SSC-SR-1043

SSC-SR-1043

Superconducting Super Collider Laboratory

Field Measurements and Analyses of Underground Vibrations at the SSC Site

December 1989

Report No. SSC-SR-1043

GR-13

FIELD MEASUREMENTS AND ANALYSES OF UNDERGROUND VIBRATIONS AT THE SUPERCONDUCTING SUPER COLLIDER (SSC) SITE WAXAHACHIE, TEXAS

Prepared by:
Kerry Hennon and Dale Hennon
The Earth Technology Corporation
100 W. Broadway
Suite 5000
Long Beach, California 90802

Prepared for:
RTK Joint Venture
1800 Harrison Street
P.O. Box 23210
Oakland, California 94623-23321

Project No. 87-888-0011

December 1989

TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
1.1 BACKGROUND	1
1.2 SCOPE	3
2.0 SUMMARY OF RESULTS	5
3.0 SITE DESCRIPTION	8
3.1 REGIONAL GEOLOGY	8
3.2 MEASUREMENT SITES	8
4.0 INSTRUMENTATION	16
4.1 GEOPHONES	16
4.2 VIBRATION SURVEY	18
4.3 SEISMIC VELOCITY SURVEY	18
5.0 VIBRATION SURVEY	19
5.1 TECHNIQUE OVERVIEW	19
5.2 NEAR-SOURCE RESULTS	23
5.3 DISTANT-SOURCE RESULTS	25
6.0 SEISMIC VELOCITY SURVEY	26
6.1 TECHNIQUE OVERVIEW	26
6.2 RESULTS	26
7.0 REFERENCES	28

LIST OF APPENDICES

A Geophone Calibration Procedures and Results
B Functional Tests of Dynamic Signal Analyzer
C Vibration Survey Procedures
D Seismic Velocity Survey Procedures
E Site VF-1.7 Data and Results
F Site VE-3.5 Data and Results
G Site VF-5.4 Data and Results
H Site VE-9.3A Data and Results
I Data and Results for Horizontally Traveling Waves - Sites VE-3.5 and VE-3.5A
J Data and Results for Horizontally Traveling Sites - Sites VF-1.7 and VE-3.5
K Data and Results for Horizontally Traveling Waves - Sites VF-1.7 and VF-5.4

LIST OF FIGURES

		Page
1-1	SSC Base Map Showing Vibration Measurement Locations	2
3-1	Geological Profile Around the SSC Ring	9
3-2	Site VF-1.7 Map	11
3-3	Sites VE-3.5 and VE-3.5A Map	12
3-4	Site VF-5.4 Map	13
3-5	Site VE-9.3A Map	15
4-1	Diagram of Downhole Geophone Packages	17
5-1	Vibration Survey - Processing Flow Chart	22

LIST OF TABLES

2-1	Results	6
5-1	Description of Measured Vibration Sources	20
5-2	Vibration Survey Results	24
6-1	Seismic Velocity Survey Results	27

FOREWORD

The goal of the geotechnical studies at the Texas Superconducting Super Collider (SSC) site is to better understand the geological structures and geotechnical properties of the site. Increased knowledge will reduce the risk of encountering geotechnical conditions during construction that would significantly increase costs or delay schedules. The characterization program is designed to meet the following objectives:

- Confirm the site's suitability and optimize the ring location (the "footprint") and experimental hall positions on the ring
- Provide data for preliminary structural design
- Provide a rational framework for formulating construction contracts and schedules.

To meet these objectives, the geotechnical program is divided into the following three phases of study:

- Footprint Validation (present phase)
- Global (planned)
- Structure-specific (planned).

The primary purpose of Footprint Validation is to quickly assess whether individual components of the collider footprint, or the entire footprint, need to be relocated because of geotechnical constraints. Accordingly, the following issues are being studied:

- Areas where tunnel placement is shallow and crosses transportation corridors (railroads and major highways) may have unacceptably large amplitude ground vibrations at tunnel depth.
- Areas on the Footprint's west side, where the tunnel and experimental halls are close to Eagle Ford Shale, which may present foundation problems due to weak, deformable rock.
- Zones of potentially poor rock quality and high water inflow that should be avoided for experimental hall excavations.

This topical report is one in a series prepared for Footprint Validation. Each report includes results of field measurements concerned with one key geotechnical issue. Three topical reports planned for this phase are Underground Vibration Studies, Geomechanical Properties of the Eagle Ford Shale, and Structure and Stratigraphy of the Near-Cluster.

Future planned program phases (global and structure-specific data collection) will concentrate on (1) evaluating ring areas where few geotechnical data are currently available and (2) conducting more detailed studies at the sites of the injector and experimental halls.

ACKNOWLEDGEMENTS

Many people contributed to the success of this vibration study. Data acquisition, reduction, and results reporting were constantly improved with suggestions from the following people. Jack Peterson, Dave Goss, and Bill Ng (SSC Labs) patiently described their data needs, which helped formulate the work scope. Dr. Ken Stokoe (University of Texas, Austin) provided valuable technical guidance and insight into measuring and understanding ground vibrations. Dr. Soheil Nazarian (University of Texas, El Paso) helped develop the data collection and processing procedures. Both Dr. Stokoe and Dr. Nazarian reviewed this report. Collecting blast and train data would have been impossible without the cooperation of Kenneth Reed and Dale Hanks at the TXI quarry, who constantly informed us of their operating schedule, and Mr. Hobbs, Southern Pacific Railroad trainmaster, who told us about the daily train schedule.

1.0 INTRODUCTION

1.1 BACKGROUND

- *Vibrations affect collider*

Underground vibrations were measured at the Superconducting Super Collider (SSC) site near Waxahachie, Texas, as part of Footprint Validation. Vibrations were measured because excessive movement could adversely affect collider performance.

Measurement locations for this study were chosen to record the largest displacements (worst case condition) that could influence the quadrapole magnets guiding the particle beam. These locations (Figure 1-1) are at intersections of the ring alignment with railroad lines and highways. Vibration spectra were obtained for several sources at each location. Large vibration displacements (vertically oriented) are expected directly below surface sources (transportation corridors). Smaller displacements (vertically and horizontally oriented) will occur across the ring from distant sources (quarry blasts and train corridors).

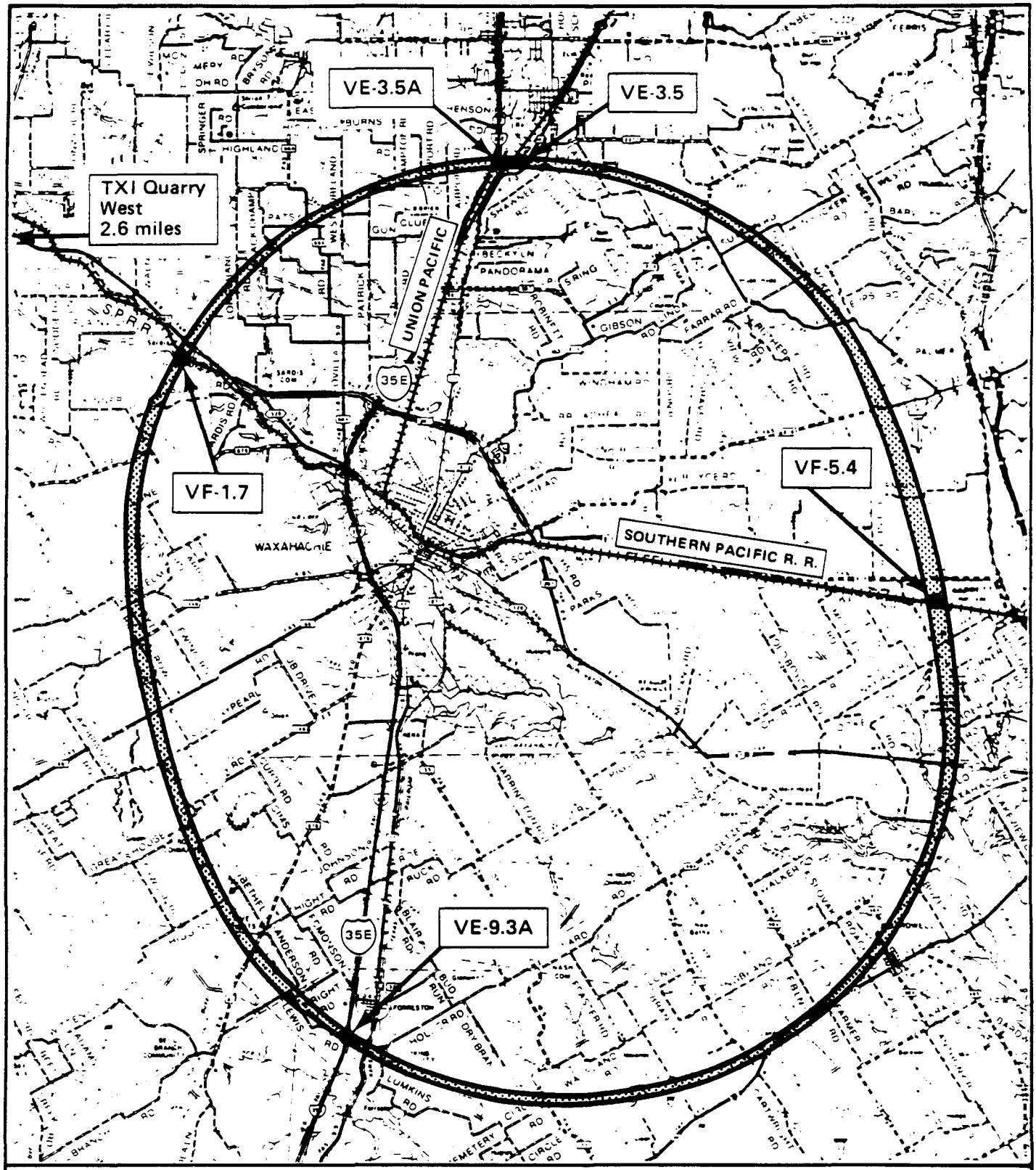
Criteria for vibration magnitude that could affect SSC operations are stated in the Invitation for Site Proposal (ISP), U.S. Department of Energy (1987):

- *ISP vibration criteria*

> "The beams are sensitive to ground motion in the frequency range from a fraction of a hertz to several tens of hertz. At about 3 hertz there is a resonant beam response to the ground motion. However, by using a feedback system, ground motion of up to 0.5 thousandths of an inch amplitude at the interaction region and 2 thousandths of an inch elsewhere can be controlled. A larger ground motion may require a feedback system stronger than practical. Because there is considerable variation, data suggest that a railroad line should not pass within approximately 3,000 feet of an interaction point, unless measurements demonstrate that the ground motion is within the above tolerance. Major public roads or freeways should be no closer than about 600 ft from an interaction point."

Vibration effects on collider performance was studied by the SSC Labs (Ng and Peterson, 1989; Goss, 1989). The smallest beam diameter at the interaction points is about 390 microinches (10 micrometers). If the two beams miss by more than one-tenth their diameter, or about 39 microinches (1 micrometer), then the collision's effectiveness is severely degraded. The SSC Labs developed a computer model for estimating vibration displacements along the ring caused by surface vibration sources. The model uses the general geometry of the ring at the Texas site and assumes the geology to be an ideal, uniform, half-space. The model predicts displacement levels significantly greater than the 39-microinch (1-micrometer) tolerance. Ng and Peterson arrived at the following conclusion:

- *1-micrometer tolerance*
- *Predictive model*



Scale (miles)

0 1 2 3 4

EXPLANATION

PROPOSED COLLIDER RING ALIGNMENT USED DURING FOOTPRINT VALIDATION

The Earth Technology Corporation

PROJECT NO.: 87-888-0011

RTK Joint Venture

SSC Base Map
Showing Vibration Meaurement Locations

12-89

Figure 1-1

"Measurement of ground motion amplitude at many representative points of the tunnel and also of the absorption coefficient are required before dependable correlations can be reached. The SSC site in Texas is much more complicated than the simple model employed here, so that our results are only suggestive of the magnitude of the effects to be expected."

Accordingly, ground vibrations were measured at approximately tunnel depth (in use during Footprint Validation) to provide more detailed information. This study addressed the following issues stated by the SSC Labs (1989):

- *Study goals*

  - Determine vibration displacement spectra
  - Estimate attenuation
  - Determine seismic velocities.

These quantities were correlated with the type of vibration source and local geology. Displacement levels may be estimated away from the point measurement locations using these correlations.

1.2 SCOPE

Field measurement procedures generally followed the process described by Stokoe et al. (1987) and the Tennessee SSC site proposal (State of Tennessee, 1987). These procedures were studied by a number of SSC project participants and deemed to be a state-of-the-art approach for vibration studies. The general plan is described in two Earth Technology reports: A Plan for Startup Geotechnical Characterization (1988) and Work Description - Geophysical Testing (1989a).

Two types of measurements were made at the SSC site.

- *Vibration spectra*
- *Attenuation*

  1. Vibration spectra of natural and cultural sources were determined at various depths in borings located near prominent vibration sources. The results show displacement spectra and time histories at the proposed tunnel depth (in use during Footprint Validation). By comparing spectra measured at a single site from nearby sources, attenuation constants for vertically traveling waves were estimated based on far-field assumptions. By comparing spectra at different sites from distant sources, attenuation constants for horizontally traveling waves were estimated based on the same assumptions.

- *Seismic velocities*

  2. Seismic velocities (compressional, P, and shear, S, waves) were determined. Velocities of vertically traveling waves from nearby sources were determined at each site. Velocities of horizontally traveling waves from distant sources were determined between sites. Dynamic elastic moduli, Poisson's ratio, and Rayleigh (R) wave velocities were calculated from the measured data and material densities. The frequency axis on the spectra can be converted to wavelength using these velocities.

"Measurement of ground motion amplitude at many representative points of the tunnel and also of the absorption coefficient are required before dependable correlations can be reached. The SSC site in Texas is much more complicated than the simple model employed here, so that our results are only suggestive of the magnitude of the effects to be expected."

Accordingly, ground vibrations were measured at approximately tunnel depth (in use during Footprint Validation) to provide more detailed information. This study addressed the following issues stated by the SSC Labs (1989):

- *Study goals*

  - Determine vibration displacement spectra
  - Estimate attenuation
  - Determine seismic velocities.

These quantities were correlated with the type of vibration source and local geology. Displacement levels may be estimated away from the point measurement locations using these correlations.

1.2 SCOPE

Field measurement procedures generally followed the process described by Stokoe et al. (1987) and the Tennessee SSC site proposal (State of Tennessee, 1987). These procedures were studied by a number of SSC project participants and deemed to be a state-of-the-art approach for vibration studies. The general plan is described in two Earth Technology reports: A Plan for Startup Geotechnical Characterization (1988) and Work Description - Geophysical Testing (1989a).

Two types of measurements were made at the SSC site.

- *Vibration spectra*
- *Attenuation*

  1. Vibration spectra of natural and cultural sources were determined at various depths in borings located near prominent vibration sources. The results show displacement spectra and time histories at the proposed tunnel depth (in use during Footprint Validation). By comparing spectra measured at a single site from nearby sources, attenuation constants for vertically traveling waves were estimated based on far-field assumptions. By comparing spectra at different sites from distant sources, attenuation constants for horizontally traveling waves were estimated based on the same assumptions.

- *Seismic velocities*

  2. Seismic velocities (compressional, P, and shear, S, waves) were determined. Velocities of vertically traveling waves from nearby sources were determined at each site. Velocities of horizontally traveling waves from distant sources were determined between sites. Dynamic elastic moduli, Poisson's ratio, and Rayleigh (R) wave velocities were calculated from the measured data and material densities. The frequency axis on the spectra can be converted to wavelength using these velocities.

Measurements of vibration data from several sources were made between May 24 and June 23, 1989, at five locations (Figure 1-1), as summarized in the table below.

Measurement Location	Near Source	Distant Source	Distance to Distant Source	
			Miles	Kilometers
VF-1.7	Southern Pacific RR	TXI Quarry	5.9	9.4
VE-3.5	Union Pacific RR	TXI Quarry	12.2	19.5
VE-3.5A	–	Union Pacific RR	0.2	0.3
VF-5.4	Southern Pacific RR	TXI Quarry	20.8	33.3
VE-9.3A	Interstate 35E	TXI Quarry	17.2	5.2

2.0 SUMMARY OF RESULTS

Field measurements of vibration sources were made at the Texas SSC site. Measurement locations were at intersections of the ring alignment (used during Footprint Validation) with four principal transportation corridors (Figure 1-1). These locations are thought to represent worst case (large-amplitude) vibration conditions.

- *Survey description*

Vibrations caused by natural phenomena, trains, traffic, and quarry blasts were recorded in five borings. Displacement spectra were obtained simultaneously at three depths in each boring for several vibration sources. Attenuation in the vertical direction was estimated by comparing these spectra. Velocities of vertically traveling seismic waves were obtained in each boring using a controlled source. Horizontally traveling seismic wave velocities and attenuation were estimated by comparing spectra from different borings. Data were processed in the field and preliminary results were used to optimize subsequent data acquisition. The results are summarized below and shown in Table 2-1 and are in general agreement with previous studies (Lesmes and Morgan, 1988; Goss, 1989).

- *ISP Criteria comparison*

No vibration displacements measured at tunnel depth were greater than those stipulated by the criteria in the Invitation for Site Proposal (U. S. Department of Energy, 1987). Measured ambient vibrations are less than one one-hundreth of the 1-micrometer tolerance. Displacements measured for nearby sources (trains and traffic) were less than the 39-microinch (1-micrometer) tolerance at depths greater than 5.0 feet (1.5 meters) except for one train passage at VF-5.4. (Data set 4 recorded a single displacement peak of 94 microinches [2.4 micrometers] at 5.6 Hz). Generally, train-induced vibrations are less than half, and traffic-induced vibrations are less than one-hundredth, the 1-micrometer tolerance. Train engines and railroad cars with "flat wheels" caused the largest amplitude ground vibrations. Displacements measured from distant sources (quarry blasts) were generally less than one-fifth the 1-micrometer tolerance except at VF-1.7. A single displacement peak of 37 microinches (0.94 micrometers) at 1.3 Hz was measured. This displacement equals the 1-micrometer tolerance and, therefore, may require feedback for the machine near boring VF-1.7.

- *Trains/traffic-small displacements*

Train- and traffic-induced displacements at tunnel depth are low primarily because of two factors: significant wave attenuation while passing near-vertically through surface Quaternary deposits and reflection/refraction of seismic waves at the soil/rock interface. Vertical attenuation within the Quaternary deposits is about 2 to 8 times larger than that in the underlying rock. About two-thirds of the seismic wave amplitude reaching the surface deposits/rock interface is reflected upward and becomes 'trapped' in the upper deposits (calculated from velocity and density contrasts at the interface). Most of the displacement peaks are in the 1-10 Hz frequency span because attenuation has rapidly reduced higher frequency vibrations. Attenuation reduces train vibrations to background ambient level when the train-to-boring distance is greater than about 0.5 mile (0.8 kilometer). Therefore, train vibrations measured by this study should affect the ring magnets only locally near the corridor crossings. Traffic vibrations are too small to affect machine operations.

TABLE 2-1. RESULTS

Site	Maximum Vertical Displacement* Micro inch	Micro meter	Depth Range ft	(m)	Compressional Velocity ft/sec	(m/sec)	Shear Velocity ft/sec	(m/sec)	Rayleigh Velocity ft/sec	(m/sec)
VERTICALLY TRAVELING WAVES										
VF-1.7 **	16	(0.42)	0-13	(0-4)	1450	(442)	500	(152)	470	(143)
			13-45	(4-14)	3600	(1097)	2050	(625)	1900	(579)
			45-65	(14-20)	5700	(1737)	3300	(1006)	3000	(914)
VE-3.5	6	(0.15)	0-7	(0-2)	1200	(366)	750	(229)	680	(208)
			7-31	(2-9)	4600	(1402)	2900	(884)	2650	(808)
			31-78	(9-24)	8900	(2713)	5100	(1554)	4750	(1448)
VF-5.4	9	(0.22)	0-23	(0-7)	2100	(640)	500	(152)	480	(146)
			23-110	(7-34)	5700	(1737)	2500	(762)	2350	(716)
			110-260	(34-79)	6800	(2073)	3700	(1128)	3450	(1052)
VE-9.3A	0.1	(0.004)	0-12	(0-4)	1320	(402)	420	(128)	400	(122)
			12-89	(4-27)	4900	(1494)	2300	(701)	2150	(655)
			89-165	(27-50)	8300	(2530)	4000	(1219)	3750	(1143)
HORIZONTALLY TRAVELING WAVES										
VF-1.7***	37	(0.94)			10,700	(3261)	4550	(1387)		
VE-3.5	7	(0.19)								
VF-5.4	3	(0.07)								
VE-9.3A	within ambient levels									

*Measured between frequencies of 0.8 - 18.0 Hz at tunnel depth (in use during Footprint Validation).
**Velocities calculated from seismic waves with frequencies of 50-150 Hz.
***Velocities calculated using VF-1.7 and VE-3.5 data recorded from quarry blast producing seismic waves with frequencies of 1-20 Hz.

- *Quarry blast - large displacements*

Blast-induced displacements at tunnel depth at VF-1.7 are large for several reasons. Rock attenuation in the horizontal direction is about 10 times lower than in the vertical direction. Blasts originate within the Austin Chalk at approximate tunnel depths: therefore, seismic waves do not pass through the surficial deposits and are not significantly attenuated or reflected/refracted upward. Blast displacements measured at the other four sites are low because of significant geometric spreading as the waves travel long distances from the quarry.

- *Extrapolate results*

Correlations were developed among the vibration survey results, type of vibration source, and local geology to guide extrapolation of these results away from the point measurement locations. The frequency axis of vibration spectra can be converted to wavelength using measured velocities of the geological formations.

3.0 SITE DESCRIPTION

3.1 REGIONAL GEOLOGY

- *Tunnel mostly in chalk*

Regional geology of the SSC site is described in detail in the Texas site proposal (Texas National Research Laboratory Commission, 1987). Most of the ring will be excavated in Austin Chalk; the rest in Taylor Marl and Eagle Ford Shale. Quaternary deposits of varying thickness overlie these formations. Major formations are shown as a profile around the ring in Figure 3-1 and are described below.

Quaternary Deposits
These deposits consists of Recent alluvium and terraces. The alluvium is unconsolidated clay and silty clay with local occurrences of calcareous, clayey sand and gravel. The terrace deposits are unconsolidated clay, silt, and sand. The basal parts commonly include stratified, water-bearing clayey sands and gravels. Quaternary deposits range from 0 to 25 feet (0 to 7.6 meters) thick and may be as deep as 50 feet (15.2 meters) locally.

Taylor Marl
This material is characteristically fine grained, laminated, calcareous claystone with interbedded chalk. The claystone contains illite and montmorillonite clays, calcium carbonate cement, and bentonite layers. The maximum thickness of the unit is 500 feet (152 meters).

Austin Chalk
This formation is primarily microgranular calcite with interbedded calcareous claystone. The chalk is uniform and has an average carbonate content of 85 percent. Chalk crops out frequently and is about 400 feet (120 meters) thick.

Vibration data were not measured in the Eagle Ford Shale.

3.2 MEASUREMENT SITES

- *Boring construction*

Five borings were drilled (rotary wash) to a depth of about 5 feet (1.5 meters) below the proposed tunnel depth (in use during Footprint Validation). Careful procedures and use of mud helped reduce horizontal stress during drilling, which minimized soil disturbance around the boring. Geophysical wireline surveys were completed in the fluid-filled, open holes. Borings were cased with 4-inch (0.1-meter) diameter PVC schedule 40 pipe and grouted into place to further relieve stress and prevent caving. The grout provided good coupling between PVC and formation to minimize seismic wave attenuation or conversion. Intimate contact between geophone, casing, and formation is one of the critical factors in recording truly representative seismic waveforms (Mok, 1987).

Boring logs and wireline data for each boring are described in a series of data reports (Earth Technology, 1989b,c,d,e). The stratigraphy encountered at each boring and the nearby vibration source are described below. Railroad conditions were rated according to Federal Railway Administration Track Standards (1972).

Site VF-1.7

- *Thick Quaternary deposits*
- *Austin Chalk*

Quaternary deposits, comprising stiff silty clay, are 21 feet (6.4 meters) thick. Water was encountered at a depth of 14.5 feet (4.4 meters). Weathered Austin Chalk occurs between depths of 21 and 22.5 feet (6.4 to 6.9 meters). Underlying fresh chalk is continuous with occasional thin, shaly limestone layers. The boring was terminated at a depth of 69 feet (21.0 meters).

This site is 25 feet (7.6 meters) from the northwest-oriented Southern Pacific railroad line (Figure 3-2). The track was judged to be in fair to good condition for 1 mile (1.6 kilometers) on each side of the boring. The rails have several large pits. Rail segments are welded. There are very few loose or missing spikes. The ties are in fair to good condition; several ties had been recently replaced. Ballast is plentiful and in good condition with no obvious slumping. There are short bridges over creeks about 1 and 0.05 miles (1.6 and 0.06 kilometers) southeast of the boring and about 0.75 miles (1.2 kilometers) northwest of the boring.

Sites VE-3.5 and VE-3.5A

Boring VE-3.5 is 25 feet (7.6 meters) west of the railroad (Figure 3-3). Boring VE-3.5A is 1,050 feet (320 meters) southwest and 27.0 feet (8.2 meters) higher than VE-3.5.

- *Austin Chalk*

Quaternary deposits, comprising stiff clay, are 7.5 feet (2.3 meters) thick at boring VE-3.5 and 3 feet (0.9 meters) thick at Boring VE-3.5A. The weathered Austin Chalk is between depths of 7.5 and 10 feet (2.3 to 3.0 meters) at boring VE-3.5. Underlying fresh Austin Chalk is continuous to boring termination at depths of 83 feet (25.3 meters) and 105 feet (32 meters) at Borings VE-3.5 and VE-3.5A, respectively.

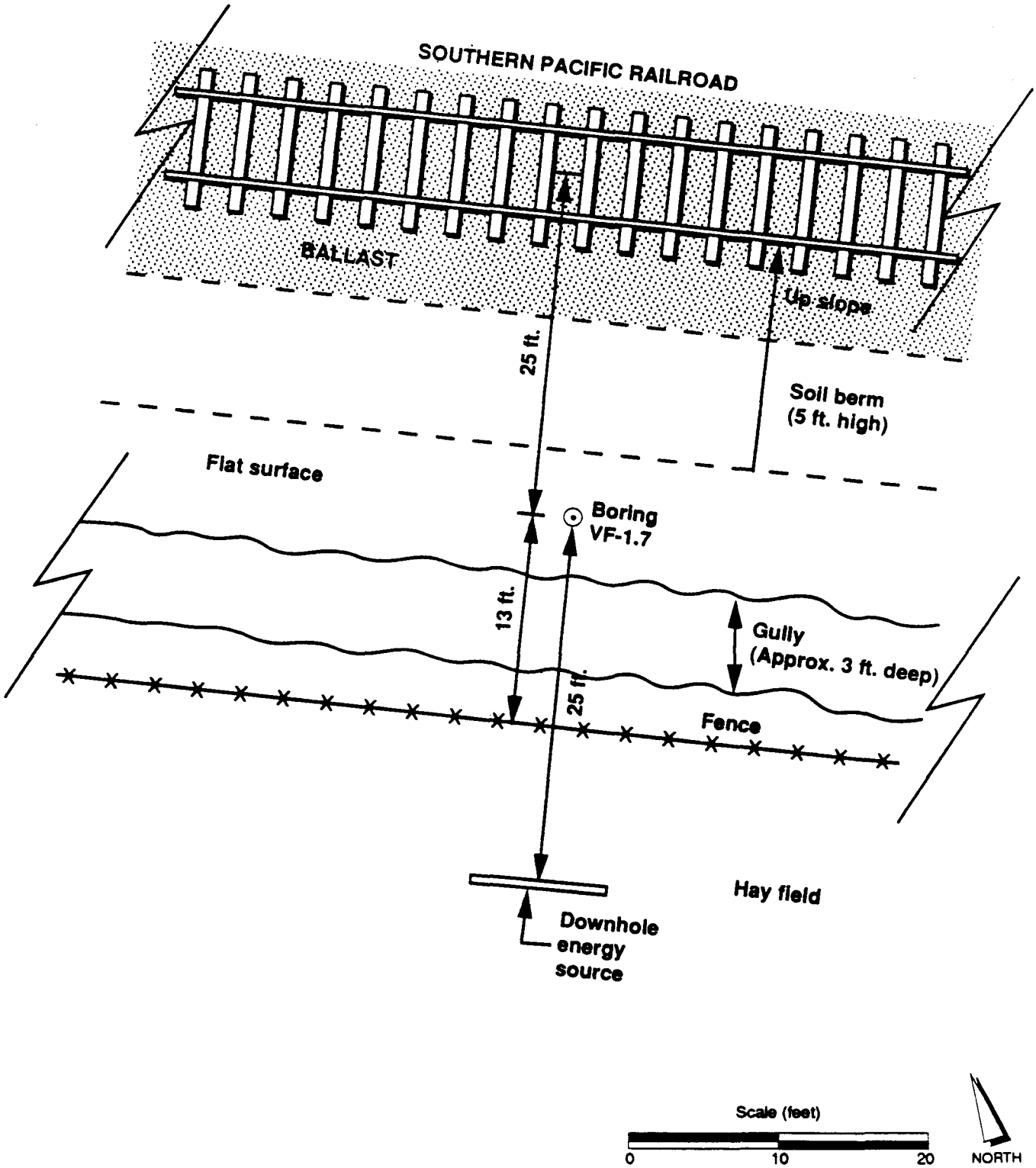
The rails of the northeast-oriented Union Pacific line were judged to be in poor to fair condition for 1 mile (1.6 kilometers) on each side of Boring VE-3.5. The rails have many large pits. Rail sections are welded. There are many loose or missing spikes and ties are in poor condition. Ballast is plentiful and in good condition with no obvious slumping.

Site VF-5.4

- *Thick Quaternary deposits*
- *Taylor Marl*

Quaternary deposits, comprising stiff silty clay, are 22.5 feet (6.9 meters) thick. Beneath the surface layer is the Taylor Marl, which contains several thin bentonite layers. Marl is fairly continuous to the boring termination at a depth of 270 feet (82.3 meters). Water was encountered at depths of 9 and 46 feet (2.7 and 14.0 meters).

This site (Figure 3-4) is 33.0 feet (10.0 meters) from the same northwest-oriented Southern Pacific railroad line that passes Site VF-1.7. Rails were judged to be in poor condition for 1 mile (1.6 kilometers) on each side of the boring. There are many locations with large pits, vertical splits, flaking, and even missing fragments. Rail segments are welded.



The Earth Technology Corporation

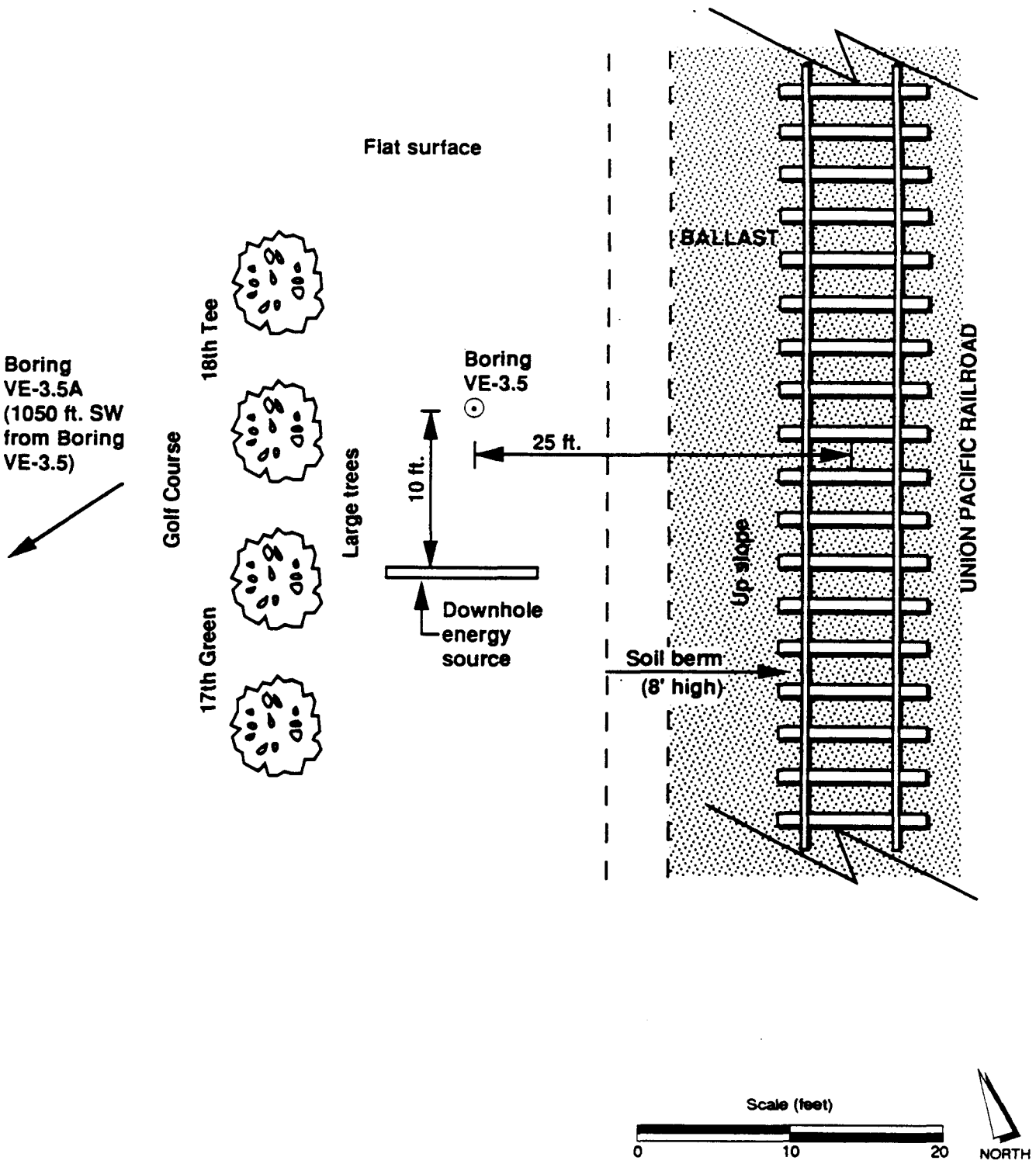
Project No.: 87-888-0011

RTK Joint Venture

Site VF-1.7 Map

12-89

Figure 3-2



The Earth Technology Corporation

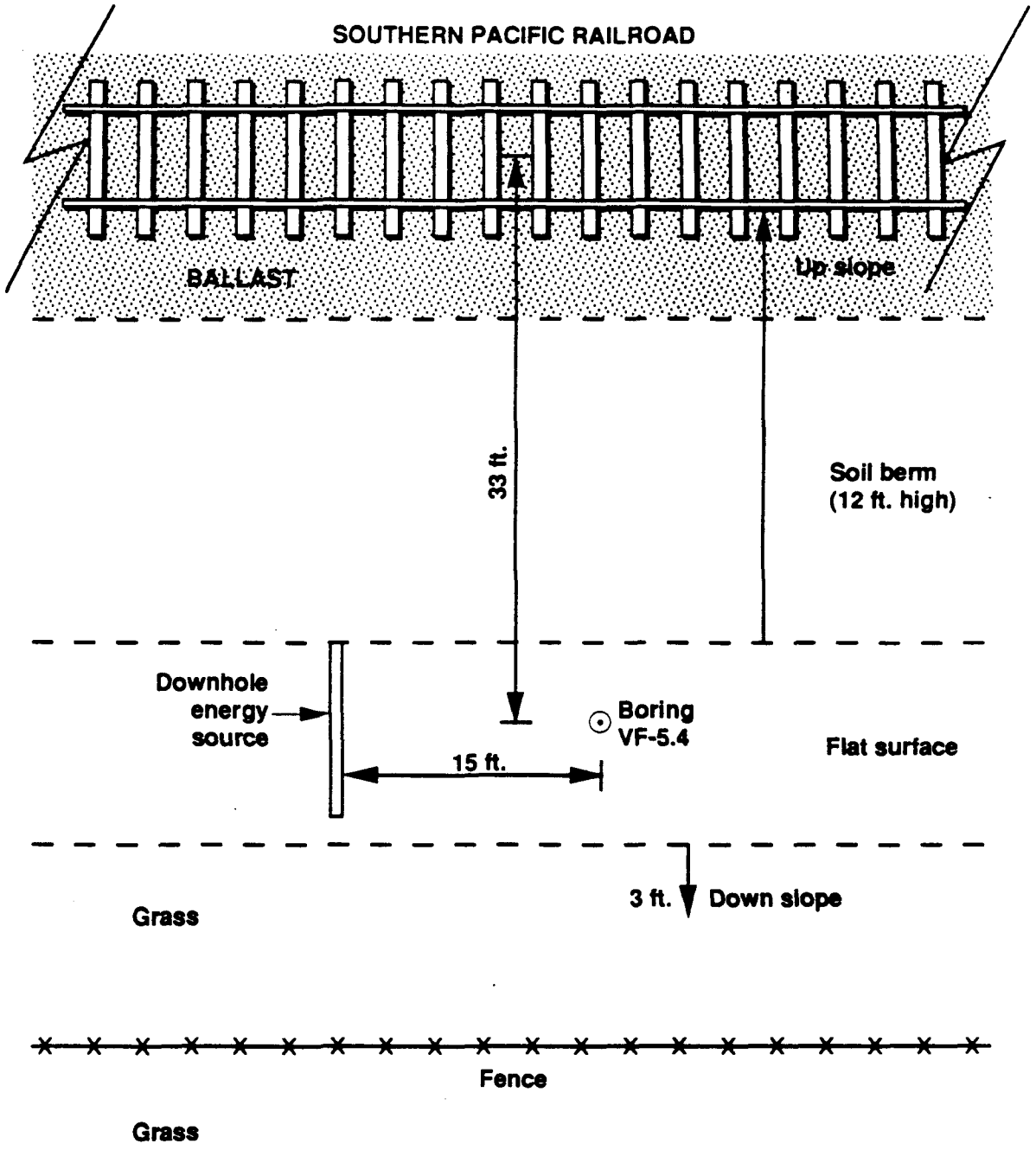
Project No.: 87-888-0011

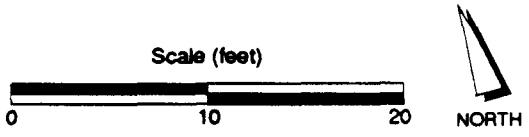
RTK Joint Venture

Sites VE-3.5 and VE-3.5A Map

12-89

Figure 3-3





The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Site VF-5.4 Map

12-89

Figure 3-4

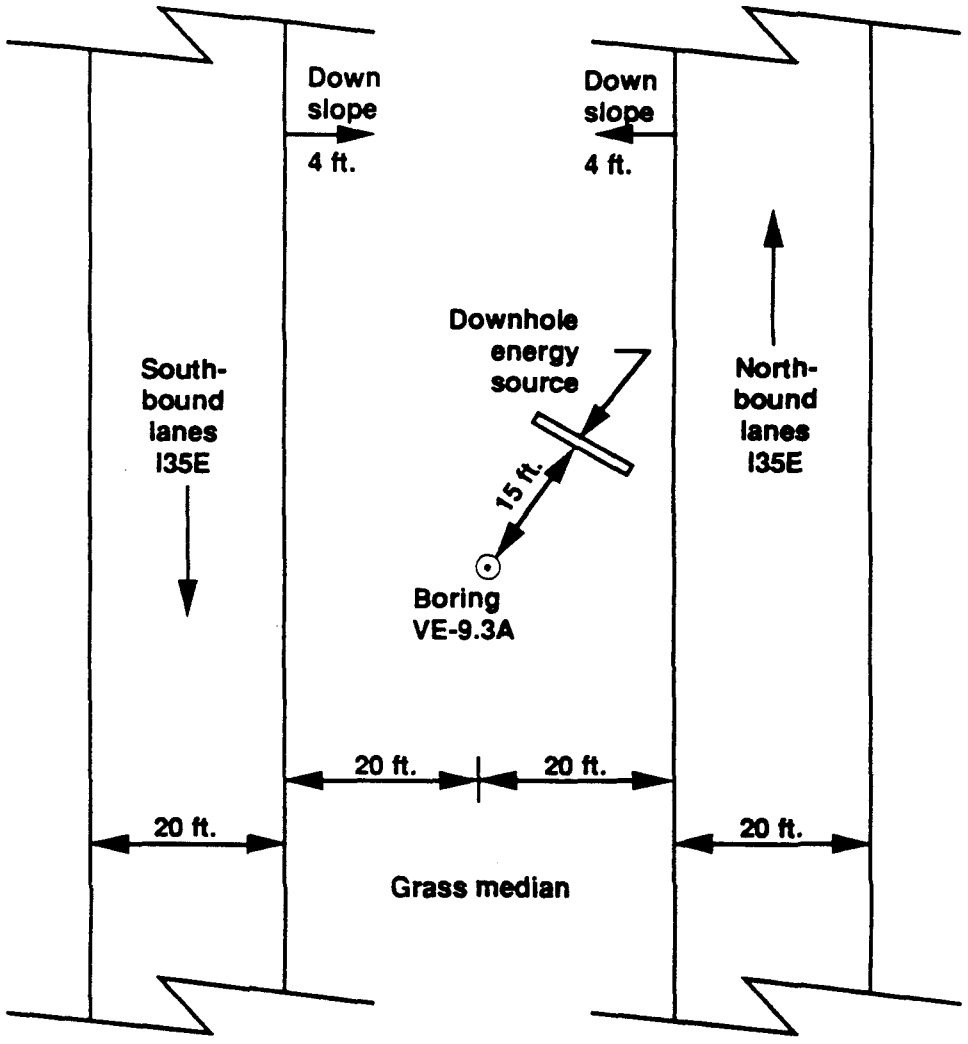
There are many loose or missing spikes. Ties were mostly covered with ballast; the exposed parts are in poor condition. Ballast was plentiful and in good condition with no obvious slumping.

- *Thick Quaternary deposits*
- *Austin Chalk*

Site VE-9.3A

Quaternary deposits, consisting of silty clay, are 18 feet (5.5 meters) thick at this site. Water was encountered at a depth of 9 feet (2.7 meters). A gravel layer exists between the depths of 18 and 20 feet (5.5 and 6.1 meters). Severely weathered Austin Chalk lies between the depths of 20 and 28 feet (6.1 and 8.5 meters). Underlying fresh Austin Chalk, with occasional shale layers, is continuous to the boring termination at a depth of 172 feet (52 meters).

This site is on the center median of the north-oriented Interstate 35E highway (Figure 3-5). There are two northbound and two southbound lanes with a soil median drainage ditch that is a maximum of 4 feet (1.2 meters) deep. The highway surface is judged to be in good condition for 1 mile (1.6 kilometers) on each side of the boring.



Scale (feet)

0 20 40

NORTH

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Site VE-9.3A Map

12-89

Figure 3-5

4.0 INSTRUMENTATION

4.1 GEOPHONES

Ground vibrations were sensed by downhole geophone packages. Because geophones have only one degree of freedom, ground motion must be roughly parallel to the geophone axis to be accurately sensed. The optimum sensor for measuring vibrations would be a triaxial arrangement of mutually perpendicular geophones that could measure fractions of Hz to several hundred Hz. Such a low-frequency package is not commercially available because a package with three 1-Hz geophones would not fit within standard-diameter, engineering borings.

- *Triaxial geophones*

Vibration data were recorded using two different packages. A triaxial arrangement of Mark Products model L-10-3WD geophones (28 Hz resonant frequency) can quantitatively measure three-dimensional vibrations from 10 to greater than 400 Hz (top of Figure 4-1). Data measured with this package will show vertical and horizontal vibrations. Results of comparing the geophones' output are as expected: the maximum measured displacements were vertically oriented and occurred when surface sources were close to the borings. Therefore, the majority of the subsequent measurements were made with vertically oriented, low-frequency geophones (Mark Products model L-4C with 1-Hz resonance frequency). The advantage of these geophones (bottom of Figure 4-1) is their usable frequency span of 0.8 to 200 Hz.

- *Vertical, 1-Hz geophone*

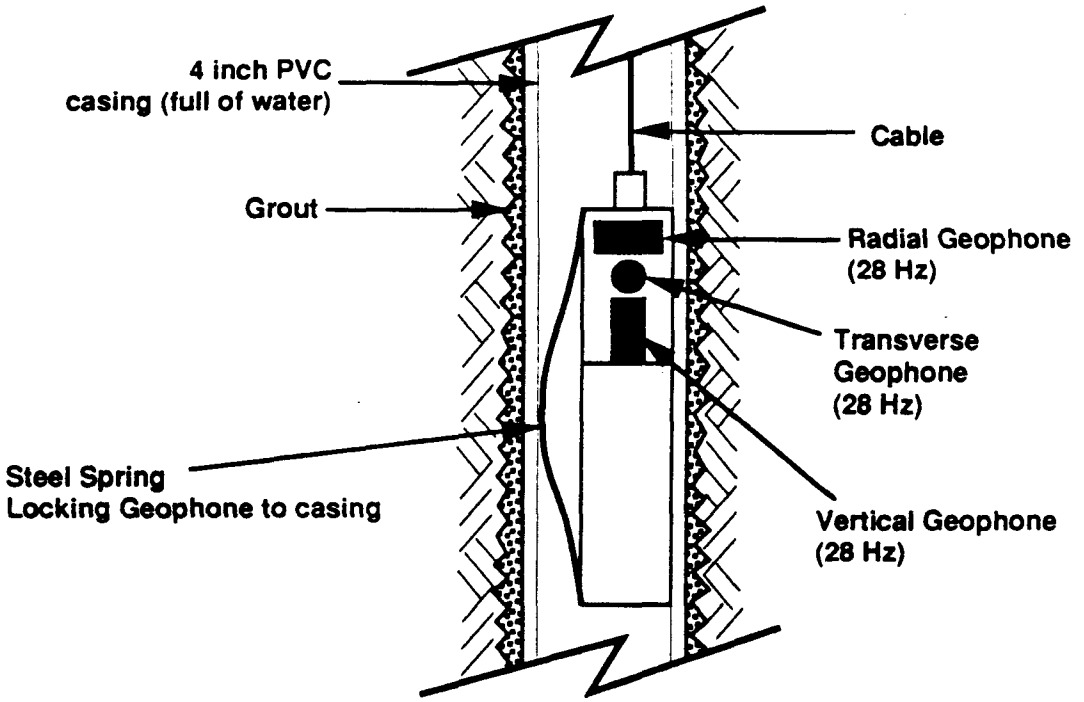
All geophone packages were calibrated at the University of Texas (Austin) using the standard shake table test. Test procedures and resulting geophone calibration curves are described in Appendix A. Composite curves for the 1-Hz geophones show that their response is almost flat for frequencies greater than 5 Hz.

- *Locking mechanism*

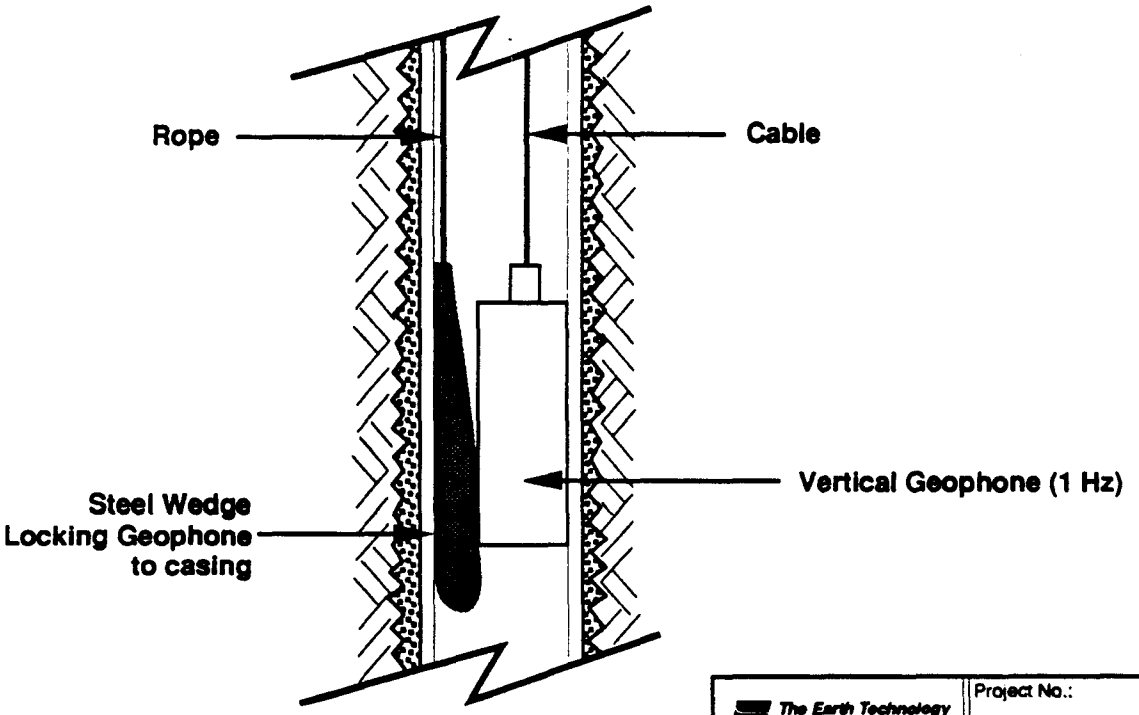
Geophone packages must be held tightly against the casing to accurately measure ground vibrations. There must be no relative motion between the geophones and the formation (Hoar, 1982). Spring-loaded steel wedges were used on two triaxial packages to press the geophones against the casing. The packages' diameters were increased with duct tape until a tight fit was obtained. The tape also minimized mechanical resonance of the spring.

The 1-Hz geophones were held in place by separate steel wedges connected to a rope, thus avoiding mechanical resonance of a spring (Hoar, 1982). When the geophone was positioned at the proper depth, the wedge was quickly pulled up and snugly held the geophone in place. As a check, all tension was released from the geophone cable to see if the wedge was truly holding the geophone. This method worked so well that uncoupling the geophones was difficult. Once in place, all cables were pulled snug and held in place at the casing top with a clamp. A cloth rag was stuffed in the casing to minimize cable vibrations and acoustical noise traveling down the casing. The casing was filled with water in an attempt to reduce acoustical noise transmission.

Triaxial Geophone Package



1 Hz Vertical Geophone



The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture
Diagram of Downhole Geophone Packages	
12-89	Figure 4-1

4.2 VIBRATION SURVEY

- *Dynamic signal analyzer*

Time-series data collected for the vibration survey were recorded with a Hewlett Packard model HP-3562A Dynamic Signal Analyzer with peripheral disk drives (model HP-9122D) and plotter (model HP-7470A). This digital system can acquire, process, store, and display time and/or frequency domain data and results. The capability to process the data in real time allowed preliminary analysis in the field. Functional tests of the analyzer's operation are described in Appendix B.

The analyzer can measure two channels of data simultaneously. During this study, two analyzers were used. Geophones were electrically connected to the analyzer using twin-conductor, shielded cable. The same connecting cable was always connected to the same geophone and the same analyzer channel during the entire study. The analyzer chassis was connected to ground to minimize 60-Hz AC noise.

4.3 SEISMIC VELOCITY SURVEY

- *Seismograph*

Vertically traveling seismic waves were recorded with a 12-channel, signal enhancement seismograph, EG&G Geometrics model ES-1210F. Seismic signals were digitized and stored in memory. For a given measurement setup, waveforms from several impacts were stacked (added together) and the sum stored. Signal-to-noise ratio is increased by stacking, because background seismic noise is random and does not add at the same rate as the true signal.

During data acquisition, seismic waves were displayed on an oscilloscope. When the proper sequence of traces was displayed, a hard copy record was made with full-width timing lines. Times required for the seismic wave to travel from the point of energy generation to the geophones were measured relative to the timing lines.

Horizontally traveling waves were recorded between pairs of sites as part of the vibration survey (Section 5).

5.0 VIBRATION SURVEY

5.1 TECHNIQUE OVERVIEW

- *Statistical sampling*

This survey determined actual vibration displacements at the measurement sites for near and distant sources. Measurements made for a variety of sources are described in Table 5-1. Approximately 7 million data points were collected -- one triaxial geophone data set and four to six 1-Hz geophone data sets at each site. Considering this large database, the vibration results are thought to represent a good statistical sampling of actual conditions. Data acquisition and reduction procedures are described in detail in Appendix C.

- *Critical record selection*

Vibrations sensed by geophones are recorded as raw time-series data. Simultaneous recordings were made from geophones at two or three depths for each source. Processing all data sets was impractical and unnecessary. Two data sets with the overall largest amplitudes were chosen for each site. Next, individual records within each set were selected as representing critical segments of the overall time-series data. Usually three candidate, maximum-amplitude records were processed and the largest value reported. Processing more than one candidate record reduced the results' dependency on the selection process.

- *Formalized main processing*

The formalized processing sequence and independent check procedure are shown in Figure 5-1. During processing, the most critical step is applying the geophone calibration, which is a complex function in the frequency domain. Frequency domain processing was used because spectral representation of data and results is the most useful format for dynamic analysis (Hoar, 1982). Raw time-series data were converted to the frequency domain using a fast Fourier transform and then divided by the complex calibration function. Calibration changes the geophone output from volts to a velocity unit (inches/second). This calibrated velocity spectrum was integrated to a displacement spectrum and converted to SI units for comparison with the 39-microinch (1-micrometer) tolerance. The displacement spectrum was filtered to remove frequency components less than the lower limit of geophone calibration and the inverse fast Fourier transform applied to yield a displacement time history. The time histories have the same general shape and frequency content as the raw time-series data.

- *Independent check*

Time domain processing of the raw time-series data provided an independent check of the analyzer's operation. Time-series data were divided by a constant calibration factor (approximation of entire calibration curve) determined for each geophone and then integrated to yield displacement time history. This time history was compared to the one derived from frequency domain processing; both results have similar frequency content and differ in amplitude mostly at low frequencies because the geophone calibration curves are not linear at frequencies less than 5 Hz. Time histories were grossly similar to the raw time-series data.

- *Attenuation*

Displacement spectra at and between sites were compared on a color composite graph to qualitatively assess vertical and horizontal attenuation, respectively. Order-of-magnitude estimates were calculated using the spectral ratio technique described by Mok (1987, 1988).

Table 5-1. Description of Measured Vibration Sources

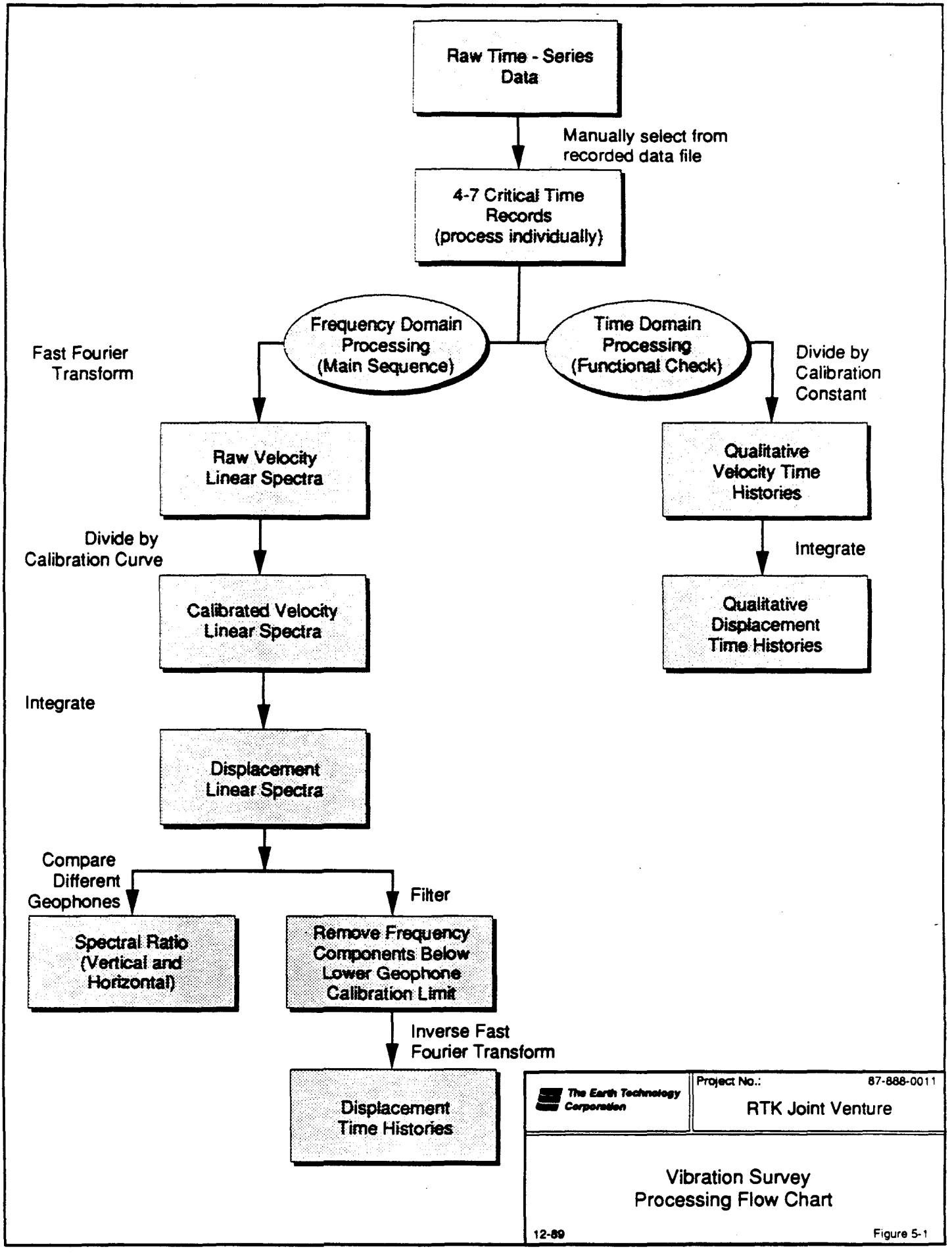
Vertically traveling waves data sets				
Measurment Data Set	Date Recorded	Geophones	Source Description	Comments
Site VF-1.7				
171	5-26-89	Triaxial	Train	Data lost
172*	5-27-89	4-1 Hz	Train	Direction NW @ about 45 mph; 3 engines + 54 RR cars, 1/3 rock (full), 1/3 coal or grain (full), 1/3 misc. (full)
173	5-29-89	4-1 Hz	Ambient	
174*	5-29-89	2-1 Hz	Train	Direction SE @ 31 mph; 4 engines + 62 RR cars, 1/2 grain (full), 1/2 auto carriers (1/2 full)
175	5-29-89	4-1 Hz	Ambient	
176	5-30-89	4-1 Hz	Ambient	
177	5-30-89	4-1 Hz	Train	Direction SE @ about 30 mph; 4 engines + 12 RR cars, all empty
178	5-30-89	4-1 Hz	Ambient	
179*	5-30-89	Triaxial	Train	Direction NW @ 38 mph; 4 engines + 39 RR cars, 1/3 tanks, 1/3 grain, 1/3 misc.
Downhole Vel.	5-30-89	Triaxial	Hammer	
Site VE-9.3A				
931	6-2-89	4-1 Hz	Traffic	North 61 cars + 13 trucks, South 64 cars + 11 trucks
932	6-2-89	4-1 Hz	Traffic	North 69 cars + 11 trucks, South 89 cars + 9 trucks
933*	6-2-89	4-1 Hz	Traffic-Quarry	North 103 cars + 3 trucks, South 98 cars + 10 trucks; TXI quarry 3500 pounds explosives
934*	6-2-89	4-1 Hz	Traffic	North 100 cars + 9 trucks, South 132 cars + 8 trucks
935	6-6-89	Triaxial	Traffic	North 14 cars + 7 trucks, South 16 cars + 4 trucks
936*	6-6-89	Triaxial	Traffic	North 23 cars + 7 trucks, South 16 cars + 7 trucks
Downhole Vel.	6-6-89	Triaxial	Hammer	
Site VE-3.5				
351	6-3-89	4-1 Hz	Ambient	
352*	6-5-89	4-1 Hz	Train	Direction north @ > 40 mph; 3 engines + 57 RR cars, 1/2 flat (empty), 1/4 tank, 1/4 grain
353	6-5-89	4-1 Hz	Quarry	TXI quarry; 3460 pounds explosives
354	6-5-89	4-1 Hz	Train	Direction north @ 32 mph; 1 engine + 19 RR cars, all empty
355	6-5-89	4-1 Hz	Train	Direction north @ about 30 mph; 2 engines + 31 RR cars, 1/2 misc. (full), 1/2 misc. (empty)
356*	6-5-89	4-1 Hz	Train	Direction south @ unknown mph; 2 engines + 30 RR cars, 1/2 flat (1/2 full), 1/2 misc. (1/2 full)
357	6-6-89	4-1 Hz	Train	Direction south @ 25 mph; 1 engine + 17 RR cars, all grain (empty)
358*	6-6-89	Triaxial	Train	Direction north @ 43 mph; 7 engines + 36 RR cars, 1/2 grain (full), 1/2 tank (full)
359	6-6-89	4-1 Hz	Train	Direction south @ about 10 mph; 3 engines + 72 RR cars, 1/2 grain and tank (full), 1/2 misc. empty
Downhole Vel.	6-7-89	Triaxial	Hammer	
Site VF-5.4				TXI quarry; 5858 pounds explosives
541	6-9-89	4-1 Hz	Quarry	Direction NW @ 40 mph; 2 engines + 41 RR cars, 1/2 grain (full), 1/4 tank (full), 1/4 box (full)
542*	6-9-89	4-1 Hz	Train	Direction SE @ 20 mph; 5 engines + 106 RR cars, all coal (full)
543*	6-21-89	Triaxial	Train	Direction SE @ 10-15 mph; 3 engines + 101 RR cars, all coal (full)
544*	6-22-89	2-1 Hz	Train	Direction SE @ < 10 mph; 1 engine + 7 RR cars, all rock (full)
545	6-22-89	2-1 Hz	Train	Direction NW @ < 5 mph; 3 engines + 30 RR cars, all box cars
546	6-22-89	2-1 Hz	Train	Direction NW @ < 2 mph; 2 engines + 29 RR cars, 1/2 coal (full), 1/2 box (full)
547	6-23-89	2-1 Hz	Train	Direction SE @ 10-15 mph; 5 engines + 126 RR cars, all coal (full)
549	6-23-89	2-1 Hz	Train	
Downhole Vel.	6-21-89	Triaxial	Hammer	

* Data sets processed

Table 5-1. Description of Measured Vibration Sources (Cont.)

Horizontally traveling waves data sets				Comments
Measurement Data Set	Date Recorded	Geophones	Source Description	
Sites VE-3.5 & VE-3.5A				
3510*	6-13-89	4-1 Hz	Train	Direction SE @ about 40 mph; 5 engines + 84 RR cars, all grain (full)
3511	6-13-89	4-1 Hz	Train	Direction NW @ about 30 mph; 1 engine + 24 RR cars, all flat (1/2 full)
3512	6-13-89	Triaxial	Train	Direction SE @ about 35 mph; 5 engines + 107 RR cars, all grain (full)
Sites VE-3.5 & VF-1.7				
35A17	6-14-89	4-1 Hz	Quarry	Blasted early, no data
3517B	6-14-89	4-1 Hz	Quarry	Blasted early, no data
35A171*	6-20-89	4-1 Hz	Quarry	TXI quarry; 4243 pounds explosives
3517B1*	6-20-89	4-1 Hz	Quarry	TXI quarry; 4243 pounds explosives
Sites VF-5.4 & VF-1.7				
54A171*	6-23-89	4-1 Hz	Quarry	TXI quarry; 2108 pounds explosives
5417B1*	6-23-89	4-1 Hz	Quarry	TXI quarry; 2108 pounds explosives

* Data Sets Processed


Raw Time - Series Data
Manually select from recorded data file
4-7 Critical Time Records (process individually)
Frequency Domain Processing (Main Sequence)
Time Domain Processing (Functional Check)
Fast Fourier Transform
Divide by Calibration Constant
Raw Velocity Linear Spectra
Qualitative Velocity Time Histories
Divide by Calibration Curve
Integrate
Calibrated Velocity Linear Spectra
Qualitative Displacement Time Histories
Integrate
Displacement Linear Spectra
Compare Different Geophones
Filter
Spectral Ratio (Vertical and Horizontal)
Remove Frequency Components Below Lower Geophone Calibration Limit
Inverse Fast Fourier Transform
Displacement Time Histories
The Earth Technology Corporation
Project No.: 87-888-0011
RTK Joint Venture
Vibration Survey Processing Flow Chart
12-89
Figure 5-1

Data and processed spectra for near-source data sets are shown in Appendices E through H; distant-source data sets are shown in Appendices I through K. Results are in rough agreement with previous studies (Lesmes and Morgan, 1988; Goss, 1989). Results are shown in Table 5-2 and described below.

5.2 NEAR-SOURCE RESULTS

In general, the near-source displacement spectra show relatively low-amplitude, high-frequency vibrations at tunnel depth as compared to the distant source data. Displacement spectra and time histories are very complex, as would be expected from train and traffic data (line source consisting of multiple point sources). Ambient vibrations are generally less than one one-hundredth of the 1-micrometer tolerance.

- *Largest train-induced displacement at tunnel depth*

Site VF-1.7
Triaxial geophone data show that the vertical geophone's output is larger than either horizontal geophone's output whether the train is near or distant from the boring. Maximum displacements measured with the lower 1-Hz geophone are about 16 microinches (0.42 micrometers), which represent the largest displacements measured at tunnel depth generated by a train during this survey. Vertical attenuation is the largest measured during this survey, primarily due to the thick, unconsolidated Quaternary deposits (21 feet [6.4 meters] thick). Wave attenuation through 26 feet (7.9 meters) of chalk is about 8 times less than that through surface deposits.

Site VE-3.5
Triaxial geophone data show that the vertical geophone's output is larger than either horizontal geophone's output when the train is near the boring. All three geophones' outputs are very similar when the train is distant from the boring. Maximum displacements measured with the lower 1-Hz geophone are about 6 microinches (0.15 micrometers). Vertical attenuation is relatively large because of the unconsolidated Quaternary deposits (7.5 feet [2.3 meters] thick) and an underlying weathered Austin Chalk layer (2.5 feet [0.76 meters] thick). Wave attenuation through 70 feet (21 meters) of fresh chalk is similar to that through surface deposits plus the weathered chalk.

Site VF-5.4
Triaxial geophone data show that the vertical geophone's output is larger than either horizontal geophone's output whether the train is near or distant from the boring. The shallow 1-Hz geophone, at a depth of 5 feet (1.5 meters), recorded a single displacement peak of 94 microinches (2.4 micrometers) at 5.6 Hz from a train passage (data set 4). This peak is the only displacement measured at any depth to exceed the 1-micrometer tolerance during this survey. Maximum displacements measured with the lower 1-Hz geophone are about the same as those measured at VE-3.5. Wave attenuation is large because of thick unconsolidated Quaternary deposits (22.5 feet [6.9 meters]). Vertical attenuation in the marl is similar to that in the fresh chalk.

TABLE 5-2. VIBRATION SURVEY RESULTS

NEAR SOURCE	VF-1.7	VE-3.5	VF-5.4	VE-9.3A
TRIAXIAL GEOPHONE DATA				
Geophone depth in feet (meters)	64 (19.5)	78 (23.8)	245 (74.7)	165 (50.3)
Distance between boring and start of intermediate field* in feet (meters)	1400 (427)	1600 (488)	2600 (792)	-
Vertical: Horizontal displacements with train at boring	8:1	3:1	10:1	3:1
Vertical: Horizontal displacements when train distant from boring	2:1	1:1	2:1	-
Increase in vertical displacement from intermediate to near field	150 times	50 times	100 times	-
1-HZ GEOPHONE DATA				
Geophone depth in feet (meters)	64 (19.5)	77 (23.5)	253 (77.1)	166 (50.6)
Frequency span in Hz containing most displacement peaks	0.8-12.5	0.8-15.5	2.0-9.5	0.8-18.0
Max displacement in microinches (micrometers) @ frequency in Hz	16 (0.41) @ 2.8 12 (0.31) @ 2.5	6 (0.15) @ 4 4 (0.09) @ 2	9 (0.22) @ 5.5 5 (0.13) @3	0.1 (0.004) @ 16-18
Near-field: Ambient displacement	10:1	10:1	10:1	5:1
Estimated "Bulk" attenuation constant** in sec/ft (sec/km)	35×10^{-4} (12.0)	7.0×10^{-4} (2.0)	-	2.0×10^{-4} (0.8)
Estimated "Rock" attenuation constant*** in sec/ft (sec/km)	-	9.0×10^{-4} (3.0)	10×10^{-4} (3.1)	5.0×10^{-4} (1.7)

DISTANT SOURCE	VE-3.5 to VE-3.5A	VF-1.7 to VE-3.5	VF-1.7 to VF-5.4
1-HZ GEOPHONE DATA			
Geophone depth in feet (meters)	VE-3.5 76(23.2) VE-3.5A 97(29.6)	VF-1.7 62(18.9) VE-3.5 19(5.8)	VF-1.7 63(19.2) VF-5.4 245(74.7)
Distance between sites in feet (meters)	1050 (320)	38,400 (11,704)	80,000 (24,384)
Frequency span in Hz containing most displacement peaks	0.8-37.0	0.8-5.0	0.8-4.0
Max displacement in microinches (micrometers) @ frequency in Hz	VE-3.5 6 (0.15) @ 9 VE-3.5A 11 (0.03) @ 11	VF-1.7 37(0.94) @ 1 VE-3.5 7(0.19) @ 1	VF-1.7 24 (0.60) @ 1.5 VF-5.4 3 (0.07) @1
Maximum: Ambient displacement	15:1	8:1	6:1
Near: Distant source displacements	4:1	5:1	10:1
Estimated attenuation constant for P wave in sec/ft (sec/km) in rock	-	0.10×10^{-4} (0.04)	0.02×10^{-4} (0.01)
Estimated attenuation constant for S wave in sec/ft (sec/km) in rock	-	0.04×10^{-4} (0.01)	0.10×10^{-4} (0.03)
Estimated attenuation constant for large amplitude wave in sec/ft (sec/km) in rock	-	0.27×10^{-4} (0.09)	0.05×10^{-4} (0.02)

*Start of intermediate field is when the train is close enough to the geophones to contribute to measured vibration levels. This point is defined with 1 Hz geophone data (Appendix C).
**"Bulk" attenuation estimated between the near-surface and tunnel depth geophones. Estimate probably violates far-field assumptions.
***"Rock" attenuation estimated between top of rock and tunnel depth geophones.

Site VE-9.3A

- *Very low traffic displacement*

Triaxial geophone data show the vertical geophone's output to be larger than either horizontal geophone's output. Maximum displacements measured with the lower 1-Hz geophone are less than 0.39 microinch (0.01 micrometer). Wave attenuation is relatively large because of thick Quaternary deposits (18 feet [5.5 meters]). Vertical attenuation through 116 feet (35 meters) of chalk is about 2 times less than that through surface deposits.

5.3 DISTANT-SOURCE RESULTS

In general, the distant-source displacement spectra contained large-amplitude, low-frequency vibrations at tunnel depth as compared to the near-source data. Displacement spectra and time histories were relatively uncomplicated because they consisted of only a few superimposed, low-frequency seismic waves. The constant phase shift between the displacement histories and raw time-series data is caused by a phase shift increase in the frequency filter at low frequencies.

Sites VE-3.5 and VE-3.5A

- *Vertical attenuation controlling factor*

Simultaneous measurements were made at sites VE-3.5 and VE-3.5A as a train passed by VE-3.5. Maximum displacements at VE-3.5 are similar to those already discussed. Attenuation cannot be reliably estimated because the ratio of inter-boring distance relative to the source-to-VE-3.5 distance is too large (violates far-field assumptions). Qualitative comparisons can be made from the composite spectra. Maximum displacements at VE-3.5A are about one-fourth the displacements measured at VE-3.5. Horizontal attenuation is relatively small compared to the vertical attenuation measured at VE-3.5. Therefore, vertical attenuation might be the controlling factor in determining the distance at which train vibrations may affect machine operation.

Sites VF-1.7 and VE-3.5

- *Largest blast-induced displacement at tunnel depth*

Simultaneous measurements were made at sites VF-1.7 and VE-3.5 on the north edge of the ring from a TXI quarry blast (Figure 1-1). The P and S waves generated by the blast arrived at Site VF-1.7 with little time difference and appear on the same data record. Accordingly, the displacements generated by these two waves were combined during processing. Blasting caused the maximum displacement of 39 microinches (1 micrometer) at VF-1.7 as measured by this survey. Maximum displacements at VE-3.5 are about one-fifth the displacements measured at VF-1.7. High-frequency vibrations (greater than 5 Hz) have been severely attenuated because of the long travel paths from the quarry to each site. Horizontal attenuation is about one fiftieth of the vertical attenuation measured at these two sites.

Sites VF-1.7 and VF-5.4

Simultaneous measurements were made across the ring at sites VF-1.7 and VF-5.4 from a TXI quarry blast (Figure 1-1). The maximum displacement of 23 microinches (0.6 micrometer) was measured at VF-1.7. (The displacement is smaller then measured previously during the VF-1.7 to VE-3.5 data set because only half the amount of explosives were detonated, Table 5-1.) Maximum displacement at VF-5.4 is about ten times smaller than that measured at VF-1.7. Horizontal attenuation is about one one-hundredth of the vertical attenuation measured at these two sites.

6.0 SEISMIC VELOCITY SURVEY

6.1 TECHNIQUE OVERVIEW

Seismic waves were measured over known distances to determine in situ P and S wave velocities. Vertically traveling waves were generated at the surface and recorded at a number of depths in borings. Wave travel times were measured from the data records and plotted versus measurement depth. Velocity zones were interpreted from these data.

Seismic energy was also generated at the TXI quarry and the resulting horizontally traveling waves were recorded simultaneously in several pairs of borings as part of the vibration survey. Wave arrivals were identified from the raw time data and used with the boring-to-boring distances to calculate velocities.

Dynamic elastic moduli were calculated from the interpreted velocities. Data acquisition and reduction procedures are described in Appendix D.

6.2 RESULTS

Data and interpreted velocity profiles for each site are shown in Appendices E through H. Velocities (vertical and horizontal) and dynamic elastic moduli are shown in Table 6-1. In general, velocities are highly variable within each formation. Velocities of vertically traveling waves increase with depth. Quaternary deposits have velocities two to three times lower than those of weathered rock. Velocities recorded in the Taylor Marl are slightly lower than those recorded in the Austin Chalk. Velocities in the Austin Chalk at site VF-1.7 are much lower and attenuation coefficient estimates are much higher than those measured at sites VE-3.5 and VE-9.3A, which is in agreement with Goss (1989). The chalk may be more fractured at VF-1.7, causing the velocity anomaly.

- *Velocities and moduli agree with other studies*

These interpreted velocities are in rough agreement with results from previous studies (Goss, 1989). Calculated elastic moduli are similar to those measured in the laboratory, except that Poisson's ratio is two to three times higher than that measured in the laboratory (Earth Technology, 1989f).

- *Surface deposits trap energy*

Low-velocity (and low-density) Quaternary deposits are quite thick at several sites. About two-thirds of the seismic wave amplitude is reflected upward from the rock interface because of the large velocity difference between the surface deposits and the rock. Displacements are low at tunnel depth because most of the seismic energy from trains and traffic is 'trapped' and attenuated in the upper deposits.

Table 6-1. Seismic Velocity Survey Results

Site	Depth Range		Geological Formation	Velocities						Bulk Density	Poisson's Ratio	Dynamic Elastic Moduli		
				P		S		R						
	Feet	(Meters)		f/s	(m/s)	f/s	(m/s)	f/s	(m/s)	p/f^3		Young's $x10^5$ psi	Shear $x10^5$ psi	Constrained $x10^5$ psi
Vertically Traveling Waves														
VF-1.7	0-13	(0-4)	Quaternary Deposits	1450	(442)	500	(152)	470	(143)	129.7	0.433	0.20	0.07	0.59
	13-45	(4-14)	Austin Chalk	3600	(1097)	2050	(625)	1900	(579)	134.7	0.260	3.08	1.22	3.77
	45-65	(14-20)	Austin Chalk	5700	(1737)	3300	(1006)	3000	(914)	134.7	0.248	7.91	3.17	9.45
VE-3.5	0-7	(0-2)	Quaternary Deposits	1200	(366)	750	(229)	680	(208)	129.7	0.179	0.37	0.16	0.40
	7-31	(2-9)	Austin Chalk	4600	(1402)	2900	(884)	2650	(808)	134.7	0.170	5.73	2.45	6.16
	31-78	(9-24)	Austin Chalk	8900	(2713)	5100	(1554)	4750	(1448)	134.7	0.256	19.00	7.57	23.05
VF-5.4	0-23	(0-7)	Quaternary Deposits	2100	(640)	500	(152)	480	(146)	129.7	0.470	0.21	0.07	1.23
	23-110	(7-34)	Taylor Marl	5700	(1737)	2500	(762)	2350	(716)	139.2	0.381	5.19	1.88	9.77
	110-260	(34-79)	Taylor Marl	6800	(2073)	3700	(1128)	3450	(1052)	139.2	0.290	10.62	4.11	13.90
VE-9.3A	0-12	(0-4)	Quaternary Deposits	1320	(402)	420	(128)	400	(122)	129.7	0.444	0.14	0.05	0.49
	12-89	(4-27)	Austin Chalk	4900	(1494)	2300	(701)	2150	(655)	134.7	0.359	4.18	1.54	6.99
	89-165	(27-50)	Austin Chalk	8300	(2530)	4000	(1219)	3750	(1143)	134.7	0.349	12.56	4.66	20.04
Horizontally Traveling Waves														
VF-1.7 and VE-3.5	-	(-)	Austin Chalk	10700	(3261)	4550	(1387)	4250	(1295)	134.7	0.389	16.74	6.02	33.31

Explanation

f/s = Feet per second
(m/s) = Meters per second
p/f^3 = Pounds per cubic feet
psi = Pounds per square inch

7.0 REFERENCES

Earth Technology, 1988. A Plan for Startup Geotechnical Characterization of the Texas SSC Site, Long Beach, California, Report prepared for RTK Joint Venture.

Earth Technology, 1989a. Work Description - Geophysical Testing, Long Beach, California, Report prepared for RTK Joint Venture.

Earth Technology, 1989b. Data Report for Vibration Monitoring Hole VF-1.7, Long Beach, California, Report prepared for RTK Joint Venture.

Earth Technology, 1989c. Data Report for Vibration Monitoring Holes VE-3.5 and VE-3.5A, Long Beach, California, Report prepared for RTK Joint Venture.

Earth Technology, 1989d. Data Report for Vibration Monitoring Hole VF-5.4, Long Beach, California, Report prepared for RTK Joint Venture.

Earth Technology, 1989e. Data Report for Vibration Monitoring Holes VE-9.3 and VE-9.3A, Long Beach, California, Report prepared for RTK Joint Venture.

Earth Technology, 1989f. Data Report for Corehole BK1', Long Beach, California, Report prepared for RTK Joint Venture.

Goss, D., 1989. Some Characteristics of Ground Vibrations at the SSC Site, SSC-N-635, SSC Labs, Berkeley, California.

Heiland, C.A., 1963. Geophysical Exploration, Hofner Publishing Co., New York, New York.

Hewlett Packard, 1985. The Fundamentals of Signal Analysis, Application Note 243, Palo Alto, California.

