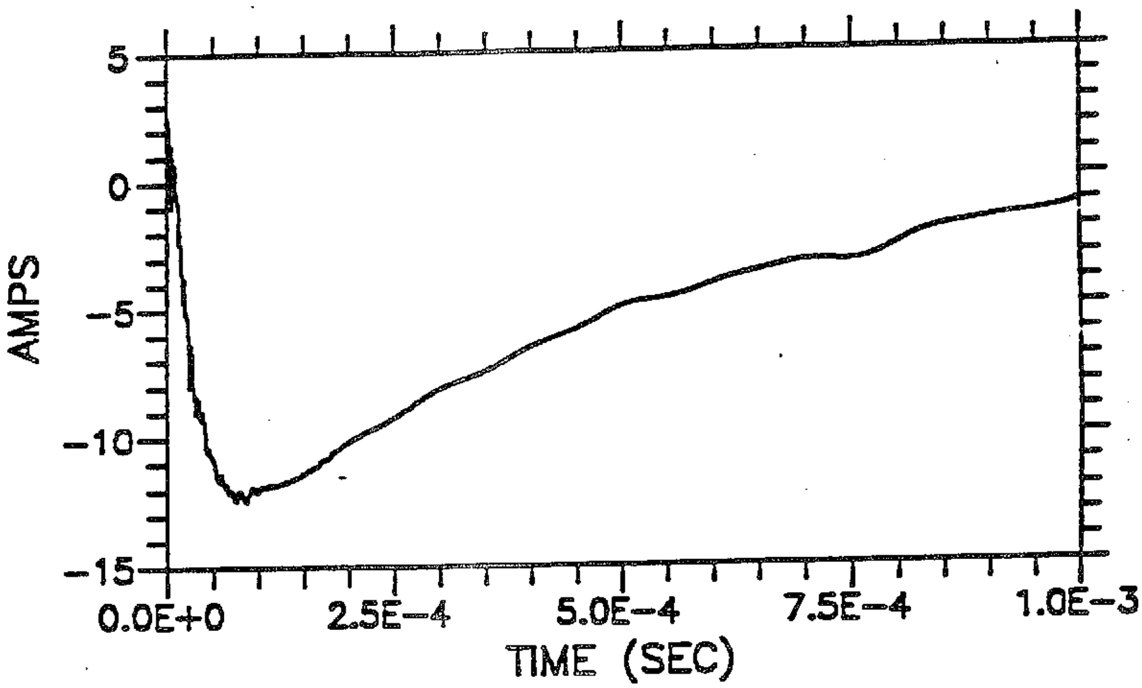

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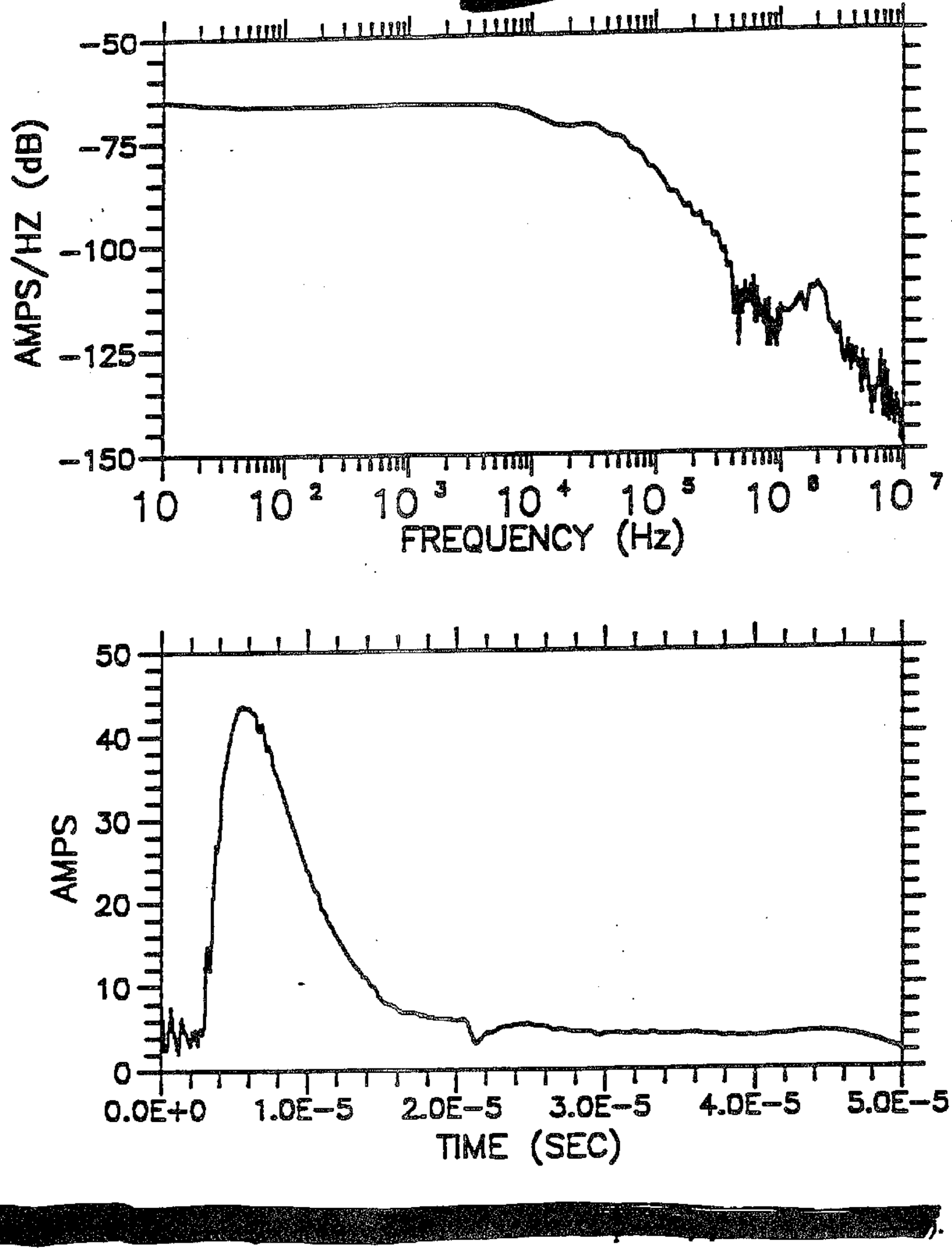

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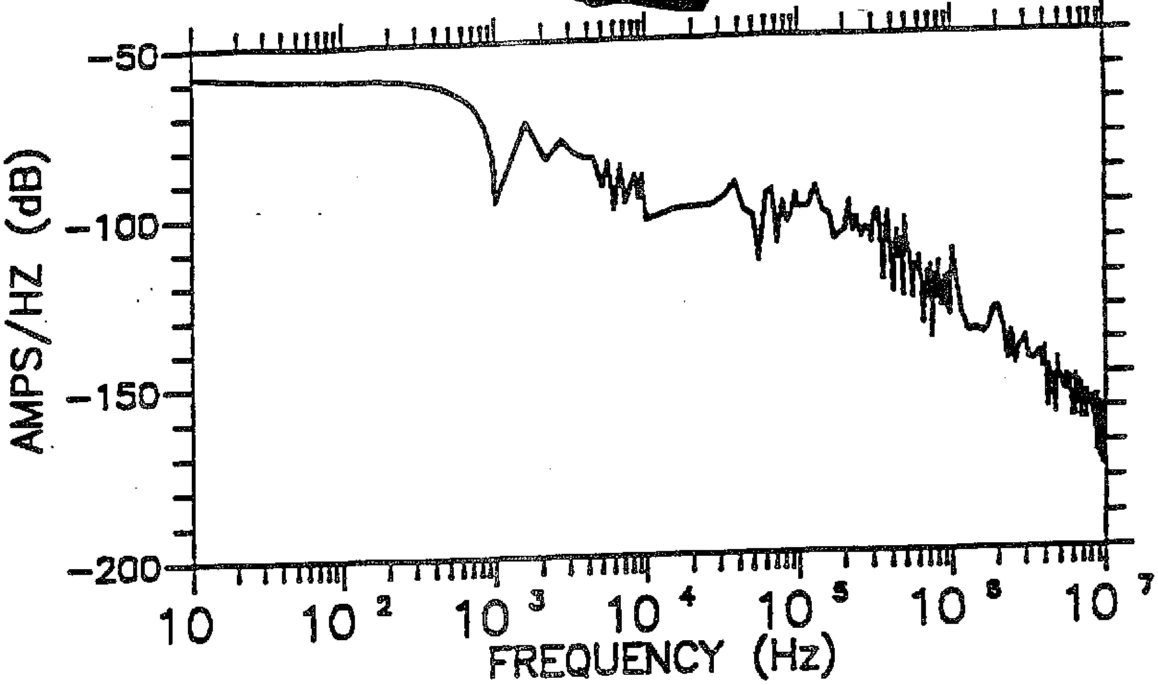

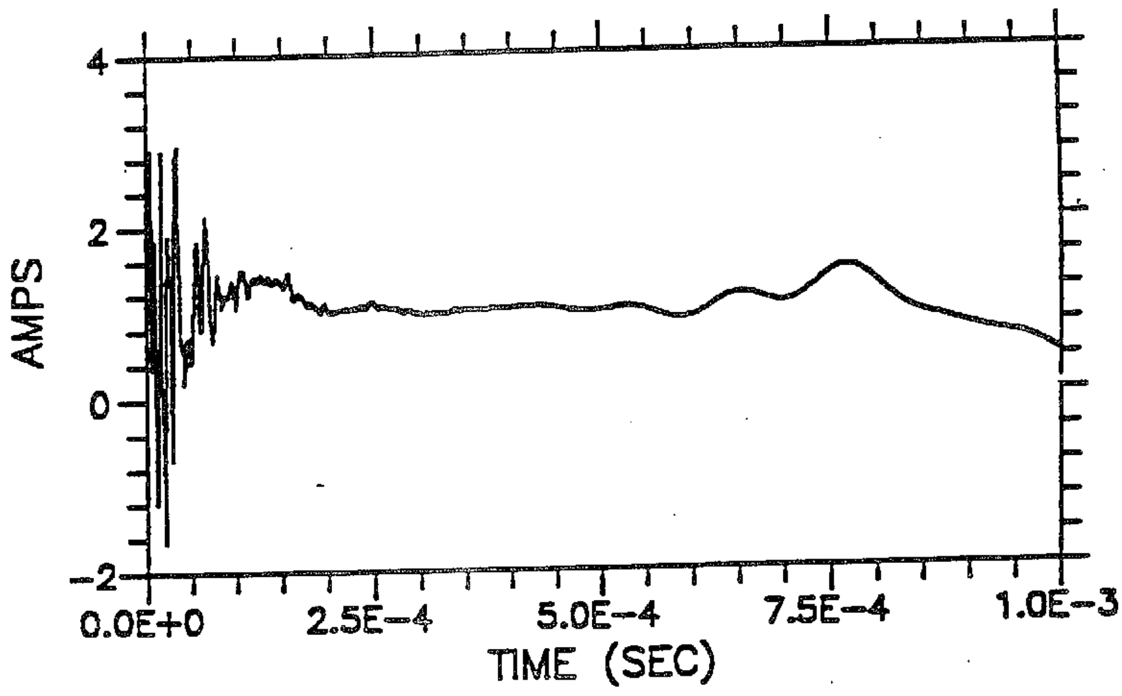

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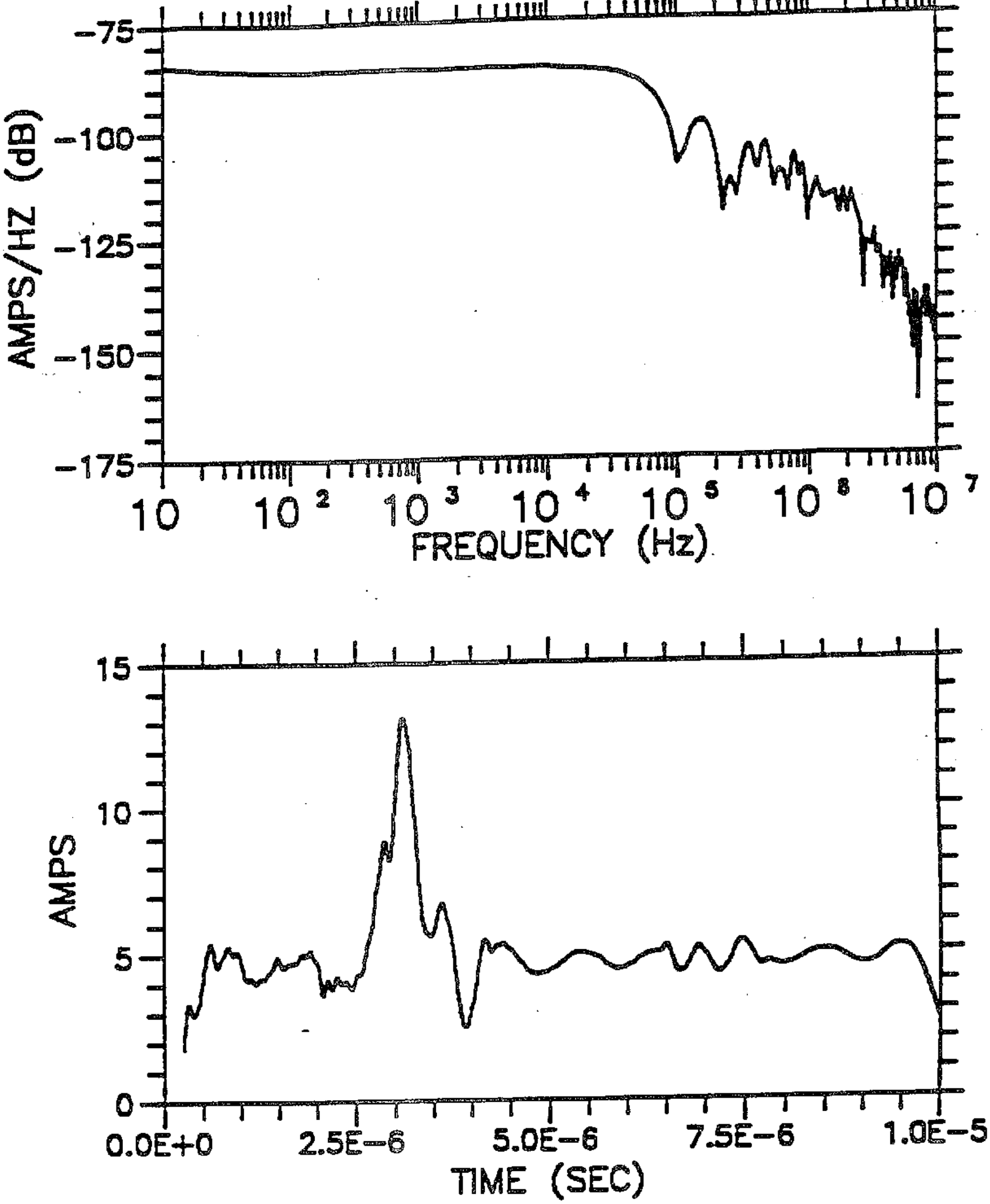

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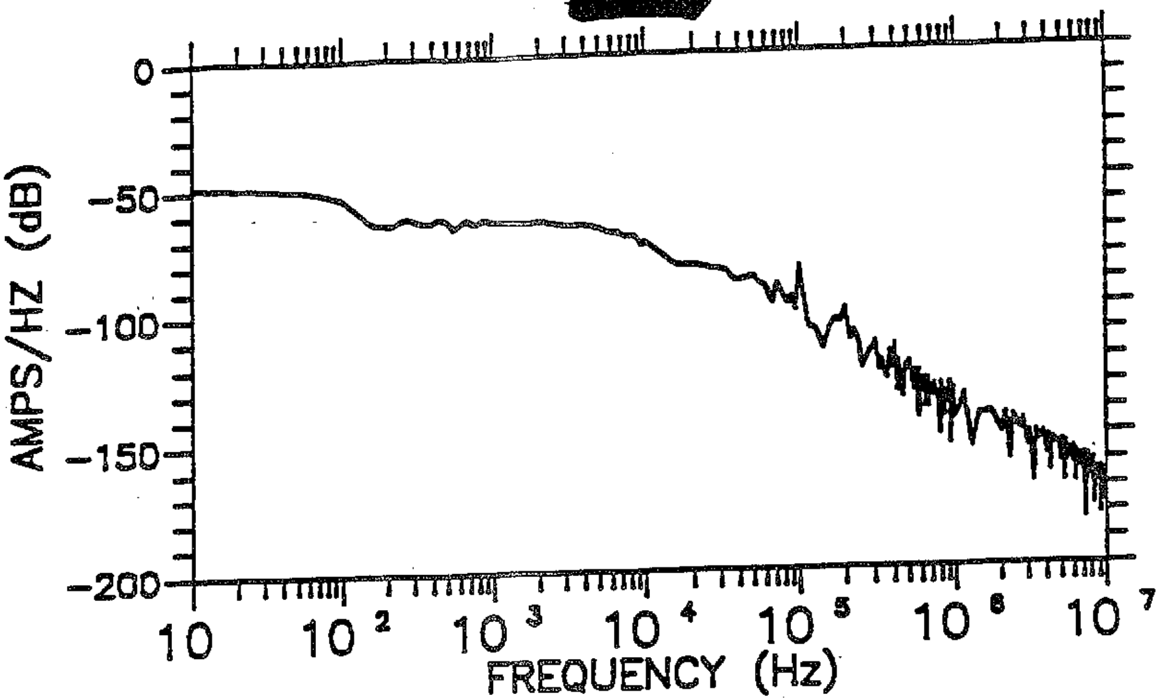

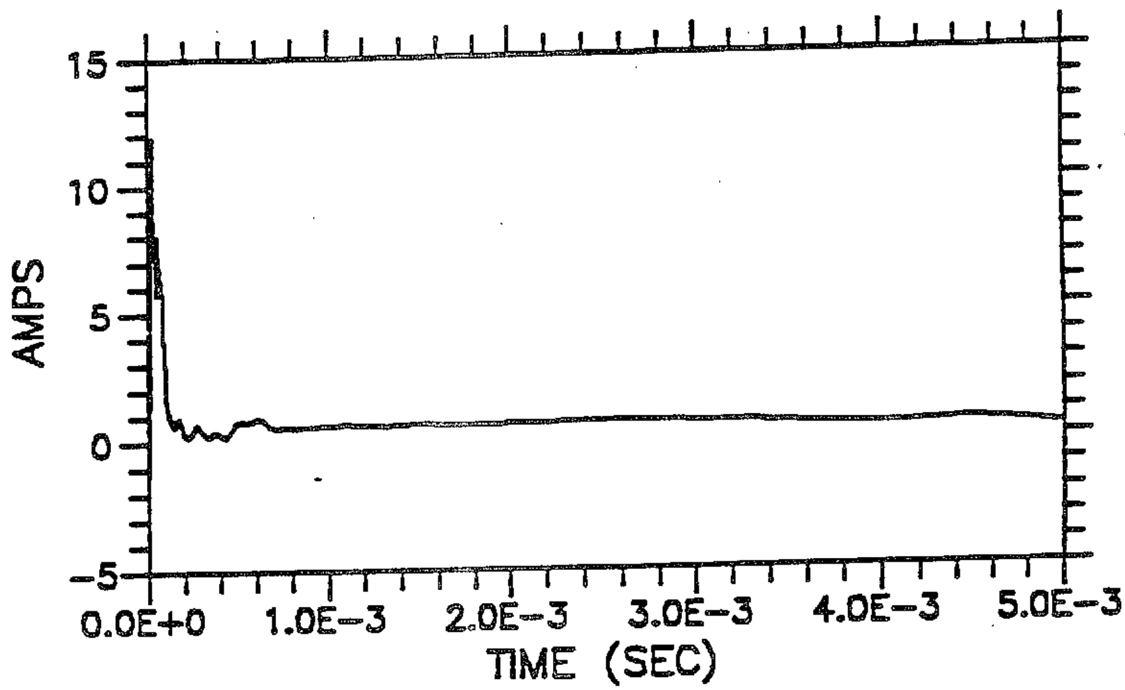

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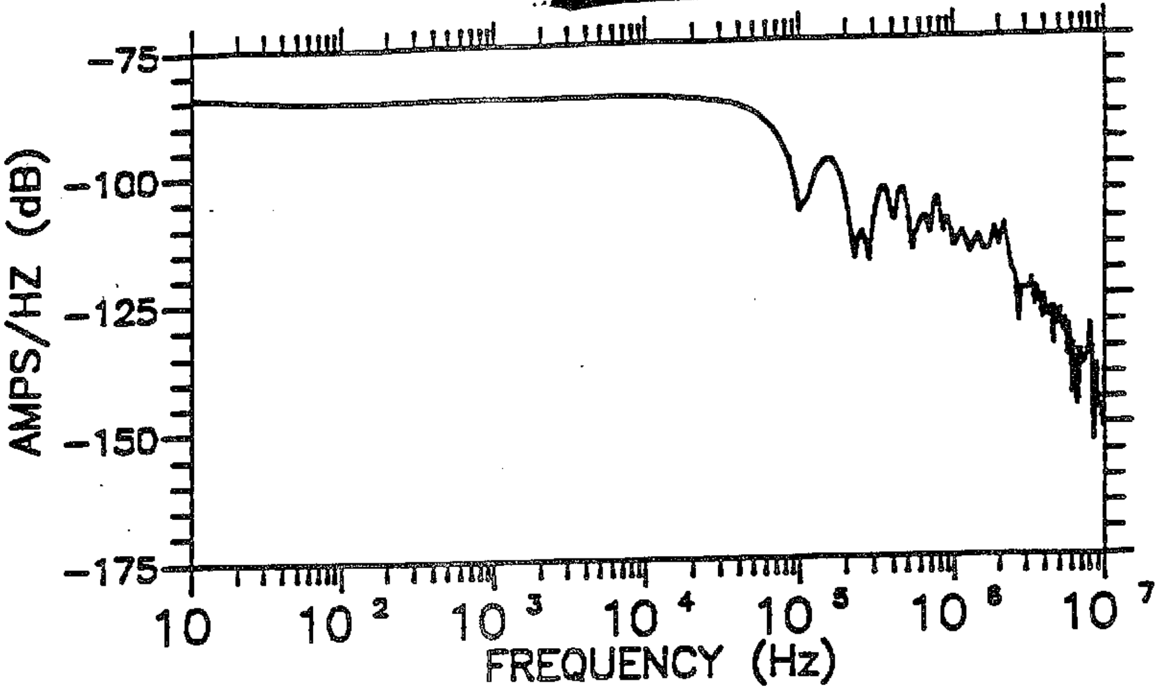

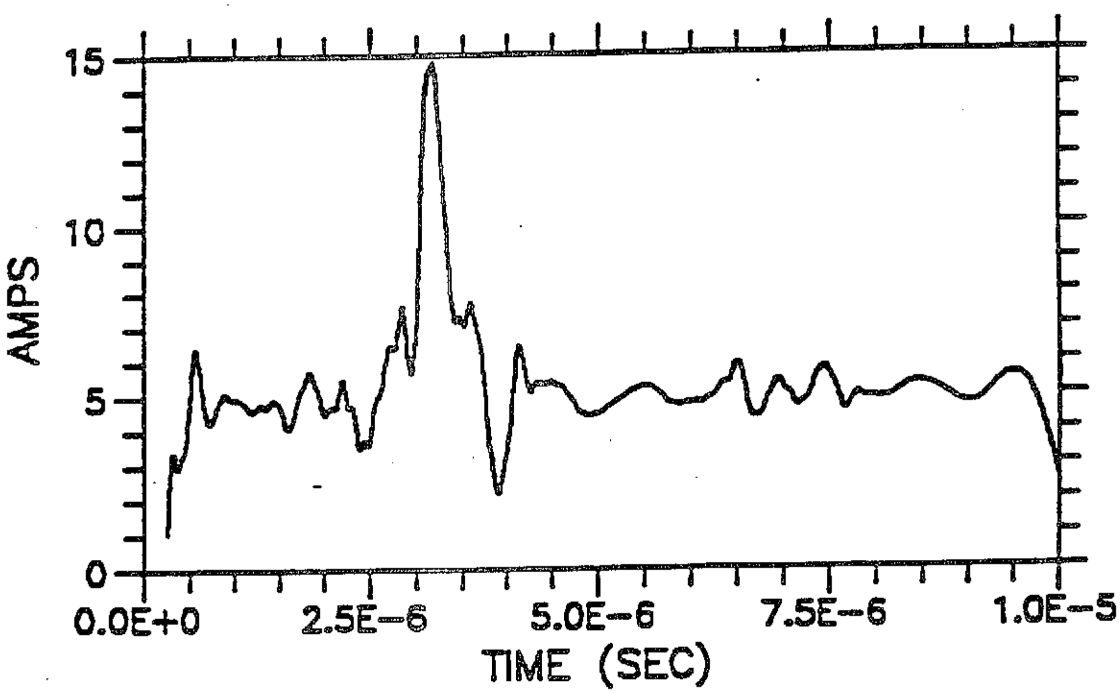

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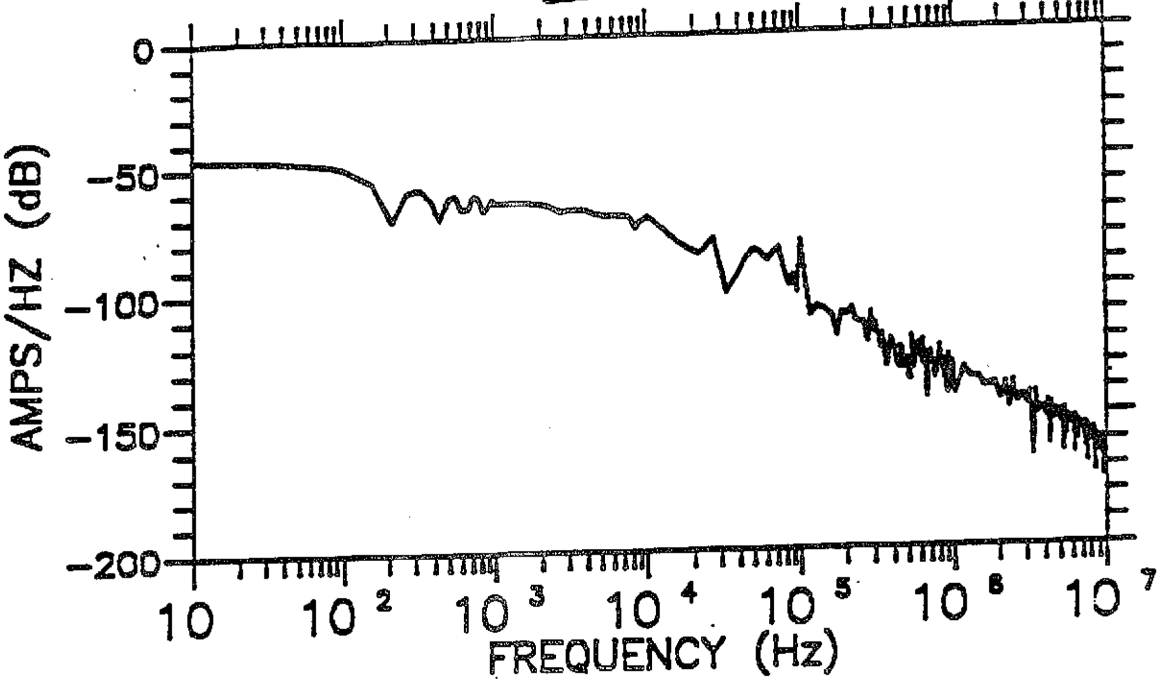

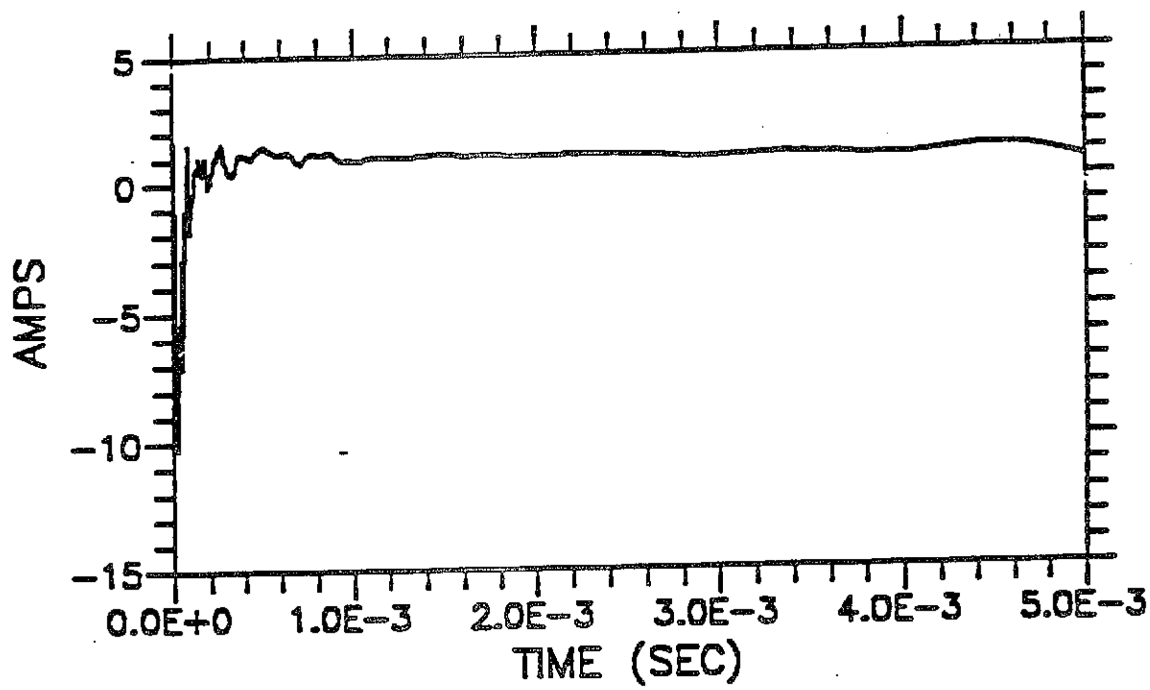

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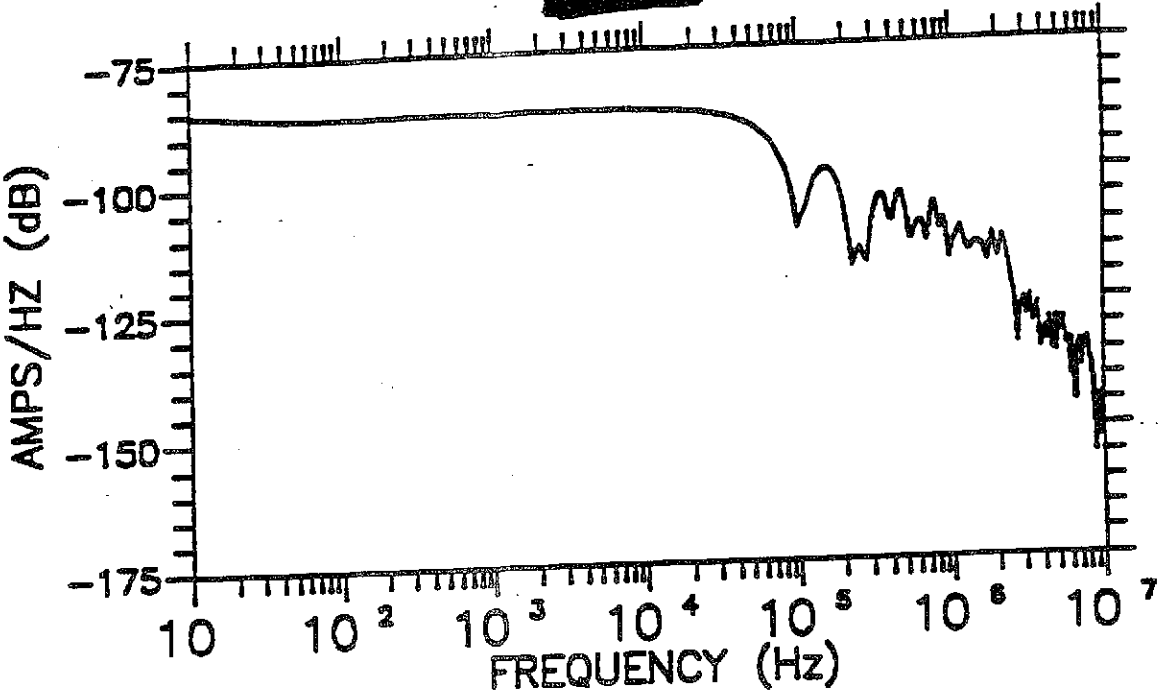

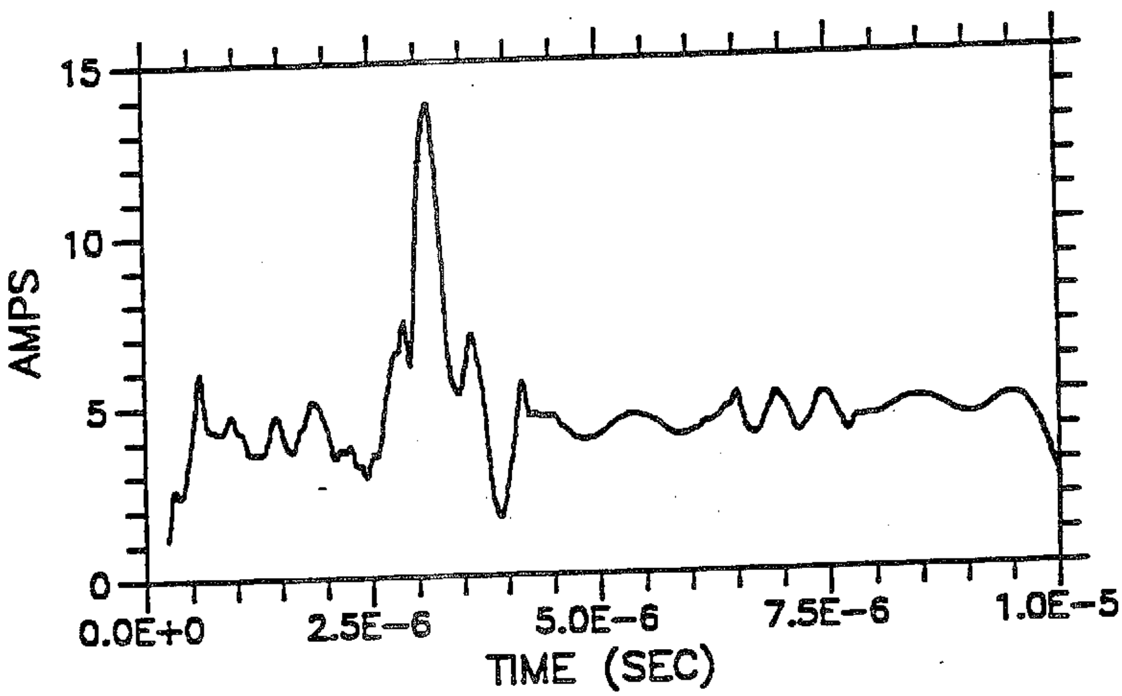

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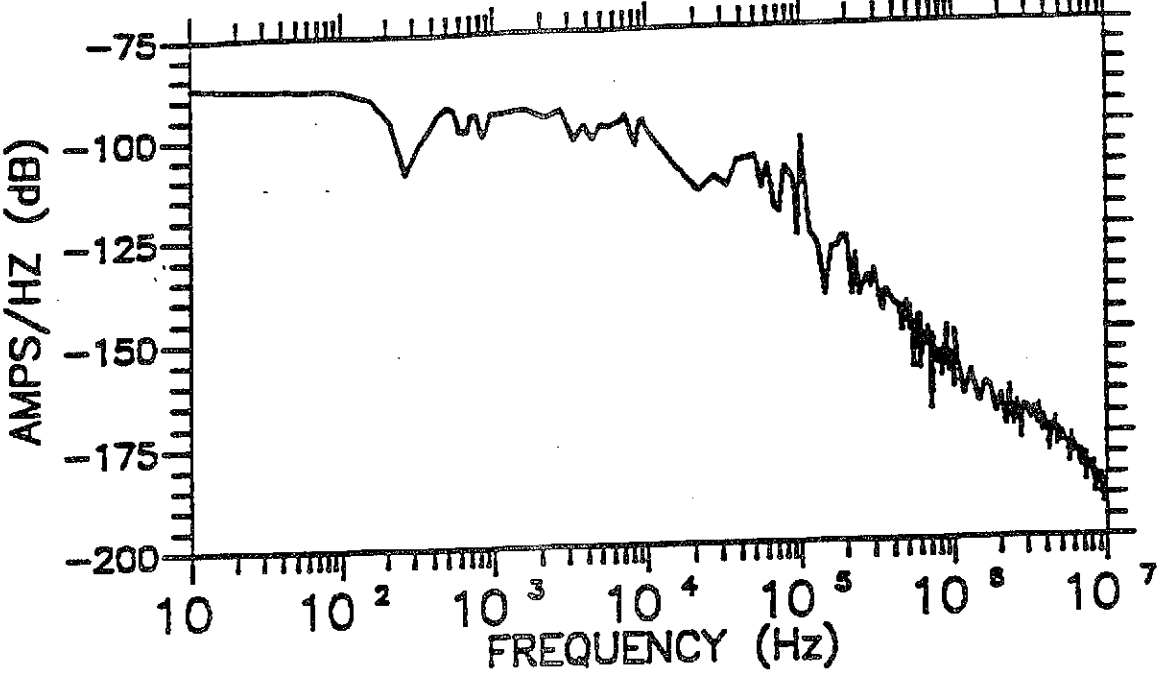

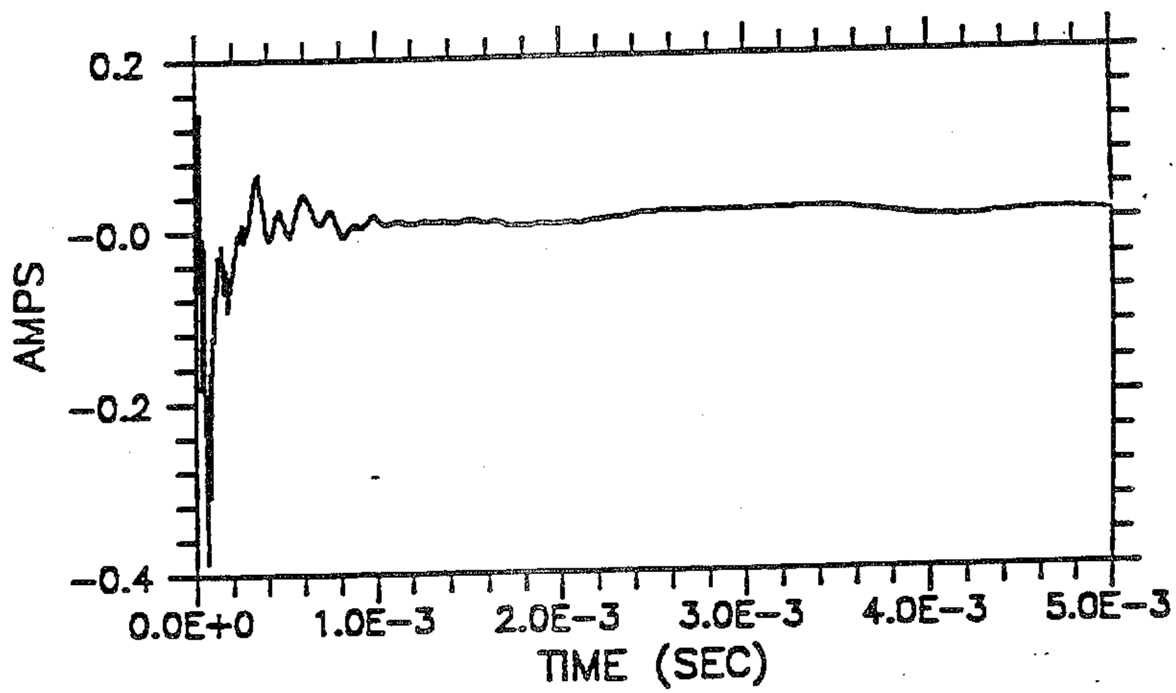

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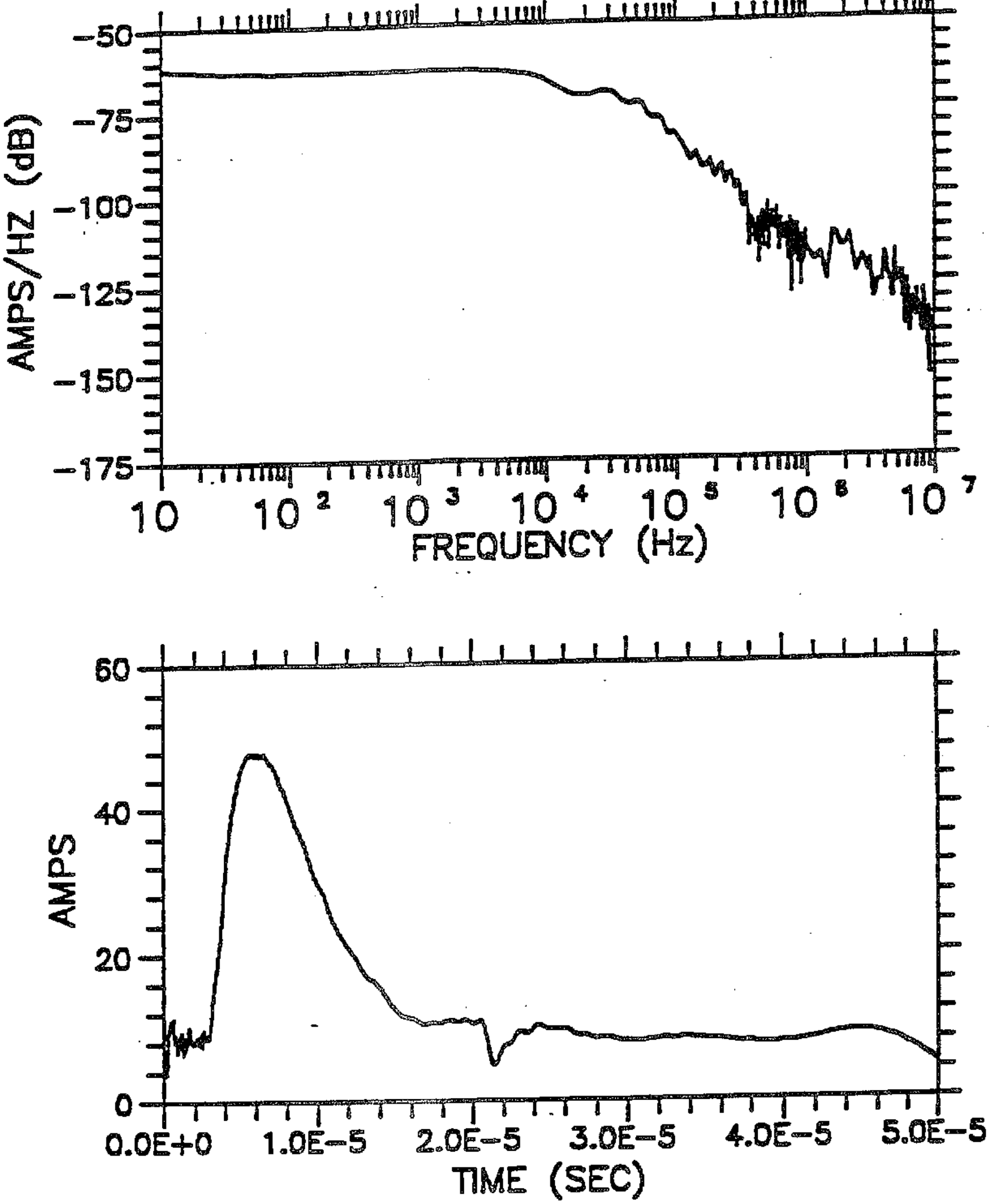

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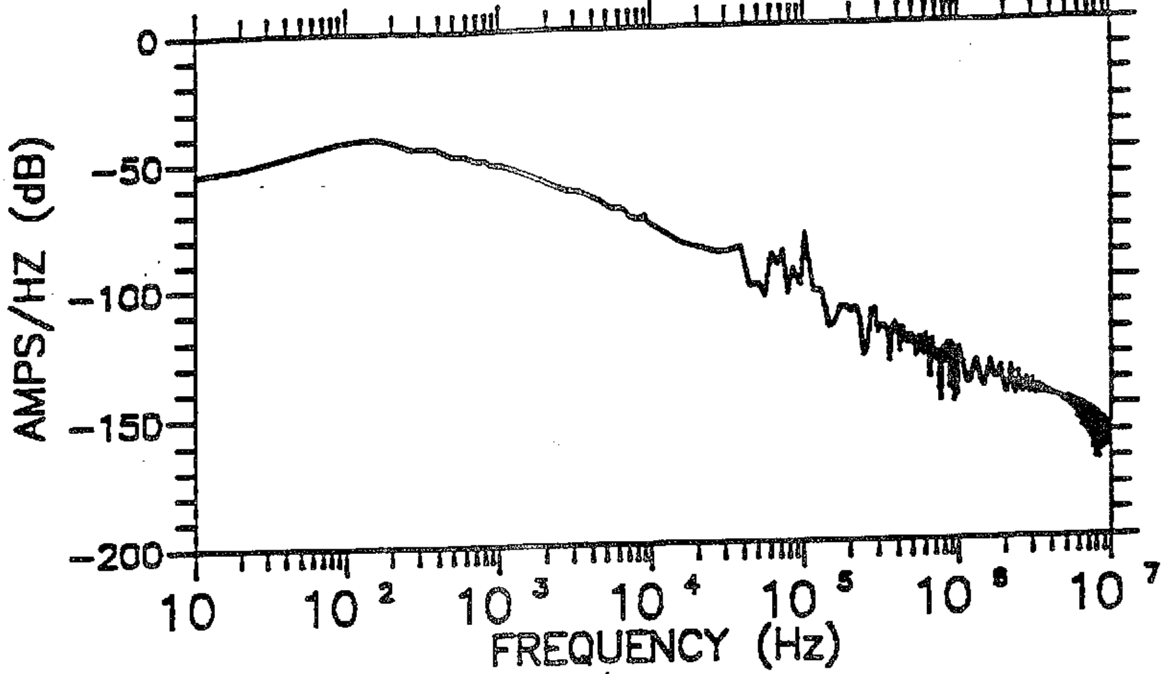

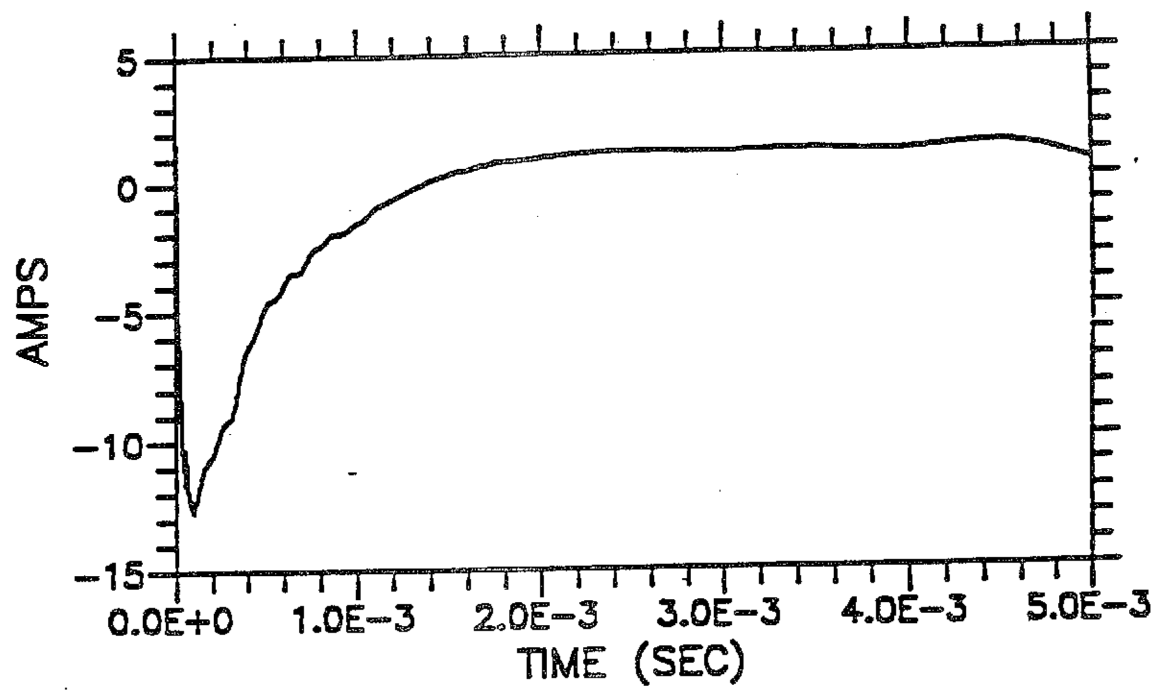

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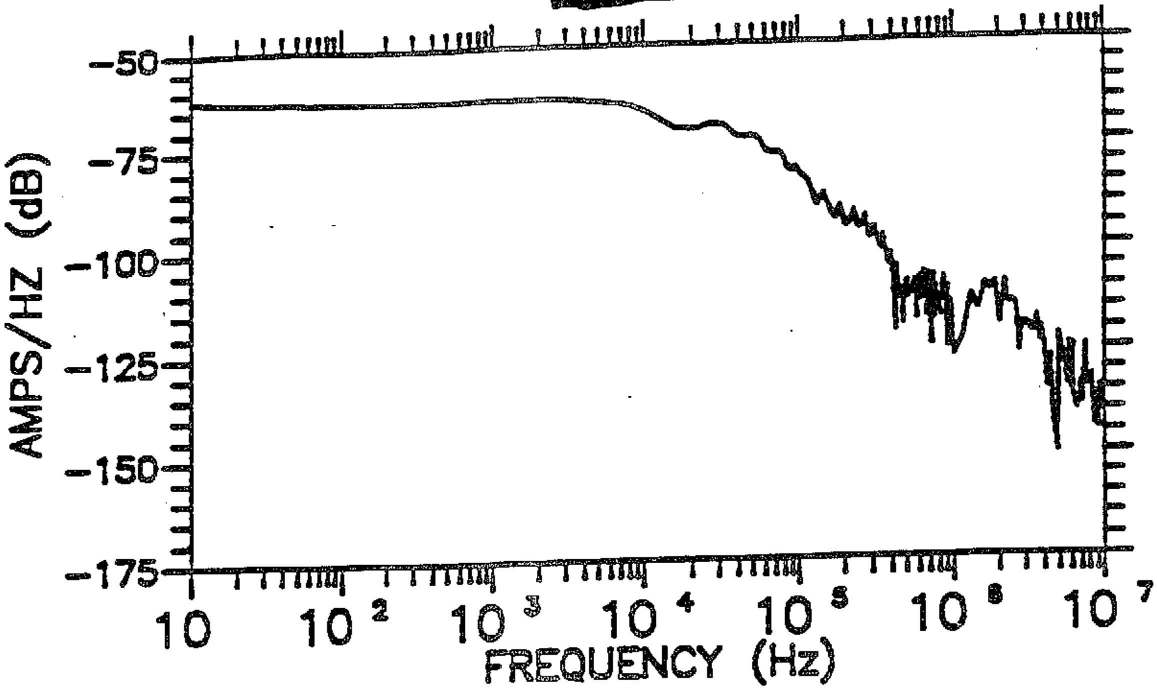

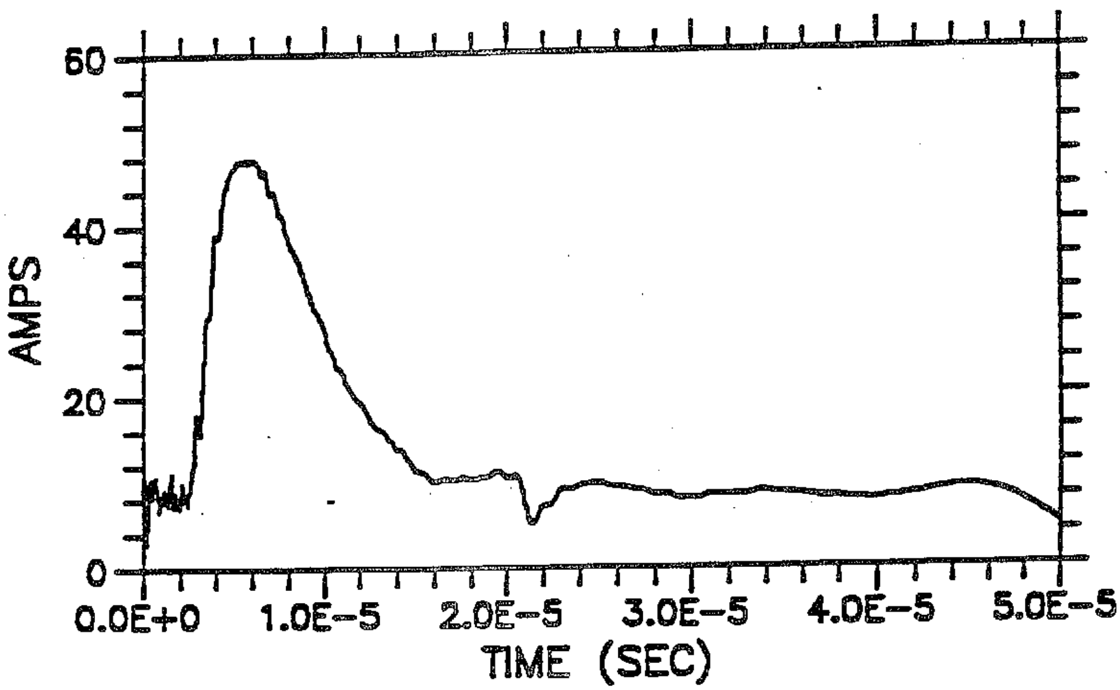

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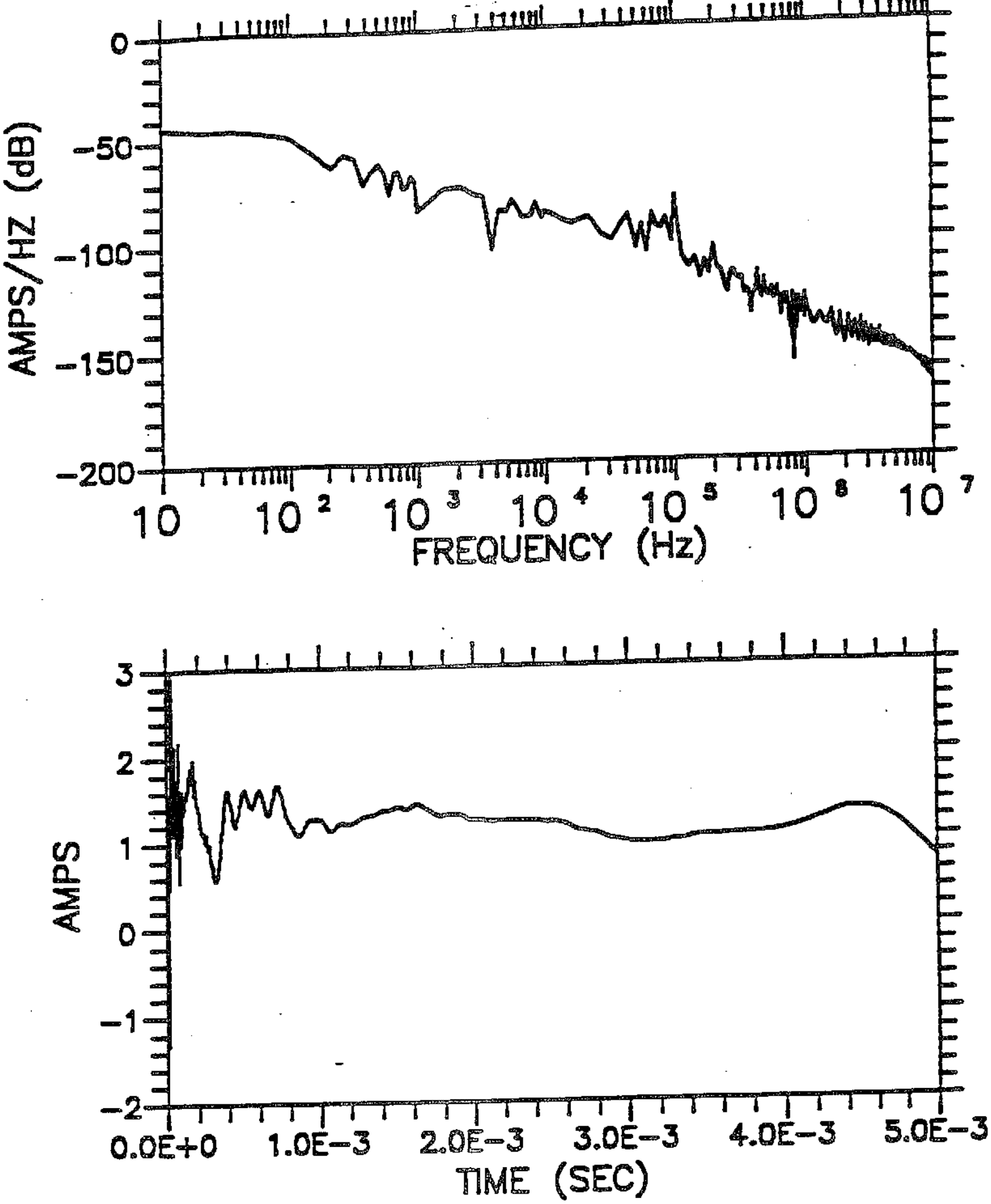

