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Development of Measurement Capability for Micro-Vibration Evaluations with Application to Chip Fabrication Facilities

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Technical Report MCEER-99-0020

December 1, 1999

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NOTICE

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Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies, the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

The study described in this report was funded by Erie County, the Town of West Seneca, Empire State Development Corp. and the West Seneca Development Corp. through an innovative partnership between government, the business sector and academia. Matching resources were provided by the University at Buffalo and MCEER.

In this project, MCEER researchers conducted vibration tests at a site in West Seneca, New York to determine its suitability for attracting and supporting a ChipFab facility. ChipFab, a short name for a semiconductor chip fabrication facility, is a high-tech manufacturing facility where the electronic chips for items ranging from computers to cellular phones to automobiles are manufactured. The industrial park site (North American Park) is located near a railroad, a major expressway and an active mining operation. The level of micro-vibrations of ground motion is critical for this type of facility.

Several locations were instrumented within the industrial park. Three direction acceleration components were measured at each location, during the period between November 1 and December 1, 1998. These acceleration data were subsequently converted into RMS velocity (one-third-octave band) through specially derived analytical relationships. It was found that the proposed ChipFab site in the northern section of the industrial park was suitable for the manufacturing facility.

The measurement system used to conduct this testing was developed specifically for this project. This report describes the measurement system in detail, including its sensory system, data acquisition and recording, sensor installation and distribution of the measurement locations. The procedure to obtain measurements, data evaluation, and results and analyses related to the West Seneca site are also described in the report.

Abstract

This report summarizes a study to measure micro-vibrations of ground motions at a proposed site to fabricate electronic IC chips. The micro-vibration level of ground motion is critical for this type of manufacturing facility. Current guidelines for semi-conductor fabrication facilities recommend that they be subjected to less than 100 micro-inches per second RMS (root-mean-square) velocity in every one-third octave frequency band with a preferred range of 60 to 70 micro-inches per second. The site under study is located near a major expressway, a train thoroughfare and an active mining operation.

There is currently no official specification on how to conduct the evaluation process. A reliable method based on proper vibration theory was therefore developed before the field investigation. An appropriate measuring system and data processing procedure was adopted. The total cost was kept low so that the procedure would be suitable for conducting a preliminary assessment.

It was found that at the proposed location, the RMS values of velocity in the one-third octave frequency band are less than 70 micro-inches per second, in spite of expressway traffic, passing trains, and operations in a near by rock mine.

In addition to the encouraging results at the specific site (North America Center, West Seneca, NY), the ground vibration measuring procedure developed can potentially be used as an industrial standard for delicate manufacturing site evaluation.

The report also introduces the theoretical development for the relationship between frequency spectra and RMS values, which can be adopted for a wide range of applications on interpretations of the data obtained from up-to-date data acquisition systems.

ACKNOWLEDGMENT

The authors express their appreciation to the County of Erie, the Town of West Seneca, and the West Seneca Development Corporation for their sponsorship of the study reported herein. They also wish to acknowledge the contribution of the state-of-the-art sensors (393B31 ICP) from PCB Piezoelectronics in this study. The State University of New York at Buffalo and the Multidisciplinary Center for Earthquake Engineering Research provided matching resources.

The authors would also like to acknowledge the comments and advice from the ChipFab Selecting Committee and the help of Professor T. Niu for his technical assistance during the field measurement period.

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SECTION 1
INTRODUCTION

1.1 Background

Jointly sponsored by the Multidisciplinary Center for Earthquake Engineering Research (MCEER), the County of Erie, the Town of West Seneca, the Empire State Development Corporation, and the West Seneca Development Corporation, an investigation of micro-vibrations of ground motion at a proposed site for a ChipFab facility in the North America Center, West Seneca, New York was carried out. The purpose of this investigation was to measure the ground vibration level, in order to determine if the proposed site was suitable for fabrication of the second generation of electronic IC chips (ChipFab). This task required knowledge in different domains, including structural and geotechnical engineering, vibration analysis, and electronics.

The measurements were carried out between November 3 to 25, 1998. The records were obtained during adverse conditions, and included several vibration sources (trains, ground traffic, blasts, and windy weather with heavy water waves in Lake Erie, 10 miles away from the site).

The key issues discussed in this report include: (1) the selection of suitable sensors with sufficient sensitivity, low measurement frequency and other appropriate qualifications, (2) the configuration of the measurement system set up, including calibration, acoustic isolation and data acquisition, (3) procedures to ensure the signal pickup, and (4) development of appropriate methods for data analyses.

1.2 Objectives

The primary objective of this research was to develop an accurate, inexpensive, user-friendly, and academically appropriate procedure for early evaluation of candidate sites for microelectronic fabrication facilities and validate the procedure by applying it to an actual site.

Both a systematic review of current measurement capabilities and development beyond existing techniques for micro-vibration evaluations were needed. Some very commonly used methods of measurement were not suitable for obtaining the measurements required for approval of a ChipFab facility. For example, in existing buildings, issues of noise isolations and calibration of sensor fixtures are not significant, but in field testing, these issues become critical and can greatly affect the measurement results. Cost of obtaining the measurements is another consideration. Usually, expensive equipment must be used to collect weak and low frequency signals of micro-vibrations. New products (sensors and cables) must be tested and verified by careful calibrations and practice. This issue was emphasized in this study.

The North America Center, located in West Seneca, New York, was proposed as a potential site for fabrication of the second generation of electronic IC chips (ChipFab). A detailed map of the site is given in figure 1-1. The micro-vibration level of the ground motion is critical for such a manufacturing facility. The demand on ground vibration level can be quantified as a maximum vibration of 100 micro-inches per second RMS velocity in every one-third-octave band with a preferred range of 60 to 70 micro-inches per second.

A railway of the Conrail Main Line and the Route 400 expressway are located at the southern side of this site. The railway and Route 400 are almost parallel to the principal axis of the site in the east-west direction. In addition, about three miles away, in the northeast direction, a rock mine operates with daily explosions. This study is concerned with determining the ground vibration levels at this site and comparing them with the recommended limit.

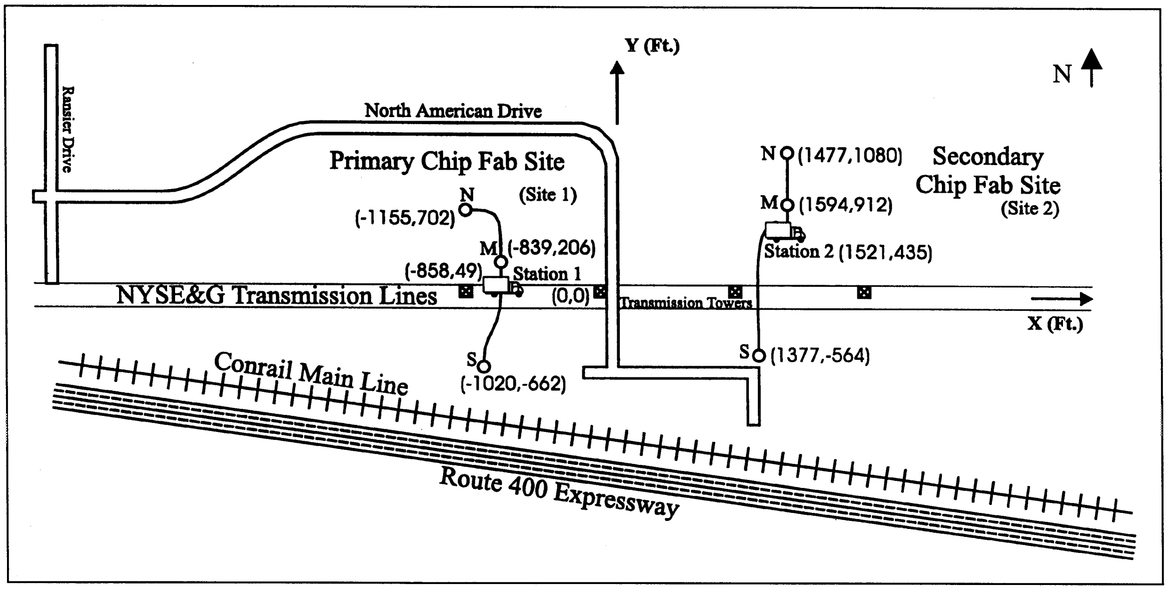


Figure 1-1 Site Map

SECTION 2
REVIEW OF EXISTING STANDARDS, PROCEDURES, AND EQUIPMENT

2.1 Vibration Criteria

To evaluate the level of ground vibration, the measurements must be collected in a common format with enough information for further investigation.

The International Organization for Standardization (ISO) specifies some vibration criteria regarding human comfort in workshops, offices, residences, and theatres (ISO 2631/DAD1). In each application, the limit is a constant velocity between 8 and 80 Hz and a constant acceleration between 4 and 8 Hz. The velocity is in a form of RMS (root-mean-square) value in every one-third octave frequency band. Gordon (1987) points out that the equipment maximum sensitivities at different frequencies form a constant velocity line. Since the one-third-octave frequency band happens to be close to the resonance bandwidth of equipment with 10% loss factor, the vibration criteria for the microelectronic industry can be in the same form as ISO human comfort criteria. The BBN (Bolt, Beranek and Newman) criteria suggests five additional vibration criteria over the ISO standard at velocity levels 2000, 1000, 500, 250, and 125 micro-inch per second (8, 3, 1, 0.3, and 0.1 micron/sec). Klein et al. (1995), Ammann et al. (1995), and DeSilva (1983) recommend 100 micro-inch per second RMS velocity in every one-third-octave band for ChipFab site criterion.

Powered by today's high-speed personal computers, the narrow-band analysis utilizing FFT (Fast Fourier Transform) has become more and more popular (see Owen and Hale, 1991 and Gordon, 1991). It provides more detailed information about the vibration component in different frequencies. The FHA (Frank Hubach Associates) criteria were established under FFT algorithm with a frequency resolution of 0.125 Hz and were compared with BBN criteria by Owen.

2.2 Measuring Settings

The vibration criteria stated above are specified as "floor vibrations." Before the facility is built, no floor vibration can be directly measured. On the other hand, the ground (site) vibration is an important factor for designing the facility or even in deciding whether or not it will be built. Therefore, establishing the relationship between measured ground vibrations and expected floor vibrations is the first step in the evaluation process. Jendrzejczyk and Wambsganss (1991) developed a feedback design process that modifies the preliminary design based on predicted vibration level with all the site information in hand until the predicted floor vibration is acceptable. Although this procedure is logical and reliable, it is very expensive in both money and time. It is not suitable for this type of project, where a potential site is being investigated prior to actual construction. Brochet (1991) suggested a less exhaustive approach for site selection that ignores the soil-structure interaction but reserves a buffer of 6 to 12 dB (100% to 300% difference) between ground and required floor vibration levels. This approach is also not suitable before a final site has been selected.

Seismographs are the most common setup used in civil and earthquake engineering for low frequency, low amplitude, and long duration vibrations while accelerometers are used for medium to high frequency structural vibrations. Some of these devices are mounted on structures and others on or in the ground. The mounting of the vibration sensors is crucial to the measuring results. However, there is not much guidance regarding mounting. The ideal ground mounting system measures the "particle vibration" of the soil without disturbing it. Crouse et al. (1984) suggest that the entire setup should be as small as possible. Stiffer soil and flexible shelter can help to reduce soil-structure interaction. Novak (1985) found increasing the foundation depth results in increasing both stiffness and damping in the soil-foundation interface. Gap or different backfill between the soil and foundation cause significant changes to the dynamic properties of the system.

Different types of accelerometers have various advantages and disadvantages. The general characteristics are listed in table 2-1 (Bouche, 1974). As new technology improvements arise, some of the advantages or disadvantages may disappear. Sensitivity and frequency range is usually the most important index for selecting accelerometers. Higher sensitivity is usually preferred. ISO vibration criteria range from 1 Hz to 80 Hz (Gordon, 1991). BBN criteria use 4 to 100 Hz while FHA criteria use 5 to 50 Hz. Nugent and Amick (1991) suggest that the appropriate frequency range is between 2 Hz and 100 Hz.

Table 2-1 Regular Performance of Accelerometers

Characteristics	**Piezoelectric Accelerometer**	**Piezoresistive Accelerometer**	**Servo (Force-Balanced) Accelerometer**
Sensitivity (pC/g, mV/g)	12	20	250
Frequency Range (Hz)	2-5500	0-750	0-500
Resonance Frequency (Hz)	27000	2500	1000
Amplitude Range (g)	10000	25	15
Shock Rating (g)	10000	2000	250
Temperature Range (^oF)	-300 to +500	0 to +200	-45 to +185
Total Mass (g)	27	28	80

SECTION 3
PROCEDURE DEVELOPMENT

3.1 Vibration Criteria

Different vibration criteria provide different information to people who make judgements or create the design for the facility to be constructed. Although the vibration limitations for this specific site had been chosen to be 100 micro-inches per second RMS velocity in every one-third octave, other standards were observed to keep the results from this study versatile.

Most standards found in the literature use RMS velocity in every one-third-octave frequency band. It is a convenient format for both analog and digital data acquisition systems in field measurements. The frequency domain analysis in analog systems can be accomplished by applying band-pass filters. An integration circuit can transform acceleration output to velocity. The RMS value can be read by instruments as simple as multi-meters. The record presents the measure of total power in each frequency band. A white noise, of which the power spectrum density is constant, will appear to have amplitude increasing with frequency by the one-third-octave RMS presentation.

The digital data acquisition becomes very convenient with the use of fast and portable personal computers. The FFT vibration criteria, e.g. FHA criteria, become feasible for vibration evaluations. The differences between using different criteria vary with the characteristics of the vibration, i.e. narrow band or broad band. Generally, the FHA criteria are stricter in the lower frequency range. Regardless of which criteria are used, the FFT method provides more information than the one-third octave records. The results of the FFT presentation can be easily transformed into one-third octave presentation. Although there are not many cases where these criteria have been used to date, increasing usage can be expected.

The procedure developed in this study is based on the one-third octave RMS velocity criteria, but utilizes digital sampling and the FFT algorithm.

3.2 Measurement System

3.2.1 Sensors

Sensor selection is decided primarily by the resolution (sensitivity), frequency range, and cost. Some additional factors in the specific application of this study include weight, size, and roughness. Usually, higher sensitivity is better unless the data acquisition system does not have enough dynamic range to cover both the weakest and strongest vibration. Judgement on the rest of the properties depends on the task to be fulfilled.

The seismograph is rather a permanent setup that is both expensive and lacks mobility. The force-balanced type of accelerometers is sophisticated and versatile. Although they have a relatively low maximum frequency and are heavier, their performance is adequate for most civil engineering applications. The piezoresistive accelerometer is much simpler and smaller than the force-balanced type, yet it carries similar or even better frequency range. The thermal-stability is, nonetheless, unacceptably low for field tests. The piezoelectric accelerometer has the simplest mechanical structure, which makes it the roughest accelerometer of all. The commonly used type cannot be employed for low frequency measurement due to its poor frequency response and low resolution. Recent developments, however, have overcome these problems and they are now at the same performance level as force-balanced accelerometers.

Resonance frequencies of all accelerometers are much higher than the working frequency needed for measuring the ground micro-vibration of ChipFab sites to avoid sensitivity change with frequency. The weight of the sensor can greatly influence the resonance frequency of the whole measuring system, which is often not much higher than the working range for a soil–mounted station. A lighter sensor is much better for this application.

The force-balanced accelerometer has a much higher cost than the others. It is not as accessible, unless the project has a very large budget.

The temperature in the field cannot be easily manipulated. If some of the equipment needs to be protected from temperature extremes, the originally difficult job will become even harder. Stability against temperature therefore becomes another important issue.

Considering the above comparison, along with the fact that working conditions in the field of a candidate site are usually poor, a newly developed piezoelectric accelerometer was chosen for its performance, size, roughness, and reasonable price.

3.2.2 Mountings

Many factors must be taken into account when establishing a design methodology for the mounting system. A variety of different types of soil, rocks, water content, and other environmental conditions may be encountered. With all the possible selections of shapes and configurations of the mounting systems, creating specifications for the details of the mounting would be tedious and inefficient. In this research, some of the most important principles for designing the mounting systems have been generated. A fast, simple and academically reliable method to check the feasibility of the system after it is installed has been developed.

The mounting of the sensors serves as a mechanical filter between the ground and the sensor. If a single-degree-of-freedom (SDOF) system is used to simulate this filter (a second order filter), the equation of motion can be written as:

$$m\ddot{x} + c\dot{x} + kx = c\dot{x}_g + kx_g \qquad (3.1)$$

where:
m, c, k = the equivalent mass, damping coefficient, and stiffness of the mounting system
x = the displacement with respect to a stationary reference
x_g = the displacement of the ground. It can be rewritten as:

$$\ddot{x} + 2\xi\omega_n\dot{x} + \omega_n^2 x = 2\xi\omega_n\dot{x}_g + \omega_n^2 x_g \qquad (3.2)$$

where $\xi = \frac{c}{2\sqrt{km}}$ is the damping ratio and $\omega_n = \sqrt{\frac{k}{m}}$ is the natural frequency (in rad/sec). By solving for the general solution, the complex frequency-response function can be found to be:

$$H(\omega) = \frac{A_a(\omega)}{A_g(\omega)} = \frac{2j\xi\omega_n\omega + \omega_n^2}{\omega_n^2 - \omega^2 + 2j\xi\omega_n\omega} \qquad (3.3)$$

where:
A_a =the complex amplitude of acceleration with respect to a stationary reference ($\ddot{x}$)
A_g =the complex amplitude of ground acceleration ($\ddot{x}_g$)
$j = \sqrt{-1}$
ω=the input frequency (in rad/sec)

The frequency response function of a system that has a natural frequency of 70 Hz and damping ratio of 2% is shown in figure 3-1. A_g is the amplitude of ground acceleration while A_m is the amplitude of acceleration measured by the sensor, which is the same as A_a. It illustrates that for lightly damped mounting systems, the measured acceleration is very close to the ground acceleration if the majority of the interested ground vibration components lie fairly far under the natural frequency of the system.

The common criterion on the valid frequency limit is where the drop or rise of the frequency response function is 3 dB. For a requirement of the highest measured frequency to be f (Hz), the required system natural frequency can be found by solving the equation:

$$\left| \frac{2j\xi(2\pi f_n)(2\pi f) + (2\pi f_n)^2}{(2\pi f_n)^2 - (2\pi f)^2 + 2j\xi(2\pi f_n)(2\pi f)} \right| = 10^{3/20} \qquad (3.4)$$

where f_n is the natural frequency in Hz.

The solution is a relation between f_n and ξ. If the highest frequency to be measured is set to be 50 Hz, the solution can be expressed as shown in figure 3-2. The horizontal axis is natural frequency while the vertical axis is damping ratio. The dark area is the valid combination of natural frequency and damping ratio.

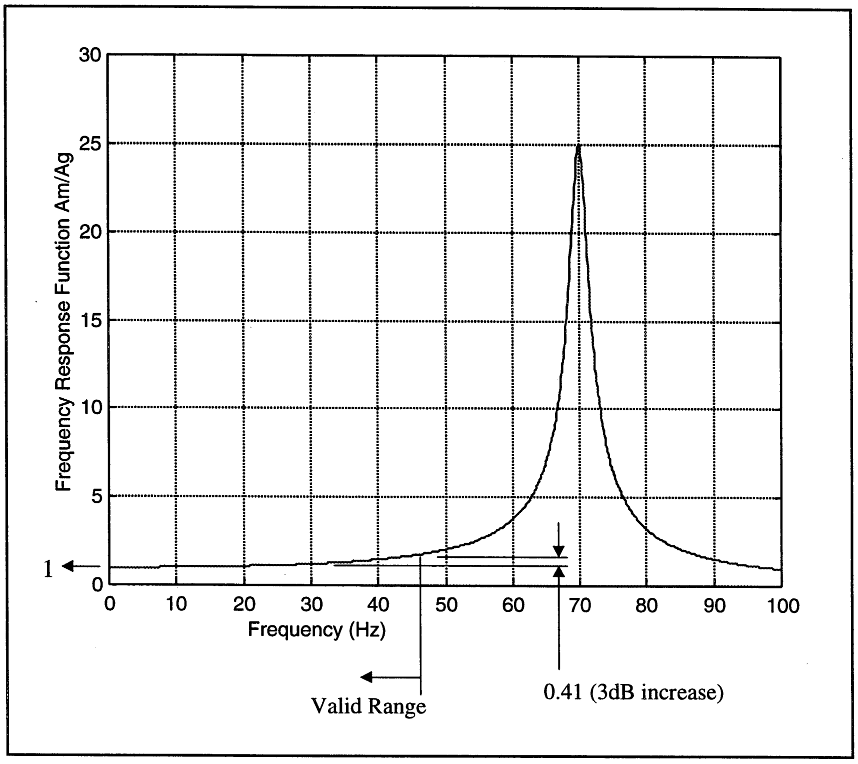


Figure 3-1 Typical Frequency Response Function

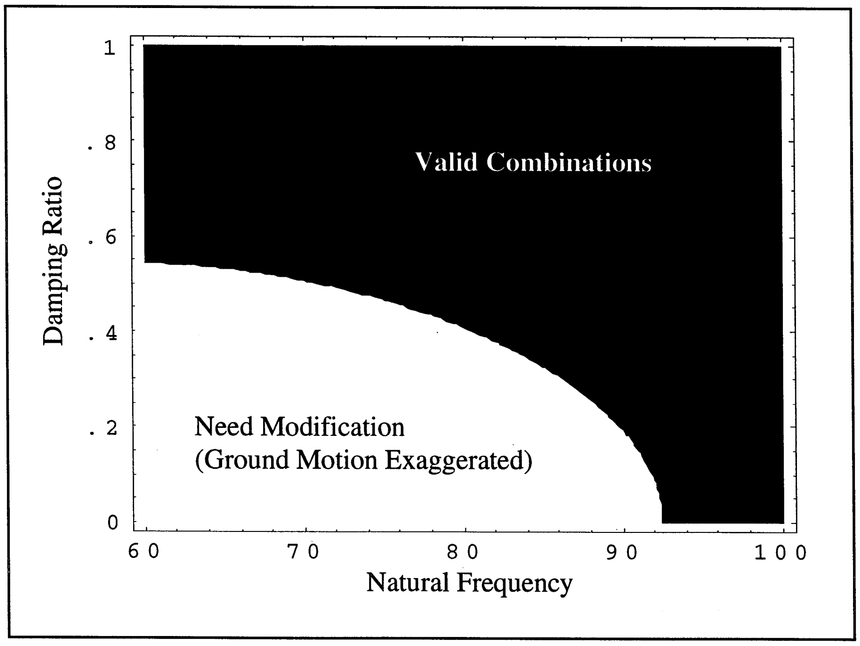


Figure 3-2 Valid Combinations of Natural Frequencies and Damping Ratios

From this point of view, the mounting system should be as stiff and lightweight as possible. A common option is to use a concrete block or slab a few feet in dimensions embedded in the ground. It is widely used in seismological surveillance. However, for application in early evaluation for potential construction sites, the measuring stations sometimes need to be moved to cover a large area and, eventually, removed from the site. The necessity of backfill when concrete base is not fabricated at the exact position to be measured makes the situation more complicated. Some smaller and more portable mounting sets are preferred. Another option is to use pile style mounting. This is usually a steel rod driven into the ground. The steel is not a favorable material for the job because of a higher density and smaller contact surface to the soil. However, the rod can be hammered or squeezed into the soil and therefore increase the contact stiffness. The total size and weight are small so that it is portable and has less influence on the measured object—the ground. The length of the rod needs to be long enough to establish sufficient bond with the soil but significantly shorter than the wavelength of soil to avoid cancellation of opposite motions. For example, the typical p-wave velocity for soil is about 1000~2500m/sec (Das). The s-wave is commonly 4 to 5 times slower than the p-wave. For a frequency range under 100Hz, the minimum wavelength is:

$$\frac{V_s}{f_{max}} \geq \frac{1000/5}{100} = 2\,(\mathrm{m}) \tag{3.5}$$

where V_s is the shear wave velocity and f_{max} is the highest frequency to be measured. The rods should not exceed 1 m in length. The topsoil sometimes can have a p-wave velocity as low as 200m/sec. This should be avoided. Setting up the mounting system on the soil layer under the topsoil can both increase the interfacial stiffness and the upper limit of the system dimensions.

The discussion above has been limited to SDOF systems. The real mounting system involves a partially flexible structure interacting with comparatively very flexible soil. The problem can be greatly simplified by making the man-made part of the mounting system as rigid as possible. Since most engineering materials have much greater elastic modulus than the soil, the man-made part is usually stiff enough provided it is not extraordinarily thin. This reduces the problem into a 6-DOF-vibration system (three translations and three rotations). For the sensory system conceptually shown in figure 3-3, eccentricity of the sensors on x-y plane is small. The rotation on x-y plane (θ_z) is not significant. Each of the other two rotations is coupled with one of the translation, i.e. θ_y with x and θ_x with y.

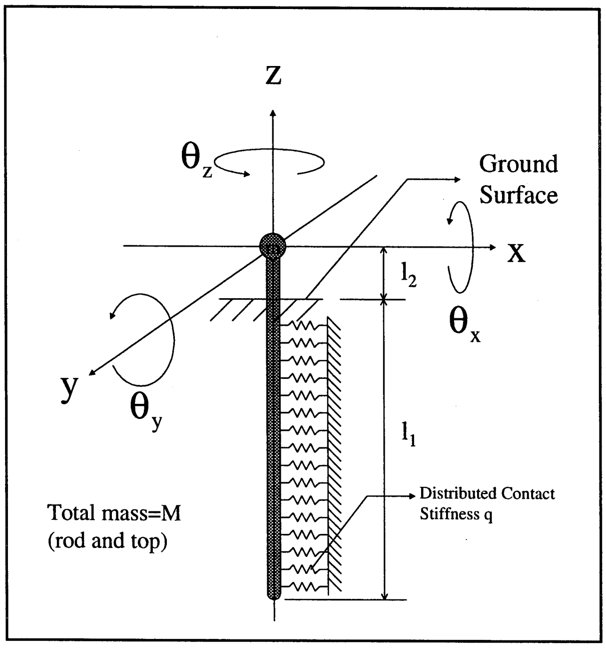


Figure 3-3 A Sketch of Steel-bar Mounting Systems

For one set of the translation and rotation, the equation of motion can be written as:

$$\overline{M}\begin{Bmatrix}\ddot{x}\\ \ddot{\theta}\end{Bmatrix}+\overline{C}\begin{Bmatrix}\dot{x}\\ \dot{\theta}\end{Bmatrix}+\overline{K}\begin{Bmatrix}x\\ \theta\end{Bmatrix}=-\begin{Bmatrix}M\\ \frac{(M-m)(l_1+l_2)}{2}\end{Bmatrix}a_g \tag{3.6}$$

where:

$$\overline{M}=\begin{bmatrix}M & \frac{(M-m)(l_1+l_2)}{2}\\ \frac{(M-m)(l_1+l_2)}{2} & I\end{bmatrix}$$

$$\overline{K}=\begin{bmatrix}l_1 q & \frac{l_1+2l_2}{2}l_1 q\\ \frac{l_1+2l_2}{2}l_1 q & \left(l_2^2+l_1 l_2+\frac{l_1^2}{3}\right)l_1 q\end{bmatrix}$$

M = the total mass of the system
M = the portion of mass concentrated at the sensory block
l_1 = the length of the rod submerged in the soil
l_2 = the length of the rod exposed over the ground
a_g = the ground acceleration (time history)

Since the corresponding damping force is quite small, the assumption of $\overline{C}=c_0\overline{K}$ is reasonable, which will yield a quite small error. The particular solution is:

$$\begin{Bmatrix}x\\ \theta\end{Bmatrix}=-\left(-\omega^2\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}+j\omega c_0\overline{M}^{-1}\overline{K}+\overline{M}^{-1}\overline{K}\right)^{-1}\overline{M}^{-1}\begin{Bmatrix}M\\ \frac{(M-m)(l_1+l_2)}{2}\end{Bmatrix}A_g e^{j\omega t} \tag{3.7}$$

or written in acceleration:

$$\begin{Bmatrix} \ddot{x} \\ \ddot{\theta} \end{Bmatrix} = -\left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \frac{c_0}{j\omega} \overline{M}^{-1}\overline{K} - \frac{1}{\omega^2} \overline{M}^{-1}\overline{K} \right)^{-1} \overline{M}^{-1} \begin{Bmatrix} M \\ \frac{(M-m)(l_1+l_2)}{2} \end{Bmatrix} A_g e^{j\omega t} \tag{3.8}$$

where:
A_g = the amplitude (or Fourier coefficient) of the ground acceleration

The horizontal acceleration amplitude with respect to a stationary reference is:

$$\ddot{X}_a = \ddot{X} + A_g = \left(-\begin{bmatrix} 1 & 0 \end{bmatrix} \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \frac{c_0}{j\omega} \overline{M}^{-1}\overline{K} - \frac{1}{\omega^2} \overline{M}^{-1}\overline{K} \right)^{-1} \overline{M}^{-1} \begin{Bmatrix} M \\ \frac{(M-m)(l_1+l_2)}{2} \end{Bmatrix} + 1 \right) A_g \tag{3.9}$$

$$= H(\omega, M, m, l_1, l_2, q) A_g$$

where:
$\ddot{X}_a$ = the amplitude of the response acceleration with respect to a stationary reference.

If $|H|$ has a less than 3dB variation in the frequency range, this system is considered valid. Some of variables (M, l_1, l_2) can be roughly measured while others cannot be obtained directly.

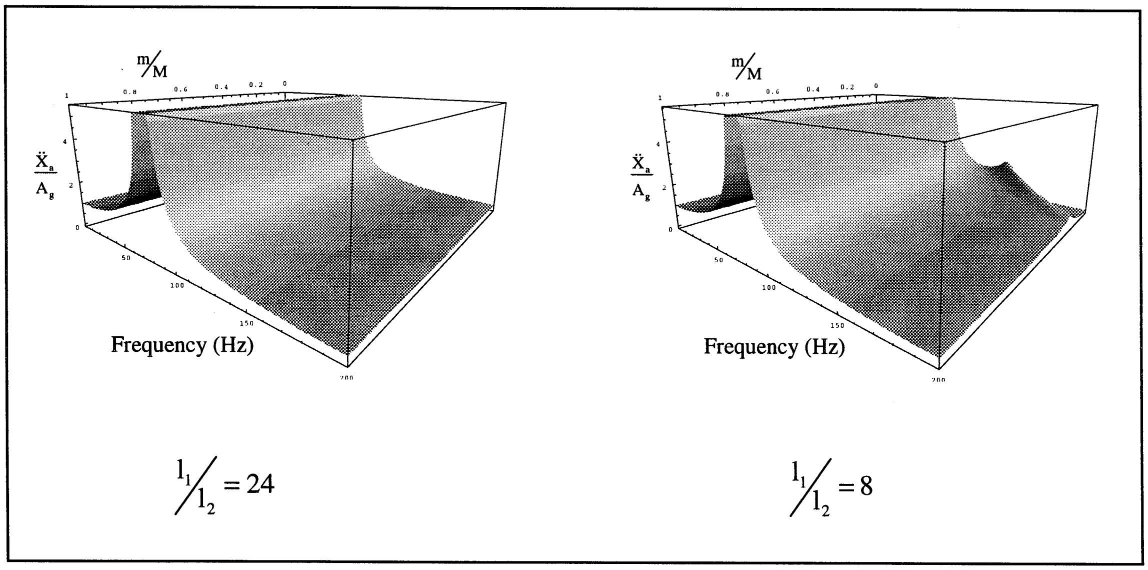
Since the natural frequency and damping ratio of the system can be easily obtained by a simple hammer-test, they can be set as controlled variables. If ϕ is the modal shape matrix of the system (real valued and weighted orthogonal because of proportional damping) and define $\begin{Bmatrix} x \\ \theta \end{Bmatrix} = \phi Y$, the equation of motion becomes:

$$\phi^T \overline{M} \phi \ddot{Y} + \phi^T \overline{C} \phi \dot{Y} + \phi^T \overline{K} \phi Y = -\phi^T \begin{Bmatrix} M \\ \frac{(M-m)(l_1+l_2)}{2} \end{Bmatrix} a_g \tag{3.10}$$

where all matrices become diagonal. It can be easily derived that the natural frequencies are the square roots of eigenvalues for $\overline{M}^{-1}\overline{K}$ and the damping ratio of the i^{th} mode is $\frac{c_0 \omega_i}{2}$ (ω_i is the ith natural frequency). By solving the eignvalues of $\overline{M}^{-1}\overline{K}$ and forcing them to be equal to ω_i^2, the contact stiffness q can be presented as a function of ω and m. The result can be examined by substituting q back into the frequency response function H. Two results with same natural frequency (60Hz), same damping ratio (1%), and different length exposed over ground (l_2) are shown in figure 3-4. It can be seen that although a higher l_1 to l_2 ratio makes less impact on the frequency response function, it does not matter as much when a considerable amount of mass is concentrated on top of the system. This demonstrates that the only important factors of the system are natural frequency and damping ratio for the 1st mode providing that the majority of the mounting rod is submerged in soil and the sensor mounting block is heavier than the rest of the system. It is evident that none of the variables except for the natural frequency and damping ratio need to be measured accurately under the prescribed condition.

The principles of the mounting system configuration can be concluded as follows:

1. Total weight should be as small as possible.
2. Larger surface area of the embedded part is preferred.
3. The dimensions of the embedded part should be significantly smaller than the minimum wavelength of the soil corresponding to the maximum frequency to be measured.
4. The majority of the system weight should be concentrated on the top, where the sensors are located (e.g. 50%).
5. Validity of the system should be checked by hammer tests, which provide the first natural frequency and damping ratio.
6. Natural frequency lower than the maximum frequency to be measured is not acceptable because the ground motion may be underestimated.
7. The legitimate combination of the natural frequency and damping ratio is governed by equation 3-4.



$l_1/l_2 = 24$

$l_1/l_2 = 8$

Figure 3-4 Frequency Response Function for Different Mounting Configuration

3.2.3 Noise Insulation

When high sensitivity transducers are used to measure the micro-vibration, even talking can be a serious noise source. The sensors should be protected from the interference from other environmental events such as wind, rain, snow, and animal activities.

To prevent electromagnetic interference, the entire system must be well shielded. The sensors and the data acquisition systems are usually well shielded as shipped. The cable that connects these two systems must be carefully selected to ensure signal protection.

3.3 Data Acquisition System

Digital data acquisition allows easy data processing at a low cost. With proper filtering, the FFT algorithm can directly derive the one-third-octave RMS presentation. It can even account for the design of a structure without further processing.

Proper analog filtering is, on most occasions, needed to ensure that no frequency interference occurs. According to the Nyquist sampling theory, the highest frequency component that can be properly identified is half of the sampling frequency. A low-pass filter that has a cut-off frequency lower than one half of the sampling frequency can satisfy this requirement. If it is found that the mechanical filter such as that of the sensory system or that of the measured object itself can satisfy the condition, the electronic low-pass filter can be ignored. A high-pass filter is optional. It can reduce the data offset given by some sensors.

Dynamic range of an analog to digital (A/D) converter is specified by the number of bits assigned to each data point. The new products on the market almost all use over 16 bits for a data point. 16 bit acquisition cuts the full range into 65536 levels to provide 96 dB digital dynamic range. It should be noted that some existing systems have only 72 dB dynamic range (12 bits) and are not suitable for field measurements of micro-vibration.

There are some concerns about the attenuation of weak signals and noise buildup along the long cables since the distance considered in the field is thousands of feet. To increase the signal-noise ratio, the charge or voltage amplifier needs to be as close as possible to the sensors. The sensors with built-in amplifying circuits are preferable.

Noise accumulation along the signal cables can be reduced by using differential signal connections where none of the signal wire is directly grounded at any point. With this connection, the interference to the signal in cables applies uniformly to both wires. They will be cancelled when subtracting one from the other in the A/D converter.

Another important advantage of the differential connection is to eliminate the different potential of the ground in multiple locations. Many sensors are locally grounded through the shell by assuming no difference between the electric potential at the local grounding and the grounding used by the data acquisition system. This is often correct in the laboratory since the distance is small and every circuit shares the same grounding with the foundation of the structure. In the field, this may not be true. The potential difference at multiple sites can induce significant error or even damage equipment. Therefore, the sensors insulated from the shells were chosen. Otherwise, additional insulation between sensors and mounting systems is required.

SECTION 4
APPLICATION TO A CANDIDATE SITE

To ensure valid data collection and follow-up analysis, the measuring system must be set up correctly. The system includes a sensory system with suitable sensors, and data acquisition and recording systems. The sensors must be correctly installed with precise calibrations and be suitably distributed. These issues are critical for obtaining accurate measurements and are discussed in the following subsections.

4.1 Sensory System

The study is concerned with measuring micro-vibrations throughout an approximately 200-acre site. Usually, for high precision measurement, a special type of accelerometer, called a force-balanced accelerometer, is used for its high sensitivity, high measurement resolution and low frequency range. After some intensified national searching, it was decided to use a newly developed piezoelectric type accelerometer, 393 B31 ICP (PCB). This sensor was tested before formal data acquisition and was proven to be a suitable choice for the proposed measurement. This new sensor is more economical than other state-of-the-art force-balanced sensors.

The specifications of this sensor which relate to measuring micro-vibrations are as follows:

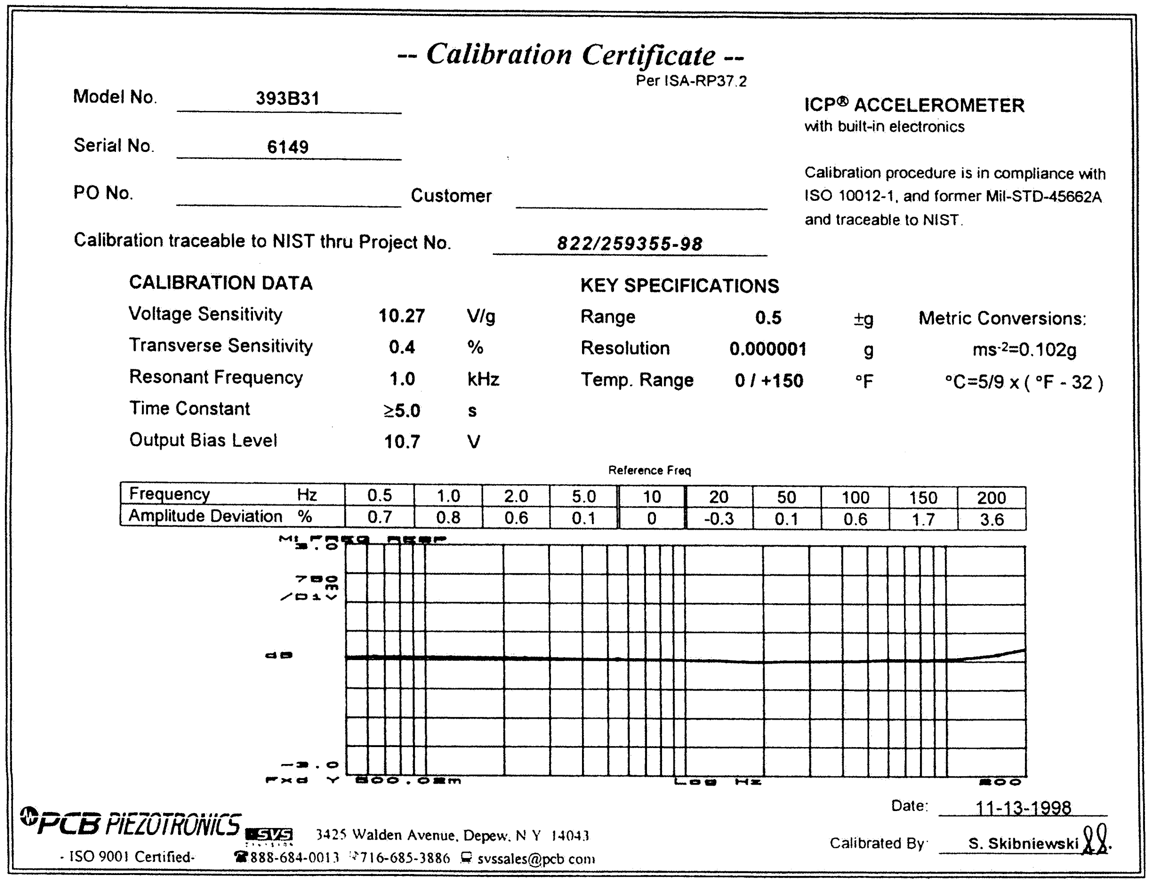
Resolution: 1 μg
Sensitivity: 10V/g
Frequency Range: 0.05-200 Hz
Non-linearity: < 1%

A power unit, 480 E09 ICP (PCB) was used with the accelerometer (sensor), which can provide x10 amplification of the signals, necessary to increase the measurement sensitivity. The output of the signal was taken as floating ground differential output. The power supply was run with batteries.

Calibration data of the sensor and the measuring system with 1000 ft cables are provided in figures 4-1 and 4-2. These are necessary to ensure the accuracy of the long distance measurements.