Hoar, R.J., 1982. Field Measurement of Seismic Wave Velocity and Attenuation for Dynamic Analysis, Ph.D Thesis, Geotechnical Engineering Center, Civil Engineering Department, University of Texas, Austin.

Lesmes, D., D. Morgan, et al., 1988. Dallas SSC Site Vibration Study, Department of Engineering Geoscience, Texas A&M University, Byran.

Mok, Y.J., 1987. Analytical and Experimental Studies of Borehole Seismic Methods, Ph.D Thesis, Geotechnical Engineering Center, Civil Engineering Department, Univeristy of Texas, Austin.

Mok, J.M., 1988. In Situ Damping Measurements by Crosshole Seismic Method, American Society of Civil Engineers, Specialty Conference on Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground Motion Evaluation, Park City, Utah.

Nazarian, S., 1984. In-Situ Determination of Elastic Moduli of Soil Deposits and Pavement Systems by Spectral-Analysis-of-Surface-Waves Method, PhD Thesis, Geotechnical Engineering Center, Civil Engineering Department, University of Texas, Austin.

Ng, K.Y., and J.O. Petersen, 1989. Ground Motion Effects on the SSC, SSC-212, SSC Labs, Berkeley, California.

Sanchez-Salinero, I., J.M. Roesset, and K.H. Stokoe, 1986. Analytical Studies of Body Wave Propagation and Attenuation, Geotechincal Engineering Report GR86-15, Geotechnical Engineering Center, Civil Engineering Department, University of Texas, Austin.

SSC Labs, 1989. Ground Motion Study, in SSC Monthly Report, January, 1989, Berkeley, California.

Stokoe, K.H., G.J. Rix, and Y-J. Mok, 1987. Field Measurements of Ground Borne Vibrations Resulting from Railroad Operations near Chapel Hill, Tennesse, Geotechnical Engineering Report GR87-6, Geotechnical Engineering Center, Civil Engineering Department, University of Texas, Austin.

State of Tennessee, 1987. Tennessee SSC Site Proposal, Vol. 7 - Regional Conditions at Site 15, Chapel Hill, Tennesse.

Texas National Research Laboratory Commission, 1987. SSC Dallas-Fort Worth Site Proposal, Austin, Texas.

The Earth Technology Corporation; see Earth Technology.

U.S. Department of Energy, 1987. Invitation for Site Proposal for the Superconducting Super Collider (SSC), DOE/ER-0315, Section C5 - Vibration Criteria, Office of Energy Research, SSC Site Task Force, Washington D.C.

APPENDIX A

GEOPHONE CALIBRATION PROCEDURES AND RESULTS

A1.0 PROCEDURES

- *Physical properties*

A geophone is calibrated by measuring three of its physical properties: natural frequency, transductivity, and damping. Natural frequency is the undamped resonant frequency of the system. Transductivity is the proportionality between the geophone's output voltage signal and the actual amplitude of particle velocity. Damping indicates attenuation of geophone motion with time.

Geophone frequency response H(f) for a given frequency (f) is expressed below.

$$H(f) = \frac{r^2}{(1 - r^2) + i\,(2Dr)}$$

where:

$r = f/f_n$

f_n = natural frequency

$i = \sqrt{-1}$

$D = c/C_c$ (damping ratio)

c = damping at frequency f

C_c = critical damping

- *Complex function*

The response is a complex quantity that can be represented by real (magnitude) and imaginary (phase) parts. Magnitude, M(f), and phase angle, θ(f), are calculated from the following equations:

$$M(f) = \frac{r^2}{\sqrt{(1 - r^2)^2 + (2Dr)^2}}$$

$$\theta(f) = \arctan\left(\frac{2Dr}{1 - r^2}\right)$$

These quantities are measured for one frequency at a time across the geophone's usable frequency span. A composite calibration curve is assembled from these single measurements. Both the magnitude and phase MUST be used to calibrate the geophone's voltage output. If only the magnitude is used, then the data spectrum will be seriously distorted.

- *Shake table*

The measurement process consists of several steps. First, the geophone and a reference transducer (accelerometer or proximeter) are secured to a shake table. An accelerometer accurately measures particle acceleration at frequencies from 5 Hz up to several thousand Hz and was used to calibrate the triaxial geophones (28 Hz resonant frequency). A proximeter accurately measures particle displacement at frequencies from a fraction of 1 Hz to about 100 Hz and was used to calibrate the 1-Hz geophones.

The shake table is vibrated by a function generator in a swept-sine mode. One frequency at a time is excited and the geophone and reference transducer outputs are recorded. Accelerometer data must be integrated and proximeter data differentiated before comparison with the geophone's velocity data. Frequency response spectra are calculated as a ratio of geophone output (volts) to reference transducer adjusted output (inches/second).

- *Curve fit*

A curve fit function was calculated from the actual shake table test data. The fit function was constrained to one pole (complex pair) and one zero (fixed at 0.0 Hz) because the geophone has only one degree of freedom. Calibration curves can be synthesized from these curve fit parameters for the specific frequency span used to collect the vibration data.

A2.0 RESULTS

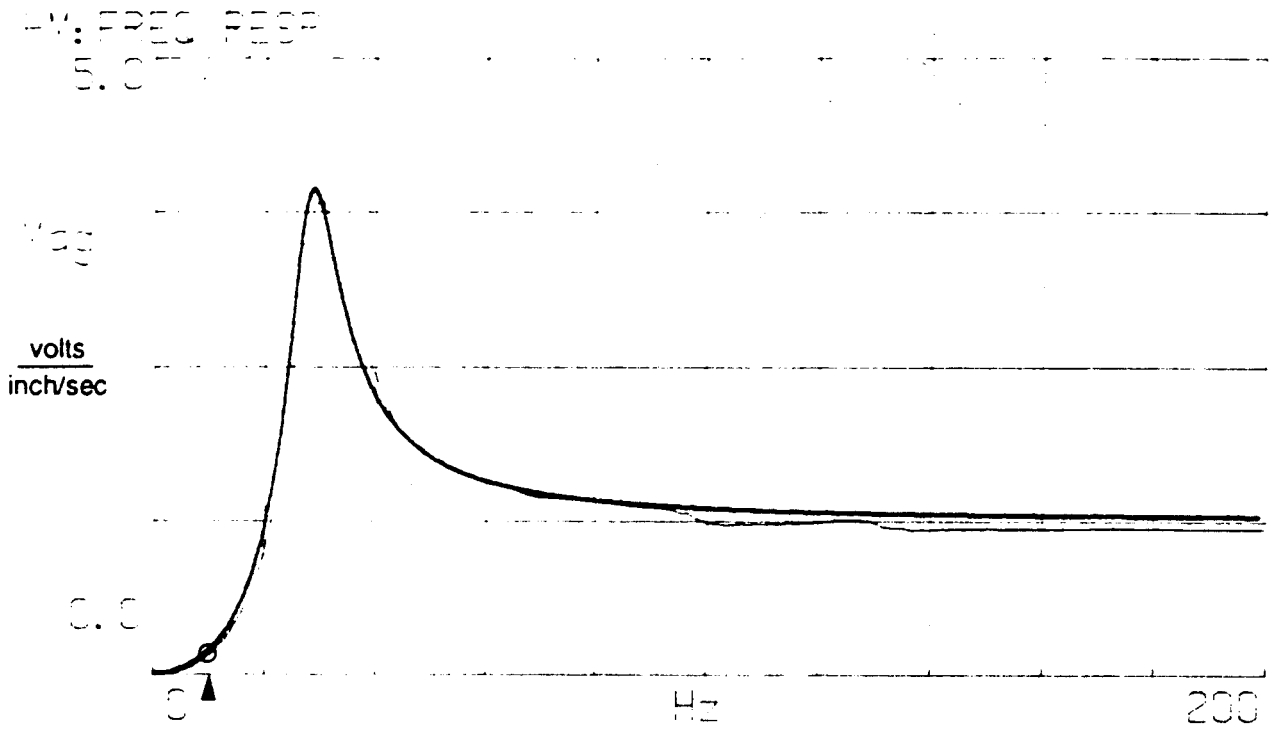
- *Calibration curves*

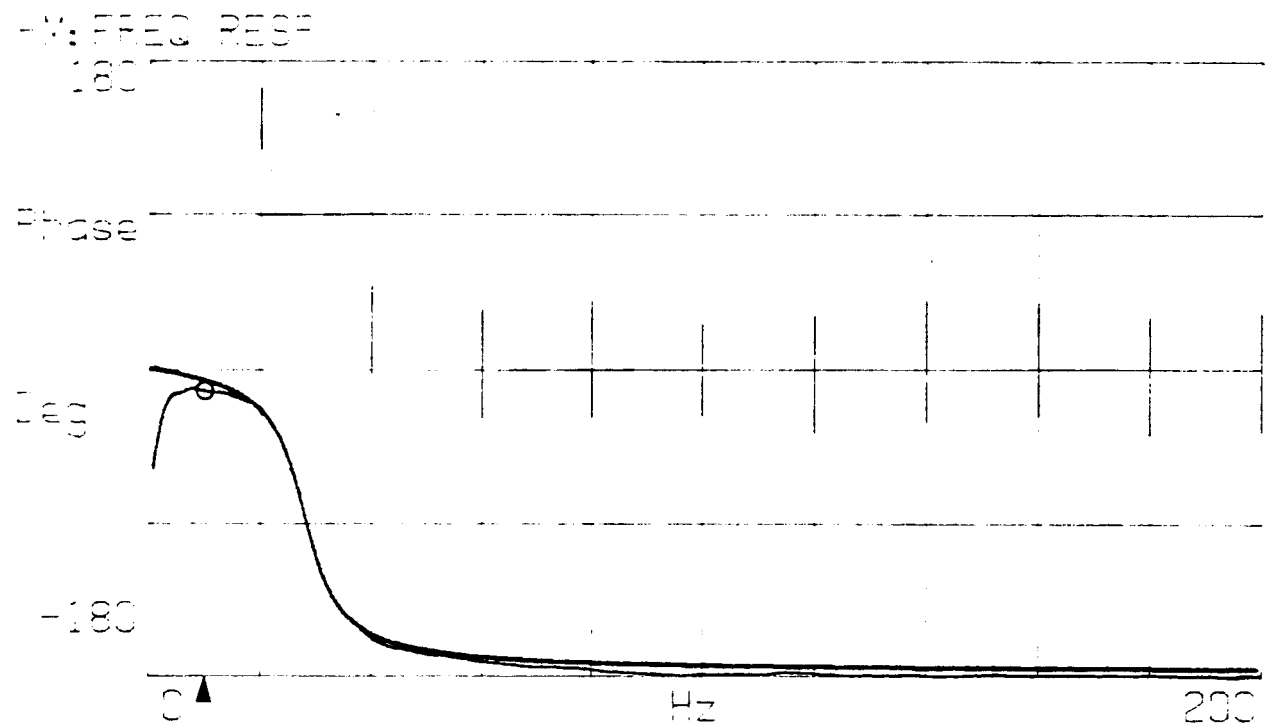
Calibration curves for two triaxial geophone packages are shown in Figures A-1 through A-6. Curve fit parameters are shown on the figures. The lower limit of calibration is 10 Hz and the upper limit is greater than 200 Hz. The geophones have very similar frequency responses, as shown by the composite spectra (Figures A-7 and A-8).

Calibration curves of four 1-Hz geophones are shown in Figures A-9 through A-12. Curve fit parameters are shown on the figures. The lower limit of calibration is 0.8 Hz and the upper limit is greater than 200 Hz. The geophones have very similar frequency responses, as shown by the composite spectra (Figure A-13).

- *Spectral distortion*

Notice that magnitude and phase of the 1-Hz geophones do not become constant until about 5 Hz. Serious spectral distortion at frequencies less than 5 Hz will occur if the entire complex calibration function is not used to calibrate raw data. Most maximum displacements measured during this survey occurred in the 0.8-5 Hz frequency span.





EXPLANATION

28 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = -4.55082 Hz ± j 28.4194 Hz
Gain = -1.228 $\frac{\text{volts}}{\text{inch/sec}}$

Lower Frequency Limit of Calibration

The Earth Technology Corporation

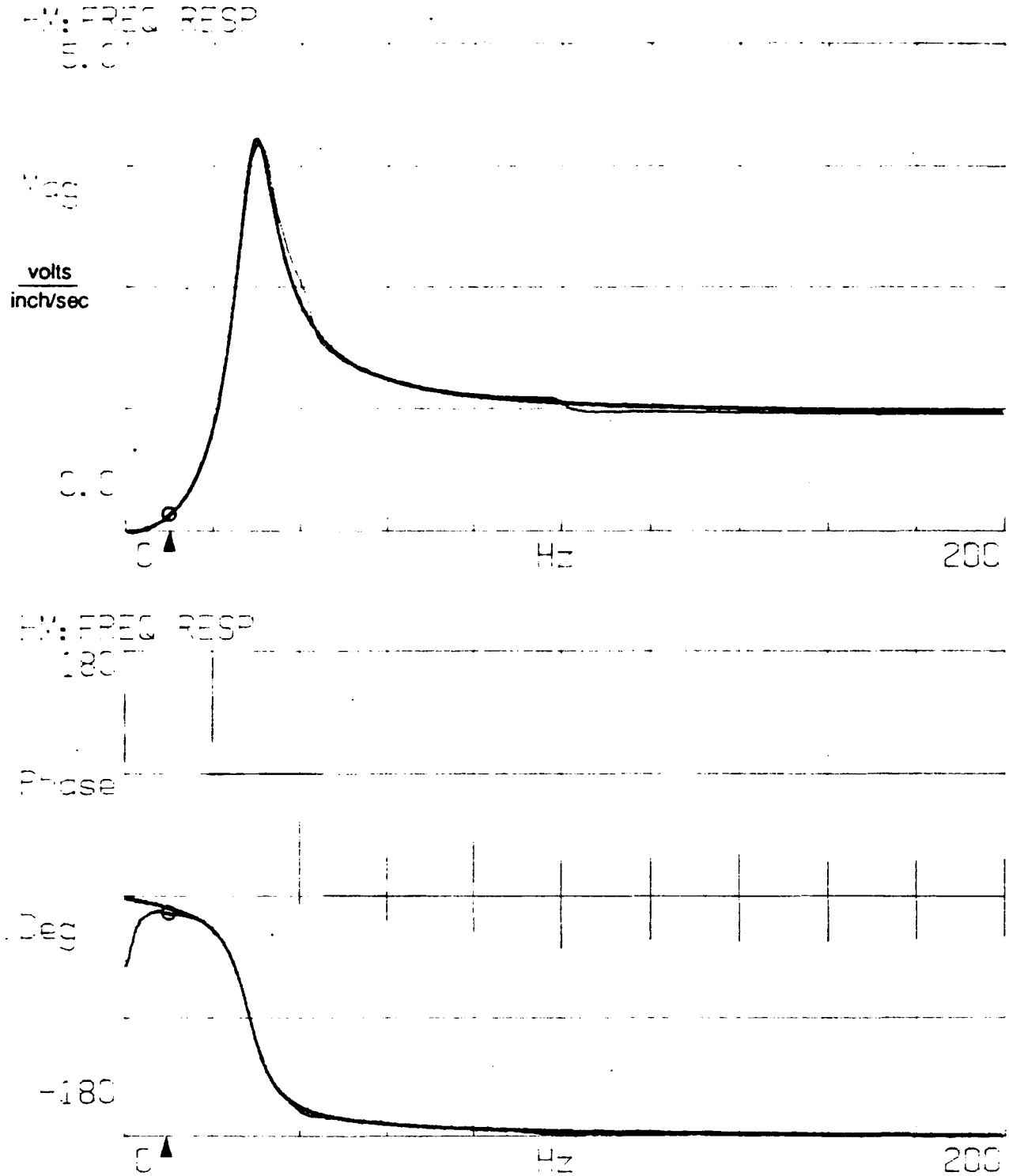
Project No.: 87-888-0011

RTK Joint Venture

Calibration Curve
Triaxial Geophone Package No. ET-1
Radial Geophone

12-89

Figure A-2



EXPLANATION

28 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = -4.48773 Hz $\pm$ j 28.8586 Hz
Gain = -1.228 $\frac{\text{volts}}{\text{inch/sec}}$

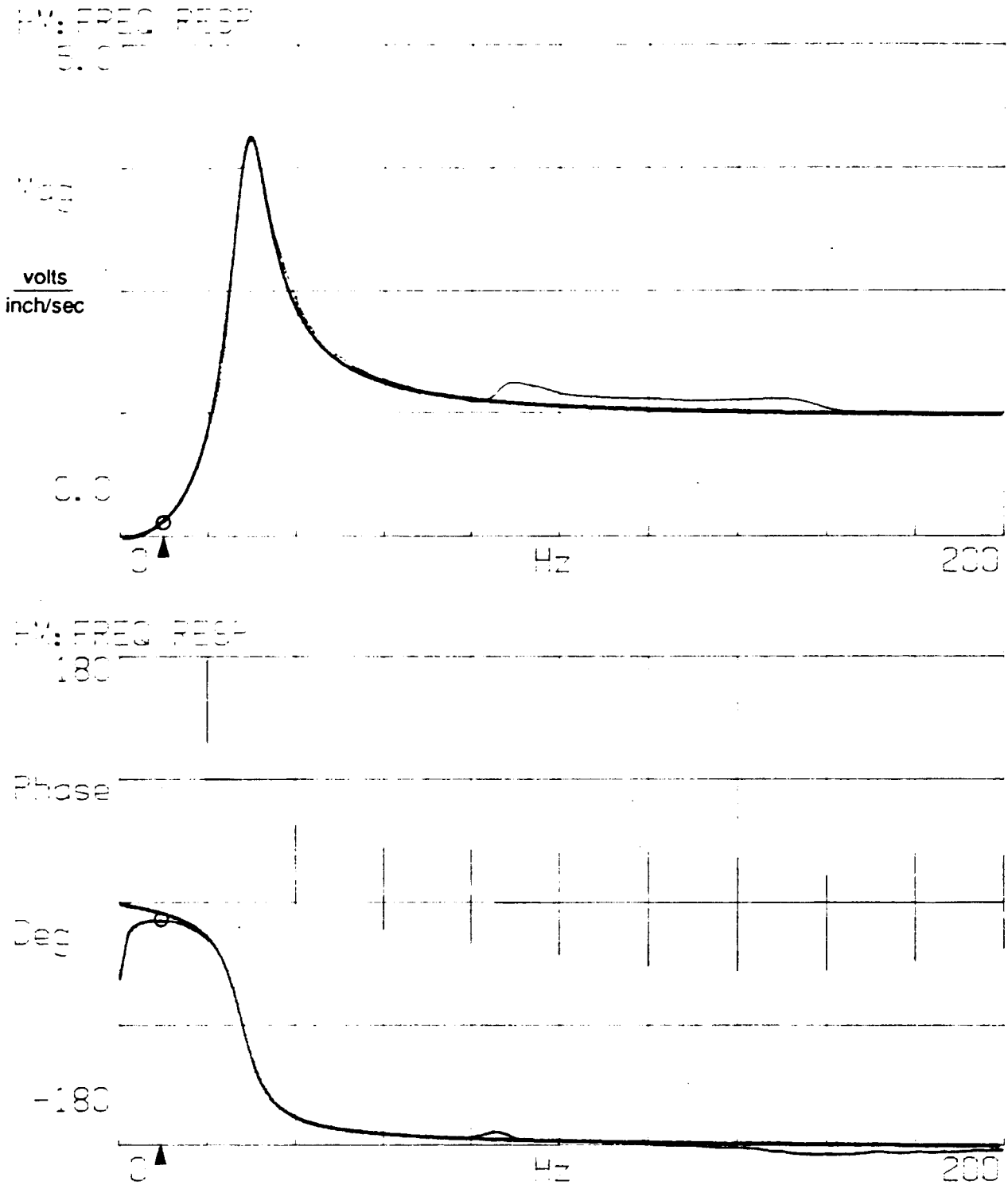
Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Calibration Curve
Triaxial Geophone Package No. ET-1
Transverse Geophone

12-89

Figure A-3



EXPLANATION

28 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = -4.43042 Hz ± j 28.4506 Hz
Gain = -1.243 $\frac{\text{volts}}{\text{inch/sec}}$

Lower Frequency Limit of Calibration

The Earth Technology Corporation

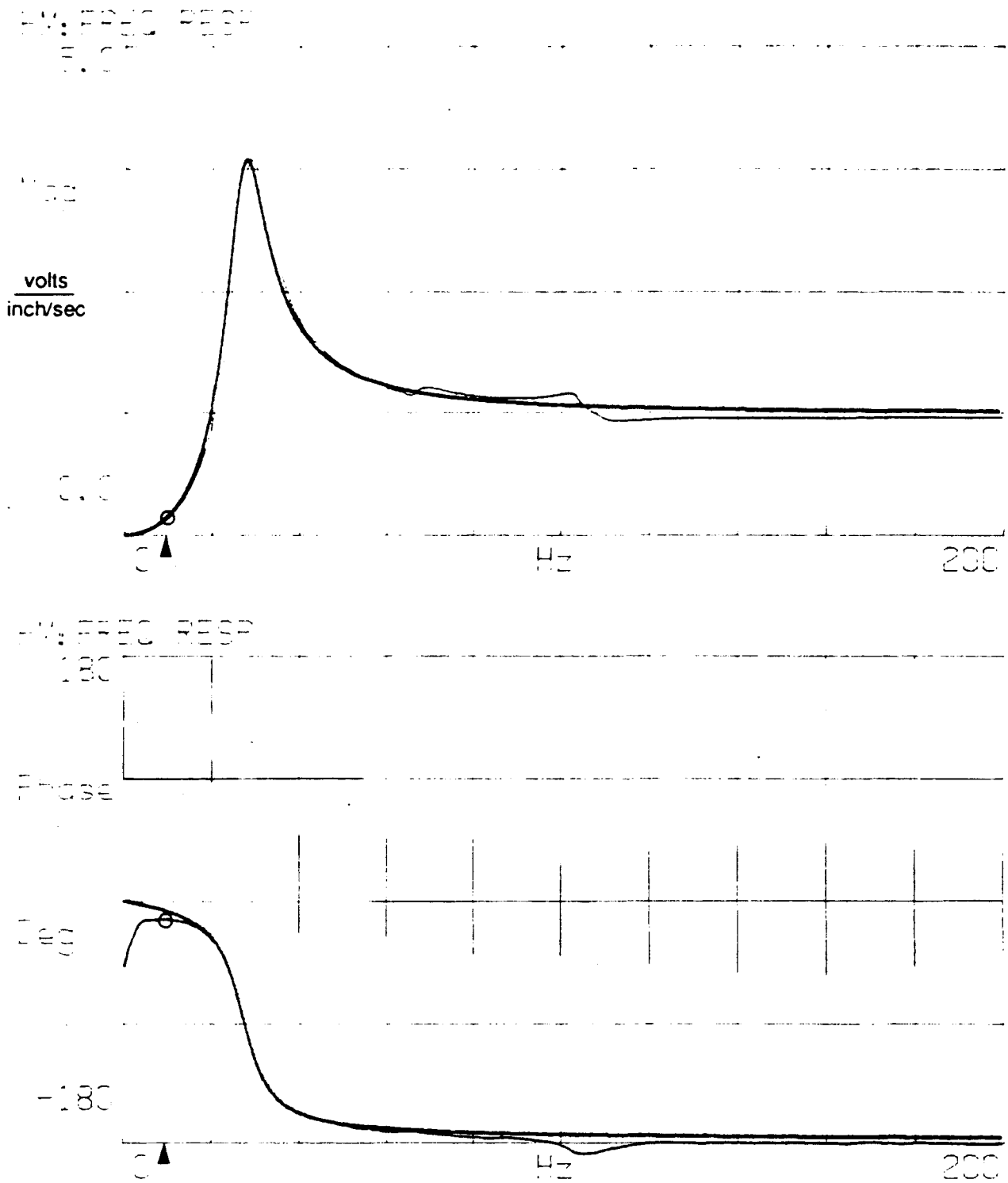
Project No.: 87-888-0011

RTK Joint Venture

Calibration Curve
Triaxial Geophone Package No. ET-2
Vertical Geophone

12-89

Figure A-4



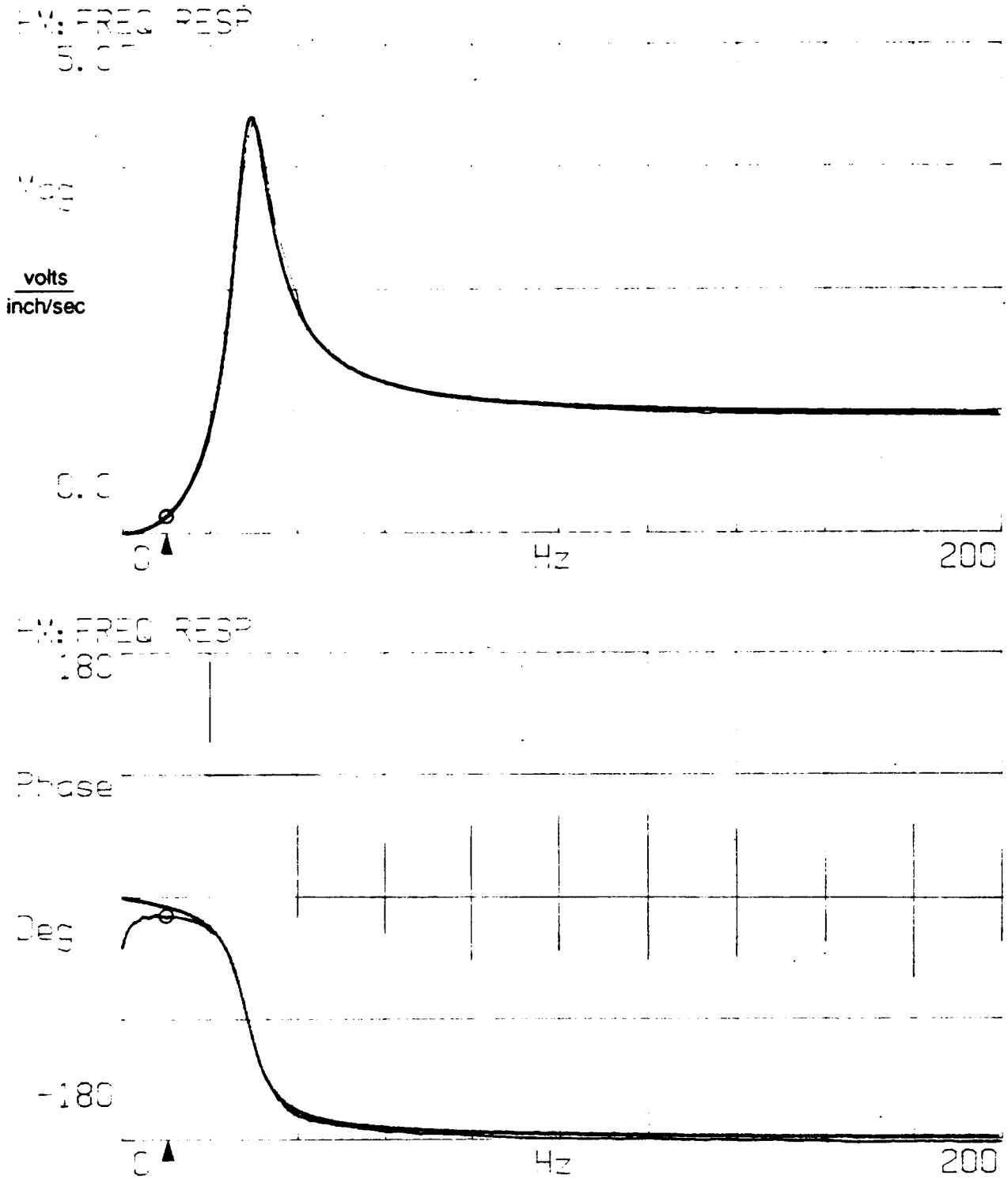
EXPLANATION

28 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = -4.46778 Hz ± j 27.5647 Hz
Gain = -1.215 $\frac{\text{volts}}{\text{inch/sec}}$
Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Calibration Curve
Triaxial Geophone Package No. ET-2
Radial Geophone

12-89 Figure A-5



EXPLANATION

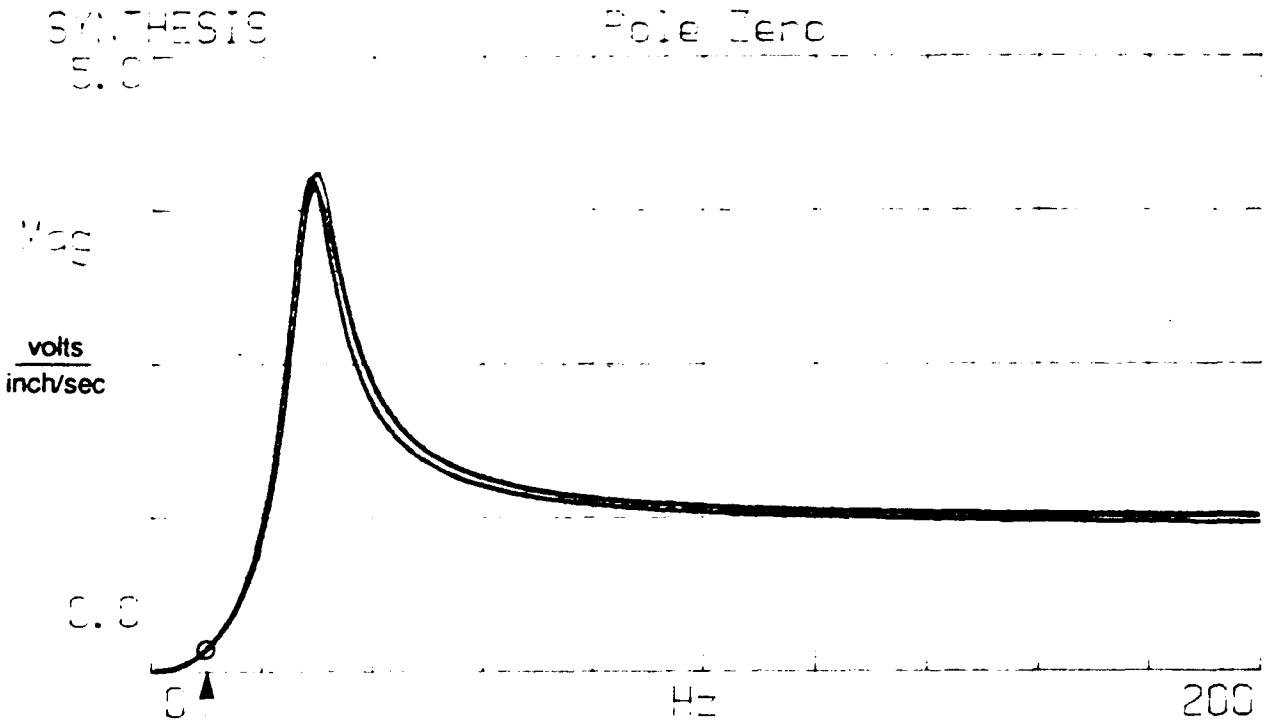
28 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = -4.15009 Hz $\pm$ j 28.7968 Hz
Gain = -1.205 $\frac{\text{volts}}{\text{inch/sec}}$

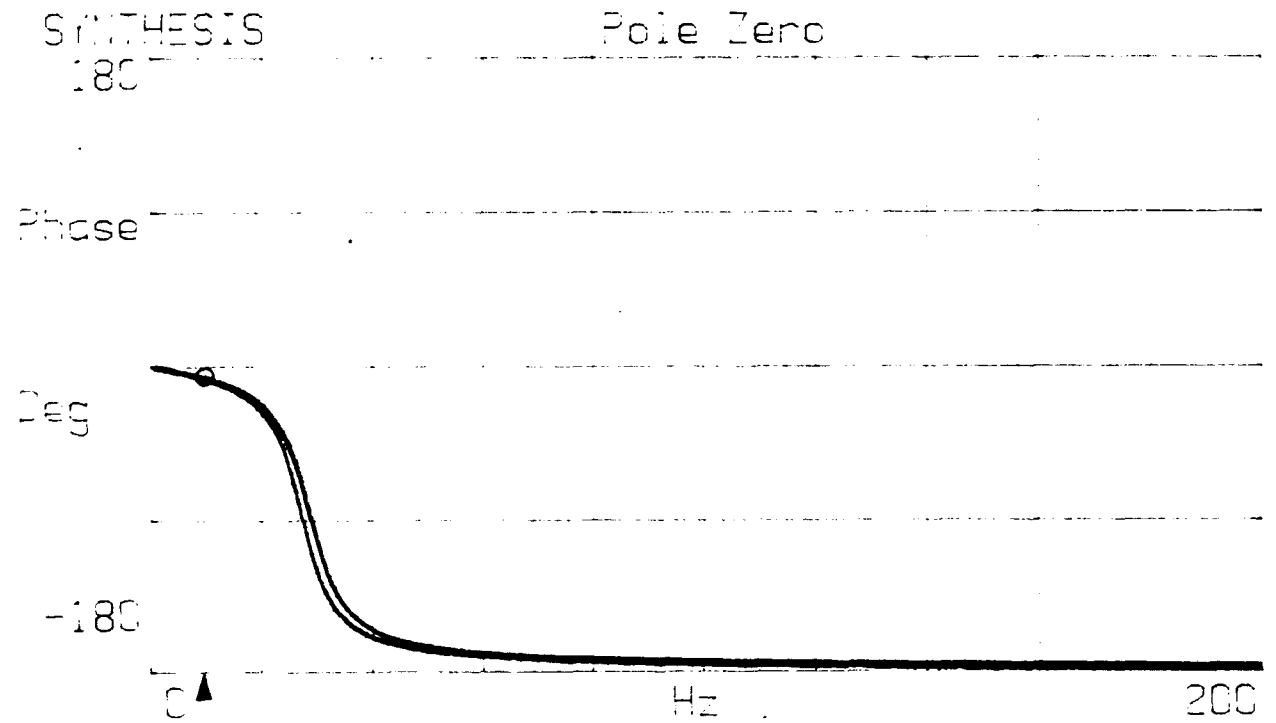
Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Calibration Curve
Triaxial Geophone Package No. ET-2
Transverse Geophone

12-89 Figure A-6





EXPLANATION

28 Hz Geophone Data
Red = Vertical Geophone
Black = Radial Geophone
Green = Transverse Geophone
Lower Frequency Limit of Calibration

The Earth Technology Corporation

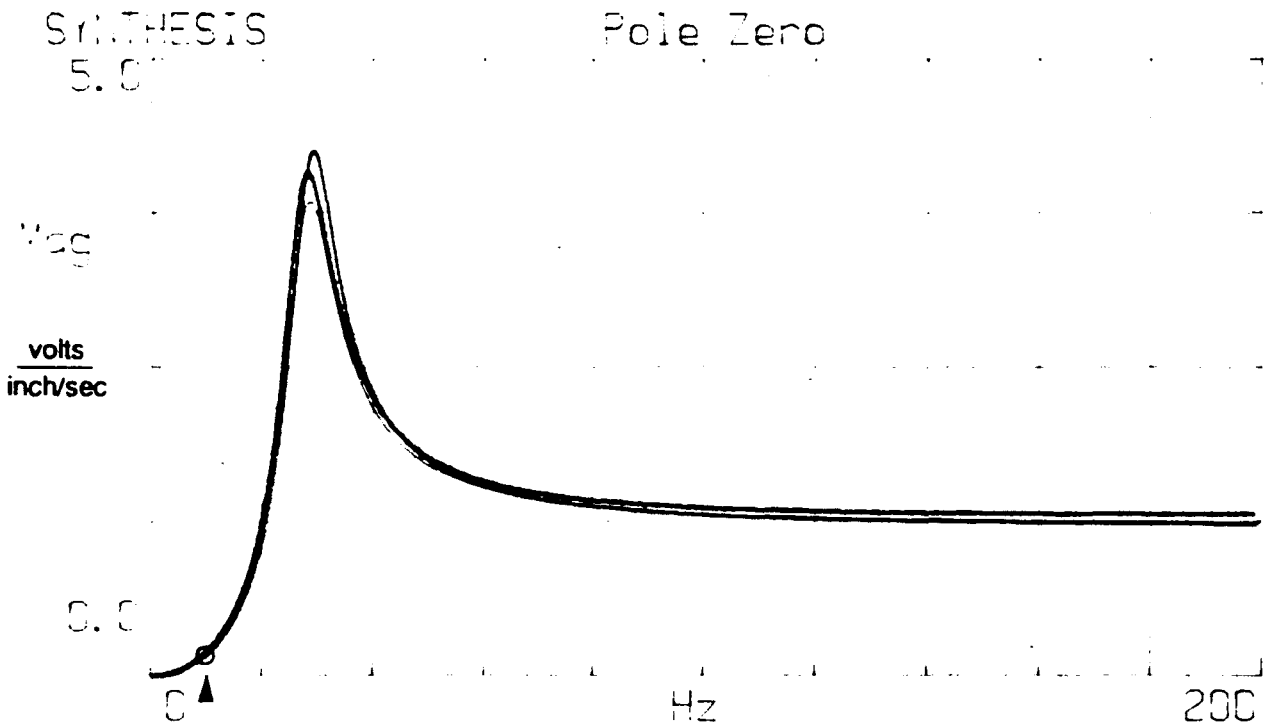
Project No.: 87-888-0011

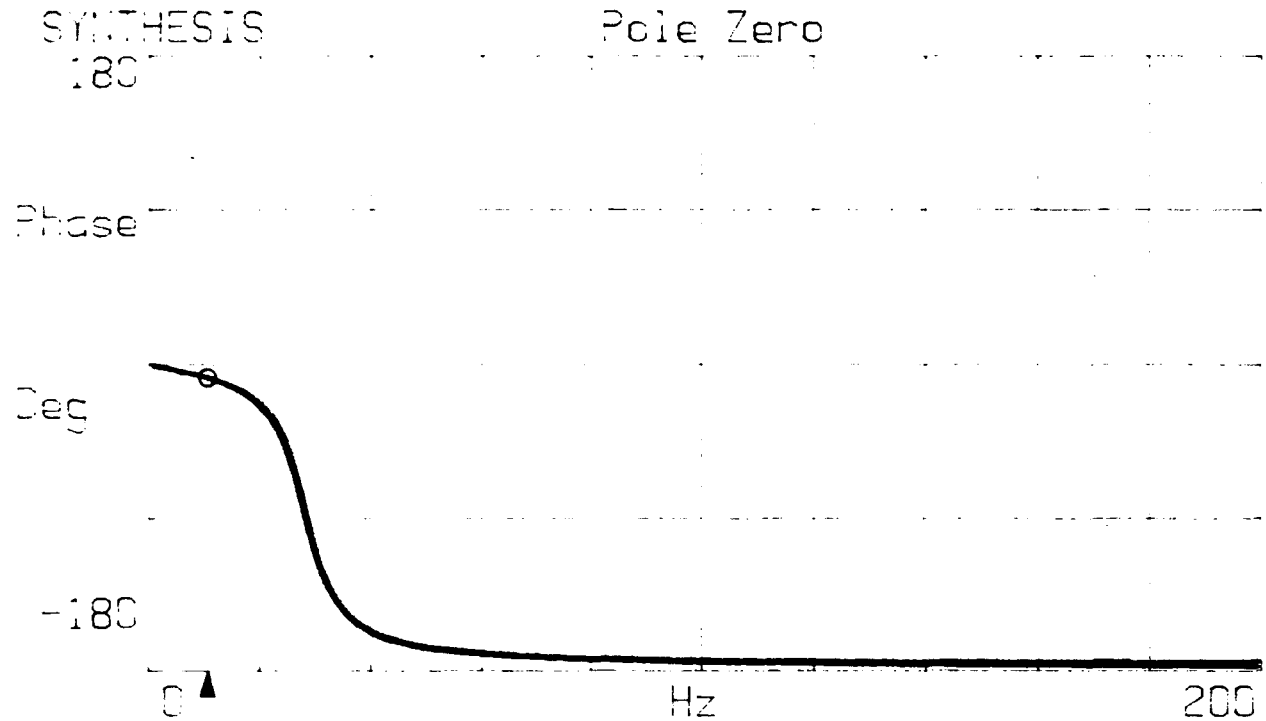
RTK Joint Venture

Composite Calibration Curves
(Curve Fit Functions)
Triaxial Geophone Package No. ET-1

12-89

Figure A-7





EXPLANATION

28 Hz Geophone Data
Red = Vertical Geophone
Black = Radial Geophone
Green = Transverse Geophone
⊙ Lower Frequency Limit of Calibration

The Earth Technology Corporation

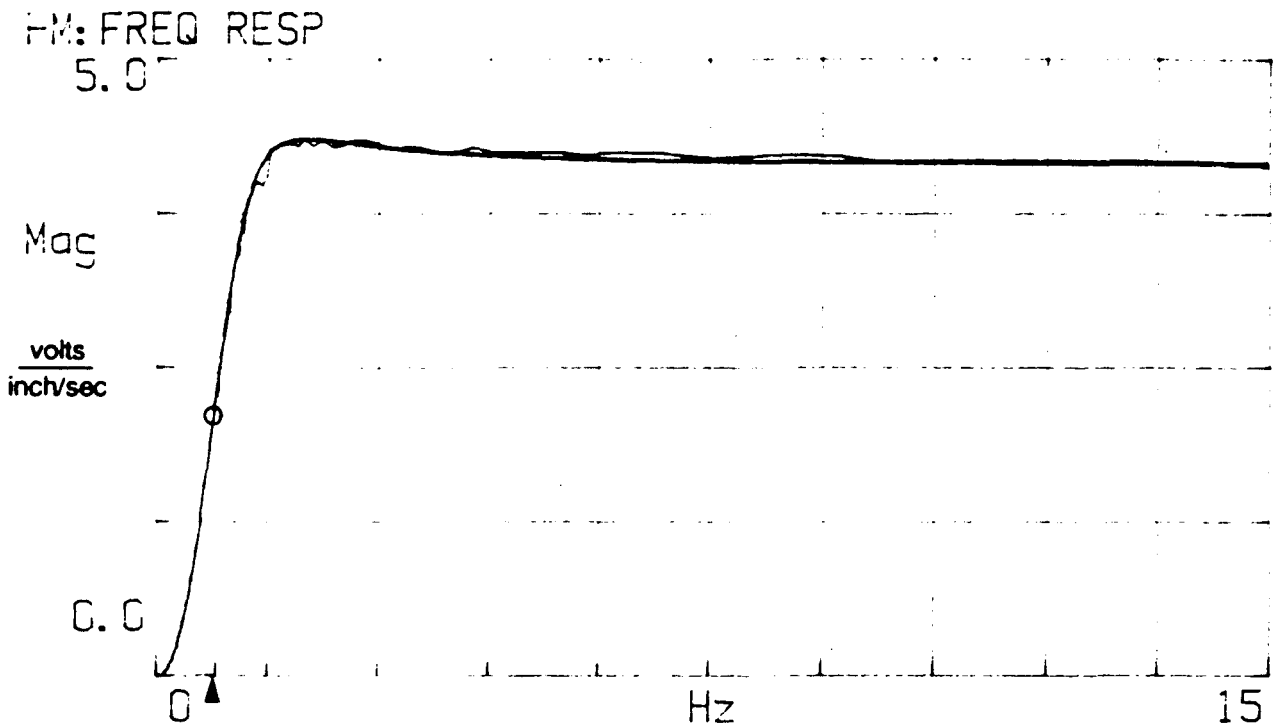
Project No.: 87-888-0011

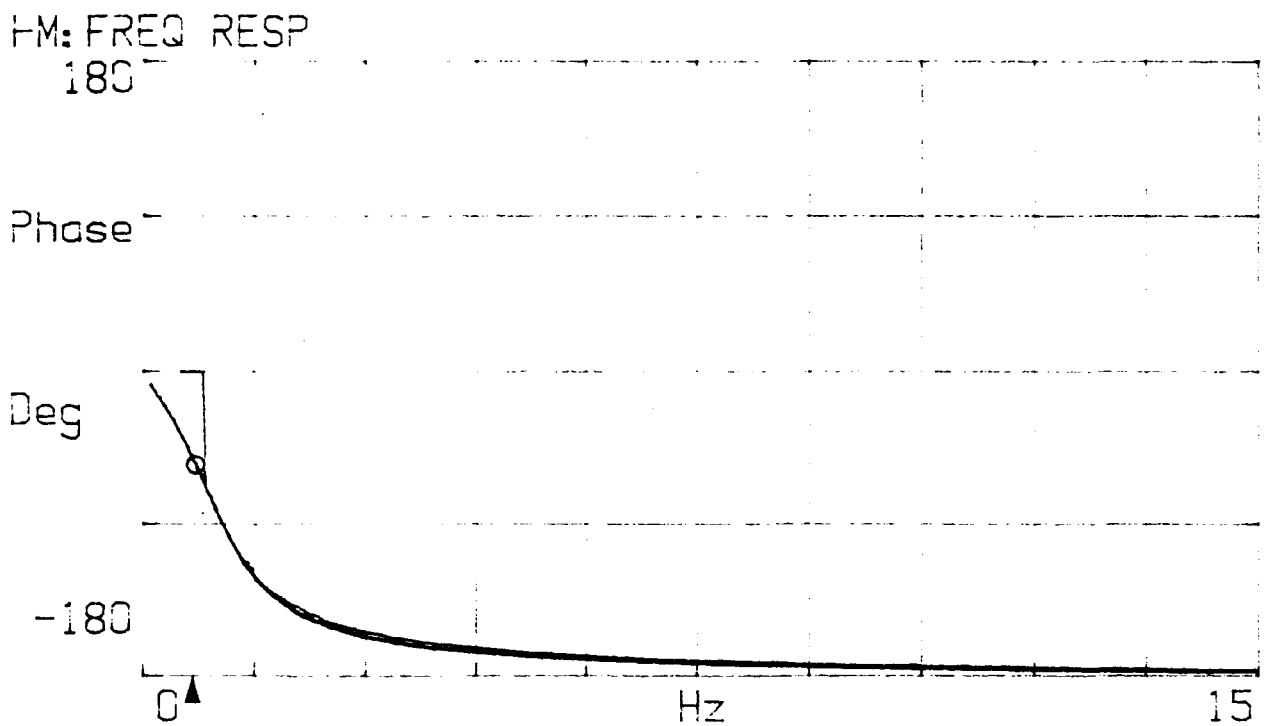
RTK Joint Venture

Composite Calibration Curves
(Curve Fit Functions)
Triaxial Geophone Package No. ET-2

12-89

Figure A-6



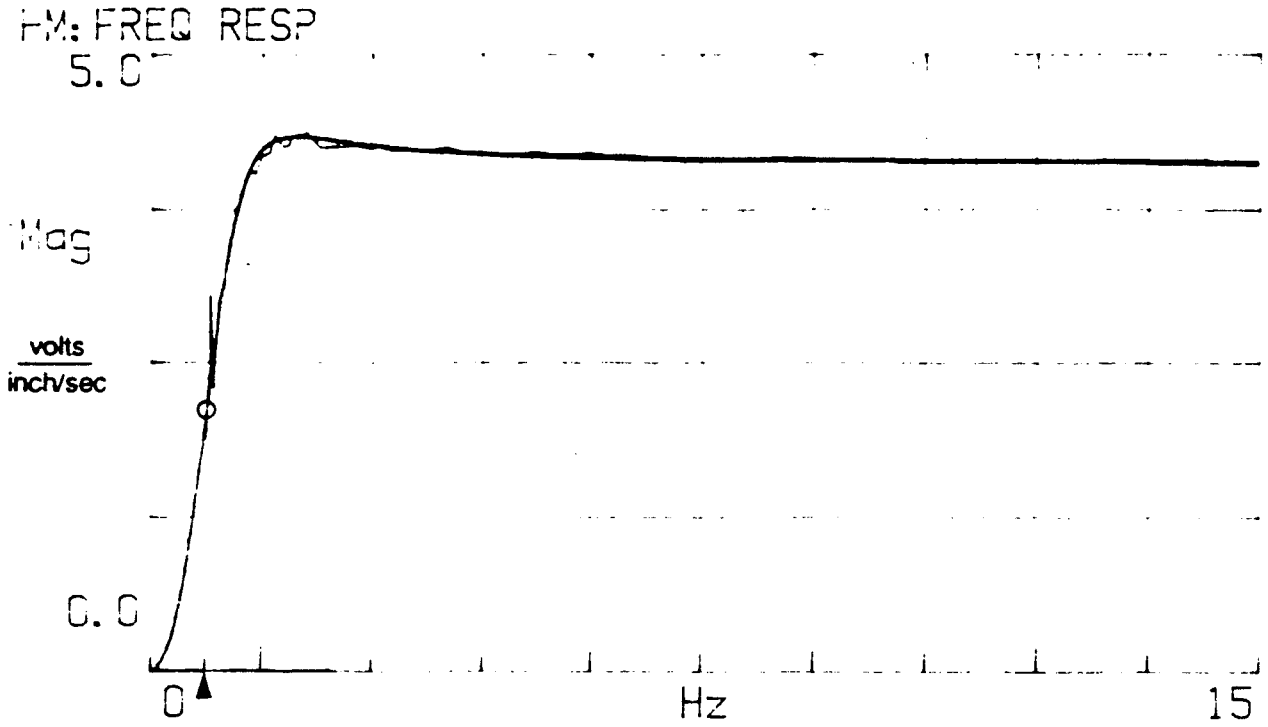


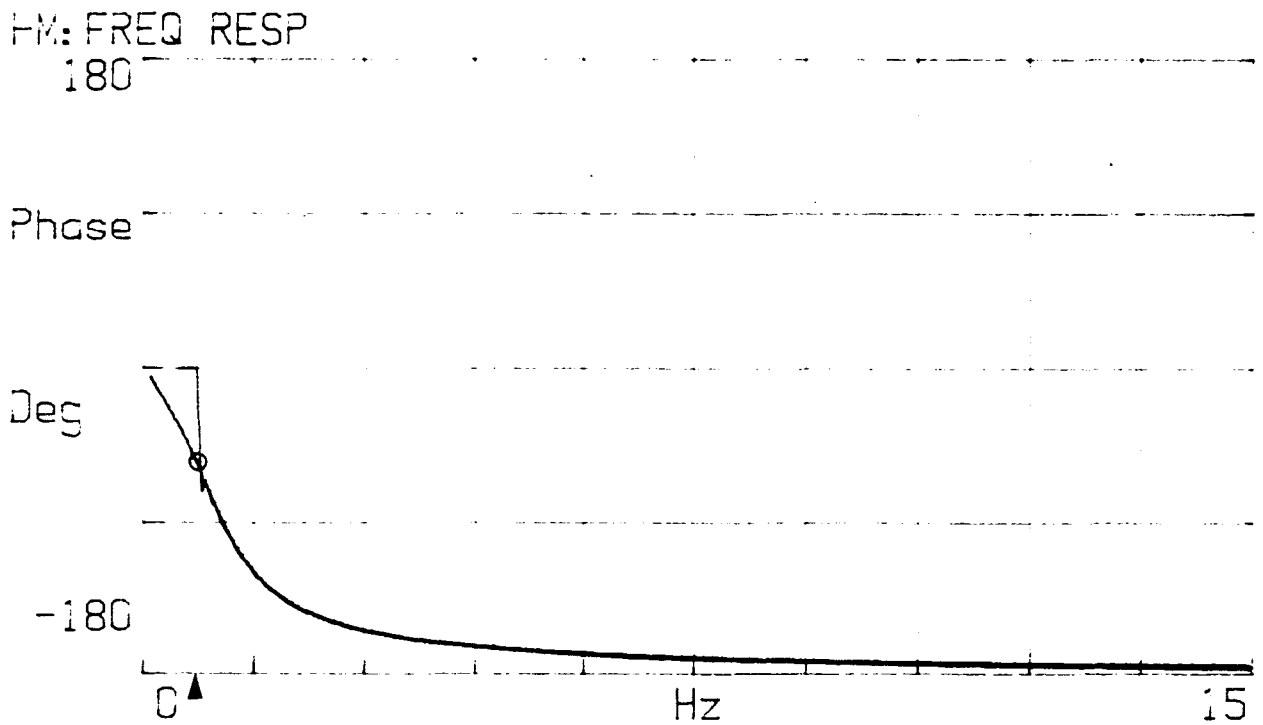
EXPLANATION

1 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = -0.64892 Hz ± j 0.88691 Hz
Gain = -4.185 $\frac{\text{volts}}{\text{inch/sec}}$

Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture
Calibration Curve 1 Hz Geophone No. 2676	
12-89	Figure A-9

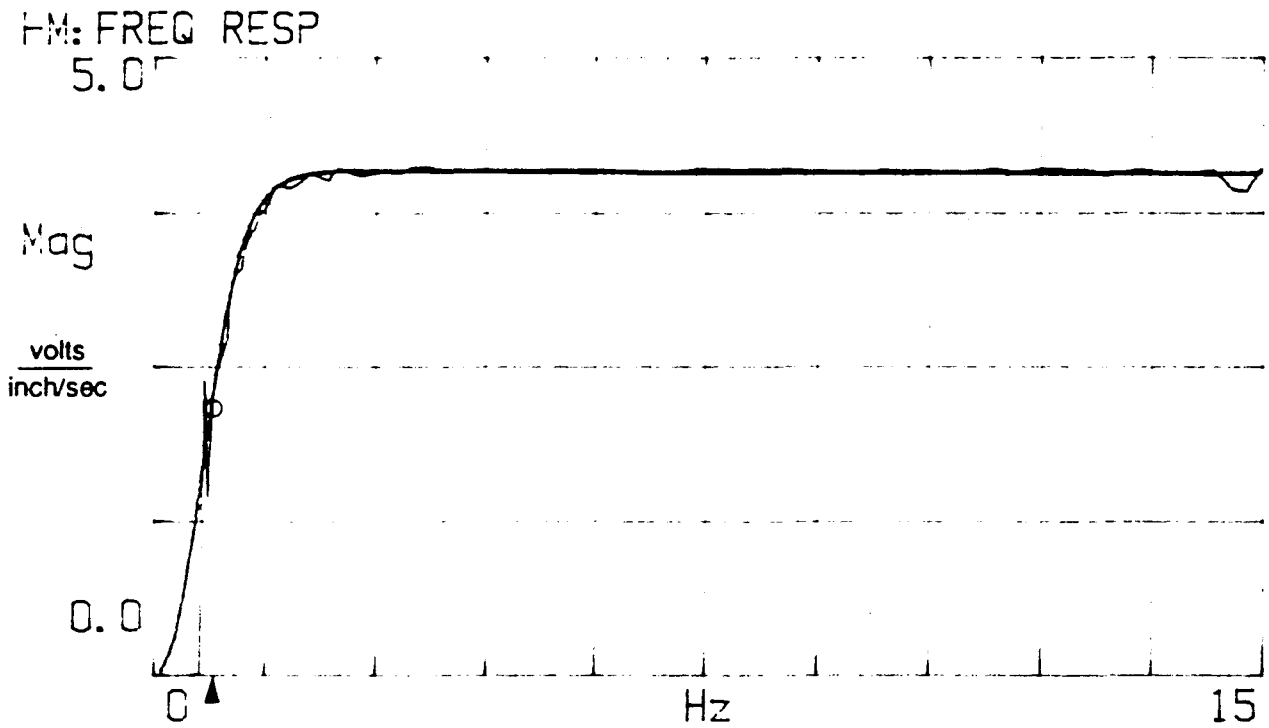


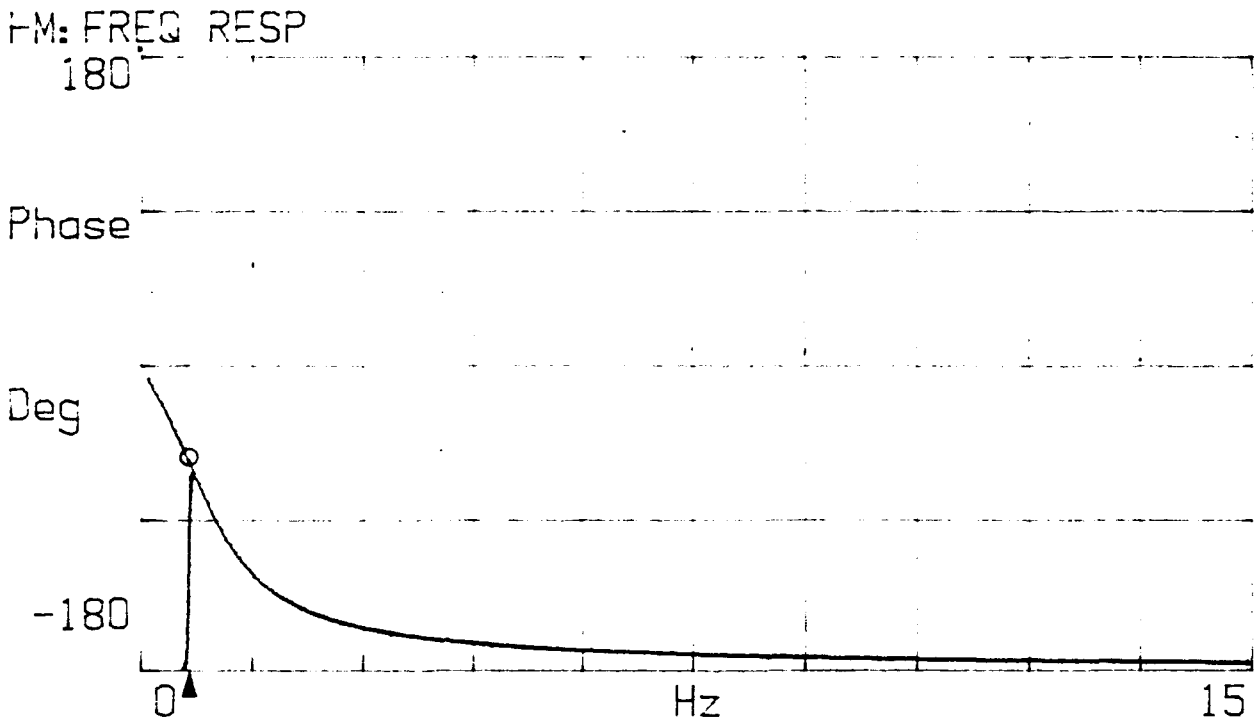


EXPLANATION

1 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = - 0.63682 Hz ± j 0.87711 Hz
Gain = -4.128 $\frac{\text{volts}}{\text{inch/sec}}$
Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture
Calibration Curve 1 Hz Geophone No. 4105	
12-89	Figure A-10





EXPLANATION

1 Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = -0.67779 Hz $\pm$ j 0.76550 Hz
Gain = -4.077 $\frac{\text{volts}}{\text{inch/sec}}$

Lower Frequency Limit of Calibration

The Earth Technology Corporation

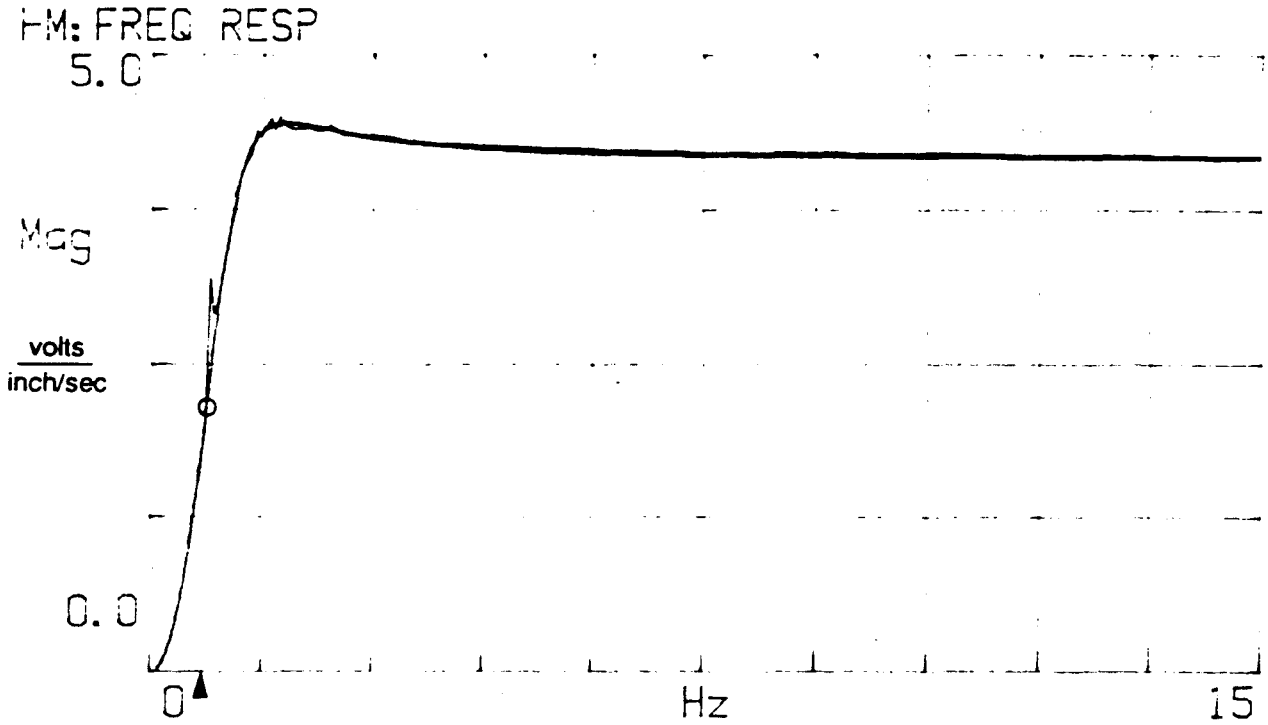
Project No.: 87-888-0011

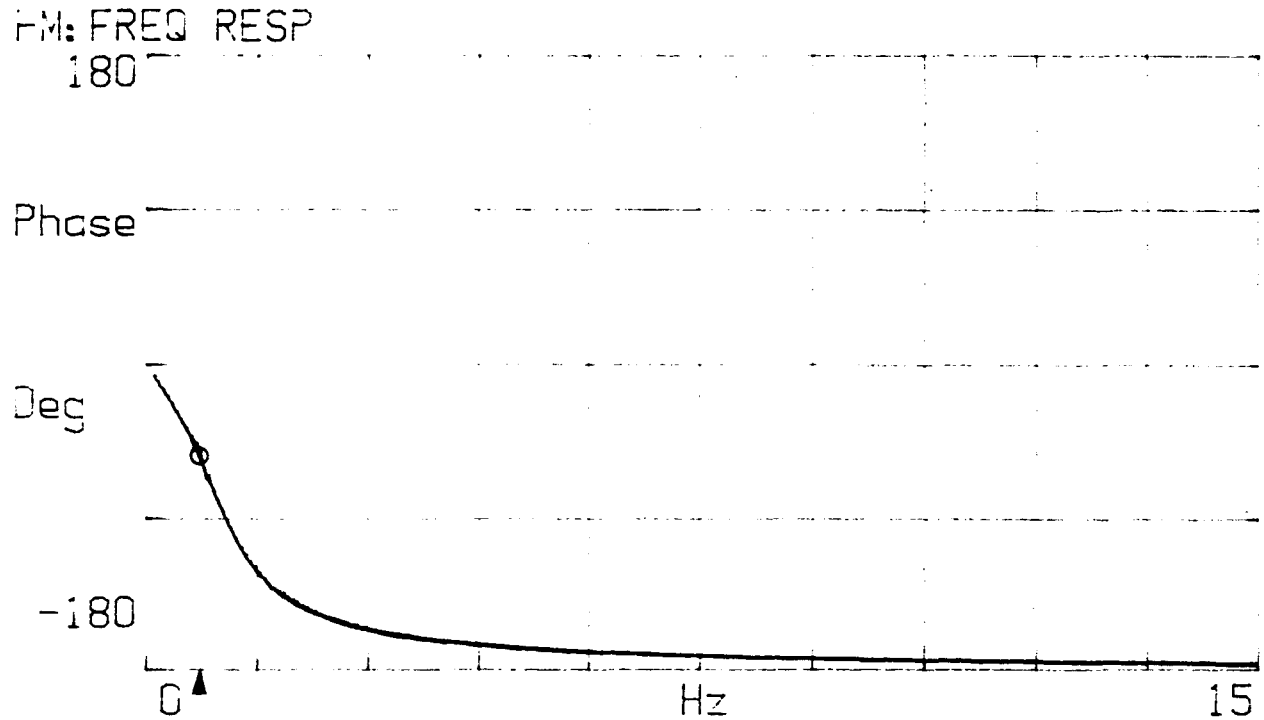
RTK Joint Venture

Calibration Curve
1 Hz Geophone No. 8219

12-89

Figure A-11



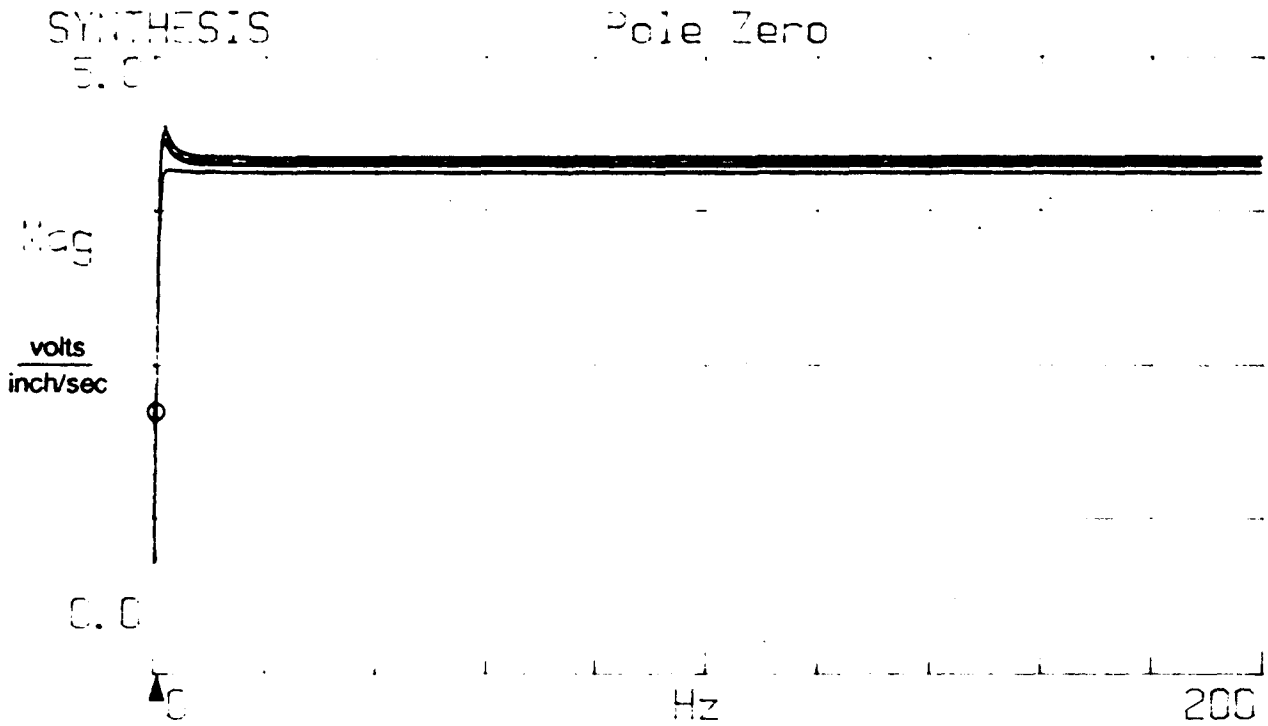


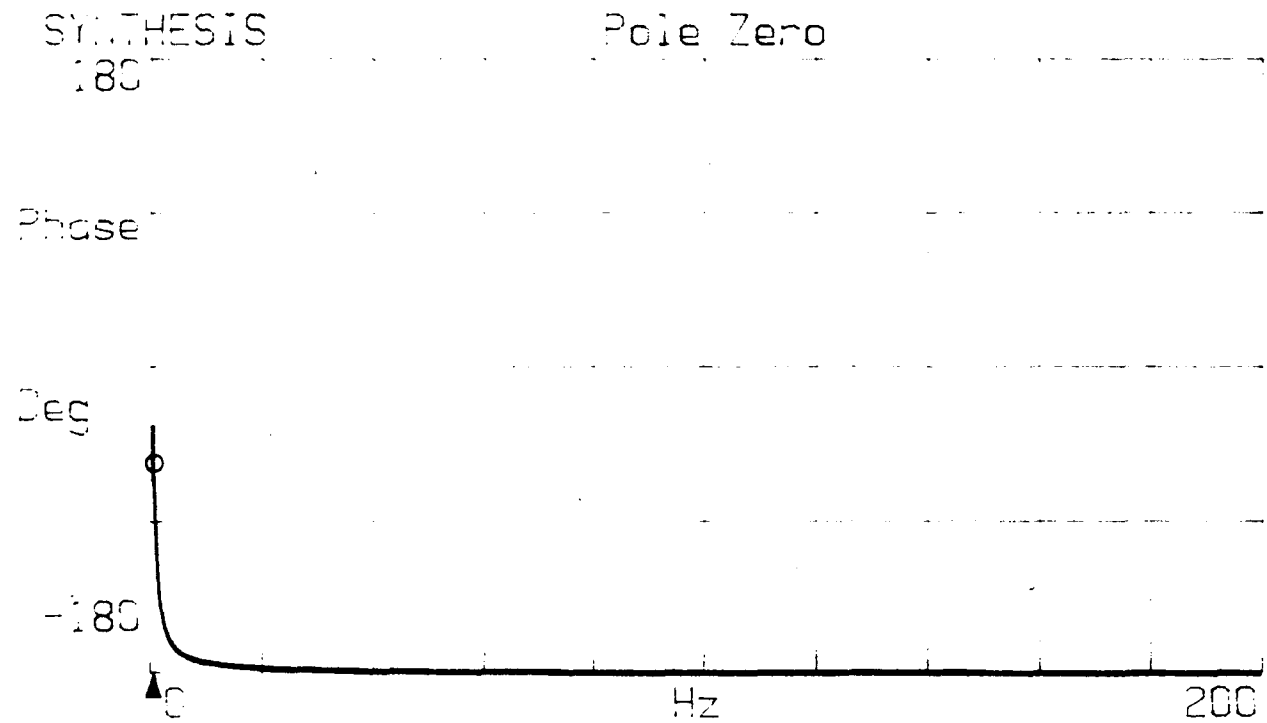
EXPLANATION

1Hz Geophone Data
Black = Shake Table Test Data
Red = Curve Fit Function
Curve Fit Parameters
Poles = - 0.61710 Hz ± j 0.89784 Hz
Gain = -4.177 $\frac{\text{volts}}{\text{inch/sec}}$

Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture
Calibration Curve 1 Hz Geophone No. 4106	
12-89	Figure A-12





EXPLANATION

1 Hz Geophone Data
Black = Geophone No. 2676
Red = Geophone No. 4105
Green = Geophone No. 8219
Blue = Geophone No. 4106
Lower Frequency Limit of Calibration

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Composite Calibration Curves
(Curve Fit Functions)
1 Hz Geophones

12-89

Figure A-13

APPENDIX B

FUNCTIONAL TESTS OF DYNAMIC SIGNAL ANALYZER

B1.0 FUNCTIONAL TESTS

Several functional tests were run on the analyzer to verify its operations. Confidence in the analyzer's abilities to process data needed to be established before the vibration survey results were accepted. Three tests were performed:

- *Three tests*

1. The analyzer's ability to determine the voltage and frequency of controlled electrical signals was tested.
2. Shake table tests of two transducers measuring different quantities were compared after the analyzer manipulated the data.
3. Displacement time histories were calculated using both frequency and time domain processing.

- *Electrical signal test*

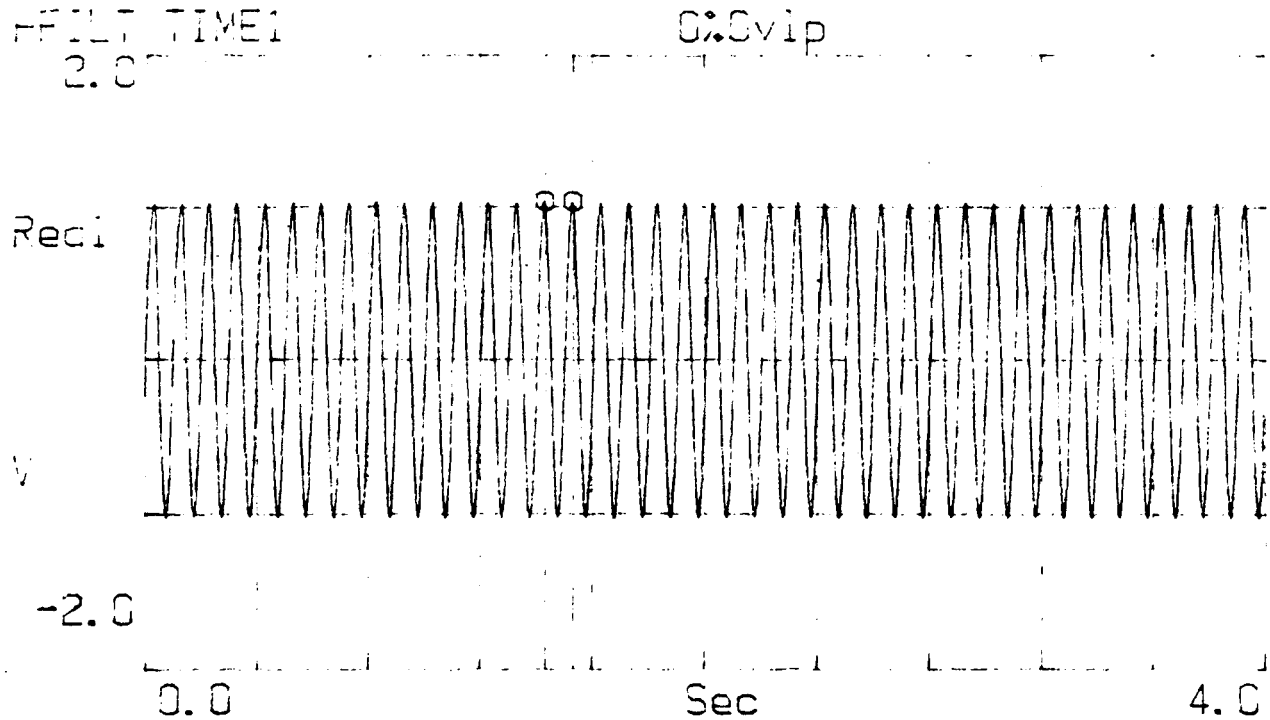
In the first test, controlled electrical signals from a Tektronix Model 2630 Fourier Analyzer were input to the analyzer and the calculated spectra were compared to the input signal's amplitude and frequency. Figure B-1 shows two input electrical signals and Figure B-2 shows a scale enlargement of B-1. Figures B-3 and B-4 show the calculated linear spectral densities and linear spectra of these two signals. In all cases, the analyzer's calculated results are within 0.5 percent of the input signal characteristics, which empirically confirms that the analyzer is operating properly.

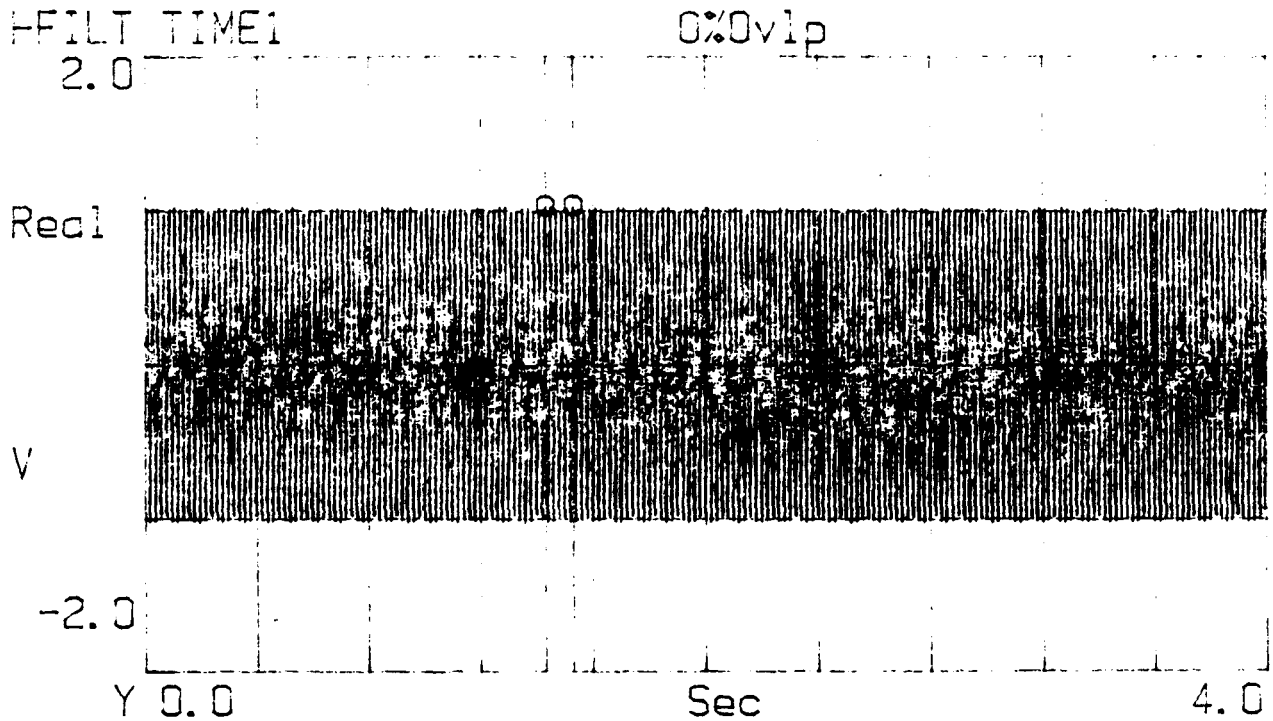
- *Shake table test*

In the second functional test, the outputs of two transducers (geophone and linear variable differential transformer, LVDT) were recorded using the standard shake table test procedures. The geophone measures particle velocity and was previously calibrated using a proximeter (Appendix A). The LVDT measures particle displacement directly and requires no processing. A narrow-band time signal (broad-band frequency signal) was sent from a function generator to the shake table amplifier (top of Figure B-5). The input signal was modified by the amplifier as shown at the bottom of Figure B-5 and actuated the shake table. Figure B-6 shows the raw time-series data output from the geophone and LVDT. The geophone data were processed to a displacement time history using the frequency domain processing shown on the left side of Figure 5-1. The LVDT data were multiplied by a constant gain factor (determined by the manufacturer). The two time histories shown in Figure B-7 agree within 3 percent. Therefore, the analyzer must be correctly manipulating the geophone data.

- *Time history test*

Displacement time histories presented in this report were calculated in two ways. Frequency domain processing followed the sequence shown on the left side of Figure 5-1. As a check on the final time histories, time domain processing was also completed following the sequence shown on the right side of Figure 5-1. Time domain results are only a qualitative check because this sequence assumes that the geophone complex calibration function can be approximated by a constant value (geophone gain). This approximation is valid at frequencies greater than 5 Hz where the curves are linear (Appendix A). Time domain processing also does not remove spurious, large-amplitude, frequency components less than the lower limit of geophone calibration. Displacement time histories derived from both processing sequences were plotted together for all data sets shown in the appendices. Both curves have similar frequency content and differ only in amplitude at low frequencies. The two time histories also have the same general shape and frequency content as the corresponding raw time-series data. Therefore, the analyzer's operations are internally consistent.



