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Ground Motion Measurements at the LBL Light Source Site, the Bevatron and at SLAC

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Abstract

This report describes the technique for measuring ground motion at the site of the 1.0 to 2.0 GeV Synchrotron Radiation Facility which was known as the Advanced Light Source (in 1983 when the measurements were taken). The results of ground motion measurements at the Light Source site at Building 6 at LBL are presented. As comparison, ground motion measurements were made at the Byerly Tunnel, the Bevatron, Blackberry Canyon, and SLAC at the Spear Ring.

Ground Motion at the Light Source site was measured in a band from 4 to 100 Hz. The measured noise is primarily local in origin and is not easily transported through LBL soils. The background ground motion is for the most part less than 0.1 microns. Localized truck traffic near Building 6 and the operation of the cranes in the building can result in local ground motions of a micron or more for short periods of time. The background ground motion at Building 6 is between 1 and 2 orders of magnitude higher than ground motion in a quiet seismic tunnel, which is representative of quiet sites world wide. The magnitude of the ground motions at SLAC and the Bevatron are comparable to ground motions measured at the Building 6 Light Source site. However, the frequency signature of each site is very different.

Background

The Lawrence Berkeley Laboratory has proposed the construction of a 1.0 to 2.0 GeV Synchrotron Radiation Source as a source of photons of high spectral brilliance in the ultra-violet and soft x-ray regions of the electromagnetic spectrum. The Light Source would consist of a 1.5 GeV electron storage ring, an injection system to feed electrons into the storage ring, various wigglers, undulators and bending magnets to produce the photon beams, and the numerous external beam lines containing optical elements which transport, focus and filter the photon beams which are delivered to experimental apparatus. When the machine was first proposed and when the ground motion measurements were made, the machine was known as the Advanced Light Source. More recently, the machine has been renamed as the 1.0 to 2.0 GeV Synchrotron Radiation Facility, and from here on out will be known as the "Light Source".

The Light Source is an electron ring which is nominally about 60 meters in diameter. This ring is designed to store electrons up to an energy of 1.9 GeV. The basic parameters of the Light Source are shown in Table 1.[1]

The design shown in Table 1 has a horizontal betatron wave length (circumference divided by horizontal tune value) of 13.8 meters and a vertical betatron wave length of 24.1 meters. Ground motion waves which have lengths which approach these values will have the largest affect on the performance of the Light Source machine.

In order to obtain photon beams of high spectral brilliance, the proposed Light Source storage ring has been designed to have a very small electron beam size of δ_x = 0.201 mm and δ_y = 0.038 mm (one standard deviation in the radial and vertical directions respectively). It is desirable that the beam location remain stable to a small fraction of a beam size, say 10 μm. Displacement of the quadrupole focusing magnets of the order of 1 μm can cause electron beam orbit displacements up to 10 μm depending on location in

Table 1

Light Source Design Parameters

(Electron Storage Ring, June 1986 Design)

Electron Energy (GeV)	1.5 (1.9 max)
Electron Current (mA)	400
Circumference (m)	196.8
Horiz. Emittance (πm-rad)	4.08×10^{-9}
No. of Superperiods	12
No. of Long Straight Sections	12
Length of Long Straight Sections (m)	6.75
Max. Horiz. Beta (m)	12.0
Max. Vert. Beta (m)	22.6
Horizontal Beam Size* (μM)	201
Vertical Beam Size (10% emittance)*(μm)	38
Horiz. Tune	14.28
Vert. Tune	8.18
Horiz. Chromaticity	-24.1
Vert. Chromaticity	-28.5
Energy Loss per Turn - Dipoles Only (keV)	111.7
Radio frequency (MHz)	499.65
Harmonic Number	328
1.9-GeV Operation:	
Dipole Field (T)	1.58
Max. Quad. Gradient (T/m)	17.0
Energy Loss per Turn - Dipoles Only (keV)	228

*at insertion symmetry point

the ring. The foregoing suggests that ground motions of less than 0.1 μm are benign, while motions of 1 μm might be of concern, and motions of 10 μm or more could definitely be troublesome. Ground motion at frequencies below five hertz are not as significant because their wave length is long compared to the diameter of the Light Source ring. This would result in all of the magnets moving more or less in unison.

The measurements reported here were undertaken to assess the ground motion displacements that can be expected at the proposed Light Source site (Building 6 at LBL). These displacements are compared with measurements made at other sites in Berkeley and at SLAC. All of the sites have similar surface soil.

The effect of ground motion on sensitive optical components (e.g. mirror, slits, etc.) along the photon beam lines and in experimental apparatus itself is beyond the scope of this report. The reasons are: 1) the motion tolerance varies for different experiments, and 2) the resonant frequencies and amplification factor are dependent on the final design configuration of the experiment which cannot be assessed at this time. However, at a quick glance, it appears that motion on beam lines is not as critical as it is for the storage ring unless amplification factors exceed the aforementioned factor of ten associated with ring quadrupole magnet motion.

Measurement Format

In order to assess the amount of ground vibration displacement at the Light Source site in the vicinity of Building 6 at LBL, a comprehensive ambient ground motion study was undertaken by members of the Earth Sciences Division at LBL. The purpose of this study was to determine the ground displacement in the frequency range from 4 to 100 Hz at the Light Source site including the effects of various noise sources such as pumps, cranes, generators and various mechanical equipment in Building 6, as well as vibration sources outside of Building 6 such as cooling towers, vehicle traffic, motor generator sets, etc. It was also desirable to know if such facilities as the Bevatron or traffic on the bridge in front of Building 46 would cause significant ground motion at Building 6.

The general procedure was to measure the ground motion at Building 6 with as many as possible of the potential noise sources not in operation and then to repeat the measurements with each of the noise sources in operation to determine the effect of each source. The procedure for making the ground motion measurements had the following steps:

1) Quiet background ground motion measurements were made at the University of California Seismographic Station Byerly Tunnel in Strawberry Canyon. (See Figure 1) This set of measurements, made at a quiet location, were used as a calibrated reference for the other ground motion studies.

2) Background ground motion measurements were made at 30 locations within and around Building 6 as shown in Figure 2. These measurements were made on a day when most of the major noise sources were operating. Both the 184-inch Cyclotron and the Neutral Beam Test Facility were operating fully.

3) Ground motion measurements were made at the Bevatron and in Blackberry Canyon and at Station 1 in Building 6. (See Figure 1) These measurements were made in order to determine the ground motion due to Bevatron noise sources, such as the main motor-generator (M.G.) set. A comparison of the Blackberry Canyon and the Building 6 measurements with ground motion measurement at the Bevatron permits one to estimate

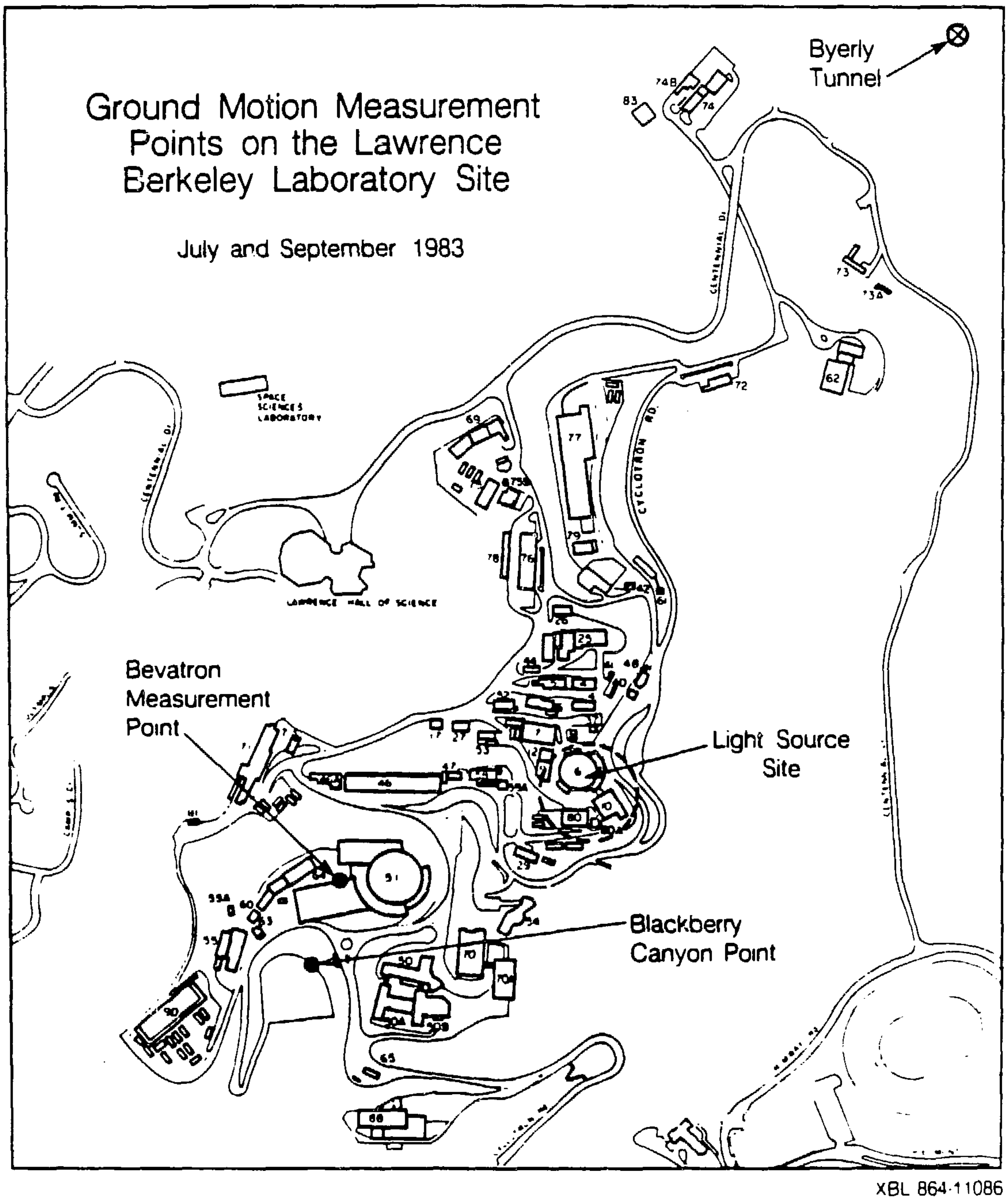

Figure 1. Ground Motion Measurement Points at LBL. Note: The ALS site contains 30 measurement points.

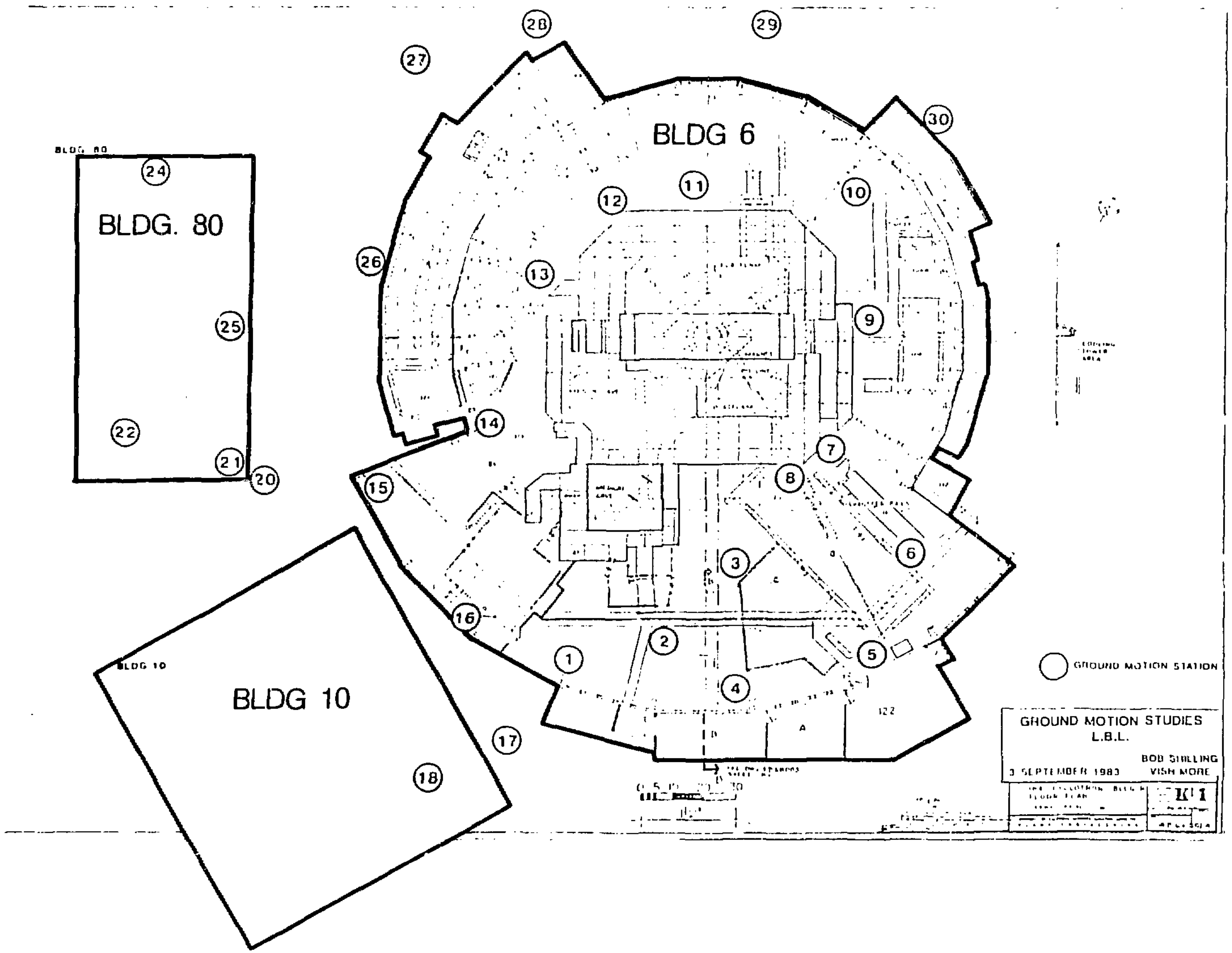

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Figure 2. Ground Motion Measurement Stations Around Building 6 at LBL (the ALS site)

the attenuation of seismic waves in typical LBL soils. In addition one can determine whether the Bevatron has any effect on ground motion at Building 6.

4) Ground motion measurements were made at Building 6 with noise sources, such as operating cranes, and heavy vehicle traffic outside the building.

5) As a comparison, ground motion measurements were made at SLAC in the vicinity of the SPEAR ring. (See Figure 3) These measurements were made during a relatively quiet period of time during a summer shut down.

The ground motion measurements were made on the following dates: July 6, 1983 - the Building 6 and Byerly Tunnel, a normal operating day for Building 6; September 18, 1983 - the Bevatron, Blackberry Canyon and Station 1 at Building 6 with the Bevatron running; September 20, 1983 - the measurements with noise at Building 6 without the Bevatron running (but with everything else running); and August 28, 1983 - the comparison measurements at SLAC during a quiet period.

The Sensors and Preprocessing

Figure 4 shows a schematic diagram of the field sensing system from the three-axis sensor through the amplifiers and filters through the multiplexer and digitizer to a digital cassette recorder which records the signal for later processing on the LBL Vax computer system.