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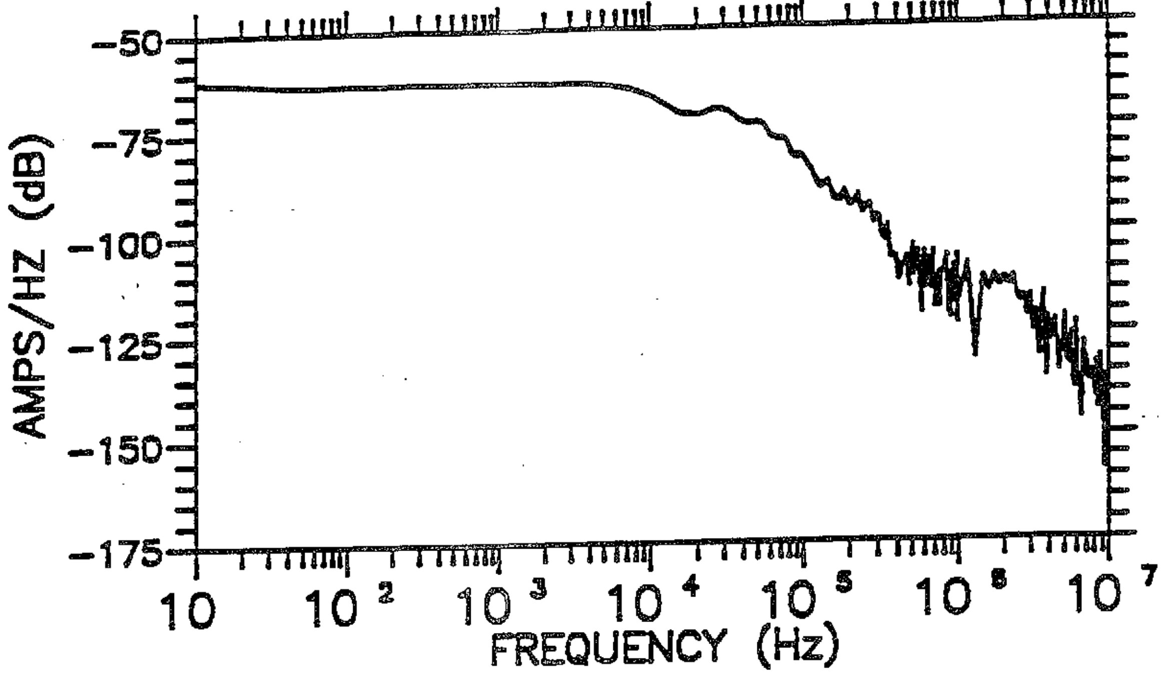

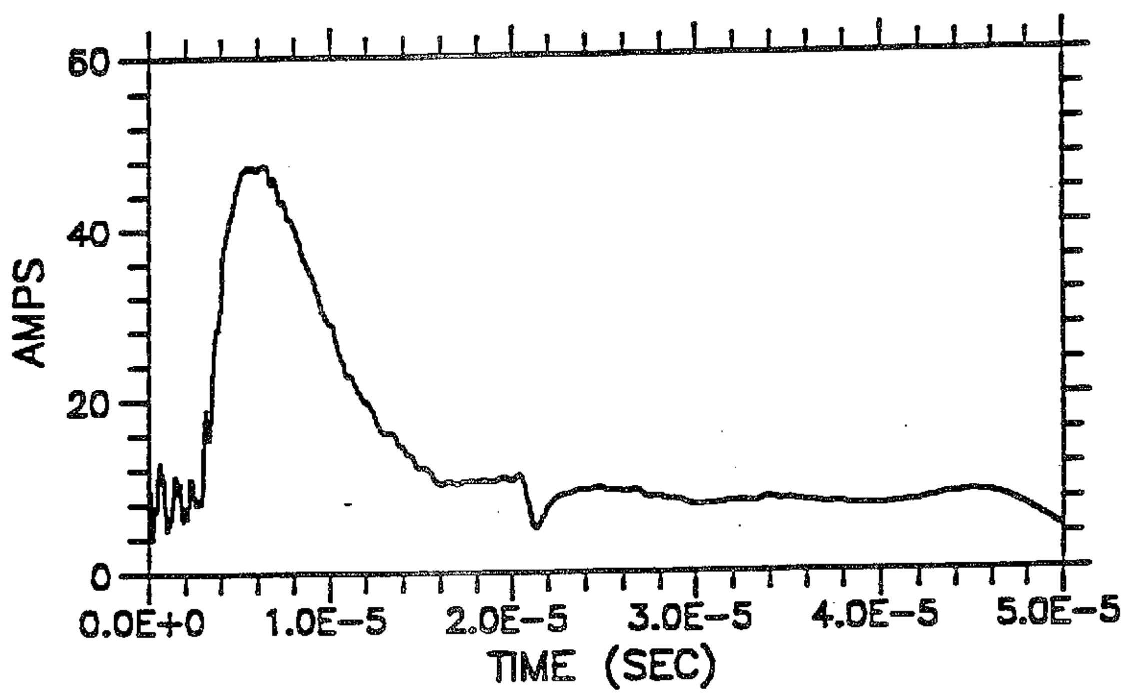

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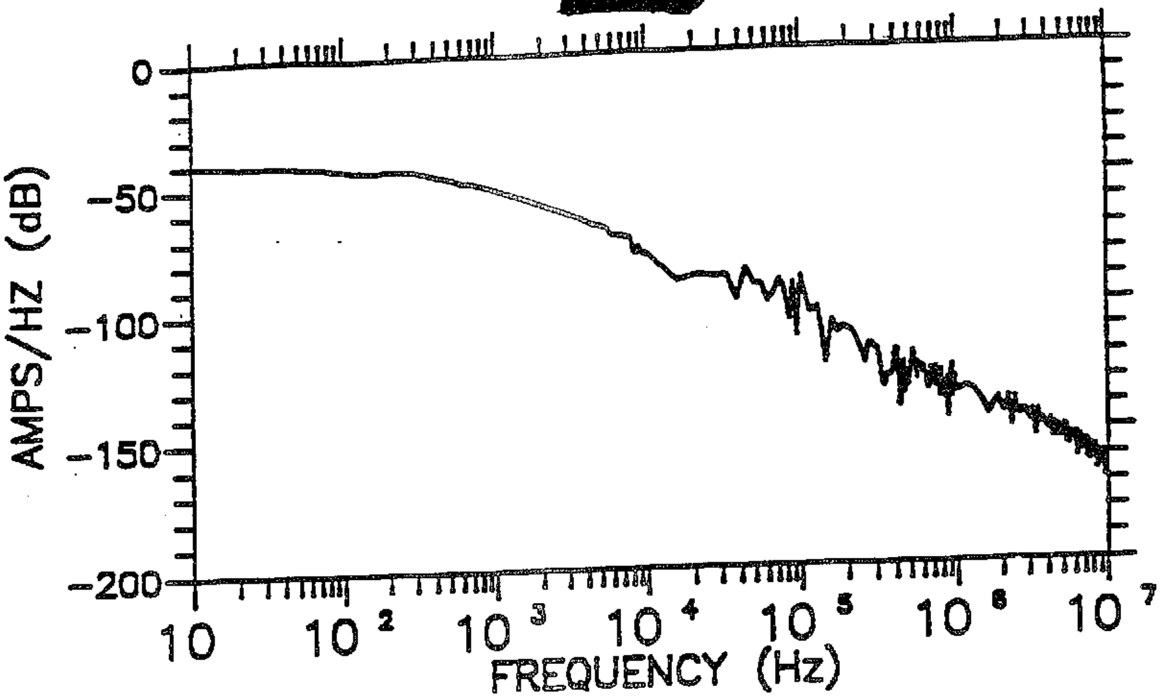

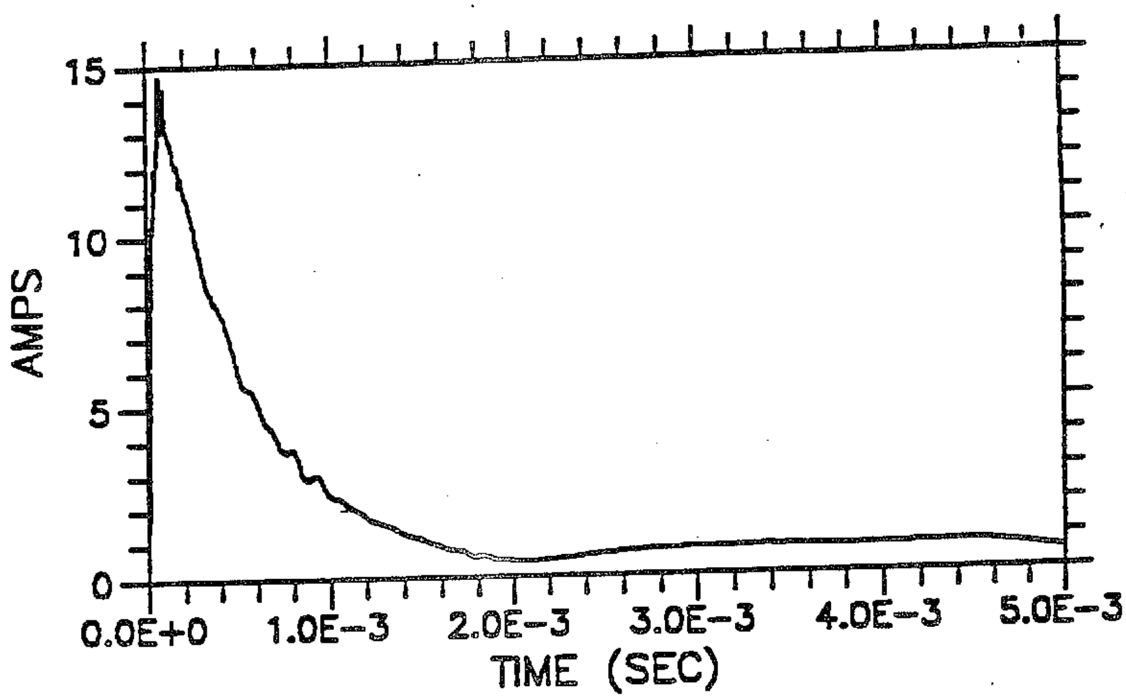

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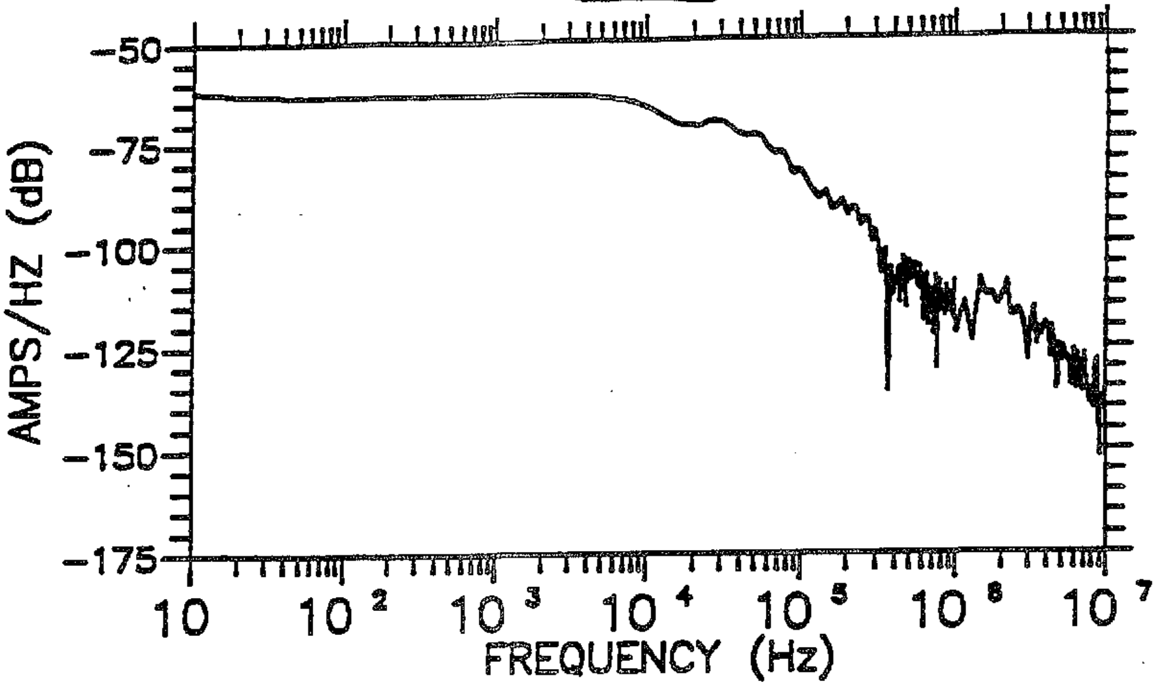

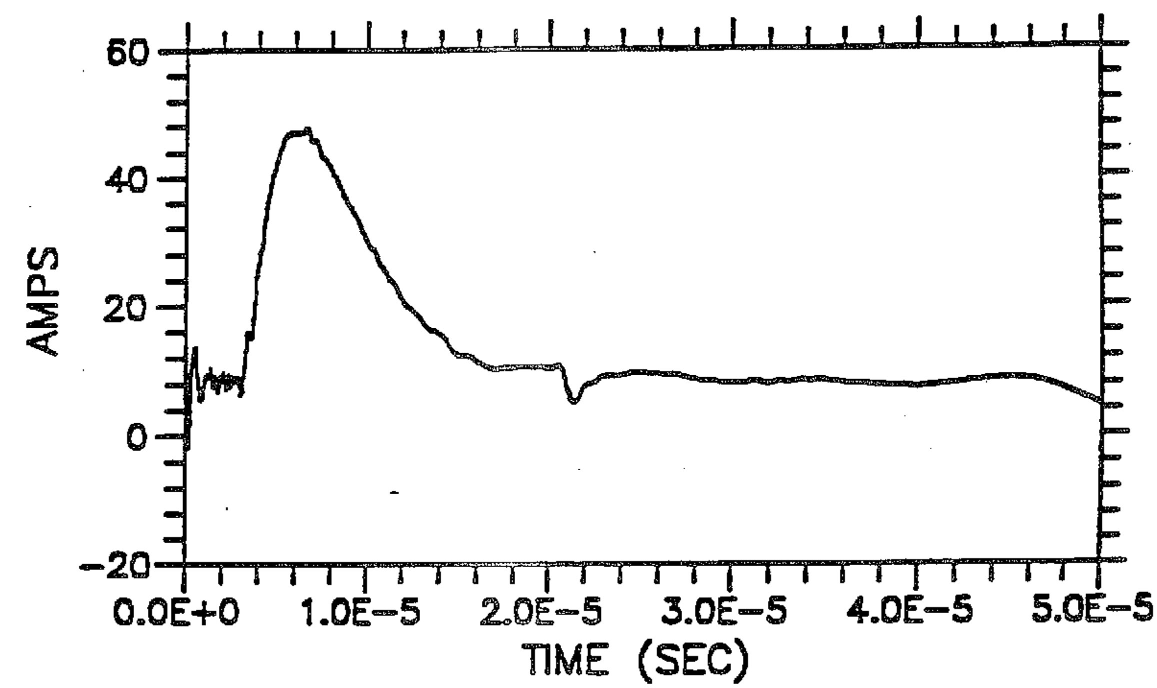

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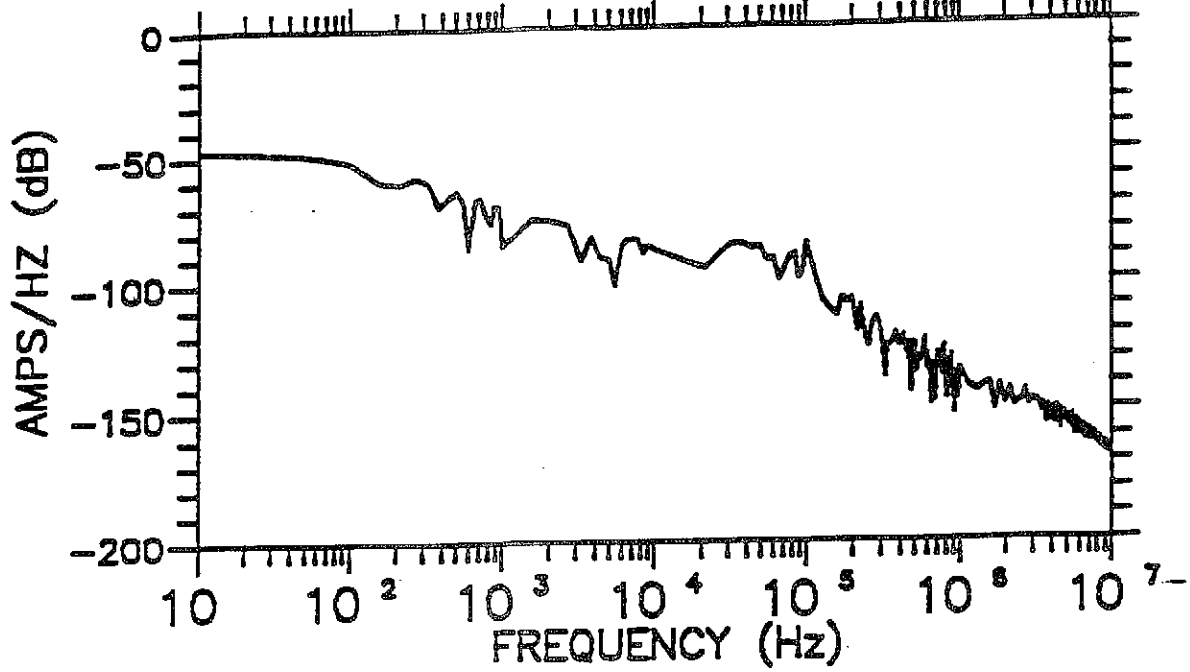

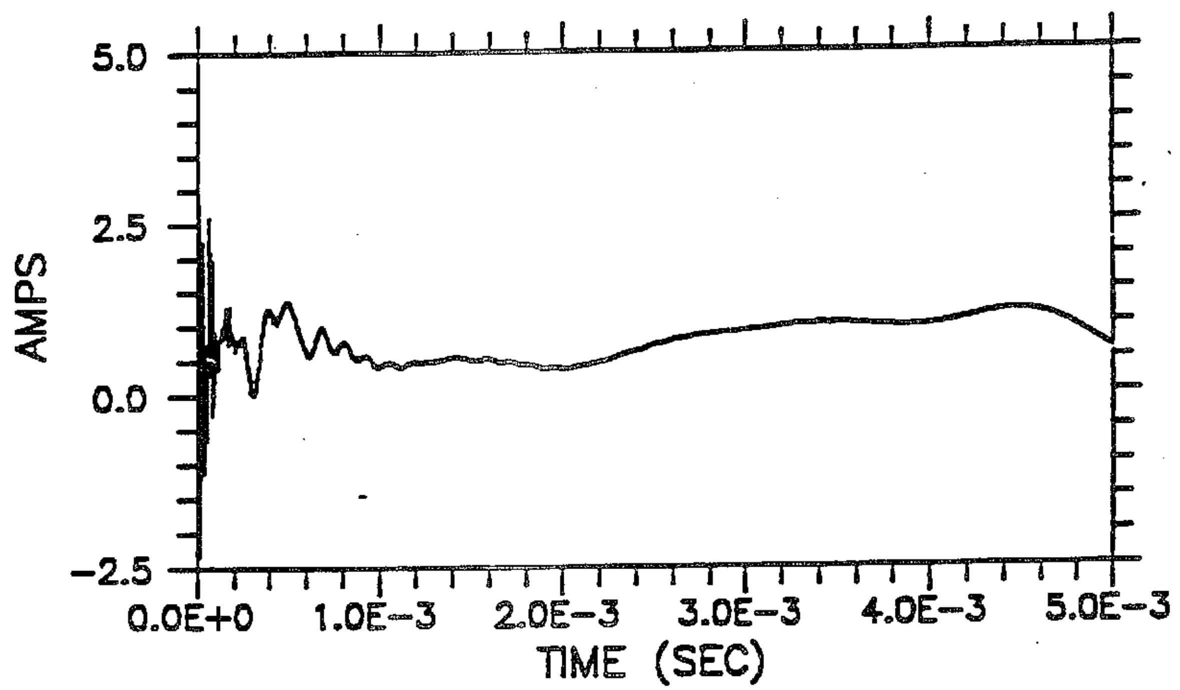

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SECTION 4

HEMP COUPLING MEASUREMENTS TO [redacted] ANTENNAS

4.1 OBJECTIVES AND OVERVIEW OF DATA ACQUIRED.

[redacted] antennas [redacted] were selected for CW illumination to measure the field-to-antenna transfer functions. These frequency domain measurements were then extrapolated to the HEMP environments, and inverse Fourier transformed.

From the time domain transients, the waveform descriptors [redacted] were calculated. [redacted]

Table 4-1 lists the acquired measurements (files). [redacted]

[redacted] antennas were illuminated with a field polarized parallel to the principal radiating structure to simulate worst-case HEMP coupling. In addition, most were also illuminated with a cross-polarized field (i.e., the simulator field was perpendicular to the antenna radiating structure). [redacted]

[redacted] Hence, Table 4-1 indicates two measurements (I_{sc}, I_{50}) for each illumination.

4.2 [redacted] ANTENNAS TESTED.

Brief descriptions of each antenna and simulation configurations are provided in the following subsections.

[redacted]

Table 4-1. CW illumination measurements of [redacted] antennas.

No.	Antenna	File	Polar.	load (ohms)	$R_o(x,y,z)$	$R_1(x,y,z)$	$F(R_o)/F(R_1)$ file	Peak (A)	[redacted]	[redacted]	Inside CWMS volume	Peak Error (dB)
1	[redacted]	H011	worst case	0	$H_z(45,0,1)$	$E_y(133,-3,13)$	HR1	2880	[redacted]	[redacted]	yes	
		H012	worst case	50	$H_z(45,0,1)$	$E_y(133,-3,13)$	HR1	1320	[redacted]	[redacted]	yes	2
		H021	perp.	0	$H_z(45,0,1)$	$E_y(133,-3,13)$	HR1	539			yes	
		H022	perp.	50	$H_z(45,0,1)$	$E_y(133,-3,13)$	HR1	304			yes	2
2	[redacted]	H051	perp.	0	$H_z(22,2,1)$	$E_y(79,8,13)$	HR5	250	[redacted]	[redacted]	yes	
		H052	perp.	50	$H_z(22,2,1)$	$E_y(79,8,13)$	HR5	125	[redacted]	[redacted]	yes	4

Table 4-1. CW illumination measurements of [redacted] antennas. (Continued)

No.	Antenna	File	Polar.	load (ohms)	$R_o(x,y,z)$	$R_1(x,y,z)$	$F(R_o)/F(R_1)$ file	Peak (A)	[redacted]	[redacted]	Inside CWMS volume	Peak Error (dB)
3	[redacted]	H061	perp.	0	$H_z(22,2,1)$	$E_y(79,8,13)$	HR5	372	[redacted]	[redacted]	yes	
	[redacted]	H062	perp.	50	$H_z(22,2,1)$	$E_y(79,8,13)$	HR5	180	[redacted]	[redacted]	yes	< 1
4	[redacted]	V091A	worst case	0	$H_y(54,0,1)$	$E_z(54,0,13)$	VR9C	47	[redacted]	[redacted]	yes	
		V092A	worst case	50	$H_y(54,0,1)$	$E_z(54,0,13)$	VR9C	10	[redacted]	[redacted]	yes	5
		H091	perp.	0	$H_z(41,-35,1)$	$E_y(41,-35,13)$	HR9	8			no	
	[redacted]	H092	perp.	50	$H_z(41,-35,1)$	$E_y(41,-35,13)$	HR9	2			no	

Table 4-1. CW illumination measurements of [redacted] antennas. (Continued)

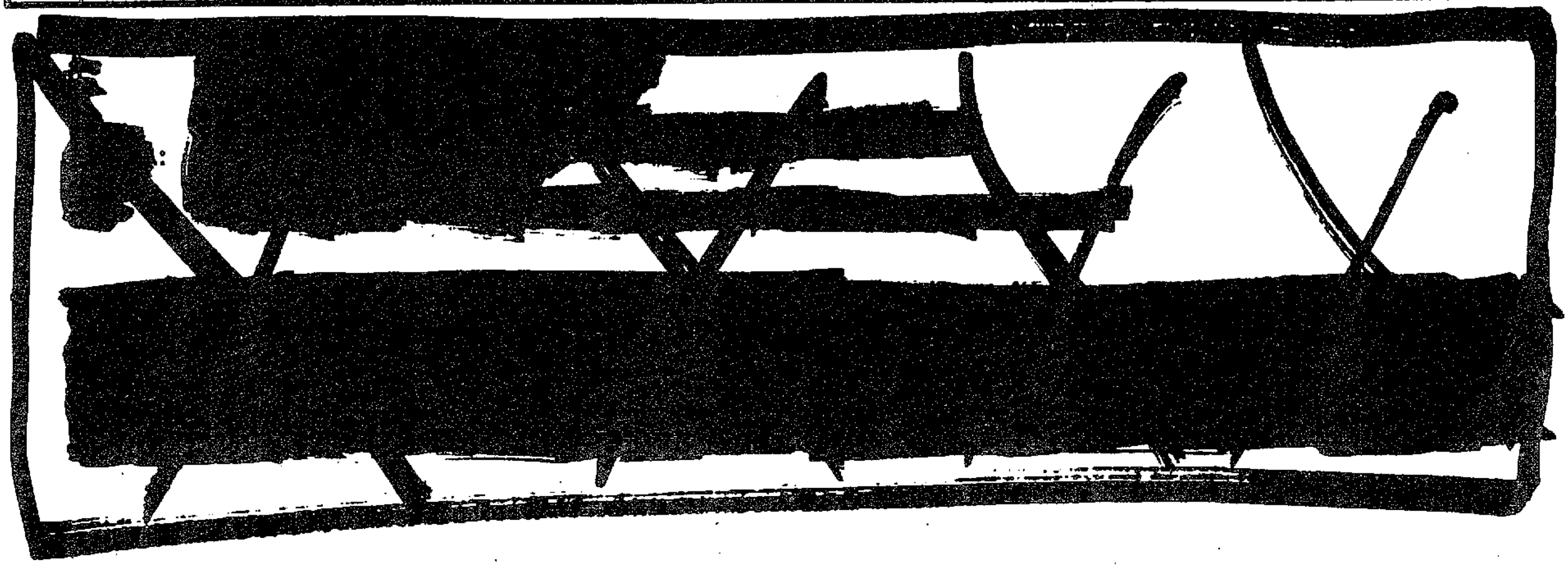
No.	Antenna	File	Polar.	load (ohms)	$R_o(x,y,z)$	$R_1(x,y,z)$	$F(R_o)/F(R_1)$ file	Peak (A)	[redacted]	[redacted]	Inside CWMS volume	Peak Error (dB)
[redacted]	[redacted]	V101	worst case	0	$H_y(54,0,1)$	$E_z(54,0,13)$	VR9C	25	[redacted]	[redacted]	yes	
		V102	worst case	50	$H_y(54,0,1)$	$E_z(54,0,13)$	VR9C	12	[redacted]	[redacted]	yes	5
		H101	perp.	0	$H_z(41,-35,1)$	$E_y(41,-35,13)$	HR9	11			no	
	[redacted]	H102	perp.	50	$H_z(41,-35,1)$	$E_y(41,-35,13)$	HR9	5			no	
[redacted]	[redacted]	V111	worst case	0	$H_y(54,0,1)$	$E_z(54,0,13)$	VR9C	52	[redacted]	[redacted]	yes	
		V112	worst case	50	$H_y(54,0,1)$	$E_z(54,0,13)$	VR9C	20	[redacted]	[redacted]	yes	5
		H111	perp.	0	$H_z(41,-35,1)$	$E_y(41,-35,13)$	HR9	39			no	
	[redacted]	H112	perp.	50	$H_z(41,-35,1)$	$E_y(41,-35,13)$	HR9	21			no	-

Table 4-1. CW illumination measurements of [redacted] antennas. (Continued)

No.	Antenna	File	Polar.	load (ohms)	$R_o(x,y,z)$	$R_1(x,y,z)$	$F(R_o)/F(R_1)$ file	Peak (A)	[redacted]	[redacted]	Inside CWMS volume	Peak Error (dB)
[redacted]	[redacted]	H031A	worst case	0		$E_y(43,66,13)$	live ref.	827	[redacted]	[redacted]	no	
		H032A	worst case	50		$E_y(43,66,13)$	live ref.	472	[redacted]	[redacted]	no	3
		V031	perp.	0	$H_y(63,0,1)$	$E_z(79,0,13)$	VR3	191			yes	
		V032	perp.	50	$H_y(63,0,1)$	$E_z(79,0,13)$	VR3	156			yes	3
[redacted]	[redacted]	H041	worst case	0	$H_x(11,-19,1)$	$E_y(28,-50,13)$	FLDCHK1	2320	[redacted]	[redacted]	no	
		H042	worst case	50	$H_x(11,-19,1)$	$E_y(28,-50,13)$	FLDCHK1	1370	[redacted]	[redacted]	no	2
		V041	perp.	0	$H_y(22,0,1)$	$E_z(57,0,13)$	VR4	711			yes	
		V042	perp.	50	$H_y(22,0,1)$	$E_z(57,0,13)$	VR4	405			yes	2

Table 4-1. CW illumination measurements of [redacted] antennas. (Continued)

No.	Antenna	File	Polar.	load (ohms)	$R_o(x,y,z)$	$R_i(x,y,z)$	$F(R_o)/F(R_i)$ file	Peak (A)	[redacted]	[redacted]	Inside CWMS volume	Peak Error (dB)
[redacted]	[redacted]	V071	worst case	0	$H_y(38,0,1)$	$E_z(191,0,13)$	VR7	402	[redacted]	[redacted]	yes	
		V072	worst case	50	$H_y(38,0,1)$	$E_z(191,0,13)$	VR7	196	[redacted]	[redacted]	yes	1



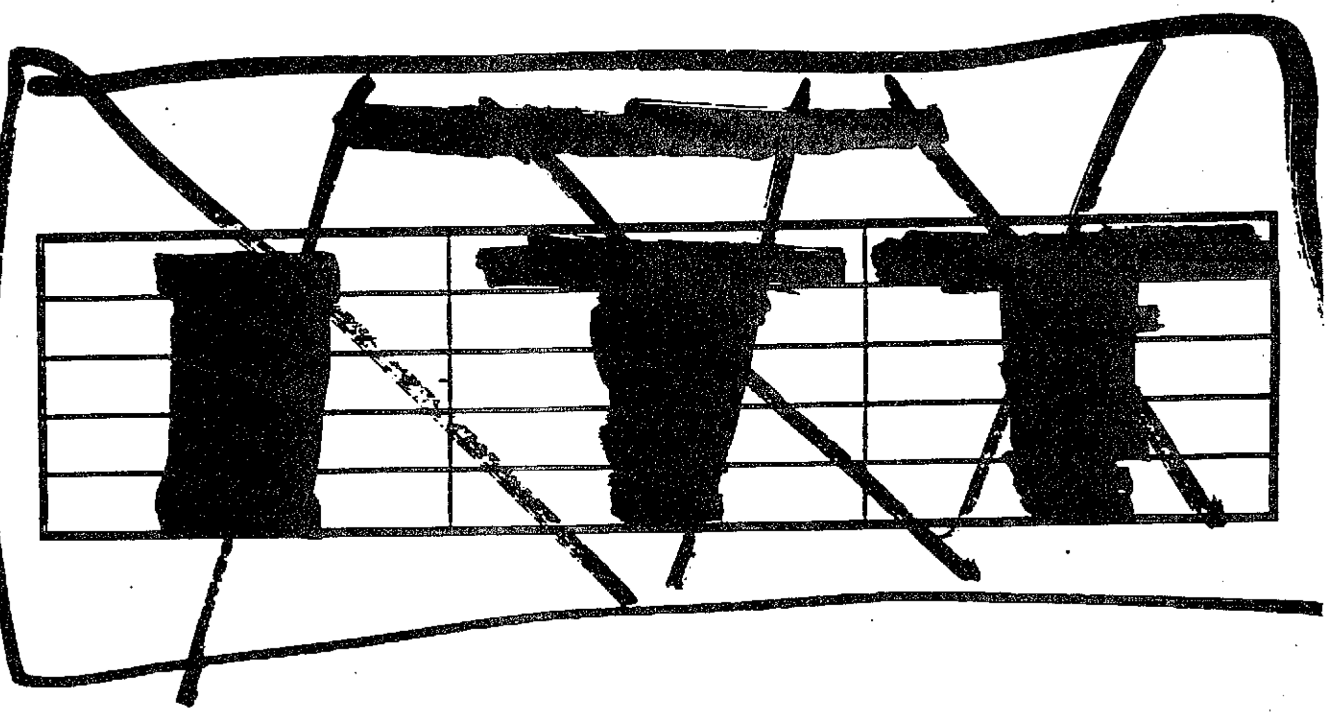
[redacted]. First, the center line [redacted] was aimed at the supporting tower for the CWMS drooping dipole antenna. This orientation is depicted as [redacted] worst case threat (filenames H011 and H012). [redacted]s parallel to the CWMS drooping dipole [redacted] depicted as arrow 2 in Figure 4-2 (filenames H021 and H022). [redacted] operating volume of the CWMS horizontally polarized simulator.

4.2.2 [redacted]

[redacted]

4.2.3 [redacted]

[redacted]



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4.2.5 [redacted]

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4.3 DESCRIPTION OF THE TESTS AND DATA PROCESSING.

4.3.1 Horizontally Polarized Illumination.

Test Setup: Figure 4-9 shows the CWMS simulator used to radiate horizontally polarized fields; i.e., the major electric field is parallel to the ground. The simulator uses an inverted-V dipole to radiate at discrete frequencies between 100 kHz to 102 MHz, and a logperiodic antenna from 102 MHz to 1 GHz. [redacted]

Ideally, one would measure the transfer function I_{ANT}/E_y, where I_{ANT} is the current in the antenna line, and E_y is the field at the antenna location, but with the antenna removed (i.e., the undisturbed total field at the antenna location). If this transfer function could be measured, the HEMP induced current could simply be obtained by multiplying this transfer function by the E_y produced by HEMP at the same location.

In practice, the antenna cannot be "temporarily removed." To measure the undisturbed (i.e., not affected by the antenna scatter) simulation field, the field sensor is placed away from the antenna in an open area. In addition, due to test equipment constraints and the rough terrain, it was also necessary to utilize an intermediate field measurement closer to the simulator. These field measurements are referred to as "reference sensor" measurements below.

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In sum, the measurement setup was as shown in Figure 4-9. Hence, the antenna current relative to the simulator field at R_1 is:

$$\frac{I_{ANT}}{E_y\,(R_1)}\,(\omega) = \left[\frac{I_{ANT}}{H_z\,(R_o)}\right] \cdot \left[\frac{H_z\,(R_o)}{E_y\,(R_1)}\right] \qquad (A \cdot m/V) \tag{4-1}$$

where the quantities in the square brackets indicate measurements. The first measurement is the antenna current relative to the magnetic field at R_0, and the second is the electric field at R_1; i.e., closest to the antenna, relative to the magnetic field at R_0. Since the magnetic field cancels out (in theory and in practice), the antenna current relative to E_y at R_1 is obtained. The reference locations R_0 and R_1 are identified in Table 4-1 for each measurement.

Processing: To calculate the antenna response due to a HEMP, the transfer function in Equation (4-1) is extrapolated; i.e., it is multiplied by the electric field strength which a HEMP would produce at R_1. The denominator of the transfer function is the total (incident plus reflected off the ground) electric field at 13 m above ground. Since the extrapolation function must be consistent with the simulation, we need to calculate the total HEMP field at that location per Appendix A. Thus, the extrapolated current is

$$I_{ANT}^{HEMP}\,(\omega) = \frac{I_{ANT}}{E_y\,(R_1)} \cdot E_y^{inc,HEMP}\,(\omega) \left[\, 1 + R_H e^{-j\alpha} \,\right] \qquad (A/Hz) \tag{4-2}$$

where R_H and α are from Appendix B. The incident field $E_y^{inc,HEMP}$ is the unclassified HEMP waveform EMP-1 defined by Reference 10:

$$E_{EMP-1}^{inc}\,(t) = 6.425E4\,\left(e^{-at} - e^{-bt}\right) \qquad (V/m) \tag{4-3}$$
$$a = 3.00E7\ \sec^{-1},\ b = 4.76E8\ \sec^{-1}$$

The result is the frequency spectrum of the antenna current due to a HEMP, and the current transient is obtained by taking the Fourier inverse transform:

$$i_{ANT}^{HEMP}(t) = \frac{1}{\pi}\int_{\omega_L}^{\omega_U} I_{ANT}^{HEMP}(\omega)e^{j\omega t}\,d\omega \qquad (A) \tag{4-4}$$

With two exceptions,[1] the antenna currents measured with the horizontal illumination field were processed accordingly. The results are contained in Appendix C. In addition, the ambient noise was measured at several antennas. Comparison plots of CWMS signal measured vs. ambient noise are included in Appendix D.

4.3.2 Vertically Polarized Illumination.

Test Setup: Figure 4-10 shows the CWMS simulator used to radiate vertically polarized fields; i.e., the major electric field is perpendicular to the ground. The simulator uses a monopole fed on the ground to radiate at frequencies between 100 kHz to 102 MHz, and a vertical logperiodic on top of the monopole at frequencies up to 1 GHz. Hence, the radiation source for the low frequency simulation is near the ground, while the radiation source above 102 MHz is about 21 m above the ground (the logperiodic antenna is mounted on top of the monopole structure). The consequences of this inconsistency are discussed below. [redacted]

For the reasons discussed in the previous section, two reference (field) sensors were employed. The antenna current relative to the vertical electric field at R_1 is:

$$\frac{I_{ANT}}{E_z(R_1)}(\omega) = \left[\frac{I_{ANT}}{H_y(R_o)}\right]\cdot\left[\frac{H_y(R_o)}{E_z(R_1)}\right] \qquad (A\cdot m/V) \tag{4-5}$$

where the quantities in the square brackets indicate measurements. The first measurement is the antenna current relative to the magnetic field at R_0, and the second is the electric field at R_1; i.e., closest to the antenna, relative to the magnetic field at R_0. Since the magnetic field cancels out, the antenna current relative to E_z at R_1 is obtained. The reference locations R_0 and R_1 are identified in Table 4-1 for each measurement.

---

[1]The only exceptions are files H031A and H032A, where the antenna currents were directly measured relative to the horizontal electric field at R_1. This is indicated in Table 4-1 by the comment "live ref."

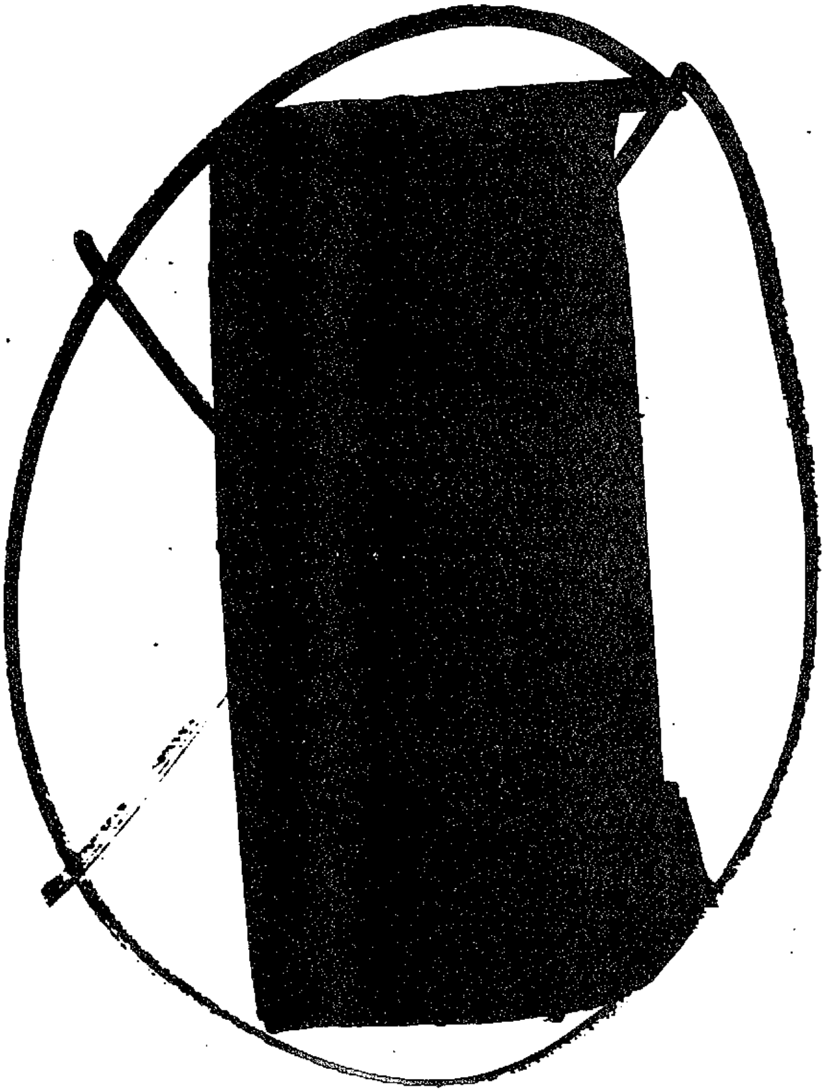


Figure 4-10. [redacted]

Processing: To calculate the antenna response due to a HEMP, the transfer function in Equation (4-5) is extrapolated; i.e., it is multiplied by the electric field strength which a HEMP would produce at R_1. As before, the extrapolation function must be consistent with the reference field (i.e., the denominator of Equation (4-5)). Since the simulator has two different source locations, we must consider two cases:

- 100 kHz to 102 MHz: The radiating element is a monopole above a lossy ground. If the ground were a good conductor, the simulator would be electromagnetically equivalent (by image theory) to a dipole in free space; i.e., the radiated fields would be purely incident fields. Since the ground is a moderate conductor, the fields are incident fields, modified by a correction term to account for the finite earth conductivity. For the present purposes, the correction term is neglected; and, hence, the extrapolation is:

$$I^{HEMP}(\omega) = \frac{I_{ANT}}{E_z(R_1)} \cdot E_z^{inc,\,HEMP}(\omega) \qquad (A/Hz) \tag{4-6}$$

As before, the unclassified waveform EMP-1 is used for $E_z^{inc,\,HEMP}$.

- 102 MHz to 1 GHz: The radiating element is a logperiodic antenna, roughly 21 m above ground. It produces a total field (incident plus reflected off the ground) at the reference sensor at R_1. Accordingly, the extrapolation function (from Appendix A) is:

$$E_z^{inc,\,HEMP}(\omega)\left[1+R_v e^{-j\phi}\right] \approx E_z^{inc,\,HEMP} \qquad \left(\frac{V/m}{Hz}\right) \tag{4-7}$$

The approximation follows from Appendix B which shows that R_V is much smaller than unity; hence, the extrapolation function in Equation (4-6) can be also be used at high frequencies.

The resulting frequency spectra for the HEMP induced antenna currents, and the inverse Fourier transforms are presented in Appendix C.

4.4 HEMP INDUCED ANTENNA CURRENTS.

All measurements were processed as described in Section 4-2, and are contained in Appendix C. The results are summarized in Table 4-1 of Section 4-1. [redacted]d. The file name indicates whether the horizontal CWMS simulator was used (prefix "H"), or the vertical simulator (prefix "V"). The column entitled "Polar" describes whether the simulator fields were parallel to the principal antenna radiating structure ("WORST CASE"), or perpendicular ("PERP"). The next column identifies the load on the antenna coaxial cable; i.e., whether the current was measured into 50 ohms or into a short circuit.

The waveform descriptors peak current [redacted]

The column entitled "Inside CWMS Volume" indicates whether the test object (antenna) was outside the simulation volume.

The last column accounts for the fact that the reference location R_1 was not at each test object as discussed in Section 4-2, but closer to the simulator. Since the simulation field strength decreases as 1/distance (cf. References 9, 11), the error is 20 log(d/R_1), where d is the distance from the simulator to the antenna, and R_1 is the distance from the simulator to the reference location R_1.

4.4.1 Representative Results for Each Antenna.

Table 4-1 shows that worst case polarization indeed produces the largest currents in the antennas. The currents induced in a 50 ohm test load and into a short circuit are overlaid in the following figures (Figures 4-11 to 4-19) for the worst case polarization of the incident field, except in the two cases indicated. Each figure displays the spectra and the time domain transients.

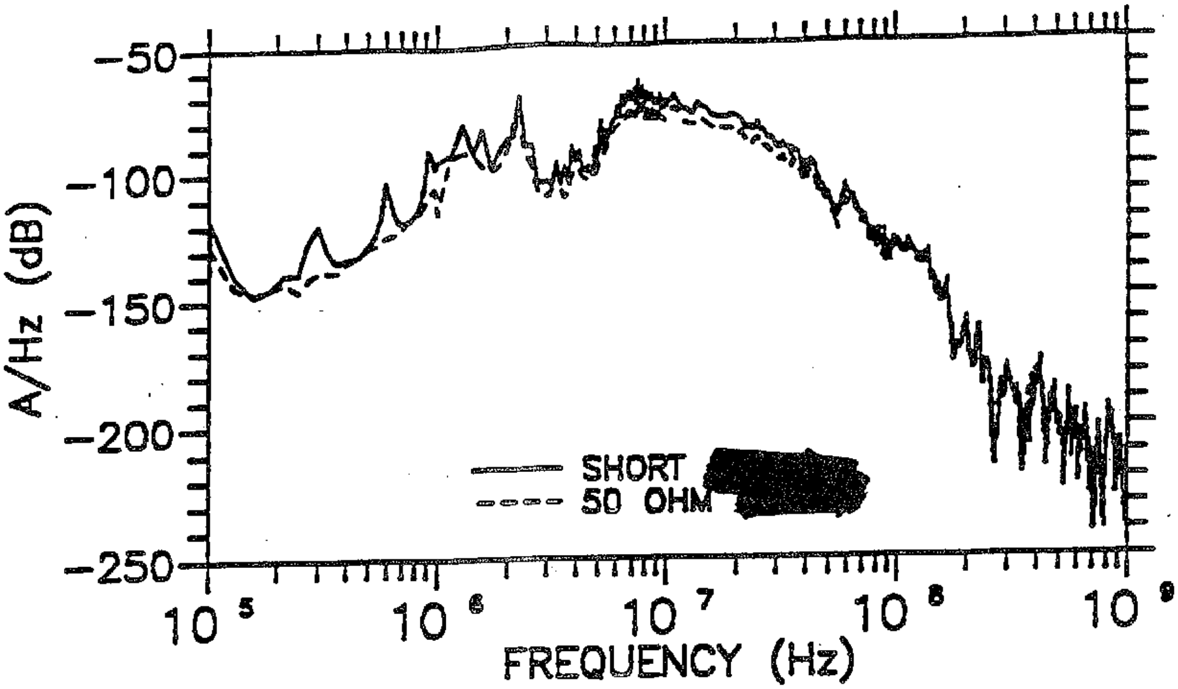
Note that the short-circuit and 50 ohm current waveforms are quite similar; i.e., the short-circuit current is about twice the current into 50 ohms. The reason for this is discussed in the next section.

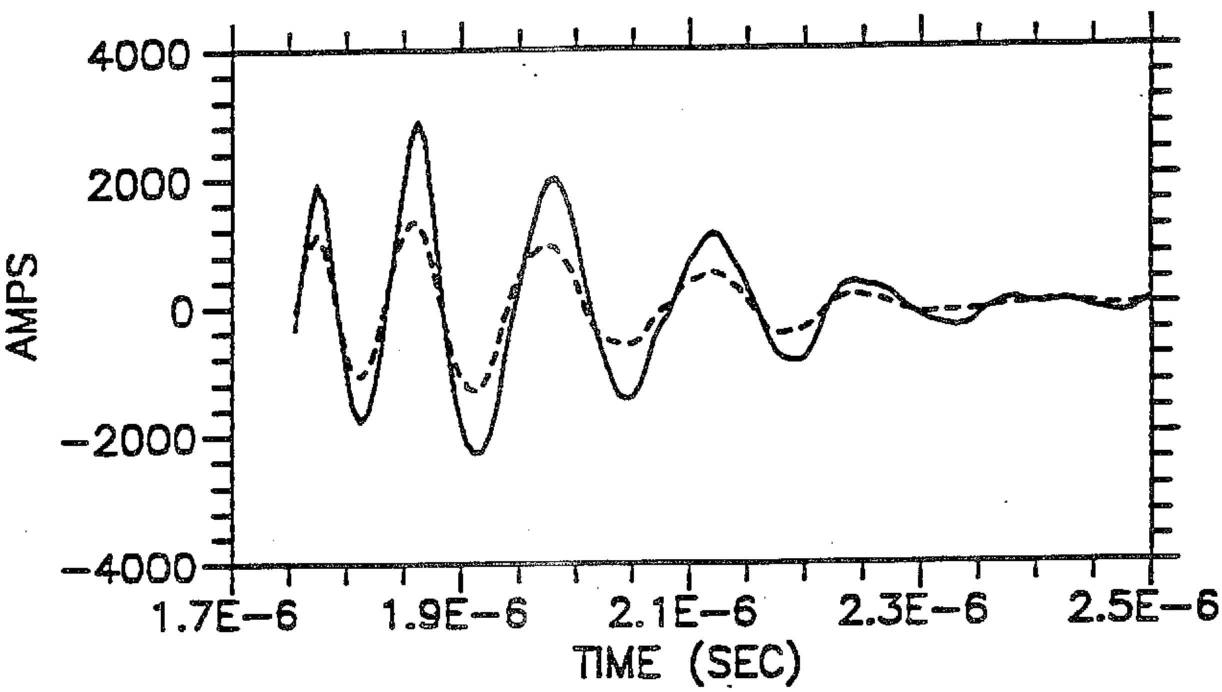
4.4.2 Antenna Impedance.

Figure 4-20 shows the electrically important elements of the coupling path from the voltage generated at the antenna terminals to the test load, and the equivalent circuit for this path. This circuit represents the HEMP stress seen by the radio equipment; hence, it is the ideal injection test simulator.

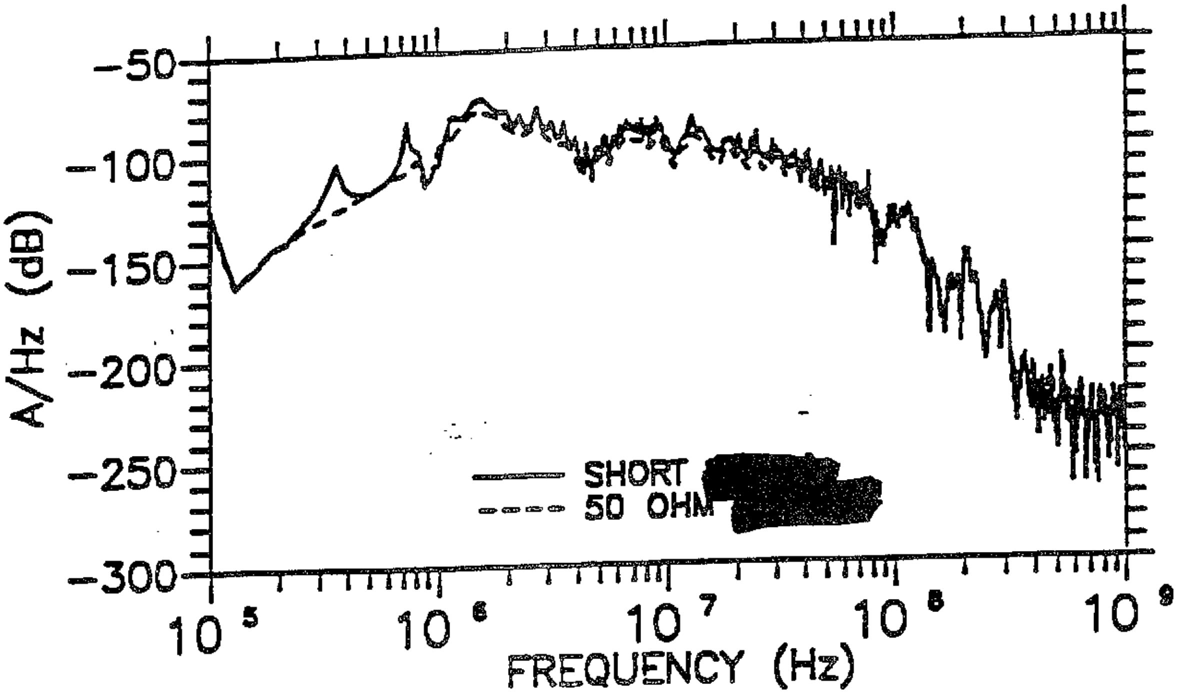
The only unknown in this circuit is the input or source impedance Z_{in}, which can be calculated by

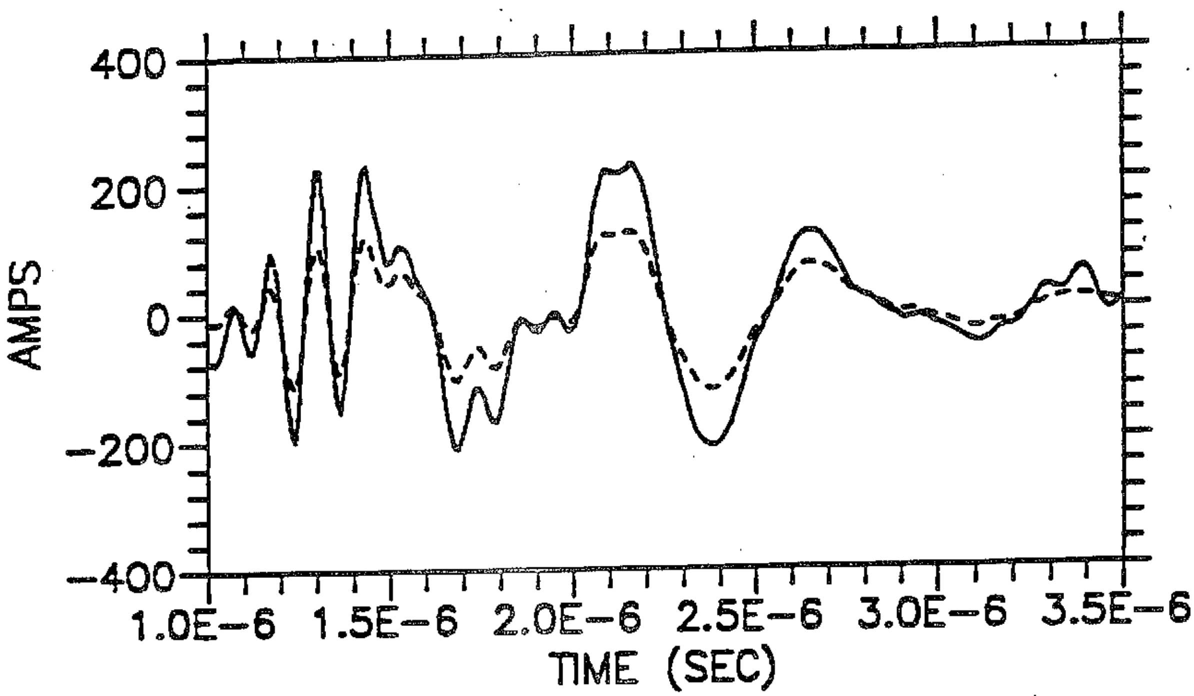
$$Z_{in} = 50 \frac{I_{50}}{I_{sc} - I_{50}} \quad (\Omega) \qquad (4\text{-}8)$$


-50
-100
-150
-200
-250
A/Hz (dB)
SHORT
50 OHM
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

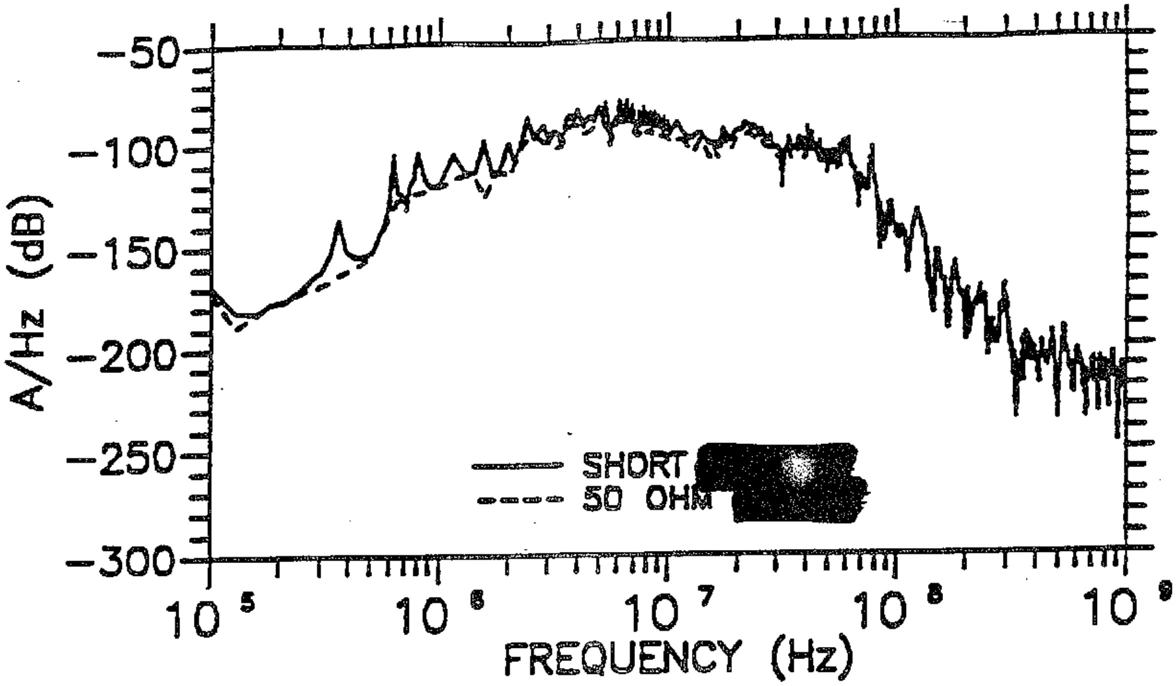

4000
2000
0
-2000
-4000
AMPS
1.7E-6
1.9E-6
2.1E-6
2.3E-6
2.5E-6
TIME (SEC)

