

MASTER

**Gas Centrifuge Enrichment Plant
Seismic Time History Development**

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T. G. Carley

OAK RIDGE NATIONAL LABORATORY
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Oak Ridge National Laboratory

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Union Carbide Corporation

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126

CONTENTS

	<u>Page</u>
List of Figures	ii
Abstract	1
1. INTRODUCTION	1
2. THEORETICAL BACKGROUND	3
2.1 Program ARTEQ	4
2.2 Fast Fourier Transform	6
2.3 Spectral Shaping	6
2.4 Accelerometer	7
3. INPUT	9
4. OUTPUT ACCELEROGRAMS	11
5. REFERENCES	13

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1	Program ARTEQ - Block Diagram	14
2	San Fernando Earthquake - February 9, 1971	15
3	Lower California Earthquake - November 12, 1954	16
4	Northern California Earthquake - September 12, 1966	17
5	Northern California Earthquake - December 18, 1967	18
6	Borrego Mountain Earthquake - April 8, 1968	19
7	GATH.02 Accelerogram	20
8	GATH.04 Accelerogram	21
9	GATH.09 Accelerogram	22
10	GATH.10 Accelerogram	23
11	GATH.1E Accelerogram	24
12	Amplitude Frequency Spectra - GATH.02	25
13	PSV Response Spectra - GATH.02	26
14	Acceleration Response Spectra - GATH.02	27
15	Amplitude Frequency Spectra - GATH.04	28
16	PSV Response Spectra - GATH.04	29
17	Acceleration Response Spectra - GATH.04	30
18	Amplitude Frequency Spectra - GATH.C9	31
19	PSV Response Spectra - GATH.09	32
20	Acceleration Response Spectra - GATH.09	33
21	Amplitude Frequency Spectra - GATH.10	34
22	PSV Response Spectra - GATH.10	35
23	Acceleration Response Spectra - GATH.10	36
24	Amplitude Frequency Spectra - GATH.15	37
25	PSV Response Spectra - GATH.15	38
26	Acceleration Response Spectra - GATH.15	39
27	GATH.02 - Acceleration	40
28	GATH.02 - Velocity	41
29	GATH.02 - Displacement	42
30	GATH.04 - Acceleration	43
31	GATH.04 - Velocity	44

LIST OF FIGURES (Cont'd.)

<u>Figure No.</u>		<u>Page</u>
32	GATH.04 - Displacement	45
33	GATH.09 - Velocity	46
34	GATH.09 - Velocity	47
35	GATH.09 - Displacement	48
36	GATH.10 - Acceleration	49
37	GATH.10 - Velocity	50
38	GATH.10 - Displacement	51
39	GATH.15 - Velocity	52
40	GATH.15 - Velocity	53
41	GATH.15 - Displacement	54
42	Normalized Cross-Correlation, GATH.02 - GATH.04	55
43	Normalized Cross-Correlation, GATH.02 - GATH.09	56
44	Normalized Cross-Correlation, GATH.02 - GATH.10	57
45	Normalized Cross-Correlation, GATH.02 - GATH.15	58
46	Normalized Cross-Correlation, GATH.04 - GATH.09	59
47	Normalized Cross-Correlation, GATH.04 - GATH.10	60
48	Normalized Cross-Correlation, GATH.04 - GATH.15	61
49	Normalized Cross-Correlation, GATH.09 - GATH.10	62
50	Normalized Cross-Correlation, GATH.09 - GATH.15	63
51	Normalized Cross-Correlation, GATH.10 - GATH.15	64

GAS CENTRIFUGE ENRICHMENT PLANT
SEISMIC TIME HISTORY DEVELOPMENT

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Abstract

The objective of this study is to generate a number of artificial-spectrum consistent-time histories for use in the seismic analysis of the Gas Centrifuge Enrichment Plant (GCEP) service modules (SM).

The method used in the generation of the artificial time histories presented in this report makes use of the fast Fourier transform (FFT) algorithm to modify the Fourier frequency spectrum of a recorded accelerogram. The response spectrum of the generated accelerogram is consistent with the spectrum specification given by USAEC Regulatory Guide 1.60.

Five statistically independent time histories have been developed. These accelerograms are based on recorded West Coast accelerations that meet specific requirements associated with the location of the recording station with regard to the epicenter. The acceleration time history, Fourier and response spectras, and integrated velocity and displacement records are presented.

1. INTRODUCTION

The objective of this study is to generate a number of artificial, spectrum-consistent, time histories for use in the seismic analysis of the Gas Centrifuge Enrichment Plant (GCEP) Service Modules.

The methodology associated with the development of artificial-spectrum consistent-time histories that meet the requirements stipulated per Y/EN 204,¹ "Seismic Design Criteria for the Gas Centrifuge Enrichment Plant - GCEP," is presented herein. This report meets the requirements of Task IV of the Engineering Analysis Department (EA) Support to Y-12 Civil and Architectural Engineering (YCA) service module design.²

The method used in the development of the time histories uses the fast Fourier transform (FFT) algorithm to modify the frequency spectrum of a recorded earthquake to produce an accelerogram with a response spectrum that envelops the U. S. Atomic Energy Commission (USAEC) Regulatory Guide 1.60³ spectra.

A general description of the mathematical foundation of the program ARTEQ used in the generation of the artificial time histories is given in Section 2. The description of the input data used as the base for the generated accelerograms is included in Section 3. The synthesized accelerograms which meet the requirements of Task I² of the EA Support to YCA SM Design are shown in Section 4. The plots of the time history, pseudo velocity spectra (PVS), and acceleration response spectra, with the Regulatory Guide 1.60 spectrum superimposed in the same plot, are given in the latter part of the report.

2. THEORETICAL BACKGROUND

A number of approaches have been employed to generate earth motion time histories which have response spectra of a given nature. Tsai⁴ used a method in which the initial ground motion time history is directly modified, based on the difference between the response spectrum and the design spectrum. Response spectrum suppression was accomplished by passing the time history through a series of filters whose parameters were optimized to give the desired suppression and band width. The raising of the response spectrum was accomplished by adding sinusoidal motions to the time history, with the amplitude and phase determined by the design and response spectra difference and the time of maximum response. Rizzo et al.⁵ used a method in which the modifications to the ground motion were made by adjusting the Fourier spectrum of the ground motion time history. Response-spectrum suppression was applied directly to the Fourier spectrum in the frequency bands surrounding the response-spectrum frequency at which the response spectrum was to be decreased. The spectrum raising was accomplished by adding to the Fourier spectrum the frequency spectrum of a damped sinusoid with frequency equal to that of the point on the response spectrum at which the spectrum increase was desired.

Levy and Wilkinson⁶ employ a superposition of sinusoids with alternating algebraic sign upon which is impressed an enveloping function of time. The minimum response-spectrum-frequency interval is specified which causes overlapping of the half-power points of the responses of adjacent oscillator to the sinusoidal excitations. Since the frequencies are not harmonically related, convergence does not increase beyond a certain spacing, implying an apparent optimum interval.

Kaul⁷ has developed a procedure in which the difference between the design and computed response spectrum is related directly to the required change in time history, through a response integral. This iterative process converges to the accelerogram whose response spectrum is consistent with the design spectrum. Other approaches to the problem of generating spectrum-compatible time histories include the method

presented by Scanlan and Sacrs⁸ in which the ground motion is synthesized by adding together a number of randomly phased sinusoids with amplitudes adjusted to give the desired response spectra.

The method used in the generation of the artificial time histories presented in this report makes use of the FFT algorithm to modify the Fourier frequency spectrum of a recorded earthquake accelerogram. This methodology has been implemented in the digital program ARTEQ that is described in the next section.

2.1 Program ARTEQ

Program ARTEQ implements a Fourier frequency spectra-shaping scheme in the development of artificial, spectrum-consistent, time-history accelerograms. This program is implemented in Fortran compatible with the compilers in use at the Oak Ridge National Laboratory (ORNL) computing facility. The program is operational on either the IBM 360/91 or the 360/75 computers.

Input environment to ARTEQ consists of punched cards (logic unit 5) and unlabeled, 9-track, 800 BPI tape on logic unit 8. Normally, the cards are used for input of control information and the tape contains the input accelerogram that is used as a basis for the generation of the output accelerogram.

Program ARTEQ implements a spectral-shaping scheme that operates on the Fourier spectra of the input accelerogram. These Fourier spectra are computed using the FFT algorithm. The magnitude of the changes to the Fourier frequency spectra are based on the difference that exists between the response spectra of the accelerogram and the target or design spectra which is specified normally by Regulatory Guide 1.60.

The response spectra of the accelerogram are computed for each of 200 discrete frequency points, also using the FFT algorithm. The response at each of the frequency points is calculated by multiplying in the frequency domain, the forward transform of the excitation, and the transfer function of a single degree of freedom-damped oscillator. It

should be noted that multiplication in the frequency domain is equivalent to convolution in the time domain.

In the development to the response spectra, the frequency spacing in cycles/second is as follows: the first 45 points are spaced at 0.05-Hz intervals, the next 20 points at 0.10-Hz, and the remaining 134 points at 0.20-Hz. The lowest frequency considered is equal to 0.10 Hz, and the highest frequency point is equal to 31.2 Hz.

Adjustments to the Fourier frequency spectra are made to either lower or raise the calculated response spectra with respect to the specified value. These adjustments are made for each of the 200 points that form the response spectra. Once all the frequency points are adjusted, the inverse transform yields the time history that corresponds to the modified Fourier spectrum. The process is repeated until the number of iterations requested is completed. The program does not have a specific convergence criteria that must be met. Convergence is subjective and based on the inspection of the output response spectra.

Program ARTEQ contains logic that permits the user to shape a general envelope that contains the output time history. This shaping may be required to confine the region of strong motion of the event to a specified region on the time scale of the accelerogram. This program also includes logic associated with baseline correction so that final values of the integrated acceleration record (velocity and displacement) can be controlled.

Figure 1 presents a block diagram of the steps involved in the generation of the required time history. The steps associated with instrument and baseline correction and interpolation of the raw data, that are discussed in a latter section, are external to the program ARTEQ logic. These steps are not required components of the computational procedure of ARTEQ.

2.2 Fast Fourier Transform

The fast Fourier transform (FFT) computational algorithm is used for the determination of the response and frequency spectrum of the accelerograms.

The FFT algorithm is implemented in Fortran in the subroutine FOUR2. This package codes the Cooley-Tukey fast Fourier transform algorithm for the calculation of the discrete Fourier transform of finite input accelerograms.

The FFT algorithm is restricted to operate on a time series specified by a total number of points that is a power of two. The resolution in the frequency domain as well as the frequency content of the time series are limited by the sampling rate of the input data.

The relationship between the time-sampling rate, Δt , the number of points of the time series, N , and the spacing of two consecutive points in the frequency domain is given by the expression:

$$\Delta\omega = \frac{2\pi}{N\Delta t} .$$

Only $N/2$ unique frequency points are generated, the highest of these points is the "folding" or Nyquist frequency and is equal to $\omega_n = \pi/\Delta t$. This frequency is significant in that any energy present in the data with a frequency above ω_n will appear erroneously at a lower frequency.

2.3 Spectra Shaping

The Fourier frequency spectra of the input accelerogram are initially band-pass-filtered between 0.7 Hz and 25.0 Hz. The upper cut-off frequency is equal to the Nyquist frequency when the time sampling rate is equal to 0.02 sec, so that problems associated with aliasing are eliminated.

The objective of the program is achieved by modifications of the filtered Fourier frequency spectra, using the comparison between the magnitudes of the acceleration-response spectra and the design spectra

specified by USAEC Reg. Guide 1.60 as a reference for the magnitude of correction and location at which frequency the modifications are to be made.

If at a particular frequency the response-spectrum value is above the design-spectrum value, the Fourier spectrum amplitude is decreased in a relatively narrow frequency band by an amount proportional to the ratio of the response to the design value. The modified bandwidth includes one frequency point immediately above and immediately below the frequency point under consideration. The number of modified components of the Fourier spectrum is limited so that only one response-spectrum frequency is modified at a given time. The narrower the band of frequencies modified, the more detailed modifications to the response frequency are realizable.

If the response spectrum is less than the design-spectrum value at a particular frequency point, the Fourier frequency spectrum is modified by adding the Fourier spectrum of a damped sinusoid to the spectral components at the corresponding frequency point. The magnitude of the damping factor of the sinusoid is equal to 0.0064. This damping factor is associated with a logarithm decrement of 0.04 (the ratio of the amplitudes of two successive cycles is 0.04).

The phase angle of the added sinusoid is shifted so that the maximum response due to the sinusoidal excitation occurs at the same time that the maximum value occurred for the response-spectrum point under consideration.

2.4 Accelerogram Shaping

For the iteration just completed, the inverse transform of the modified Fourier spectra provides an acceleration history. Before going into the next iteration, the accelerogram is modified so that the maximum peak values do not exceed the prescribed maximum acceleration, and also the entire accelerogram is modified so that it fits an envelop which is believed to represent the typical characteristic of a recorded earthquake acceleration.

This cosmetic envelope is intended to confine the strong motion activity to the time interval beyond the 4 sec after initiation of the event. There is an exponential buildup in this interval so that the magnitude of the initial acceleration cannot exceed 8% of the maximum value in the strong motion region. This low amplitude acceleration region corresponds to that part of the event dominated by P-wave activity. Beyond the 4.0 sec, the event is characterized by strong activity associated with S-wave-type excitation.

In general, the latter portion of the accelerogram decays so that the maximum amplitude in this time portion of the accelerogram is in the order of 20% of the zero-period acceleration, this being the threshold that defines the duration of the earthquake as specified by Ref. 2.

The shaping of the output time histories is the input to the next iteration that computes a new response spectrum used in this interaction cycle.

3. INPUT DATA

In the process of generating an accelerogram which has a response spectra that envelops the design spectra specified by USAEC Regulatory Guide 1.60, program ARTEQ has the capability to initiate the iteration procedures, using as a basis the calculated response spectra of white noise or the response spectrum of a recorded or artificially generated accelerogram. In the current study, the input is given by the time history of a recorded acceleration of one of several West Coast earthquakes.

The input time series represent the corrected accelerograms that have compensation for instrument and baseline discrepancies⁹ in Fig. 1. These data are based on uncorrected accelerograms hand-digitized at unequally spaced intervals. The scheme used in the interpolation and correction of the input data is not a part of ARTEQ. This correction, performed externally to and before the input to ARTEQ, is described as follows: Equally spaced data with 50 points per second are interpolated from the raw data source. The interpolation is based on the following scheme: the first 100 equally spaced points per second are obtained from the uncorrected data, the equally spaced data are then low-pass-filtered with a cut-off frequency equal to 25 Hz (roll-off termination at 27.0 Hz). Next, every other point is eliminated, leaving a time series with 50 points per second that corresponds to a Nyquist frequency of 25.0 Hz.

Instrument correction is based on the integration of the response data of a single-degree-of-freedom (SDOF) oscillator where the excitation is the filtered accelerogram described in the previous paragraph. The damping ratio and natural frequency of the oscillator are determined from calibration tests of the recording instrument.

Baseline correction is effected by high-pass-filtering the data with a cut-off frequency of 0.05 Hz (roll-off termination of 0.07 Hz). The resulting histogram is claimed to represent the absolute acceleration with a frequency band between 0.07 Hz and 25.0 Hz.

The input accelerograms are then the corrected data of measured main events (not aftershock events) where the recording station is at a distance of 200 to 250 miles (322-402 km) from the event epicenter. The recording instrument is located in the basement or low-floor level of light-weight buildings.

Five accelerograms have been used in the generation of the desired time histories. These accelerograms are shown in Figs. 2 through 6.

The following is the information associated with these data:

- Accelerogram No. 1 corresponds to Record No. 173 of Tape No. X18862. This event is the February 9, 1971, San Fernando earthquake. The recording station is located in the subbasement of building at 1150 S. Hill St., Los Angeles, California.
- Accelerogram No. 2 corresponds to Record No. 170 of Tape No. X18863. This event is the November 12, 1954, lower California earthquake. The recording station is located at ground level at El Centro, Imperial Valley Irrigation District.
- Accelerogram No. 3 corresponds to Record No. 300 of Tape No. X18863. This event is the September 12, 1966, northern California earthquake. The recording station is located in the basement of the Pacific Telephone and Telegraph Building, Sacramento, California.
- Accelerogram No. 4 corresponds to Record No. 242 of Tape No. X18863. This event is the December 18, 1967, northern California earthquake. The recording station is located at ground level in the Public Library in Hollister, California.
- Accelerogram No. 5 corresponds to Record No. 331 of Tape No. X18863. This event is the April 8, 1968, Borrego Mountain earthquake. The recording station is at ground level at the Southern California Edison Co. Building in Colton, California.

4. OUTPUT ACCELERATIONS

The results of this study are given in the form of accelerograms that meet with the specified objectives set for the study. The time histories developed have response spectra that envelop the response spectra given by USAEC Regulatory Guide 1.60 for the same damping constant. The duration of the event conforms with the specifications outlined in Ref. 1.

The plots of the developed spectra-consistent accelerograms normalized to a maximum zero-period ground acceleration of 1 g are given in Figs. 7 through 11. Each of these accelerograms is based independently on a particular input accelerogram described in the previous section and shown in Figs. 2 through 6. The correspondence between the input and output accelerograms is as follows:

- GATH.02 (Fig. 7) generated from input accelerogram No. 1 (Fig. 2)
- GATH.04 (Fig. 8) generated from input accelerogram No. 2 (Fig. 3)
- GATH.09 (Fig. 9) generated from input accelerogram No. 3 (Fig. 4)
- GATH.10 (Fig. 10) generated from input accelerogram No. 4 (Fig. 5)
- GATH.15 (Fig. 11) generated from input accelerogram No. 5 (Fig. 6)

The amplitude (modulus) of the Fourier frequency spectra and the PSV and acceleration response spectra of each of the output accelerograms are shown in Figs. 12 through 26. The response-spectra plots shown correspond to the response of the SDOF oscillator with a damping factor (ratio to critical) equal to 2%. The zero-period acceleration is equal to 1 g. These plots also show the smoothed design spectra that correspond to those specified in Regulatory Guide 1.60.

The GCEP criteria¹ specify that the duration of the operating-level earthquake (OE) should be at least equal to 20 sec. The developed time histories have durations of 40.96 sec; it has been shown that the first 20 sec of these accelerations have response spectra that satisfy the requirements, and that the magnitude of the acceleration at the end of the time history complies with the requirements of Ref. 1.

The generated acceleration, velocity, and displacement for each of the output accelerograms are shown in Figs. 7 through 41. It can be

observed that the integrated displacement shows some divergence from the baseline. The reason for this behavior can be attributed mainly to the long-period errors (in the displacement records) that result from small errors in the initial values as discussed in Ref. 9. It can also be shown that the full length of the accelerogram is not necessarily base-corrected when only a portion (the first 40.96 sec) of the record are used in the input to ARTEQ. This program contains logic to filter out (via a digital high-pass filter) the effects of long-period drift during the process of generating the required accelerogram, but it does not control final values for the integrated displacement. Final values for the velocity record can be controlled by adequate manipulation of the Fourier components associated with the steady-state (DC) contribution to the acceleration record.

In an attempt to determine the statistical independence (or dependence) of the data generated, the cross-correlation coefficients between each of the output records have been computed and presented in plot form in Figs. 42 through 51.

For complete statistical independence, the cross-correlation coefficient for any time lag should be equal to zero. Conversely, the cross-correlation coefficient of 1.0 implies that the two functions used in the calculations are statistically dependent.

There is not an established value for the normalized cross-correlation coefficient between two time series that indicates that these functions are statistically independent. If the two separate records are used simultaneously for a two-axes excitation of a structure, the value of 0.16 or less indicates that these functions are statistically independent for this case of excitation.¹⁰

The correlation analysis shows that the largest cross-correlation coefficient that exists between any two of the calculated histograms does not exceed the value of 0.25. It is anticipated that this low correlation coefficient implies that there is little statistical dependency between any two of the developed accelerograms.

5. REFERENCES

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10. Chen Chang, "Definition of Statistically Independent Time Histories," ASCE J. Struct. Div., Tech. Note, Vol. 101, No. ST2, pp. 449-451, February 1975.

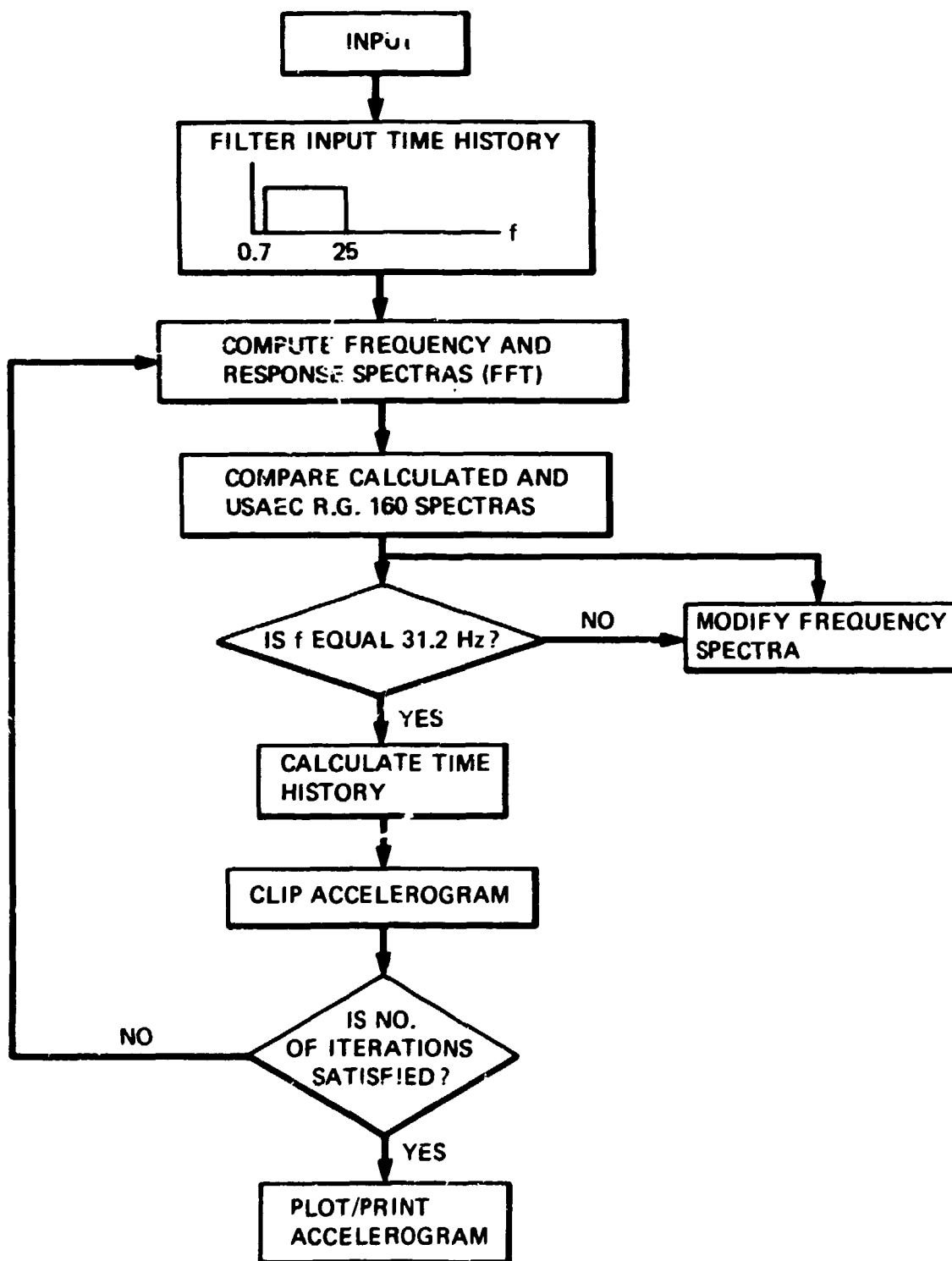


Fig. 1. Program ARTEQ -- Block Diagram.