4.2 Data Acquisition and Recording

Usually, two types of signal recording are used, an analog tape recorder and a digital computer. Generally, tape recorders offer long recording times and are simple to operate. However, their dynamic range cannot exceed 50 dB and therefore the recording accuracy is low. Another disadvantage of the analog recorder is that it is not convenient for field measurements. Digital technology has a much higher dynamic range. It is operable for in-situ testing, and allows the signals to be analyzed in real-time, so that the operator can



-- Calibration Certificate --

Per ISA-RP37.2

Model No. 393B31

Serial No. 6149

PO No. Customer

Calibration traceable to NIST thru Project No. 822/259355-98

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with ISO 10012-1, and former Mil-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	10.27	V/g
Transverse Sensitivity	0.4	%
Resonant Frequency	1.0	kHz
Time Constant	≥5.0	s
Output Bias Level	10.7	V

KEY SPECIFICATIONS

Range	0.5	±g
Resolution	0.000001	g
Temp. Range	0 / +150	°F

Metric Conversions:
ms^{-2}=0.102g
°C=5/9 x (°F - 32)

Reference Freq

Frequency Hz	0.5	1.0	2.0	5.0	10	20	50	100	150	200
Amplitude Deviation %	0.7	0.8	0.6	0.1	0	-0.3	0.1	0.6	1.7	3.6

PCB PIEZOTRONICS SVS 3425 Walden Avenue, Depew, N Y 14043
- ISO 9001 Certified- ☎888-684-0013 716-685-3886 svssales@pcb com

Date: 11-13-1998

Calibrated By: S. Skibniewski

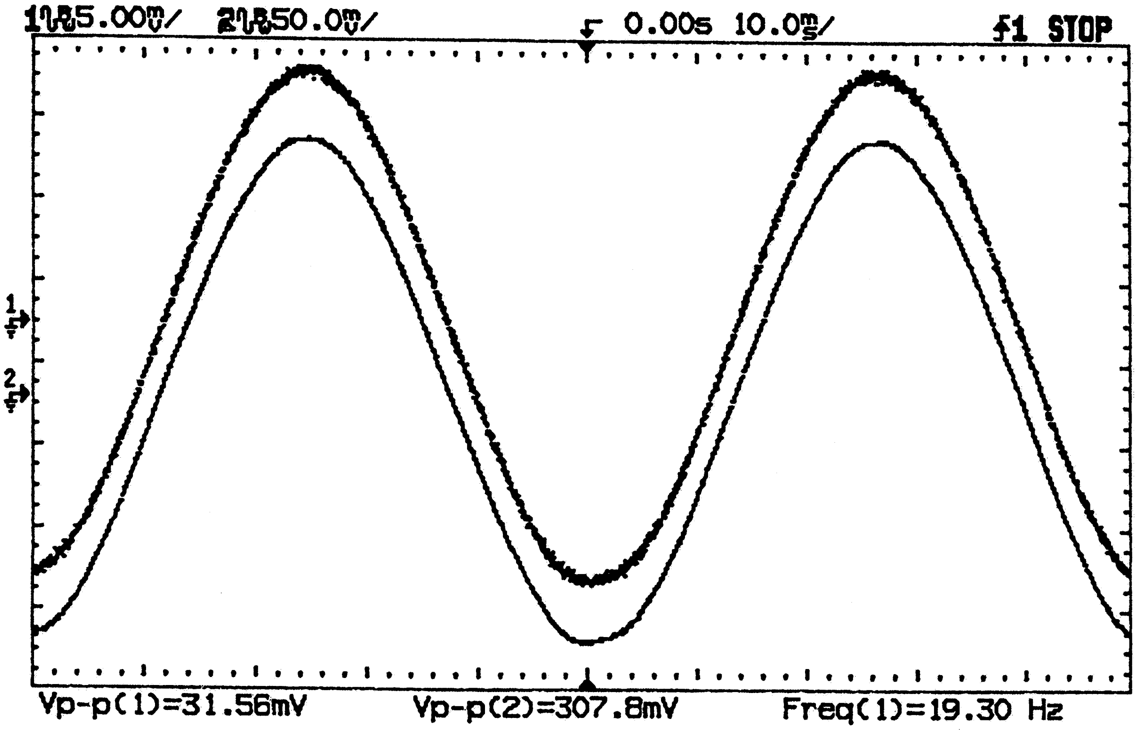


Figure 4-1 Calibration Certificate for the Sensor

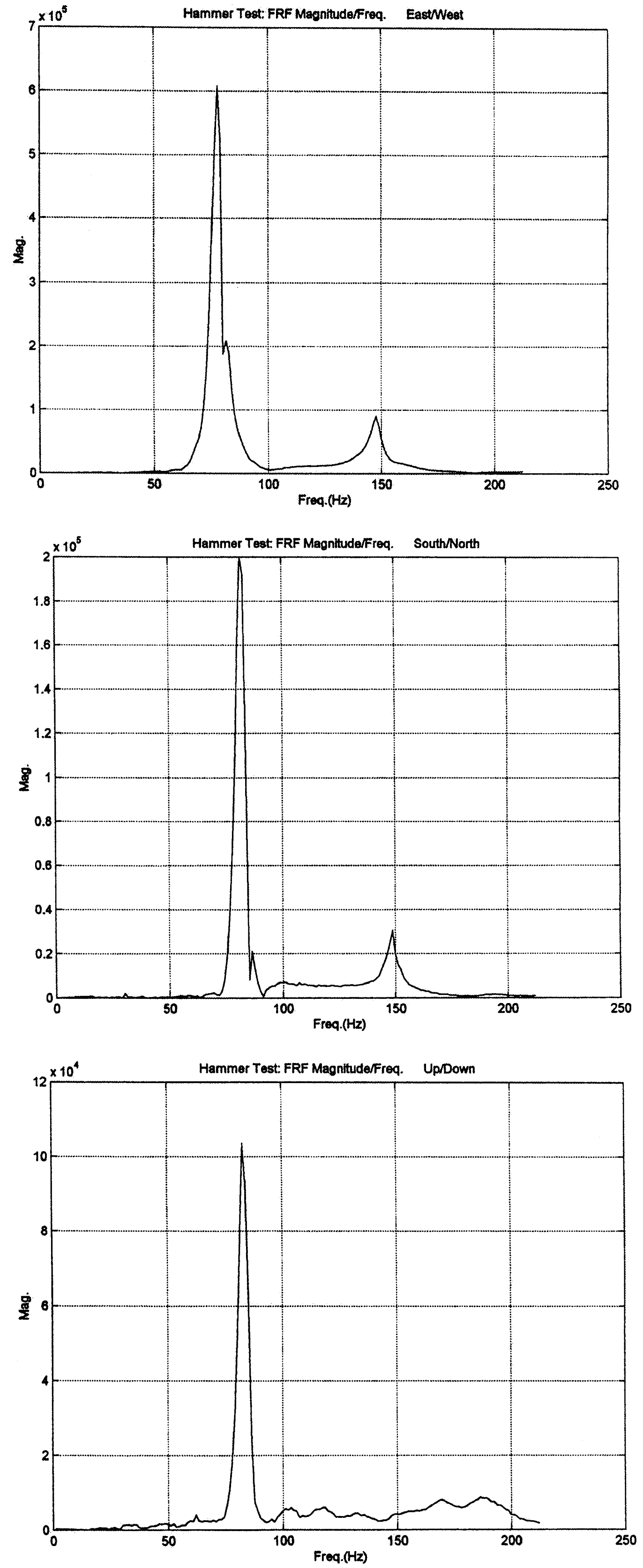


Figure 4-2 Calibration of the Measurement System with 1,000 ft. Cables

immediately reject abnormal phenomena. However, because of small memory space, the recording time is limited.

The major purpose of this project was to measure micro-vibrations, so high accuracy signal pick up was required and therefore, digital recording was used for the field tests. The data acquisition equipment included Pentium II personal computers with AT-MIO-16 XE-10 A/D boards (National Instruments), which provide a 16 bit A/D converter with a dynamic range of 96 dB. If the pre-programmable amplifier is activated, the corresponding dynamic range can be as high as 136 dB. In fact, the length of the recording digits or the dynamic range of the A/D board is critical in high precision measurements, to reduce quantification errors.

Software control of the A/D board is based on Virtual Bench (National Instruments), which can automatically activate the programmable amplifier. It allows convenient monitoring of the signal pickup and performs necessary mathematical calculations. The software can quickly write to the hard drive, which is a critical factor for obtaining transient signals due to mine explosions and passing trains. The input to the A/D board is differential with floating ground. Although the number of input channels is just one-half of the single-end manner, the signal-to-noise ratio can be greatly increased, which is suitable for obtaining ground measurements with long distance cabling. In this way, the measurement noises induced by the voltage differences of the grounding between the measurement locations and the computers can be greatly reduced.

The measurement system is conceptually shown in figure 4-3.

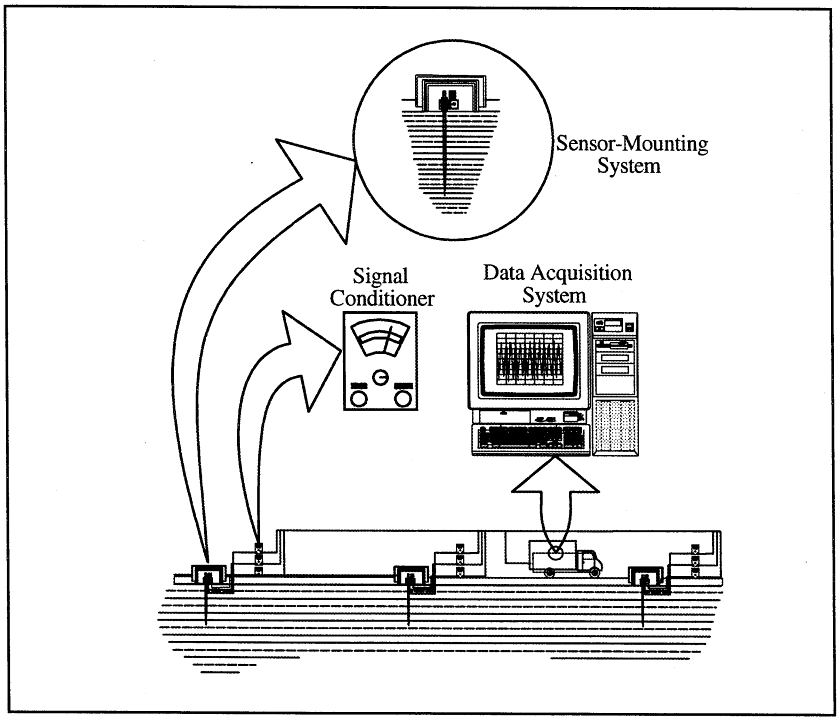


Figure 4-3 Field Measurement Setup

4.3 Sensor Installation

The installation of sensors is one of the most important steps in the whole process. The challenge is determining how to accurately detect the signal from the ground through the mounting fixture within the proper frequency range. According to Klein, et al., 1995, the frequency resolution for analyzing signals is between 3.15 Hz and 56.12 Hz. The lowest natural frequency of the fixture must be at least 56.12+ 1/3 x 56.12 = 74.8 Hz with about 20% damping. The detail of justification on validity of the system is derived in Section 3.

The fixture used in this project and its dimensions are shown in figure 4-4. It can be seen that the sensors are arranged to have two perpendicular horizontal directions and one vertical direction measurement, to measure the 3D ground motions. About 60% of the system weight was concentrated at the top, which extended 2 inches above the ground surface.

The installation is conceptually shown in figure 4-5. Grass and soft soils are first removed until hard soil appears. This ensures a solid setting for the fixture. The ground hole is dug to fit inner and outer acoustic boxes to isolate the influence of ambient noise. The acoustic box is necessary to increase the measurement signal-to-noise ratio.

In-field calibration was carried out to fit the measurement standard. A piezoelectric modally tuned force hammer was used to measure the input force. The resulting frequency response functions were averaged to reduce noise level. A least-square estimation was used to find the natural frequency and damping ratio.

Since the required measurement sensitivity is very high, sufficient noise reduction must be provided to reduce its level. Figure 4-5 shows the sensor and its fixture, and figures 4-6 through 4-11 show the layout of acoustic boxes, and a step-by-step view of their assembly. The acoustic box can both reduce the interference from sound and protect the sensory system from direct impact of other environmental activities such as wind and curious animals.

The power units were placed close to the sensors for signal amplifications and power supplies. The amplified signals were transferred through coaxial low-noise cables.

4.4 Distribution of the Measurement Locations

The proposed land for measurement was not well developed. The site had many bushes, deep grass and trees, which made the installation of sensors and cabling quite difficult. The time window to obtain the measurements was small due to the limited number of mine explorations.

The measurement that was carried out was limited to two sections of the site, divided by North America Drive. In this way, the measurements can roughly represent the mean value of the ground vibrations of the two sections. In each section, three locations were placed. The middle location was set to be at least 200 feet away from the measurement

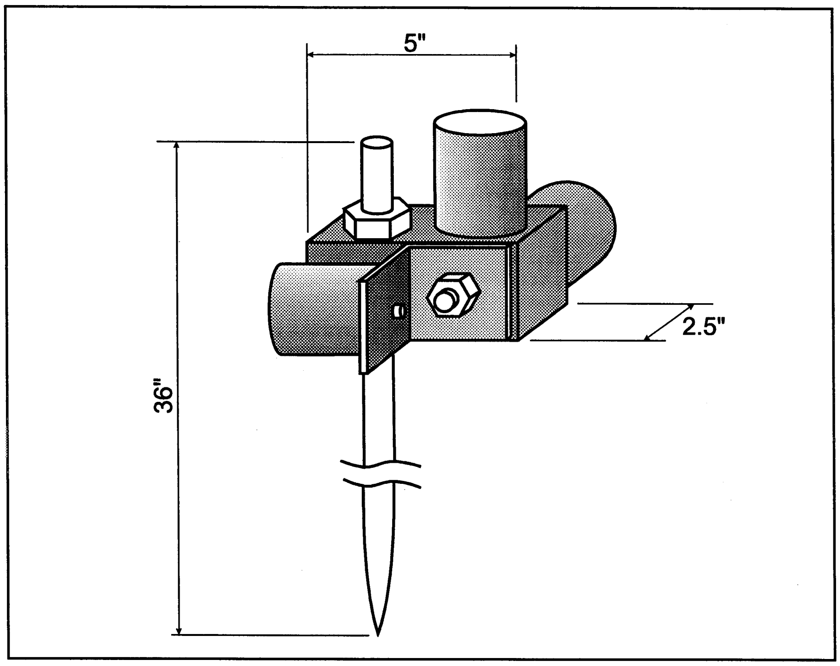


Figure 4-4 Sensor Mounting Setup

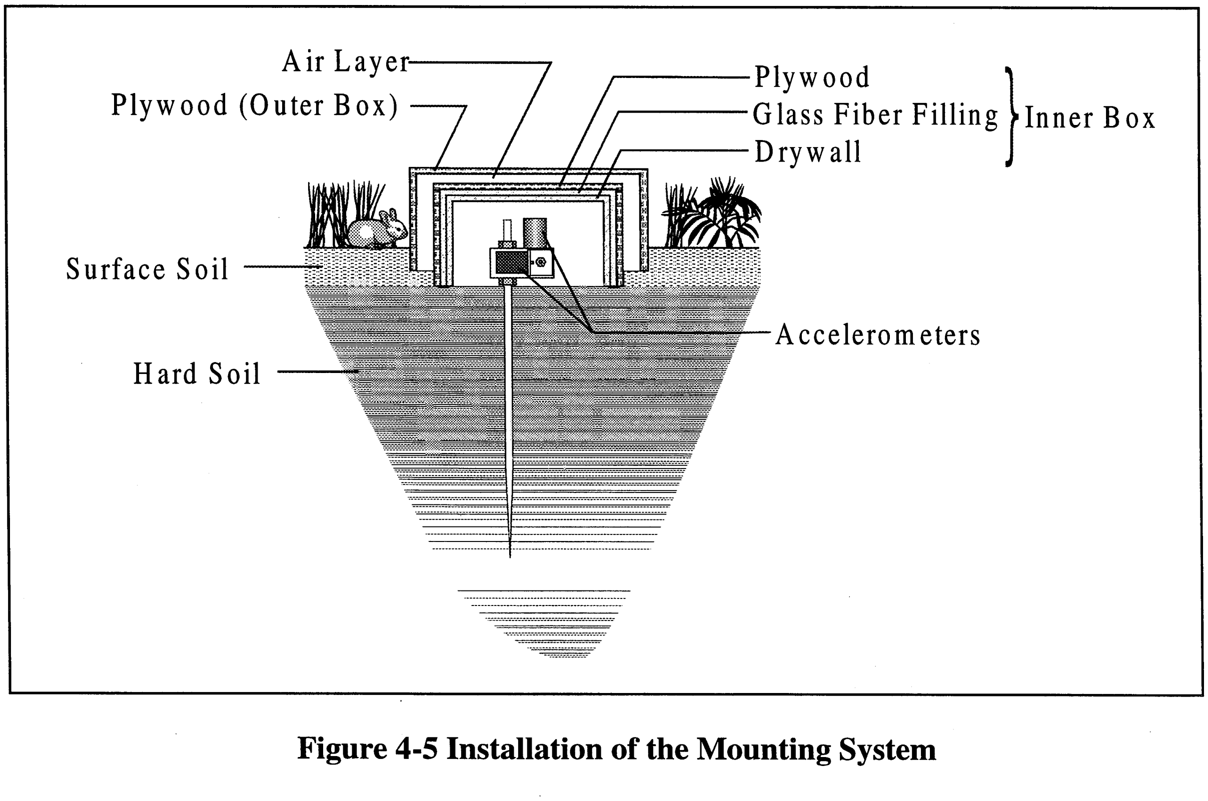


Figure 4-5 Installation of the Mounting System

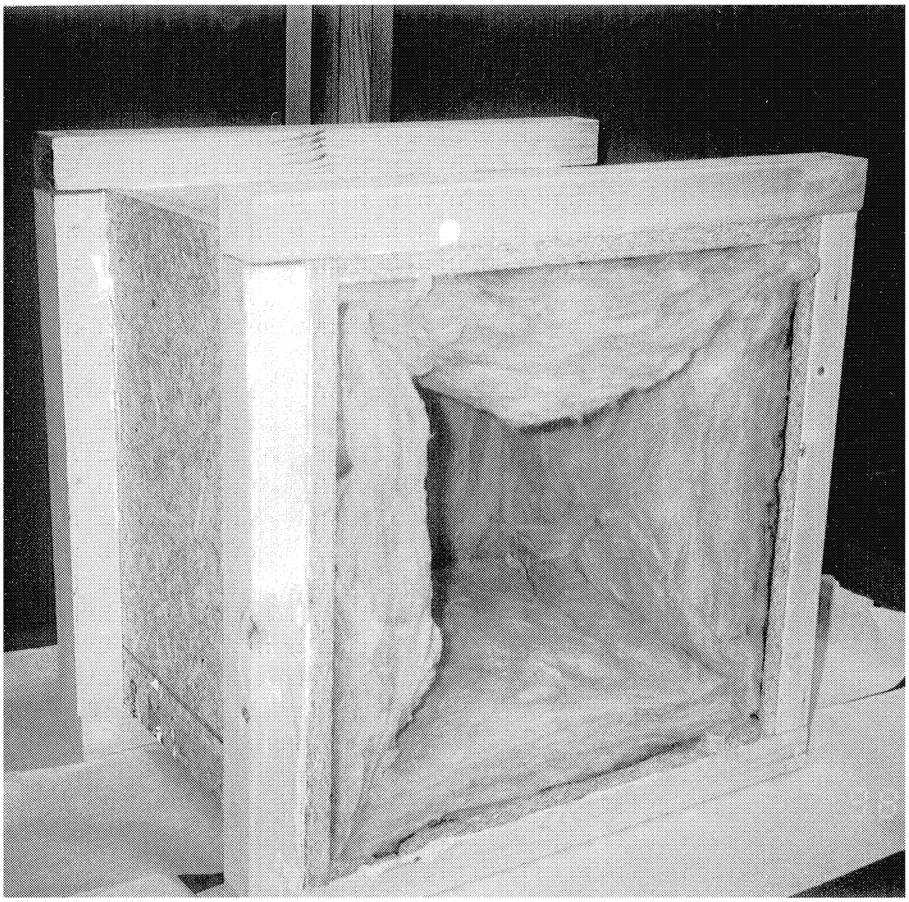


Figure 4-6 Glass Fiber Filling in the Inner Sound Box

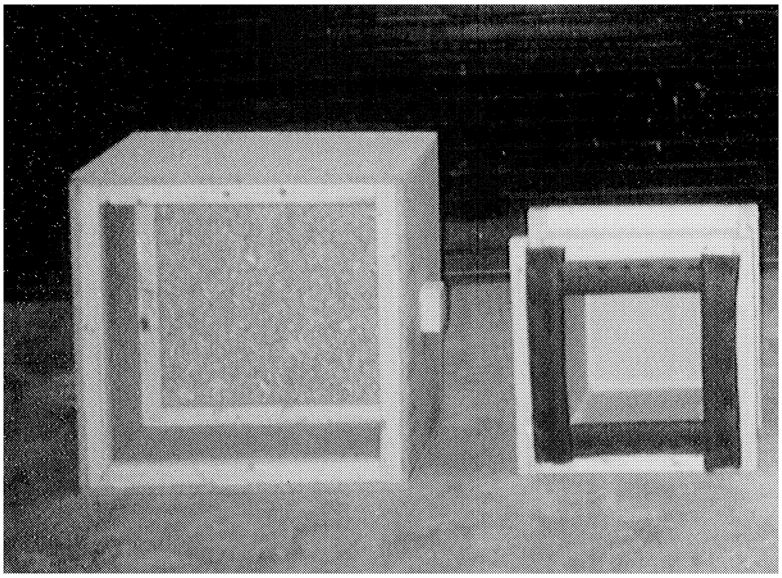


Figure 4-7 Inner and Outer Sound Boxes

Figure 4-8 Mounting Base of the Sensors

Figure 4-9 Sensor Setup

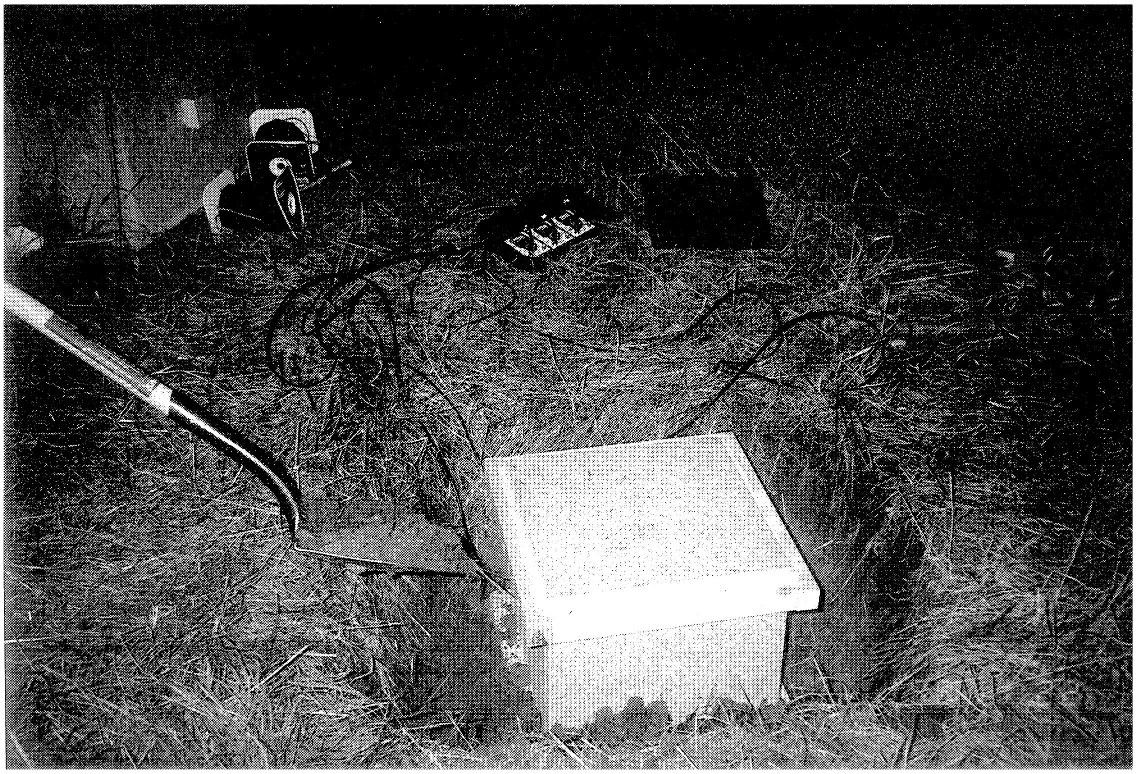


Figure 4-10 Placing Inner Sound Box

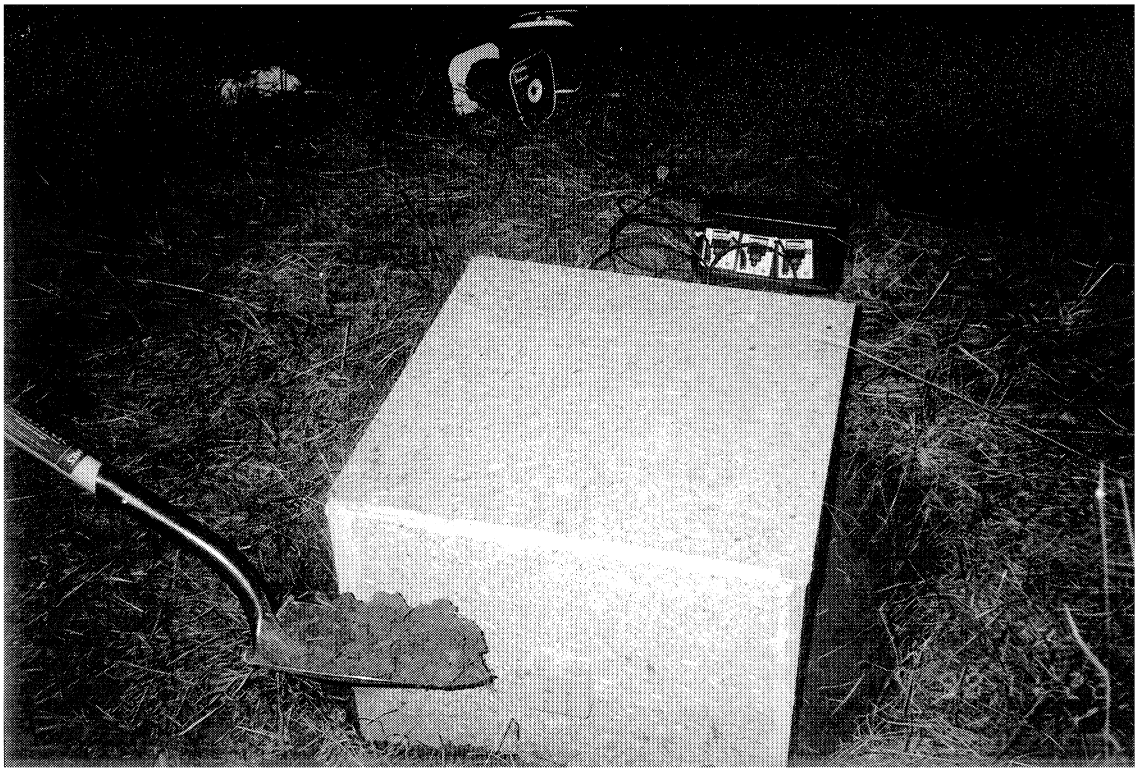


Figure 4-11 Placing Outer Sound Box

station. Since the measurement crews and electricity generator were operating, they could affect the ground signals.

At each location, three direction signals were arranged to have east-west, north-south and vertical sensors. The three locations roughly formed a measurement line. Each measurement line was roughly perpendicular to the aforementioned railway and Route 400. The arrangement was prepared to measure the influence of the vibration sources from the train and high traffic volumes. The detailed location and relative coordinates are shown in figure 4-1, where the relative coordinate was determined according to a meter using Global Positioning Systems as well as in-field measurement geographically. The coordinates, however, are not exactly accurate for the rough ambient conditions.

The measurement was first carried out in the west section. Upon finishing the first line, the measurement in the east second was performed. In this manner, signals with nine channels were picked up simultaneously in each line. Two sets of data were acquired simultaneously with two identical sets of computers and A/D boards in order to ensure that the necessary data were obtained for this study within a limited time period, from November 3 to 25, 1998.

SECTION 5
MEASUREMENT PROCEDURE

5.1 Environmental Conditions and Other Constraints

This study was conducted over a limited time period and with a minimum amount of personnel. It was not possible to complete the measurements in many locations of the site, or to consider all the probable influencing factors (i.e., the speed of trains and autos, the exact number of cars on each train, loading of trains and trucks, explosive quantity, local temperature difference and wind velocity). Therefore, the measured results contain a collection of many possible vibration sources. The results, however, did include four conditions, specified by the sponsors, which were:

a. The condition of trains passing by with normal speed, normal length of the train and normal loading.
b. The condition of regular mine exploration.
c. Daily highway traffic with heavy volume (both cars and truckers).
d. Nightly highway traffic with light volume.

5.2 Data Acquisition and Sampling Rate

The sampling rate for both data acquisition systems was chosen to be 2,000 Hz with standard anti-aliasing treatment. In this way, the follow up FFT-analysis can have up to 1,000 Hz bandwidth. In fact, since the output of the accelerometer does not show significant peaks after 150 Hz, the selected sampling rate has already satisfied the Nyquist sampling theory, no aliasing can be found even without low-pass filters.

The sampling length was about 10 second for each record. In order to obtain sufficient records for follow up averaging, for each event, the recording contained at least five continuous pieces.

SECTION 6
MATHEMATICAL BACKGROUND

According to the ISO standard, in order to evaluate the effects of ambient (site, building, etc.) vibration with high-precision equipment, the root-mean square velocity with one-third-octave band must be used. The acceleration signal is therefore first measured and then the velocity is calculated correspondingly. It is noted that conventional signal processing for such a measurement is often done through analog instruments. Although the ISO standard is intended for the analog instruments, such as the one-third-octave along filters, RMS meters, etc., it is best to use the digital computer to replace the traditional measurement. However, the validity of the digital signal treatment must be justified and several formulae of the numerical treatment must be proven. In the following, such a treatment is briefly discussed as the mathematical background for the proposed signal analyses.

6.1 Transformation from Acceleration to Velocity

Since the required value is velocity and the measured signal is acceleration, it is necessary to transform the measured data to velocity. This can be done in both the time domain and the frequency domain. The latter, however, will yield better results because of dealing with integration constant. The following transformation is well known:

Let $x_a(t)$ and $x_v(t)$ denote the acceleration and the velocity signals respectively. After the FFT, the relation in the frequency domain can be written as

$$X_a(f) = j\omega\, X_v(f)$$

$$X_v(f) = 1/j\omega\, X_a(f)$$

where the $X_a(f)$ and $X_v(f)$ stand for signals expressed in the frequency domain. The above equations are used to transfer the acceleration into the velocity.

In the time domain, they become

$$x_a(t) = \mathrm{IFFT}[\, X_a(f)\,]$$

$$x_v(t) = \mathrm{IFFT}[\, X_v(f)\,]$$

where the $x_a(t)$ and $x_v(t)$ stand for signals expressed in the time domain. The computerized Fast Fourier Transform (FFT) and the Inverse Fast Fourier Transform (IFFT) are easy to perform with little computational burden. Therefore, the entire data processing and analyses are based on the spectrum analyses described by the above equations.

6.2 Relationship between the Frequency Spectra and RMS Value

The next step is to calculate the RMS valued velocity from the spectra directly obtained from the FFT operation on the measured data. The formulae derived in the following are not used in the literature. However, they are easy to use under the above mentioned spectrum analyses. The deduction of these formulae is presented in the following.

In the operation of discrete Fourier Transformation, the following formulae are true:

Forward transformation: $X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi\frac{nk}{N}}$ $(k = 0, 1, 2, \ldots N\text{-}1)$ (6.1)

Inverse transformation: $x_n = \sum_{k=0}^{N-1} X_k e^{j2\pi\frac{nk}{N}}$ $(n = 0, 1, 2, \ldots N\text{-}1)$ (6.2)

where N is the total number of measurement points. k and n stand for specific points. Note that, X_k is symmetric in terms of the following relationship

$$X_k = X_{N-k}^{*} \tag{6.3}$$

where the super script * stands for the complex conjugate.

In equation (6.2), the term $e^{j2\pi\frac{nk}{N}}$ has certain properties, which shall be used to evaluate the summations and to derive the applicable formula for the calculation of the RMS values in the one-third-octave band.

First let $E_n = \sum_{k=0}^{N-1} e^{j2\pi\frac{nk}{N}}$ $(n = 0, 1, 2, \ldots 2N\text{-}2)$ (6.4)

Here, n can be treated as a variable. When n = 0, apparently one can have

$$E_0 = N \tag{6.5}$$

Furthermore, when n = N, one can also have

$$E_n = \sum_{k=0}^{N-1} e^{j2\pi k} \tag{6.6}$$

Except the above two cases, n will fall between 0 to 2N-1. In such a circumstance, n will not be dividable integrally. Therefore, the value of E_n should be evaluated separately. Note that, E_n is nothing but integration of sine and/or cosine functions over an integral period. Therefore, the following is true:

$$E_n = 0 \; (n = 1, 2, \; 3, ... 2N\text{-}2, n \quad N) \qquad (6.7)$$

The root mean square value of a function in the time domain is defined as follows:

$$R = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt}$$

In the discrete time domain, the above relationship becomes:

$$R = \sqrt{\frac{1}{T}\sum_{n=0}^{N-1} x_n^2(t)\Delta t} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} x_n^2(t)} \qquad (6.8)$$

Substitution of (6.2) into (6.8) yields

$$R = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}\left(\frac{1}{N}\sum_{k=0}^{N-1} X_k e^{j2\pi\frac{nk}{N}}\right)^2} = \sqrt{\frac{1}{N^3}\sum_{n=0}^{N-1}\sum_{k=0}^{N-1}\sum_{m=0}^{N-1} X_k X_m e^{j2\pi\frac{n(m+k)}{N}}}$$

then,

$$R == \sqrt{\frac{1}{N^3}\sum_{n=0}^{N-1}\sum_{k=0}^{N-1} X_k X_m \sum_{m=0}^{N-1} e^{j2\pi\frac{n(m+k)}{N}}} \qquad (6.9)$$

Using the notation

$$S = \sum_{m=0}^{N-1} e^{j2\pi\frac{n(m+k)}{N}} \qquad (6.10)$$

one can arrive at the expression of the value of R in three different cases. It is seen that,

a) When m = k = 0, from equation (6.5), one can have

$$S = N, \; X_0 X_0 = |X_0|^2,$$

b) When m = k = N, that is m = N- k, from combination of equations (6.6) and (6.3), one has

$$S = N, \; X_k X_{n-k} = |X_k|^2$$

Note that, X_k is real-valued here. Finally,

c) When m = k = 1, 2, ... N-1, N = 1, ... 2N-2, one can find from equation (6.7),

$$S = 0.$$

Using the complete set of results described in a), b) and c), we have

$$R = \sqrt{\frac{1}{N^2}\sum_{k=0}^{N-1}|X_k|^2} = \sqrt{\sum_{k=0}^{N-1}\left(\frac{1}{N}X_k\right)^2}$$

Furthermore, one can have

$$R \approx \sqrt{2\sum_{k=0}^{\frac{N}{2}-1}\left(\frac{1}{N}X_k\right)^2} \qquad (6.11)$$

where it is provided that

$$f_s \geq 2\, f_{max}$$

Here f_s is the sampling frequency and f_{max} is maximum frequency component contained in the signal x(t). Note that

$$\Delta fk = \frac{1}{T}k$$

therefore, one can have the corresponding relationship between k = 0 up to N/2 -1 and that f = 0 up to 1/2 f_s.

6.3 The RMS Value in the One-third-Octave Band

With the above derivation, the RMS valued velocity in the one-third-octave band can be further discovered. On the axis of frequency, denote the lower frequency to be f_l whereas the upper frequency to be f_2. If one has

$$f_2 = 2\, f_l$$

then the center frequency, denoted by f_o becomes

$$f_0 = (f_l\, f_2)^{1/2} = 2^{1/2}\, f_l = 2^{-1/2}\, f_2 \qquad (6.12)$$

Equation (6.12) stands for the full octave band.

For the one-third-octave band, the above equation should be rewritten as

$$f_0 = (f_l\, f_2)^{1/6} = 2^{1/6}\, f_l = 2^{-1/6}\, f_2 \qquad (6.13)$$

In such a frequency bandwidth, one can have the RMS valued signal with the rest of the frequency component outside the band equal to zero. This is equivalent to using a band pass filter to remove the frequency component outside the band between f_l and f_2 and calculate the RMS of the remaining signal. In this case, one can use equation (6.11) to directly obtain the summation of the signal within a proper frequency band. According to the ISO standard, the central frequency and the lower and upper frequency should be taken as that shown in table 6-1.

Using table 6-1, one can have standard frequencies in terms of one-third-octave band. Then, the RMS value can be calculated by using formula (6.11).

Table 6-1 Frequencies in One-third-Octave Band

f_0	f_1	f_2
3.15	2.80	3.54
4.00	3.54	4.49
5.00	4.49	5.61
6.30	5.61	7.07
8.00	7.07	8.98
10.0	8.98	11.22
12.5	11.22	14.03
16.0	14.03	17.96
20.0	17.96	22.45
25.0	22.45	28.06
31.5	28.06	35.36
40.0	35.36	44.90
50.	44.90	56.12

SECTION 7
RESULTS AND ANALYSES

7.1 Calibration

Hammer tests were carried out on both sites. The natural frequency ranges from 78 Hz to 88 Hz with damping ratios of 1.8% to 3.5%. This is near the edge of the proper frequency-damping ratio combinations. The frequency meets the Klein criterion but the damping ratio is lower. If the ground vibration measured later is higher but close to the criteria, appropriate modifications according to the excessive amplification must be performed. If the result is equal to or lower than the criteria, there is no need for any modifications since the ground vibration has been exaggerated and therefore, the process is conservative.

7.2 Ground Vibration Measurement

Based on the formulae discussed in Section 6, the signals detected during the measurement were presented and the RMS values of velocity in the 1/3 octave band were obtained as given in Appendix A.

The first measurement section (west section) is referred to as site one (see figure 1-1). This measurement was carried out from December 3 to 8, 1998. At site one, the only case of explosion was not well measured (the level of the explosion was too small to give significant values). This case is not listed in the appendix.

The second measurement section is referred to as site two (also see figure 1-1).

7.2.1 Site One

From table 7-1, the maximum RMS values at the middle and north locations were comparatively small. The signals in the three measurement directions were all less than 60 micro-inches per second. The signal in the north location was not greater than 30 micro-inches per second. Both were considered to be sufficiently small.

However, the south location was only 400 ft away from the railroad and the Route 400 expressway, and the ground vibrations were affected by the heavy traffic. By comparing the signals measured during the day with those measured at night, it can be determined that the RMS value in the E-W direction increased slightly. However, the maximum value of the signal in the N-S direction was almost double. The signal in the vertical direction also increased about 30%.

This implies that the traffic signals during the day and at night are quite different at the south location.

Table 7-1 Maximum RMS Value of Velocity in one-third-Octave Band at Different Locations

		Location S			Location M			Location N		
		E-W	S-N	V	E-W	S-N	V	E-W	S-N	V
Site I	Night 10:40 pm 11/20/98	95.04 Hz	40.1 4Hz	31.84 Hz	16.4 4Hz	17.54 Hz	23.9 4Hz	14.74 Hz	12.6 4Hz	4.38 Hz
Site I	Train 10:50 pm 11/20/98	298.4 25Hz	171.4 25Hz	113.7 16Hz	54.0 10Hz	31.9 16Hz	23.1 4Hz	28.2 6.3Hz	24.2 8Hz	16.4 10Hz
Site I	Day 2:33 pm 11/21/98	98.84 Hz	78.4 4Hz	41.1 4Hz	52.9 3.15Hz	46.73 15Hz	48.1 3.15Hz	17.52 0Hz	20.6 50Hz	12.52 0Hz
Site II	Night 1:20 am 11/23/98	41.26 .3Hz	15.6 20Hz	11.42 0Hz	28.8 3.15Hz	11.82 0Hz	5.5 5Hz	9.502 0Hz	8.41 50Hz	5.5 20Hz
Site II	Train 2:41 am 11/23/98	121.1 5Hz	45.5 8Hz	33.41 2.5Hz	40.9 3.15Hz	16.5 20Hz	16.4 20Hz	10.18 Hz	14.4 8Hz	6.7 20Hz
Site II	Day 4:00 pm 11/23/98	47.92 0Hz	70.3 20Hz	35.12 0Hz	50.6 3.15Hz	50.63 15Hz	26.4 3.15Hz	16.8 20Hz	11.1 3.15Hz	12.2 20Hz
Site II	Train 5:40 pm 11/23/98	92.88 Hz	82.1 8Hz	62.11 2.5Hz	38.7 3.15Hz	23.78 Hz	18.7 20Hz	13.62 0Hz	23.8 8Hz	10.6 20Hz
Site II	Train 11:11 pm 11/23/98	104.5 10Hz	93.9 10Hz	78.31 2.5Hz	39.3 3.15Hz	32.61 0Hz	14.5 3.15Hz	25.31 0Hz	34.9 10Hz	10.81 2.5Hz
Site II	Day 11:50 pm 11/24/98	71.7 16Hz	108.8 16Hz	69.51 6Hz	62.3 3.15Hz	49.84 Hz	36.5 4Hz	32.41 6Hz	11.51 0Hz	16.93 15Hz
Site II	Blast 1 1:58 am 11/24/98	78.82 0Hz	119.1 20Hz	76.41 6Hz	69.1 3.15Hz	53.44 Hz	37.1 4Hz	35.71 6Hz	17.1 10Hz	17.43. 15Hz

(In table 7-1, data in each of the first rows indicate RMS velocity in micro-inches/sec. The second row indicates the center frequency where maximum value of velocity occurs)

The trains made the signals increase by factors of 214%, 327% and 258%, in the E-W, N-S and vertical directions, respectively.

7.2.2 Site Two

Similar to the cases in site one, at the middle and northern locations, the measured RMS values were all quite small. The maximum value does not exceed 70 micro-inches per second. However, the southern location detected considerably larger signals, especially those generated by trains. The measurement in the E-W direction shows the RMS values were about 100 micro-inches per second. The averaging value was about 106.1 micro-inches per second. Compared to the night measurement without any trains, the increase was about 58%. It was noted that different measurements exhibited different values, which were affected by the length, speed and loading of the trains.

It was noted that, since the southern location in site two was further away from the railway and the expressway than in site one, the average values were all smaller than those measured at site one. It further implies the capability of attenuation in vibration level by the soil.

From table 7-1, it was also seen that the magnification of the vibration level by the mine explosion was relatively small. It was seen that the maximum magnification occurred at the northern location, in the E-W directions. About a 48.7% enlargement can be seen clearly. However, since the absolute value of the explosion was quite small, it was concluded that the explosion does not have a notable effect at that location.

The explosion magnified the measurement at the middle and the southern locations, also. About a 10.9% and 9.5-9.9 % increase in vibration levels in the E-W direction was found, which was considerably smaller than the case at the northern location. It was further concluded that the explosion had little effect on ground vibration at any of the locations within the entire site though only two measurement lines were used.

In table 7-2, the maximum value of velocity of the worst case in each location is listed. At the southern location, the recorded data shows the maximum values were greater than 120 micro-inches per second. At the middle location, the highest value was close to 70 micro-inches per second. At the northern location, the highest value was about 36 micro-inches per second.

Briefly speaking, the trains and the traffic on the expressway were relatively significant. Notable magnification was found within the section south of the New York Electric & Gas Transmission Lines, where the ground motions with the RMS value of velocity exceed 100 micro-inches per second.

About 200 feet north of the line, regardless of the vibration source, the RMS value was smaller than 70 micro-inches per second. According to information provided by the Town of West Seneca, the major work areas of the proposed Phase I ChipFab sites are all located 600 feet north of the line. In addition, the southern portion of the proposed

ChipFab site is planned to be used for an Energy Center, Utility Service Yard, etc. Therefore, the vibration level at this site should be able to satisfy the basic requirements for the ChipFab facility.

Table 7-2 Maximum Values at Each Location

		Location S			Location M			Location N		
		E-W	S-N	V	E-W	S-N	V	E-W	S-N	V
Site I	Train 10:50 pm 11/20/98	298.4 25Hz	171.4 25Hz	113.7 16Hz	54.0 10Hz	31.9 16Hz	23.1 4Hz	28.2 6.3Hz	24.2 8Hz	16.4 10Hz
Site II	Train 2:41 am 11/23/98	121.1 5Hz	45.5 8Hz	33.41 2.5Hz	54.0 10Hz	31.9 16Hz	23.1 4Hz	28.2 6.3Hz	24.2 8Hz	16.4 10Hz
Site II	Blast 11:58 am 11/24/98	78.82 0Hz	119.1 20Hz	76.41 6Hz	69.1 3.15Hz	53.44 Hz	37.1 4Hz	35.71 6Hz	17.1 10Hz	17.43 15Hz

(In table 7-2, data in each of the first row indicates RMS velocity in micro-inches/sec. The second row indicates the center frequency where maximum value of velocity occurs)

SECTION 8
CONCLUSIONS

This study was concerned with the ground vibration level of the proposed ChipFab site within the North America Center in West Seneca, New York due to trains, expressway traffic (Route 400) and nearby mining operations. The following conclusions were obtained:

1. MCEER has developed a complete measurement procedure, including necessary equipment and computer software, for systematic measurement of ground micro-vibration.