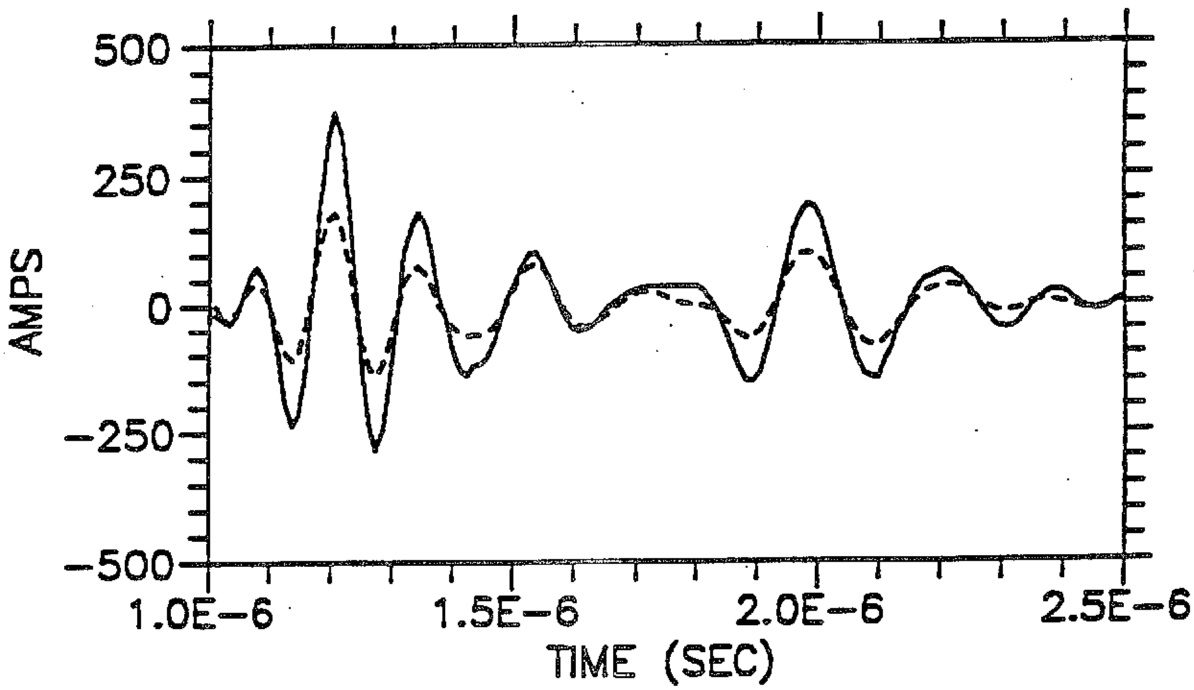
[redacted]


-50
-100
-150
-200
-250
-300
A/Hz (dB)
SHORT [redacted]
50 OHM [redacted]
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

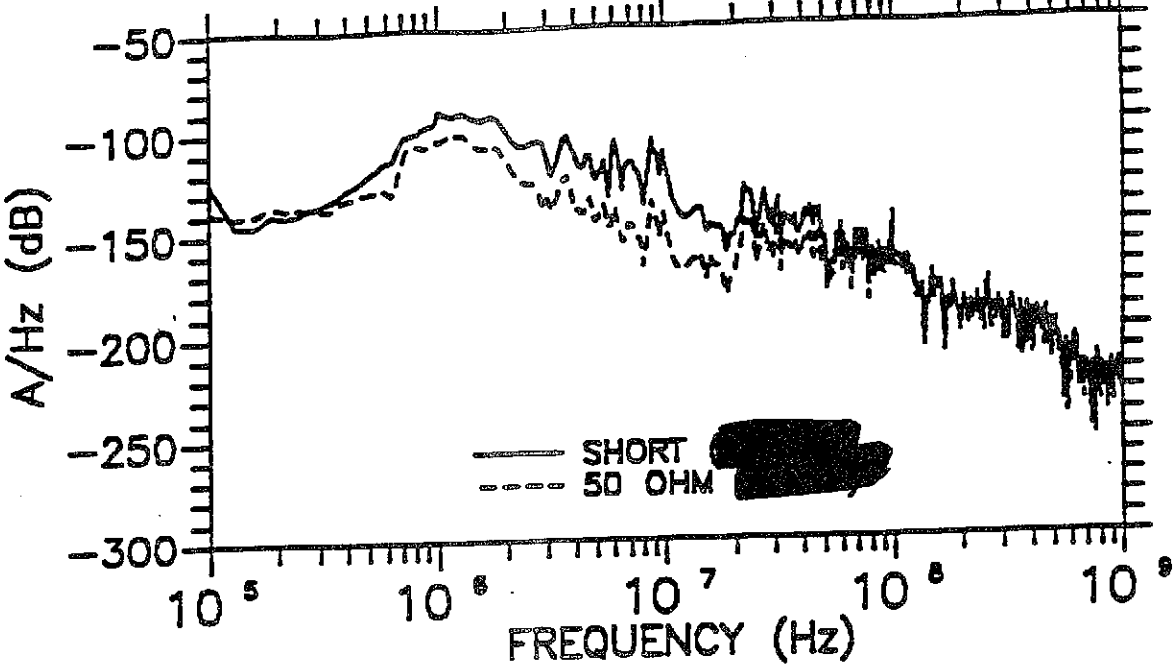

400
200
0
-200
-400
AMPS
1.0E-6
1.5E-6
2.0E-6
2.5E-6
3.0E-6
3.5E-6
TIME (SEC)

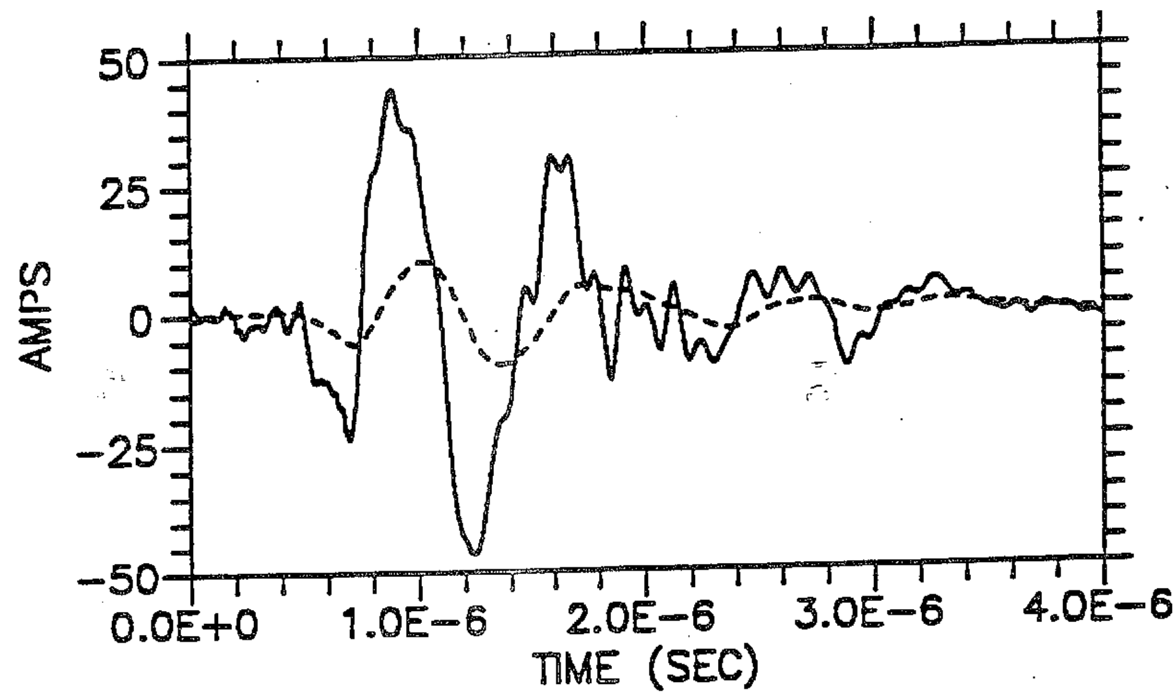
[redacted]


A/Hz (dB)
-50
-100
-150
-200
-250
-300
SHORT [redacted]
50 OHM [redacted]
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


AMPS
500
250
0
-250
-500
1.0E-6
1.5E-6
2.0E-6
2.5E-6
TIME (SEC)

[redacted]


-50
-100
-150
-200
-250
-300
A/Hz (dB)
SHORT [redacted]
50 OHM [redacted]
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


50
25
0
-25
-50
AMPS
0.0E+0
1.0E-6
2.0E-6
3.0E-6
4.0E-6
TIME (SEC)

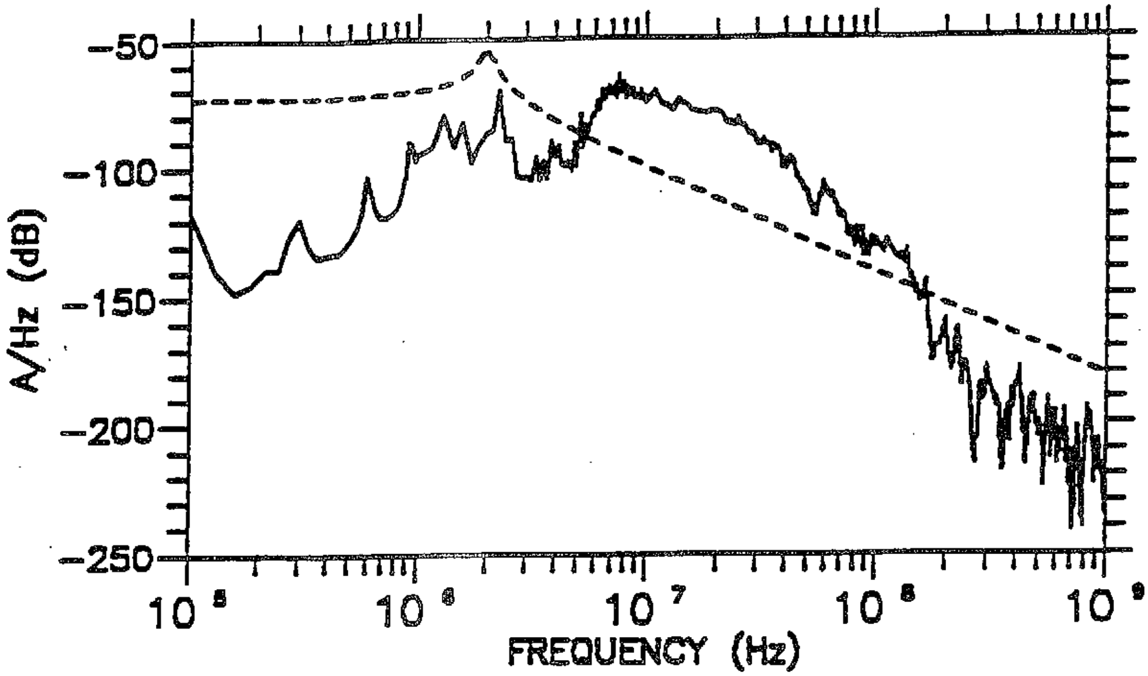
[redacted]

Table 4-3. [redacted]

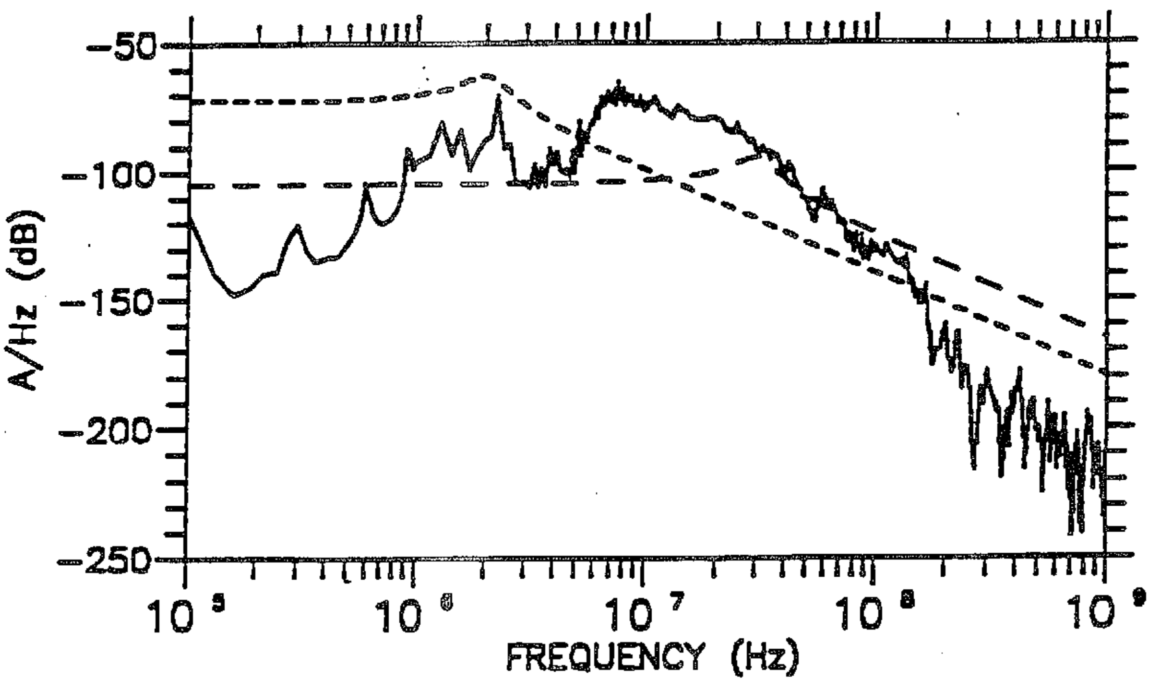
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted] compare the extrapolated short-circuit currents with the two test requirements. The test coverage provided by the standard appears deficient. The revision suggested by Reference 7 improves the [redacted]

[redacted]

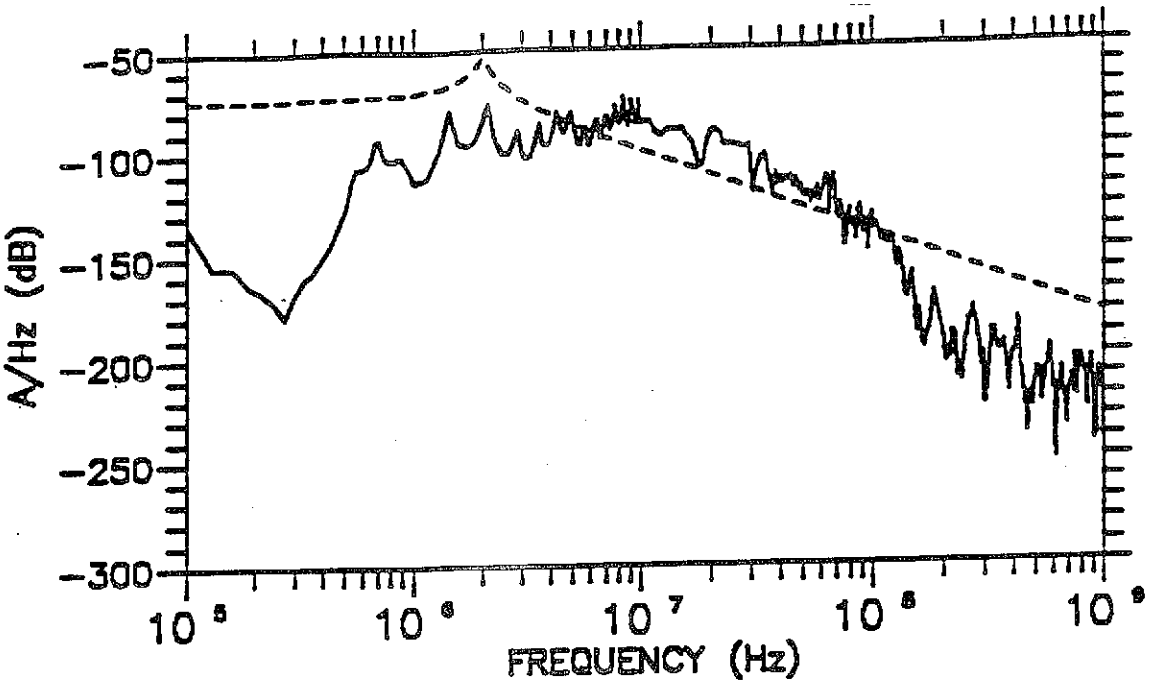


A/Hz (dB)
-50
-100
-150
-200
-250
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

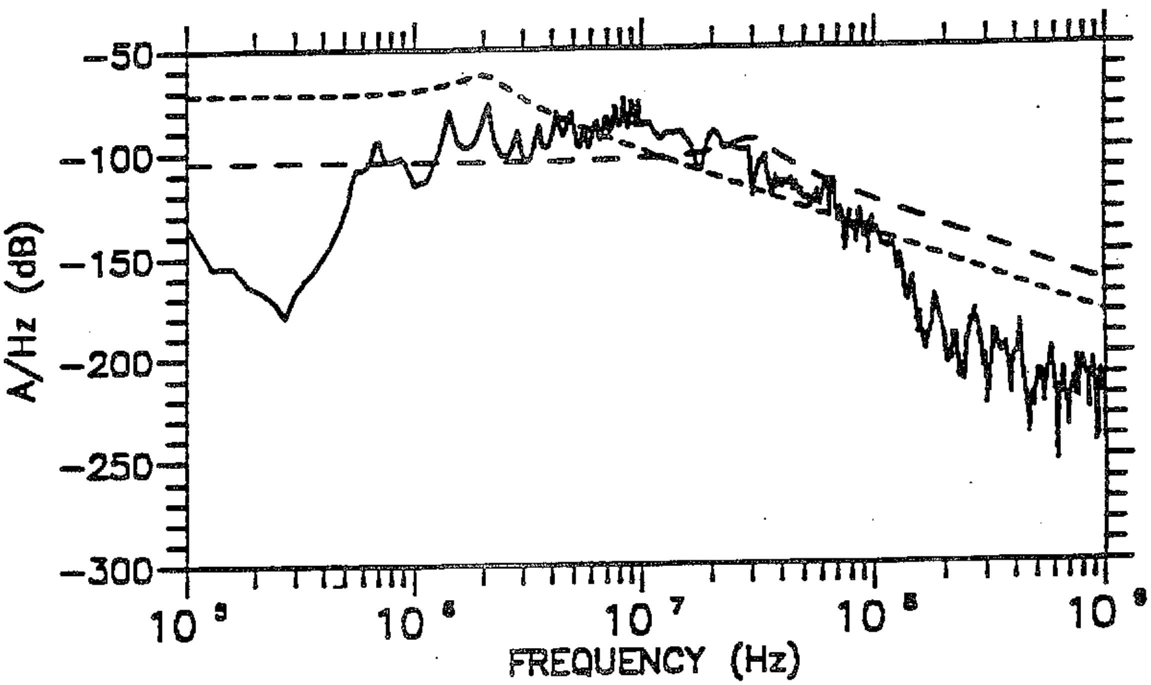


A/Hz (dB)
-50
-100
-150
-200
-250
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

[redacted]

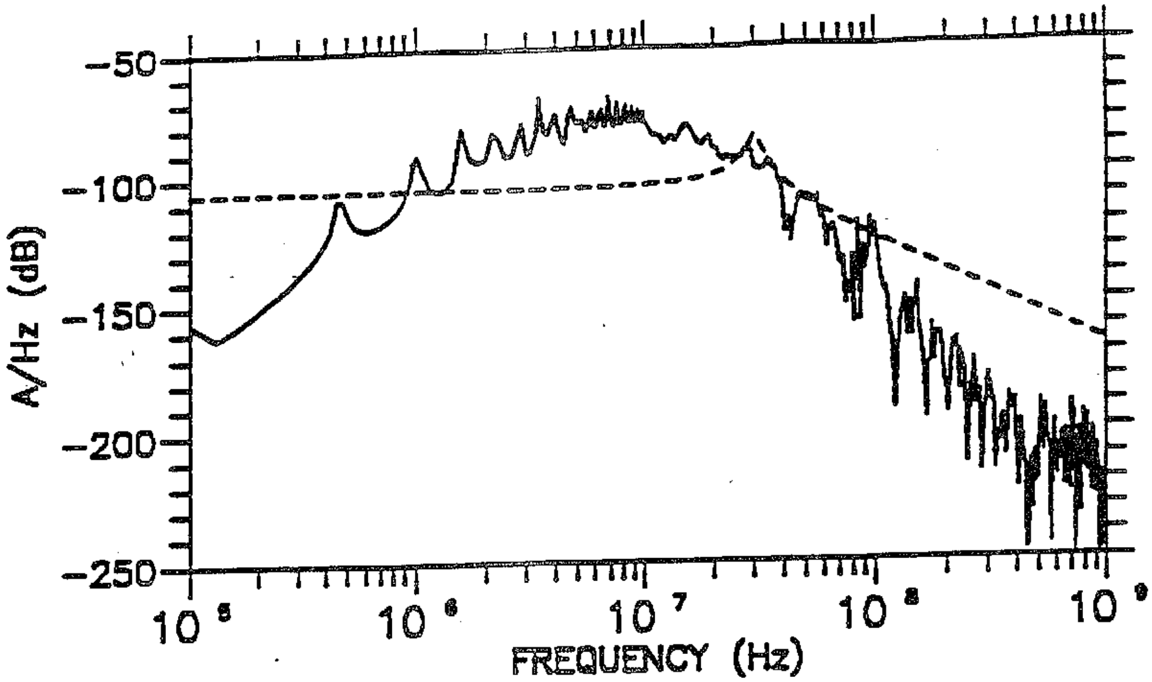


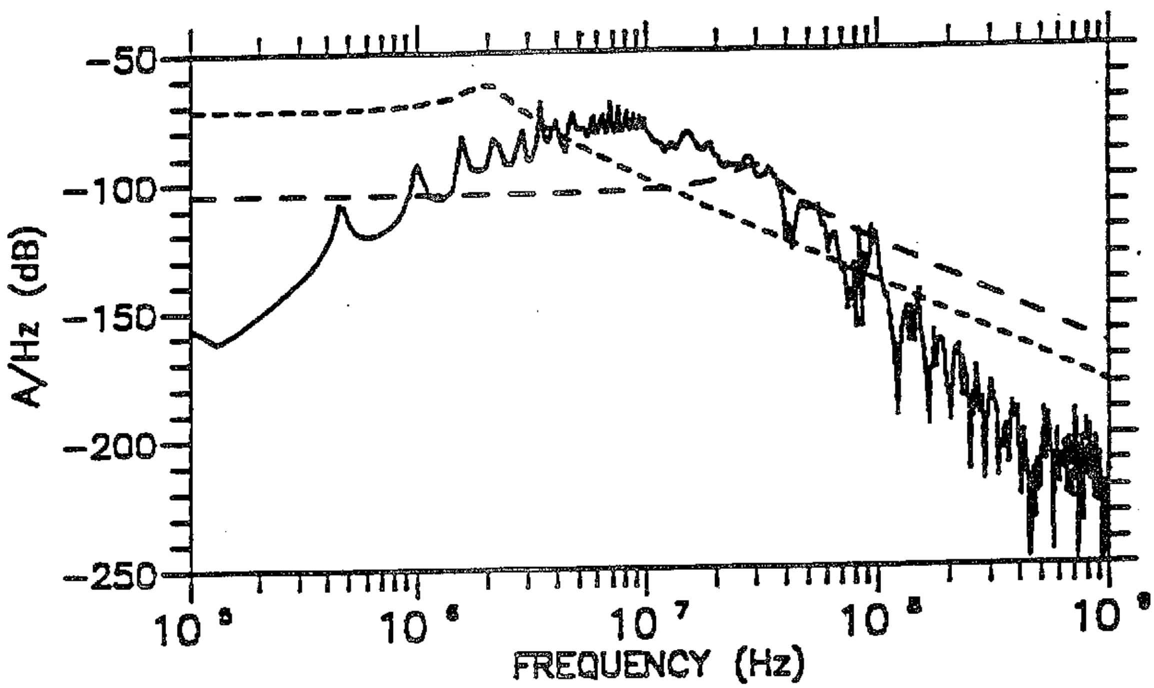
-50
-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



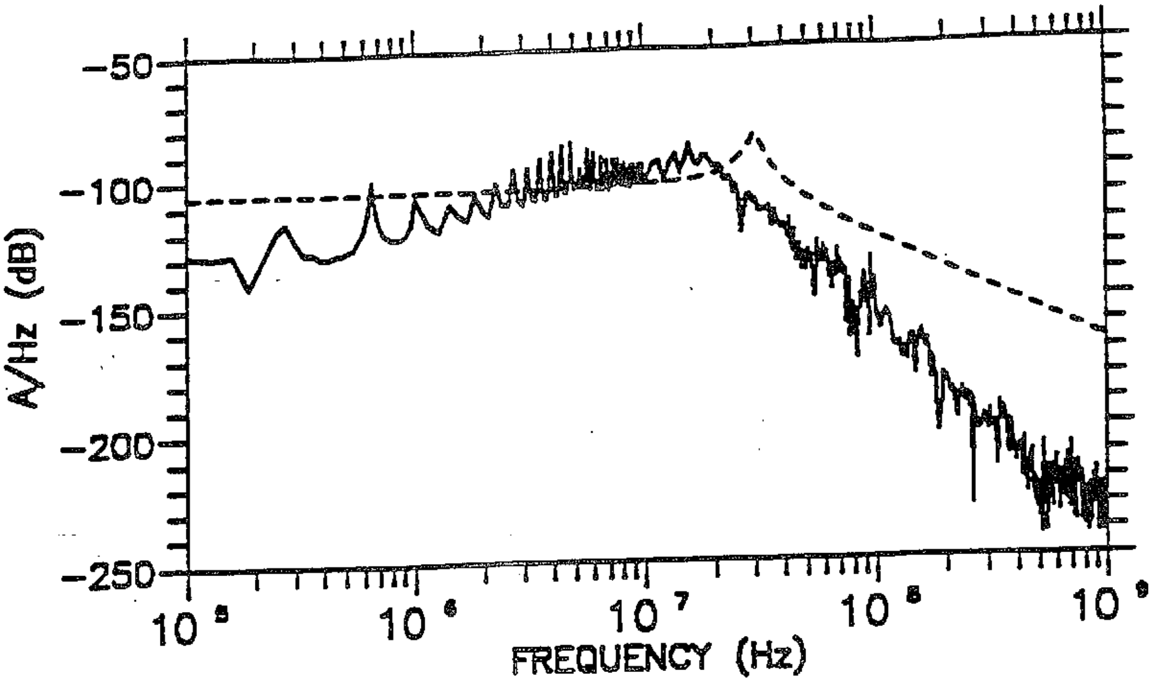
-50
-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

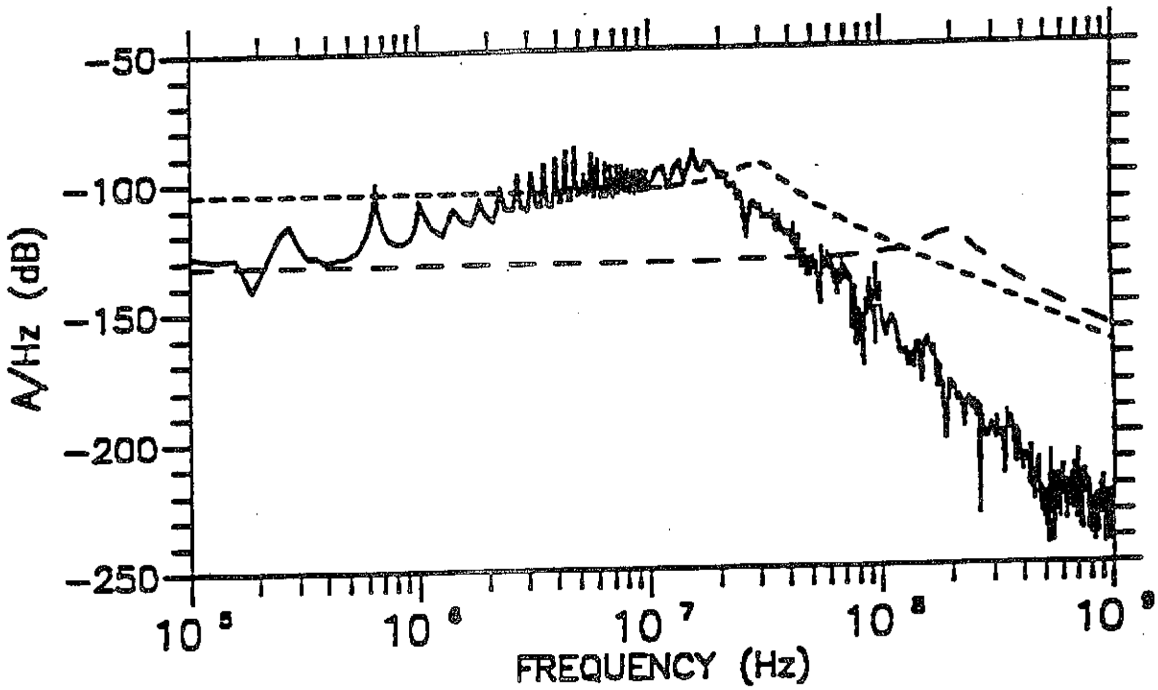
[redacted]


A/Hz (dB)
-50
-100
-150
-200
-250
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

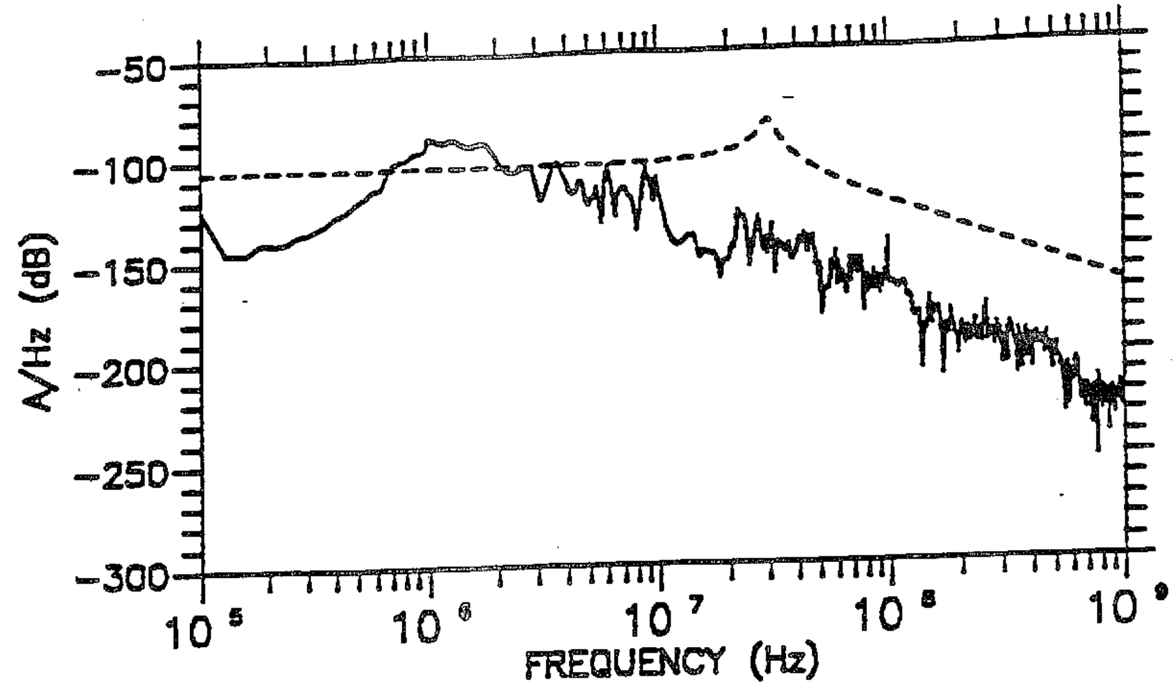

A/Hz (dB)
-50
-100
-150
-200
-250
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

[redacted]

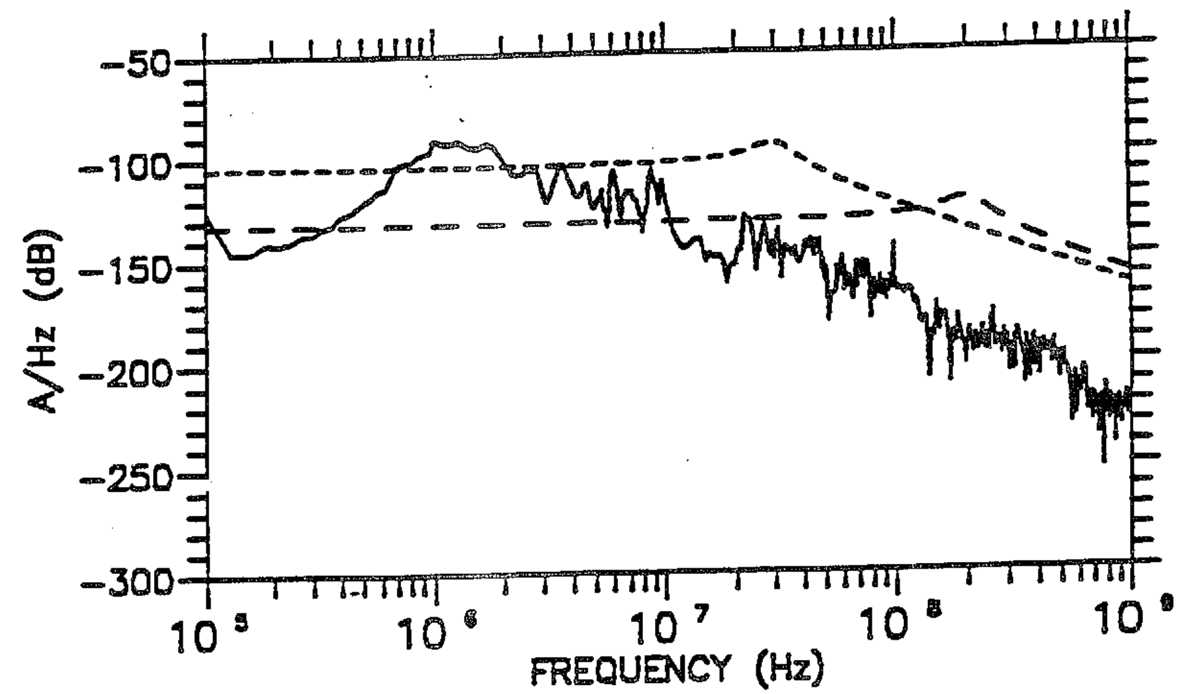

-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

[redacted]

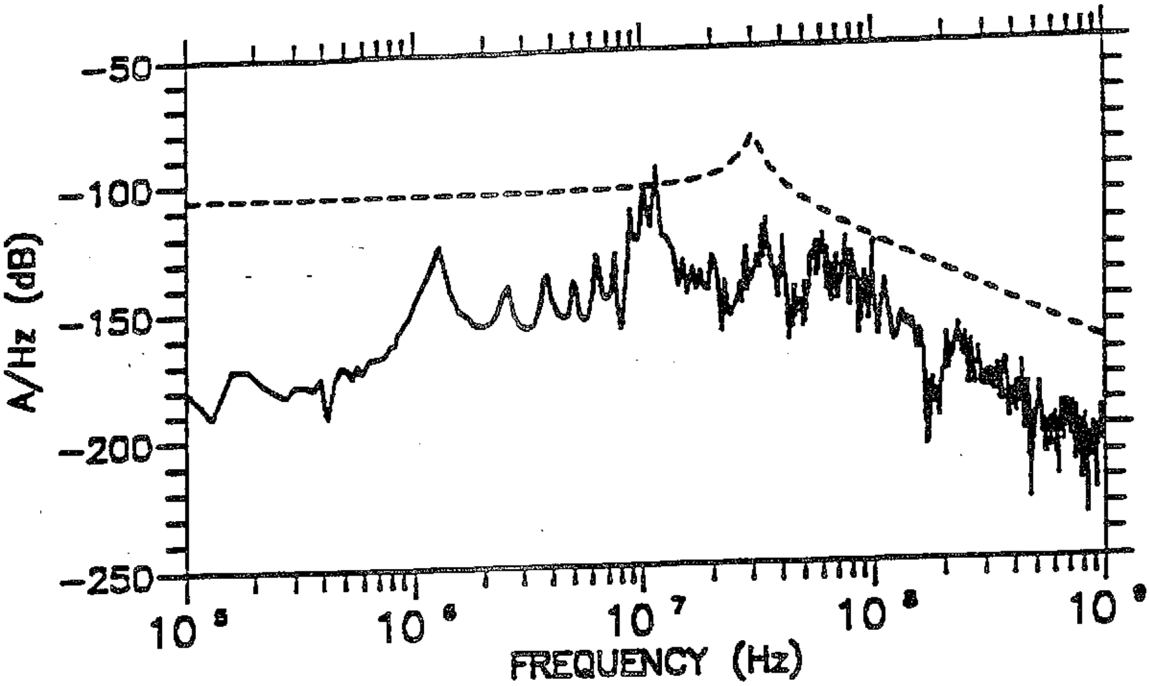


-50
-100
-150
-200
-250
-300
A/√Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

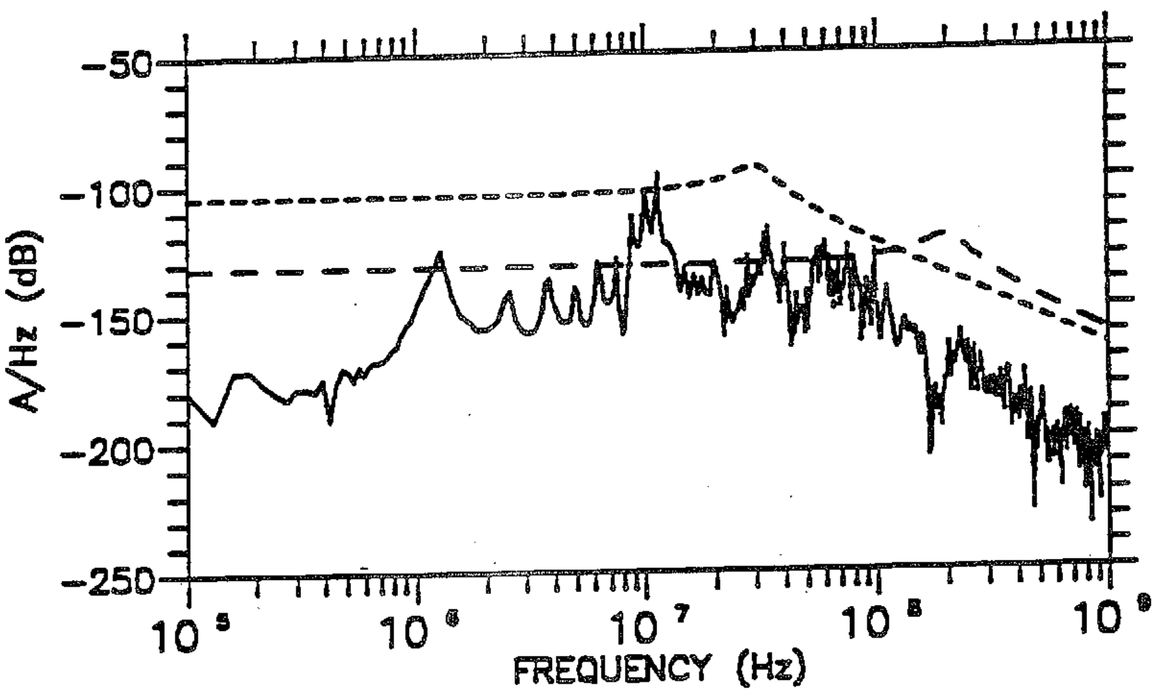


-50
-100
-150
-200
-250
-300
A/√Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

[redacted]

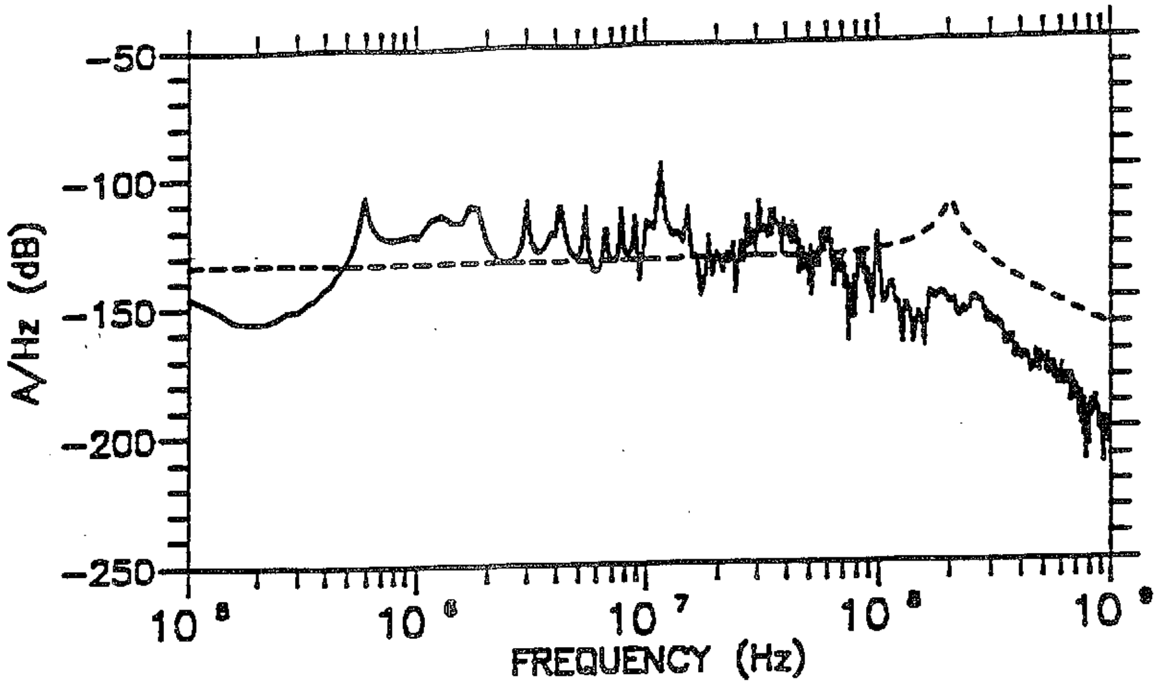


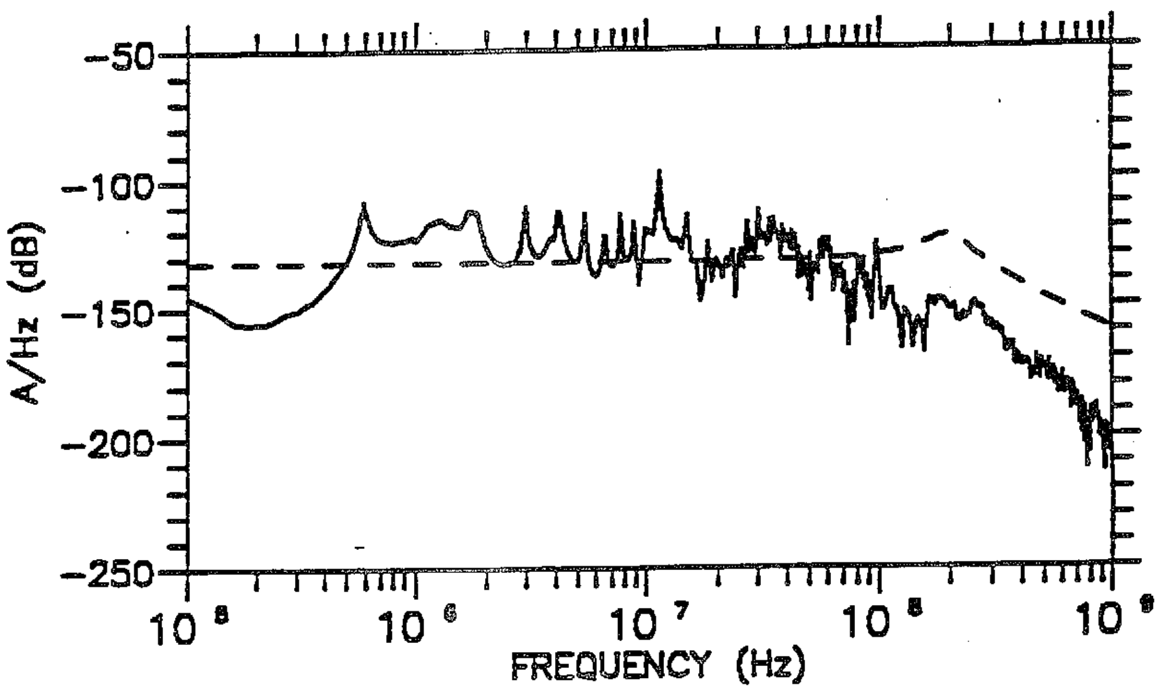
-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

[redacted]


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

[redacted]

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The test met all objectives. The test results provide complete answers to all issues [redacted] Each issue is addressed [redacted] discussed separately below.

[redacted]

[redacted]

ISSUE:

What test waveforms adequately simulate HEMP stresses on test radio equipment connected to antennas?

OBSERVATIONS:

HEMP coupled stresses to antennas can be adequately simulated with damped sinusoids as suggested by MIL-STD-188-125.

The revision to the standard in Reference 7 provides better test coverage because it uses two damped sinusoids for each antenna.

[redacted]k.

The transients stressing the radio equipment can be represented by an equivalent Thevenin circuit with source impedance of 50 to 100 ohms. Observed quality factors (Q) are lower than the Q = 10 required by MIL-STD-188-125.

CONCLUSIONS:

Neither MIL-STD-188-125 nor previously suggested revisions account for the effects of a tower.

RECOMMENDATIONS:

- Adopt the suggested revision in Reference 7, but add the requirement that the radio equipment must also be tested with a damped sinusoid at 2 MHz with 500 [redacted]

SECTION 6

REFERENCES

1. "Military Standard, High-Altitude Electromagnetic Pulse Protection for Ground-Based C4I Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125, 26 June 1990.

2. T. Zwolinski, "Test Director's Report for the [redacted] HEMP Simulation Test," MRC/COS-R-1309, July 1992.

3. D. Schafer, "E3 Pulser and Data Line Coupler/Isolator Acceptance Test," MRC/ABQ-R-1494, March 1992.

4. G. Estepp and D. Schafer, "Operation and Maintenance Manual" (for E3 Pulser), MRC/ABQ-R-1446, January 1992.

5. H. Fowles and D. Schafer, "Long Pulse Current Injection Experiments on an Operating GBC4I Facility Mockup," MRC/ABQ-R-1524, August 1992.

6. B. Harlacher, "Characterization of the E2 Pulse Generator," MRC/COS-M-95-7, 3 January 1992.

7. J. Lubell, "Changes to Appendix B" (of MIL-STD-188-125), Memorandum to W. Scott, Maj. R. Launstein, J. Zych, 13 March 1992.

8. R. Shoup, "Field Mapping Test of the DNA CW Antenna System," DNA-TR-84-168, 7 September 1983.

9. W. Bereuter and R. Racca, "Processing of CWMS Field Map Measurements," MRC/COS-N-131, 9 November 1987.

10. Classification Guide for "Advanced Fixed GBC4I Testing Program," 1 July 1989.

11. R. Racca and S. Dunivin, "[redacted]ntenna Field Map Test," MRC/COS-R-1082, 5 October 1990.

12. R. Racca, W. Bereuter, and S. Dunivin, [redacted] Antenna Test [redacted] MRC/COS-N-179, 29 January 1991.

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APPENDIX A

[redacted]

1.0 BACKGROUND

Section 3 describes the simulated HEMP testing [redacted] Pulser qualification testing indicates that the E2 pulser delivers a double exponential *short-circuit current* with peak amplitudes up to 500 A, rise times less than 1 μs, and durations (FWHM) of about 5 ms (Reference 6). [redacted]

The purpose of this appendix is to describe the circuit models used to estimate the responses [redacted]

2.0 CIRCUIT MODELS

[redacted]

The schematic in Fig. 1(a) can be reduced to an equivalent circuit shown in Fig. 1(c) using standard circuit equivalences. The first reduction reflects the 2 ohm load resistance [redacted]

[redacted]

Pages A-3 & A-4
removed in their
entirety.

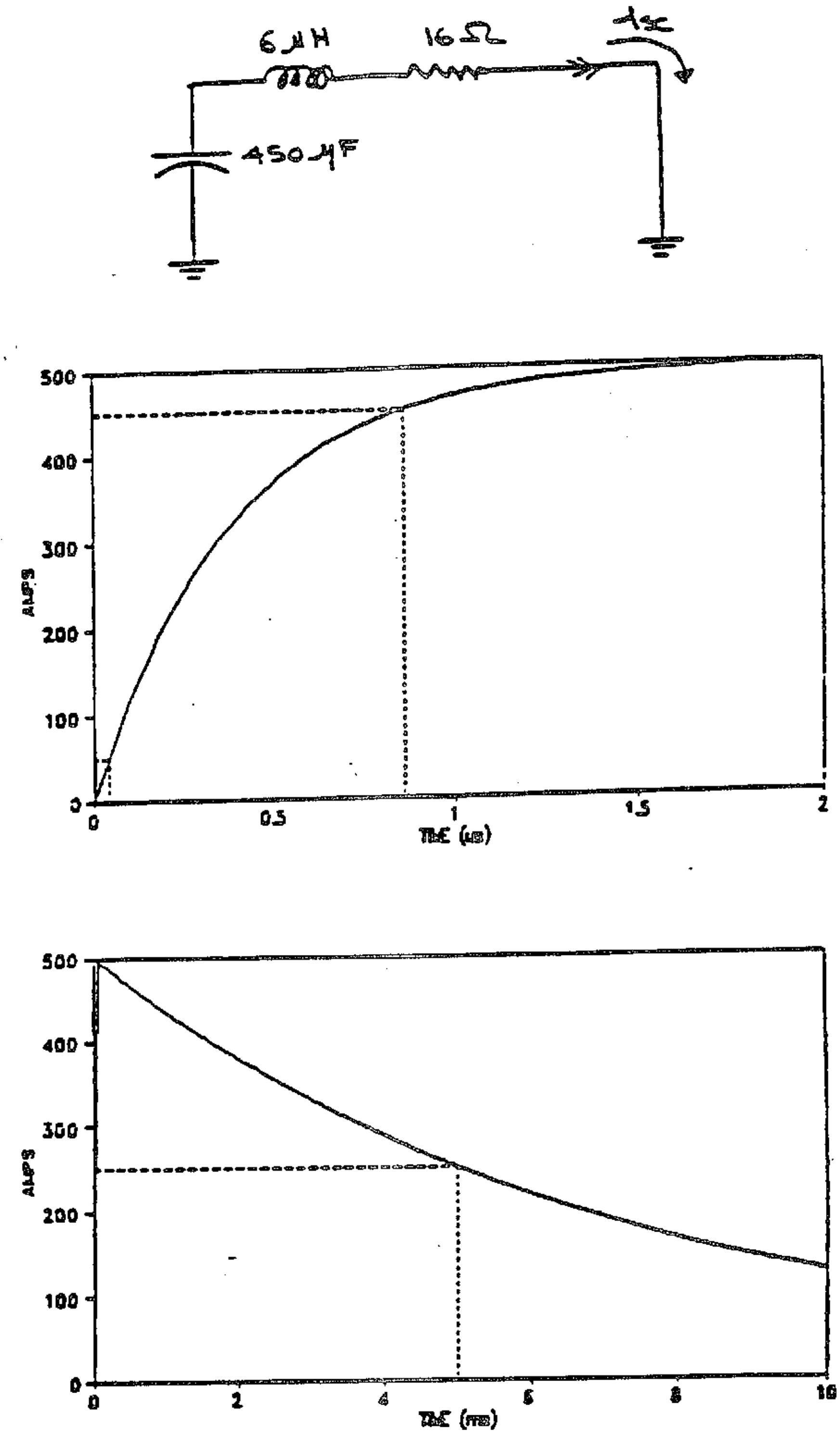

Figure 2. Circuits and responses for the E2 pulser: (a) circuit model, (b) early-time response, and (c) late-time response.

Pages A-6 through A-9 are removed in their entirety.

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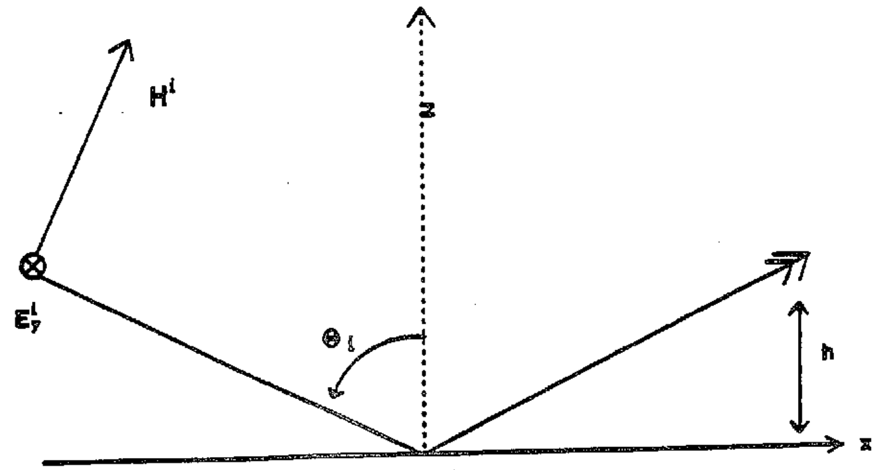
APPENDIX B

CALCULATION OF TOTAL FIELDS

This Appendix contains the equations to calculate the total (incident plus ground reflected) fields at a height h above the ground. The equations are for a horizontally polarized plane wave (incident electric field is parallel to the ground), and for a vertically polarized plane wave (incident magnetic field is parallel to the ground). The plane waves are incident along a propagation direction which is in the xy plane and forms an angle θ_i with the z-axis.

The angles of incidence are between 68° and 83°, depending on the antenna distance to the CWMS simulator and the height of the antenna tested. The earth parameters E_r, σ were estimated by matching the calculated field transfer functions to the measured transfer functions. The estimated values are $\epsilon_r = 5$, and $\sigma = .01$ to 1 mho/m.

The approximations for small x are provided for convenience. They are valid at frequencies where the ground is a good conductor.



$$R_H = \frac{\cos\theta_i - \left[\epsilon_r\,(1+\chi) - \sin^2\theta_i\right]^{1/2}}{\cos\theta_i + \left[\epsilon_r\,(1+\chi) - \sin^2\theta_i\right]^{1/2}} \approx -1 + 2\cos\theta_i \sqrt{\frac{j\omega\epsilon_o}{\sigma}}$$

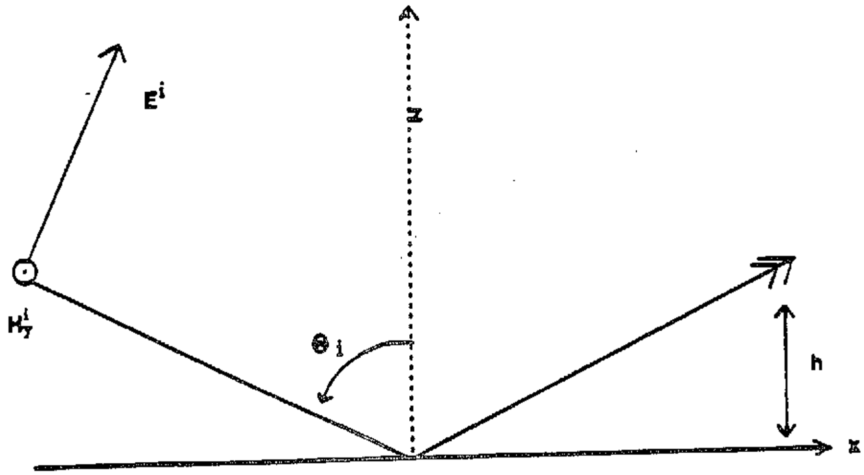
$$E_y^{TOT} = E_o(1 + R_H e^{-j\alpha}) \approx 2\,E_o \cos\theta_i \sqrt{\frac{j\omega\epsilon_o}{\sigma}}$$

$$H_x^{TOT} = \frac{E_o}{\eta_o}\cos\theta_i\,(1 - R_H e^{-j\alpha}) \approx \frac{E_o}{\eta_o}\,2\cos\theta_i\left(1 - \cos\theta_i \sqrt{\frac{j\omega\epsilon_o}{\sigma}}\right)$$

$$H_z^{TOT} = \frac{E_o}{\eta_o}\sin\theta_i\left(1 + R_H e^{-j\alpha}\right) \approx \frac{E_o}{\eta_0}\,2\sin\theta_i\ \cos\theta_i \sqrt{\frac{j\omega\epsilon_o}{\sigma}}$$

$\alpha = 2k_o h \cos\theta_i$; $\chi = \sigma/j\omega\epsilon$, approx. valid for $|\chi| >> 1$

VERTICAL POLARIZATION



$$R_v = \frac{\epsilon_r(1+\chi)\,\mathrm{COS}\theta_i - \left[\epsilon_r\,(1+\chi) - \sin^2\theta_i\right]^{1/2}}{\epsilon_r\,(1+\chi)\,\mathrm{COS}\theta_i + \left[\epsilon_r\,(1+\chi) - \sin^2\theta_i\right]^{1/2}} \approx 1 - \frac{2}{\mathrm{COS}\theta_i}\sqrt{\frac{j\omega\epsilon_o}{\sigma}}$$

$$E_x^{TOT} = E_o\,\mathrm{COS}\theta_i\left(1 - R_v e^{-j\alpha}\right) \approx E_o 2\sqrt{\frac{j\omega\epsilon_o}{\sigma}}$$

$$E_z^{TOT} = E_o \sin\theta_i\left(1 + R_v e^{-j\alpha}\right) \approx E_o\,2\,\sin\theta_i\left(1 - \frac{1}{\mathrm{COS}\theta_i}\sqrt{\frac{j\omega\epsilon_o}{\sigma}}\right)$$

$$H_y^{TOT} = \frac{E_o}{\eta_o}\left(1 + R_v e^{-j\alpha}\right) \approx \frac{E_o}{\eta_o}\,2\left(1 - \frac{1}{\mathrm{COS}\theta_i}\sqrt{\frac{j\omega\epsilon_o}{\sigma}}\right)$$

$\alpha = 2k_o h\,\mathrm{COS}\theta_i$; $\chi = \sigma/j\omega\epsilon$, approx. valid for $|\chi| >> 1$

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APPENDIX C

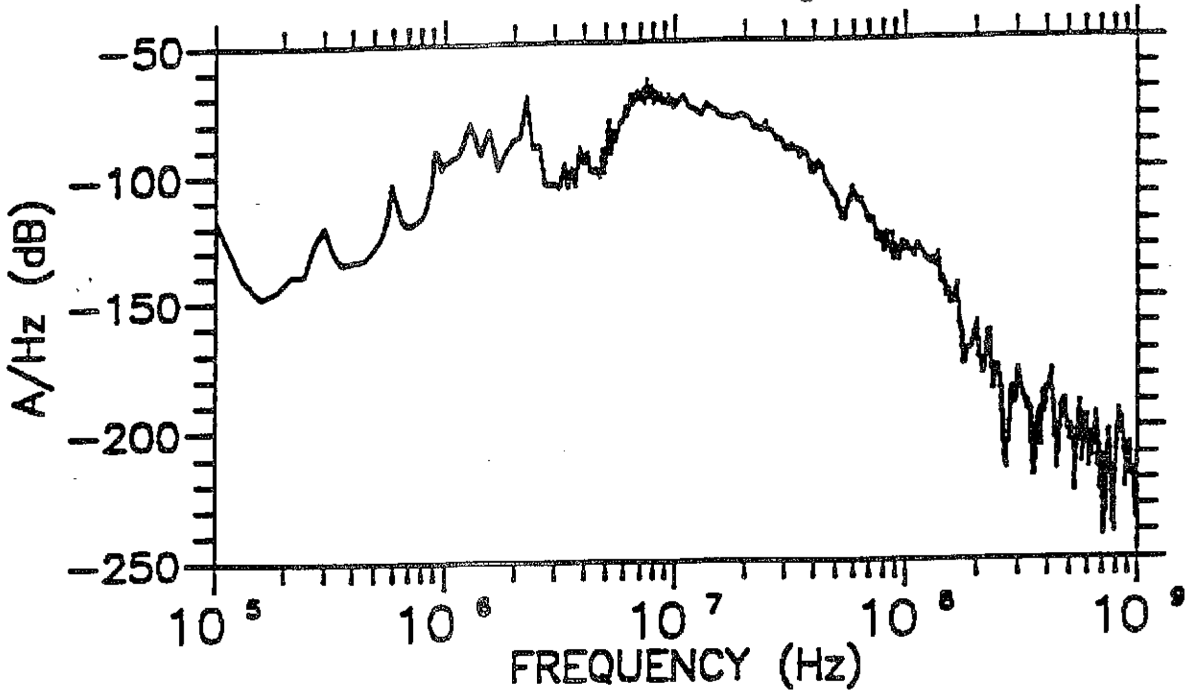
ANTENNA CURRENTS

This appendix contains plots of the antenna currents measured [redacted] and extrapolated to HEMP environments. Measurements with prefix "H" were extrapolated to the total electric field (cf. Section 4.3.1), and measurements with prefix "V" were extrapolated to the incident electric field (cf. Section 4.3.2).