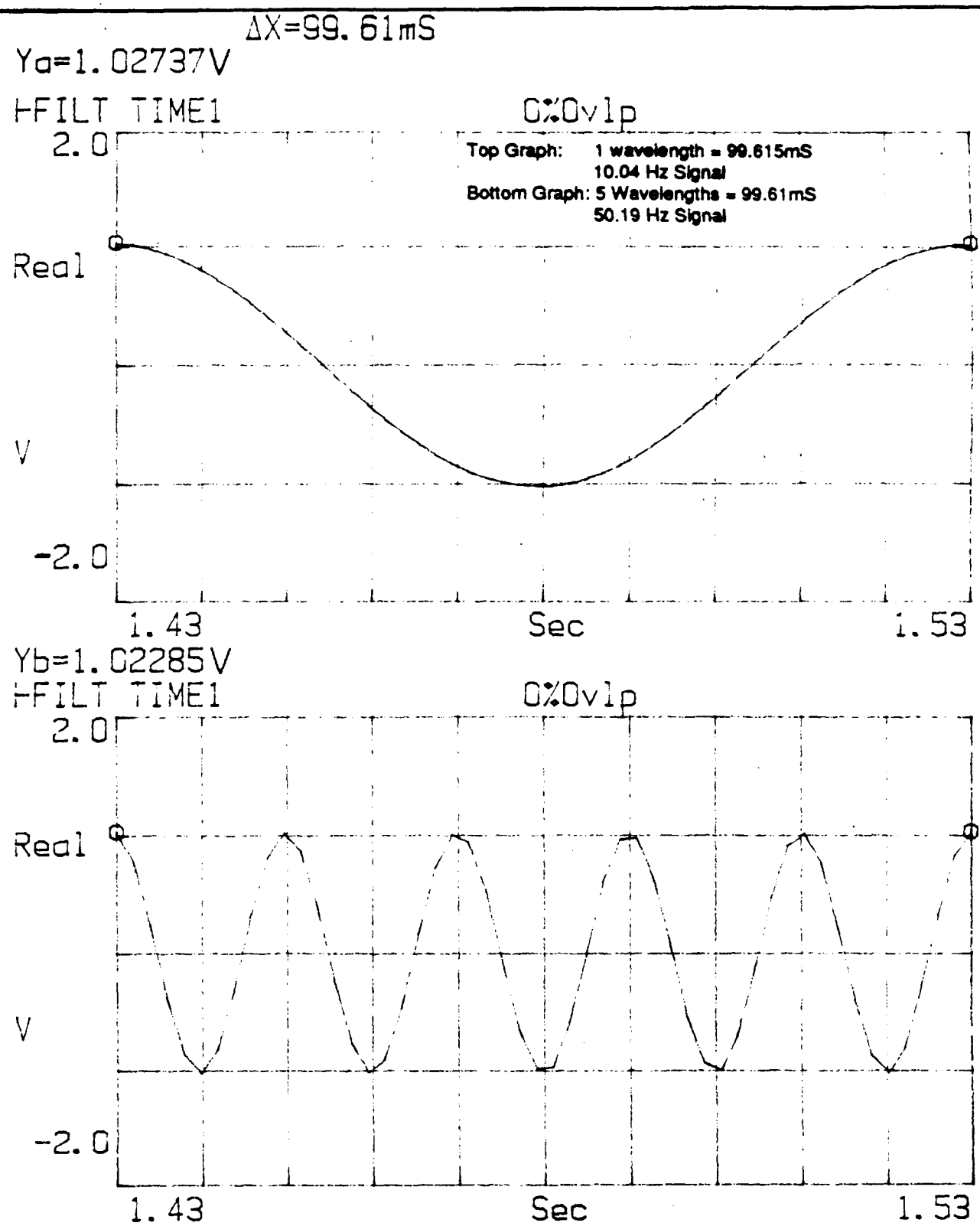


EXPLANATION

Top Graph
Input: 10 Hz Signal
1 Volt Amplitude
Sine Wave

Bottom Graph
Input: 50 Hz Signal
1 Volt Amplitude
Sine Wave

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture
Electrical Signal Test Controlled Input Signals	
12-89	Figure B-1



EXPLANATION

Top Graph
Input: 10 Hz Signal
1 Volt Amplitude
Sine Wave

Bottom Graph
Input: 50 Hz Signal
1 Volt Amplitude
Sine Wave

The Earth Technology Corporation

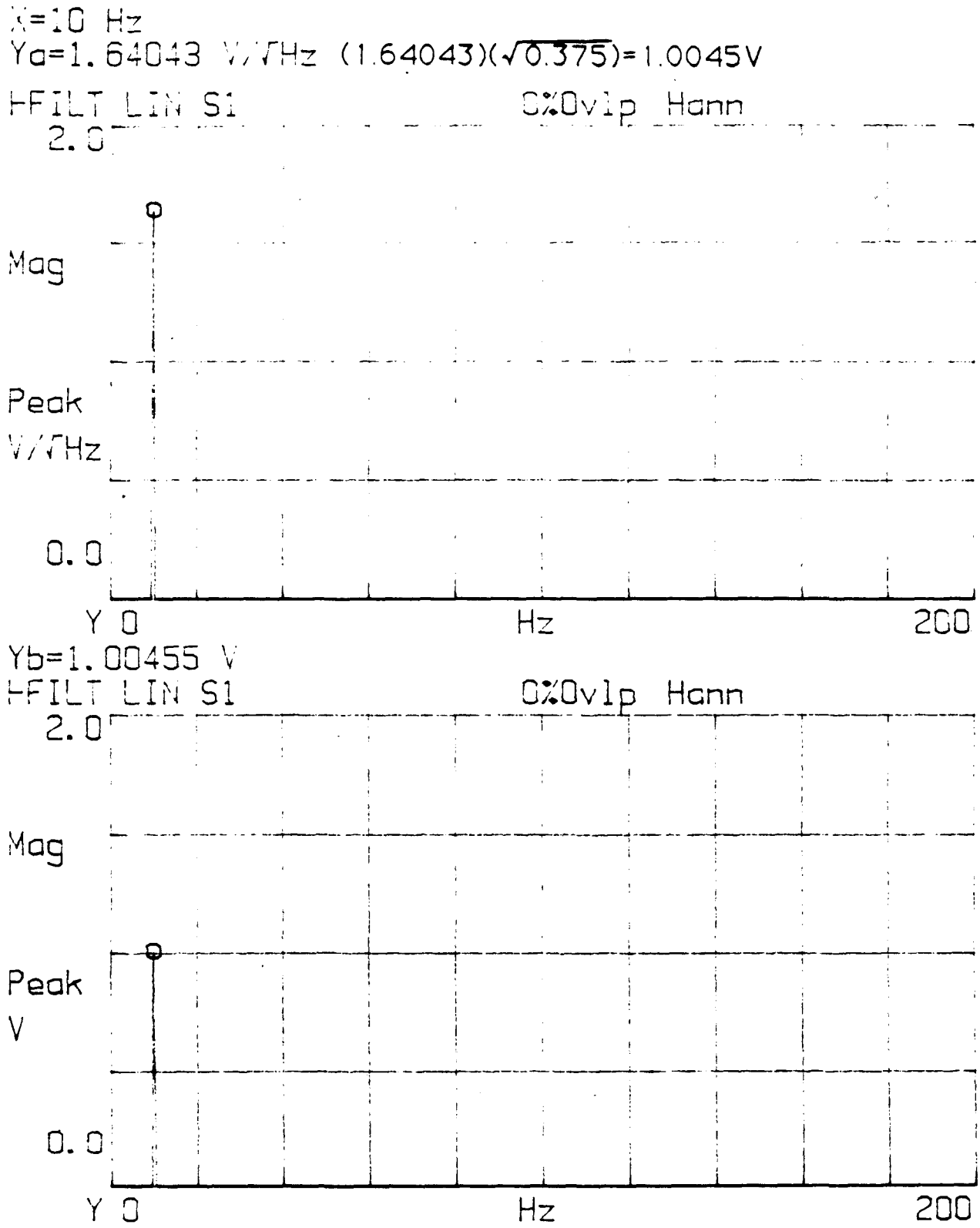
Project No.: 87-888-0011

RTK Joint Venture

Electrical Signal Test
Controlled Input Signals
(Expanded Scale)

12-89

Figure B-2



EXPLANATION

Top Graph: Linear Spectral Density

Bottom Graph: Linear Spectrum

Bandwidth = 0.375 Hz

The Earth Technology Corporation

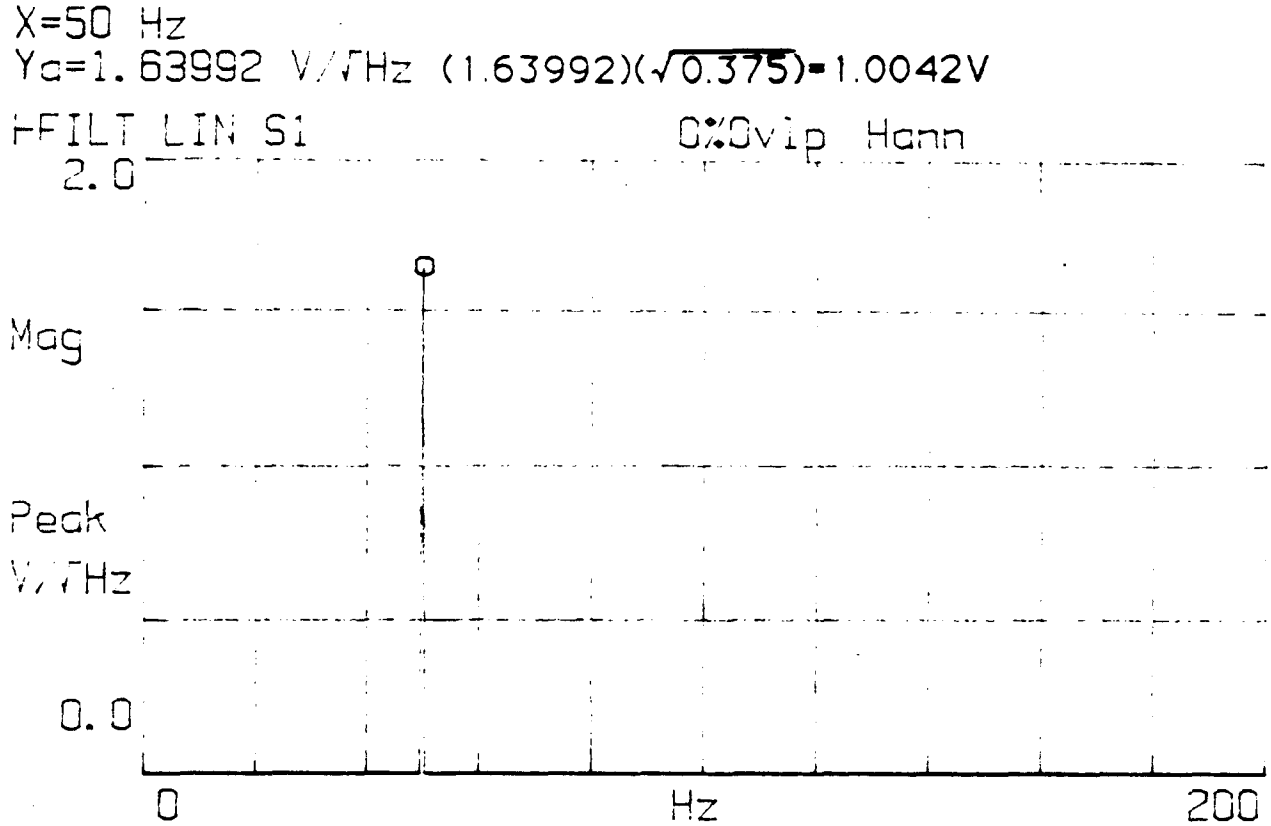
Project No.: 87-888-0011

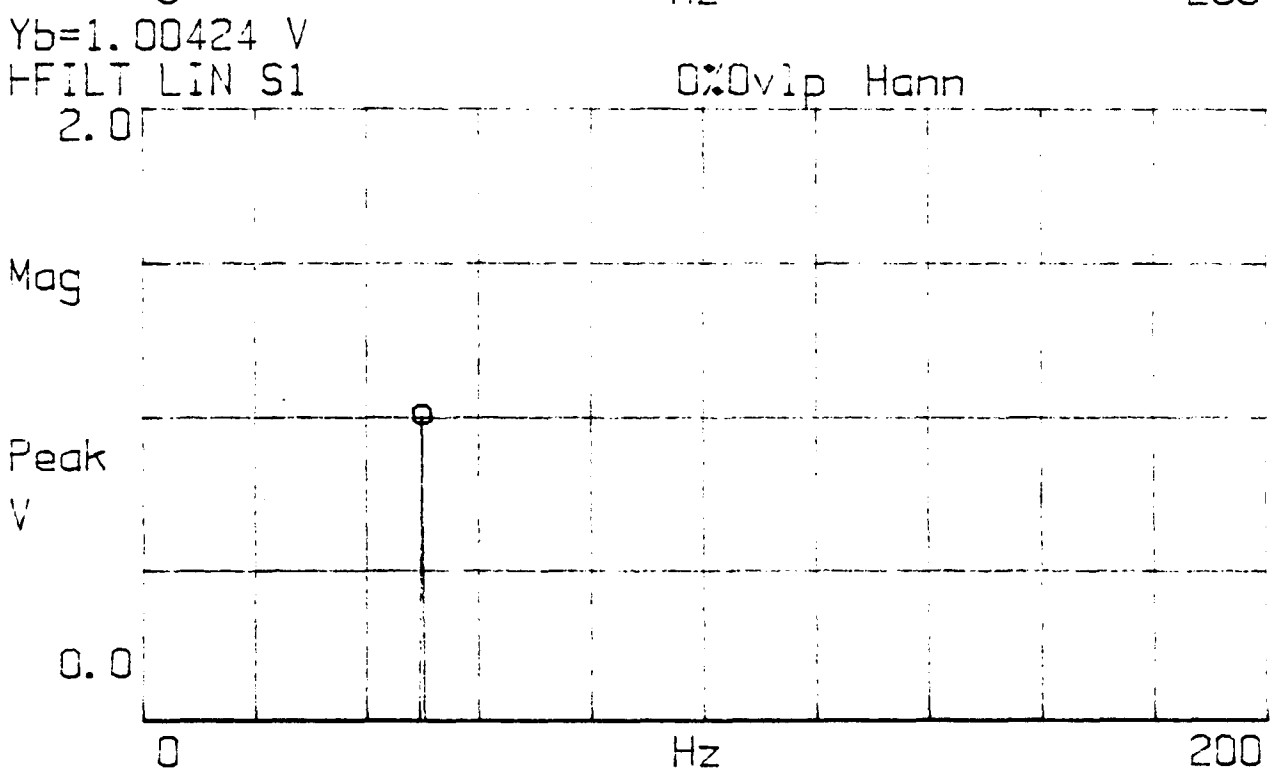
RTK Joint Venture

Electrical Signal Test
Linear Spectral Density
of 10 Hz Signal

12-89

Figure B-3





EXPLANATION

Top Graph: Linear Spectral Density

Bottom Graph: Linear Spectrum

Bandwidth= 0.375 Hz

The Earth Technology Corporation

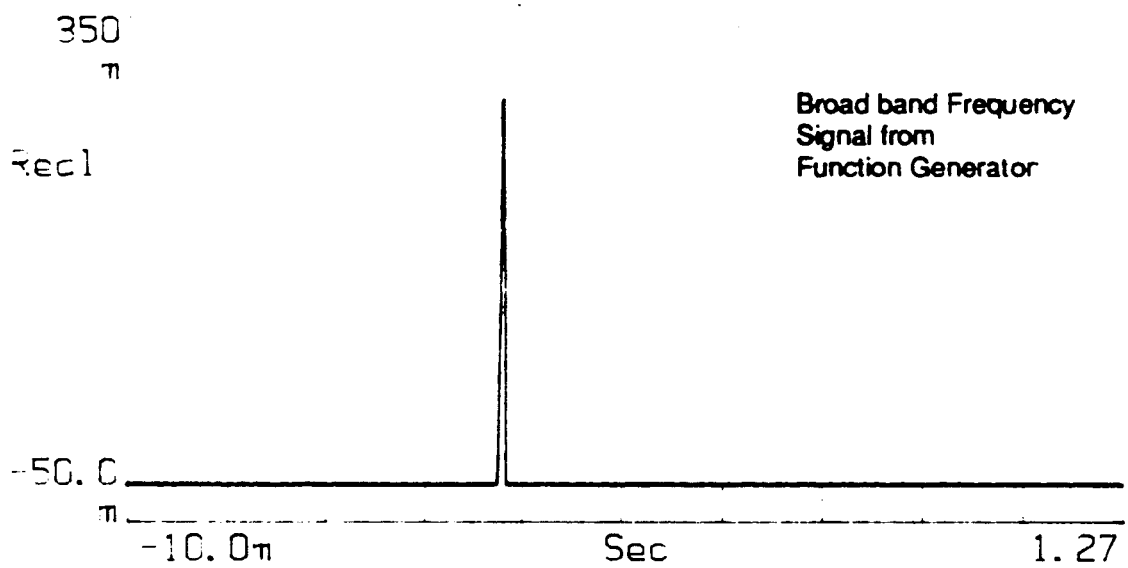
Project No.: 87-[illegible]-0011

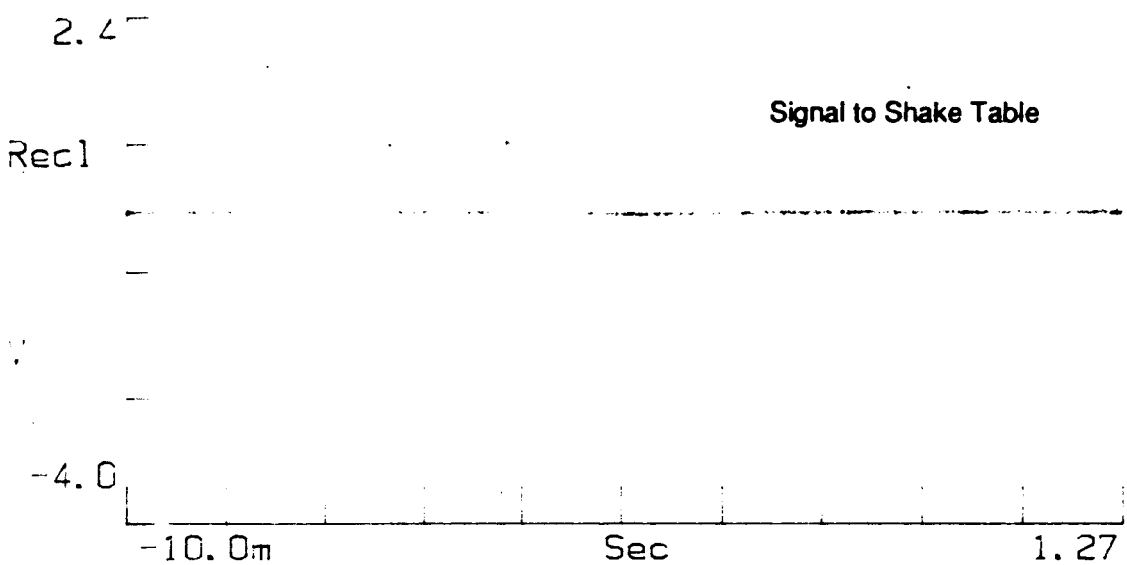
RTK Joint Venture

Electrical Signal Test
Linear Spectral Density
of 50 Hz Signal

12-89

Figure B-4





The Earth Technology Corporation

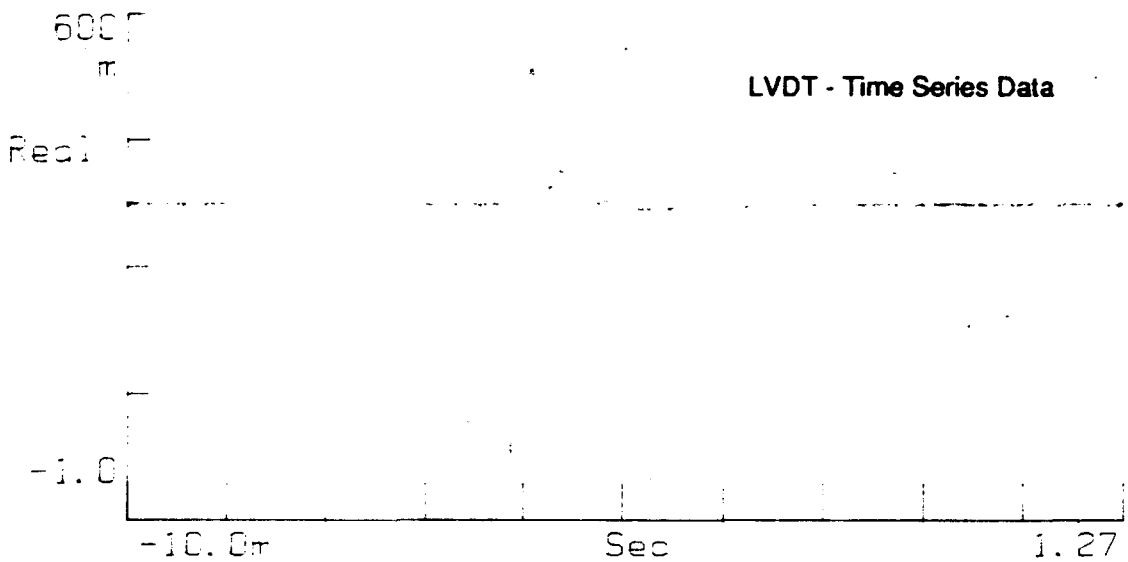
Project No.: 87-868-0011

RTK Joint Venture

Shake Table Test
Input Signal

12-89

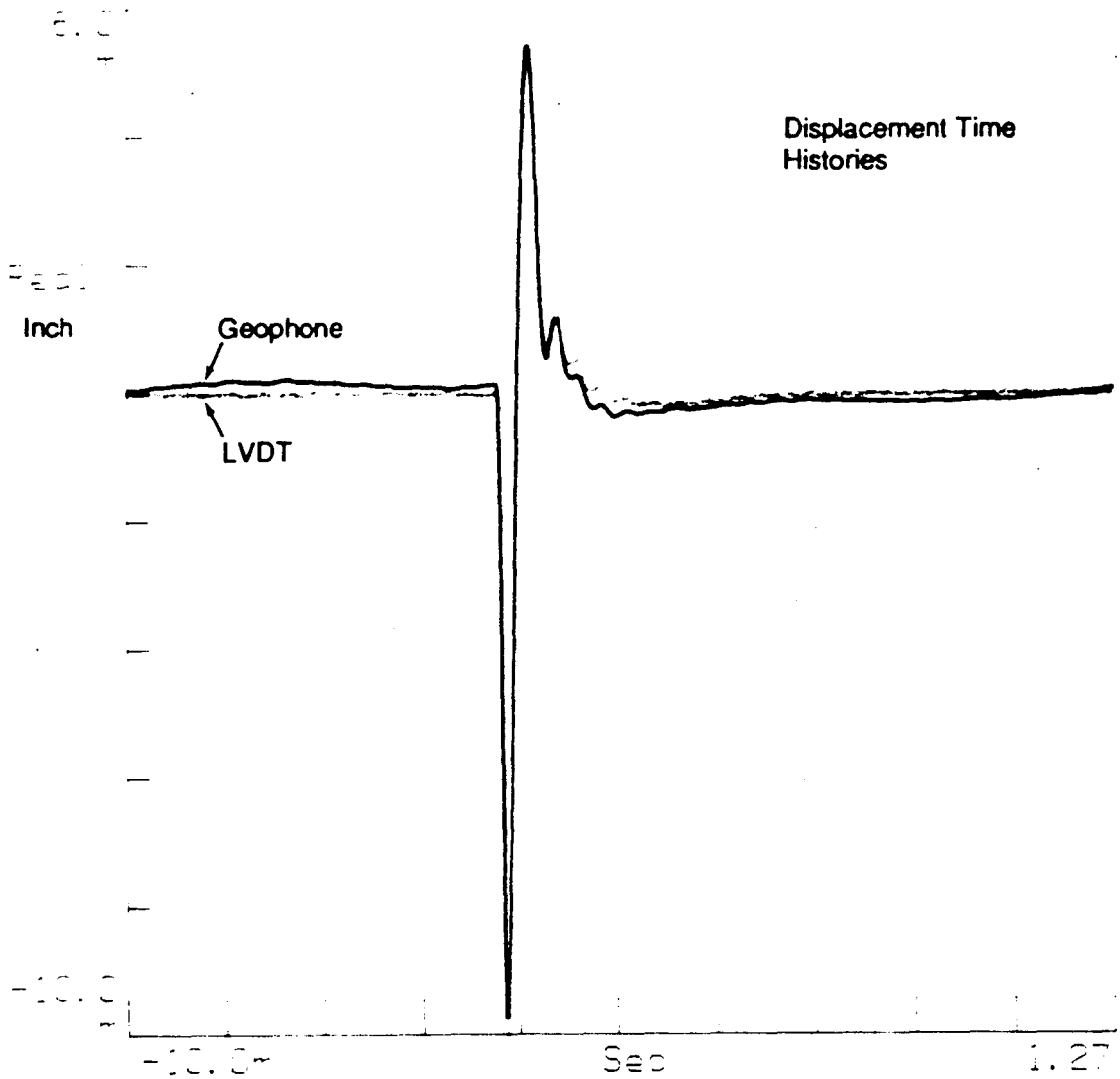
Figure B-5



The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Shake Table Test
Raw Time-Series Data of Both Transducers

12-89 Figure B-6



The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Shake Table Test
Displacement Time Histories of Both Transducers

12-89

Figure B-7

APPENDIX C

VIBRATION SURVEY PROCEDURES

C1.0 DATA ACQUISITION

- *Geophone depths*

Vibrations were measured simultaneously with three geophones in a boring to obtain displacement spectra at different depths from the same source. A sonic log was completed in the boring before and after casing/grouting. Grouting effectiveness was estimated by comparing these logs. Geophone depths were selected within zones showing no anomalous conditions. The shallow geophone, a few feet deep, measured displacements as close to the source as practical. The intermediate geophone was positioned several feet below the rock top, away from the interface to minimize wave reflection, refraction, and conversion effects. The deep geophone was located within the proposed tunnel depth (in use during Footprint Validation).

- *Through-put recording*

Geophone output is a continuous voltage signal over time. These time-series data were input to the analyzer, which digitized and then recorded the data on diskette (through-put processing). Data were collected using two frequency spans to provide a combination of high digitizing resolution and long recording times. The digitizing parameters are shown below.

FREQUENCY SPAN (Hz)	RECORD LENGTH (sec)	TIME DIGITIZING INTERVAL (sec)	FREQUENCY DIGITIZING INTERVAL (BANDWIDTH) (Hz)
100	8	0.0039	0.187
200	4	0.0020	0.375

The following relations describe the analyzer's digitizing resolution with no window function applied (Hewlett Packard, 1985):

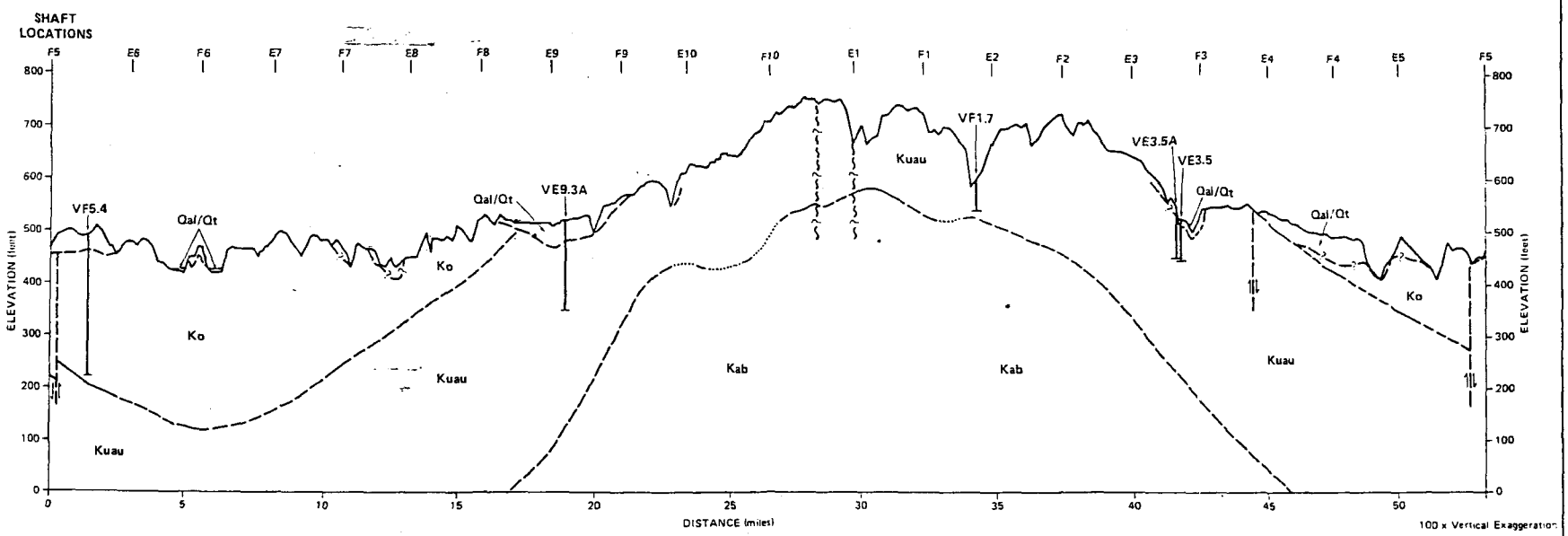
$$\text{Time record length (sec)} = \frac{\text{800 intervals (frequency domain)}}{\text{Frequency span (Hz)}}$$

$$\text{Time digitizing interval (sec)} = \frac{\text{Time Record Length (sec)}}{\text{2048 intervals (time domain)}}$$

$$\text{Frequency digitizing interval (Hz)} = \frac{\text{Frequency span (Hz)}}{\text{800 intervals (frequency domain)}}$$

The frequency digitizing interval is increased by 50 percent when the Hanning window is used during Fourier transformation. This window reduces ringing in the frequency domain when a finite length time record is tranformed.

Data were recorded with no filtering, averaging, or clipping (because of the analyzer's large dynamic range). To measure long time periods, up to 60 contiguous records were recorded as a single data set. The analyzer reports the status of each set during recording; there were no time gaps between the individual records. An example raw time record appears in Figure C-1. The top three graphs show maximum displacement measured



EXPLANATION

Qal/Qt	ALLUVIAL DEPOSITS		CONTACT
Ko	TAYLOR MARL – OZAN FORMATION		INFERRED CONTACT
Kuau	AUSTIN CHALK		INFERRED CONTACT (WELL CONTROL SPARSE OR NON-EXISTENT)
Kab	ARCADIA PARK FORMATION – "EAGLE FORD SHALE"		FAULT (ARROWS SHOW RELATIVE MOVEMENT)
	GROUND ELEVATION DETERMINED FROM USGS MAPS		FAULT INDICATED BY SURFACE GEOLOGICAL MAPPING

Source: Texas National Research Laboratory Commission (1987) Superconducting Super Collider, Tunnel Profile Volume 3.
Revised Geology Based on June 1989 Geotechnical Investigation.

The Earth Technology Corporation

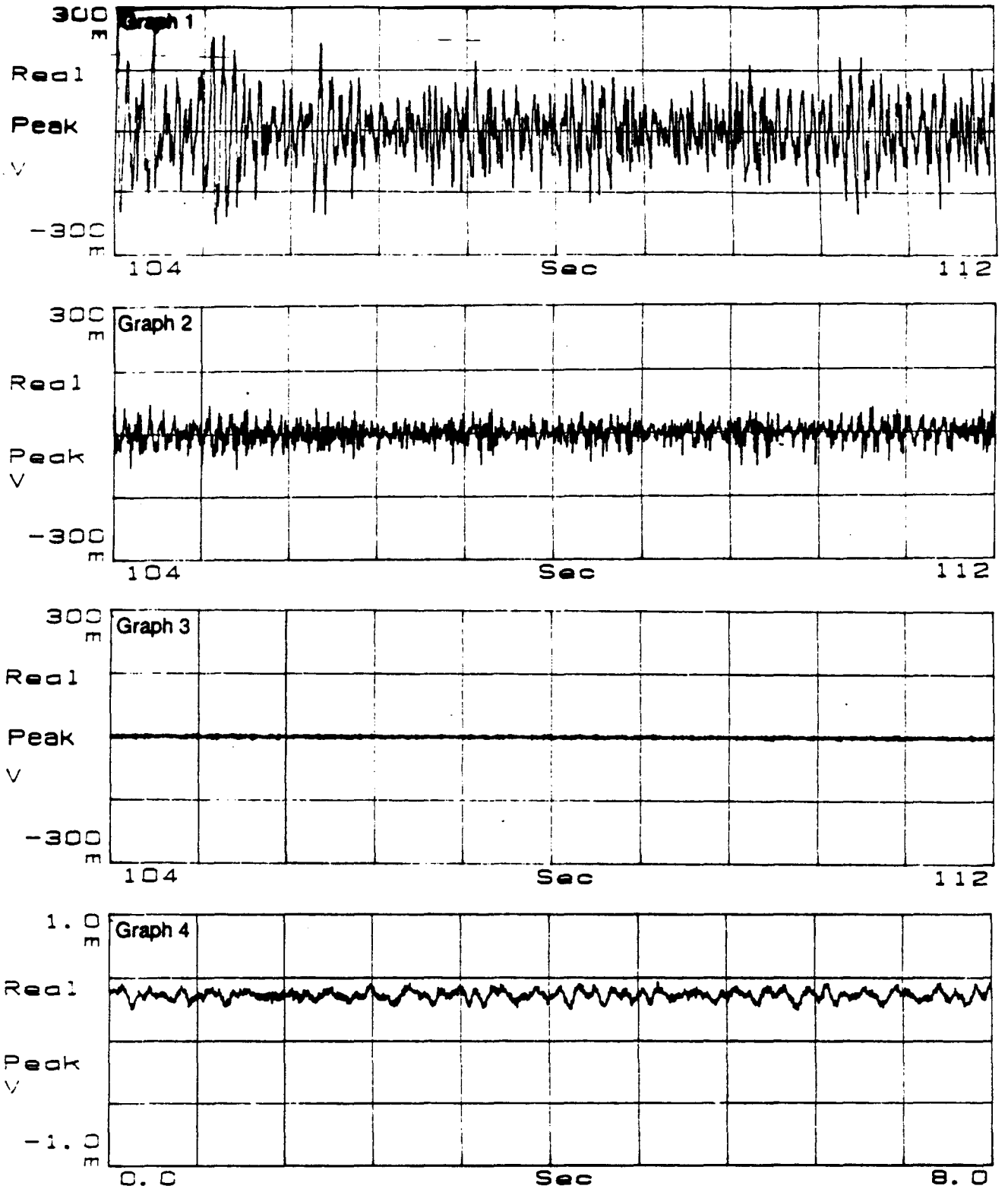
PROJECT NO.: 87-888-0011

RTK Joint Venture

Geological Profile Around the SSC Ring

12-89

Figure 3-1



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 1: Geophone 4106 @ 5.0 (1.5) - Train
Graph 2: Geophone 2676 @ 30.0 (9.1) - Train
Graph 3: Geophone 4105 @ 261.5 (79.7) - Train
Graph 4: Geophone 4105 @ 261.5 (79.7) - Ambient
Record made at Site VF-5.4 (Data set 2)

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Vibration Measurement
Raw Time Series Data Records
Example

12-89

Figure C-1

for a train passage. For all example graphs, the same Y axis scale is used to qualitatively show vibration attenuation with depth. The bottom graph shows ambient background vibrations. (The Y axis scale has been enlarged relative to the top three graphs.) The remaining examples shown in this appendix are processed results of these records.

Two types of vibration sources (Figure C-2) were measured: random (traffic and ambient) and controlled (train and quarry blast). Random sources occur with no pattern. Ambient and traffic vibrations were measured during different times of the day to statistically sample random vibrations.

Controlled vibration sources require the measurements to capture a discrete event, such as a train passing the boring. Measurements were started when the train was 0.5 to 1.0 mile (0.84 to 1.6 kilometers) from the boring and ended when the caboose was at least the same distance past the boring. (Recording started when the engine passed a flagman who was in radio contact with the instrument operator.) Quarry blast measurements were started several minutes before the blast; they could not be synchronized with the detonation because of communication equipment restrictions. The two recording analyzers were roughly synchronized.

C2.0 DATA SELECTION

- *Critical record selection*

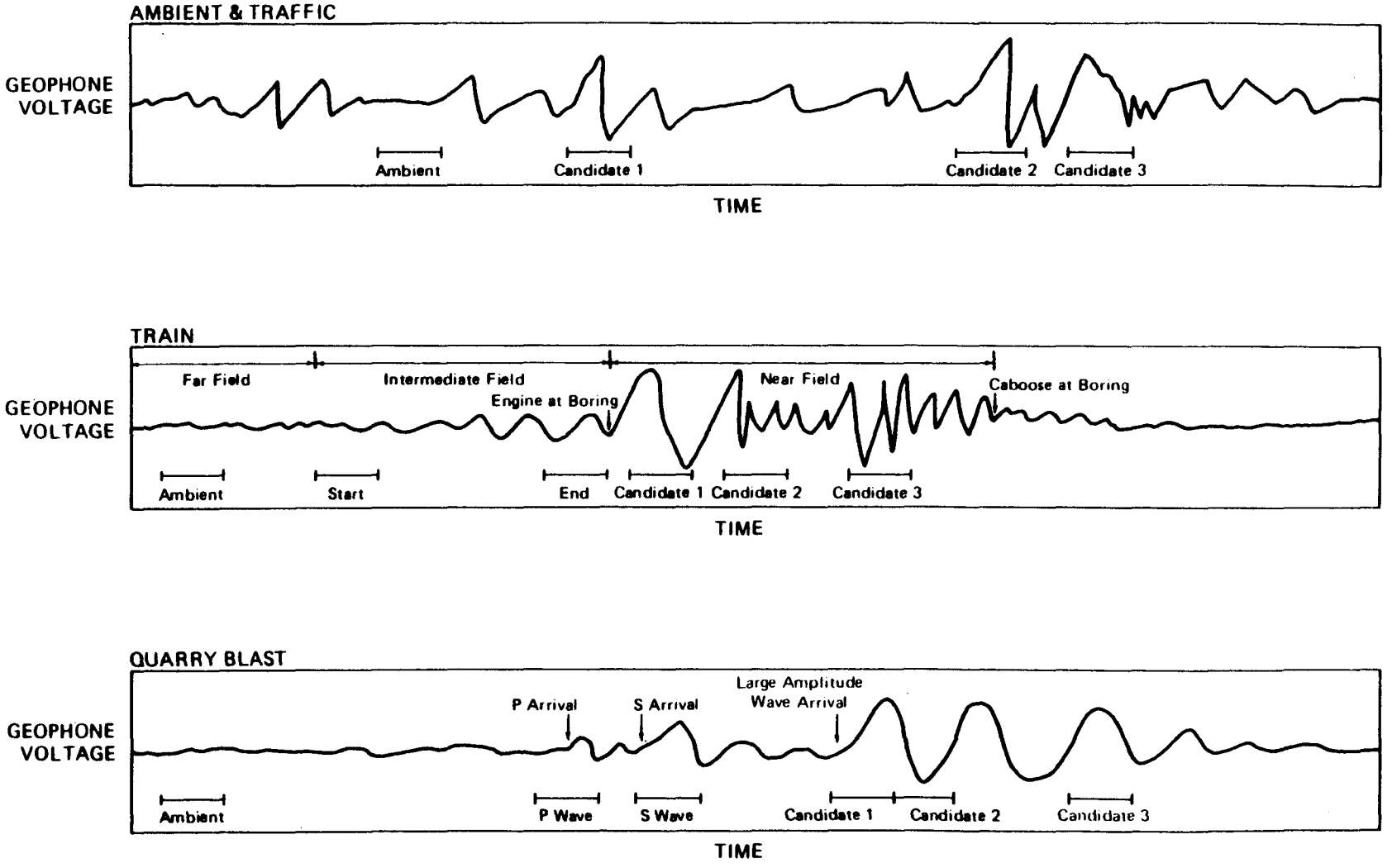
Many data sets were collected at each site to obtain a good statistical sampling. Instead of processing and analyzing all data, two criteria were used to select individual records for processing. First, the two data sets containing the overall maximum amplitude time records for each site were chosen. Usually, 4 to 7 records (out of 60 records per set) representing critical events in these data sets were manually selected using the criteria described below (Figure C-2). Maximum displacements were reported instead of averages to represent the largest amplitude vibrations (worst-case conditions).

Ambient and Traffic Data

Ambient data were chosen by selecting individual records near the data set start: during this time there were no train- or blast-induced vibrations. Three candidate records were chosen as representing traffic maximum amplitude vibrations. All three were processed and compared; the largest displacements were reported. Three records were processed to obtain statistical results about the data and to reduce dependency on the selection process.

Train Data

Train data can be divided into three distinct time/distance ranges or fields depending on the train-to-boring distance. When the train is far from the geophones in the boring, then only background ambient vibrations are measured. First records of the data sets were found to be similar to data sets measuring only ambient vibrations. Therefore, peak amplitudes of the first two or three records were measured and used as the ambient background vibration level.



The Earth Technology Corporation

PROJECT NO.: 87-868-0011

RTK Joint Venture

Vibration Measurement
Critical Record Selection Criteria

12-89

Figure C-2

Intermediate field starts when the train is close enough to the boring to contribute to the vibration levels being measured. Most of the amplitude peaks on the starting record of this field exceed the ambient reference level. The time difference between the start of this field and when the train crosses the boring is a qualitative measure of three-dimensional attenuation.

Near field starts when the engine crosses the boring and ends when the caboose crosses the boring. As expected, the largest displacements were measured during this time period. Surprisingly, heavy engines do not always produce maximum displacements. Railroad cars with 'flat' wheels couple large-amplitude vibrations into the ground. Three candidate records with maximum amplitude were chosen within this field. They were processed and compared, and the one with the largest displacement levels was chosen to represent the data set.

Quarry Blast Data

An ambient record was chosen near the beginning of the data set, before the detonation. The P and S wave arrivals were identified from the complex waveform generated by the blast and the individual records containing them were selected for processing. Usually three records were selected as the maximum amplitude of the blast waveform and processed.

C3.0 DATA REDUCTION

- *Proprietary software*

All processing was performed on the HP model 3562A analyzer. A list of equations used by the analyzer software to calculate the fast Fourier transform (FFT) and various spectra is considered proprietary by Hewlett Packard (Mr. Brian McCarver, personal communication, October 11, 1989). The mathematical processes are briefly described in an applications note (Hewlett Packard, 1985). Numerous graduate students at the University of Texas (Austin and El Paso) have repeatedly checked the analyzer's operation to their satisfaction. Functional tests of the analyzer are described in Appendix B.

- *Linear spectral density format*

The ISP criteria are listed as displacement versus frequency. Therefore, the formalized main processing sequence was in the frequency domain because this representation of data and results is preferred for dynamic analysis (Hoar, 1982). All spectra are displayed as linear spectral densities, that is, only the magnitude of the real part of the complex function divided by a normalization constant, square root of the digitizing interval (bandwidth) in the frequency domain. (Hewlett Packard follows the convention that linear spectral density is the square root of the power spectral density, hence the root hertz factor in the denominator.) Spectral density format is preferred because it allows direct comparison of spectra measured with different frequency spans and bandwidths. Comparing linear spectra of the same data recorded at 100- and 200-Hz frequency spans will show that the amplitude of the 100-Hz curve is $\sqrt{2}$ times greater than that of the 200-Hz curve (conservation of energy). On each spectrum is a marker showing the lower frequency limit (0.8 or 10 Hz) of geophone calibration. Many graphs are shown in this appendix to help describe the processing. Only the maximum-amplitude raw time data and several displacement spectra displays are shown in the data appendices (E through K) for simplicity.

- *Formalized processing-frequency domain*

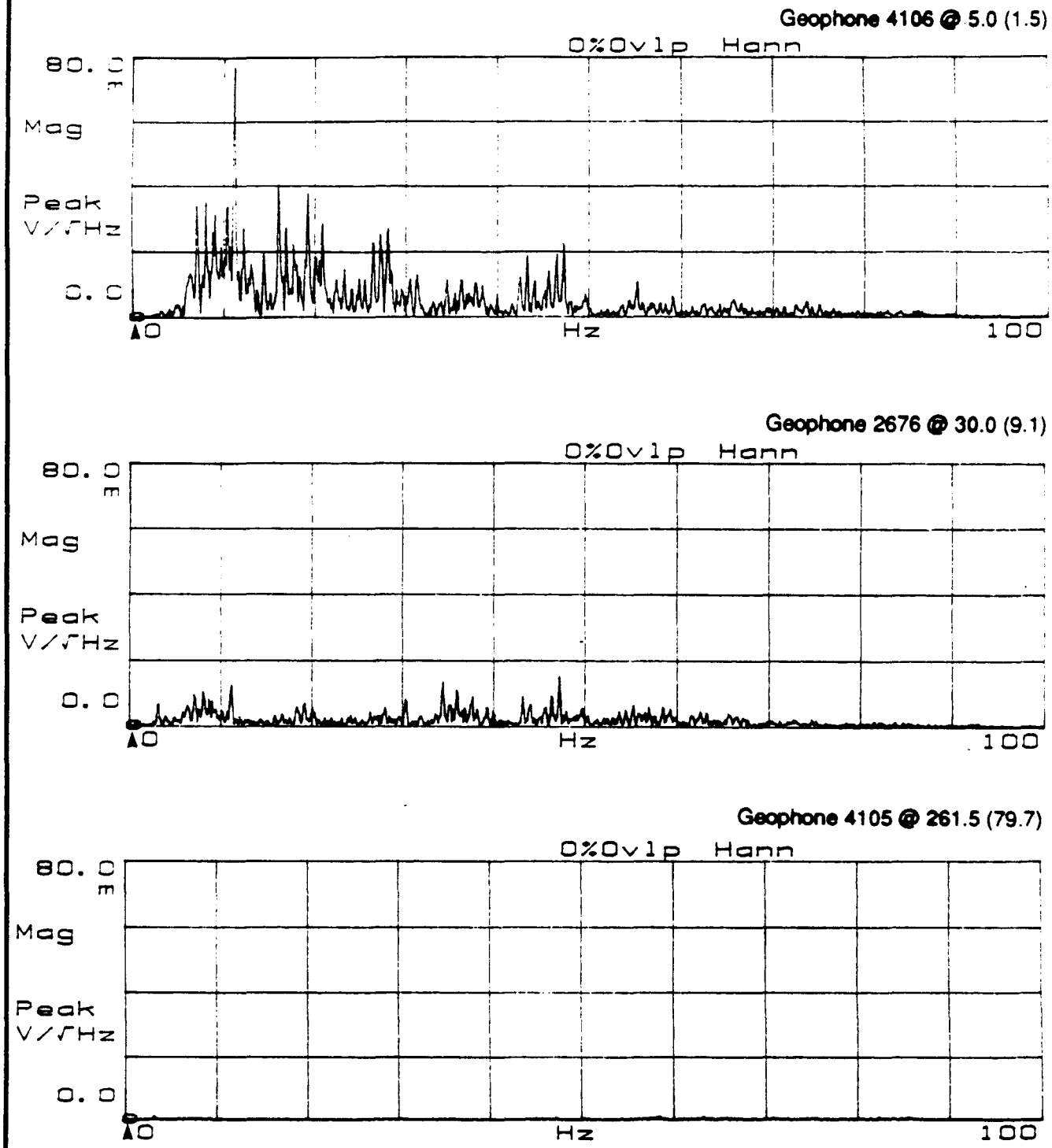
Processing the critical records consisted of two sequences, each having several steps (Figure 5-1). In the main processing sequence, the single controlling step is application of the geophone calibration. Because calibration is a complex function in the frequency domain (Appendix A), the formalized processing is performed in that domain and no approximations are made about the calibration curve. Data were transformed using the Hanning window (to minimize ringing) and the FFT to yield the raw velocity spectrum shown in Figure C-3 (in units of voltage, proportional to velocity because geophones are velocity transducers). The calibration function for the specific geophone used to acquire the data is synthesized from the curve fit parameters for the observed data frequency span. The raw velocity spectrum is divided by the calibration function, one frequency at a time. This process yields a calibrated velocity spectrum (Figure C-4), which is then integrated to a displacement spectrum (Figure C-5). The displacement units are changed to micrometers for direct comparison with the ISP criteria and 1-micrometer tolerance (as shown Figure C-6). This final displacement spectrum is expanded (Figure C-7) to show details about the low-frequency vibration levels relative to ambient levels at the proposed tunnel depth (in use during Footprint Validation). Actual displacement levels are calculated from this spectrum by measuring the displacement at a given frequency and then multiplying it by the square root of the bandwidth (shown in the figure explanation). The displacement spectrum is filtered to remove spurious frequency components less than the lower limit of geophone calibration. This filter (Figure C-8) was designed to minimize data alteration at frequencies greater than 0.8 Hz. Below this frequency, the filter will rapidly decrease the data magnitude while introducing only a small phase shift (less than 14 degrees). An inverse FFT is applied to the filtered spectrum to yield a displacement time history (Figure C-9). The time histories have the same general shape and frequency content as the corresponding raw time-series data.

- *Time domain processing*

Formalized data processing cannot be performed in the time domain because the geophone complex calibration function cannot be adequately approximated by a constant value. Simply taking the raw time-series data, dividing by a constant calibration factor, and integrating to displacement will degrade the resulting frequency spectrum. As seen in Appendix A, the magnitude and phase of the 1-Hz geophones do not approach a constant value until about 5 Hz. Therefore, time domain processing will adversely alter the low frequency (0.8 to 5 Hz) span covering the majority of maximum displacement peaks measured during this survey. Also, time domain processing does not remove the spurious frequency components less than the lower limit of geophone calibration.

- *Functional check*

Time domain processing can provide a qualitative functional check on the analyzer's operation (Figure 5-1). Displacement time histories derived from both the frequency and time domain processing are displayed in Figure C-9. Both curves have similar frequency content and differ in amplitude mainly at low frequencies because the geophone calibration curve is not linear below 5 Hz. This functional check shows that the analyzer is processing the data properly.



EXPLANATION

1Hz Geophone Data
Geophone Depths in feet (meters)
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz
Record made at Site VF-5.4 (Data set 2)

The Earth Technology Corporation

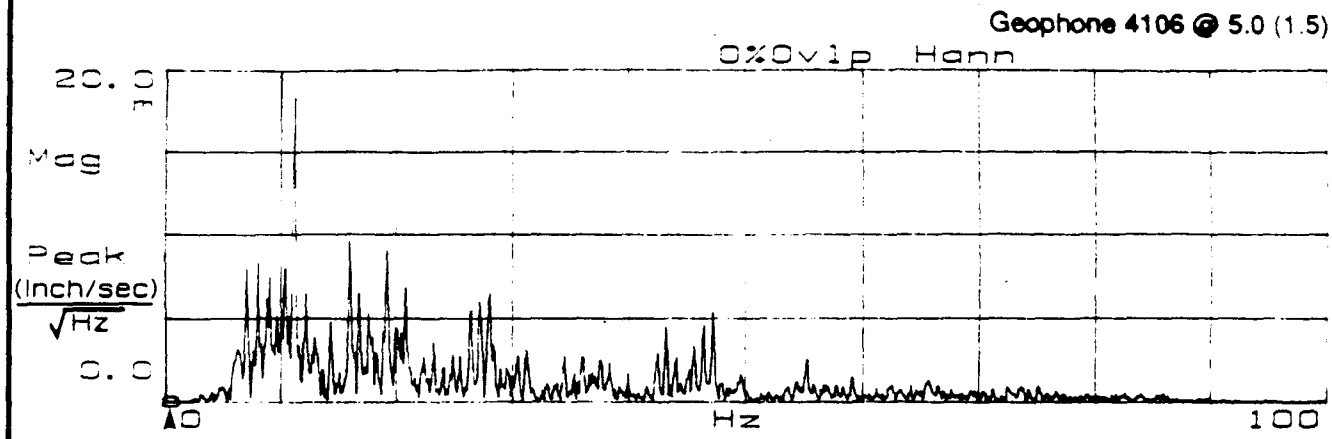
Project No.: 87-888-0011

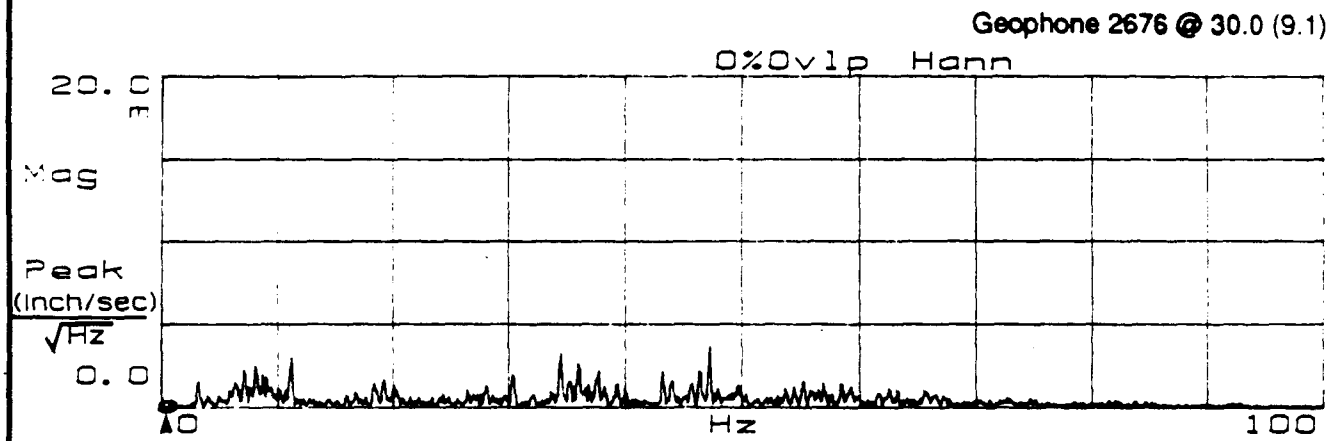
RTK Joint Venture

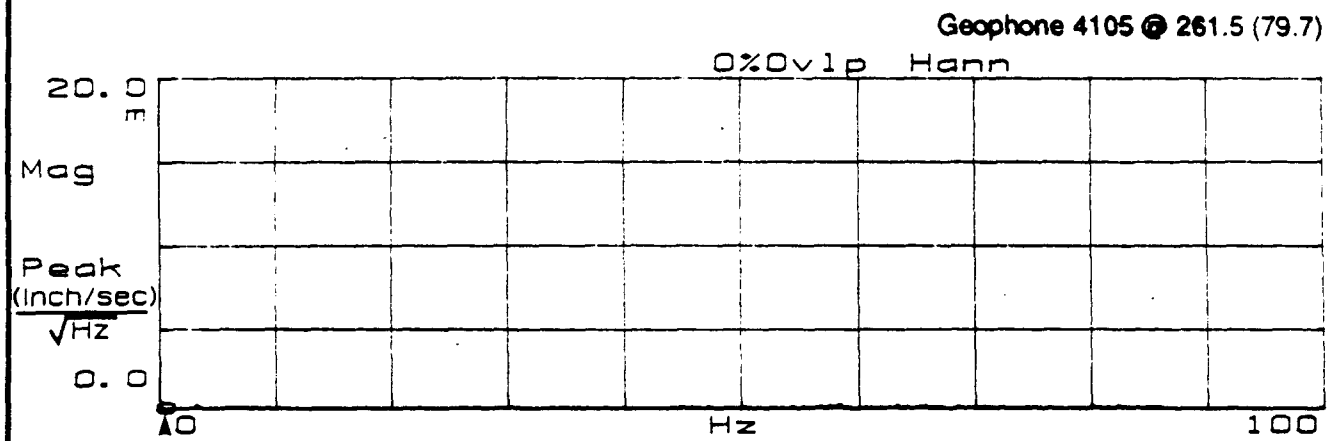
Vibration Measurement
Raw Velocity Linear Spectra
Example

12-89

Figure C-3



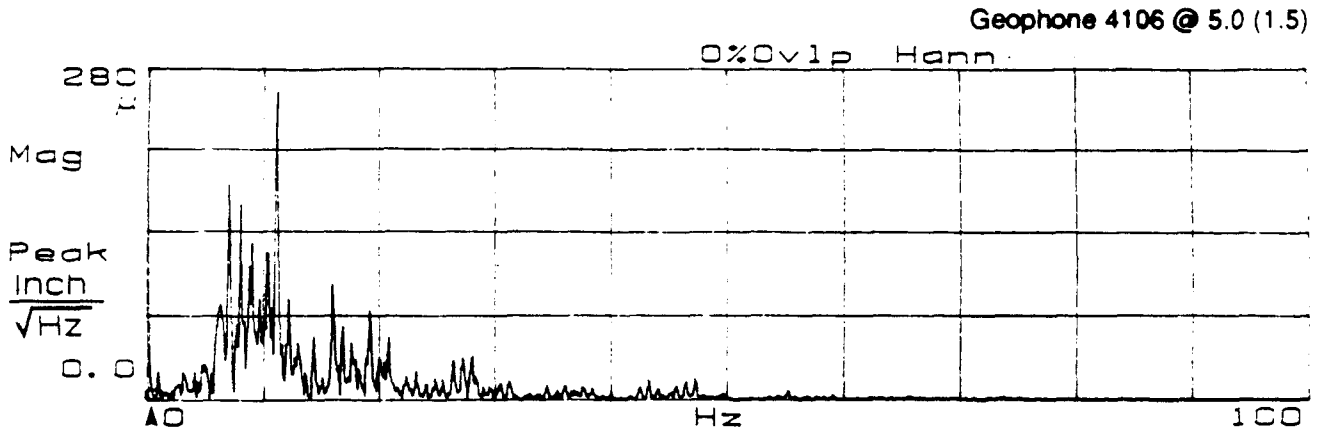


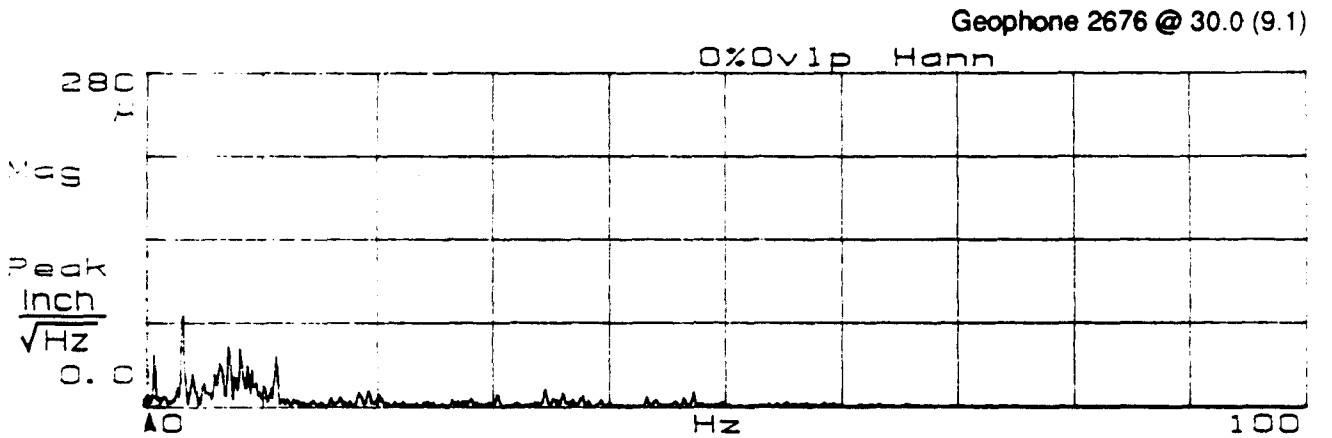


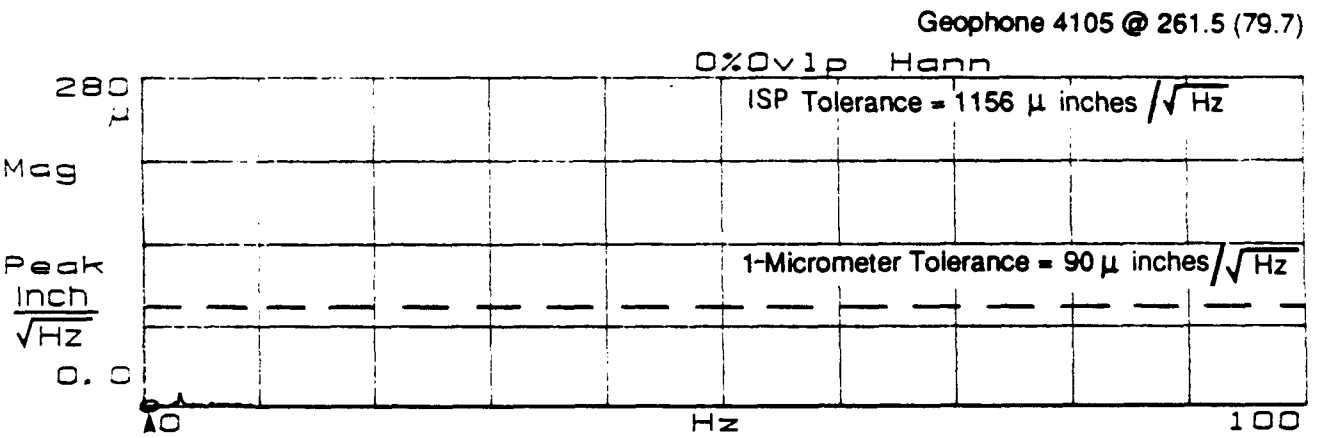
EXPLANATION

1Hz Geophone Data
Geophone Depths in feet (meters)
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz
Record made at Site VF-5.4 (Data set 2)

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture
Vibration Measurement Calibrated Velocity Linear Spectra Example	
12-89	Figure C-4







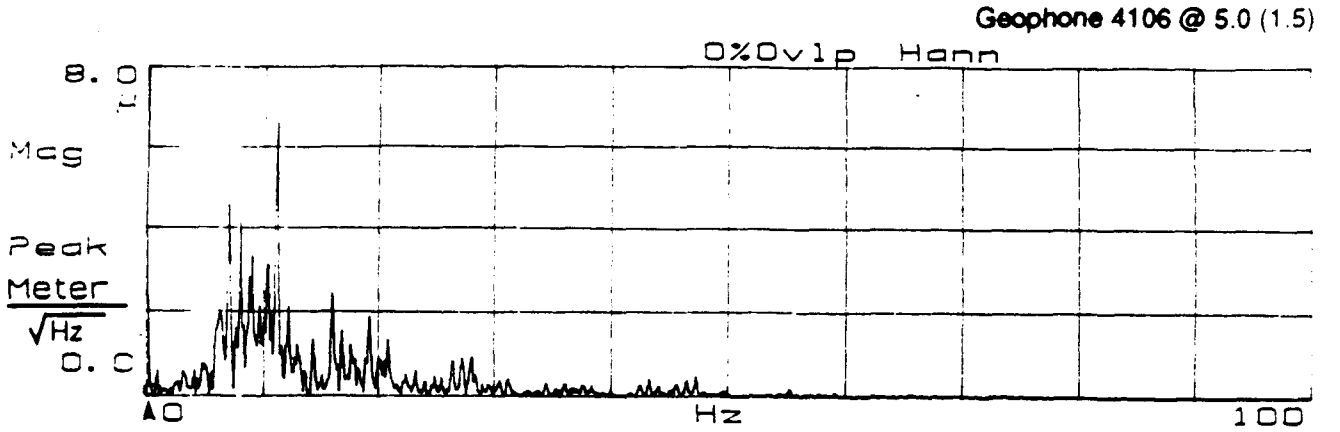
EXPLANATION

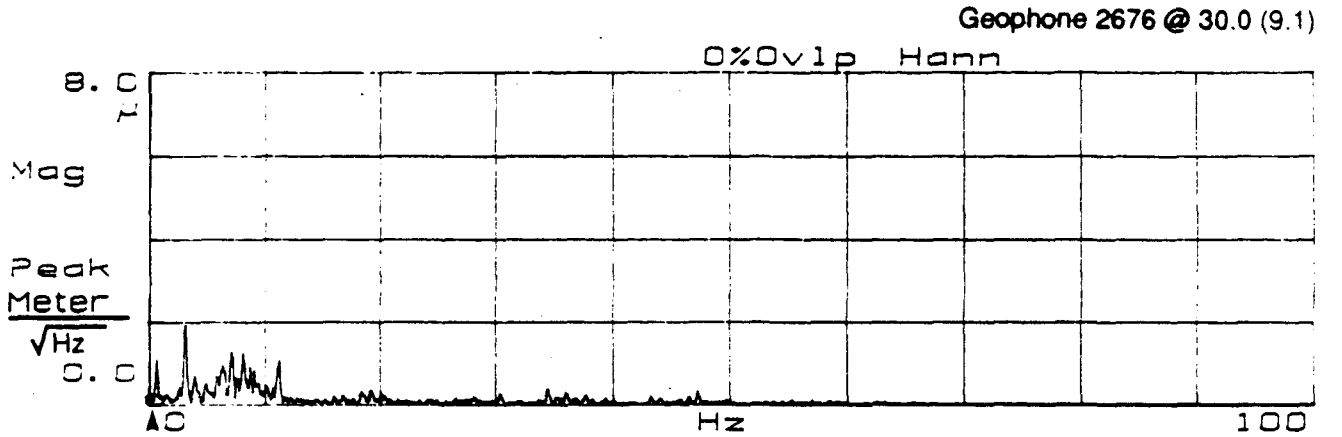
1Hz Geophone Data
Geophone Depths in feet (meters)
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz
Record made at Site VF-5.4 (Data set 2)

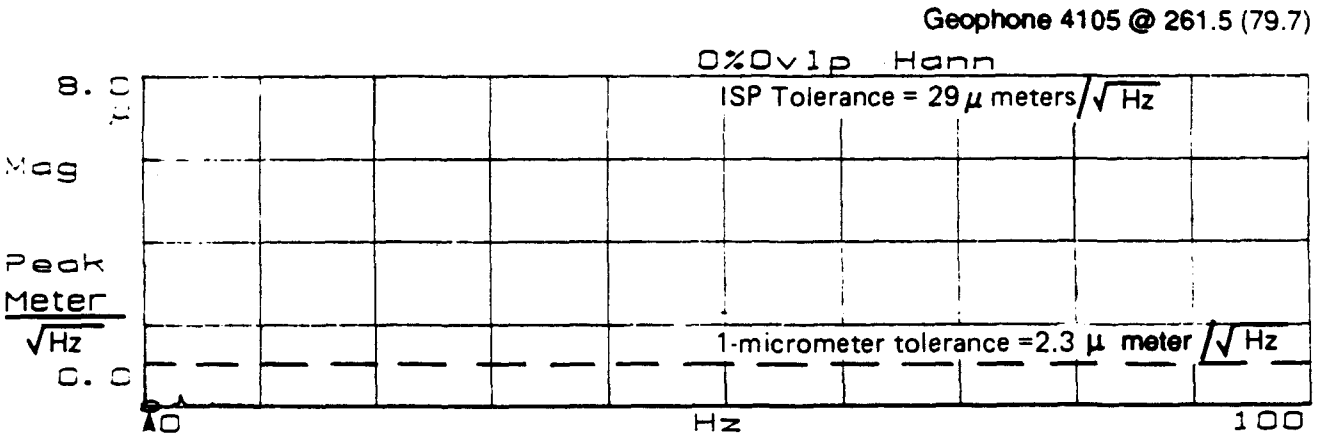
The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Vibration Measurement
Displacement (inches) Linear Spectra
Example

12-89 Figure C-5







EXPLANATION

1Hz Geophone Data
Geophone Depths in feet (meters)
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz
Record made at Site VF-5.4 (Data set 2)

The Earth Technology Corporation

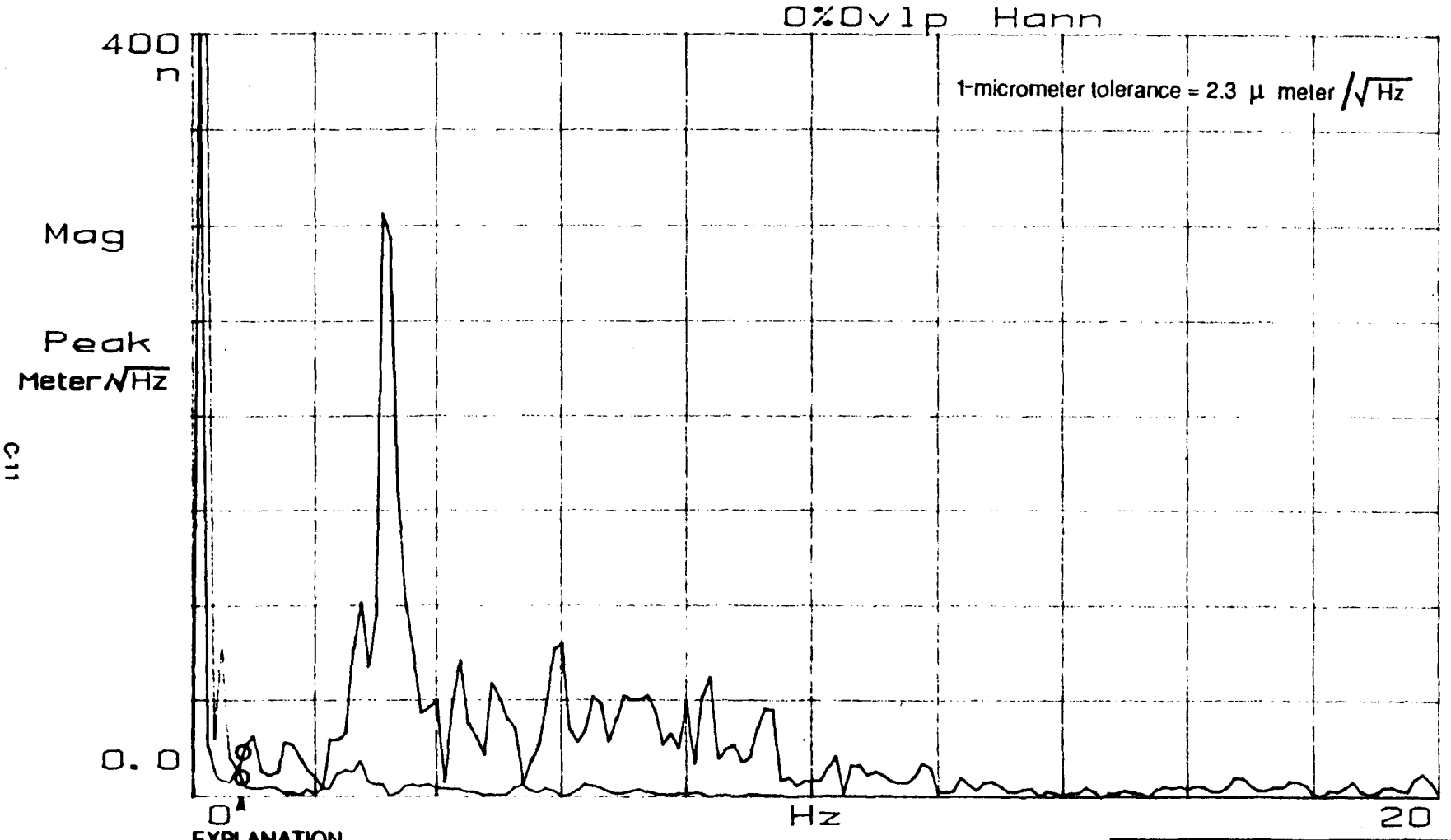
Project No.: 87-888-0011

RTK Joint Venture

Vibration Measurement
Displacement (meters) Linear Spectra
Example

12-89

Figure C-6



EXPLANATION

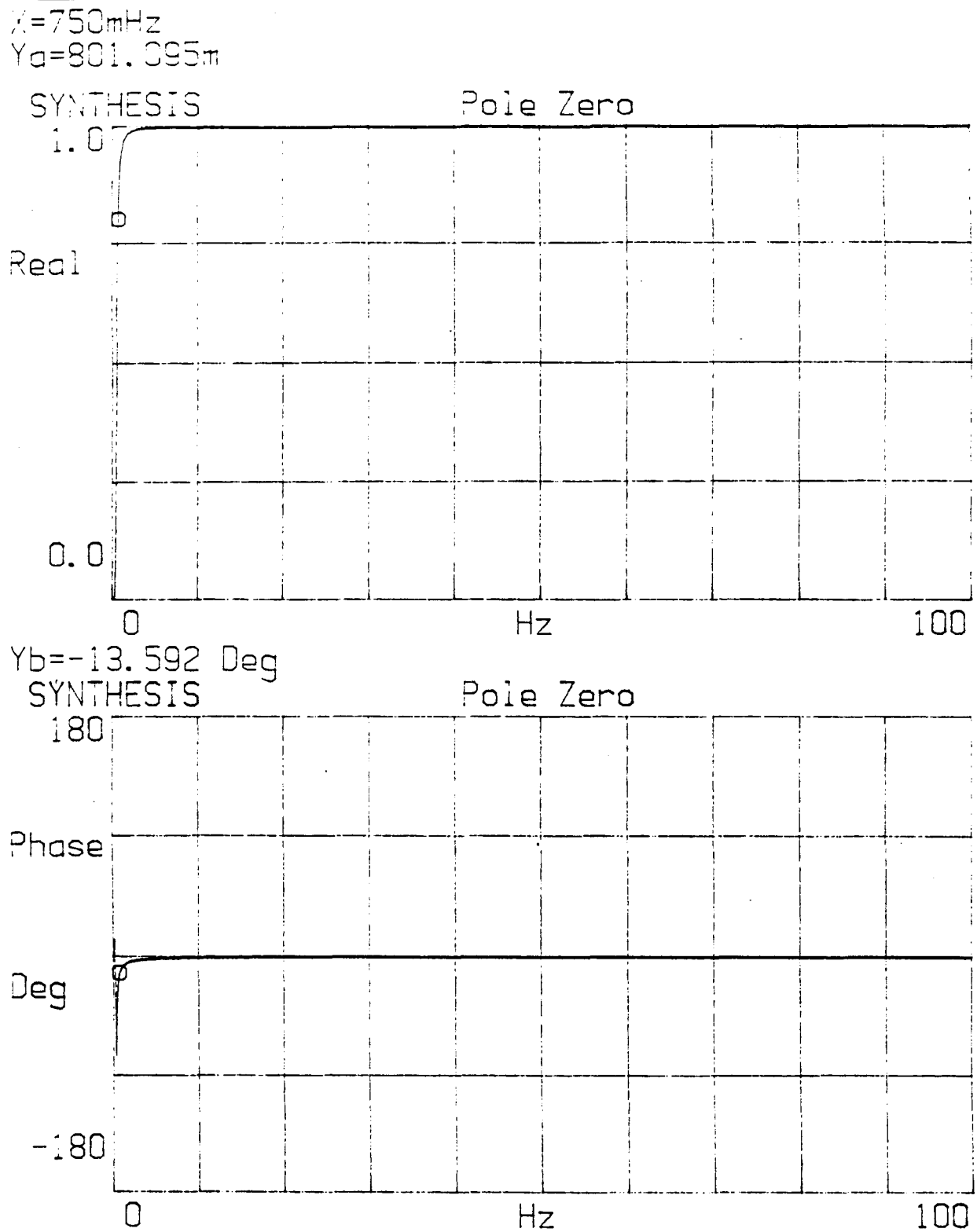
1 Hz Geophone Data
Geophone Depths in feet (meters)
Red = Max. Vibrations Measured at 261.5 (79.7)
Black = Ambient Vibrations Measured at 261.5 (79.7)
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz
Record made at Site VF-5.4 (Data set 2)

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Vibration Measurement
Displacement (meters) Linear Spectra
Example (Expanded Scale)

12-89

Figure C-7



EXPLANATION

Synthesis Parameters

Gain = 1.0

Poles:	Zeros:
-0.085 Hz±j 0.280 Hz	0±j 0.130 Hz
0.081 Hz±j 0.310 Hz	0±j 0.150 Hz
0.081 Hz±j 0.310 Hz	0±j 0.180 Hz
0.081 Hz±j 0.310 Hz	0±j 0.250 Hz
0.081 Hz±j 0.310 Hz	0±j 0.280 Hz
-0.084 Hz±j 0.300 Hz	0±j 0.320 Hz
-0.084 Hz±j 0.300 Hz	0±j 0.340 Hz
-0.084 Hz±j 0.300 Hz	0±j 0.380 Hz
0.081 Hz±j 0.310 Hz	0±j 0.470 Hz

The Earth Technology Corporation

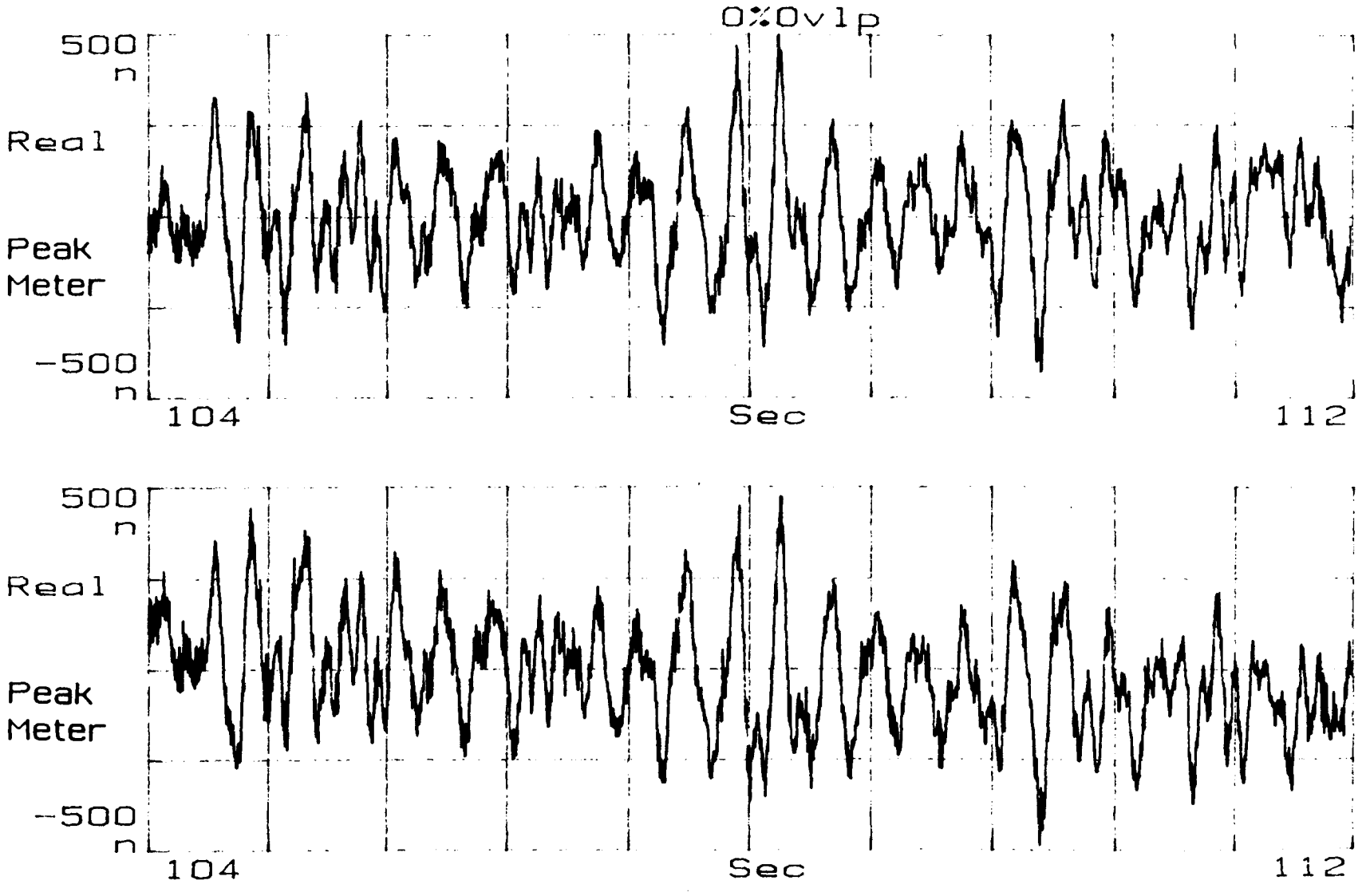
Project No.: 87-888-0011

RTK Joint Venture

Frequency Domain
High-Pass Filter

12-89

Figure C-8



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 261.5 feet (79.7 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

Record made at Site VF-5.4 (Data Set 2)

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Vibration Measurement
Displacement Time History
Example

12-89

Figure C-9

Once all records have been processed, spectra are compared to show vertical and horizontal directions. Triaxial geophone data are qualitatively compared to show vibration levels sensed by the vertical, radial, and transverse geophones. Composite spectra show the raw velocity data because only a rough comparison is necessary. Comparing these uncalibrated data is valid because the calibration curves for the three geophones in the triaxial package differ by less than 5 percent (Appendix A).