Because of the frequency range of interest (5 Hz to 100 Hz), high frequency geophones were selected for the sensing devices. A geophone is a moving coil velocity transducer. That is, the output of the device is approximately proportional to the velocity of the ground (at frequencies above 10 Hz). The output of the device is a function of the generator constant,

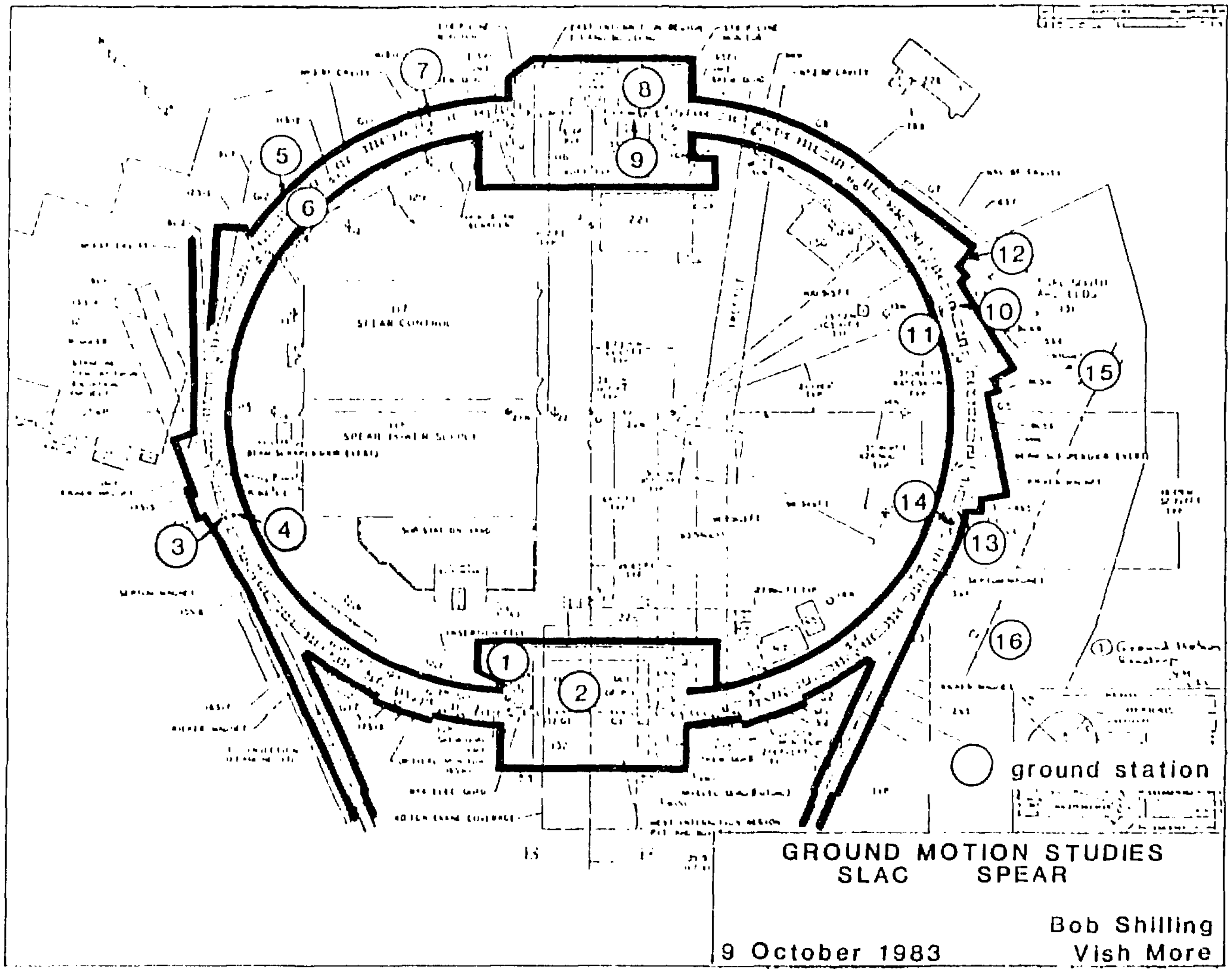

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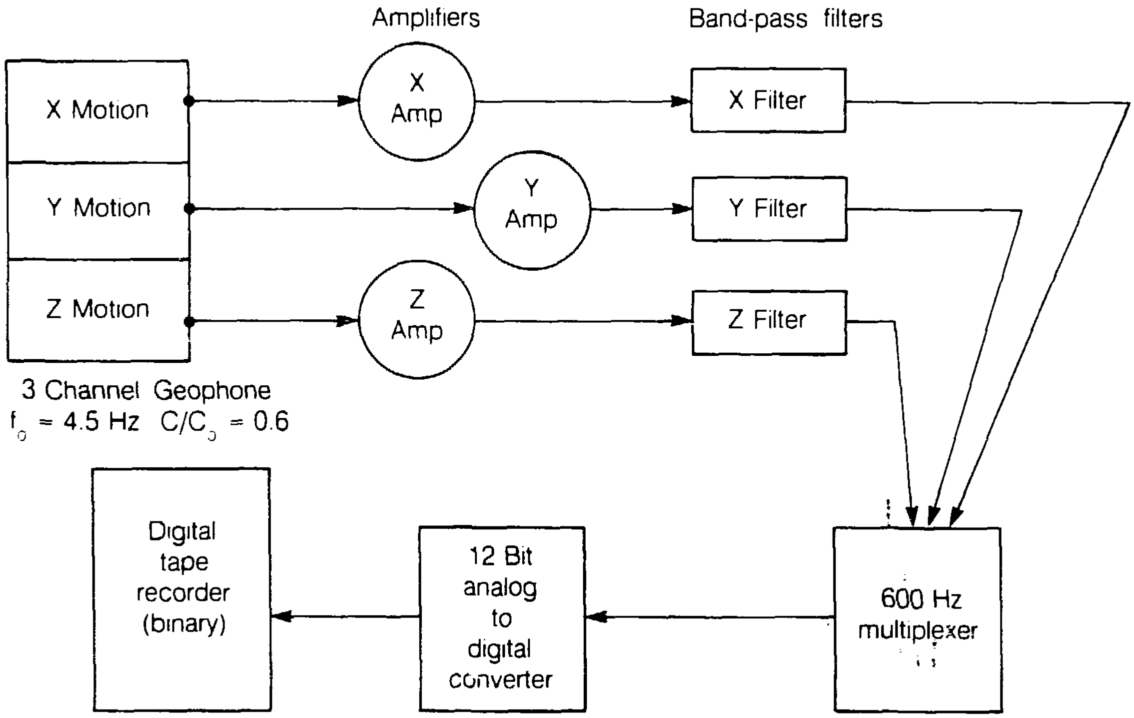
Figure 3. Ground Motion Measurement Stations Around SPEAR at SLAC



The sensor and preprocessor

Figure 4. A Schematic Diagram of the Sensing System for the Ground Motion Measurement Apparatus

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which is a fixed property of the permanent magnet and coil, and is equal to the product of the flux density B (tesla), the length of the conductor ℓ (meters) in the magnetic field, and the velocity of the coil V (meters per second) with respect to the case in the magnetic field. The catalog specifications of the AMF Geo Space GS-11D geophones used for the measurements are: natural undamped frequency = 4.5 Hz, generator constant ($B\ell V$) = 50 volts/meter/sec, and damping with the set damping resistor = .6 critical. (See Figure 5a for the geophone response curve.)[2] The geophone package consists of three identical orthogonal geophones so that two horizontal and the vertical component of the ground velocity can be obtained simultaneously.

The three signals (one vertical and two horizontal) from the low frequency geophones were amplified and filtered by band-pass filters which excludes frequencies below 0.2 Hz and frequencies above 50 Hz. (See Figure 5b for the band-pass filter response curve.) The signals from the 3 pole, low pass, Butterworth, antialias filters were sent to a multiplexer. The signal is multiplexed between the channels and is fed to the digitizer, where it is digitized at the rate of 600 samples per second (200 samples per second per channel). The signal was digitized to a 12-bit resolution. The 12-bit resolution divides the signal of $\pm$10 volts (this is the analog signal from the sensor after amplification and filtering) into 4096 steps (approximately 205 steps per volt).

The sensor was leveled before each measurement and an effort to record the orientation of the three components was made. (The orientation data appears to be lost.) At each location two 10-second records were recorded in succession for redundancy. A portable oscilloscope was used to set gain levels. Peak to peak signals were set at 2 volts, out of a maximum of peak to

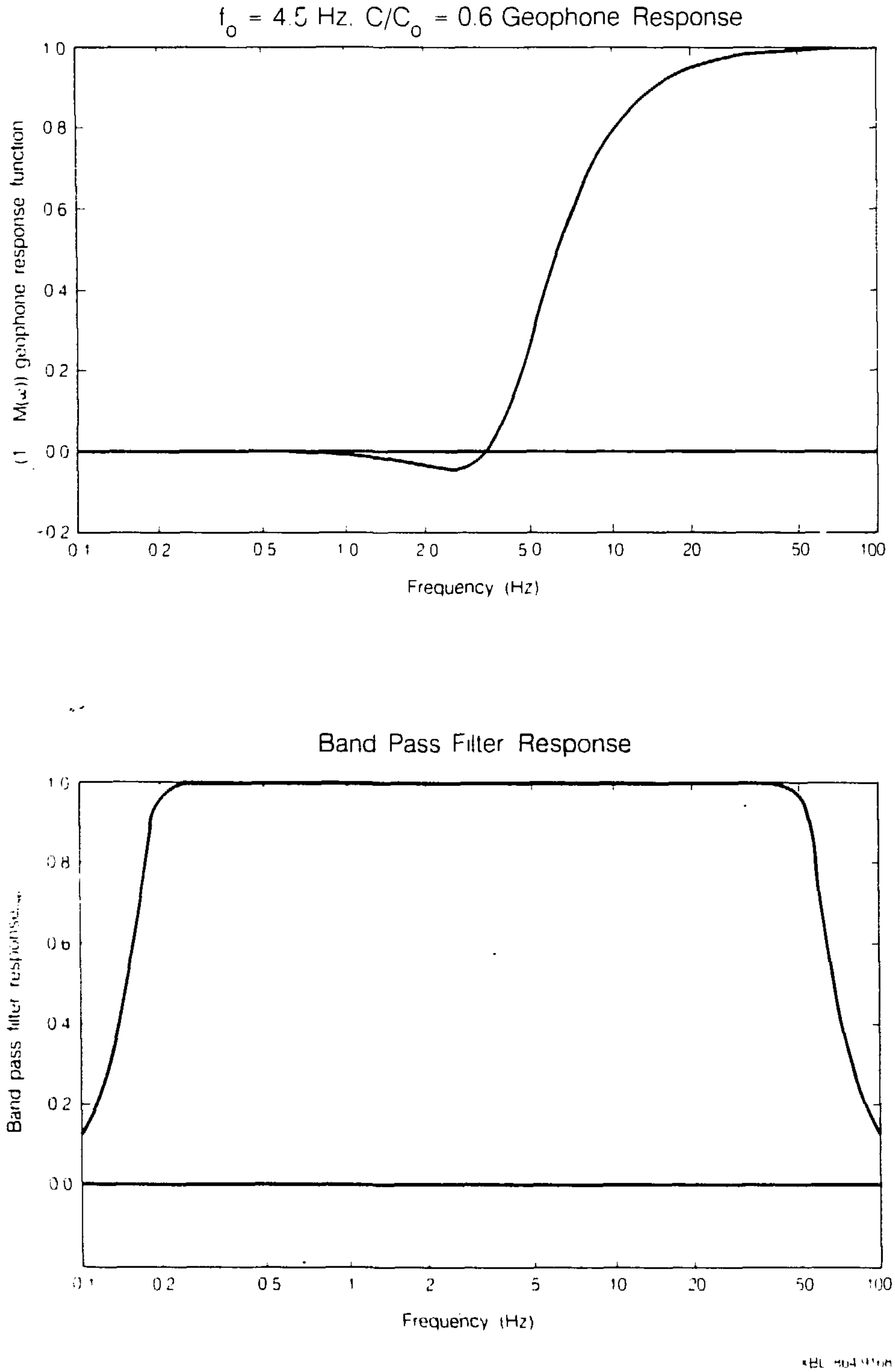

Figure 5. Geophone Response Curve and the 3 Pole Band Pass Filter Response Curve

peak of 20 volts. These levels were set to insure adequate signal levels throughout the bandwidth of interest without clipping the signals. (This technique was not always successful, for clipping was observed in a couple of instances.) The resolution of the digitized velocity signal is better than one percent even during relatively quiet times. Care was taken to use the same sensor and recording device so as not to confuse the calibration and permit one to use the sensor at lower frequencies.

The Analysis Procedure

The digital data was read from the cassette digital recording into the LBL computer for analysis. This led to a peak displacement response which represents the worst case displacement of an object mounted at the site. The analysis procedure, shown in a logic diagram in Figure 6, used the following procedural steps:

1) The digital signal of voltage, which is proportional to the velocity of the geophone coil with respect to the moving ground, is converted from binary to ASCII.
2) The ASCII signal is demultiplexed and put into files. (One file for each of the three axis of motion.) These files then can be analyzed by the NSAS Fortran program.
3) The digitized velocity versus time signal is converted to a velocity spectrum amplitude signal (per hertz) as a function of frequency through a Fast Fourier Transform (FFT) analysis in the NSAS program.
4) The velocity spectrum signal is corrected for the previously mentioned filtration and for the frequency response of the geophone sensor by the NSAS program.

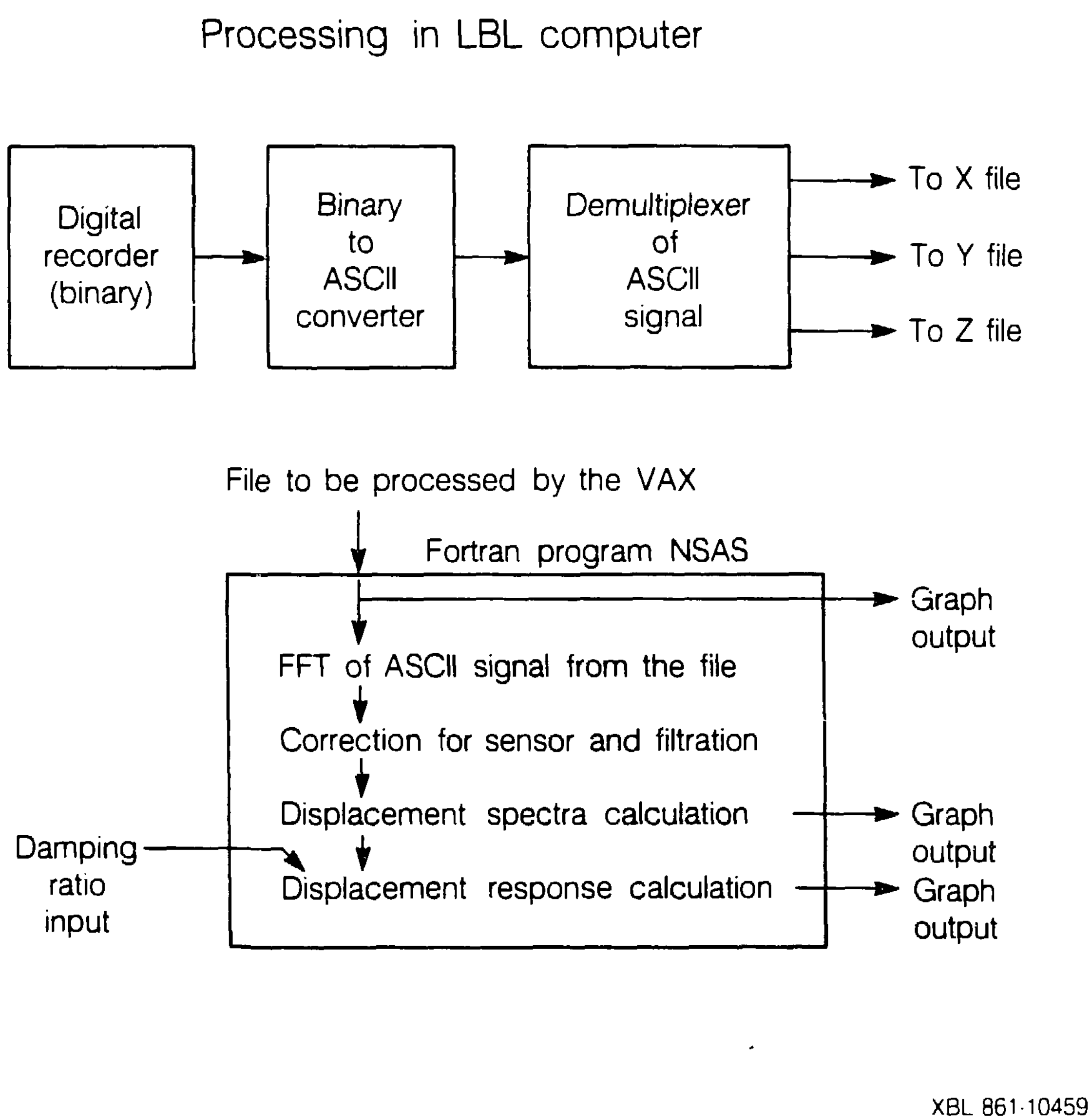

Figure 6. A Processing Schematic Diagram for Ground Motion Data Using the NSAS Computer Program

5) Calculation of the ground motion displacement spectrum is made from the ground motion velocity spectrum in the NSAS program.

6) A peak displacement response as a function of frequency is calculated from the ground motion displacement spectrum for a given damping ratio using the NSAS program. This peak displacement response is the peak displacement of an object mounted on a support system with a given damping ratio.

The FFT mentioned in Step 3 above is used for Fourier analysis of discrete, finite length time series. The essence of the Fourier transform is to decompose or separate the waveform into a sum of sinusoids of different frequencies. The Fourier transform displays the amplitude (per hertz) versus frequency of each of the waveforms. The Fourier transform frequency domain contains exactly the same information as that of the original function; they differ only in the presentation of the information. The FFT is simply a computational algorithm, to approximate the Fourier transform, which is given as follows:[3,4,5]

$$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} g(t) \exp [-i\omega t] \, dt \qquad (1)$$

where $\omega = 2\pi f$, where f is the frequency of the wave form. $F(\omega)$ also $F(2\pi f)$ is proportional to the amplitude (per hertz) of the wave at a given ω. (In other words, $F(\omega)$ is the amplitude of the signal in a given "frequency bin" which is at ω). Since $F(\omega)$ is complex, the amplitude of the amplitude spectrum is:

$$F(\omega) = [\mathrm{Re}\ (\omega)^2 + \mathrm{Im}\ (\omega)^2]^{0.5} \qquad (1a)$$

and the phase spectrum is:

$$\phi(\omega) = \mathrm{Tan}^{-1} \frac{\mathrm{Im}(\omega)}{\mathrm{Re}(\omega)} \tag{1b}$$

where $\mathrm{Re}(\omega)$ is the real part of $F(\omega)$ and $\mathrm{Im}(\omega)$ is the imaginary part of $F(\omega)$.