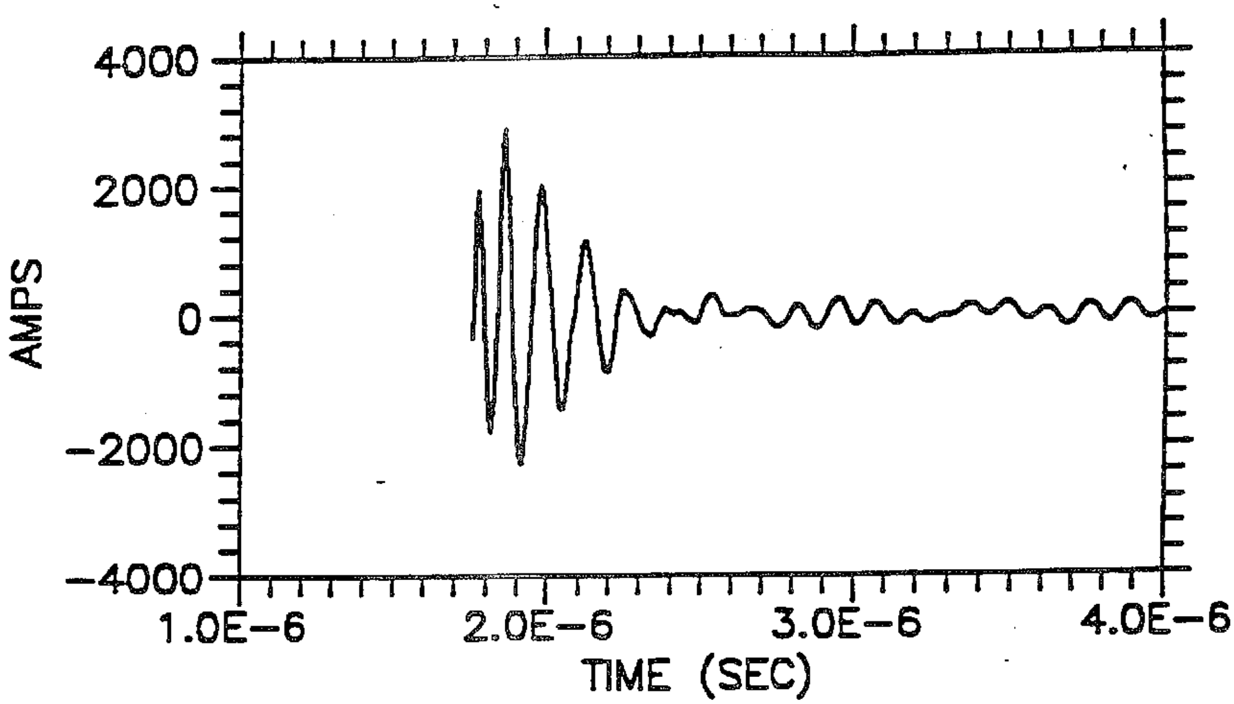
For each measurement, the frequency domain amplitude spectrum is plotted in dB = 20 log $|I(\omega)|$. On the same page, the inverse Fourier transform is shown.

[redacted]

[redacted]

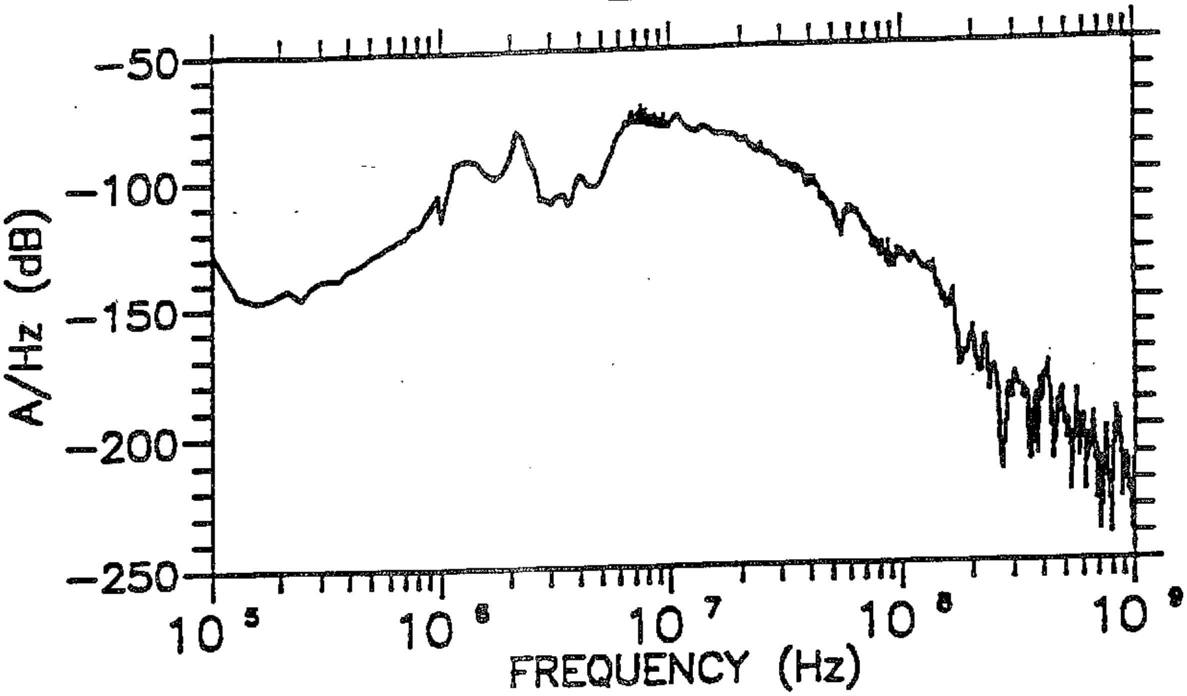


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

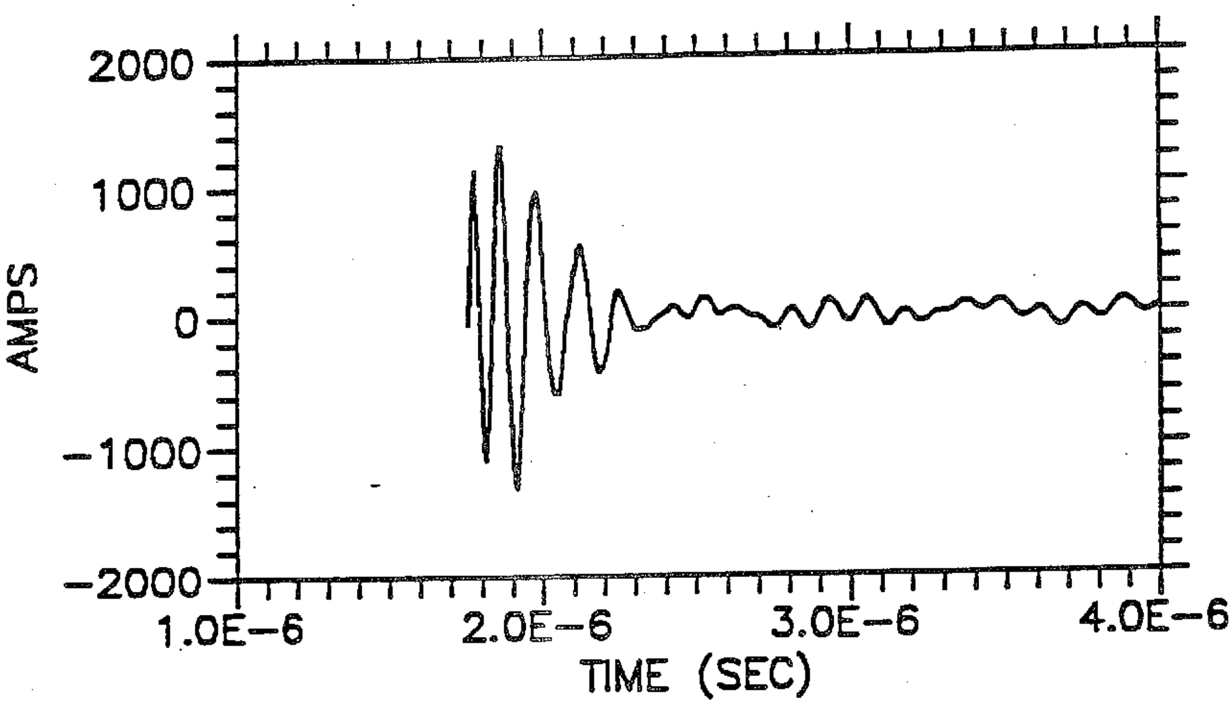


4000
2000
0
-2000
-4000
AMPS
1.0E-6
2.0E-6
3.0E-6
4.0E-6
TIME (SEC)

[redacted]

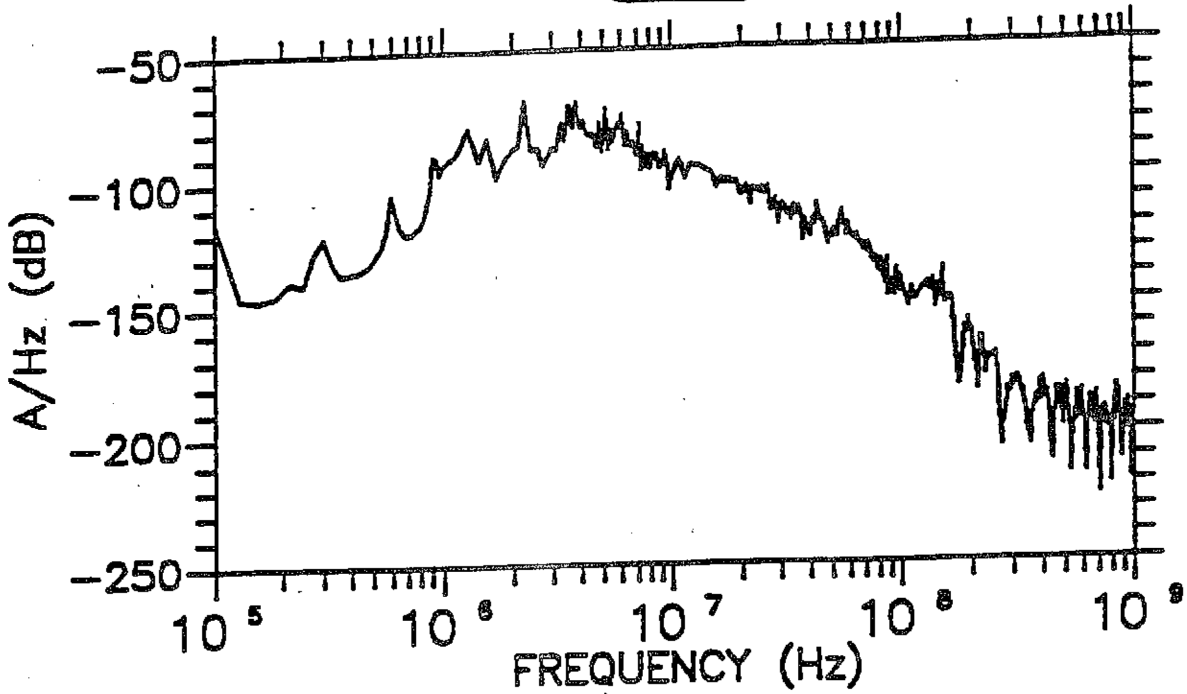


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

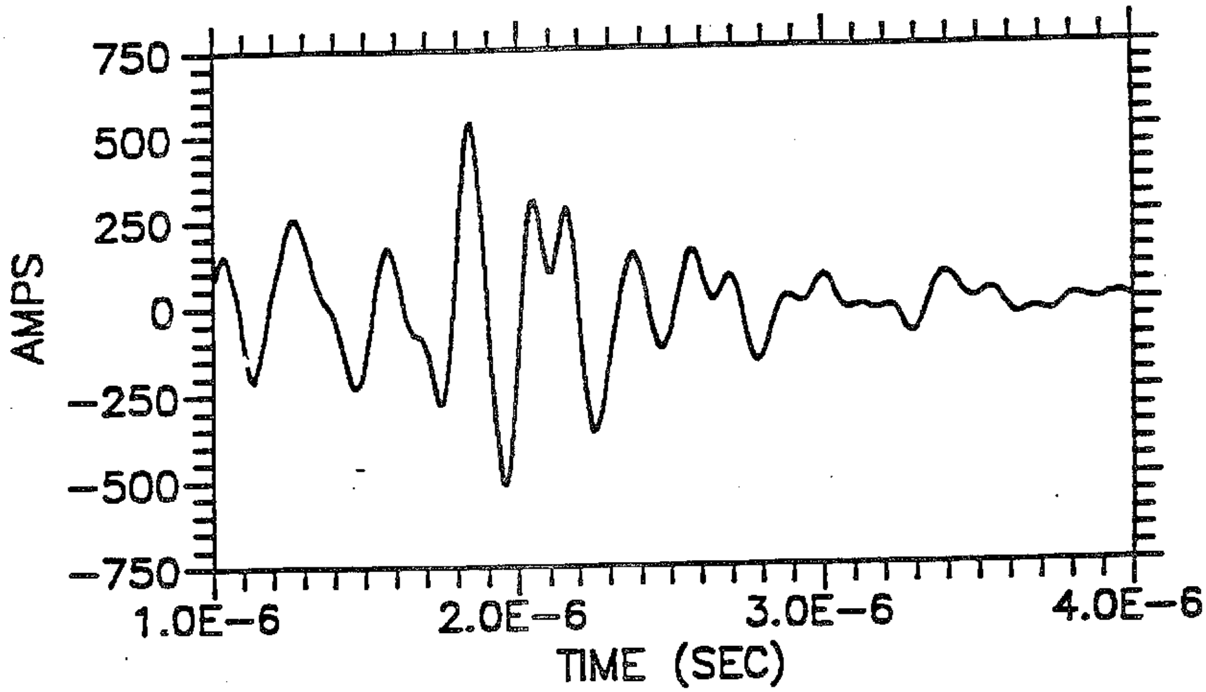


2000
1000
0
-1000
-2000
AMPS
1.0E-6
2.0E-6
3.0E-6
4.0E-6
TIME (SEC)

[redacted]

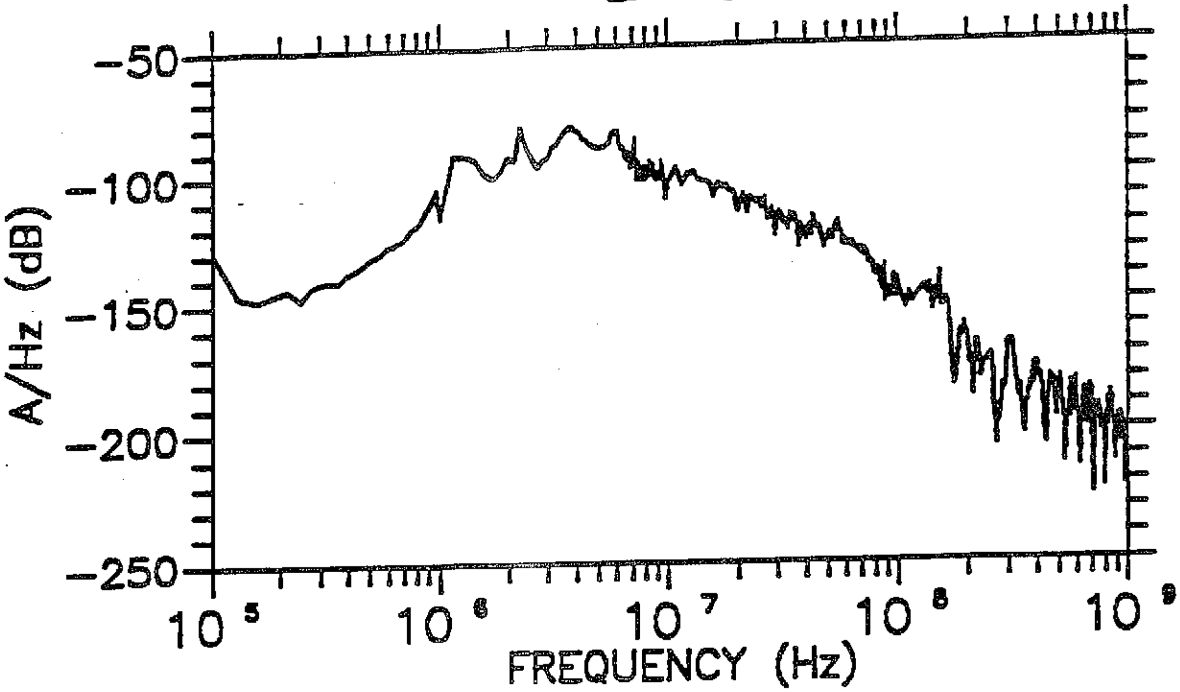


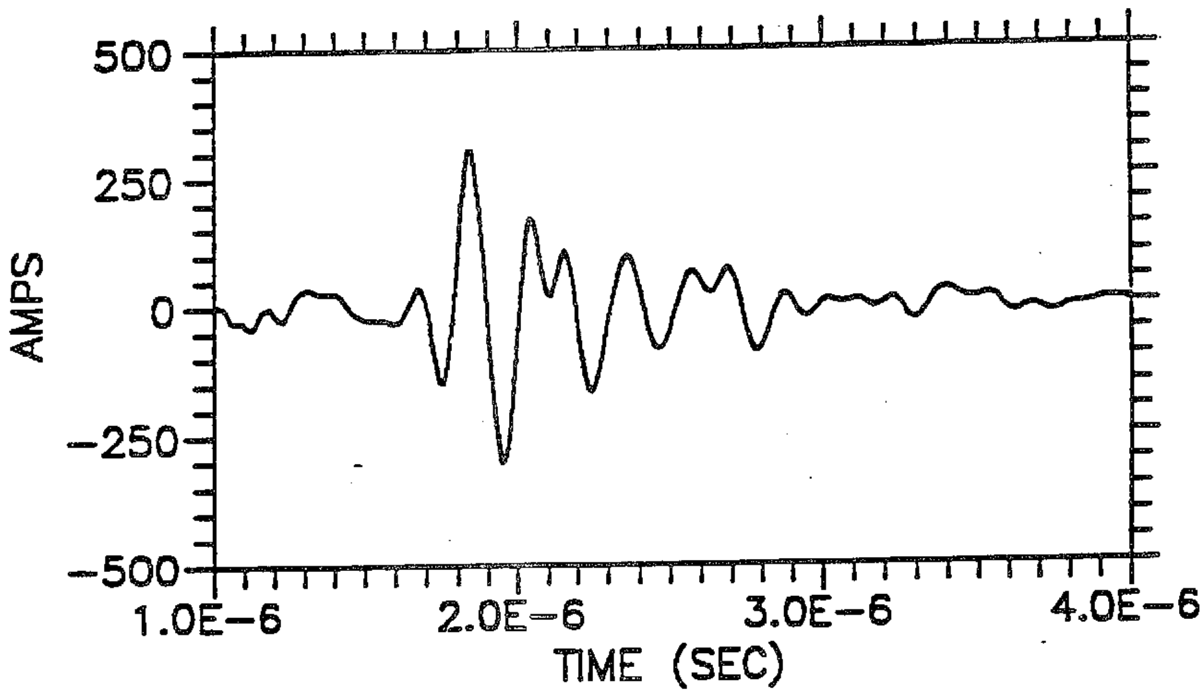
-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



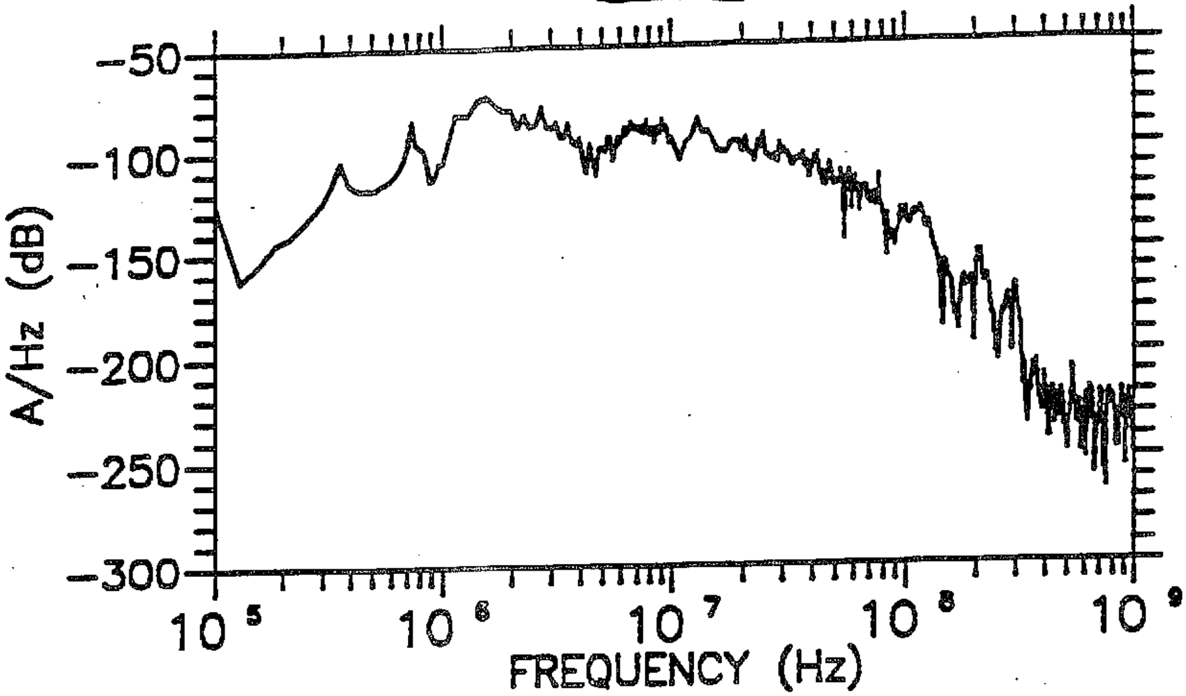
750
500
250
0
-250
-500
-750
AMPS
1.0E-6
2.0E-6
3.0E-6
4.0E-6
TIME (SEC)

[redacted]

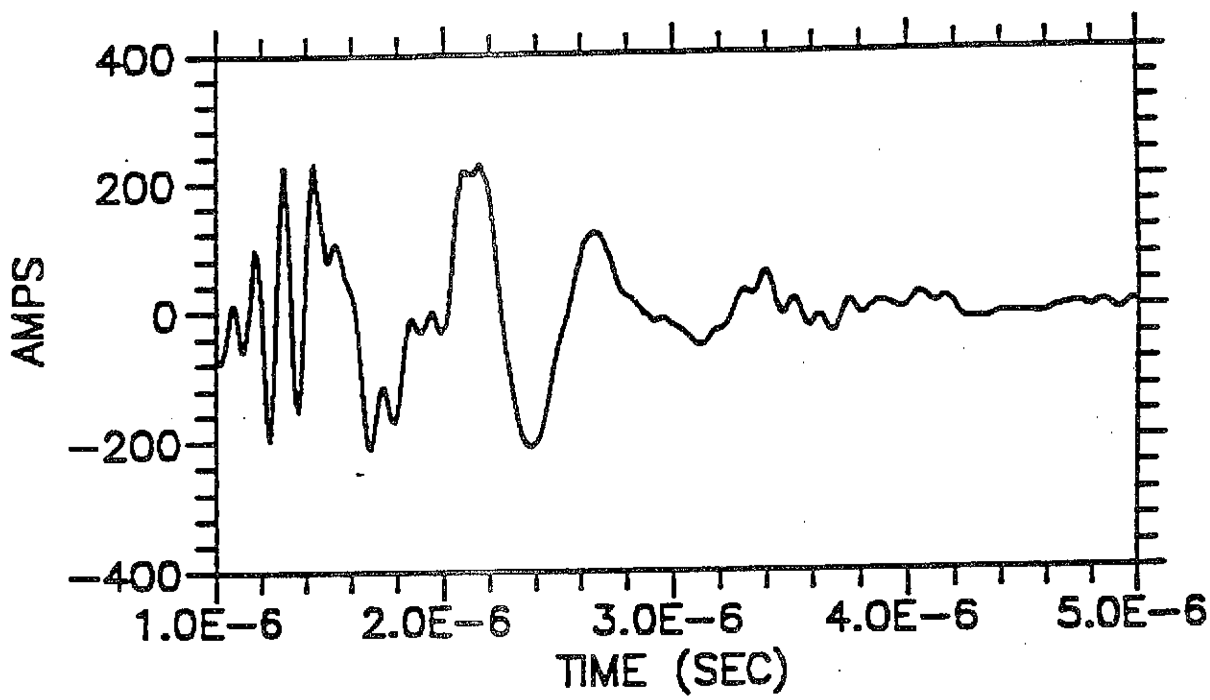

-50
-100
-150
-200
-250
A/Hz (dB)
10^5
10^6
10^7
10^8
10^9
FREQUENCY (Hz)


500
250
0
-250
-500
AMPS
1.0E-6
2.0E-6
3.0E-6
4.0E-6
TIME (SEC)

[redacted]

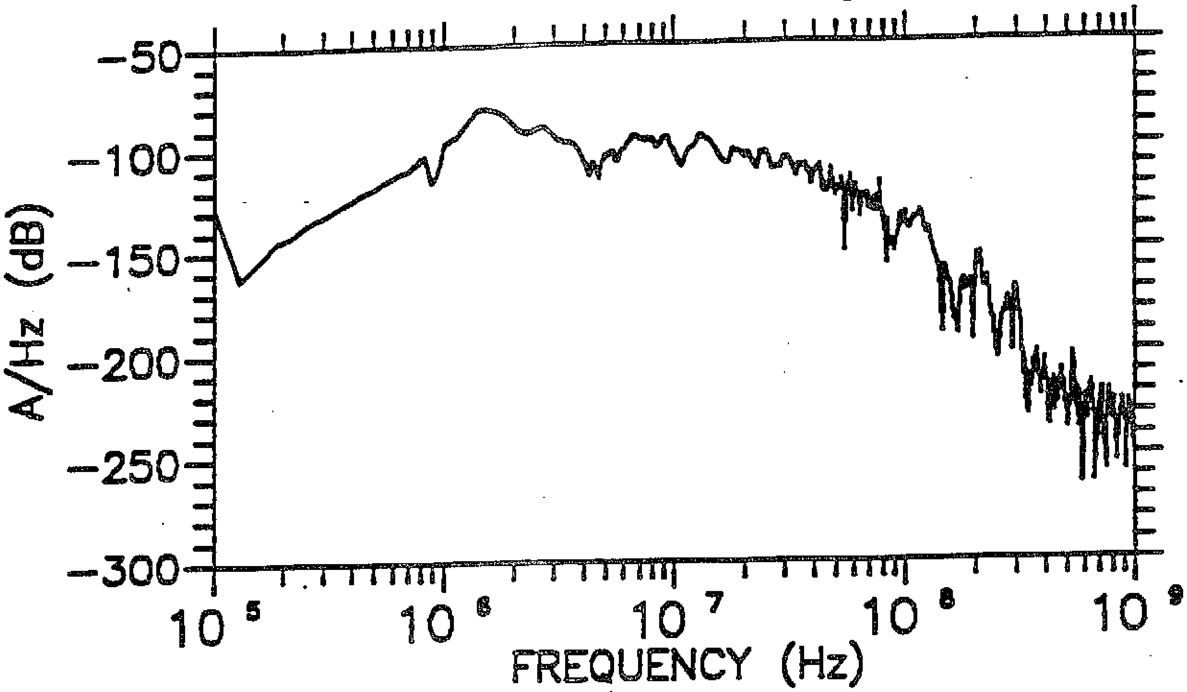


-50
-100
-150
-200
-250
-300
A/Hz (dB)
10^5
10^6
10^7
10^8
10^9
FREQUENCY (Hz)

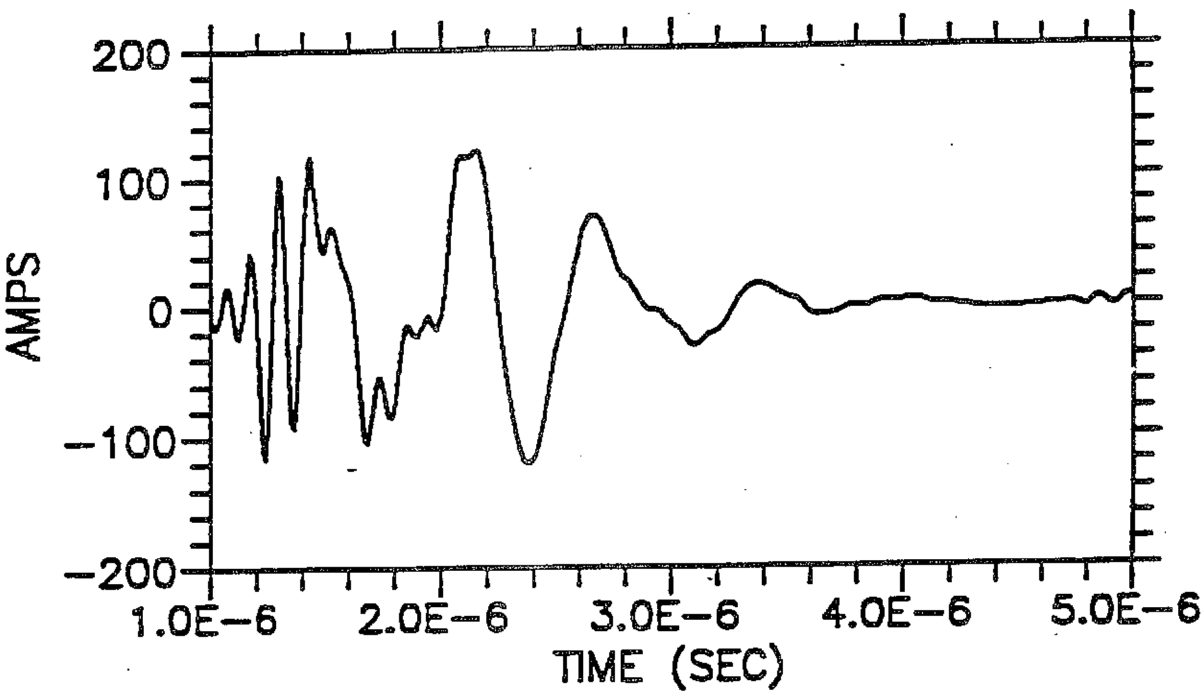


400
200
0
-200
-400
AMPS
1.0E-6
2.0E-6
3.0E-6
4.0E-6
5.0E-6
TIME (SEC)

[redacted]

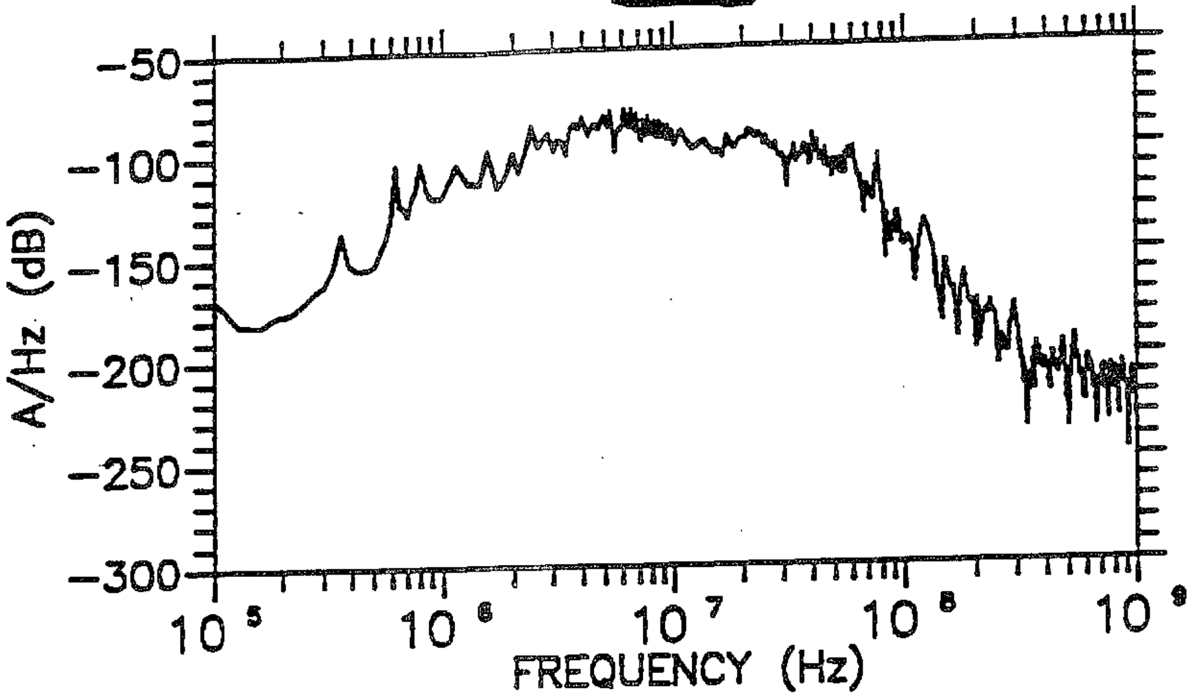


-50
-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

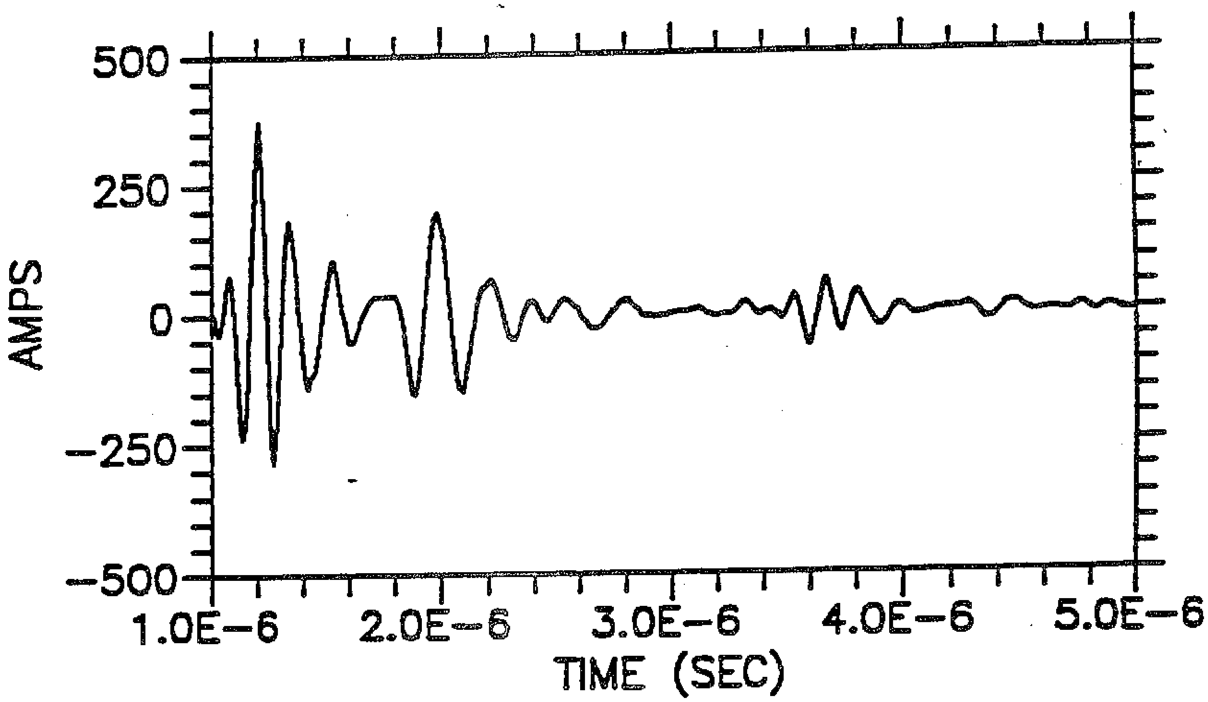


200
100
0
-100
-200
AMPS
1.0E-6
2.0E-6
3.0E-6
4.0E-6
5.0E-6
TIME (SEC)

[redacted]

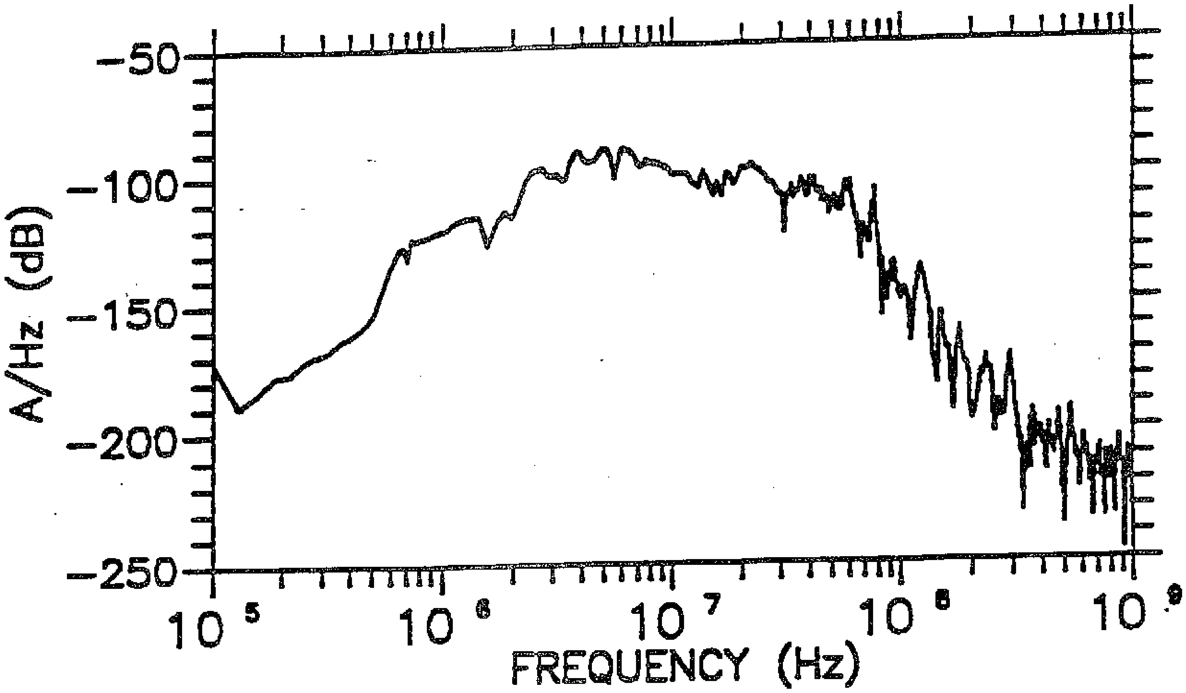


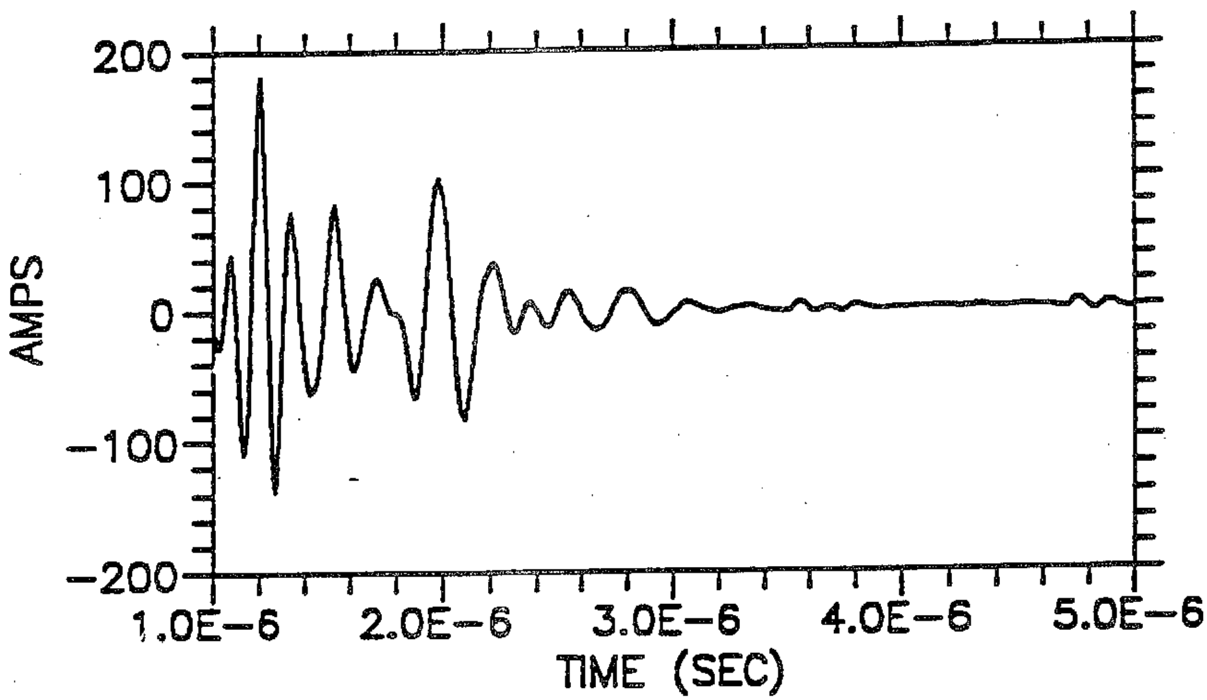
−50
−100
−150
−200
−250
−300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



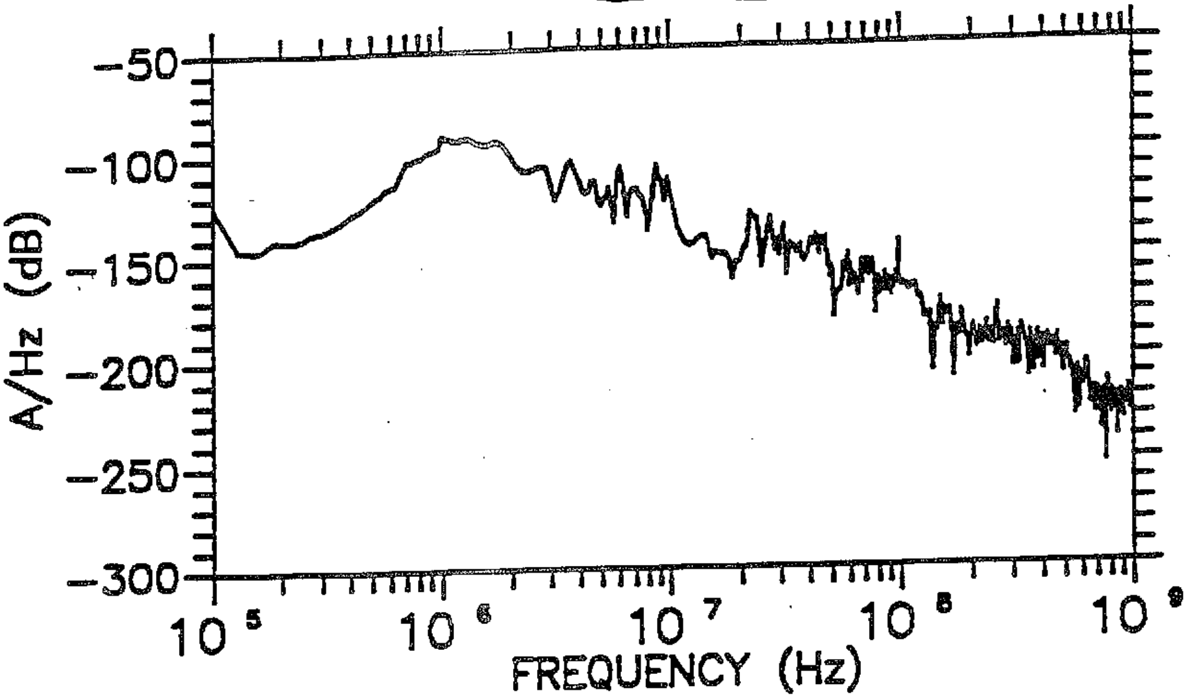
500
250
0
−250
−500
AMPS
1.0E−6
2.0E−6
3.0E−6
4.0E−6
5.0E−6
TIME (SEC)

[redacted]

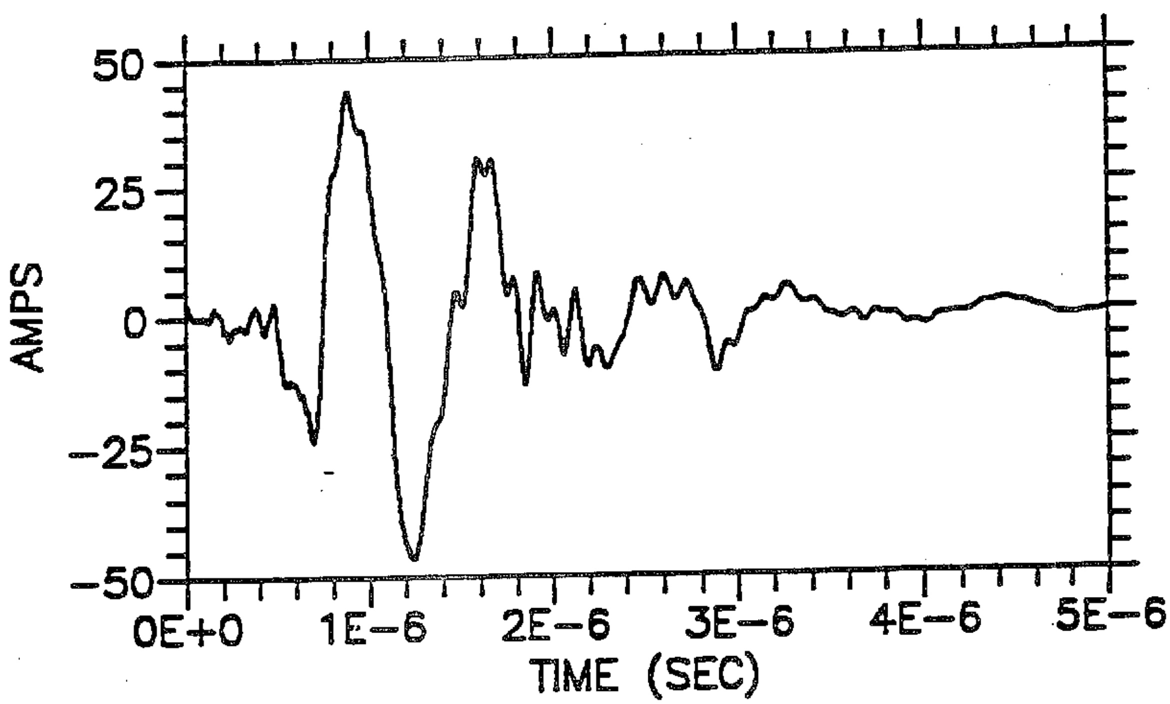

-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


200
100
0
-100
-200
AMPS
1.0E-6
2.0E-6
3.0E-6
4.0E-6
5.0E-6
TIME (SEC)

[redacted]