- *Attenuation estimates*

Composite spectra (Figure C-10) showing displacement changes in a vertical direction, as measured by three 1-Hz geophones in a boring, are constructed by plotting their displacement spectra on the same graph. (A log axis is used because of the large range of displacements measured.) Composite spectra showing displacement changes in a horizontal direction are constructed with geophone data simultaneously recorded at different borings from the same source.

Composite spectra not only show measured displacement versus frequency, but also qualitatively show either vertical- or horizontal-oriented attenuation. Order-of-magnitude attenuation estimates were calculated using a technique described by Mok (1987, 1988) and Sanchez-Salinero et al. (1986). Seismic wave amplitude decreases as the wave propagates away from the source. This decrease is caused by three mechanisms:

1. Reflection/refraction at interfaces between materials with differing densities and seismic velocities.
2. Geometric damping, which decreases the energy density because of wave front spreading during propagation.
3. Material attenuation or damping caused by dissipation of energy as frictional losses in the material.

Different frequency components of the seismic waves attenuate at different rates, which can be determined from spectral ratio changes with depth or distance. Mok (1987) shows the following relations:

$$\alpha = \frac{\ln \left[\frac{A_1}{A_2} \frac{R_1}{R_2} \right]}{R_2 - R_1} \qquad (1)$$

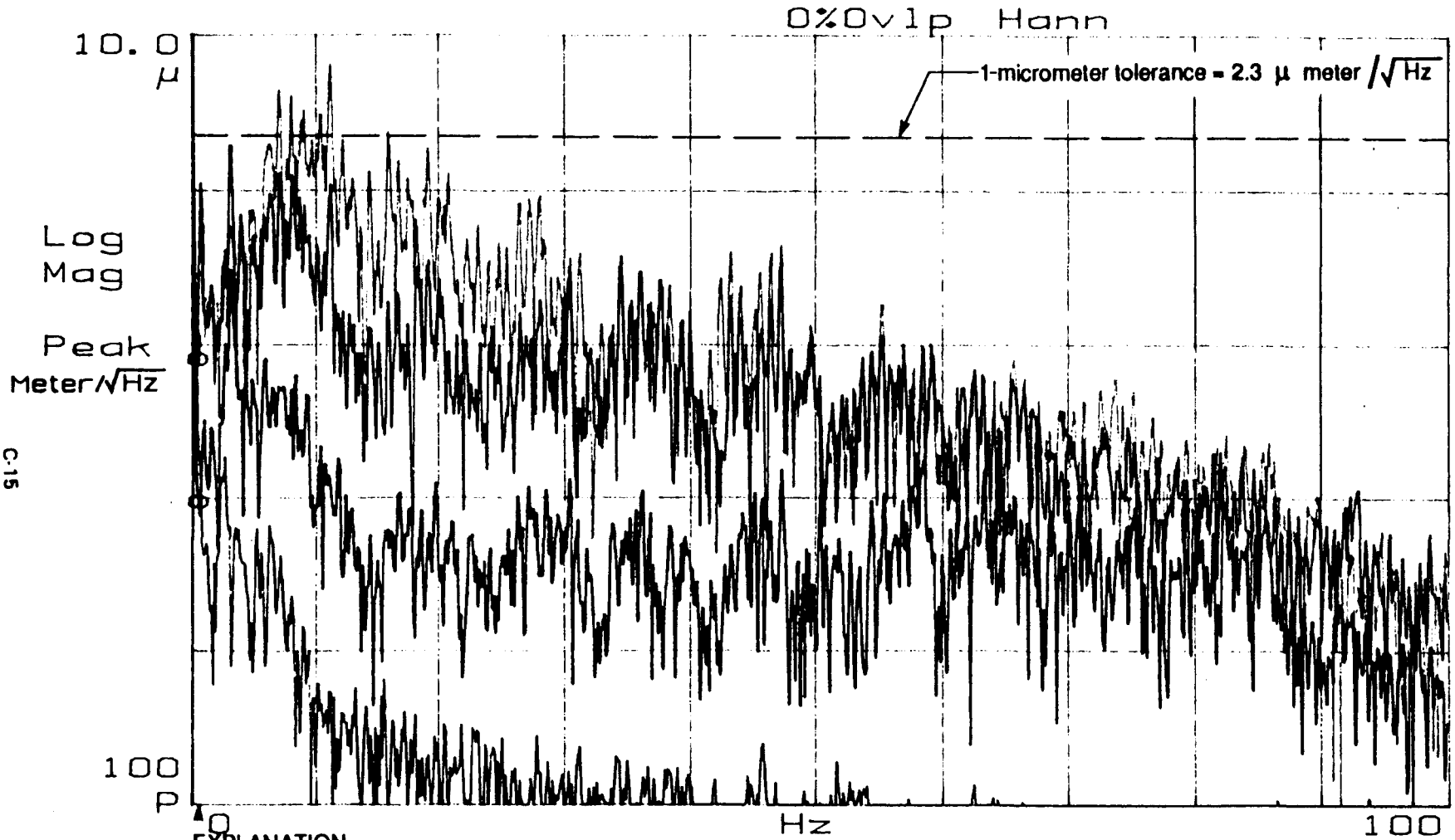
$$C = \alpha / f \qquad (2)$$

$$Q = \pi f / \alpha V \qquad (3)$$

$$D = 1/2Q \qquad (4)$$

where:

- α is the attenuation coefficient
- A_1 is the wave amplitude at distance R_1 from the source
- A_2 is the amplitude at the greater distance R_2 from the source
- C is the attenuation constant
- Q is a quality factor
- f is wave frequency
- V is wave velocity
- D is damping ratio.



EXPLANATION
1 Hz Geophone Data
Geophone Depths in feet (meters)
Blue = Max. Vibrations Measured @ 5.0 (1.5)
Green = Max. Vibrations Measured @ 30.0 (9.1)
Red = Max. Vibrations Measured @ 261.5 (79.7)
Black = Ambient Vibrations Measured @ 261.5 (79.7)
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Vibration Measurement
Composite Displacement (meters)
Linear Spectra
Example

12.89

The following assumptions apply to these equations:

1. Damping is frequency independent for small strain (less than 0.001 percent).
2. Near-field effects on amplitude are negligible.
3. Wave amplitudes are not affected by reflection/refraction.

Because the effects of assumptions 2 and 3 cannot be isolated and removed from the vibration data, the calculated attenuation constants are only rough estimates, at best. Attenuation constants calculated between geophones within a single boring may be in error because the surface geophone is too close to the source and thus violates assumption 2. Hoar (1982) and Mok (1987) describe field methods for adequately measuring attenuation and damping.

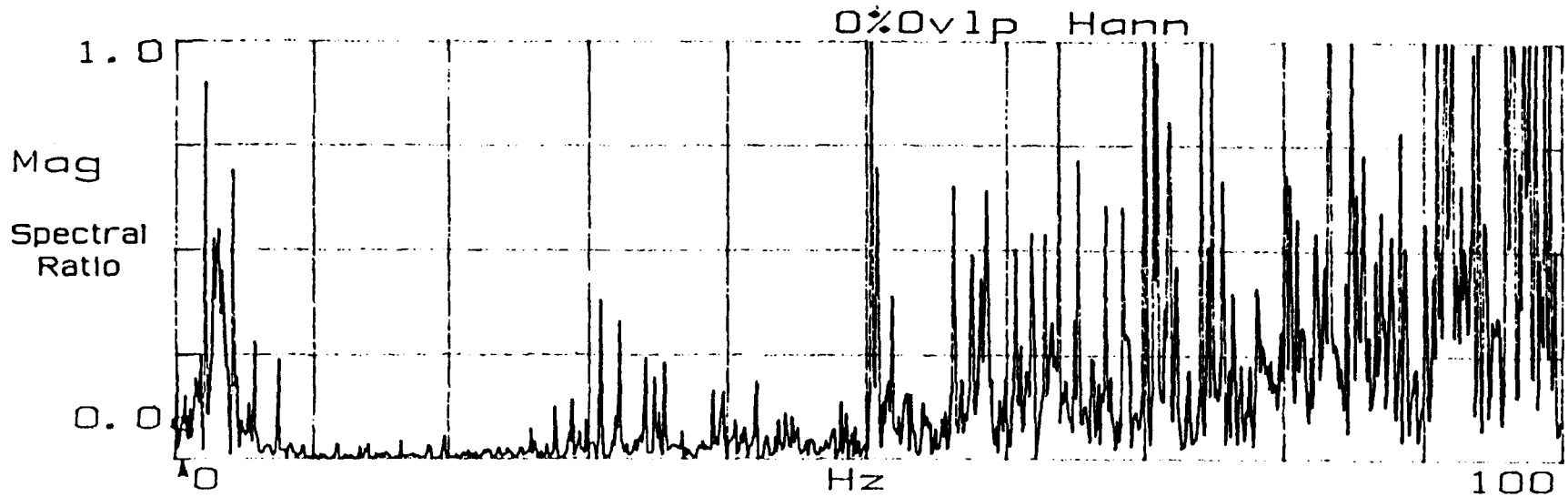
The A_2/A_1 term in equation (1) is the spectral ratio, which can be evaluated by comparing spectra obtained at two distances from the vibration source. Figure C-11 shows the spectral ratios calculated using the following equations:

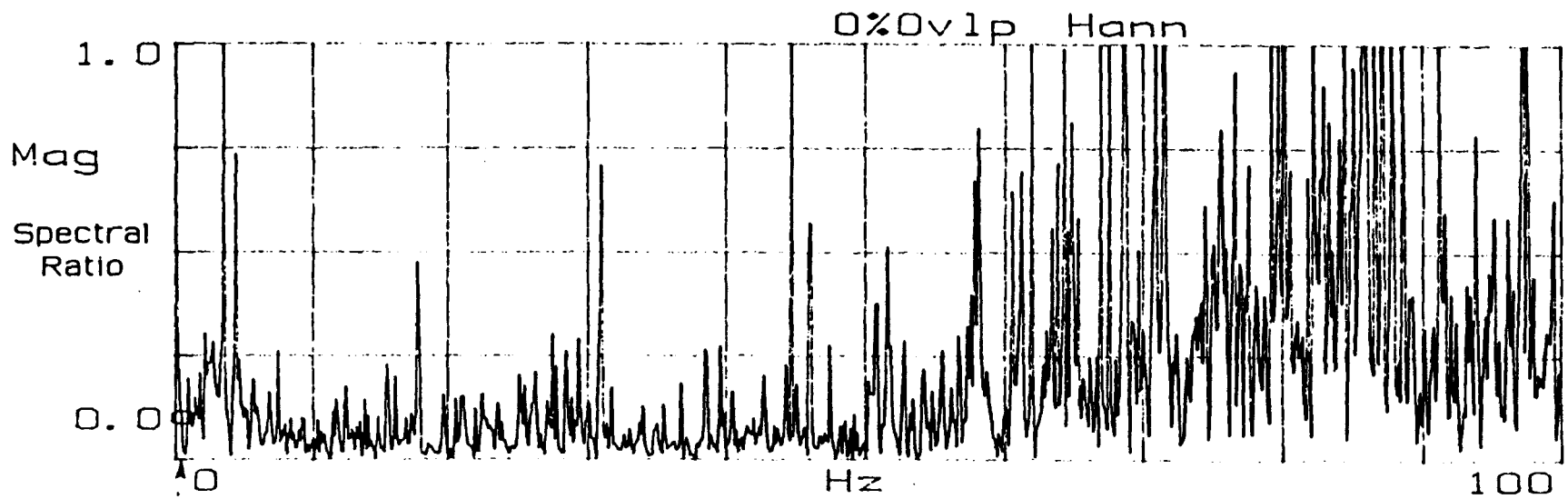
$$\text{"Bulk"} = \sqrt{\frac{\text{Deep Geophone Displacement Power Spectrum}}{\text{Shallow Geophone Displacement Power Spectrum}}}$$

$$\text{"Rock"} = \sqrt{\frac{\text{Deep Geophone Displacement Power Spectrum}}{\text{Intermediate Geophone Displacement Power Spectrum}}}$$

Spectral ratios are usually between 0 and 1, which makes it easy to compare graphs between different borings. The spectrum shows little scatter in the frequency span of useful data where coherence is high between the two recorded seismic waveforms being compared. Figure C-11 shows a dramatic increase in scatter at frequencies greater than 50 Hz; thus, the data recorded were completely random and do not represent coherent signals.

Spectral ratios were measured from the graphs at several frequencies. Near-source distance values were calculated as slant distances from surface vibration source to downhole geophones. Horizontal distances from source to geophones were used for distant source data. Attenuation constants were calculated using equations (1) and (2) and these values. Quality factor and damping ratio could be calculated once the appropriate seismic velocity is selected.





EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Top: Bulk ratio between Geophone @ 5.0 (1.5) and Geophone @ 261.5 (79.7)
Bottom: Rock ratio between Geophone @ 30.0 (9.1) and Geophone @ 261.5 (79.7)
Lower Frequency Limit of Calibration
Record made at Site VE-5.4 (Data set 2)

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Vibration Measurement
Spectral Ratio
of Vertically Separated Geophones
Example

12-89

Figure C-11

APPENDIX D

SEISMIC VELOCITY SURVEY PROCEDURES

D1.0 VERTICALLY TRAVELING WAVES

D1.1 DATA ACQUISITION

Seismic waves were generated at the surface and recorded at a number of depths in a boring. The time required for the waves to travel from the surface source directly to the geophones in the boring was measured from data records. Waves arriving at successively greater depths travel along essentially the same paths followed to shallower depths. Therefore, vertical velocity profiles were interpreted using travel time differences to calculate average wave velocities across successive depth intervals.

- *Source*

The general procedure used for determining the velocity of vertically traveling waves is shown in Figure D-1. Seismic waves were mechanically generated by hitting a 16-pound (7.3-kilogram) hammer against a metal plate and a horizontal wooden beam lying on the ground. A transistor switch on the hammer signals the instant of energy generation. These two sources were placed about 10 to 25 feet (3.0 to 7.6 meters) away from the boring. The energy source was offset from the boring to minimize coupling large-amplitude seismic waves into the casing or grout. Therefore, waves sensed by the triaxial geophone package should have traveled from the source through the soil to the geophones.

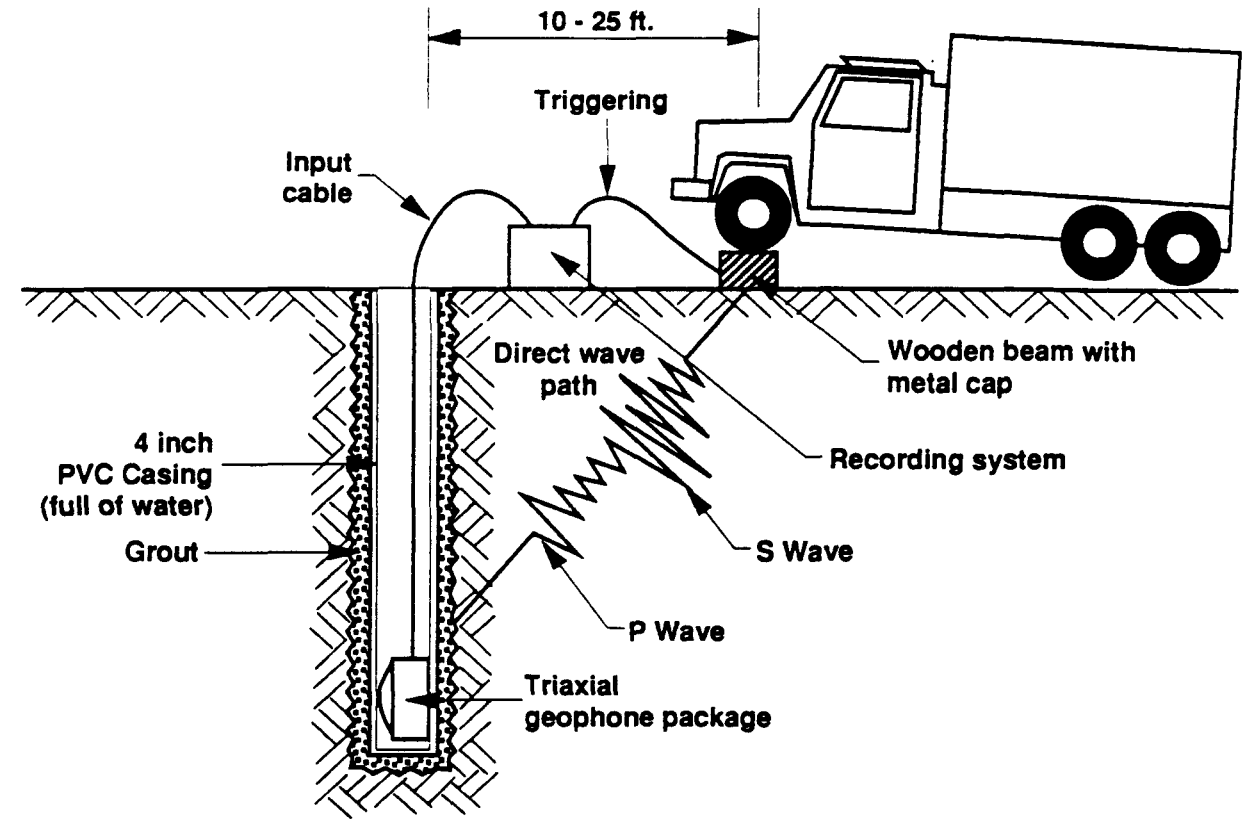
- *P waves*

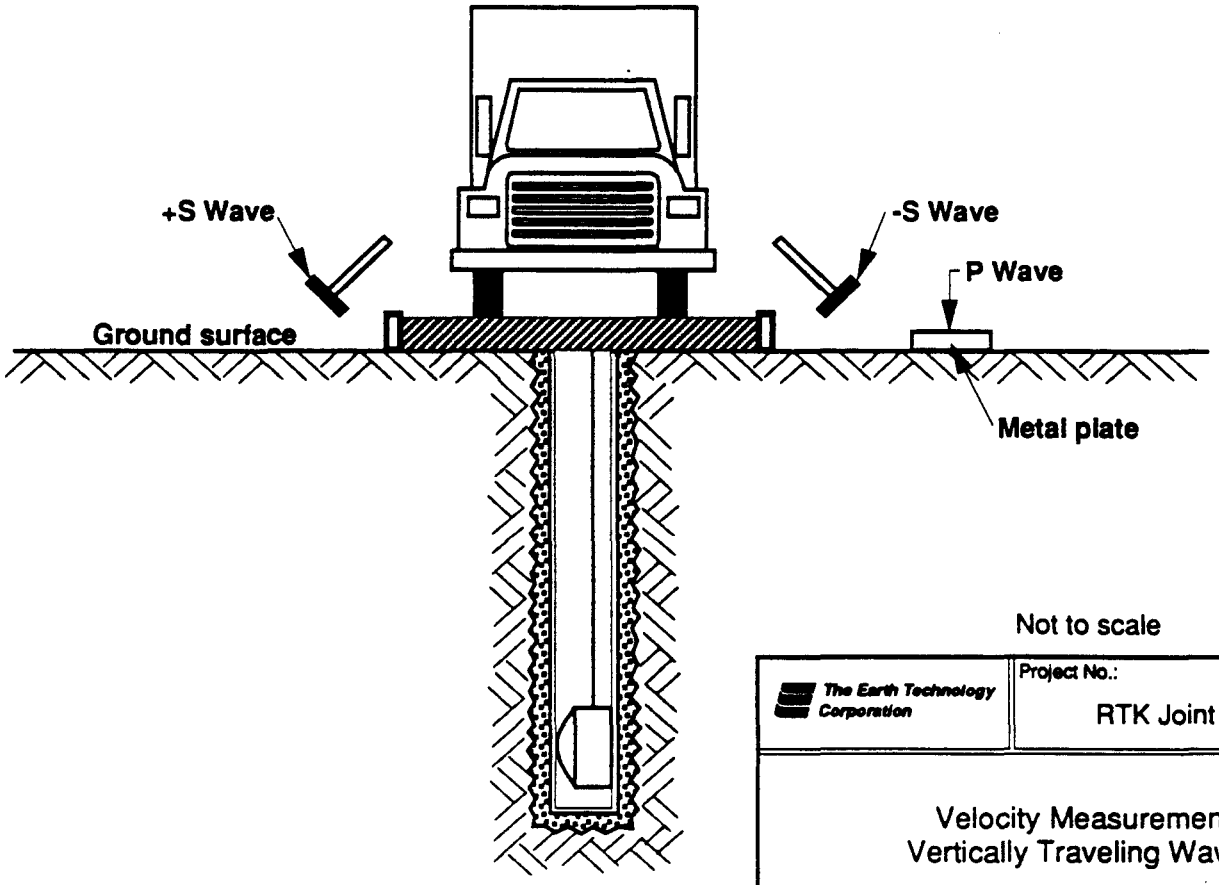
Compressional waves were generated by vertical hammer blows on the metal plate. The P waves are clearly seen on the horizontal geophone's output when the package depth was less than the energy offset distance. Below that depth, P waves were seen on the vertical geophone's output. An example raw data record is shown in Figure D-2. The record contains three groups of data; the top group is the output of all three geophones in the package when the metal plate was struck. The P wave arrival is identified as the first arrival on one of these data traces.

- *S waves*

Horizontally oriented shear waves were generated by horizontal hammer blows against the ends of the wooden beam. These waves are not converted to other types of waves when they impinge upon horizontal interfaces (Mok, 1987). The beam was oriented perpendicular to a line extending from its center to the boring. A vehicle parked on the beam provided solid coupling with the surface. The S waves have an inherent polarity; therefore, generating them with different polarities (hitting opposite ends of the beam) can help identify their arrivals within complex waveforms. The clearest display of an S wave generated by horizontal hammer blows is obtained from the horizontal geophone oriented parallel to the beam. (When necessary, the geophone package was rotated in the boring to keep one of the horizontal geophones parallel with the beam.) On the example record, the center data group shows the transverse geophone's output from hammer blows from each end of the beam. The lower data group shows the output from the radial geophone. The side-by-side data display helps identify the polarized S waves because the trace excursions marking their arrivals have opposite polarity.

- *Opposite polarity*



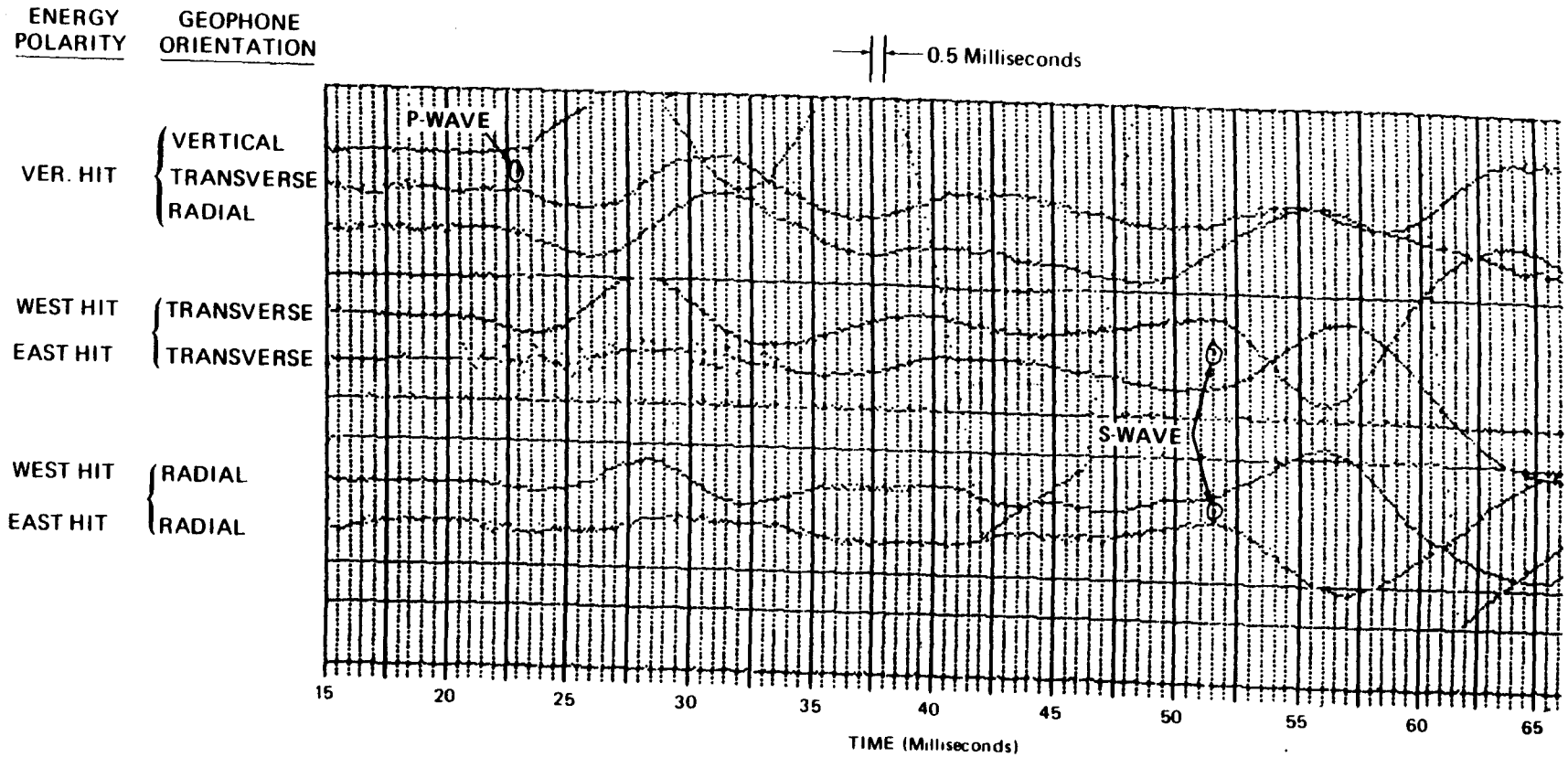


Not to scale

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Velocity Measurement
Vertically Traveling Waves

12-89 Figure D-1



NOTE: RECORD MADE AT SITE VF-1.7 AT A DEPTH OF 60 FEET

The Earth Technology Corporation

PROJECT NO.: 87 888 0011

RTK Joint Venture

Velocity Measurement
Vertically Traveling Waves
Raw Time Record
Example

12-89

Figure D 2

Records were made with the geophones located at 5- to 10-foot (1.5 to 3.1 meter) intervals from the surface to the boring termination. Measurement depths have an uncertainty of ±0.1 feet. The quality of the P and S wave arrivals was judged to be generally good. No filtering was used in recording the data.

D1.2 DATA REDUCTION

- *Identify arrivals*

The first step in data reduction was to identify P and S wave arrivals. P arrivals usually appear as a rather obvious excursion of the data traces from their rest position. The slower S wave arrived later, usually while the traces were still oscillating in the P wave's wake. The S wave typically caused an increase in amplitude and lengthening of period on the waveform. Traces recorded from hammer hits on opposite ends of the beam were compared to determine the point where the wave phase reversed, which marks the S wave arrival.

- *Interpreted velocities*

Once arrivals were identified, travel times were measured relative to the start of the record within an accuracy of ±0.0005 seconds. (The instrument starts the data record when the transistor switch signals the instant of energy generation.) Seismic waves travel along a slant path from surface source down to the geophones. Therefore, arrival times are geometrically corrected to an equivalent "vertical" time, so interpreted results appear as depth profiles. Corrected travel times were plotted versus depth, as shown in Figure D-3. Seismic velocities were interpreted by fitting line segments through groups of consecutive data points judged to represent subsurface velocity zones. The inverse slope of the line segments equals average velocity in the interpreted subsurface formations. Seismic velocities and layer interfaces are thought to have an accuracy within approximately 10 percent.

- *Elastic moduli*

Dynamic elastic moduli and Poisson's ratio were calculated using equations listed by Heiland (1963) and interpreted velocities and formation densities. Densities were either measured during Footprint Validation (Earth Technology, 1989f) or listed in the Texas proposal (Texas National Research Laboratory Commission, 1987). Rayleigh (R) wave velocities were estimated from the P and S velocity data using a nomogram described by Nazarian (1984).

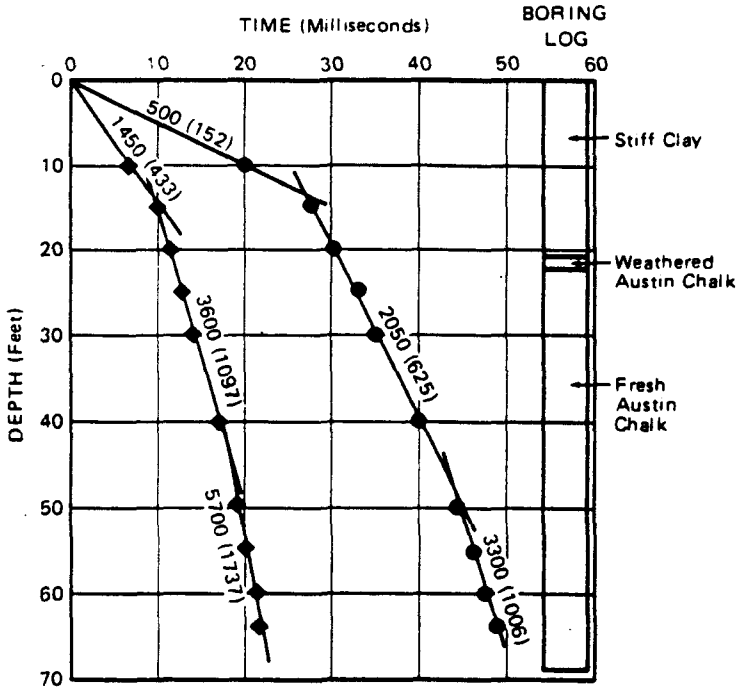
D2.0 HORIZONTALLY TRAVELING WAVES

D2.1 DATA ACQUISITION

Horizontally traveling waves were recorded from TXI quarry blasts as part of the vibration survey. Those procedures are described in Appendix C. The entire seismic waveforms were recorded between the site pairs VF-1.7/VE-3.5 and VF-1.7/VF-5.4.

D2.2 DATA REDUCTION

Horizontal velocity can not be calculated along the path from the quarry to each site because the recording analyzers were not synchronized with the blast time (due to communication equipment restrictions). Therefore, the velocities can be estimated only between site pairs simultaneously recording the same blast.



EXPLANATION

◆ P WAVE ARRIVAL TIMES

● S WAVE ARRIVAL TIMES

SEISMIC VELOCITIES IN FEET/SECOND (METERS/SECOND)
DATA FROM SITE VF-1.7

The Earth Technology Corporation	PROJECT NO.: 87-988-0011 RTK Joint Venture

Velocity Measurement
Vertically Travelling Waves
Data and Interpreted Profile
Example

12-89 Figure D-3

The P and S wave arrivals were identified on the records and timed using the procedure described in Section D1.2. The R wave could not be reliably identified. Wave arrivals have an uncertainty of ± 0.01 seconds. For the pair of sites VF-1.7/VF-5.4, the start time difference between the analyzers is questionable, therefore, horizontally traveling wave velocities cannot be calculated. For the VF-1.7/VF-3.5 sites, the two analyzers were synchronized within ± 0.5 seconds. Total uncertainty in the timing is ± 0.52 seconds. The distances between the sites were measured from USGS maps (1:24,000 scale) within an uncertainty of approximately 5 percent. The uncertainty associated with the horizontal velocities is estimated to be 25 percent.

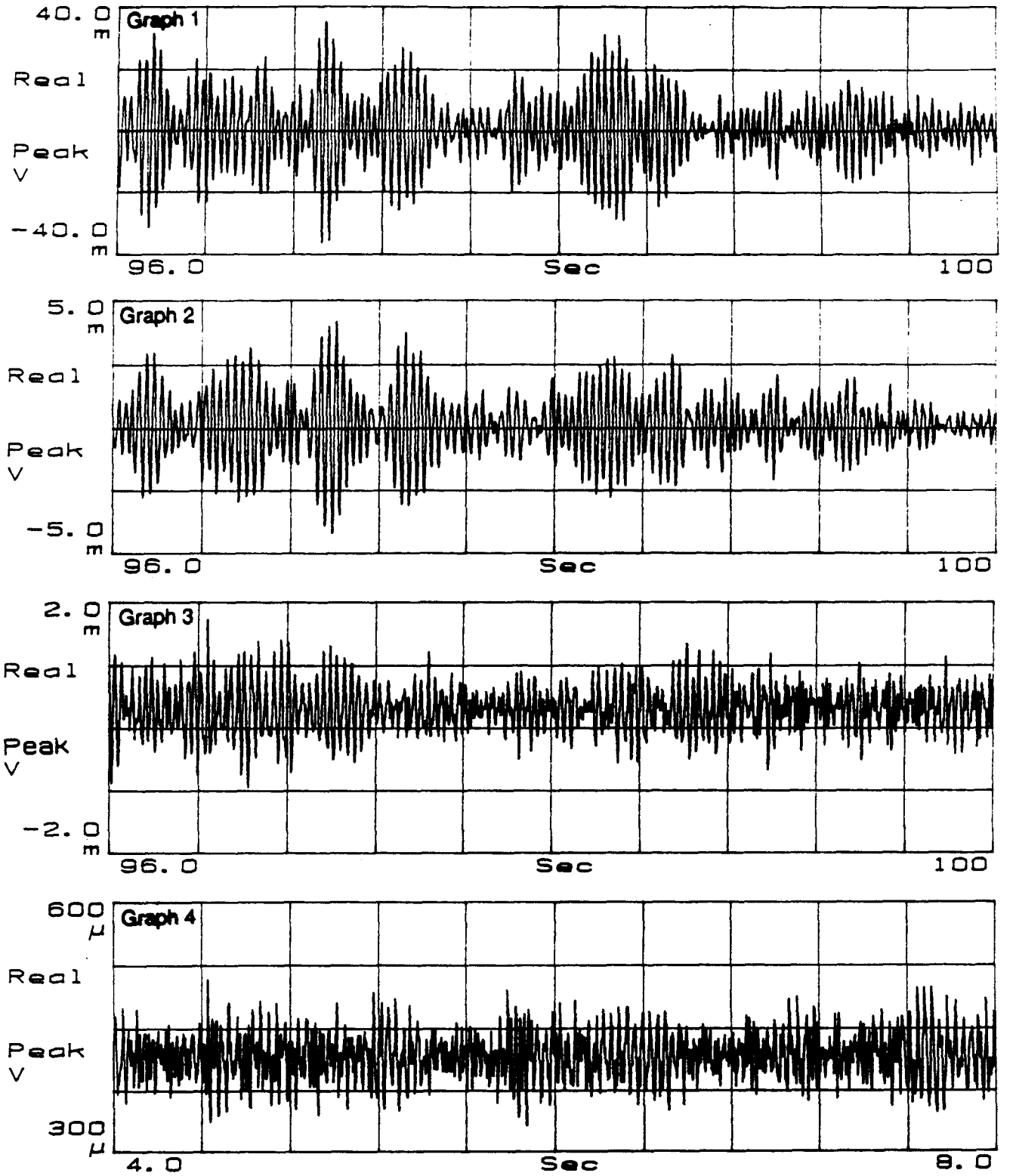
There is not a straight path from the TXI quarry through site VF-1.7 to site VE-3.5 (Figure 1-1). Seismic velocities can be estimated by comparing the distance and time intervals between the two sites, even though the seismic waves did not travel directly between them, only if the subsurface geology is assumed to be grossly homogeneous across the northern ring area. Available geological data suggest that this assumption is reasonable.

APPENDIX E

SITE VF-1.7 DATA AND RESULTS

APPENDIX INDEX

Figure No.	Data Set	Description
E-1 through E-4	9	Triaxial Geophone Comparison
E-5 through E-9	2	1 Hz Geophone - Largest Displacement Train Data
E-10 through E-14	4	1 Hz Geophone - Second Largest Displacement Train Data
E-15	–	Velocity Profile (vertically traveling waves)



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET1 @ 64.0 (19.5)
Graph 1: Vertical Geophone - Train
Graph 2: Transverse Geophone - Train
Graph 3: Radial Geophone - Train
Graph 4: Vertical Geophone - Ambient

The Earth Technology Corporation

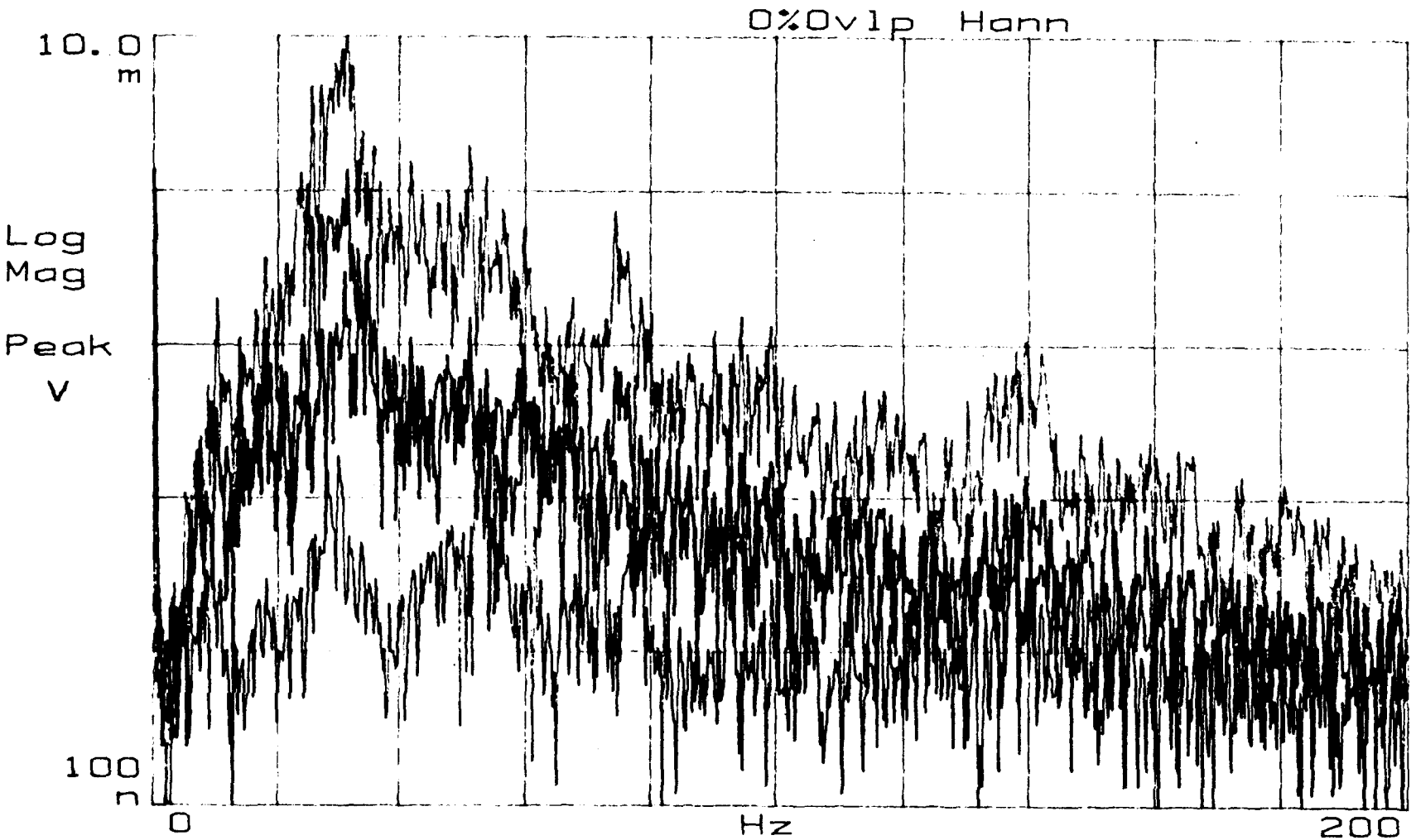
Project No.: 87-[illegible]-0011

RTK Joint Venture

Raw Time Records
Near Field Maximum
Data Set 9
Site VF-1.7

12-89

Figure E-1

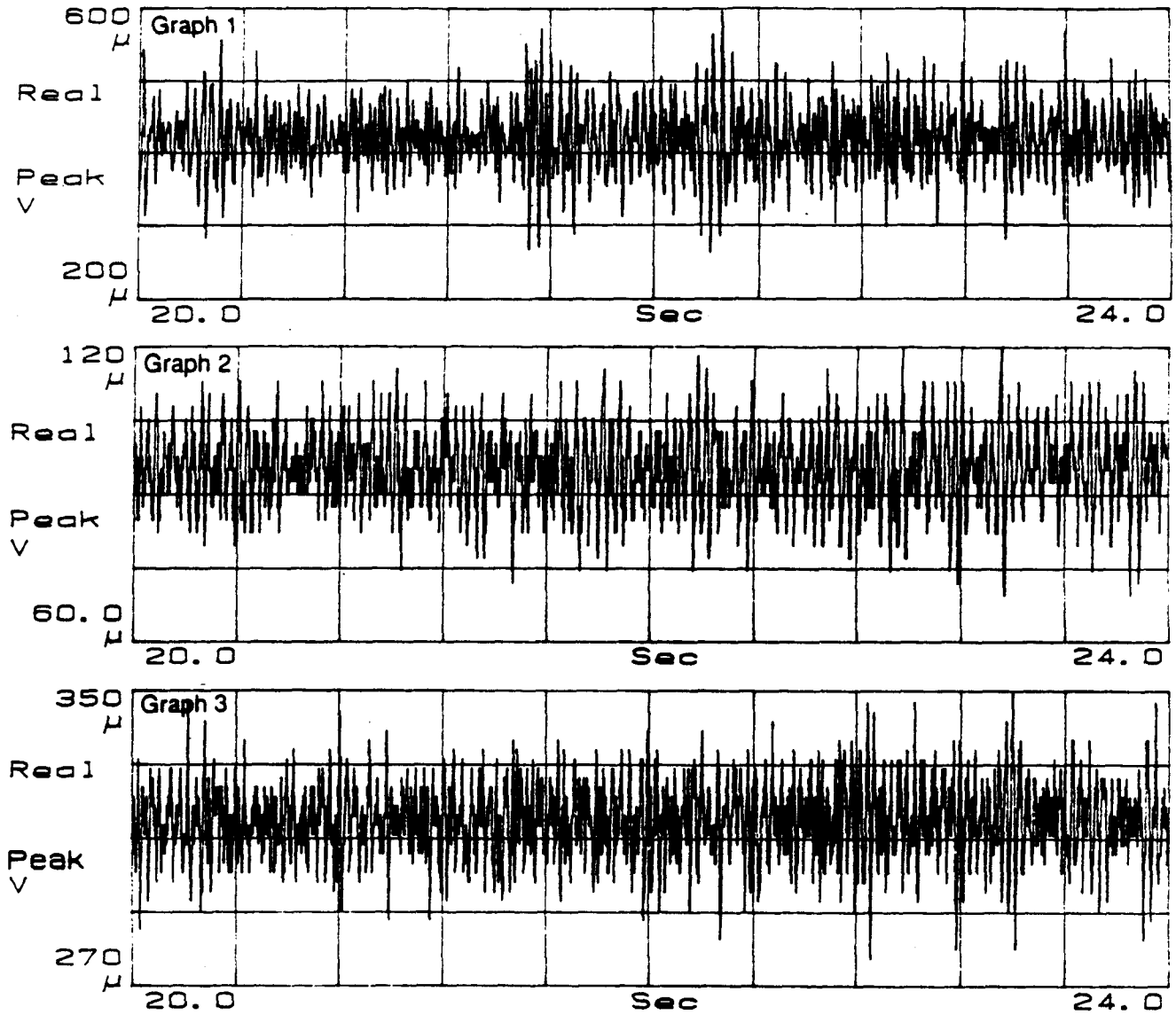


EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET1 @ 64.0 (19.5)
Blue = Vertical Geophone - Train
Green = Transverse Geophone - Train
Red = Radial Geophone - Train
Black = Vertical Geophone - Ambient

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Raw Velocity Linear Spectrum
Near Field Maximum
Data Set 9
Site VE-1.7



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET1 @ 64.0 (19.5)
Graph 1: Vertical Geophone - Train
Graph 2: Transverse Geophone - Train
Graph 3: Radial Geophone - Train

The Earth Technology Corporation

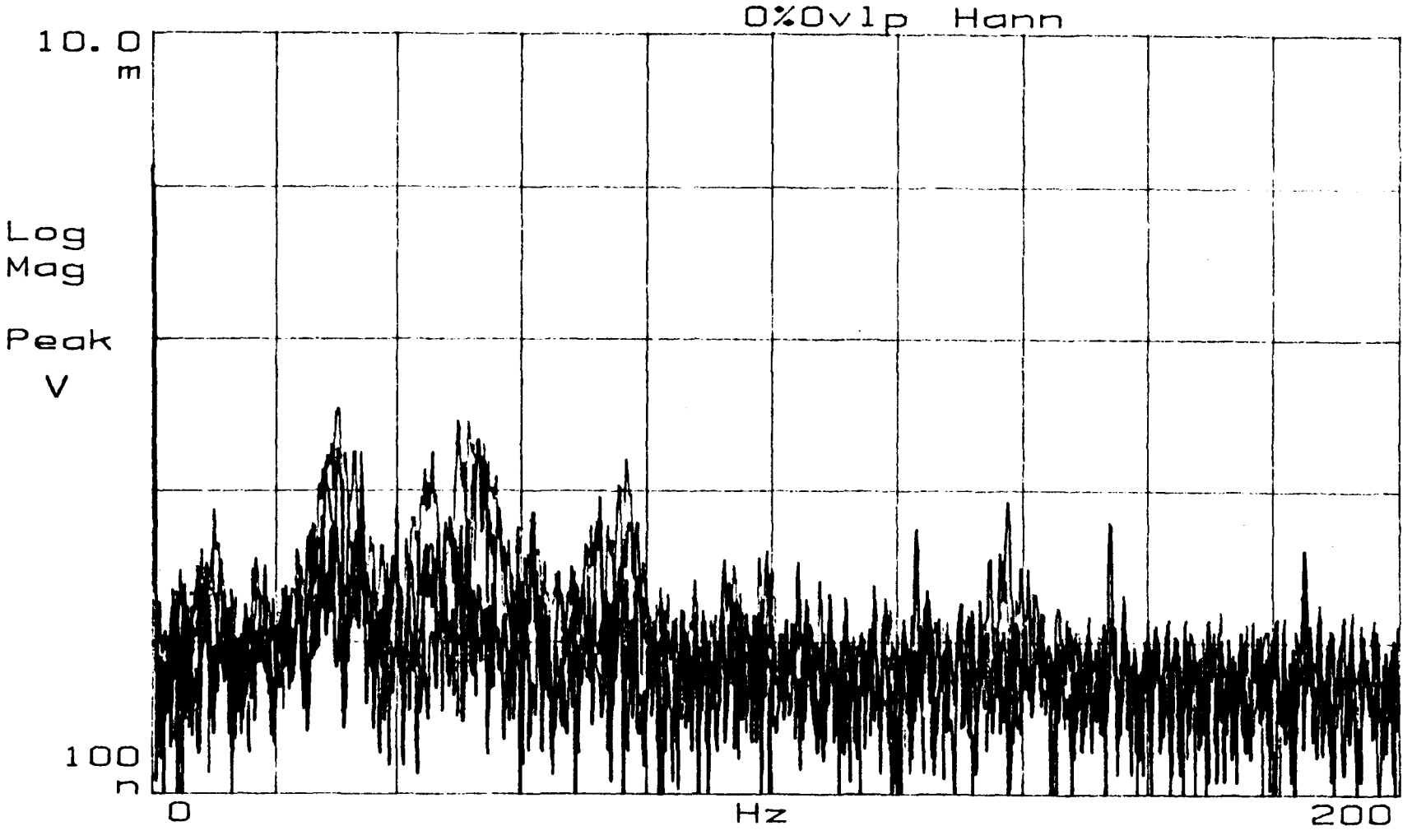
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Start of Intermediate Field
Data Set 9
Site VF-1.7

12-89

Figure E-3

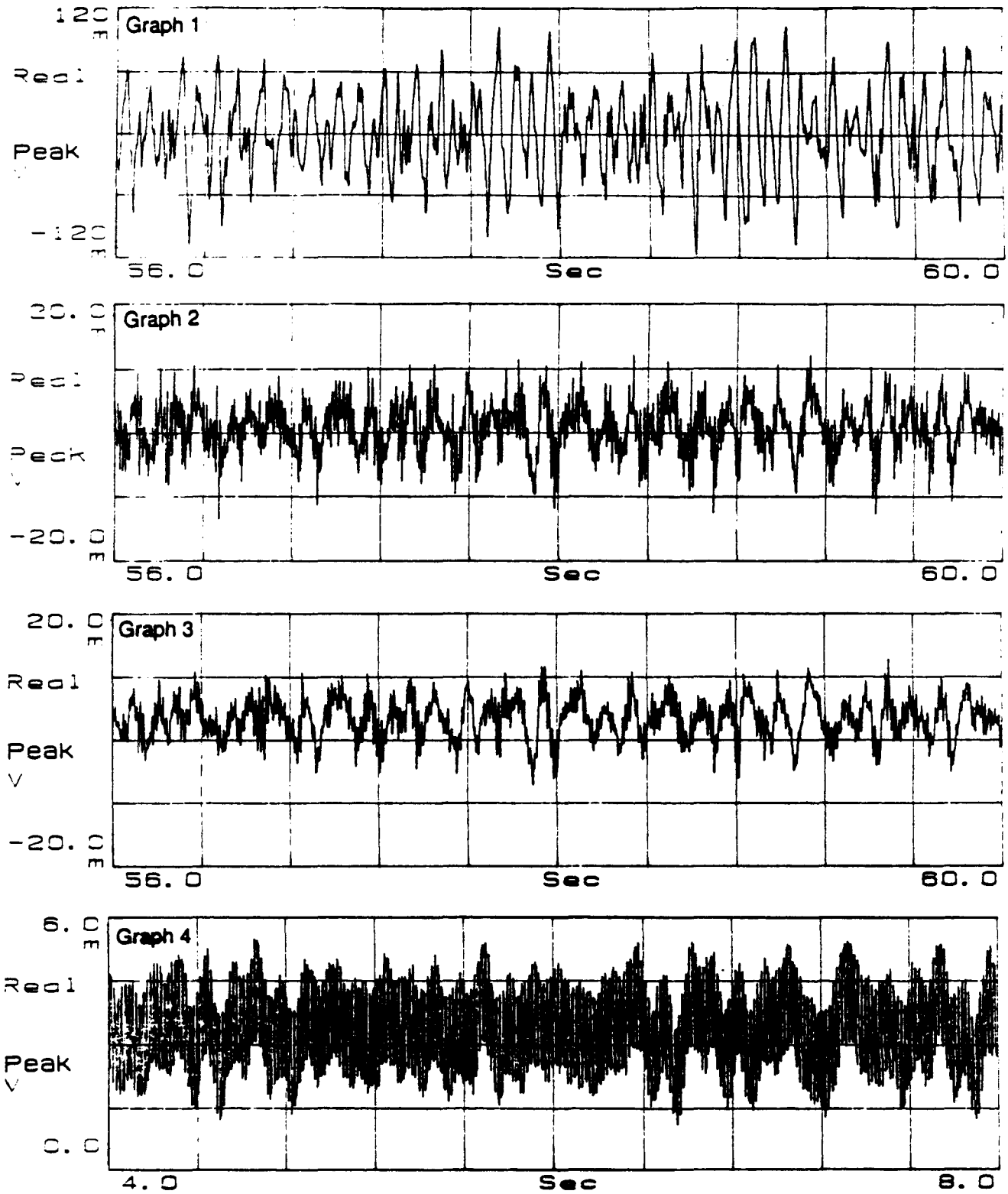


EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET1 @ 64.0 (19.5)
Blue = Vertical Geophone - Train
Green = Transverse Geophone - Train
Red = Radial Geophone - Train
Black = Vertical Geophone - Ambient

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Raw Velocity Linear Spectrum
Start of Intermediate Field
Data Set 9
Site VF-1.7



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 1: Geophone 4106 @ 2.5 (0.88) - Train
Graph 2: Geophone 2676 @ 30.0 (9.1) - Train
Graph 3: Geophone 4105 @ 64.0 (19.5) - Train
Graph 4: Geophone 4105 @ 64.0 (19.5) - Ambient

The Earth Technology Corporation

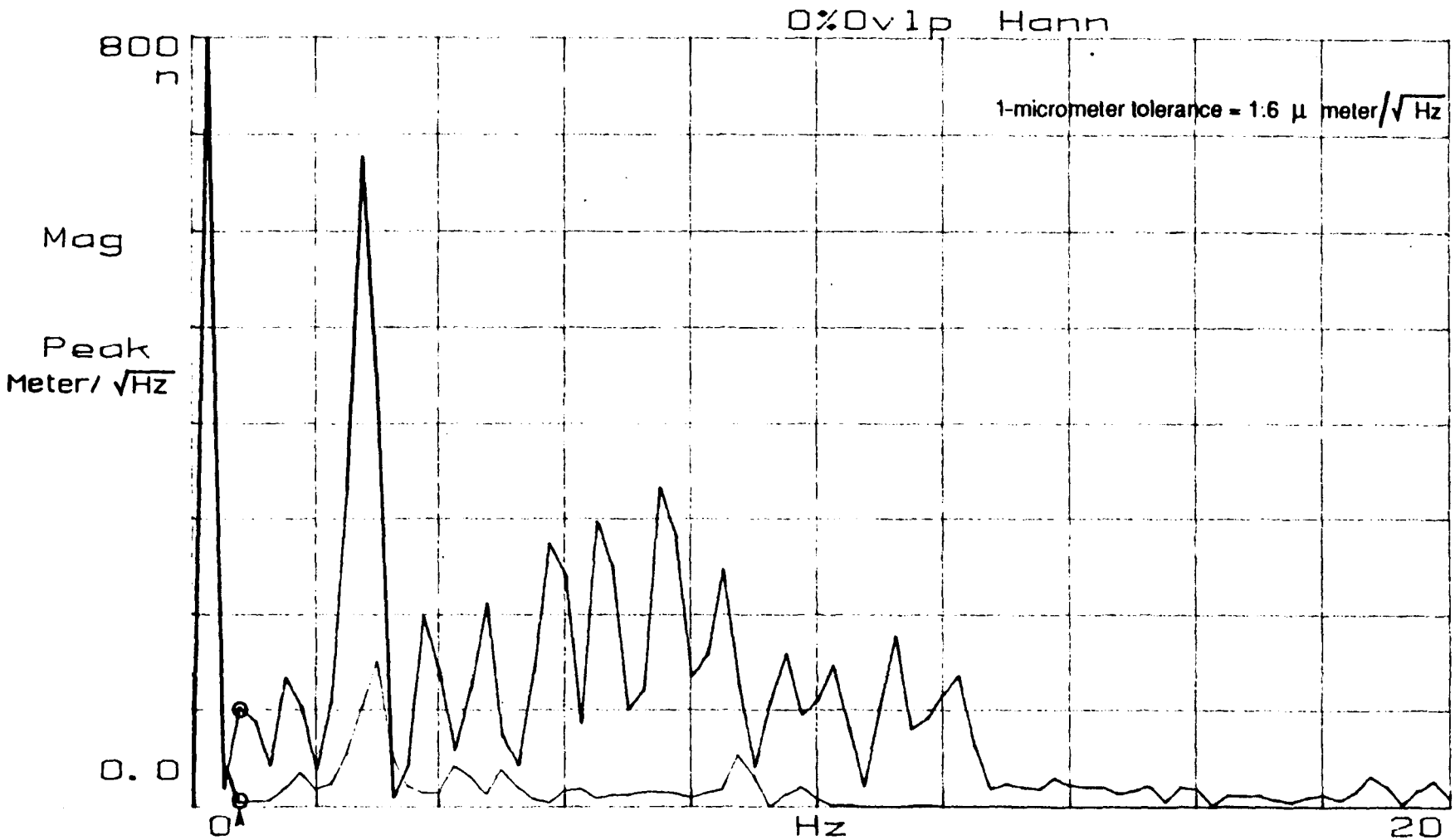
Project No.: 67-888-0011

RTK Joint Venture

Raw Time Record
Data Set 2
Site VF-1.7

12-89

Figure E-5



EXPLANATION

1 Hz Geophone Data

Red = Max. Train Vibrations Measured @ 64.0 feet (19.5 meters)
Black = Ambient Vibrations Measured @ 64.0 feet (19.5 meters)

Lower Frequency Limit of Calibration
Bandwidth = 0.375 Hz

The Earth Technology Corporation

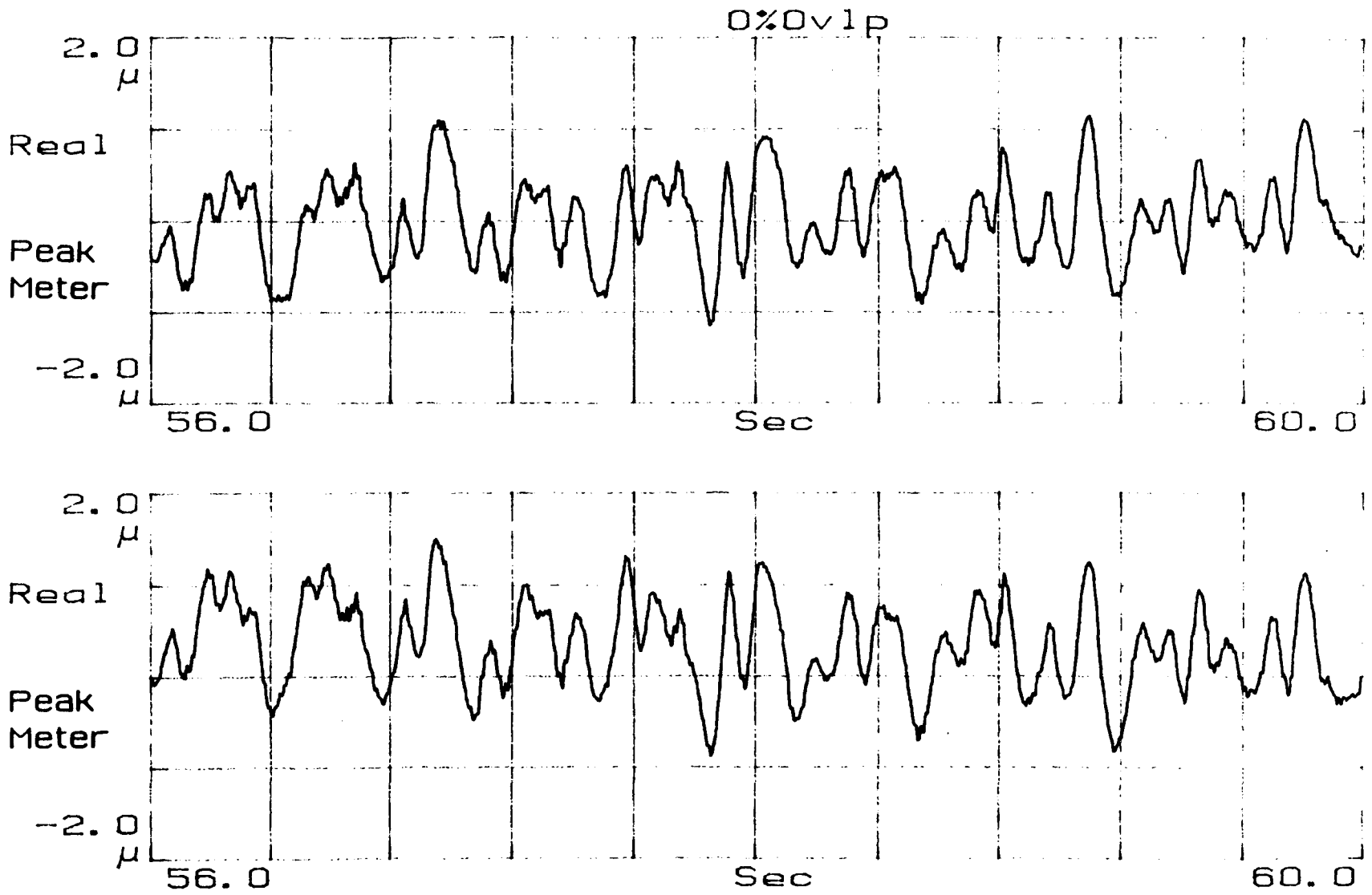
Project No.: 87-888-0011

RTK Joint Venture

Displacement Linear Spectrum
Data Set 2
Site VF-1.7

12-89

Figure E.6



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 64.0 feet (19.5 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

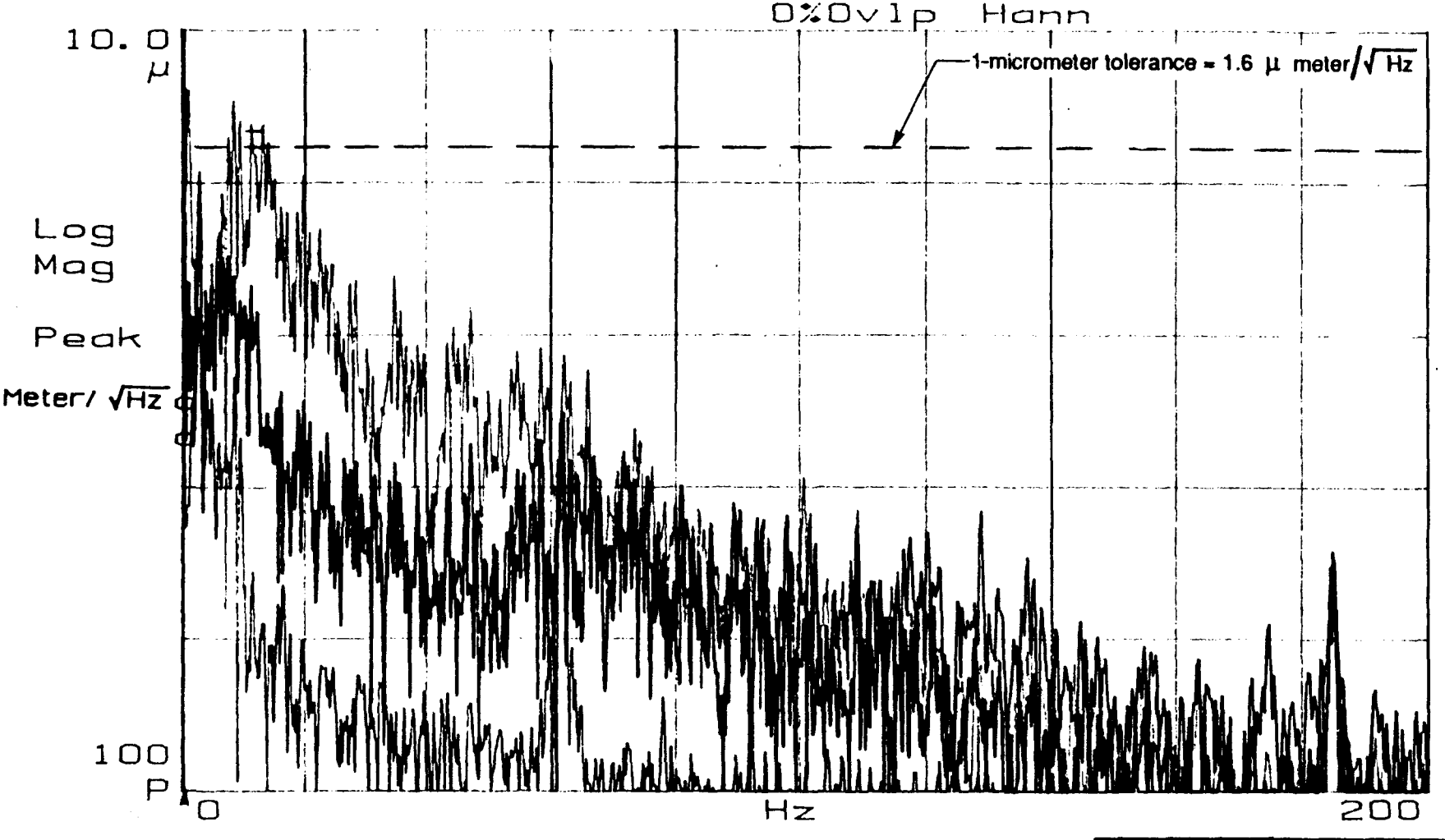
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 2
Site VF-1.7

12-89

Figure E-7



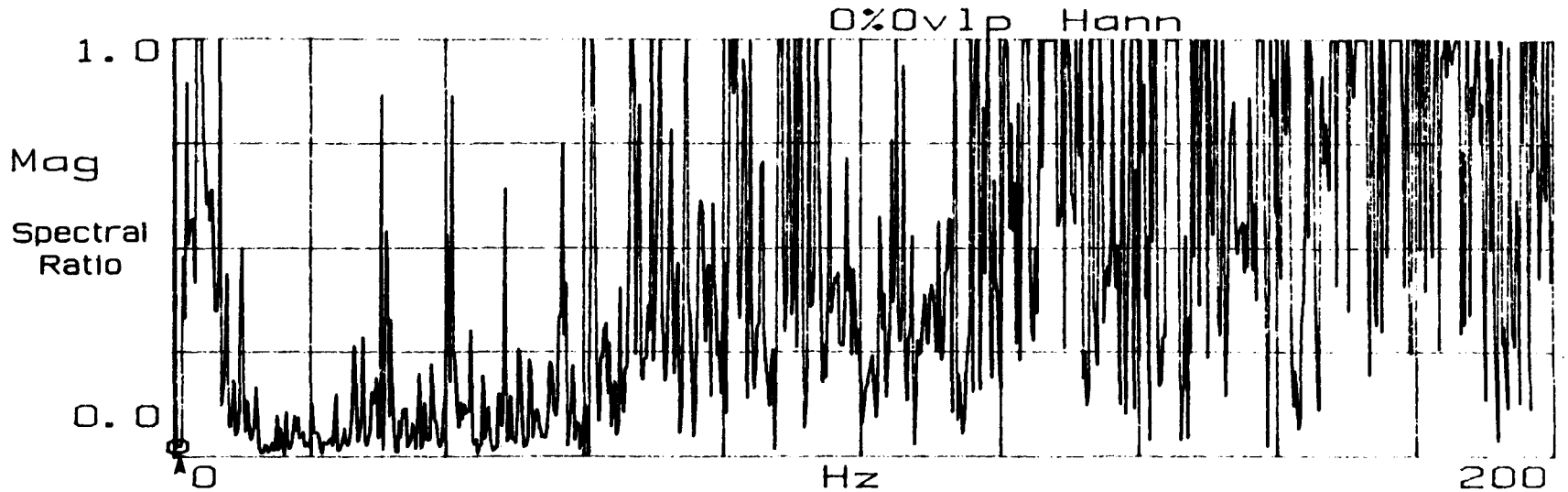
EXPLANATION

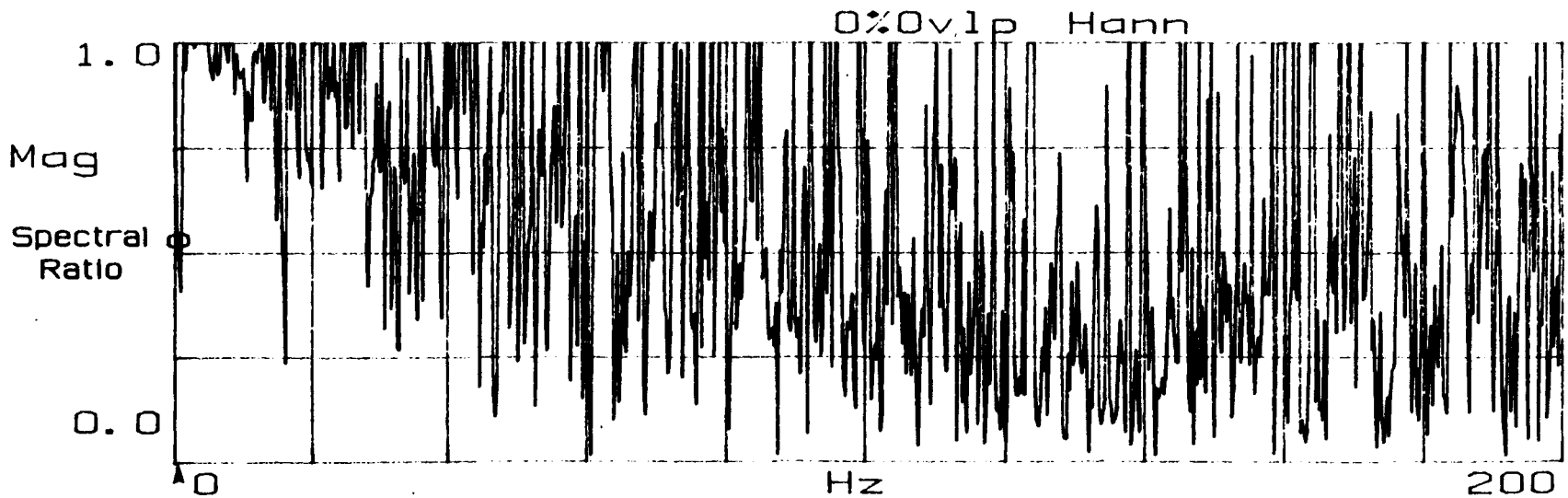
1 Hz Geophone Data
Blue = Max. Train Vibrations Measured @ 2.5 feet (0.88 meters)
Green = Max. Train Vibrations Measured @ 30.0 feet (9.1 meters)
Red = Max. Train Vibrations Measured @ 64.0 feet (19.5 meters)
Black = Ambient Vibrations Measured @ 64.0 feet (19.5 meters)

Lower Frequency Limit of Calibration
Bandwidth = 0.275 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 2
Site VF-1.7





EXPLANATION

1 Hz Geophone Data

Top: "Bulk" Ratio between Geophone @ 2.5 feet (0.88 meters) and Geophone @ 64.0 feet (19.5 meters)

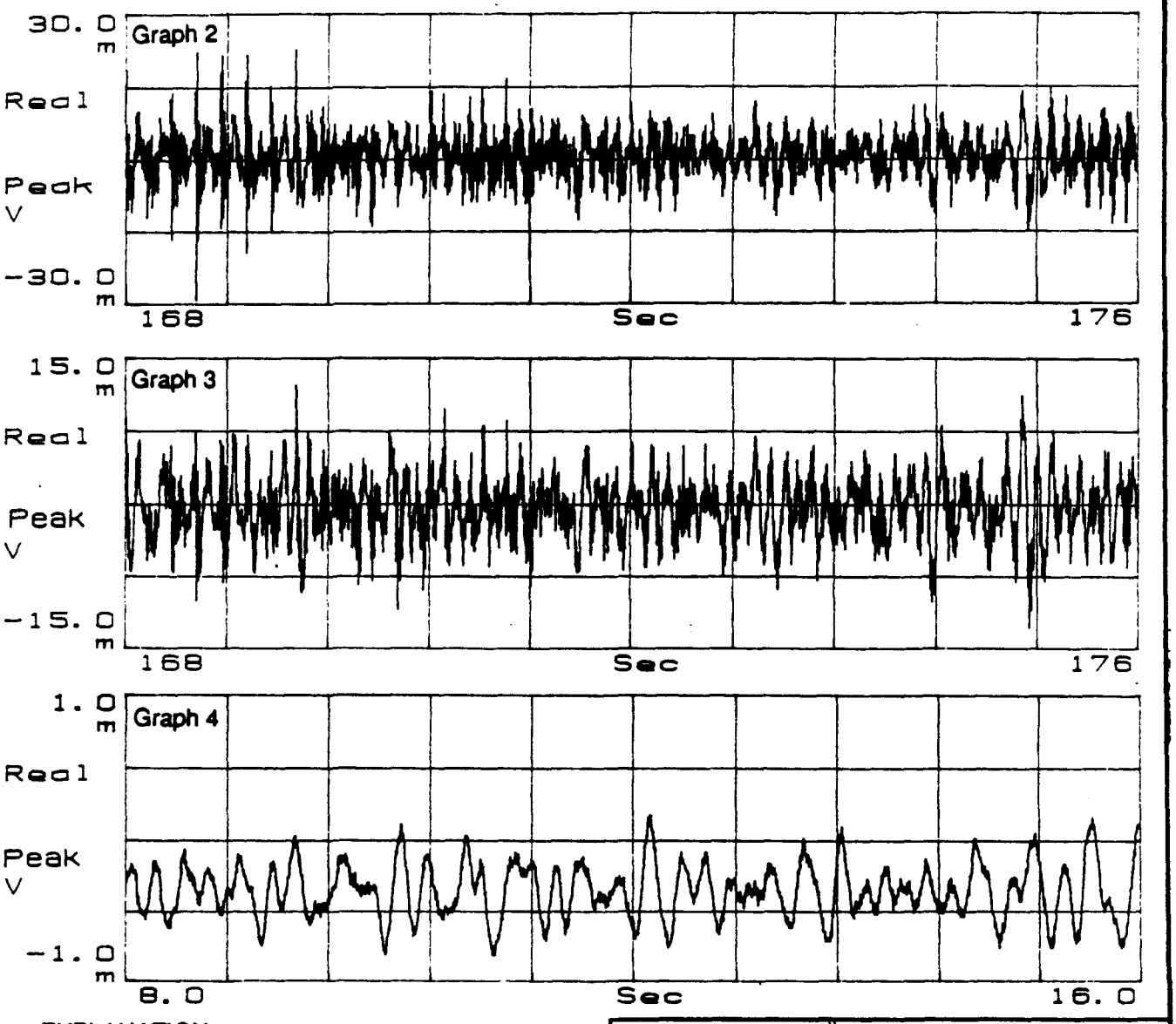
Bottom: "Rock" Ratio between Geophone @ 30.0 feet (9.1 meters) and Geophone @ 64.0 feet (19.5 meters)

⊙ Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones
Data Set 2
Site VF-1.7

No Shallow Data



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 2: Geophone 2676 @ 30.0 (9.1) - Train
Graph 3: Geophone 4105 @ 64.0 (19.5) - Train
Graph 4: Geophone 4105 @ 64.0 (19.5) - Ambient

The Earth Technology Corporation

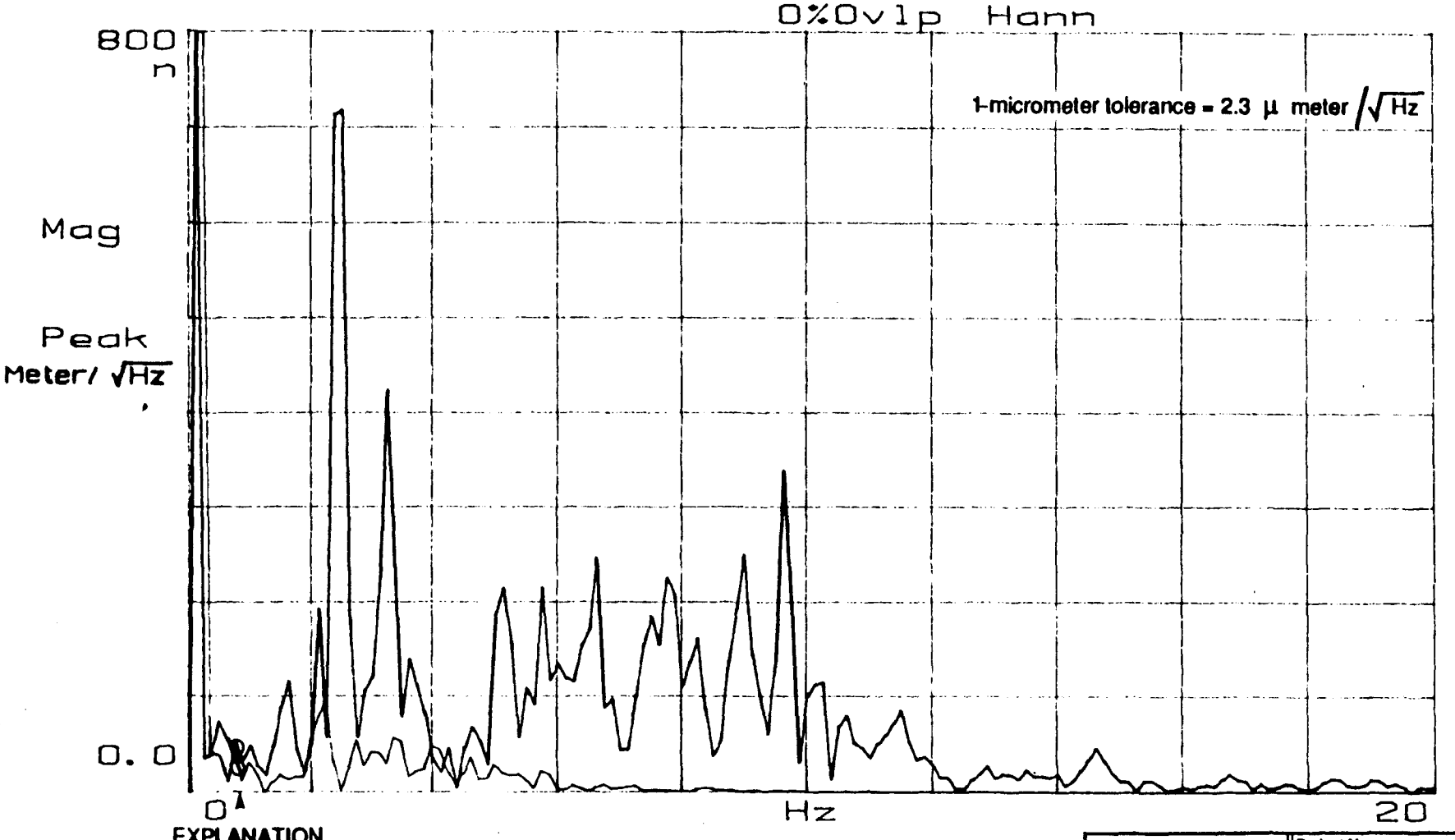
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Record
Data Set 4
Site VF-1.7

12-89

Figure E-10



EXPLANATION

1 Hz Geophone Data

Red = Max. Train Vibrations Measured @ 64.0 feet (19.5 meters)
Black = Ambient Vibrations Measured @ 64.0 feet (19.5 meters)