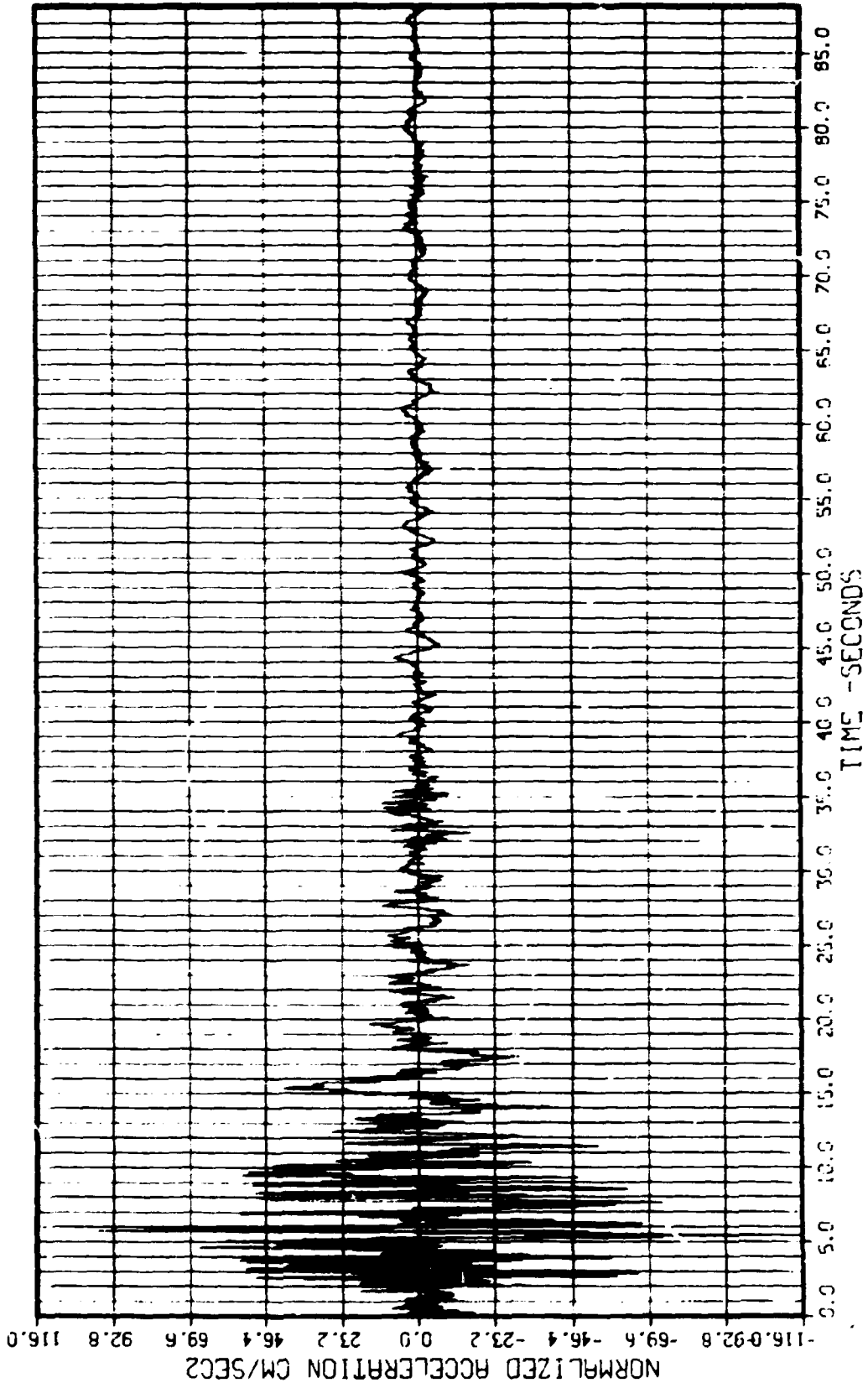


Fig. 2. San Fernando Earthquake - February 9, 1971.

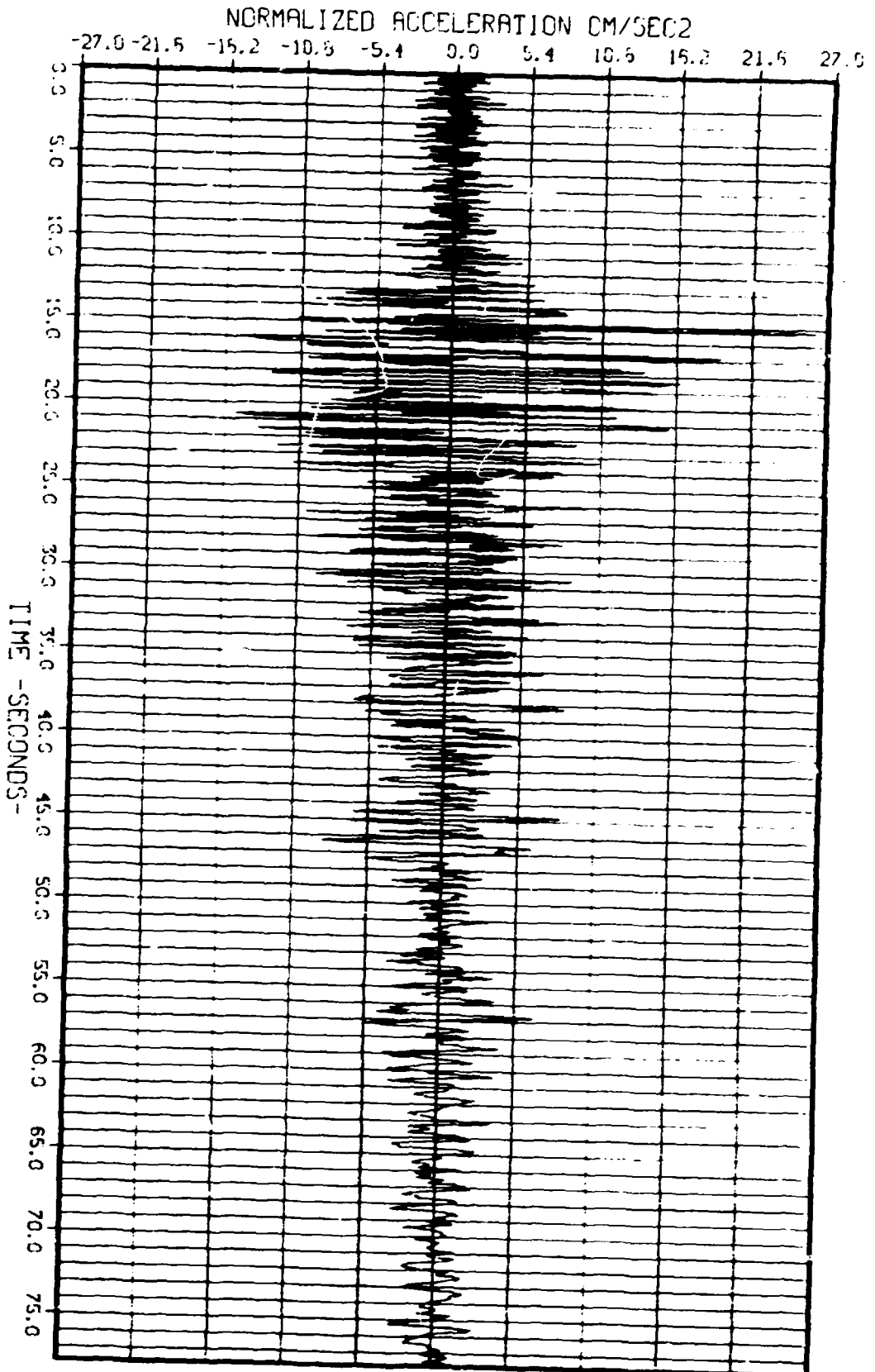


Fig. 3. Lower California Earthquake -- November 12, 1954.

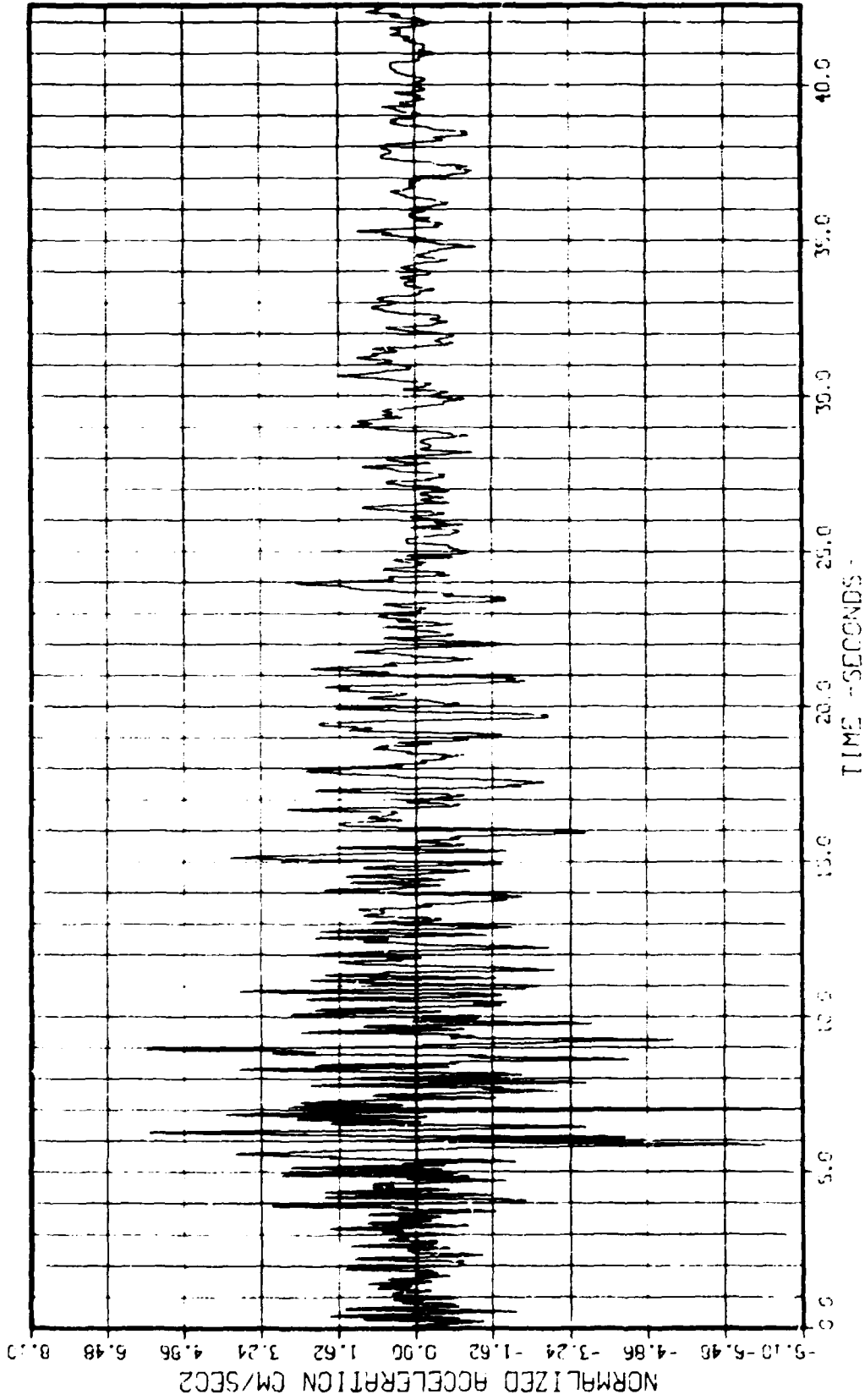


Fig. 4. Northern California Earthquake - September 12, 1966.

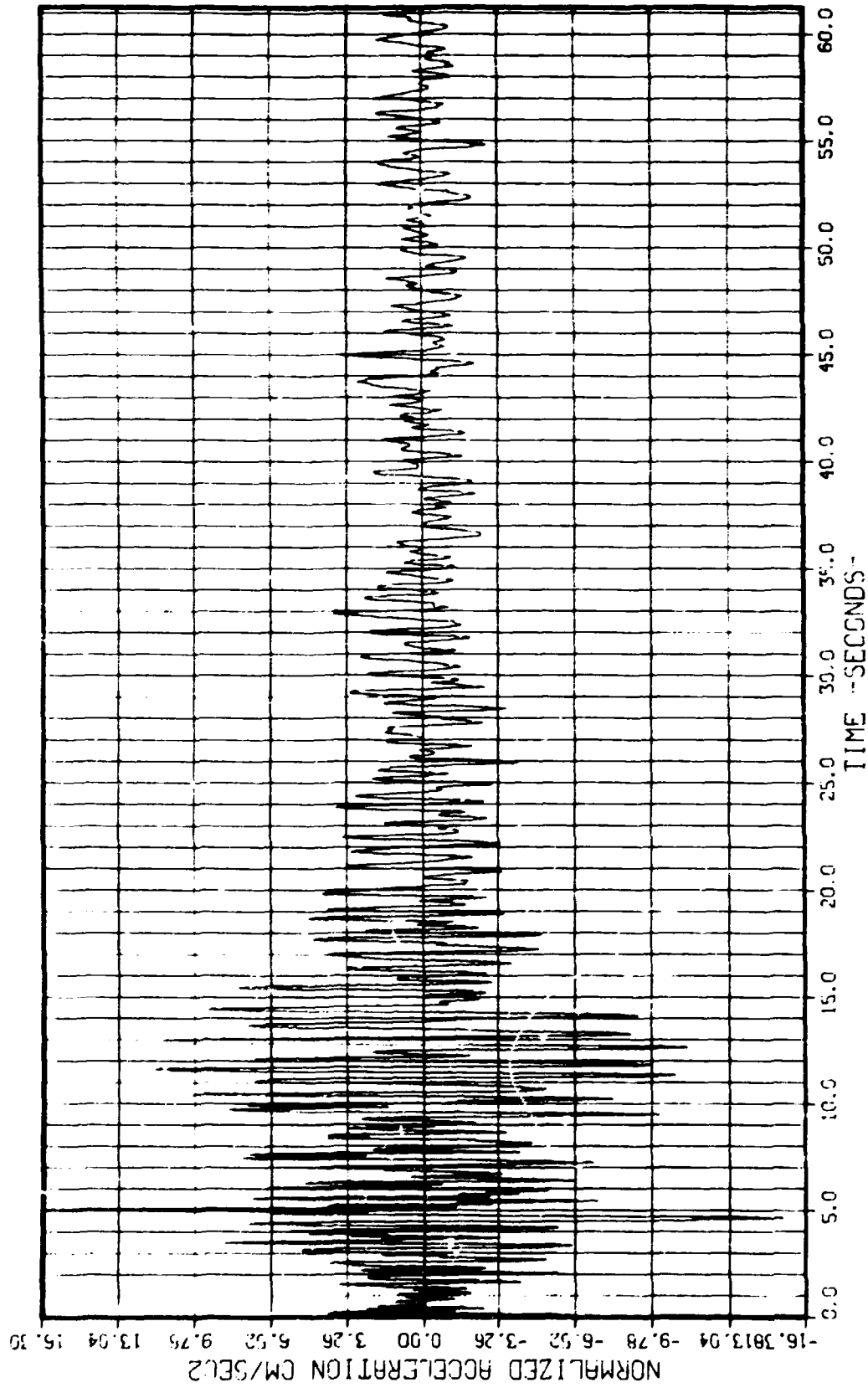


Fig. 5. Northern California Earthquake - December 18, 1967.

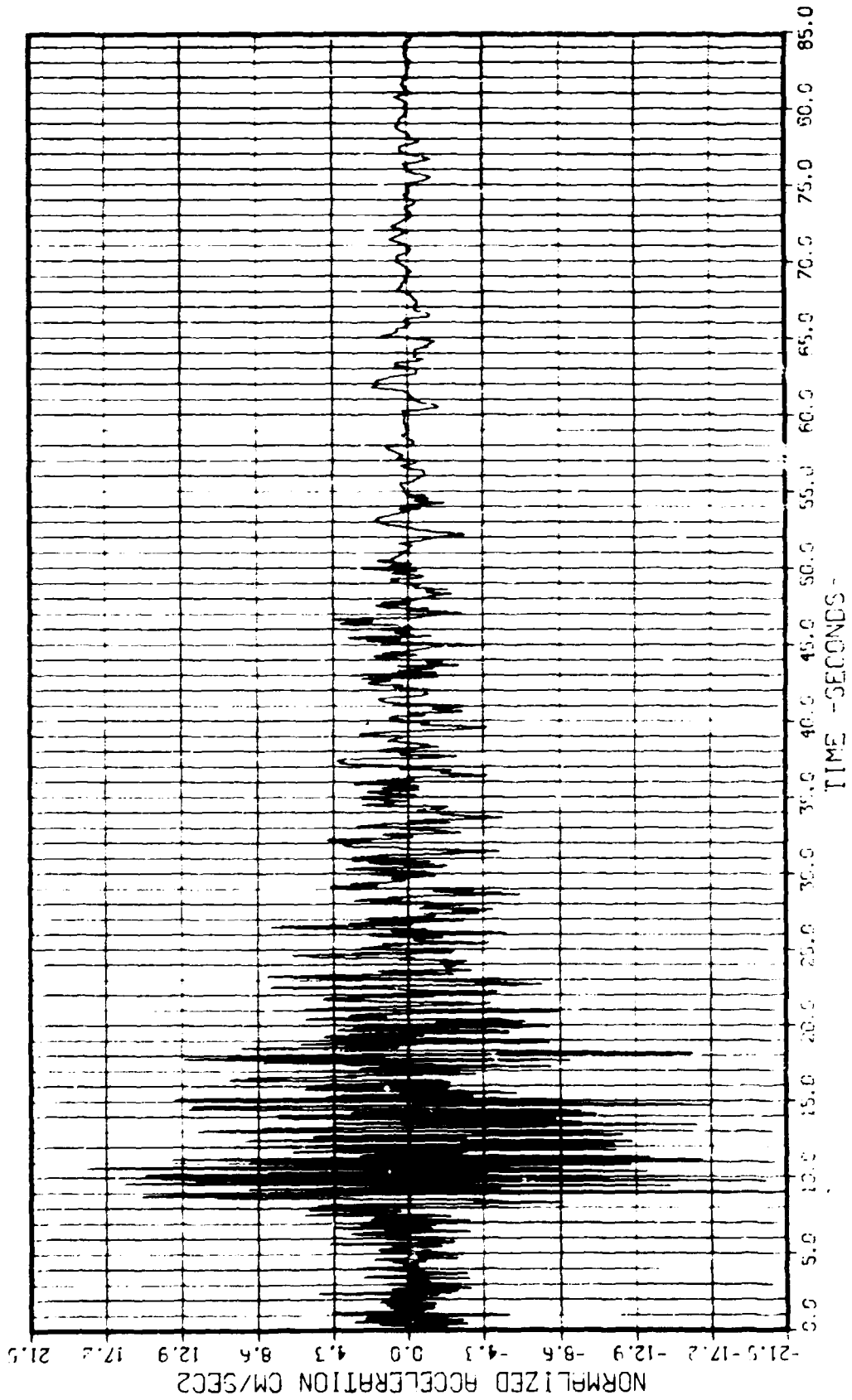


Fig. 6. Borrego Mountain Earthquake - April 8, 1968.

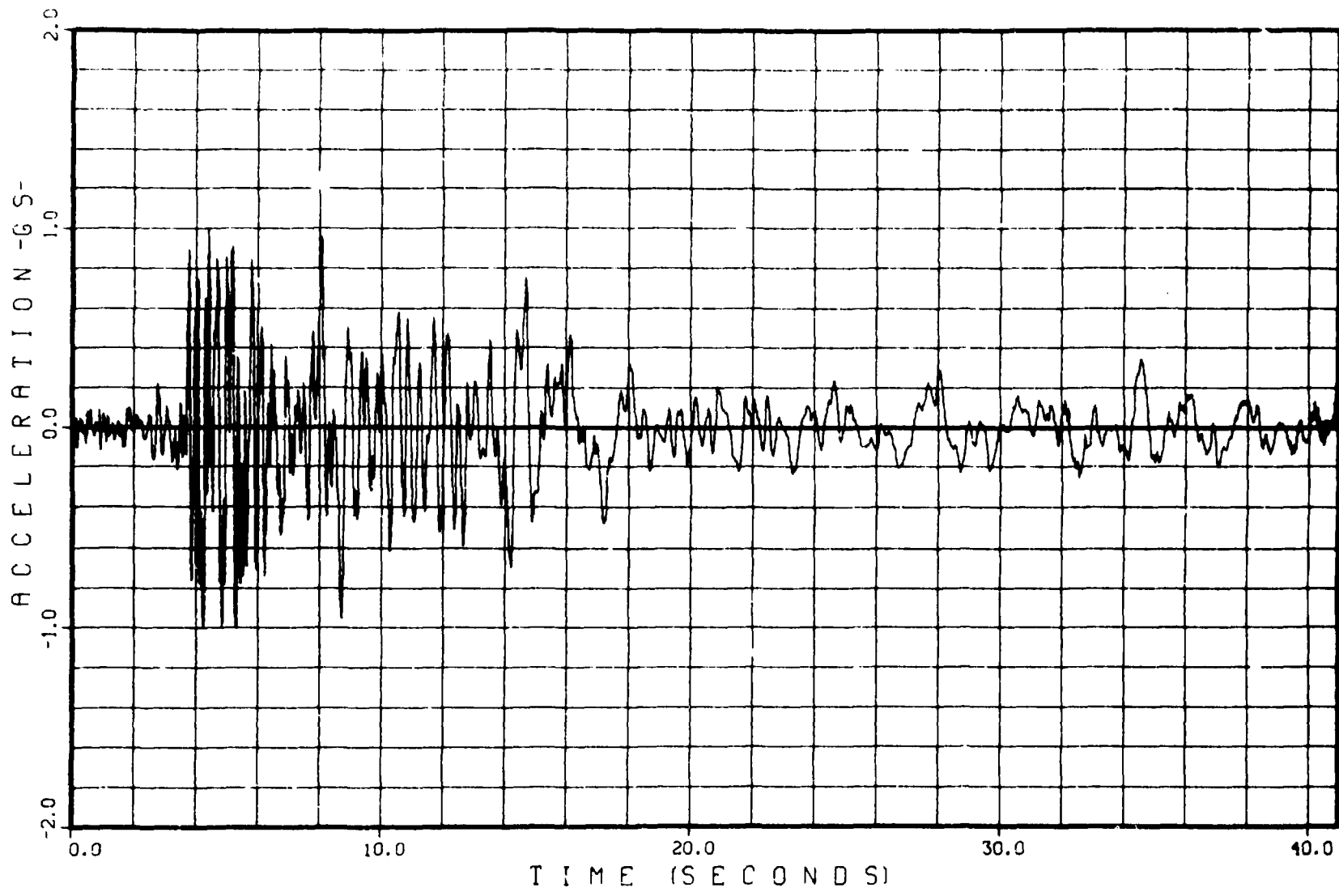


Fig. 7. GATH.02 Accelerogram.

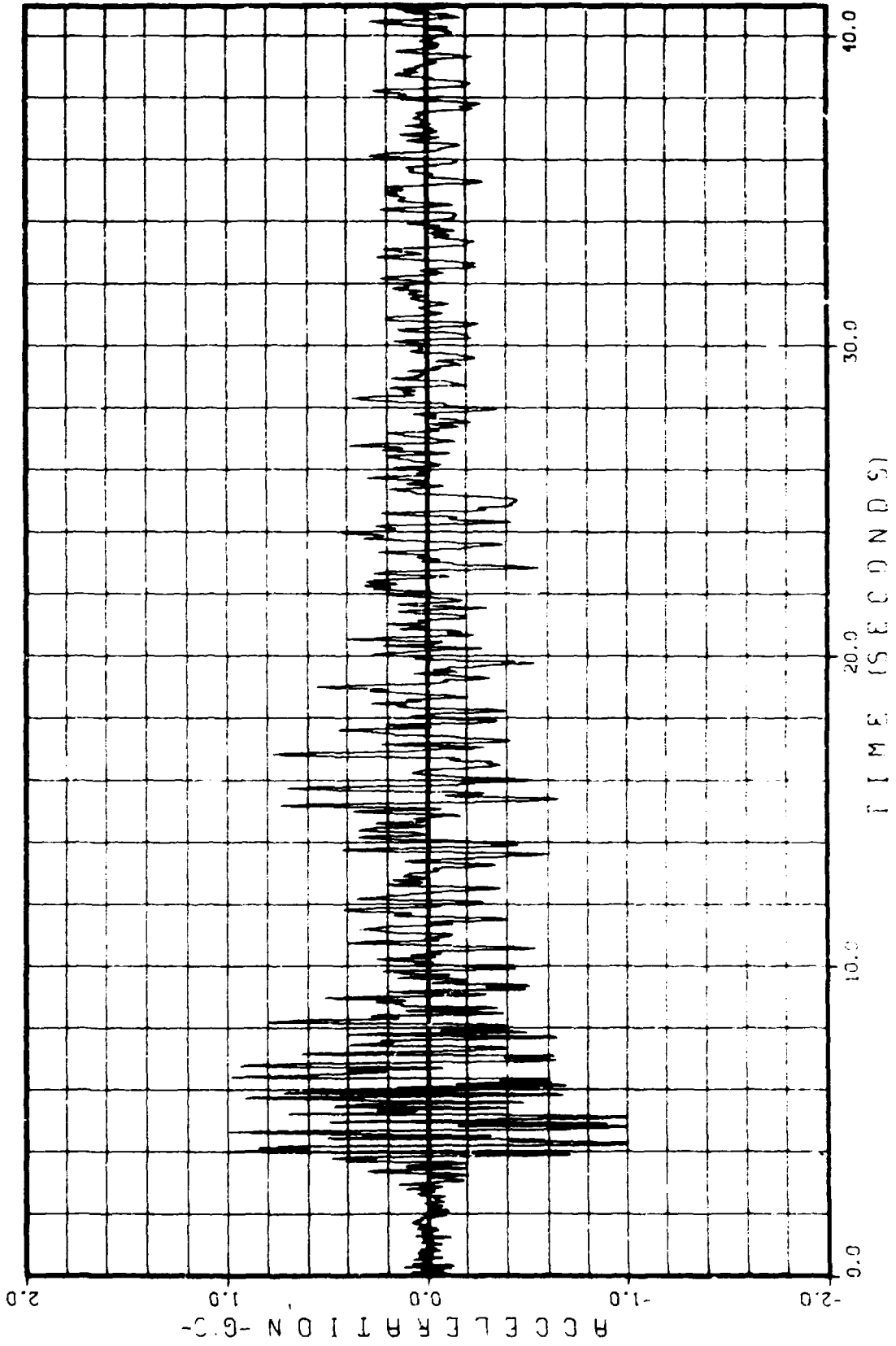


Fig. 8. GATH.04 Accelerogram.