Since the time interval over which the signal is integrated is limited, $F(\omega)$ can have a limited range of ω. The signal was filtered so that both low frequency (< 0.2 Hz) and high frequency (> 50 Hz) components were removed. Two seconds worth of data (about 400 sample points) were chosen for FFT integration. Added zero values were used to get 512 integration points. (The results are scaled to allow for the zero values.) Thus the lower limit for the frequency domain is about 0.4 Hz. (We shall see later that 0.4 Hz is much lower than the lowest frequencies which can be accurately measured by the geophone.) The NSAS program smooths the input data before performing the FFT integration. This smoothing process gets rid of characteristic peaks from chopping the f(t) data.

$|F(\omega)|$, in the case of the geophone, (a velocity transducer) has spectrum units which are in volt seconds. Since we are digitizing at 12-bit resolution with a full-scale voltage of $\pm$10 V (approximately 205 counts per volt), the resulting uncorrected spectra are given in counts. The amplifier gain range was from 84 to 102 Db, depending on the site where the noise was measured with the geophones. In order to determine the velocity and displacement of the geophone, one must remove the amplification, the effect of the geophone response, and the filter.

The geophone is treated as a damped, single degree of freedom oscillator (the resonant frequency is 4.5 Hz, the damping coefficient is 0.6 of critical damping). The equation for motion for the geophone coil as a function of time for a steady sinusoidal ground motion is represented as follows:[6] (It should be noted that the NSAS program solves a complex form of this equation. The simplified analysis shown here is used for illustration only.)

$$\frac{d^2x}{dt^2} + 2\frac{C}{C_o}\omega_o\frac{dx}{dt} + \omega_o^2 x = \omega_o^2 \delta \sin(\omega t) \qquad (2)$$

where

$$\omega_o = 2\pi f_o \qquad (2a)$$

$$\omega = 2\pi f \qquad (2b)$$

and f_o = resonant frequency of the geophone

f = frequency of the incoming wave form

x = displacement of the geophone coil with respect to a stationary point

t = time

δ = amplitude of incoming rock motion with respect to a stationary point

C/C_o = damping ratio

One can solve the above equation for the non-transient solution for the amplitude of the geophone coil displacement X_o with respect to a stationary point.[6]

$$M(\omega) = \frac{x_o}{\delta} = \left[\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(2\frac{C}{C_o}\ \frac{\omega}{\omega_0}\right)^2\right]^{-0.5} \qquad (3)$$

where $M(\omega)$ is defined as the geophone coil response magnification. The geophone measures the relative motion of the coil with respect to the moving ground. Thus, the magnification which is of interest in our case is $(1-M(\omega))$ in the frequency domain. One can convert the displacement of the geophone coil x_o to the velocity of the geophone coil as follows for a given sinusoidal motion at ω.

$$V_o = \omega\, x_o \qquad (4a)$$

A similar equation can be derived for the ground velocity V_R.

$$V_R = \omega\, \delta \qquad (4b)$$

where V_o is the amplitude of the velocity of the geophone coil, and V_R is the amplitude of the velocity of the ground. From Equations 4a and 4b one can see that the velocity magnification factor is the same as the displacement magnification factor. To convert the geophone velocity amplitude to ground velocity amplitude, simply divide the signal from the geophone in Fourier Transform form by $(1 - M(\omega))$, where $M(\omega)$ is defined by Equation 3.

One integrates the velocity spectrum to get the displacement spectrum of the rock.

$$y(t) = \int \frac{V_o}{(1 - M(\omega))} \cos(\omega t)\, dt \qquad (5a)$$

$$= \frac{V_o}{\omega(1 - M(\omega))} \sin(\omega t) \qquad (5b)$$

One divides the function $F(\omega)$ by $\omega(1 - M(\omega))$ to get the displacement spectra for the ground motion given in units of distance per hertz (distance times time). The process by which one gets from a signal measured by a sensor to a displacement spectra for the ground is illustrated in Figure 7. The case illustrated in Figure 7 has a velocity spectra with peaks of equal amplitude at 6 and 30 Hz. These peaks are about one order of magnitude above the noise. The signal measured by a geophone (resonant frequency 4.5 Hz, damping 0.6 times critical) is shown in the left hand panel marked a. The FFT of the signal is shown in the panel marked b. The corrected signal (with two equal amplitude peaks) is shown in the panel marked c. The displacement spectra, which results from integrating the velocity spectra, is shown in the final panel marked d.

For engineering studies, it is useful to convert displacement spectra into a peak displacement response for a given damping ratio. If the damping ratio chosen is low, say 0.02, a worst case calculation of the peak displacement at a given frequency results. (A damping ratio of 0.02 would be appropriate for a steel structure tightly put together which is deflected entirely within the elastic range. Most other structures would have a damping ratio higher than 0.02.) The conversion from displacement spectra to peak displacement response

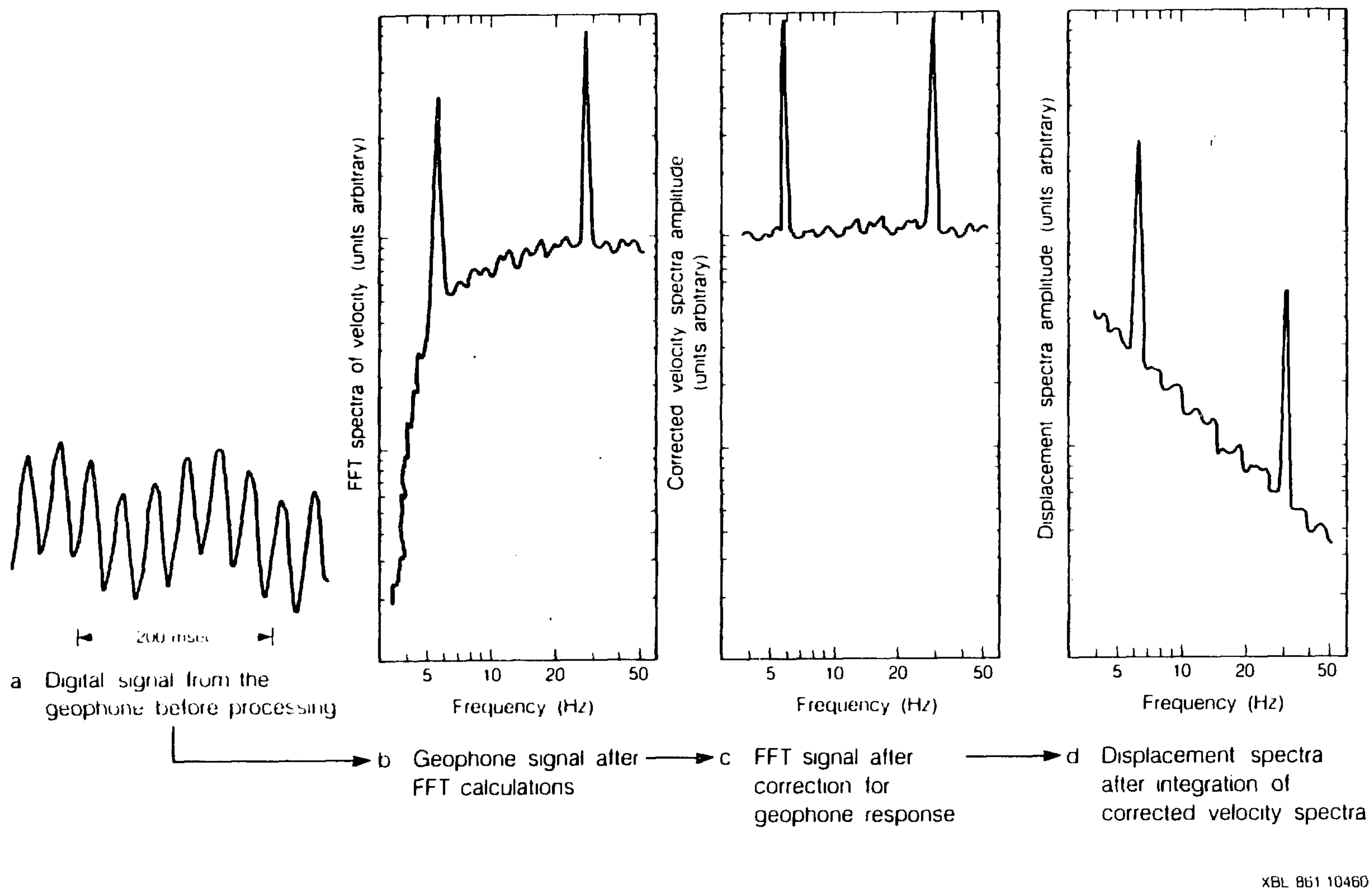

Figure 7. The Ground Motion Data After Various Steps of its Processing by the NSAS Computer Program (a simulation)

is done on a frequency band by frequency band basis. The procedure used for this process in the NSAS program is as follows:

1) For a particular frequency f_0, the displacement spectrum is multiplied by a magnification factor $M(\omega)$ given by Equation 3 for the given damping ratio C/C_0.

2) The displacement spectra modified by $M(\omega)$ is converted to the time domain by using the inverse transform which is as follows:

$$g(t) = \int_{\infty}^{\infty} F(\omega) \exp [i\omega t] \, d\omega \qquad (6)$$

3) The time signal is scanned to find the maximum amplitude. That amplitude is the peak displacement response for a frequency f_0.

4) The process given in Steps 1 through 3 is repeated for the whole range of f_0 from the minimum to maximum values. This yields the peak displacement response which as a function of frequency for the chosen damping ratio C/Co.

The peak displacement response represents the worst case displacement of an object connected to the moving ground location when a low value of damping ratio is used. The integration and selection process during the calculation of peak displacement response results in considerable smoothing of the curve. The amount of smoothing is a function of the damping ratio chosen. For the data presented in this report, a damping ratio of 0.02 was chosen in order to have the peak displacement response be truly a worst case.

Presentation of the Data

The LBL Vax computer can give one the data in several different ways. It is useful to look at samples of the data given in three different ways. Figure 8 presents data taken near the Bevatron as the computer receives it

Raw Experimental Data, Amplitude vs Time for Three Channels,
Taken at the Bevatron (September 18, 1983)

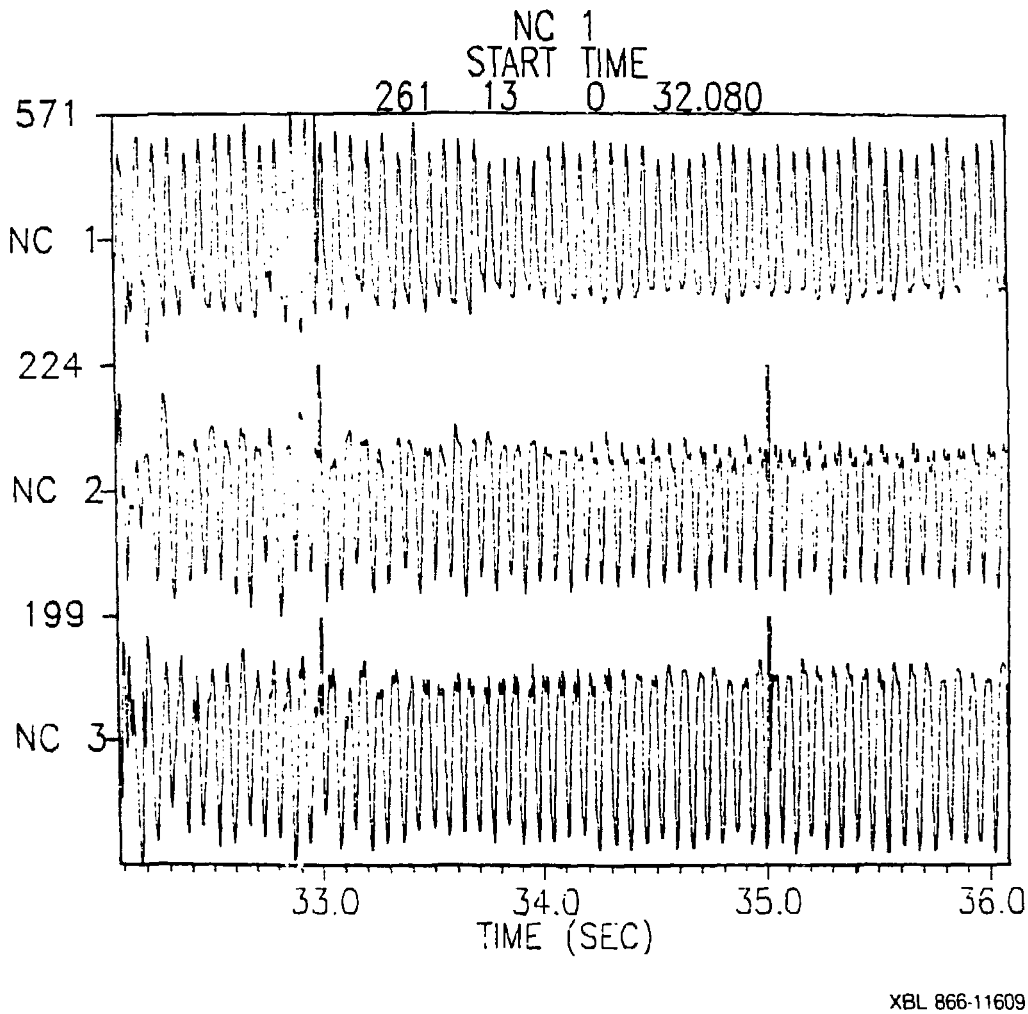

Figure 8. Raw Digitized Experimental Data for the Vertical Wave Motion (Channel NC-1) and the Two Horizontal Channels (NC-2 and NC-3). This Data is Wave Amplitude versus Time for the Three Channels.

after Binary to ASCII conversion and demultiplexing. This figure shows the three channels of raw digitized data given in computer units (0 to ±2048 units). Channel NC-1 is the vertical component of the motion signal from the geophone. Channels NC-2 and NC-3 are the two horizontal components of the motion signal. (There is no indication which directions these signals represent.) All three components show the characteristic 15 Hz signal from the Bevatron M.G. set. The NC-1 Bevatron signal shows that vertical component is the largest component. The data used to generate the displacement spectra and response spectra in general use the largest of the three signals to generate the spectra.

Figure 9 presents the Fourier amplitude of the displacement spectra given in cm-sec (cm/Hz). The characteristic peaks at 15 Hz, 30 Hz and 60 Hz can be seen. The oscillatory pattern given above the displacement spectrum is the raw data for channel NC-1. The displacement spectrum was calculated for that channel. The two vertical lines on the amplitude versus time plot above the spectra plot, which are two seconds apart on the time line, indicate the range over which the Fast Fourier Transform was created. The start time is given as follows: the first number is the day of the year (day 261 is September 18, 1983); the second number is the hour given on a 24-hour clock; the third number is the minute; and the fourth number is the second. The NC-1 above the start time indicates that the vertical component was used to generate the spectra from channel NC-1.