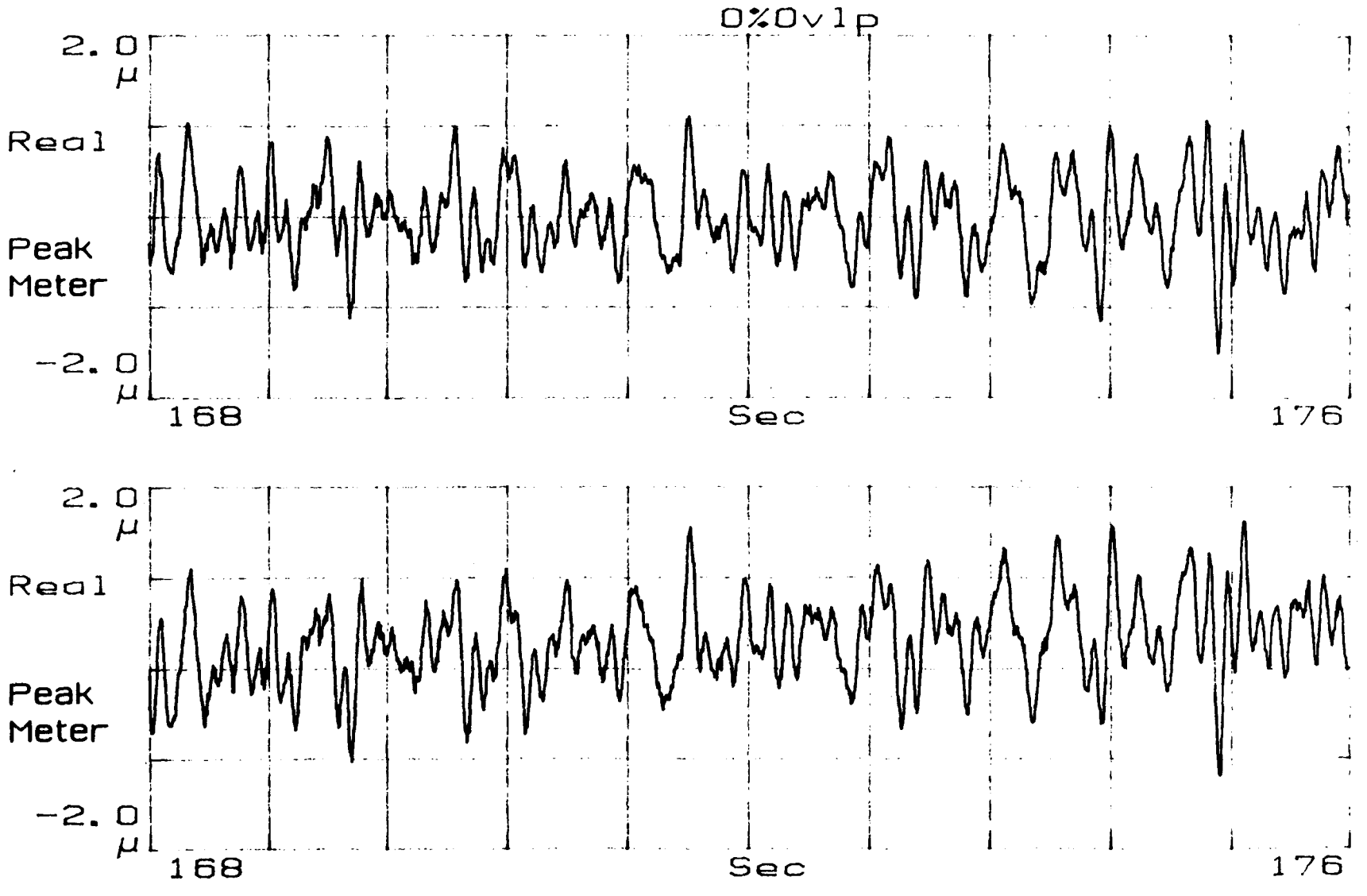
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Displacement Linear Spectrum
Data Set 4
Site VF-1.7

12-89

Figure E-11



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 64.0 feet (19.5 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

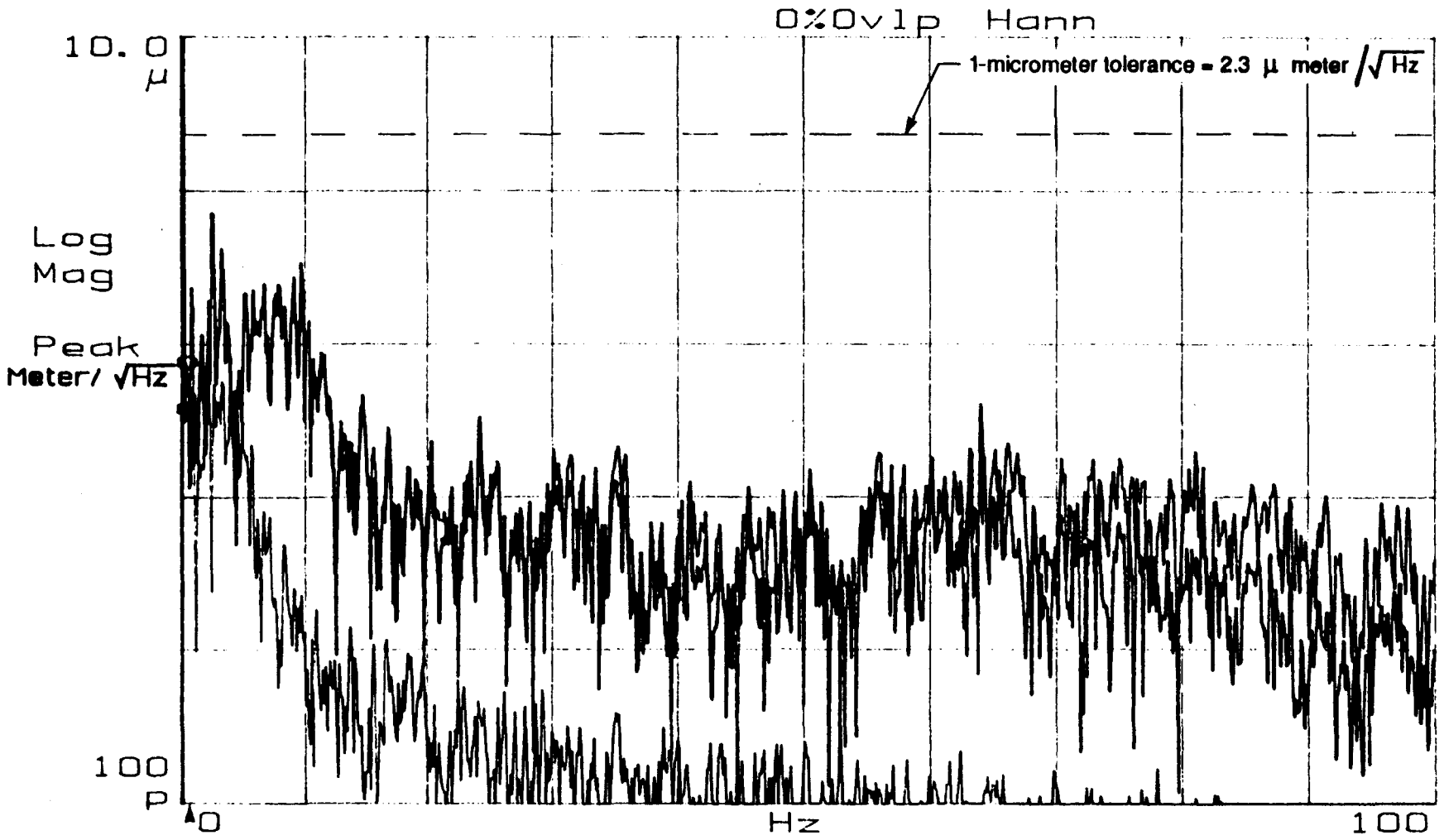
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 4
Site VF-1.7

12-89

Figure E-12



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Green = Max. Train Vibrations Measured @ 30.0 (9.1)
Red = Max. Train Vibrations Measured @ 64.0 (19.5)
Black = Ambient Vibrations Measured @ 64.0 (19.5)

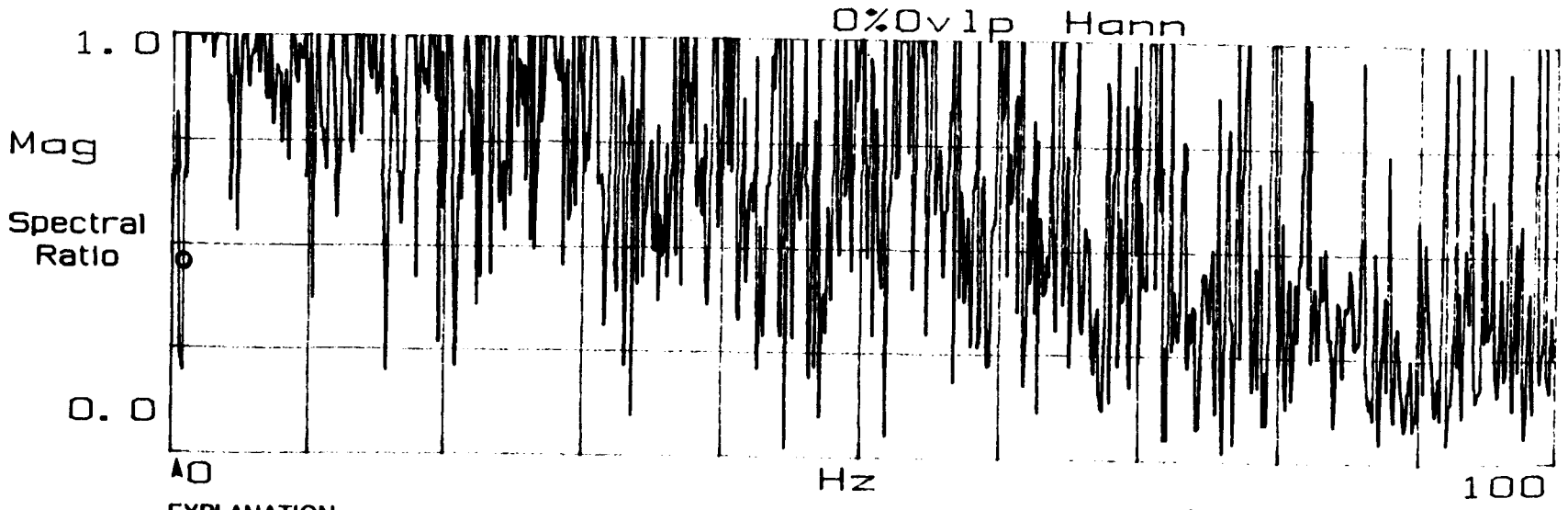
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 4
Site VF-1.7

12.89

No Shallow Data



EXPLANATION

1 Hz Geophone Data

Geophone Depths in feet (meters)

Bottom: "Rock" Ratio between Geophone @ 30.0 (9.1) and Geophone @ 64.0 (19.5)

Lower Frequency Limit of Calibration

The Earth Technology Corporation

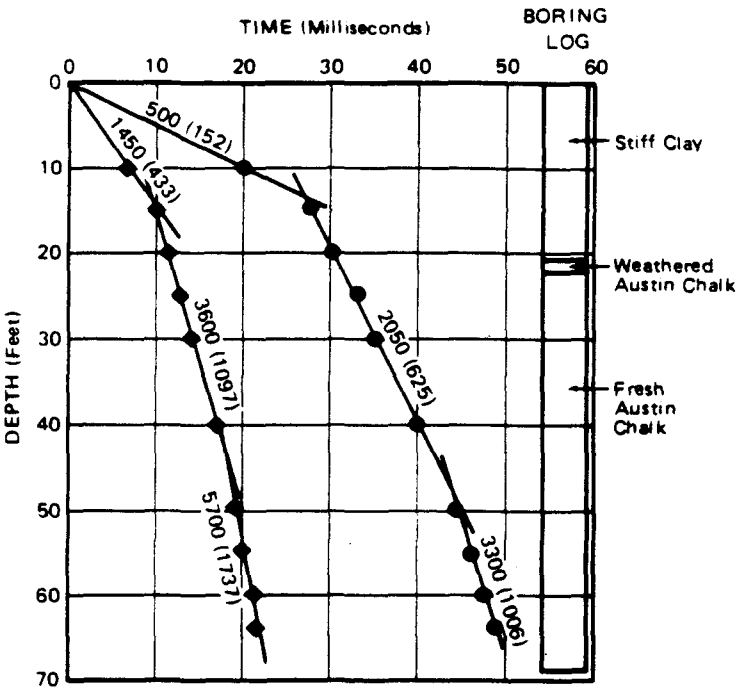
Project No.: 87-888-0011

RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones
Data Set 4
Site VF-1.7

12 89

Figure E-14



EXPLANATION

◆ P WAVE ARRIVAL TIMES

● S WAVE ARRIVAL TIMES

SEISMIC VELOCITIES IN FEET/SECOND (METERS/SECOND)

The Earth Technology Corporation	PROJECT NO.: 87-888-0011 RTK Joint Venture

Velocity Data and Interpreted Profile
Vertical Traveling Waves
Site VF-1.7

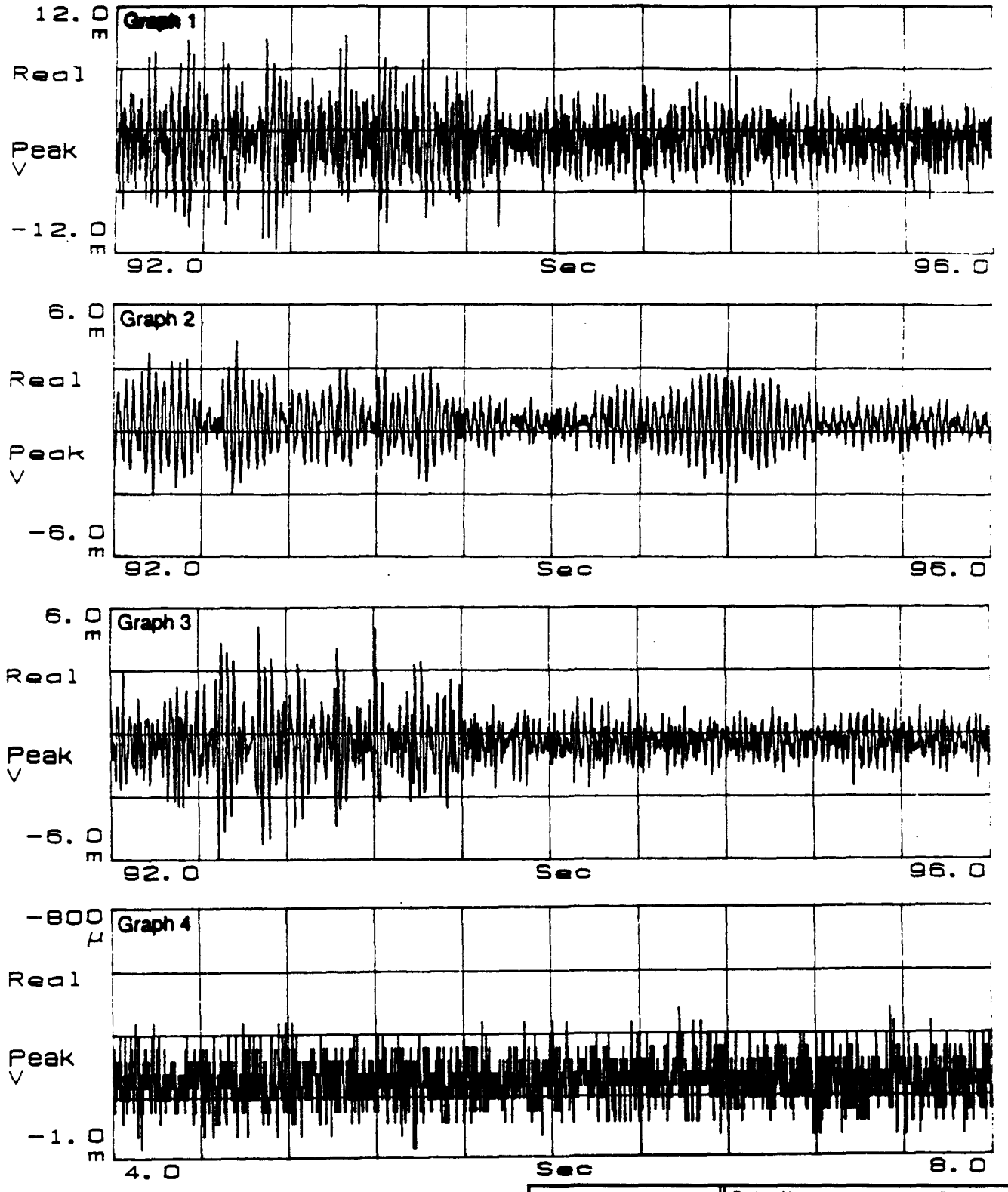
12-89 Figure E-15

APPENDIX F

SITE VE-3.5 DATA AND RESULTS

APPENDIX INDEX

Figure No.	Data Set	Description
F-1 through F-4	8	Triaxial Geophone Comparison
F-5 through F-9	2	1 Hz Geophone - Largest Displacement Train Data
F-10 through F-14	6	1 Hz Geophone - Second Largest Displacement Train Data
F-15	–	Velocity Profile (vertically traveling waves)



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 78.0 (23.8)
Graph 1: Vertical Geophone - Train
Graph 2: Transverse Geophone - Train
Graph 3: Radial Geophone - Train
Graph 4: Vertical Geophone - Ambient

The Earth Technology Corporation

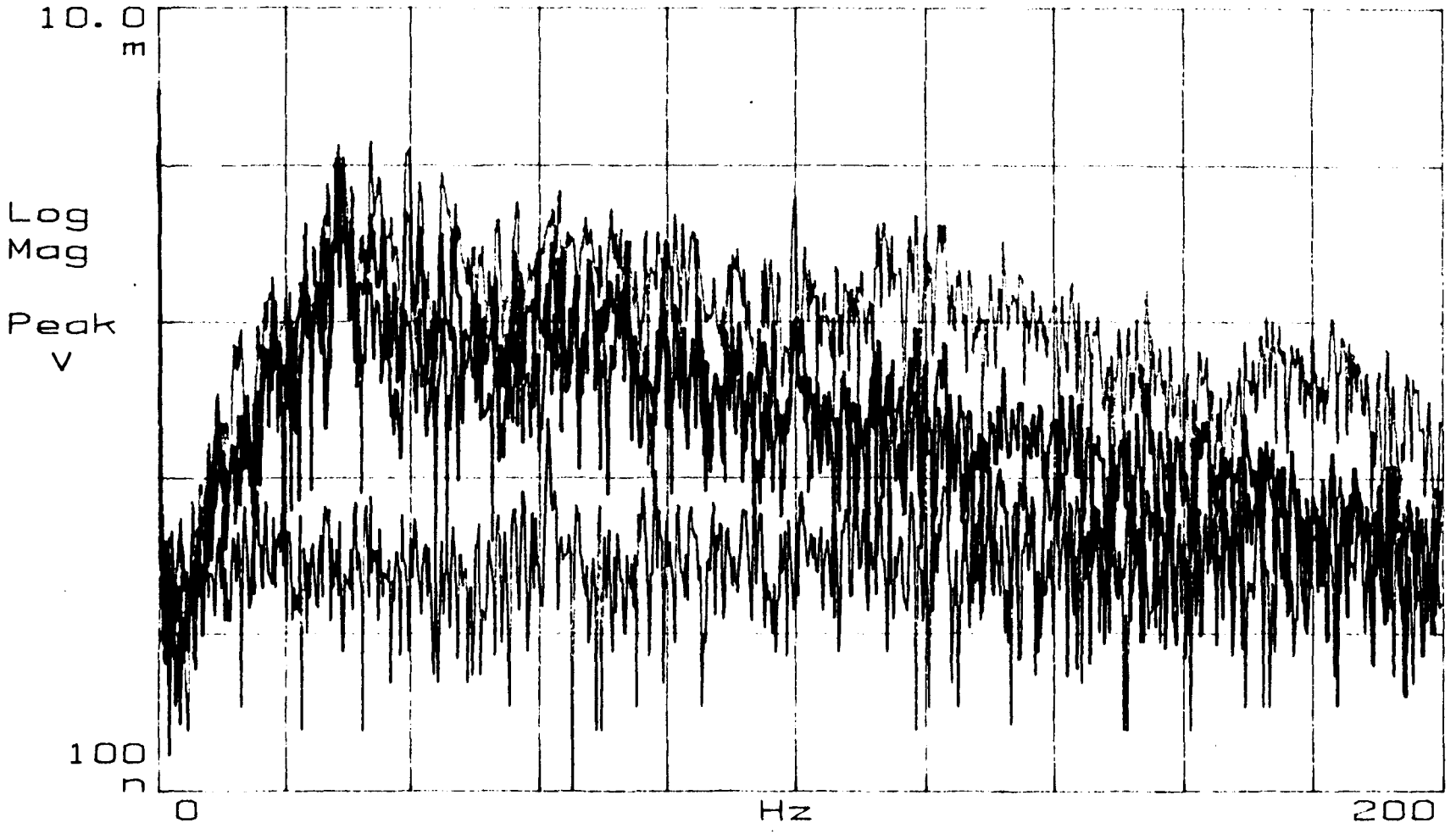
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Near Field Maximum
Data Set 8
Site VE-3.5

12-89

Figure F-1



EXPLANATION

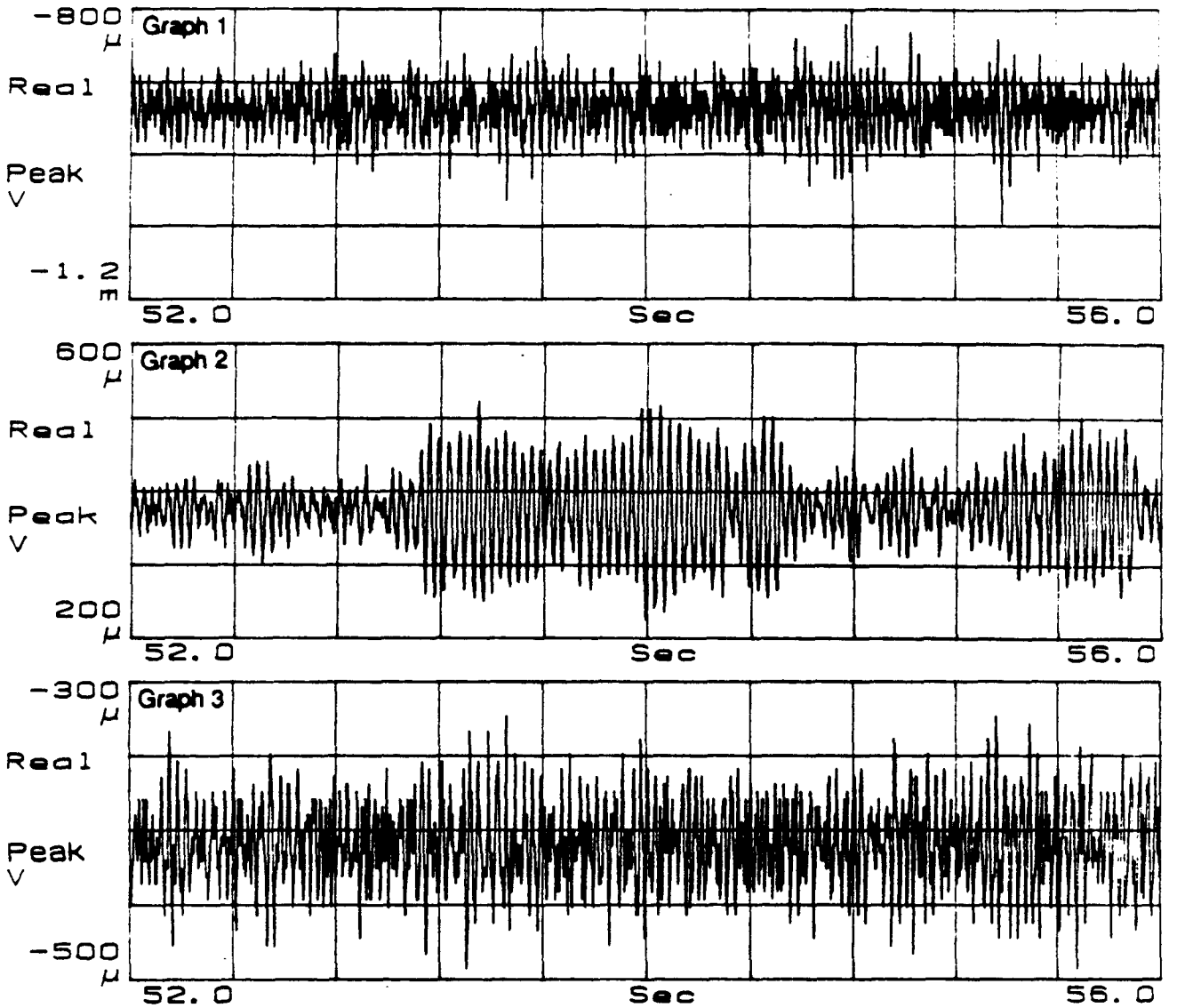
Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 78.0 (23.8)
Blue = Vertical Geophone - Train
Green = Transverse Geophone - Train
Red = Radial Geophone - Train
Black = Vertical Geophone - Ambient

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Composite Raw Velocity Linear Spectrum
Near Field Maximum
Data Set 8
Site VE-3.5



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 78.0 (23.8)
Graph 1: Vertical Geophone - Train
Graph 2: Transverse Geophone - Train
Graph 3: Radial Geophone - Train

The Earth Technology Corporation

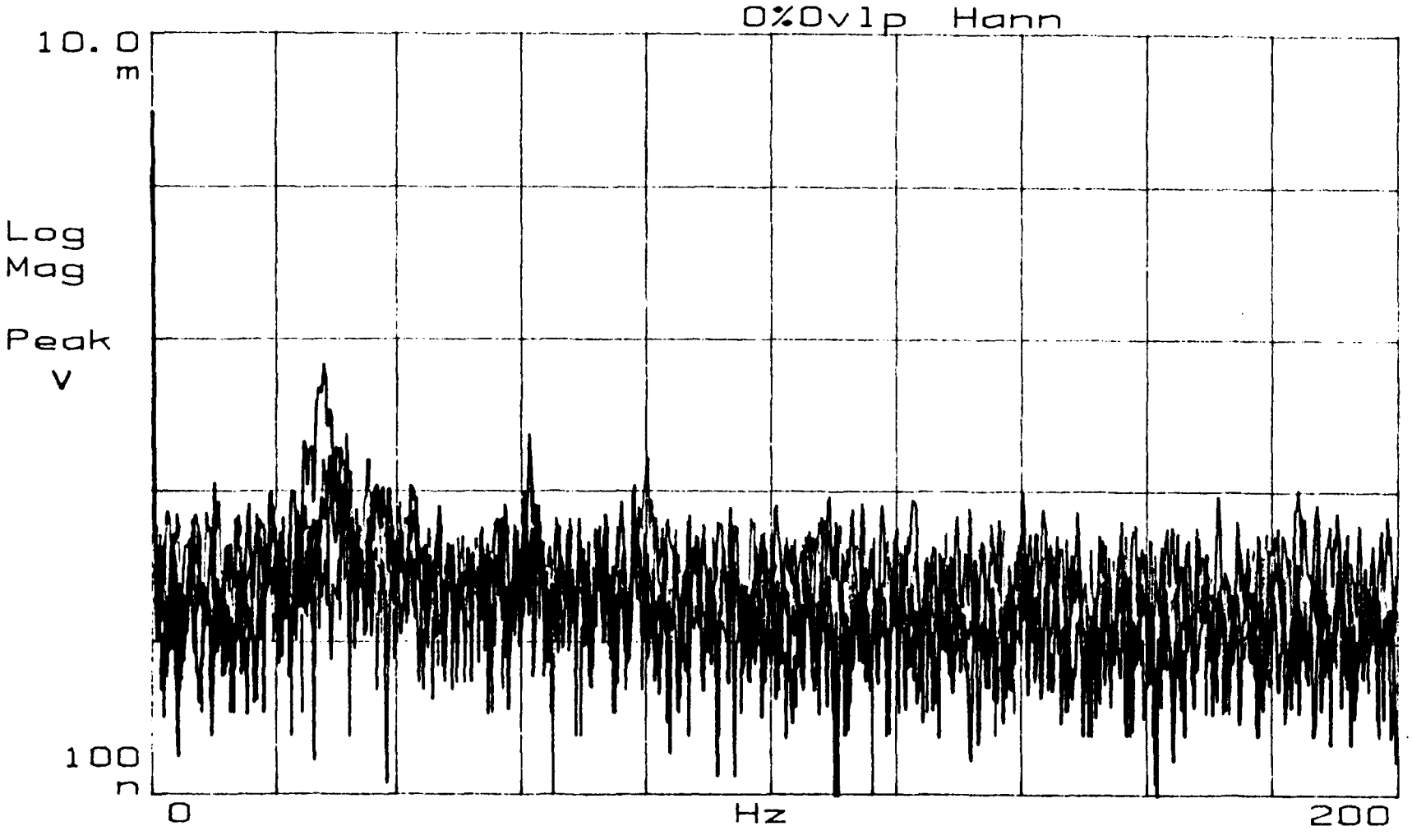
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Start of Intermediate Field
Data Set 8
Site VE-3.5

12-89

Figure F-3



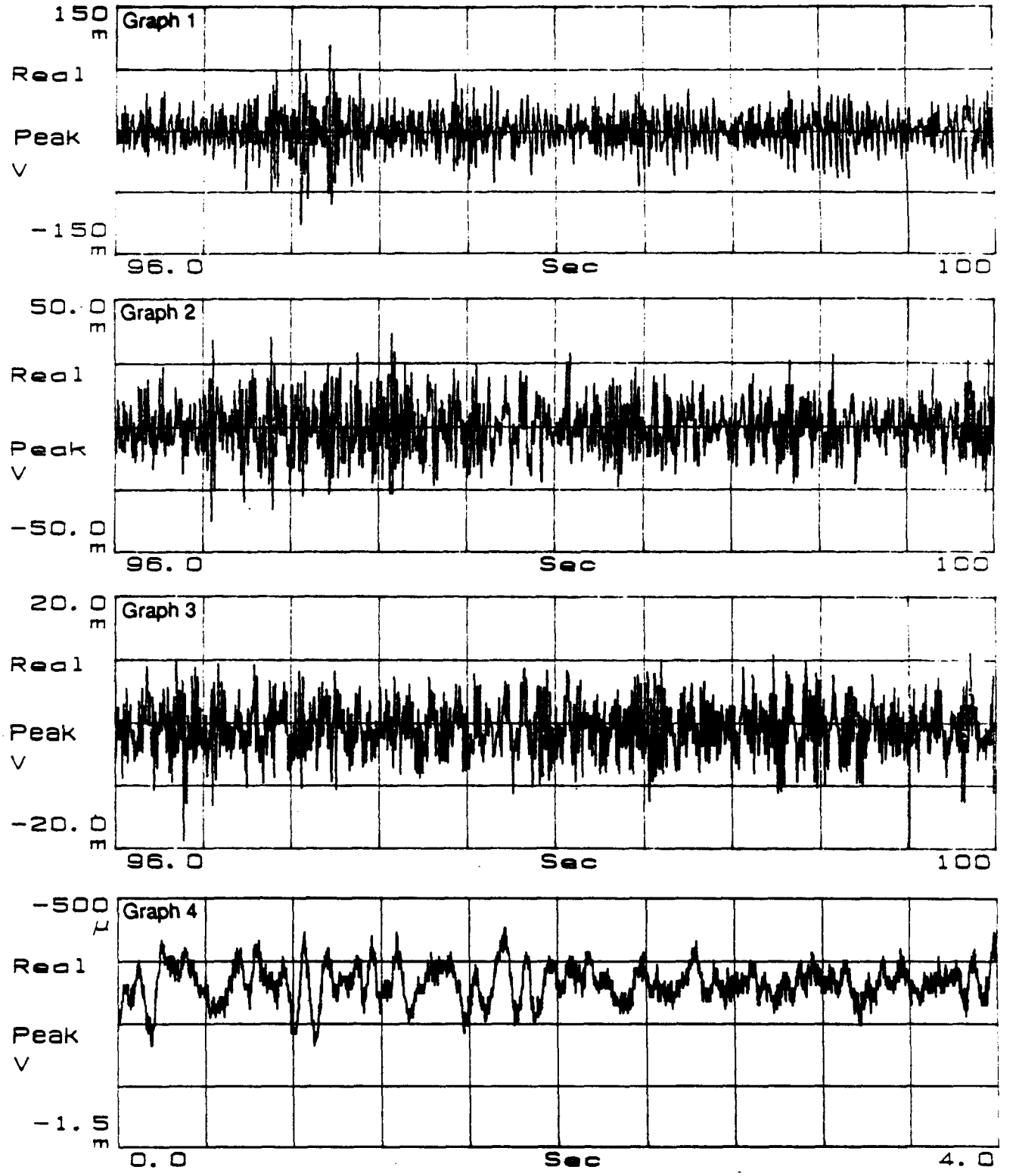
EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 78.0 (23.8)
Blue = Vertical Geophone - Train
Green = Transverse Geophone - Train
Red = Radial Geophone - Train
Black = Vertical Geophone - Ambient

The Earth Technology Corporation	Project No.: 87-868-0011
	RTK Joint Venture

Composite Raw Velocity Linear Spectrum
Start of Intermediate Field
Data Set 8
Site VE-3.5

12.89 Figure 5.4



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 1: Geophone 4106 @ 4.0 (1.2) - Train
Graph 2: Geophone 2676 @ 18.0 (5.5) - Train
Graph 3: Geophone 4105 @ 77.0 (23.5) - Train
Graph 4: Geophone 4105 @ 77.0 (23.5) - Ambient

The Earth Technology Corporation

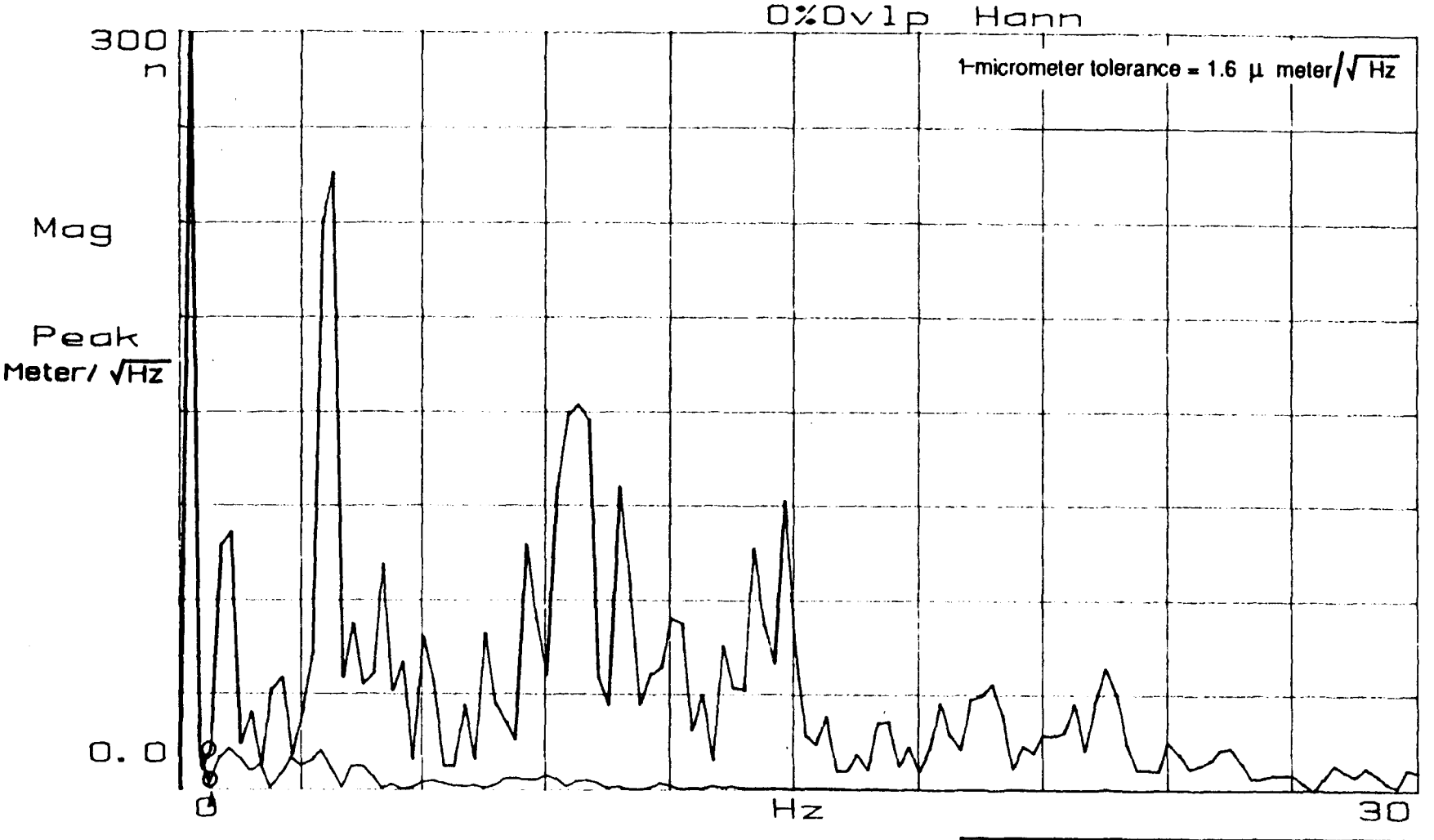
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Record
Data Set 2
Site VE-3.5

12-89

Figure F-5



EXPLANATION

1 Hz Geophone Data
Red = Max. Train Vibrations Measured @ 77.0 feet (23.5 meters)
Black = Ambient Train Vibrations Measured @ 77.0 feet (23.5 meters)

Lower Frequency Limit of Calibration
Bandwidth = 0.375 Hz

The Earth Technology Corporation

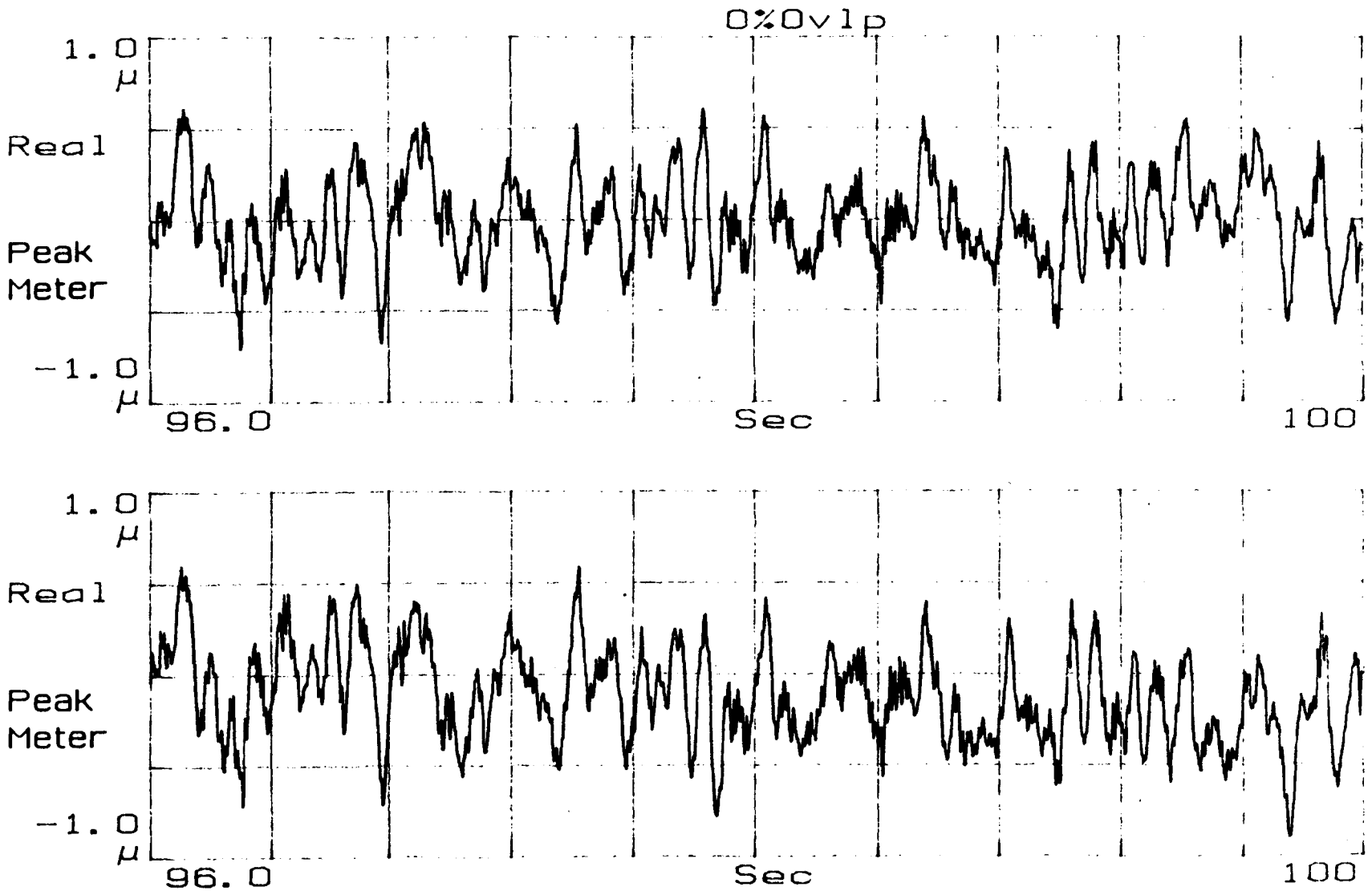
Project No.: 87-888-0011

RTK Joint Venture

Displacement Linear Spectrum
Data Set 2
Site VE-3.5

12-89

Figure E-6



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 77.0 feet (23.5 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

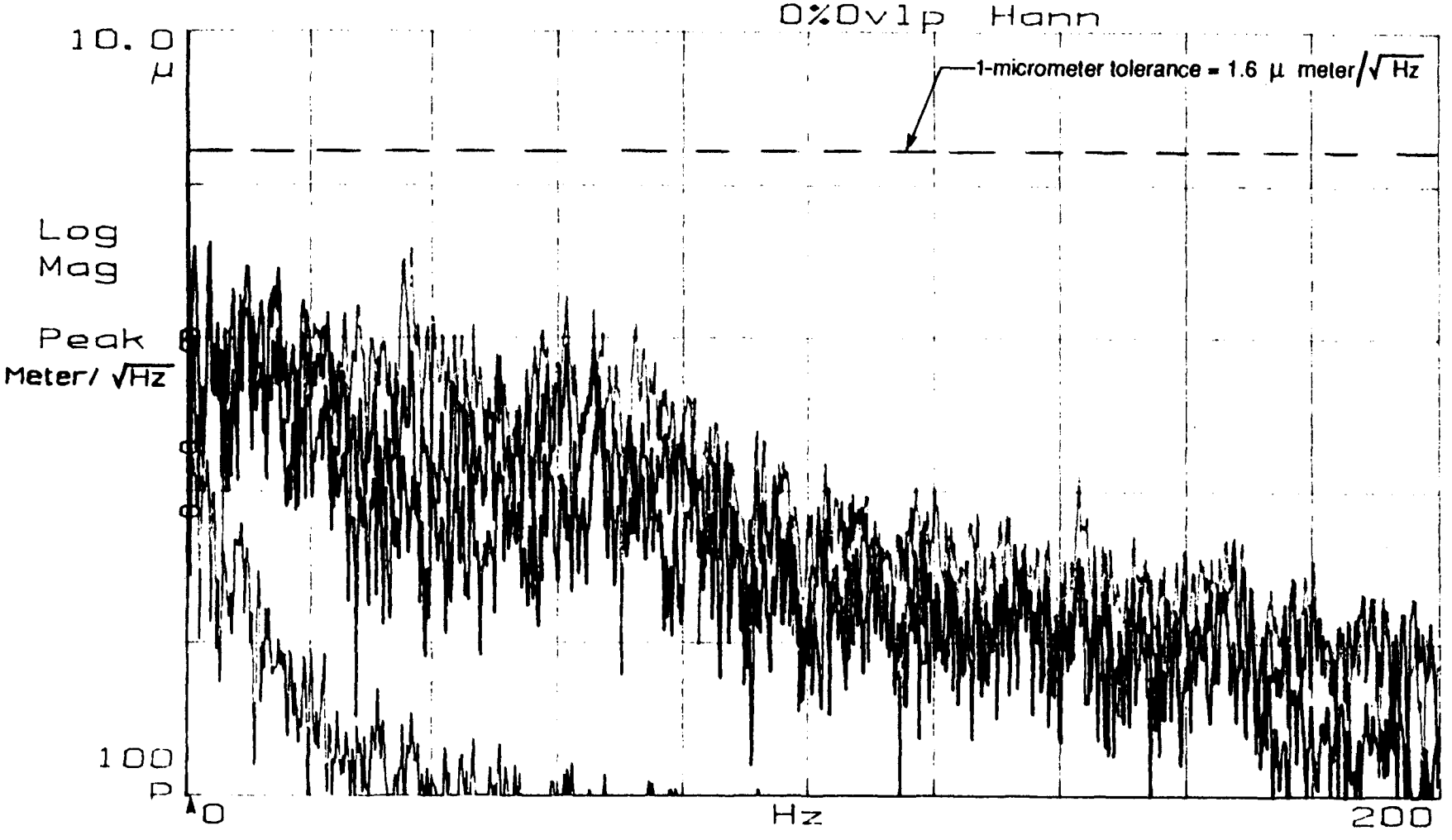
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 2
Site VE-3.5

12-89

Figure F 7



EXPLANATION

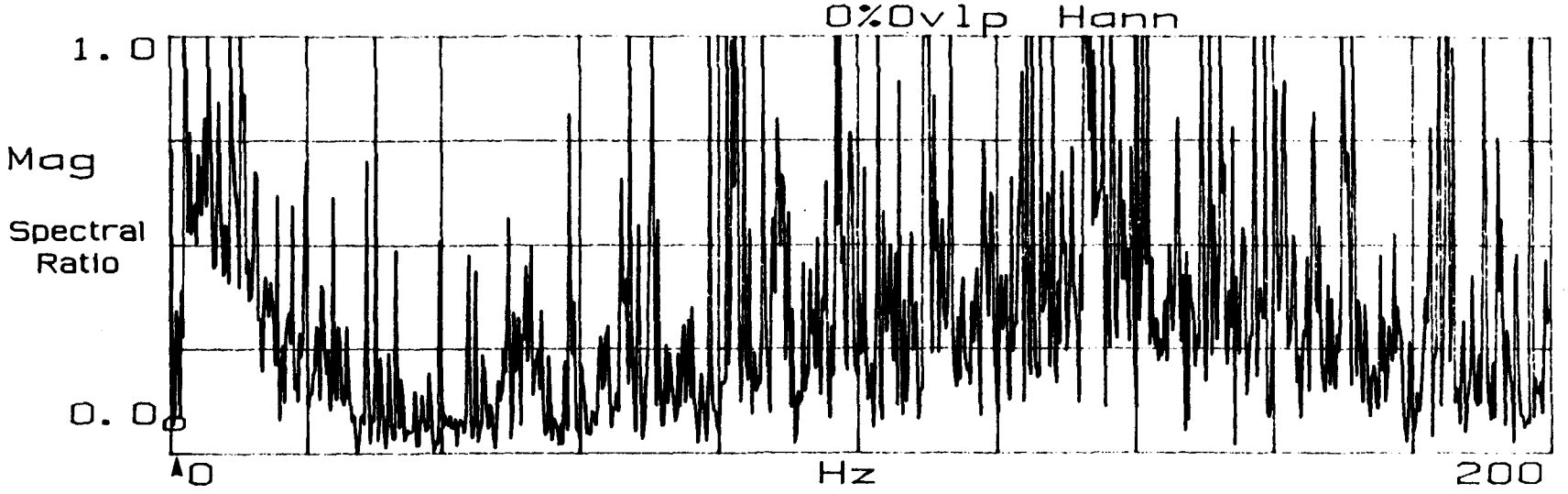
1 Hz Geophone Data
Blue = Max. Train Vibrations Measured @ 4.0 feet (1.2 meters)
Green = Max. Train Vibrations Measured @ 18.0 feet (5.5 meters)
Red = Max. Train Vibrations Measured @ 77.0 feet (23.5 meters)
Black = Ambient Vibrations Measured @ 77.0 feet (23.5 meters)

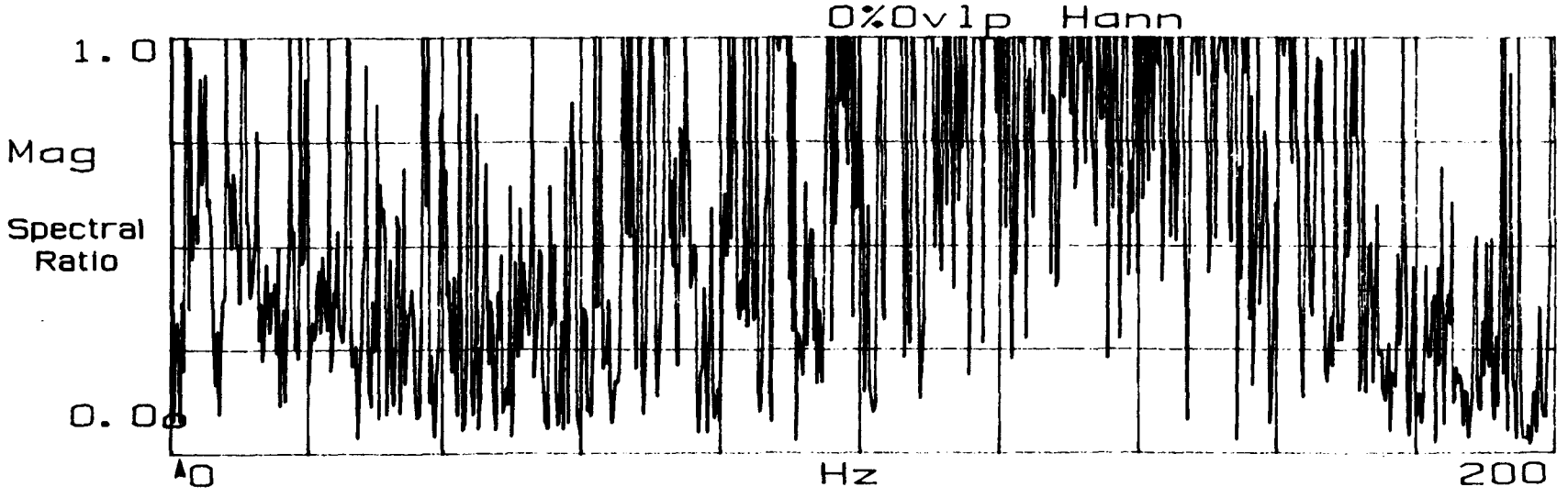
Lower Frequency Limit of Calibration
Bandwidth = 0.375 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 2
Site VE-3.5

12-89 Figure E-8





EXPLANATION

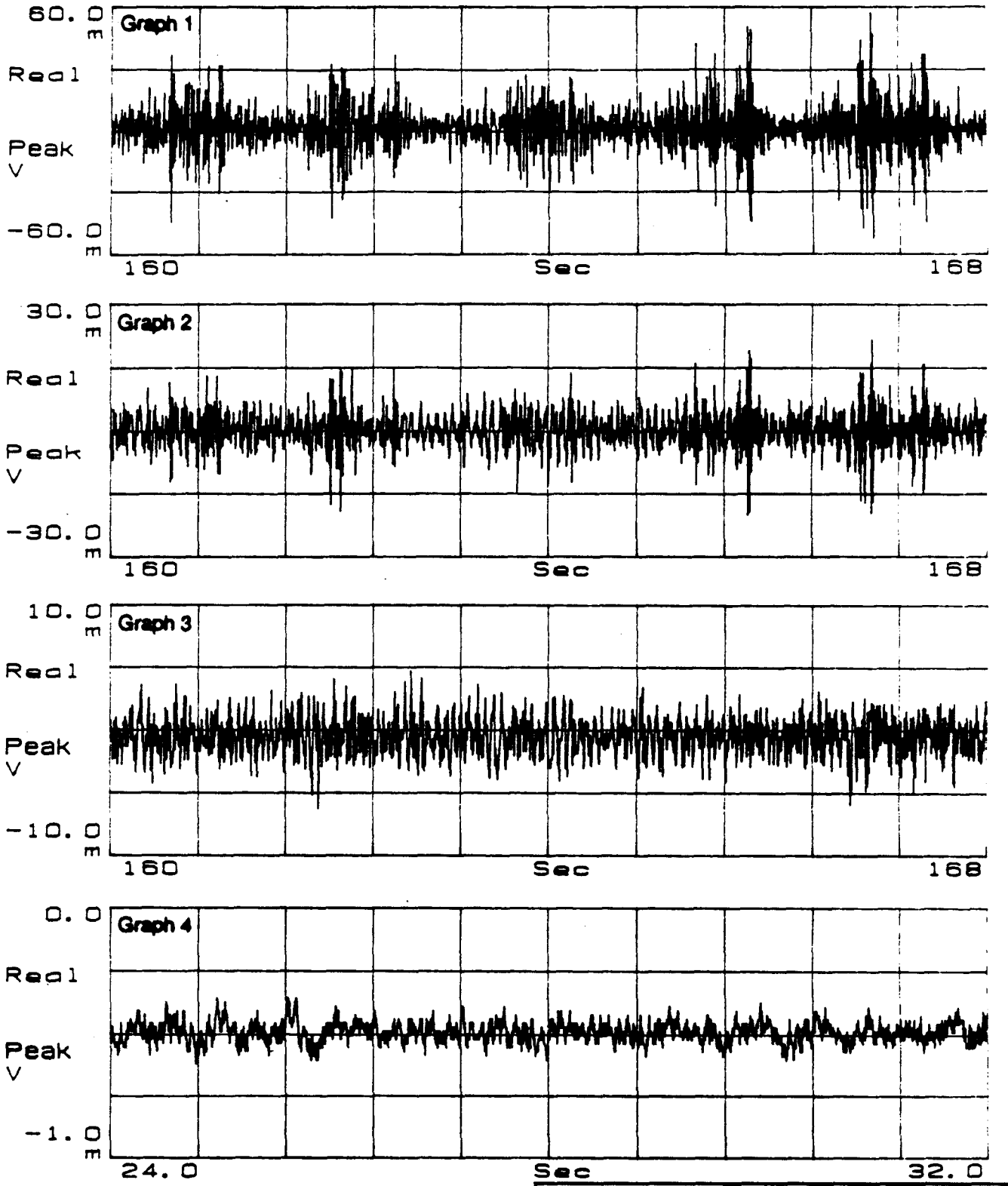
1 Hz Geophone Data

Top: "Bulk" Ratio between Geophone @ 4.0 feet (1.2 meters) and Geophone @ 77.0 feet (23.5 meters)

Bottom: "Rock" Ratio between Geophone @ 18.0 feet (5.5 meters) and Geophone @ 77.0 feet (23.5 meters)

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones
Data Set 2



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 1: Geophone 4106 @ 4.0 (1.2) - Train
Graph 2: Geophone 2676 @ 18.0 (5.5) - Train
Graph 3: Geophone 4105 @ 77.0 (23.5) - Train
Graph 4: Geophone 4105 @ 77.0 (23.5) - Ambient

The Earth Technology Corporation

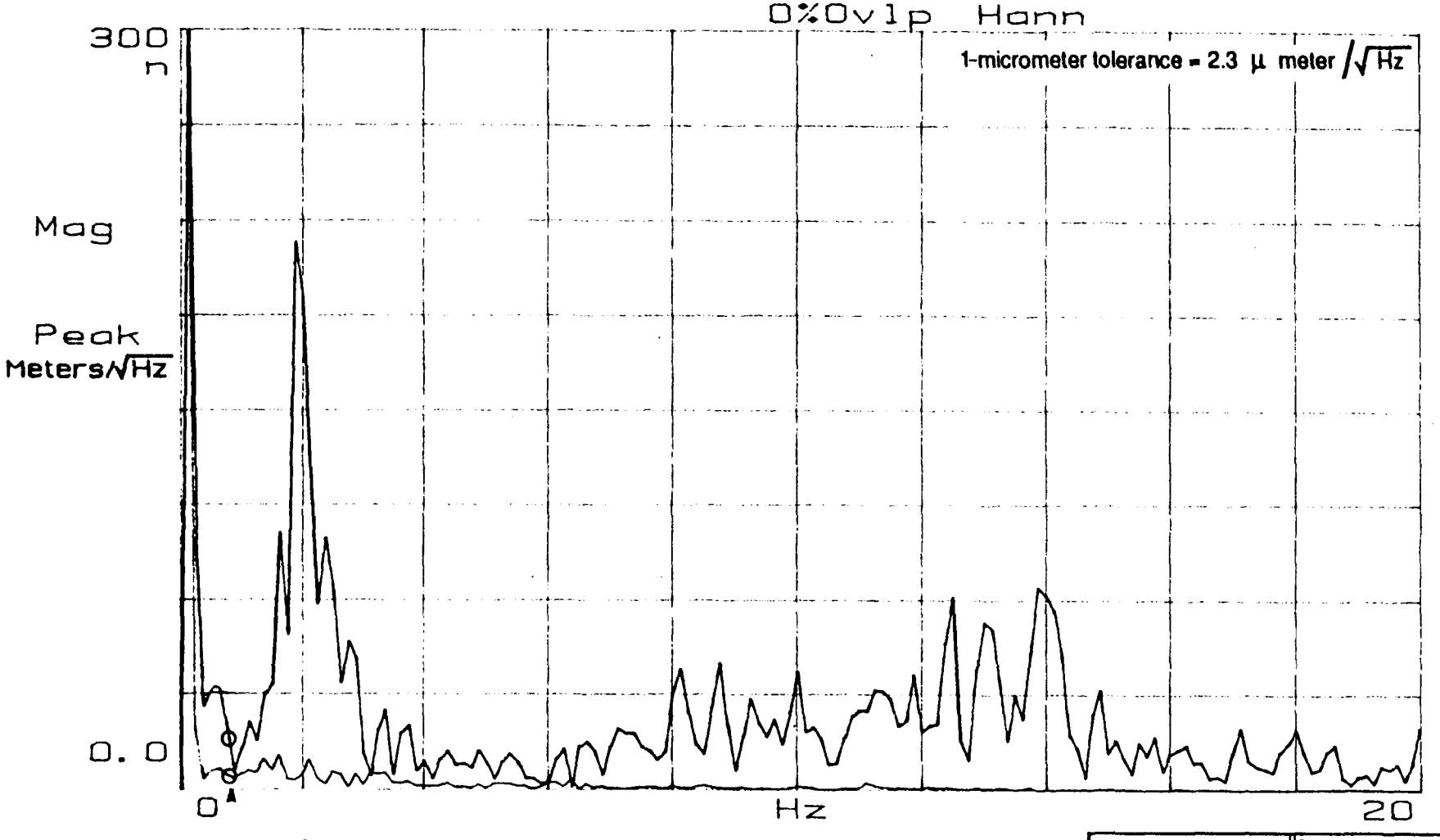
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Record
Data Set 6
Site VE-3.5

12-89

Figure F-10



EXPLANATION

1 Hz Geophone Data

Red = Max. Train Vibrations Measured @ 77.0 feet (23.5 meters)

Black = Ambient Vibrations Measured @ 77.0 feet (23.5 meters)

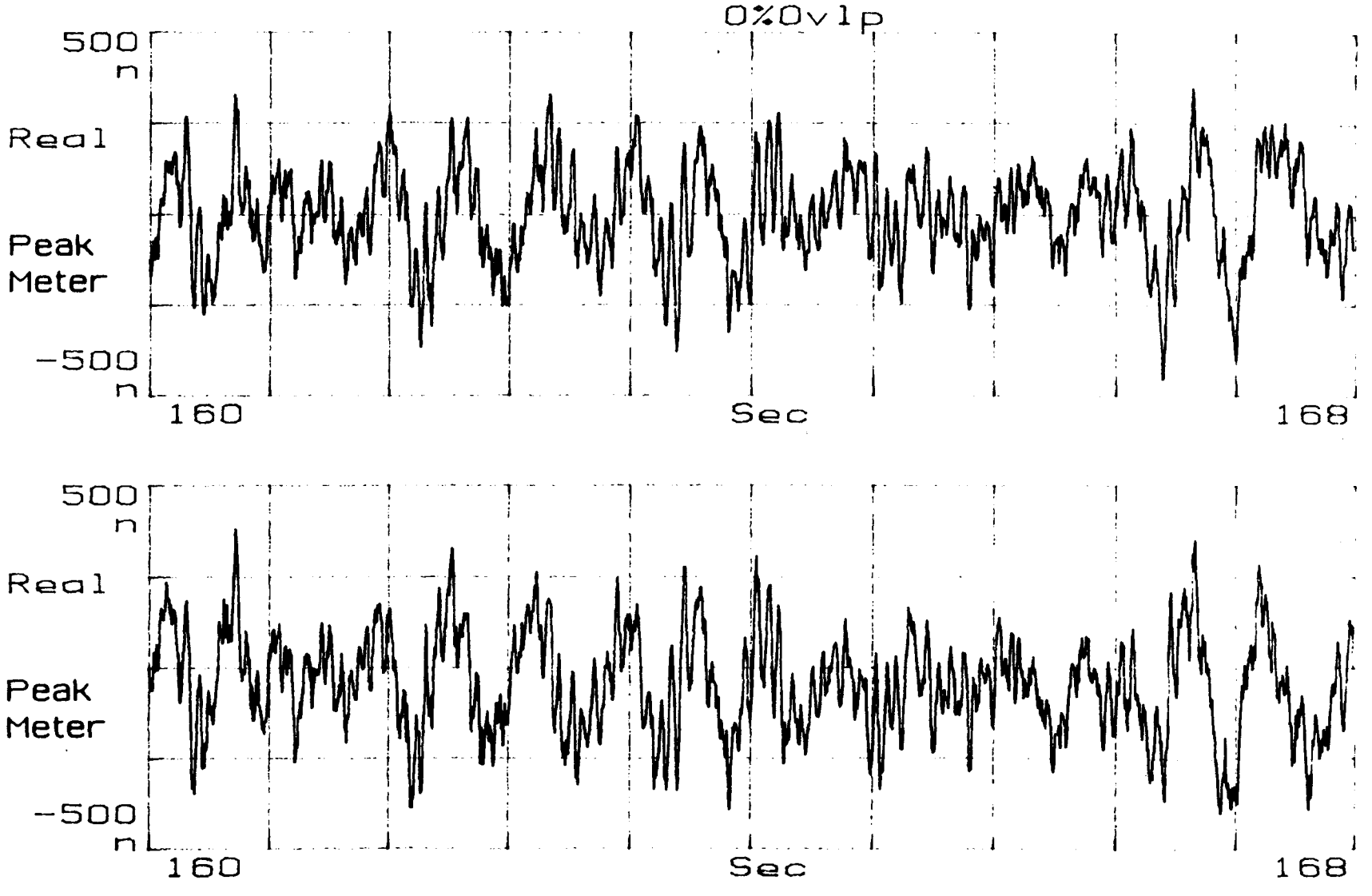
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Displacement Linear Spectrum
Data Set 6
Site VE-3.5

12-89

Figure F-11



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 77.0 feet (23.5 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

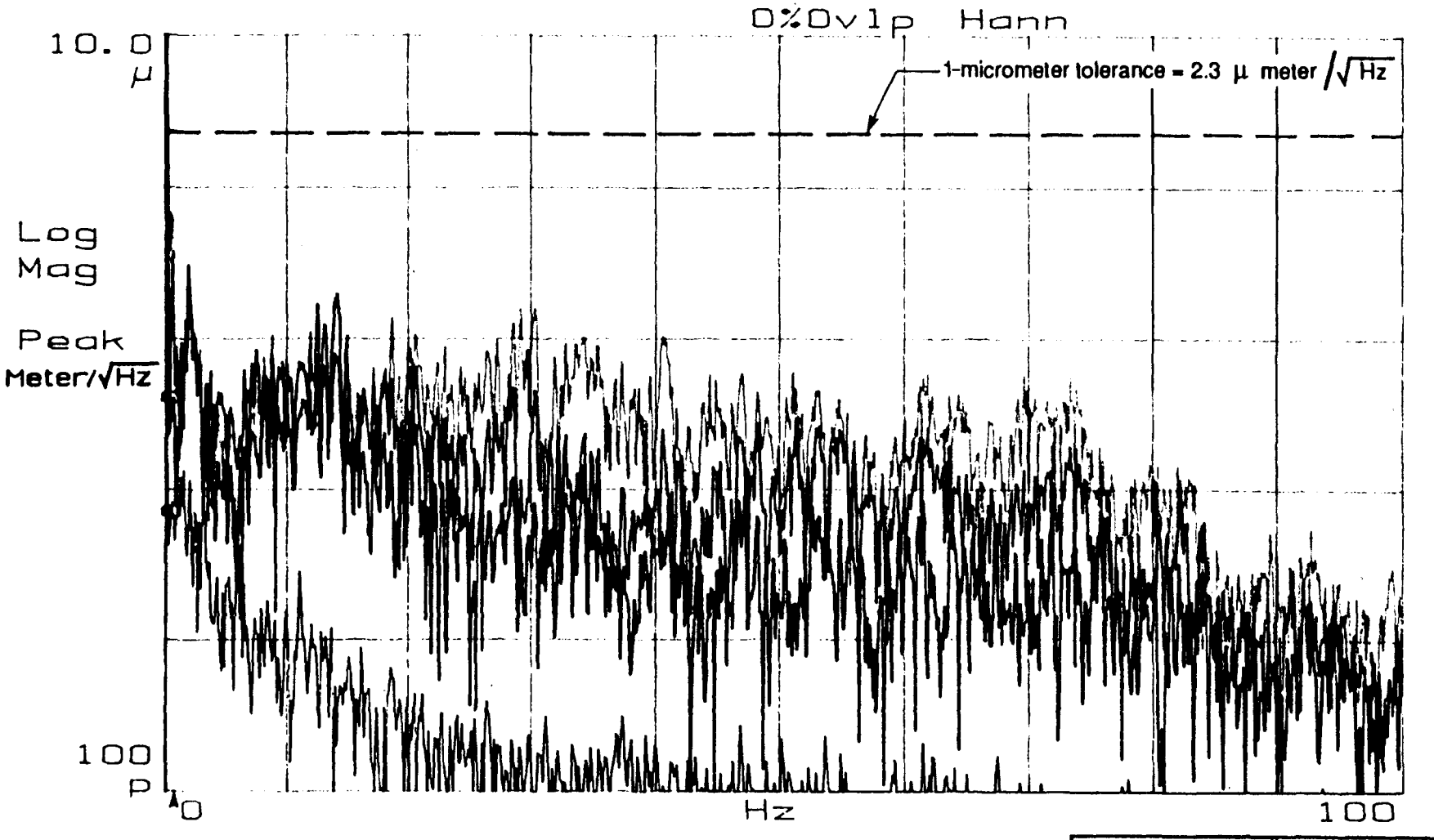
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 6
Site VE-3.5

12-89

Figure F-12



EXPLANATION

1 Hz Geophone Data
Blue = Max. Train Vibrations Measured @ 4.0 feet (1.2 meters)
Green = Max. Train Vibrations Measured @ 18.0 feet (5.5 meters)
Red = Max. Train Vibrations Measured @ 77.0 feet (23.5 meters)
Black = Ambient Vibrations Measured @ 77.0 feet (23.5 meters)

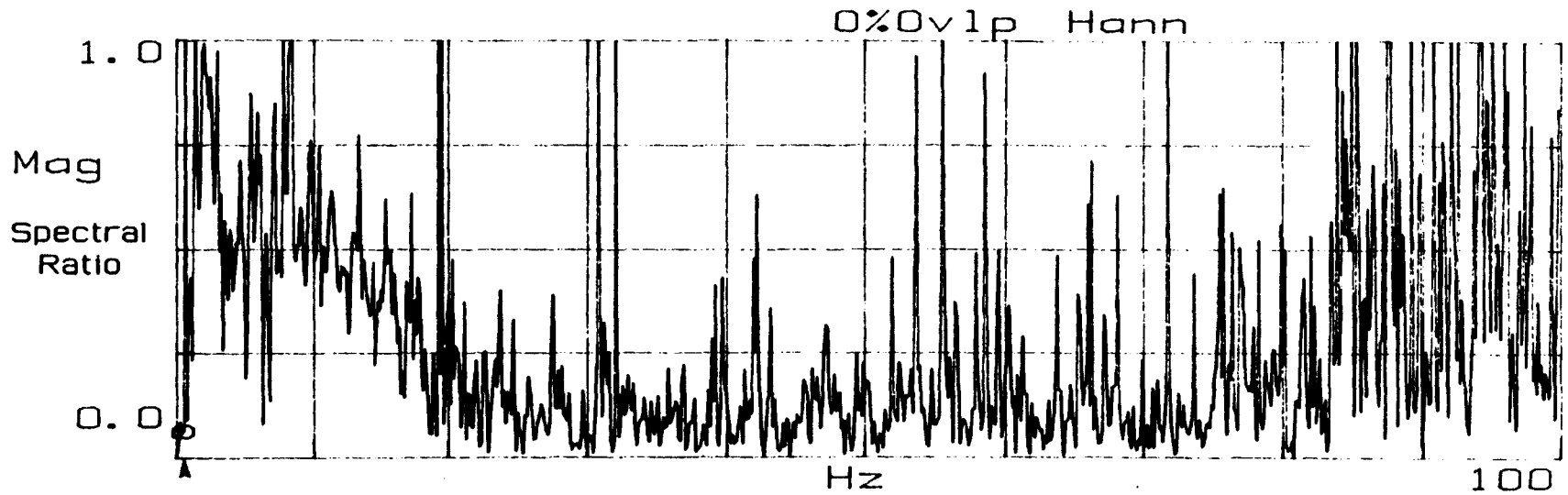
Lower Frequency Limit of Calibration
Bandwidth = 0.197 Hz

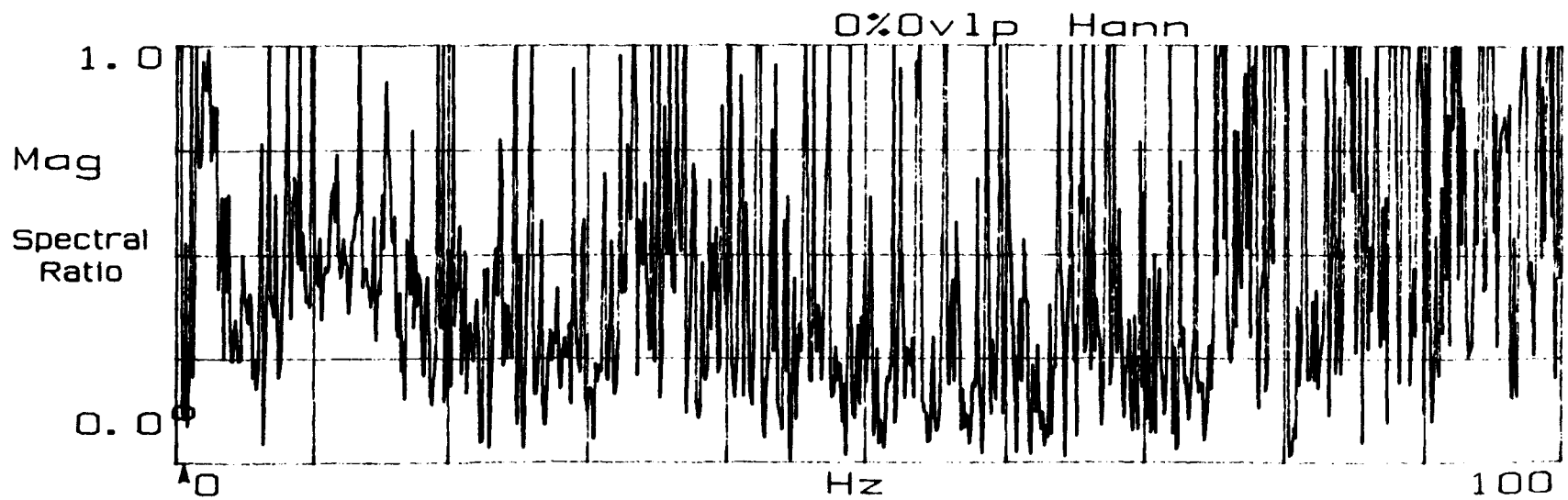
The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 6
Site VE-3.5

12-89

Figure E-13





EXPLANATION

1 Hz Geophone Data

Top: "Bulk" Ratio between Geophone @ 4.0 feet (1.2 meters) and Geophone @ 77.0 feet (23.5 meters)

Bottom: "Rock" Ratio between Geophone @ 18.0 feet (5.5 meters) and Geophone @ 77.0 feet (23.5 meters)

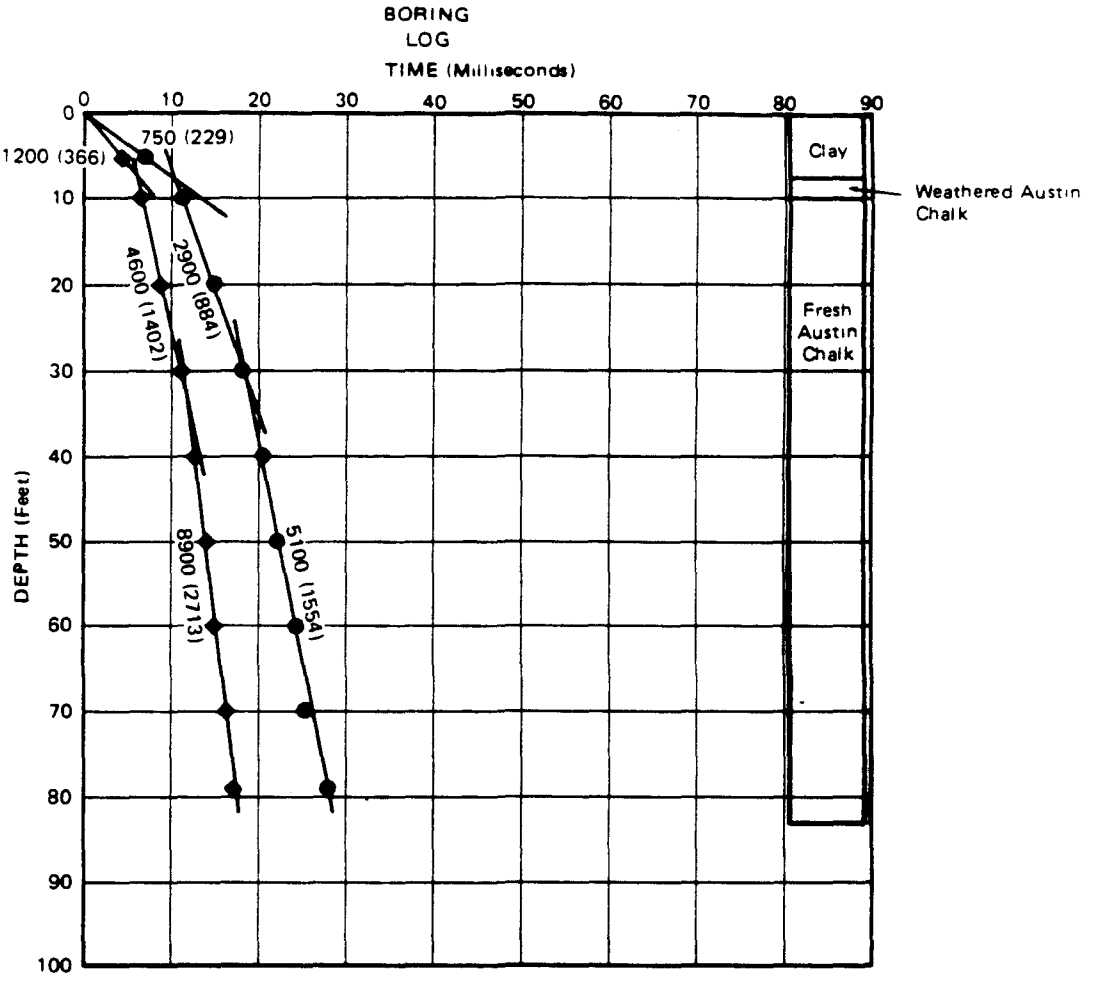
Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones
Data Set 6
Site VE-3.5

12/89

Figure F-14



EXPLANATION

◆ P WAVE ARRIVAL TIMES

● S WAVE ARRIVAL TIMES

SEISMIC VELOCITIES IN FEET/SECOND (METERS/SECOND)

The Earth Technology Corporation	PROJECT NO.: 87-888-0011 RTK Joint Venture

Velocity Data and Interpreted Profile
Vertical Traveling Waves
Site VE-3.5

12-89

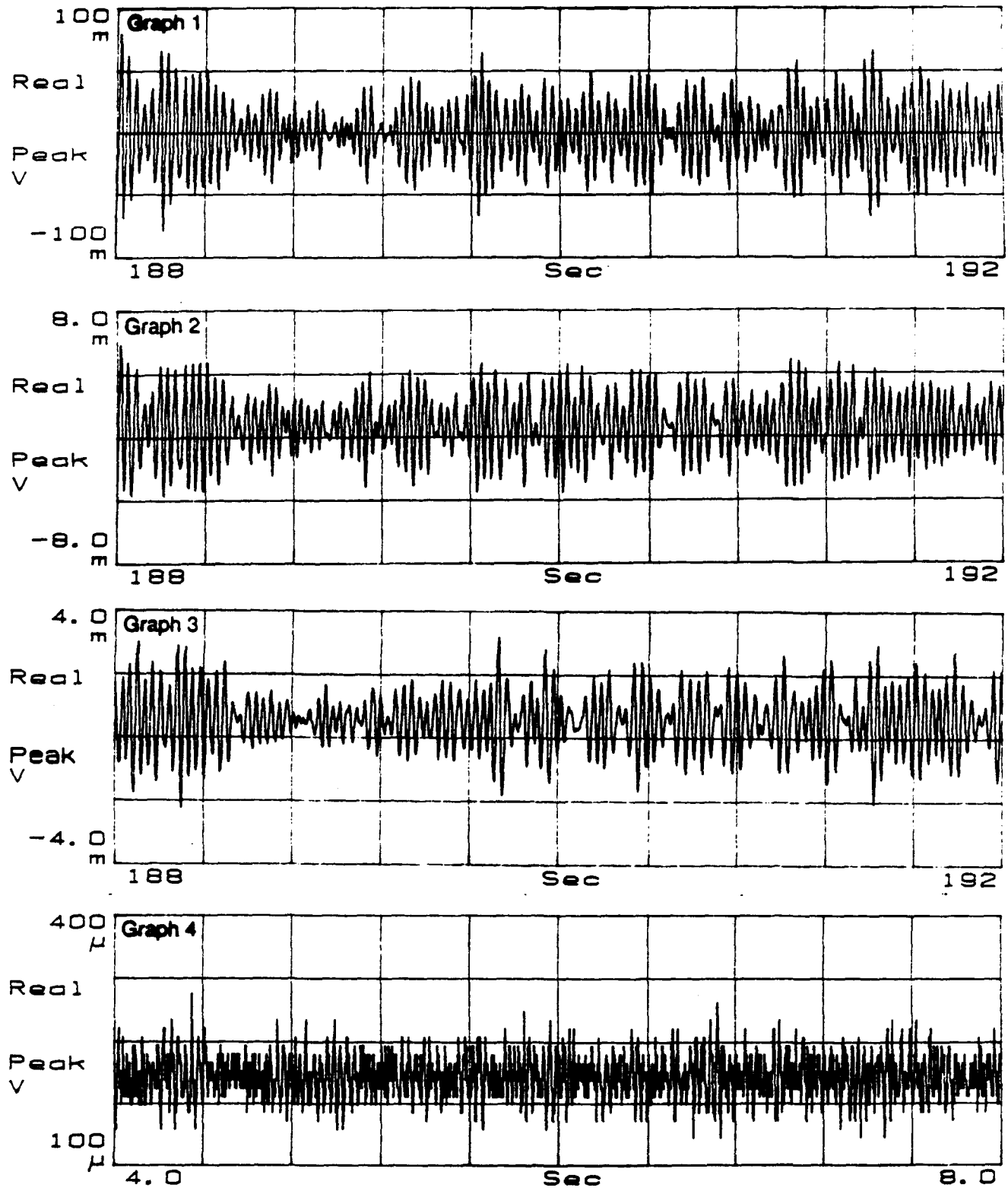
Figure F-15

APPENDIX G

SITE VF-5.4 DATA AND RESULTS

APPENDIX INDEX

Figure No.	Data Set	Description
G-1 through G-4	3	Triaxial Geophone Comparison
G-5 through G-9	4	1 Hz Geophone - Largest Displacement Train Data
G-10 through G-14	2	1 Hz Geophone - Second Largest Displacement Train Data
G-15	–	Velocity Profile (vertically traveling waves)