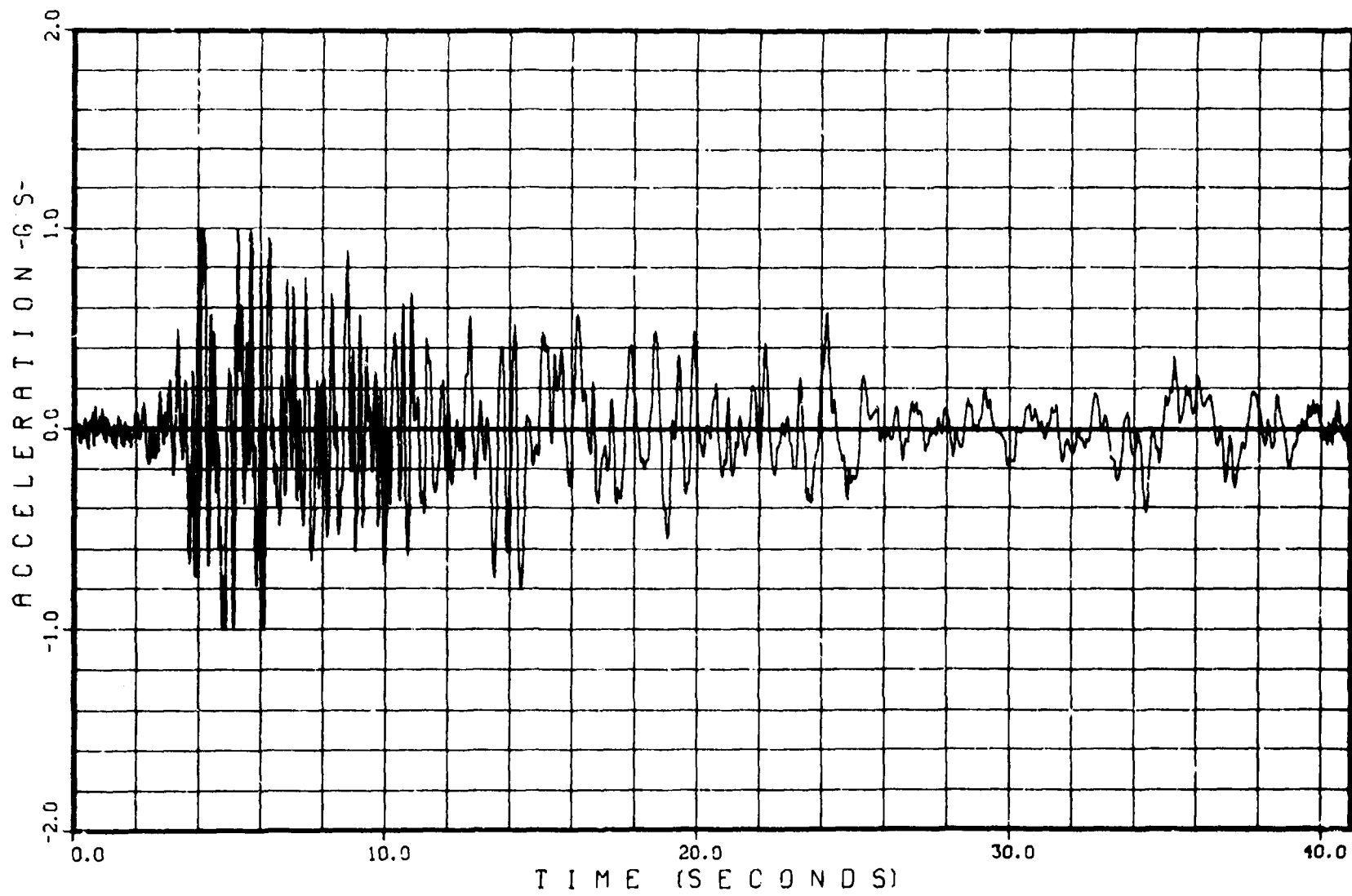


Fig. 9. GATH.09 Accelerogram.

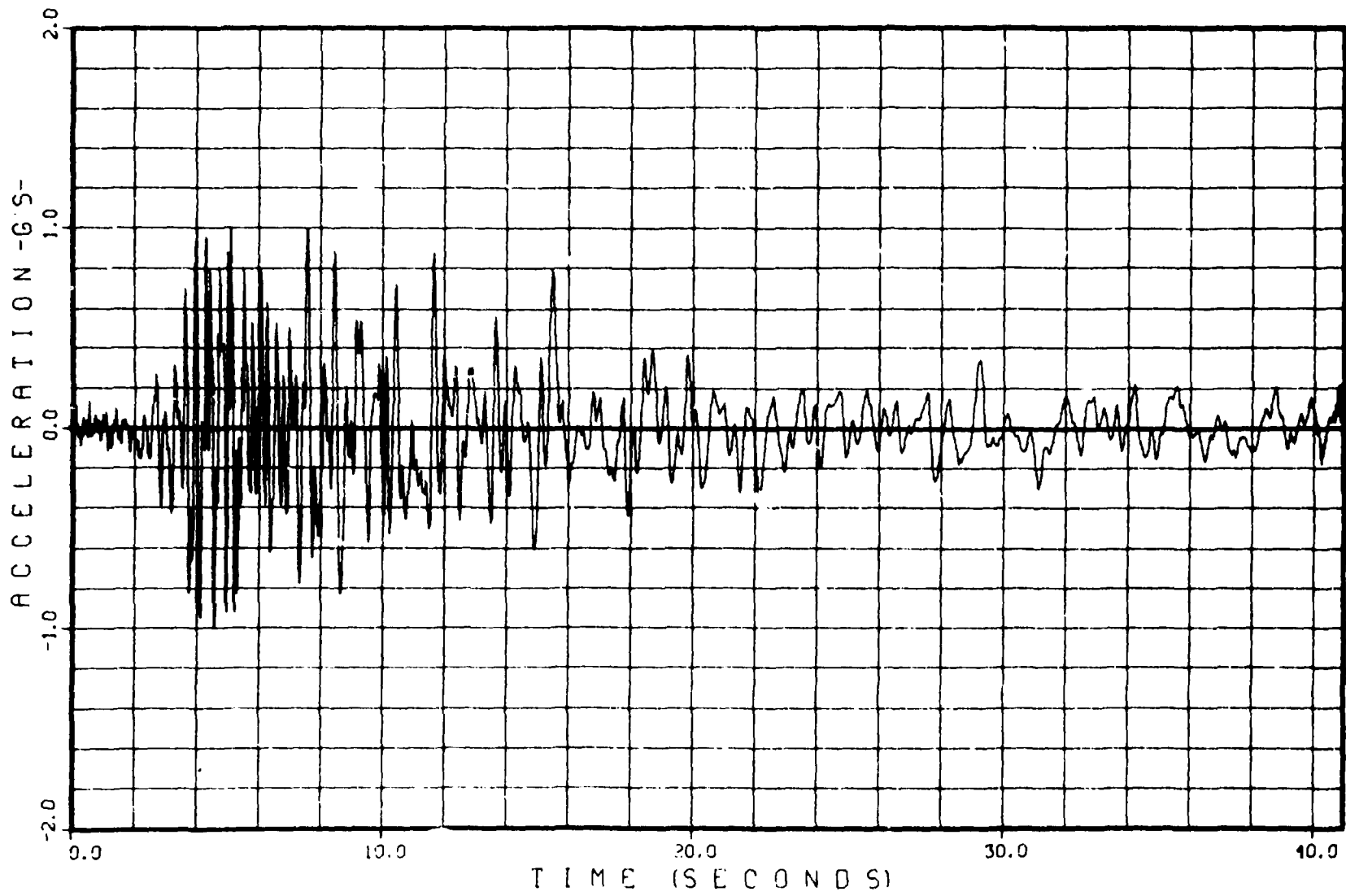


Fig. 10. GATH.10 Accelerogram.

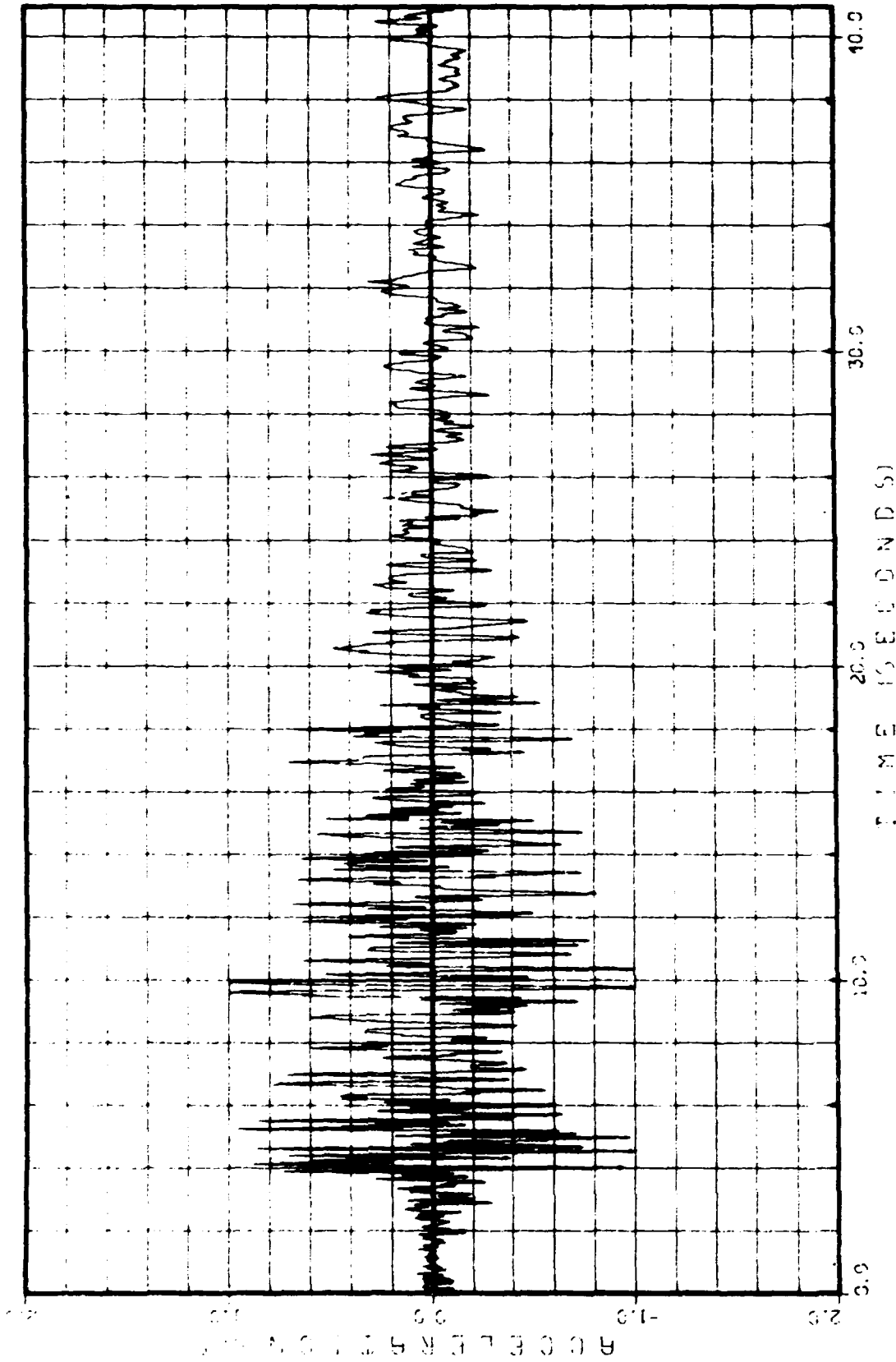


Fig. 11. GATH.IE Accelerogram.

FREQUENCY SPECTRUM

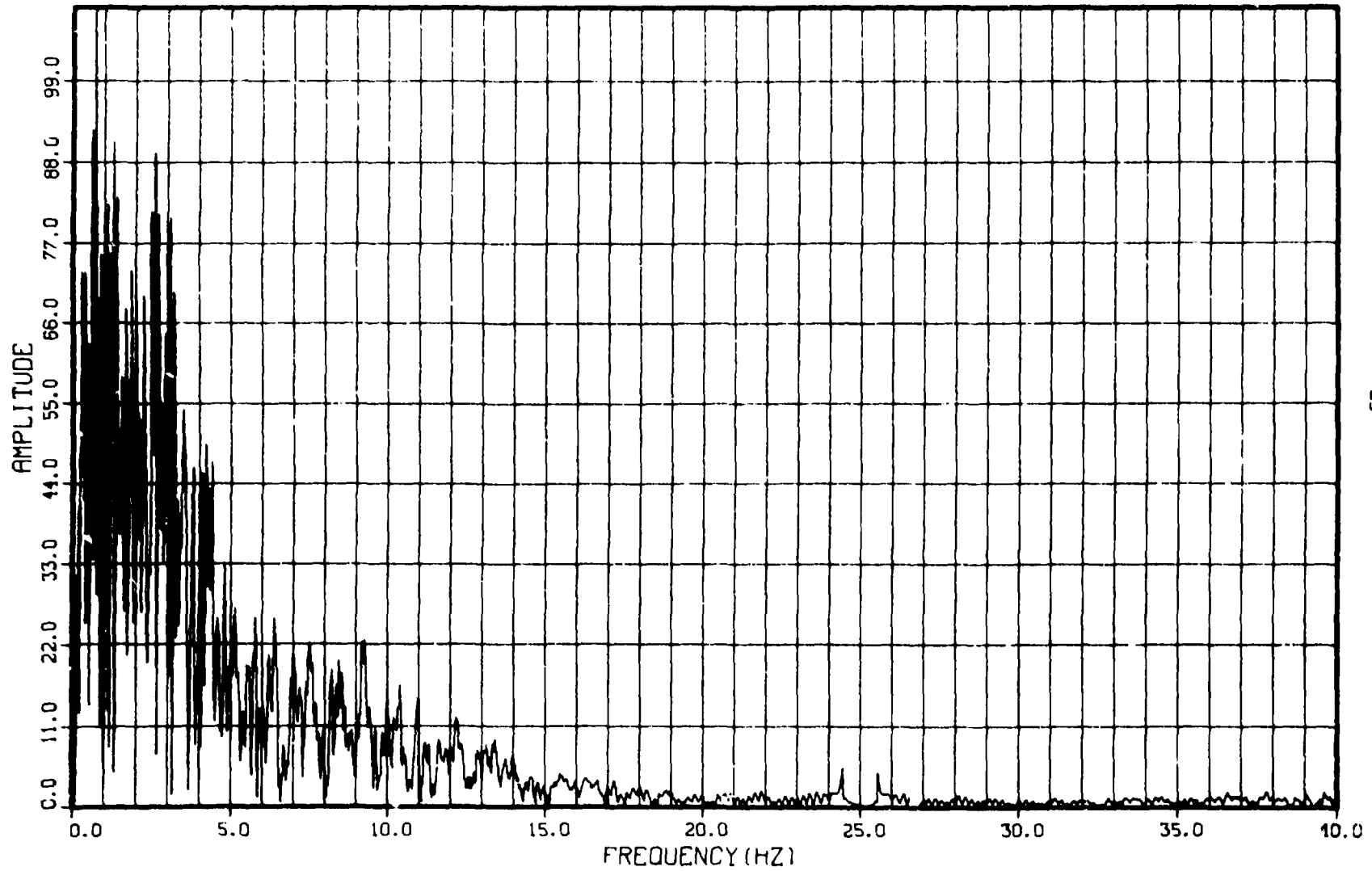


Fig. 12. Amplitude Frequency Spectra - GATH.02.

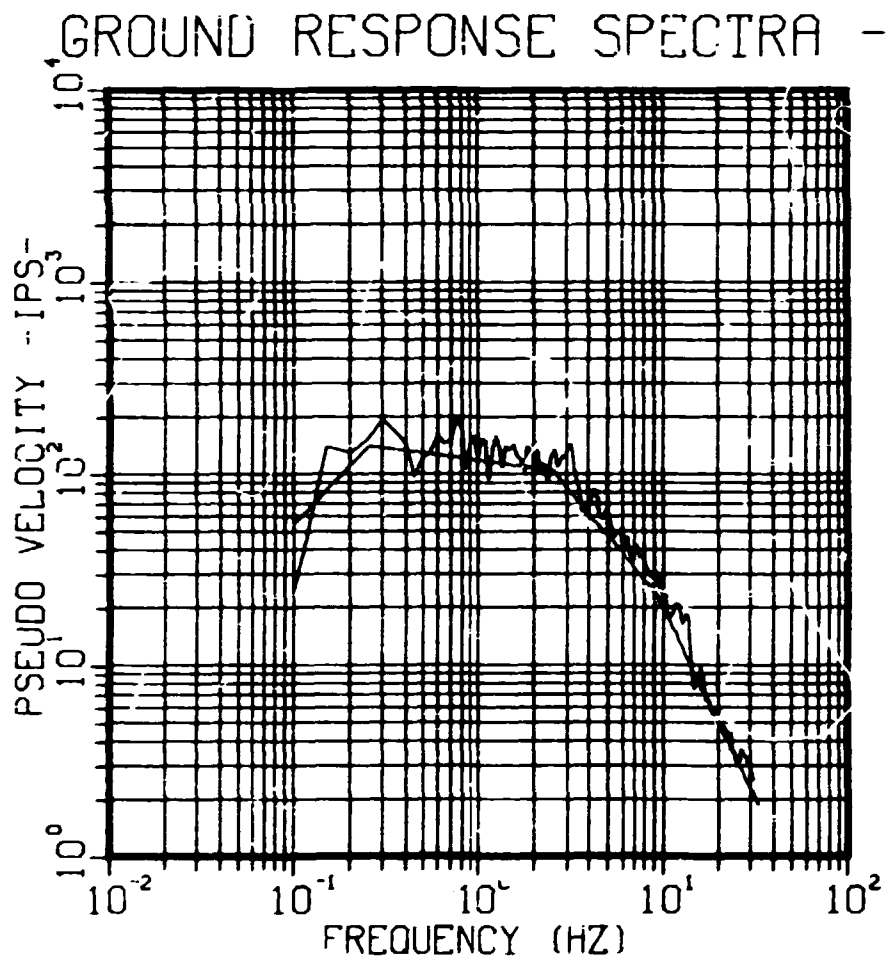


Fig. 13. PSV Response Spectra - GATH.02.

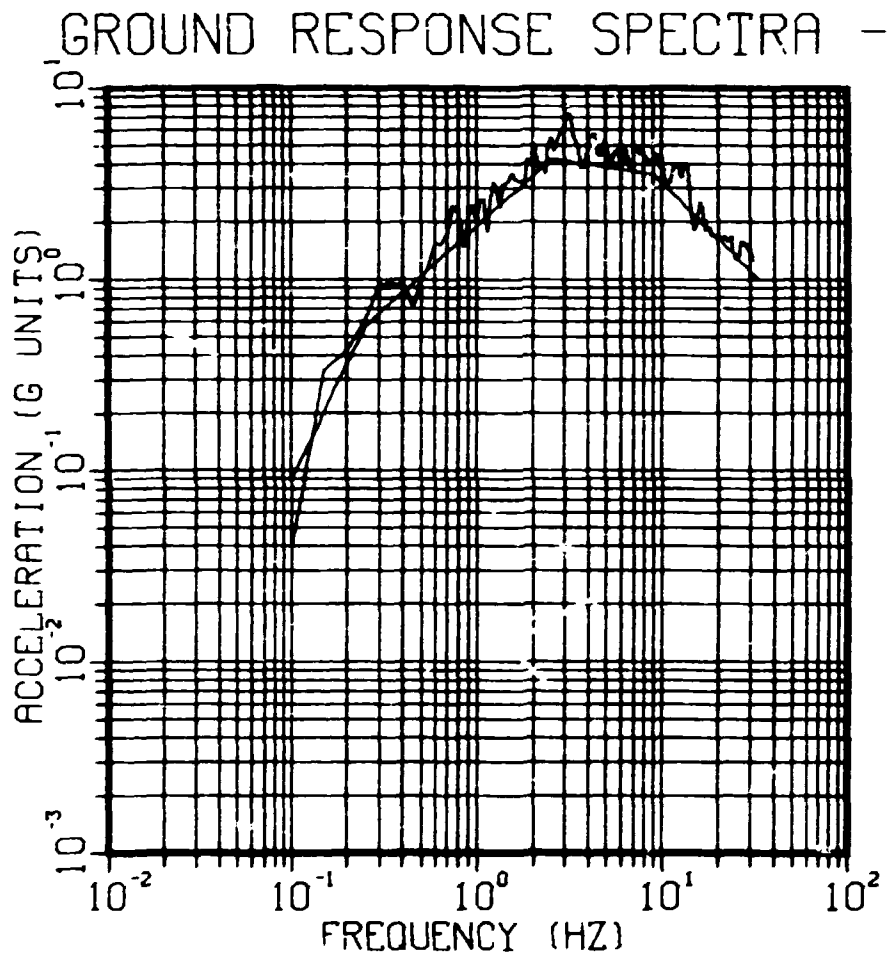


Fig. 14. Acceleration Response Spectra - GATH.02.

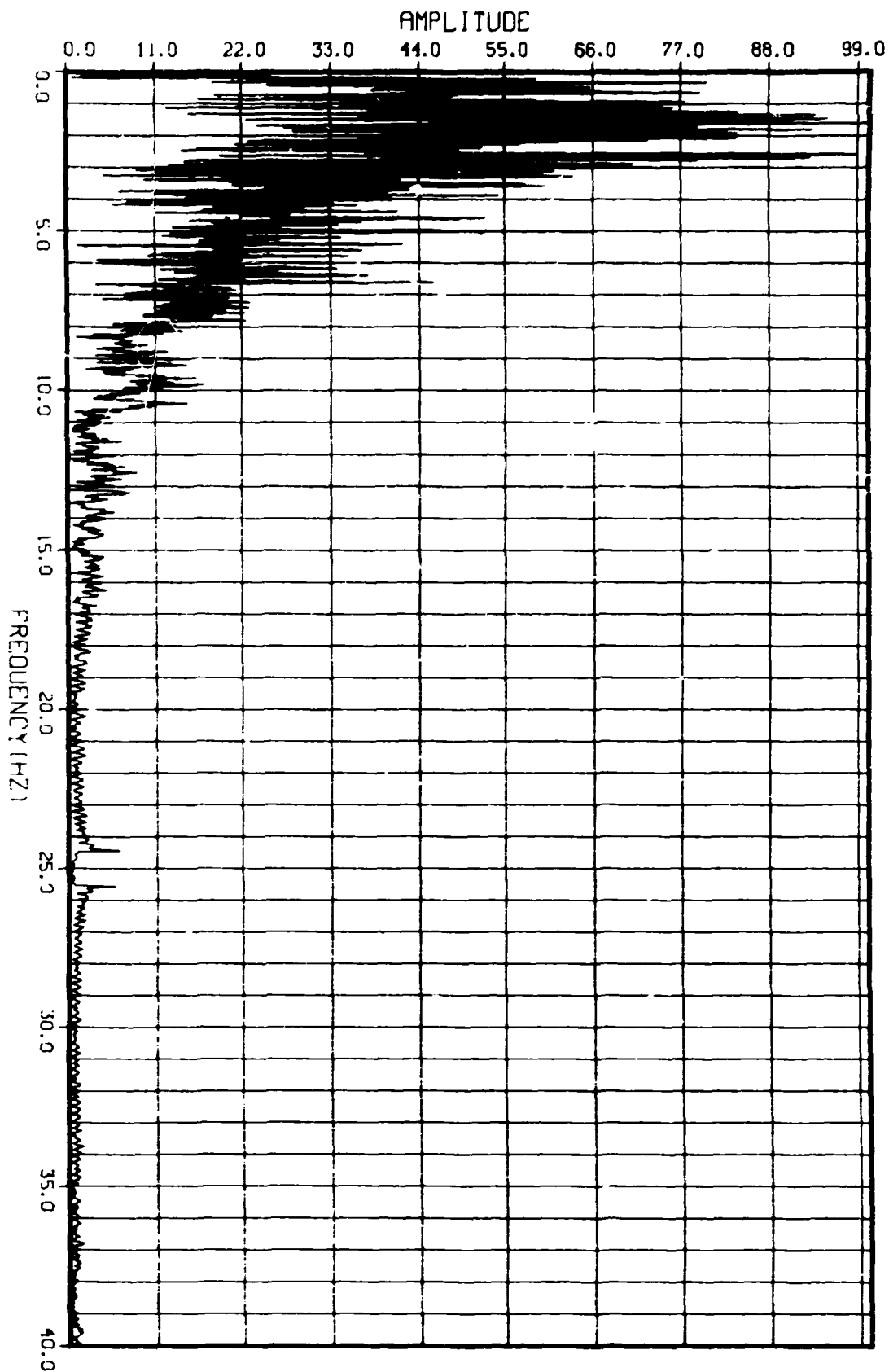


FIG. 15. Amplitude Frequency Spectra - GATH.04.

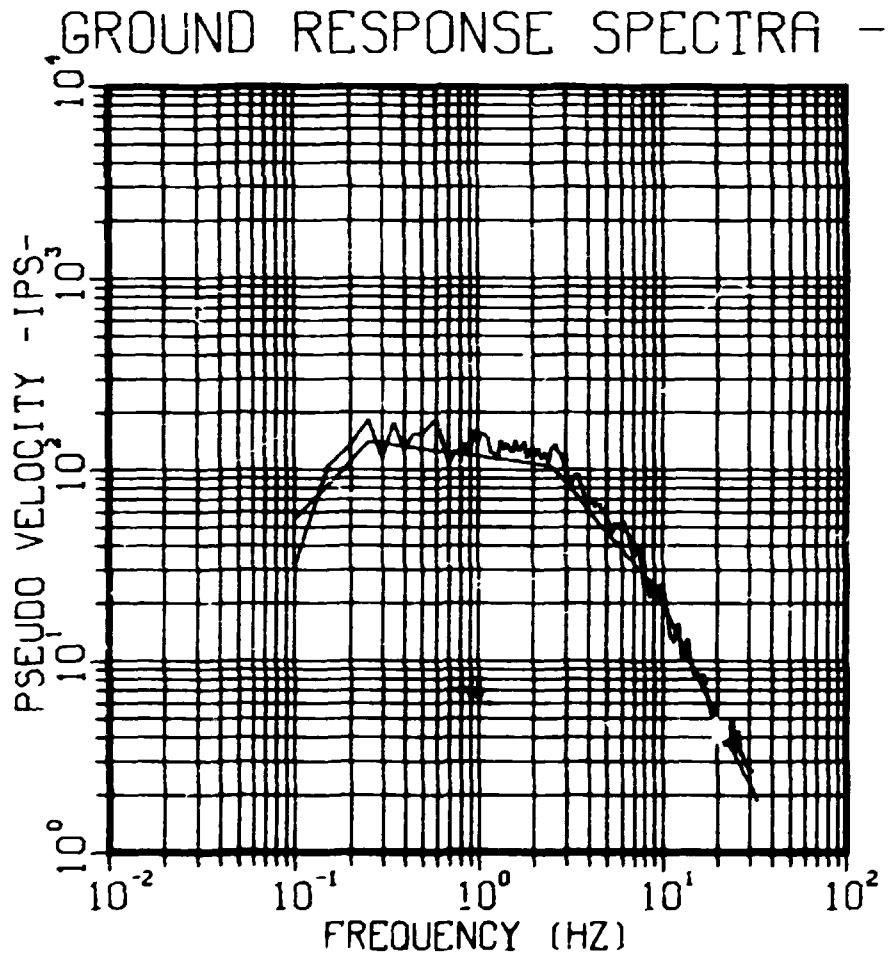


Fig. 16. PSV Response Spectra - GATH.04.