2. Under the measurement conditions described in this context, it was found that at the proposed location for the ChipFab facility within the North America Center (200 feet north of the NY Electric and Gas transmission lines), the root mean square values of velocity in one-third-octave frequency band are all less than 70 micro-inches per second.

3. The southern portion of the North America Center, however, has vibration levels larger than 100 micro-inches per second, when trains pass by.

4. The selection of low cost accelerometers with adequate low frequency, high sensitivity and high resolutions was a major factor in obtaining accurate measurements of the ground for the micro-vibrations.

5. Calibration of the installation fixtures was one of the critical steps in obtaining accurate measurements. It was found that the natural frequency of the fixture used in the measurement was higher than 74 Hz, which was suitable for detecting signals from the proposed ground motion.

6. Using acoustic isolation boxes was another critical step in obtaining the high signal-to-noise ratio in the measurement with high sensitivity sensors.

SECTION 9
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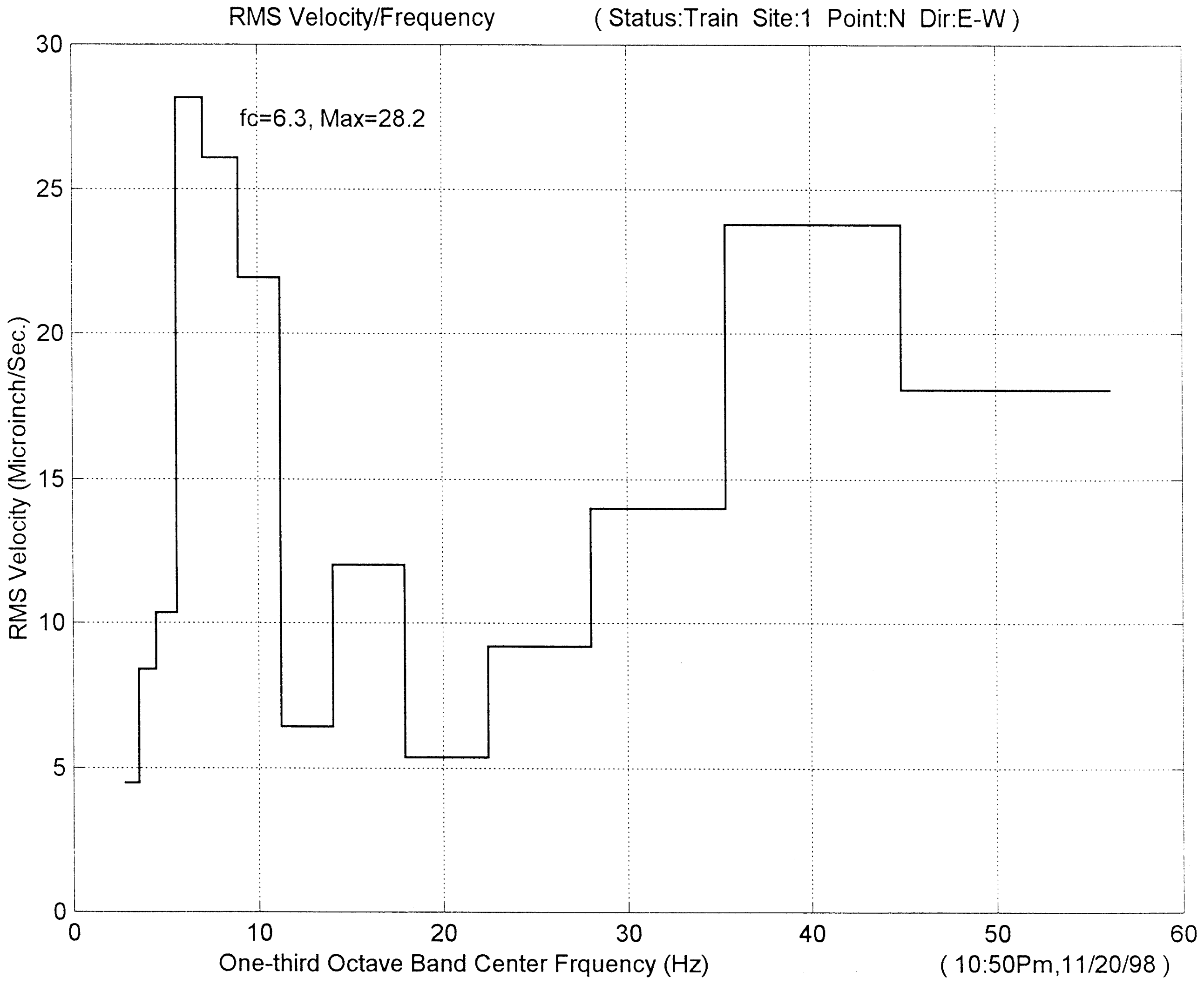
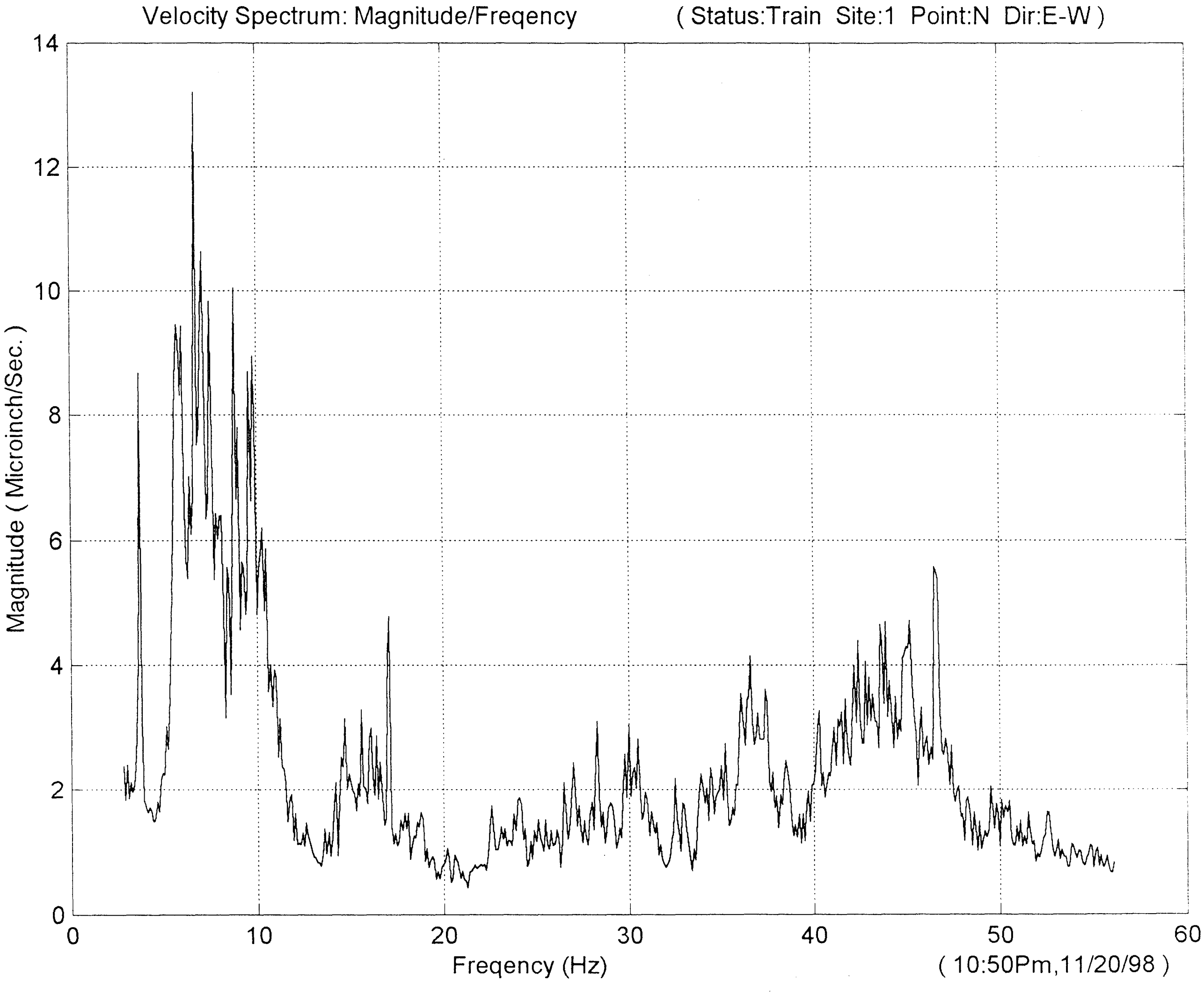
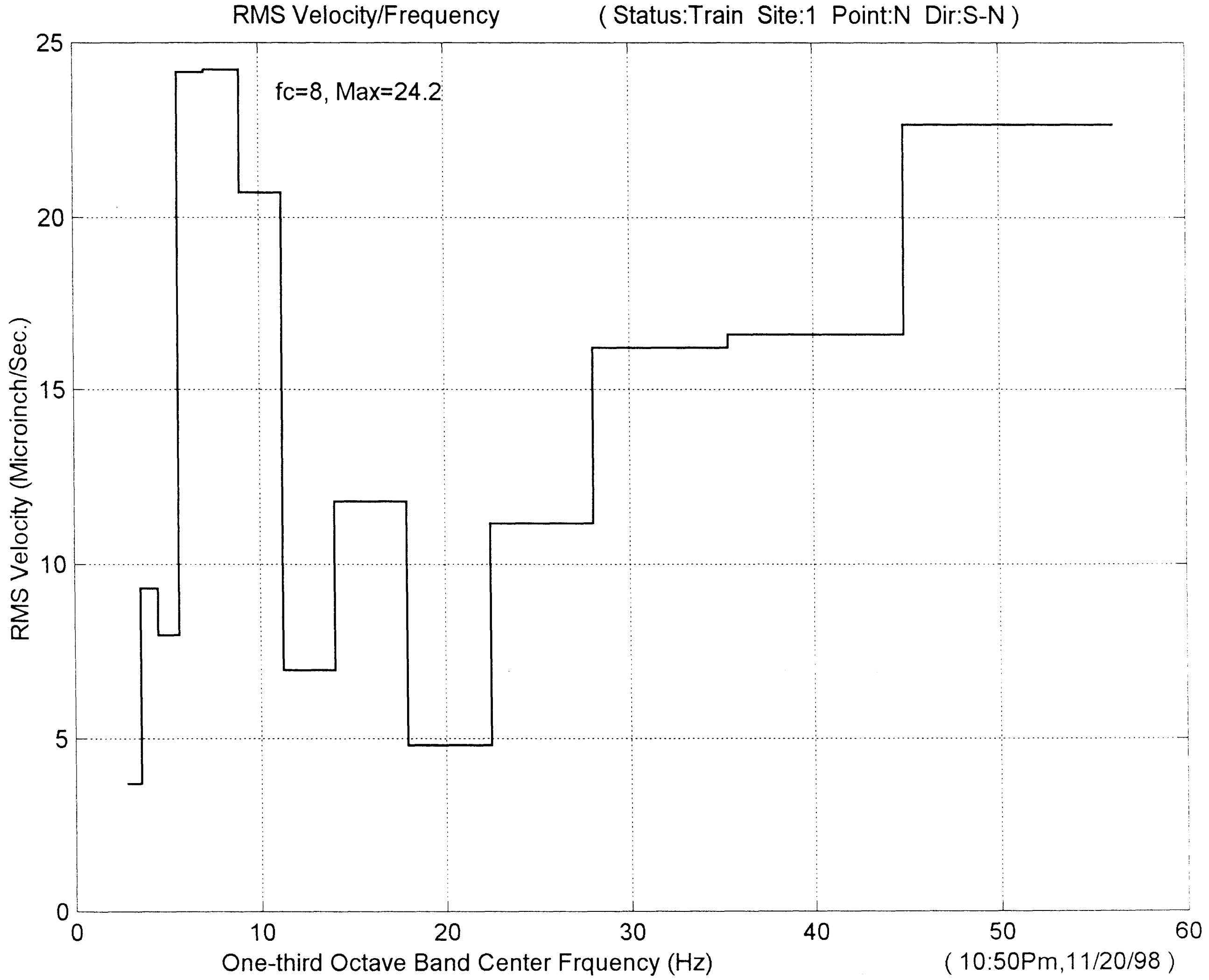
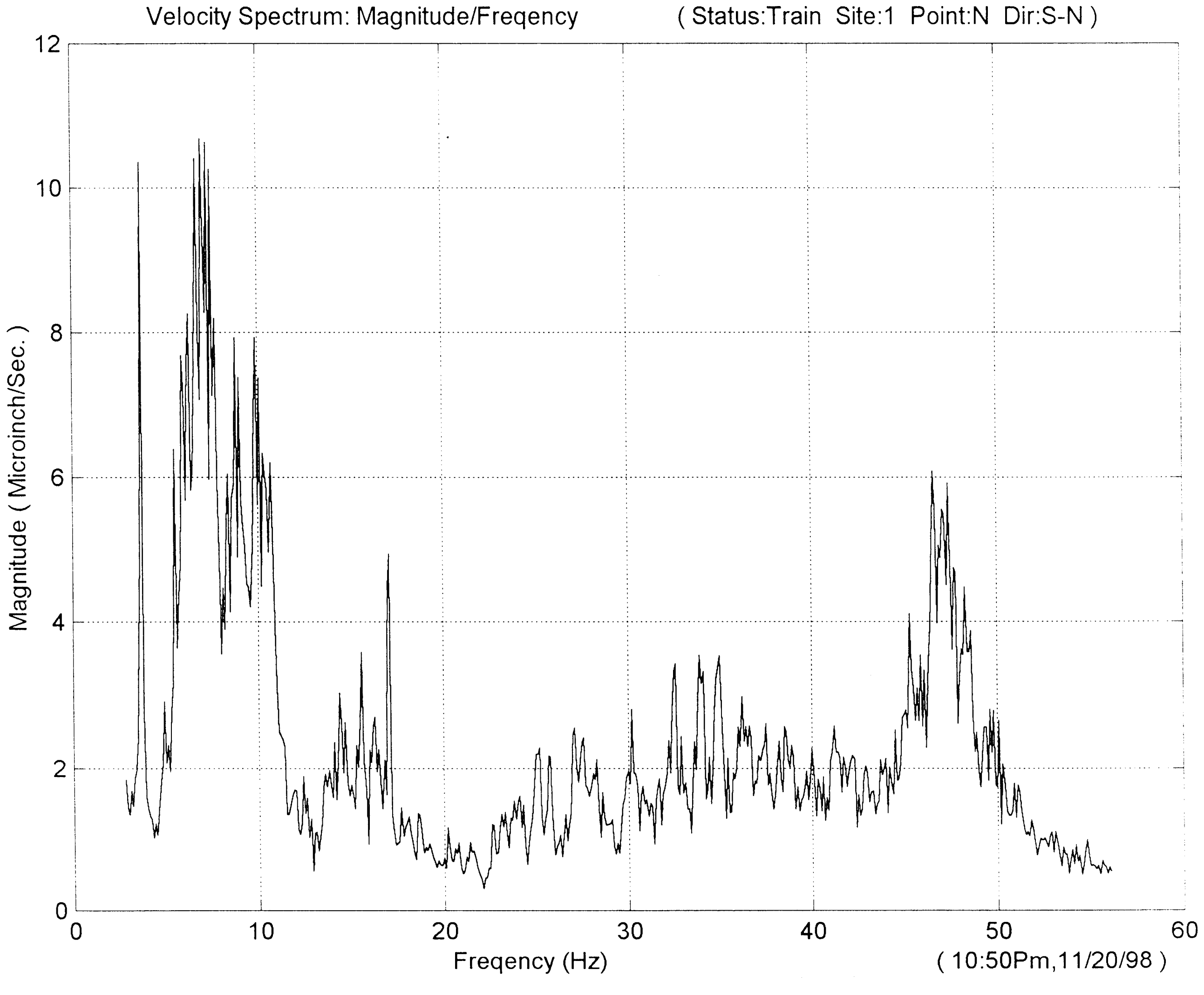
APPENDIX A
SELECTED SIGNALS

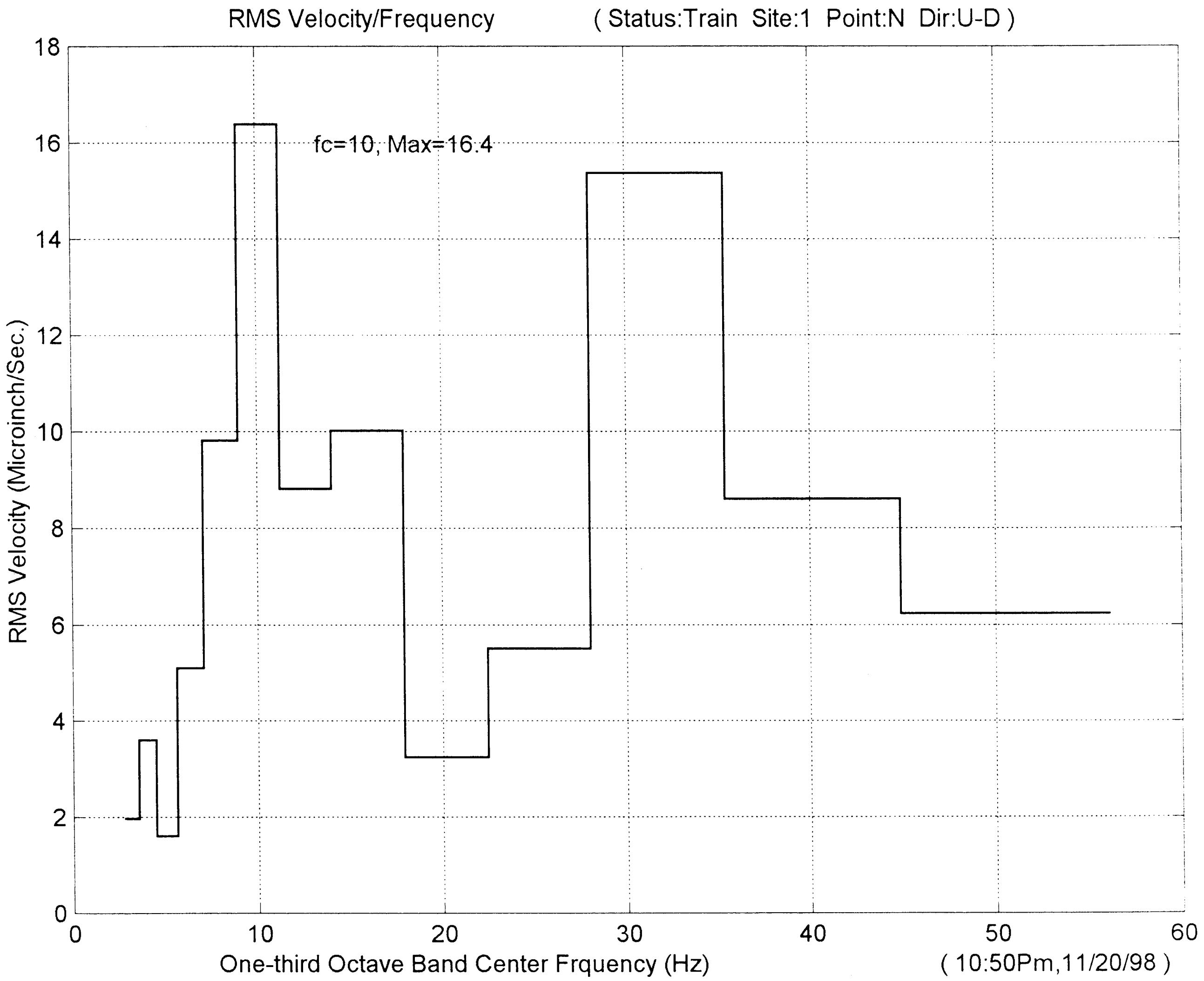
Site 1: Selected Signals with Train

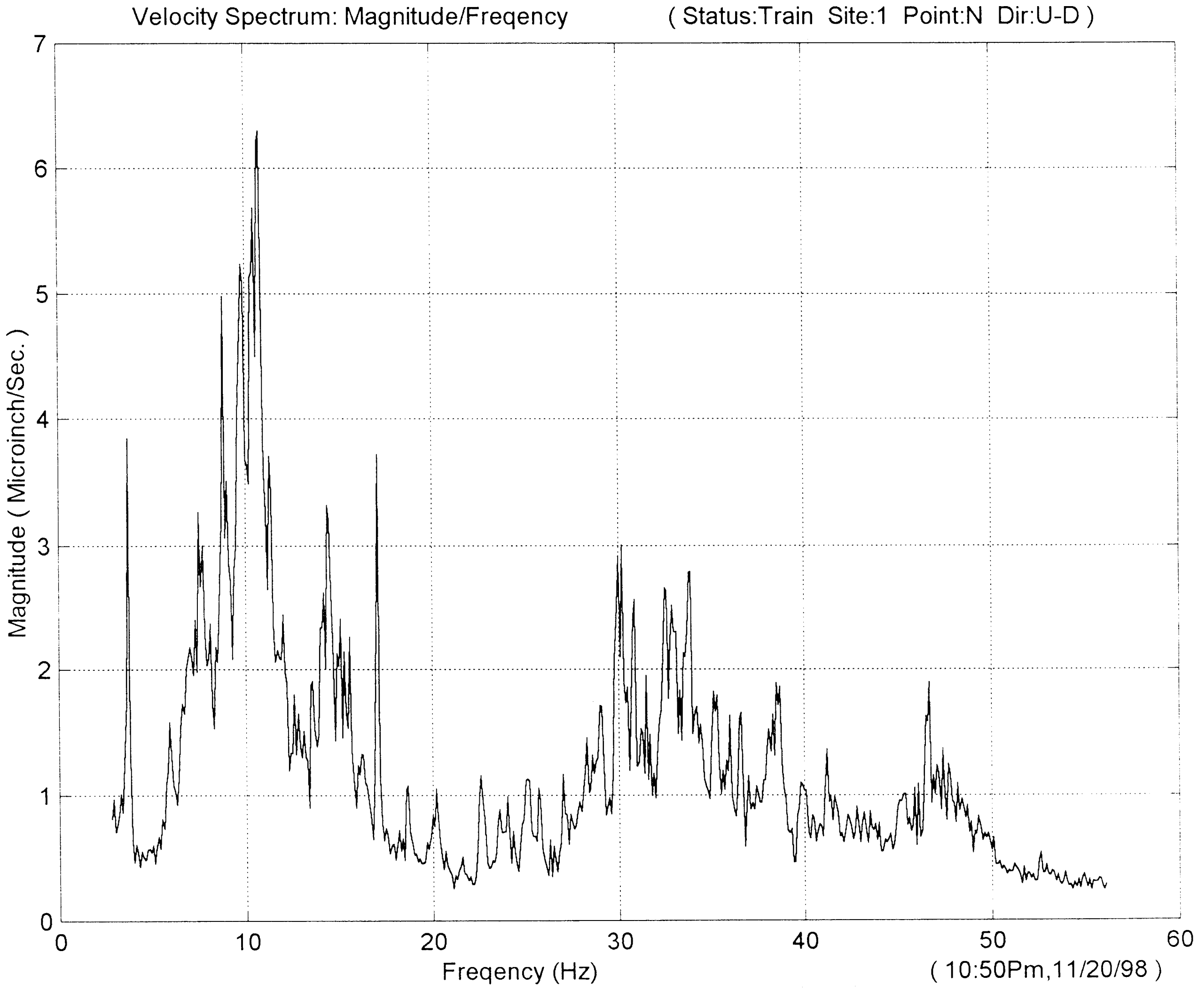


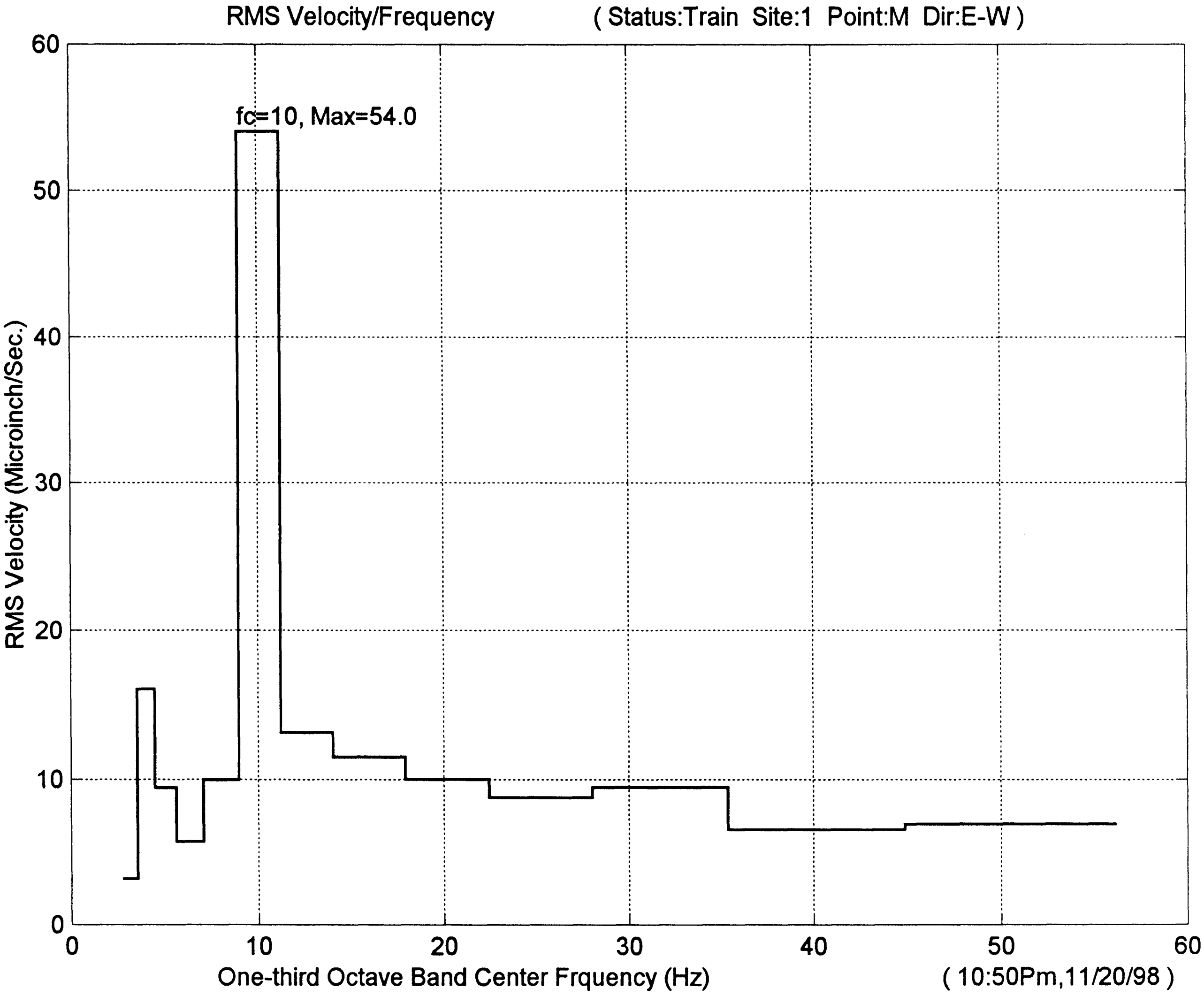

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:N Dir:E-W)
Magnitude (Microinch/Sec.)
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
Freqency (Hz)
(10:50Pm,11/20/98)

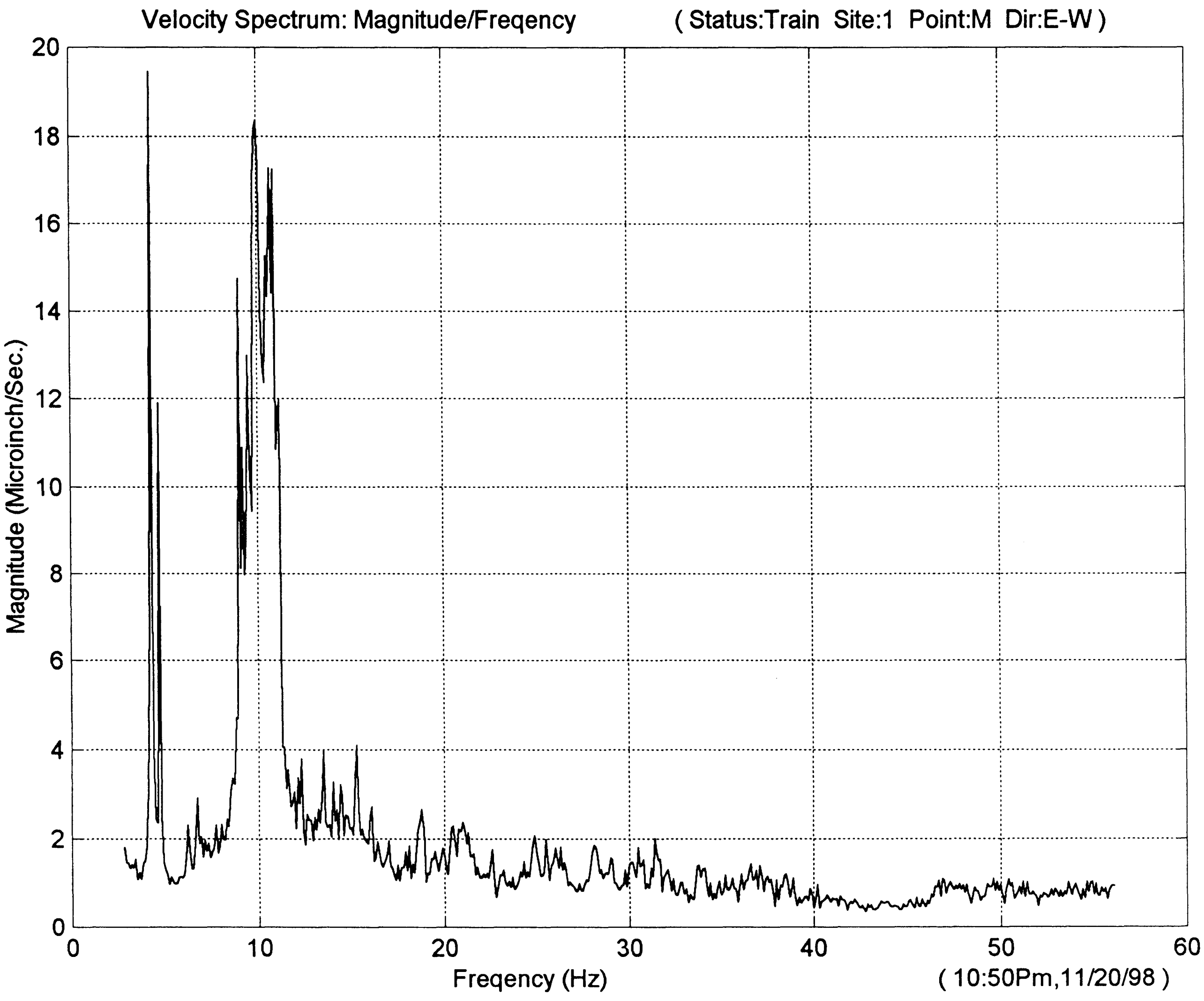

RMS Velocity/Frequency
(Status:Train Site:1 Point:N Dir:S-N)
fc=8, Max=24.2
RMS Velocity (Microinch/Sec.)
25
20
15
10
5
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)

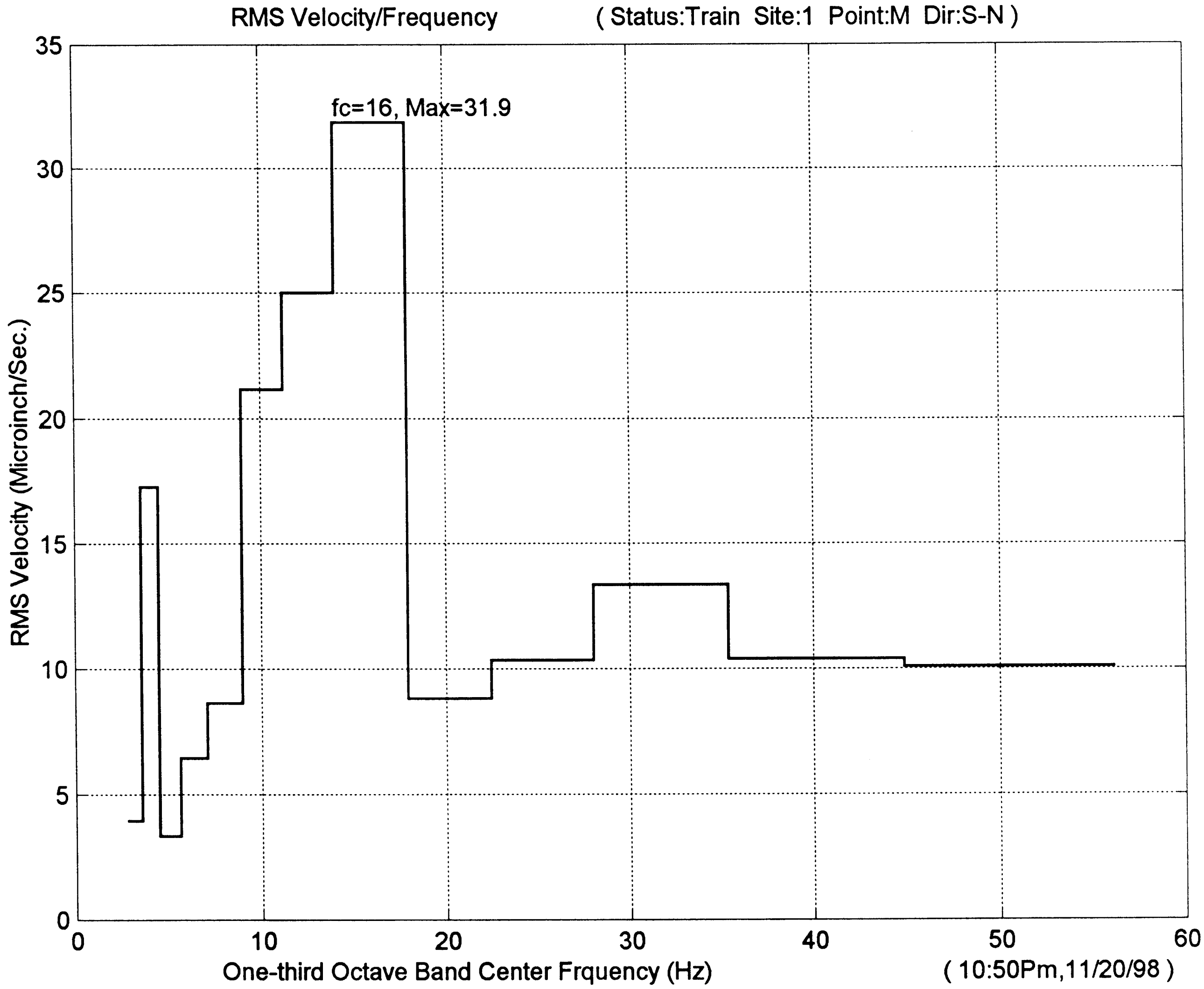

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:N Dir:S-N)
Magnitude (Microinch/Sec.)
12
10
8
6
4
2
0
0
10
20
30
40
50
60
Freqency (Hz)
(10:50Pm,11/20/98)

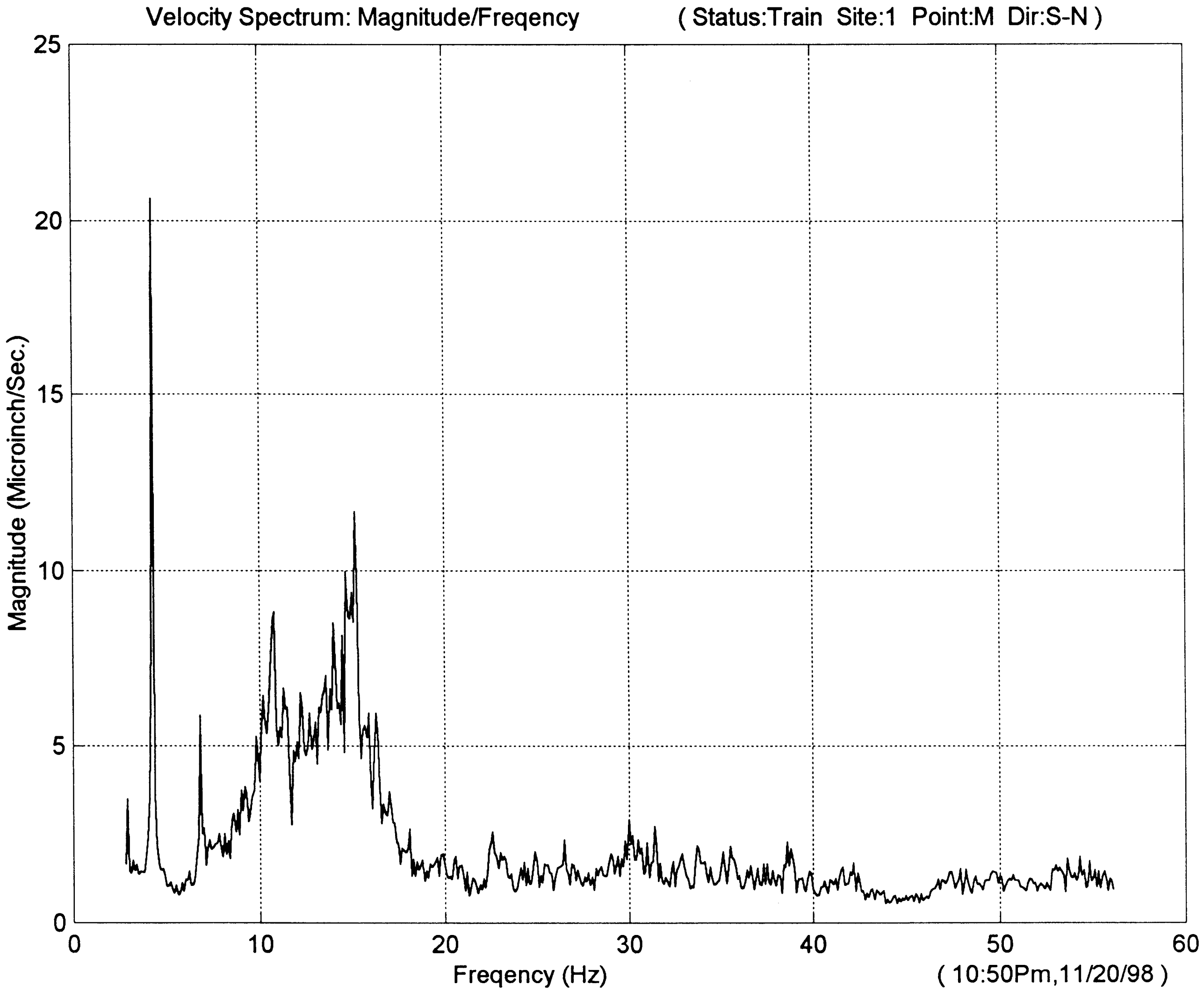

RMS Velocity/Frequency
(Status:Train Site:1 Point:N Dir:U-D)
fc=10, Max=16.4
RMS Velocity (Microinch/Sec.)
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)

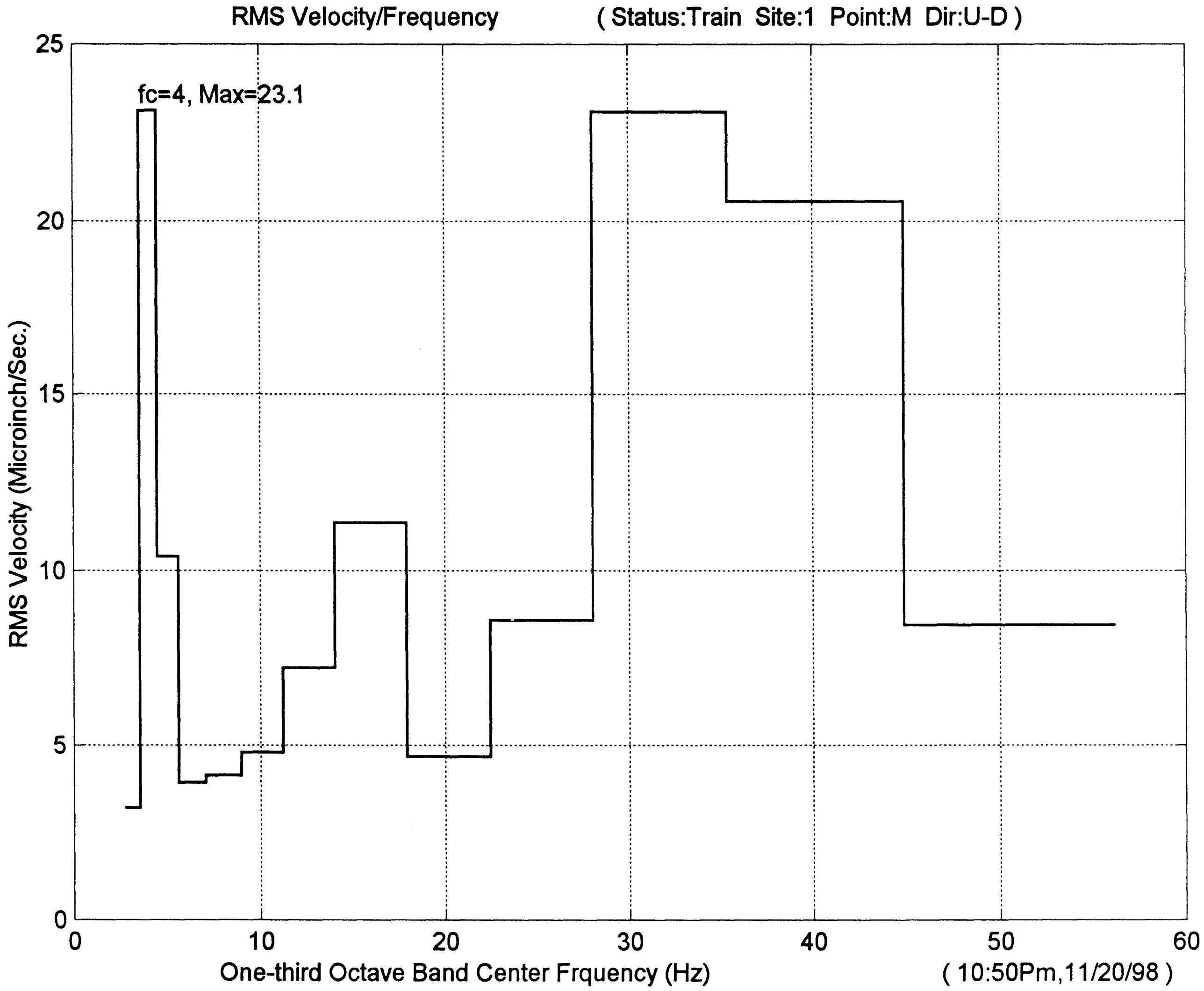

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:N Dir:U-D)
Magnitude (Microinch/Sec.)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
Freqency (Hz)
(10:50Pm,11/20/98)