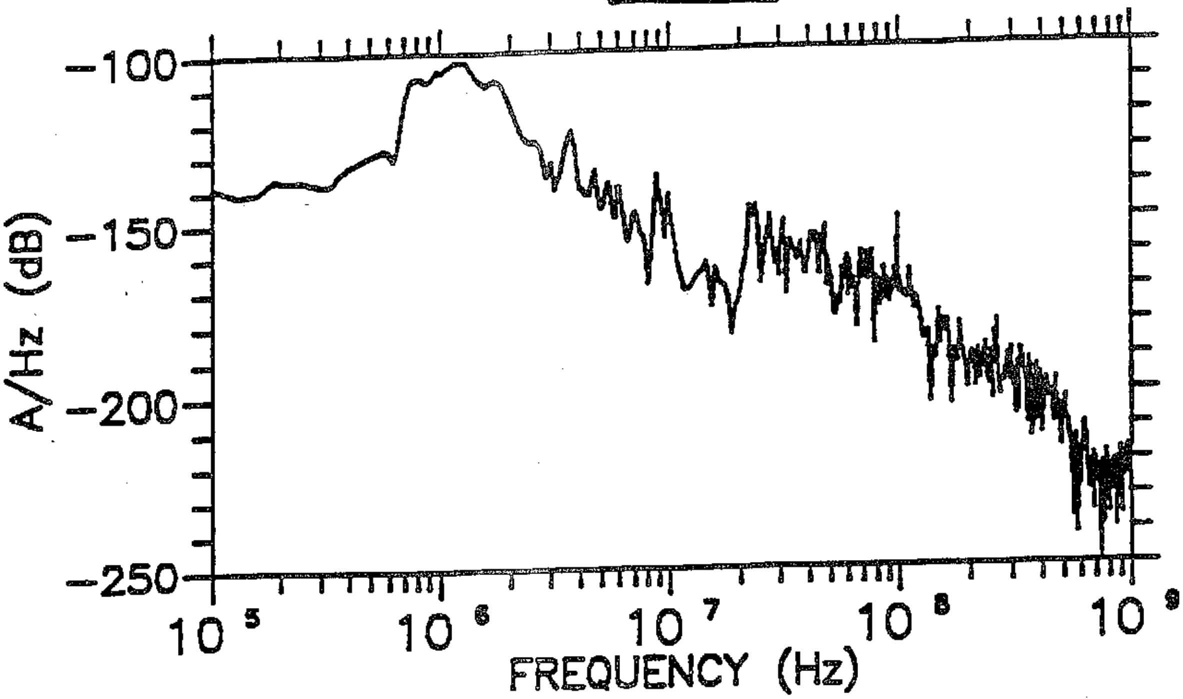


-50
-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

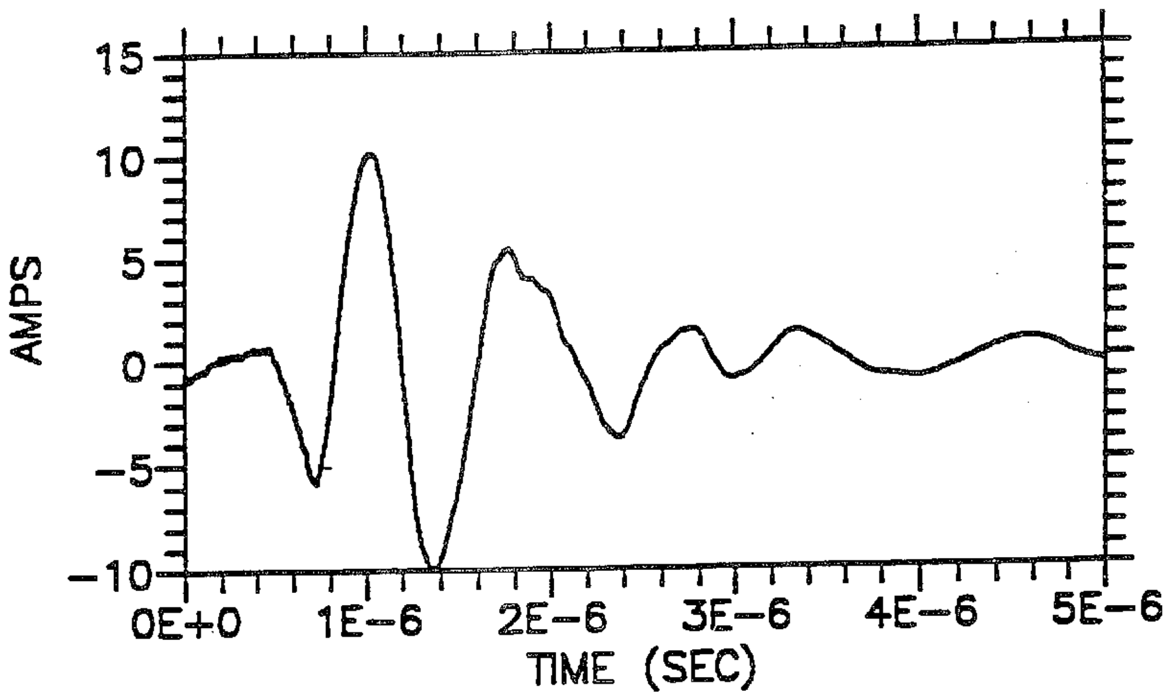


50
25
0
-25
-50
AMPS
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

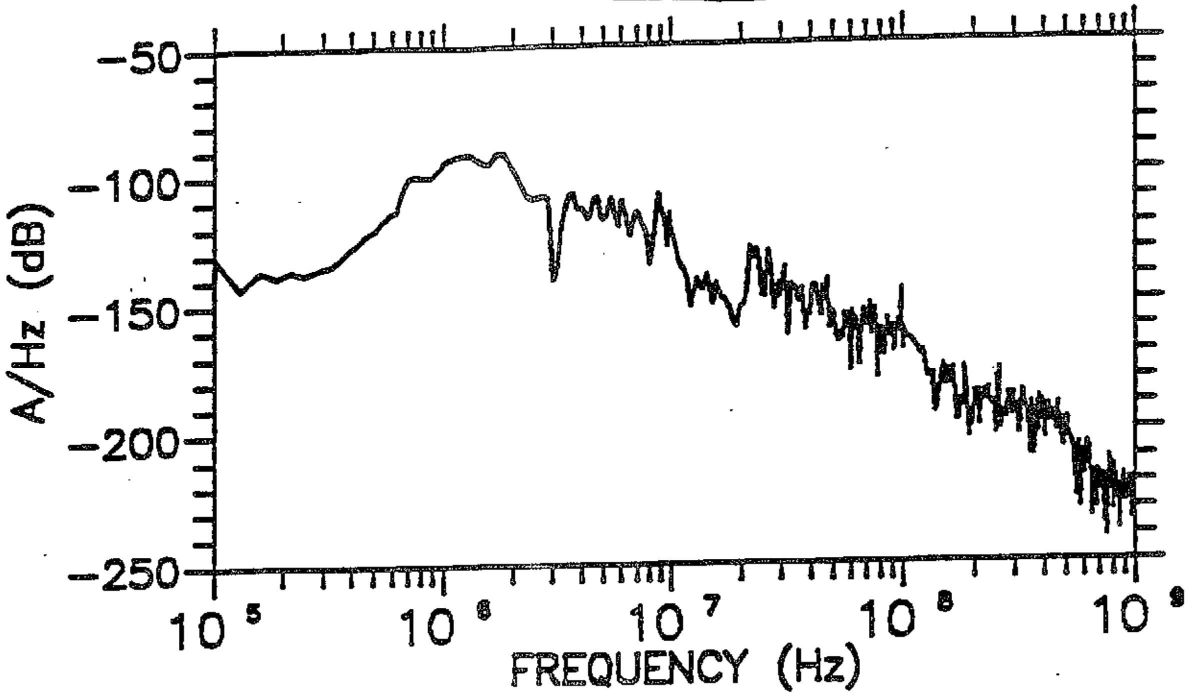


-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

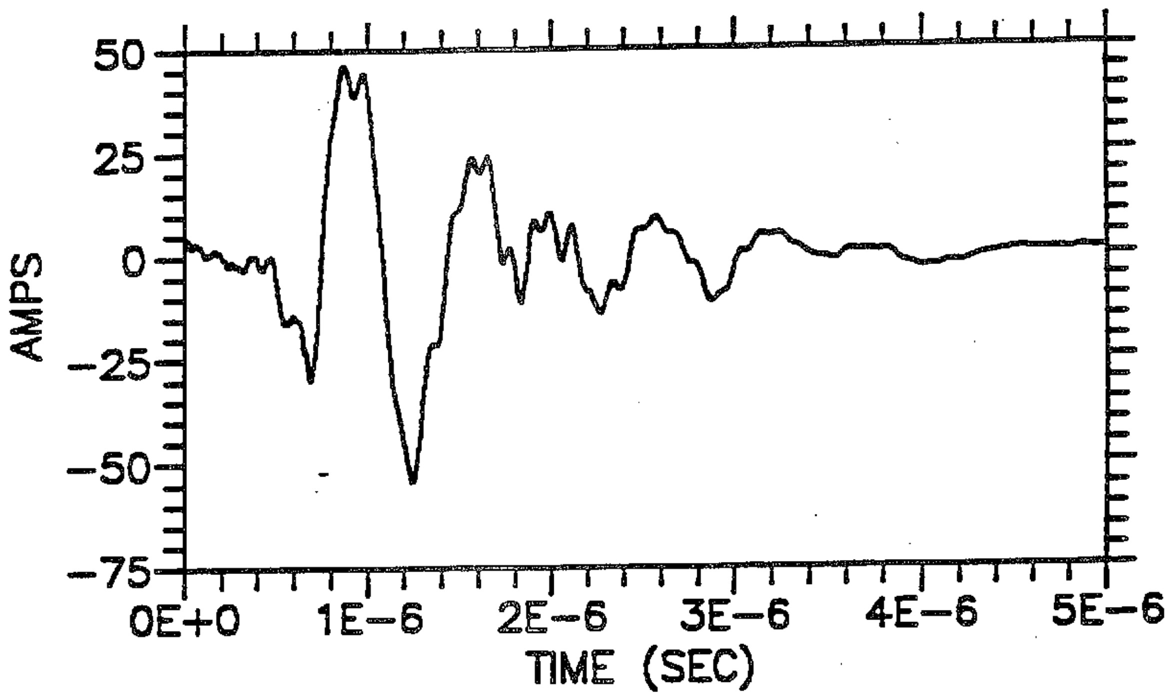


15
10
5
0
-5
-10
AMPS
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

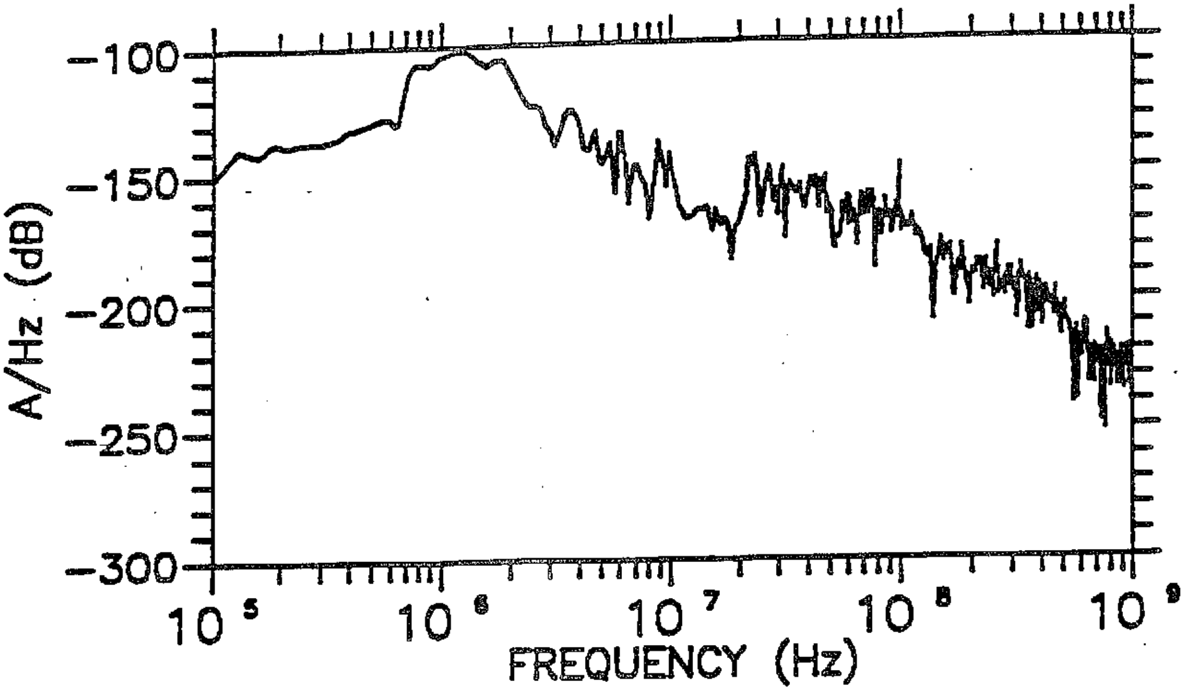


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

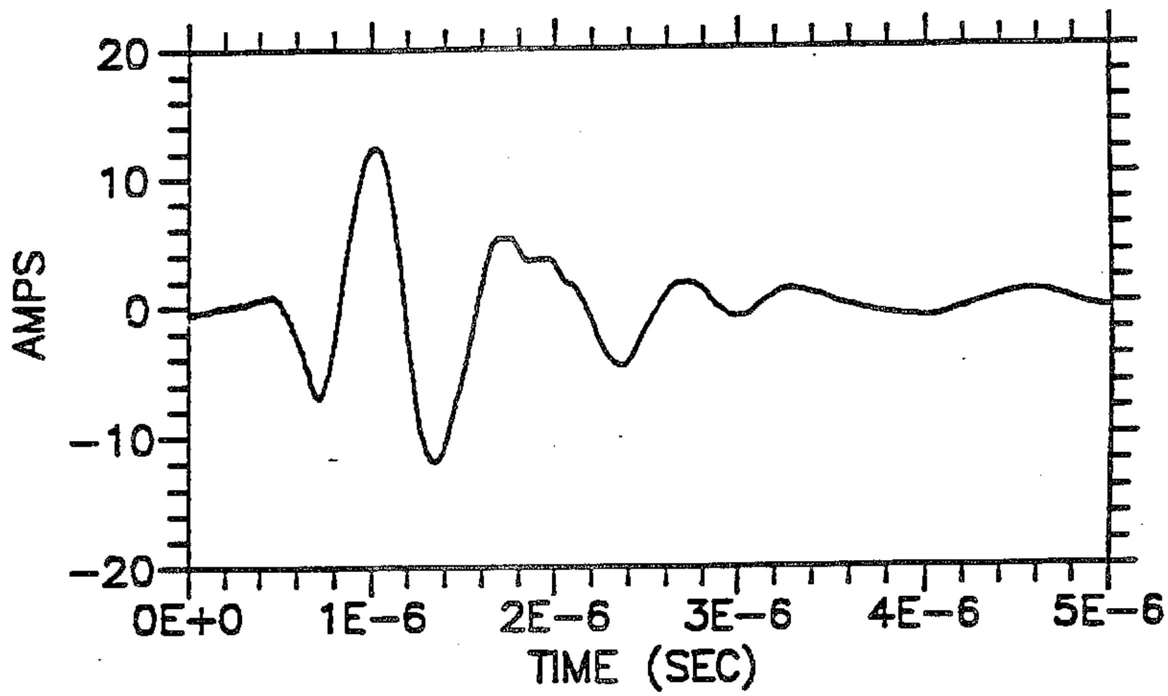


50
25
0
-25
-50
-75
AMPS
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

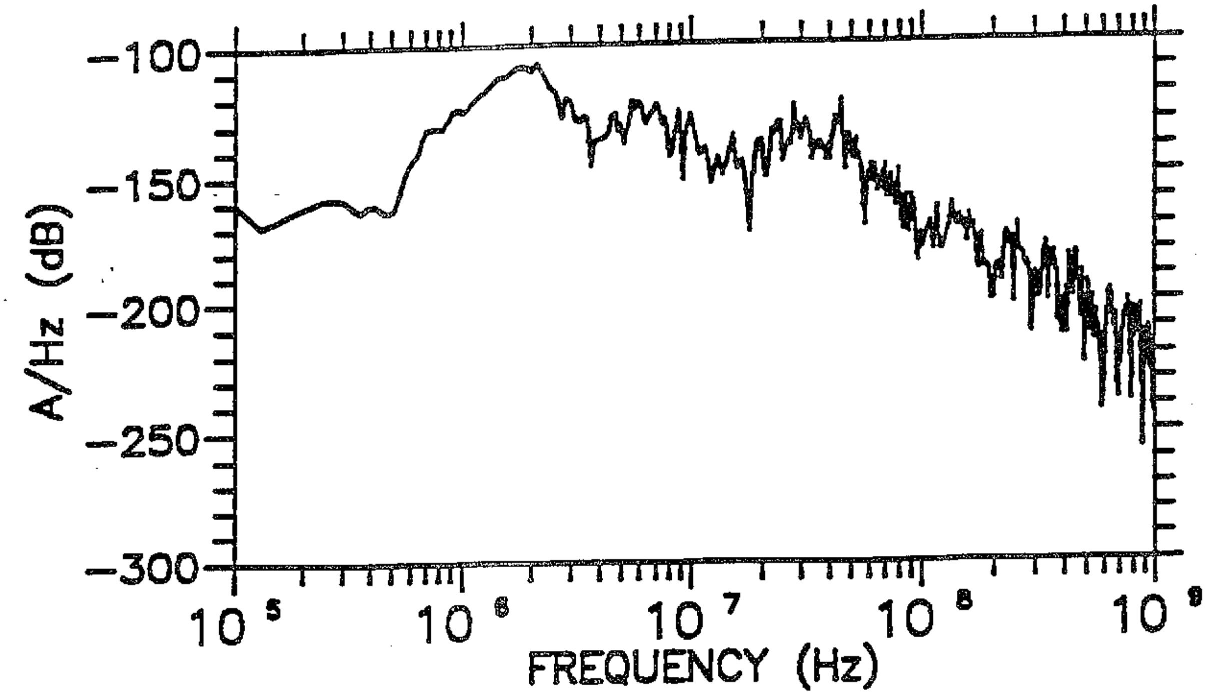


-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

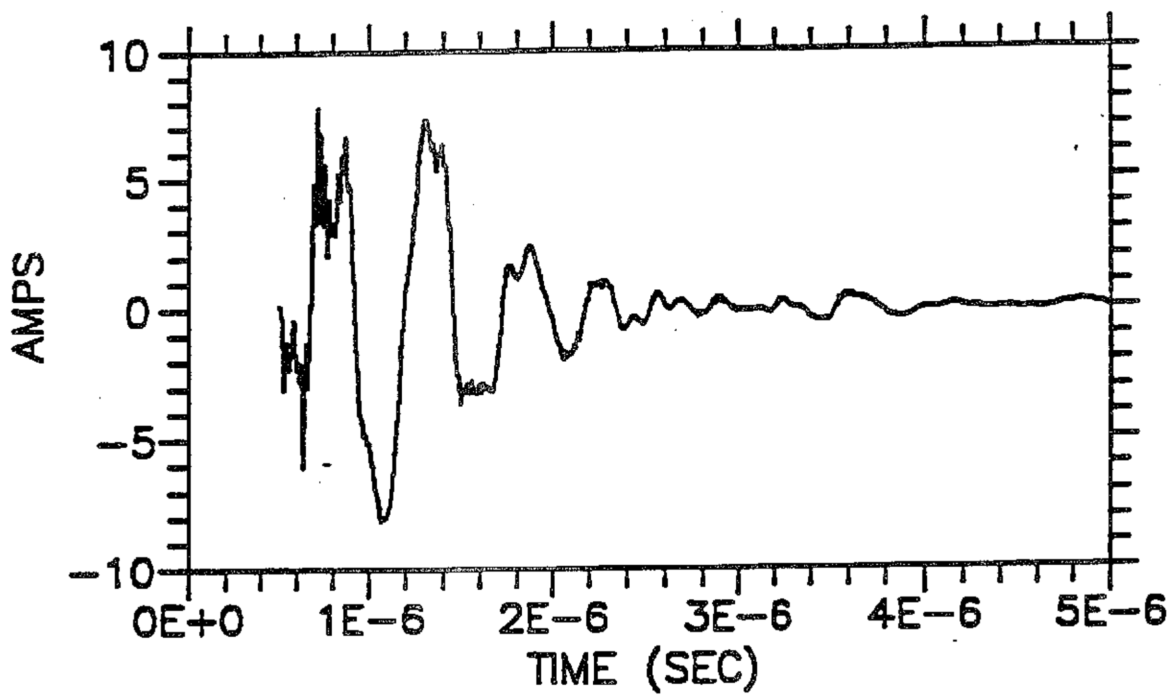


20
10
0
-10
-20
AMPS
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

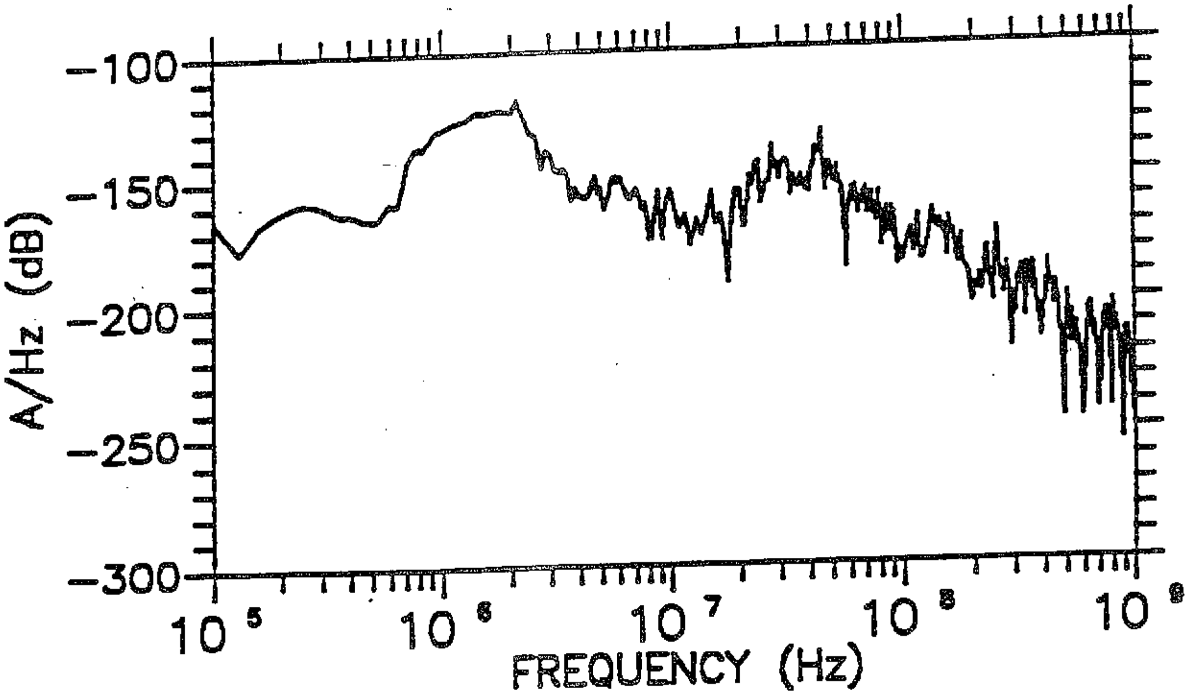


-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

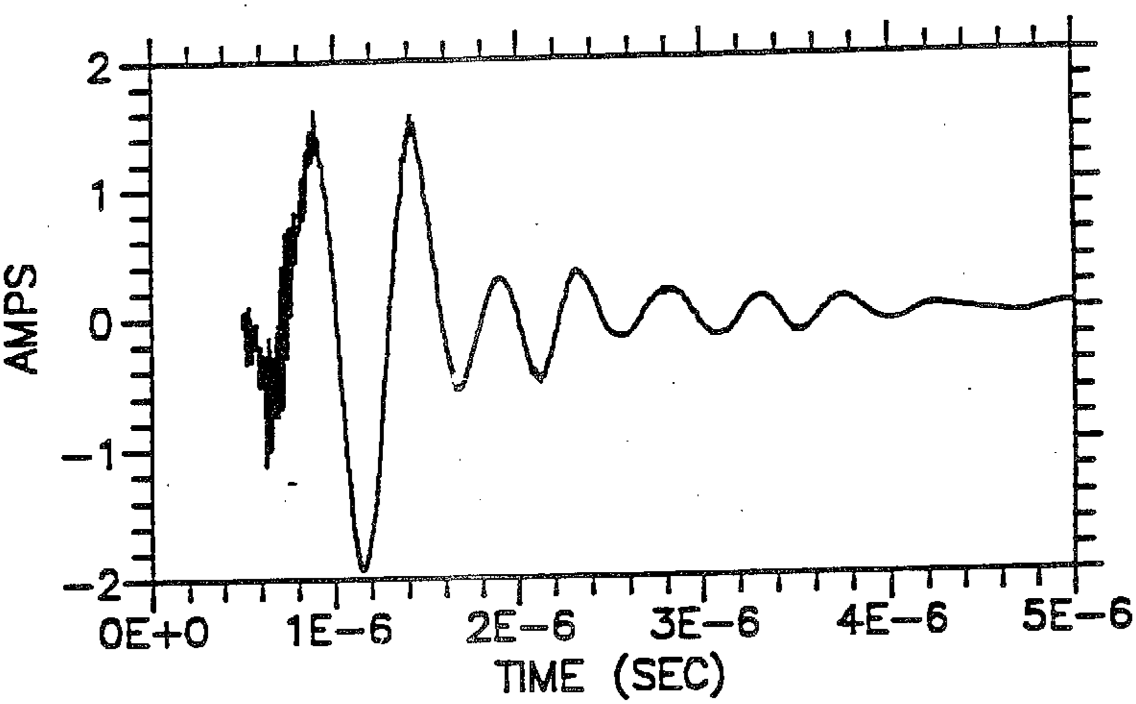


10
5
0
-5
-10
AMPS
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

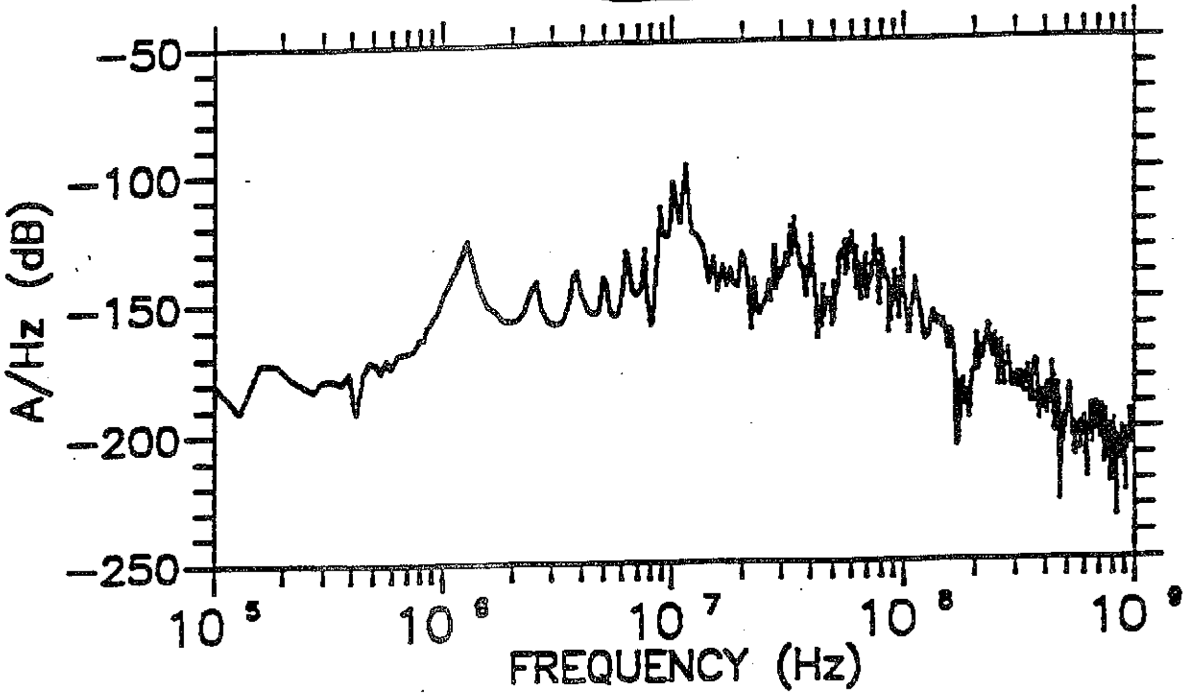


A/Hz (dB)
-100
-150
-200
-250
-300
10^5
10^6
10^7
10^8
10^9
FREQUENCY (Hz)

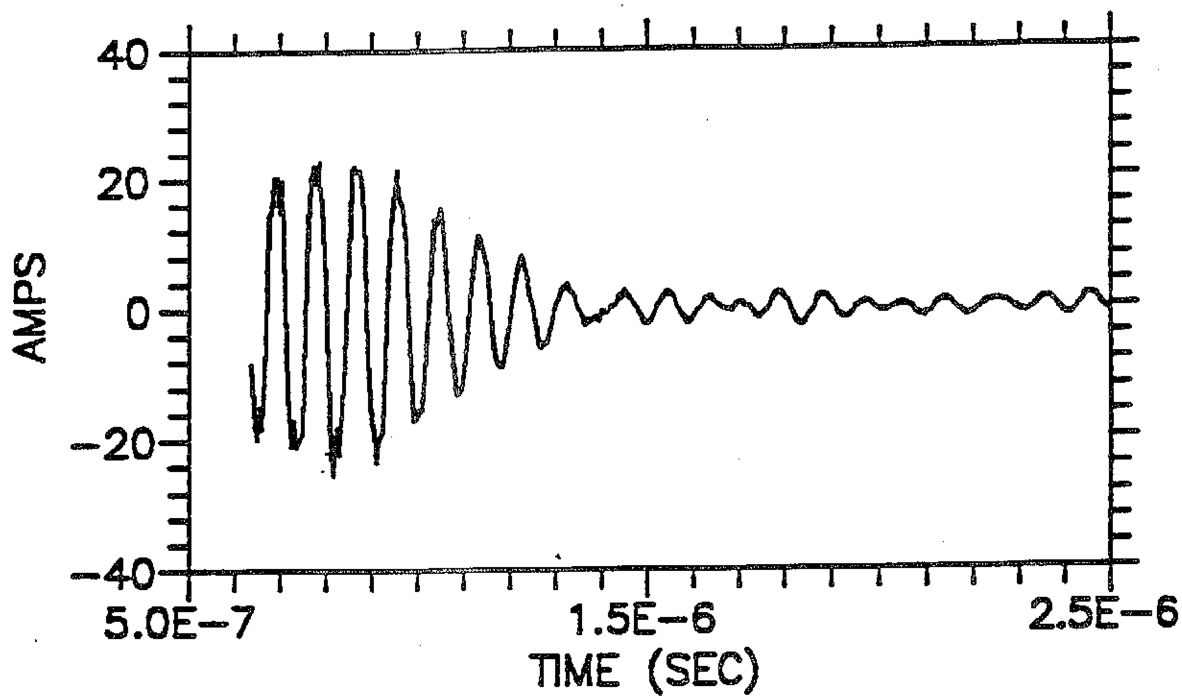


AMPS
2
1
0
-1
-2
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

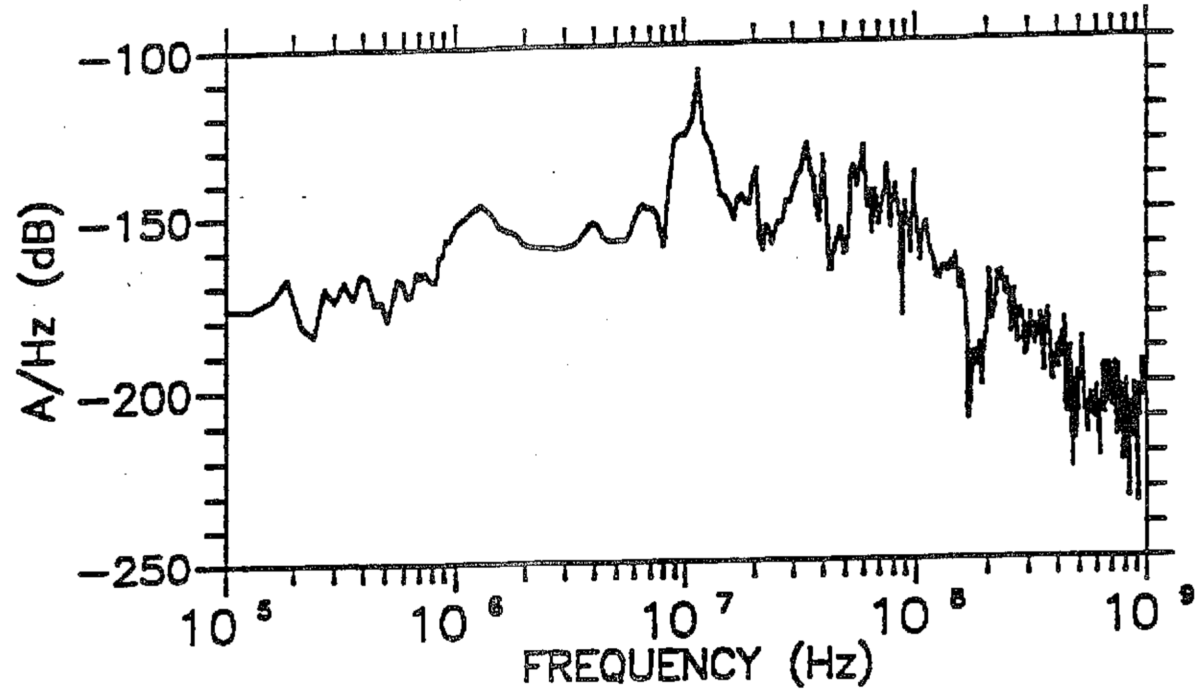


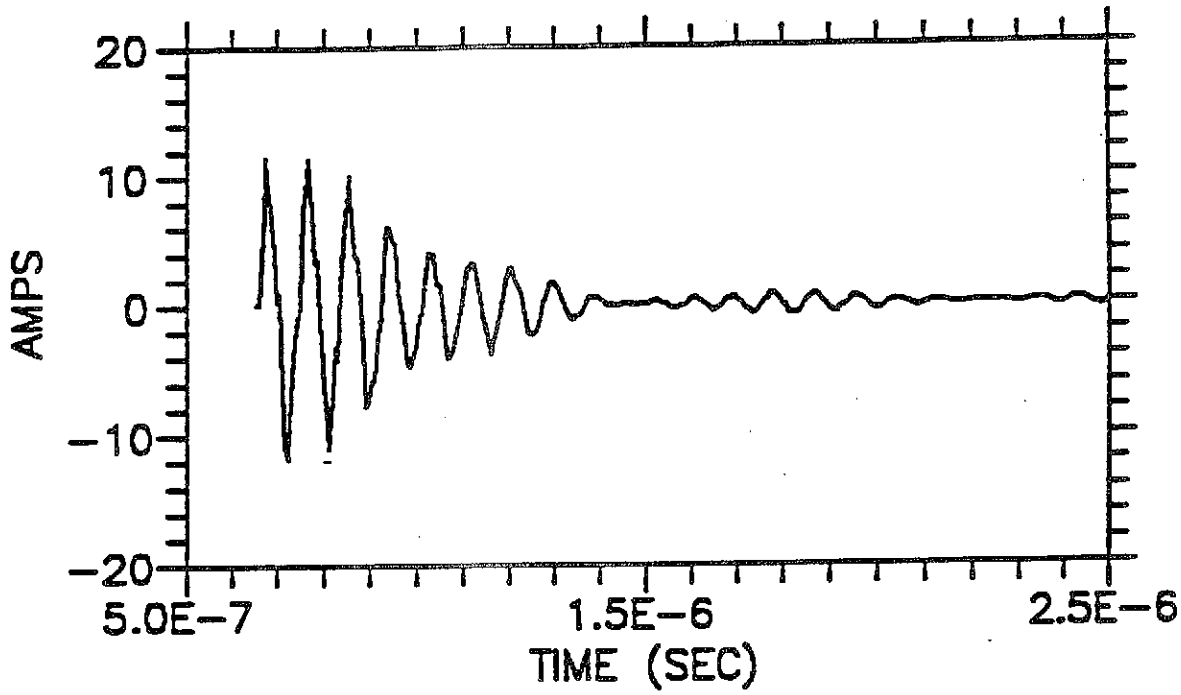
-50
-100
-150
-200
-250
A/Hz (dB)
10^5
10^6
10^7
10^8
10^9
FREQUENCY (Hz)



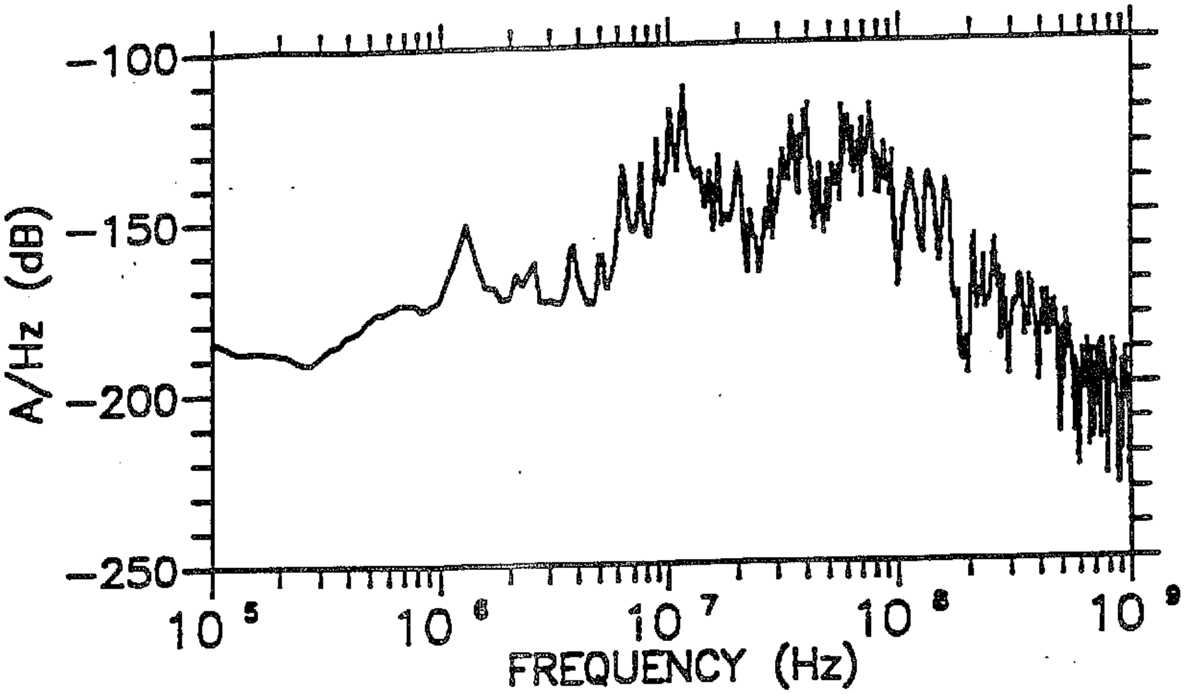
40
20
0
-20
-40
AMPS
5.0E-7
1.5E-6
2.5E-6
TIME (SEC)

[redacted]

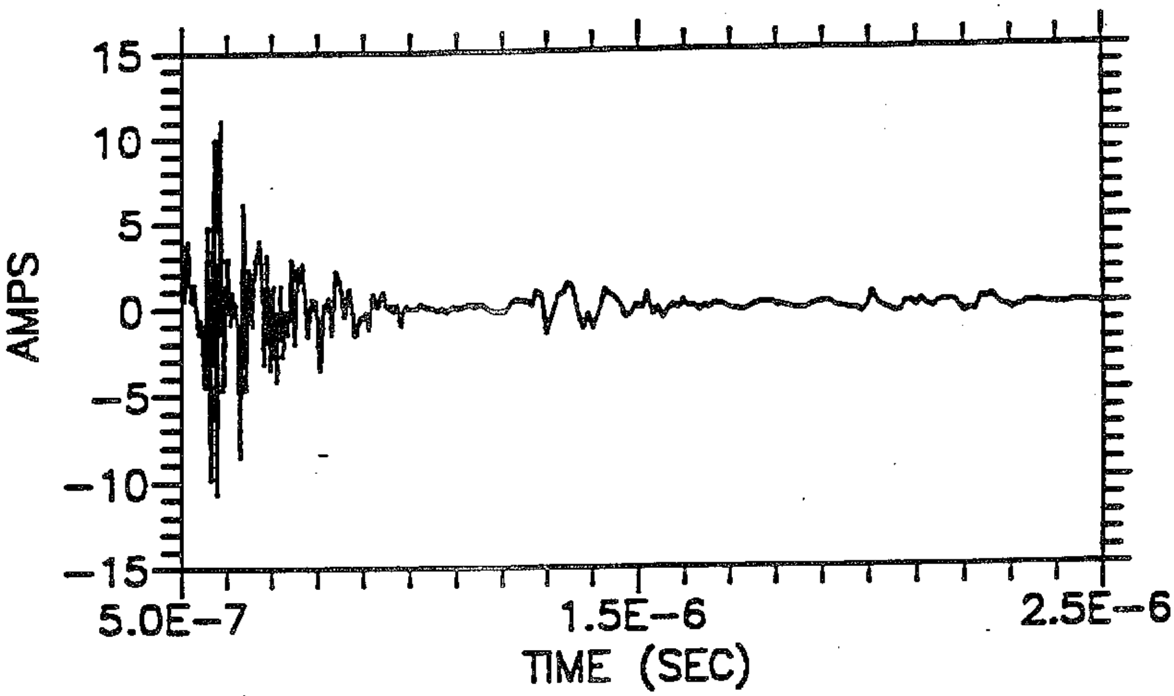

-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


20
10
0
-10
-20
AMPS
5.0E-7
1.5E-6
2.5E-6
TIME (SEC)

[redacted]

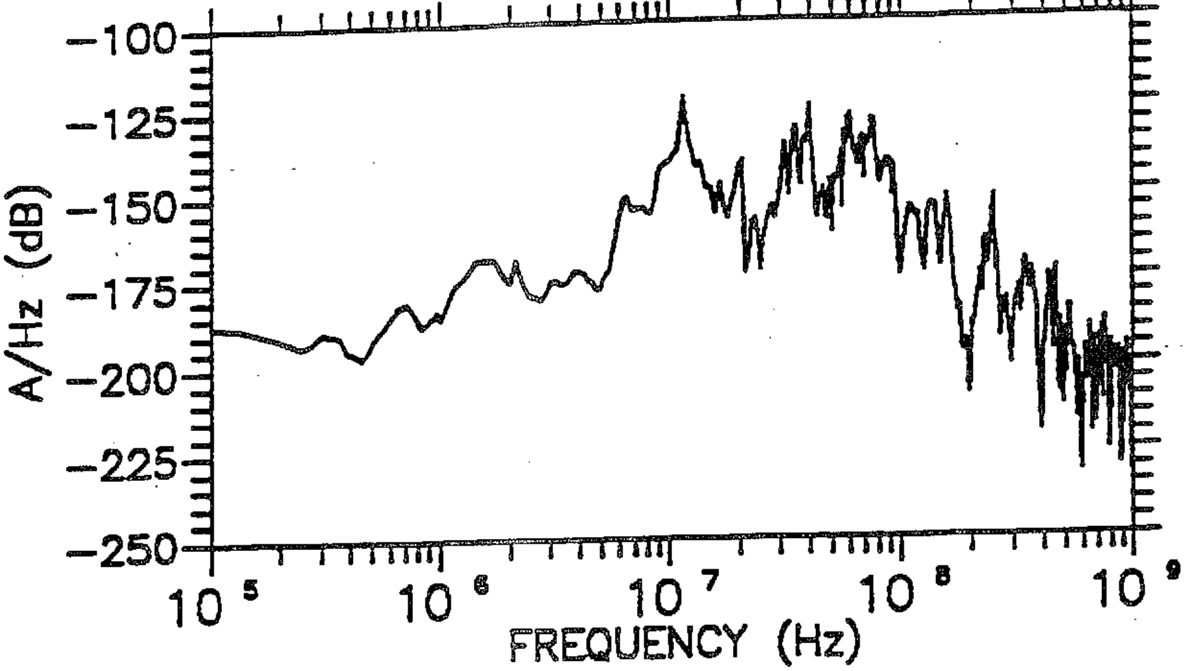


A/Hz (dB)
-100
-150
-200
-250
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

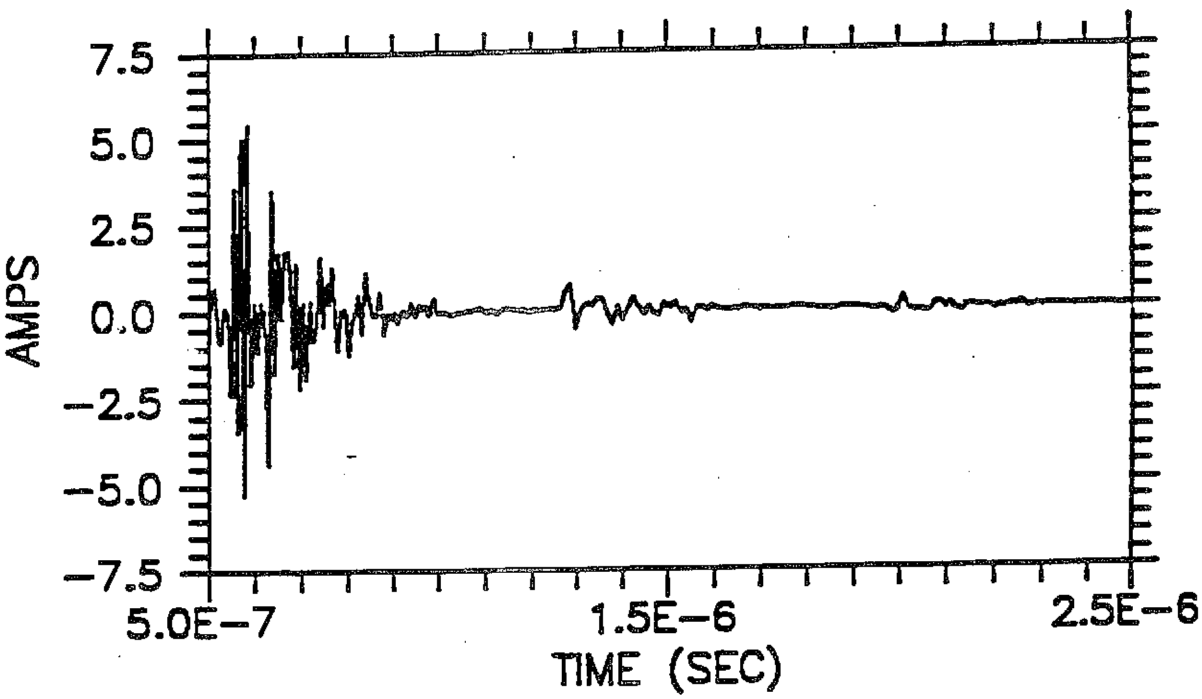


AMPS
15
10
5
0
-5
-10
-15
5.0E-7
1.5E-6
2.5E-6
TIME (SEC)

[redacted]

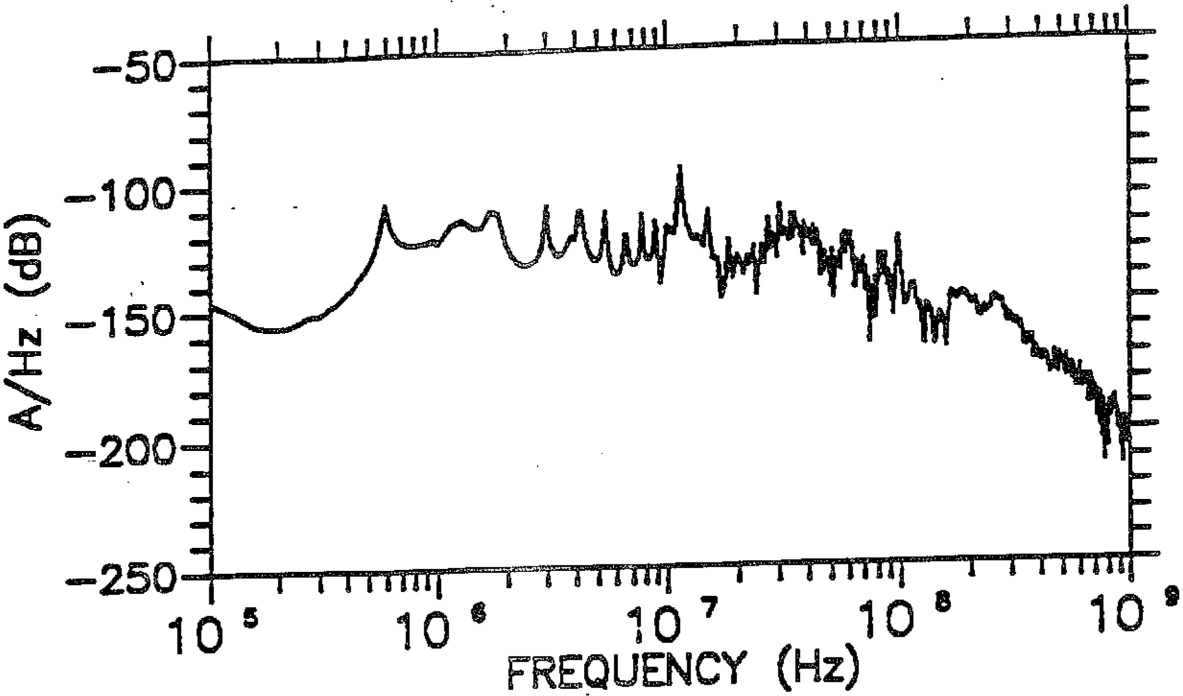


A/Hz (dB)
-100
-125
-150
-175
-200
-225
-250
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

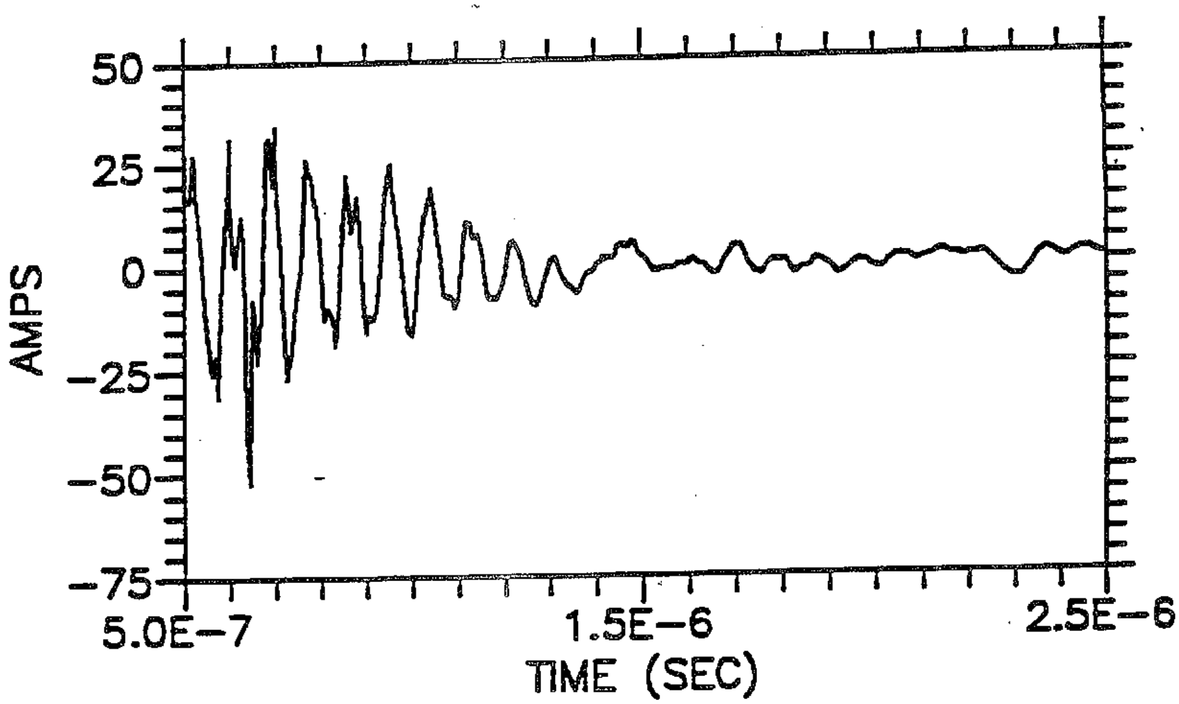


AMPS
7.5
5.0
2.5
0.0
-2.5
-5.0
-7.5
5.0E-7
1.5E-6
2.5E-6
TIME (SEC)

[redacted]

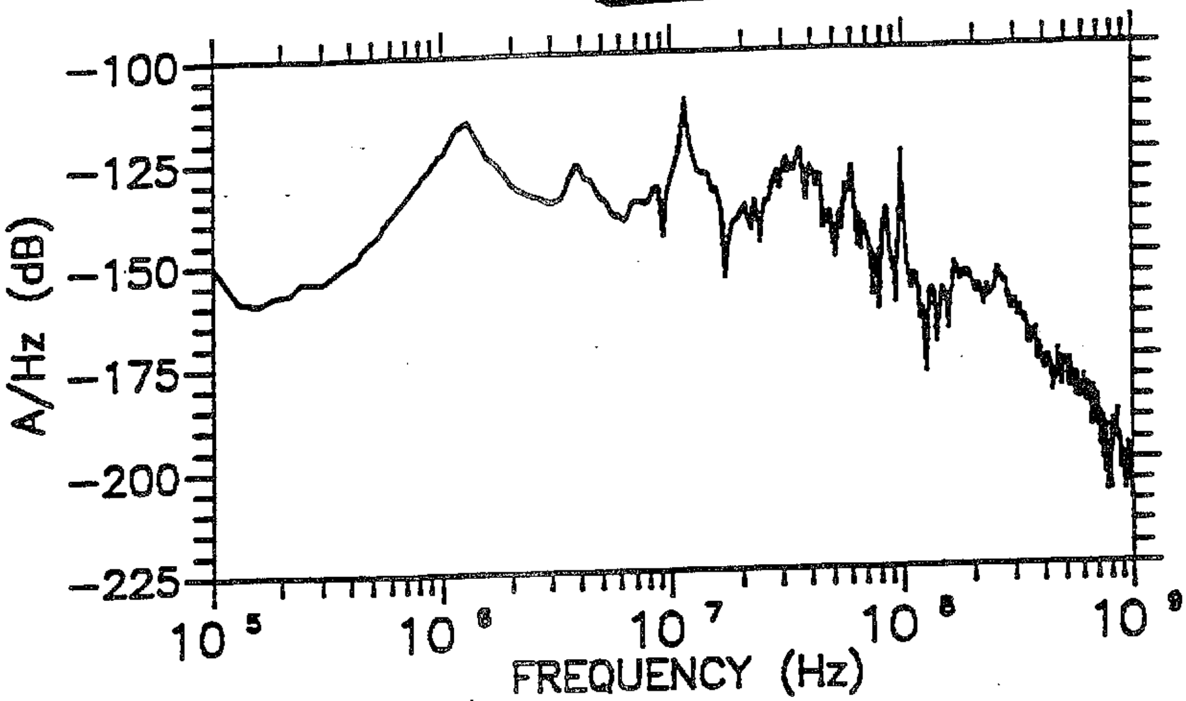


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

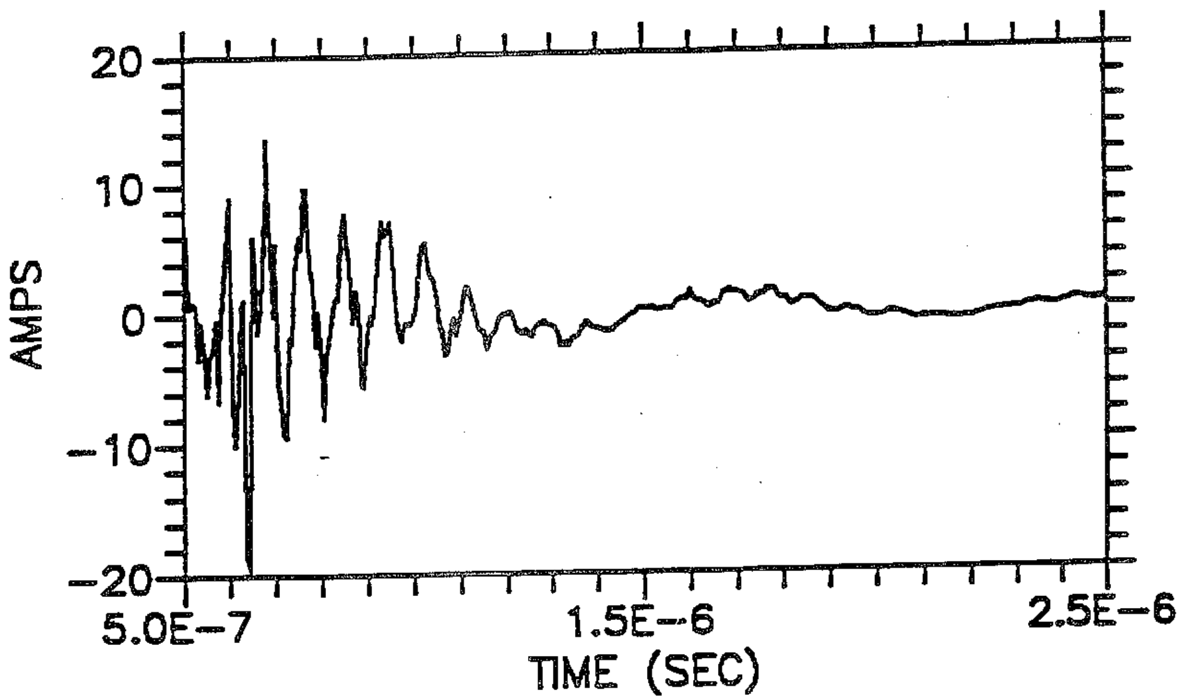


50
25
0
-25
-50
-75
AMPS
5.0E-7
1.5E-6
2.5E-6
TIME (SEC)

[redacted]

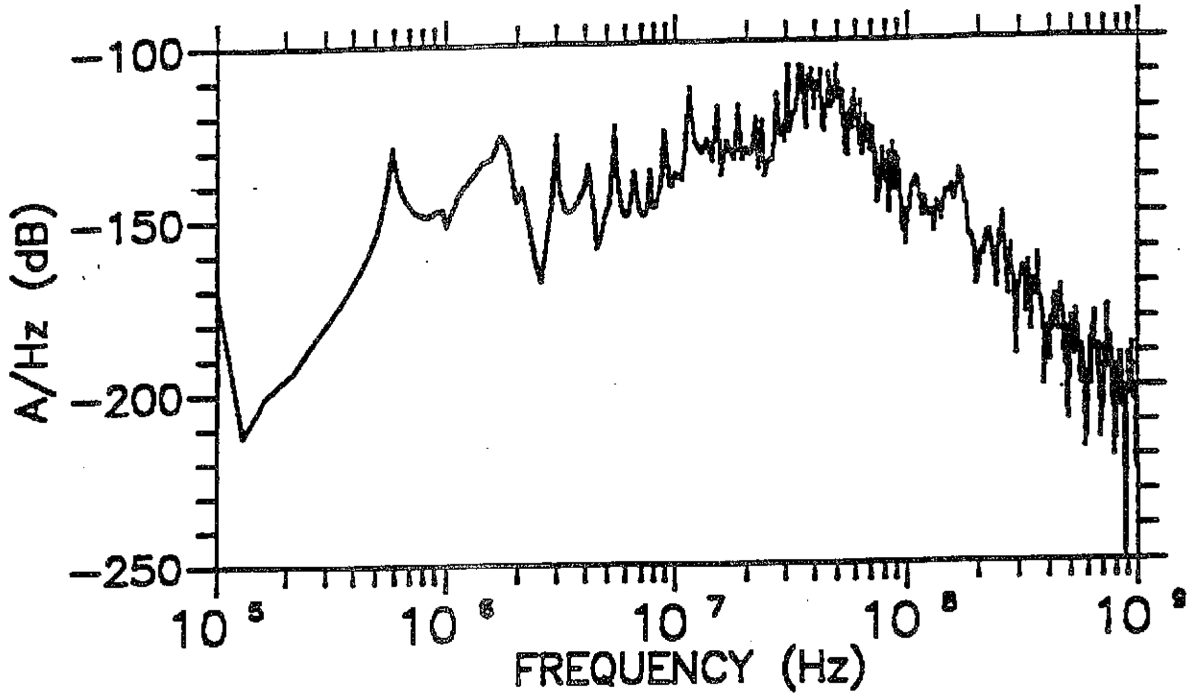


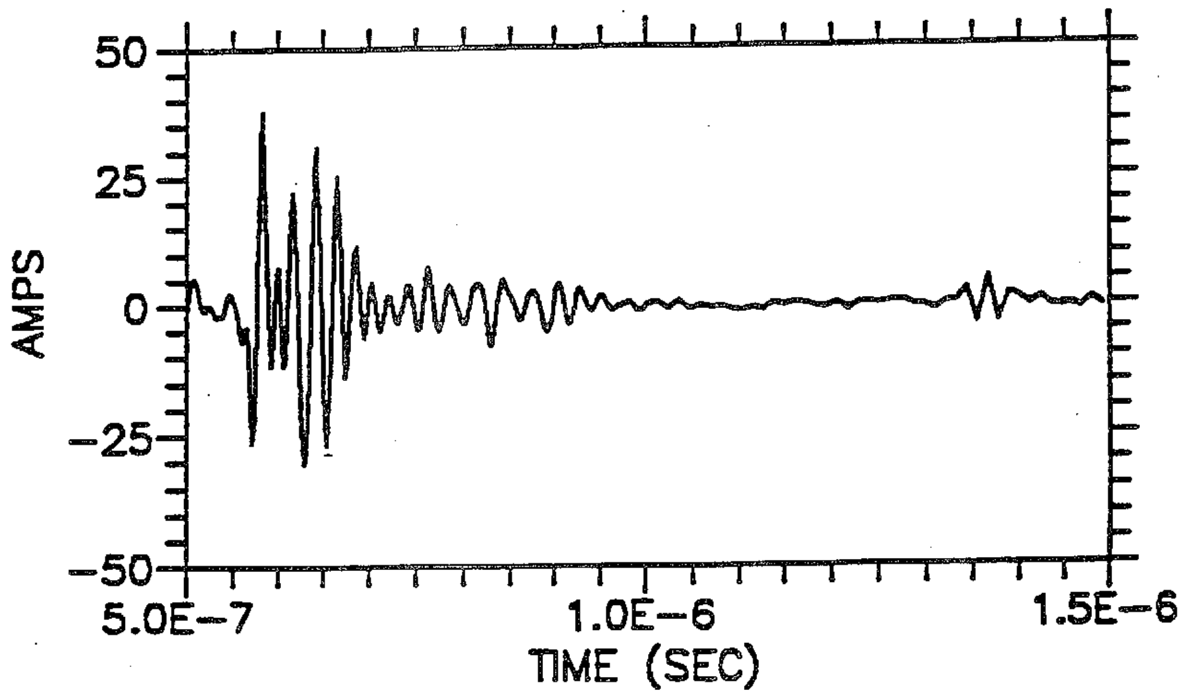
A/Hz (dB)
−100
−125
−150
−175
−200
−225
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



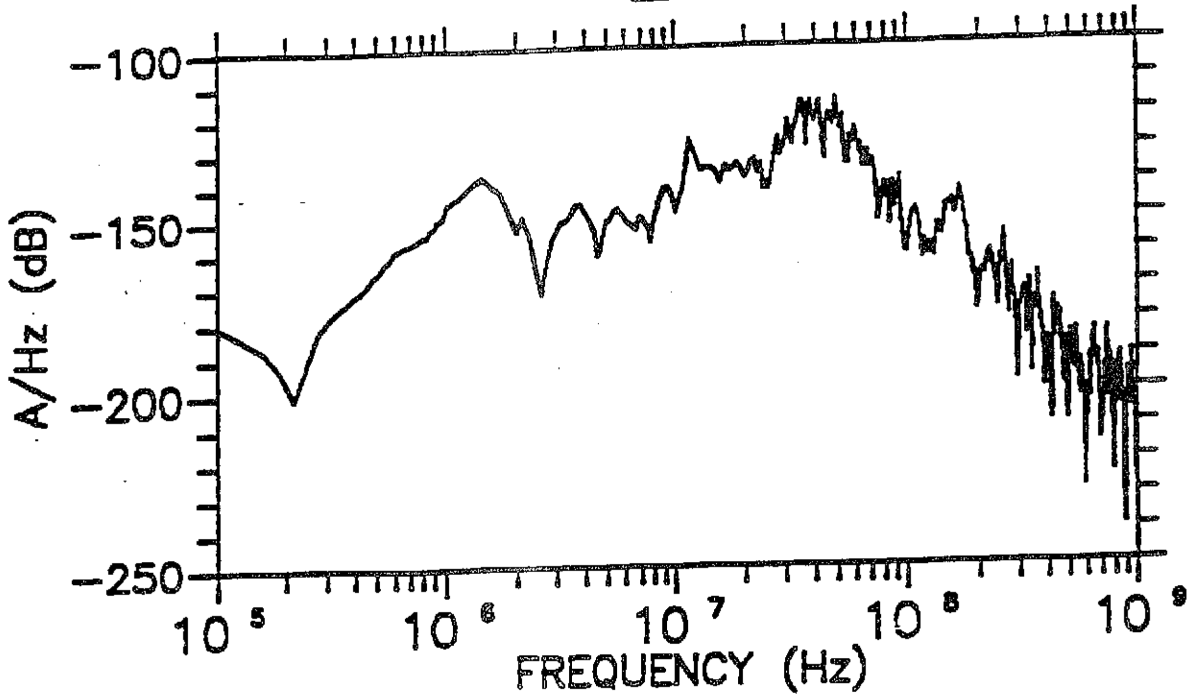
AMPS
20
10
0
−10
−20
5.0E−7
1.5E−6
2.5E−6
TIME (SEC)

[redacted]

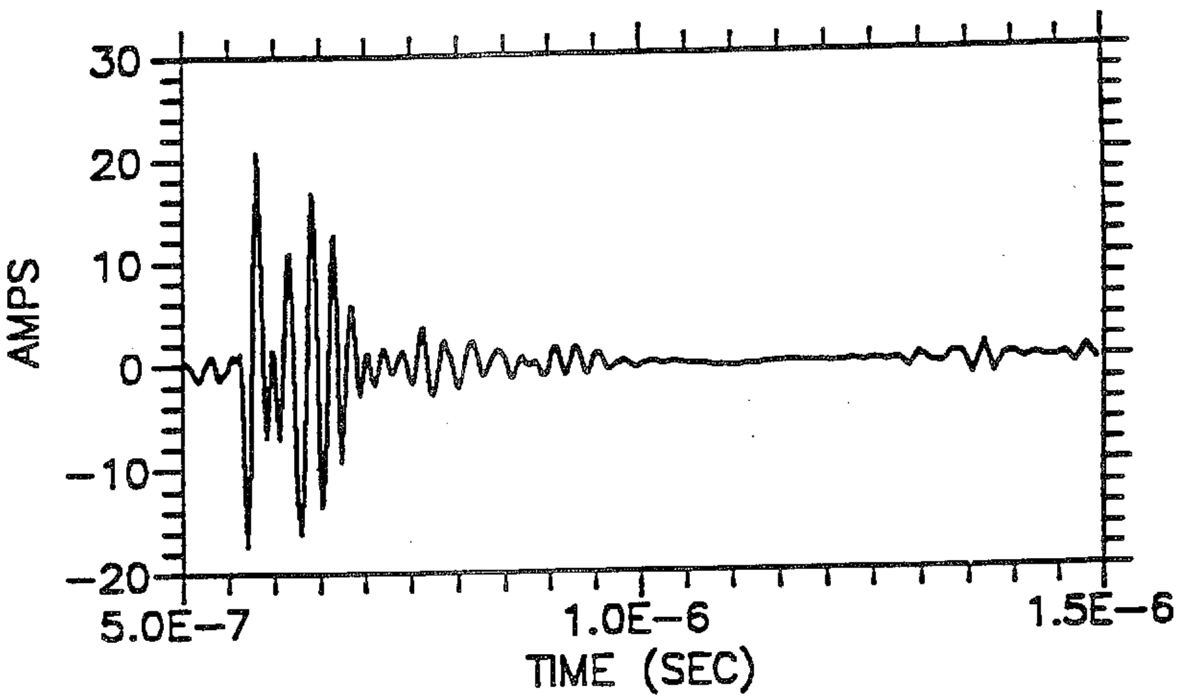

-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


50
25
0
-25
-50
AMPS
5.0E-7
1.0E-6
1.5E-6
TIME (SEC)