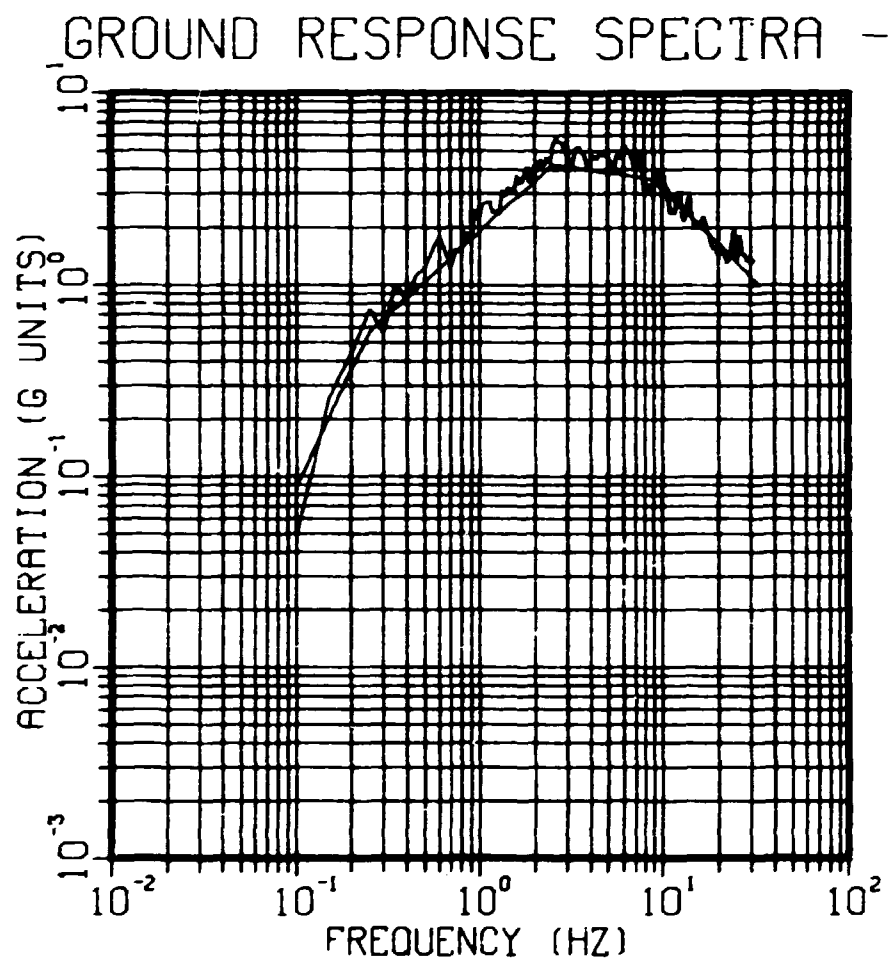


Fig. 17. Acceleration Response Spectra - GATH.04.

FREQUENCY SPECTRUM

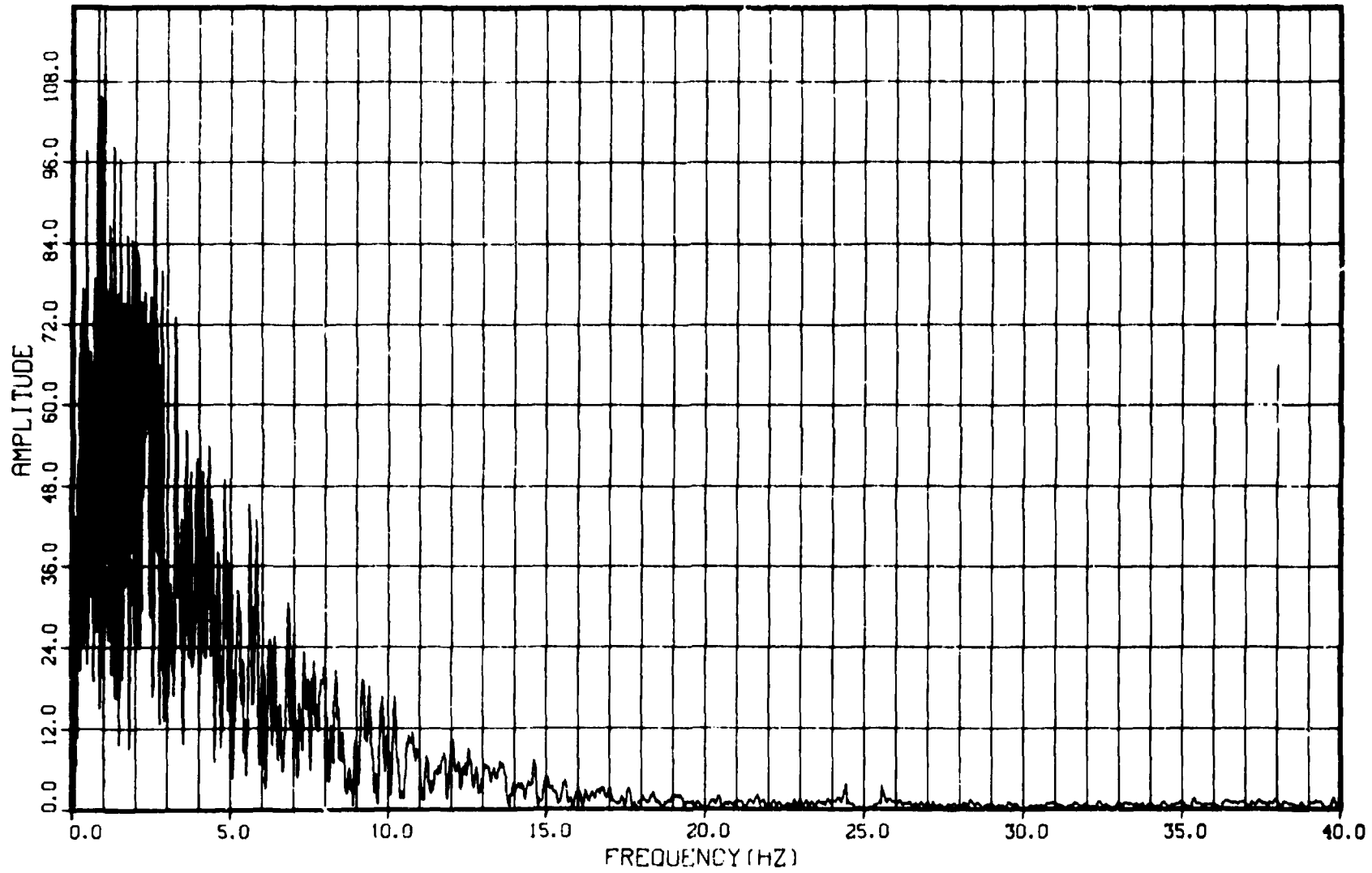


Fig. 18. Amplitude Frequency Spectra - GATH.09.

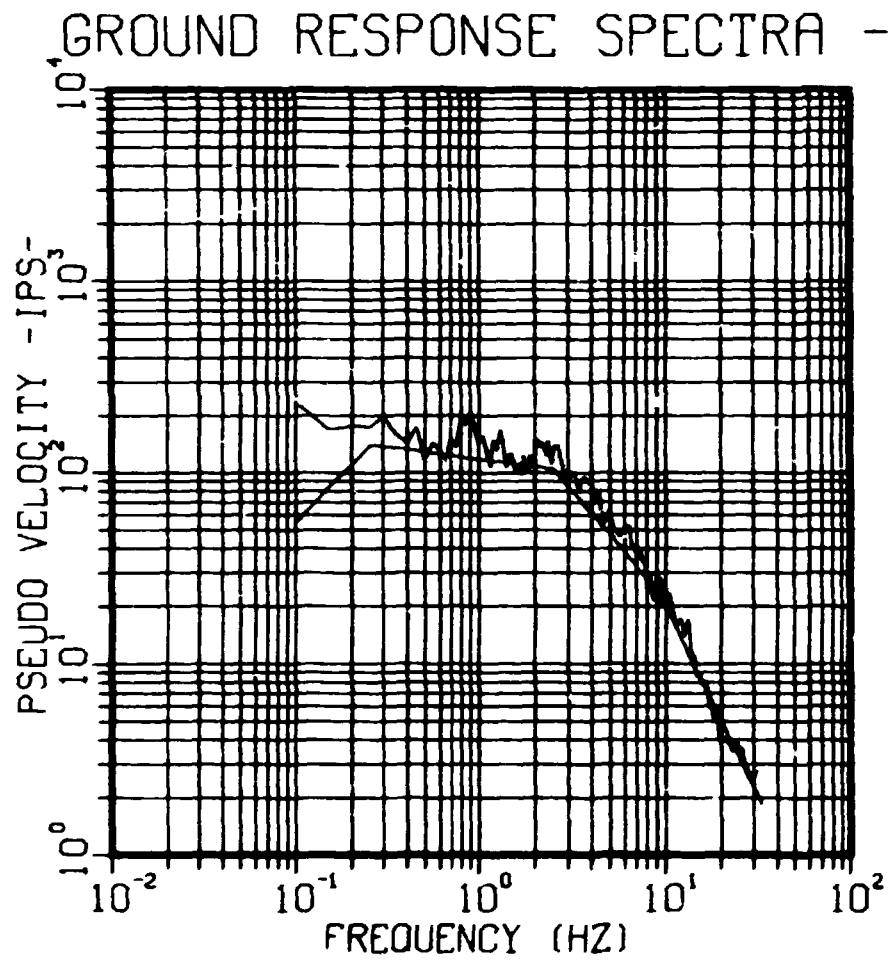


Fig. 19. PSV Response Spectra - GATH.09.

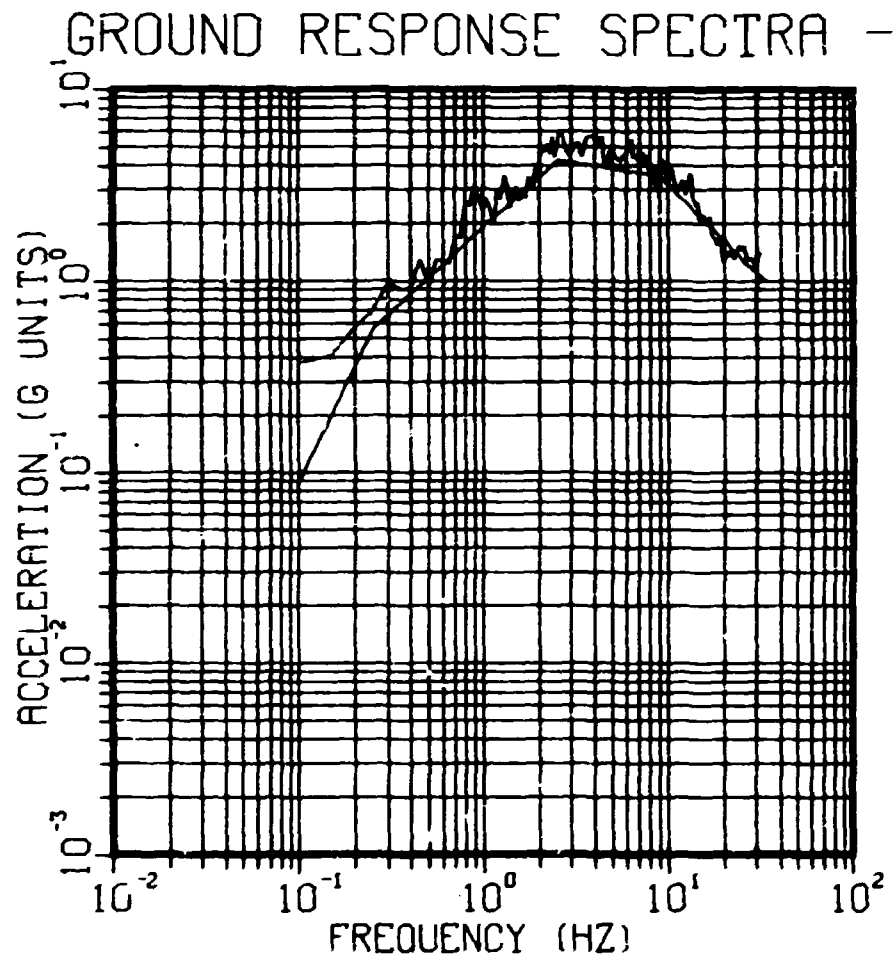
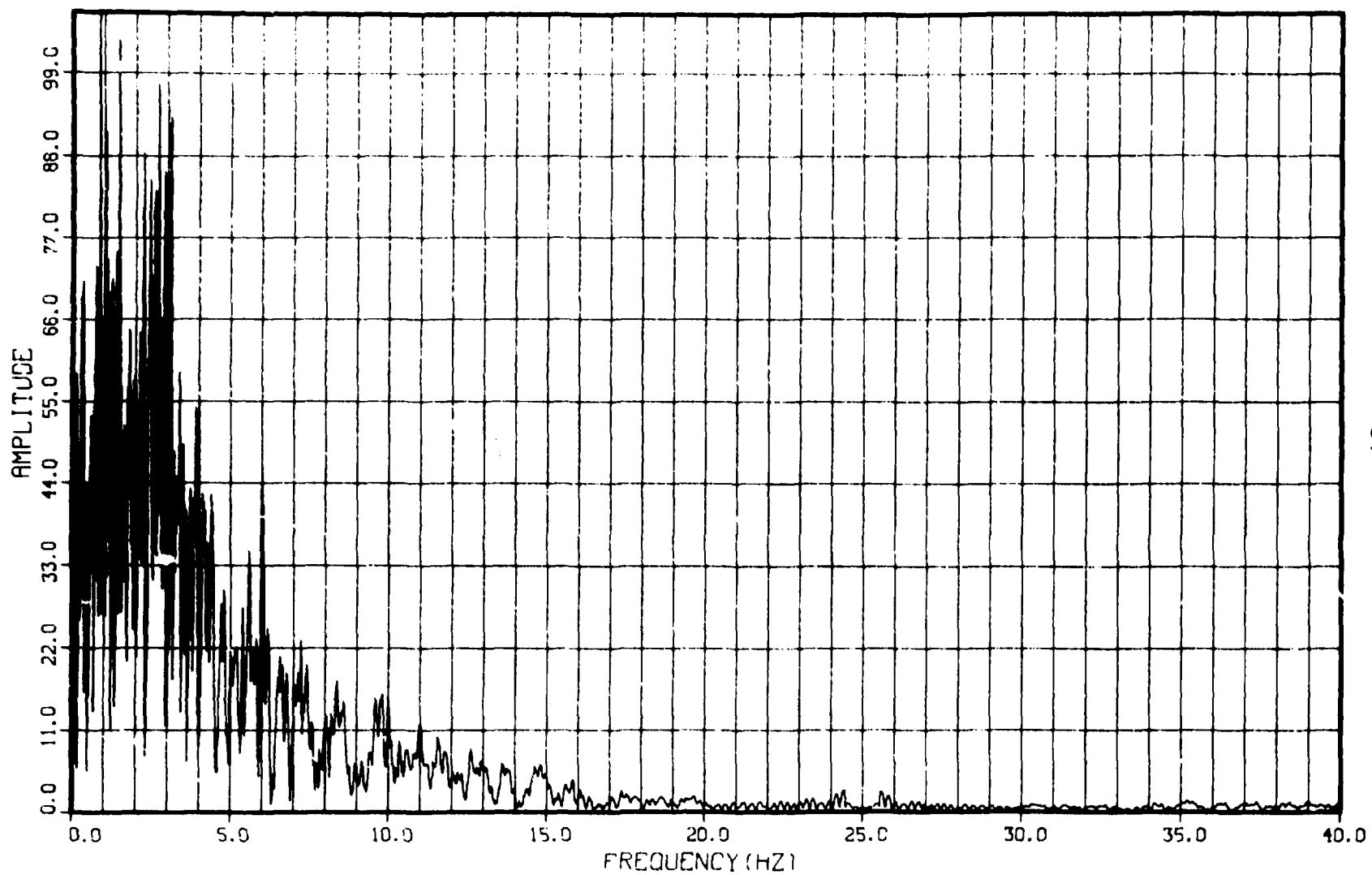


Fig. 20. Acceleration Response Spectra - GATH.09.

FREQUENCY SPECTRUM



34

Fig. 21. Amplitude Frequency Spectra - GATH.10.

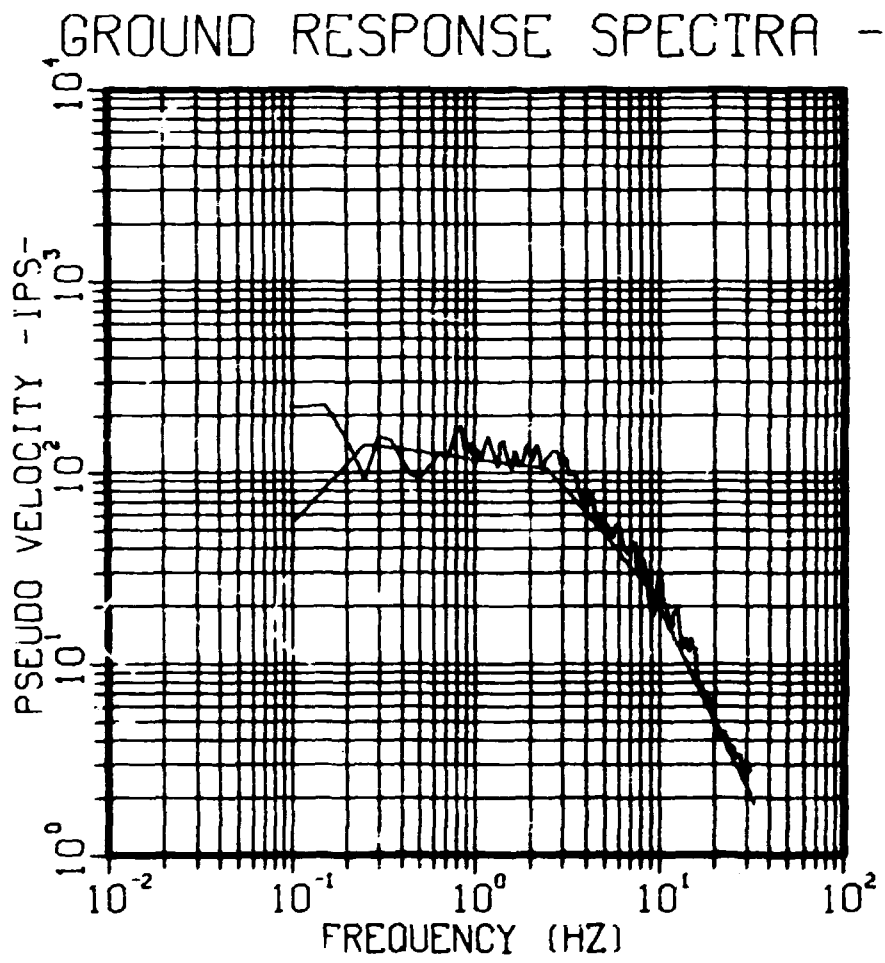


Fig. 22. PSV Response Spectra - GATH.10.

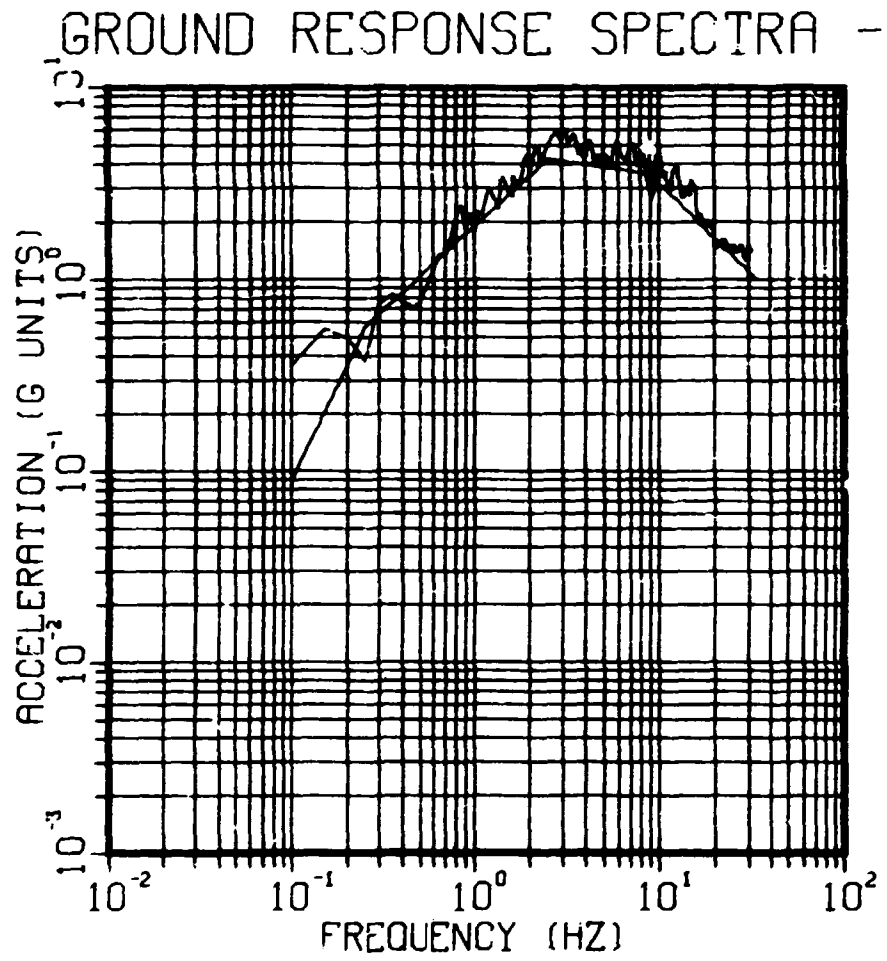


Fig. 23. Acceleration Response Spectra - GATH.10.

FREQUENCY SPECTRUM

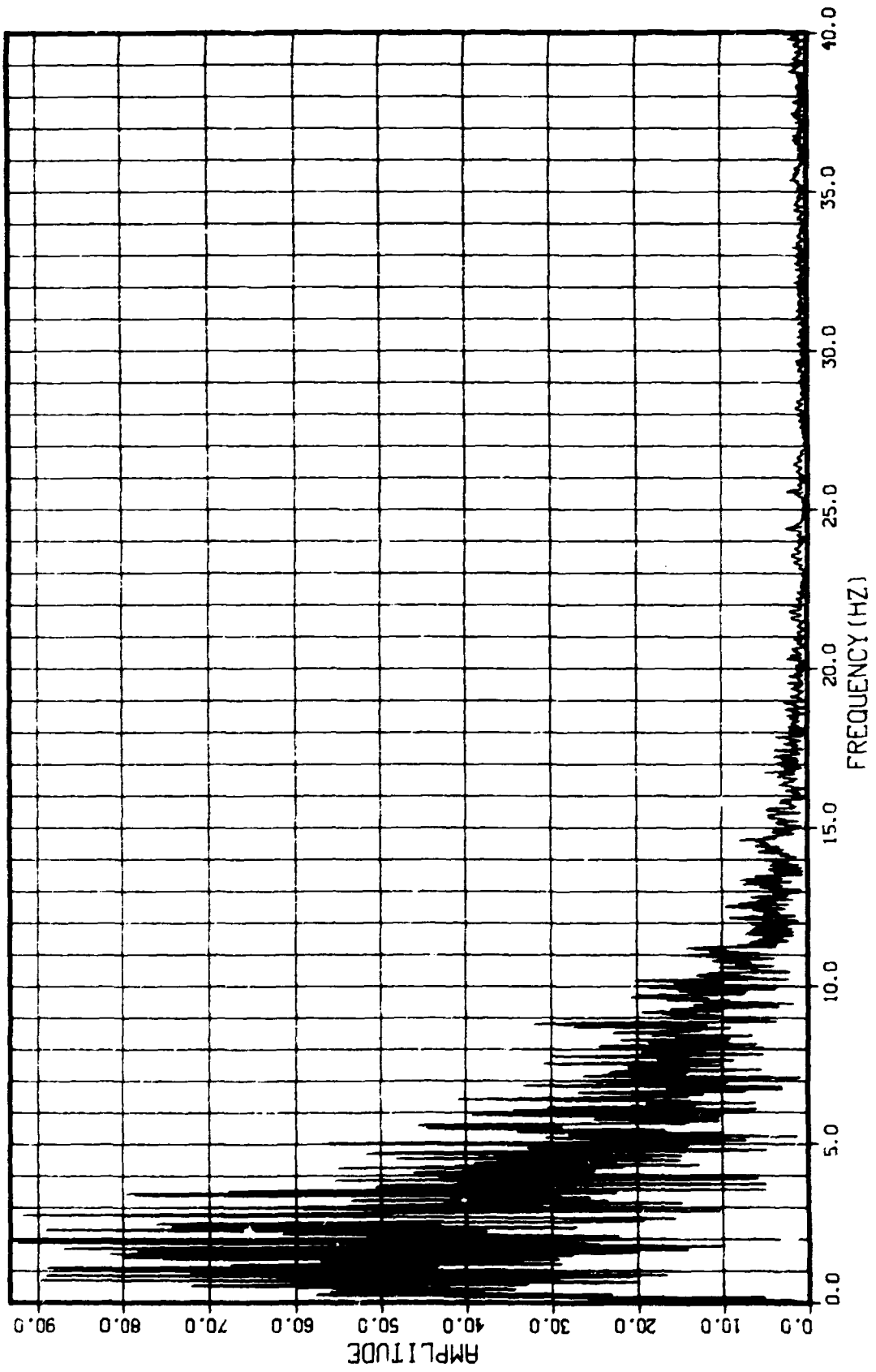


Fig. 24. Amplitude Frequency Spectra - GATH.15.