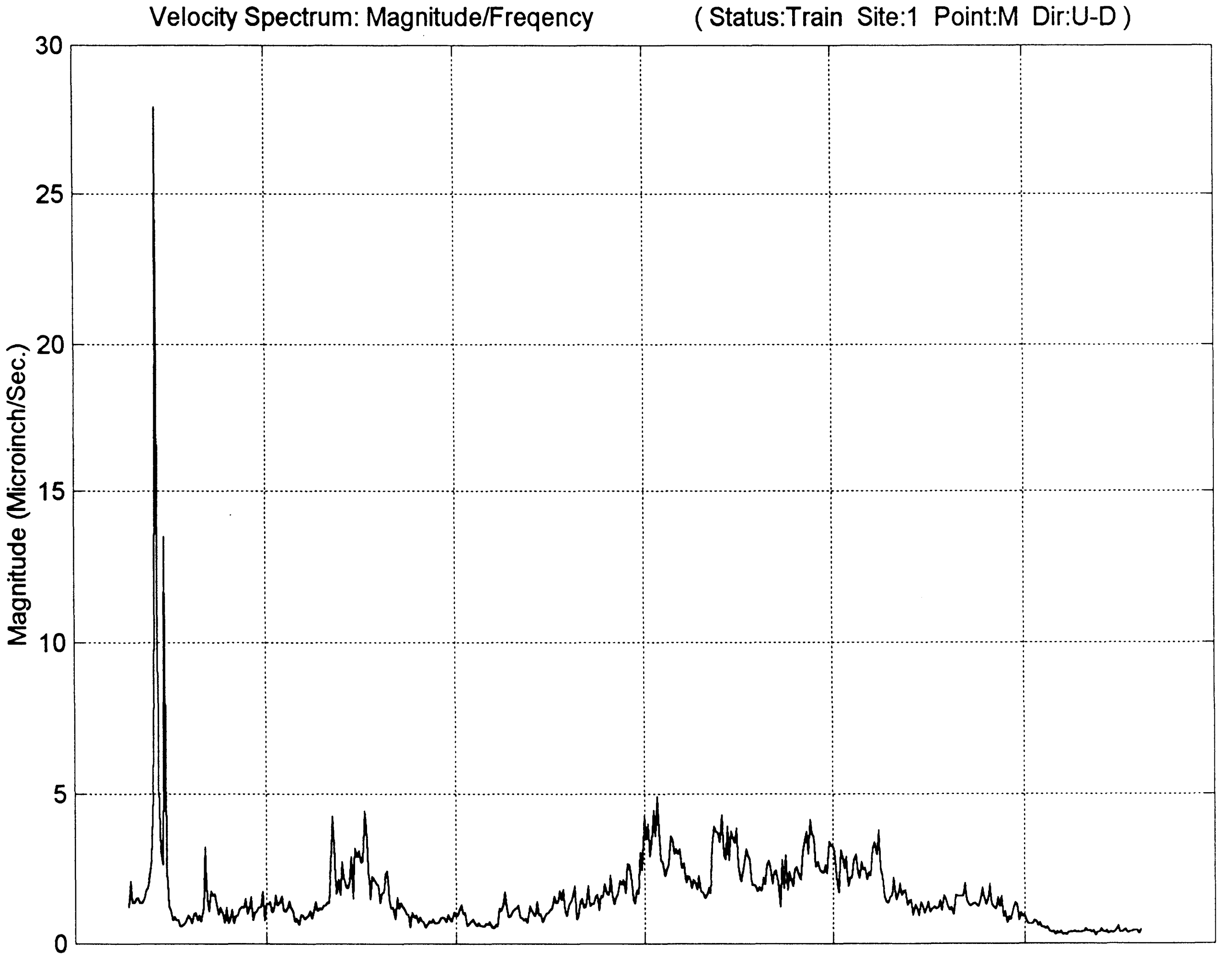

RMS Velocity/Frequency
(Status:Train Site:1 Point:M Dir:E-W)
fc=10, Max=54.0
RMS Velocity (Microinch/Sec.)
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)

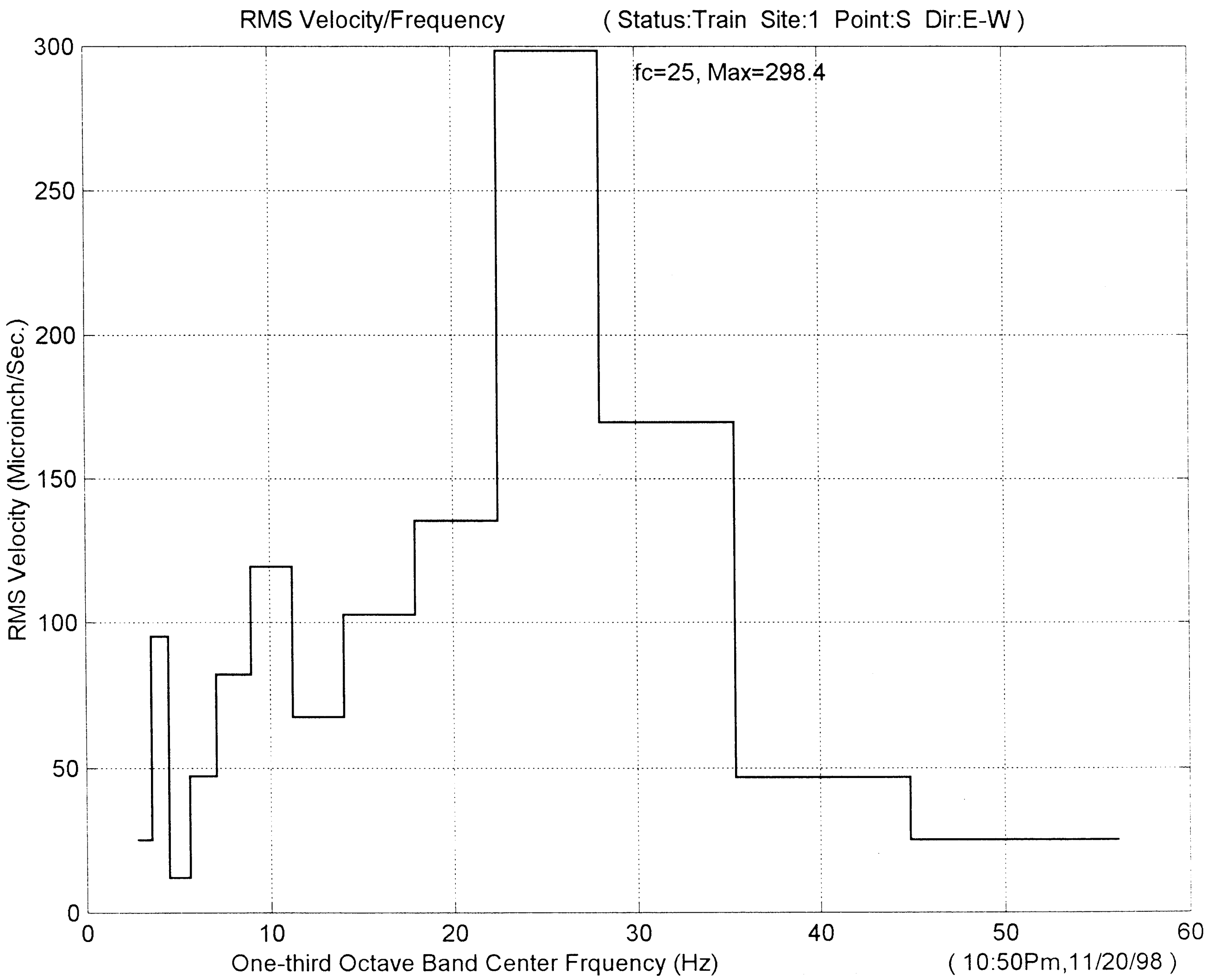

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:M Dir:E-W)
Magnitude (Microinch/Sec.)
0
2
4
6
8
10
12
14
16
18
20
Freqency (Hz)
0
10
20
30
40
50
60
(10:50Pm,11/20/98)

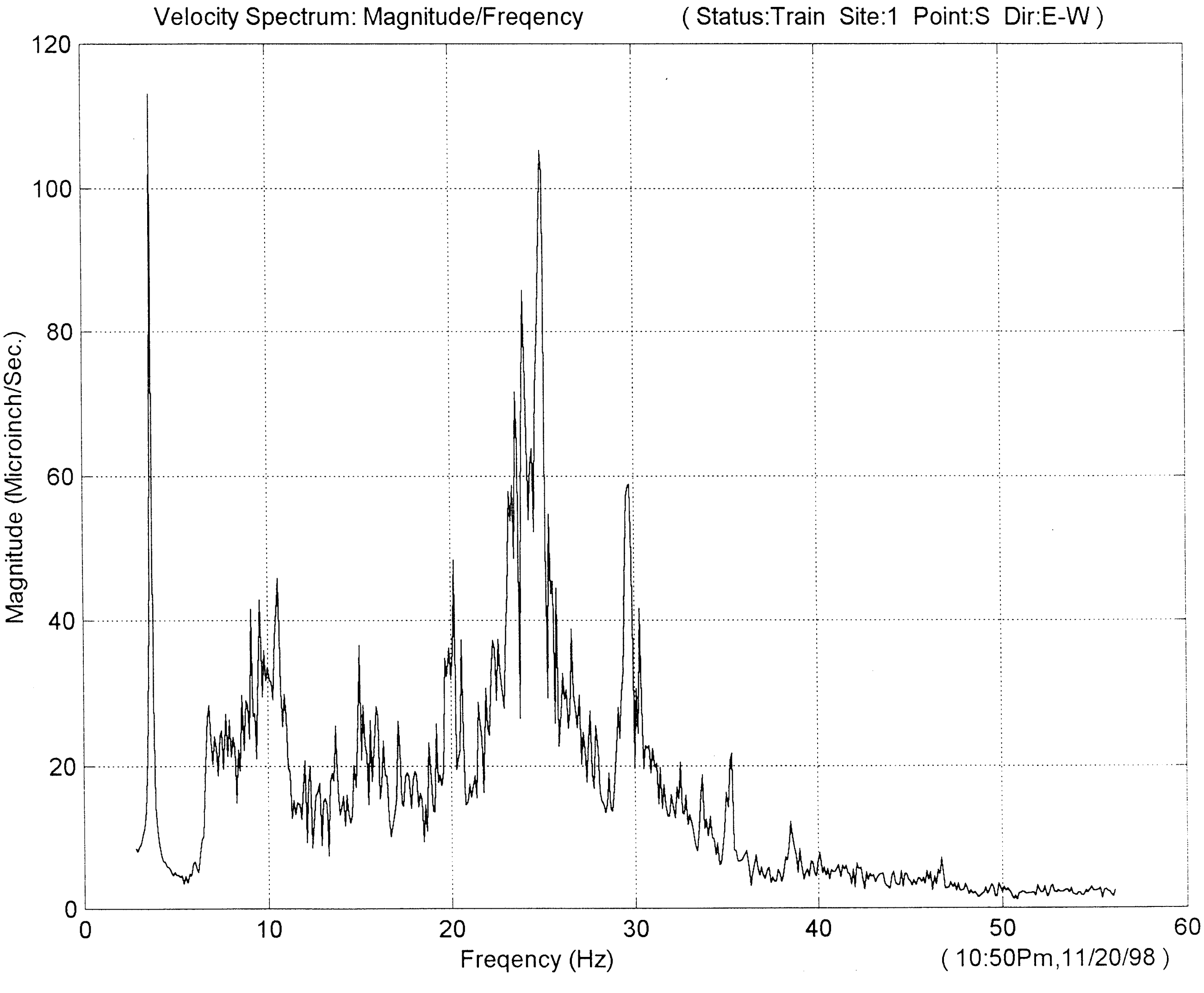

RMS Velocity/Frequency
(Status:Train Site:1 Point:M Dir:S-N)
fc=16, Max=31.9
RMS Velocity (Microinch/Sec.)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)


Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:M Dir:S-N)
25
20
15
10
5
0
Magnitude (Microinch/Sec.)
0
10
20
30
40
50
60
Freqency (Hz)
(10:50Pm,11/20/98)


RMS Velocity/Frequency
(Status:Train Site:1 Point:M Dir:U-D)
fc=4, Max=23.1
RMS Velocity (Microinch/Sec.)
0
5
10
15
20
25
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)

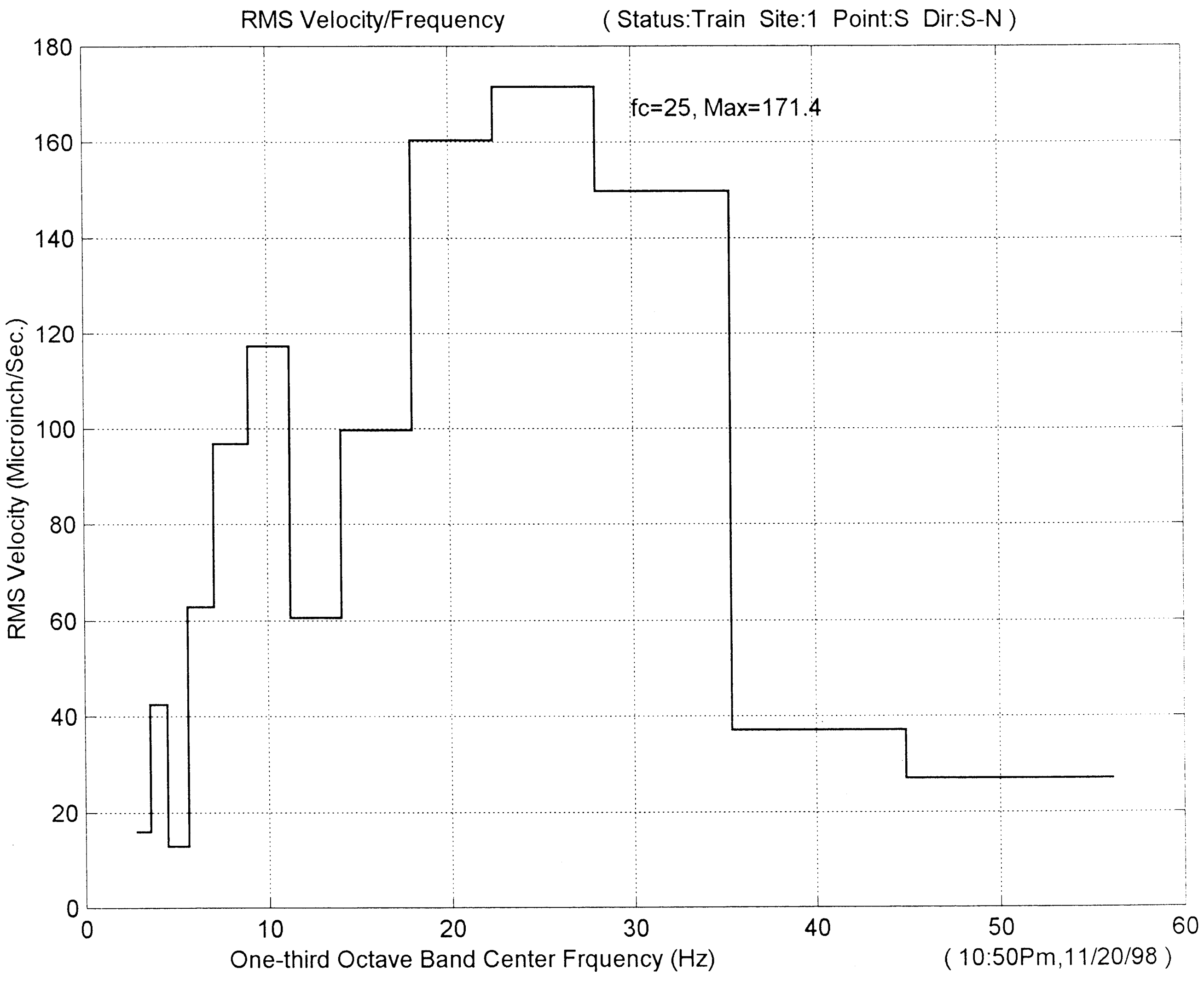

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:M Dir:U-D)
Magnitude (Microinch/Sec.)
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Freqency (Hz)
(10:50Pm,11/20/98)

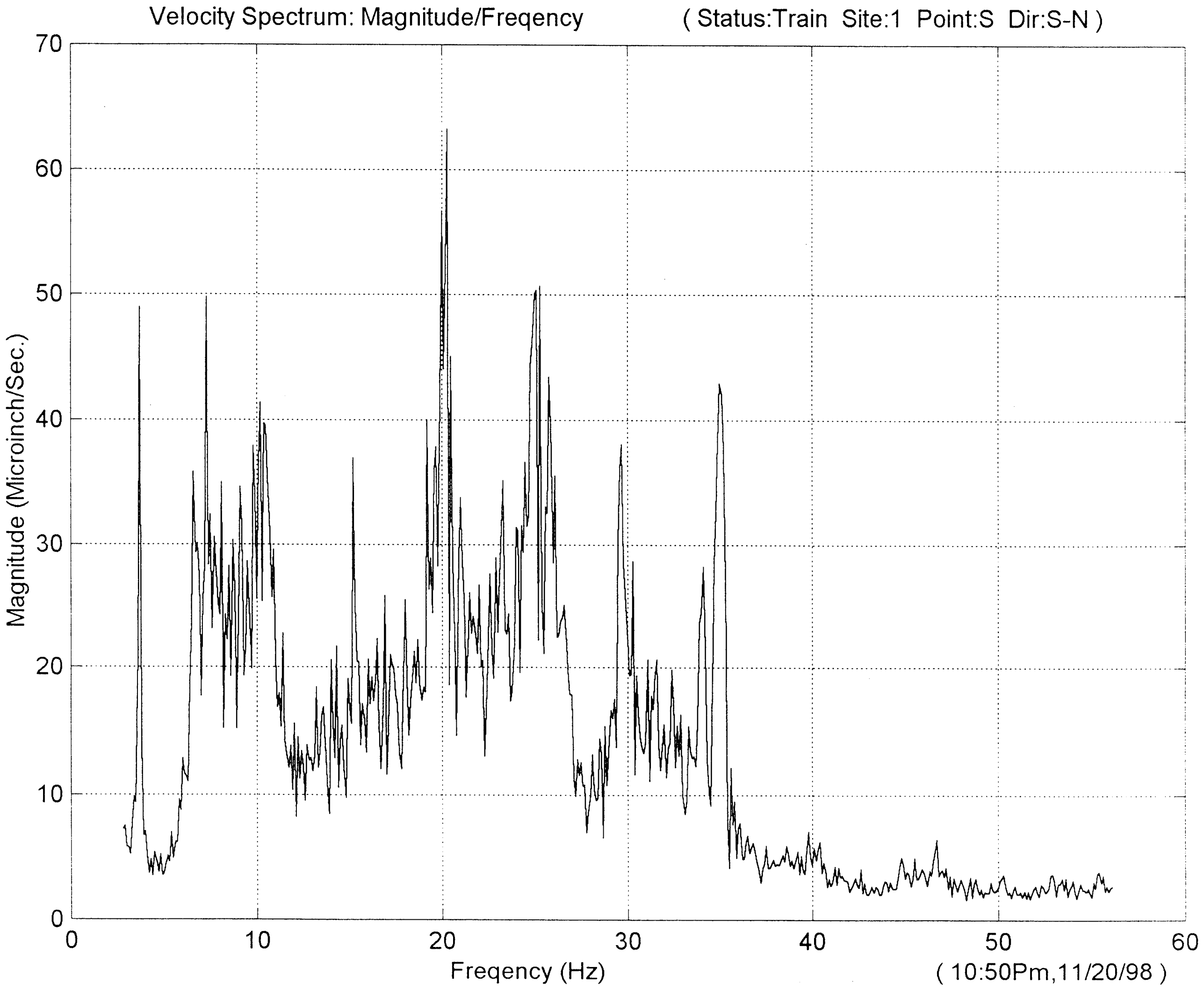

RMS Velocity/Frequency
(Status:Train Site:1 Point:S Dir:E-W)
fc=25, Max=298.4
RMS Velocity (Microinch/Sec.)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)

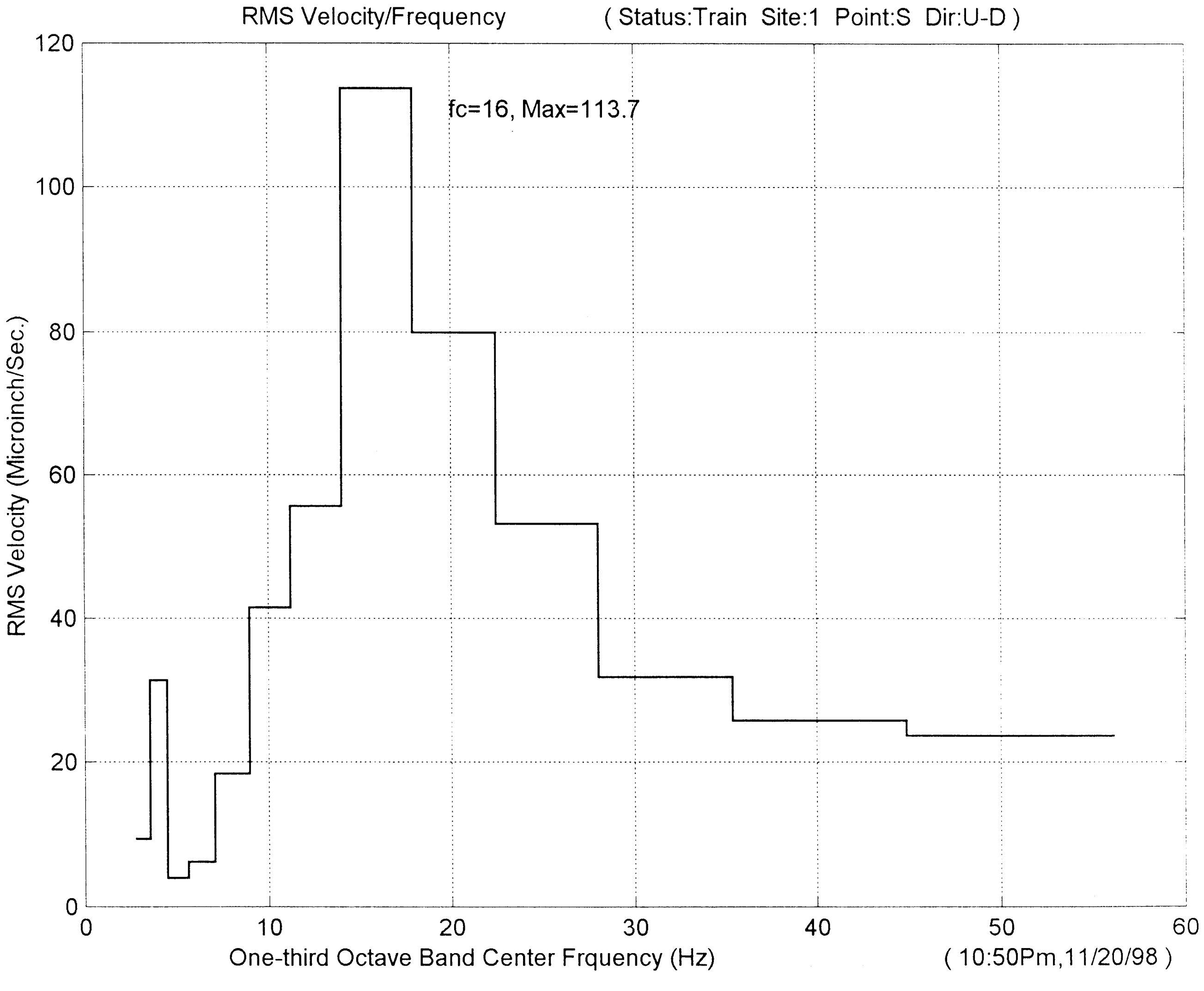


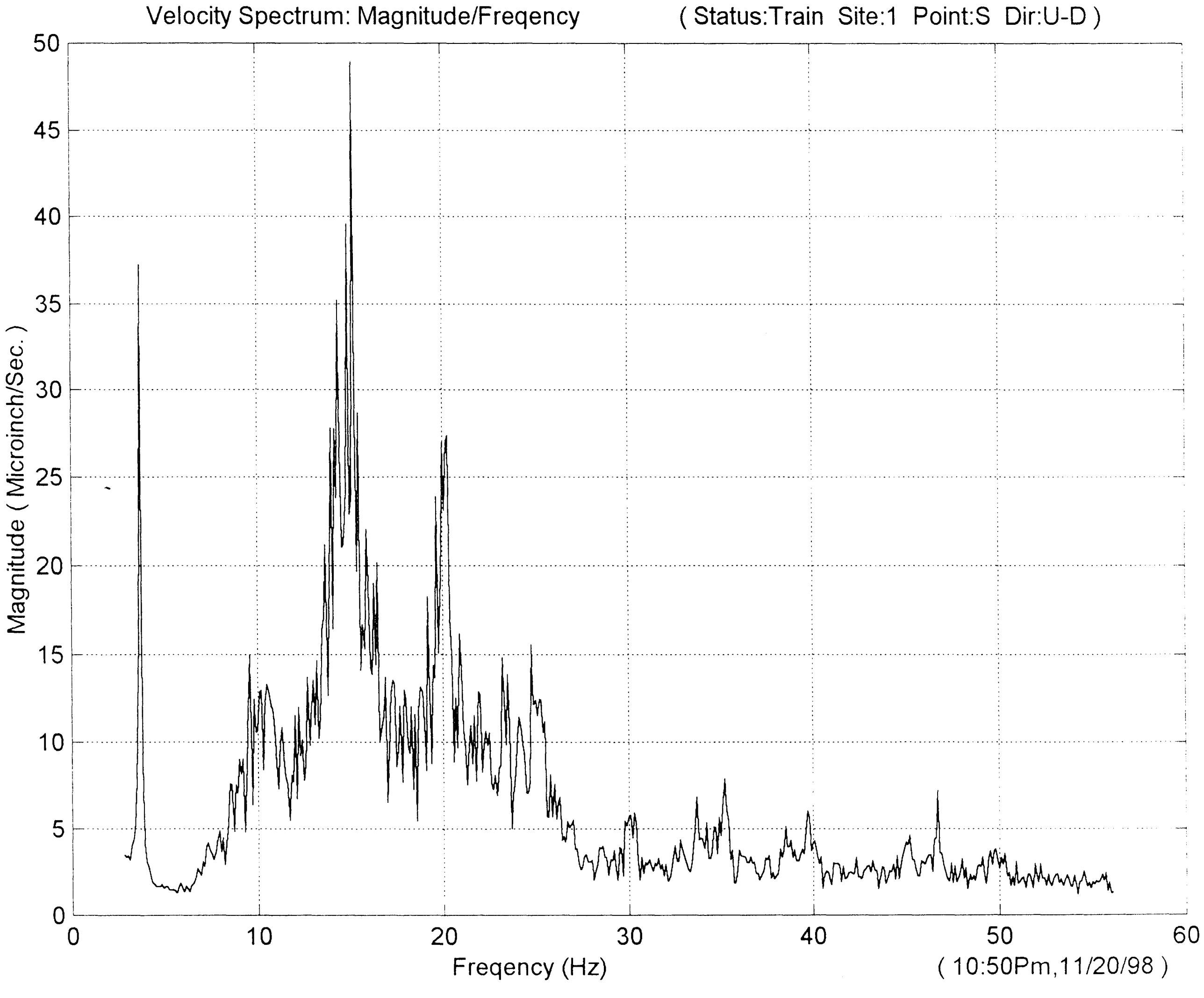
Velocity Spectrum: Magnitude/Freqency (Status:Train Site:1 Point:S Dir:E-W)

(10:50Pm,11/20/98)

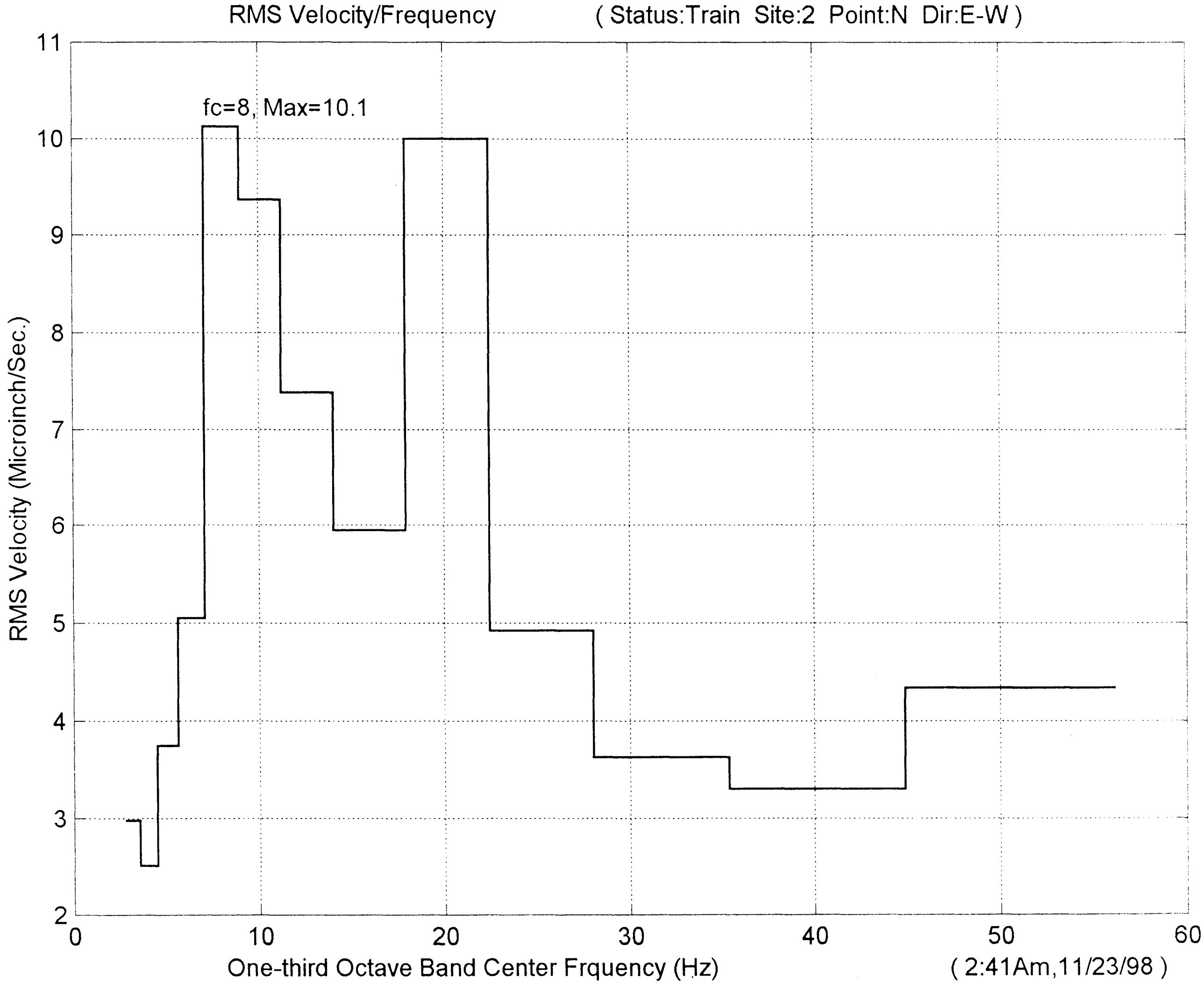

RMS Velocity/Frequency
(Status:Train Site:1 Point:S Dir:S-N)
fc=25, Max=171.4
RMS Velocity (Microinch/Sec.)
0
20
40
60
80
100
120
140
160
180
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)

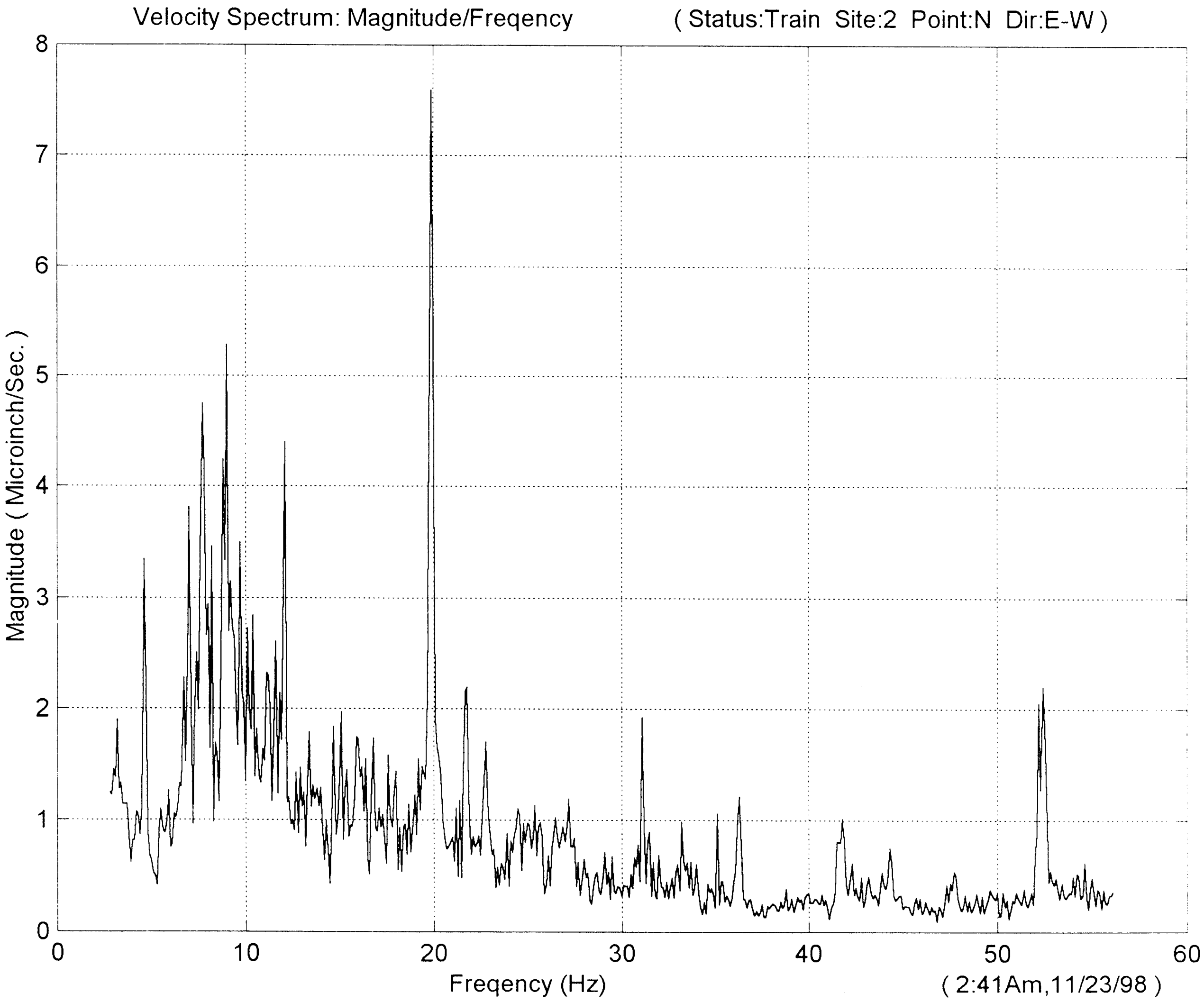

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:S Dir:S-N)
Magnitude (Microinch/Sec.)
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Freqency (Hz)
(10:50Pm,11/20/98)

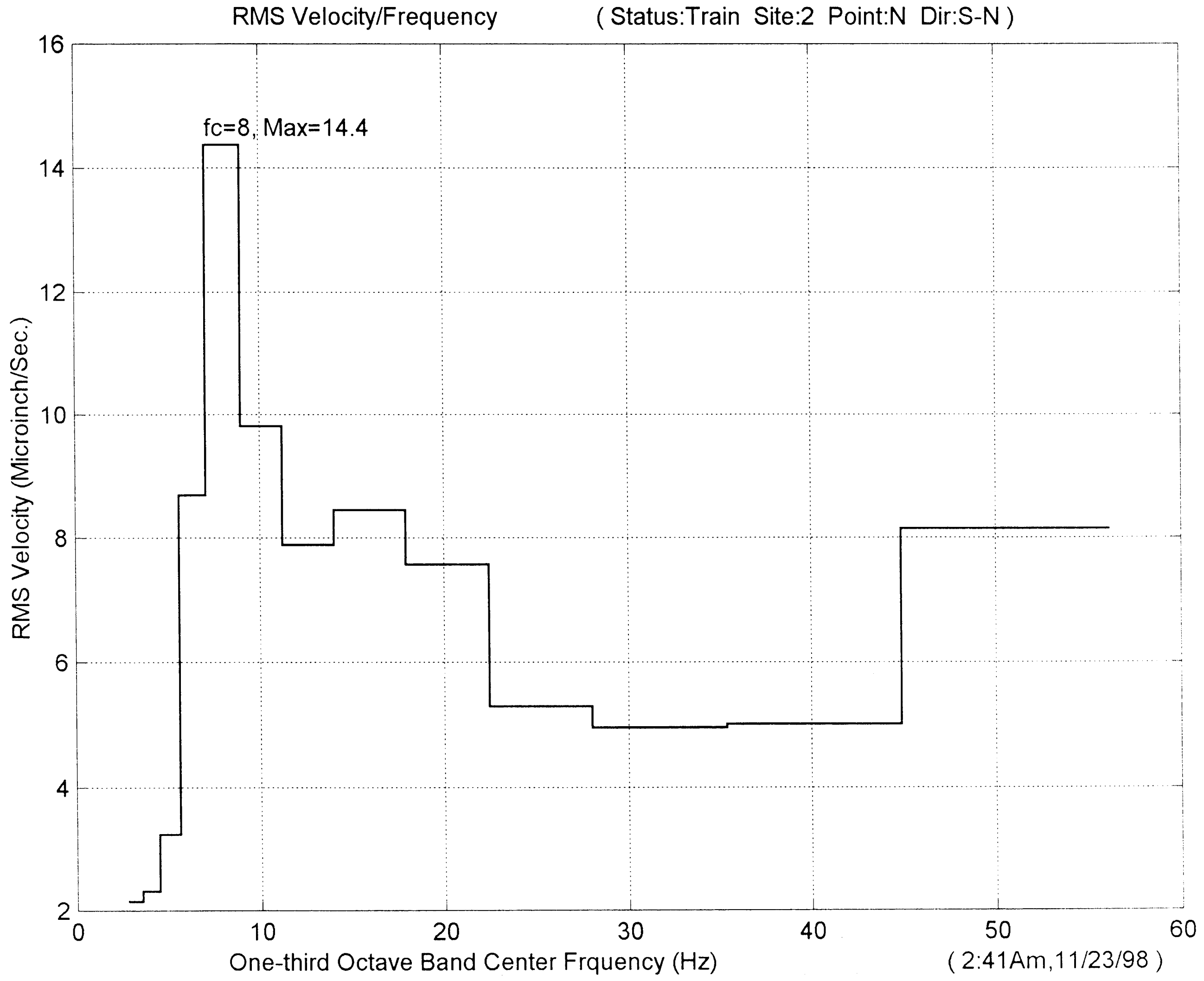

RMS Velocity/Frequency
(Status:Train Site:1 Point:S Dir:U-D)
fc=16, Max=113.7
RMS Velocity (Microinch/Sec.)
0
20
40
60
80
100
120
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(10:50Pm,11/20/98)

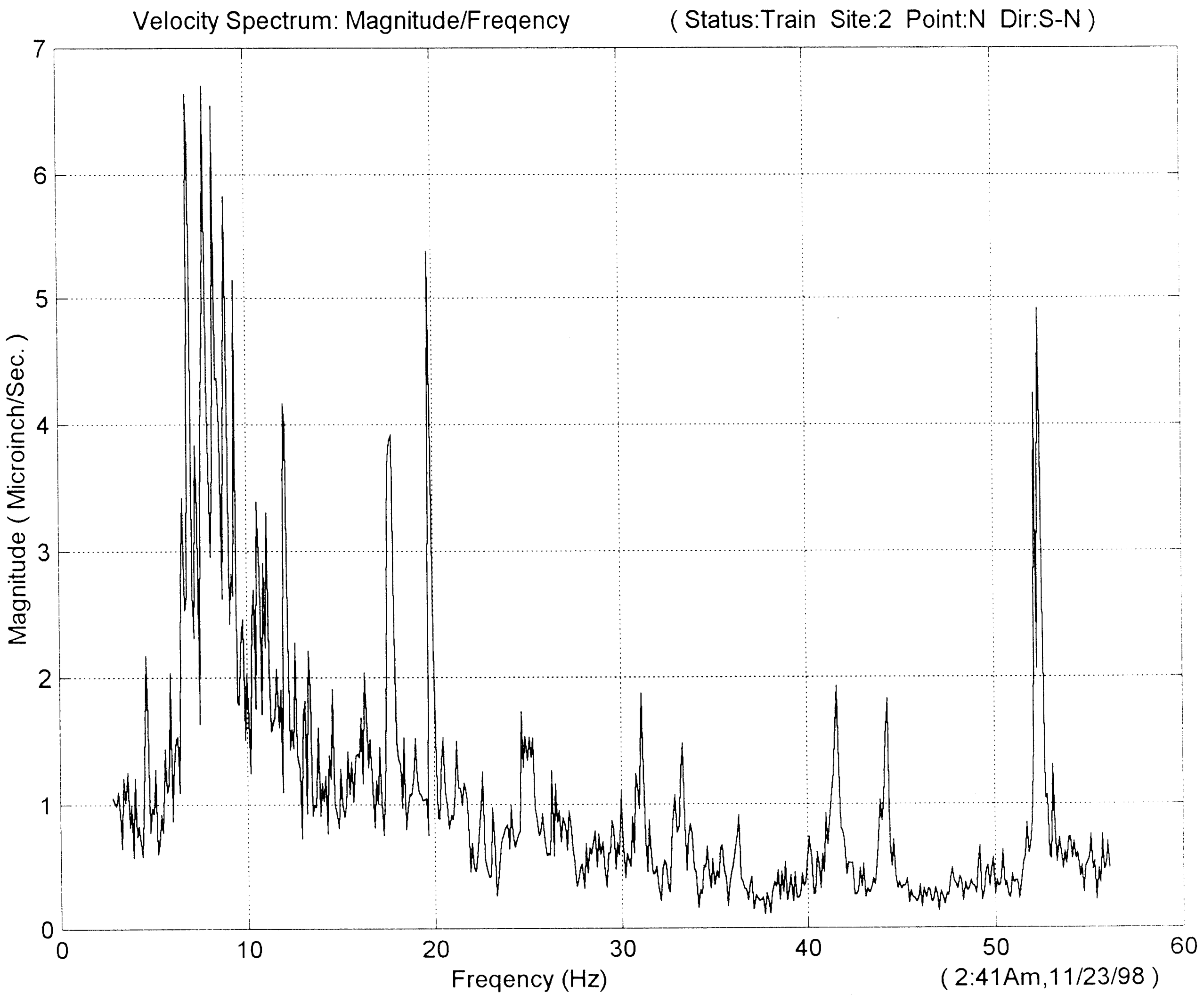

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:1 Point:S Dir:U-D)
Magnitude (Microinch/Sec.)
50
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Freqency (Hz)
(10:50Pm,11/20/98)