[redacted]

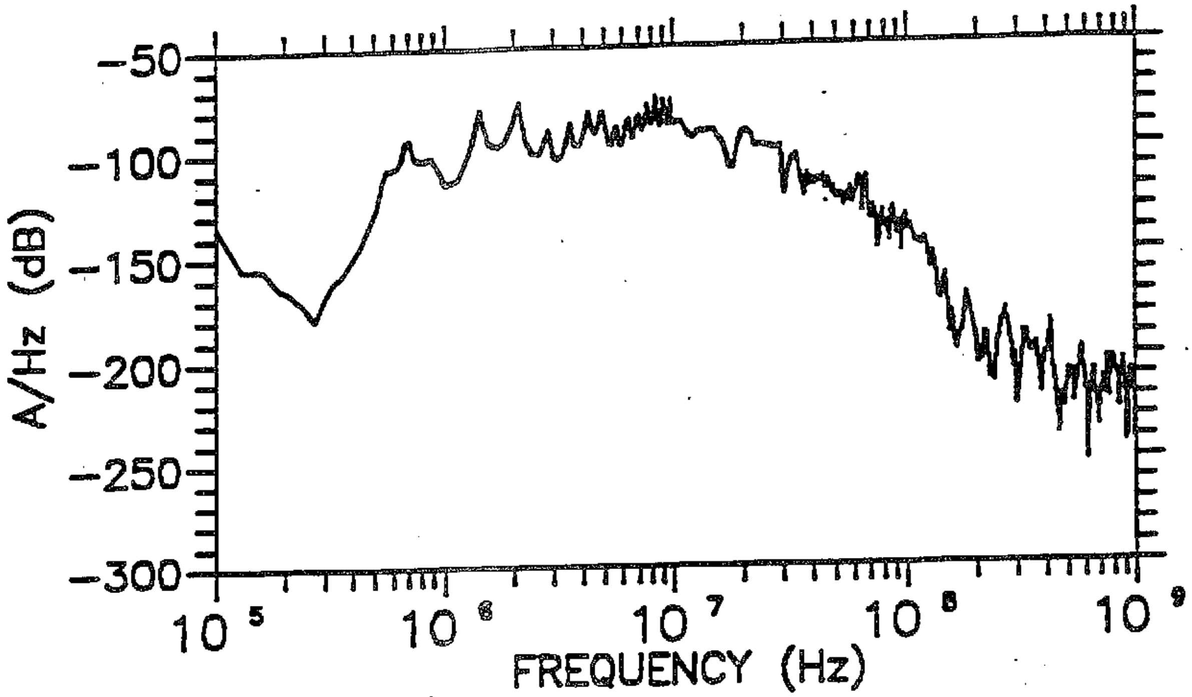


-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

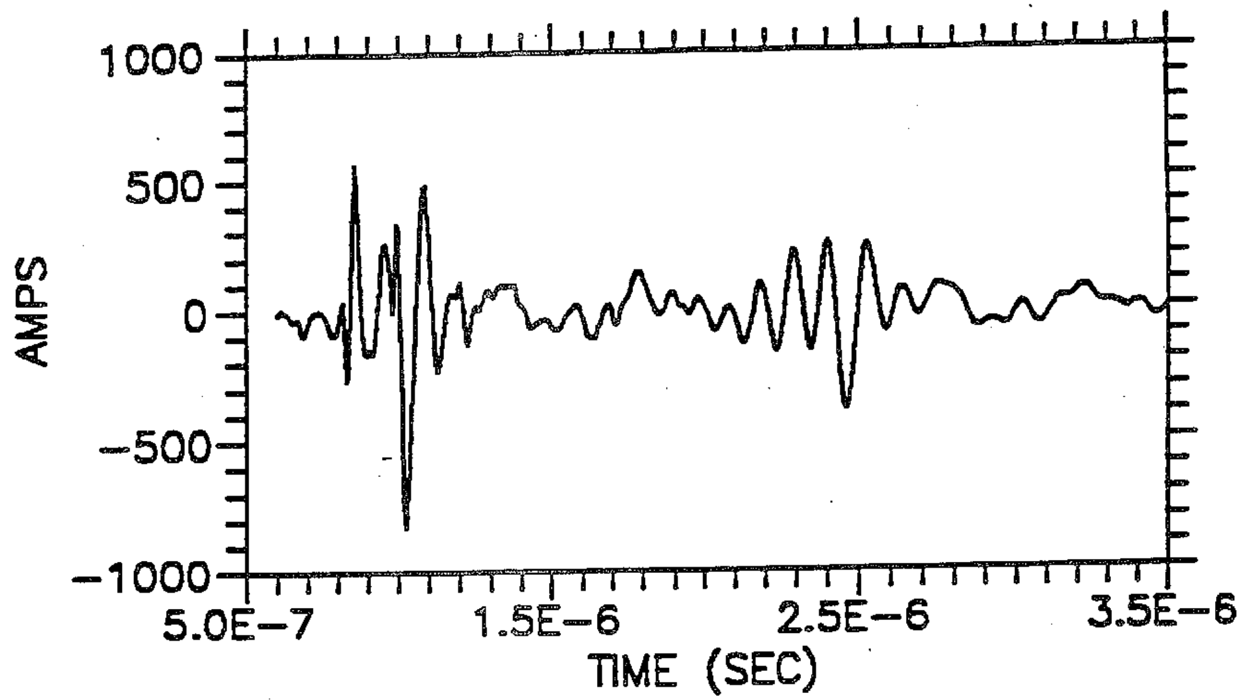


30
20
10
0
-10
-20
AMPS
5.0E-7
1.0E-6
1.5E-6
TIME (SEC)

[redacted]

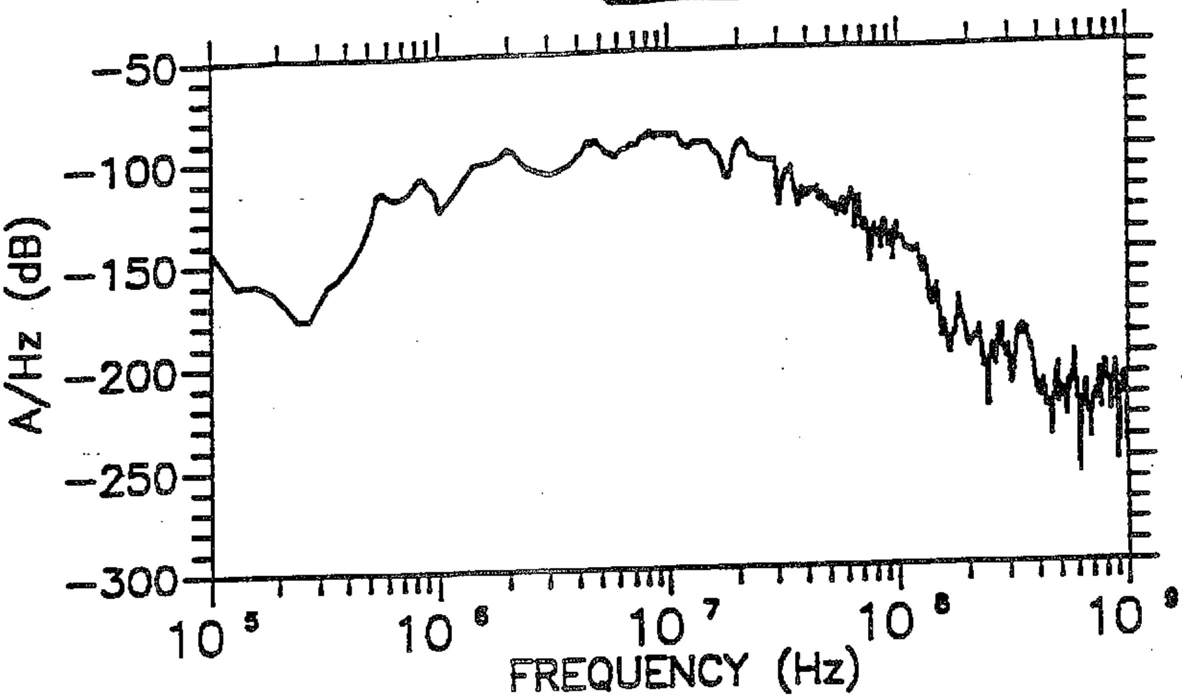


-50
-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

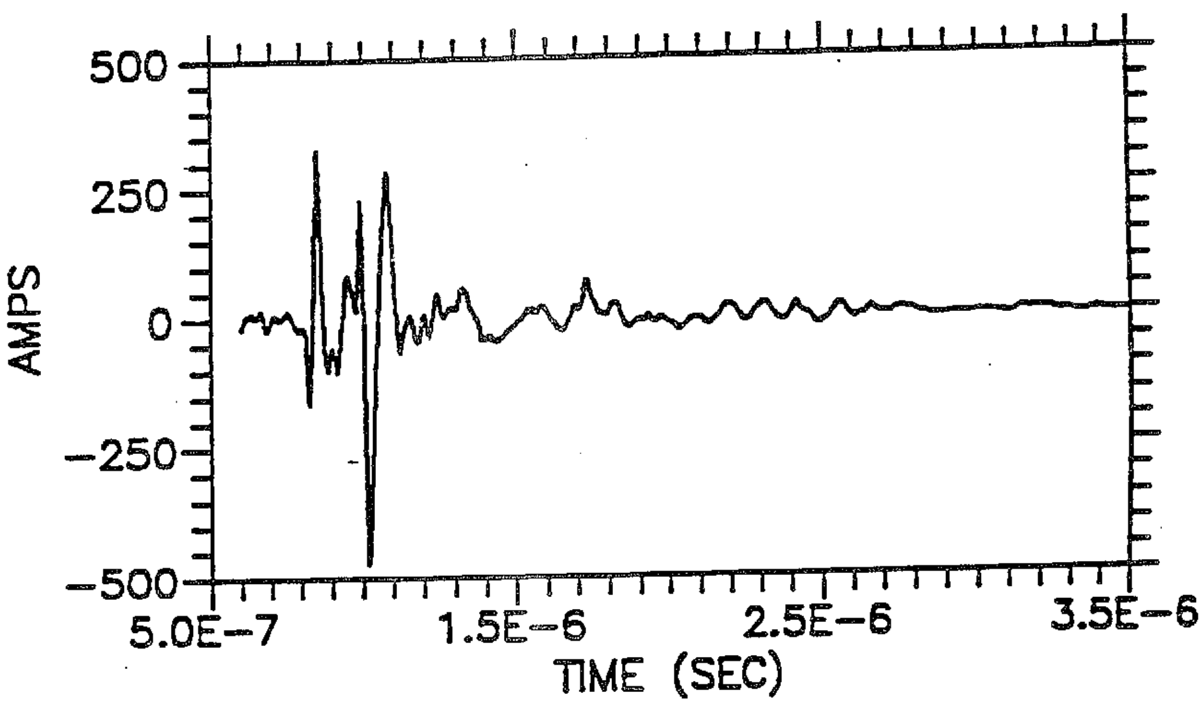


1000
500
0
-500
-1000
AMPS
5.0E-7
1.5E-6
2.5E-6
3.5E-6
TIME (SEC)

[redacted]

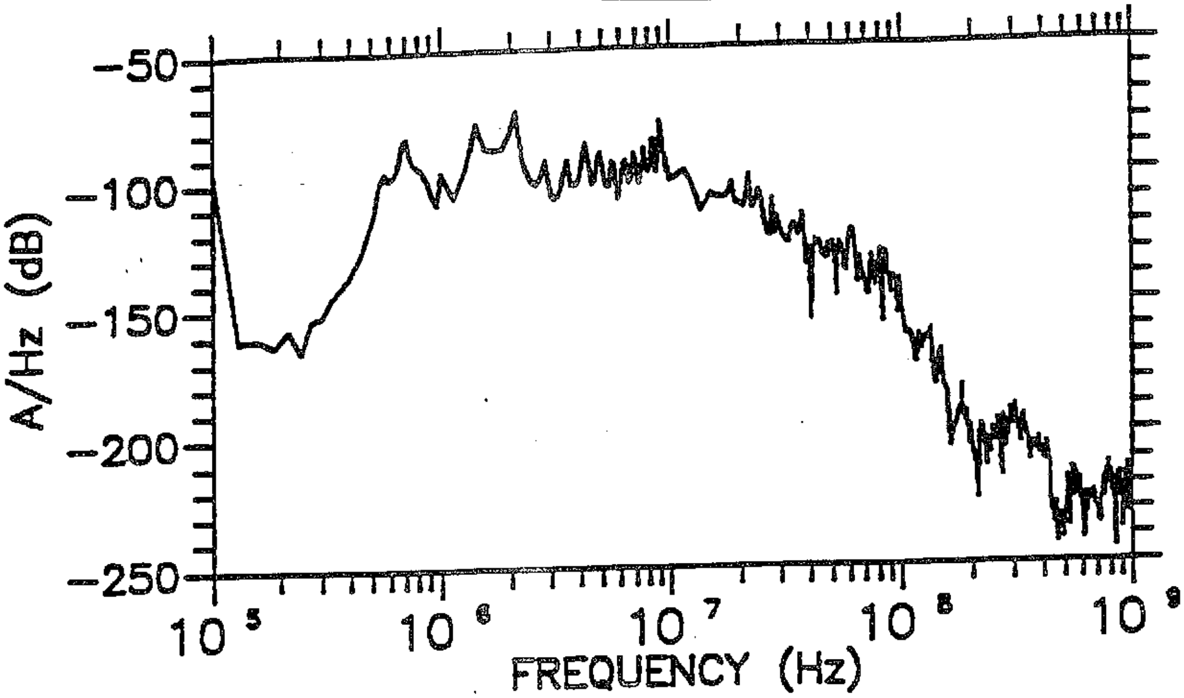


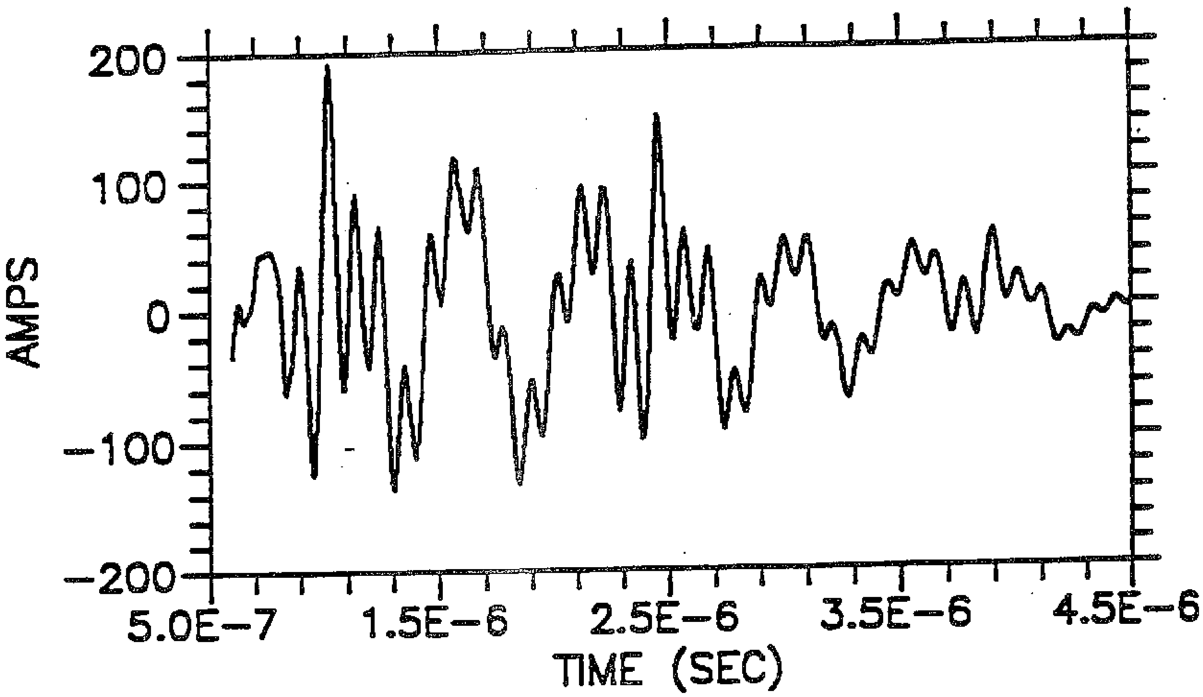
A/Hz (dB)
-50
-100
-150
-200
-250
-300
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



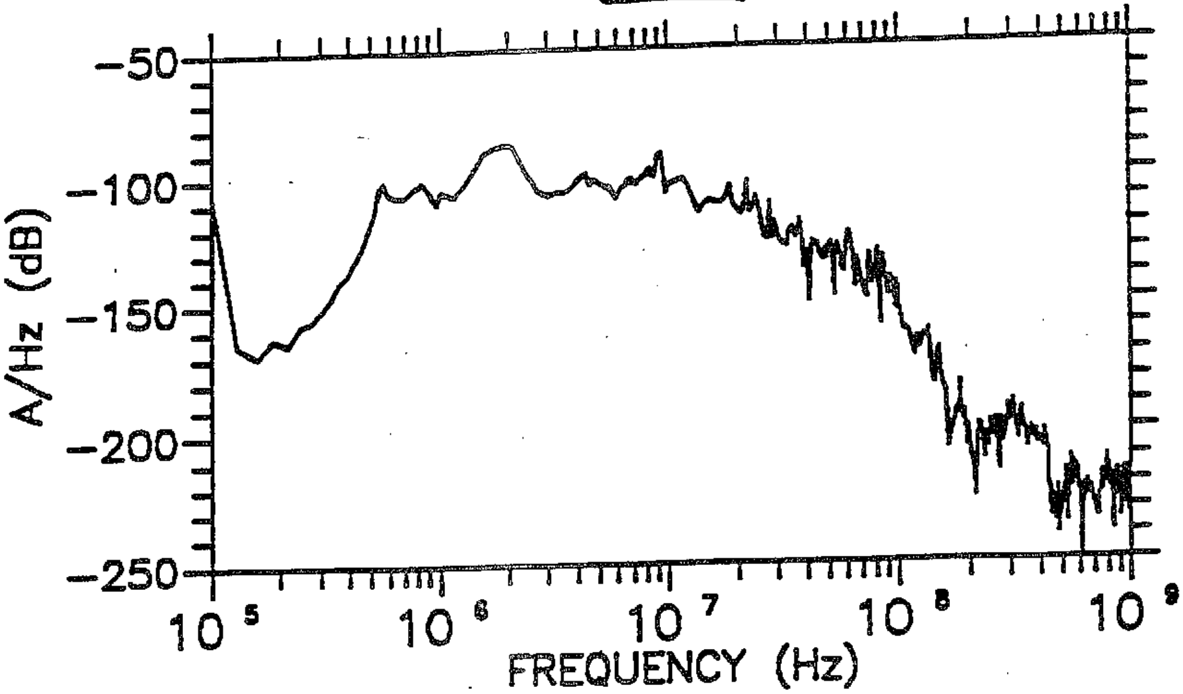
AMPS
500
250
0
-250
-500
5.0E-7
1.5E-6
2.5E-6
3.5E-6
TIME (SEC)

[redacted]

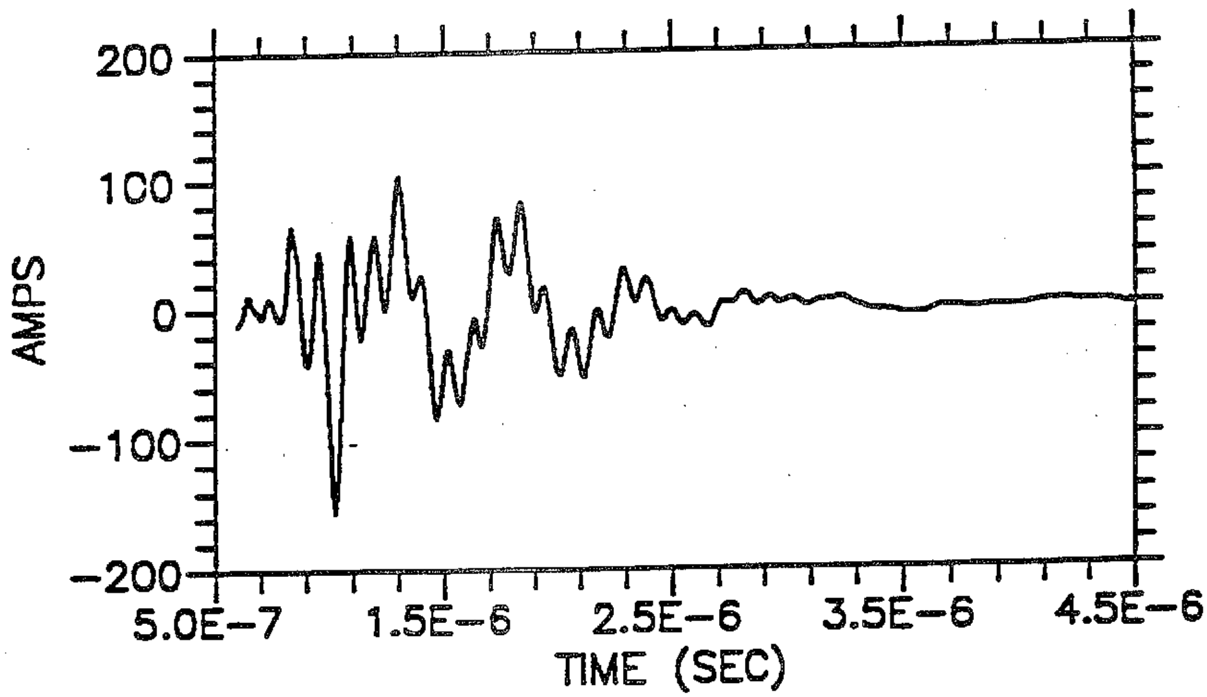

-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


200
100
0
-100
-200
AMPS
5.0E-7
1.5E-6
2.5E-6
3.5E-6
4.5E-6
TIME (SEC)

[redacted]

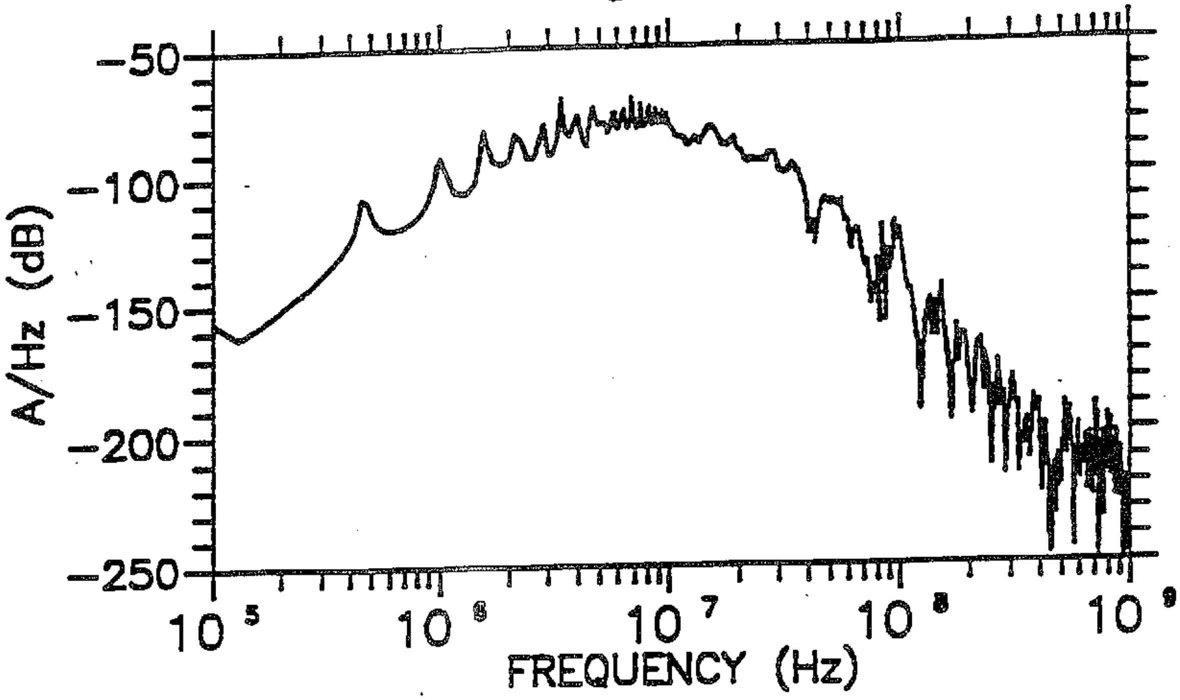


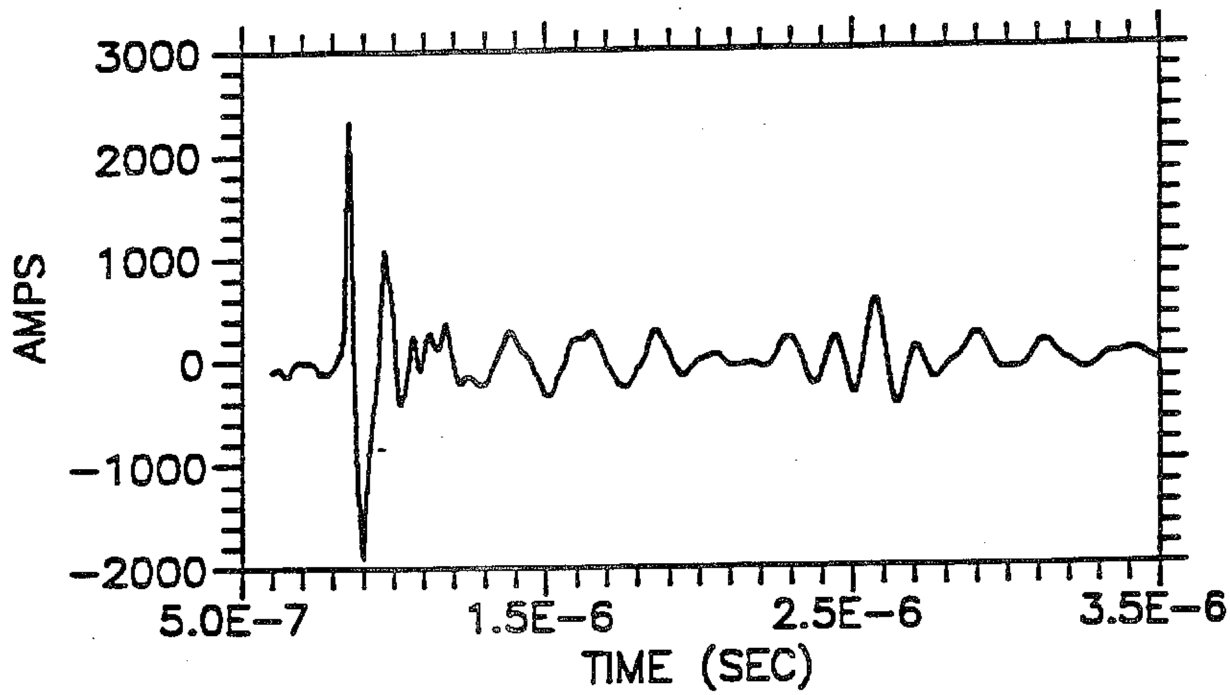
-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



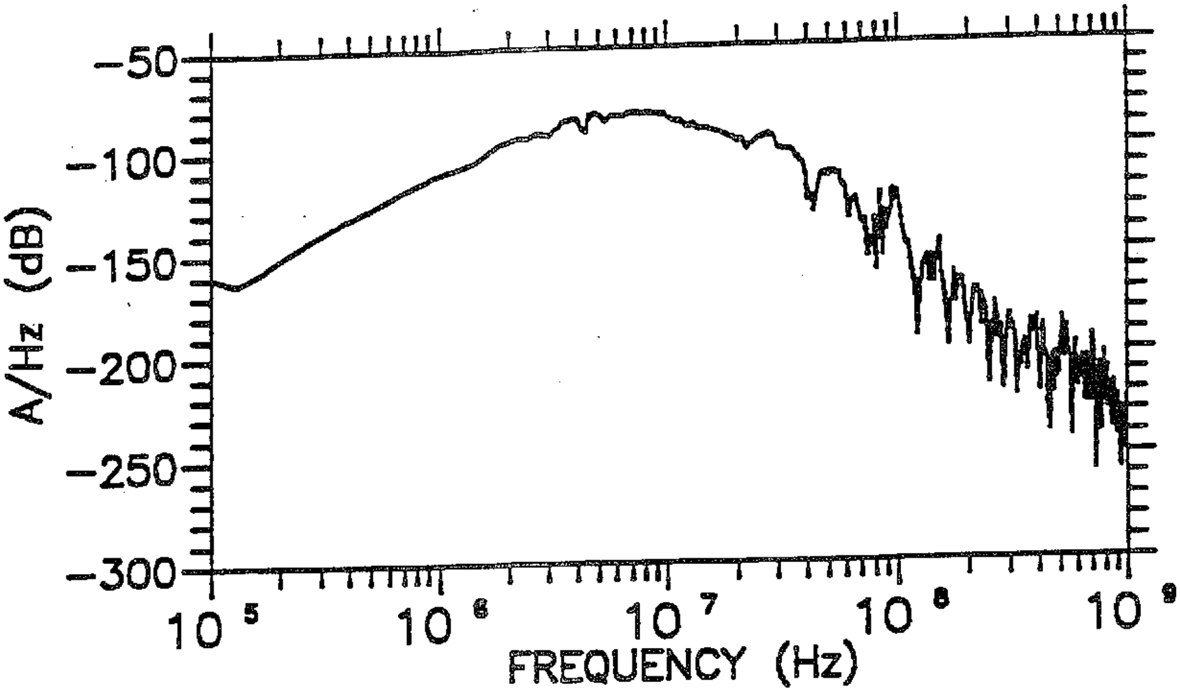
200
100
0
-100
-200
AMPS
5.0E-7
1.5E-6
2.5E-6
3.5E-6
4.5E-6
TIME (SEC)

[redacted]

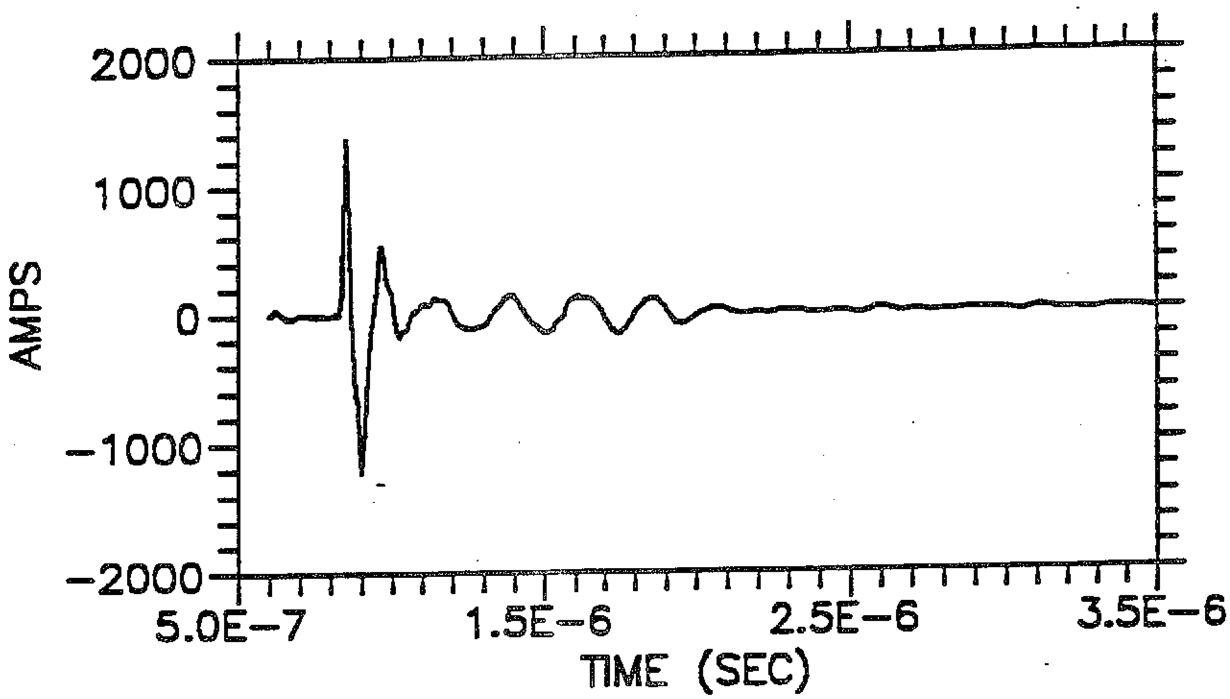

-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


3000
2000
1000
0
-1000
-2000
AMPS
5.0E-7
1.5E-6
2.5E-6
3.5E-6
TIME (SEC)

[redacted]

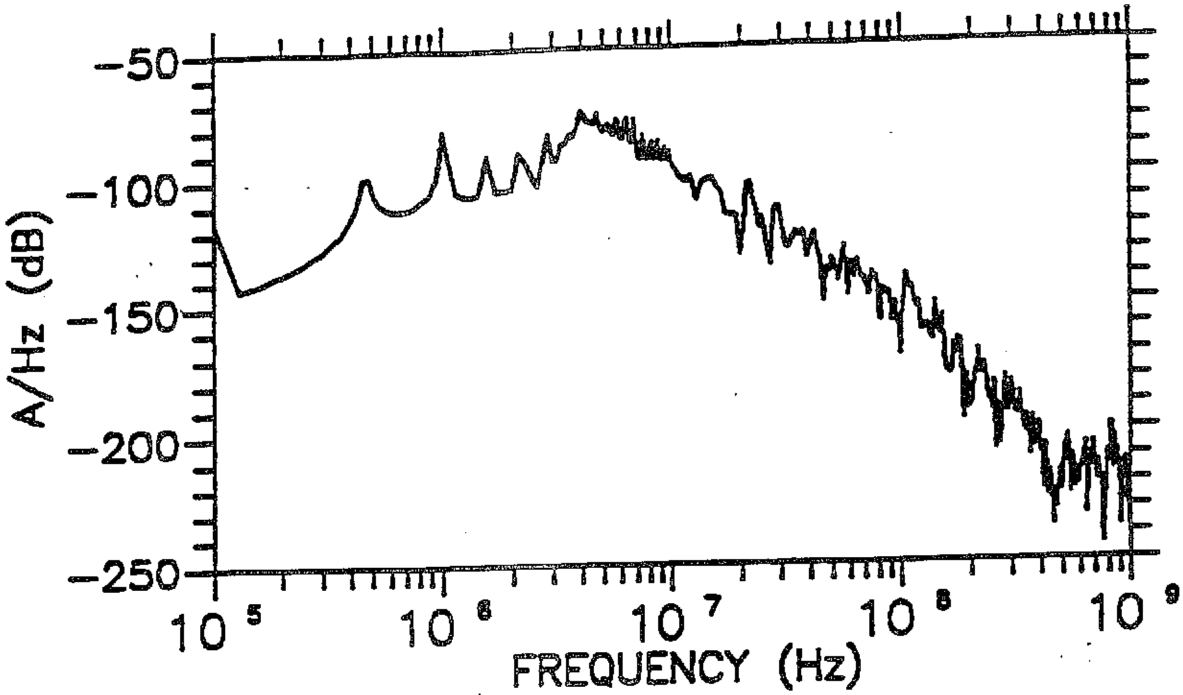


A/Hz (dB)
-50
-100
-150
-200
-250
-300
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

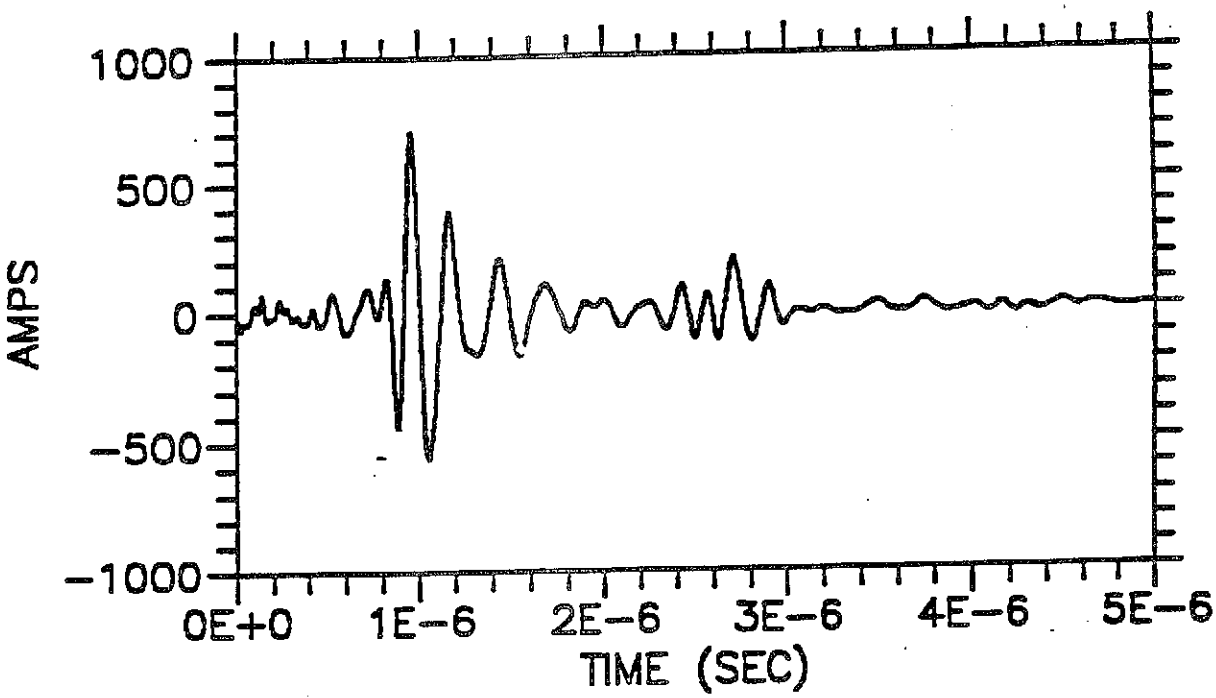


AMPS
2000
1000
0
-1000
-2000
5.0E-7
1.5E-6
2.5E-6
3.5E-6
TIME (SEC)

[redacted]

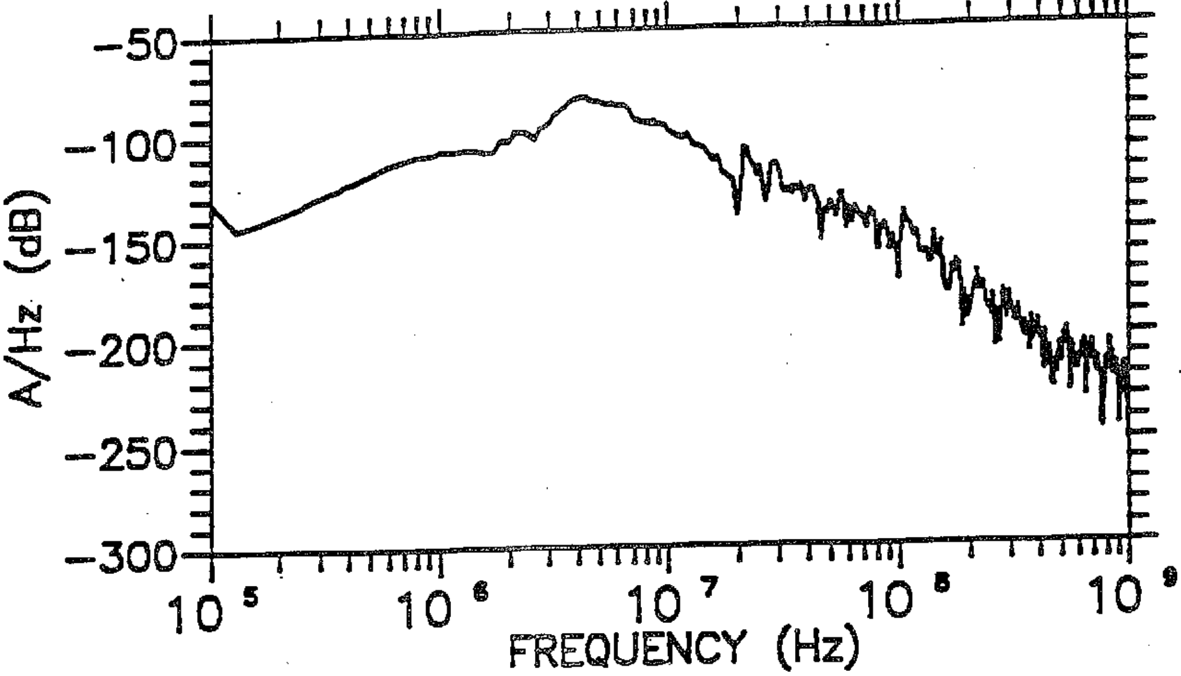


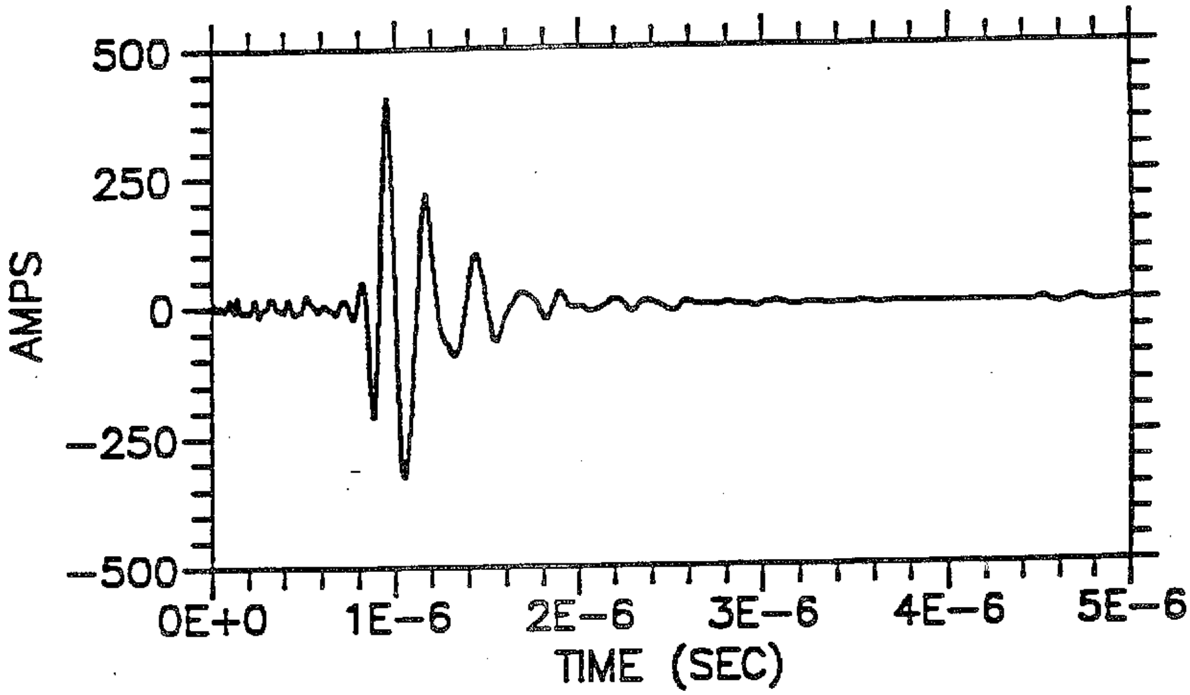
-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



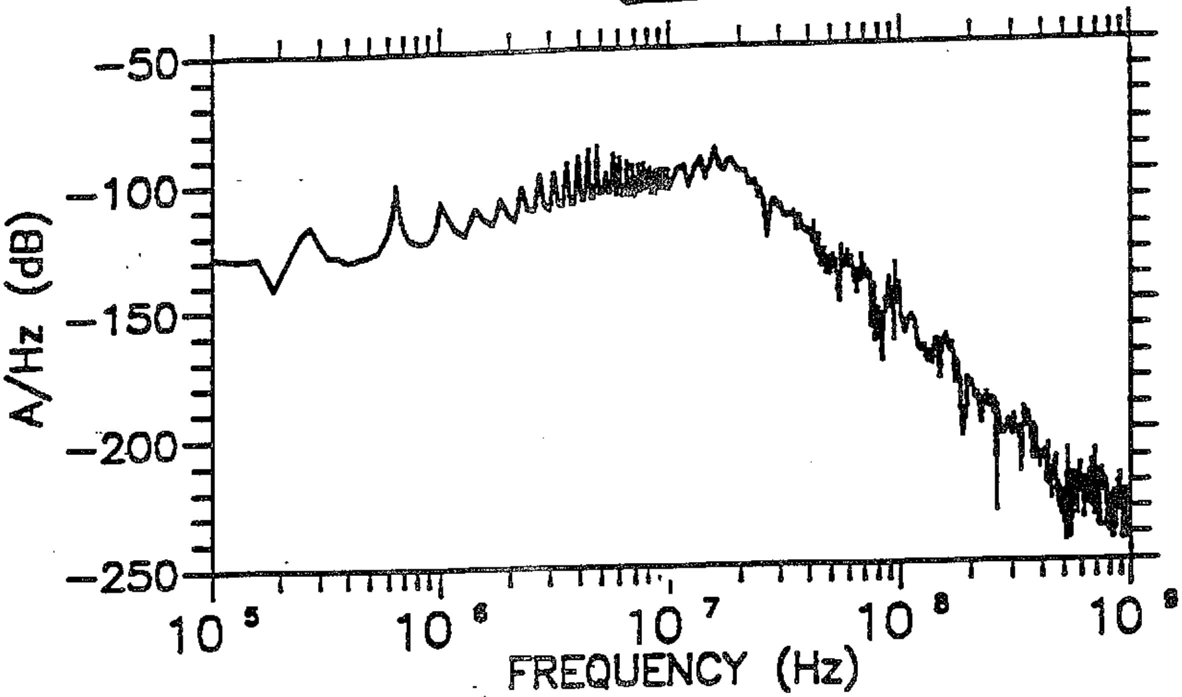
1000
500
0
-500
-1000
AMPS
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

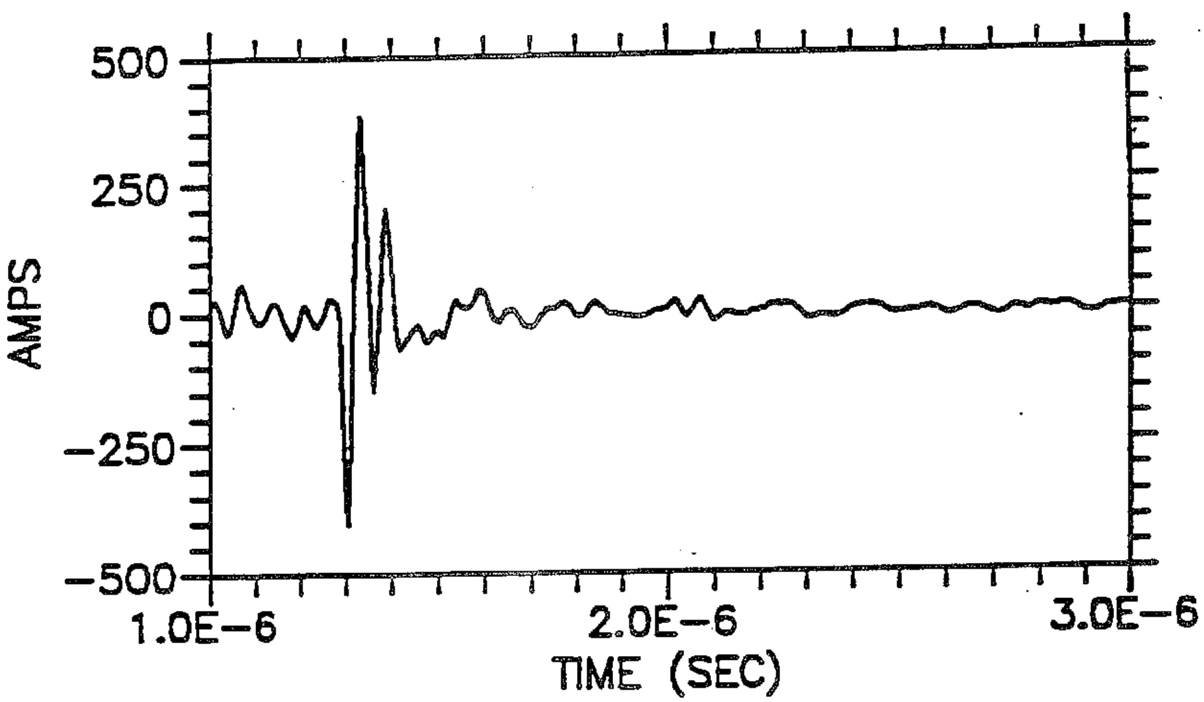

-50
-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)


500
250
0
-250
-500
AMPS
0E+0
1E-6
2E-6
3E-6
4E-6
5E-6
TIME (SEC)

[redacted]

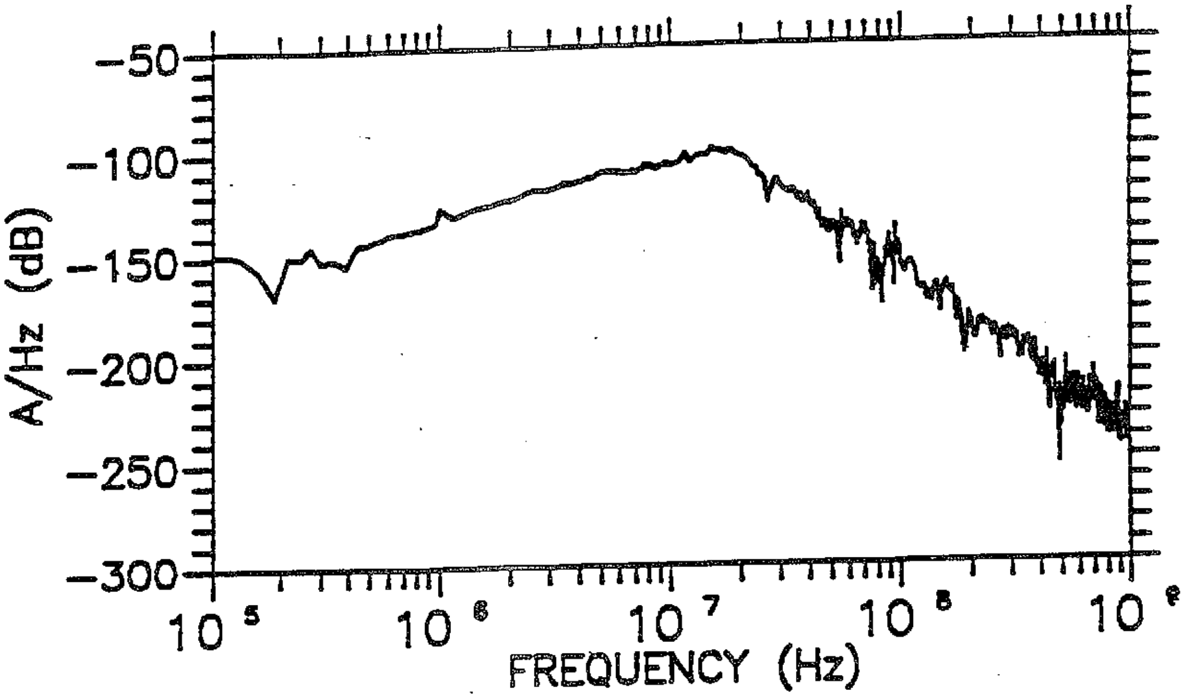


-50
-100
-150
-200
-250
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)

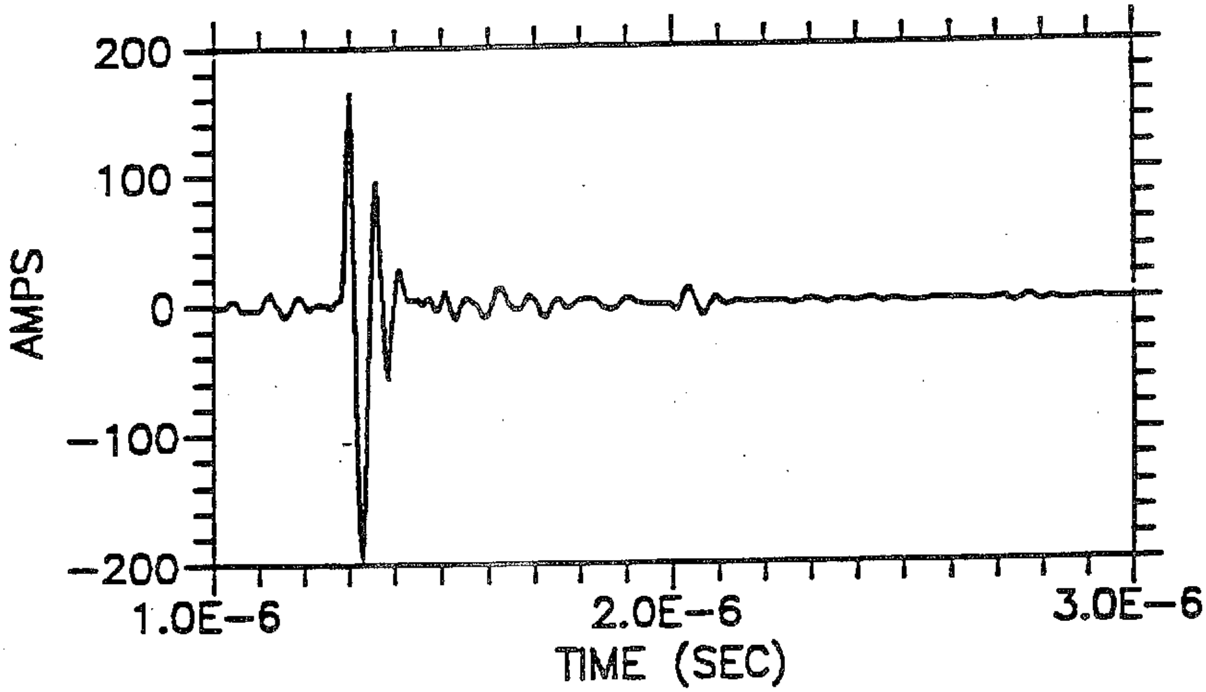


500
250
0
-250
-500
AMPS
1.0E-6
2.0E-6
3.0E-6
TIME (SEC)

[redacted]



-50
-100
-150
-200
-250
-300
A/Hz (dB)
10 5
10 6
10 7
10 8
10 9
FREQUENCY (Hz)



200
100
0
-100
-200
AMPS
1.0E-6
2.0E-6
3.0E-6
TIME (SEC)

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APPENDIX D

SIGNAL TO NOISE PLOTS FOR [redacted]
CW ILLUMINATION MEASUREMENTS OF THE [redacted]NTENNAS

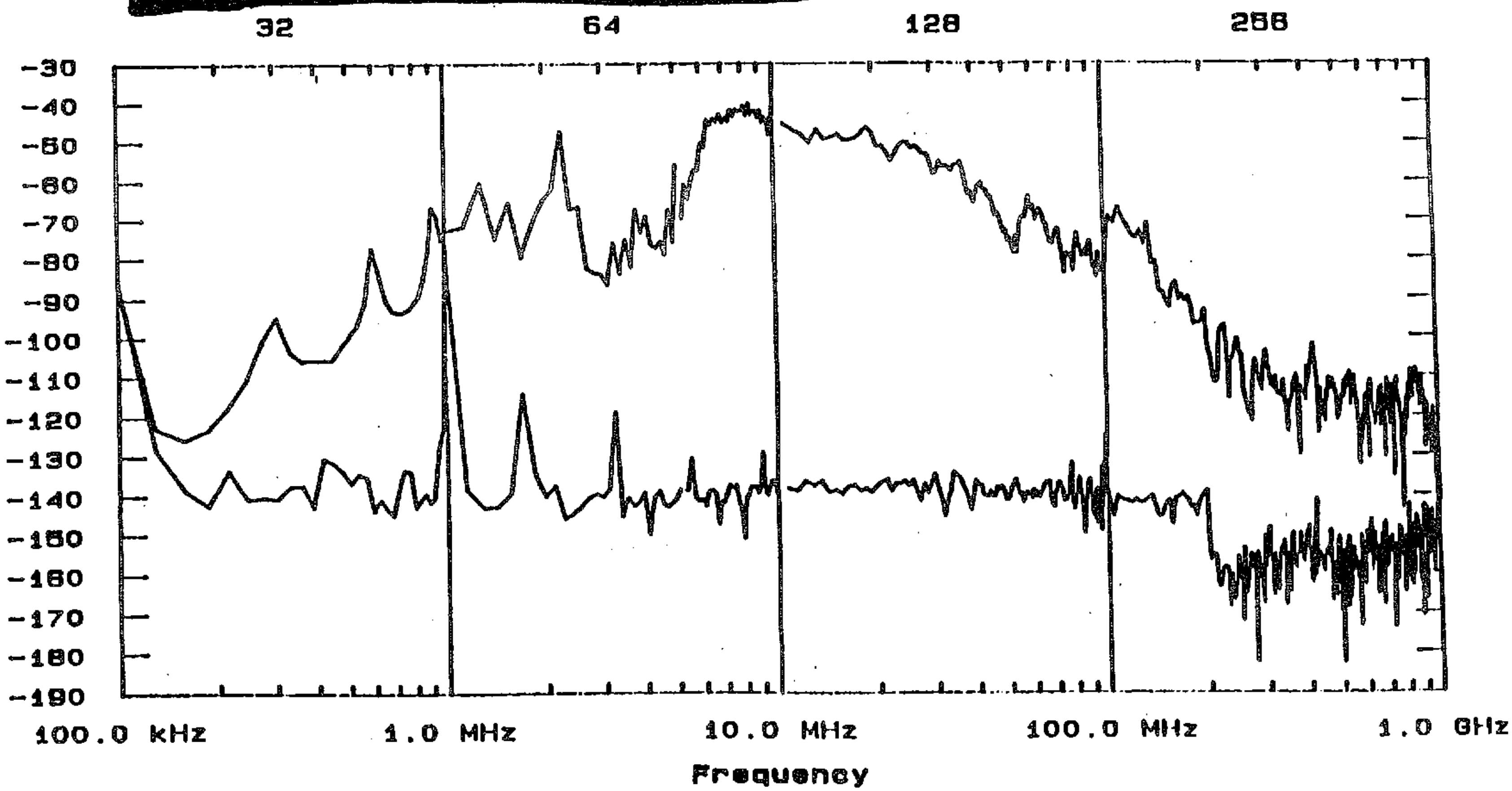
The upper trace shows the signal; the lower trace shows the corresponding ambient noise. The difference is the signal-to-noise ratio in dB.