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 245.0 (74.7)
Graph 1: Vertical Geophone - Train
Graph 2: Transverse Geophone - Train
Graph 3: Radial Geophone - Train
Graph 4: Vertical Geophone - Ambient

The Earth Technology Corporation

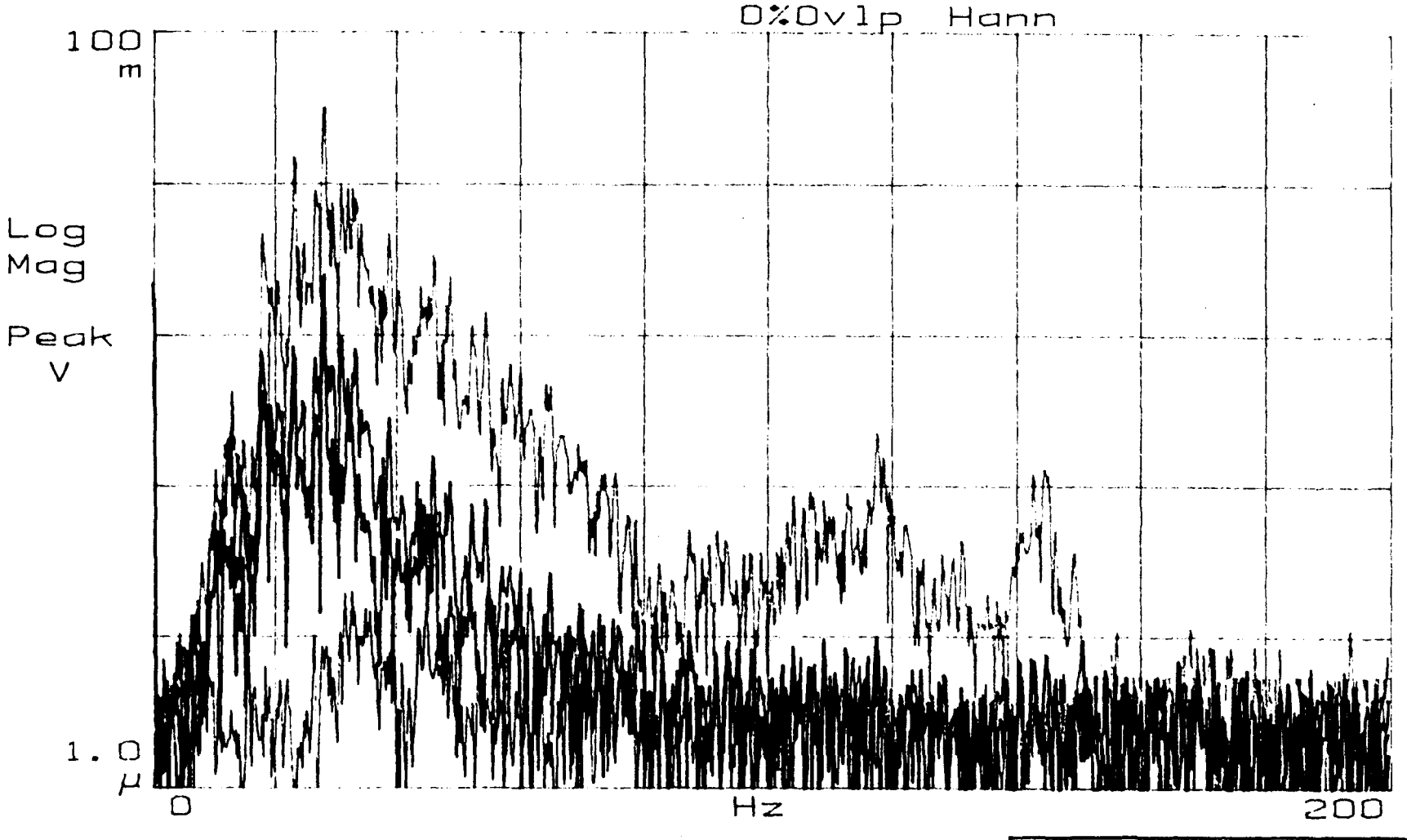
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Near Field Maximum
Data Set 3
Site VF-5.4

12-89

Figure G-1



EXPLANATION
Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 245.0 (74.7)
Blue = Vertical Geophone - Train
Green = Transverse Geophone - Train
Red = Radial Geophone - Train
Black = Vertical Geophone - Ambient

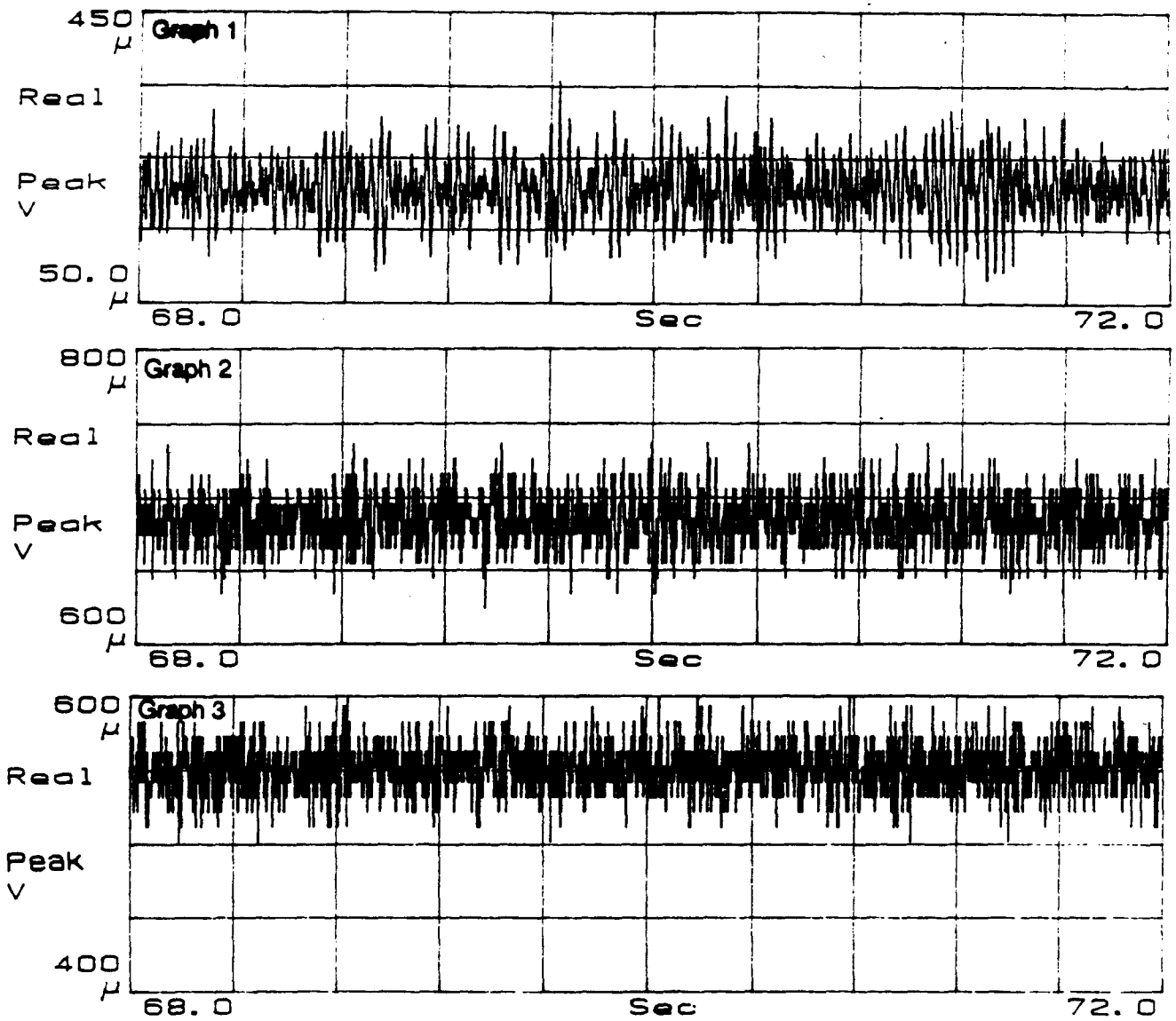
The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Composite Raw Velocity Linear Spectrum
Near Field Maximum
Data Set 3
Site VF-5.4

12.89



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 245.0 (74.7)
Graph 1: Vertical Geophone - Train
Graph 2: Transverse Geophone - Train
Graph 3: Radial Geophone - Train

The Earth Technology Corporation

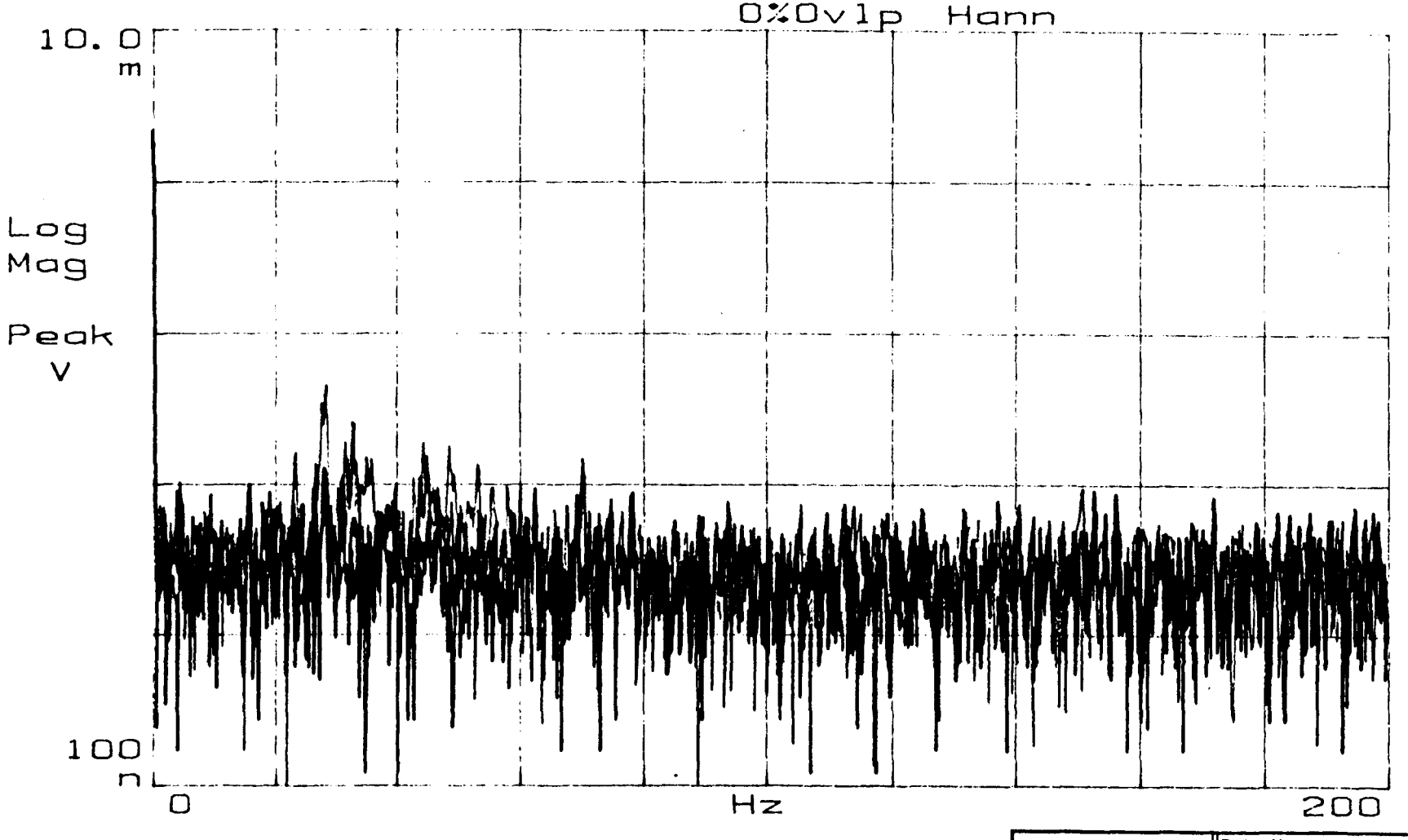
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Start of Intermediate Field
Data Set 3
Site VF-5.4

12-89

Figure G-3



EXPLANATION
Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 245.0 (74.7)
Blue = Vertical Geophone - Train
Green = Transverse Geophone - Train
Red = Radial Geophone - Train
Black = Vertical Geophone - Ambient

The Earth Technology Corporation

Project No.: 87-888-0011

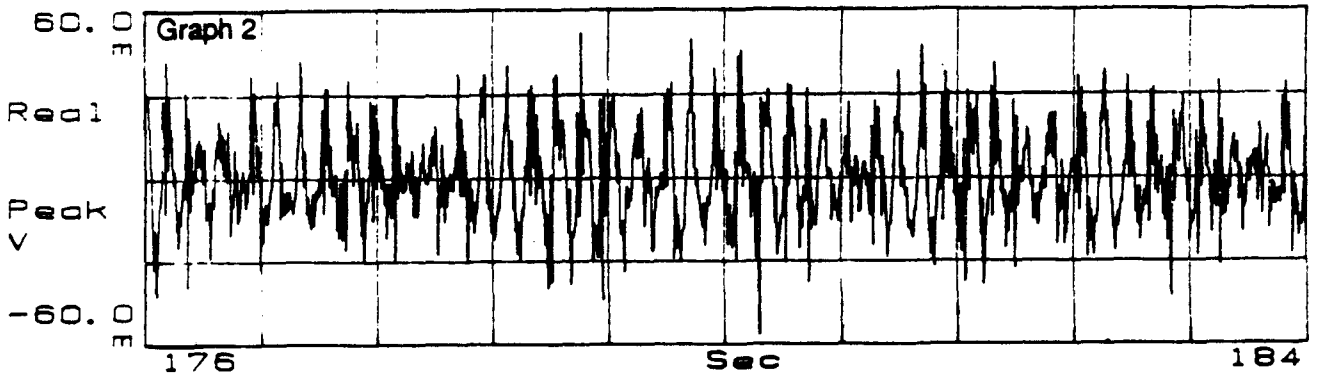
RTK Joint Venture

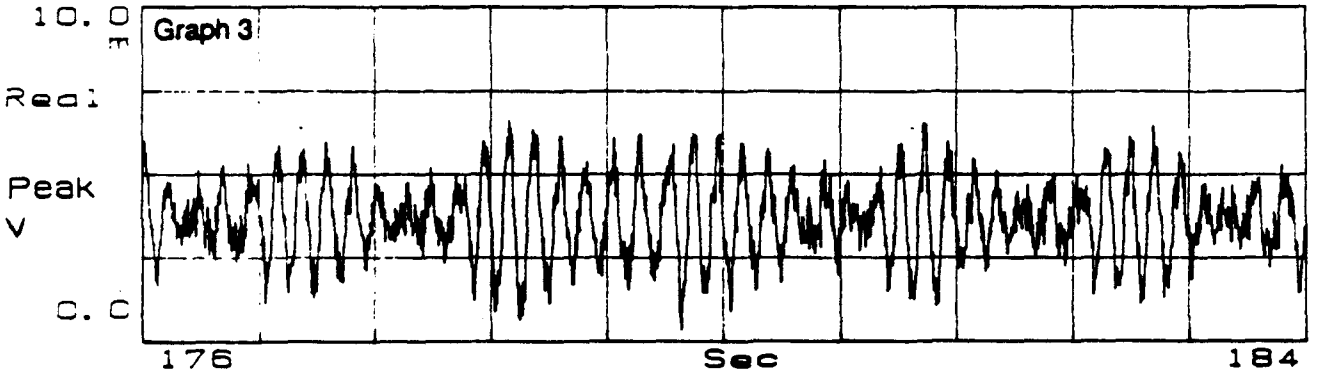
Composite Raw Velocity Linear Spectrum
Start of Intermediate Field
Data Set 3
Site VF-5.4

12-89

Figure G-4

No Shallow Data





No Ambient Data

EXPLANATION

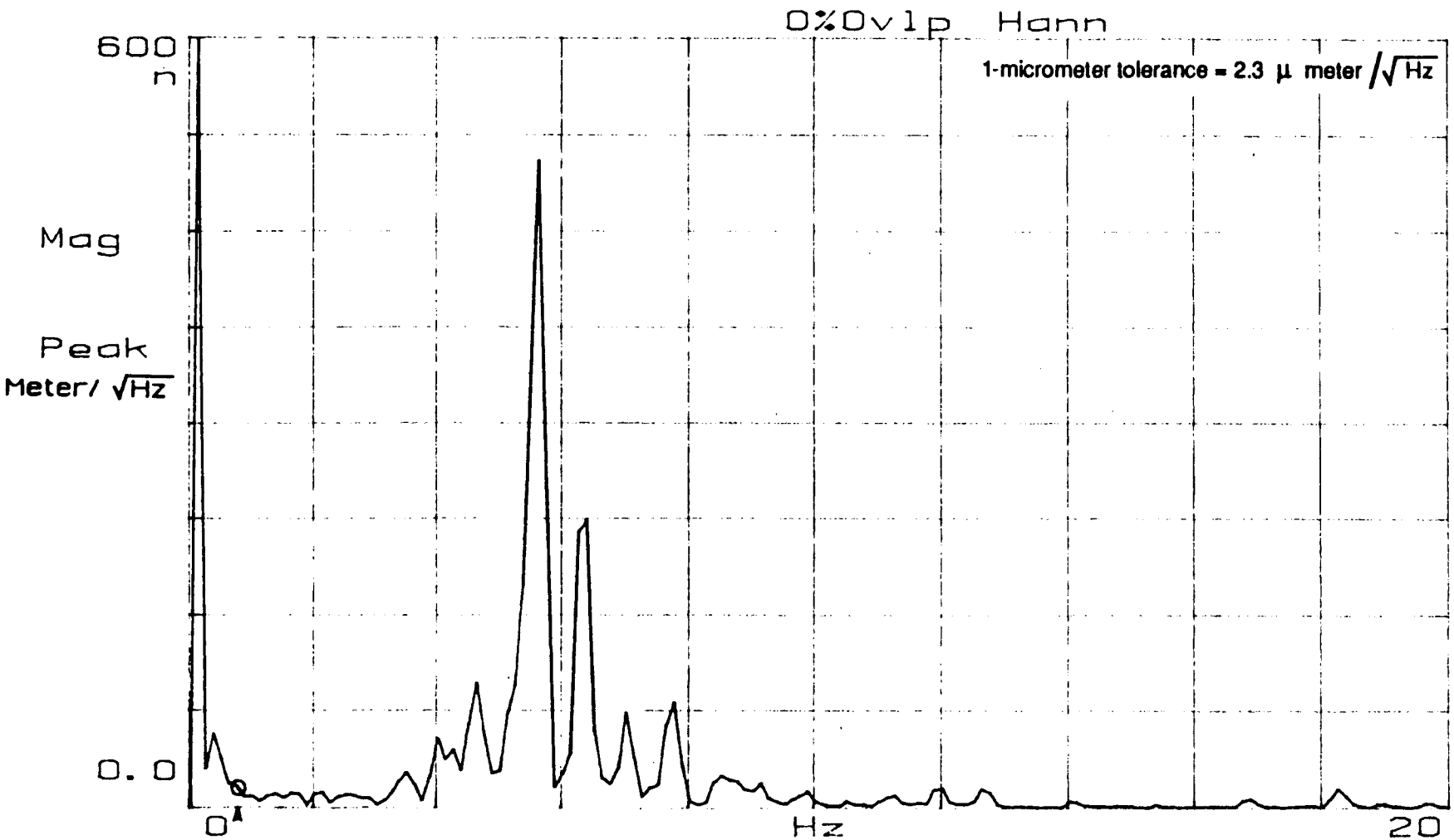
1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 2: Geophone 2676 @ 36.0 (11.0) - Train
Graph 3: Geophone 4105 @ 245.0 (74.7) - Train

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Raw Time Record
Data Set 4
Site VF-5.4

12-89

Figure G-5



EXPLANATION

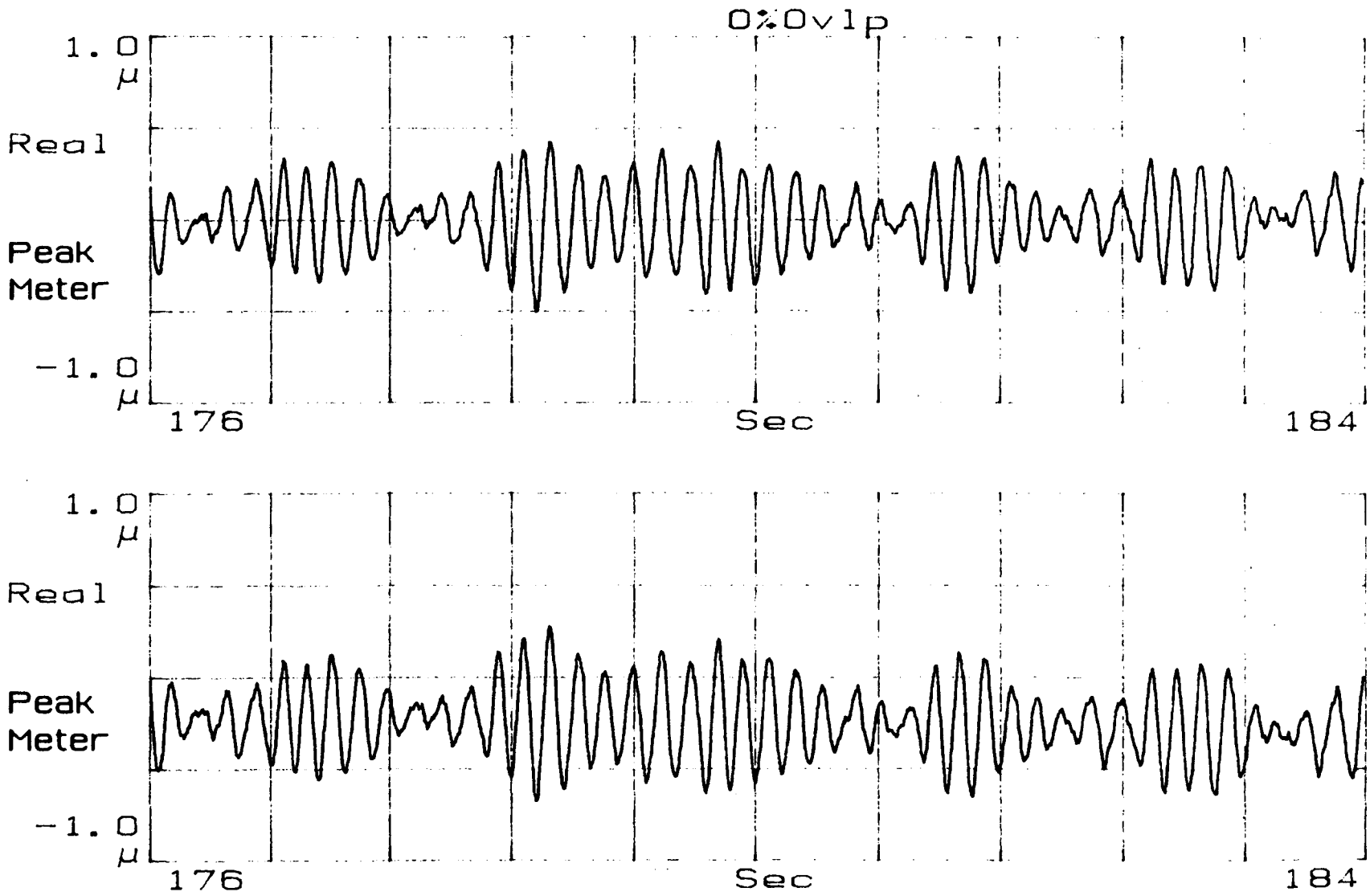
1 Hz Geophone Data
Red = Max. Train Vibrations Measured @ 245.0 feet (74.7 meters)
No Ambient Vibration Measured
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Displacement Linear Spectrum
Data Set 4
Site VF-5.4

12-89

Figure G-6



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 245.0 feet (74.7 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

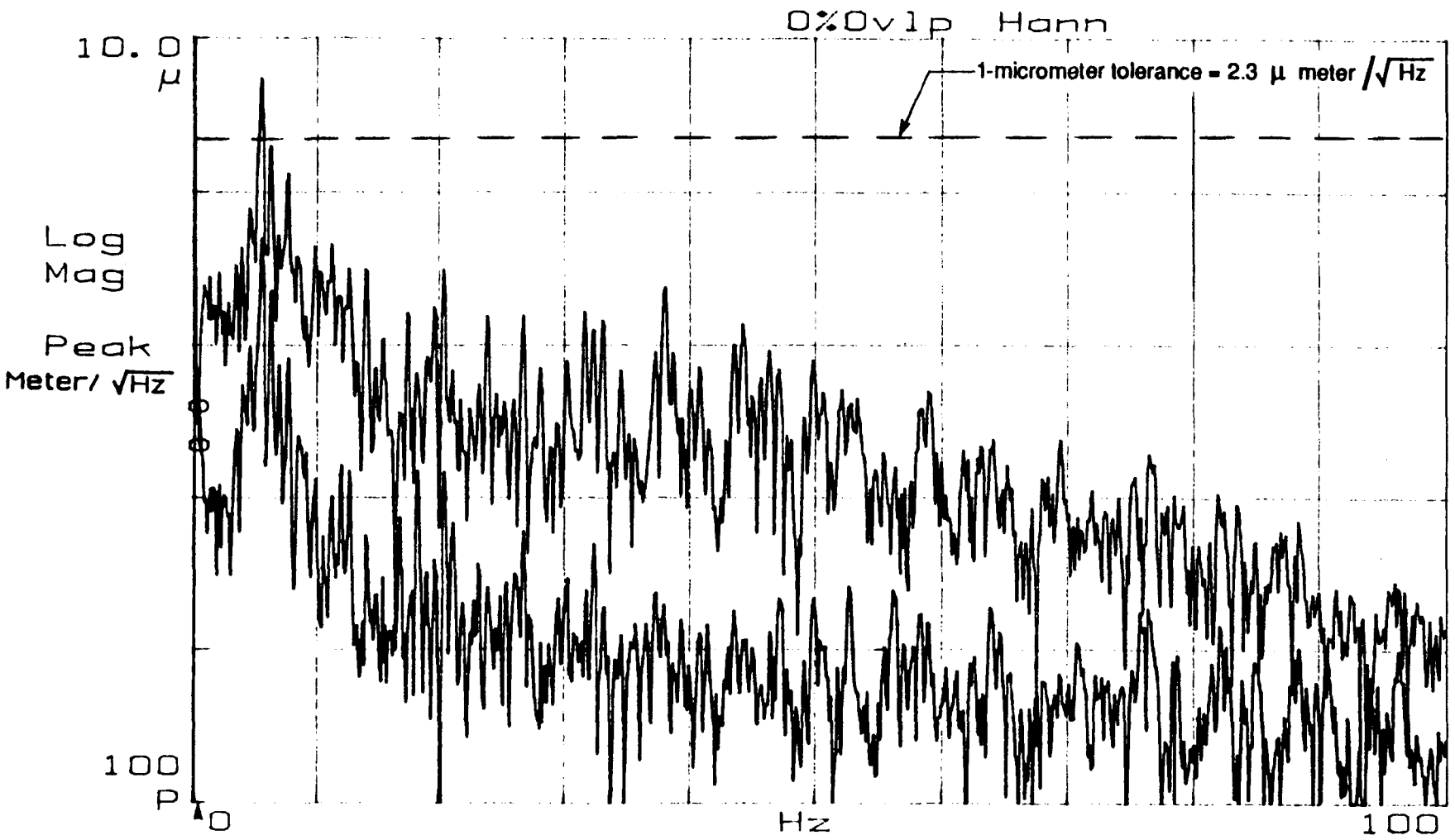
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 4
Site VF-5.4

12-89

Figure G 7



EXPLANATION

1 Hz Geophone Data
Green = Max. Train Vibrations Measured @ 36.0 feet (11.0 meters)
Red = Max. Train Vibrations Measured @ 245.0 feet (74.7 meters)
No Shallow Geophone or Ambient Vibration Measured

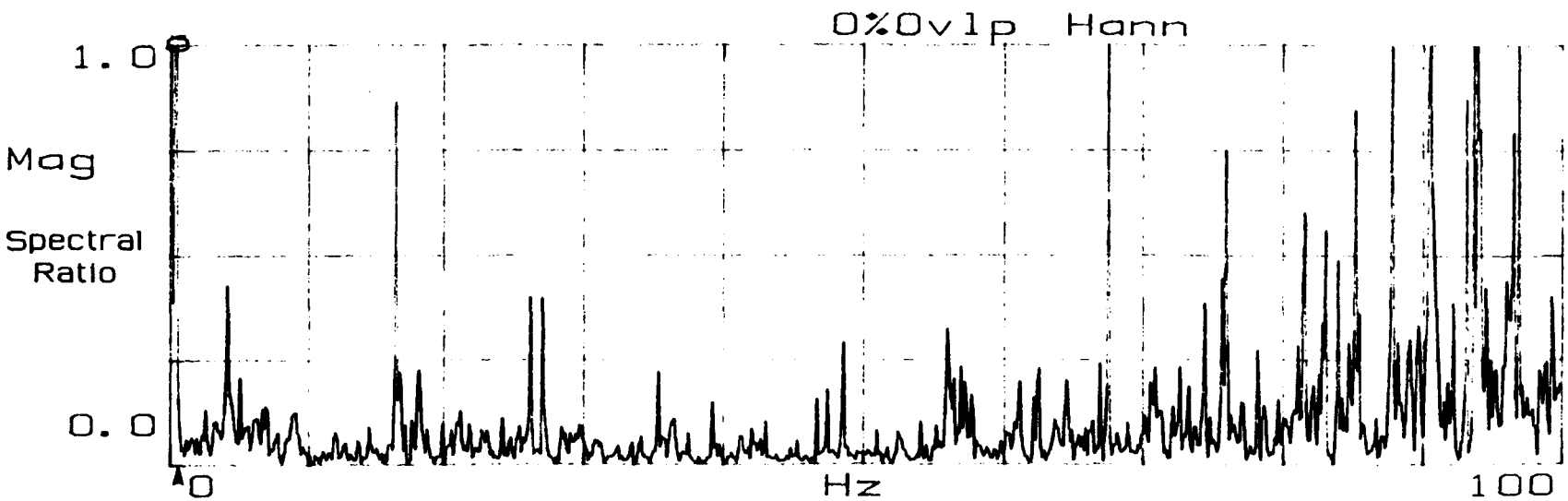
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 4
Site VF-5.4

12-89 Figure G.8

No Shallow Data



EXPLANATION

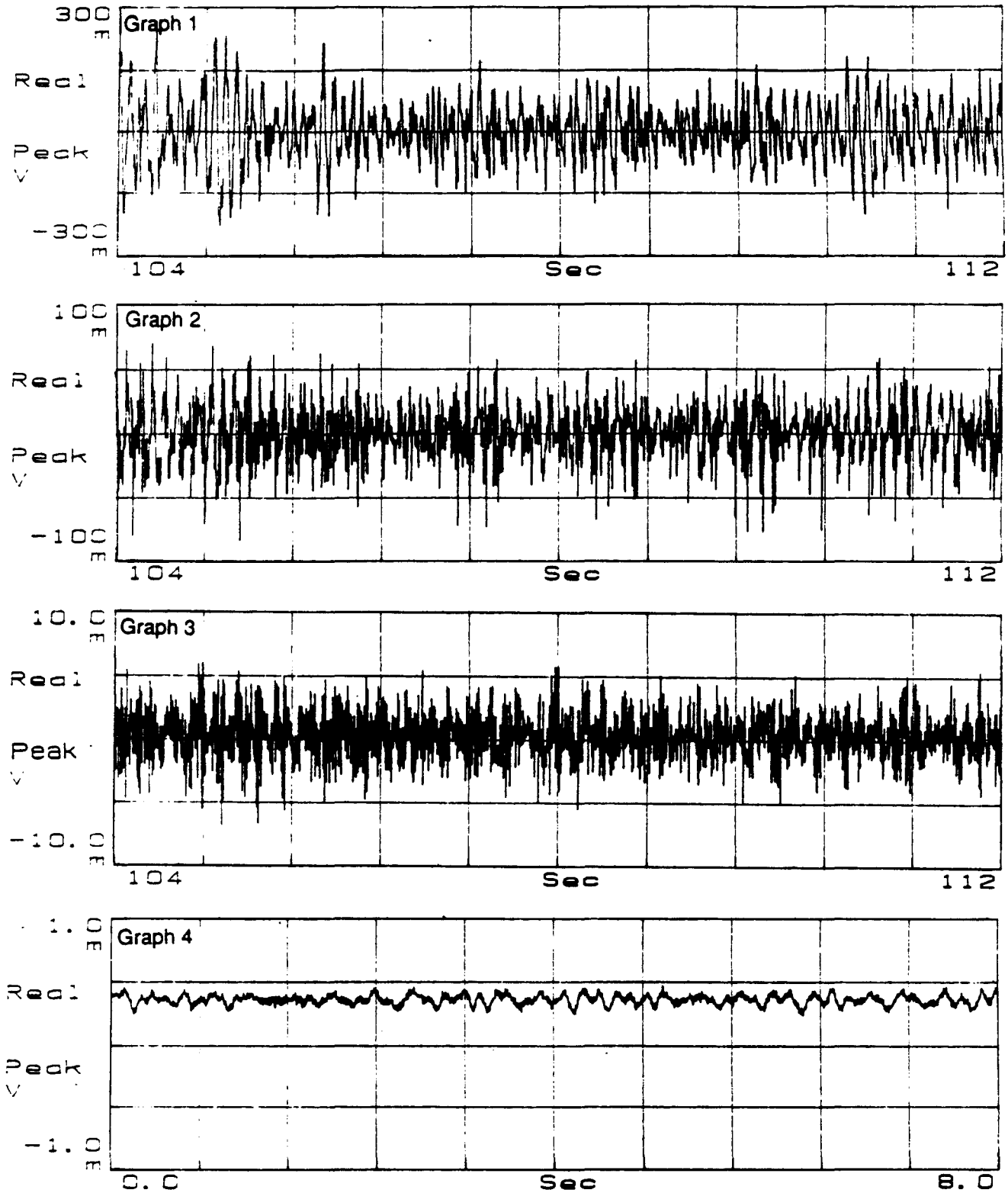
1 Hz Geophone Data

Bottom: "Rock" Ratio between Geophone @ 36.0 feet (11.0 meters) and Geophone @ 245.0 feet (74.7 meters)

Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones
Data Set 4
Site VF-5.4



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 1: Geophone 4106 @ 5.0 (1.5) - Train
Graph 2: Geophone 2676 @ 30.0 (9.1) - Train
Graph 3: Geophone 4105 @ 261.5 (79.7) - Train
Graph 4: Geophone 4105 @ 261.5 (79.7) - Ambient

The Earth Technology Corporation

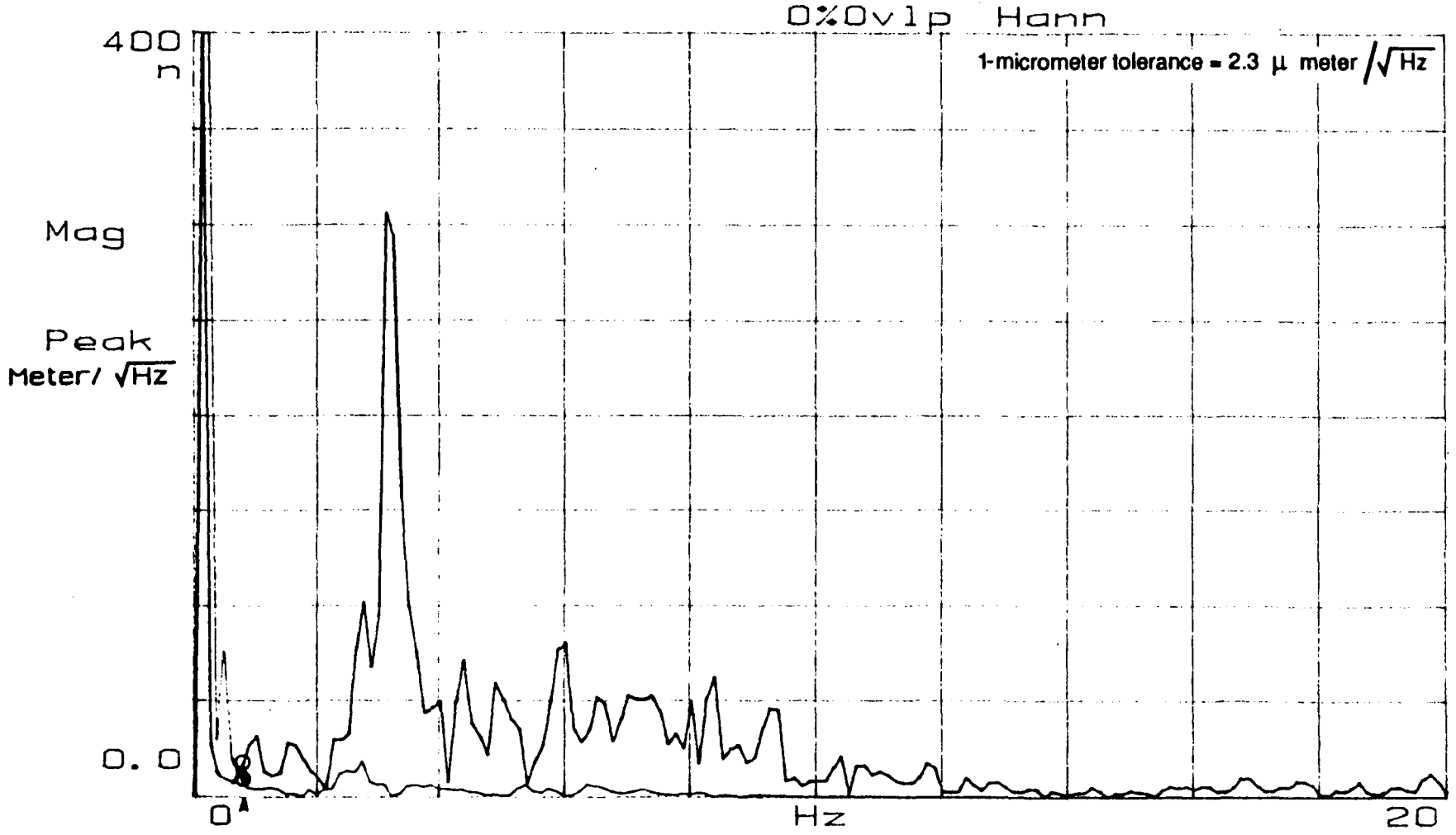
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Record
Data Set 2
Site VF-5.4

12-89

Figure G-10



EXPLANATION

1 Hz Geophone Data

Red = Max. Train Vibrations Measured @ 261.5 feet (79.7 meters)
Black = Ambient Vibrations Measured @ 261.5 feet (79.7 meters)

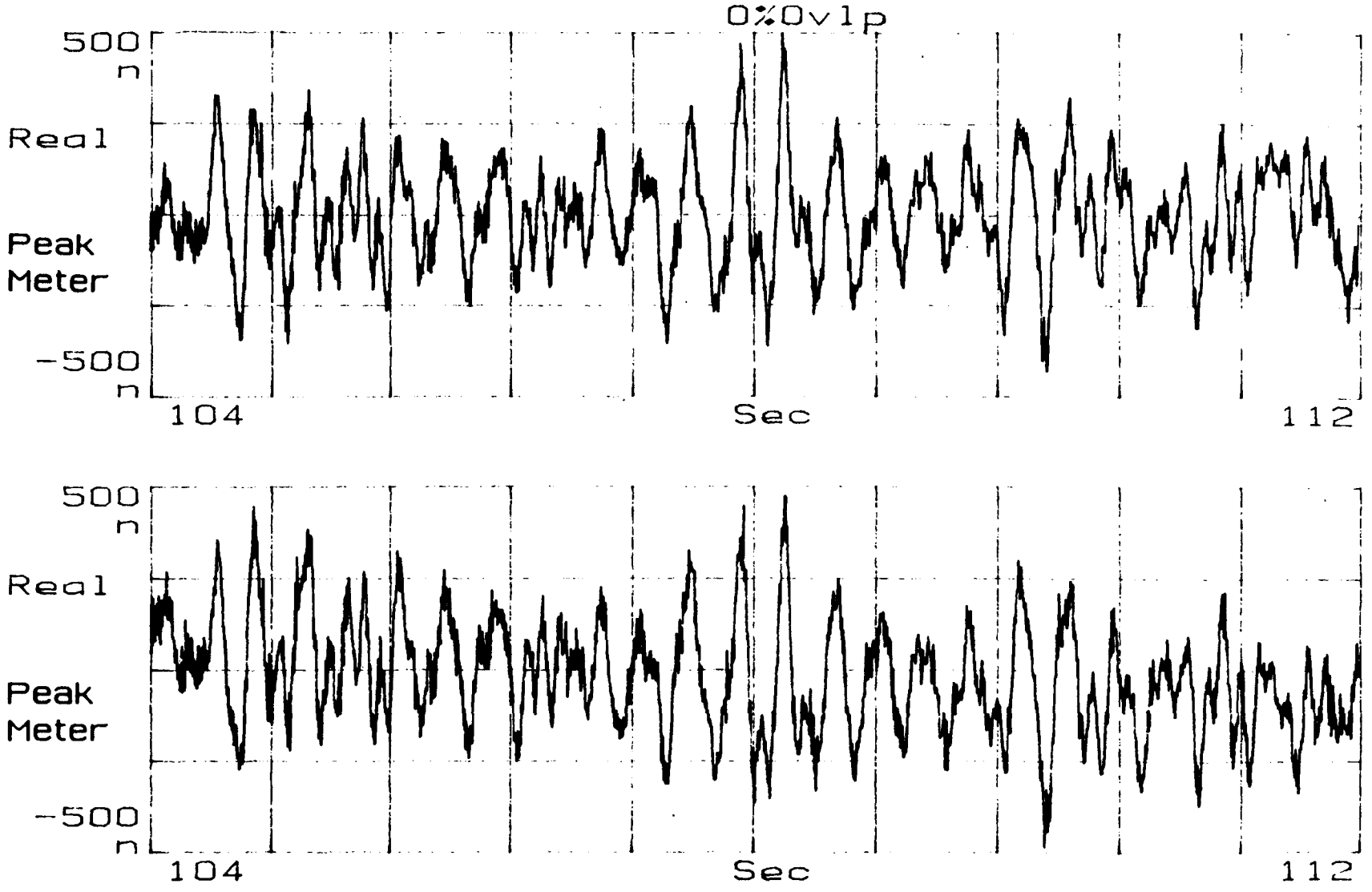
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Displacement Linear Spectrum
Data Set 2
Site VF-5.4

12-89

Figure G-11



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 261.5 feet (79.7 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

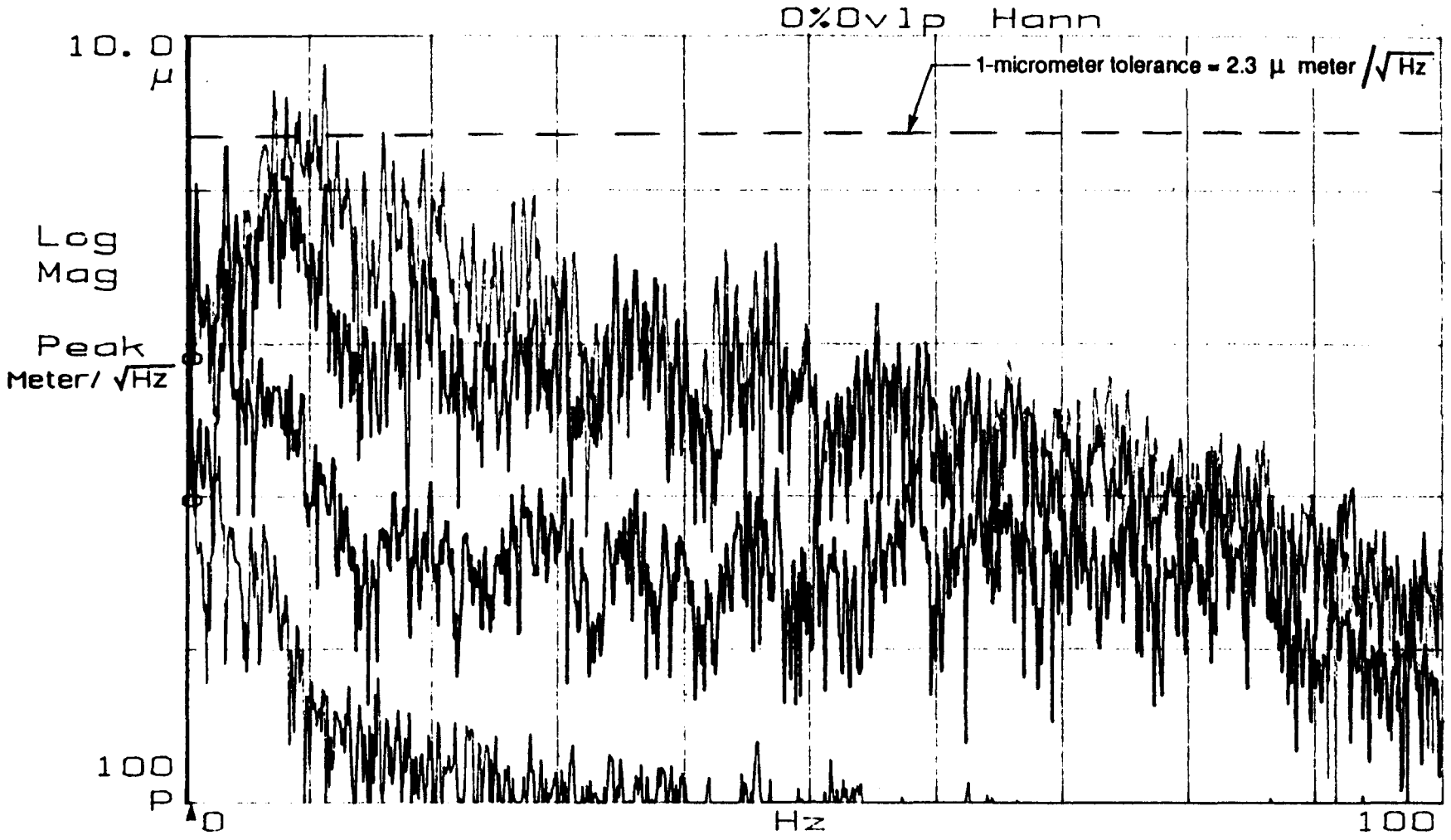
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 2
Site VF-5.4

12-89

Figure G 12



EXPLANATION

1 Hz Geophone Data
Blue = Max. Train Vibrations Measured @ 5.0 feet (1.5 meters)
Green = Max. Train Vibrations Measured @ 30.0 feet (9.1 meters)
Red = Max. Train Vibrations Measured @ 261.5 feet (79.7 meters)
Black = Ambient Vibrations Measured @ 261.5 feet (79.7 meters)

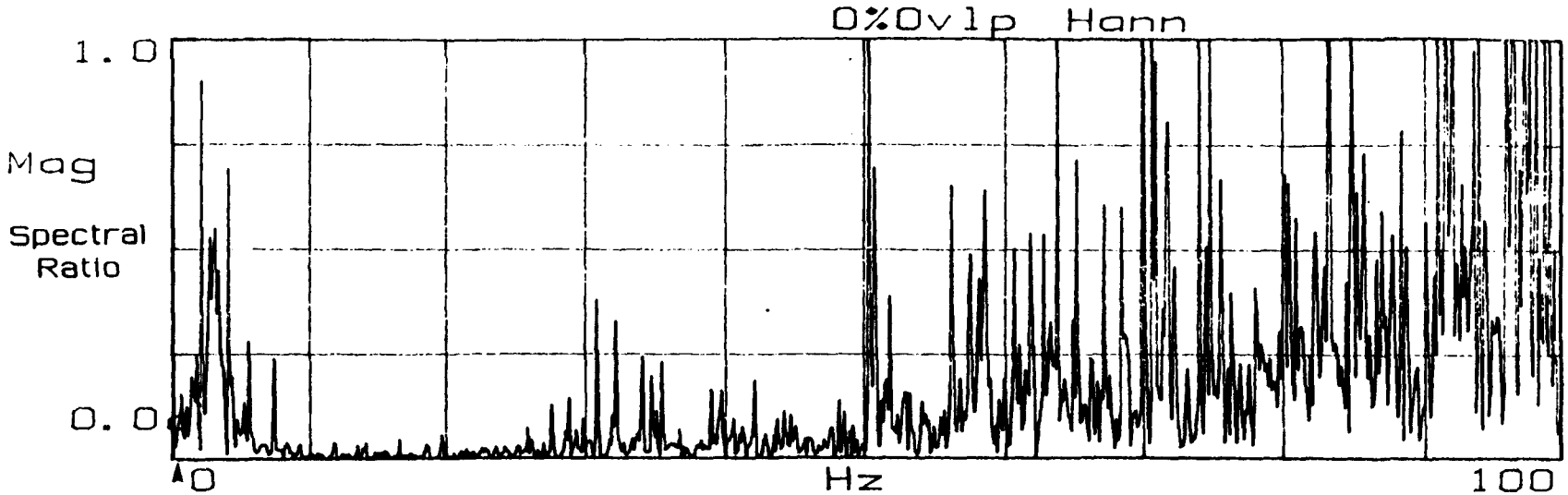
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

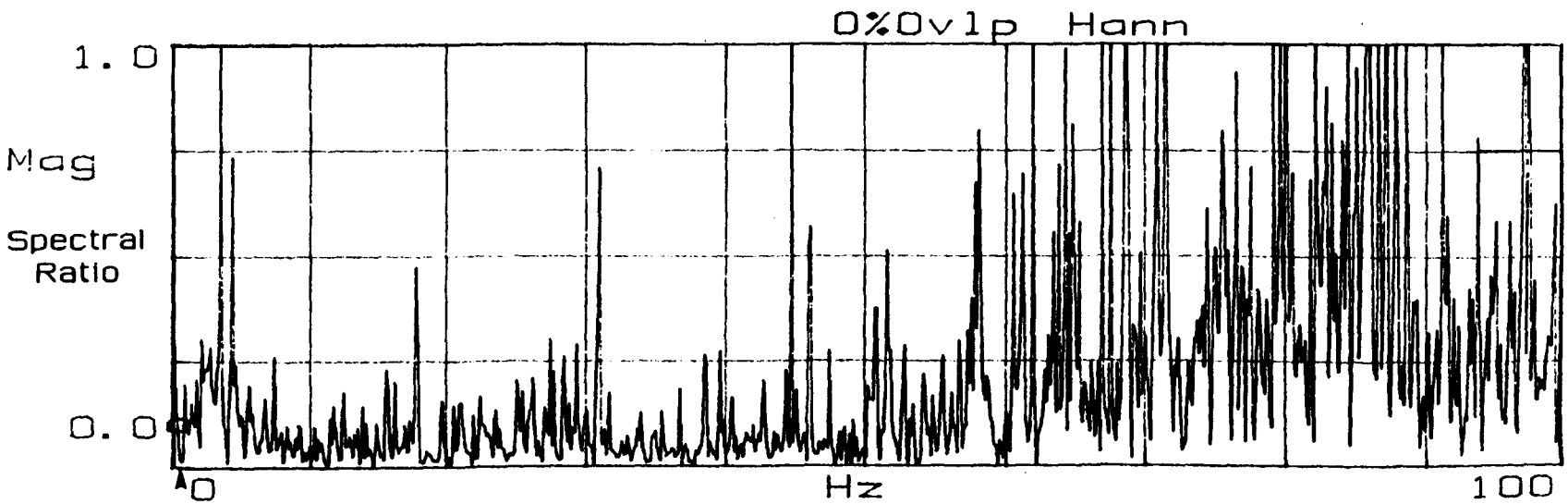
The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 2
Site VF-5.4

12-89

Figure G-13





EXPLANATION

1 Hz Geophone Data

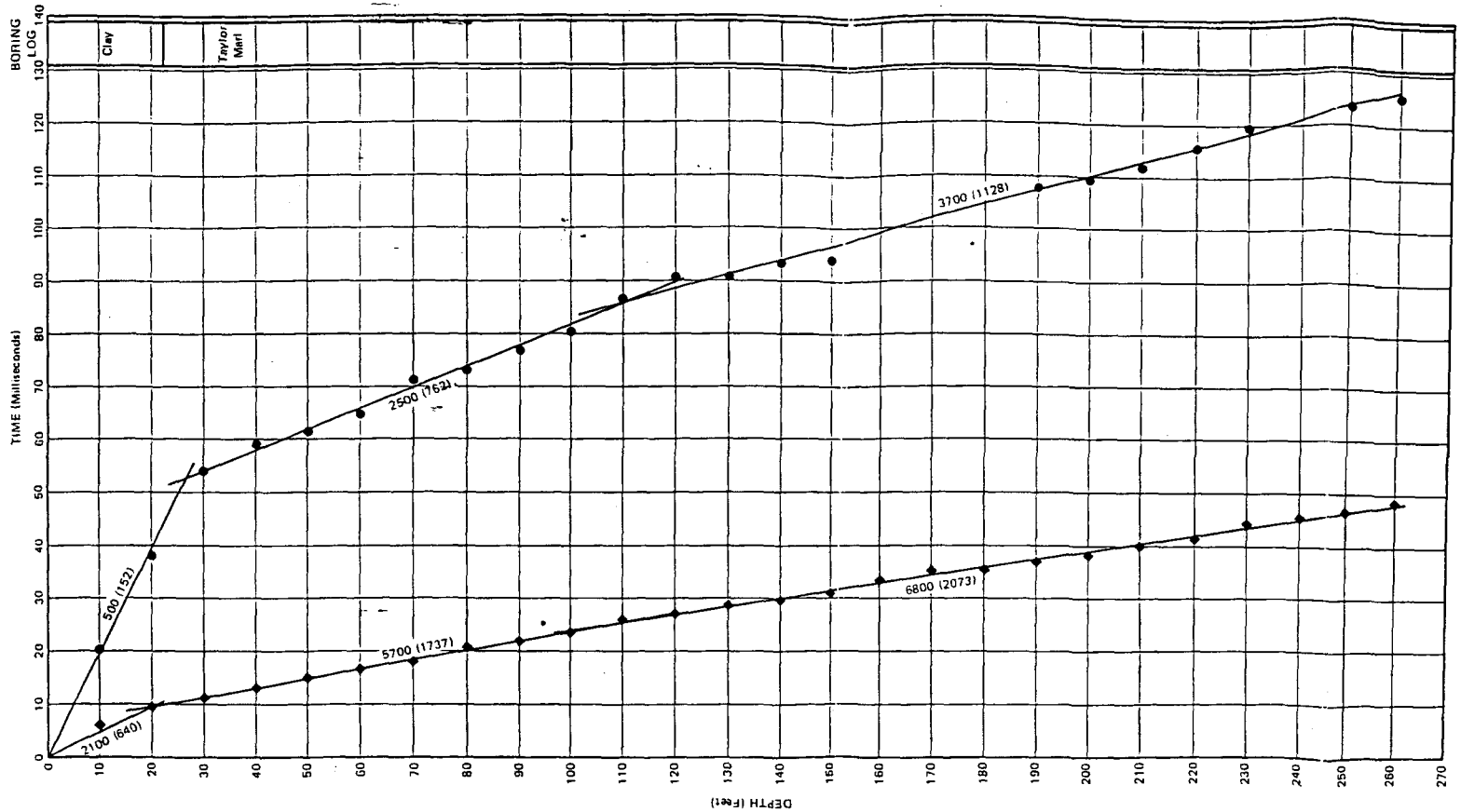
Top: "Bulk" Ratio between Geophone @ 5.0 feet (1.5 meters) and Geophone @ 261.5 feet (79.7 meters)

Bottom: "Rock" Ratio between Geophone @30.0 feet (9.1 meters) and Geophone @ 261.5 feet (79.7 meters)

Lower Frequency Limit of Calibration

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones
Data Set 2



EXPLANATION

◆ P WAVE ARRIVAL TIMES

● S WAVE ARRIVAL TIMES

SEISMIC VELOCITIES IN FEET/SECOND (METERS/SECOND)

The Earth Technology Corporation

PROJECT NO.: 87-888-0011

RTK Joint Venture

Velocity Data and Interpreted Profile
Vertical Traveling Waves
Site VF-5.4

12-89

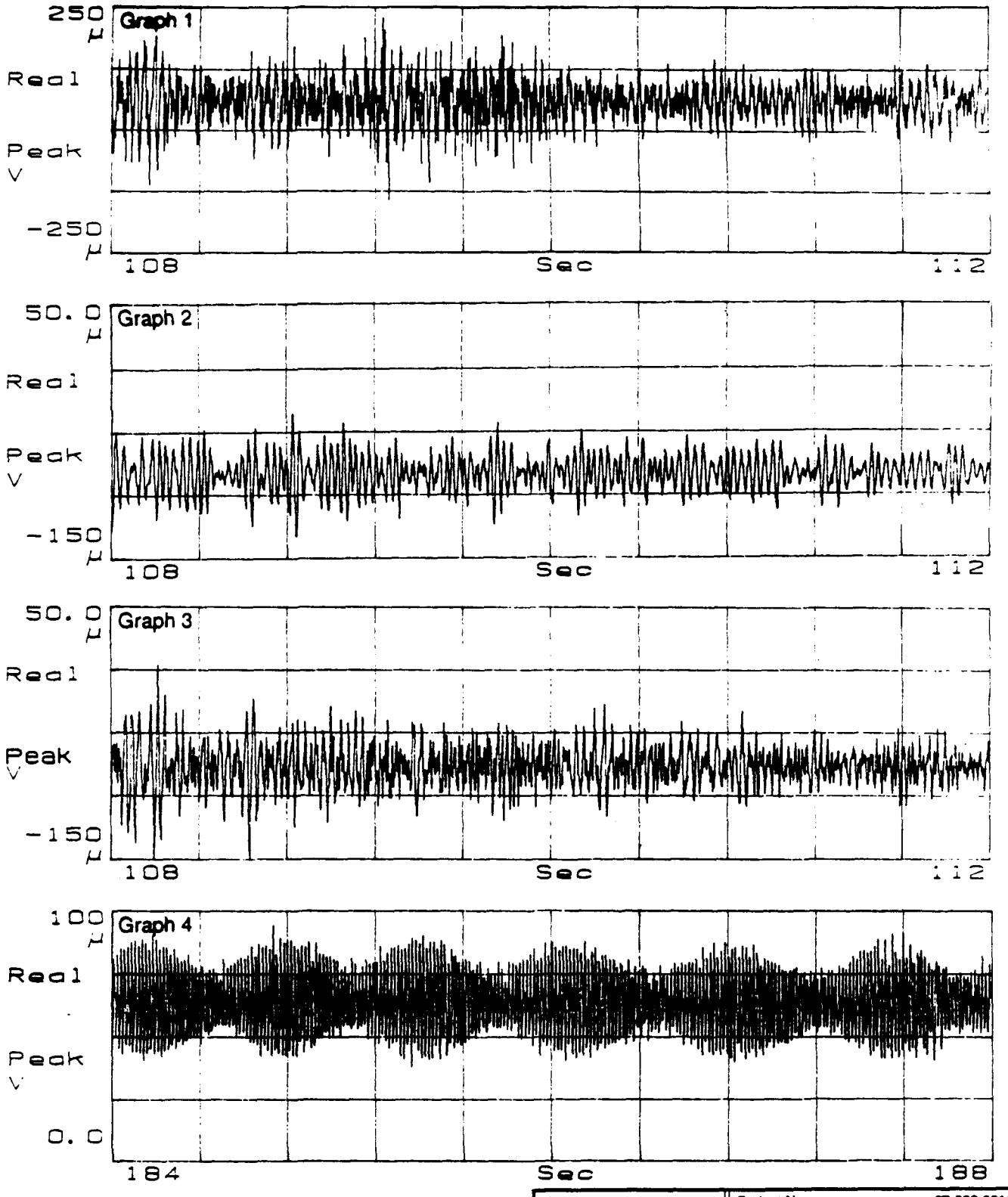
Figure G-15

APPENDIX H

SITE VE-9.3A DATA AND RESULTS

APPENDIX INDEX

Figure No.	Data Set	Description
H-1 through H-2	6	Triaxial Geophone Comparison
H-3 through H-7	3	1 Hz Geophone - Largest Displacement Traffic Data
H-8 through H-12	4	1 Hz Geophone - Second Largest Displacement Traffic Data
H-13	–	Velocity Profile (vertically traveling waves)



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 165.0 (50.3)
Graph 1: Vertical Geophone - Traffic
Graph 2: Transverse Geophone - Traffic
Graph 3: Radial Geophone - Traffic
Graph 4: Vertical Geophone - Ambient

The Earth Technology Corporation

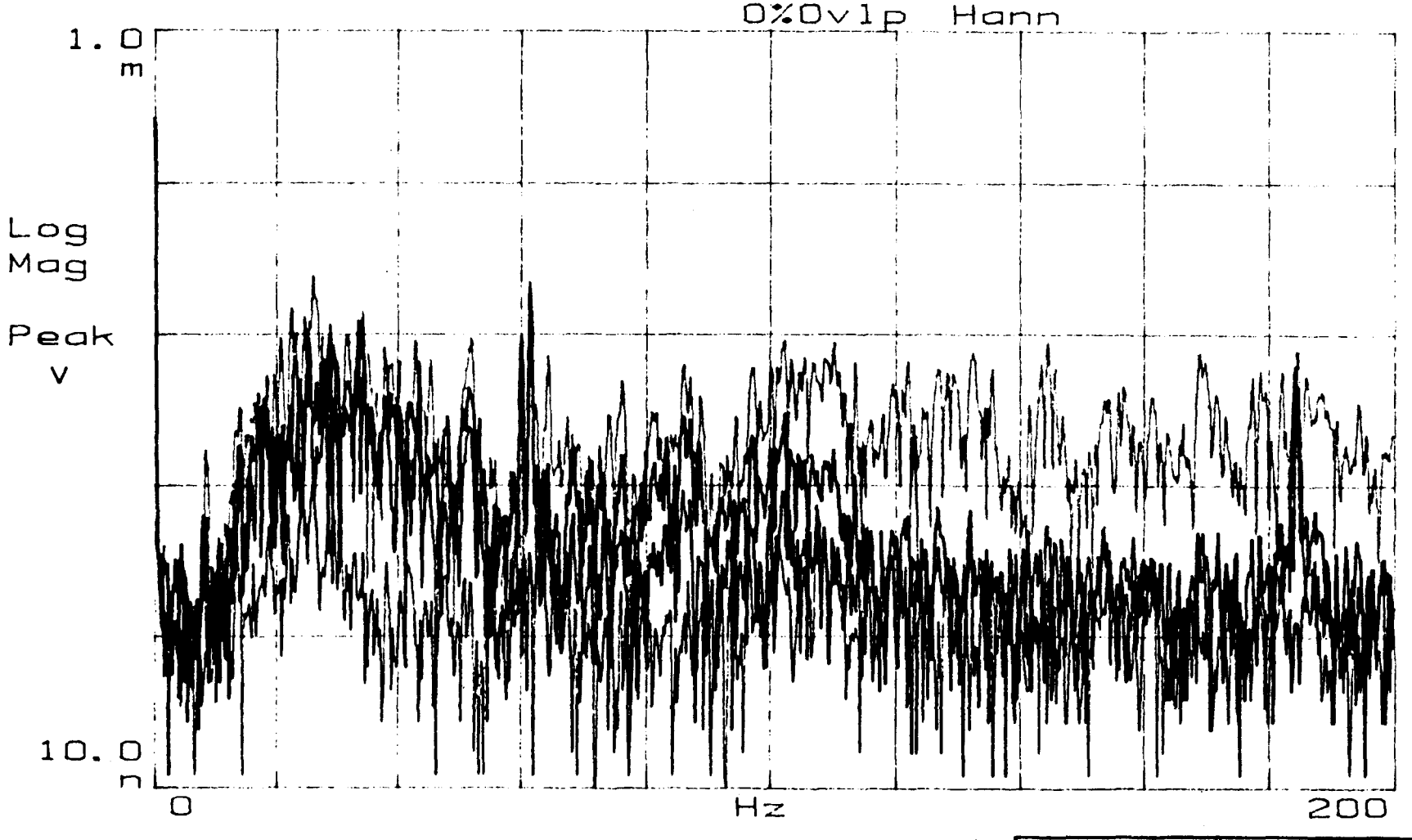
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Near Field Maximum
Data Set 6
Site VE-9.3A

12-89

Figure H-1



EXPLANATION

Geophone Depth in feet (meters)
28 Hz Triaxial Geophone ET2 @ 165.0 (50.3)
Blue = Vertical Geophone - Traffic
Green = Transverse Geophone - Traffic
Red = Radial Geophone - Traffic
Black = Vertical Geophone - Ambient

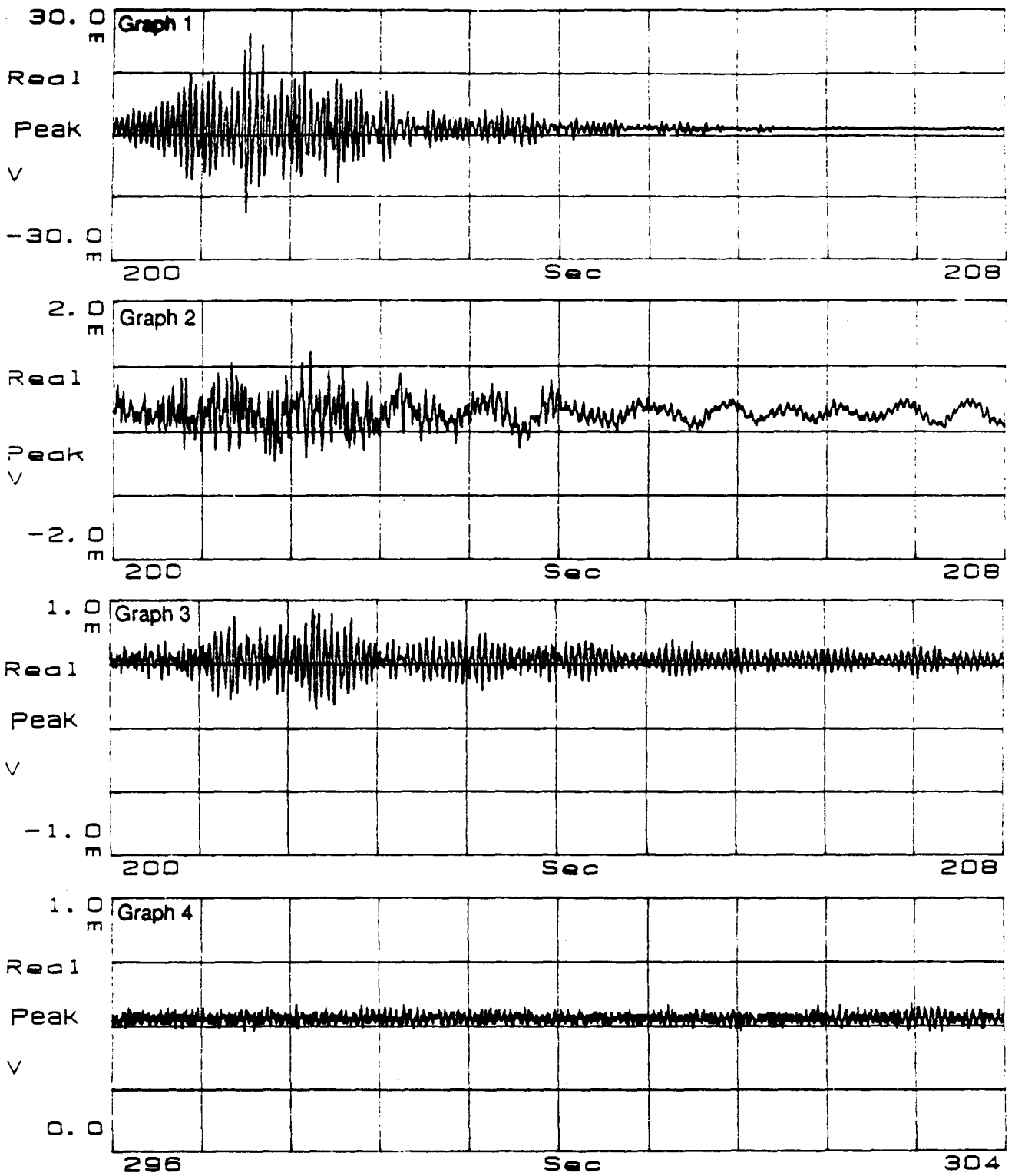
The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Composite Raw Velocity Linear Spectrum
Near Field Maximum
Data Set 6
Site VE-9.3A

12.89



EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Graph 1: Geophone 4105 @ 5.0 (1.5) - Traffic
Graph 2: Geophone 8219 @ 50.0 (15.2) - Traffic
Graph 3: Geophone 4106 @ 166.0 (50.6) - Traffic
Graph 4: Geophone 4106 @ 166.0 (50.6) - Ambient

The Earth Technology Corporation

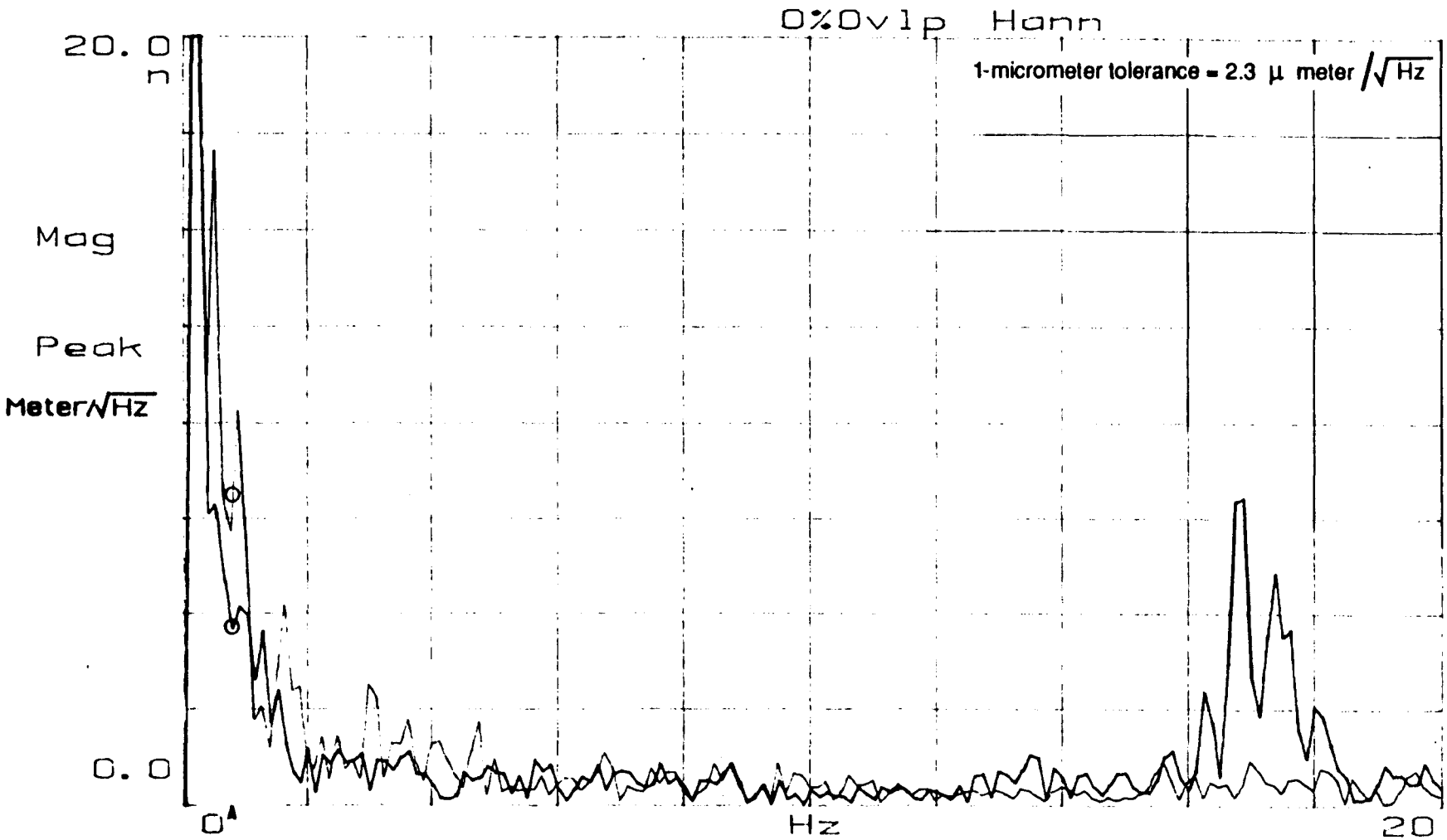
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Data Set 3
Site VE-9.3A

12-89

Figure H-3



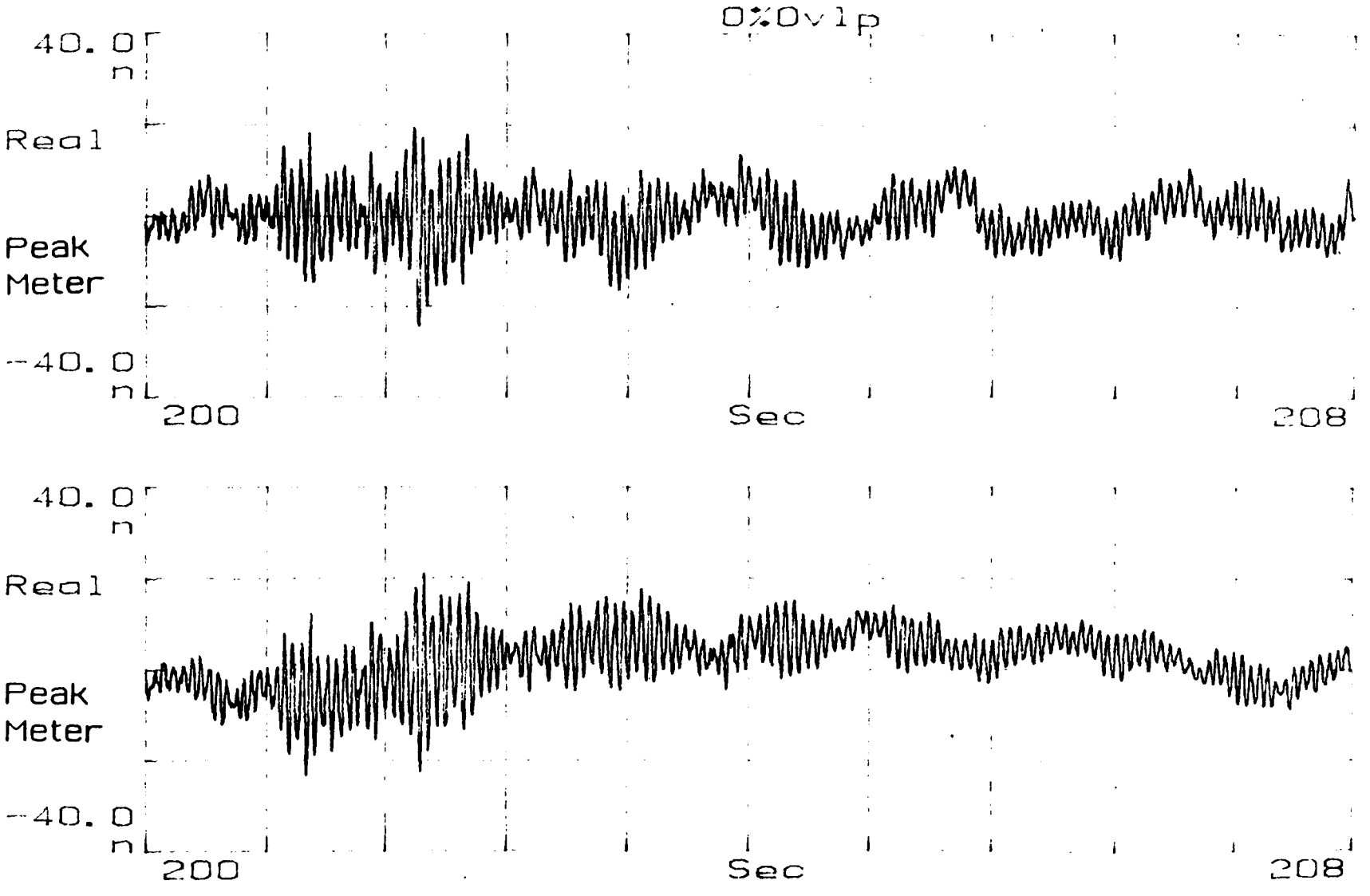
EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Red = Max. Traffic Vibrations Measured @ 166.0 (50.6)
Black = Ambient Vibrations Measured @ 166.0 (50.6)
⊙ Lower Frequency Limit of Calibration
▲ Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Displacement Linear Spectrum
Data Set 3
Site VE-9.3A

12-89 Figure H-4



EXPLANATION
1 Hz Geophone Data
Geophone 4106 @ 166.0 feet (50.6 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