The data in Figure 9 is presented for a range of values from 0.35 Hz to 100 Hz. The displacement response data is only good from 5 Hz to about 60 Hz. Below 5 Hz, the data is greatly affected by the geophone frequency response which results in 1 - $M(\omega)$ being small and in some cases even

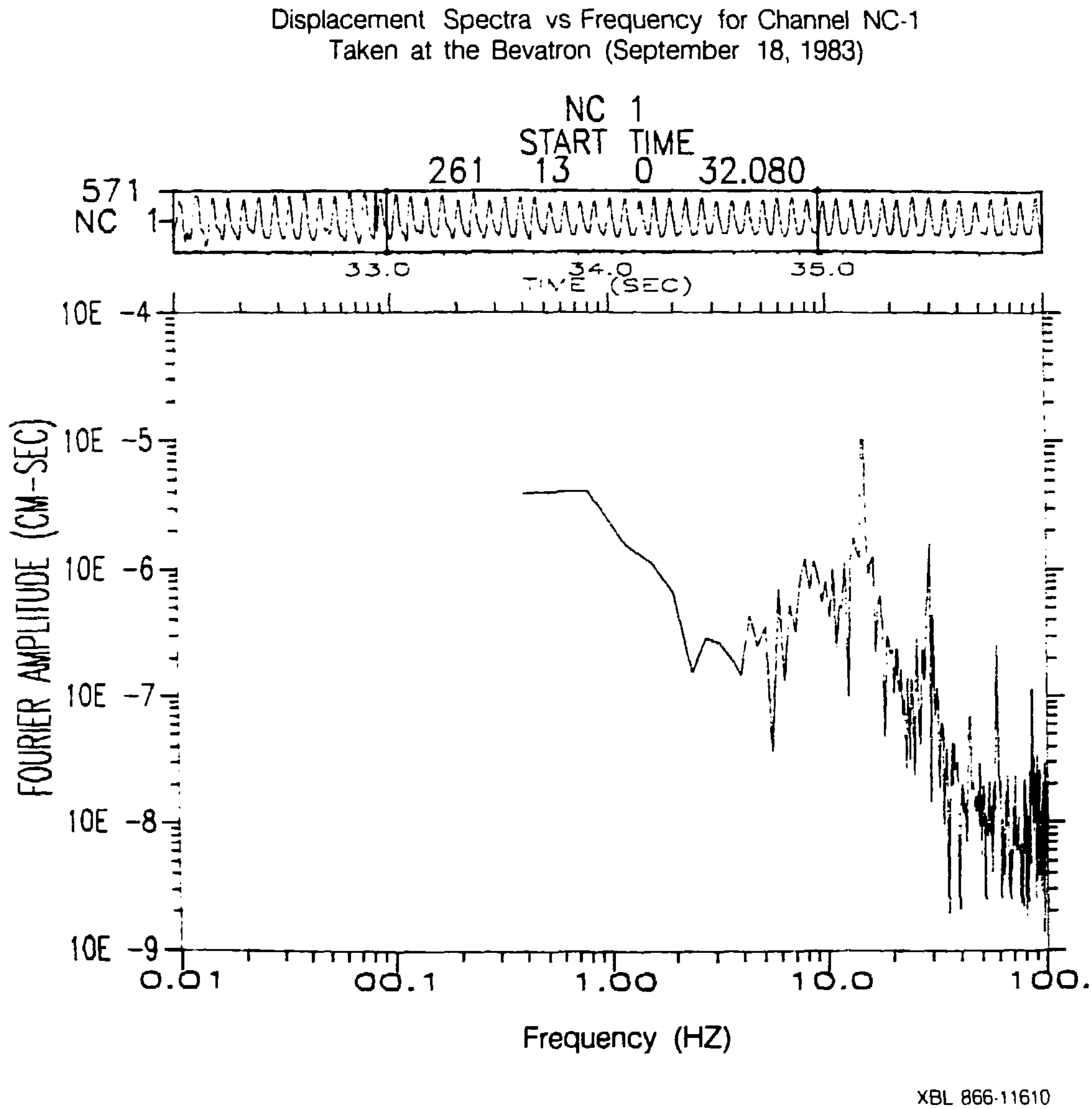

Figure 9. Displacement Spectra for the NC-1 (Vertical) Signal Given in Figure 8 taken over a Two-Second Interval (from 33 seconds to 35 seconds after the 0^{th} minute of the 13^{th} hour of the 261st day of 1983)

negative. The resonant frequency of the geophone is nominally 4.5 Hz. A 10% variation of the resonant frequency can result in errors well over 100% in the frequency range from 2 to 4.5 Hz. Below 2 Hz errors of 50 to 100% can be expected for a 10% change in f_o. A variation of the resonant frequency of the geophone f_o is much less pronounced above 5 Hz. (At 5 Hz the error can be as high as 50%; at 10 Hz the error can be 7%; and at 15 Hz the error can be as high as 2% for a 10% variation of f_o.) A change in damping ratio for the geophone will result in similarly high errors below 4.5 Hz, but above 4.5 Hz the effect of damping ratio error is lower.

One can extend the lower frequency limit of the geophone by using the same geophone for all measurements of ground motion. Without calibration on a shake table, this technique does not extend the geophone lower limit frequency much below 2.5 Hz (perhaps to 2 Hz). The geophone was not calibrated on a shake table. The only calibration which occurred was a comparison of measurements made in the Byerly seismic tunnel with the geophone and with the seismometers located there.

For frequencies above 50 Hz, the major source of error is the band-pass filter. The signal is filtered away by the time one gets to 100 Hz. Between 50 and 100 Hz, the uncertainties in the band-pass filter will contribute greatly to the measurement error.

Figure 10 shows the peak displacement response at the Bevatron with an assumed damping ratio of 0.02. In creating the peak displacement response, the computer has smoothed the curves considerably. (Larger values of damping ratio will yield somewhat smaller peaks and less smoothing.) One can see that the peak displacement response peaks occur at the same frequencies as the displacement spectra peaks. The plot above the response spectra shows the

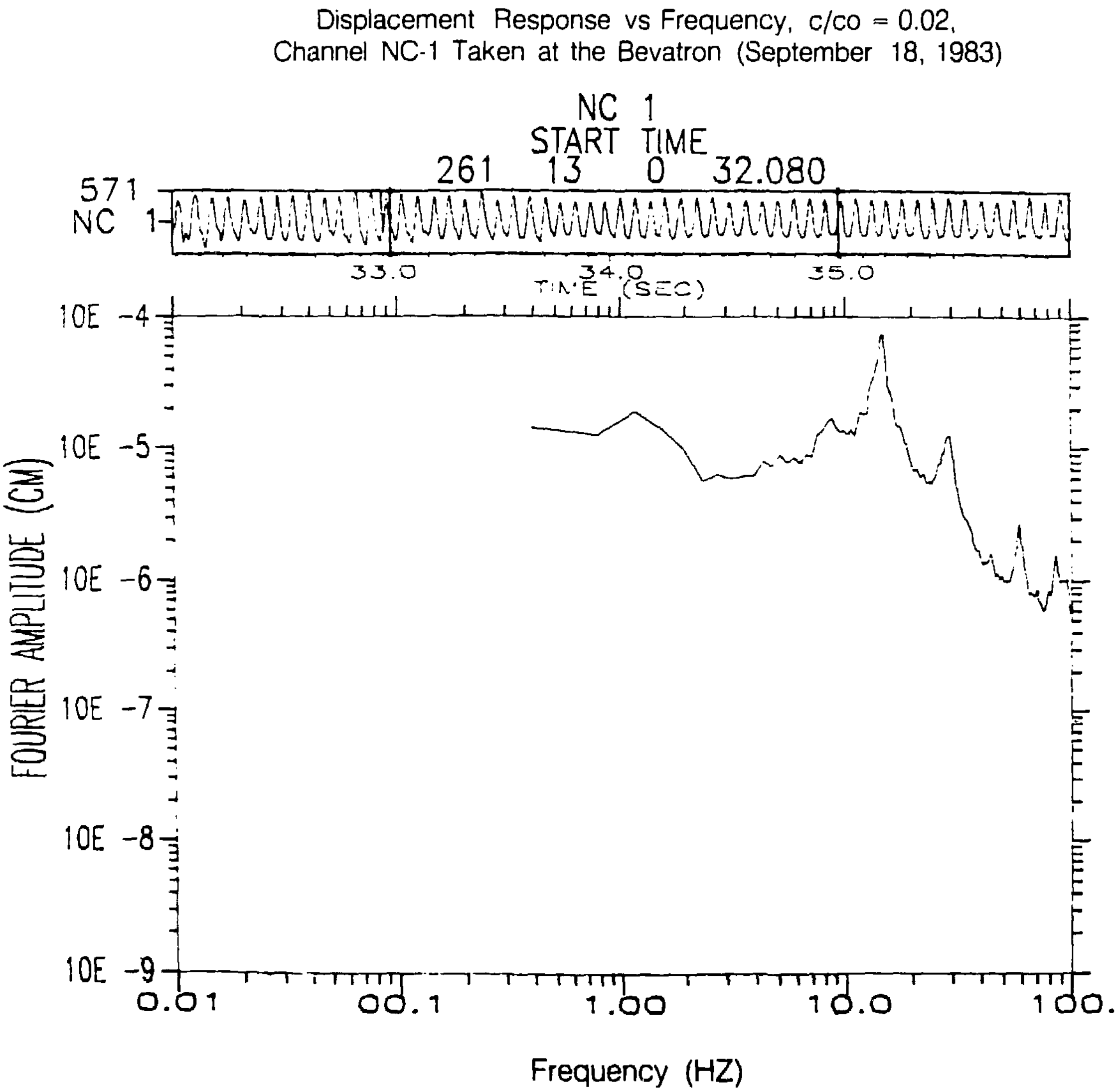

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Figure 10. The Peak Displacement Response versus Frequency for the NC-1 (vertical motion) Channel Signal Given in Figures 8 and 9. Note: The signal has been smoothed out by the insertion of the damping term (compare this signal with Figure 9); compare this figure with Figure 38, which gives the displacement response signal for Channel NC-2 (horizontal motion).

signal amplitude versus time for channel NC-1, which was used to create the response spectrum. The starting time is given as it is in Figure 9.

For comparison, Figures 11, 12 and 13, taken at Station 1 in Building 6 with the Bevatron M.G. set running, show a much less regular pattern of amplitude versus time, displacement spectra, and peak displacement response. This data was also taken on September 18, 1983. Like all of the data presented, the peak displacement response presented in Figure 13 was calculated with a damping ratio (C/C_0) of 0.02.

Results of Ground Motion Measurements

The results of the ground motion measurements in the form of response spectra are summarized in Table 2 and shown in Figure 14 and Figures 17 through 55. Table 2 summarizes the amplitude peaks at frequencies from 4 to 10 Hz (the data has limited accuracy below 3.5 Hz) and from 10 Hz on (peaks above 50 Hz are not very accurate because of the 50 Hz band-pass filter).

a) Byerly Tunnel Measurements

The low noise Byerly tunnel measurements (see Figure 14) indicate that equipment motions are 1.5×10^{-9} m or less in peak displacement response. (Real ground motions are considerably smaller.) In general, the quiet ground motions at the Byerly tunnel show a one over frequency dependence in amplitude which is consistent with the overall trend of quiet ground motion from a frequency of 0.16 Hz and above. The Byerly tunnel measurements were made on July 6, 1983.

The Byerly tunnel data is consistent with ground motions at a quiet site, even one which is in the middle of the country.[7] Typical ground motion at a

Raw Experimental Data, Amplitude vs Time for Three Channels,
Taken at Building 6, Station 1, with the Bevatron Running (September 18, 1983)

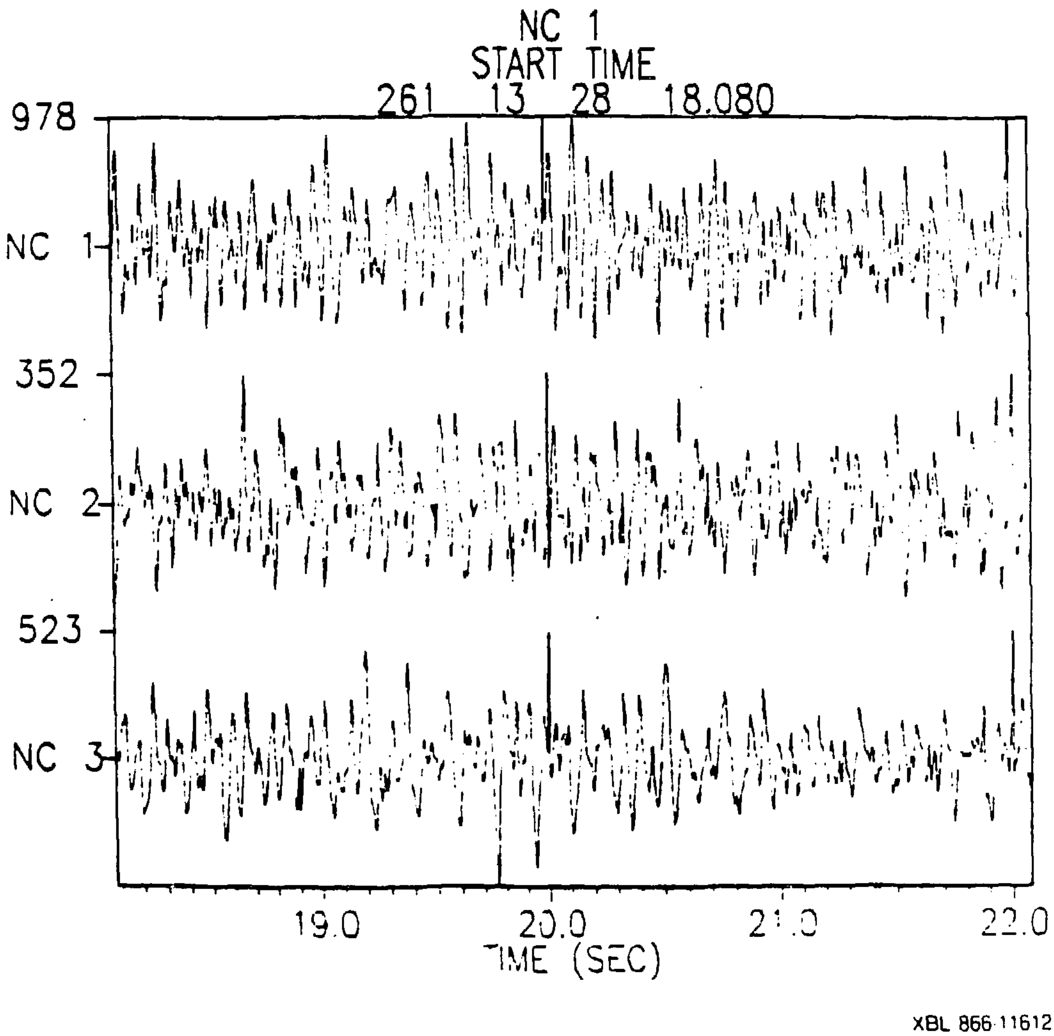
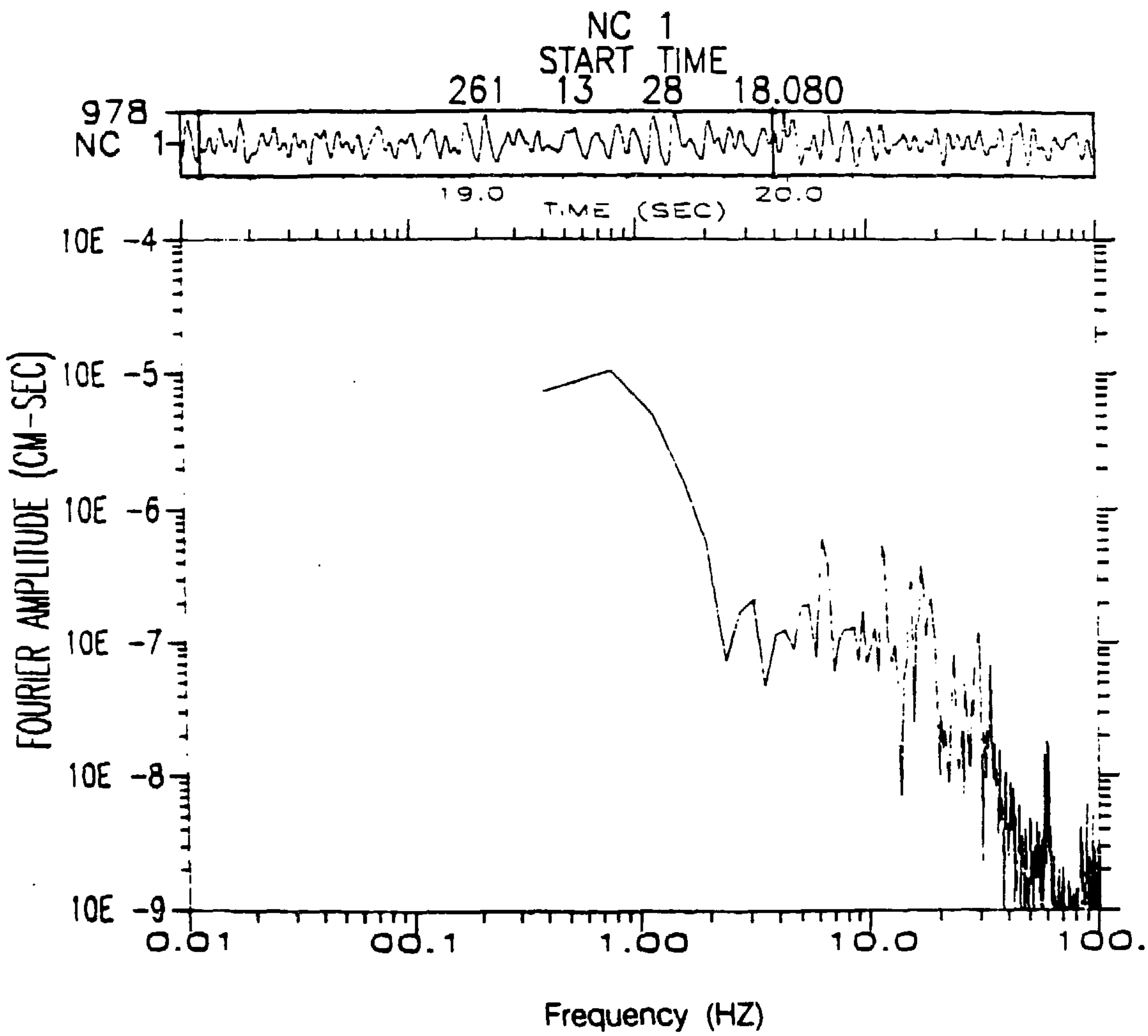


Figure 11. Raw Digitized Experimental Data of Amplitude versus Frequency of a Rather Mixed Signal Taken at Station 1 in Building 6. Note: The signals on all three channels appear to be very random. Note: There is no evidence of the Bevatron 15 Hz signal.