Signal to Noise Report

4:44 PM TUE., 16 JUNE, 1992

Test Point	H011	Freq: Min	100.00 kHz		Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz		Noise Set	H011
Facility	THE HOUSE	Ampl: Min	-182.51 dB		Sig Atten	0.0 dB
Test Time	06-16-92 16:29	Max	-40.45 dB		Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

Description [redacted]

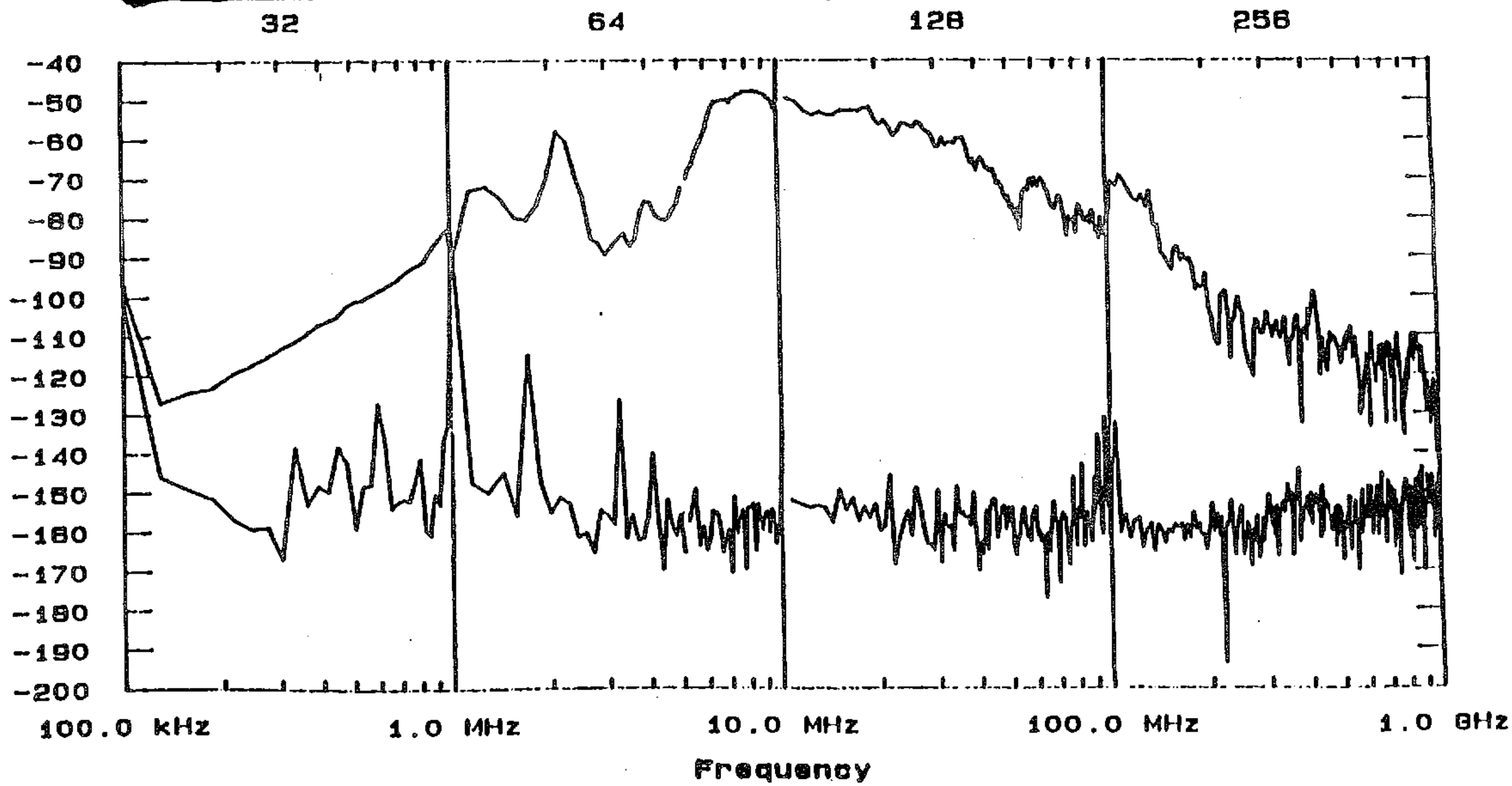


Signal to Noise Report

4: 46 PM TUE., 16 JUNE, 1992

Test Point	H012	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	H012
Facility	THE HOUSE	Ampl: Min	-193.66 dB	Sig Atten	0.0 dB
Test Time	06-16-92 16: 30	Max	-47.73 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

Description [redacted]

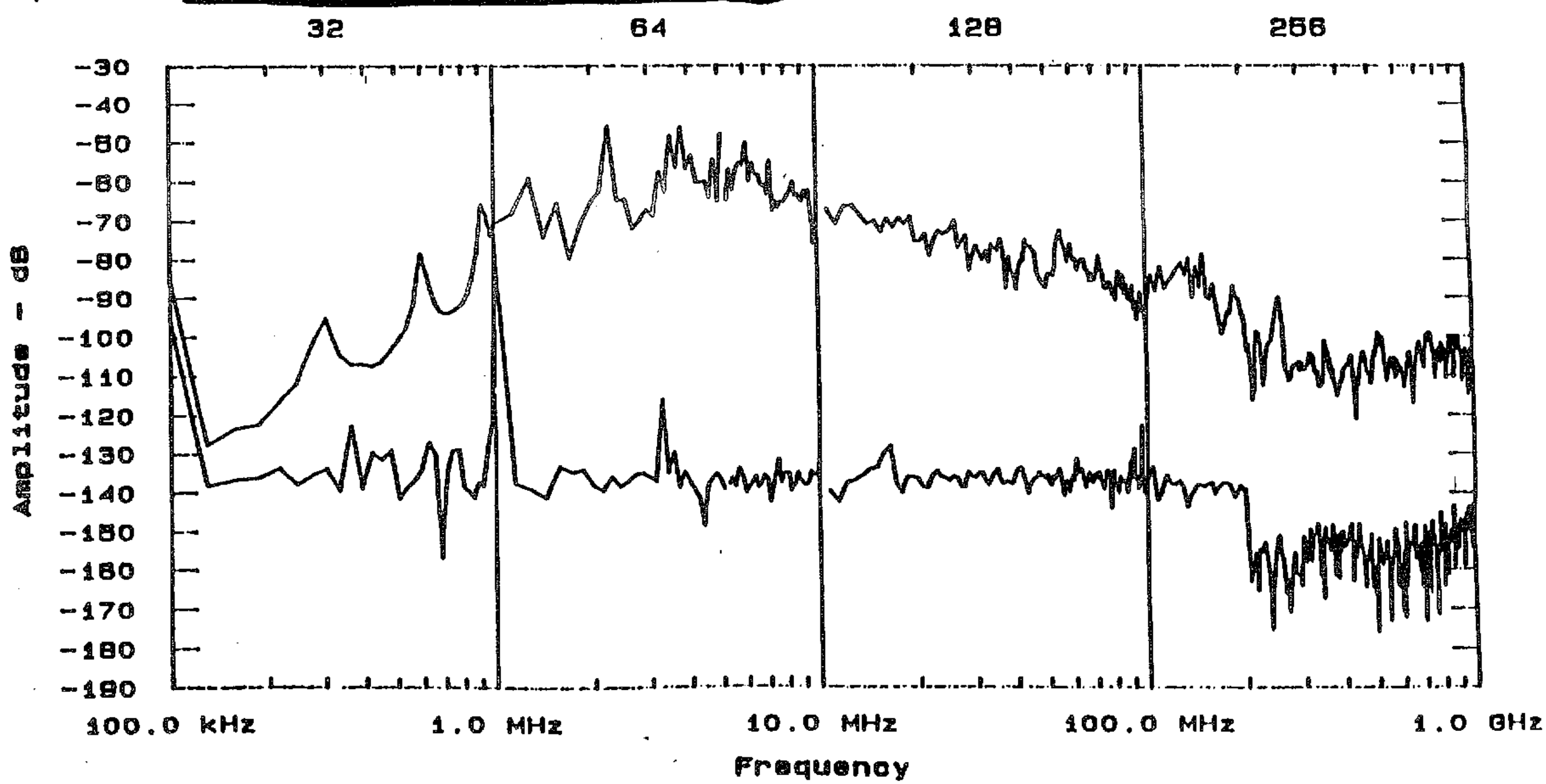


Signal to Noise Report

4:49 PM TUE., 16 JUNE, 1992

Test Point	H021	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	H021
Facility	THE HOUSE	Ampl:	Min	-175.73 dB	Sig Atten	0.0 dB
Test Time	06-16-92 16:31		Max	-45.94 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

Description [redacted]

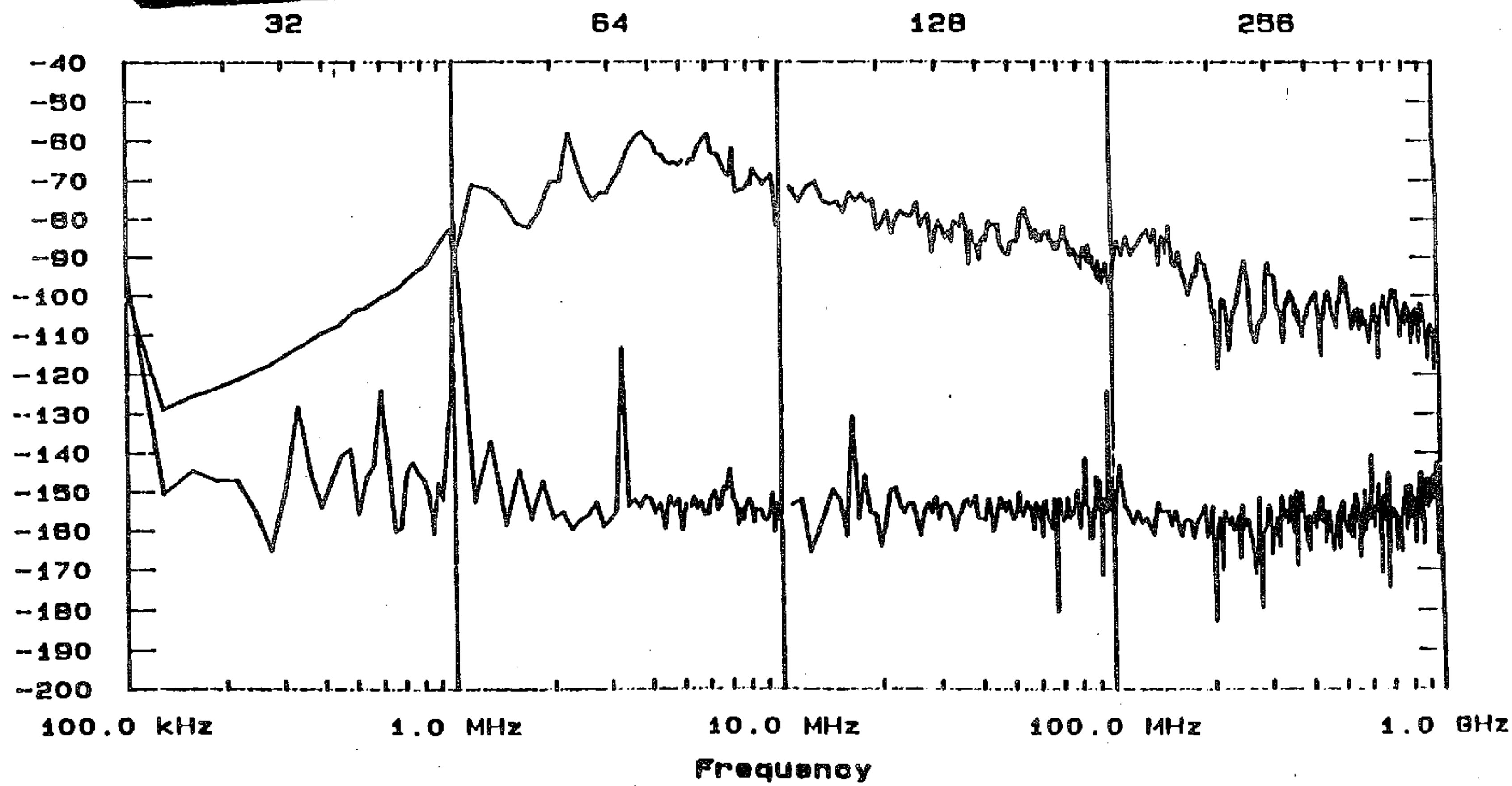


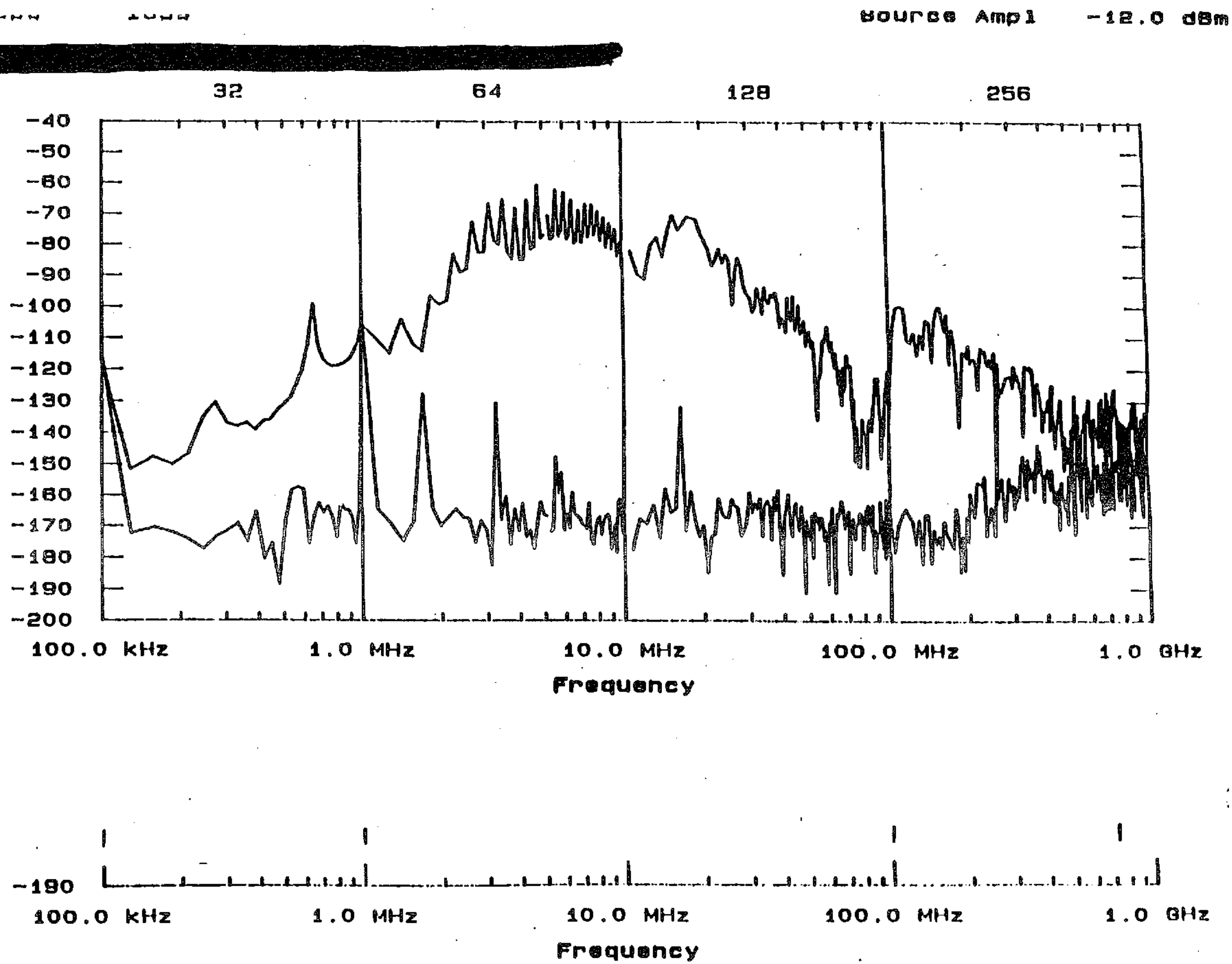
Signal to Noise Report

4:52 PM TUE., 16 JUNE, 1992

Test Point	H022	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	H022
Facility	THE HOUSE	Ampl: Min	-182.86 dB	Sig Atten	0.0 dB
Test Time	06-16-92 18:32	Max	-57.90 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

Description [redacted]



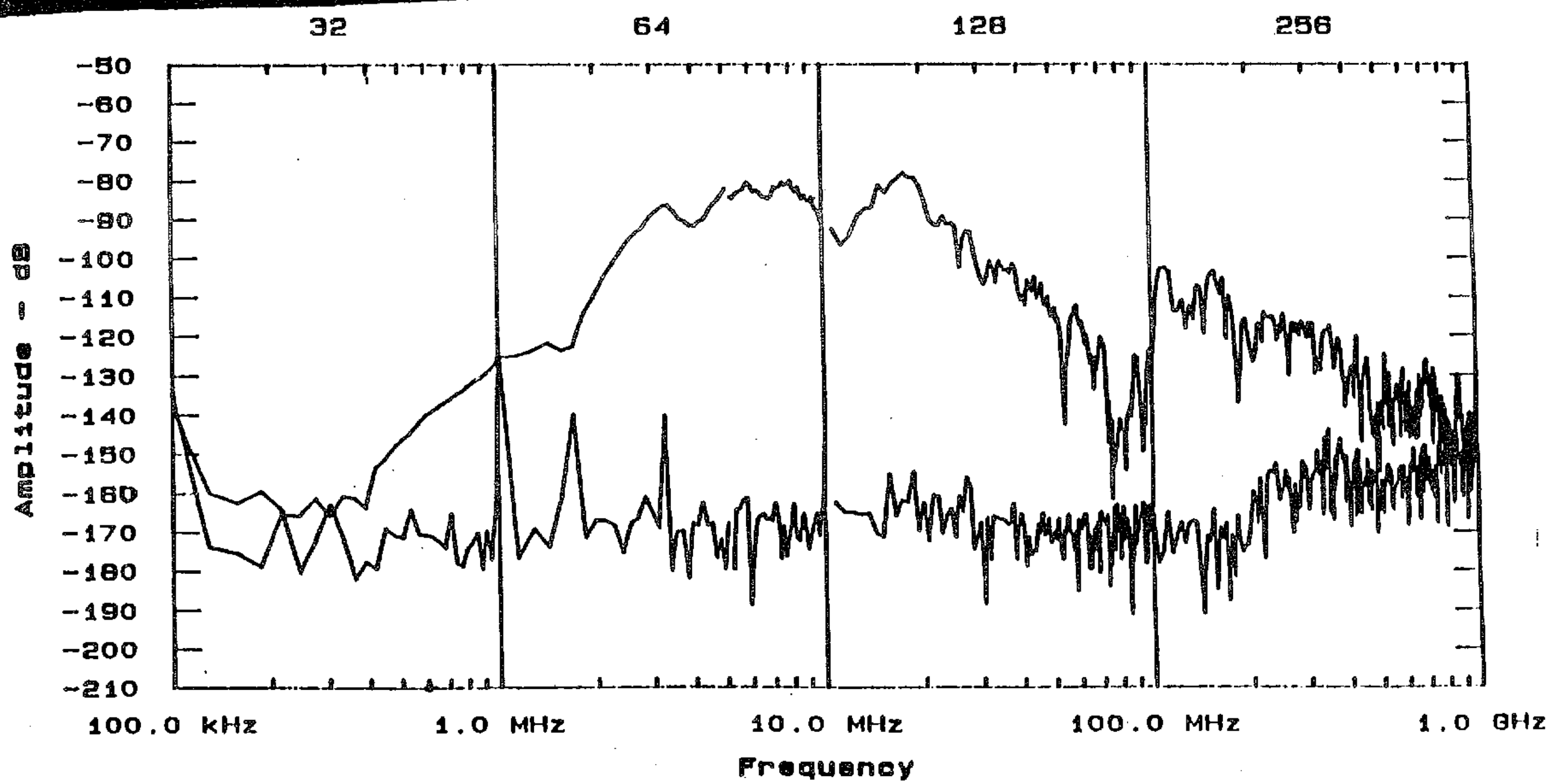

Source Ampl -12.0 dBm
32
64
128
256
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
Amplitude - dB
100.0 kHz
1.0 MHz
10.0 MHz
100.0 MHz
1.0 GHz
Frequency
-190
100.0 kHz
1.0 MHz
10.0 MHz
100.0 MHz
1.0 GHz
Frequency

Signal to Noise Report

12: 40 PM   MON.,   8   JUNE,   1992

Test Point	V072	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	V072
Facility	THE HOUSE	Ampl: Min	-191.26 dB	Sig Atten	0.0 dB
Test Time	06-08-92 12: 37	Max	-78.17 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dB

[redacted]

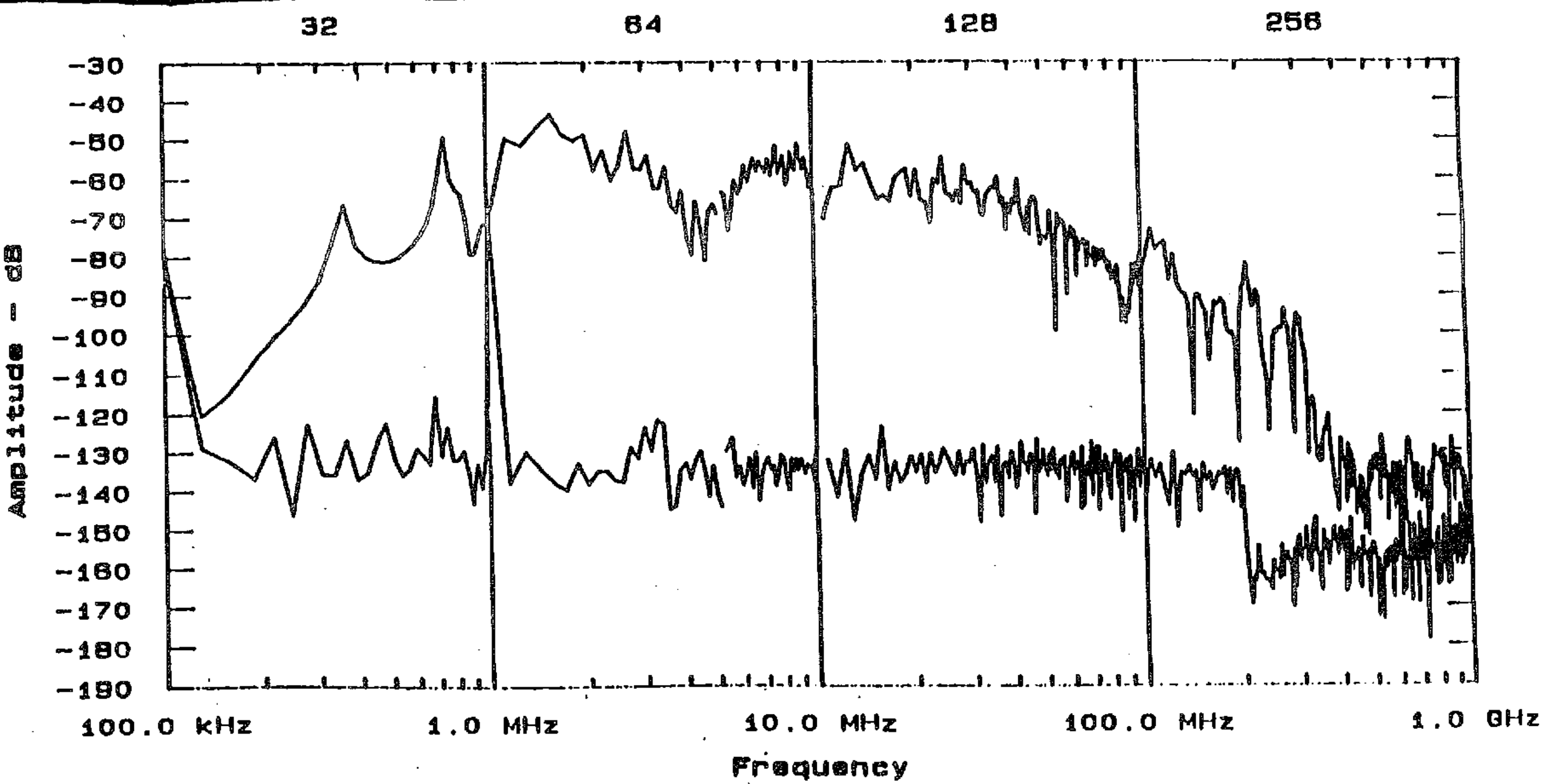


Signal to Noise Report

4:27 PM TUE., 16 JUNE, 1992

Test Point	H051	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	H051
Facility	THE HOUSE	Ampl: Min	-176.54 dB	Sig Atten	0.0 dB
Test Time	06-16-92 16:07	Max	-43.52 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

[redacted]

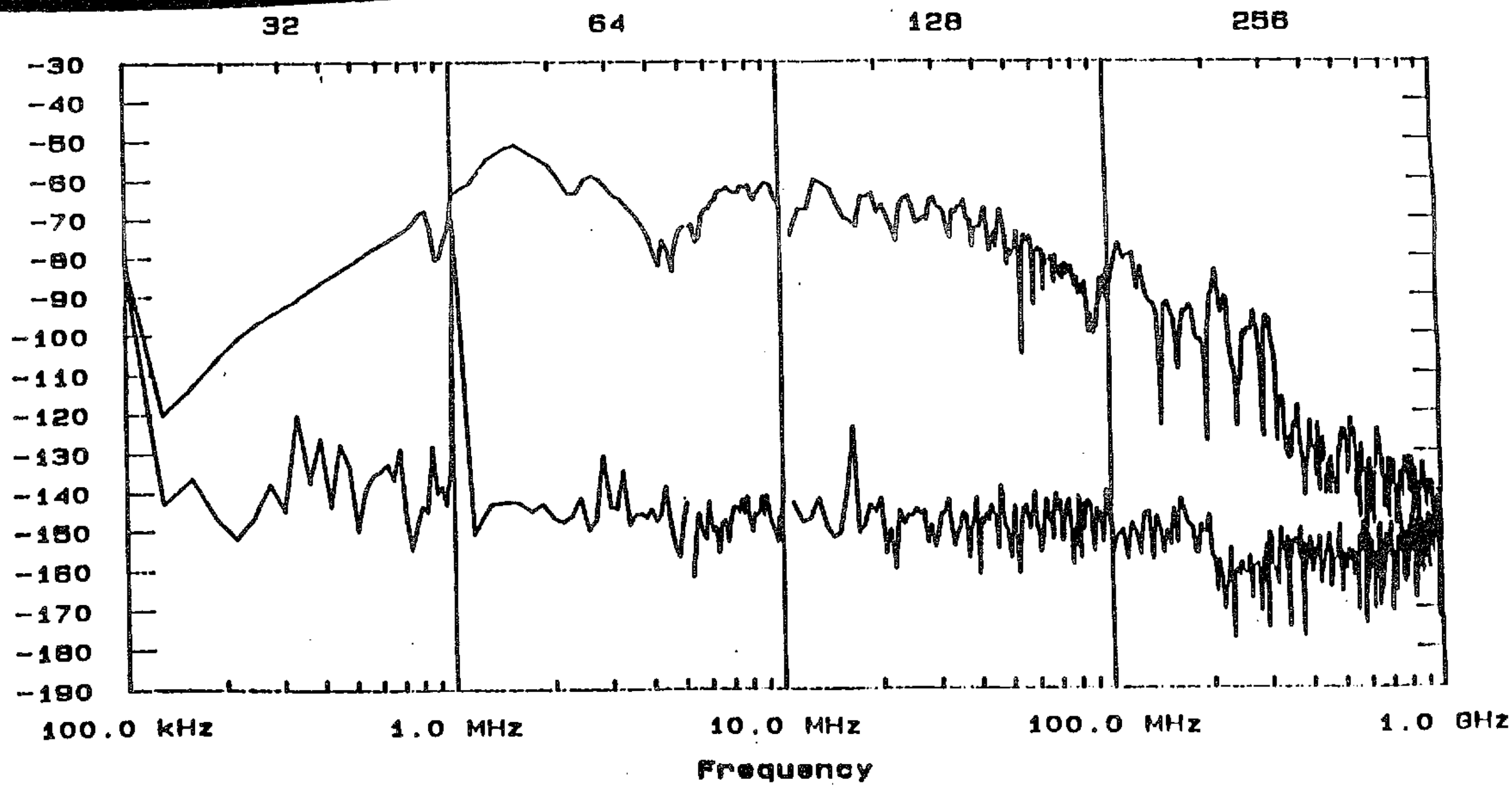


Signal to Noise Report

4:30 PM TUE., 16 JUNE, 1992

Test Point	H052	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	H052
Facility	THE HOUSE	Ampl:	Min	-177.49 dB	Sig Atten	0.0 dB
Test Time	06-16-92 16:09		Max	-51.14 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dB

[redacted]

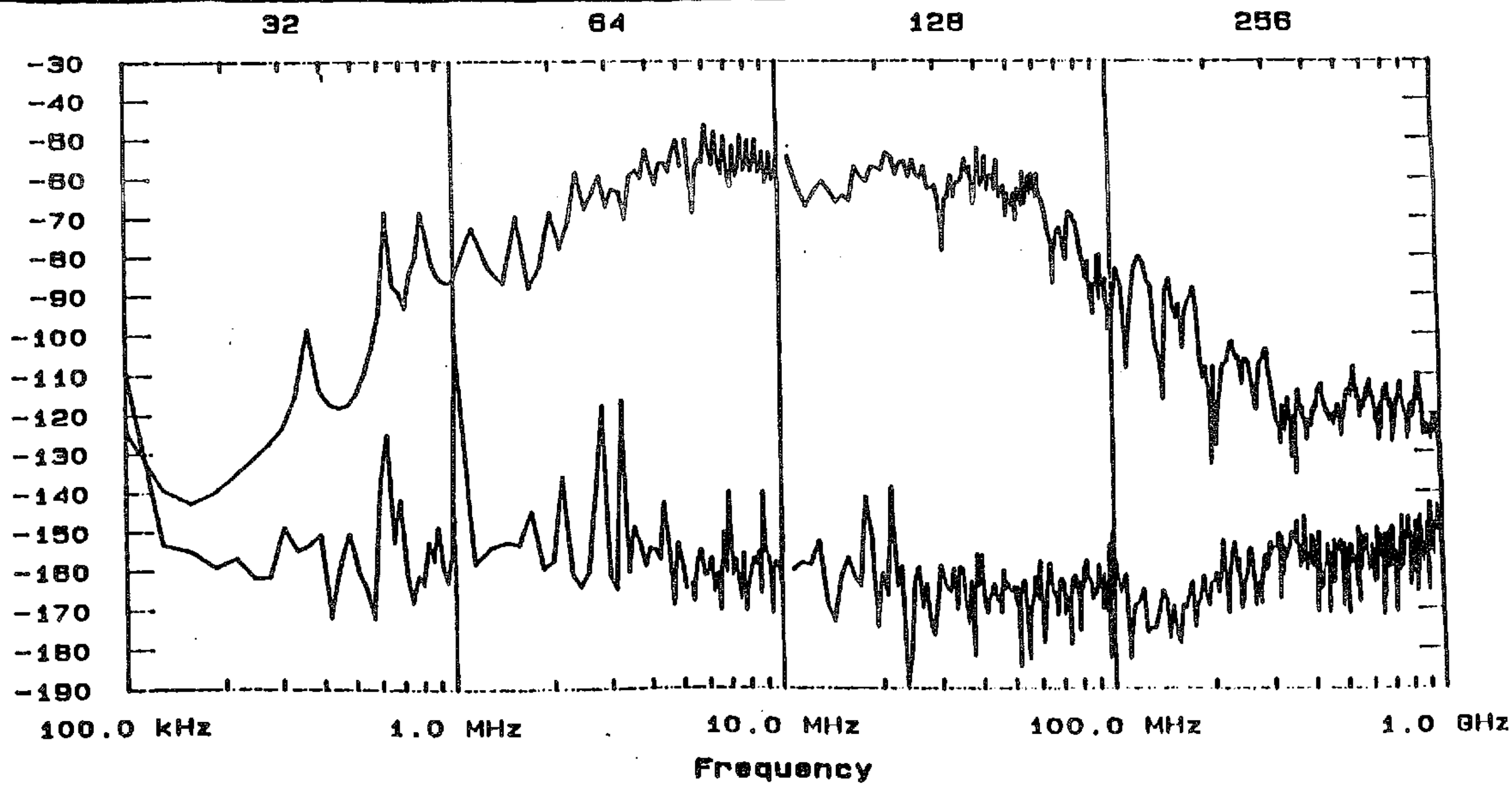


Signal to Noise Report

4: 33 PM TUE., 16 JUNE, 1992

Test Point	H061	Freq:	Min	100.00 kHz		Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz		Noise Set	H061
Facility	THE HOUSE	Ampl:	Min	-188.98 dB		Sig Atten	0.0 dB
Test Time	06-16-92 16: 19		Max	-48.71 dB		Bandwidth	10 Hz
Sig Probe	IC39					Source Ampl	-12.0 dBm

[redacted]

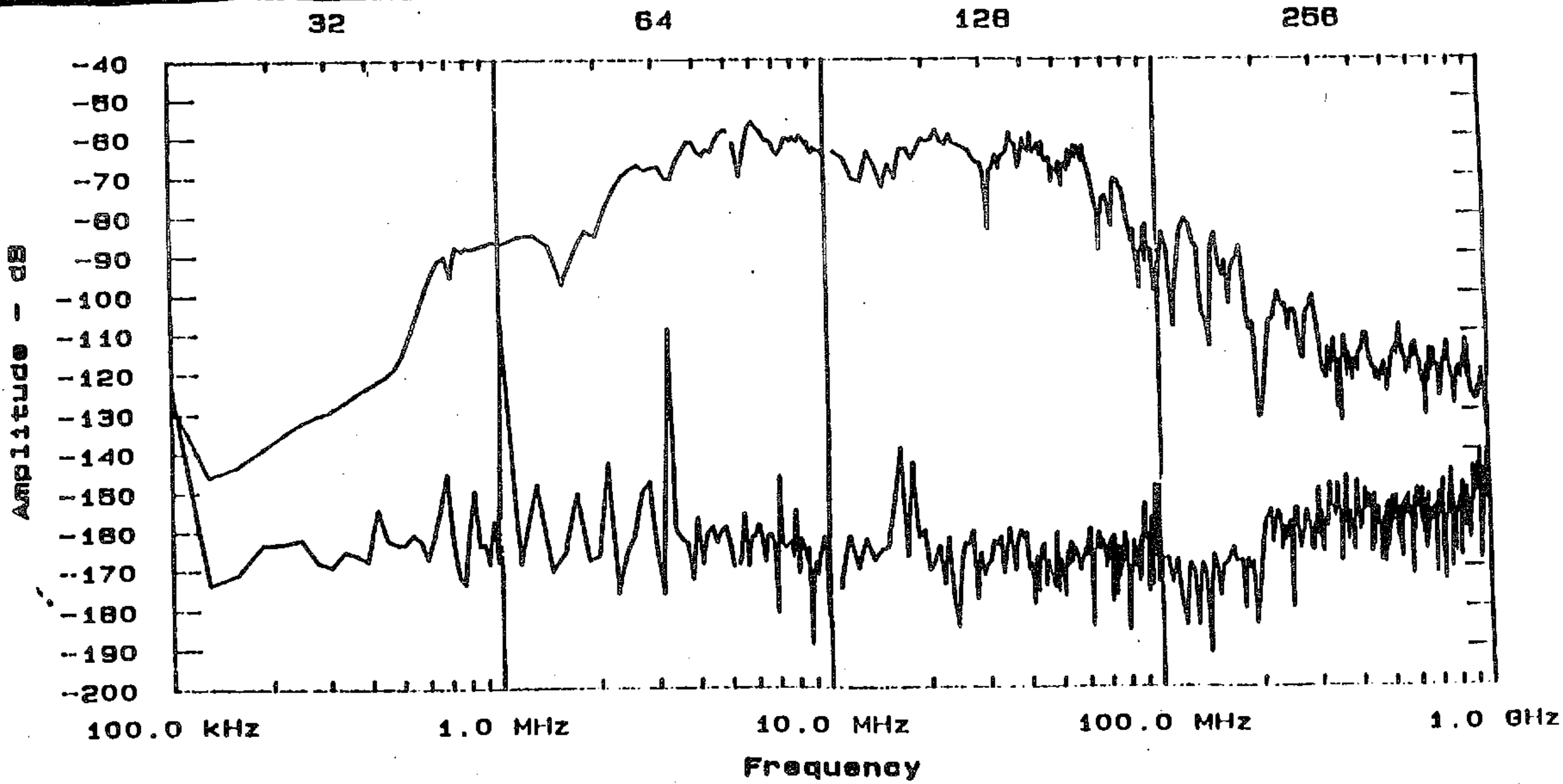


Signal to Noise Report

4:35 PM TUE., 16 JUNE, 1992

Test Point	H062	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	H062
Facility	THE HOUSE	Ampl:	Min	-191.72 dB	Sig Atten	0.0 dB
Test Time	06-16-92 16:20		Max	-56.47 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

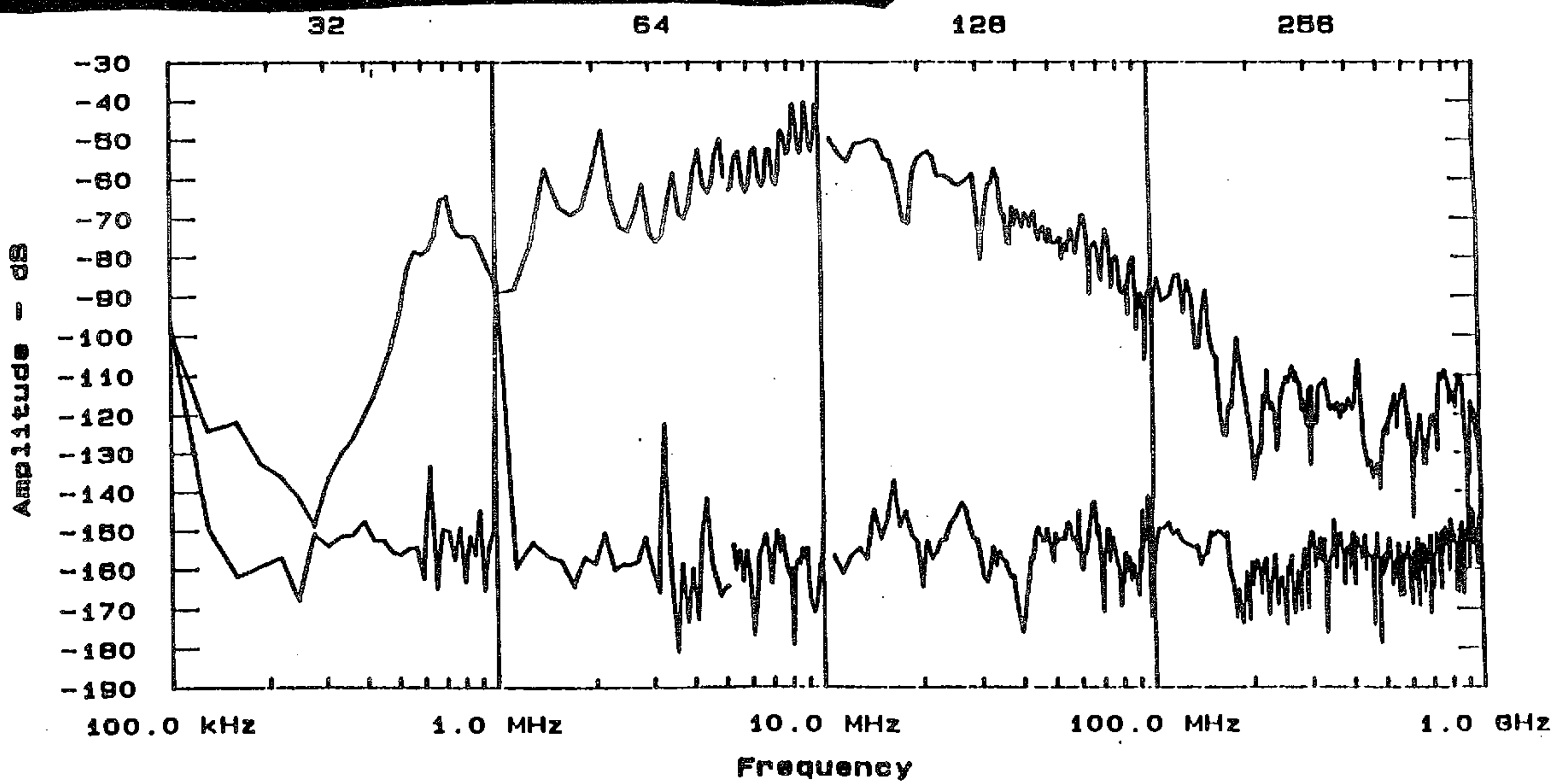


Signal to Noise Report

1: 02 PM TUE., 16 JUNE, 1992

Test Point	H031A	Freq:	Min	100.00 kHz	Inet Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V031
Facility	THE HOUSE	Ampl:	Min	-181.00 dB	Sig Atten	0.0 dB
Test Time	06-16-92 13: 00		Max	-40.44 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

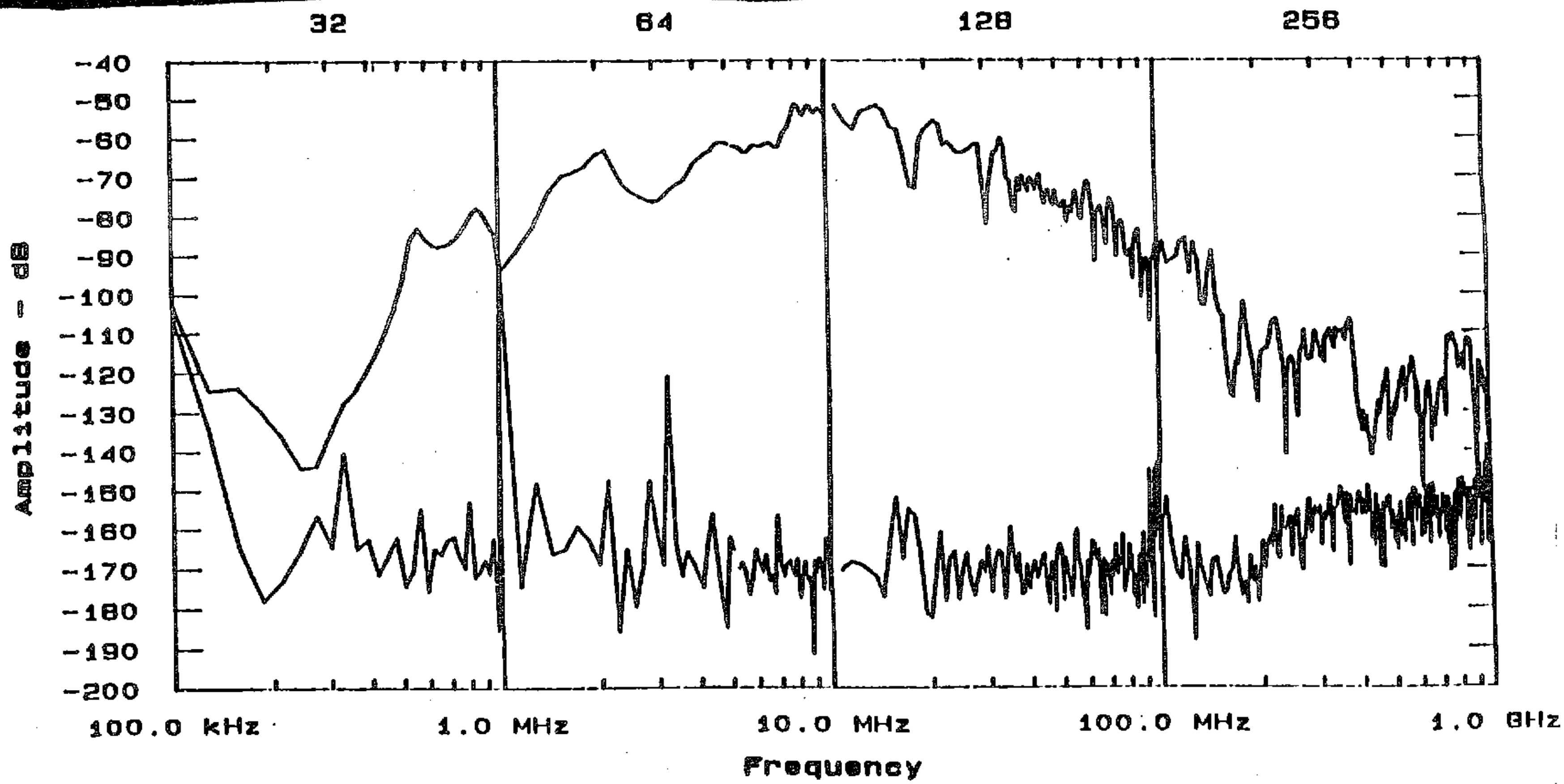


Signal to Noise Report

1:04 PM TUE., 16 JUNE, 1992

Test Point	H032A	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	V032
Facility	THE HOUSE	Ampl: Min	-191.73 dB	Sig Atten	0.0 dB
Test Time	06-16-92 13:01	Max	-51.70 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

[redacted]

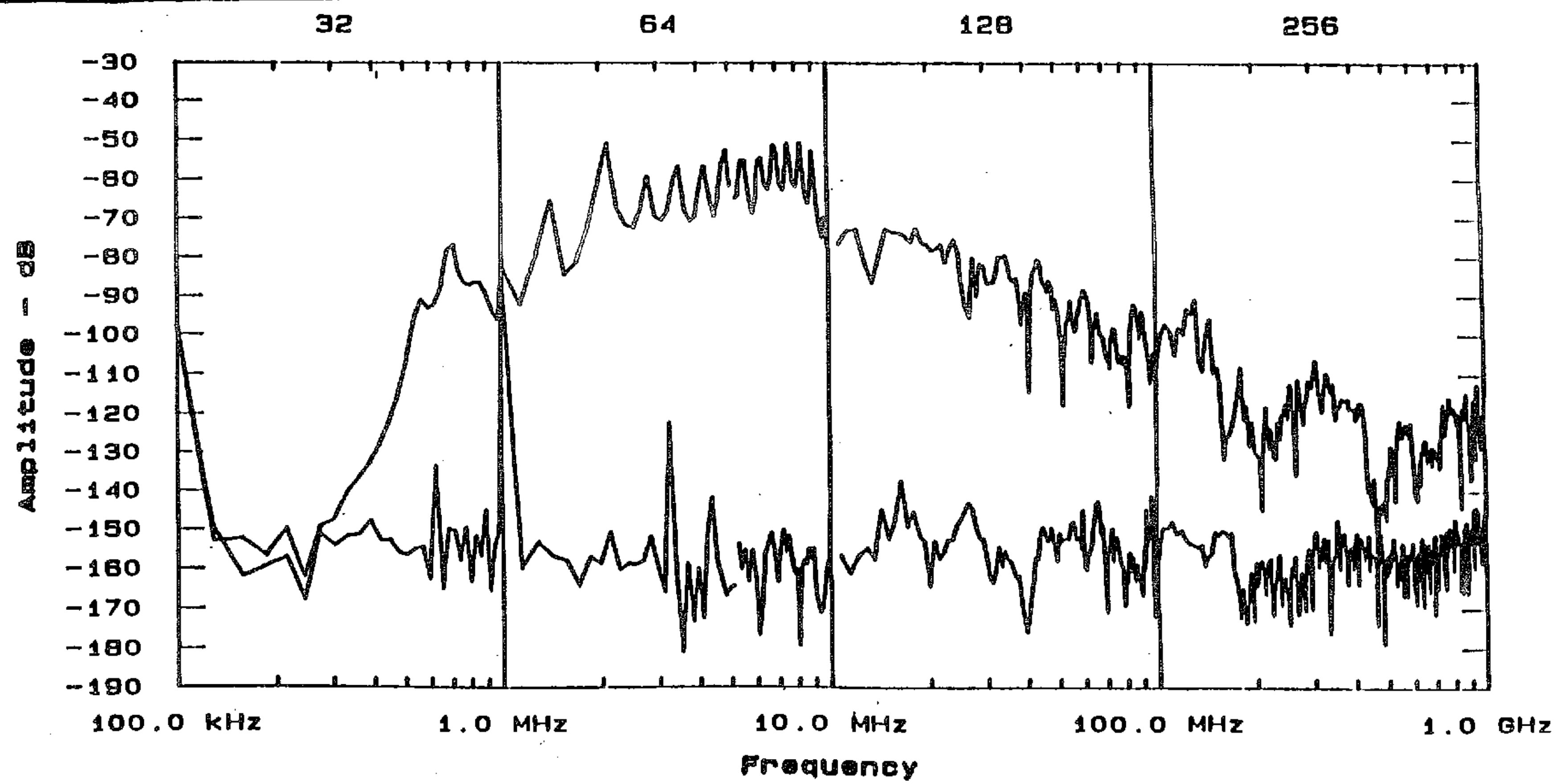


Signal to Noise Report

3: 21 PM THU., 4 JUNE, 1992

Test Point	V031	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V031
Facility	THE HOUSE	Ampl:	Min	-181.00 dB	Sig Atten	0.0 dB
Test Time	06-04-92 15: 20		Max	-50.76 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

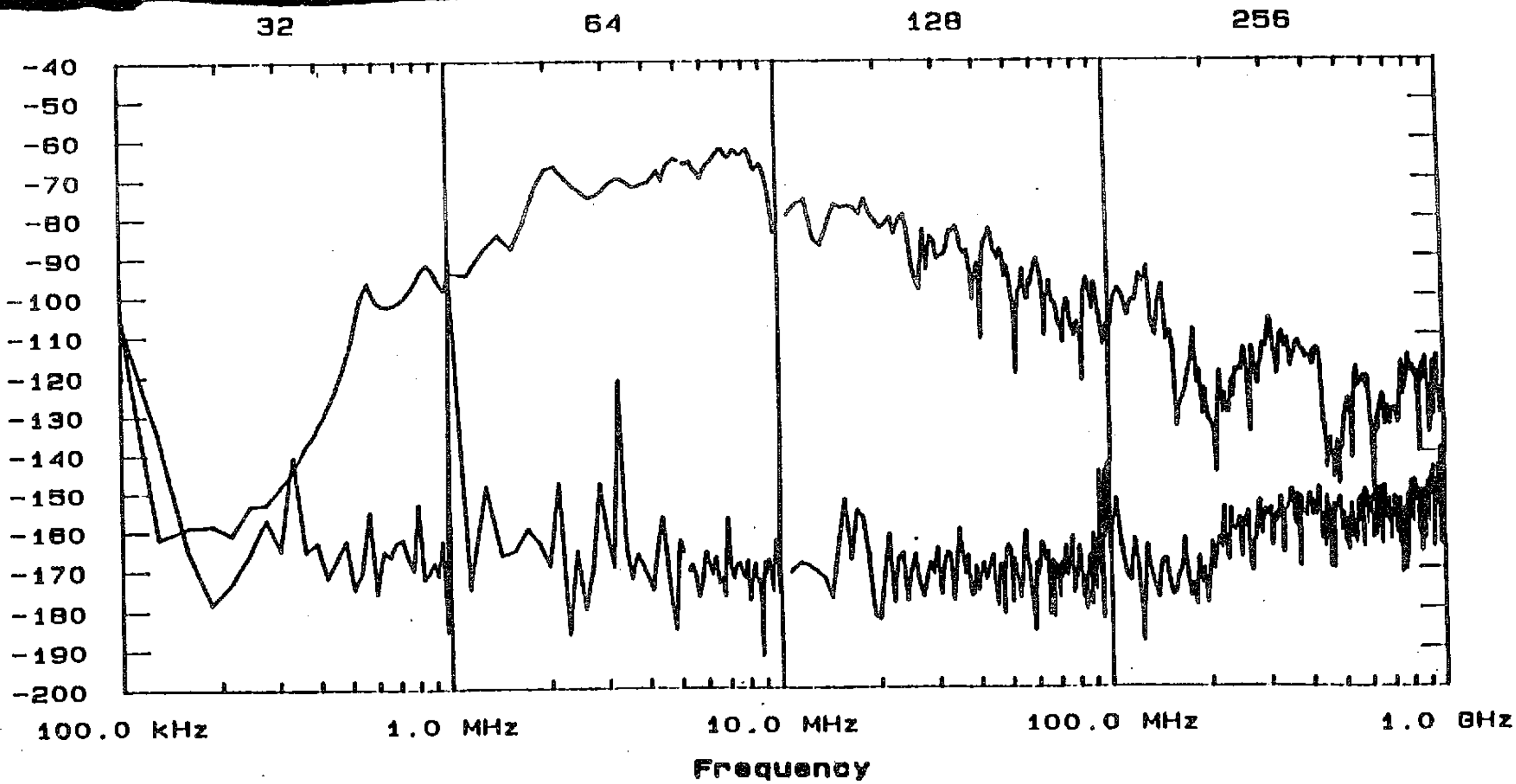


Signal to Noise Report

3:24 PM THU.. 4 JUNE, 1992

Test Point	V032	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V032
Facility	THE HOUSE	Ampl:	Min	-191.73 dB	Sig Atten	0.0 dB
Test Time	06-04-92 15:21		Max	-62.40 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

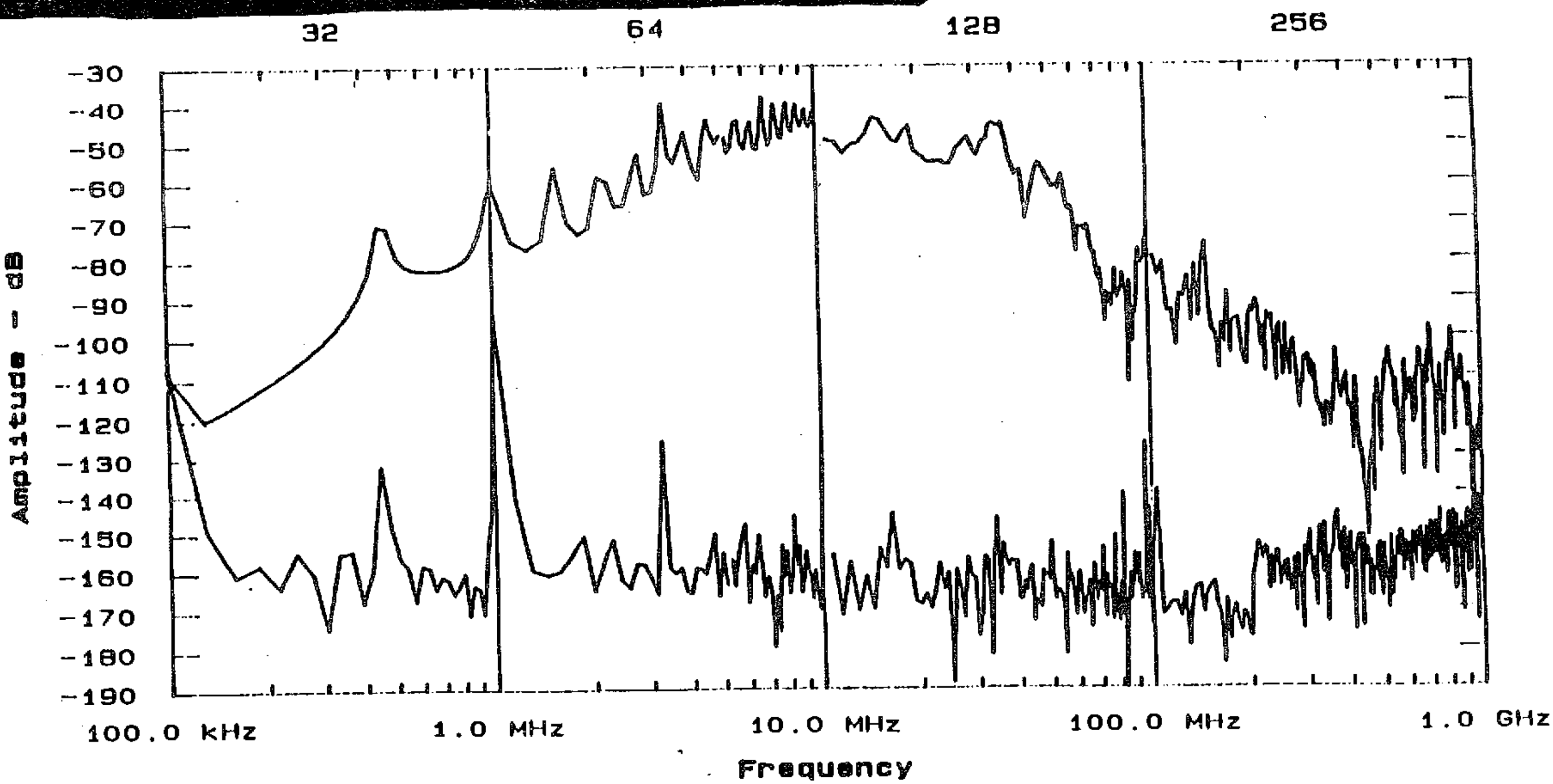


Signal to Noise Report

4: 11 PM TUE., 9 JUNE, 1992

Test Point	H041	Freq:	Min	100.00 kHz		Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz		Noise Set	H041
Facility	THE HOUSE	Ampl:	Min	-191.32 dB		Sig Atten	0.0 dB
Test Time	06-09-92 16: 09		Max	-38.28 dB		Bandwidth	10 Hz
Sig Probe	IC39					Source Ampl	-12.0 dBm