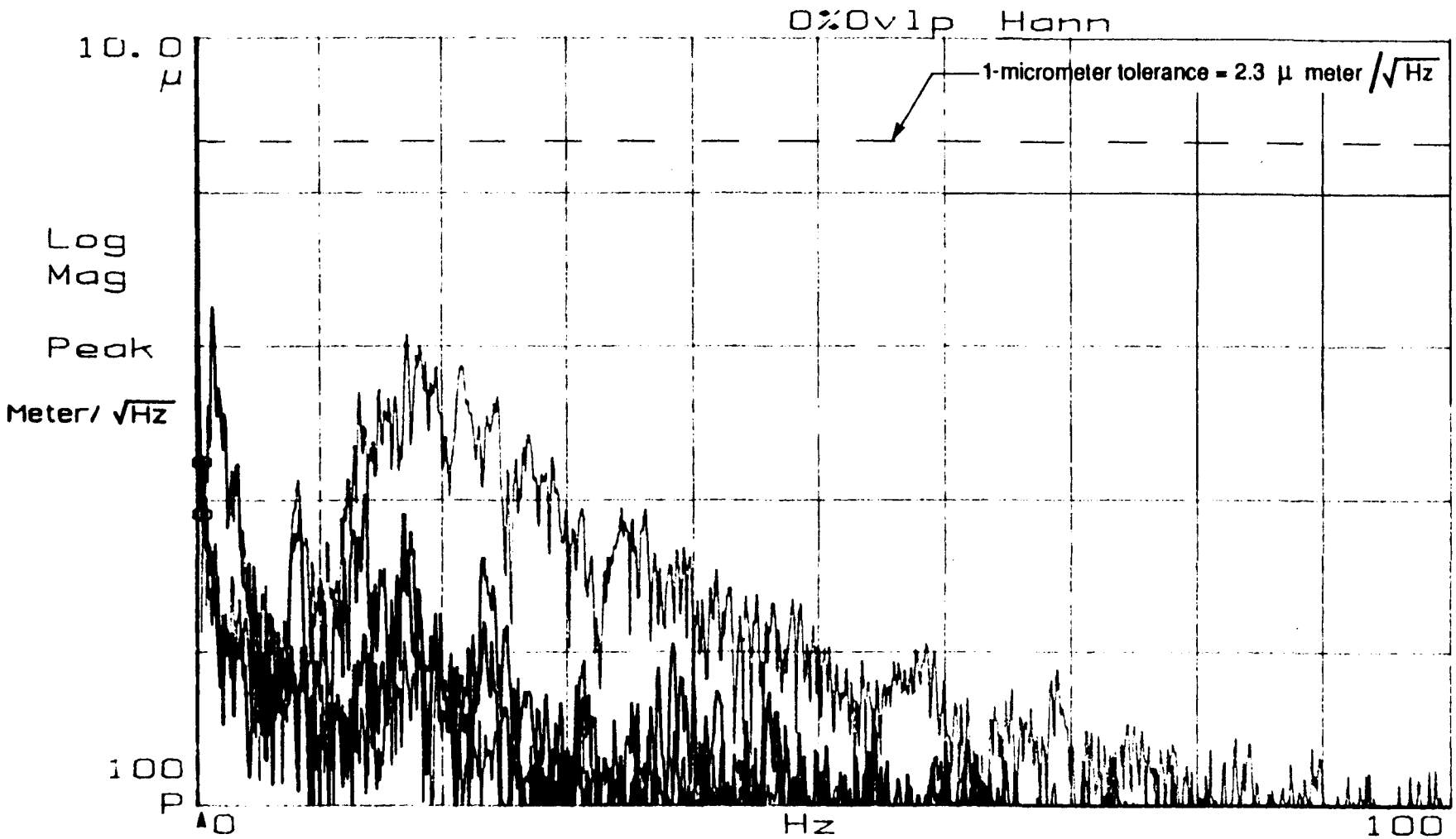
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 3
Site VE-9.3A

12-89

Figure H 5



EXPLANATION

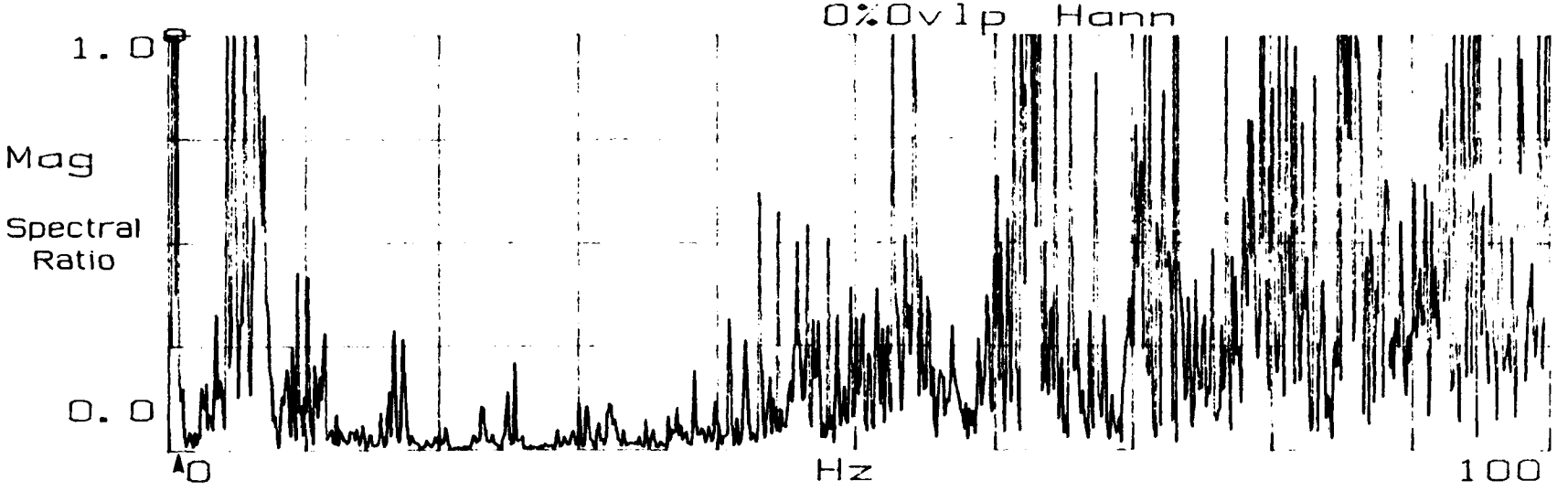
1Hz Geophone Data
Geophone Depth in feet (meters)
Blue = Max. Traffic Vibrations Measured @ 5.0 (1.5)
Green = Max. Traffic Vibrations Measured @ 50.0 (15.2)
Red = Max. Traffic Vibrations Measured @ 166.0 (50.6)
Black = Ambient Vibrations Measured @ 166.0 (50.6)
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

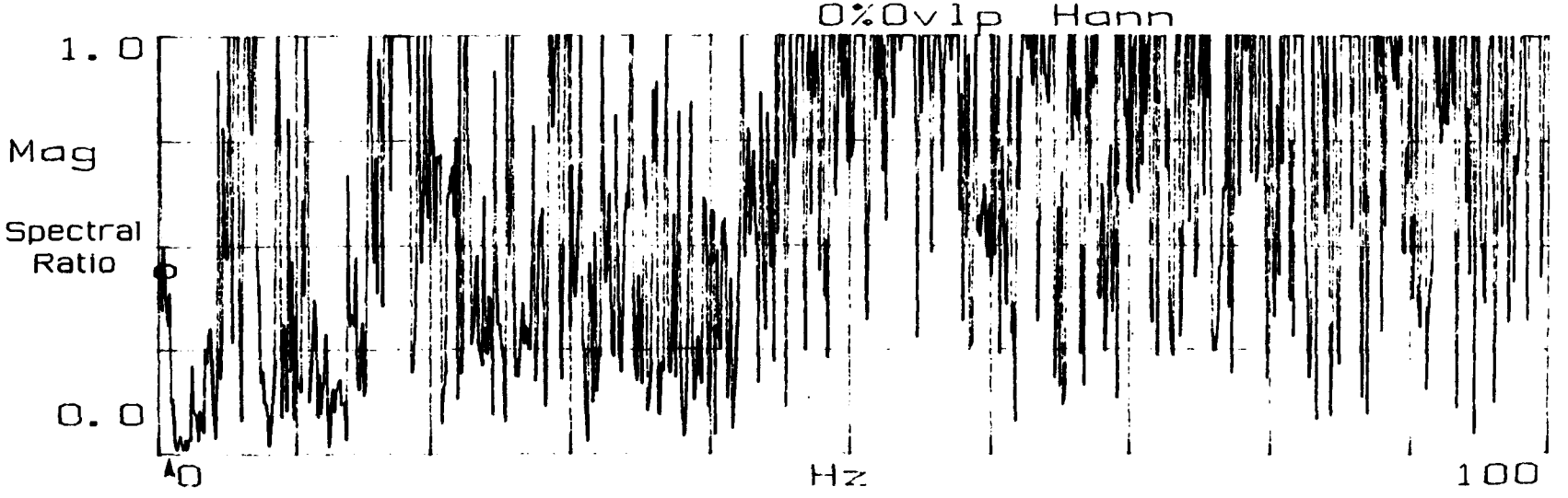
The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 3
Site VE-9.3A

12-89

Figure H-6





EXPLANATION

1Hz Geophone Data

Geophone Depth in feet (meters)

Top: "Bulk" Ratio between Geophone @ 5.0 (1.5) and Geophone @ 166.0 (50.6)

Bottom: "Rock" Ratio between Geophone @ 50.0 (15.2) and Geophone @ 166.0 (50.6)

The Earth Technology Corporation

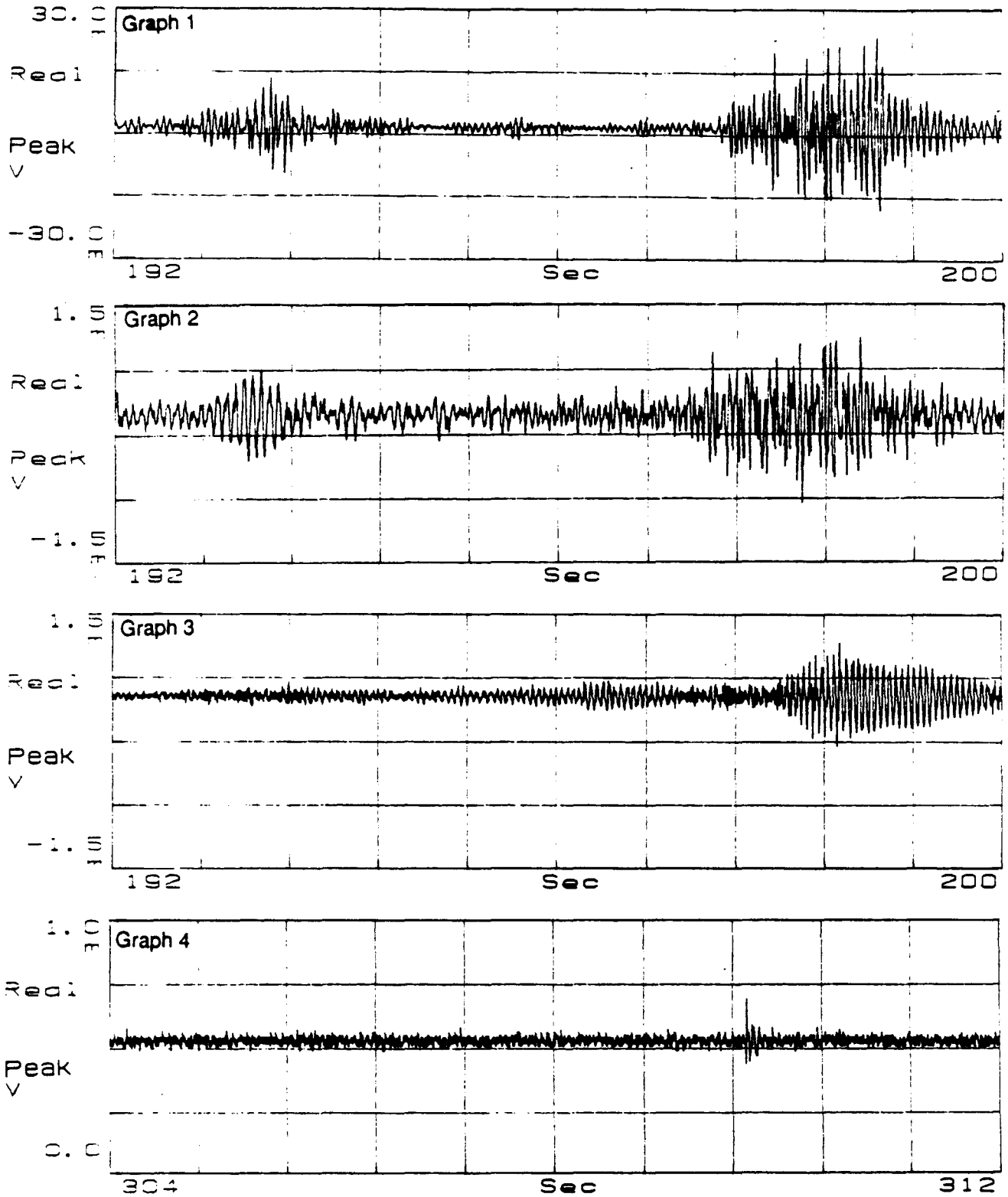
Project No.: 87-888-0011

RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones

Data Set 3

Site VE-9-3A



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 1: Geophone 4106 @ 5.0 (1.5) - Traffic
Graph 2: Geophone 2676 @ 50.0 (15.2) - Traffic
Graph 3: Geophone 4105 @ 166.0 (50.6) - Traffic
Graph 4: Geophone 4105 @ 166.0 (50.6) - Ambient

The Earth Technology Corporation

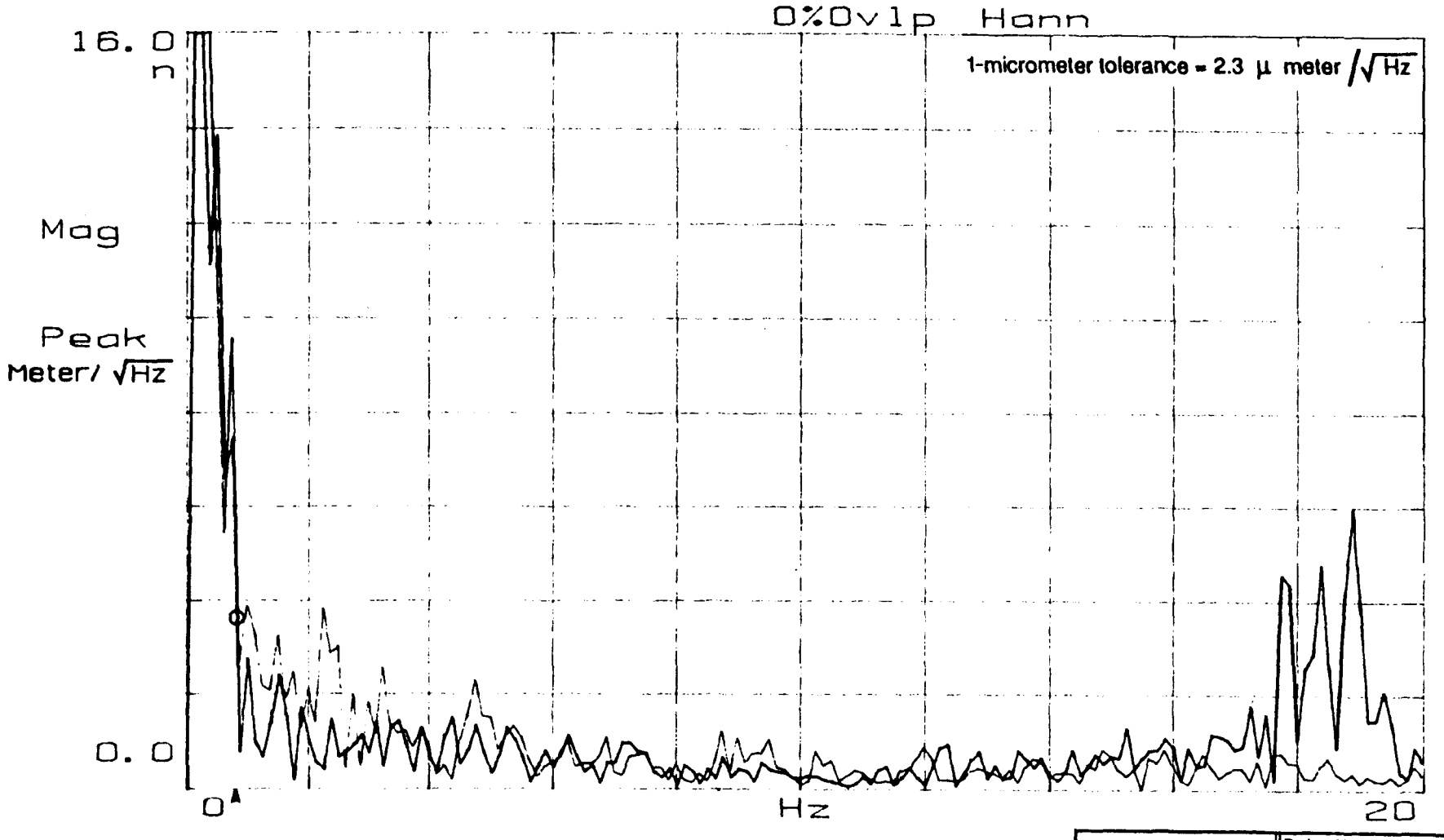
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Record
Data Set 4
Site VE-9.3A

12-89

Figure H-8



EXPLANATION

1 Hz Geophone Data

Red = Max. Traffic Vibrations Measured @ 166.0 feet (50.6 meters)
Black = Ambient Vibrations Measured @ 166.0 feet (50.6 meters)

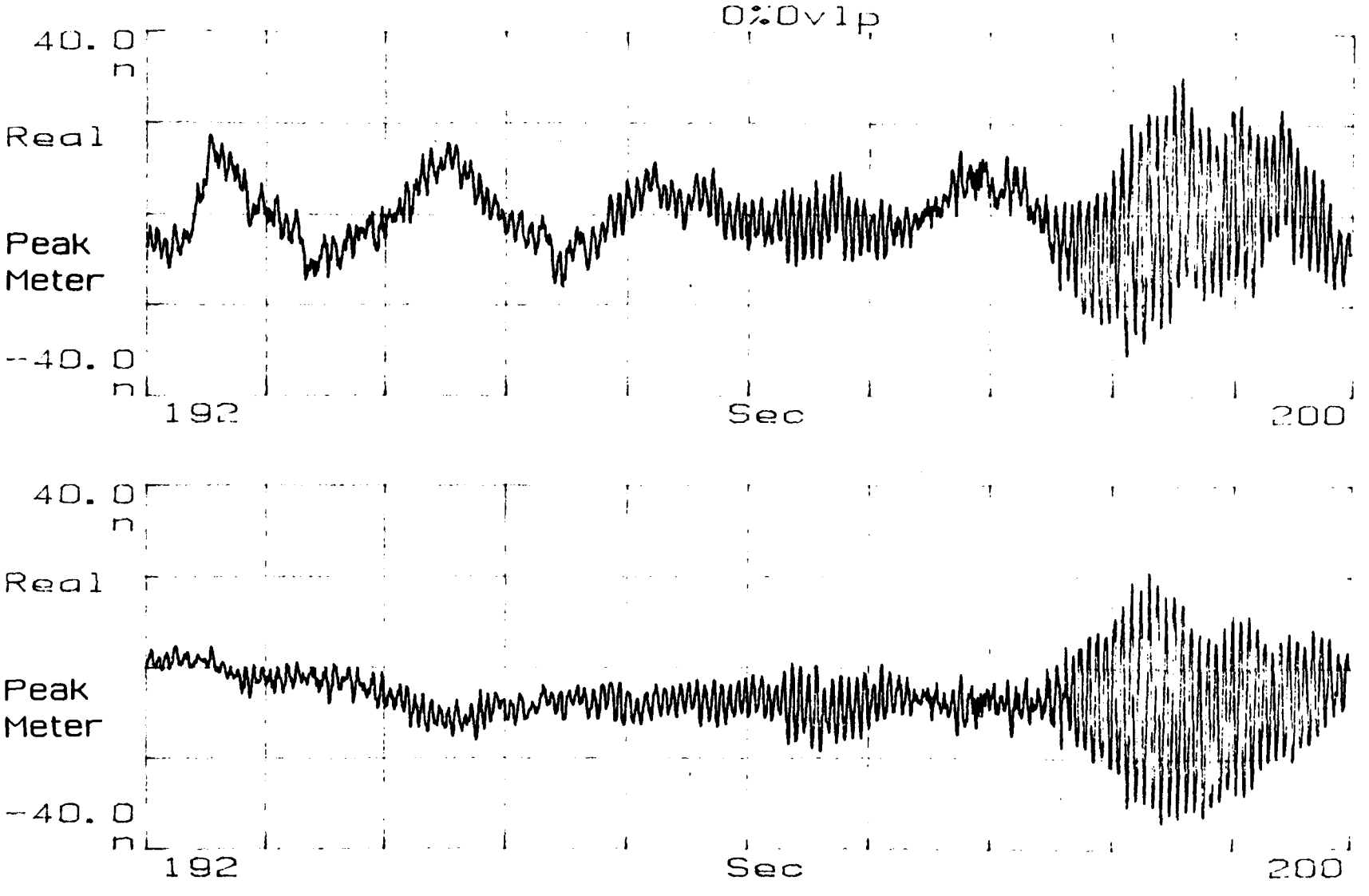
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Displacement Linear Spectrum
Data Set 4
Site VE-9.3A

12-89

Figure H-9



EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 166.0 feet (50.6 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing

The Earth Technology Corporation

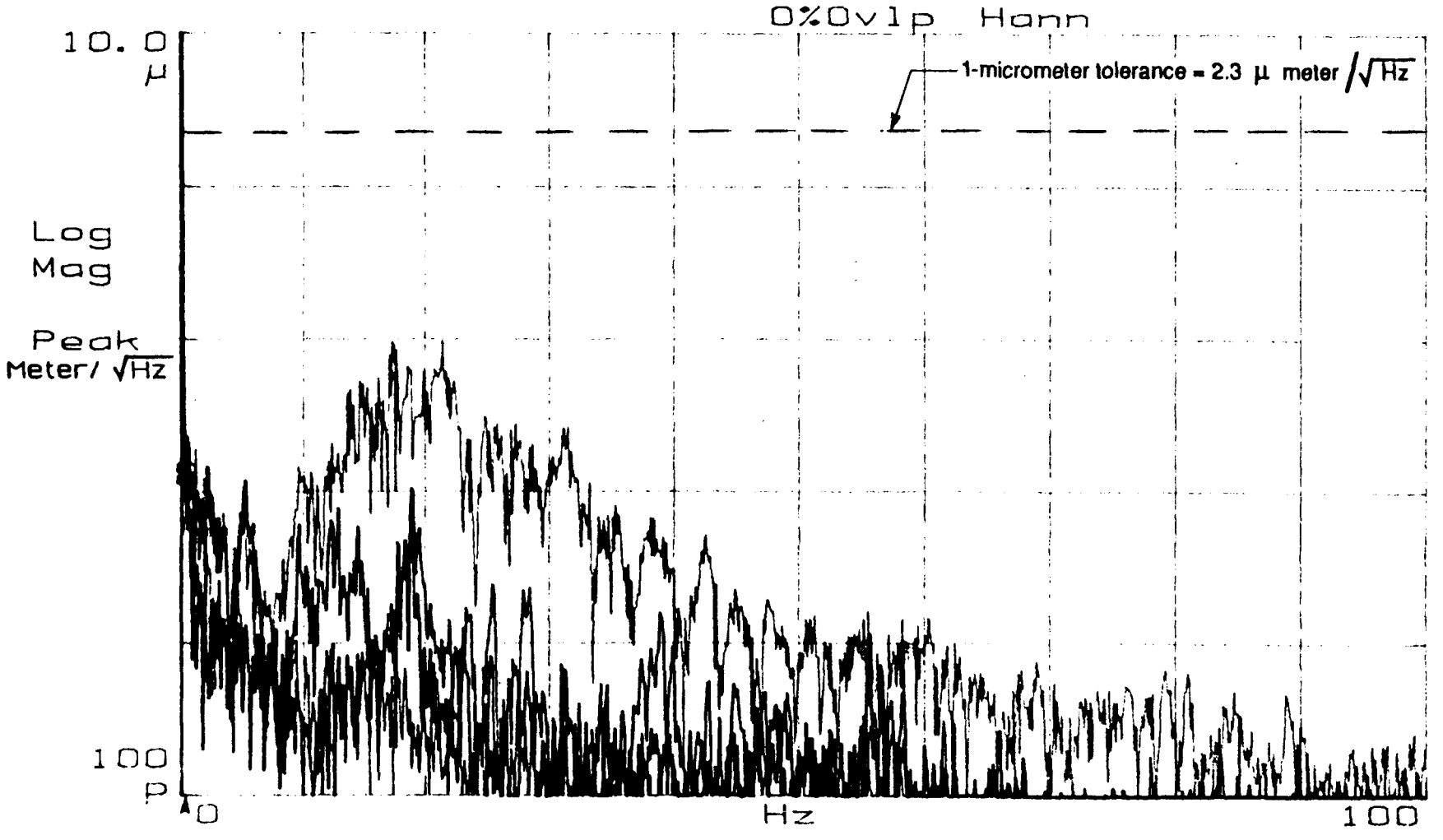
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Data Set 4
Site VE-9.3A

12-89

Figure H-10



EXPLANATION

1 Hz Geophone Data
Blue = Max. Traffic Vibrations Measured @ 5.0 feet (1.5 meters)
Green = Max. Traffic Vibrations Measured @ 50.0 feet (15.2 meters)
Red = Max. Traffic Vibrations Measured @ 166.0 feet (50.6 meters)
Black = Ambient Vibrations Measured @ 166.0 feet (50.6 meters)

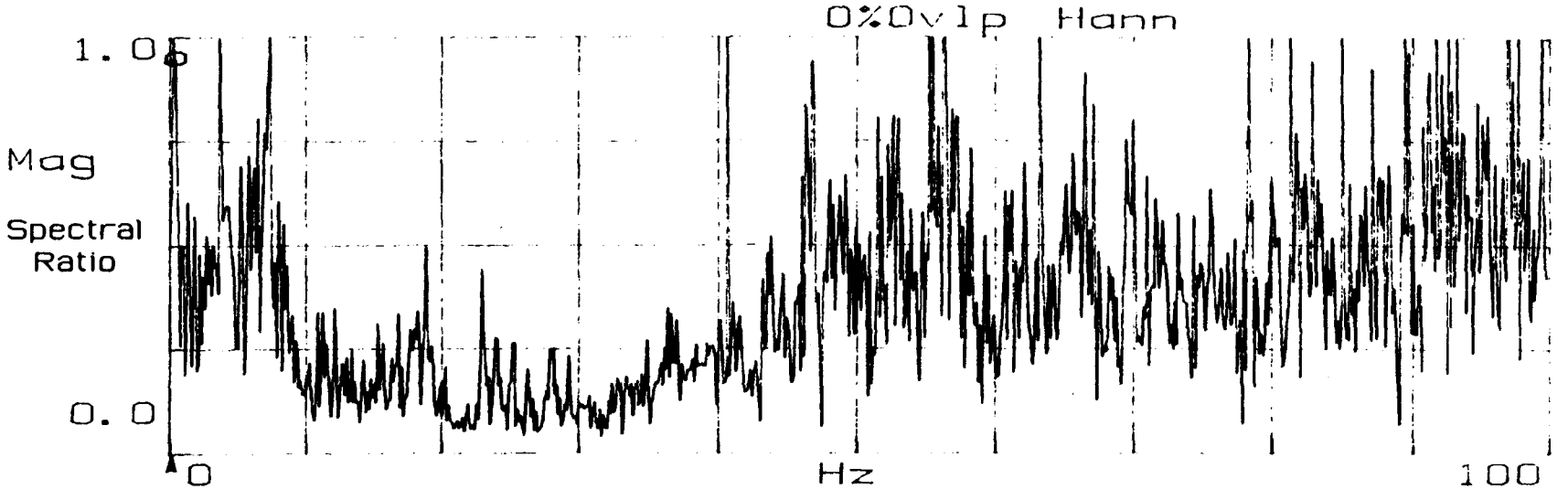
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

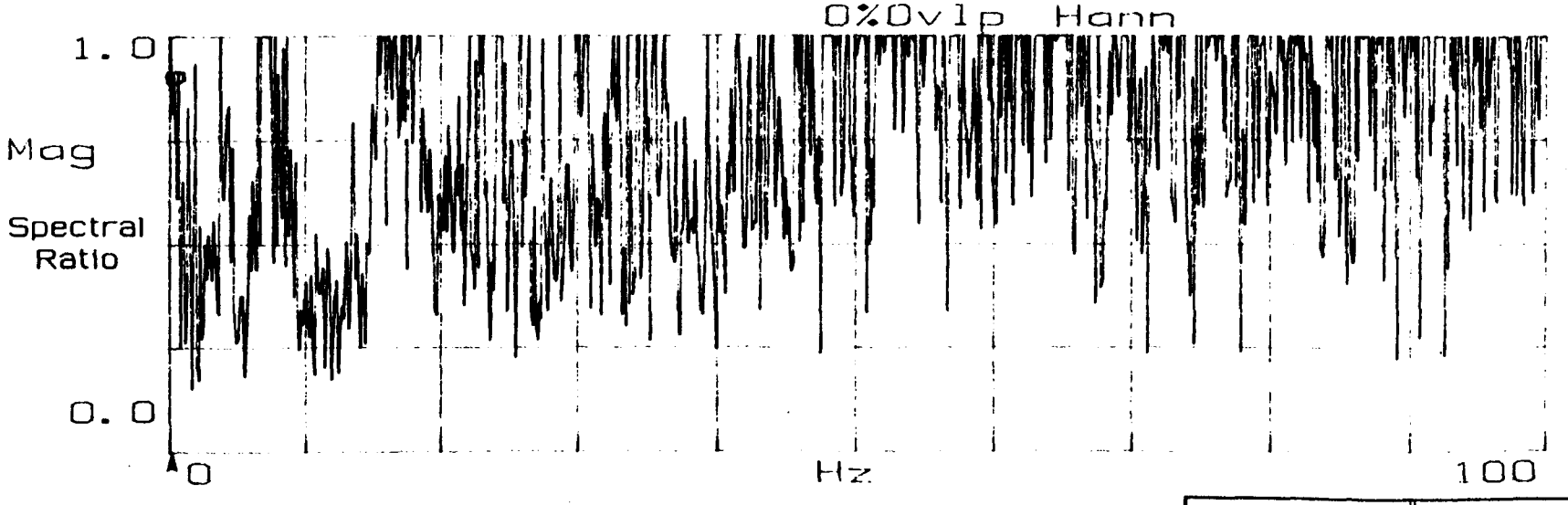
The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Vertical Change
Data Set 4
Site VE-9.3A

12-89

Figure H-11





EXPLANATION

1 Hz Geophone Data

Top: "Bulk" Ratio between Geophone @ 5.0 feet (1.5 meters) and Geophone @ 166.0 feet (50.6 meters)

Bottom: "Rock" Ratio between Geophone @ 50.0 feet (15.2 meters) and Geophone @ 166.0 feet (50.6 meters)

Lower Frequency Limit of Calibration

The Earth Technology Corporation

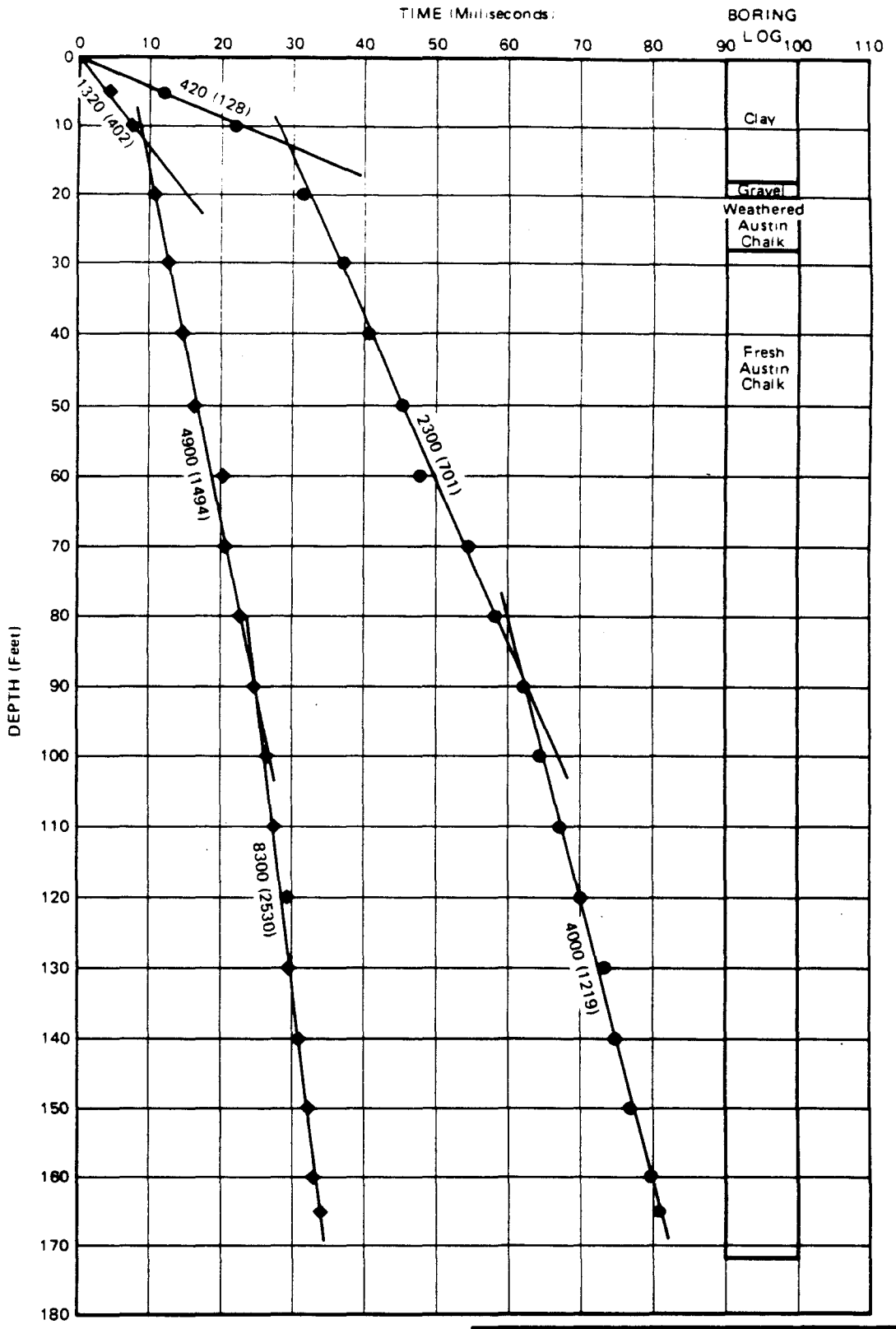
Project No.: 87-888-0011

RTK Joint Venture

Spectral Ratio of Vertically Separated Geophones
Data Set 4
Site VE-9.3A

12 89

Figure H-12



EXPLANATION

◆ P WAVE ARRIVAL TIMES

● S WAVE ARRIVAL TIMES

SEISMIC VELOCITIES IN FEET/SECOND (METERS/SECOND)

The Earth Technology Corporation

PROJECT NO.: 87-888-0011

RTK Joint Venture

Velocity Data and Interpreted Profile
Vertical Traveling Waves
Site VE-9.3A

12-89

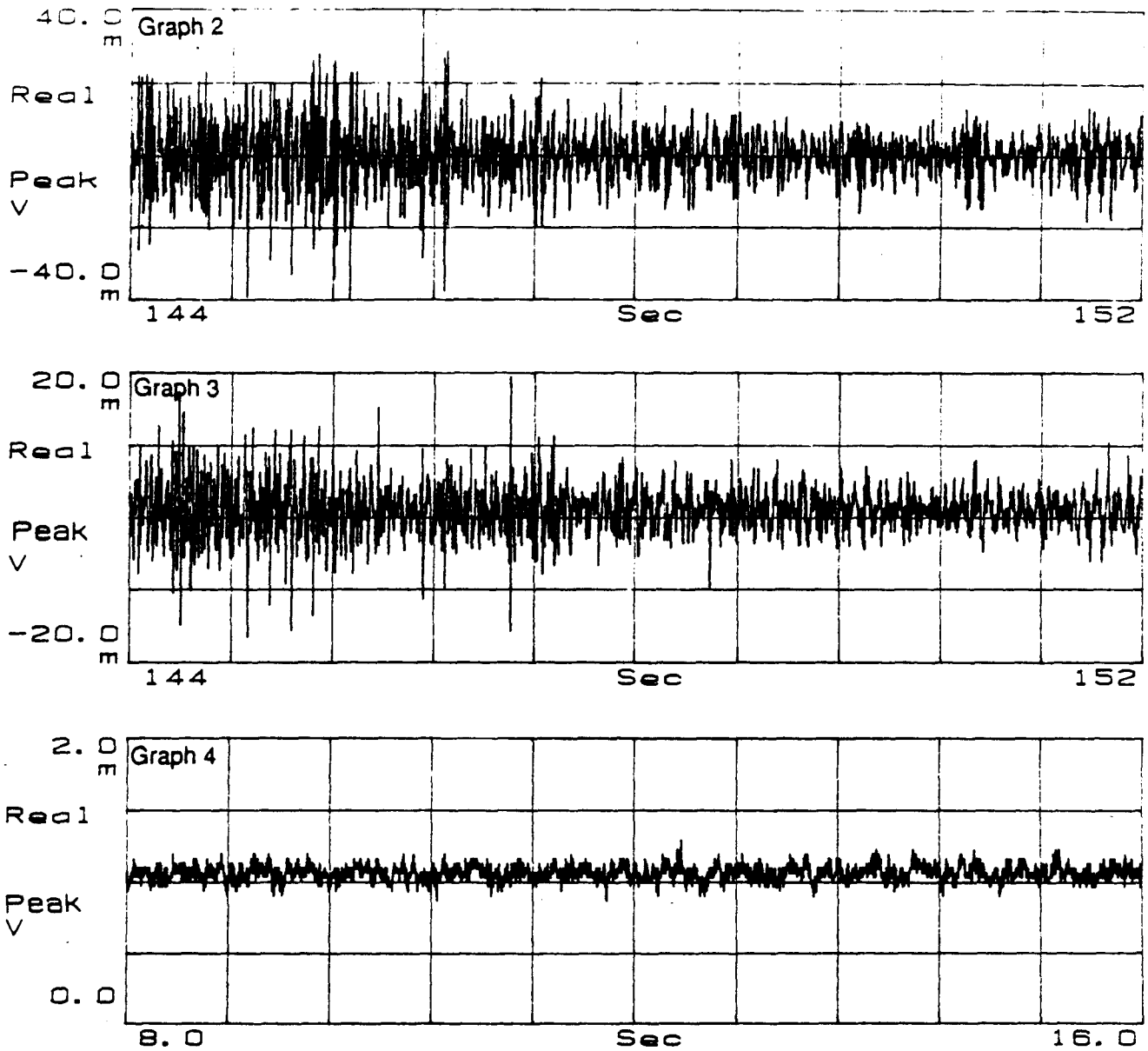
Figure H-13

APPENDIX I

DATA AND RESULTS
FOR HORIZONTALLY TRAVELING WAVES

SITES VE-3.5 AND VE-3.5A

No Shallow Data



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 2: Geophone 2676 @ 19.0 (5.8) - Train
Graph 3: Geophone 4105 @ 76.0 (23.2) - Train
Graph 4: Geophone 4105 @ 76.0 (23.2) - Ambient
(Compare with VE-3.5A)

The Earth Technology Corporation

Project No.: 87-888-0011

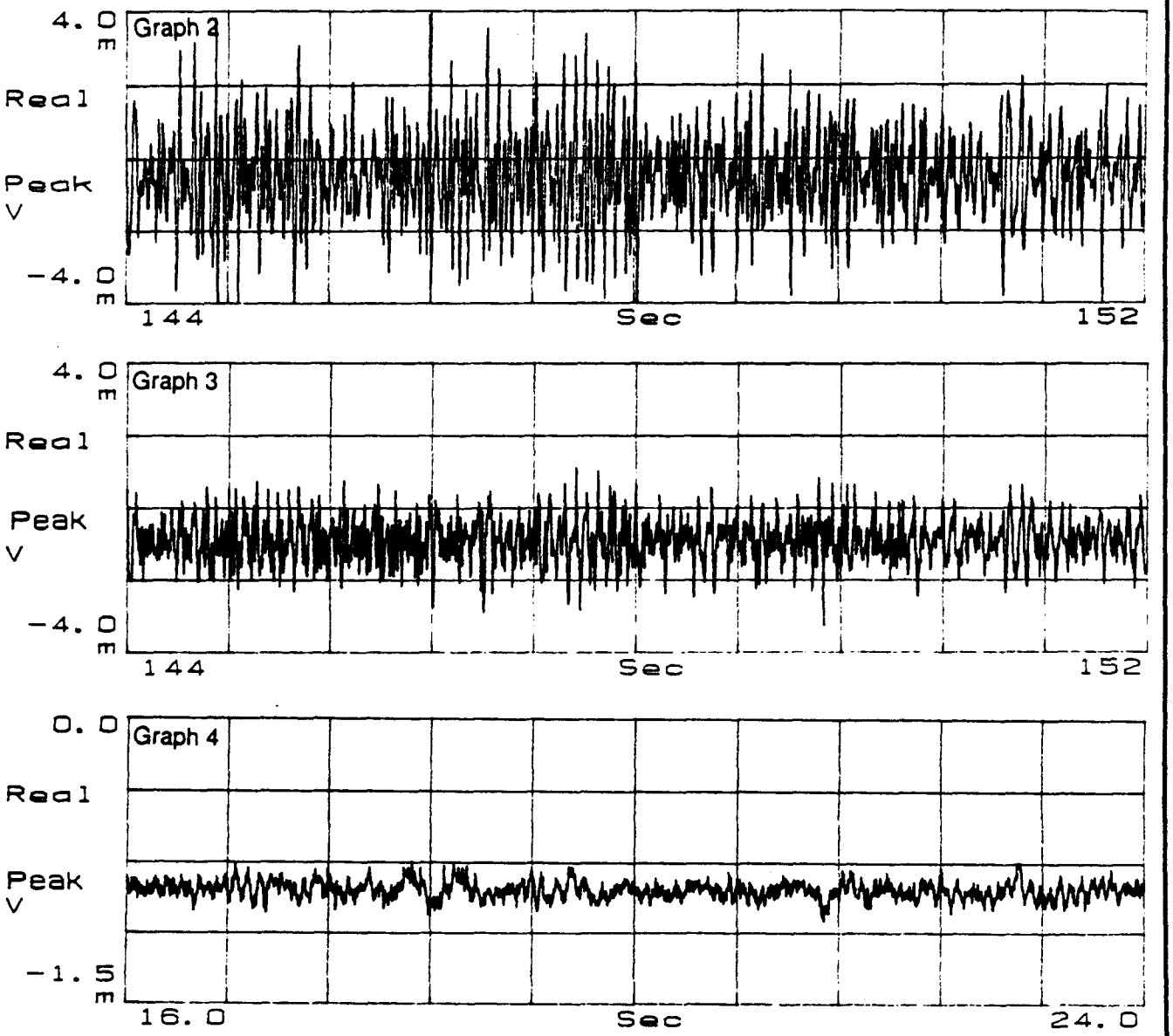
RTK Joint Venture

Raw Time Records
Site VE-3.5

12-89

Figure I-1

No Shallow Data



EXPLANATION
1 Hz Geophone Data
Geophone Depths in feet (meters)
Graph 2: Geophone 8219 @ 22.5 (6.9) - Train
Graph 3: Geophone 4106 @ 97.0 (29.6) - Train
Graph 4: Geophone 4106 @ 97.0 (29.6) - Ambient
(Compare with VE-3.5)

The Earth Technology Corporation

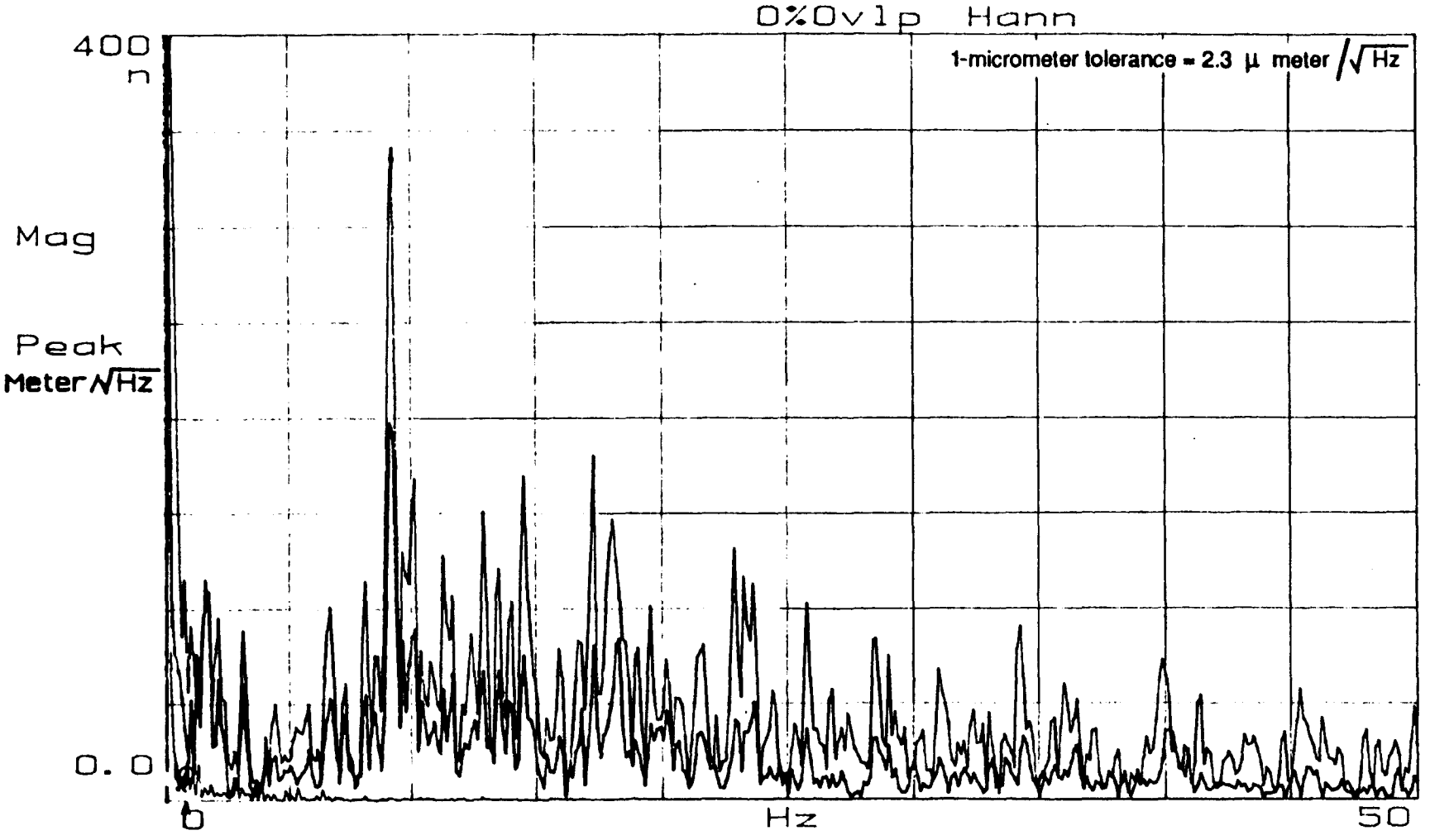
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Record
Site VE-3.5A

12-89

Figure I-2



EXPLANATION

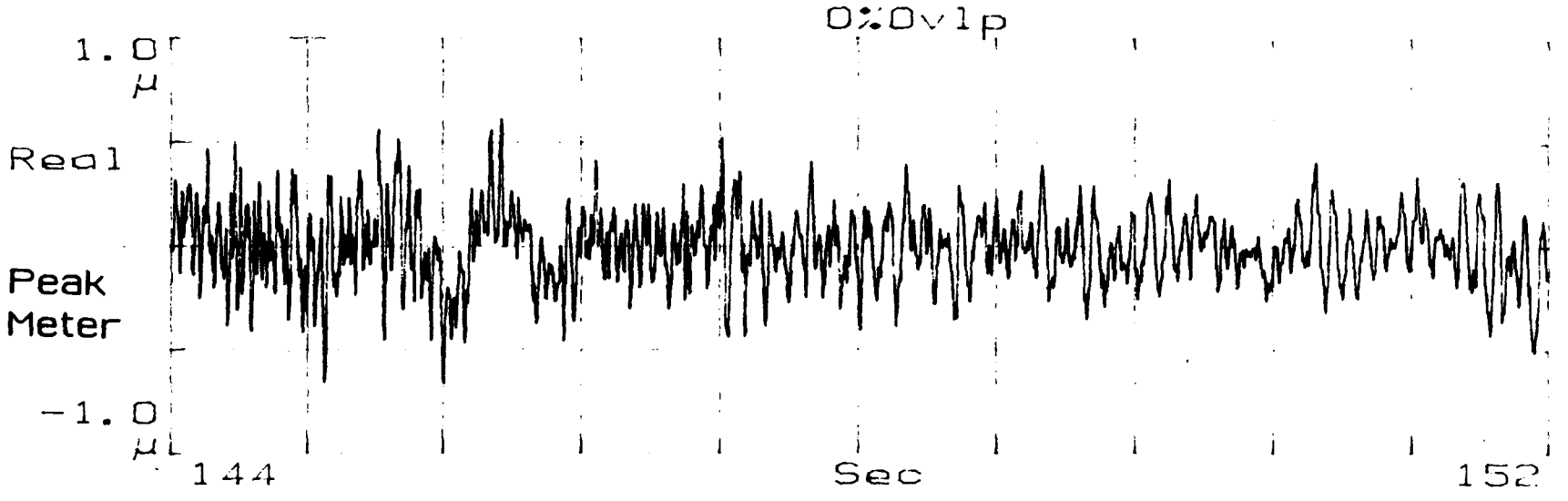
1 Hz Geophone Data
Geophone Depths in feet (meters)
Green = Geophone 2676 @ 19.0 (5.8) - Train
Red = Geophone 4105 @ 76.0 (23.2) - Train
Black = Geophone 4105 @ 76.0 (23.2)- Ambient
Lower Frequency limit of Calibration
Bandwidth = 0.187 Hz
(Compare with VE-3.5A)

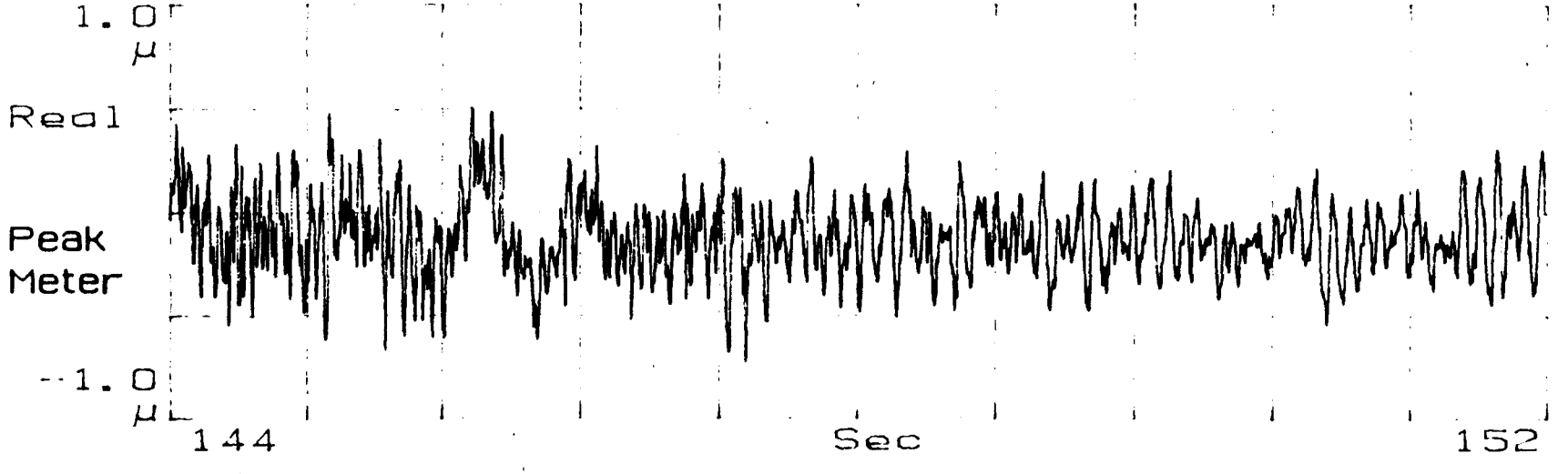
The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Dispacement Linear Spectrum
Site VE-3.5

12-89

Figure 1-3





EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 76.0 feet (23.2 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing
(Compare with VE-3.5A)

The Earth Technology Corporation

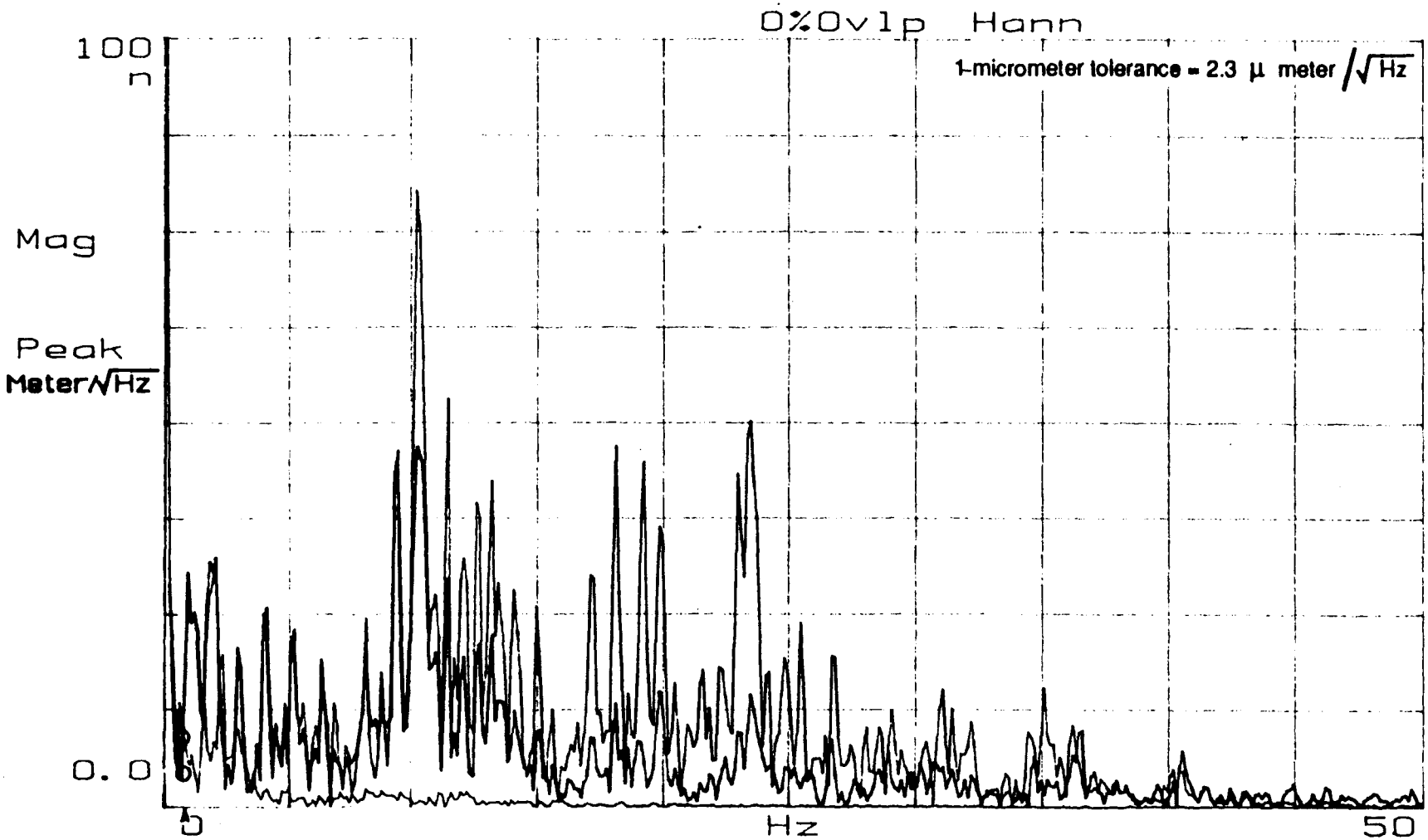
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Site VE-3.5

12-89

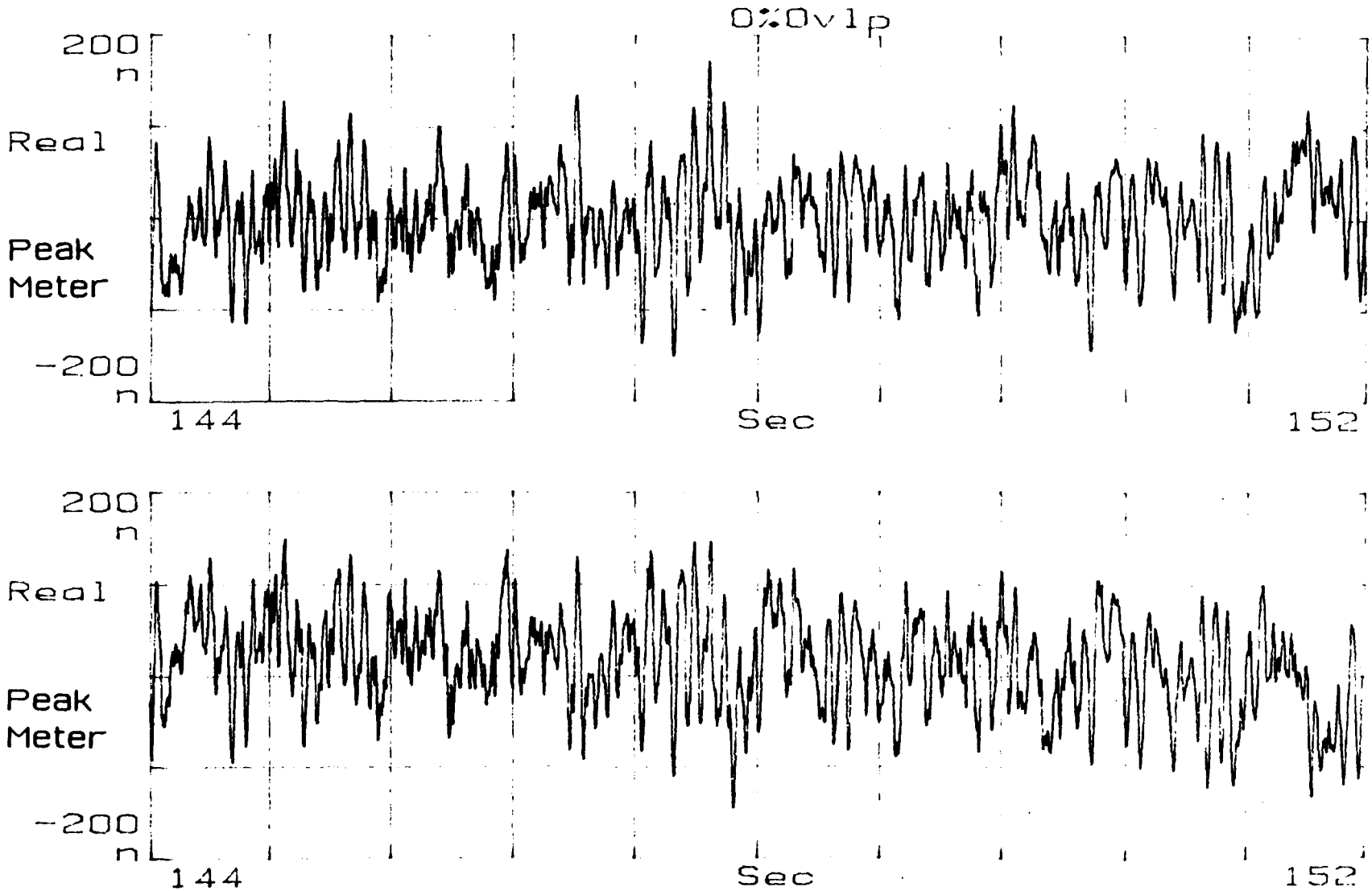
Figure 14



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Green = Geophone 8219 @ 22.5 (6.9) - Train
Red = Geophone 4106 @ 97.0 (29.6) - Train
Black = Geophone 4106 @ 97.0 (29.6) - Ambient
Lower Frequency limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture
Dispacement Linear Spectrum Site VE-3.5A	
12-89	Figure 1-5



EXPLANATION
1 Hz Geophone Data
Geophone 4106 @ 97.0 feet (29.6 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing
(Compare with VE-3.5)

The Earth Technology Corporation

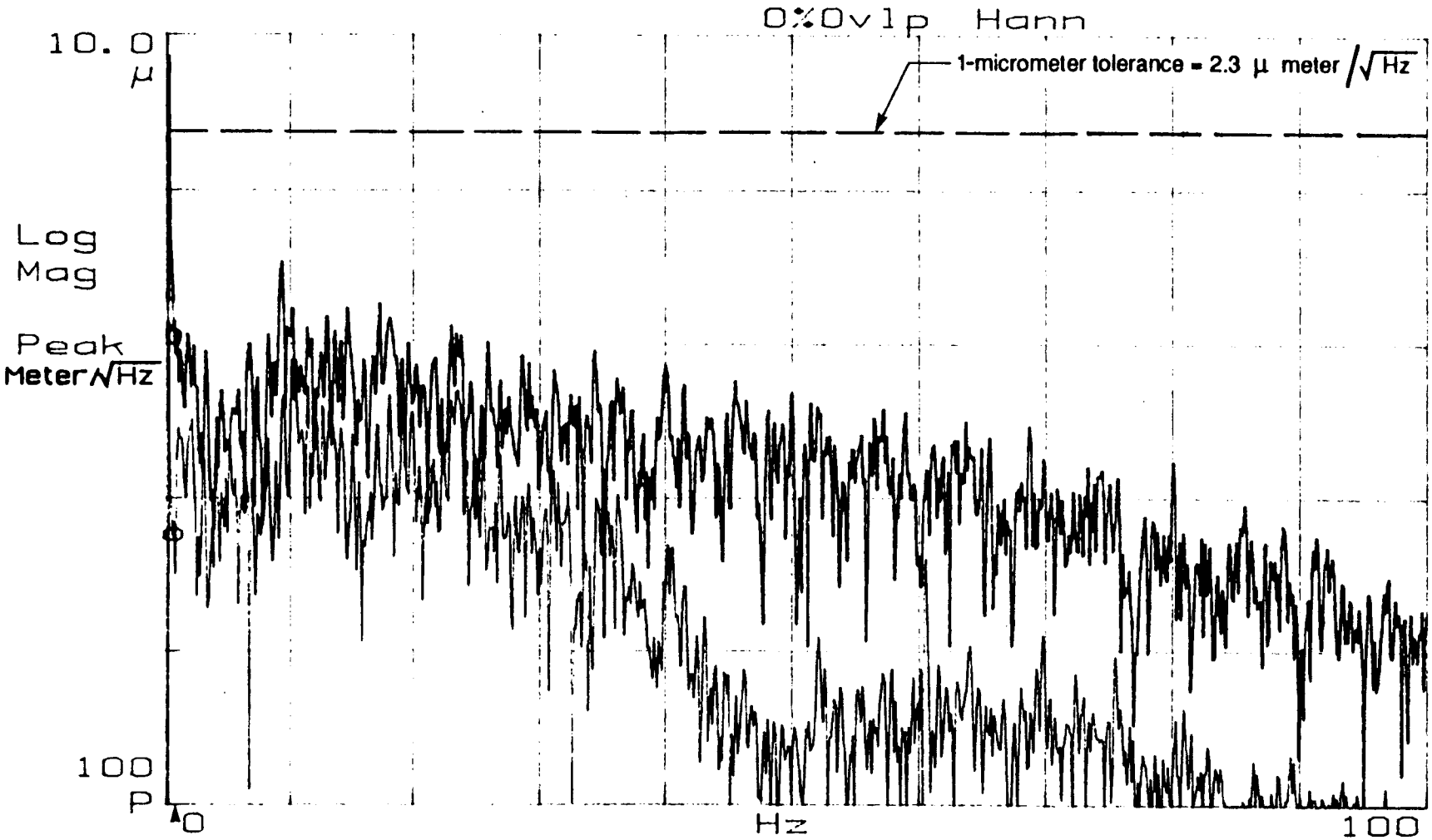
Project No.: 87-888-0011

RTK Joint Venture

Displacement Time History
Site VE-3.5A

12-89

Figure 16



EXPLANATION

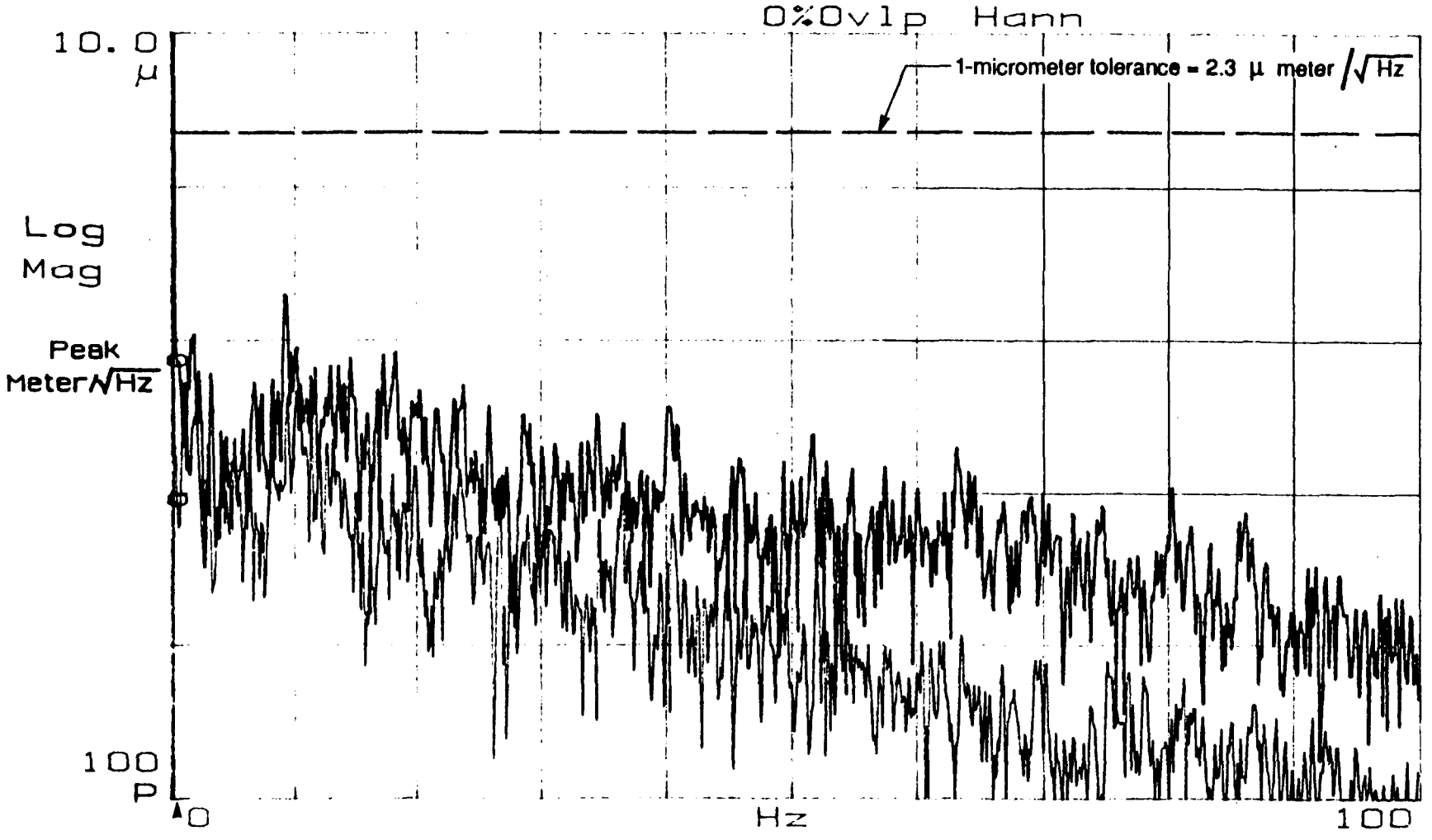
1 Hz Geophone Data
Geophone Depths in feet (meter)
Red = Site VE-3.5 Geophone 2676 @ 19.0 (5.8)
Black = Site VE-3.5A Geophone 8219 @ 22.5 (6.9)
Lower Frequency limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement
Linear Spectrum Showing Horizontal
Change Near Austin Chalk Top
Site VE-3.5 and VE-3.5A

12-89

Figure I-7



EXPLANATION
1 Hz Geophone Data
Geophone Depths in feet (meters)
Red = Site VE-3.5 Geophone 4105 @ 76.0 (23.2)
Black = Site VE-3.5A Geophone 4106 @ 97.0 (29.6)
Lower Frequency limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation

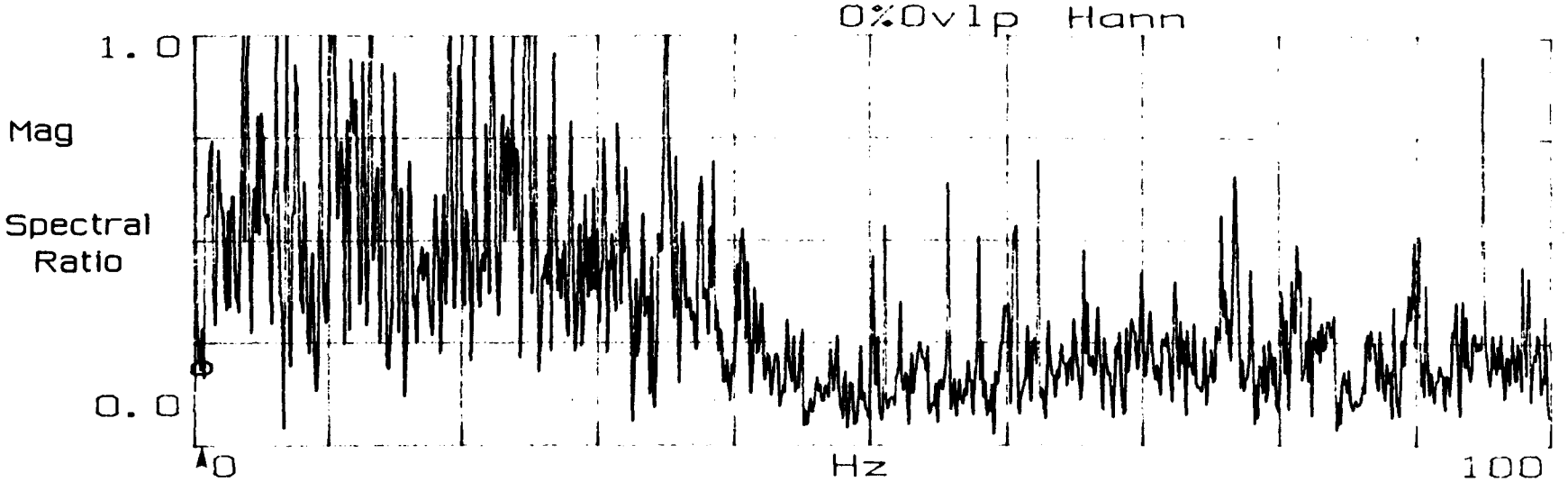
Project No.: 87-888-0011

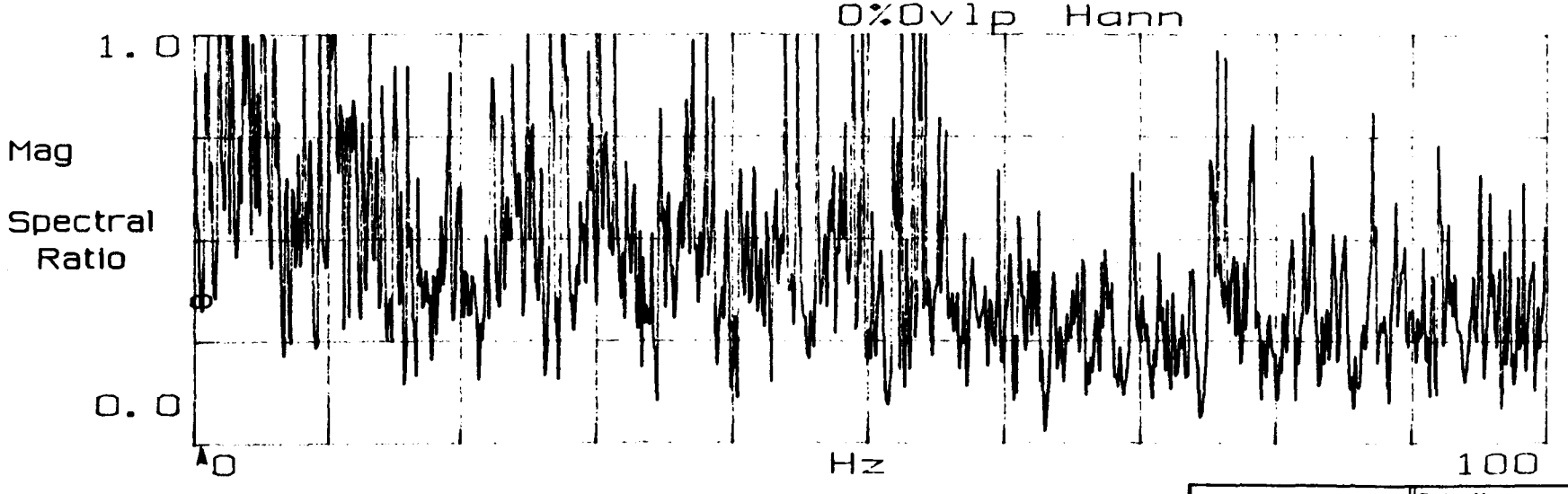
RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Horizontal Change Near
Proposed Tunnel Depth
Site VE-3.5 and VE-3.5A

12-89

Figure I-8





EXPLANATION

1 Hz Geophone Data

Geophone Depths in feet (meter)

Top: Ratio between Site VE-3.5 Geophone 2676 @ 19.0 (5.8) and Site VE-3.5A Geophone 8219 @ 22.5 (6.9)

Bottom: Ratio between Site VE-3.5 Geophone 4105 @ 76.0 (23.2) and Site VE-3.5A Geophone 4106 @ 97.0 (29.6)

The Earth Technology Corporation

Project No.: 87-888-001

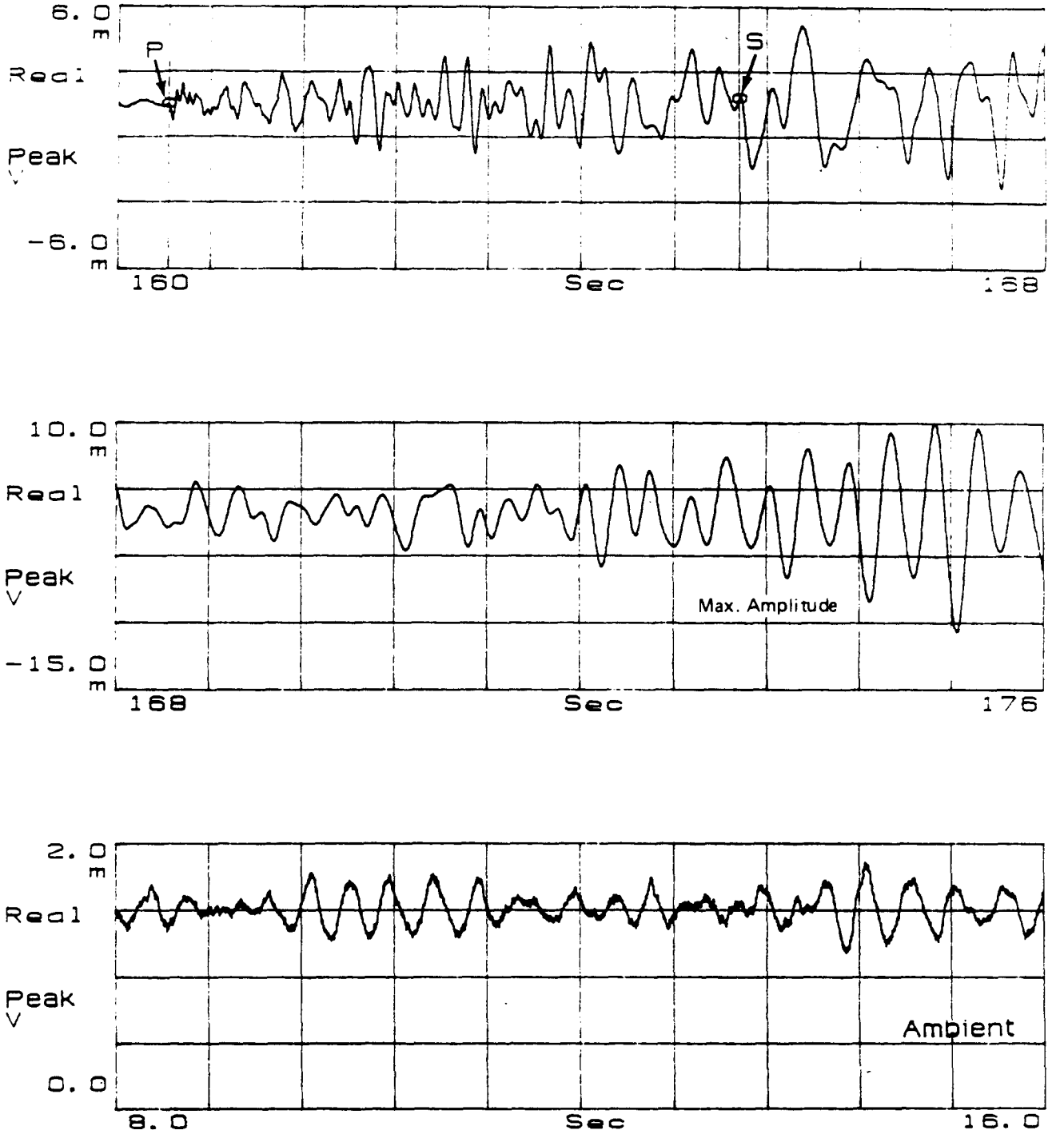
RTK Joint Venture

Spectral Ratio of Horizontally Separated Geophones Site VE-3.5 and VE-3.5A

APPENDIX J

DATA AND RESULTS
FOR HORIZONTALLY TRAVELING WAVES

SITES VF-1.7 AND VE-3.5



EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Geophone 4106 @ 62.0 (18.9)
(Compare with VE-3.5)

The Earth Technology Corporation

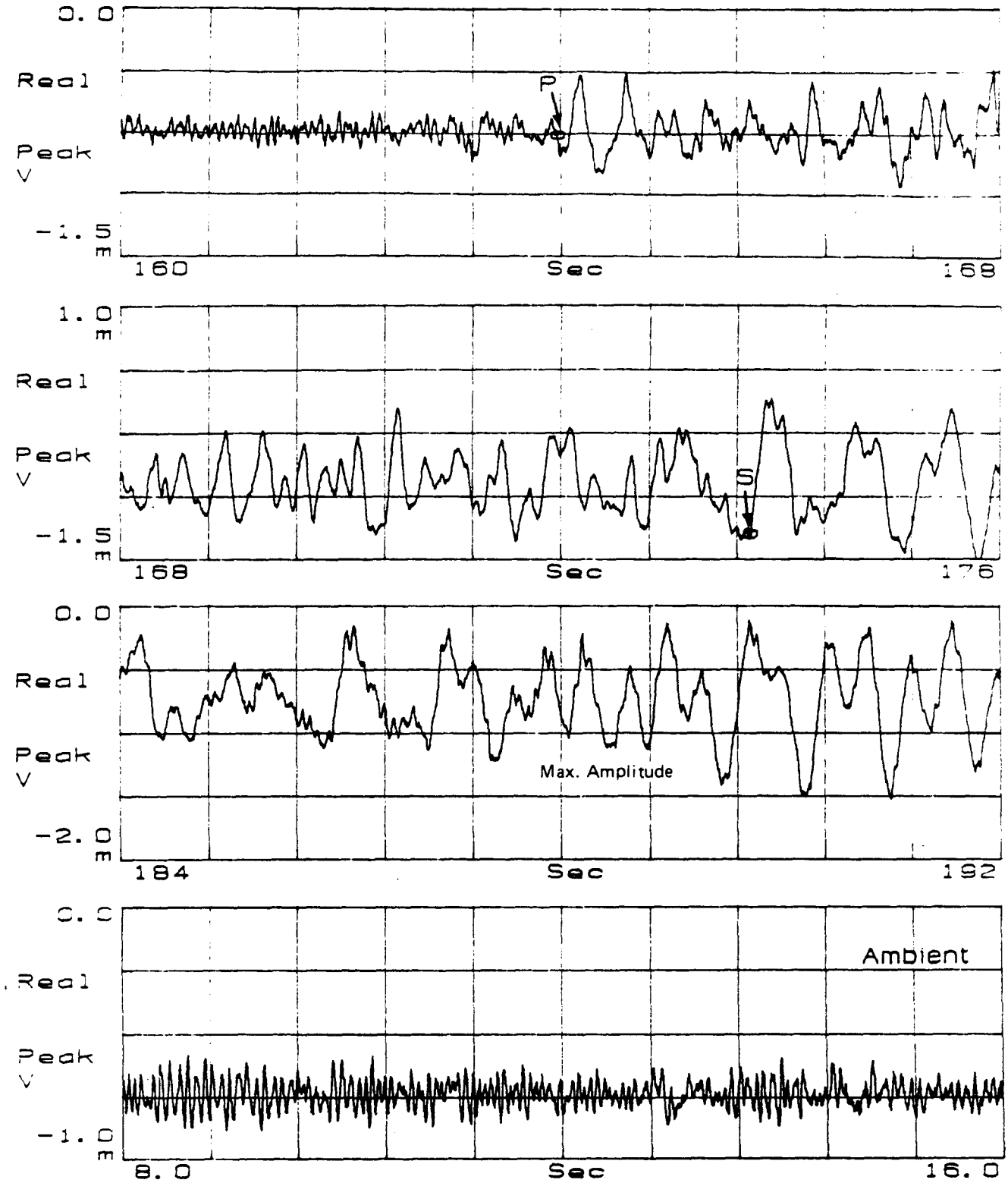
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Site VF-1.7