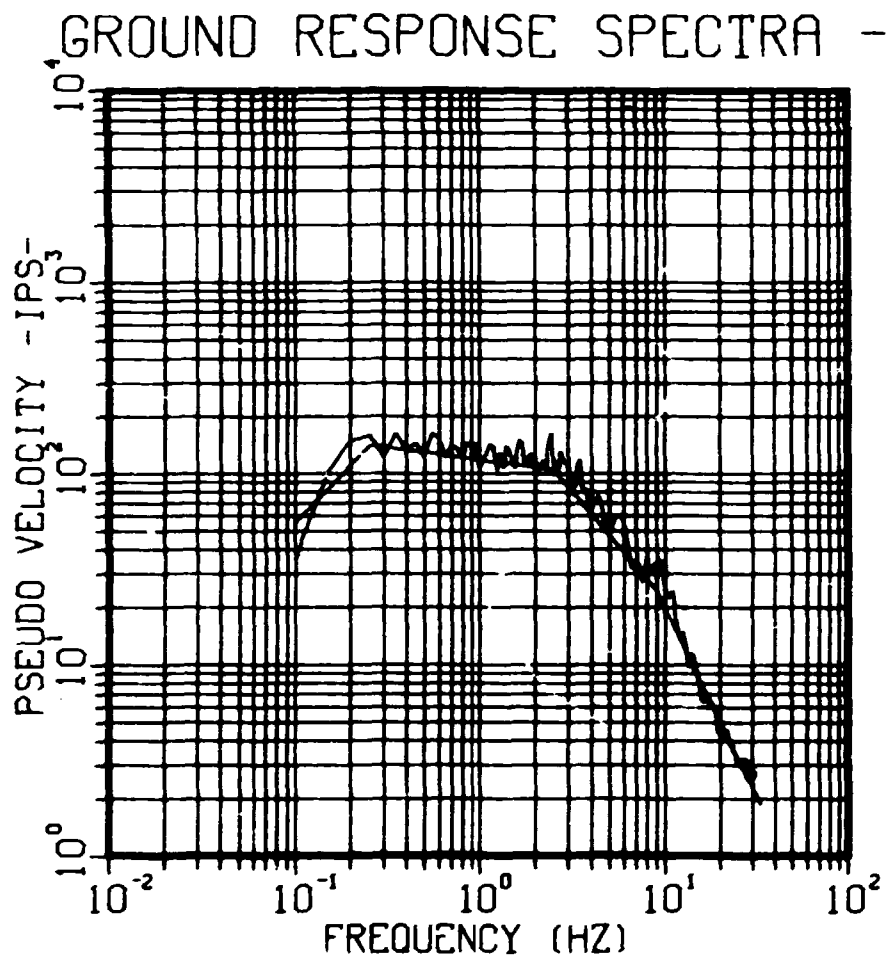


Fig. 25. PSV Response Spectra - GATH.15.

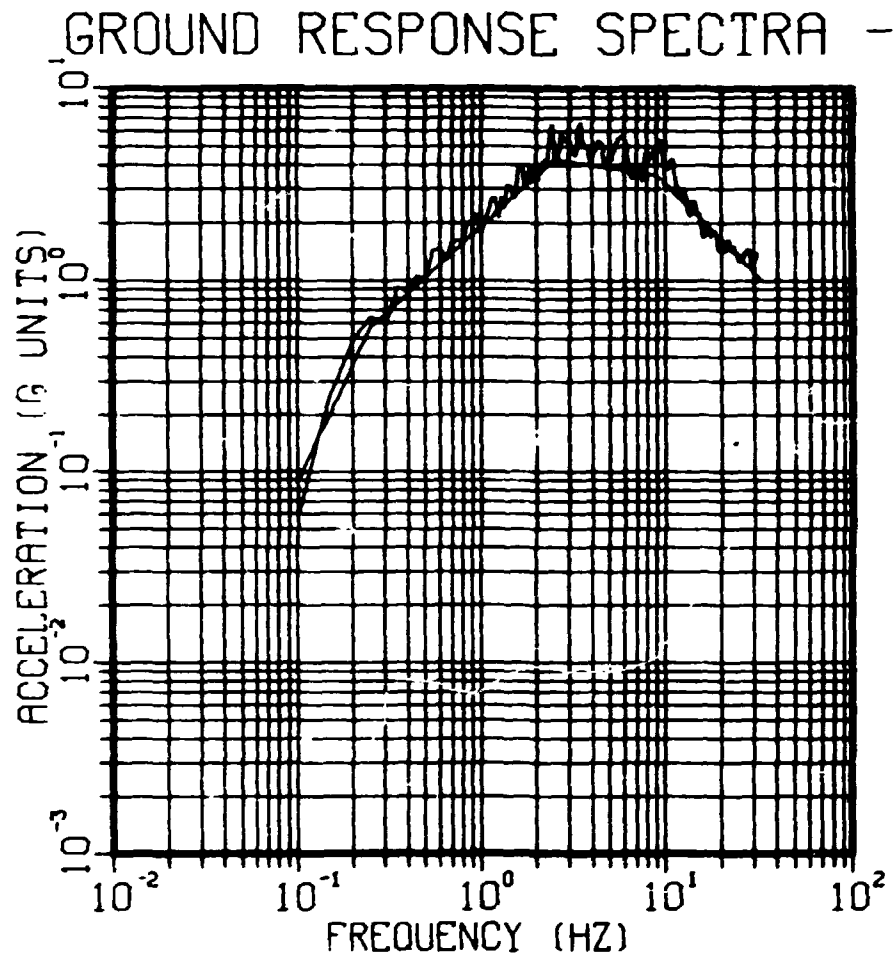


Fig. 26. Acceleration Response Spectra - GATH.15.

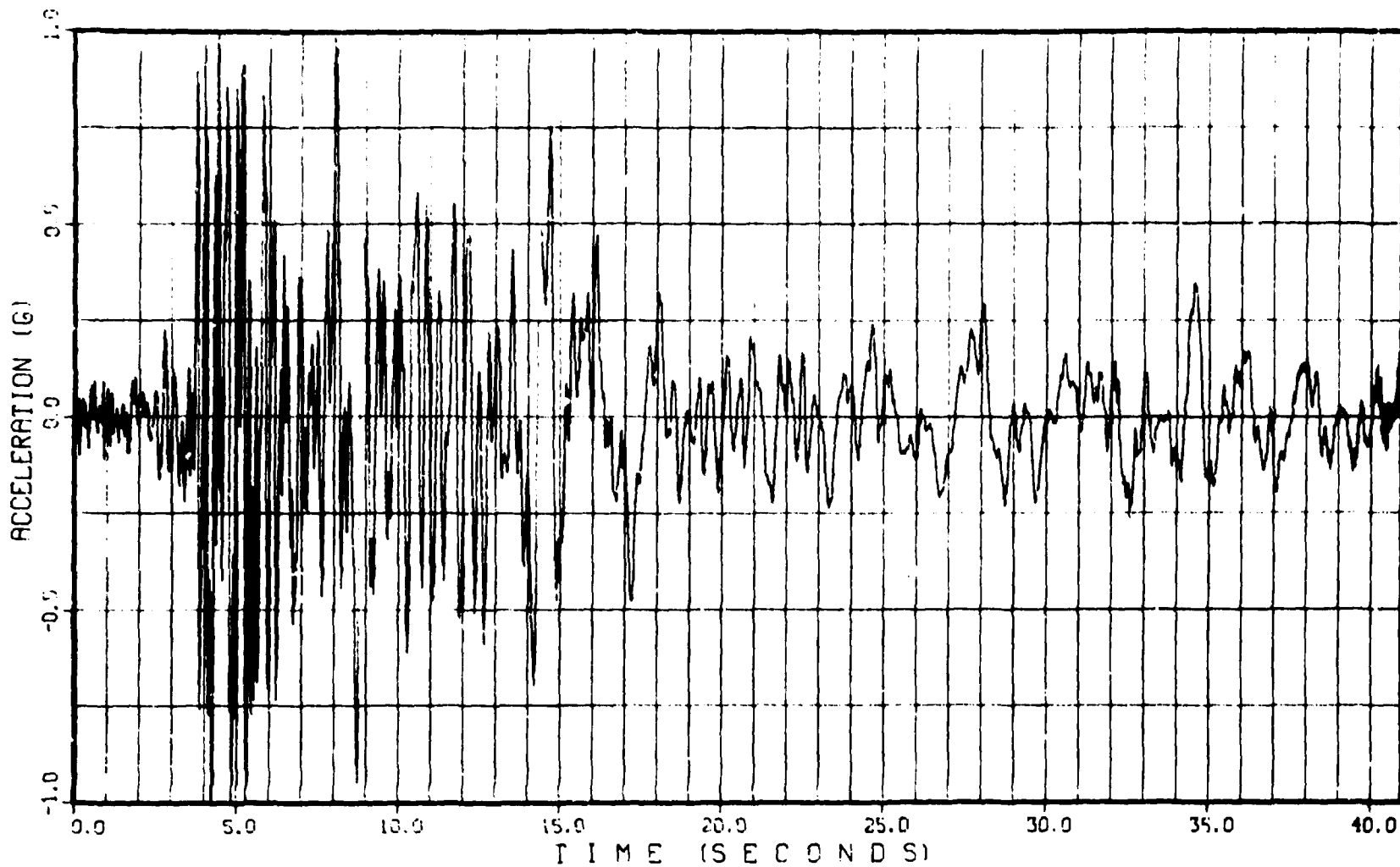


Fig. 27. GATH.02 - Acceleration.

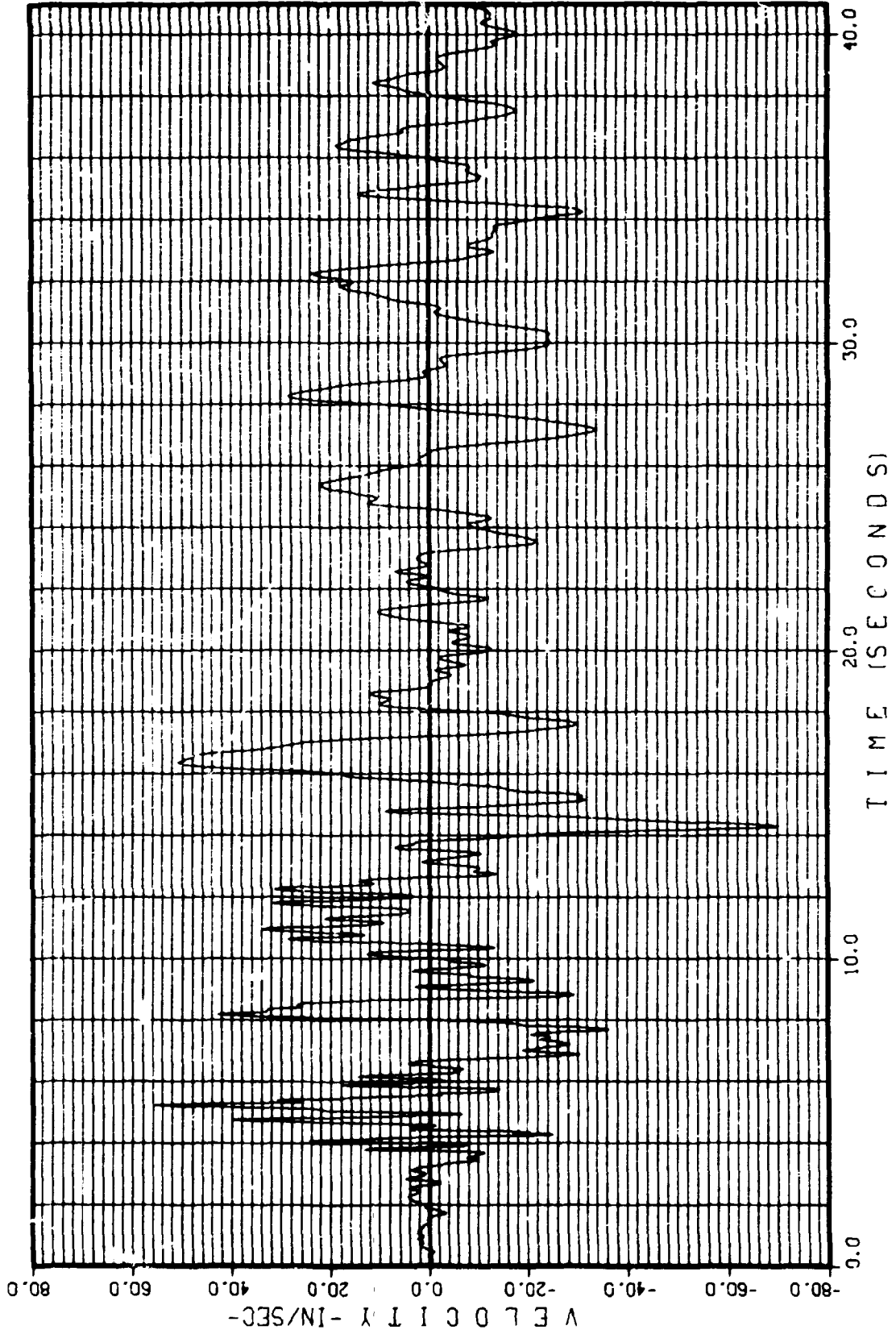


Fig. 28. GATH.02 - Velocity.

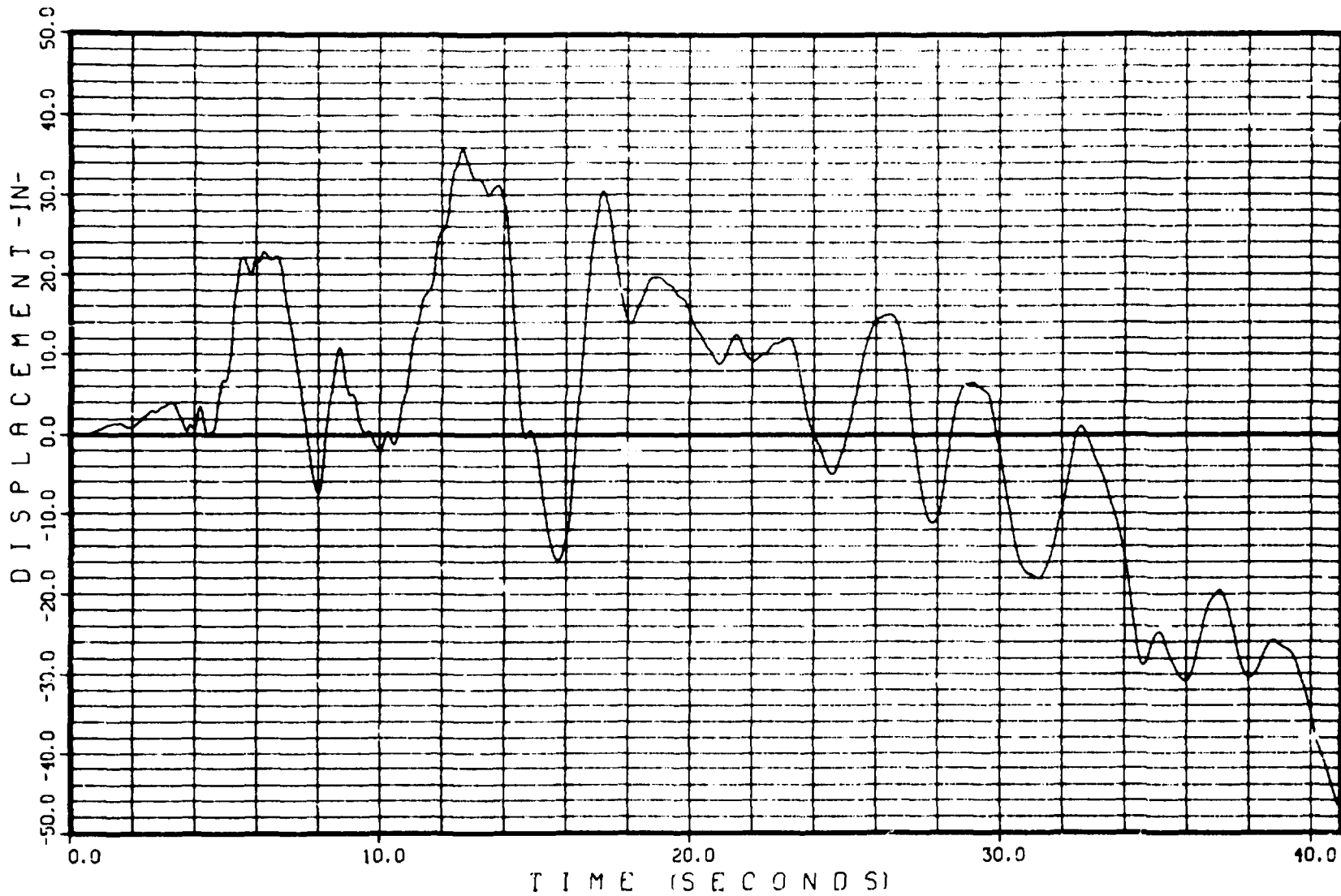


Fig. 29. GATH.02 - Displacement.

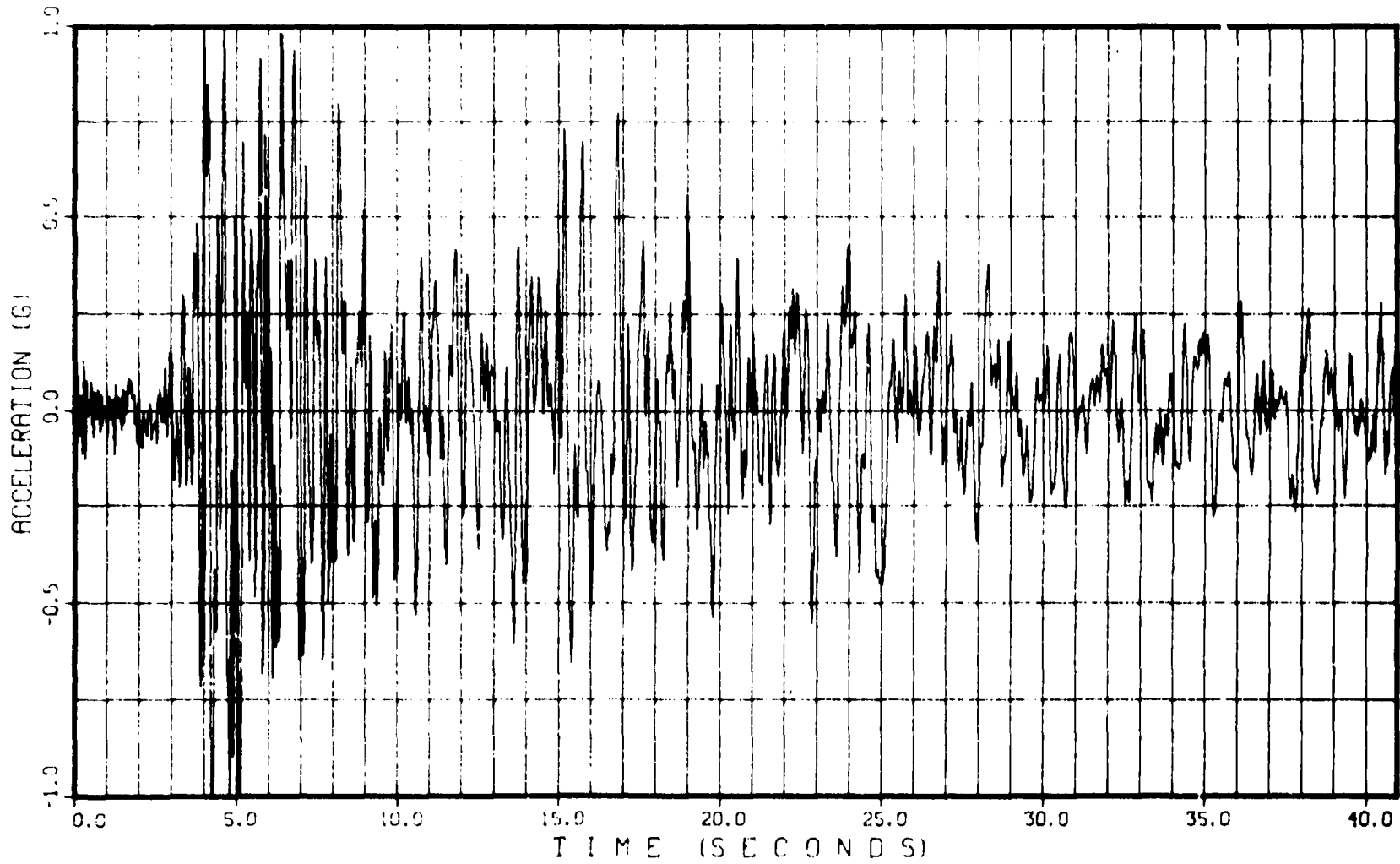


Fig. 30. GATH.04 - Acceleration.

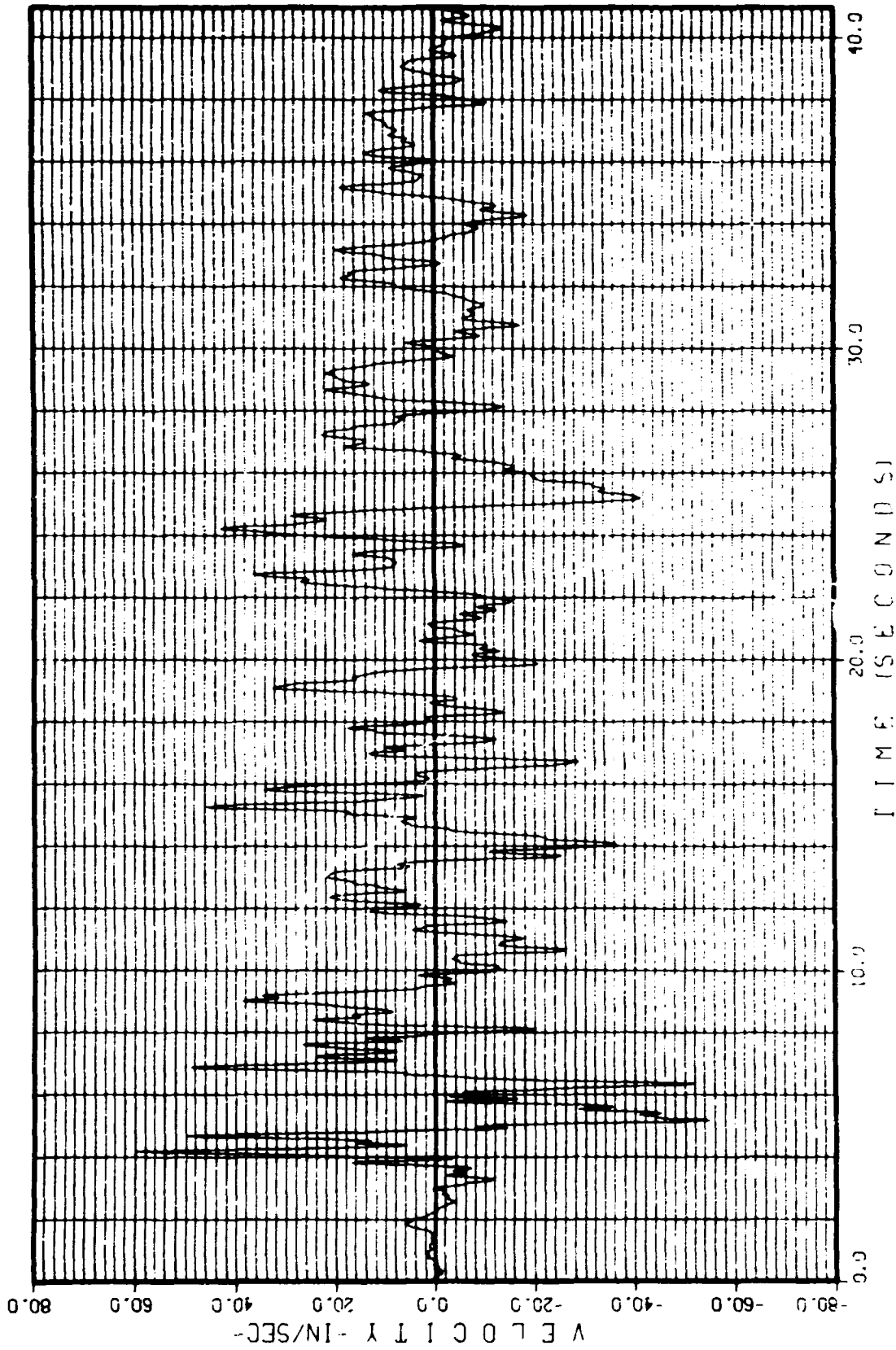


Fig. 31. GATH.04 - Velocity.