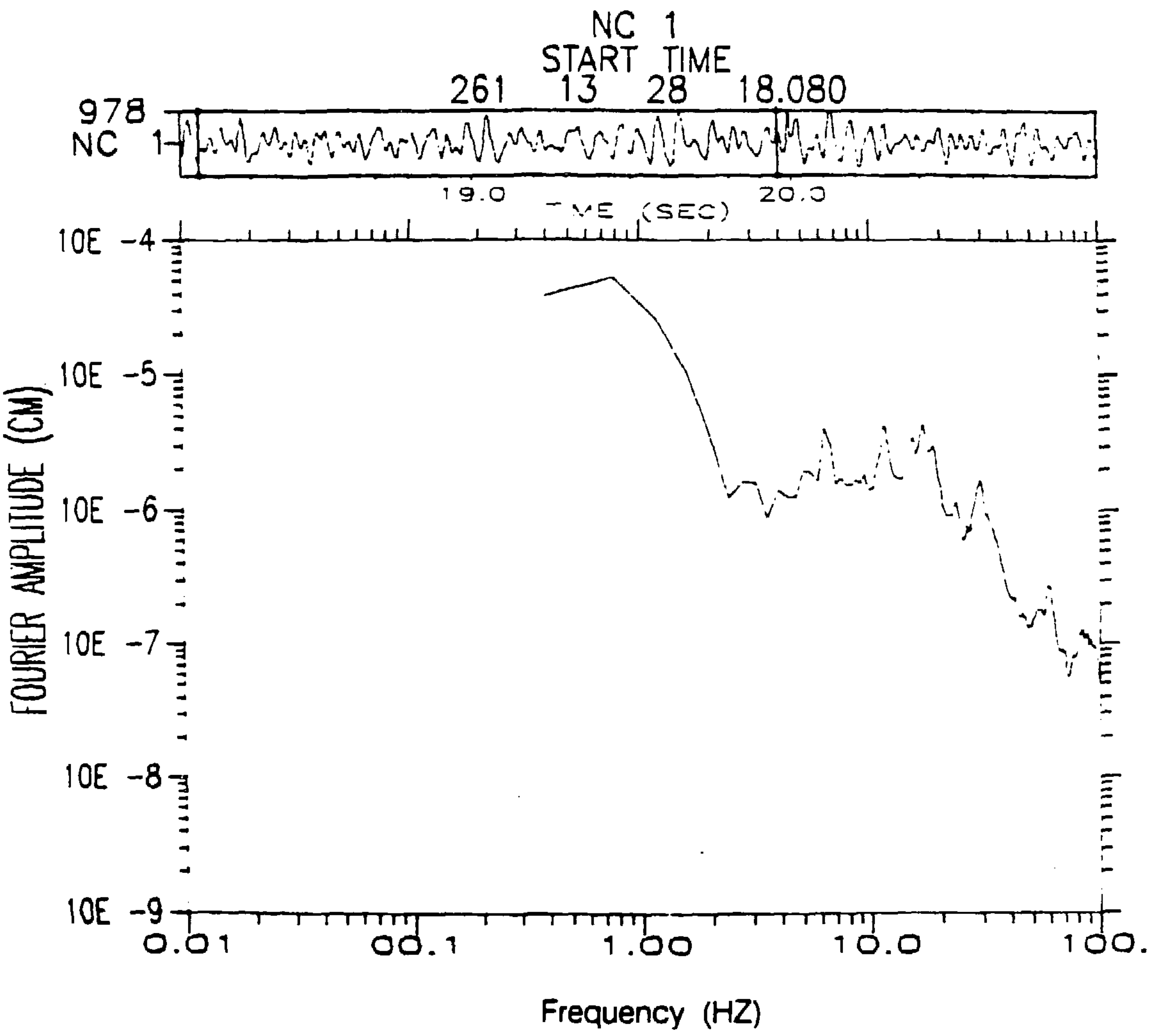
Displacement Spectra vs Frequency for Channel NC-1 Taken at Building 6, Station 1, with the Bevatron Running (September 18, 1983)



XBL 866-11613

Figure 12. Displacement Spectra versus Frequency for Channel NC-1 (vertical motion) Given in Figure 11. Note: The peak below 2 Hz is a false peak due to the error introduced by the geophone response curve.

Displacement Response vs Frequency c/co = 0.02, Channel NC-1
Taken at Building 6, Station 1, with the Bevatron Running (September 18, 1983)



XBL 866-11614

Figure 13. The Peak Displacement Response versus Frequency for Channel NC-1 (vertical motion) Taken at Station 1 in Building 6 with the Bevatron Running. Note: There is no evidence of a signal from the Bevatron. (The peak below 2 Hz is a false peak.) This figure should be compared to Figure 40 which is a separate computer run of the same signal.

Displacement Response vs. Frequency at the Byerly Tunnel
(July 6, 1983)

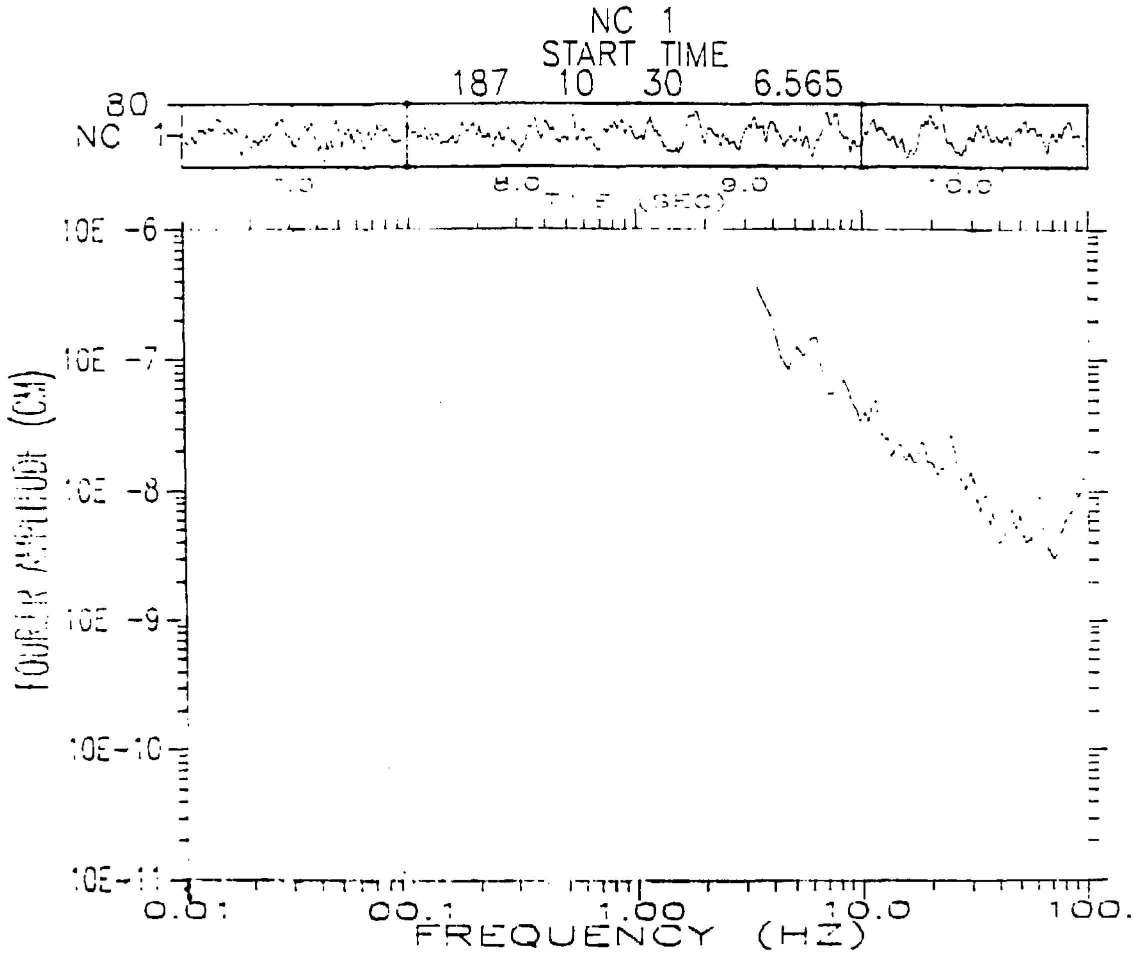


Figure 14. Displacement Response Measurements at the Byerly Tunnel. Note: There is a characteristic displacement which goes as one over frequency. This is a typical quiet site.

Table 2. Summary of Ground Motion Measurements at Various Sites

Sensor Location	Station Number	Response Amplitude Peak 4.5 to 10 Hz Amp. (m)	Freq. (Hz)	Response Amplitude Peak >10 Hz Amp. (m)	Freq. (Hz)	Remarks
Byerly Tunnel		1.5×10^{-9}	6	5×10^{-10}	12	Ground Motion decreases as 1/f
Bldg. 6 Normal	1	3×10^{-8}	6	4×10^{-8}	17	Peaks near 11, 28 and 33Hz
Bldg. 6 Normal	2	2.5×10^{-8}	5	2×10^{-8}	17	Peaks at 11 and 30Hz
Bldg. 6 Normal	5	2×10^{-8}	5	8×10^{-8}	17	Large peak at 12Hz decreasing >20Hz
Bldg. 6 Normal	6	3×10^{-8}	4	4×10^{-8}	11	Peaks at 17, 30, 40 and 50Hz
Bldg. 6 Normal	7	3.5×10^{-8}	8.5	3.5×10^{-8}	11	Peaks at 17, 22 and 33Hz
Bldg. 6 Normal	8	3.5×10^{-8}	8.5	5×10^{-8}	11	Large peaks at 17 and 33Hz
Bldg. 6 Normal	9	4×10^{-8}	5	10^{-7}	17	Peaks at 11 and 33Hz
Bldg. 6 Normal	11	3.5×10^{-8}	6	7×10^{-8}	30	Peaks at 11, 17, 22 and 33Hz, lots of hash up to 33Hz
Bldg. 6 Normal	12	3×10^{-8}	4.5	3×10^{-8}	11	Peaks at 17, 22, 30 and 33Hz, fall off >33Hz
Bldg. 6 Normal	13	2×10^{-8}	6	6×10^{-8}	11	Smaller peaks at 30, 42 and 50Hz
Bldg. 6 Normal	14	4×10^{-8}	6.5	2×10^{-8}	11	Decreasing peaks at 15, 19 and 30Hz
Bldg. 6 Normal	15	---	--	1.5×10^{-8}	11	No defined peak <10Hz, peak at 17Hz
Bldg. 10 Normal	17	---	--	4×10^{-8}	17	No defined peak <10Hz, peak at 11Hz
Bldg. 10 Normal	18	---	--	3×10^{-8}	17	No defined peaks <10Hz, peak at 11Hz
Bldg. 10 Normal	19	---	--	2×10^{-8}	19,28	Peaks at 11, 33 and 50Hz
Bldg. 80 Normal	20	---	--	3×10^{-8}	11	No defined peaks <10Hz, peaks 17 and 28Hz
Bldg. 80 Normal	23	3×10^{-8}	9	10^{-7}	11,28	Other peaks at 14 and 19Hz
Bldg. 80 Normal	24	---	--	2×10^{-7}	11	Hash at 3×10^{-8}m at <10Hz, peak at 28Hz decreasing
Bldg. 6 Normal	27	---	--	6×10^{-8}	11	Hash at 10^{-8}m at <10Hz, decreasing peak > 20Hz
Bldg. 6 Normal	30	9×10^{-8}	5	10^{-7}	11	Series of peaks near 10^{-7}m at 22, 28 and 33Hz

All of the data above was taken on Wednesday, July 6, 1983.

Table 2. Summary of Ground Motion Measurements at Various Sites (cont.)

Sensor Location	Station Number	Response Amplitude Peak 4.5 to 10 Hz Amp. (m)	Response Amplitude Peak 4.5 to 10 Hz Freq. (Hz)	Response Amplitude Peak >10 Hz Amp. (m)	Response Amplitude Peak >10 Hz Freq. (Hz)	Remarks
July 6 Quiet Zone Bldg. 80 Basement	25	1.3×10^{-8}	4.5	1.8×10^{-8}	11	Peaks at 17 and 30Hz
At Bevatron while running, 18 Sept.		---	--	2.5×10^{-7}	15	Peaks at 30 and 60Hz, M.G. set
Blackberry Canyon Bev running, 18 Sept.		---	--	9×10^{-8}	15	Hash <10Hz, no 30Hz or 60 Hz peaks, M.G. set
Bldg. 6, Bev running, 18 Sept.	1	4×10^{-8}	6	4×10^{-8}	11,17	Pattern similar to the July 6 data
Bldg. 6 No Bevatron running on 20 Sept.	1	4×10^{-8}	5.5	5×10^{-8}	11,17	Pattern similar to data taken on July 6
Building 6, fire truck on Plank Bridge, 20 Sept.	1	---	--	7×10^{-7}	12	Lots of noise at 3×10^{-7}m <10Hz, noise at 10^{-7}m >20Hz, clipped peaks
Building 6, 26 Sept. Secondary Crane on	1	4×10^{-7}	6	3×10^{-7}	16	Lots of noise >10^{-7}m at f <20Hz
Building 6, 26 Sept Both Cranes on	1	1.7×10^{-6}	8	10^{-6}	16	Peak at 40Hz, lots of noise, clipped peaks
SLAC,* in pit	1	6×10^{-8}	6	10^{-8}	11	Decreasing peaks >11Hz
SLAC,* top of beam	3	8×10^{-7}	4.6	6×10^{-8}	20	Peak at 33Hz, peak at 60Hz
SLAC,* floor	4	5.5×10^{-8}	6	2×10^{-8}	10	Peaks at 20, 30 and 60Hz
SLAC,* floor	6	10^{-7}	6	2×10^{-8}	12	Peaks at 30 and 60Hz
SLAC,* survey monument	7	10^{-7}	6	1.5×10^{-8}	12	Peaks at 18, 24 and 60Hz sharp peak at 60 Hz
SLAC,* top of support pillar	8	6×10^{-8}	6	1.2×10^{-8}	12	Decreasing peaks >10Hz peak at 4.6 Hz
SLAC,* on floor	9	4×10^{-8}	5	5×10^{-8}	12	Peaks at 17 and 30Hz
SLAC,* top of beam	13	5.5×10^{-7}	4.6	5×10^{-8}	18	Peaks at 12, 30 and 60Hz
SLAC,* outside shielding	15	6×10^{-8}	4.6	2×10^{-8}	60	Lots of hash at 7×10^{-9}m, f = 10 to 50Hz
SLAC,* hilltop	17	7×10^{-8}	4.6	8×10^{-9}	23	9Hz peak 2.5×10^{-8}m, peak at 30Hz
SLAC,* outside compressor room	18	7×10^{-7}	4.6	1.7×10^{-7}	33	9Hz peak 3×10^{-7}m, hash >10Hz

*All SLAC measurements were made on Sunday, August 28, 1983, a relatively quiet day.

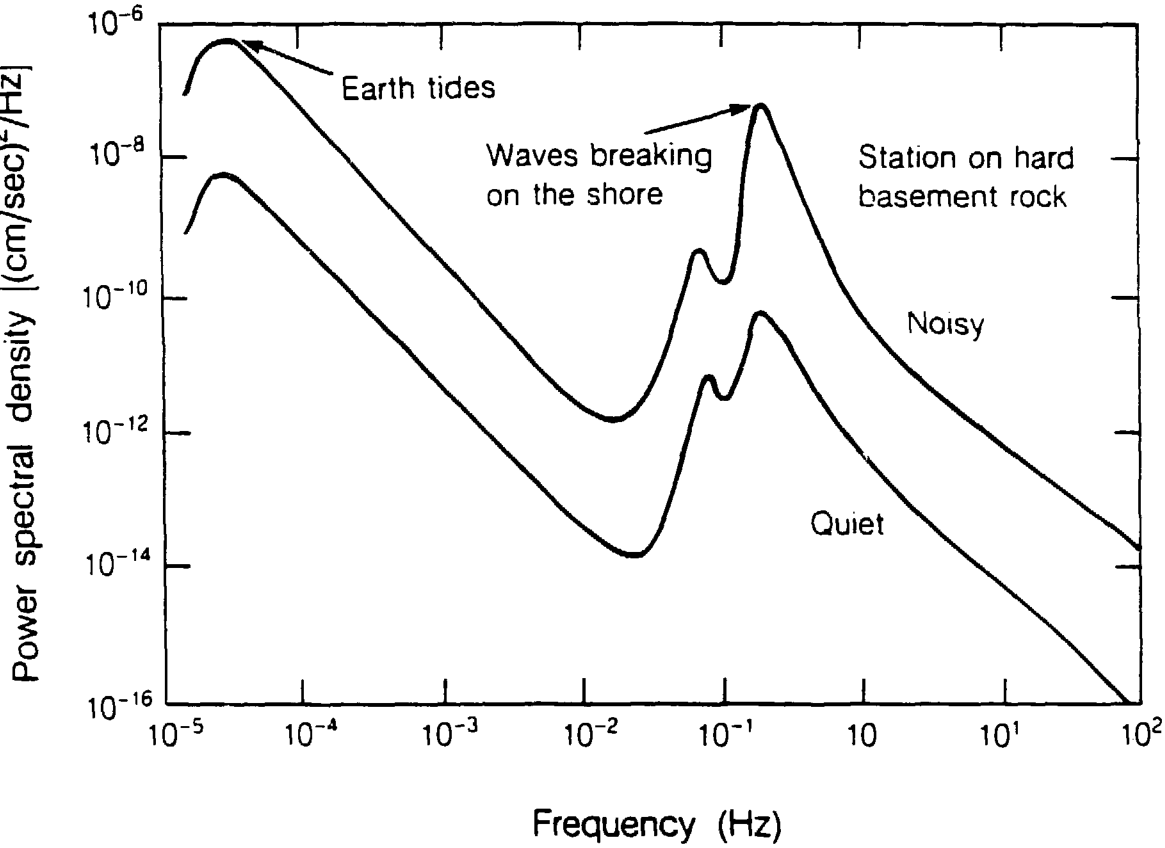
quiet site shows peaks at 2.3×10^{-5} Hz (due to earth tides) and 0.16 Hz (due to waves breaking on a distant shore). Between the two peaks is a valley which has a ground motion displacement which is a couple of orders of magnitude lower than the 0.16 Hz peak. From 0.16 Hz upward the ground motion displacement varies as about one over frequency (see Figure 15). From Figure 16 one can see the Byerly tunnel measurements compared with ground motion displacement measurements made at a number of quiet sites. (Some of these sites are over 1000 km from the ocean.)

b) Building 6 Measurements on July 6, 1983

The Building 6 measurements made on July 6, 1983 were made when all equipment was running in the Building 6 area. The Bevatron was not running on that date nor were the Building 6 cranes. The July 6, 1983 measurements for most of the sites in Figure 2 are shown in Figures 17 through 37. (Some of the data was lost.)