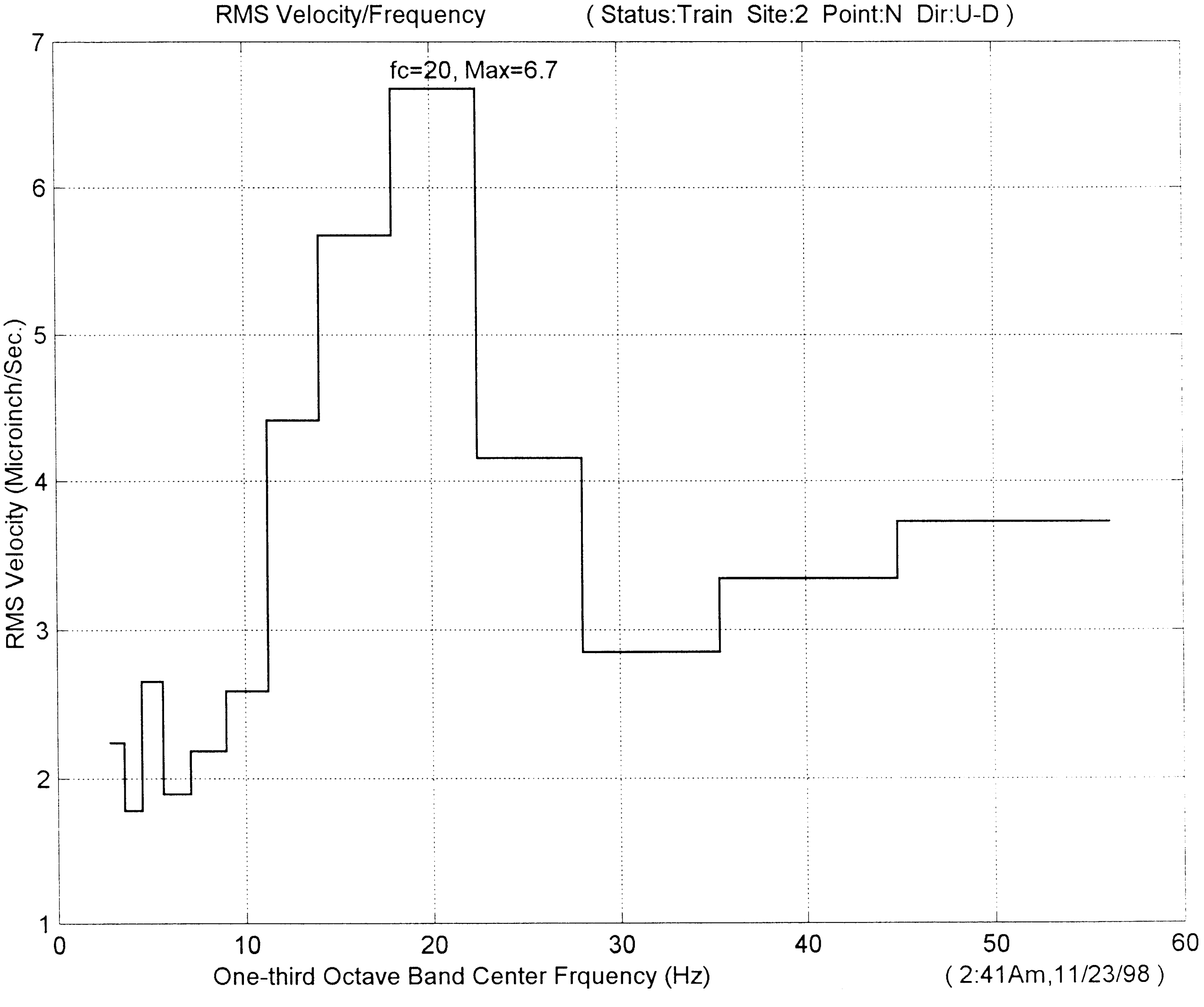
Site 2: Selected Signals with Train

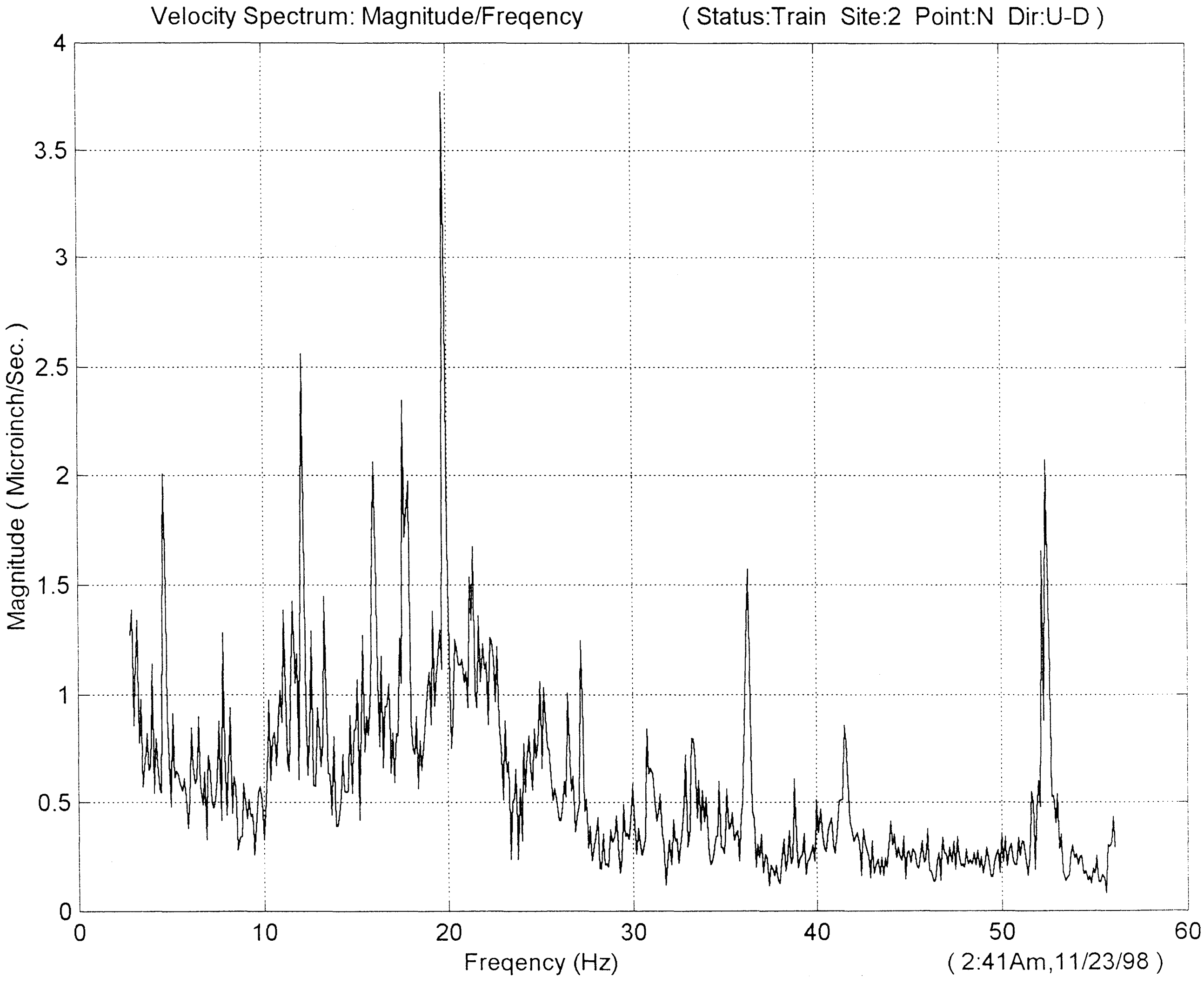


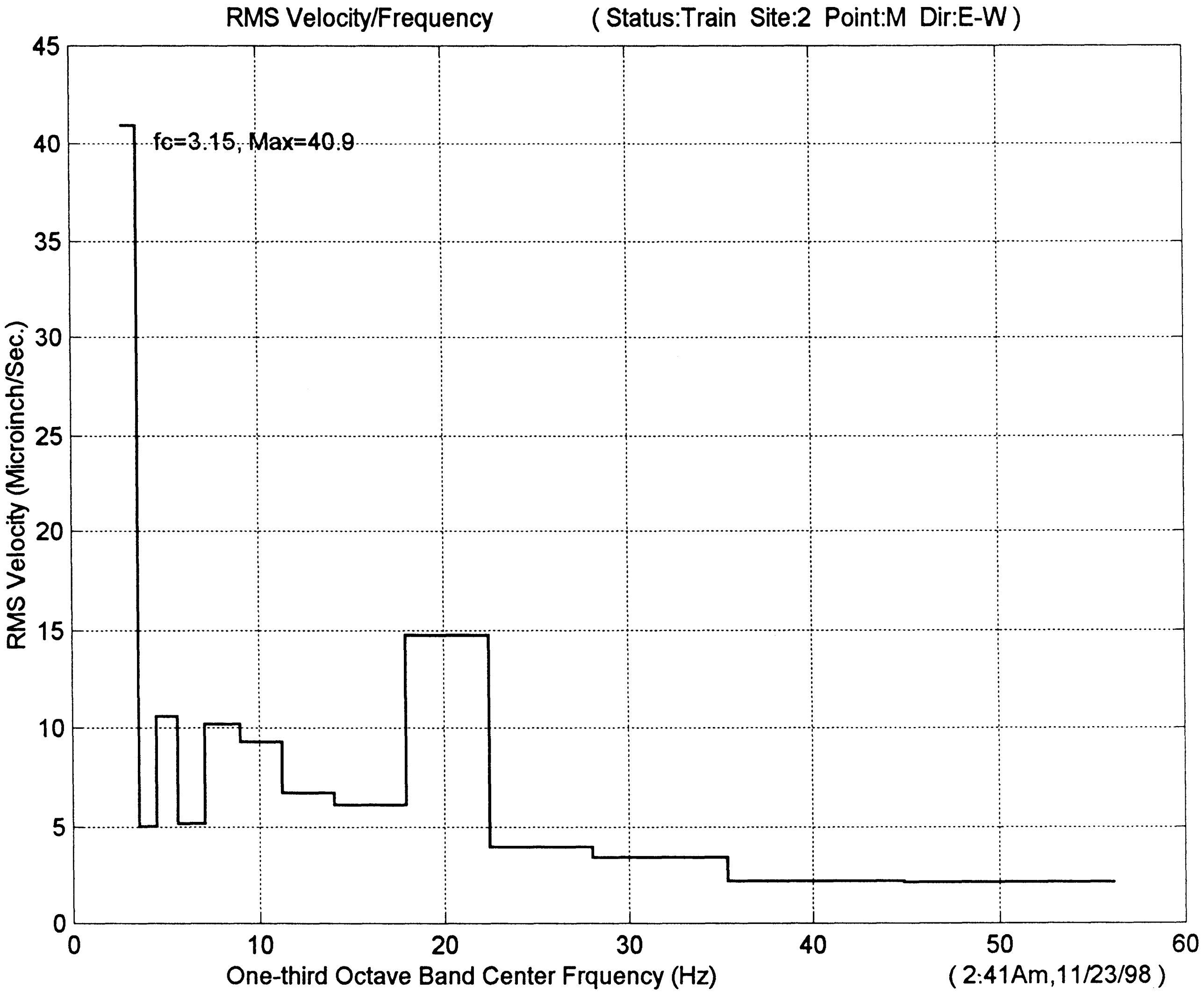

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:N Dir:E-W)
Magnitude (Microinch/Sec.)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

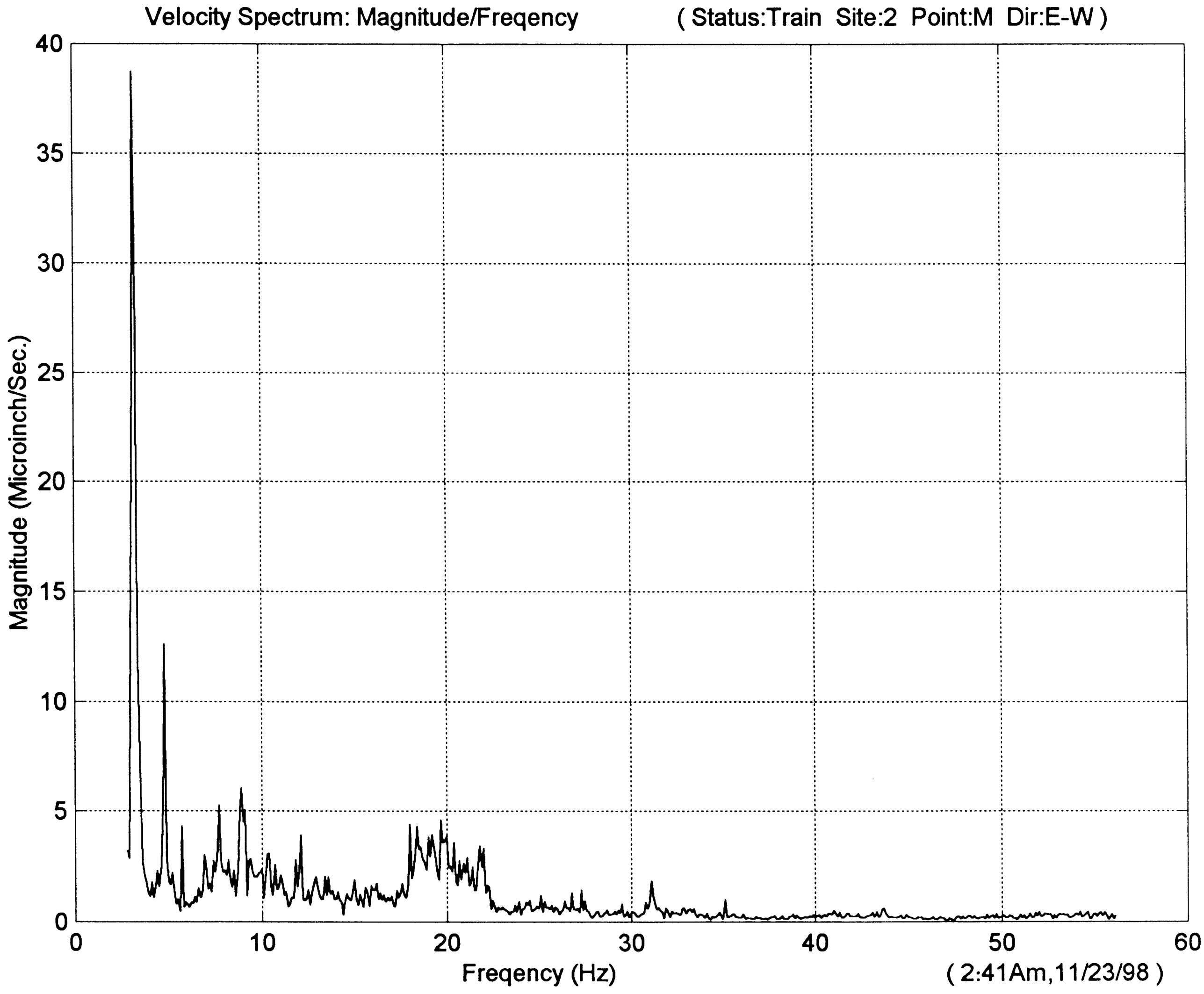

RMS Velocity/Frequency
(Status:Train Site:2 Point:N Dir:S-N)
fc=8, Max=14.4
RMS Velocity (Microinch/Sec.)
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)

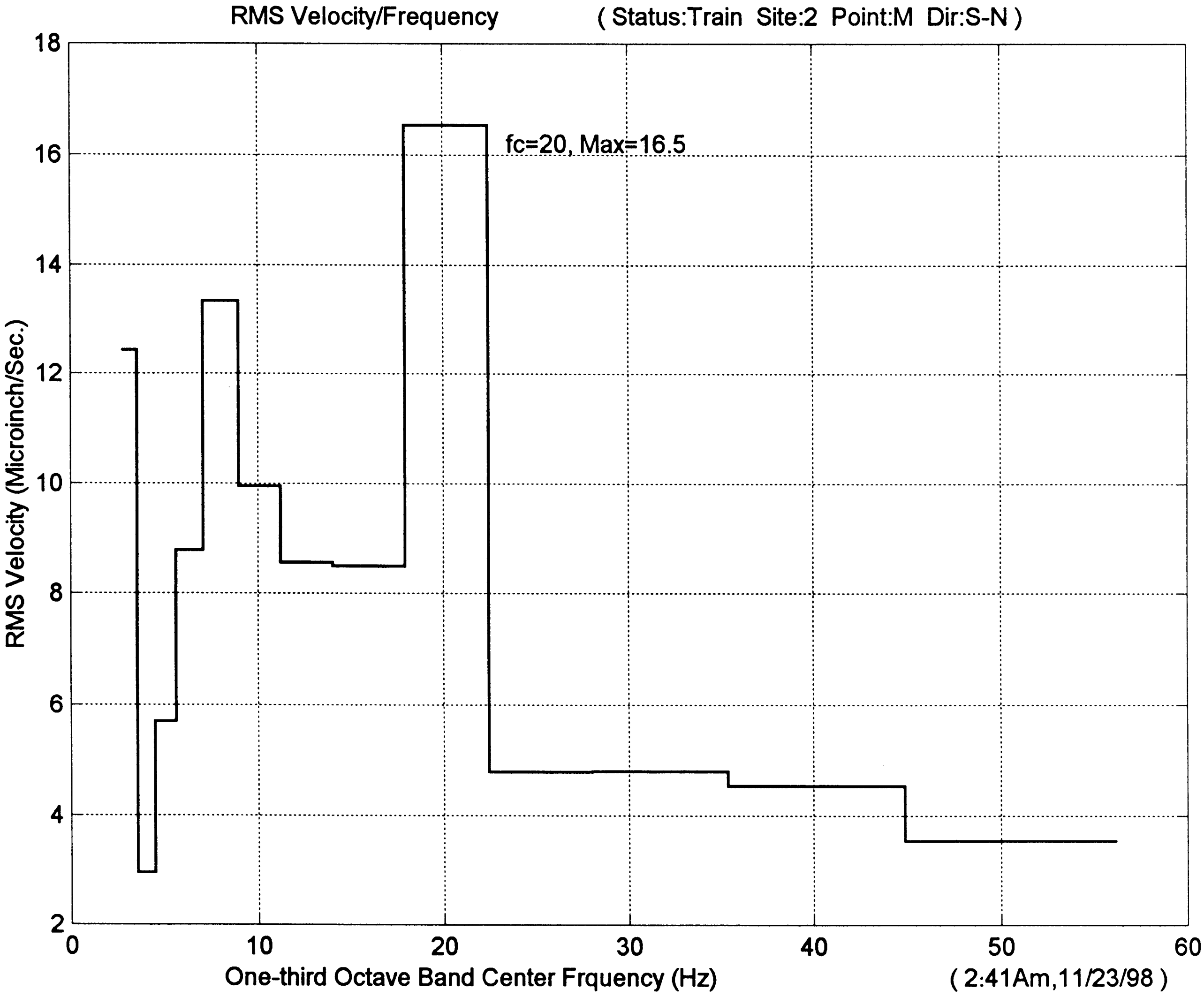

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:N Dir:S-N)
Magnitude (Microinch/Sec.)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

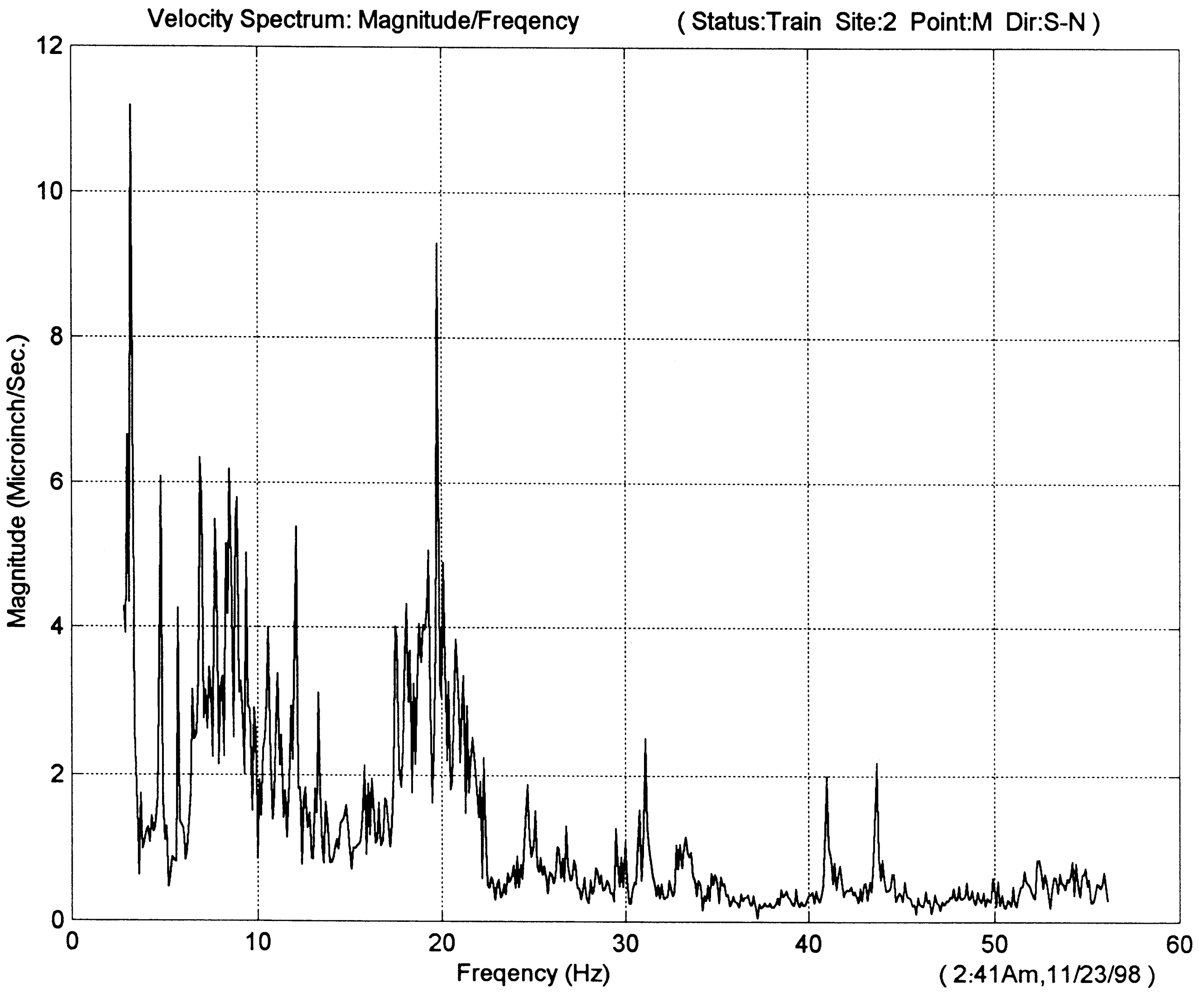

RMS Velocity/Frequency
(Status:Train Site:2 Point:N Dir:U-D)
fc=20, Max=6.7
RMS Velocity (Microinch/Sec.)
1
2
3
4
5
6
7
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)

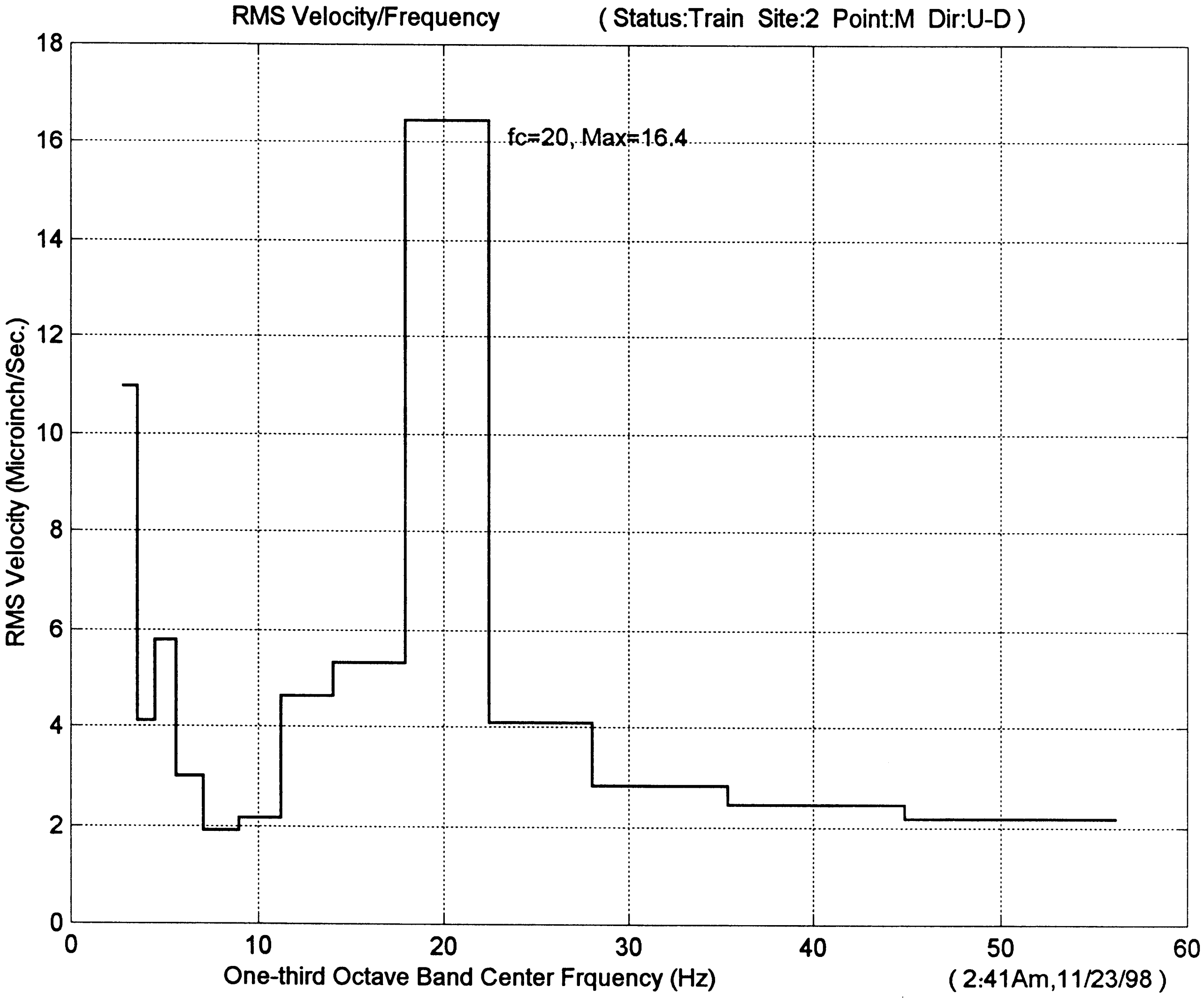

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:N Dir:U-D)
Magnitude (Microinch/Sec.)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

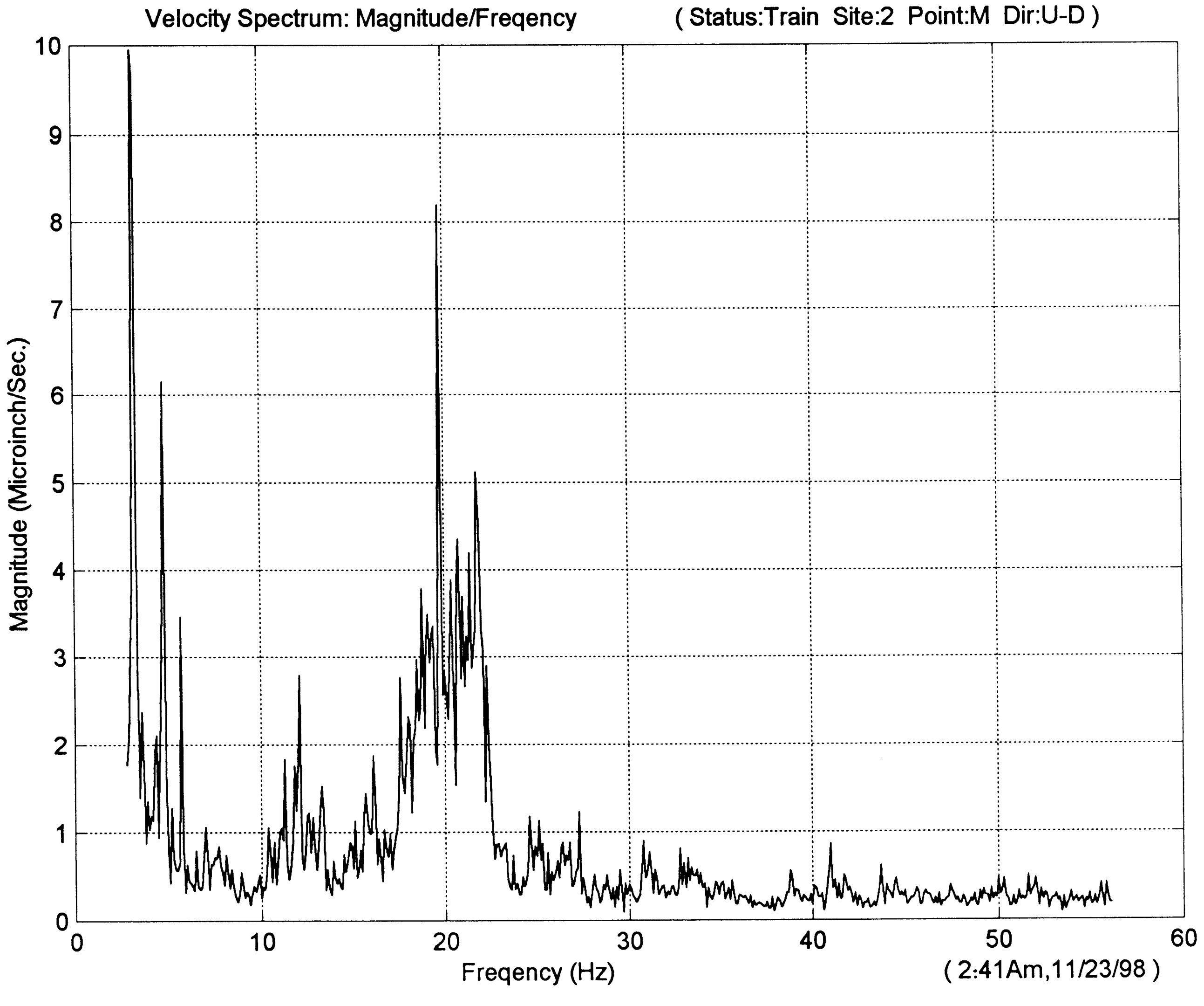

RMS Velocity/Frequency
(Status:Train Site:2 Point:M Dir:E-W)
fc=3.15, Max=40.9
RMS Velocity (Microinch/Sec.)
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)

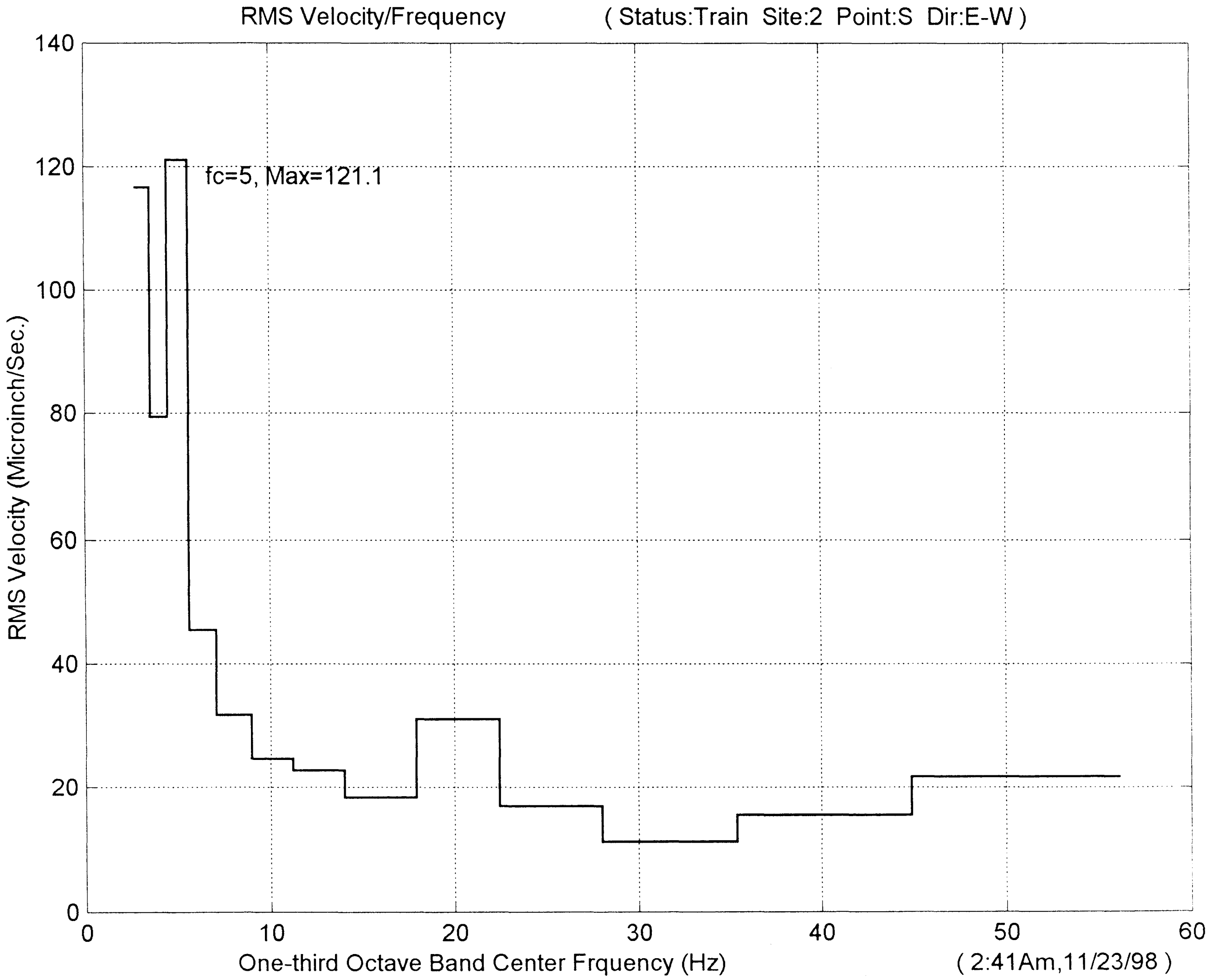

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:M Dir:E-W)
Magnitude (Microinch/Sec.)
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

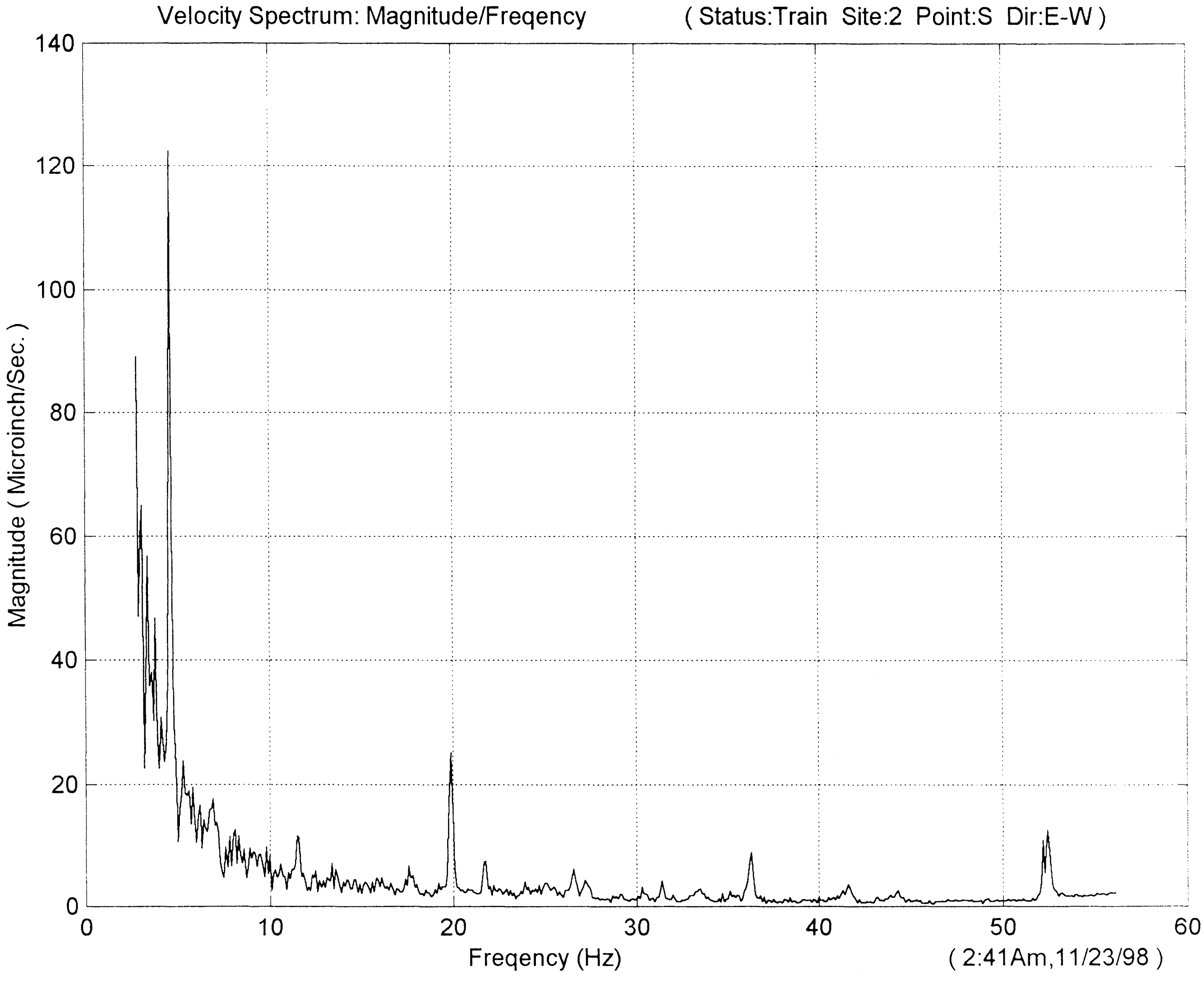

RMS Velocity/Frequency
(Status:Train Site:2 Point:M Dir:S-N)
fc=20, Max=16.5
RMS Velocity (Microinch/Sec.)
18
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)

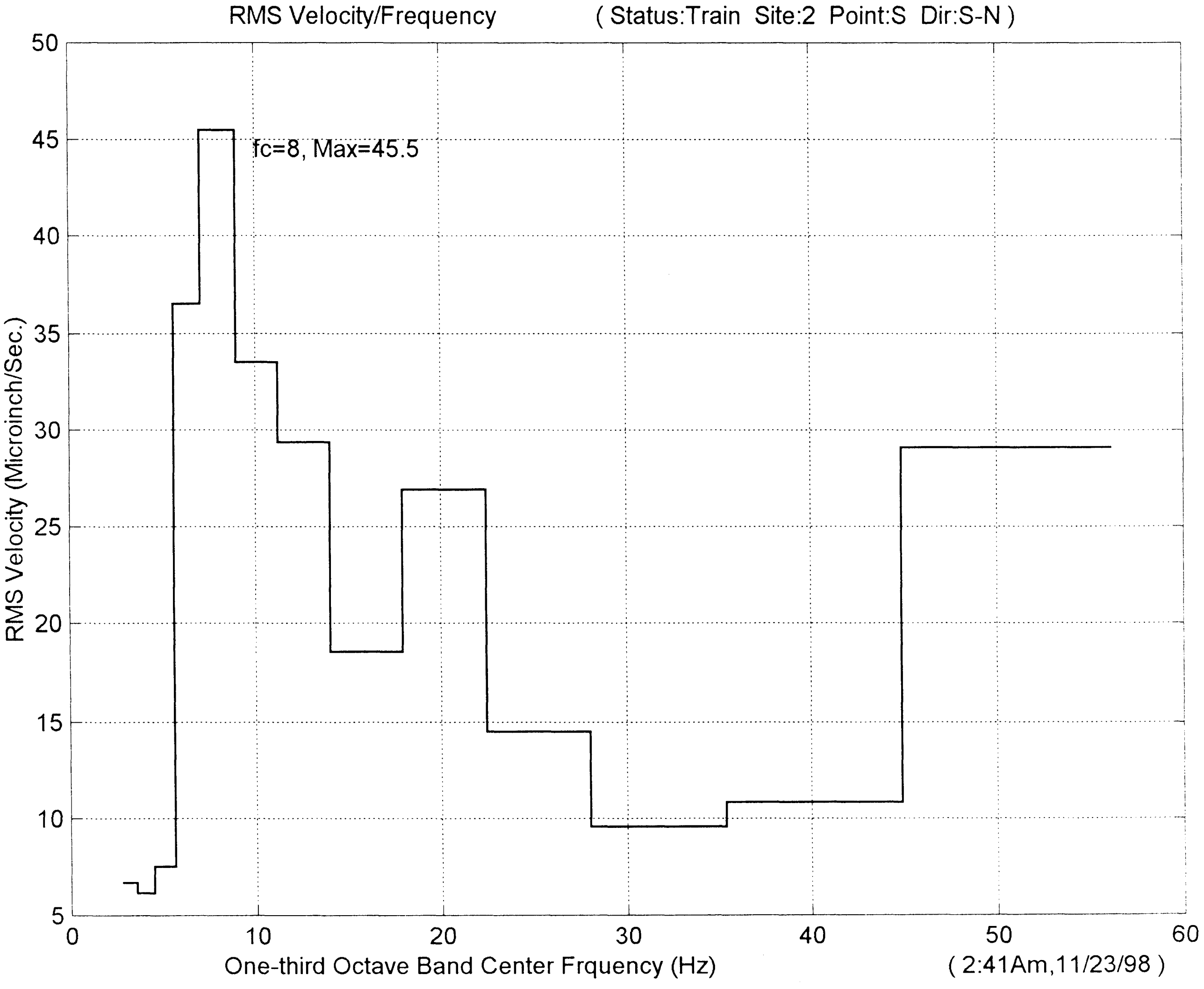

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:M Dir:S-N)
Magnitude (Microinch/Sec.)
0
2
4
6
8
10
12
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