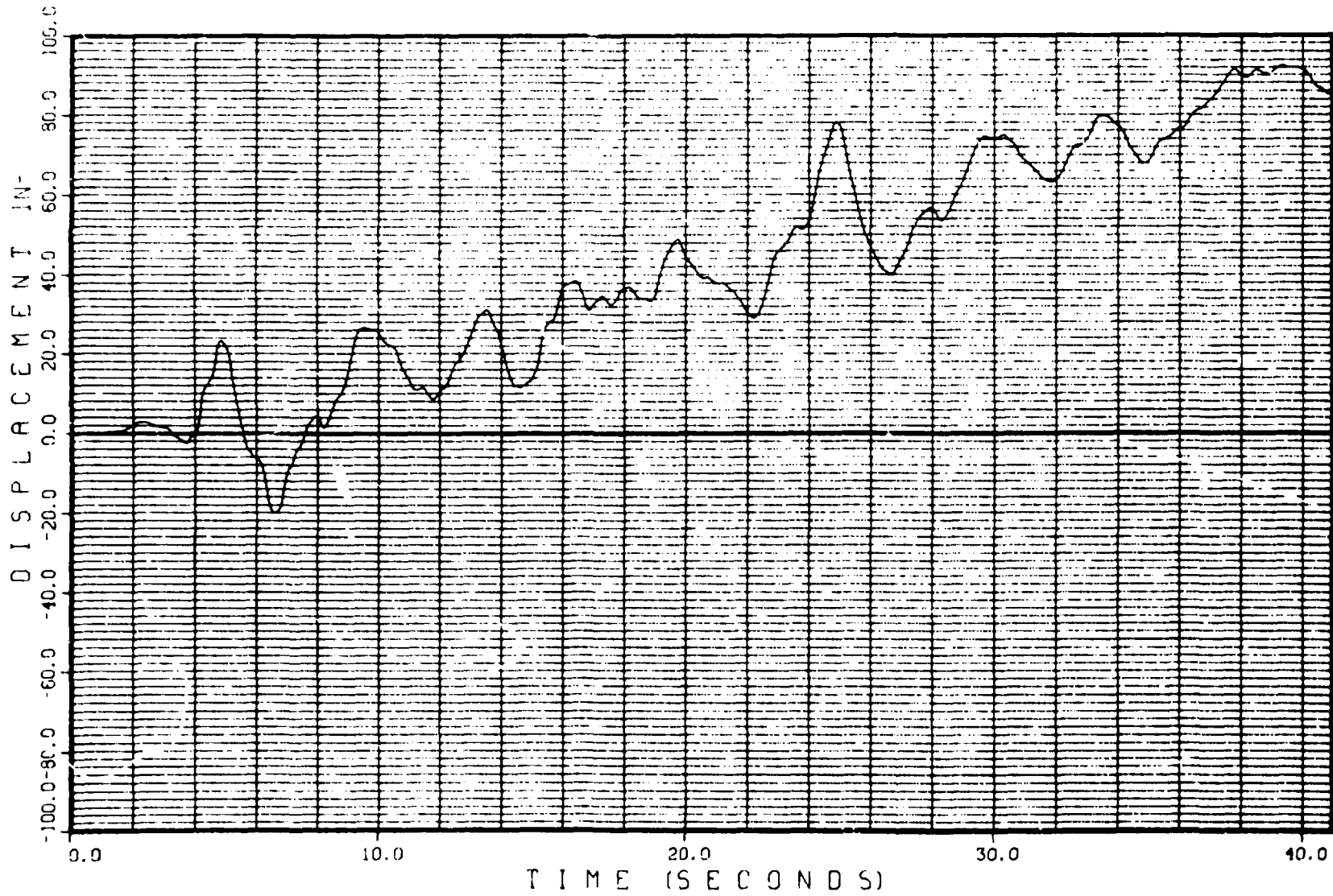
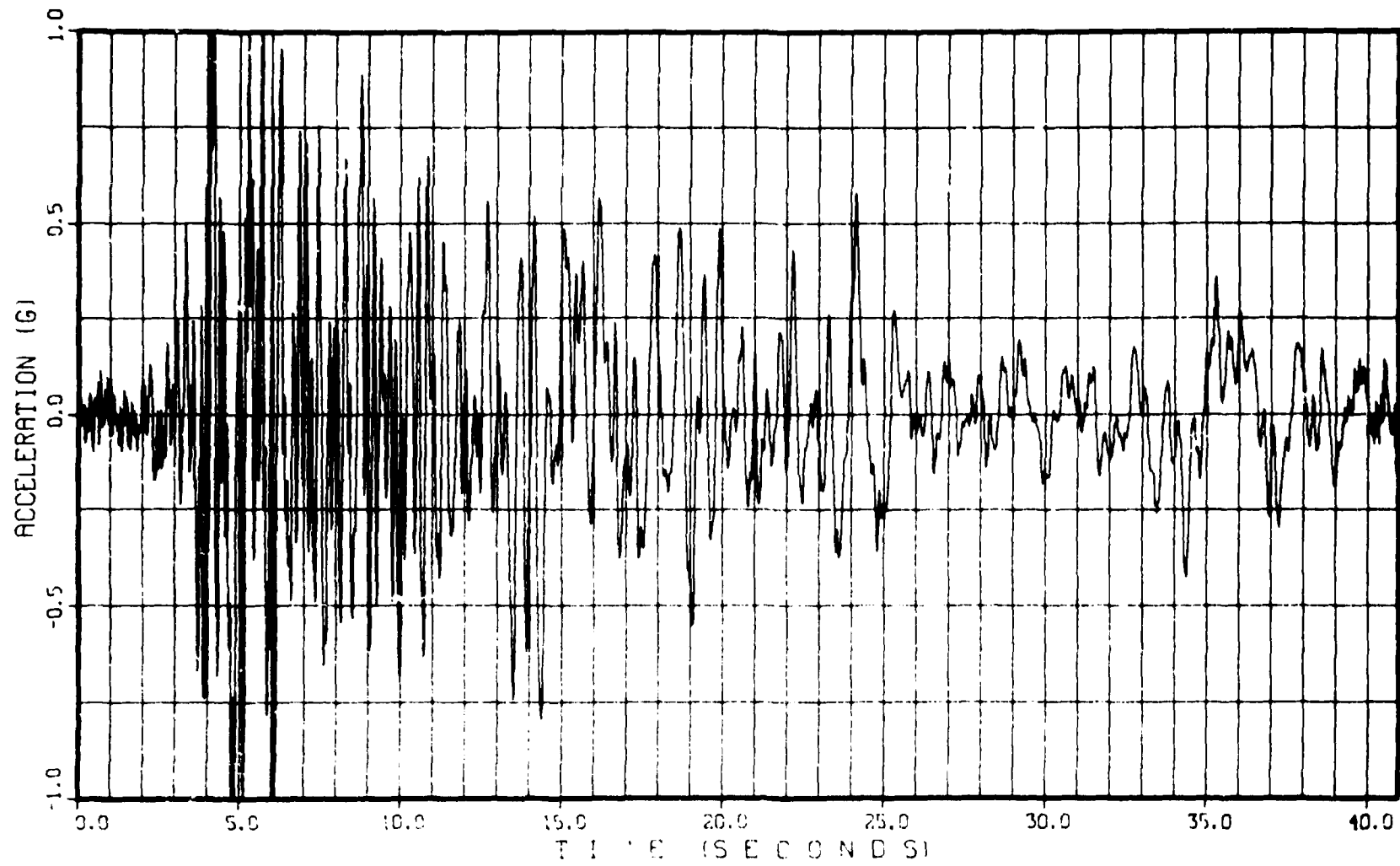


Fig. 32. GATH.04 - Displacement.



97

Fig. 33. GATH.09 - Velocity.

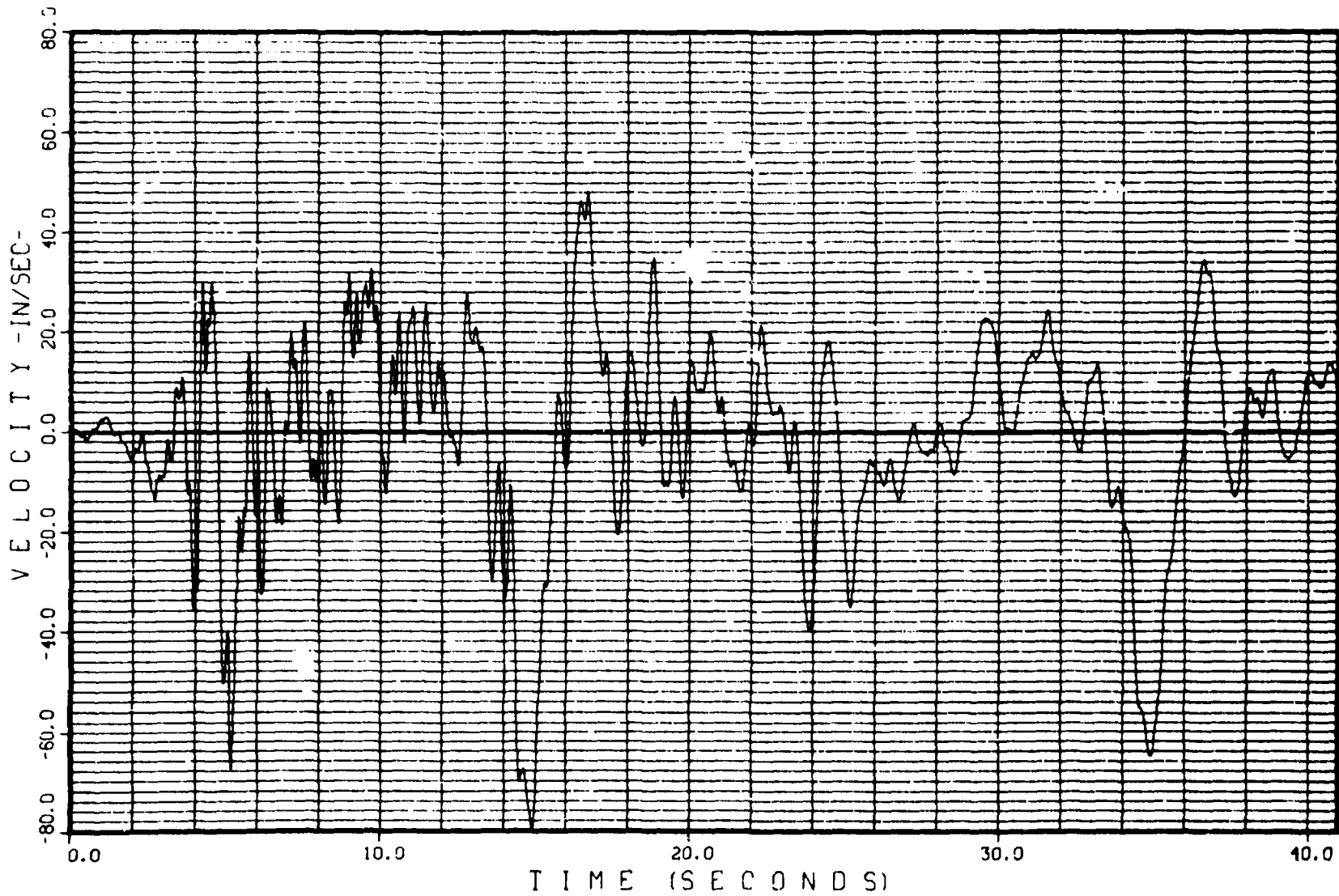


Fig. 34. GATH.09 - Velocity.

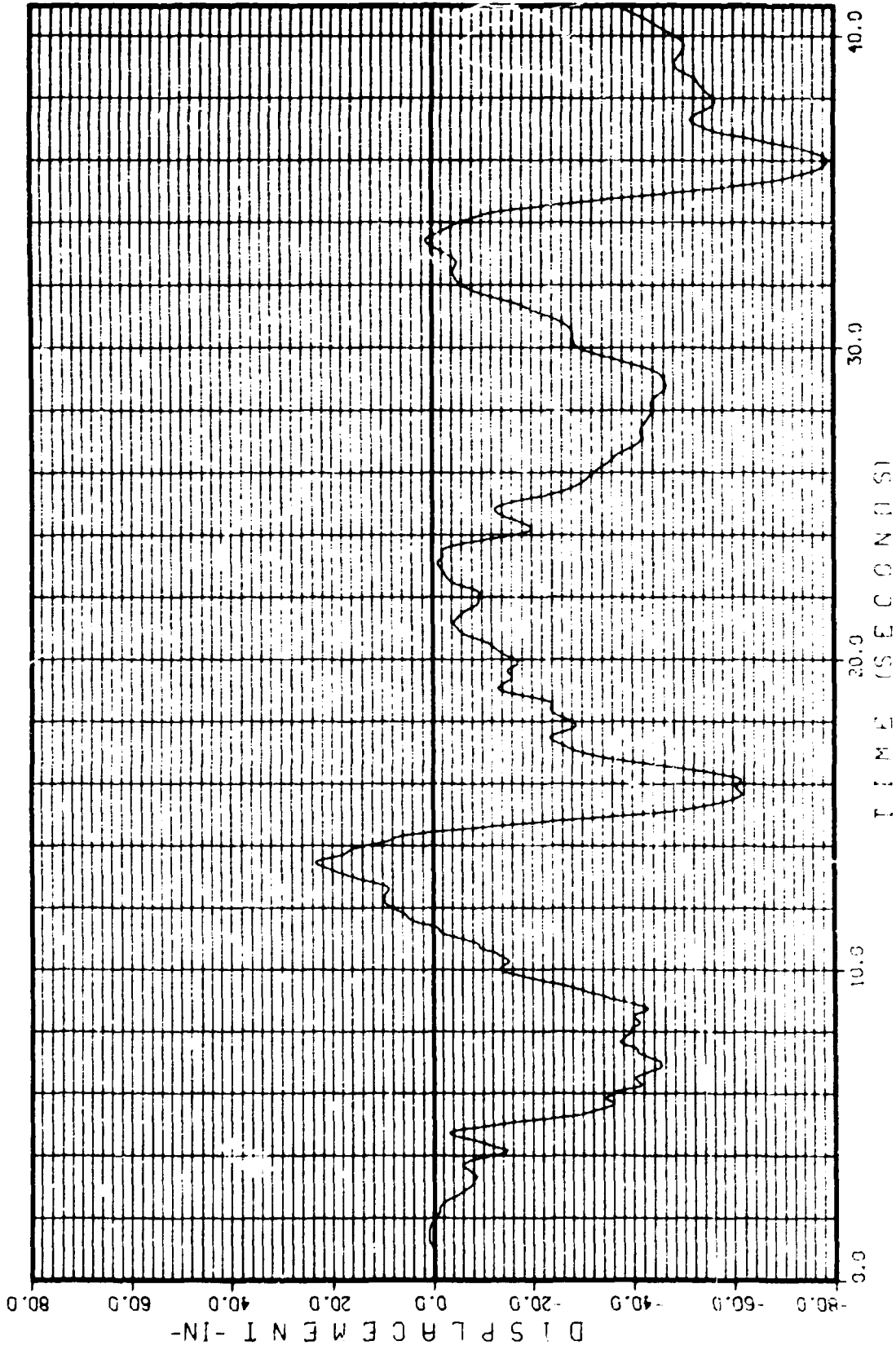


Fig. 35. GATH.09 - Displacement.

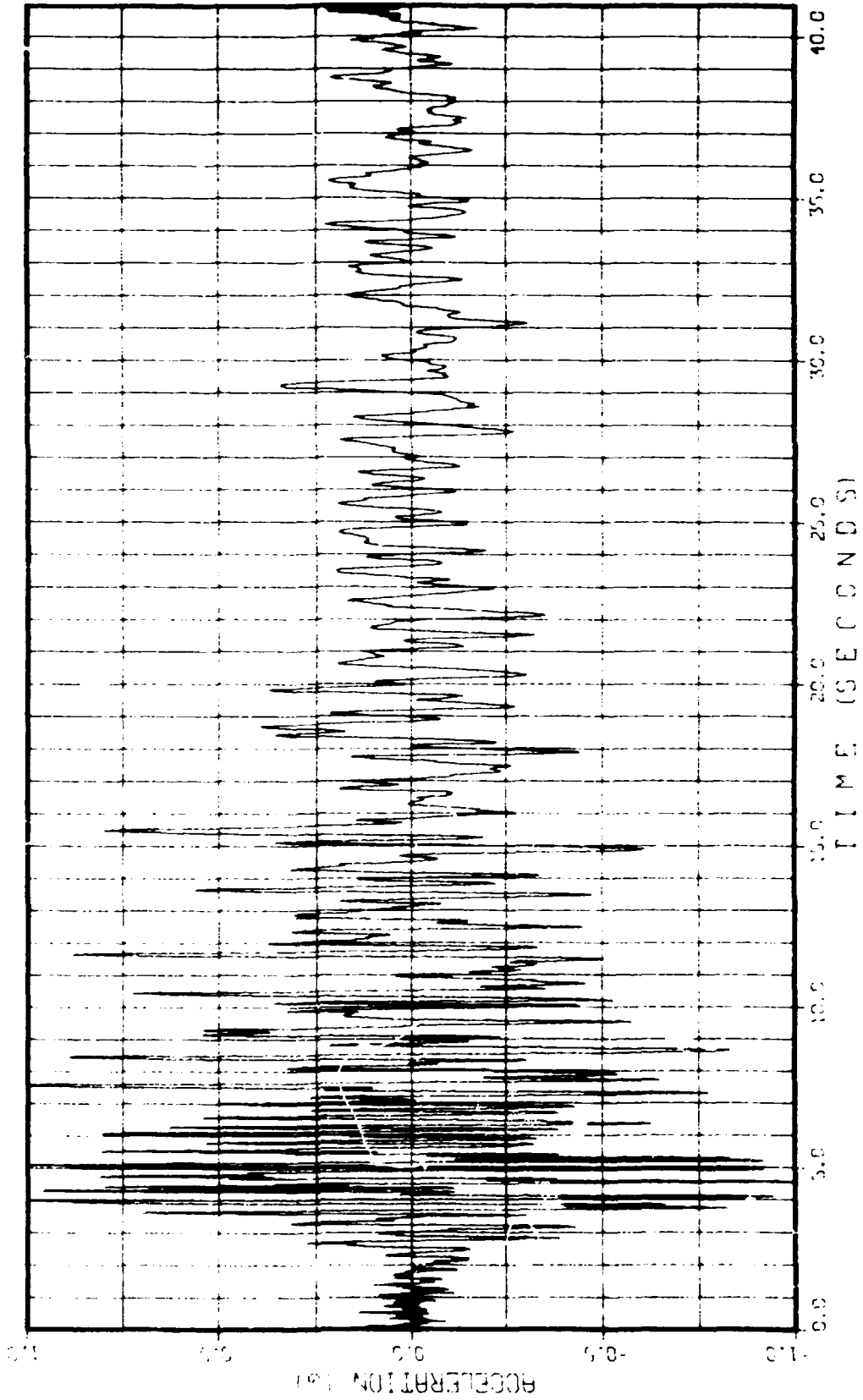


Fig. 36. GATH.10 - Acceleration.

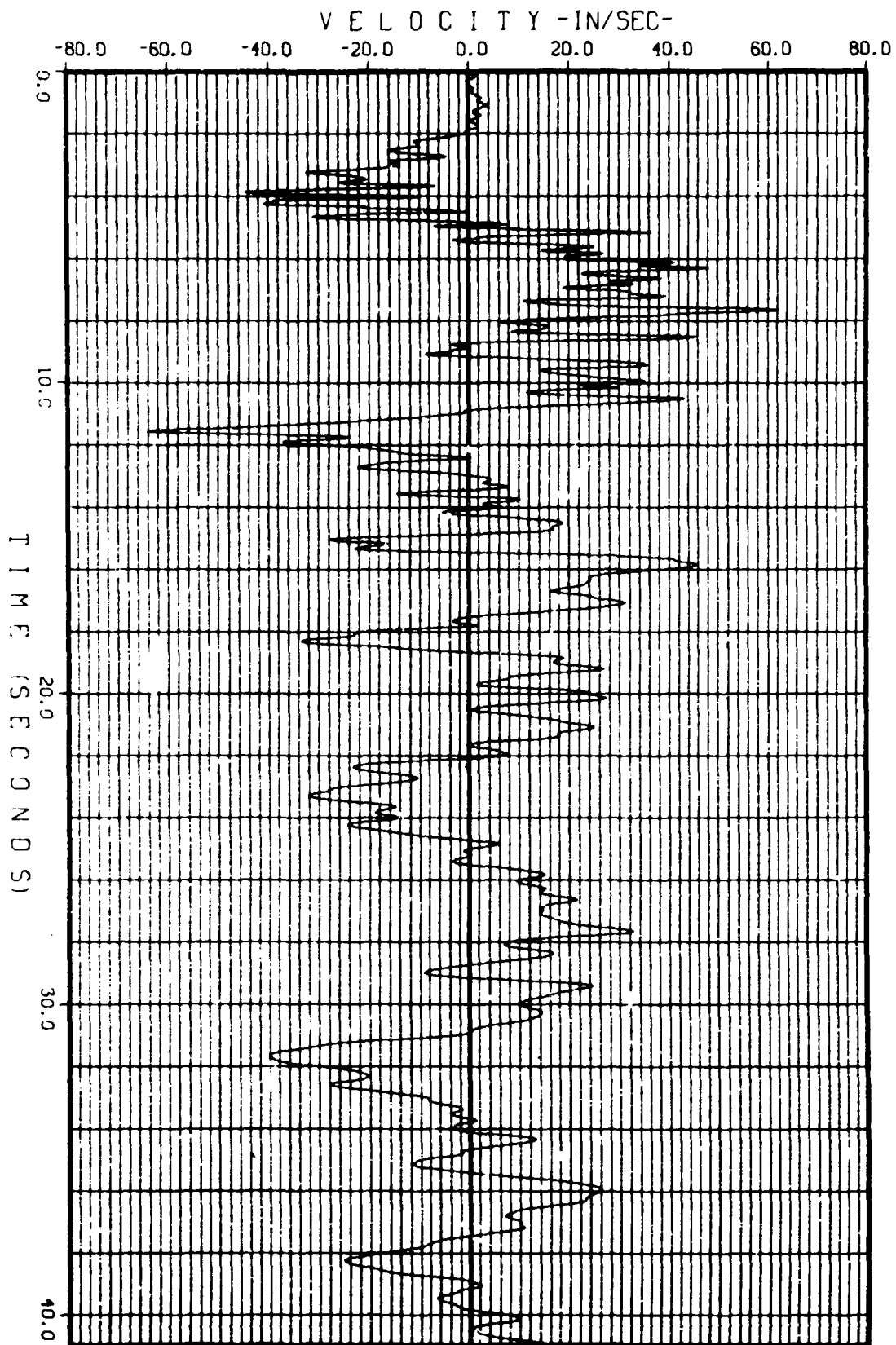


Fig. 37. GATH.10 - Velocity.

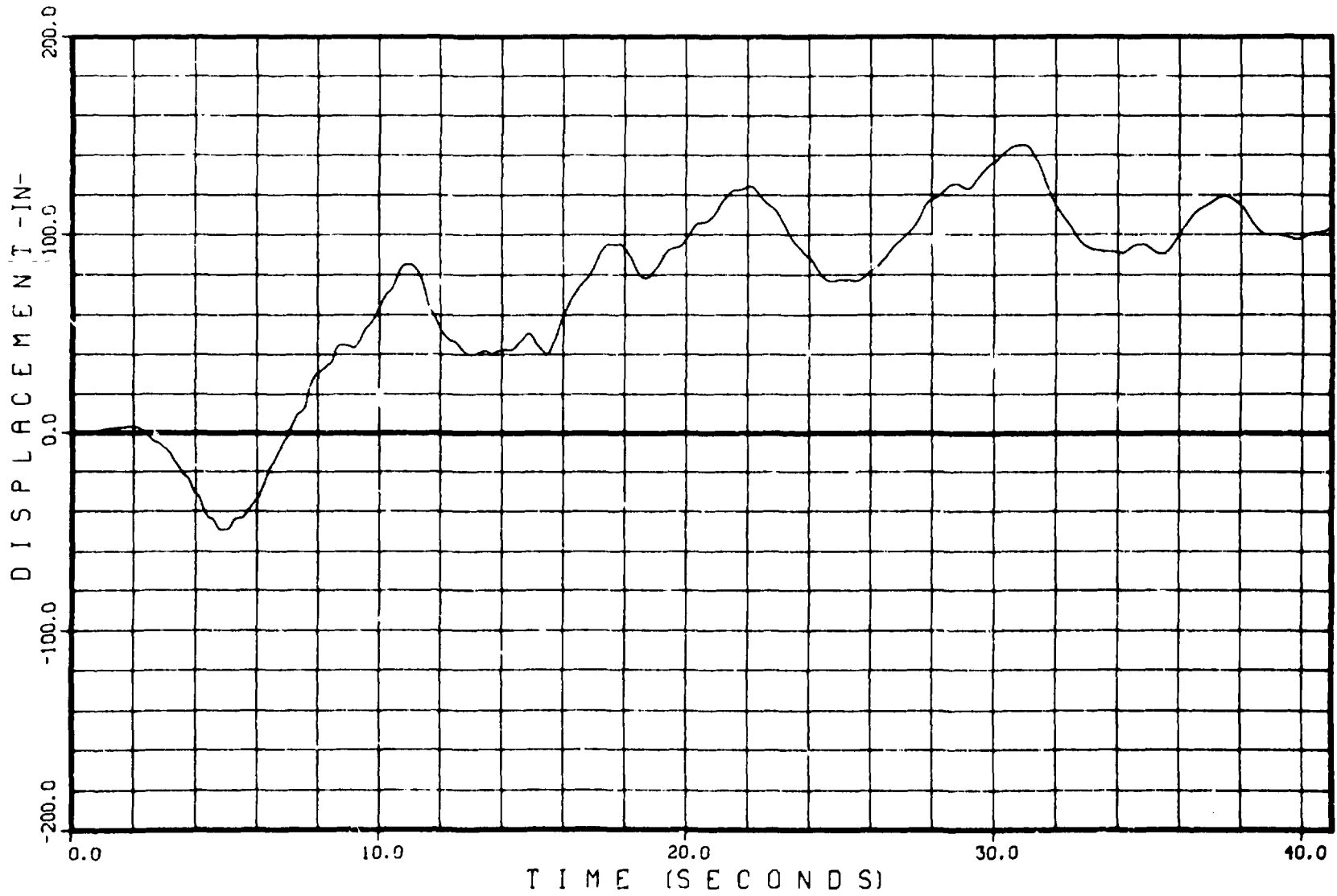


Fig. 38. GATH.10 - Displacement.