In many locations in the Building 6 area the peak displacement response was of the order of 4×10^{-8} m. The highest peaks generally occur at frequencies of 11 or 17 Hz. In some locations there is considerable noise at frequencies around 30 Hz. In most cases the vertical motion had the largest peak displacement response.

Station 1 (see Figure 17) was chosen as the Building 6 reference station. This station is very close to one of the support pillars for the building. This pillar will transmit crane motion directly to the ground. Station 1 was also close to a source of ground motion due to vehicular traffic. Station 2 (see Figure 18) showed ground motions which are somewhat lower than Station 1. This station is away from the support pillars. Station 5 (see Figure 19), which is close to the Neutral Beam Test Facility, shows a pronounced peak at 17 Hz which is related to the Neutral Beam Test Facility



XBL 868-11674

Figure 15. Power Spectral Density versus Frequency from 10^{-5} Hz to 10^{2} Hz. Note: There are double peaks that are due to earth tides and waves breaking on the shore (taken from Reference 7).

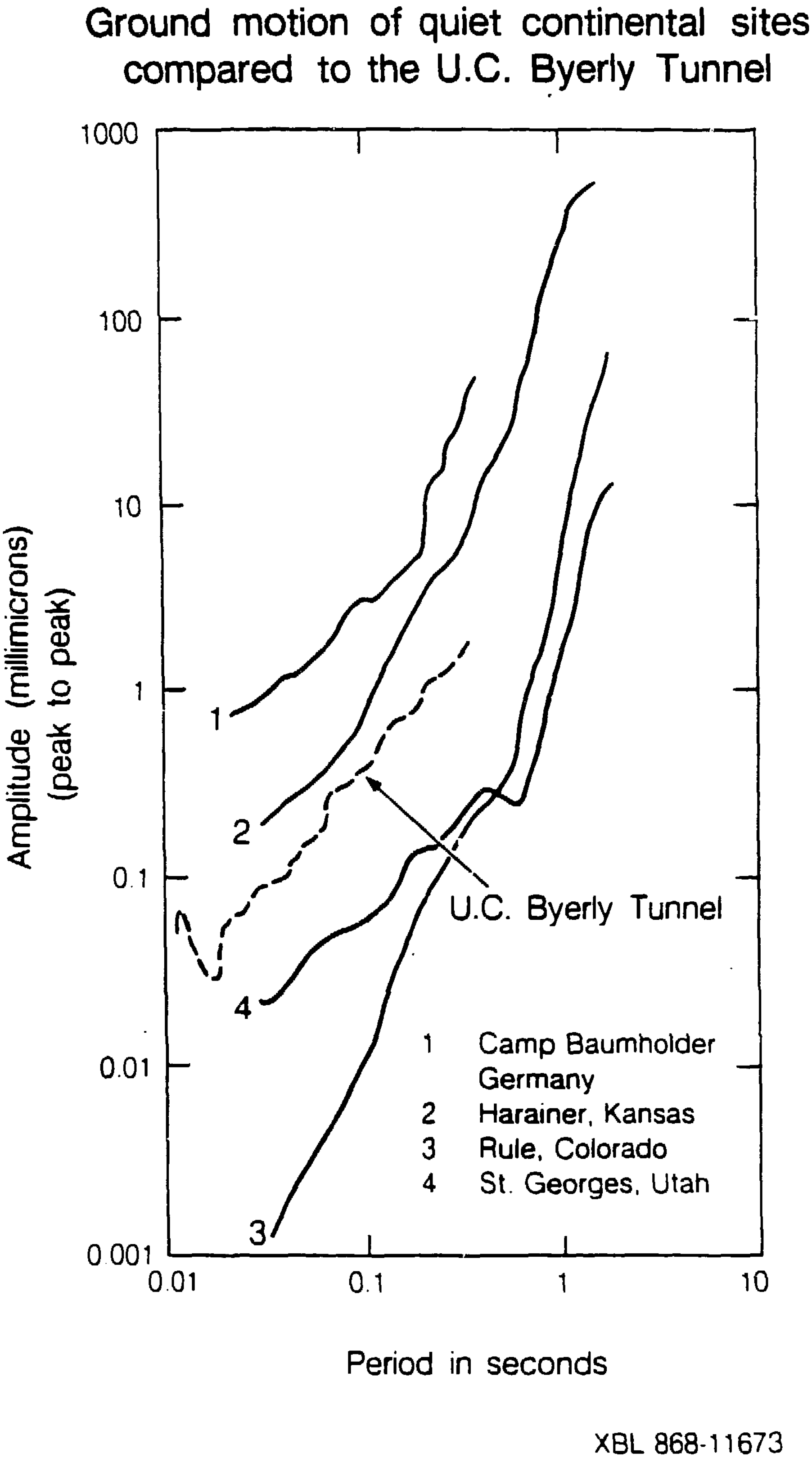
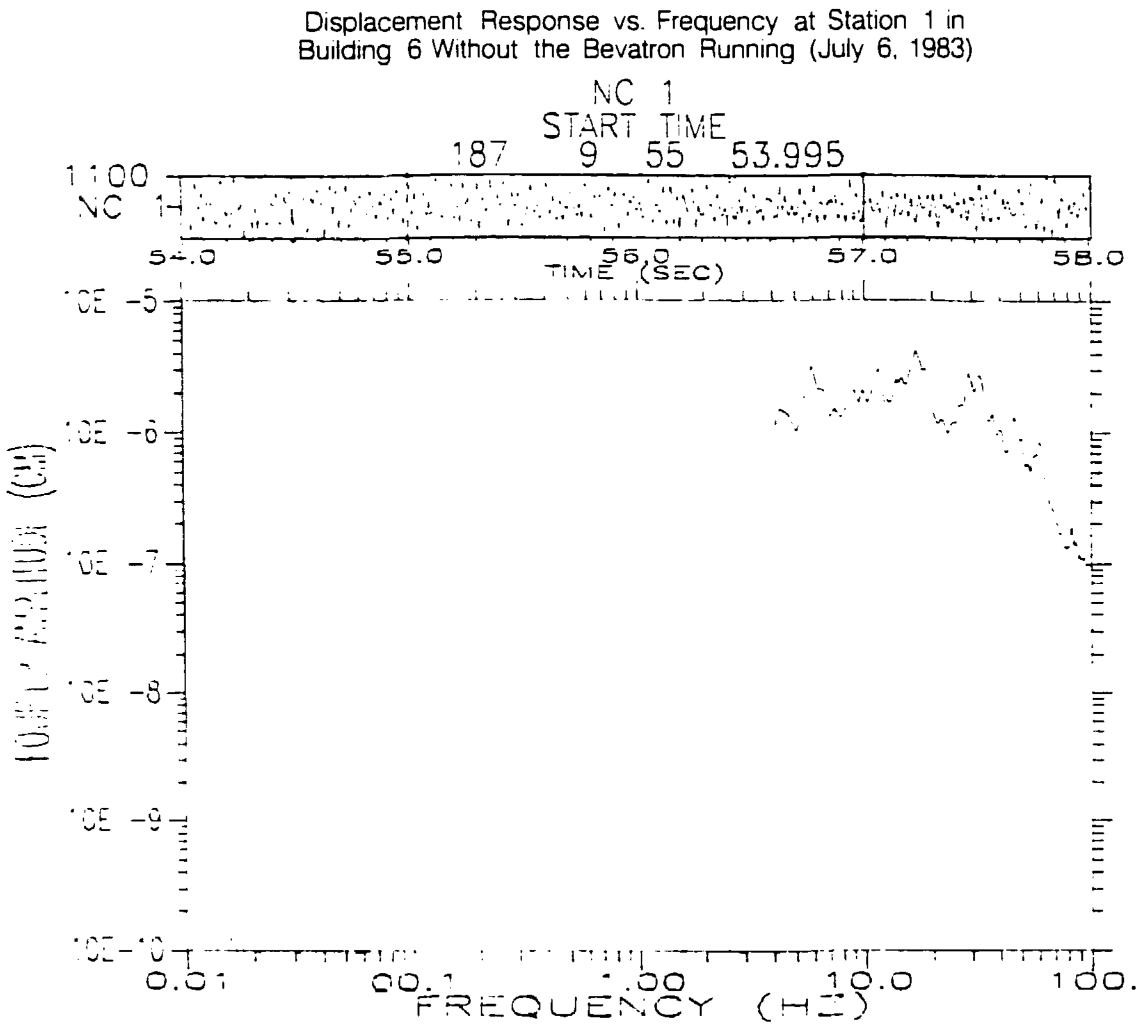


Figure 16. A Comparison of the Frequency Dependence of Ground Motion at Various Quiet Sites with Ground Motion Measured at the U.C. Byerly Tunnel (see Figure 14). The Four Inland Quiet Sites data was Taken from Reference 7.



XBL 864 11071

Figure 17. Displacement Response Measurements at Station 1 in Building 6. Note: There are peaks at 5.5, 11, 17 and 30 Hz which are characteristic of the Building 6 site.

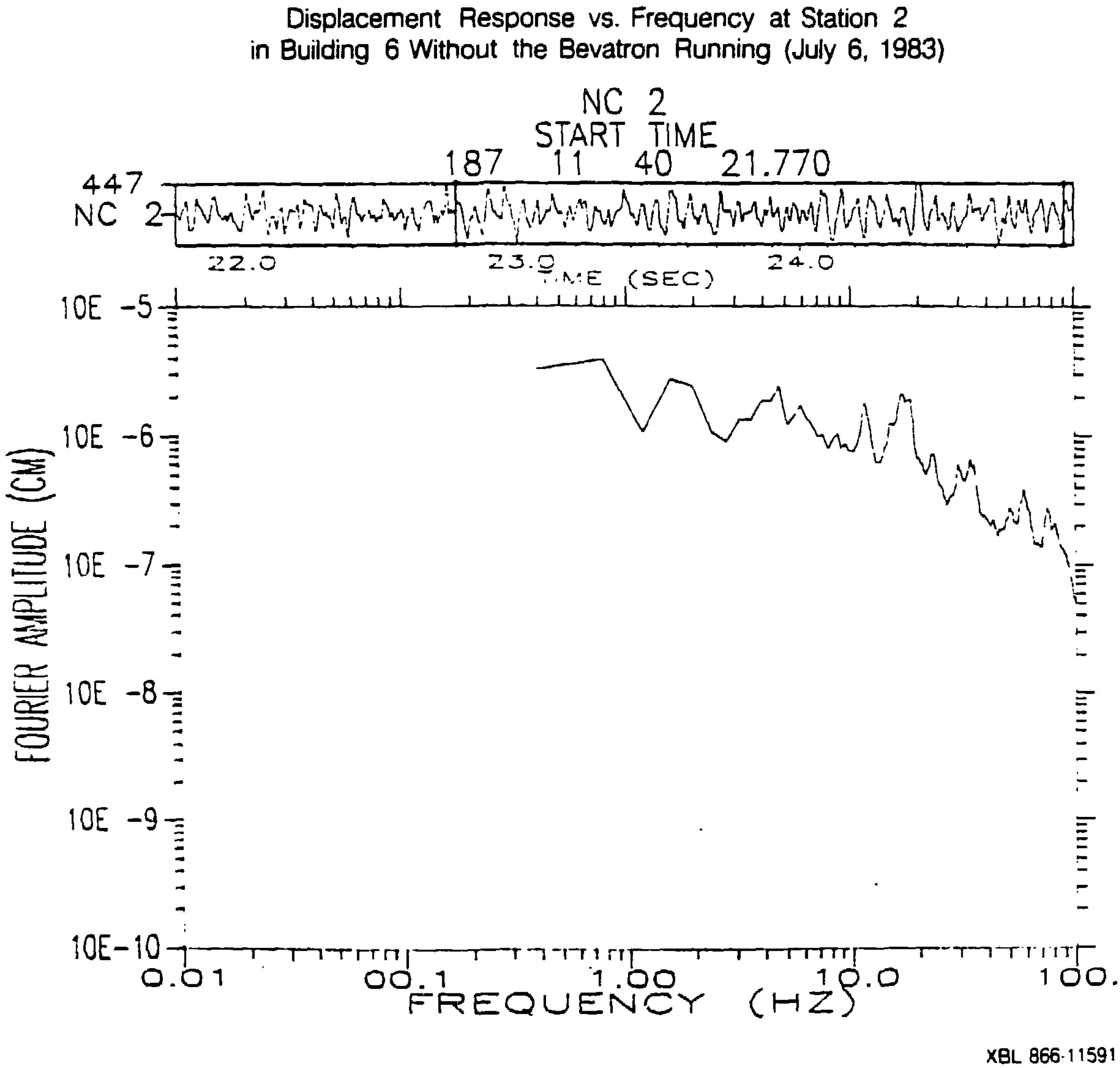
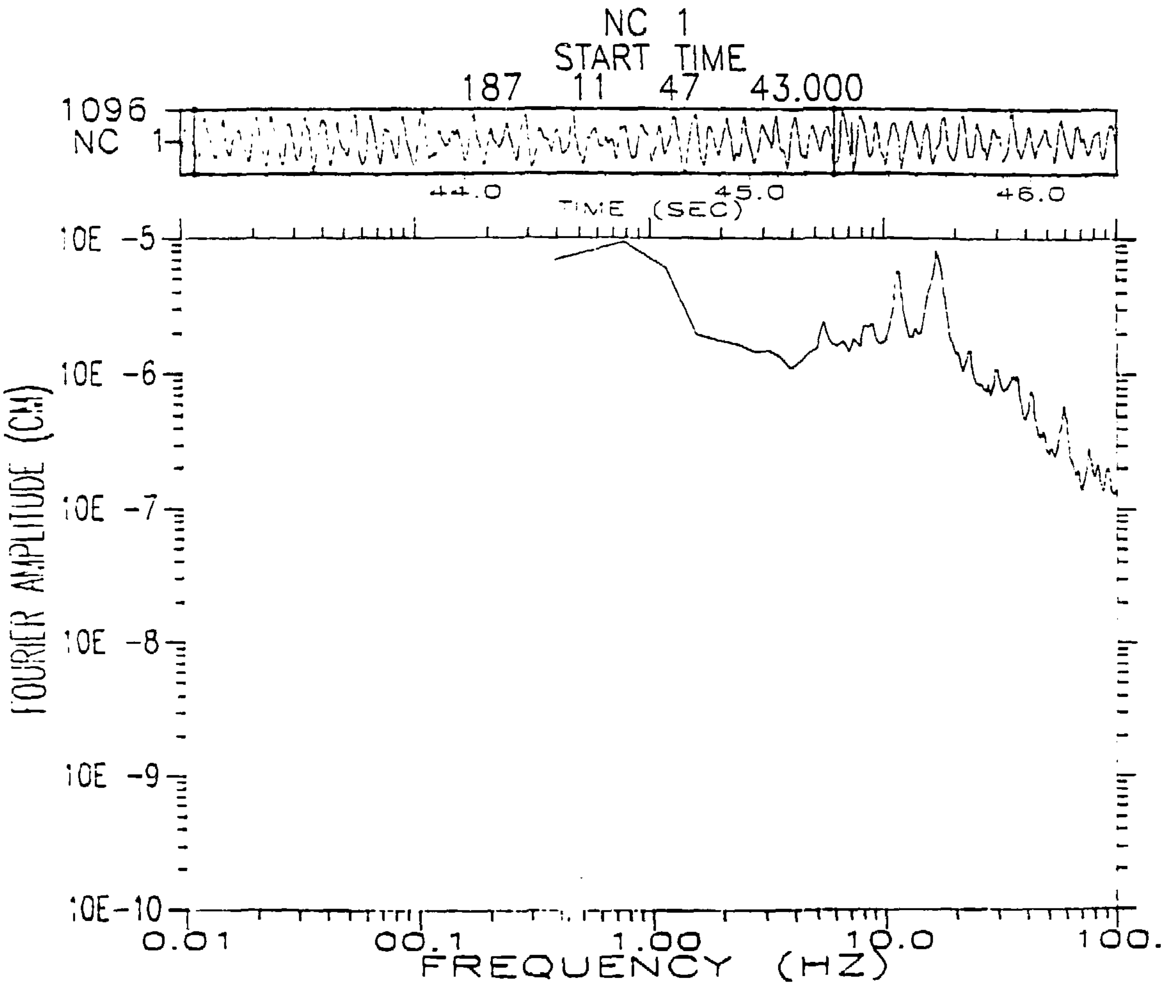


Figure 18. Displacement Response Measurements for Station 2 at Building 6. Note: There are peaks at 5.5, 11 and 17 Hz. The apparent peaks below 4 Hz should be ignored.