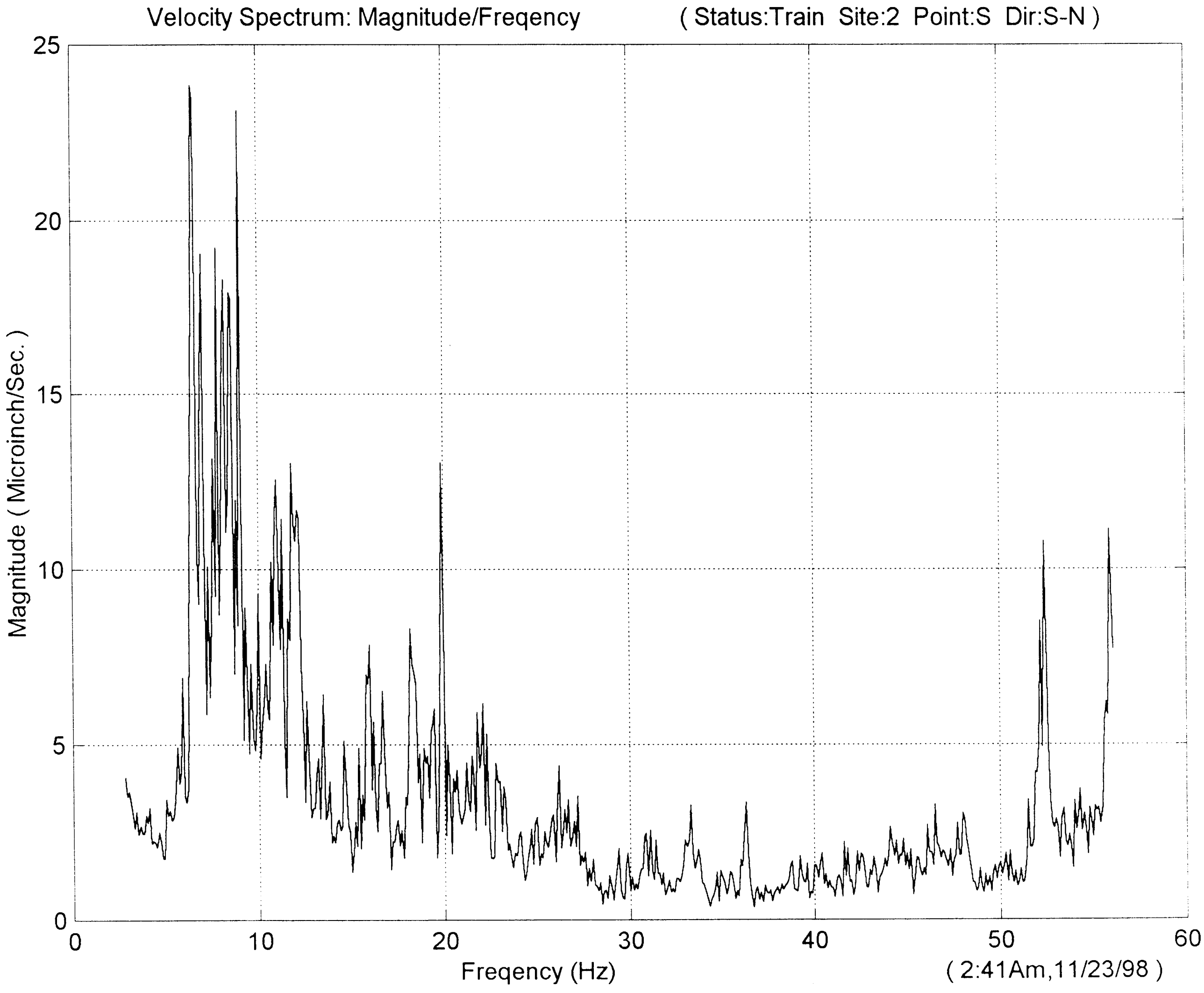

RMS Velocity/Frequency
(Status:Train Site:2 Point:M Dir:U-D)
18
16
14
12
10
8
6
4
2
0
RMS Velocity (Microinch/Sec.)
fc=20, Max=16.4
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)


Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:M Dir:U-D)
Magnitude (Microinch/Sec.)
10
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

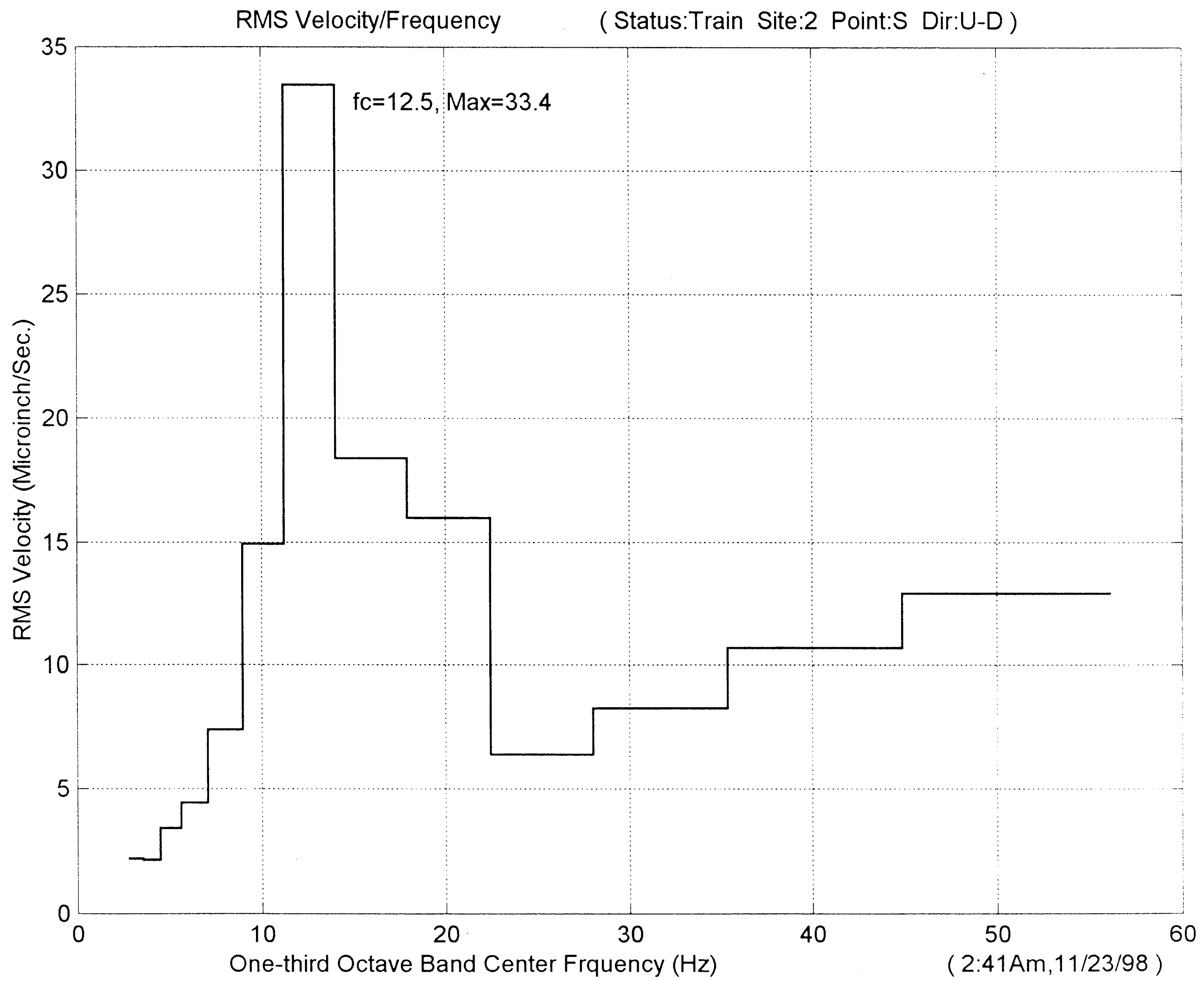

RMS Velocity/Frequency
(Status:Train Site:2 Point:S Dir:E-W)
fc=5, Max=121.1
RMS Velocity (Microinch/Sec.)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)

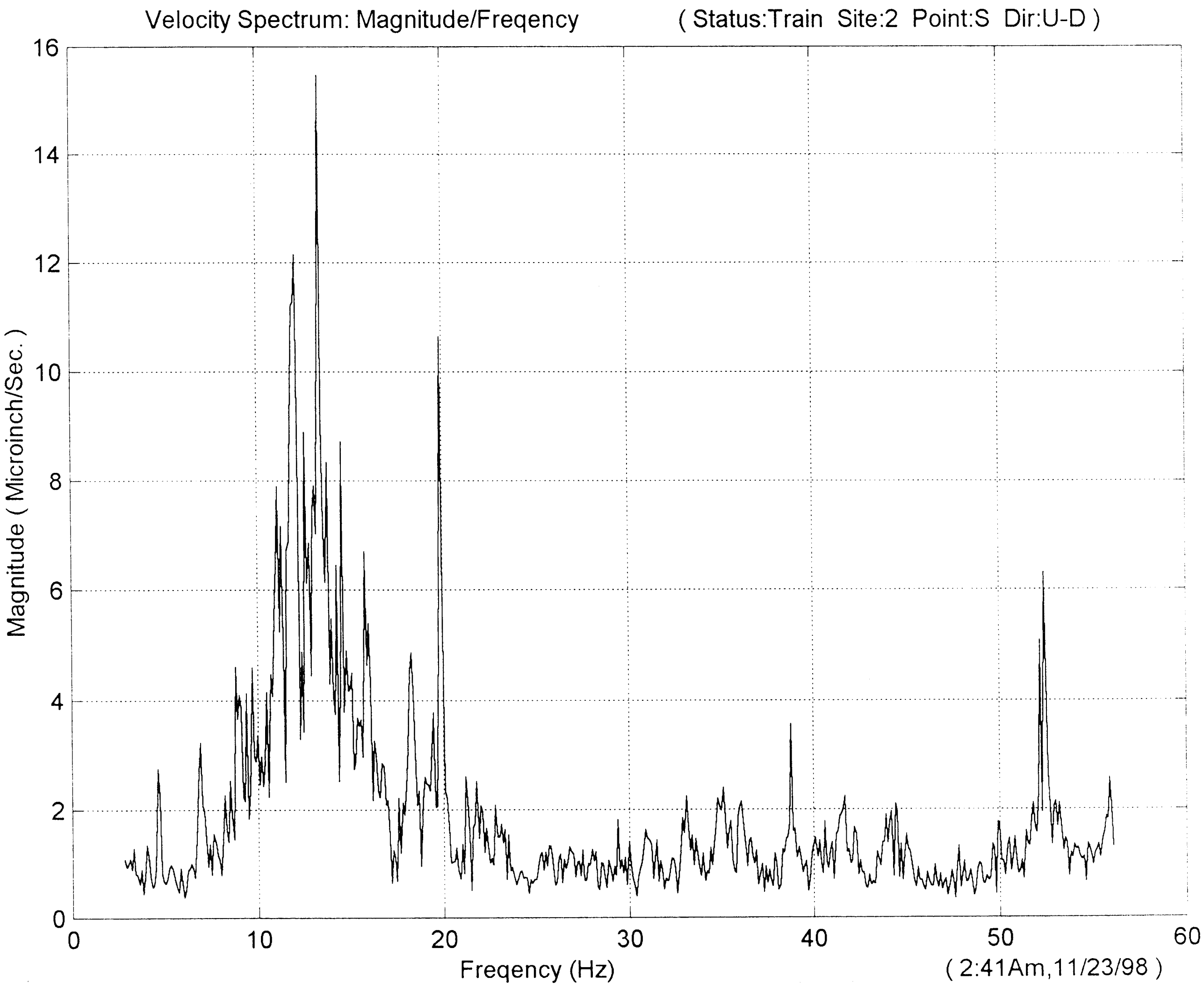

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:S Dir:E-W)
Magnitude (Microinch/Sec.)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)


RMS Velocity/Frequency
(Status:Train Site:2 Point:S Dir:S-N)
fc=8, Max=45.5
RMS Velocity (Microinch/Sec.)
50
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)

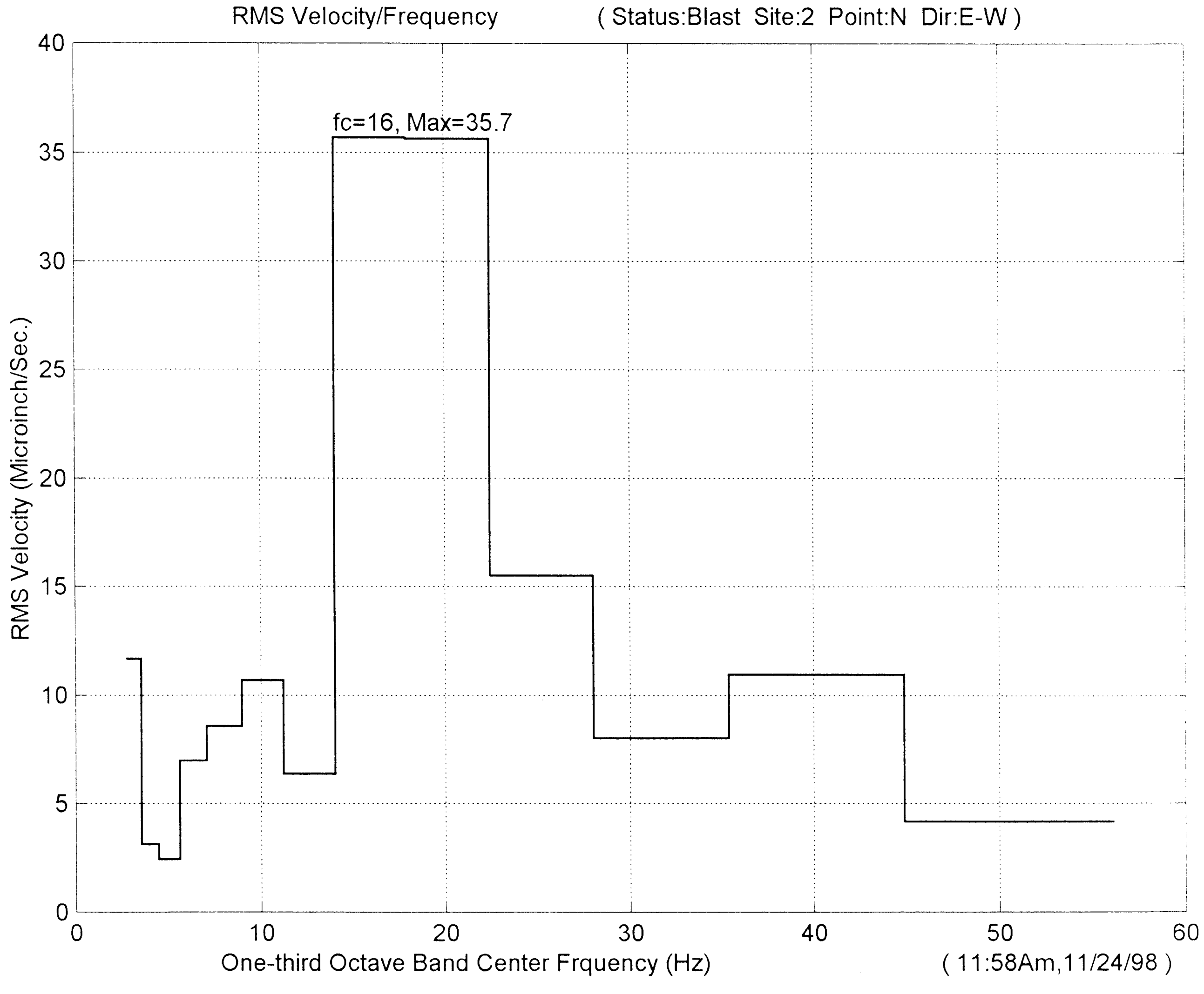


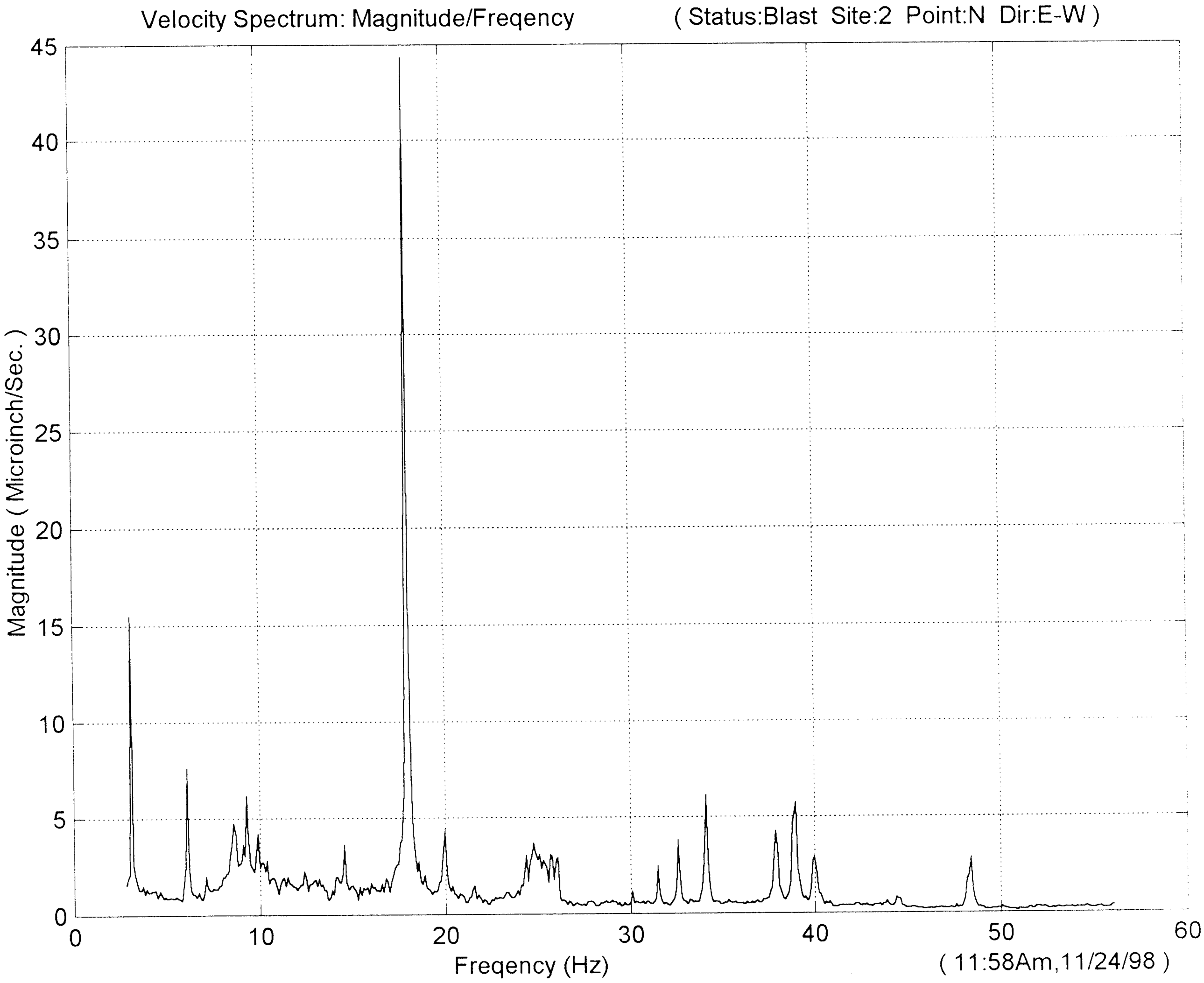
Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:S Dir:S-N)
Magnitude (Microinch/Sec.)
25
20
15
10
5
0
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

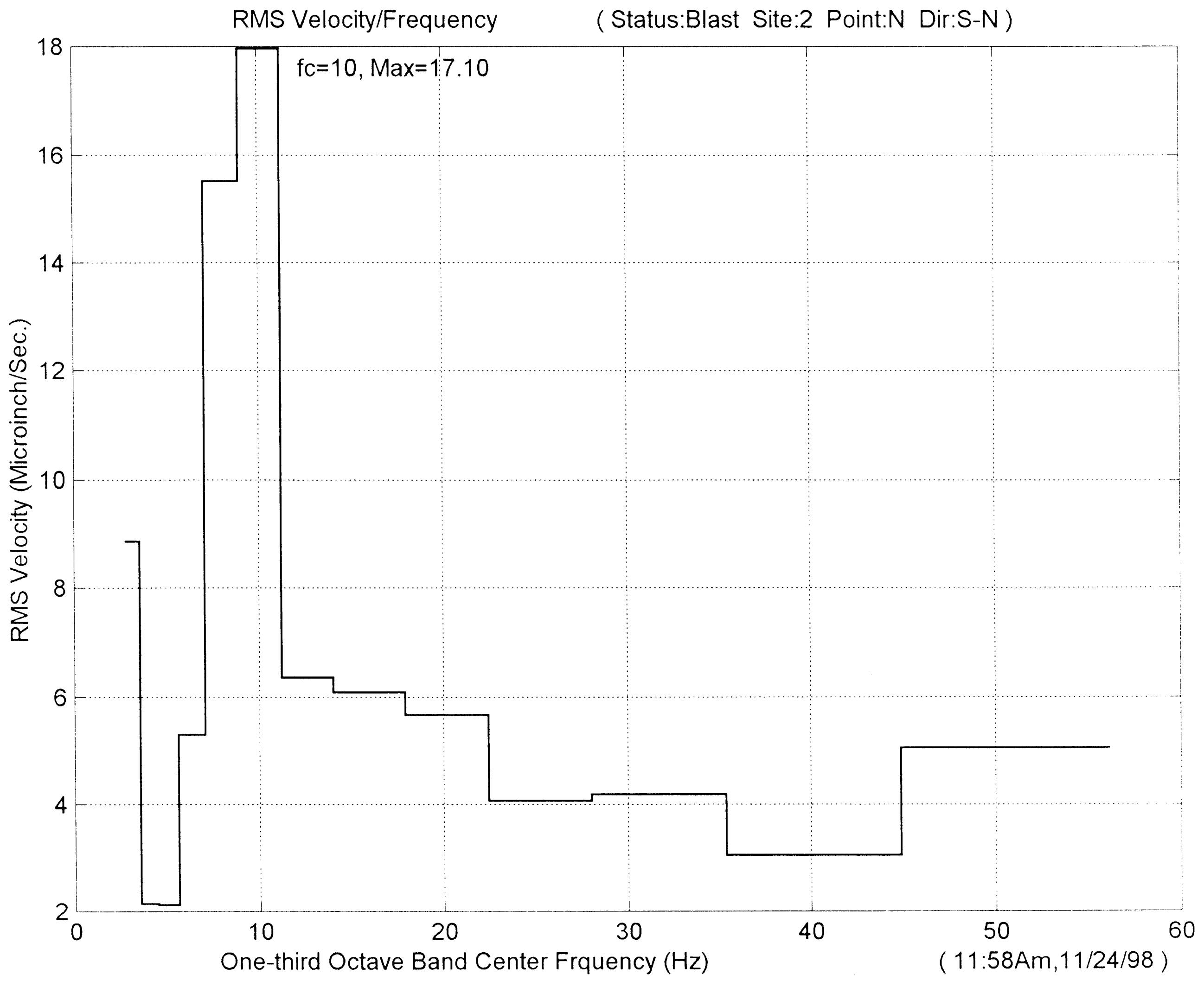

RMS Velocity/Frequency
(Status:Train Site:2 Point:S Dir:U-D)
fc=12.5, Max=33.4
RMS Velocity (Microinch/Sec.)
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(2:41Am,11/23/98)

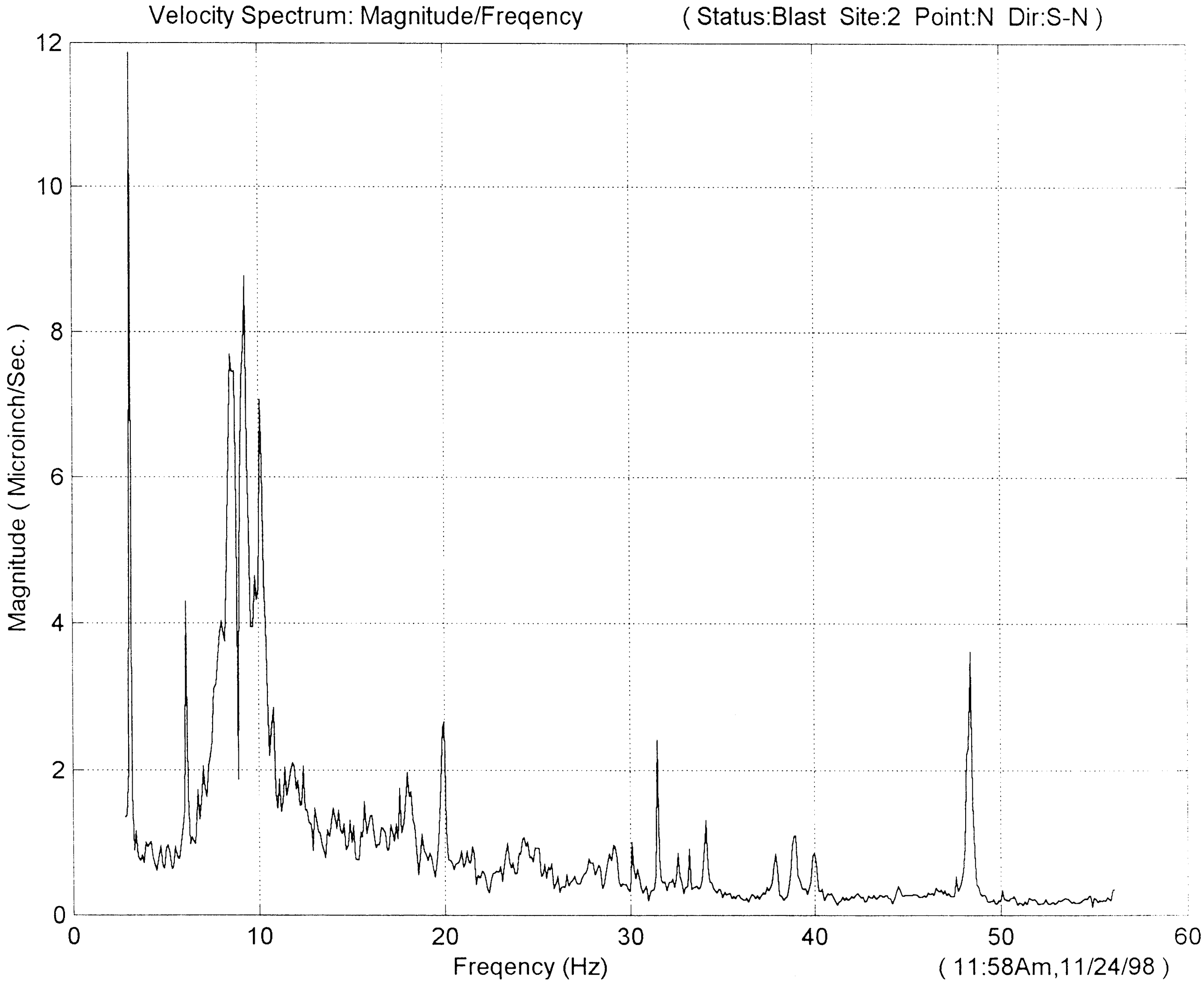

Velocity Spectrum: Magnitude/Freqency
(Status:Train Site:2 Point:S Dir:U-D)
Magnitude (Microinch/Sec.)
0
2
4
6
8
10
12
14
16
0
10
20
30
40
50
60
Freqency (Hz)
(2:41Am,11/23/98)

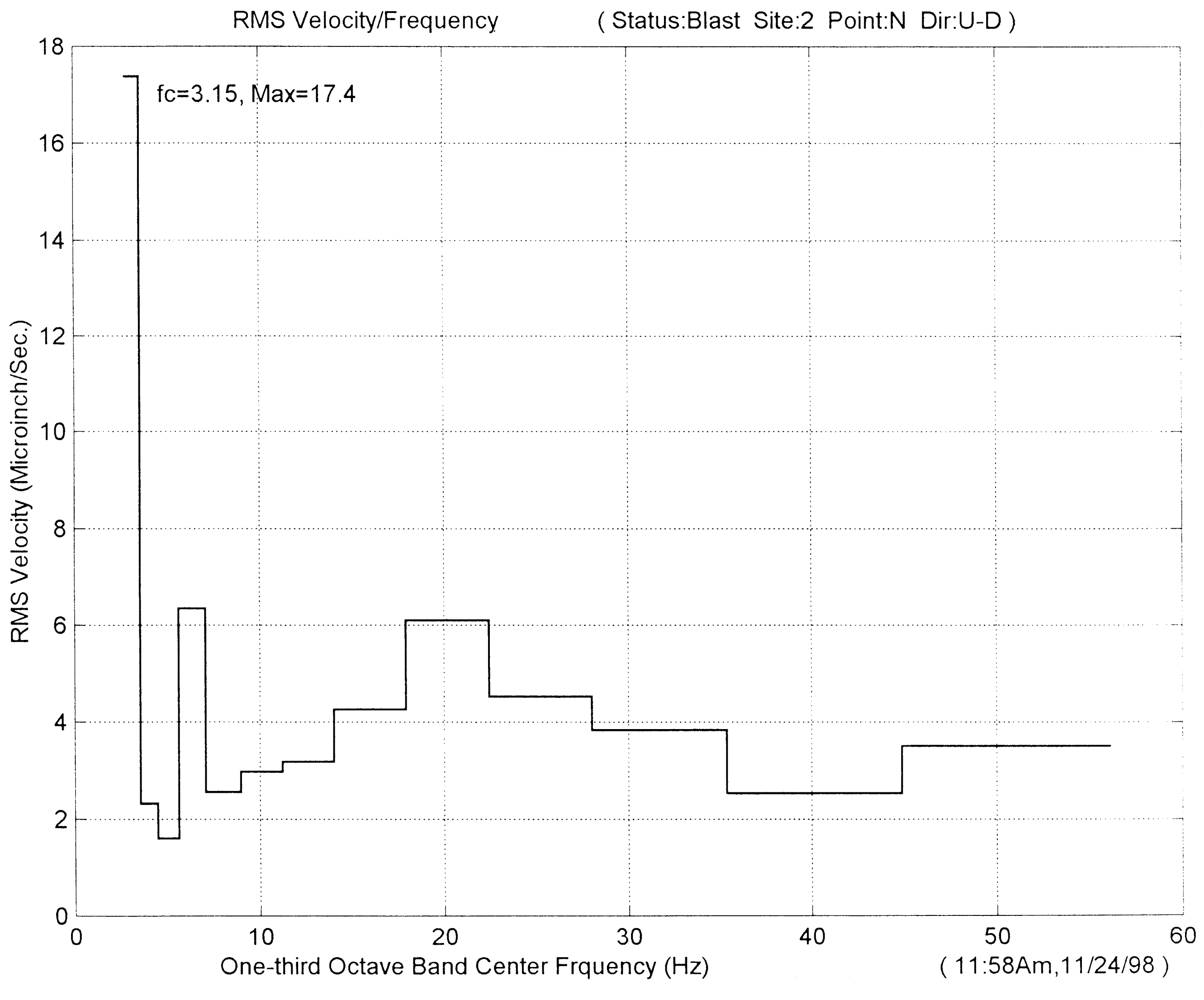
Site 2: Selected Signals with Blast

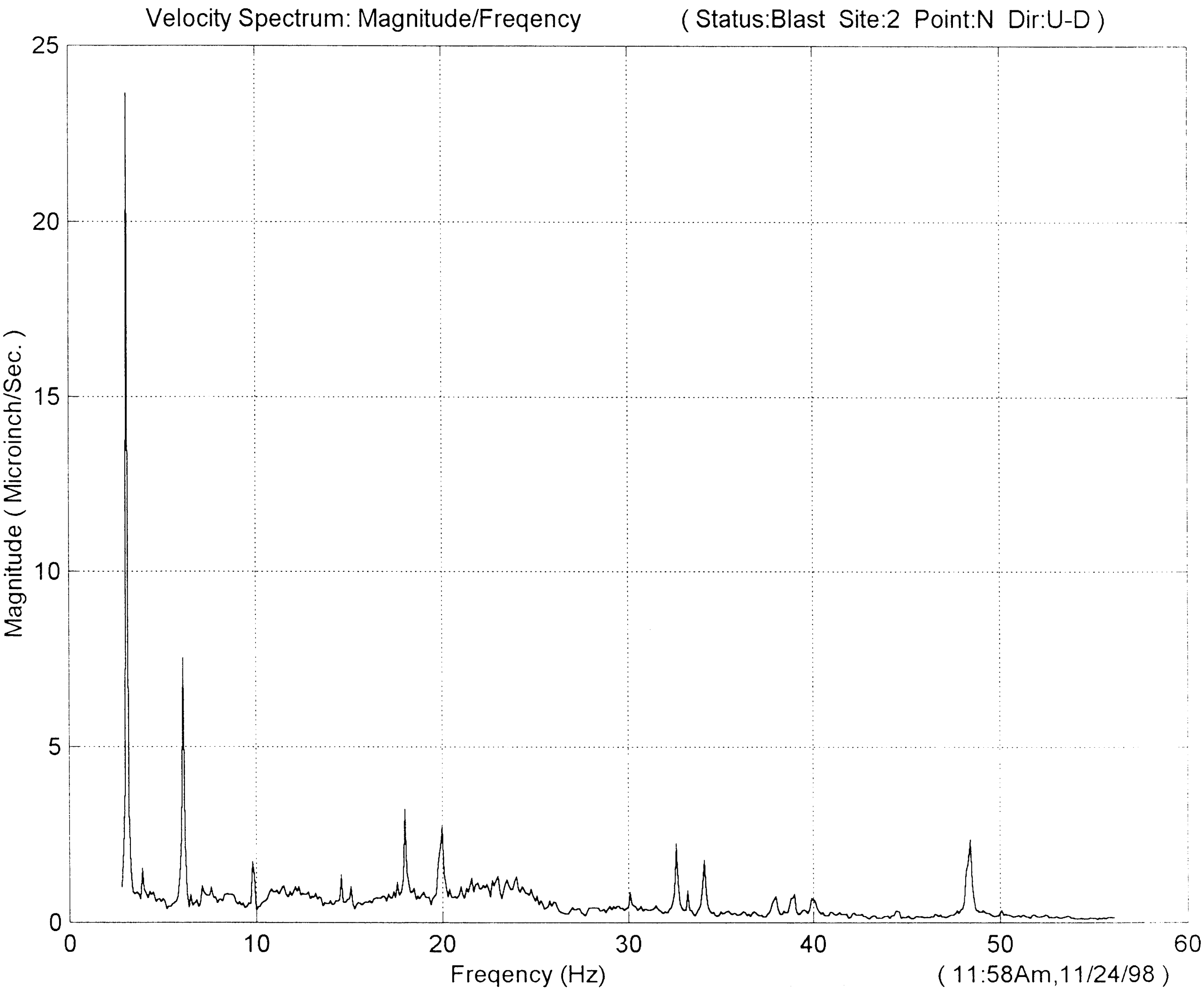


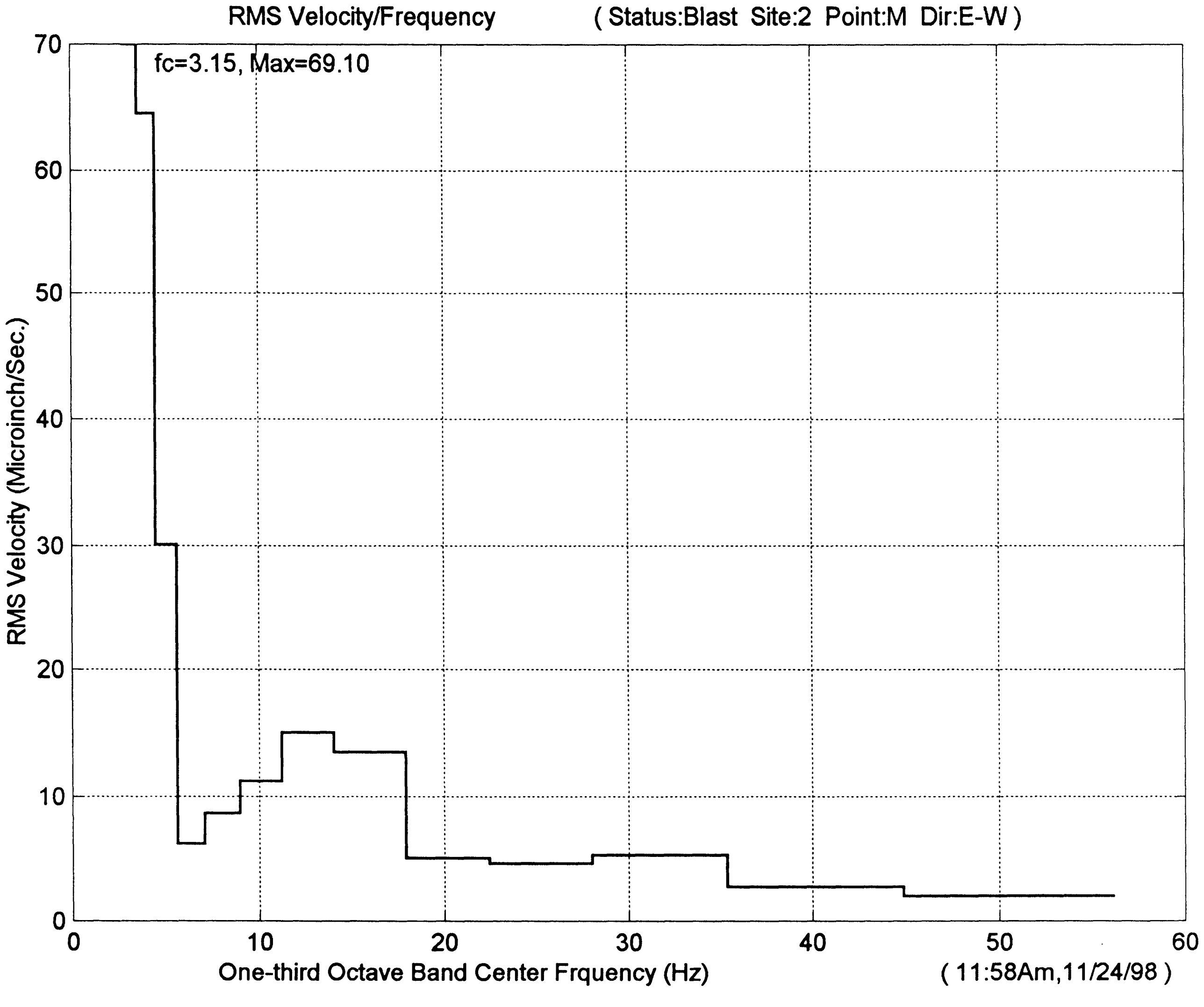

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:N Dir:E-W)
Magnitude (Microinch/Sec.)
0
5
10
15
20
25
30
35
40
45
Freqency (Hz)
0
10
20
30
40
50
60
(11:58Am,11/24/98)

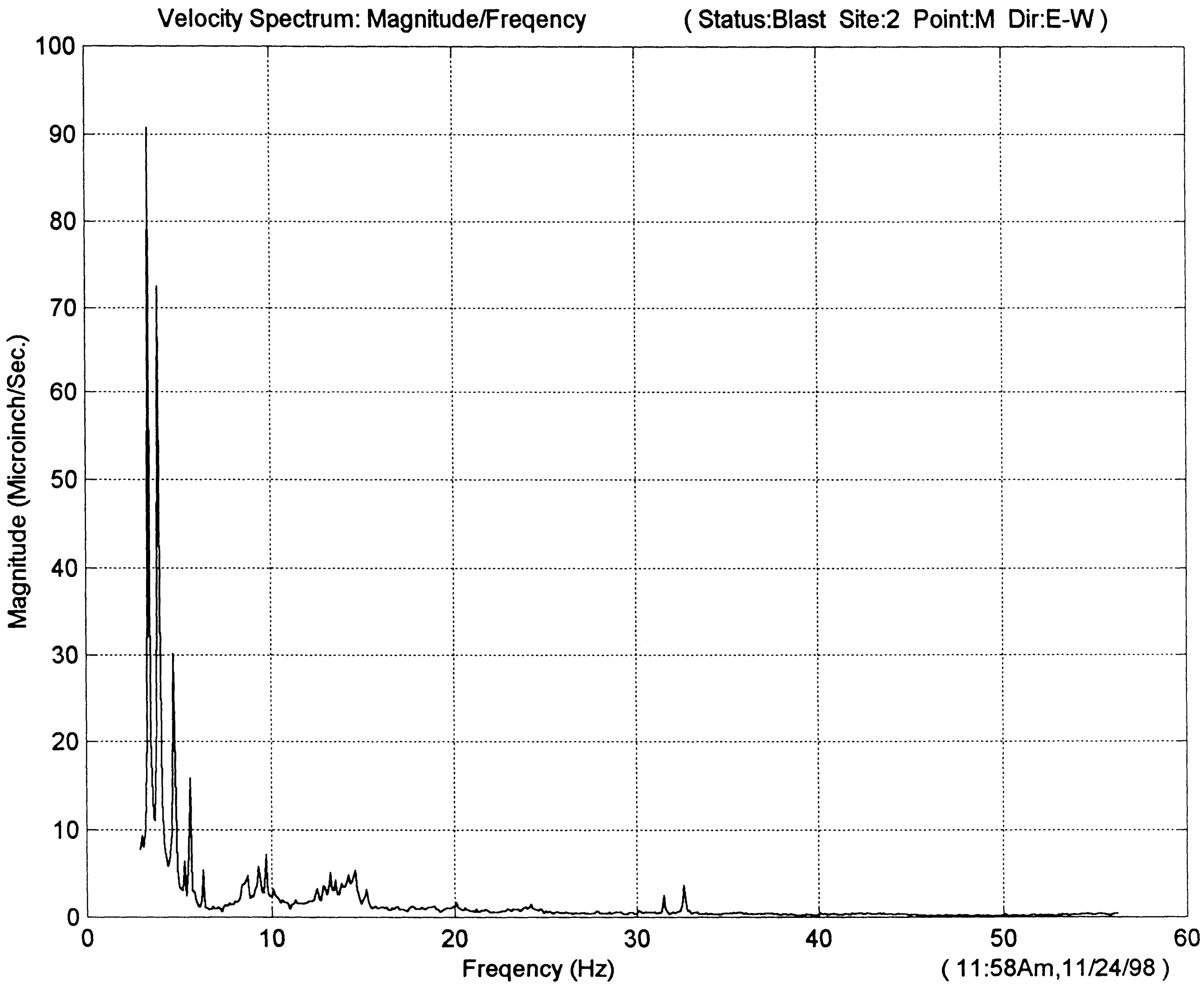

RMS Velocity/Frequency
(Status:Blast Site:2 Point:N Dir:S-N)
fc=10, Max=17.10
18
16
14
12
10
8
6
4
2
RMS Velocity (Microinch/Sec.)
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)