12-89

Figure J-1



The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

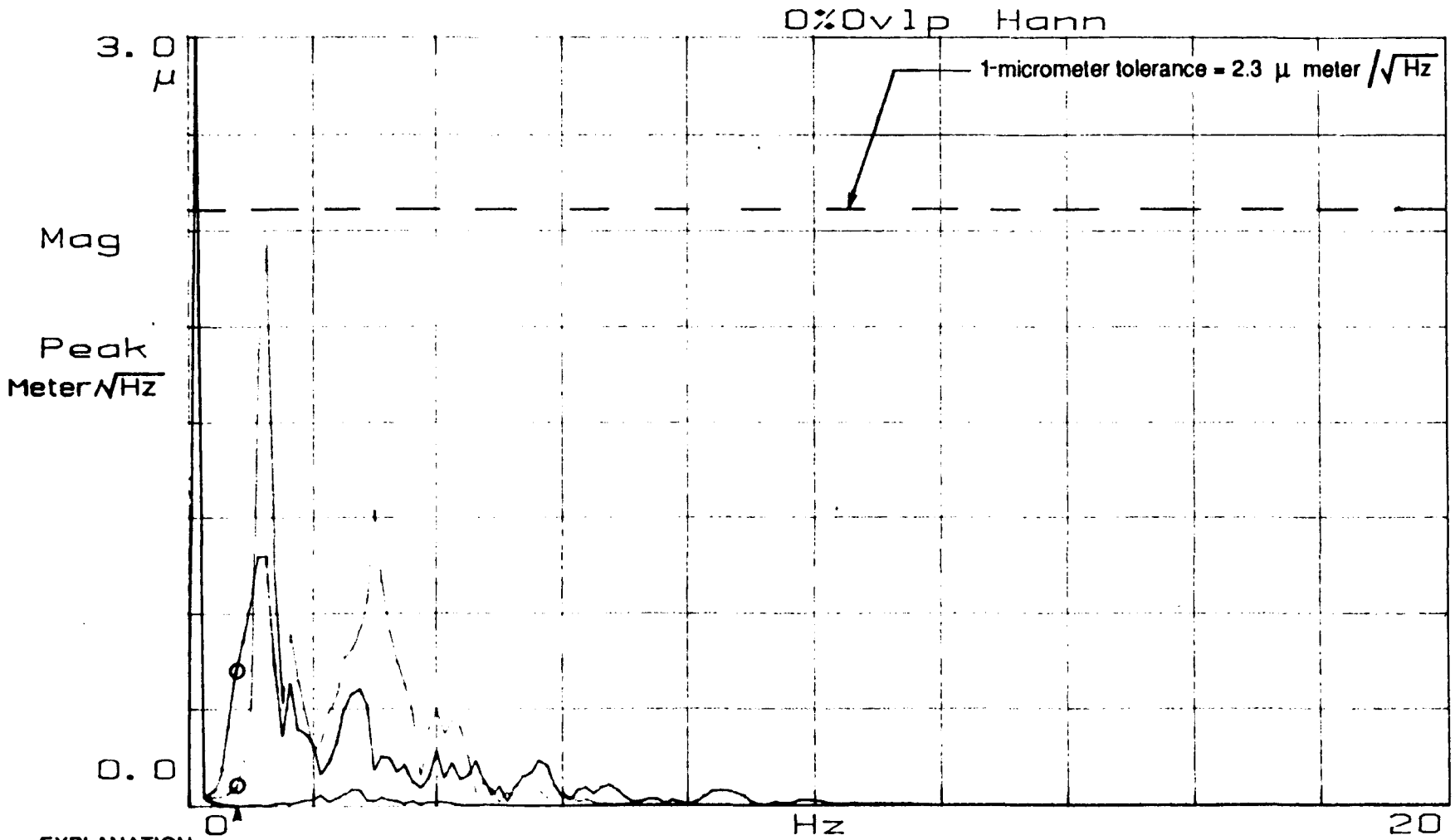
EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Geophone 2676 @ 19.0 (5.8)
(Compare with VF-1.7)

Raw Time Records
Site VE-3.5

12-89

Figure J-2



EXPLANATION

Geophone Depth in feet (meters)
1 Hz Geophone 4106 @ 62.0 (18.9)
Blue = Max. Amplitude Wave generated by Blast
Green = P & S Wave generated by Blast
Black = Ambient Vibration
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation

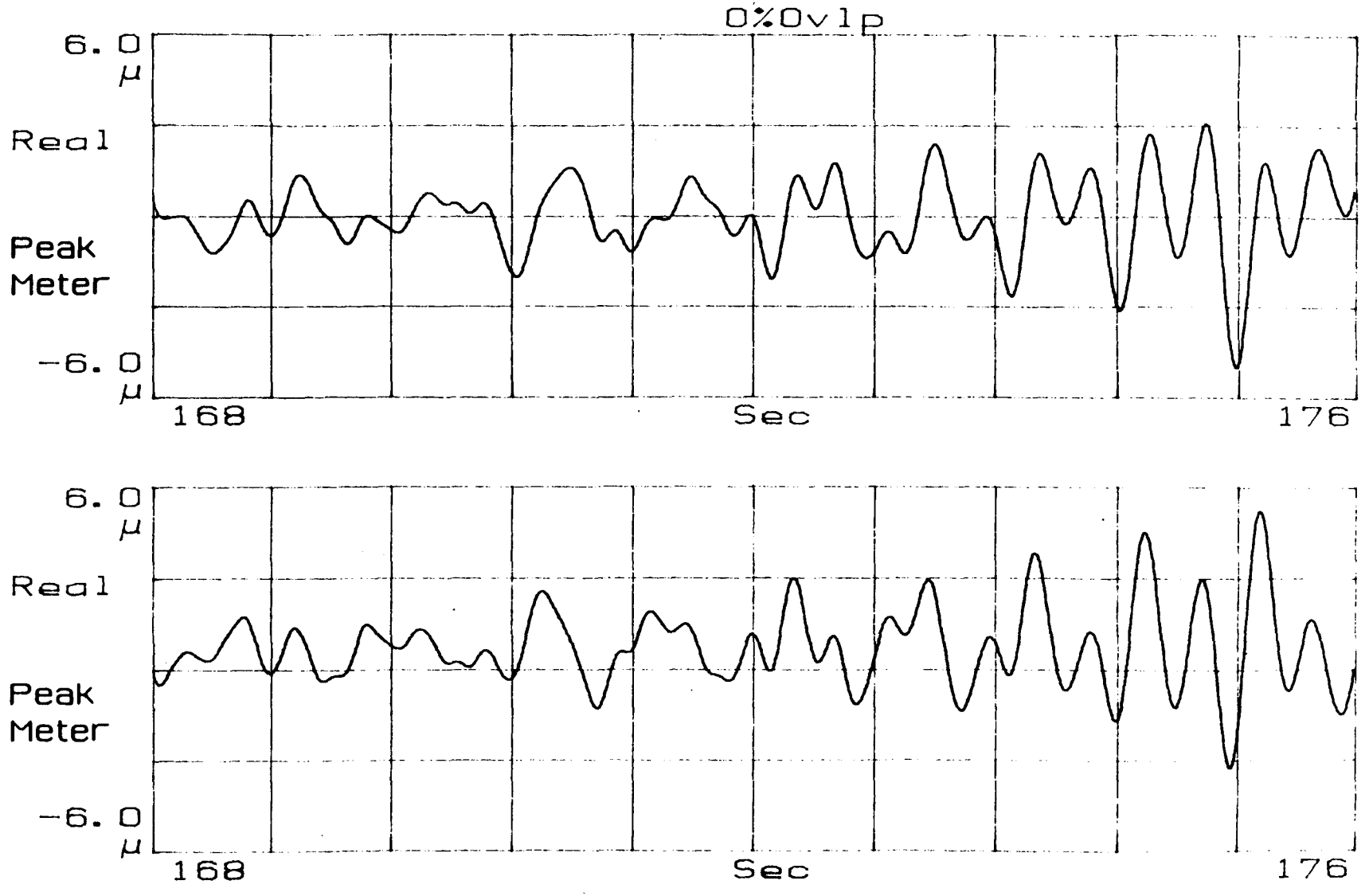
Project No.: 87-888-0011

RTK Joint Venture

Displacement Linear Spectrum
Site VF-1.7

12-89

Figure J-3



EXPLANATION
1 Hz Geophone Data
Geophone 4106 @ 62.0 feet (18.9 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing
(Compare with VE-3.5)

The Earth Technology Corporation

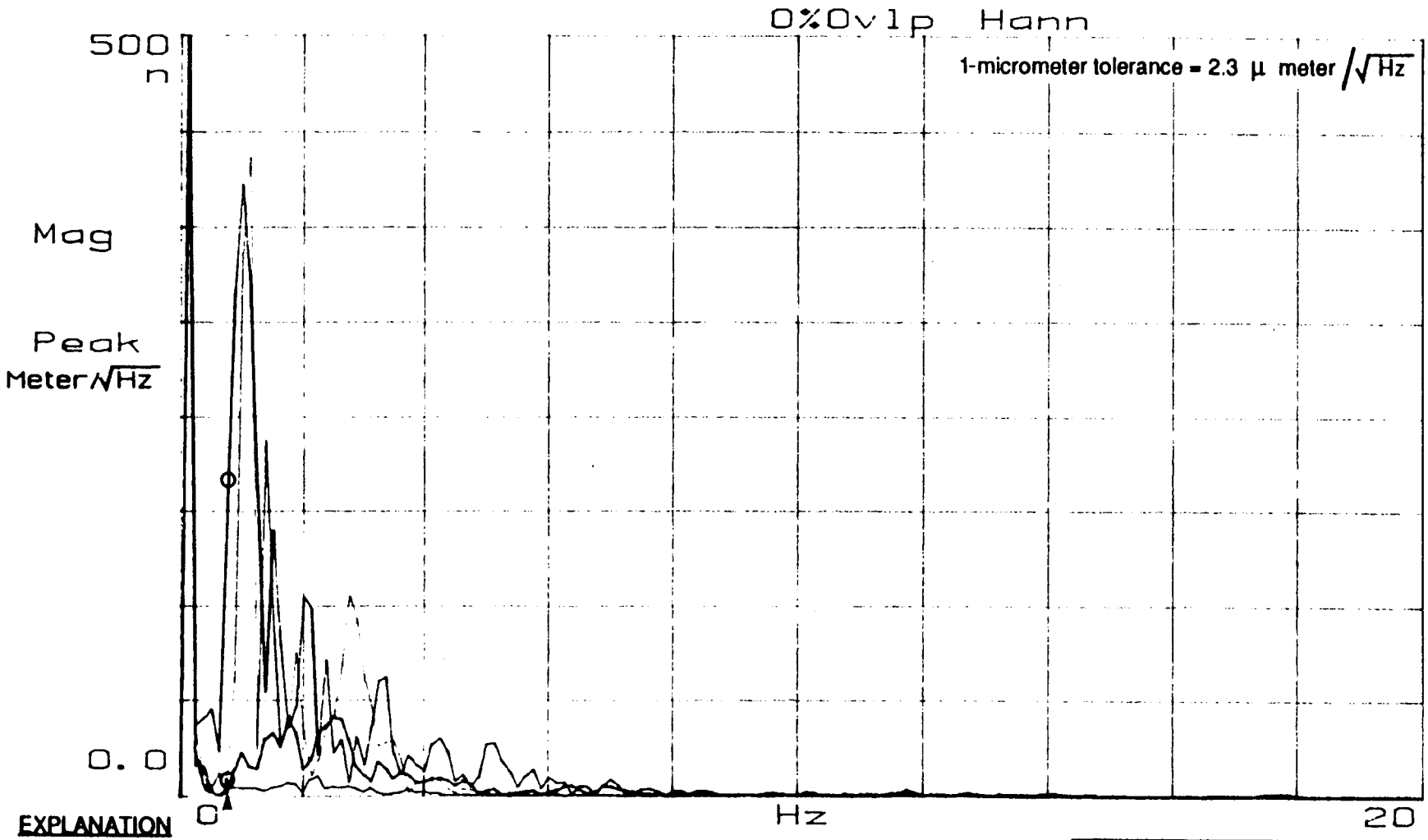
Project No. 87-888-0011

RTK Joint Venture

Displacement Time History
Site VF-1.7

12 89

Figure J 4



EXPLANATION

Geophone Depth in feet (meters)
1 Hz Geophone 2676 @ 19 (5.8)
Blue = Maximum Amplitude Wave Generated by Blast
Green = S Wave Generated by Blast
Red = P Wave Generated by Blast
Black = Ambient Vibration
Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation

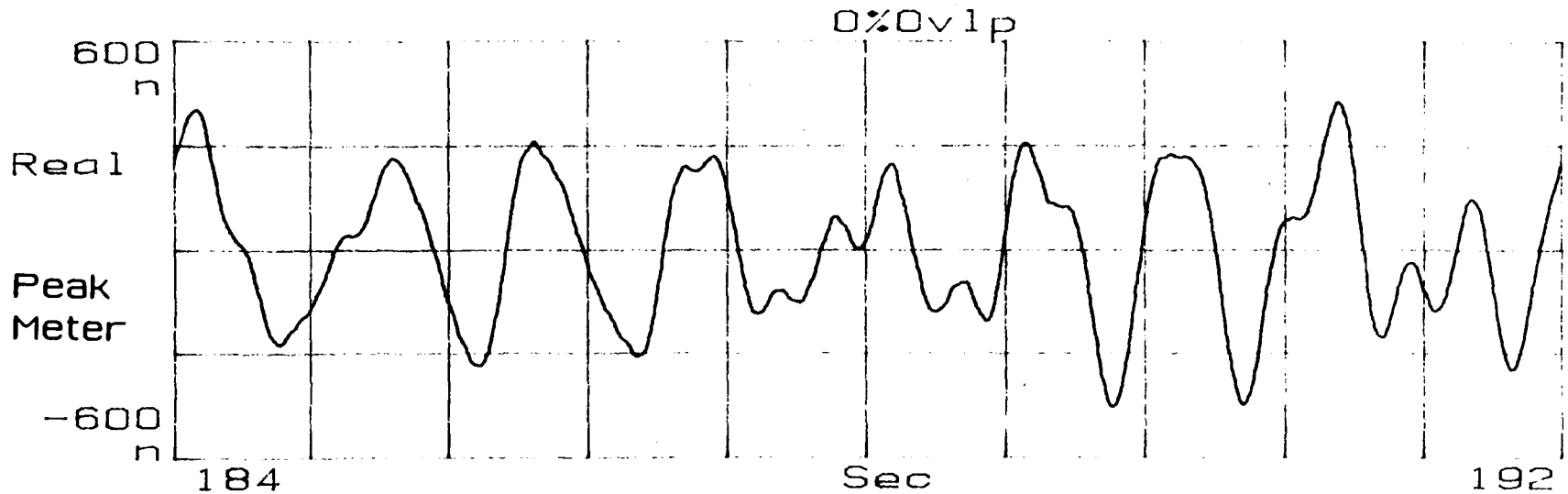
Project No.: 87-888-0011

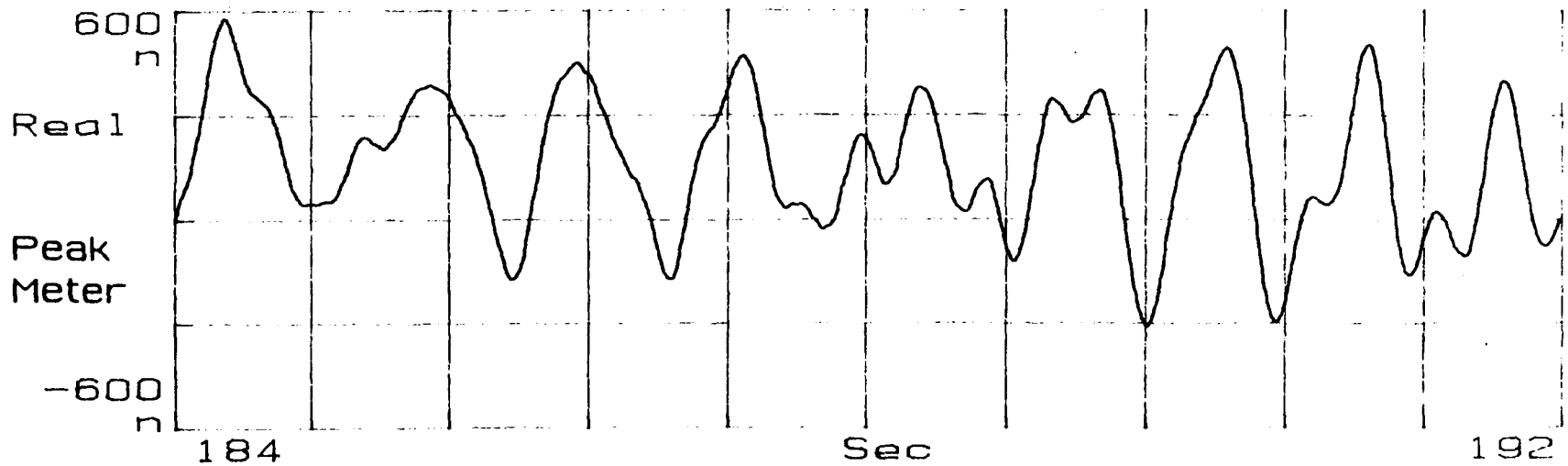
RTK Joint Venture

Displacement Linear Spectrum
Site VE-3.5

12-89

Figure J-5





EXPLANATION
1 Hz Geophone Data
Geophone 2676 @ 19.0 feet (5.8 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing
(Compare with VF-1.7)

The Earth Technology Corporation

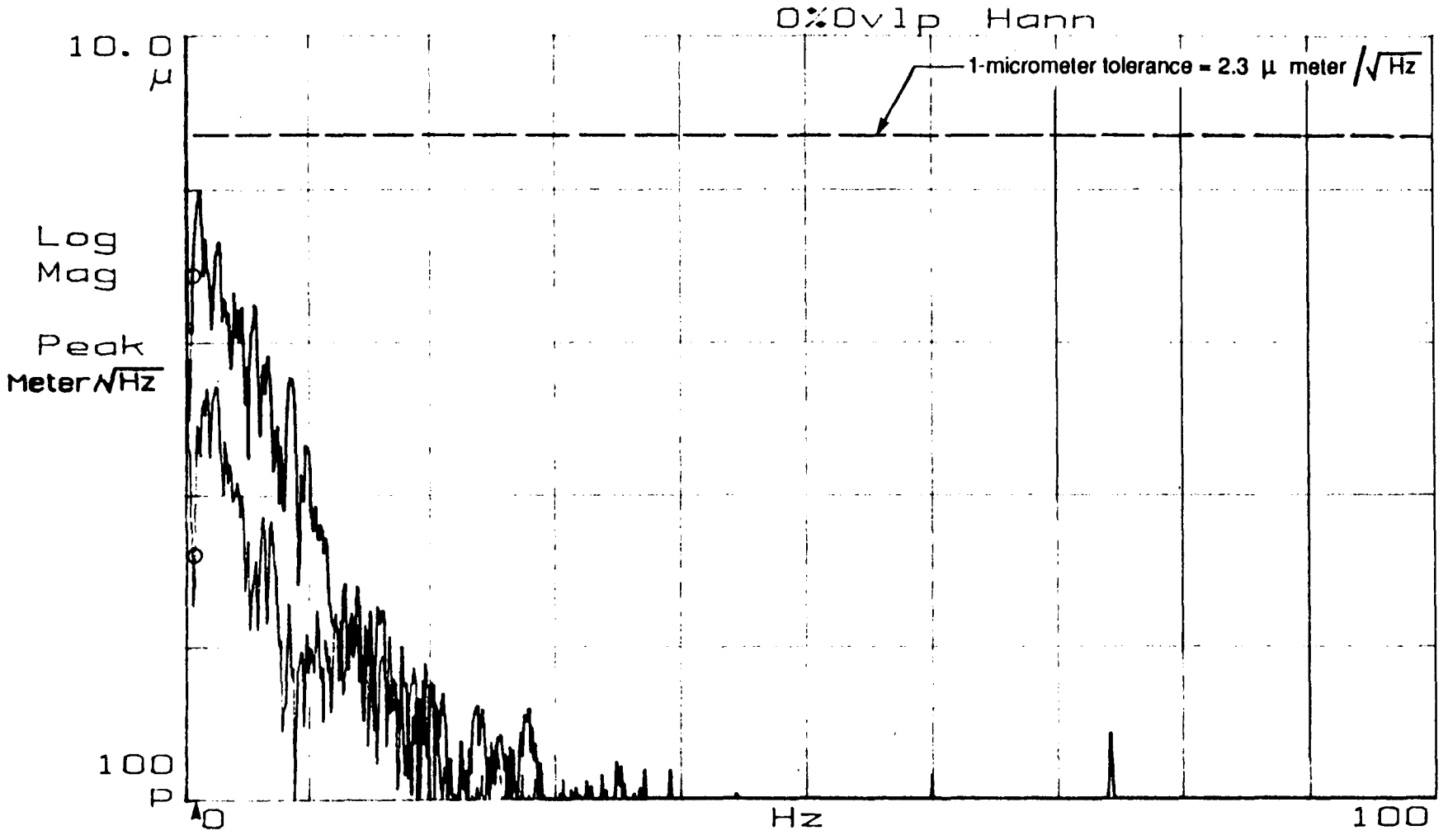
Project No. 87-888 0011

RTK Joint Venture

Displacement Time History
Site VE-3.5

12 89

Figure J 6



EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Red = Site VF-1.7 -- P & S Wave Generated by Blast - Measured @ 62.0 (18.9)
Black = Site VE-3.5 -- P Wave Generated by Blast - Measured @ 19.0 (5.8)

Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation

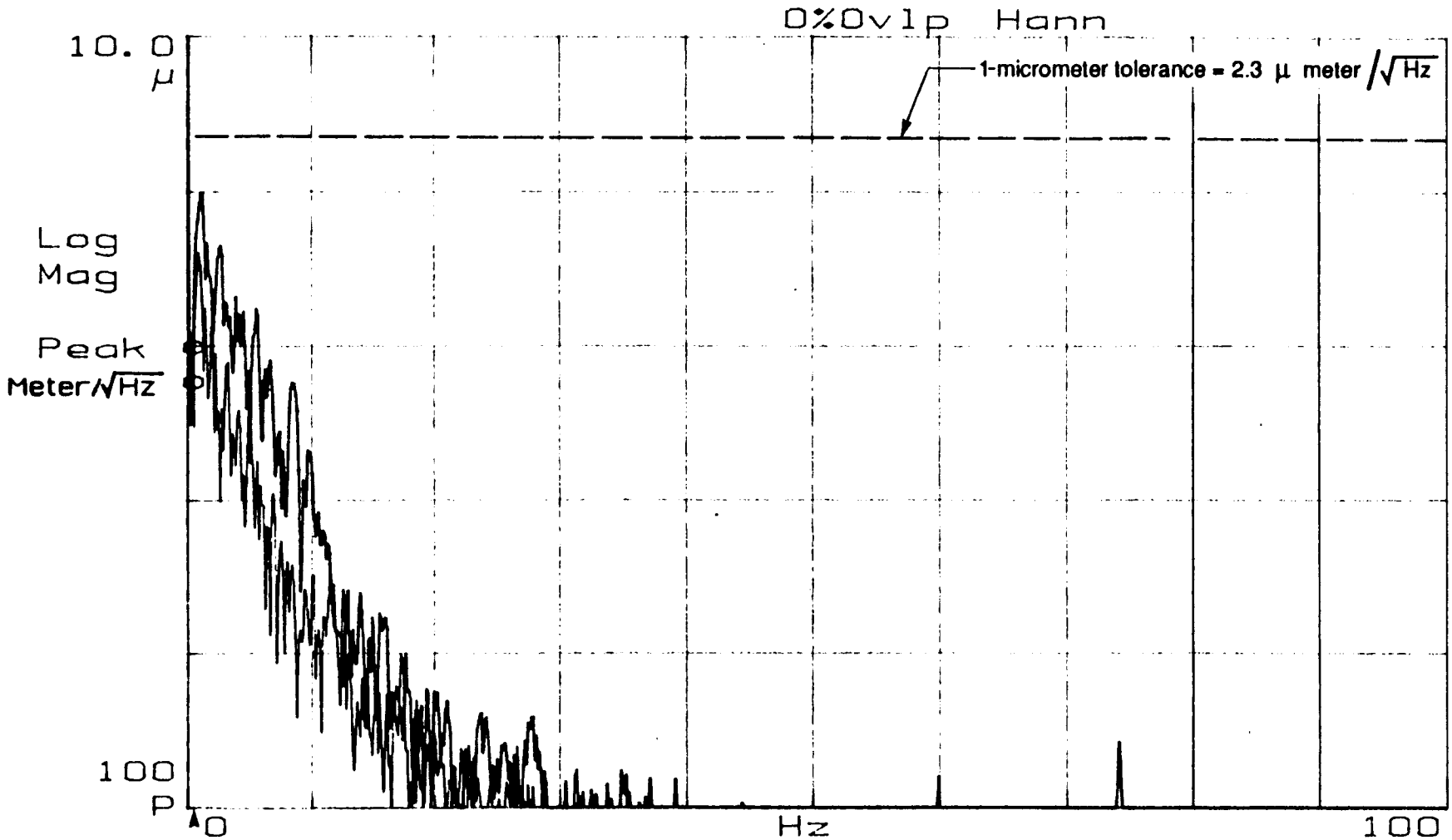
Project No.: 87-888-0011

RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Horizontal Change
P Wave
Sites VF-1.7 & VE-3.5

12-89

Figure J-7



EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Red = Site VF-1.7 -- P & S Wave Generated by Blast - Measured @ 62.0 (18.9)
Black = Site VE-3.5 -- S Wave Generated by Blast - Measured @ 19.0 (5.8)

Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation

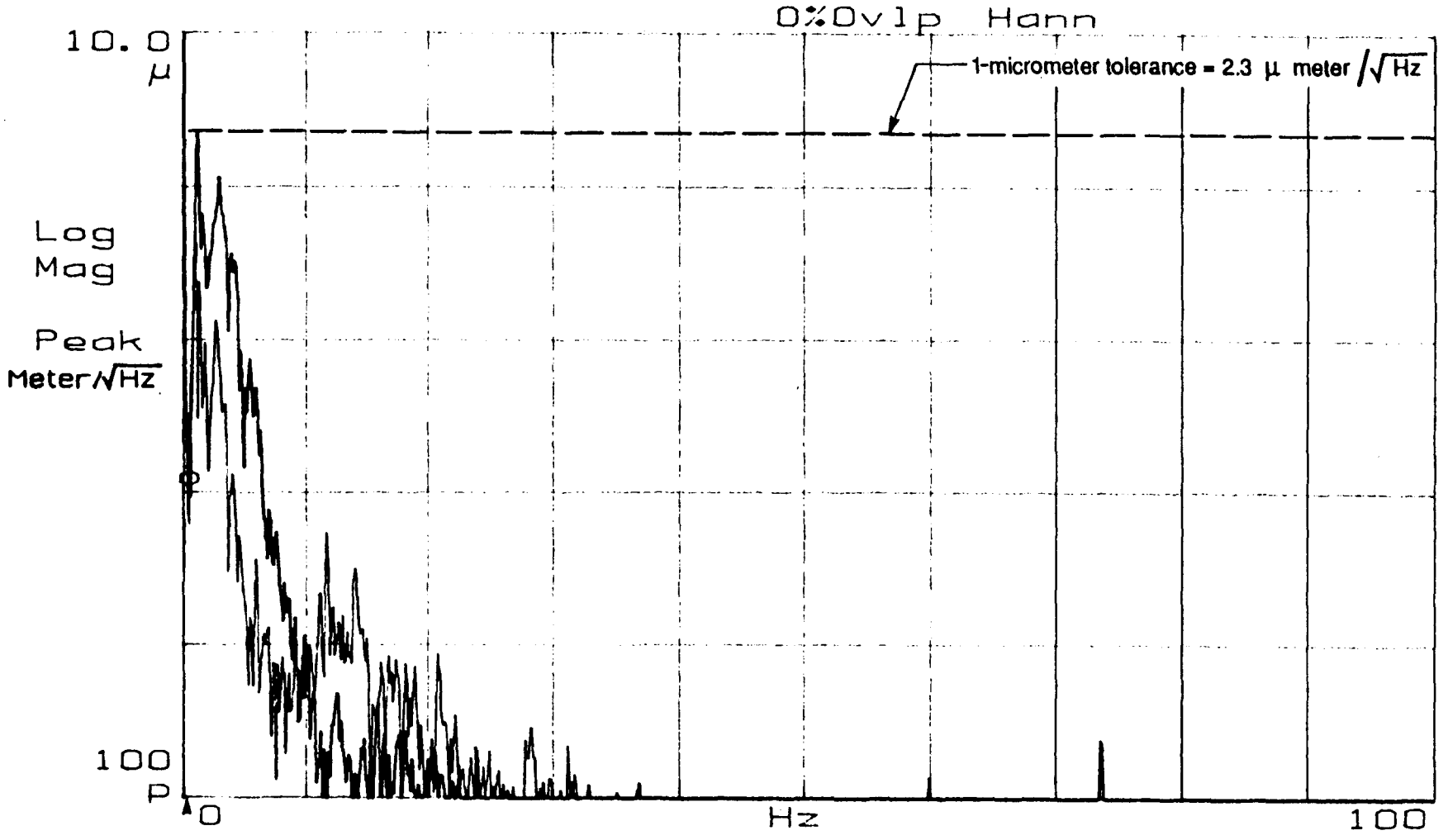
Project No.: 87-888-0011

RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Horizontal Change
S Wave
Sites VF-1.7 & VE-3.5

12-89

Figure J-8



EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Red = Site VF-1.7 -- Max. Amplitude Wave Generated by Blast-Measured @ 62.0 (18.9)
Black = Site VE-3.5 -- Max. Amplitude Wave Generated by Blast-Measured @ 19.0 (5.8)

Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation

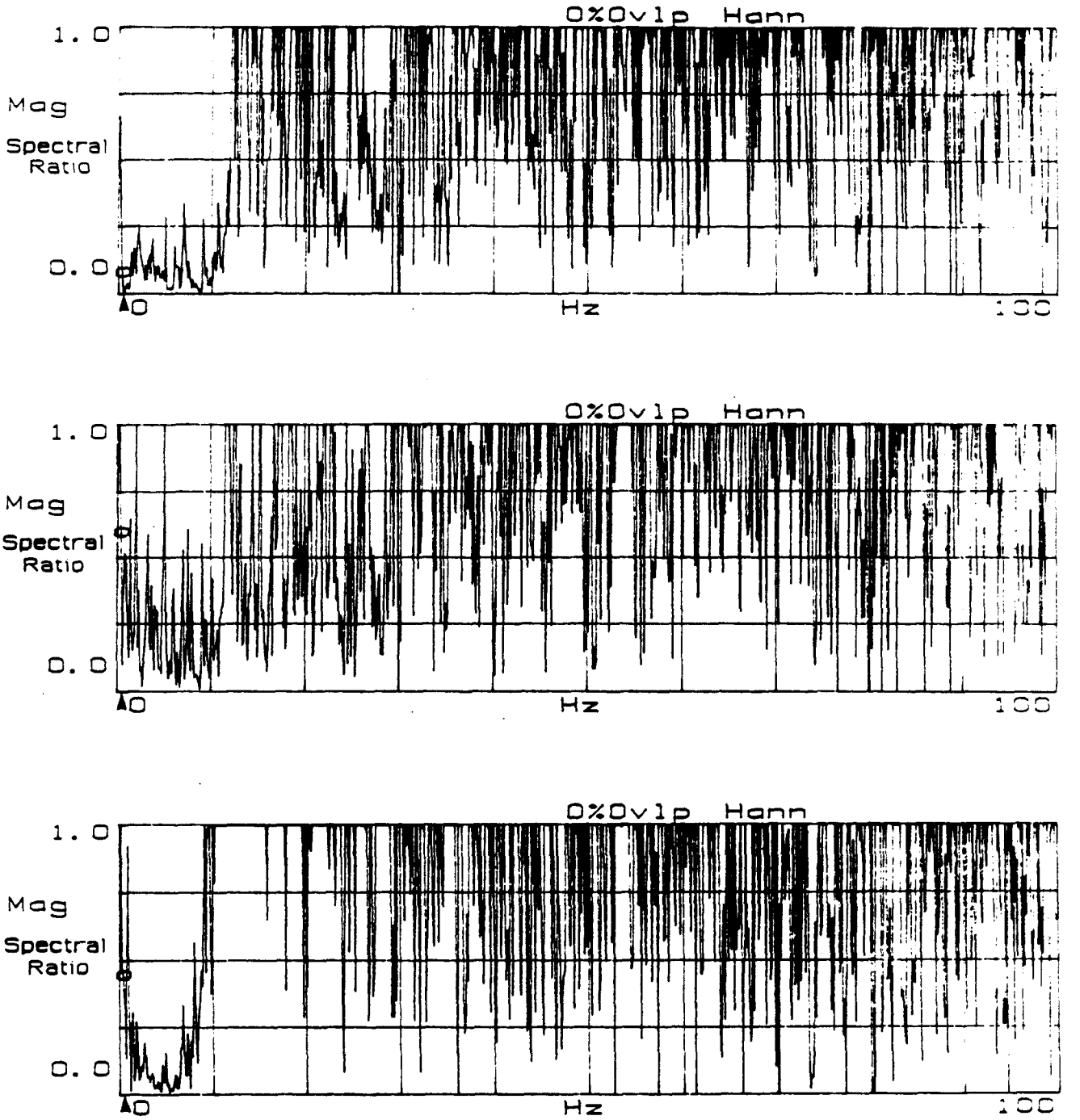
Project No.: 87-888-0011

RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Horizontal Change
Maximum Amplitude Wave
Sites VF-1.7 & VE-3.5

12-89

Figure J-9



EXPLANATION

1 Hz Geophone Data
Geophone Depth in feet (meters)
Ratio Calculated Between:
Site VF-1.7 Geophone @ 62.0 (18.9)
Site VE-3.5 Geophone @ 19.0 (5.8)
Top: P Wave Ratio (P & S Wave Combined at Site VF-1.7)
Center: S Wave Ratio (P & S Wave Combined at Site VF-1.7)
Bottom: Maximum-Amplitude Wave Ratio
Lower Frequency Limit of Calibration

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Spectral Ratio of Horizontally Separated Geophones
Sites VF-1.7 & VE-3.5

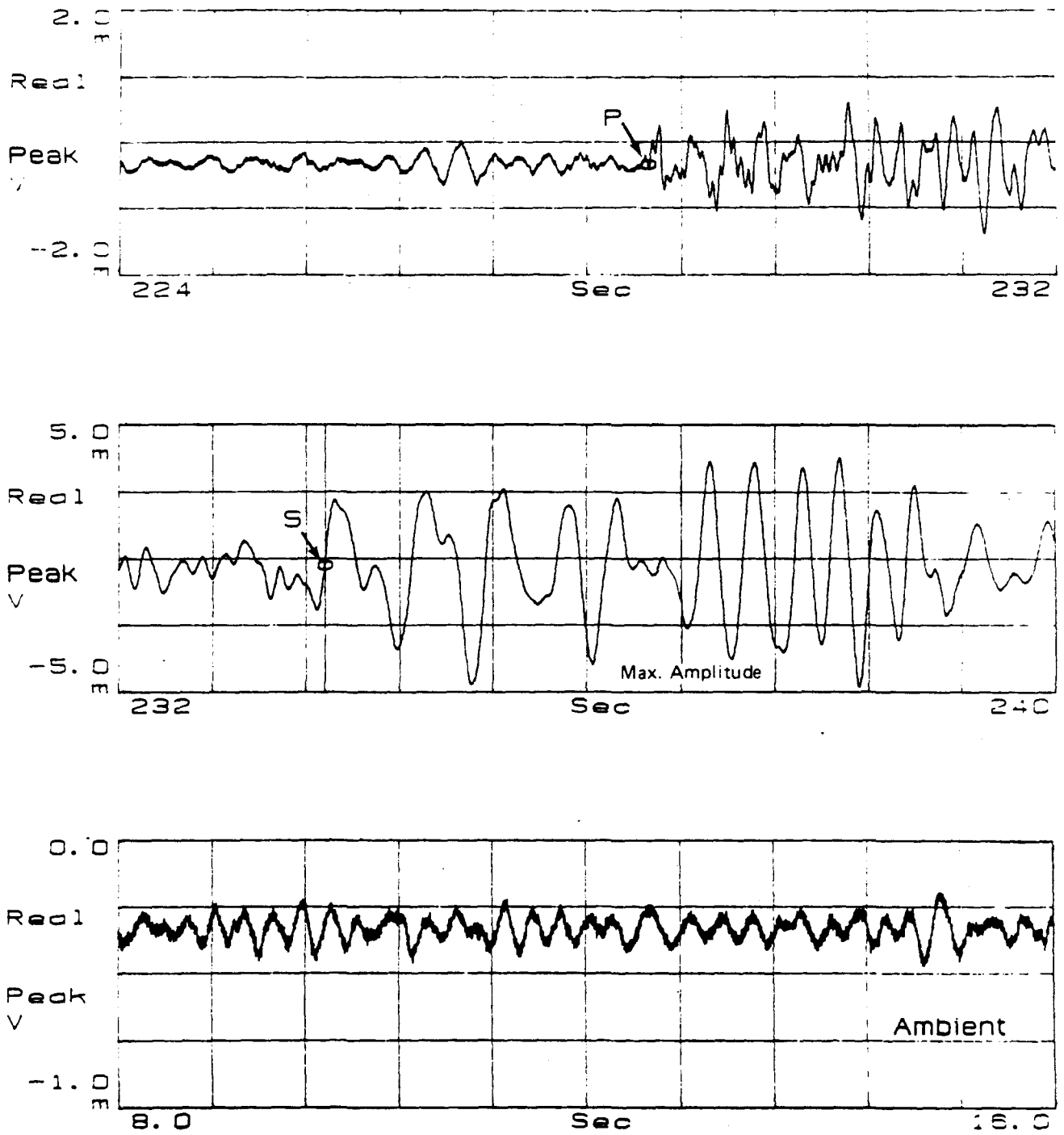
12-89

Figure J-10

APPENDIX K

DATA AND RESULTS
FOR HORIZONTALLY TRAVELING WAVES

SITES VF-1.7 AND VF-5.4



EXPLANATION

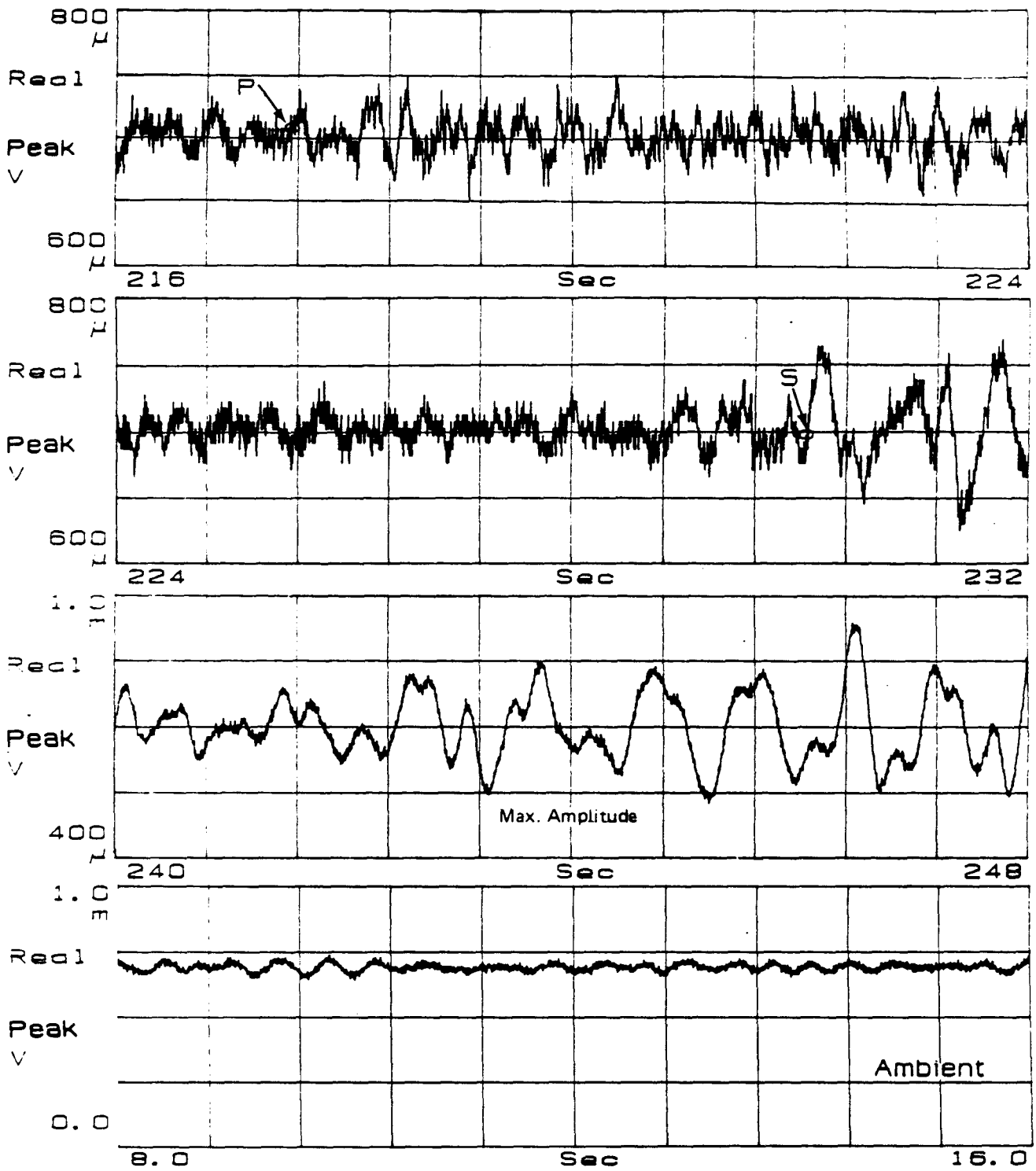
1 Hz Geophone Data
Geophone Depths in feet (meters)
Geophone 4106 @ 63.0 (19.2)
(Compare with VF -5.4)

The Earth Technology Corporation	Project No.: 87-888-0011 RTK Joint Venture

Raw Time Records
Site VF-1.7

12-89

Figure K-1



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Geophone 4105 @ 245.0 (74.7)
(Compare with VF-1.7)

The Earth Technology Corporation

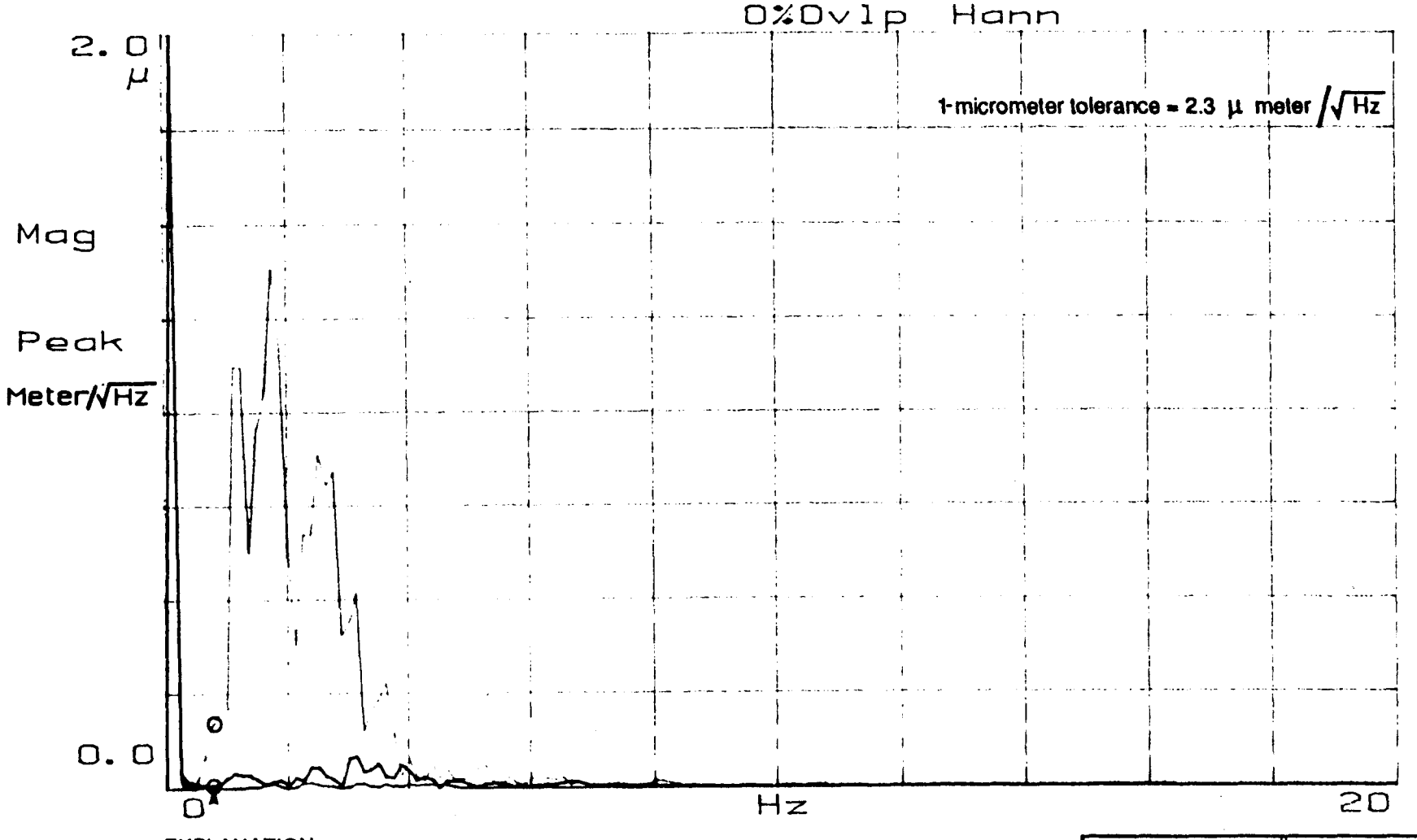
Project No.: 87-888-0011

RTK Joint Venture

Raw Time Records
Site VF-5.4

12-89

Figure K-2



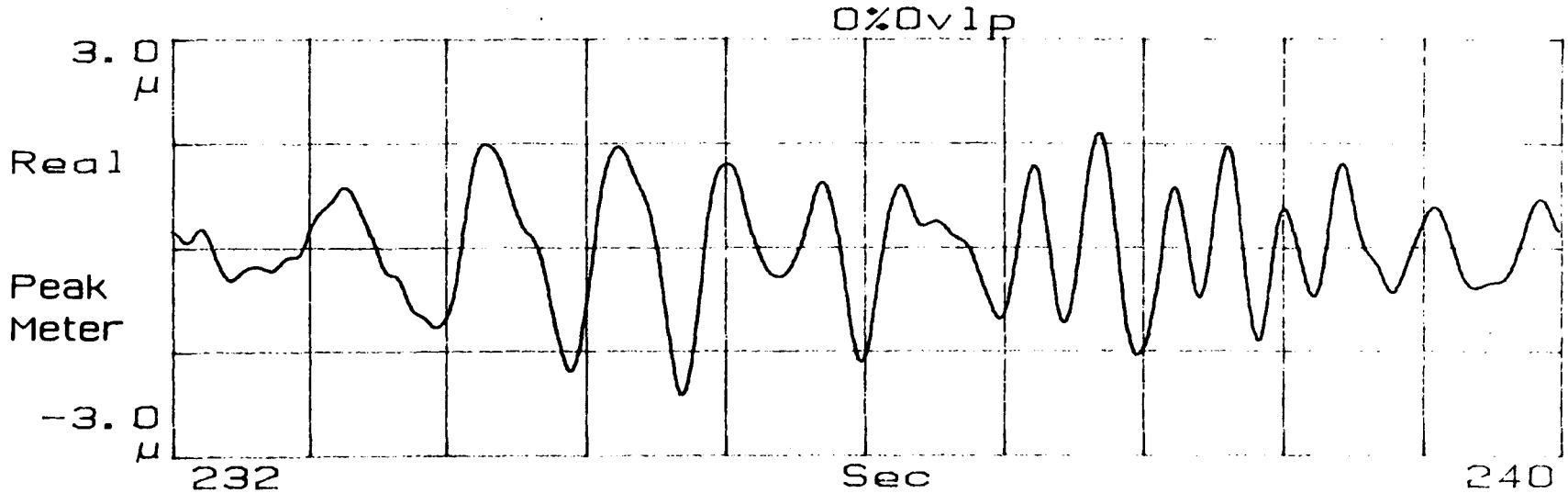
EXPLANATION

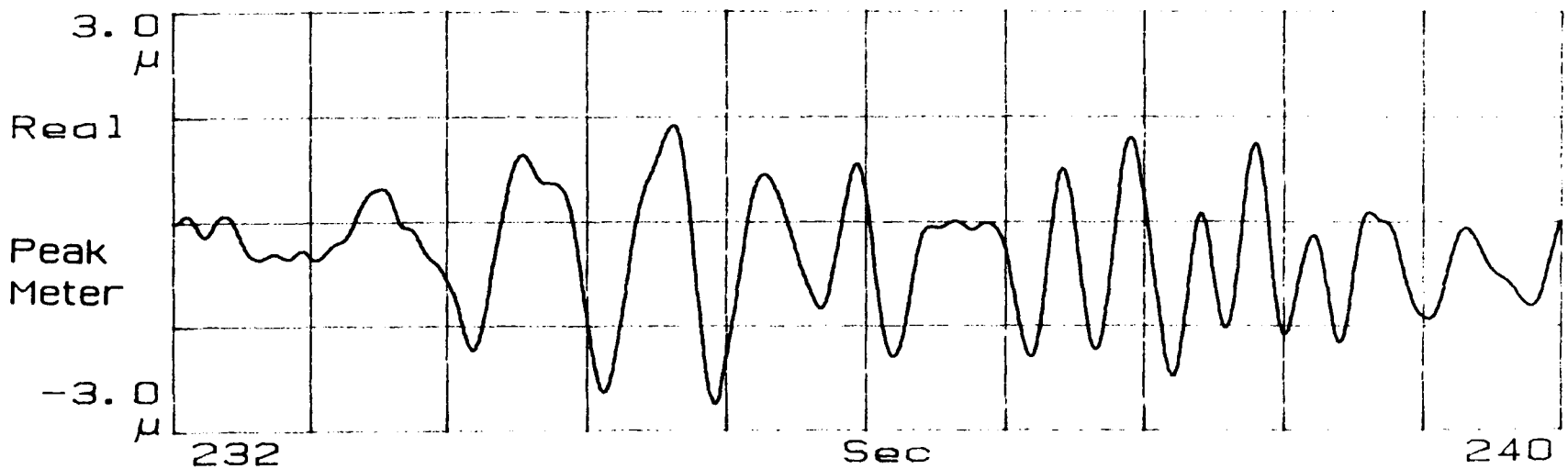
Geophone Depths in feet (meters)
1 Hz Geophone 4106 @ 63.0 (19.2)
Blue = S and max. amplitude waves generated by blast
Red = P wave generated by blast
Black = Ambient vibration
⊙ Lower Frequency Limit of Calibration
▲ Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Displacement Linear Spectrum
Site VF-1.7

12.89 Figure K-2





EXPLANATION
1 Hz Geophone Data
Geophone 4106 @ 63.0 feet (19.2 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing
(Compare with VF-5.4)

The Earth Technology Corporation

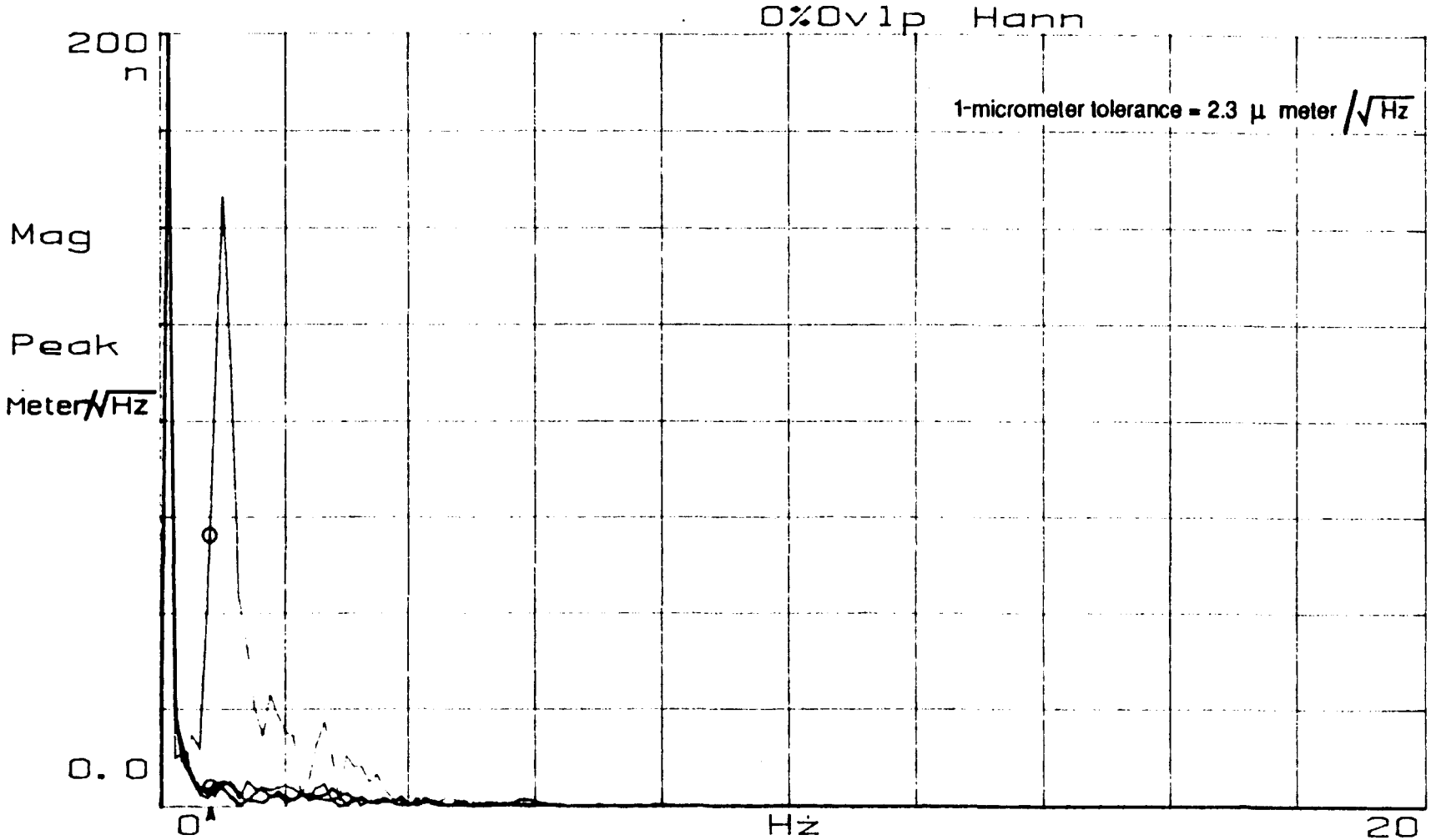
Project No. 87-888-0011

RTK Joint Venture

Displacement Time History
Site VF-1.7

12 89

Figure K 4



EXPLANATION

Geophone Depths in feet (meters)
1 Hz Geophone 4105 @ 245.0 (74.7)
Blue = Max. Amplitude Wave generated by blast
Green = S wave generated by blast
Red = P wave generated by blast
Black = Ambient vibration
⊙ Lower Frequency Limit of Calibration
▲ Bandwidth = 0.187 Hz

The Earth Technology Corporation

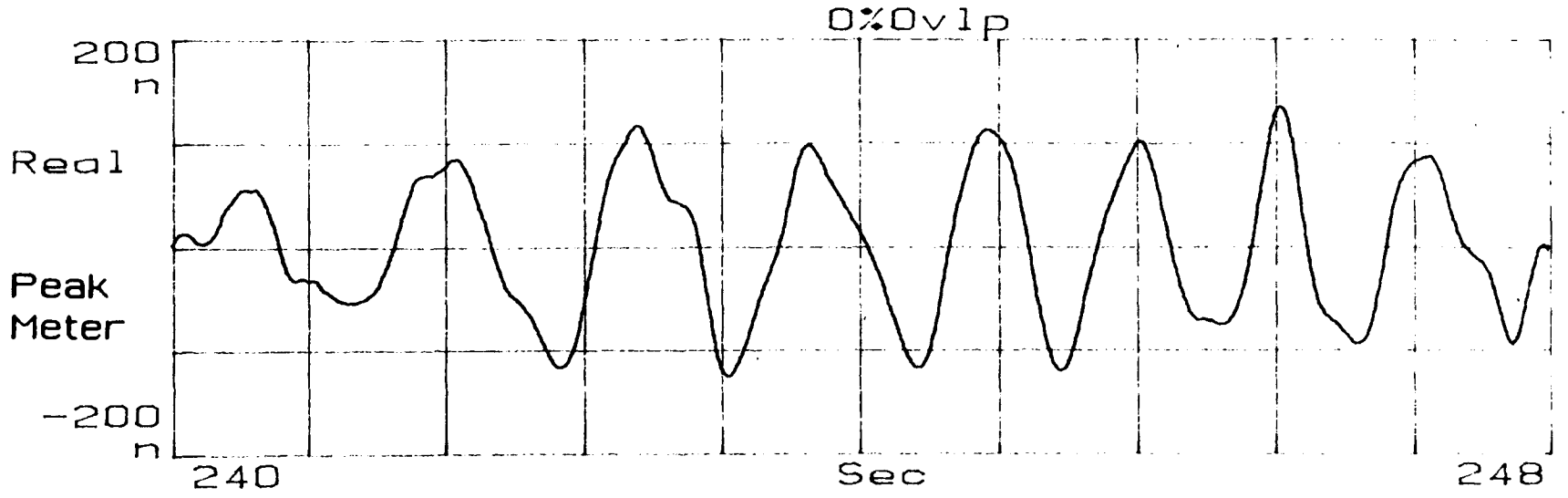
Project No.: 87-868-0011

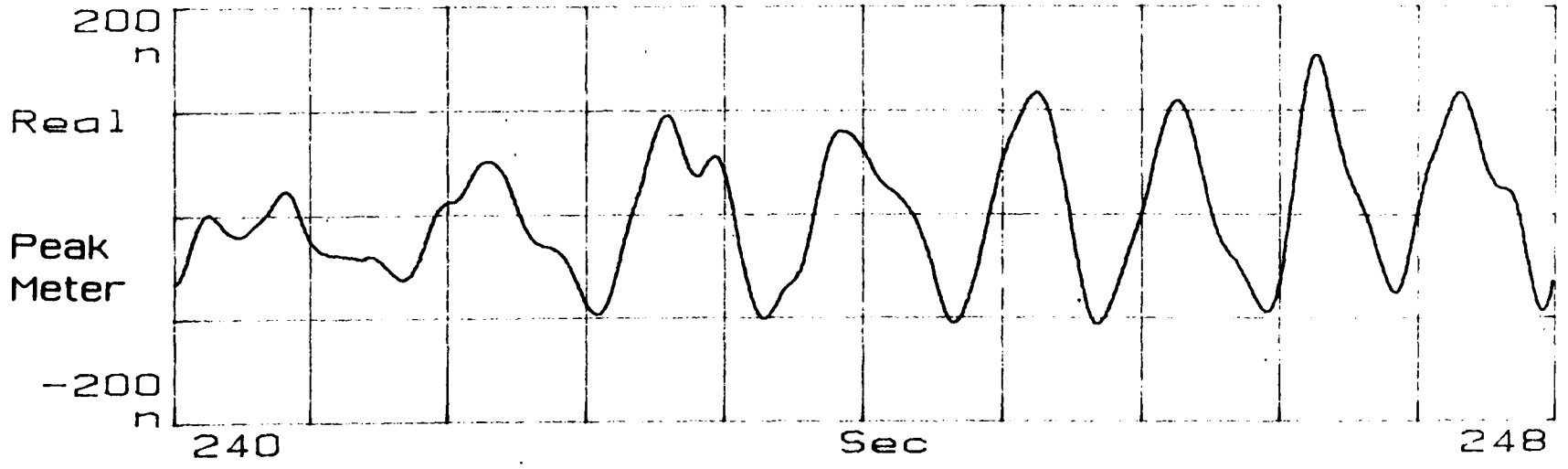
RTK Joint Venture

Displacement Linear Spectrum
Site VF-5.4

12-89

Figure K-5





EXPLANATION
1 Hz Geophone Data
Geophone 4105 @ 245.0 feet (74.7 meters)

Top Graph: Frequency Domain Processing

Bottom Graph: Time Domain Processing
(Compare with VF-1.7)

The Earth Technology Corporation

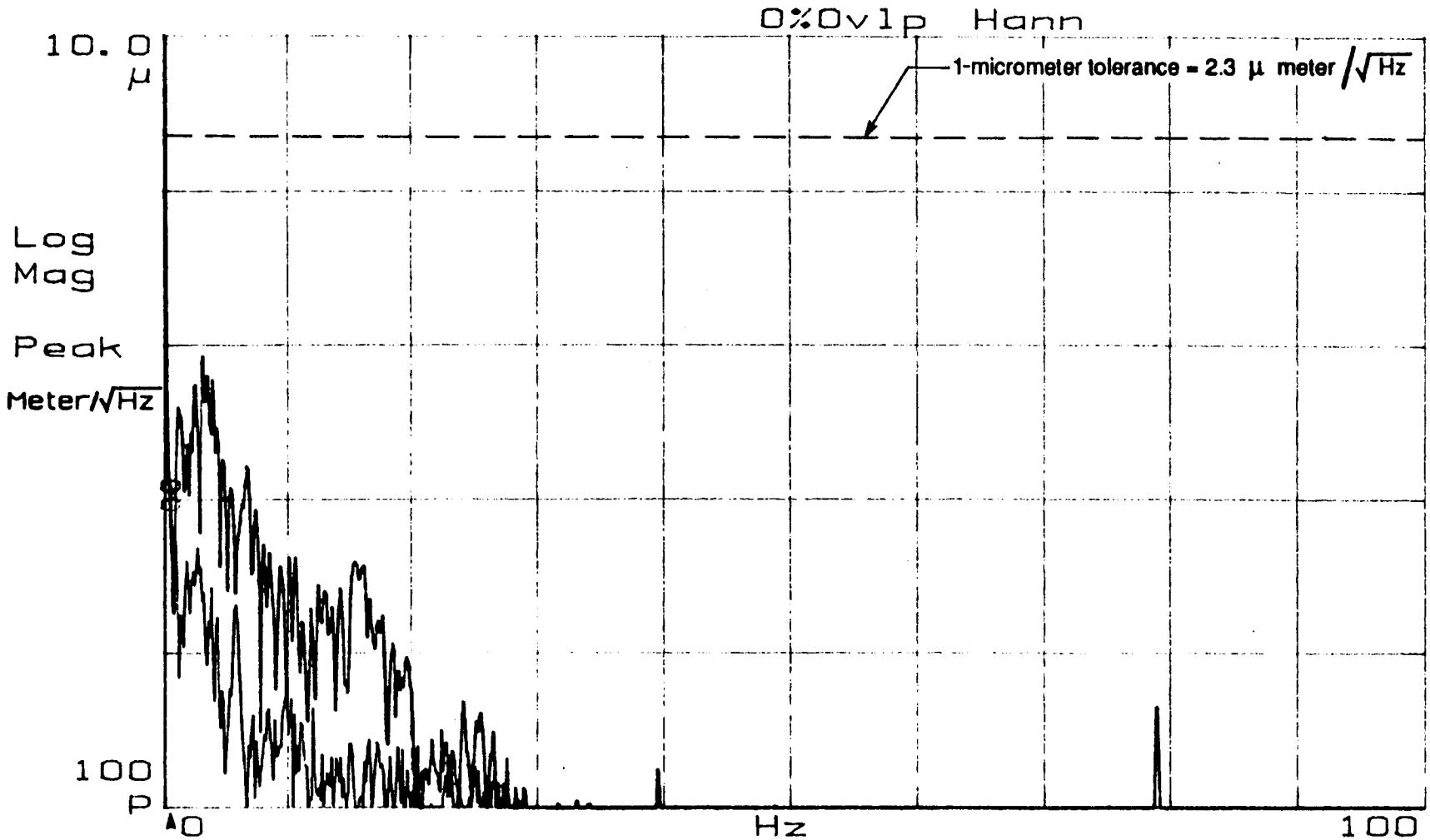
Project No. 87-888-0011

RTK Joint Venture

Displacement Time History
Site VF-5.4

12-89

Figure K 6



EXPLANATION

1 Hz Geophone Data
Geophone Depths in feet (meters)
Red = Site VF-1.7--P wave generated by blast-measured @ 63.0 (19.2)
Black = Site VF-5.4--P wave generated by blast-measured @ 245.0 (74.7)

Lower Frequency Limit of Calibration
Bandwidth = 0.187 Hz

The Earth Technology Corporation

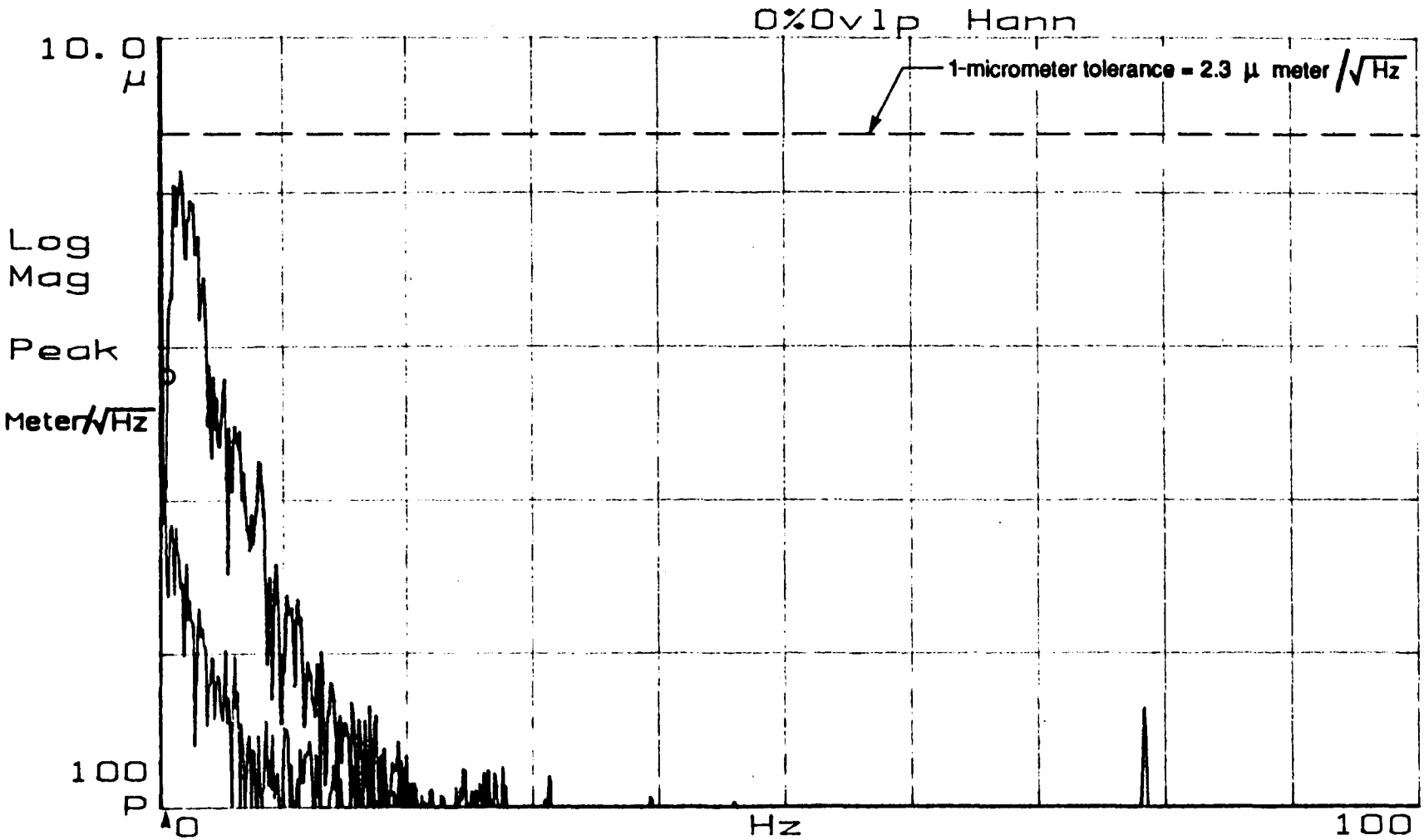
Project No.: 87-888-0011

RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Horizontal Change
P Wave
Sites VF-1.7 & VF-5.4

12-89

Figure K-7



EXPLANATION

1 Hz Geophone Data

Geophone Depths in feet (meters)

Red = Site VF-1.7--S wave generated by blast-measured @ 63.0 (19.2)

Black = Site VF-5.4--S wave generated by blast-measured @ 245.0 (74.7)

Lower Frequency Limit of Calibration

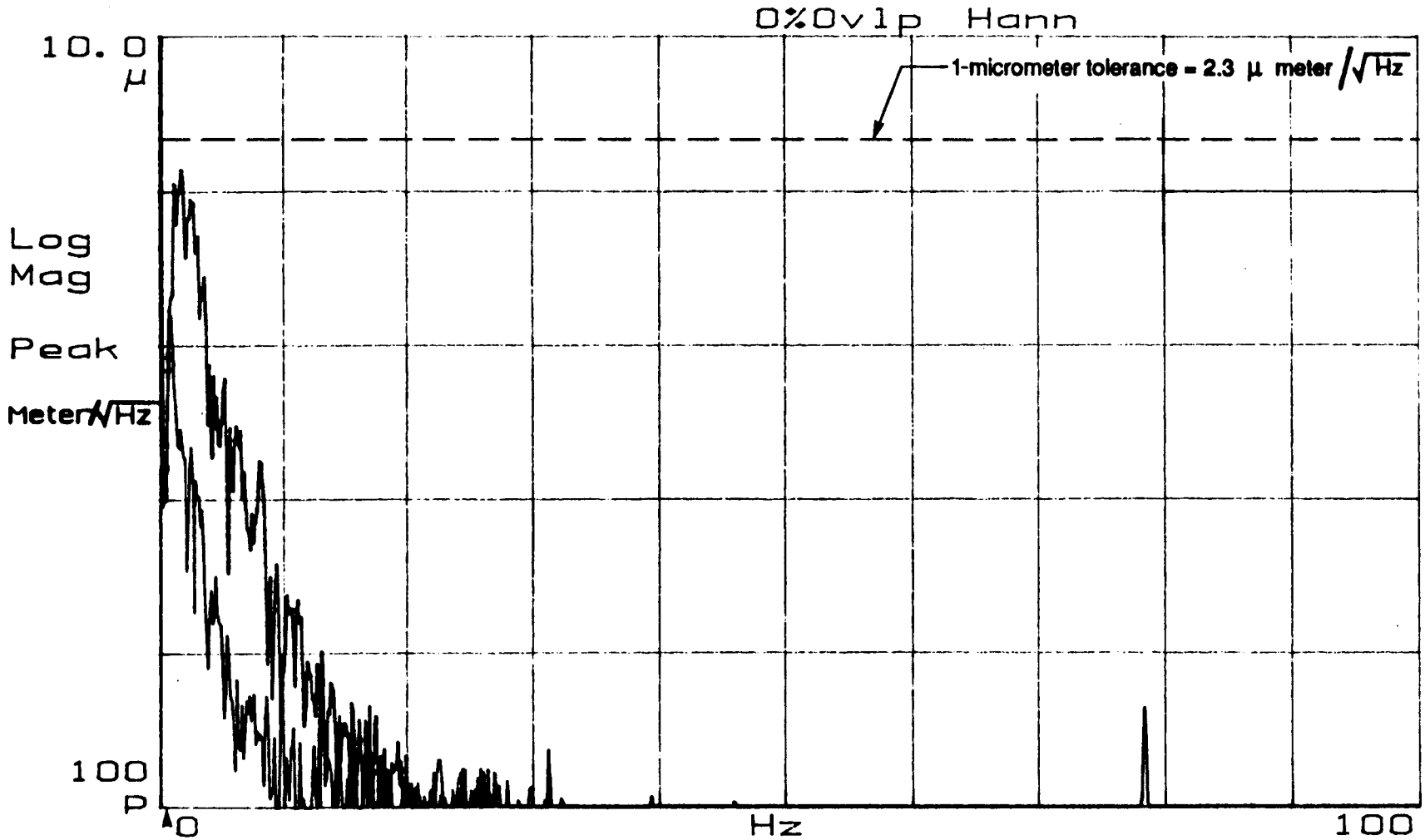
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Horizontal Change
S Wave
Sites VF-1.7 & VF-5.4

12-89

Figure K-8



EXPLANATION

1 Hz Geophone Data

Geophone Depths in feet (meters)

Red = Site VF-1.7--S Max. Amplitude Wave generated by blast-measured @ 63.0 (19.2)

Black = Site VF-5.4-- Max. Amplitude Wave generated by blast-measured @ 245.0 (74.7)

Lower Frequency Limit of Calibration

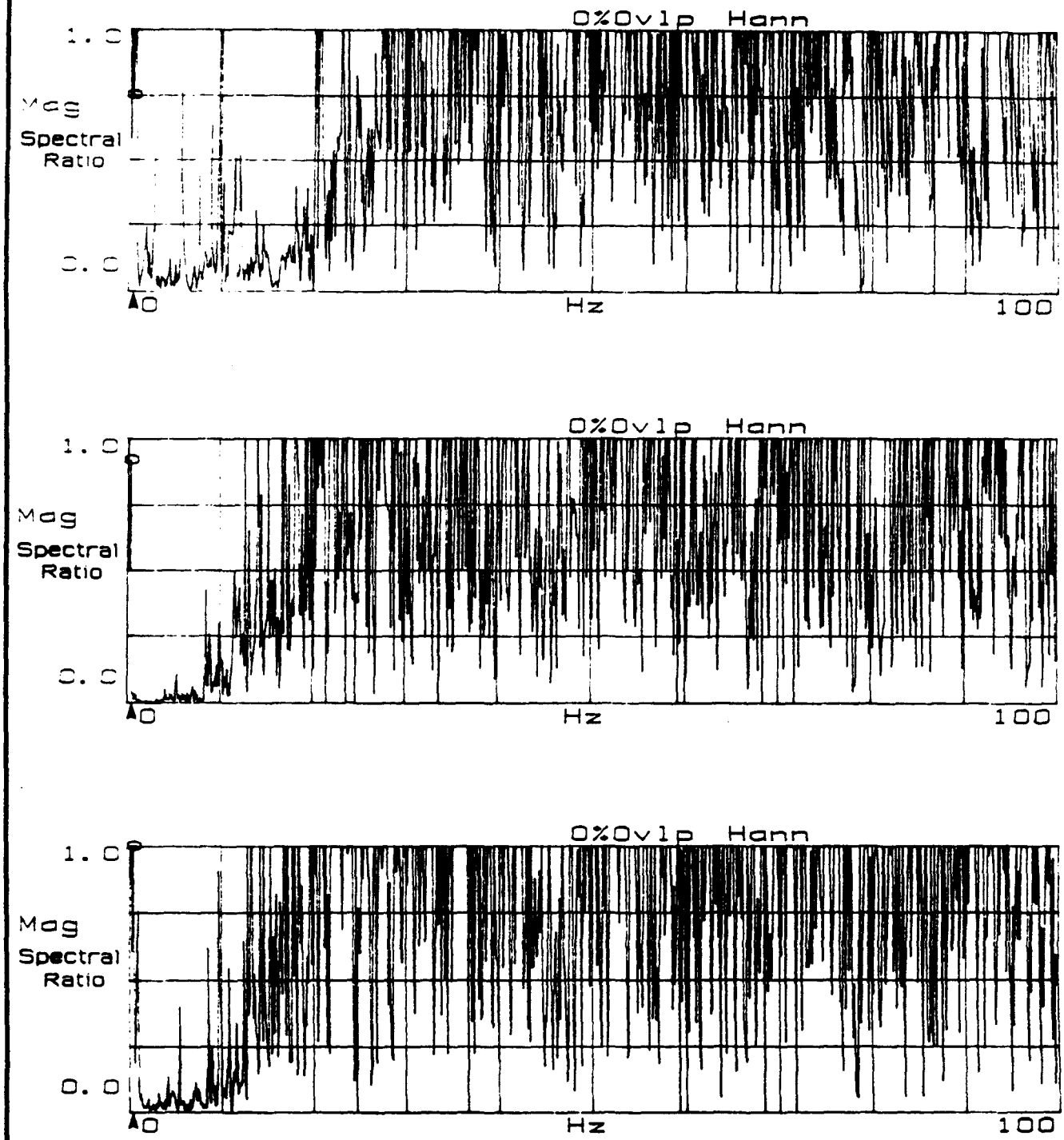
Bandwidth = 0.187 Hz

The Earth Technology Corporation	Project No.: 87-888-0011
	RTK Joint Venture

Composite Displacement Linear Spectrum
Showing Horizontal Change
Maximum Amplitude Wave
Sites VF-1.7 & VE-5.4

12-89

Figure K-9



EXPLANATION

1 Hz Geophone Data

Geophone Depths in feet (meters)

Ratio Calculated between:

Site VF-1.7 Geophone @ 63.0 (19.2)

Site VF-5.4 Geophone @ 245.0 (74.7)

Top: P Wave Ratio

Center: S Wave Ratio

Bottom: Maximum-Amplitude Wave Ratio

⊙ Lower Frequency Limit of Calibration

The Earth Technology Corporation

Project No.: 87-888-0011

RTK Joint Venture

Spectral Ratio of Horizontally Separated Geophones Sites VF-1.7 & VF-5.4

12-89

Figure K-10