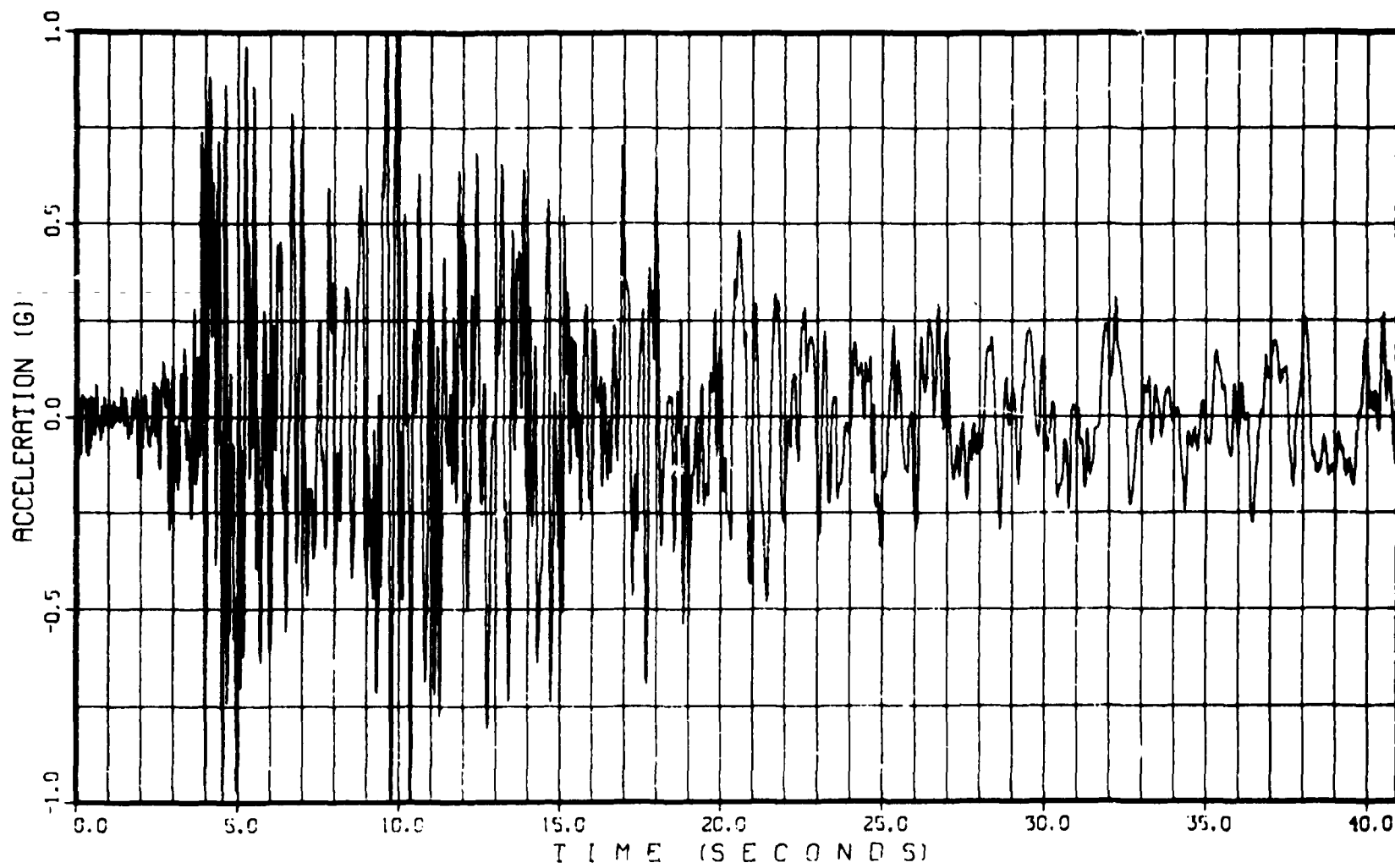


Fig. 39. GATH.15 - Acceleration.

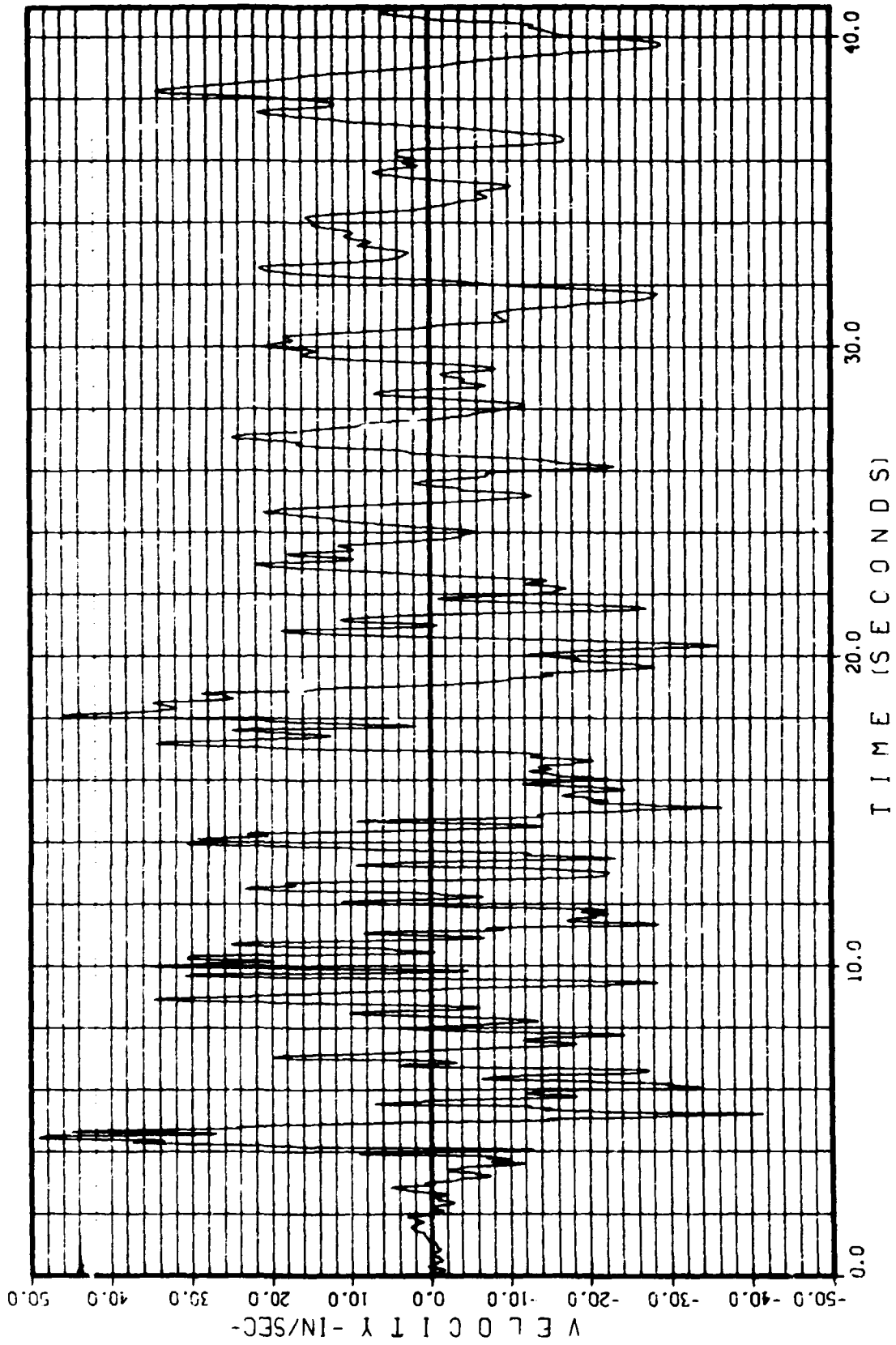


Fig. 40. GATH.15 - Velocity.

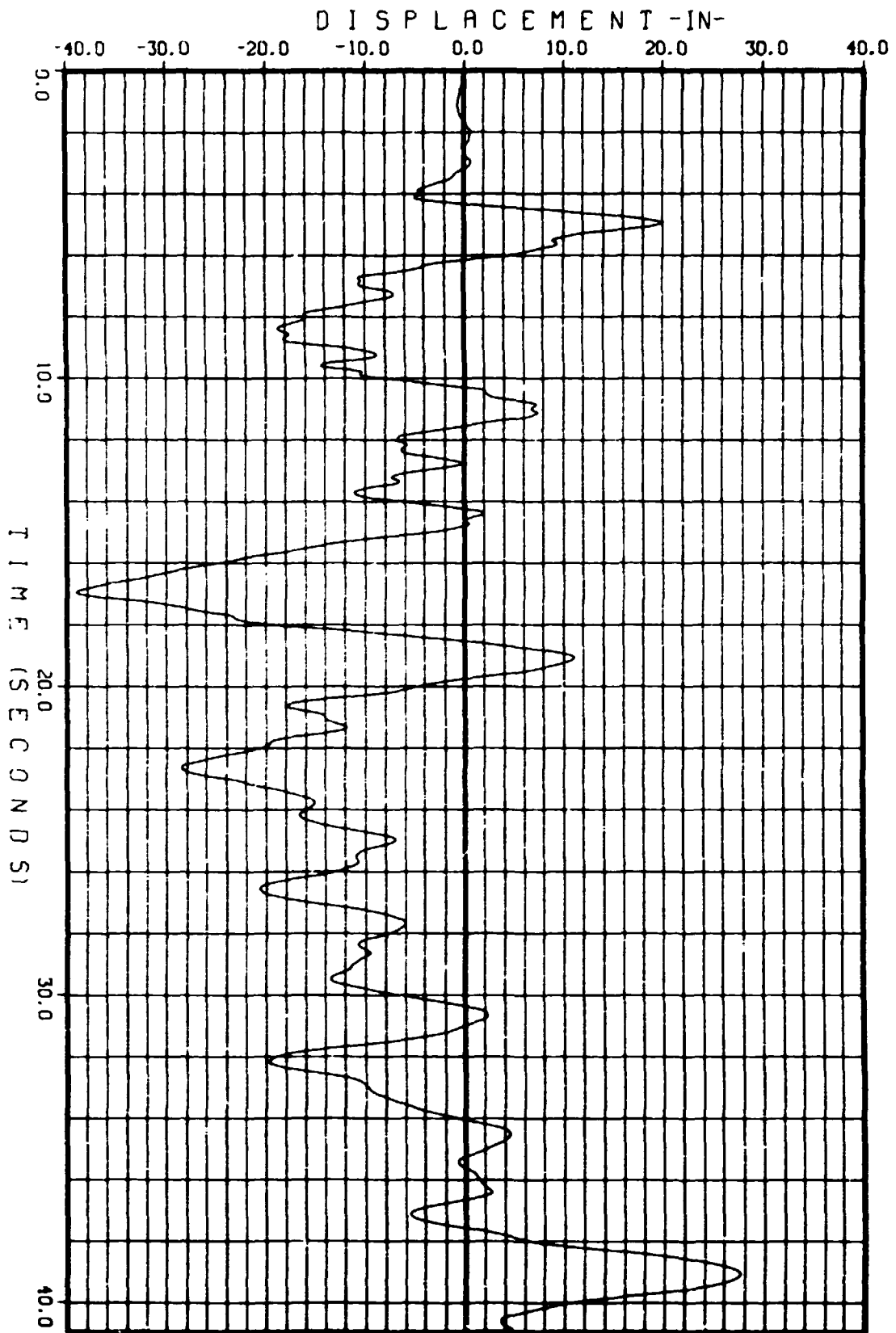


FIG. 41. GATH.15 - Displacement.

NORMALIZED CROSS-CORRELATION

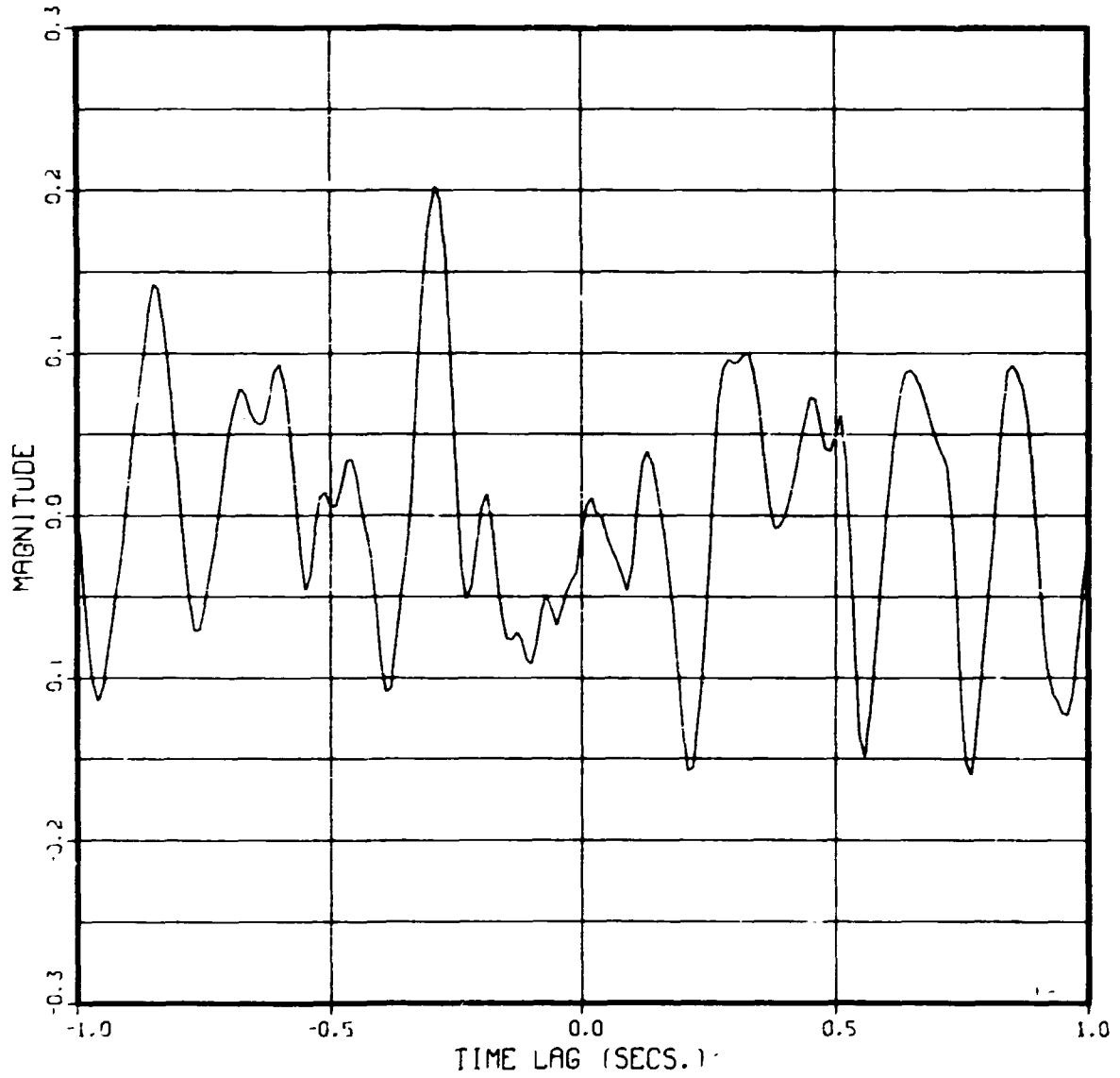


Fig. 42. Normalized Cross-Correlation, GATH.02 - GATH.04.

NORMALIZED CROSS-CORRELATION

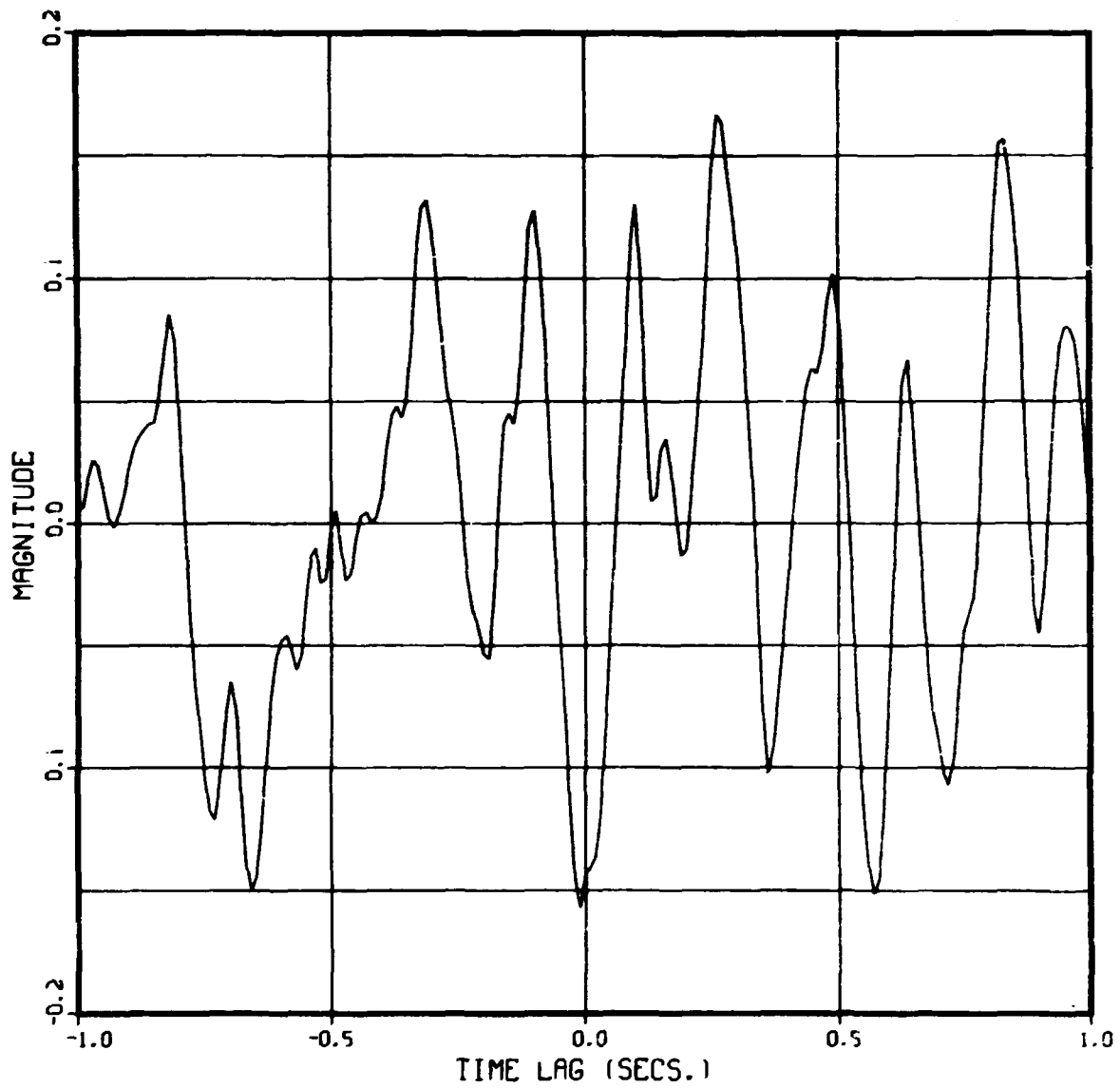


Fig. 43. Normalized Cross-Correlation, GATH.02 - GATH.09.

NORMALIZED CROSS-CORRELATION

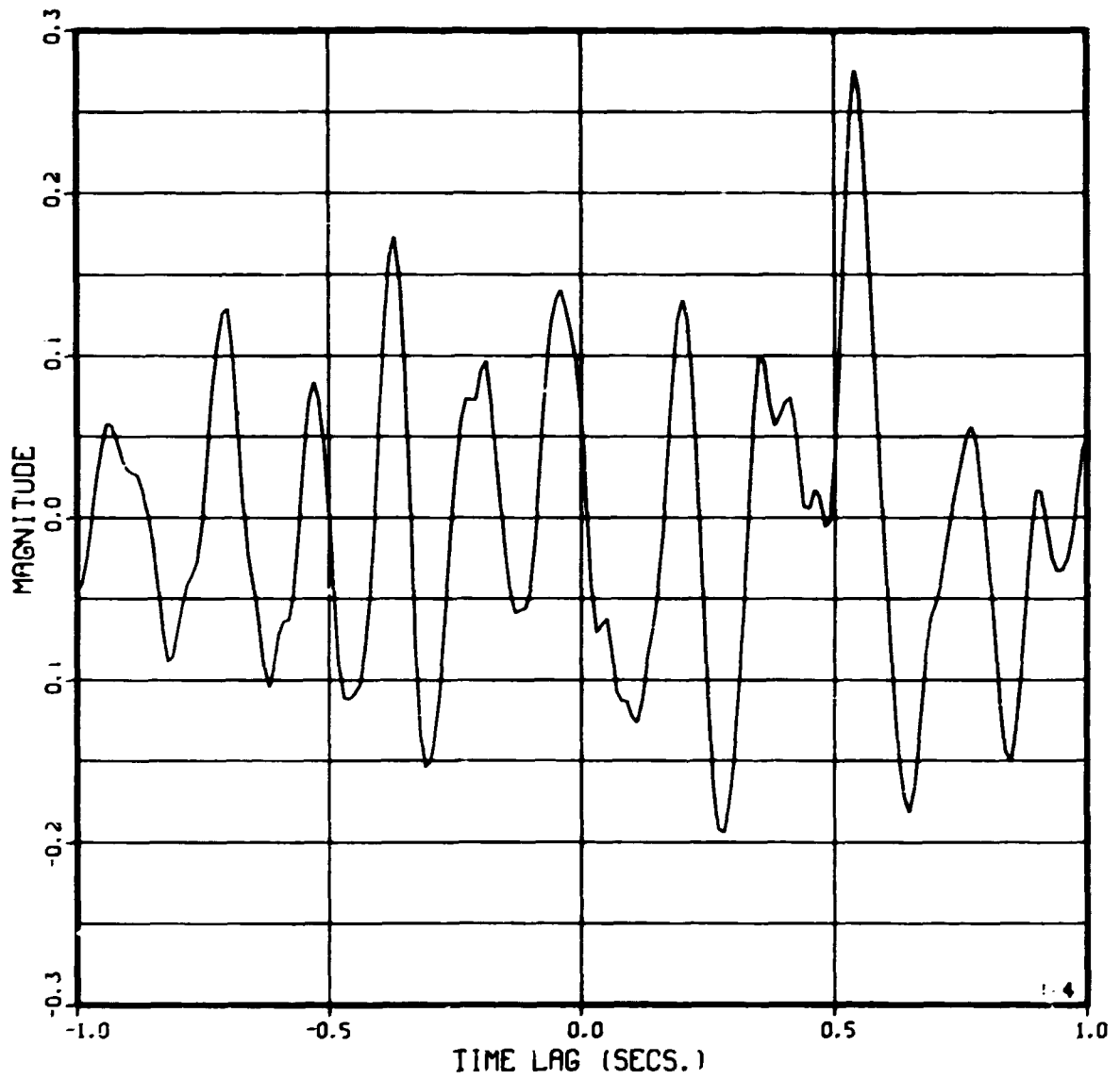


Fig. 44. Normalized Cross-Correlation, GATH.02 - GATH.10.