Displacement Response vs. Frequency at Station 5
in Building 6 Without the Bevatron Running (July 6, 1983)



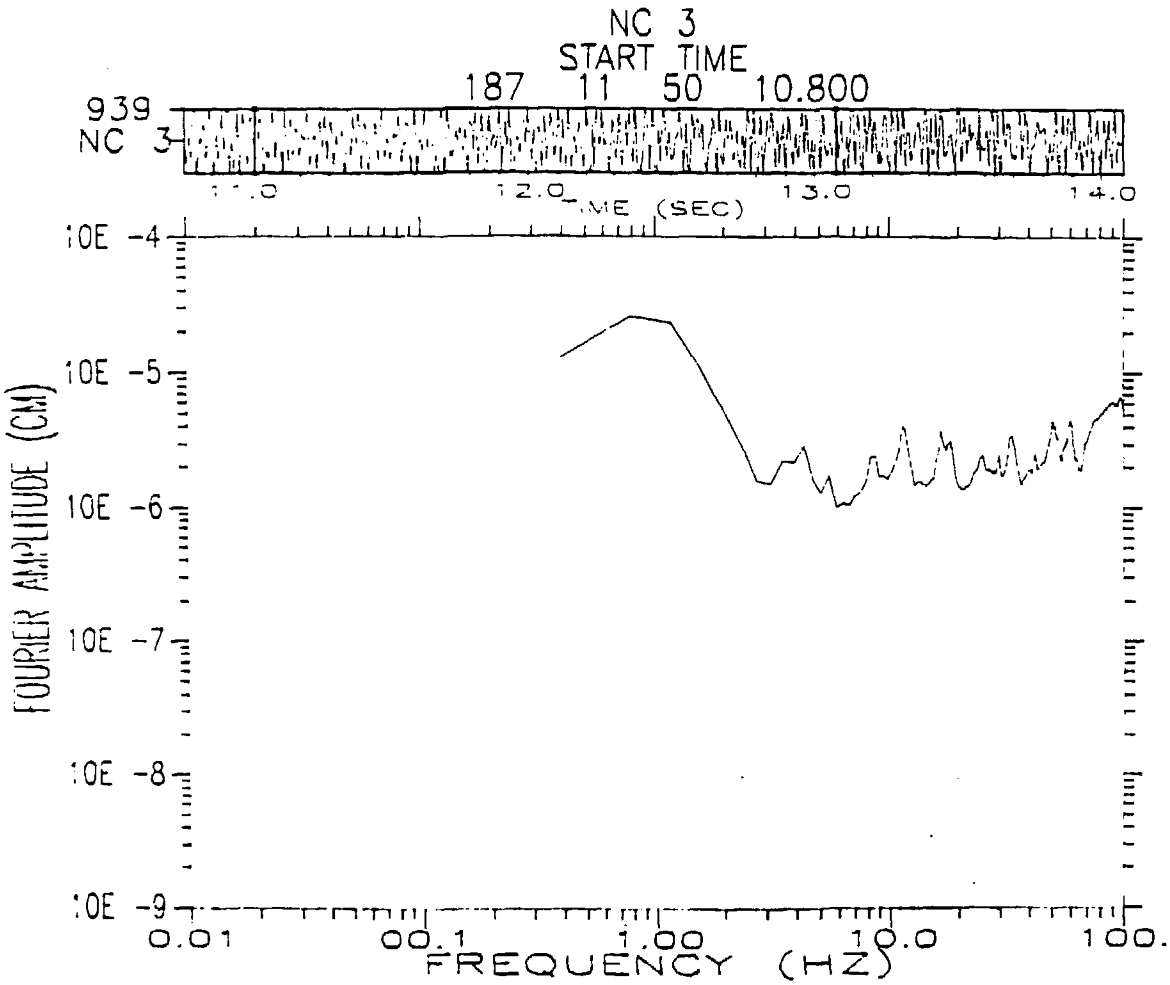
XBL 866-11592

Figure 19. Displacement Response Measurements for Station 5 at Building 6. Note: There are pronounced peaks at 11 and 17 Hz. The 17 Hz peak is probably due to the Neutral Beam Facility stokes pumps. Data below 4 Hz should be ignored.

Stokes pumps. Station 6 (see Figure 20) shows a lot of local noise due to a motor and pump on the Neutral Beam Test Facility. Stations 7 and 8 (see Figures 21 and 22) show peaks at 11 and 17 Hz, and there is considerable high frequency noise (about 30 Hz). Station 9 (see Figure 23) is one with larger than average noise peaks. This station is somewhat puzzling because it is closer to the 11 Hz source, yet the 17 Hz peak is the highest. Station 11 (see Figure 24) is fairly normal in its noise spectrum with peak displacement responses of 4 to 5 x 10^{-8} m. Station 12 (see Figure 25) is relatively quiet with the 11 Hz peak dominating. Station 13 (see Figure 26) shows a strong 11 Hz peak, but the rest of the noise is down. Station 14 (see Figure 27) is one of the quietest measured at Building 6, yet there is a strong 7 Hz peak relative to the rest of the data. This peak is not well understood; it could be local in origin. Station 15 (see Figure 28) is even quieter than Station 14.

Of the stations outside of Building 6, Station 30 (see Figure 36) is by far the noisiest. This station has a strong 11 Hz peak, and it has a series of peaks at higher frequencies. This station is located directly outside the Building 6 pump room. Stations 17, 20 and 27 (see Figures 29, 32 and 35) show peaks at 11 or 17 Hz and a fall off in peak displacement response as one goes to higher frequencies. Stations 18 and 19 (see Figures 30 and 31) in Building 10 show a similar characteristic, as does Station 24 (see Figure 34) in Building 80. Station 23 (see Figure 33) in Building 80 (the location was not precisely known) shows evidence of considerable local noise (note the 30 Hz peak) as well as 11 and 17 Hz noise characteristics of Building 6. The quietest location in the Building 6 area is Station 25 (see Figure 37) in the basement of Building 80. This location shows characteristic peaks at 11 and 17 Hz which are believed to come from Building 6 sources and a 30 Hz peak which is probably of local origin. A comparison of data at Stations 23, 24

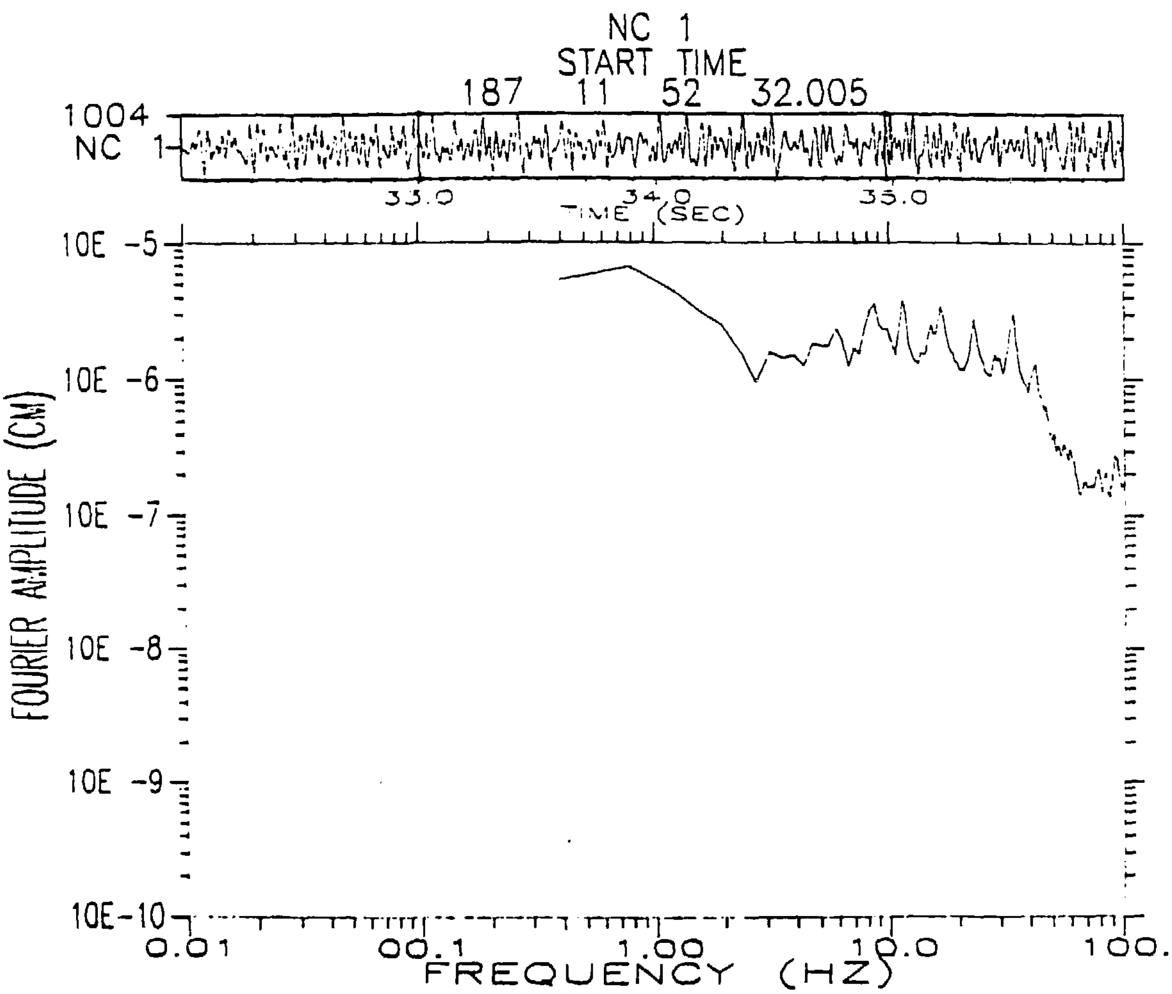
Displacement Response vs. Frequency at Station 6
in Building 6 Without the Bevatron Running (July 6, 1983)



XBL 866-11593

Figure 20. Displacement Response versus Frequency at Station 6 in Building 6. Note: There is a lot of local noise due to equipment around the Neutral Beam Facility.

Displacement Response vs. Frequency at Station 7
in Building 6 Without the Bevatron Running (July 6, 1983)



XBL 866-11594

Figure 21. Displacement Response Measurements versus Frequency at Station 7 in Building 6. Note: There is a series of peaks from 11 to 35 Hz. The peaks at 22, 28 and 33 Hz are of local origin.

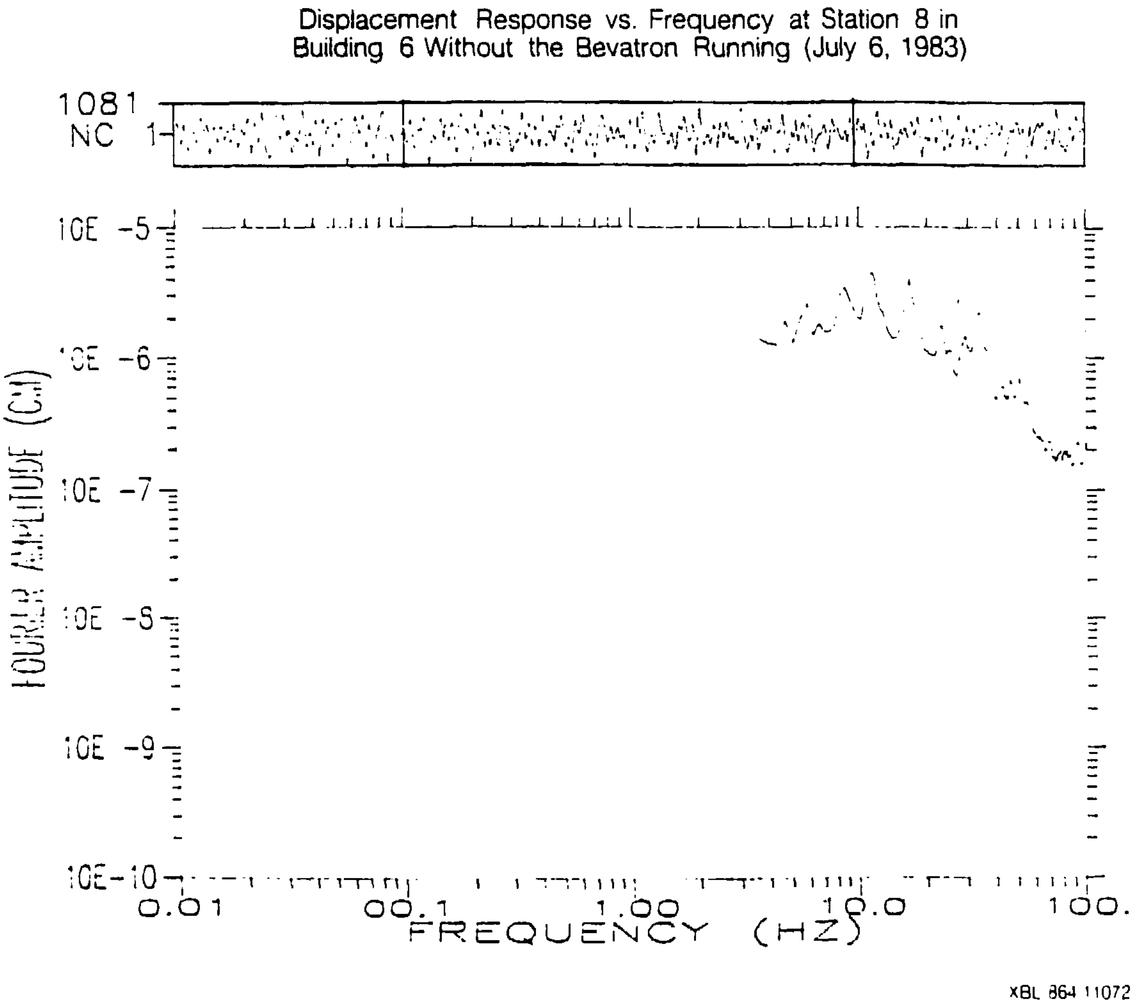


Figure 22. Displacement Response Measurements at Station 8 in Building 6. Note: The dominant 11 and 17 Hz peaks.