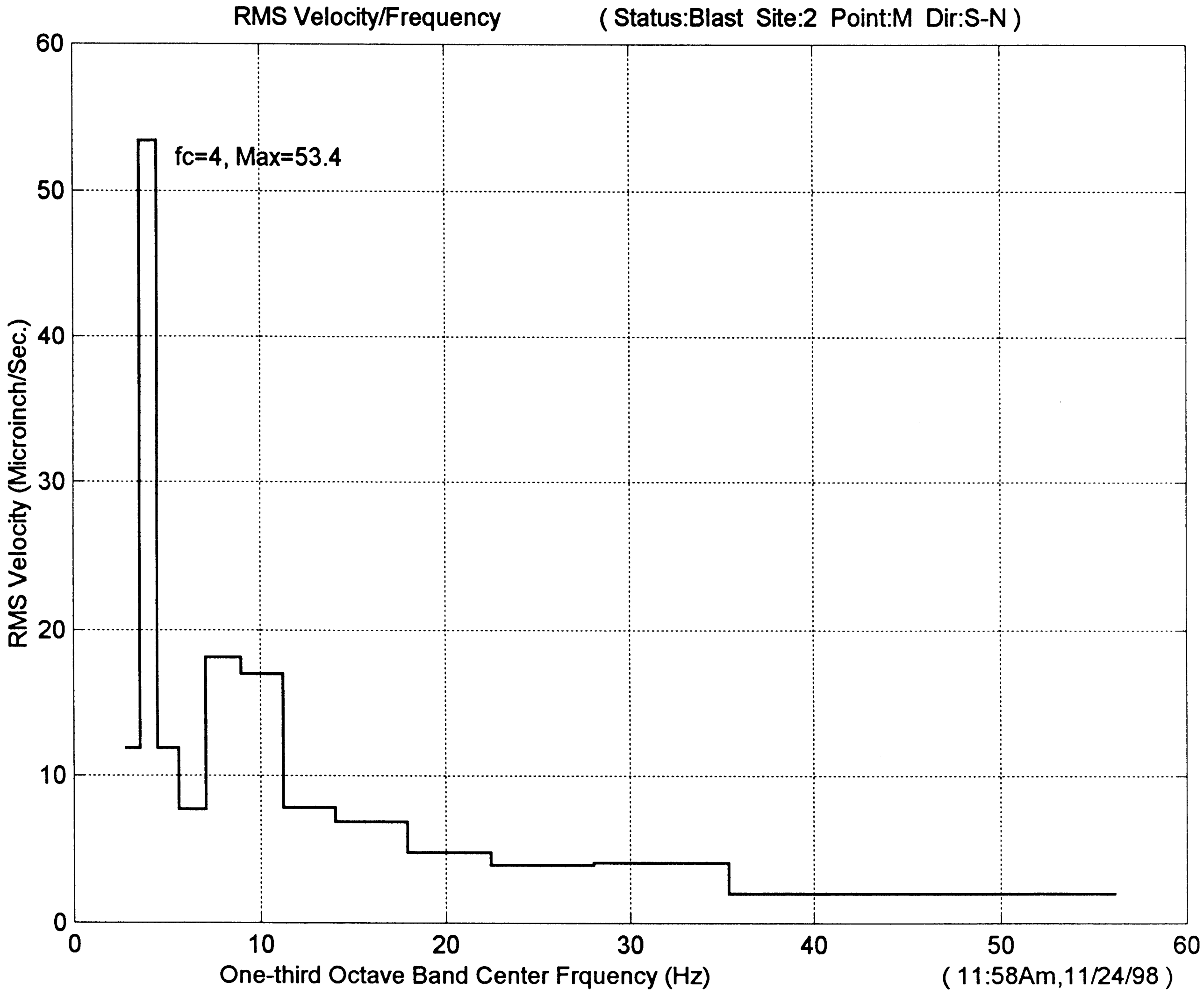

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:N Dir:S-N)
Magnitude (Microinch/Sec.)
0
2
4
6
8
10
12
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

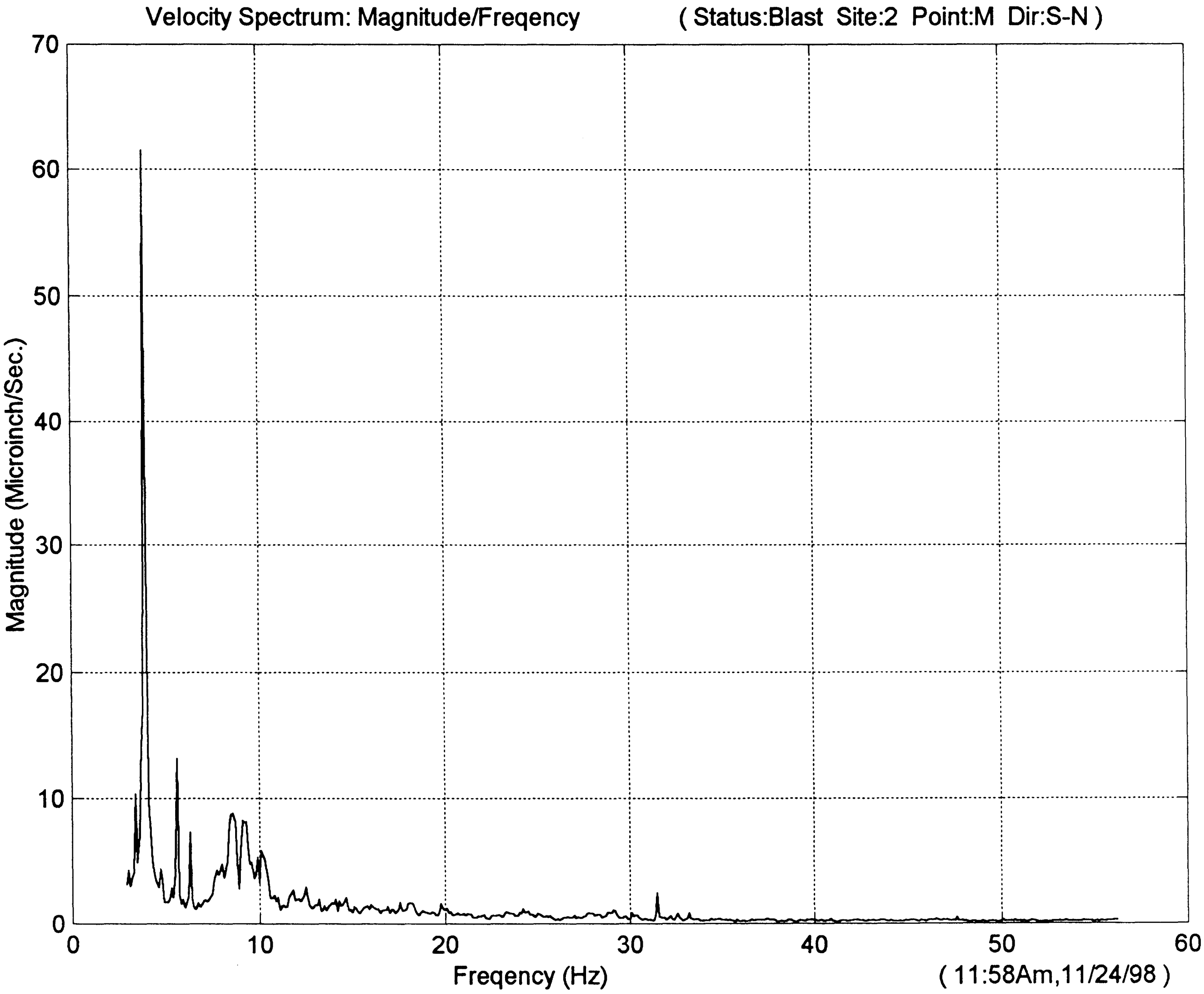

RMS Velocity/Frequency
(Status:Blast Site:2 Point:N Dir:U-D)
fc=3.15, Max=17.4
RMS Velocity (Microinch/Sec.)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)

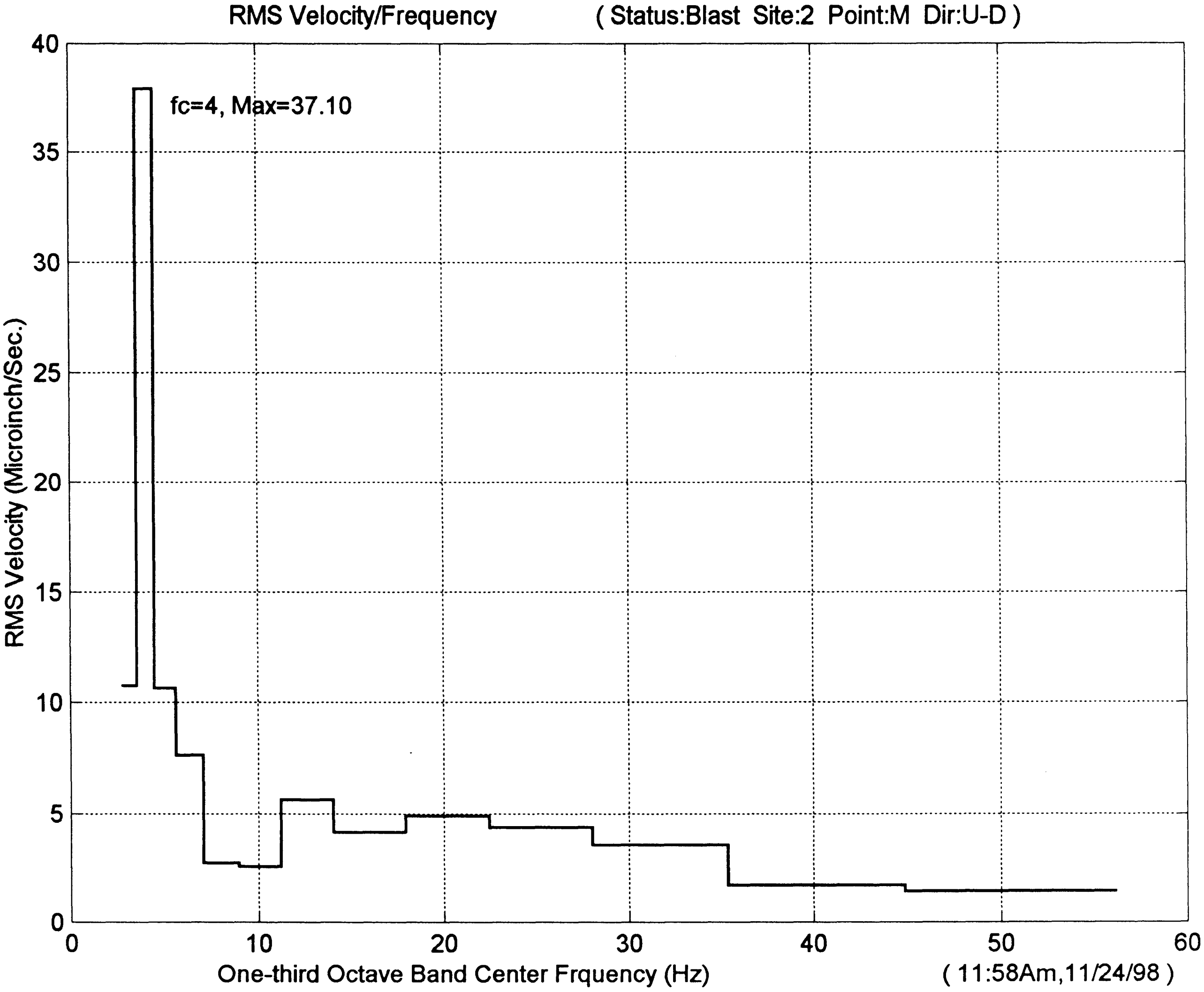

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:N Dir:U-D)
25
20
15
10
5
0
Magnitude (Microinch/Sec.)
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

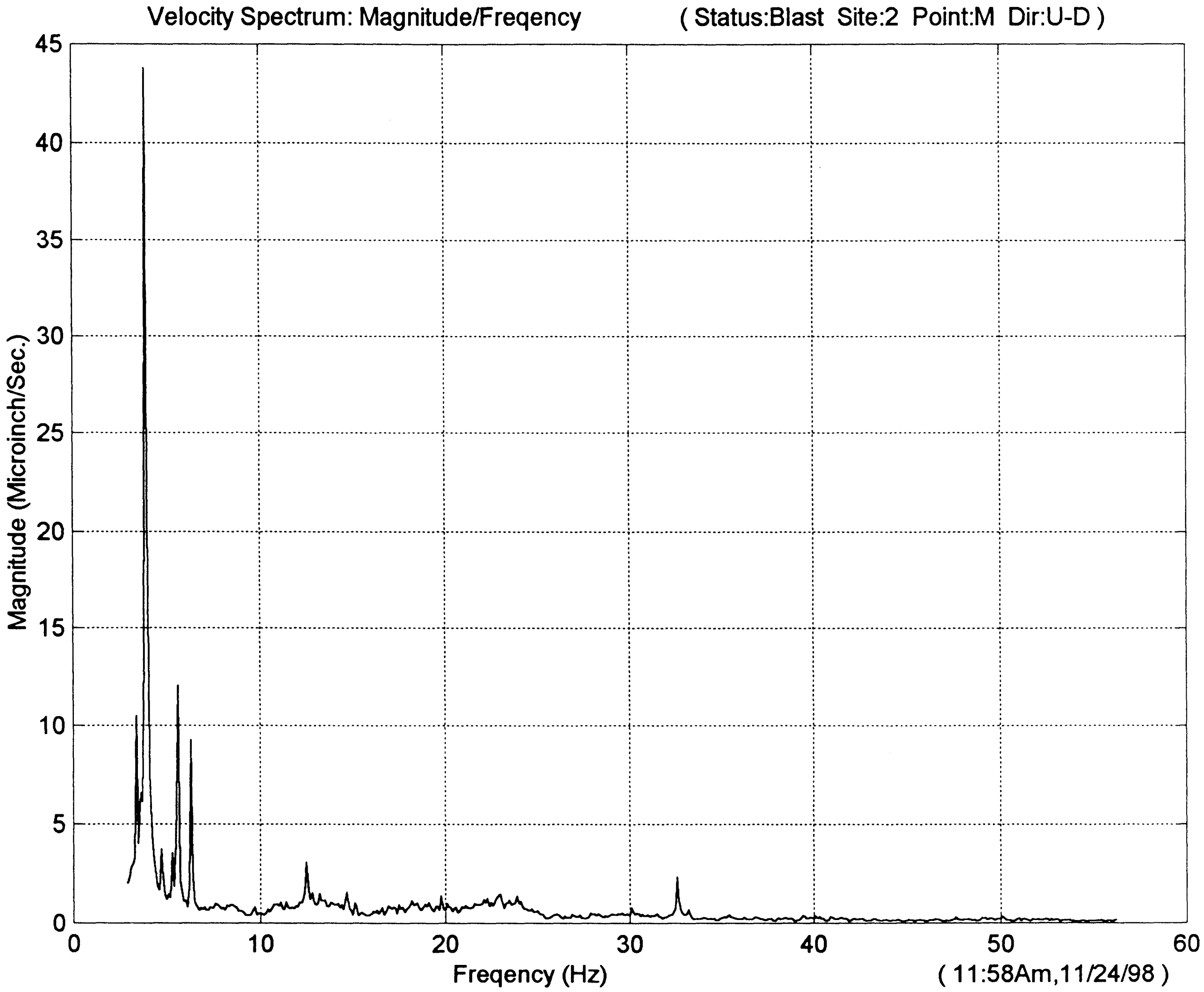

RMS Velocity/Frequency
(Status:Blast Site:2 Point:M Dir:E-W)
fc=3.15, Max=69.10
RMS Velocity (Microinch/Sec.)
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)

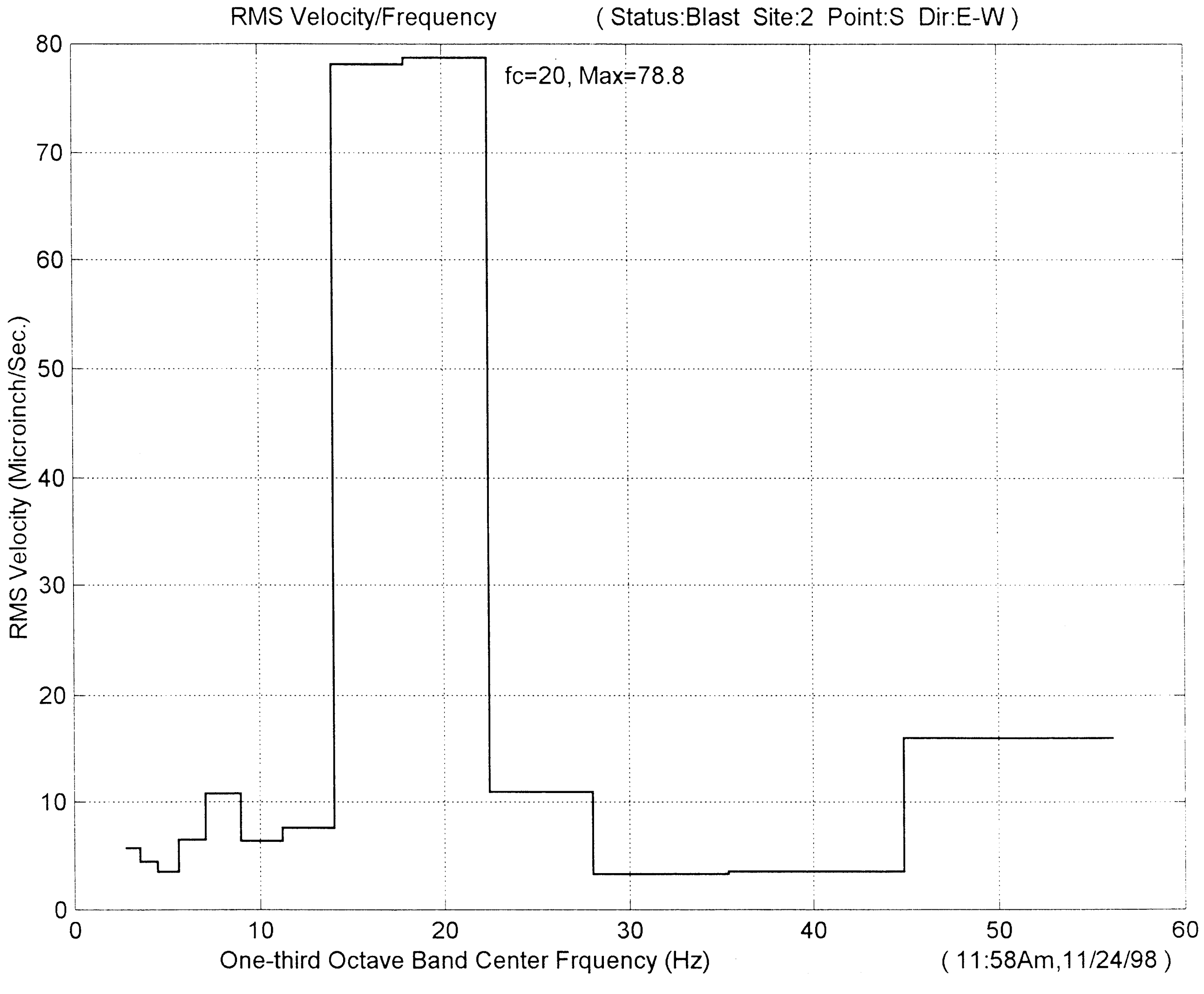

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:M Dir:E-W)
100
90
80
70
60
50
40
30
20
10
0
Magnitude (Microinch/Sec.)
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

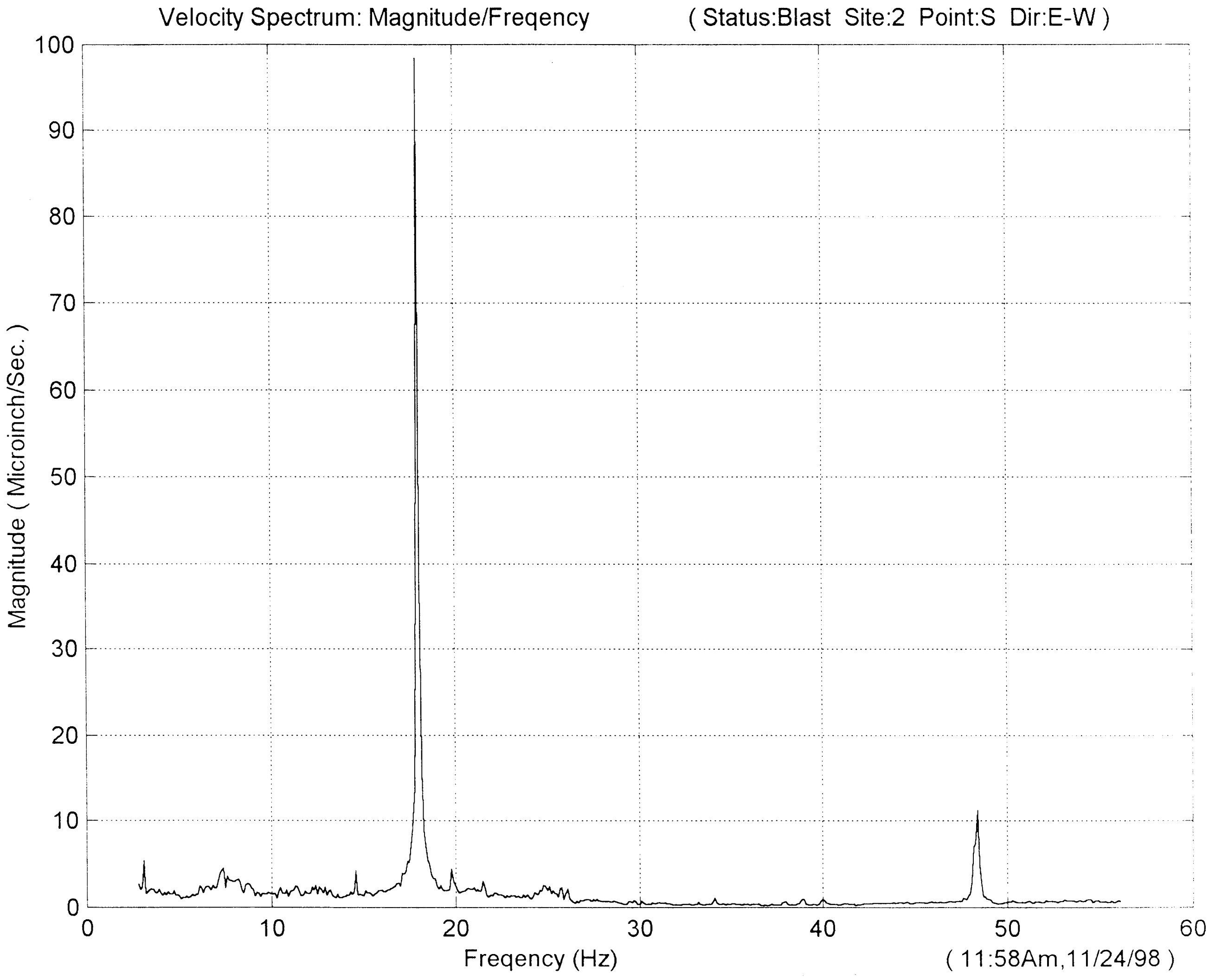

RMS Velocity/Frequency
(Status:Blast Site:2 Point:M Dir:S-N)
fc=4, Max=53.4
RMS Velocity (Microinch/Sec.)
60
50
40
30
20
10
0
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)

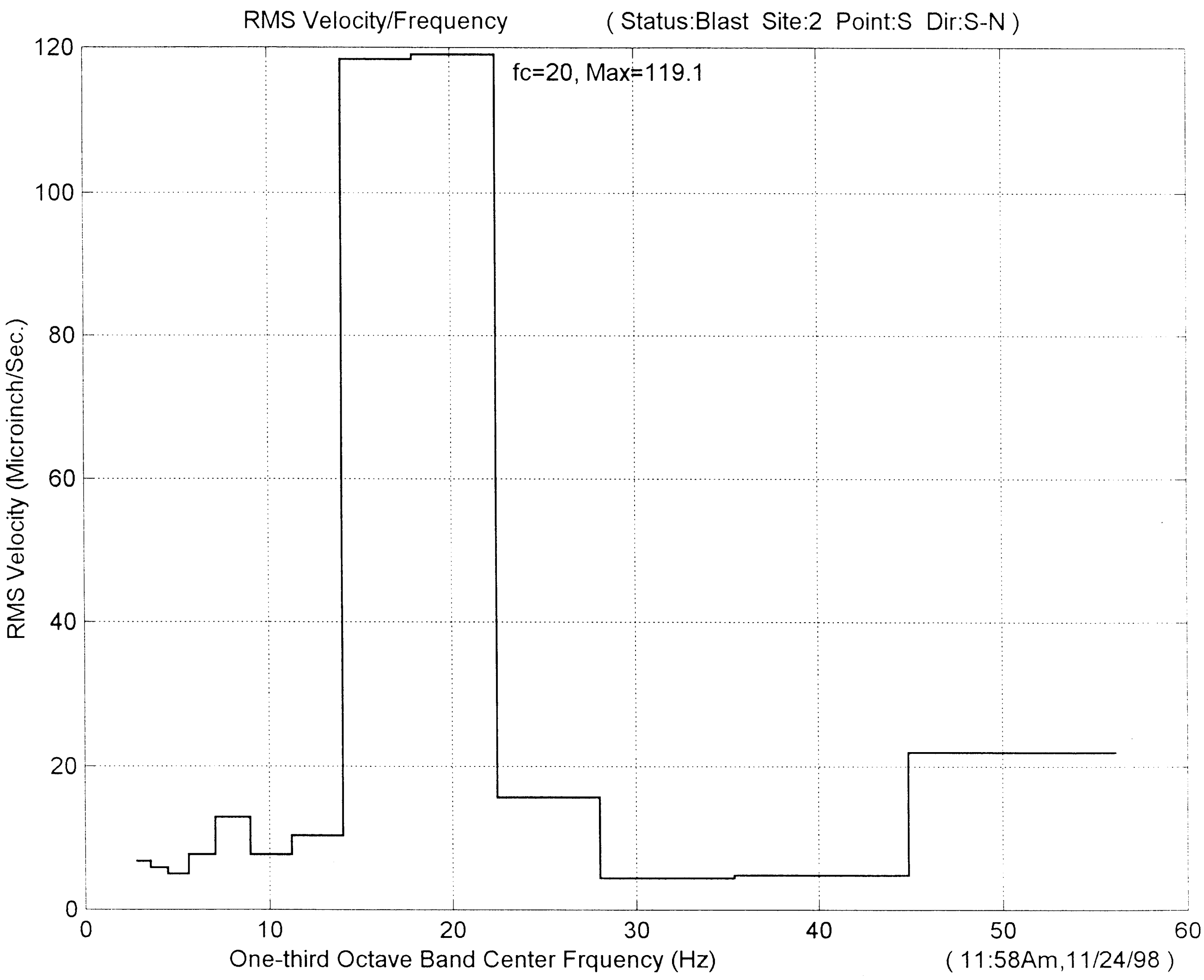

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:M Dir:S-N)
Magnitude (Microinch/Sec.)
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

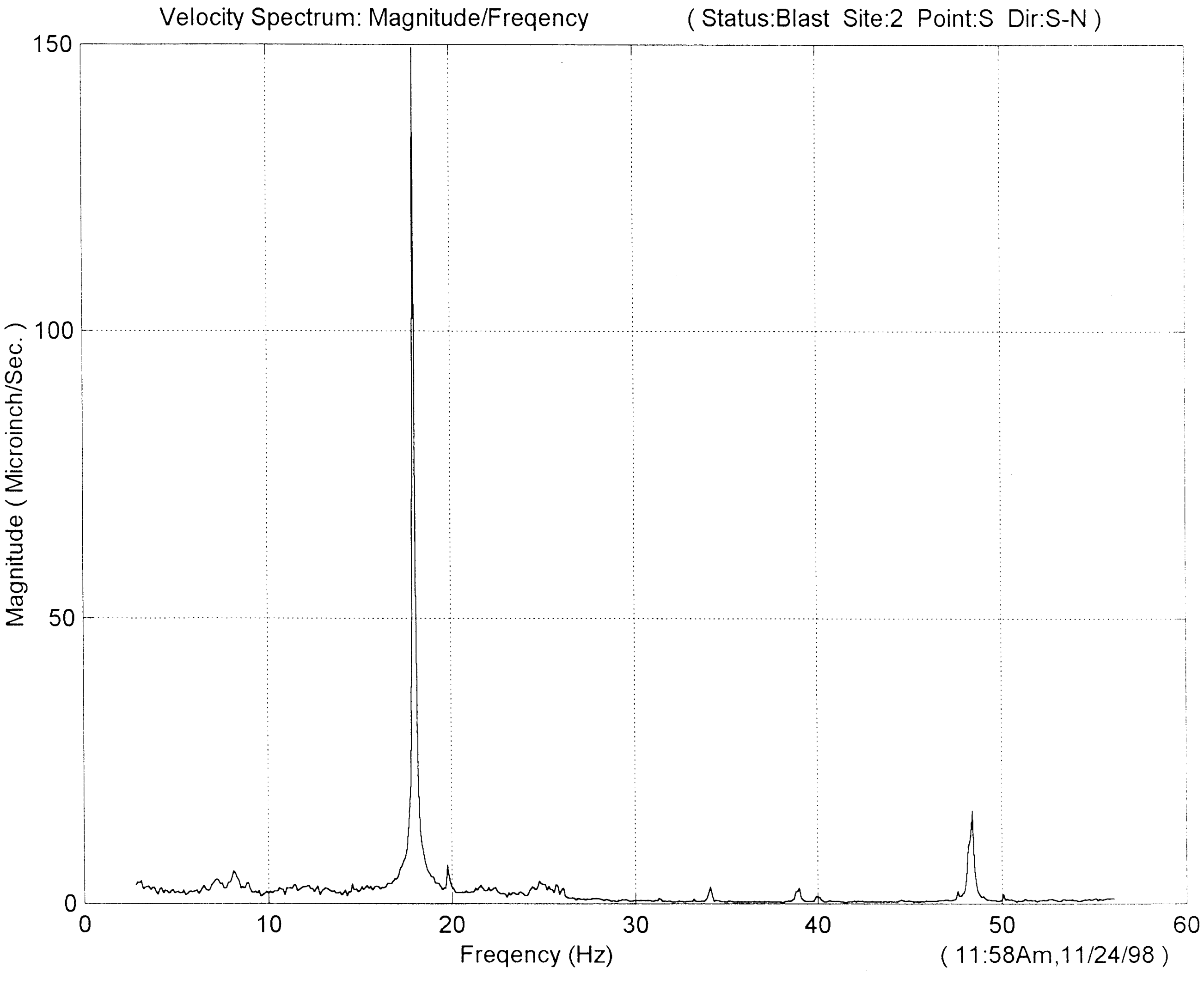

RMS Velocity/Frequency
(Status:Blast Site:2 Point:M Dir:U-D)
fc=4, Max=37.10
RMS Velocity (Microinch/Sec.)
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)

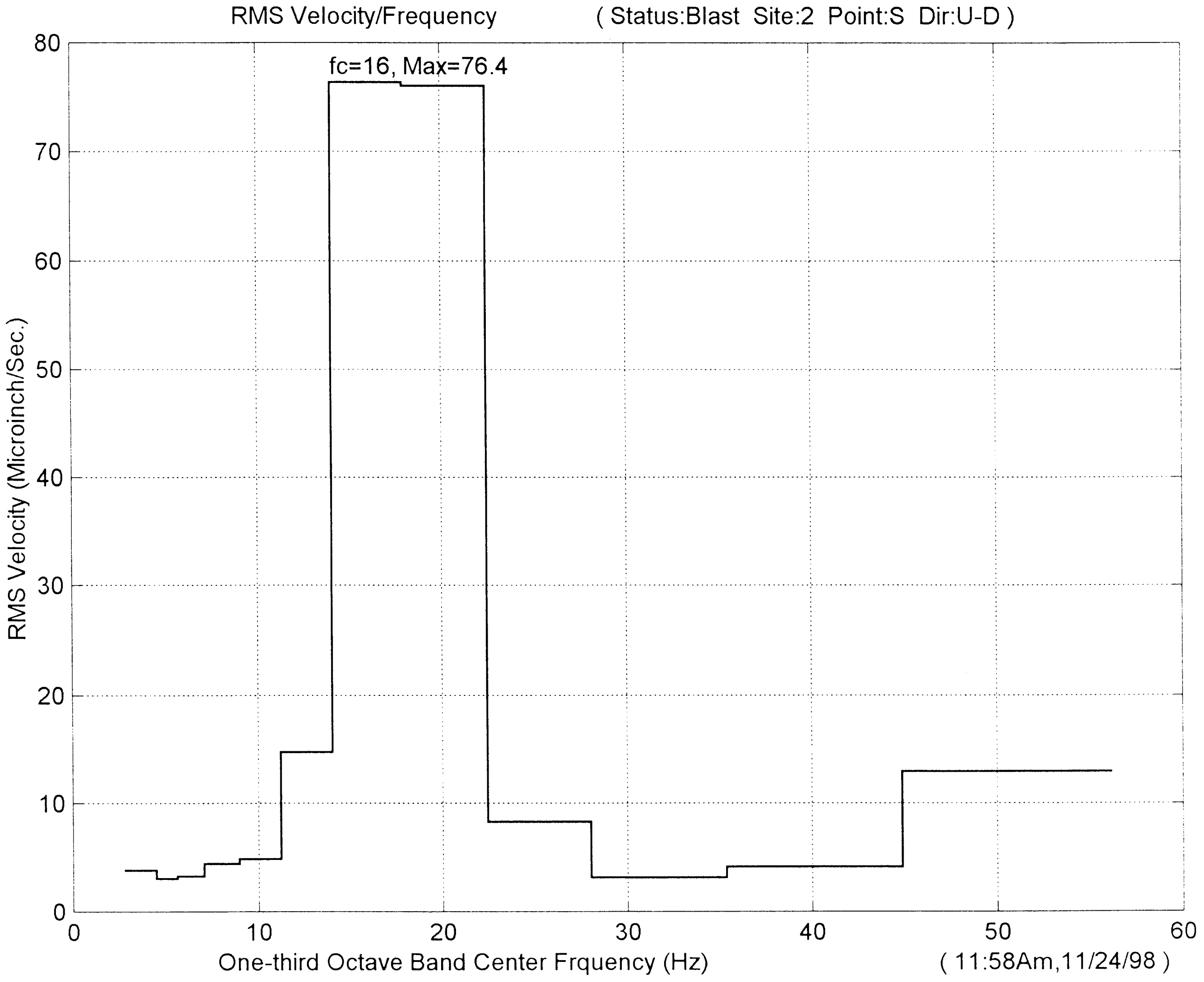

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:M Dir:U-D)
45
40
35
30
25
20
15
10
5
0
Magnitude (Microinch/Sec.)
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

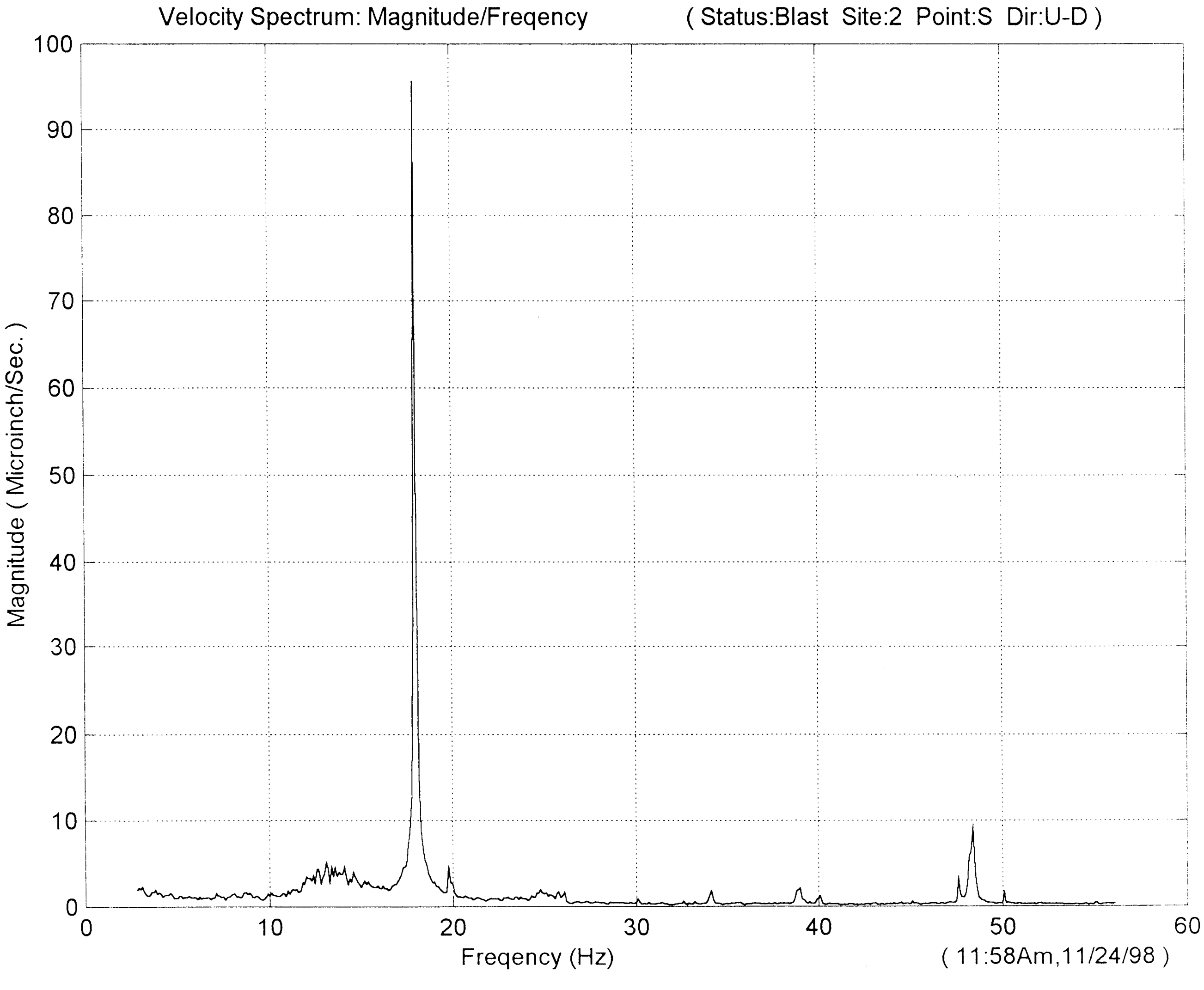

RMS Velocity/Frequency (Status:Blast Site:2 Point:S Dir:E-W)
fc=20, Max=78.8
RMS Velocity (Microinch/Sec.)
0
10
20
30
40
50
60
70
80
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)


Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:S Dir:E-W)
Magnitude (Microinch/Sec.)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

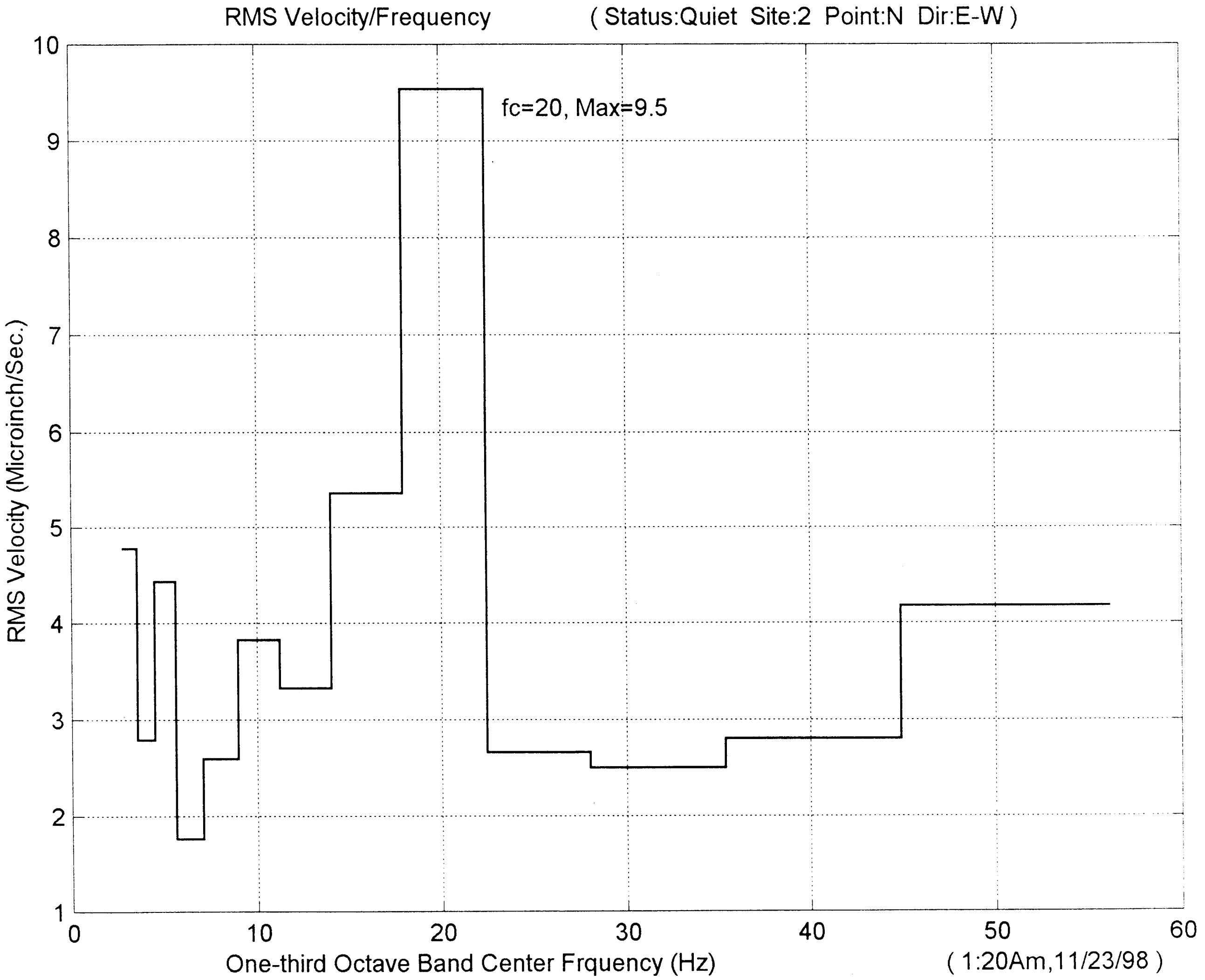

RMS Velocity/Frequency
(Status:Blast Site:2 Point:S Dir:S-N)
fc=20, Max=119.1
RMS Velocity (Microinch/Sec.)
0
20
40
60
80
100
120
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)