NORMALIZED CROSS-CORRELATION

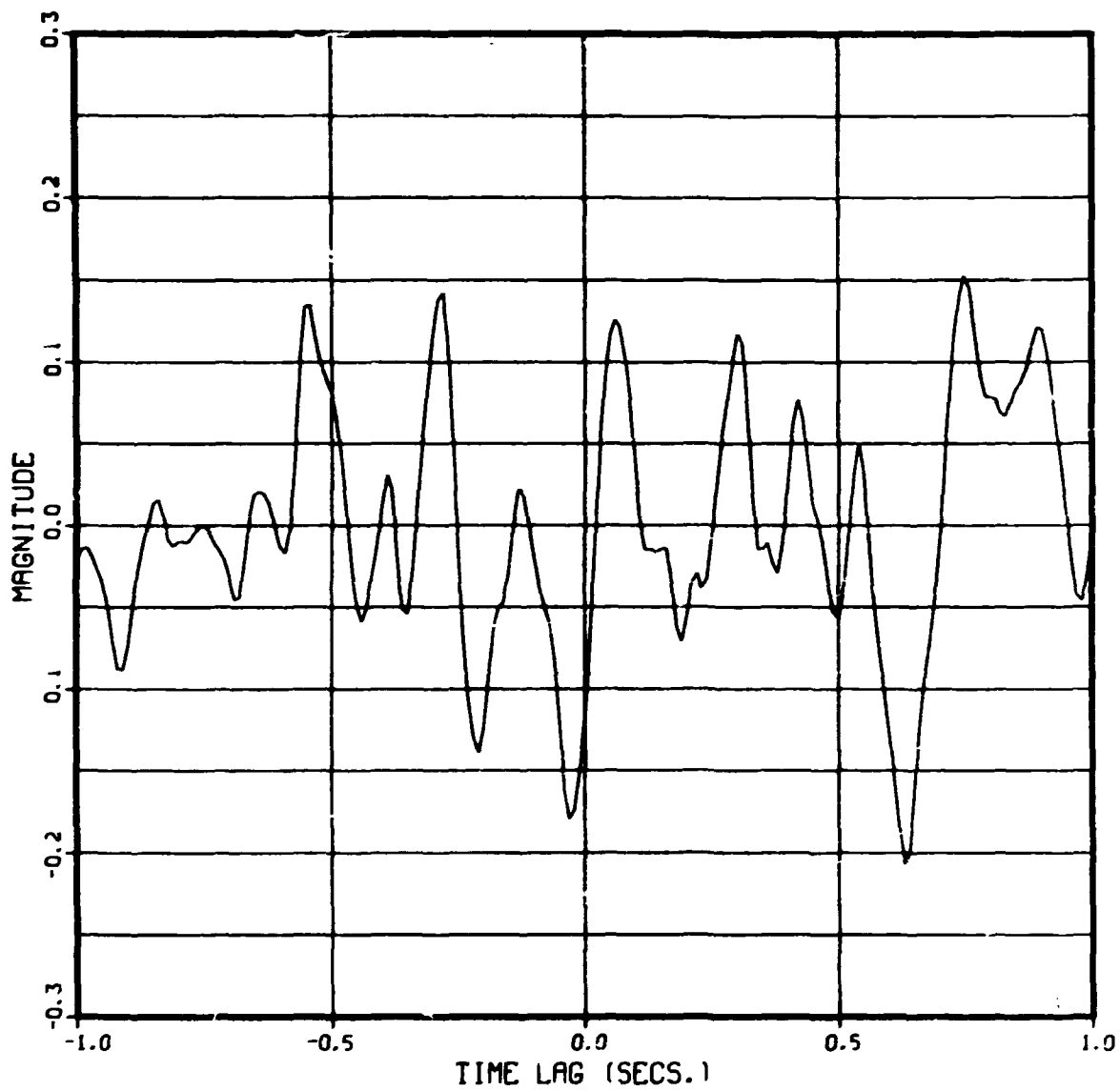


Fig. 45. Normalized Cross-Correlation, GATH.02 - GATH.15.

NORMALIZED CROSS-CORRELATION

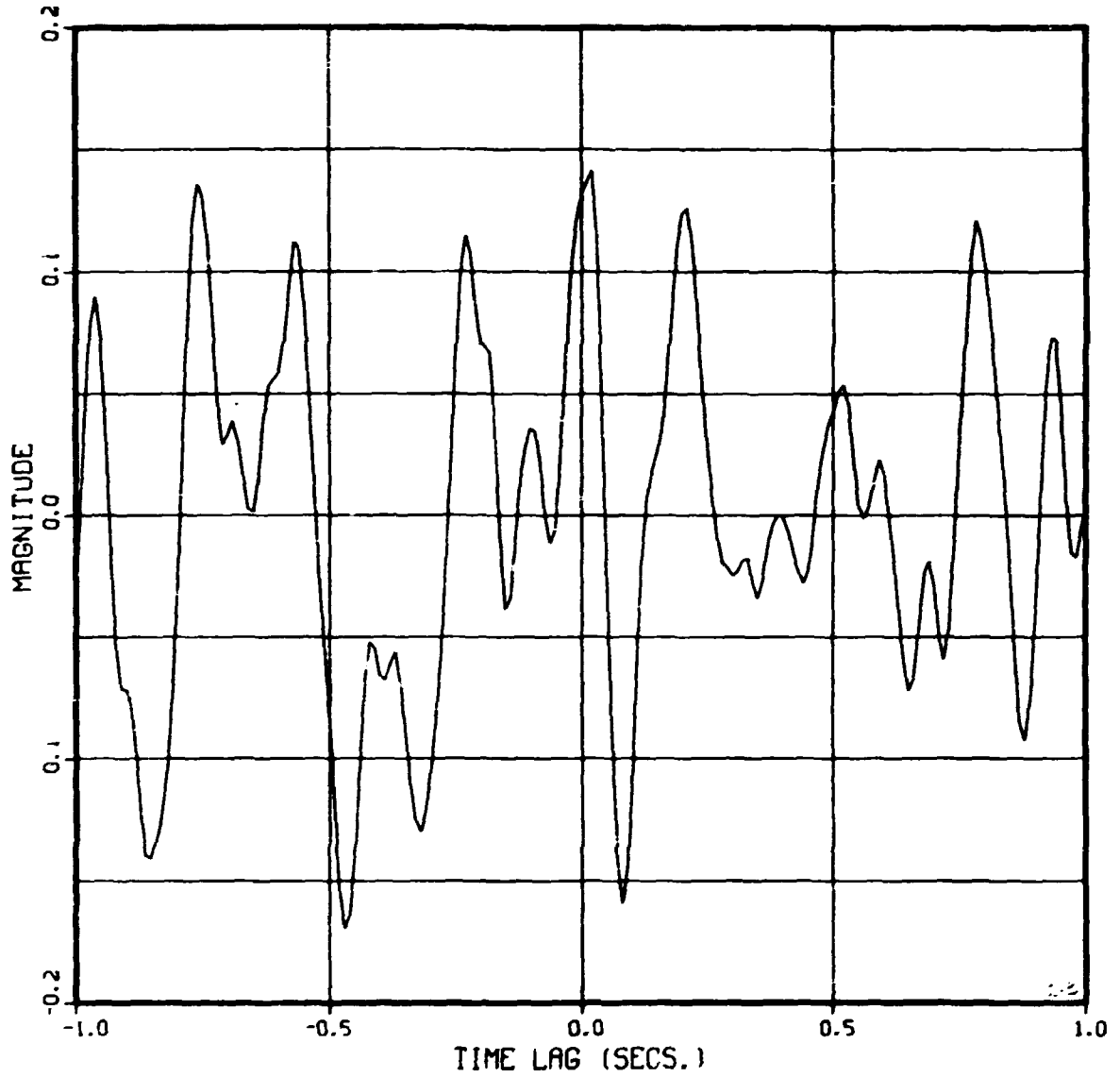


Fig. 46. Normalized Cross-Correlation, GATH.04 - GATH.09.

NORMALIZED CROSS-CORRELATION

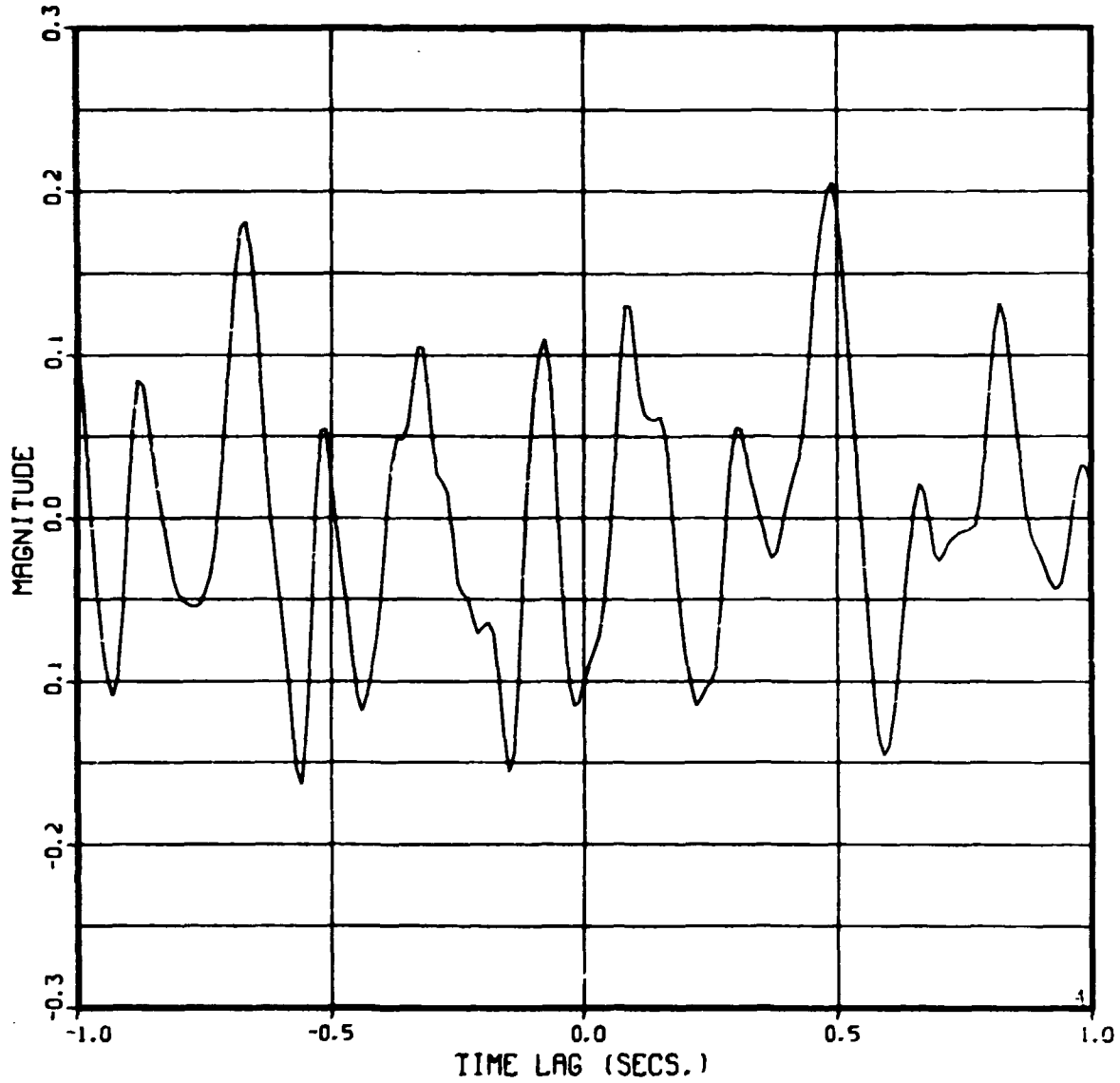


Fig. 47. Normalized Cross-Correlation, GATH.04 - GATH.10.

NORMALIZED CROSS-CORRELATION

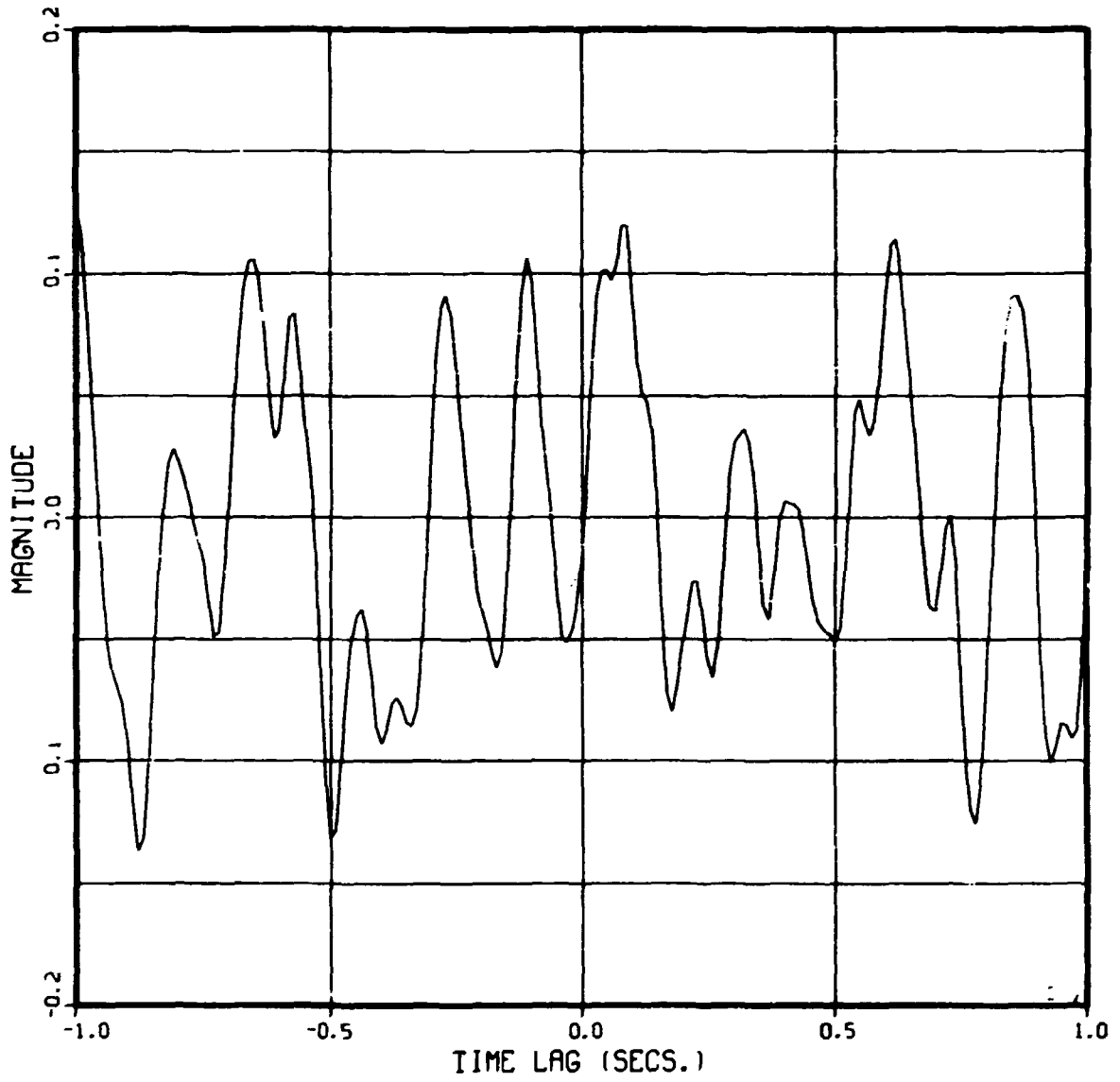


Fig. 48. Normalized Cross-Correlation, GATH.04 - GATH.15.

NORMALIZED CROSS-CORRELATION

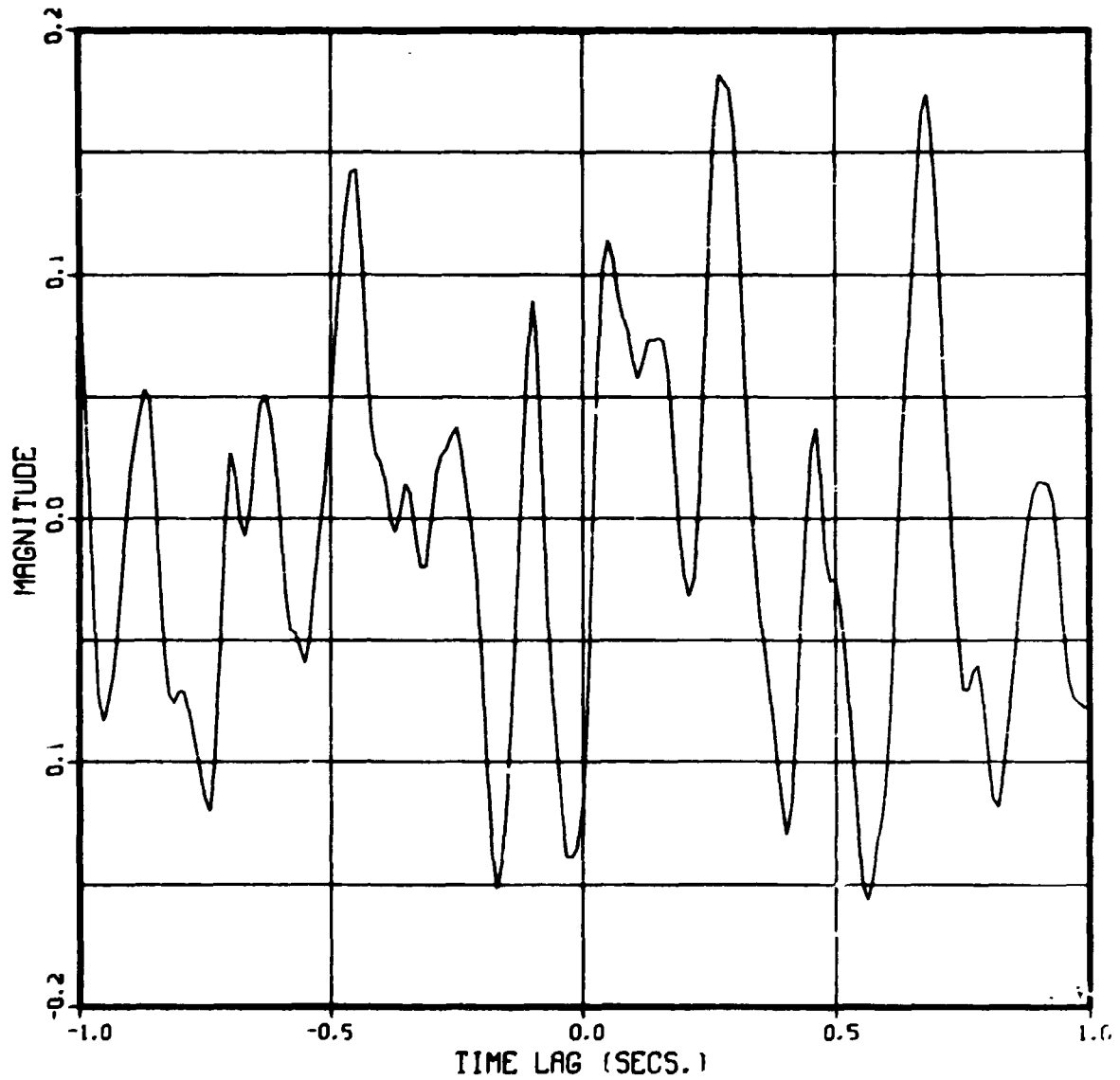


Fig. 49. Normalized Cross-Correlation, GATH.09 - GATH.10.

NORMALIZED CROSS-CORRELATION

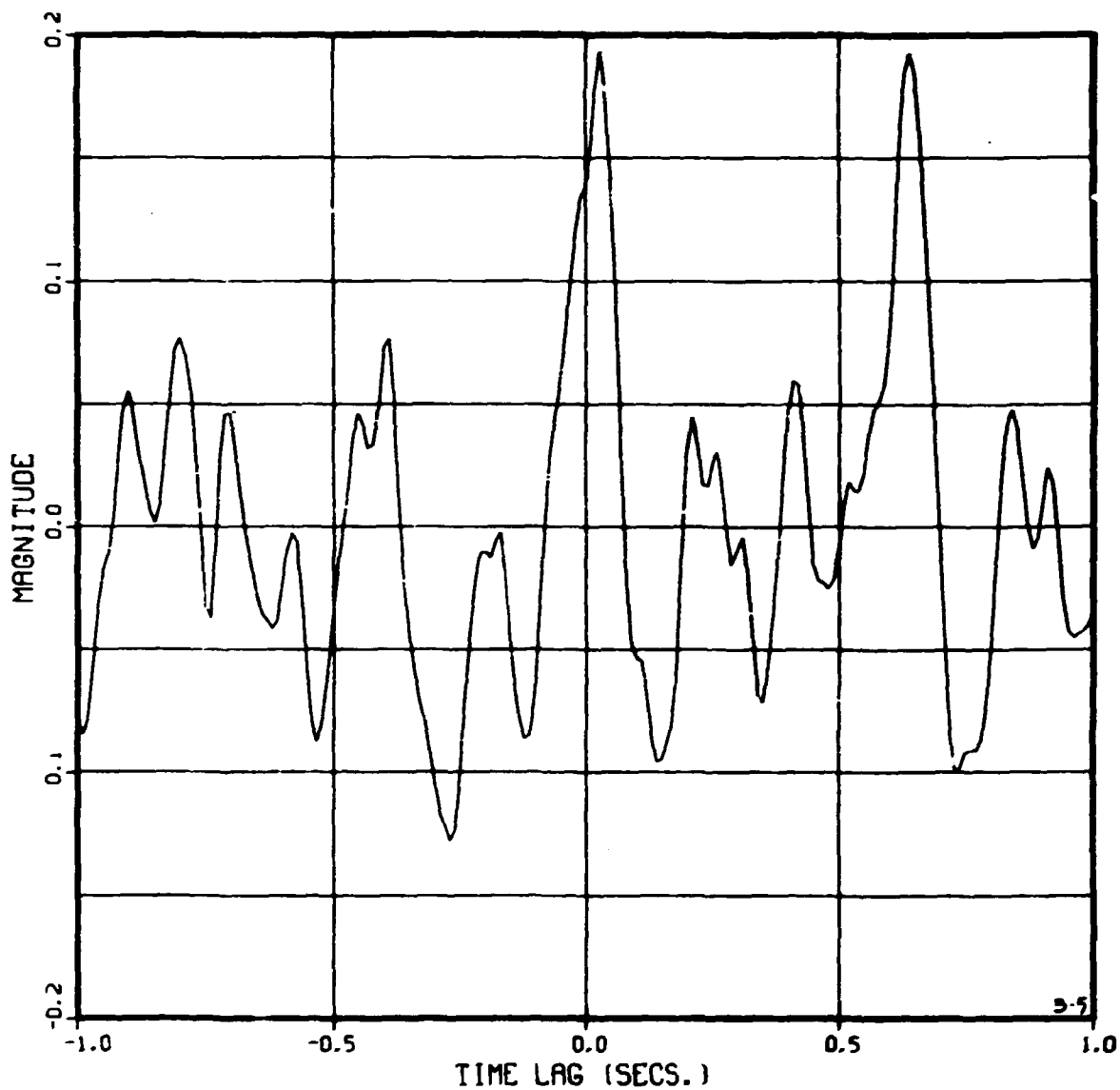


Fig. 50. Normalized Cross-Correlation, GATH.09 - GATH.15.

NORMALIZED CROSS-CORRELATION

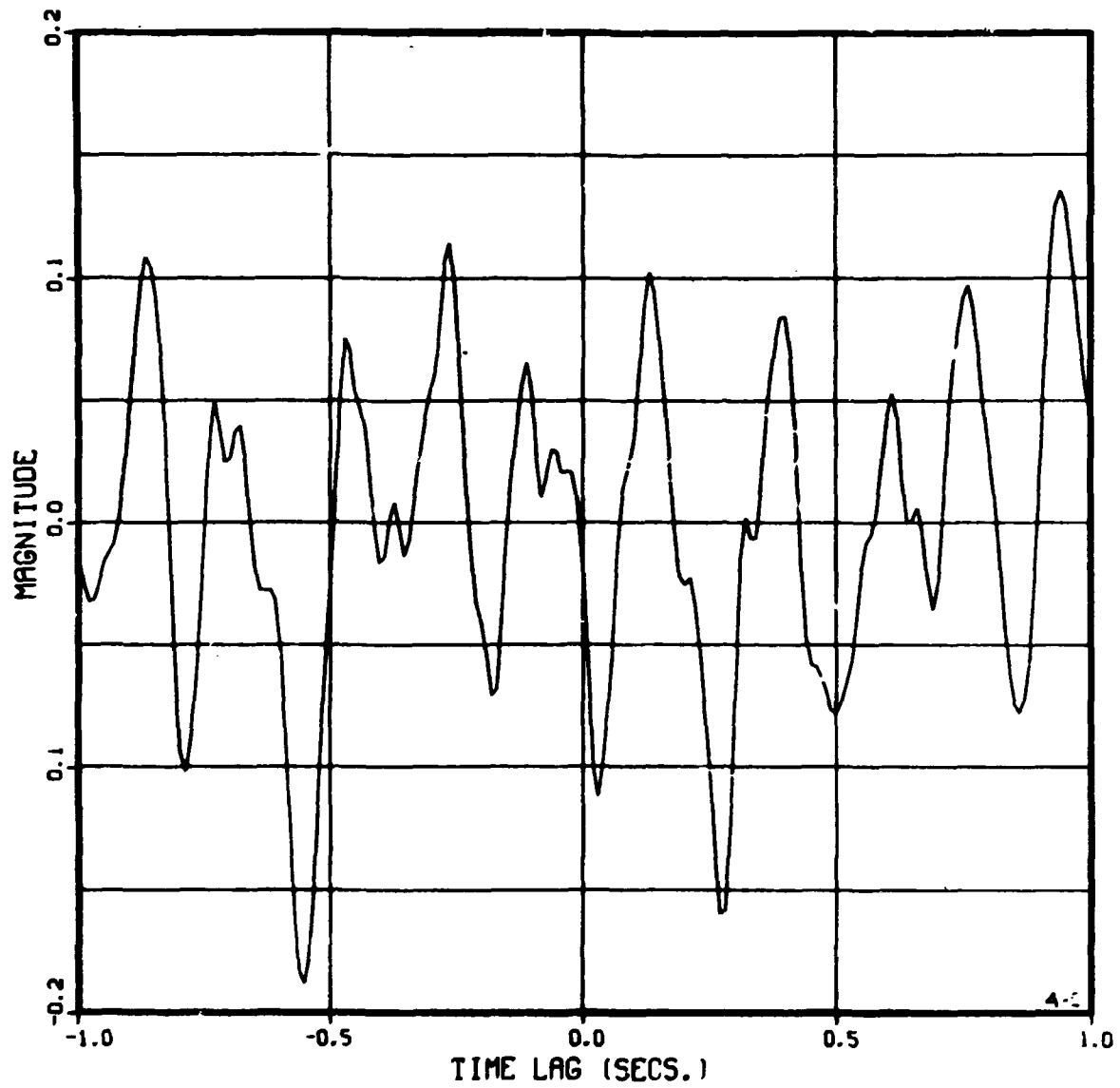


Fig. 51. Normalized Cross-Correlation, GATH.10 - GATH.15.