[redacted]

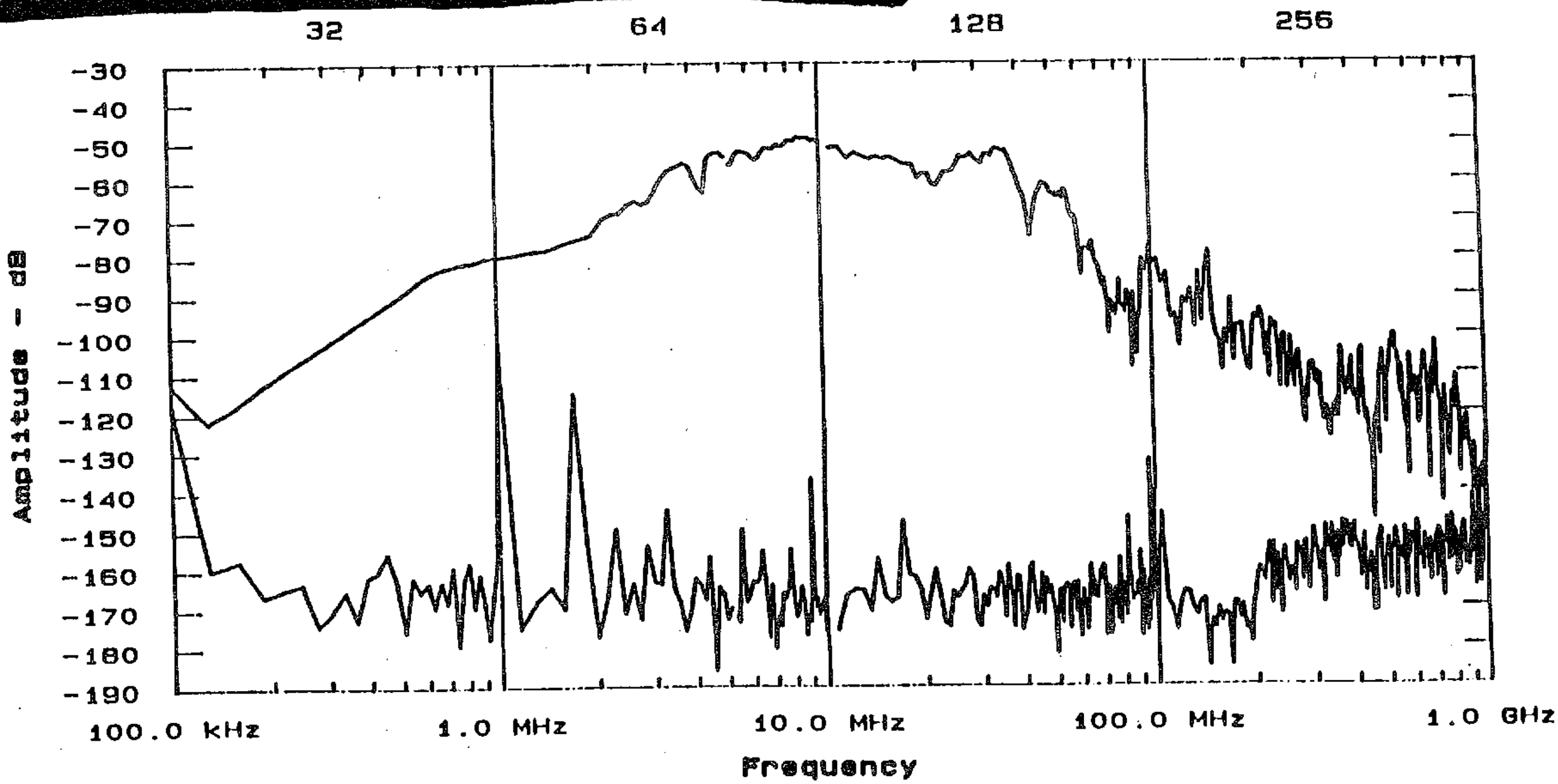


Signal to Noise Report

4: 14 PM TUE., 9 JUNE, 1992

Test Point	H042	Freq:	Min	100.00 kHz		Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz		Noise Set	V042
Facility	THE HOUSE	Ampl:	Min	-185.95 dB		Sig Atten	0.0 dB
Test Time	06-09-92 16: 10		Max	-49.02 dB		Bandwidth	10 Hz
Sig Probe	IC39					Source Ampl	-12.0 dB

[redacted]

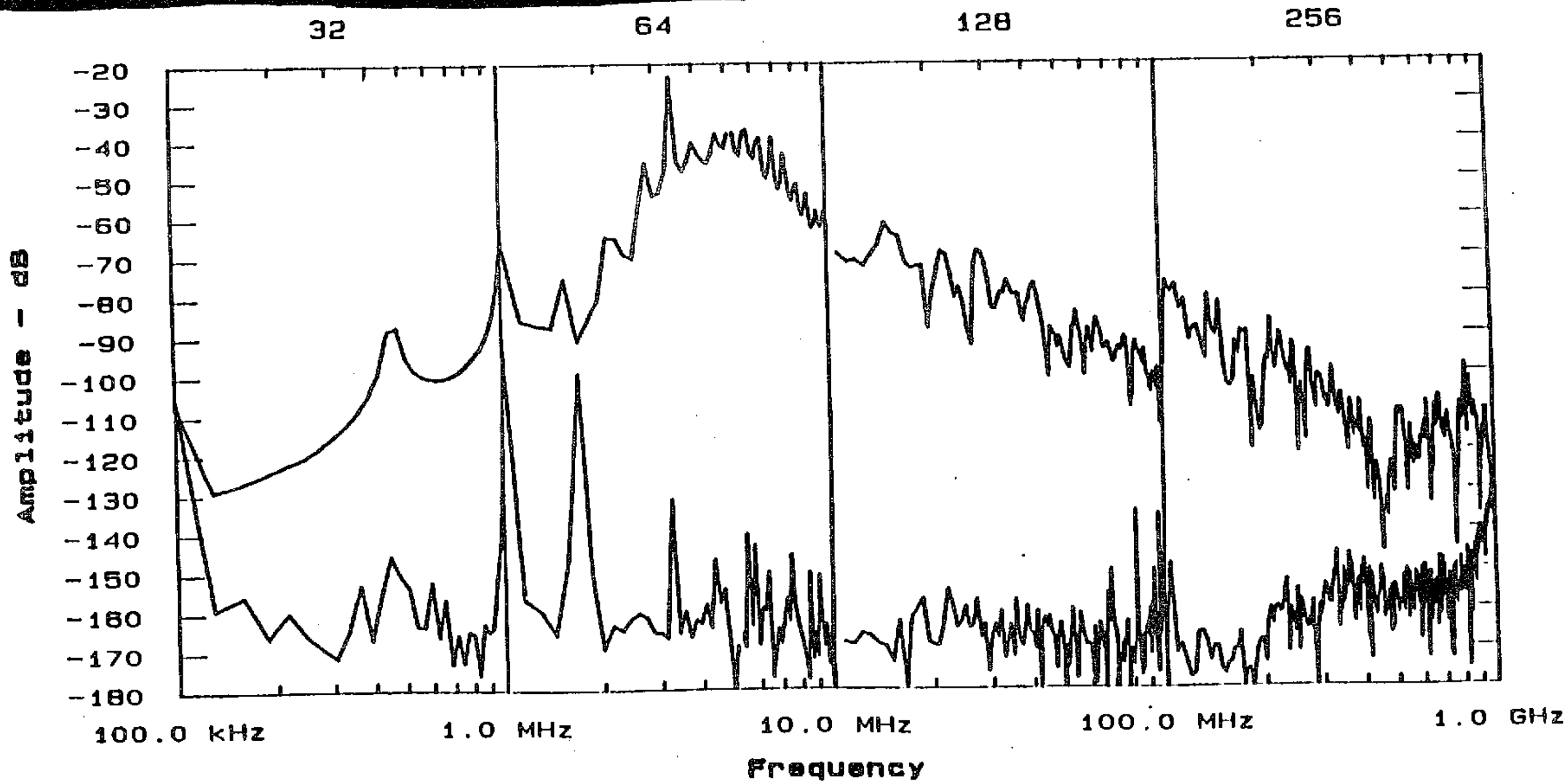


Signal to Noise Report

12: 12 PM THU., 4 JUNE, 1992

Test Point	V041	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	V041
Facility	THE HOUSE	Ampl: Min	-184.52 dB	Sig Atten	0.0 dB
Test Time	06-04-92 12: 10	Max	-23.48 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

[redacted]

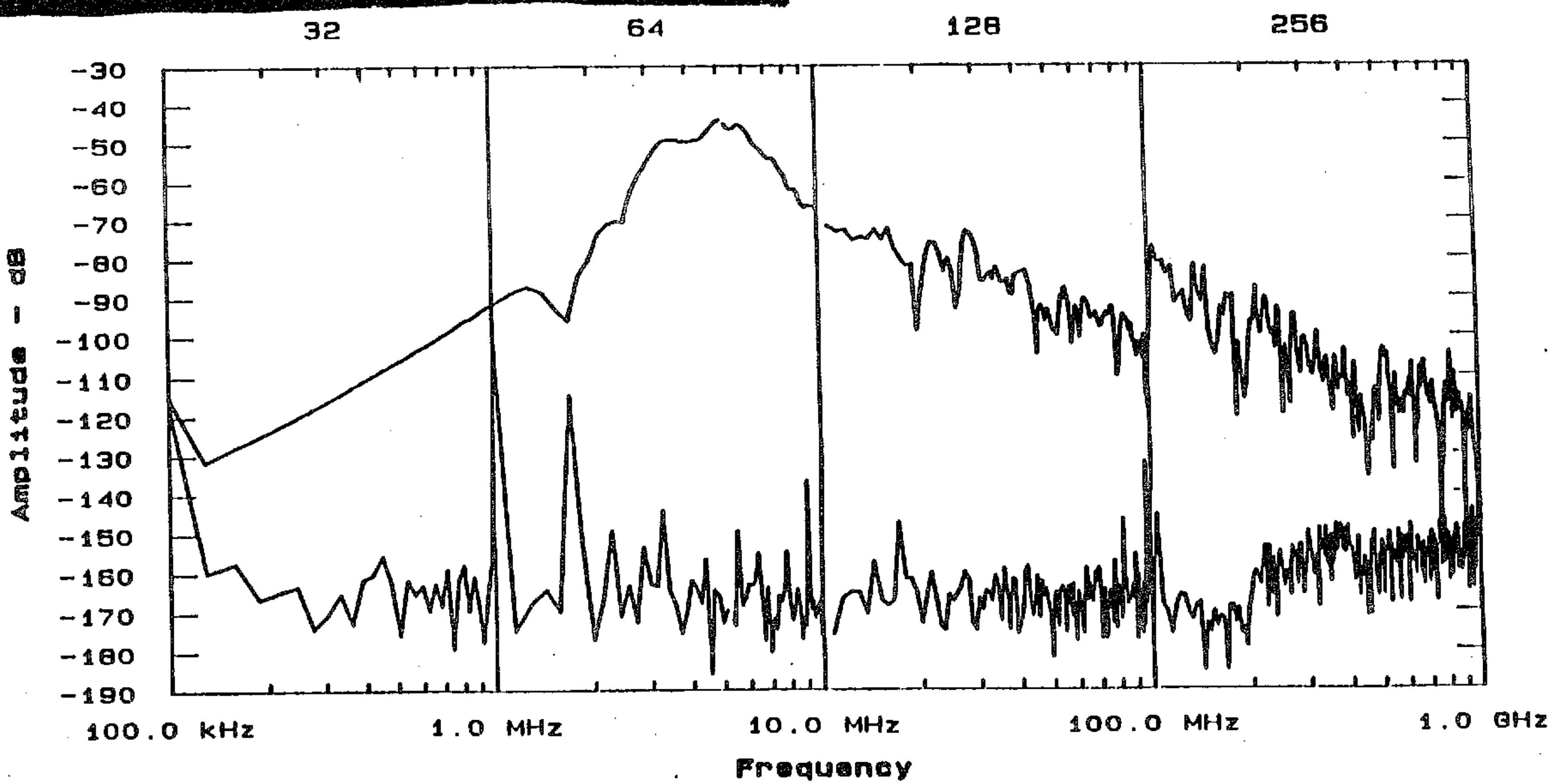


Signal to Noise Report

12: 15 PM THU.. 4 JUNE. 1992

Test Point	V042	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	V042
Facility	THE HOUSE	Ampl: Min	-185.95 dB	Sig Atten	0.0 dB
Test Time	06-04-92 12: 11	Max	-44.42 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

[redacted]

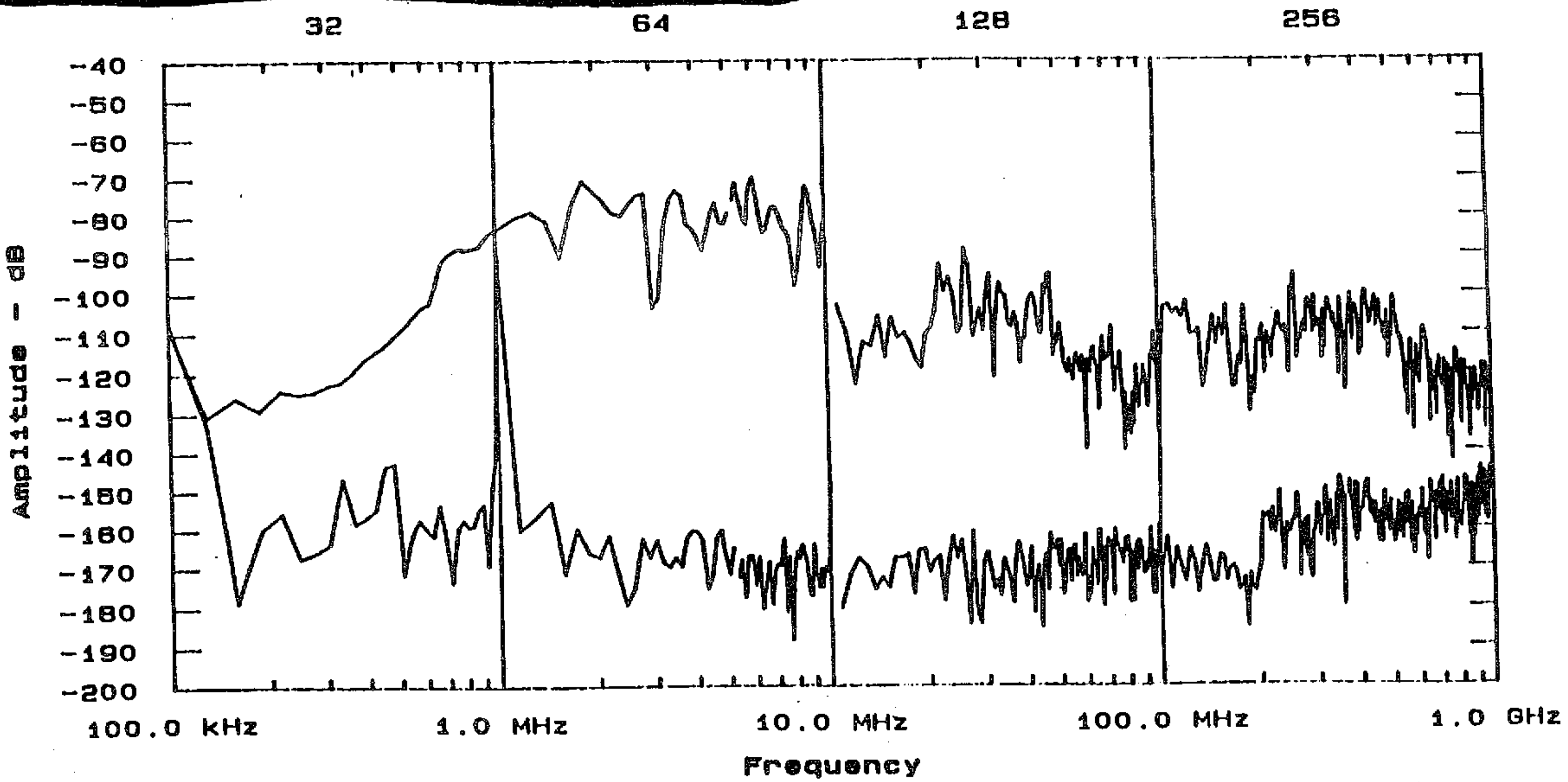


Signal to Noise Report

4:04 PM WED., 3 JUNE, 1992

Test Point	V091B	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V091A
Facility	THE HOUSE	Ampl:	Min	-188.52 dB	Sig Atten	0.0 dB
Test Time	06-03-92 16:03		Max	-70.10 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

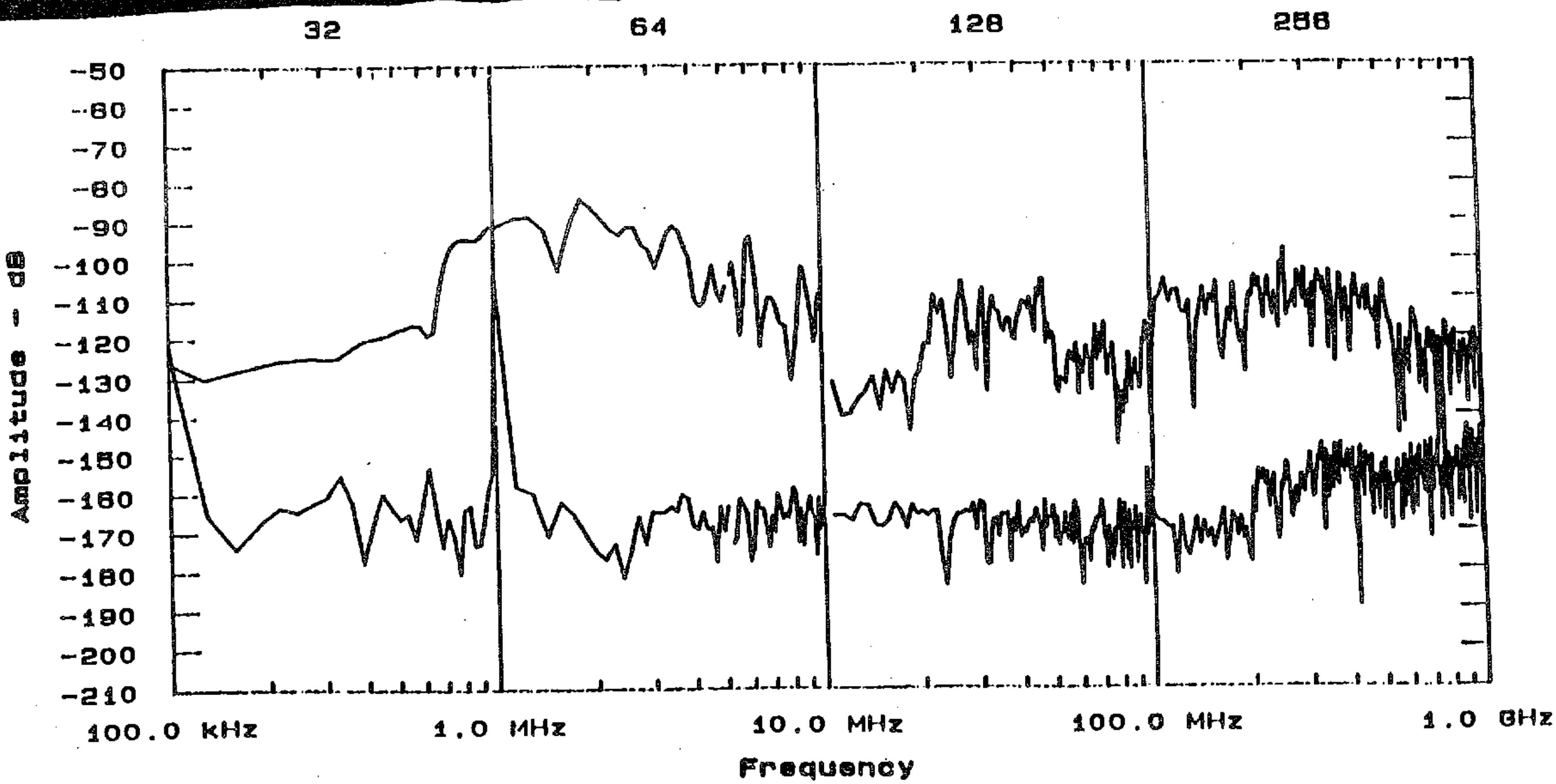


Signal to Noise Report

4:07 PM WED., 3 JUNE, 1992

Test Point	V092B	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V092
Facility	THE HOUSE	Ampl:	Min	-189.63 dB	Sig Atten	0.0 dB
Test Time	06-03-92 16:03		Max	-84.13 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

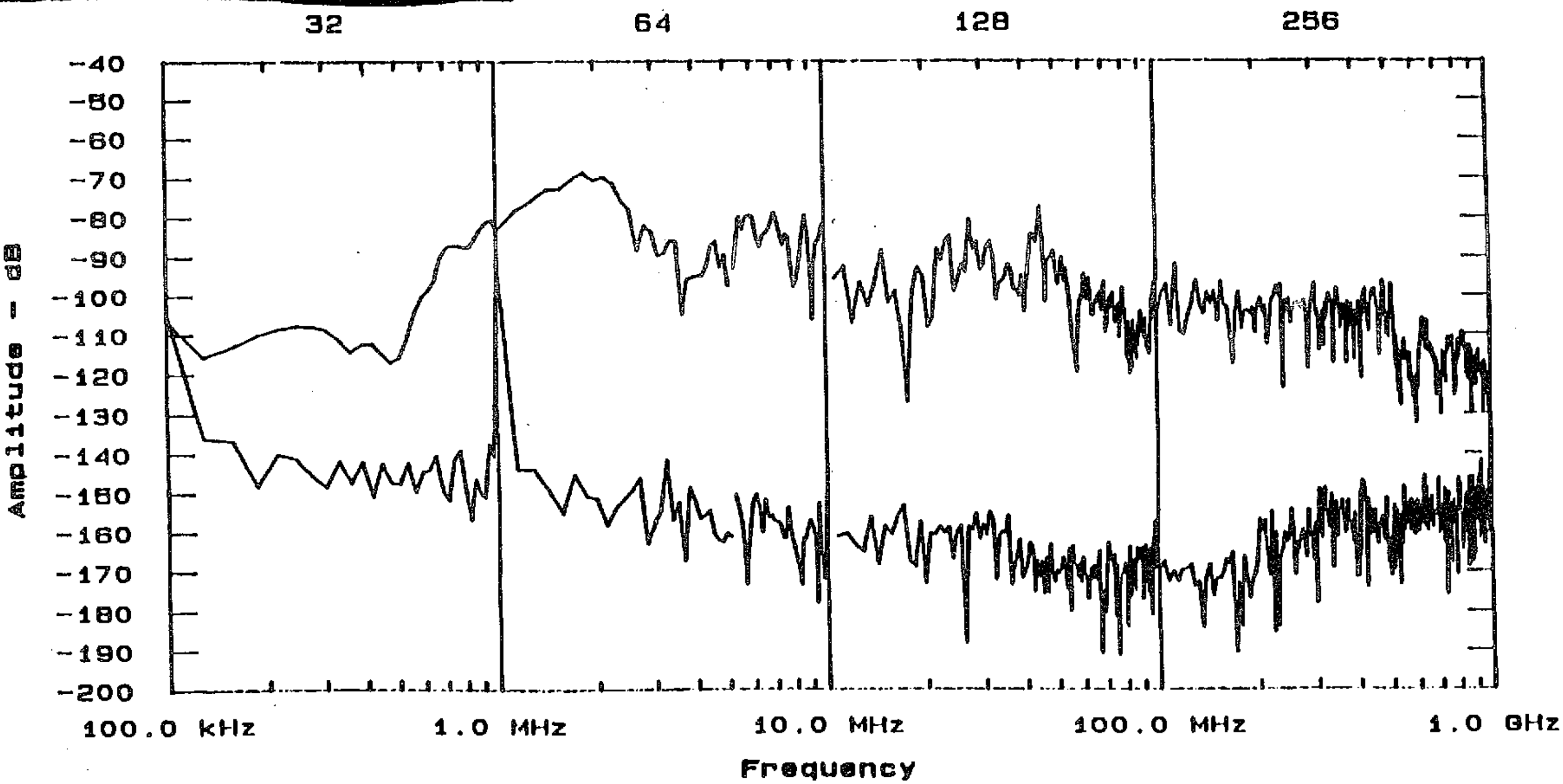


Signal to Noise Report

4:09 PM TUE., 16 JUNE, 1992

Test Point	H091	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V091
Facility	THE HOUSE	Ampl:	Min	-191.13 dB	Sig Atten	0.0 dB
Test Time	06-16-92 15:54		Max	-68.59 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

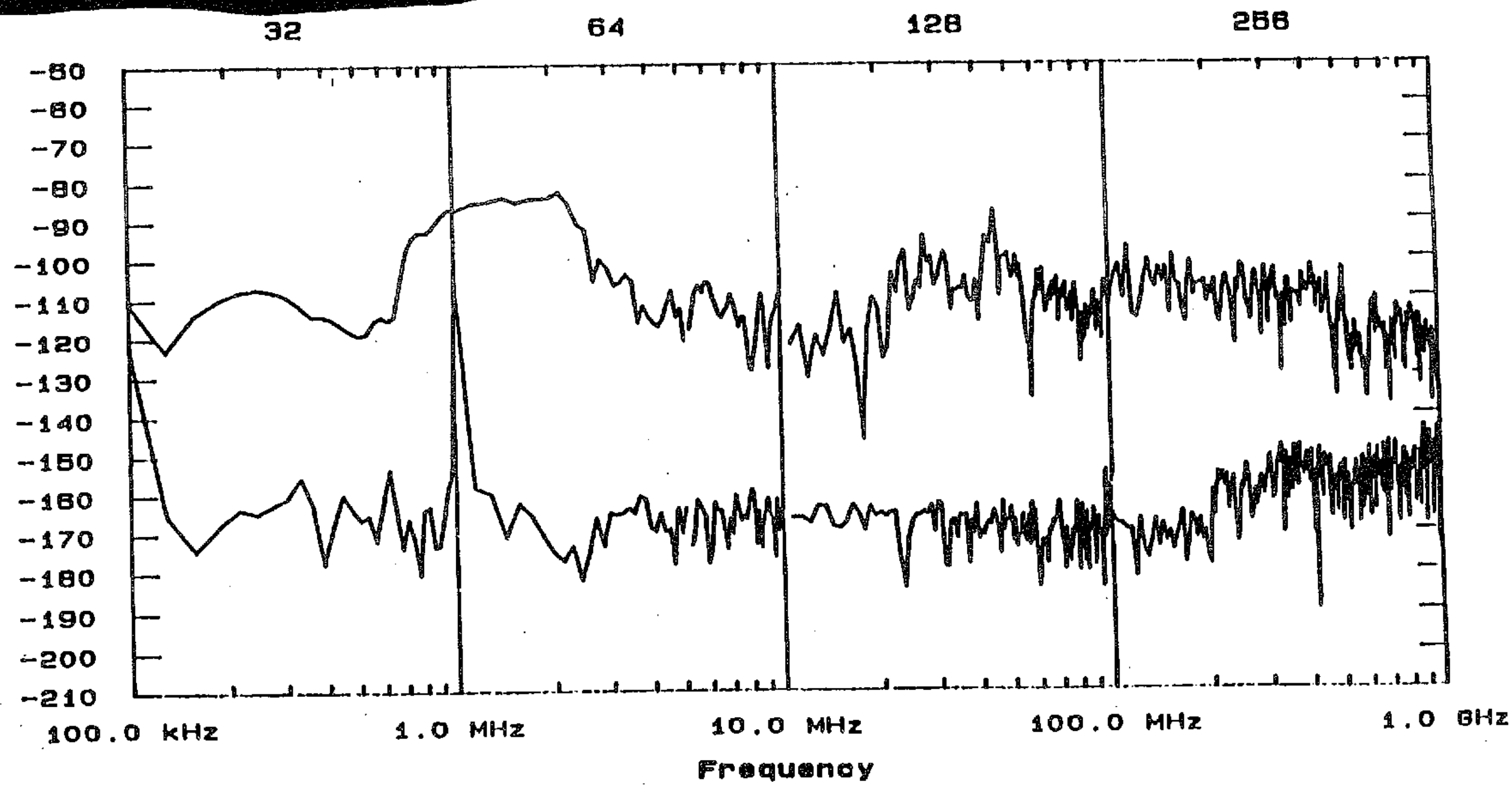


Signal to Noise Report

4:12 PM TUE., 16 JUNE, 1992

Test Point	H092	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V092
Facility	THE HOUSE	Ampl:	Min	-189.63 dB	Sig Atten	0.0 dB
Test Time	06-16-92 15:55		Max	-82.46 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

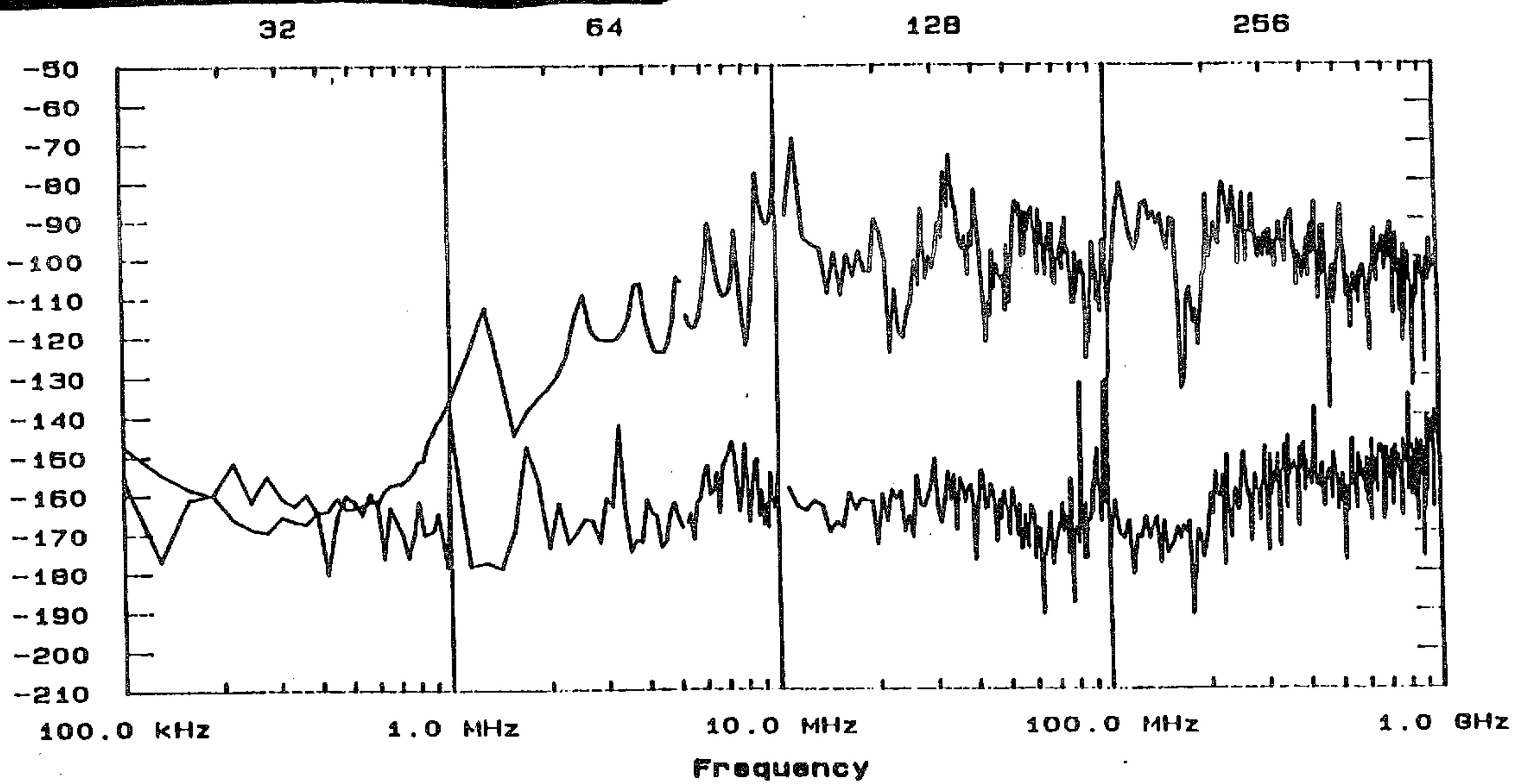


Signal to Noise Report

3: 39 PM WED.. 3 JUNE, 1992

Test Point	V101	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V101
Facility	THE HOUSE	Ampl:	Min	-191.21 dB	Sig Atten	0.0 dB
Test Time	06-03-92 15: 38		Max	-69.14 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

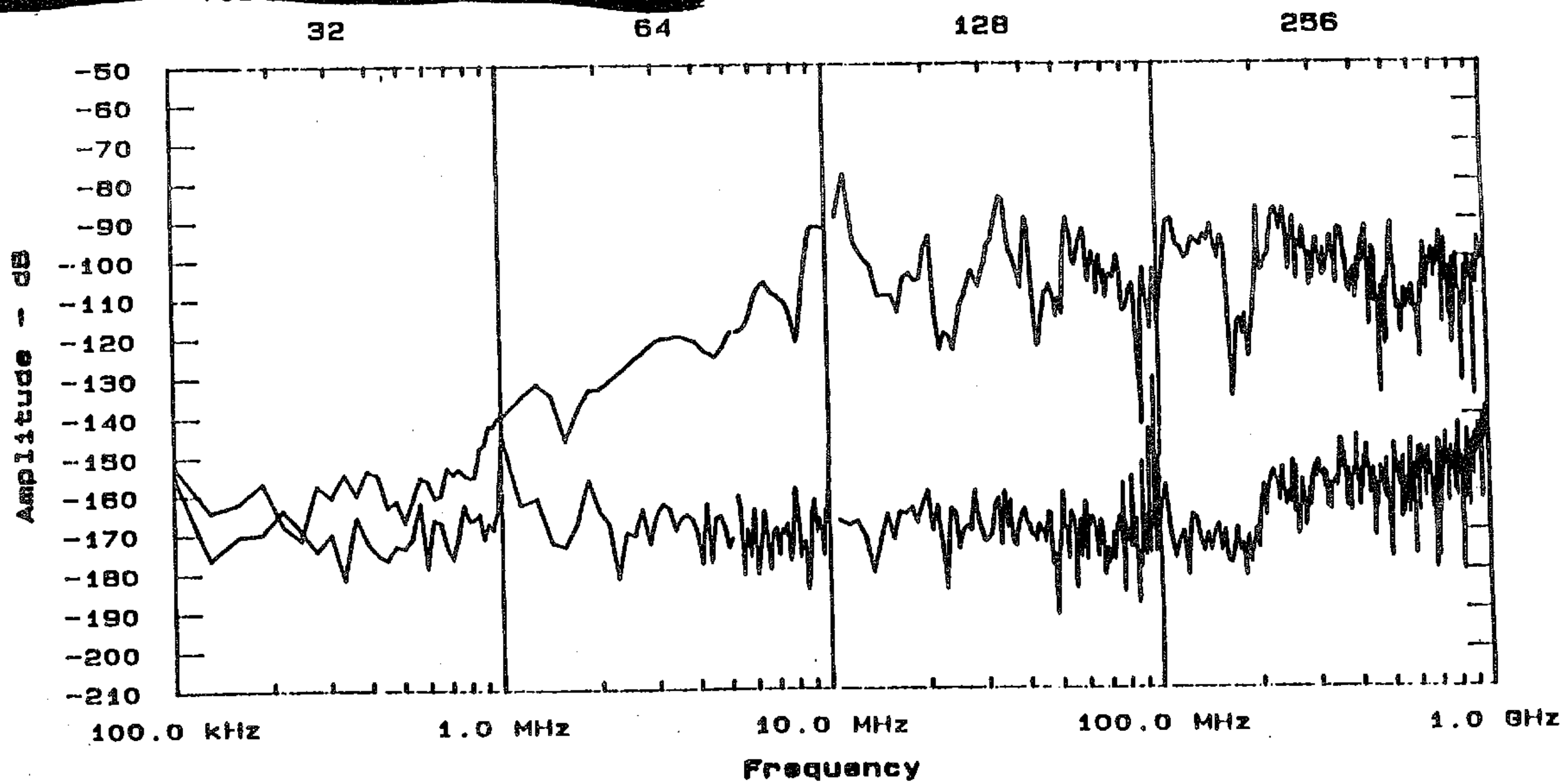


Signal to Noise Report

3: 42 PM WED., 3 JUNE, 1992

Test Point	V102	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V102
Facility	THE HOUSE	Ampl:	Min	-191.00 dB	Sig Atten	0.0 dB
Test Time	06-03-92 15: 39		Max	-78.14 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

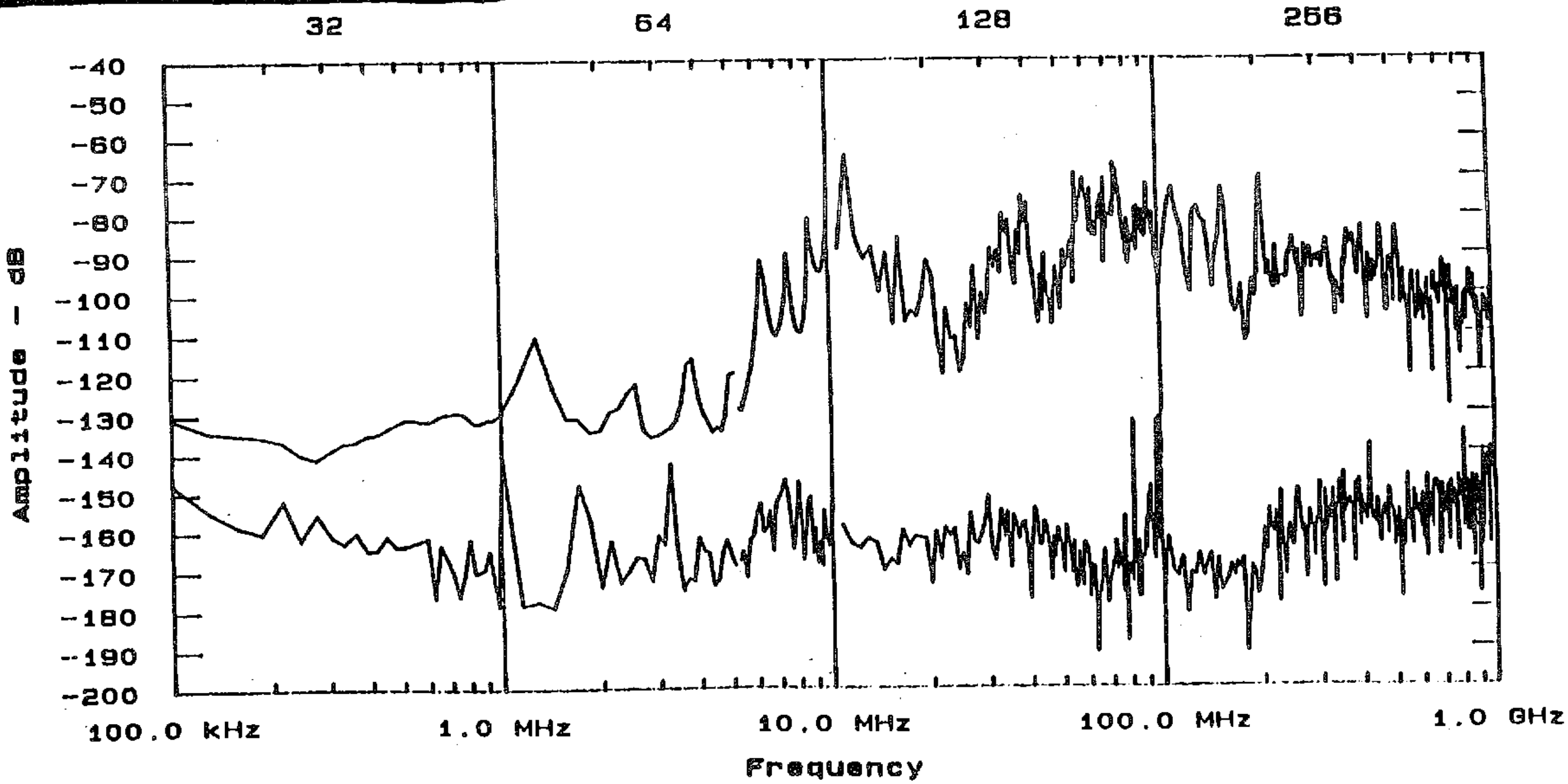


Signal to Noise Report

4: 14 PM TUE., 16 JUNE, 1992

Test Point	H101	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V101
Facility	THE HOUSE	Ampl:	Min	-191.21 dB	Sig Atten	0.0 dB
Test Time	06-16-92 15:56		Max	-64.42 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

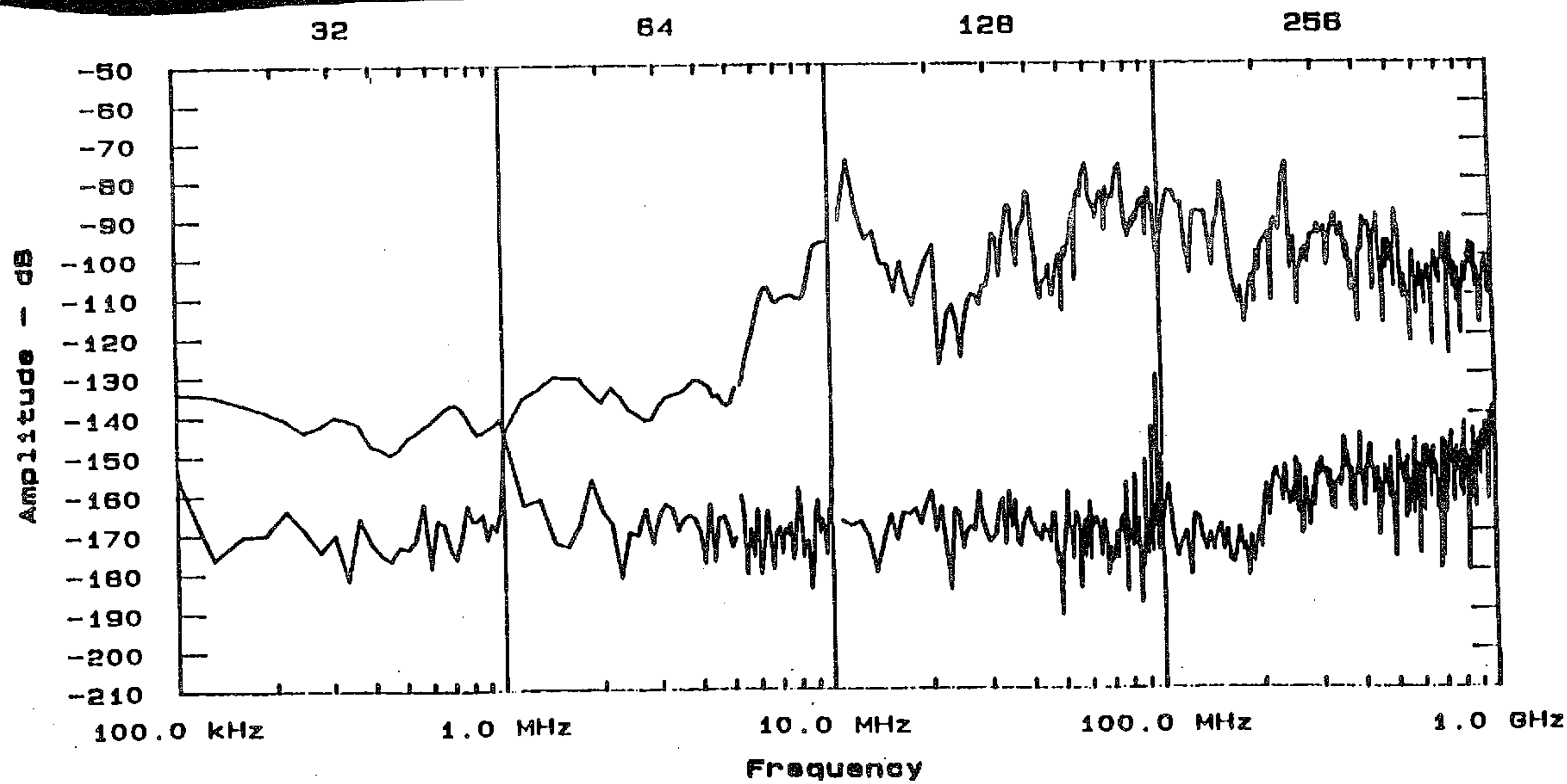


Signal to Noise Report

4: 17 PM TUE.. 16 JUNE. 1992

Test Point	H102	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	V102
Facility	THE HOUSE	Ampl: Min	-191.00 dB	Sig Atten	0.0 dB
Test Time	06-16-92 15: 57	Max	-74.98 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

[redacted]

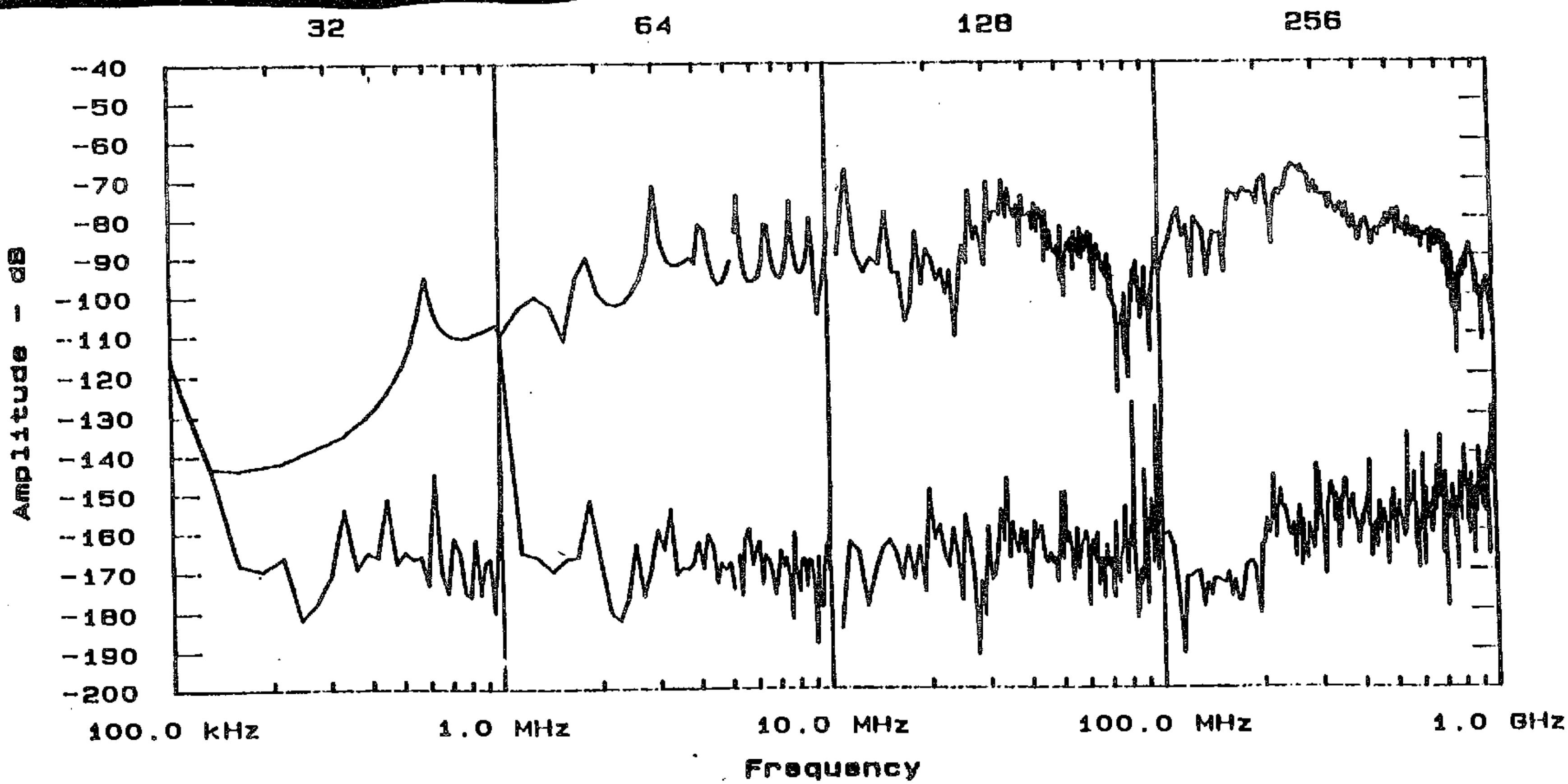


Signal to Noise Report

3: 44 PM WED.. 3 JUNE, 1992

Test Point	V111	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V111
Facility	THE HOUSE	Ampl:	Min	-191.36 dB	Sig Atten	0.0 dB
Test Time	06-03-92 15: 40		Max	-66.46 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

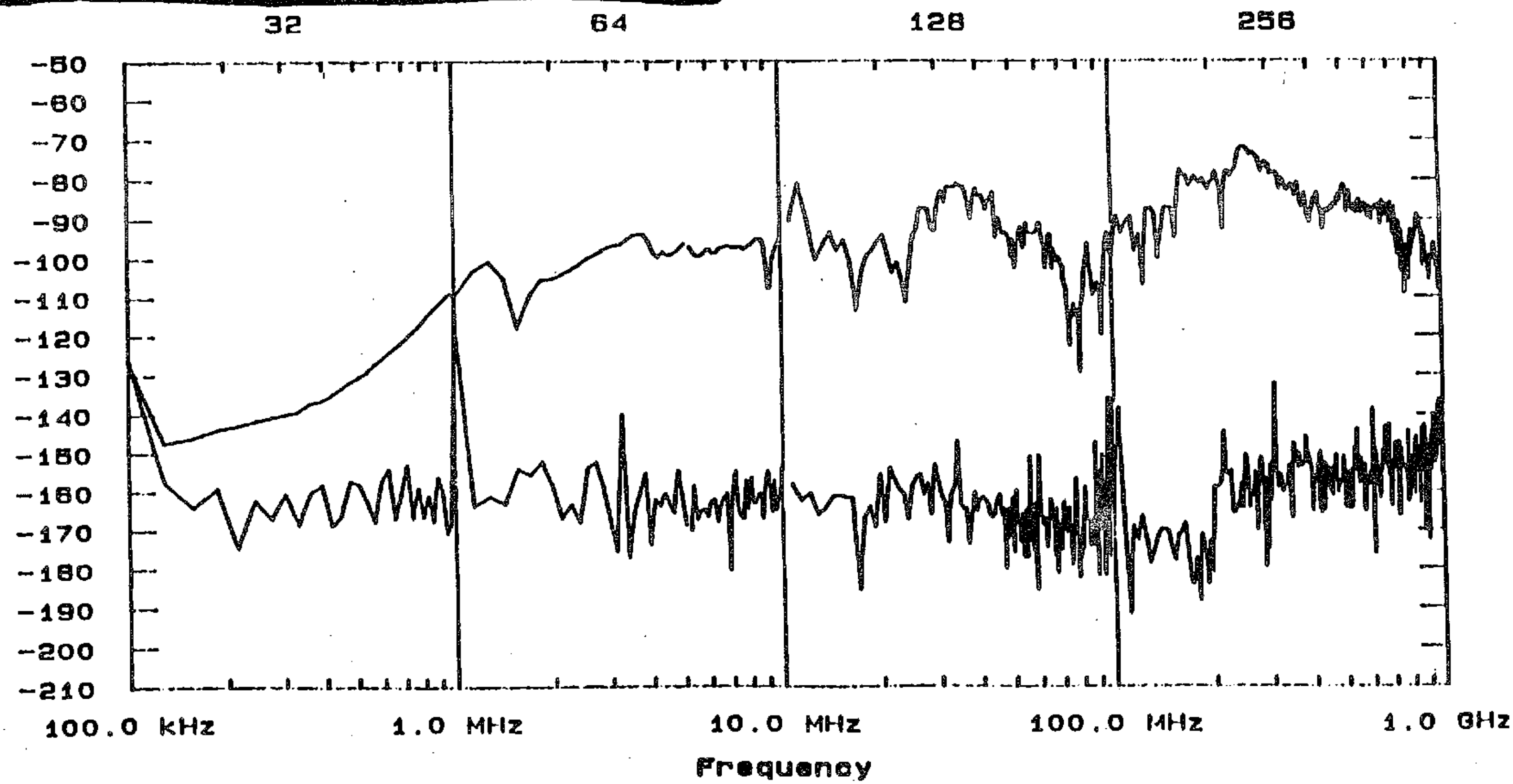


Signal to Noise Report

3: 47 PM WED.. 3 JUNE, 1992

Test Point	V112	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V112
Facility	THE HOUSE	Ampl:	Min	-191.24 dB	Sig Atten	0.0 dB
Test Time	06-03-92 15: 41		Max	-71.88 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]

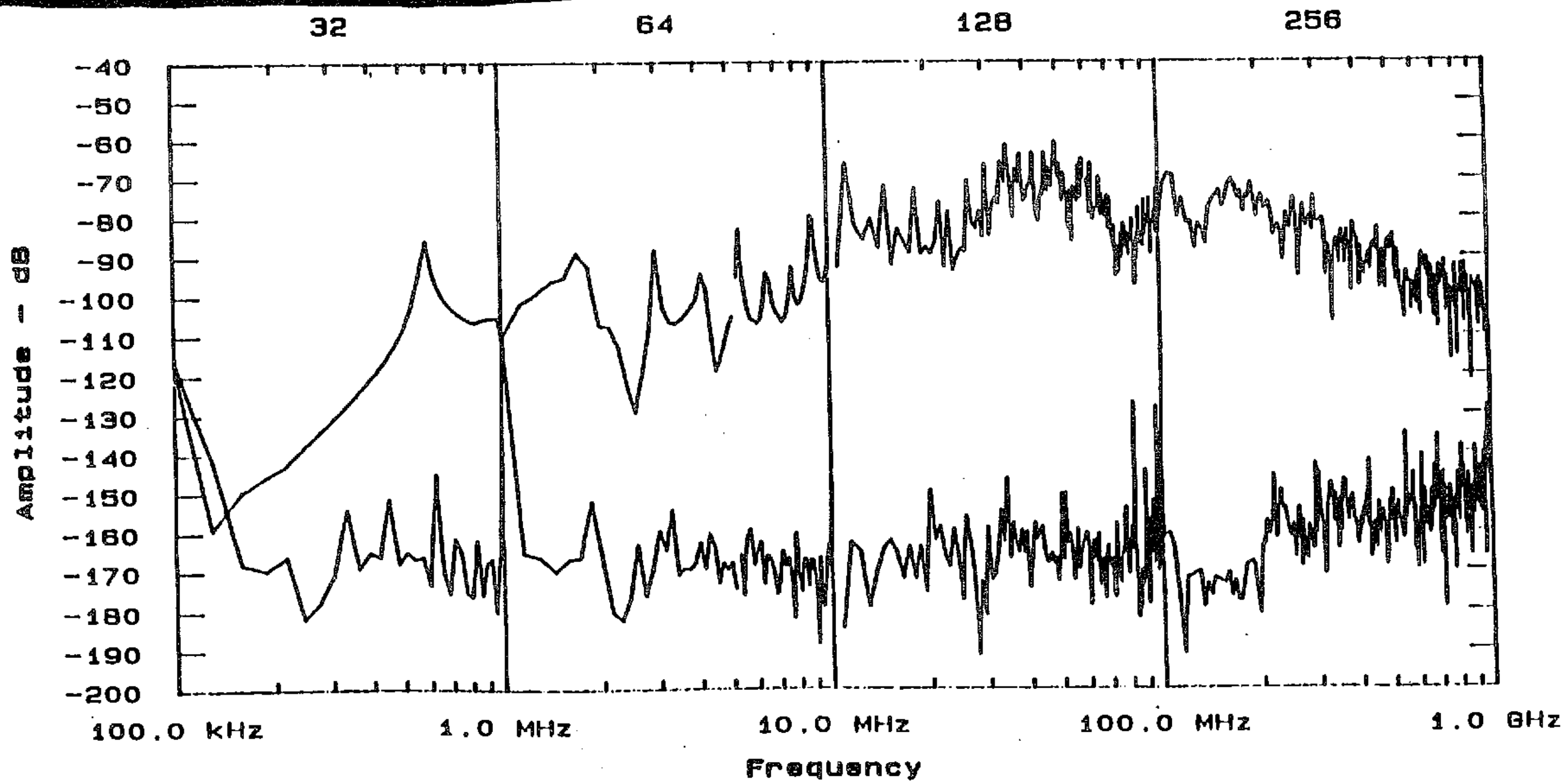


Signal to Noise Report

4: 04 PM TUE., 16 JUNE, 1992

Test Point	H111	Freq:	Min	100.00 kHz	Inst Link	A
Test Type	Wide Area		Max	1000.0 MHz	Noise Set	V111
Facility	THE HOUSE	Ampl:	Min	-191.36 dB	Sig Atten	0.0 dB
Test Time	06-16-92 15: 52		Max	-60.88 dB	Bandwidth	10 Hz
Sig Probe	IC39				Source Ampl	-12.0 dBm

[redacted]



Signal to Noise Report

4:06 PM TUE., 16 JUNE, 1992

Test Point	H112	Freq: Min	100.00 kHz	Inst Link	A
Test Type	Wide Area	Max	1000.0 MHz	Noise Set	V112
Facility	THE HOUSE	Ampl: Min	-191.24 dB	Sig Atten	0.0 dB
Test Time	06-16-92 15:53	Max	-69.10 dB	Bandwidth	10 Hz
Sig Probe	IC39			Source Ampl	-12.0 dBm

[redacted]