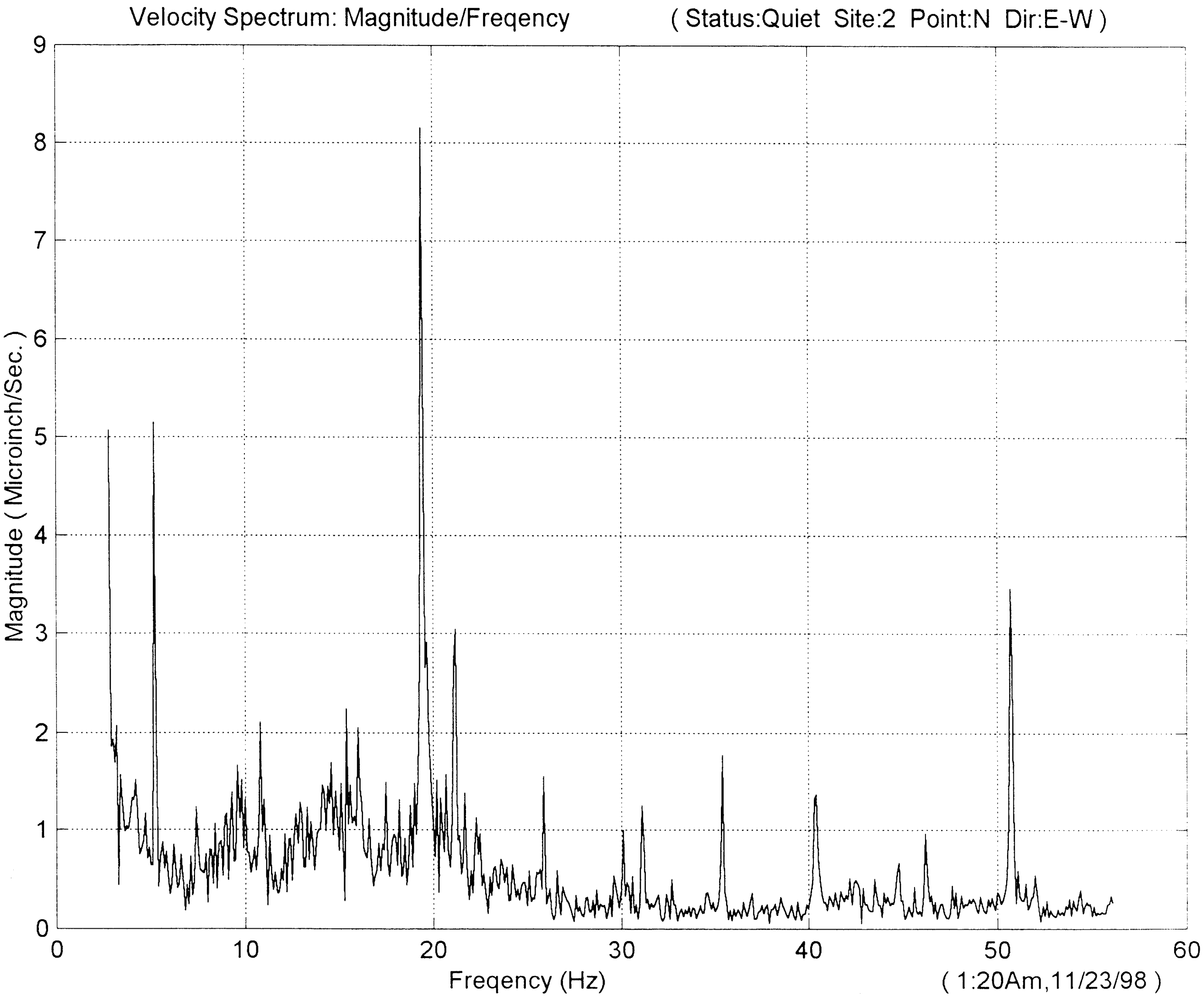

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:S Dir:S-N)
150
100
50
0
Magnitude (Microinch/Sec.)
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

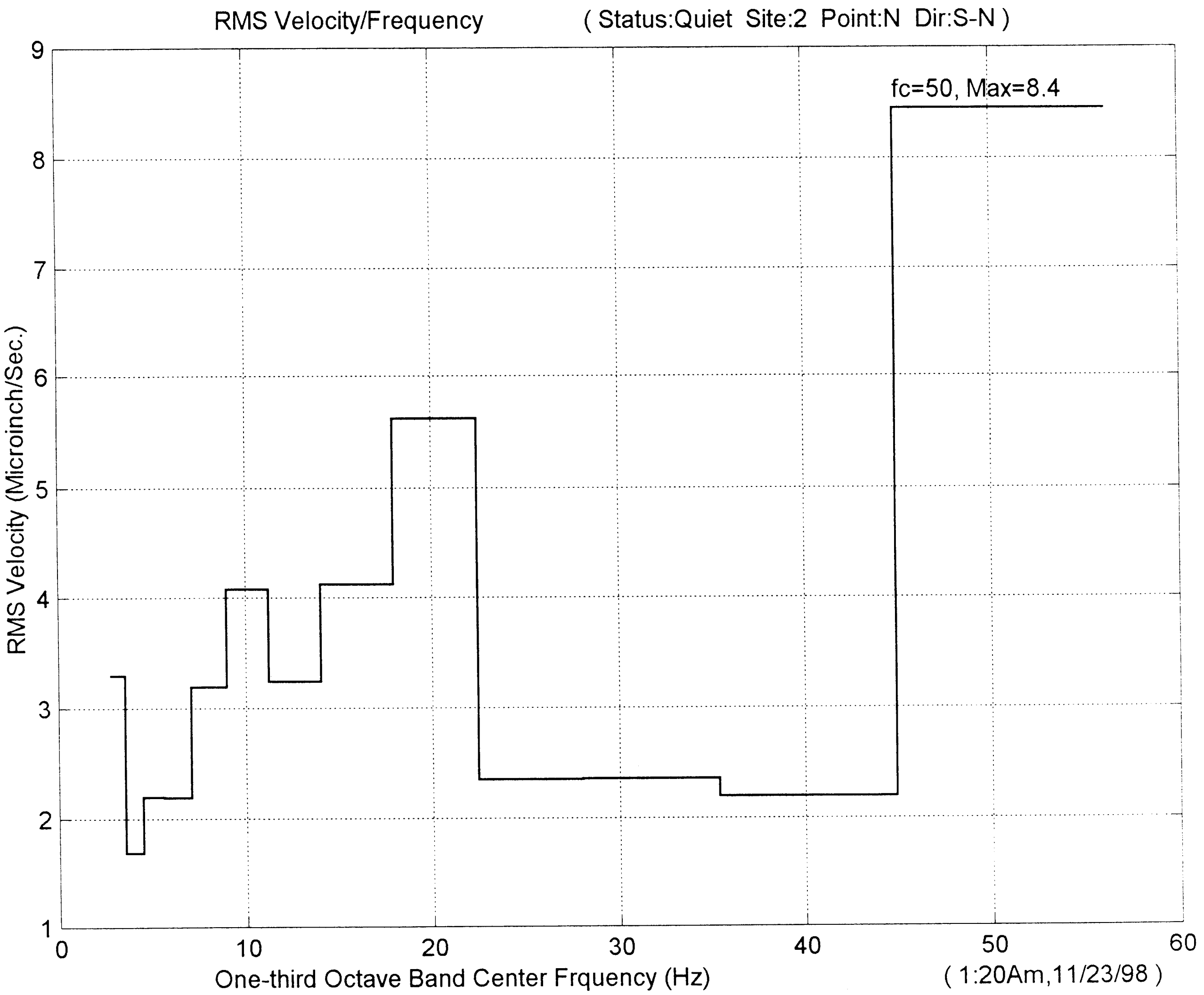

RMS Velocity/Frequency
(Status:Blast Site:2 Point:S Dir:U-D)
fc=16, Max=76.4
RMS Velocity (Microinch/Sec.)
0
10
20
30
40
50
60
70
80
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(11:58Am,11/24/98)

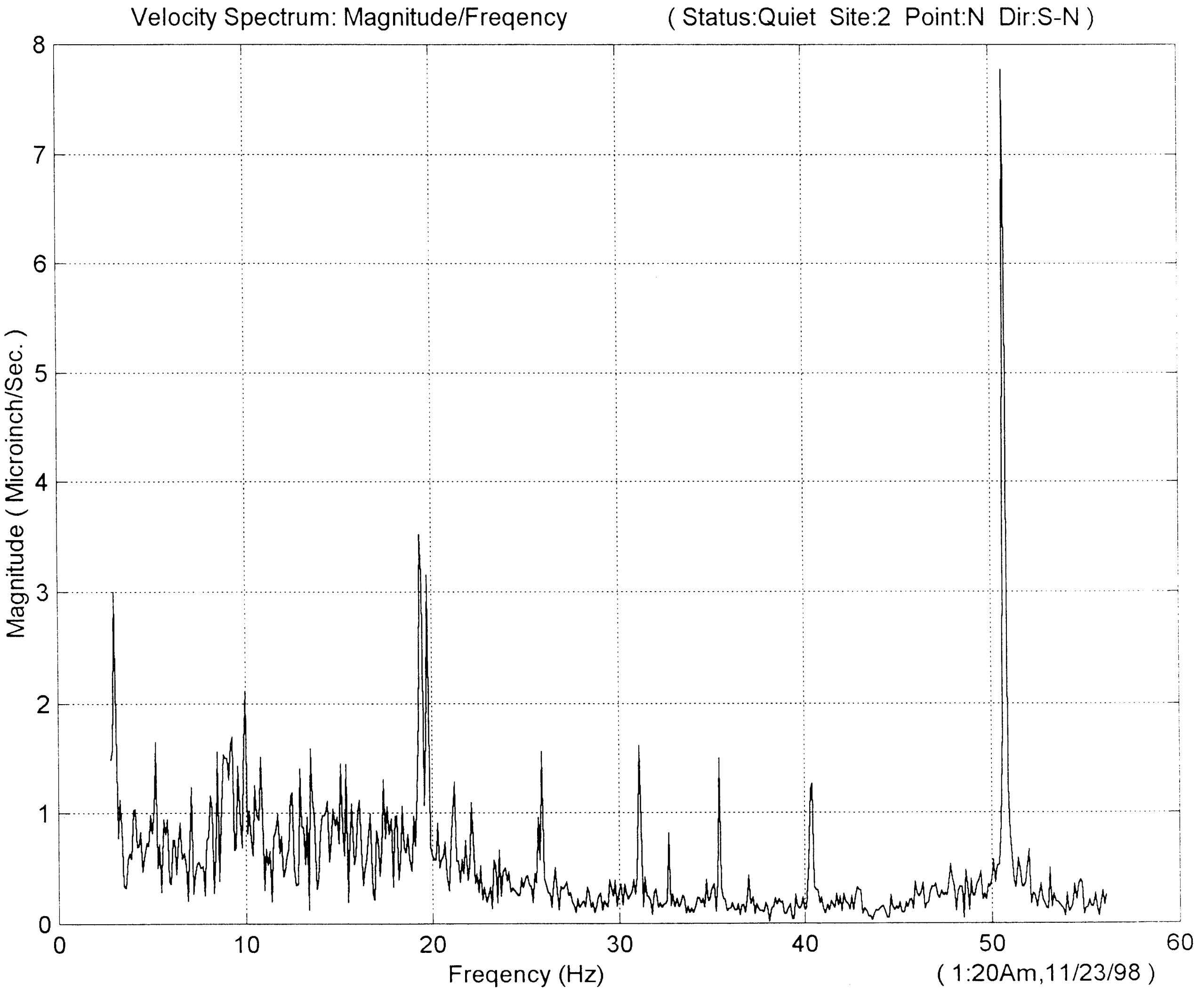

Velocity Spectrum: Magnitude/Freqency
(Status:Blast Site:2 Point:S Dir:U-D)
Magnitude (Microinch/Sec.)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Freqency (Hz)
(11:58Am,11/24/98)

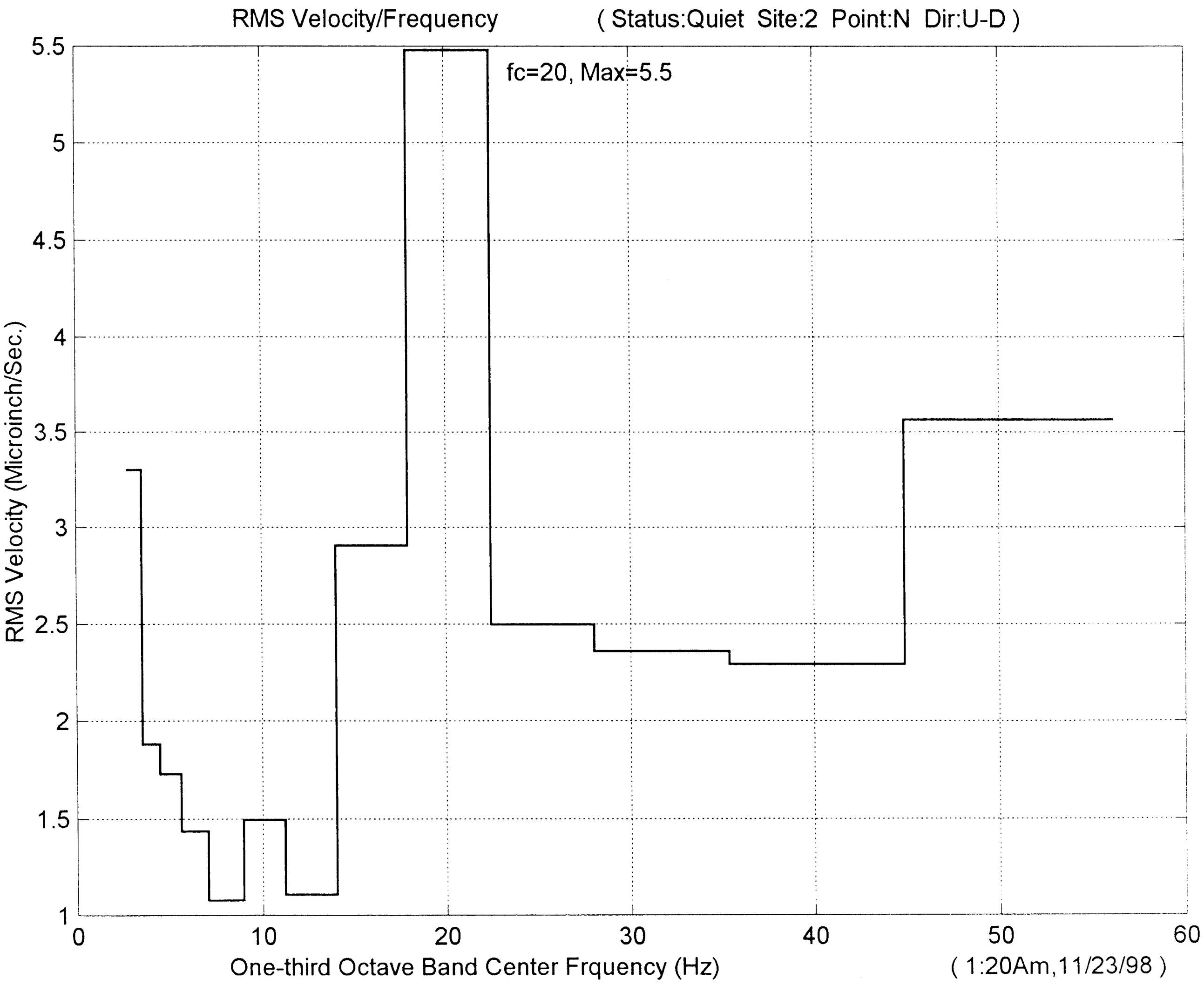
Site 2: Selected Signals - Quiet

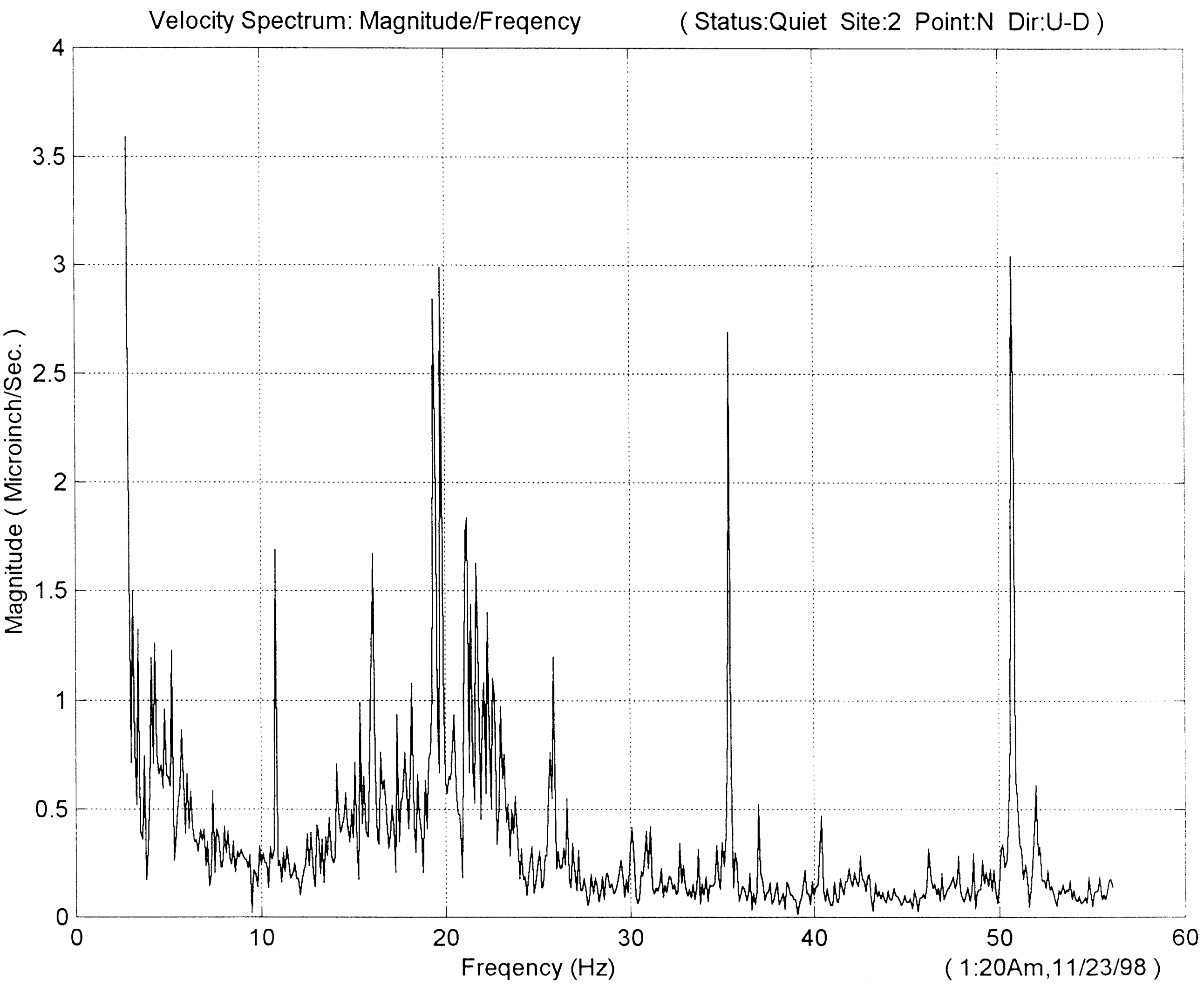


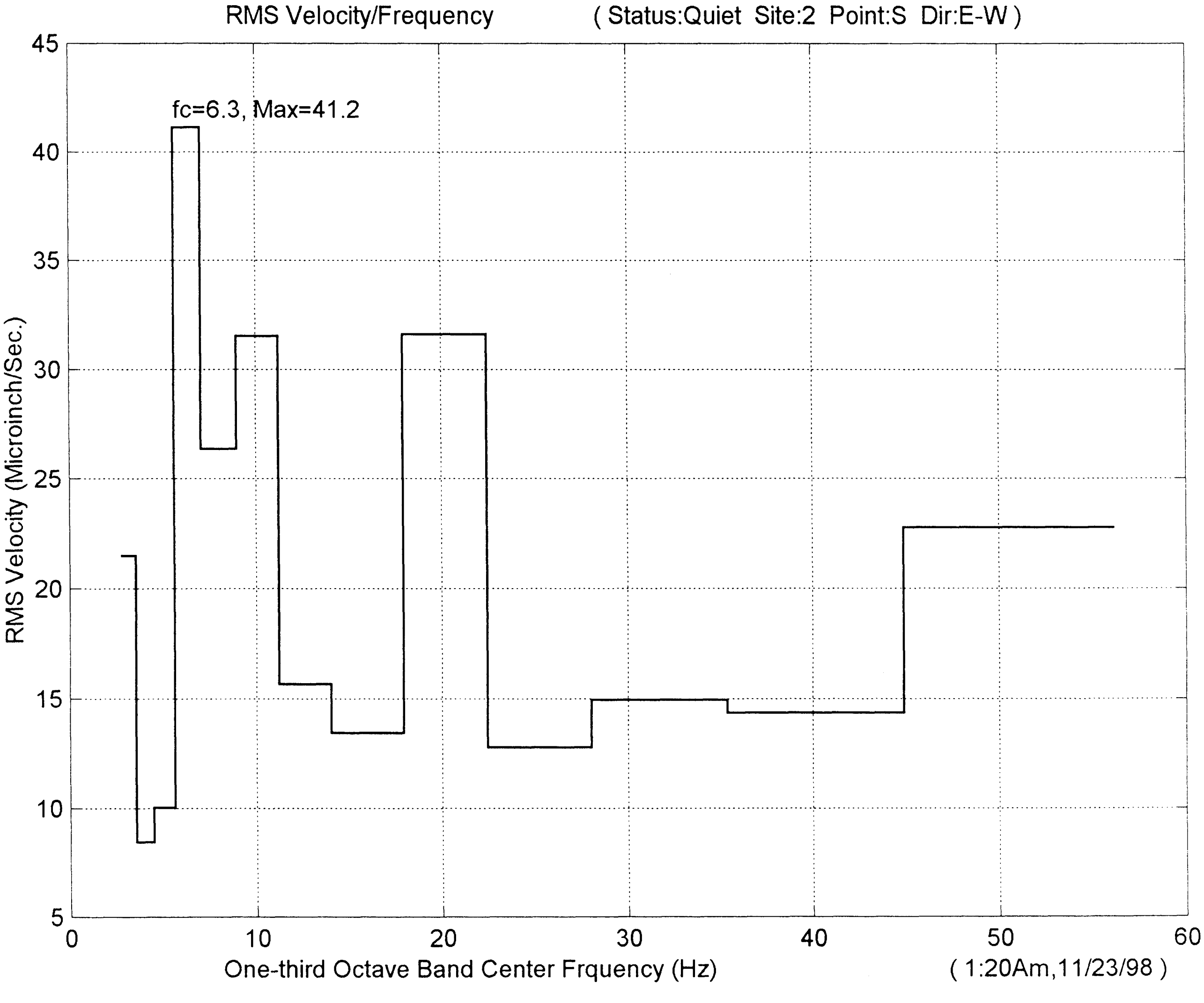

Velocity Spectrum: Magnitude/Freqency
(Status:Quiet Site:2 Point:N Dir:E-W)
Magnitude (Microinch/Sec.)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
Freqency (Hz)
(1:20Am,11/23/98)

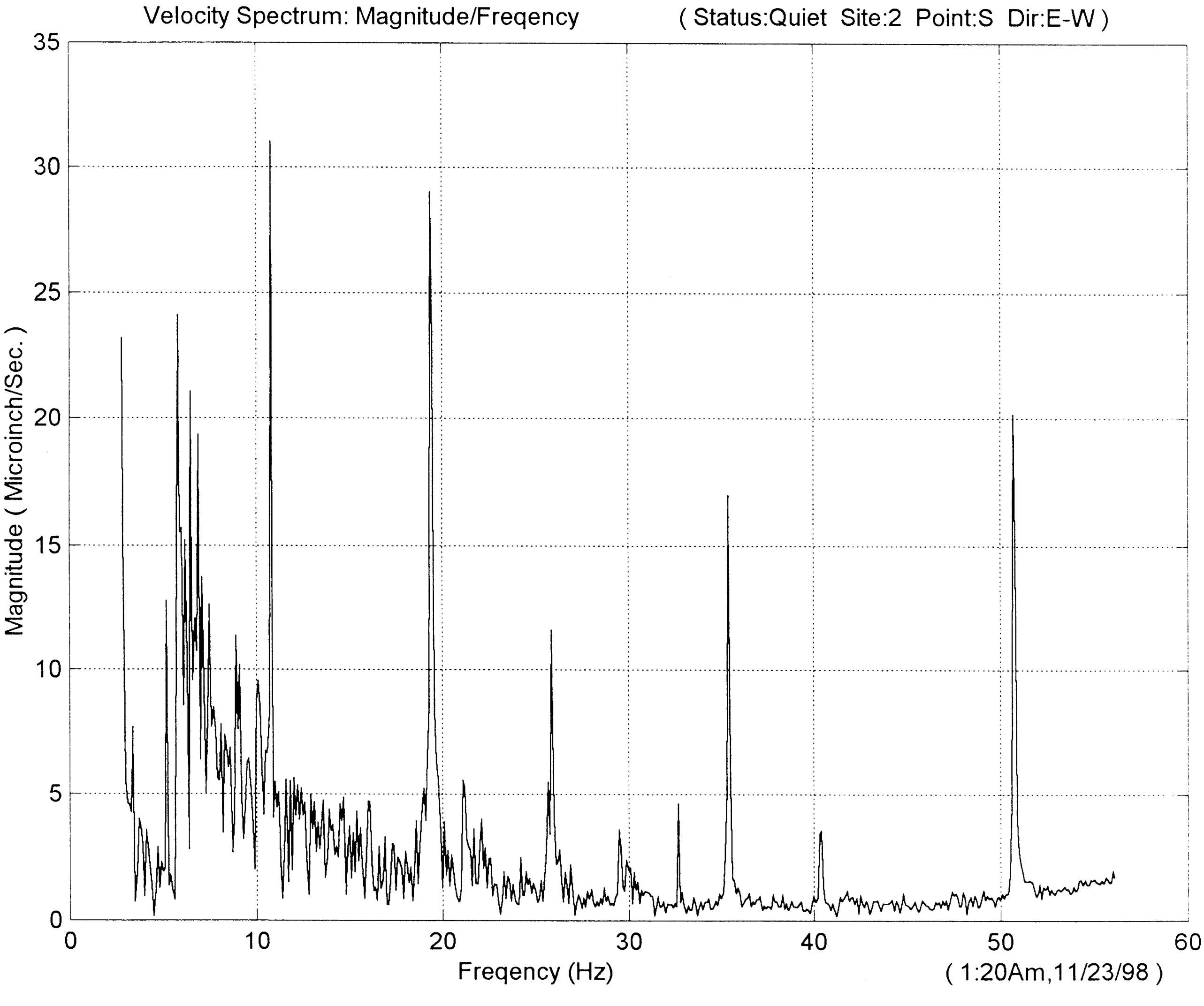

RMS Velocity/Frequency
(Status:Quiet Site:2 Point:N Dir:S-N)
fc=50, Max=8.4
RMS Velocity (Microinch/Sec.)
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(1:20Am,11/23/98)

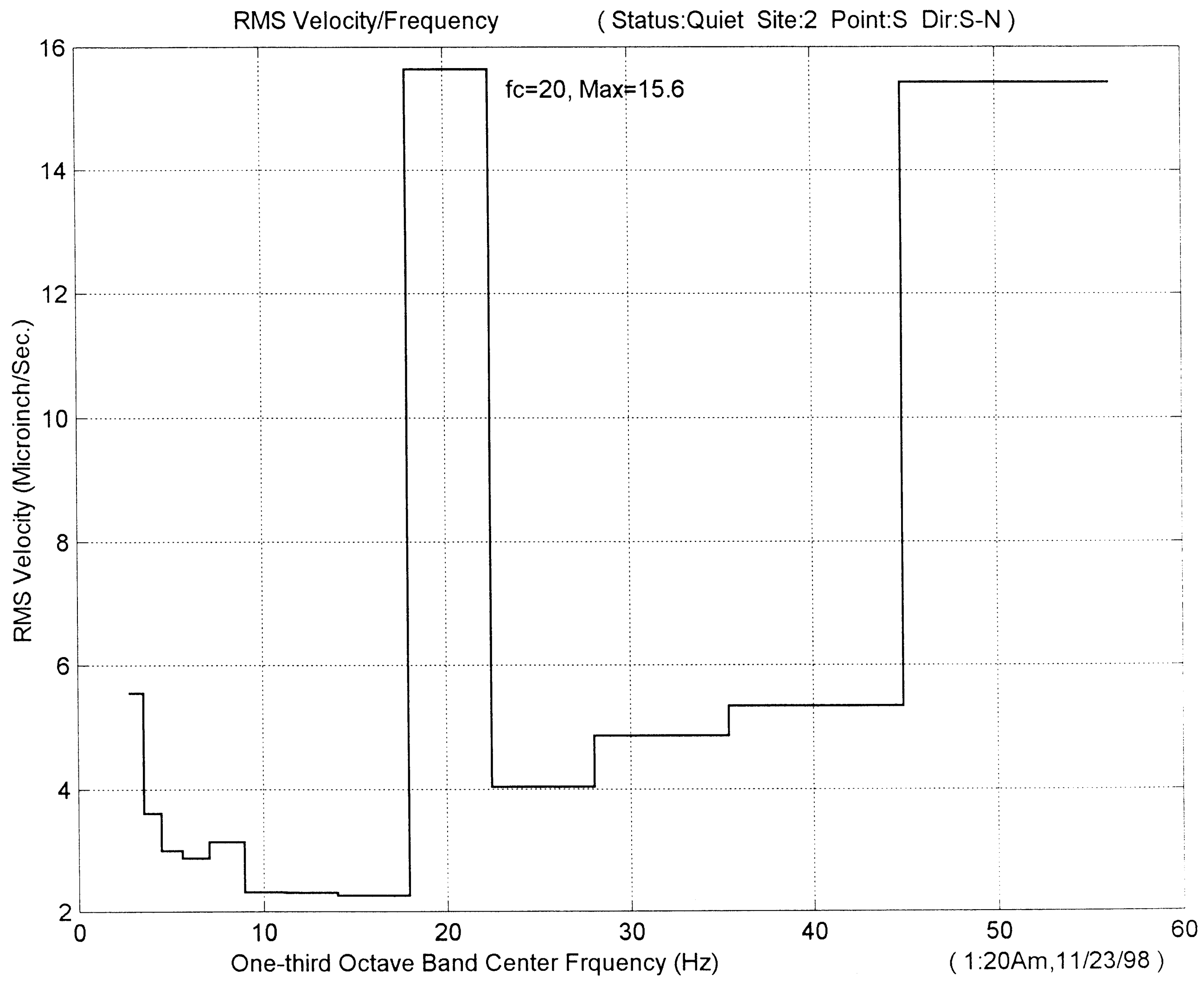

Velocity Spectrum: Magnitude/Freqency
(Status:Quiet Site:2 Point:N Dir:S-N)
Magnitude (Microinch/Sec.)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
Freqency (Hz)
(1:20Am,11/23/98)

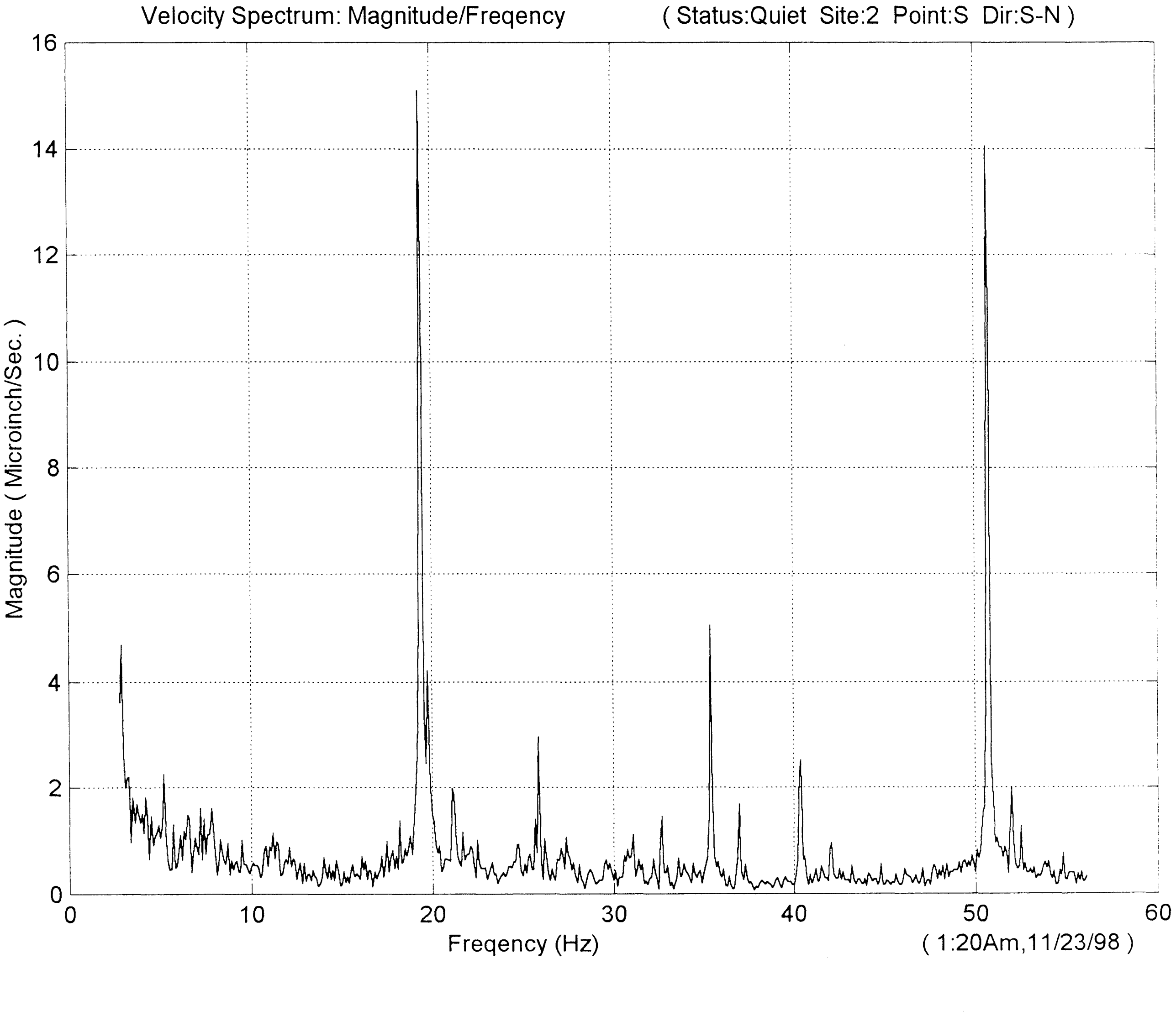

RMS Velocity/Frequency
(Status:Quiet Site:2 Point:N Dir:U-D)
fc=20, Max=5.5
RMS Velocity (Microinch/Sec.)
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(1:20Am,11/23/98)

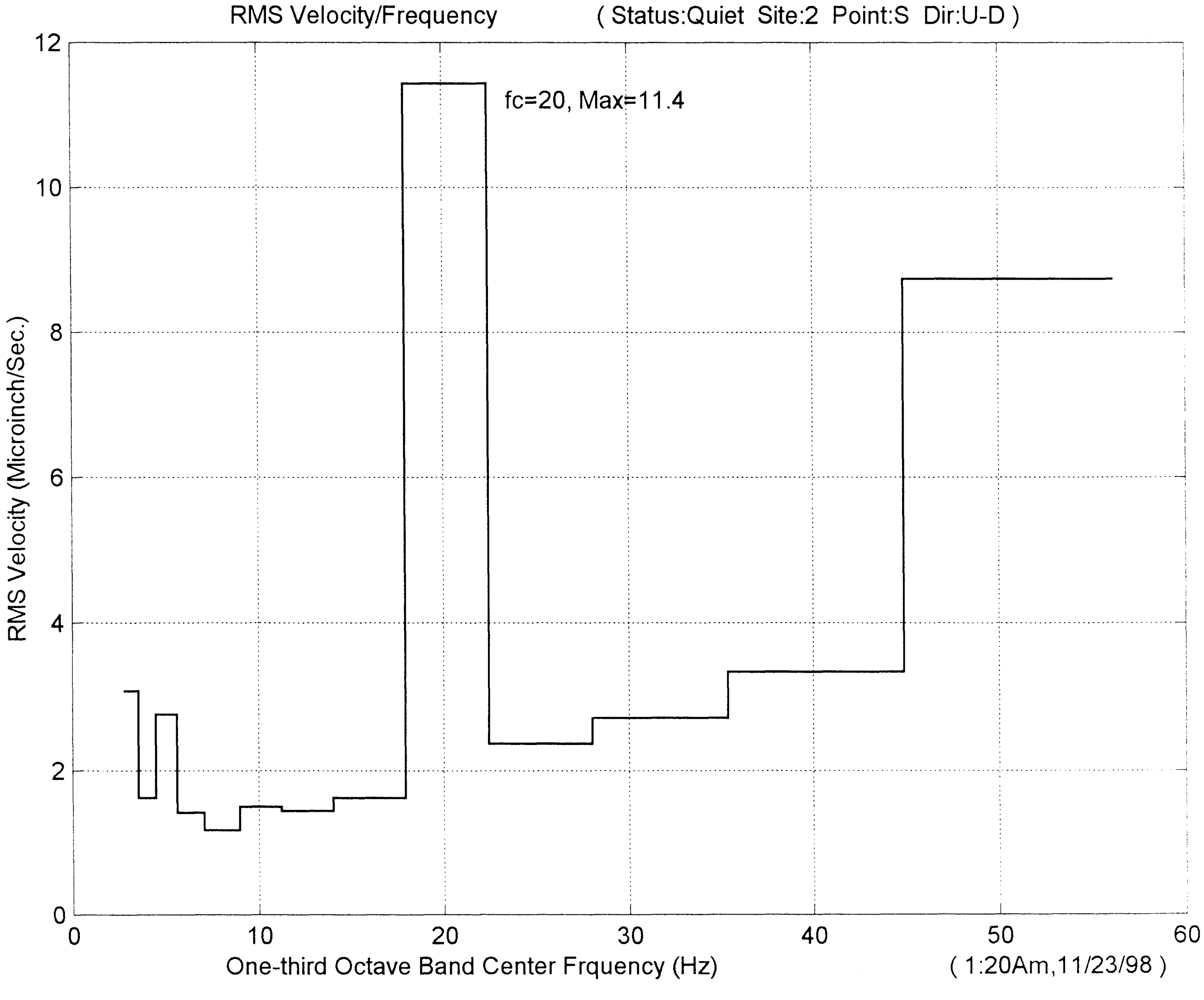

Velocity Spectrum: Magnitude/Freqency
(Status:Quiet Site:2 Point:N Dir:U-D)
Magnitude (Microinch/Sec.)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
Freqency (Hz)
(1:20Am,11/23/98)

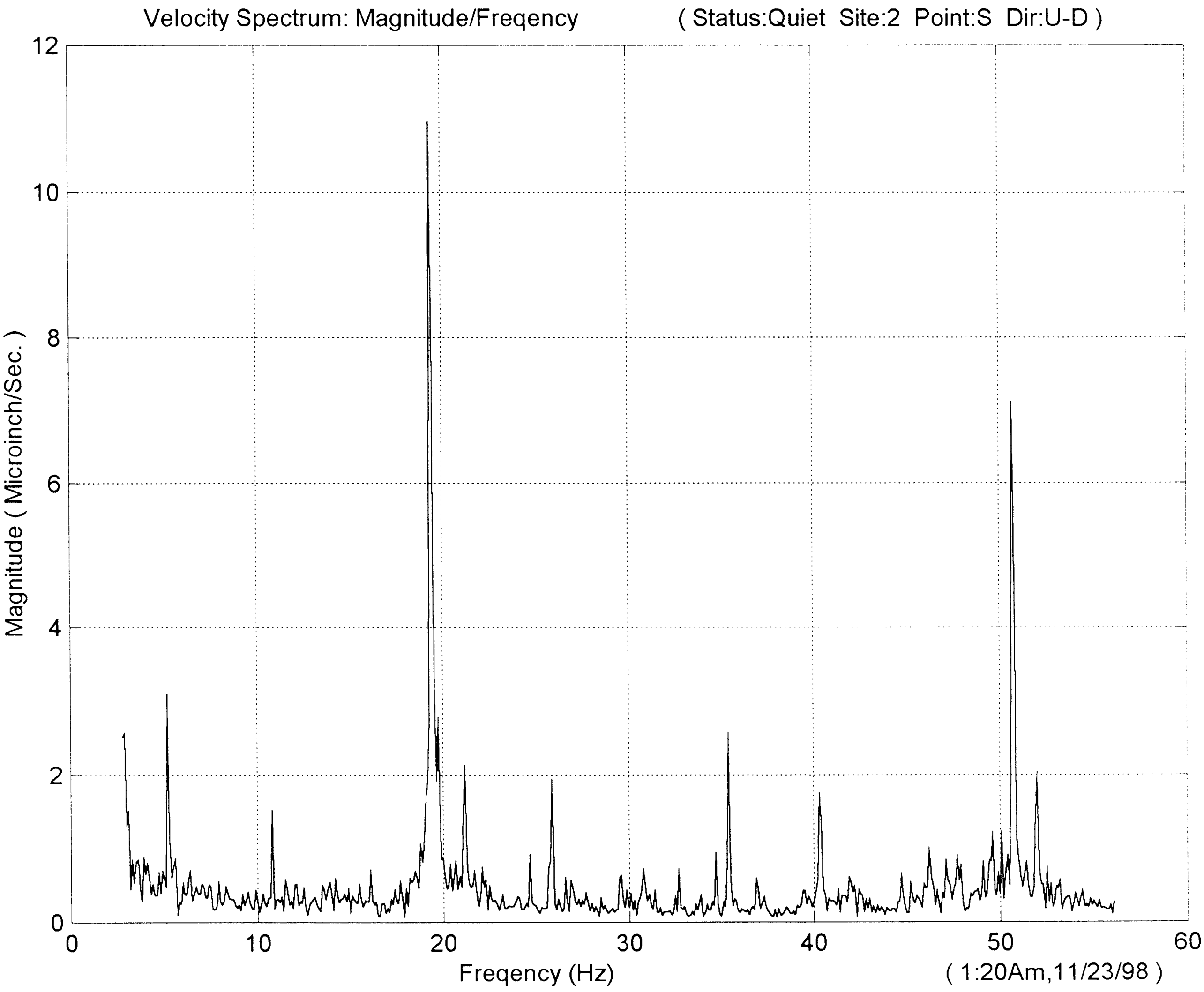

RMS Velocity/Frequency
(Status:Quiet Site:2 Point:S Dir:E-W)
fc=6.3, Max=41.2
RMS Velocity (Microinch/Sec.)
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(1:20Am,11/23/98)


Velocity Spectrum: Magnitude/Freqency
(Status:Quiet Site:2 Point:S Dir:E-W)
Magnitude (Microinch/Sec.)
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Freqency (Hz)
(1:20Am,11/23/98)

RMS Velocity/Frequency
(Status:Quiet Site:2 Point:S Dir:S-N)
fc=20, Max=15.6
RMS Velocity (Microinch/Sec.)
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(1:20Am,11/23/98)


Velocity Spectrum: Magnitude/Freqency
(Status:Quiet Site:2 Point:S Dir:S-N)
Magnitude (Microinch/Sec.)
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
Freqency (Hz)
(1:20Am,11/23/98)


RMS Velocity/Frequency
(Status:Quiet Site:2 Point:S Dir:U-D)
fc=20, Max=11.4
RMS Velocity (Microinch/Sec.)
0
2
4
6
8
10
12
0
10
20
30
40
50
60
One-third Octave Band Center Frquency (Hz)
(1:20Am,11/23/98)


Velocity Spectrum: Magnitude/Freqency
(Status:Quiet Site:2 Point:S Dir:U-D)
Magnitude (Microinch/Sec.)
12
10
8
6
4
2
0
0
10
20
30
40
50
60
Freqency (Hz)
(1:20Am,11/23/98)

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