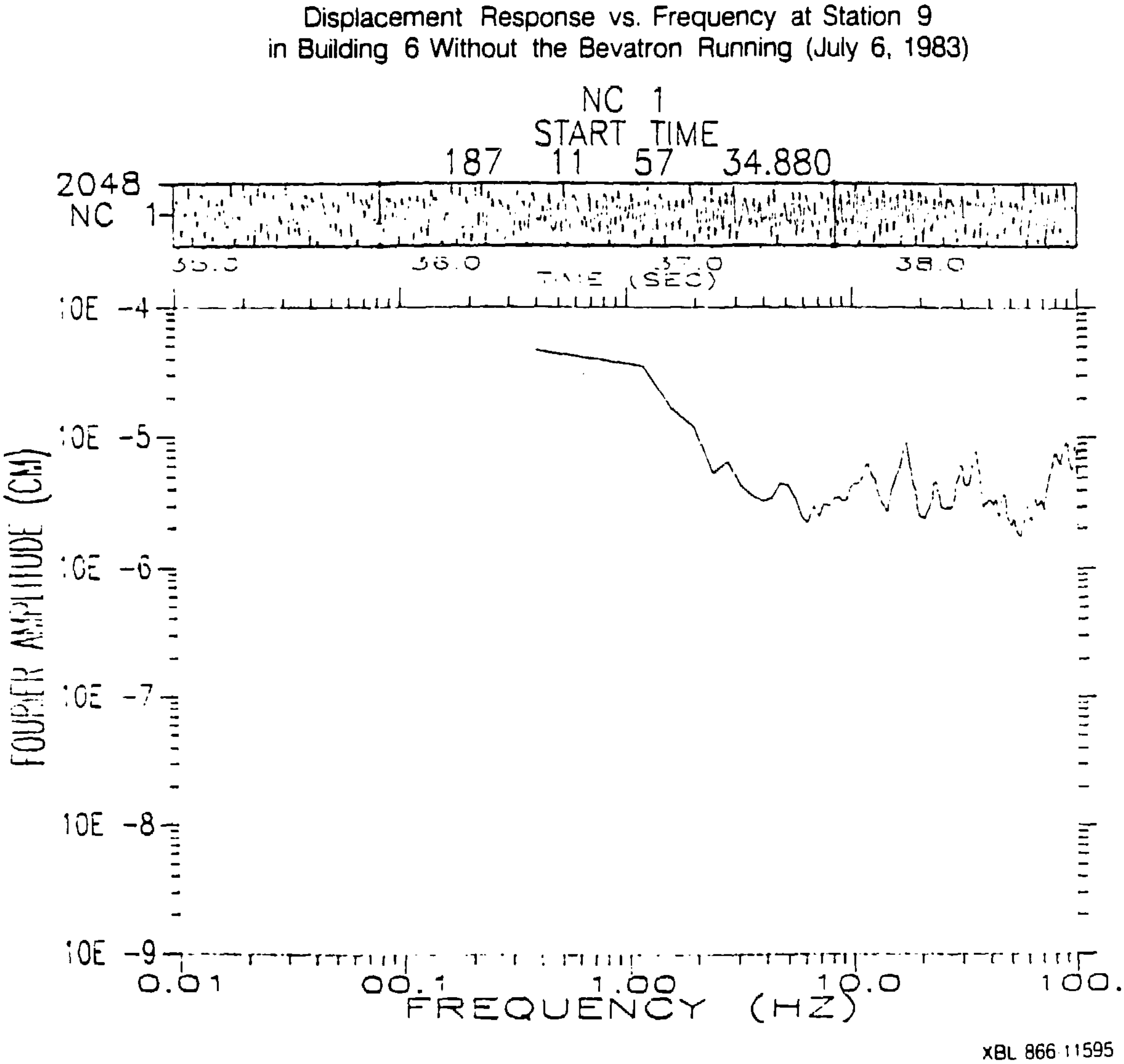
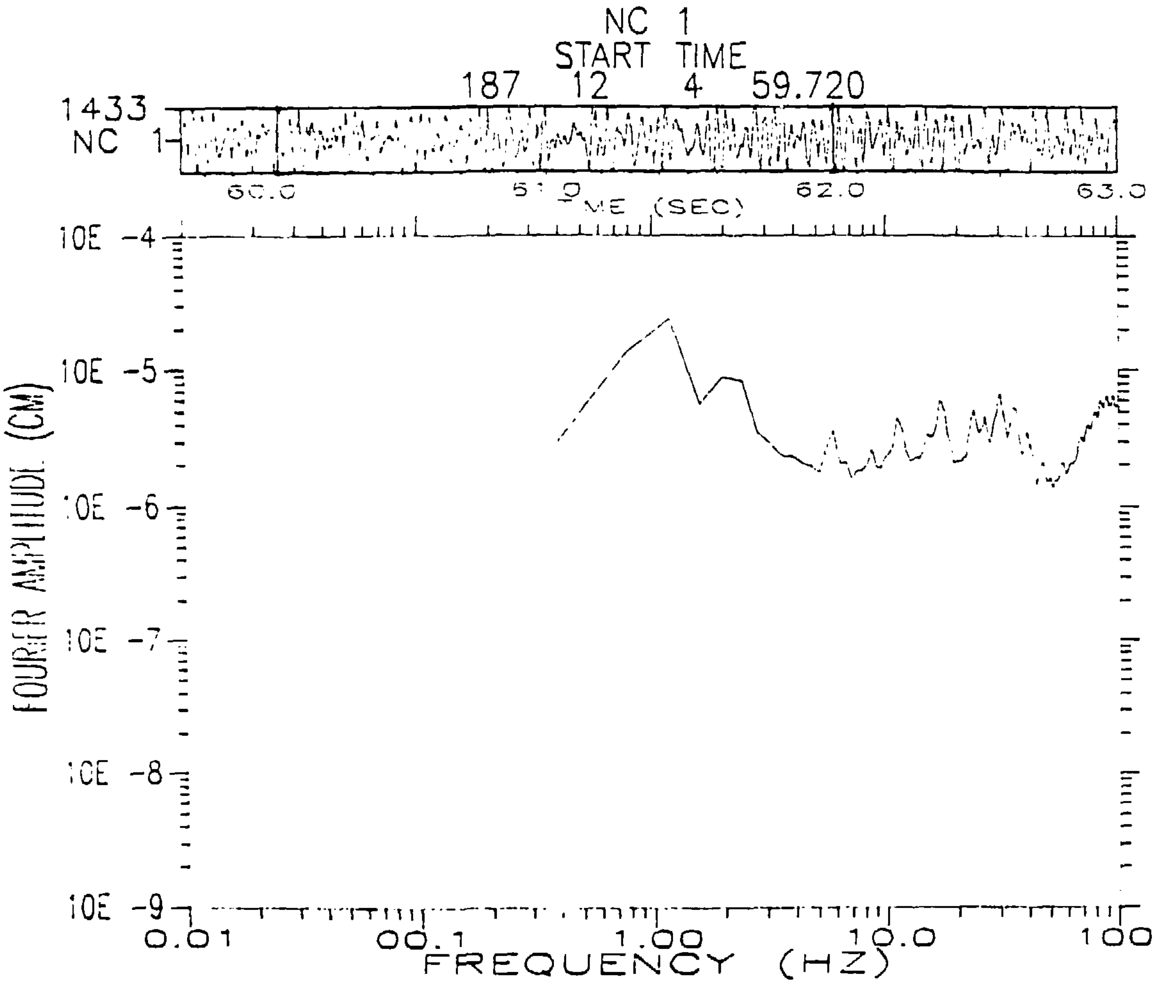


Figure 23. Displacement Response versus Frequency Measurements at Station 9 in Building 6. Note: This is one of the noisier stations in Building 6.

Displacement Response vs. Frequency at Station 11
in Building 6 Without the Bevatron Running (July 6, 1983)



XBL 866-11596

Figure 24. Displacement Response versus Frequency Measurements at Station 11 in Building 6. Note: There is a relatively flat noise spectrum at this location. Note: The peaks below 4 Hz should be ignored.

Displacement Response vs. Frequency at Station 12 in Building 6 Without the Bevatron Running (July 6, 1983)

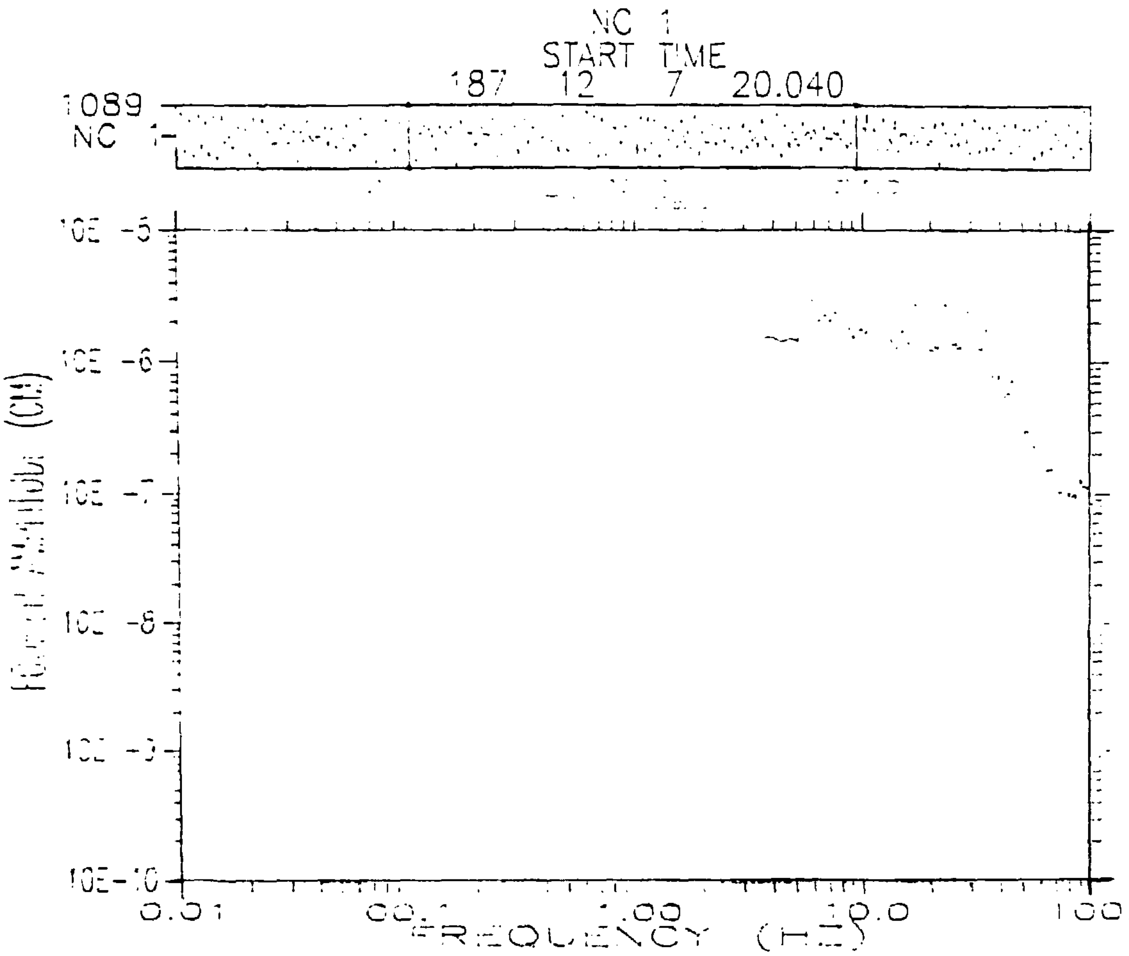


Figure 25. Displacement Response Measurements at Station 12 in Building 6. Note: The 11, 17, 22 and 30 Hz peaks.

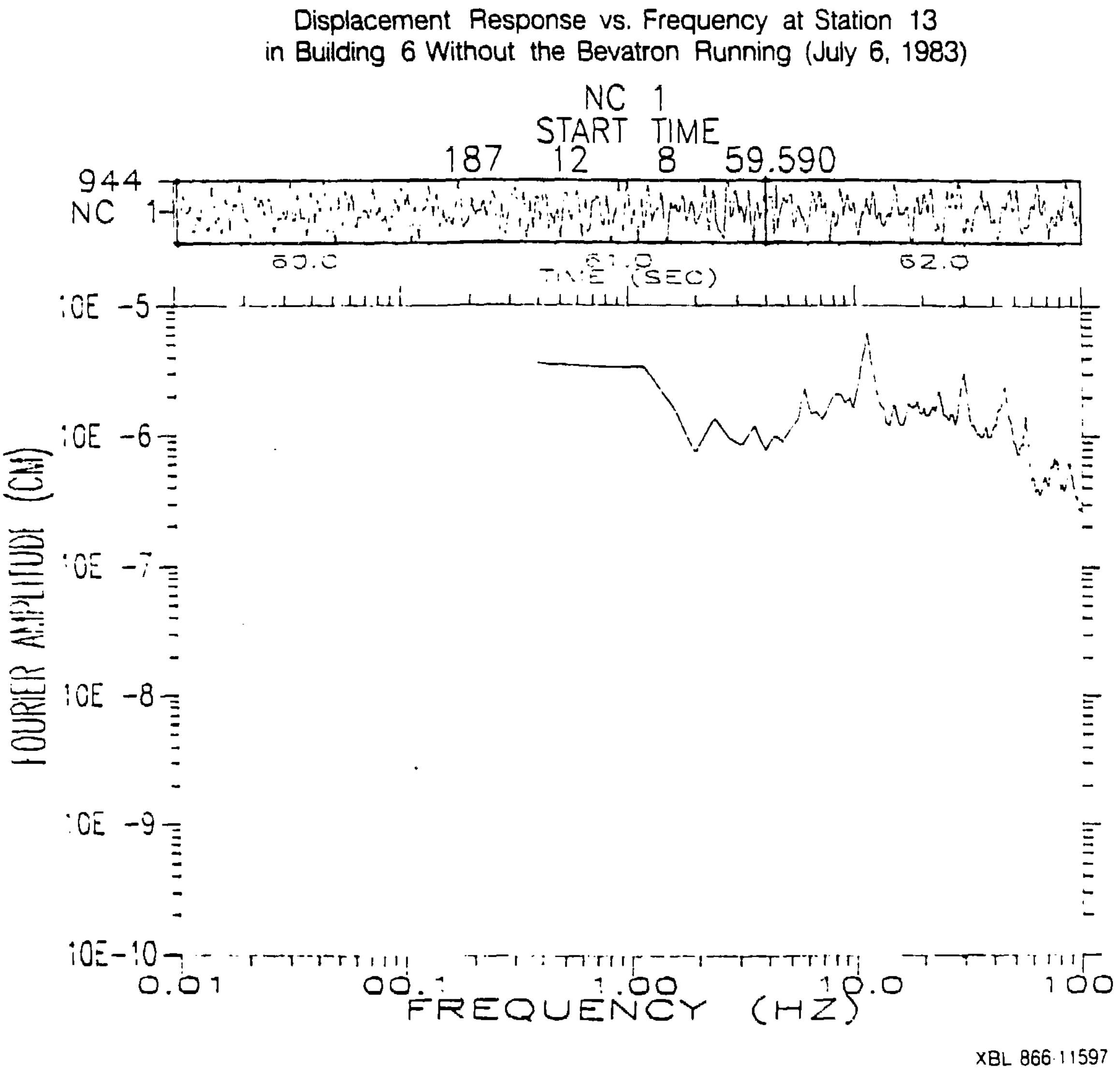


Figure 26. Displacement Response versus Frequency Measurement at Station 13 in Building 6. Note: There is a very strong 11 Hz peak from the kinney pumps in the Building 6 pump room.

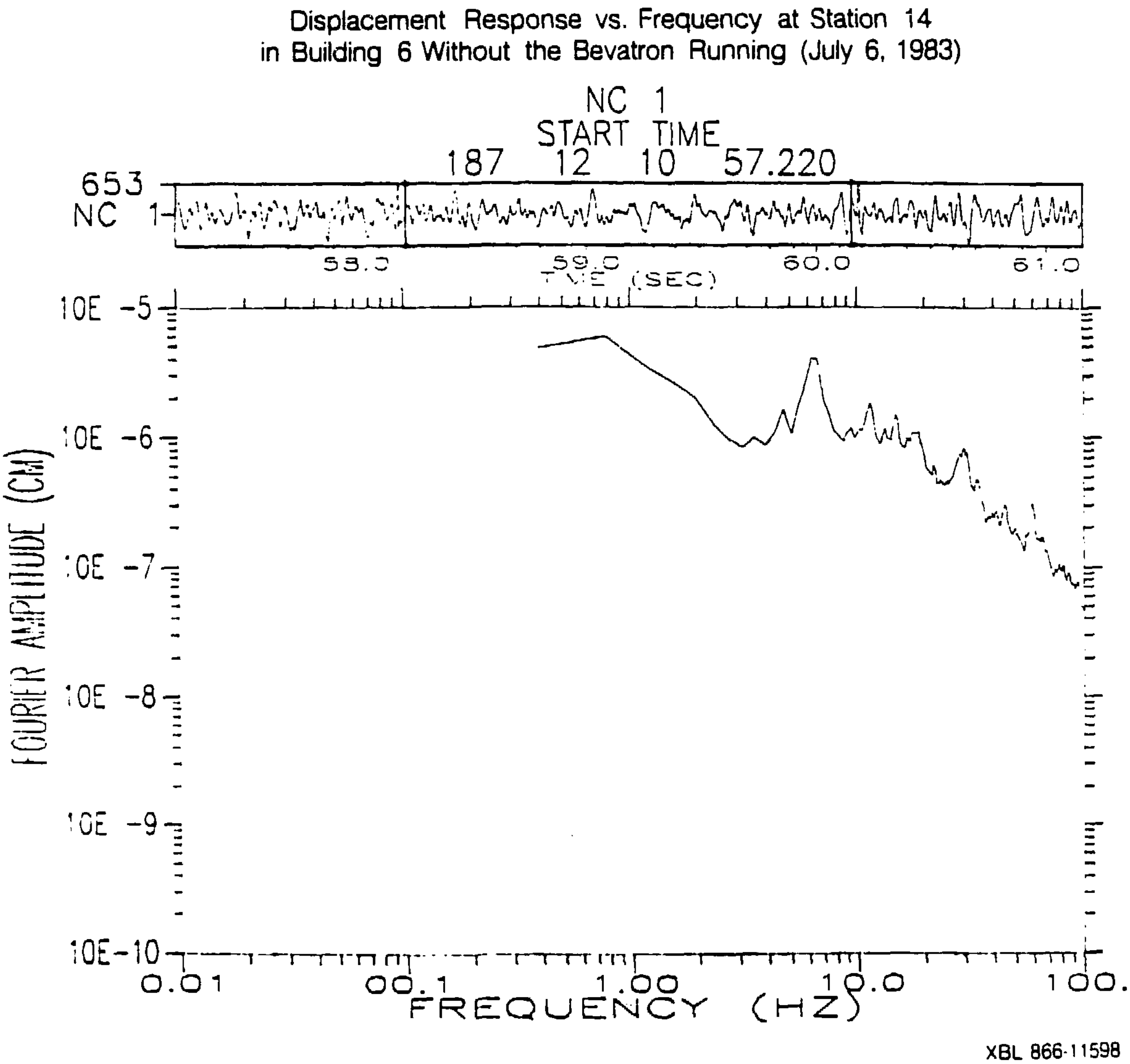


Figure 27. Displacement Response versus Frequency Measured at Station 14 in Building 6. Note: This is one of the quiet locations in Building 6.

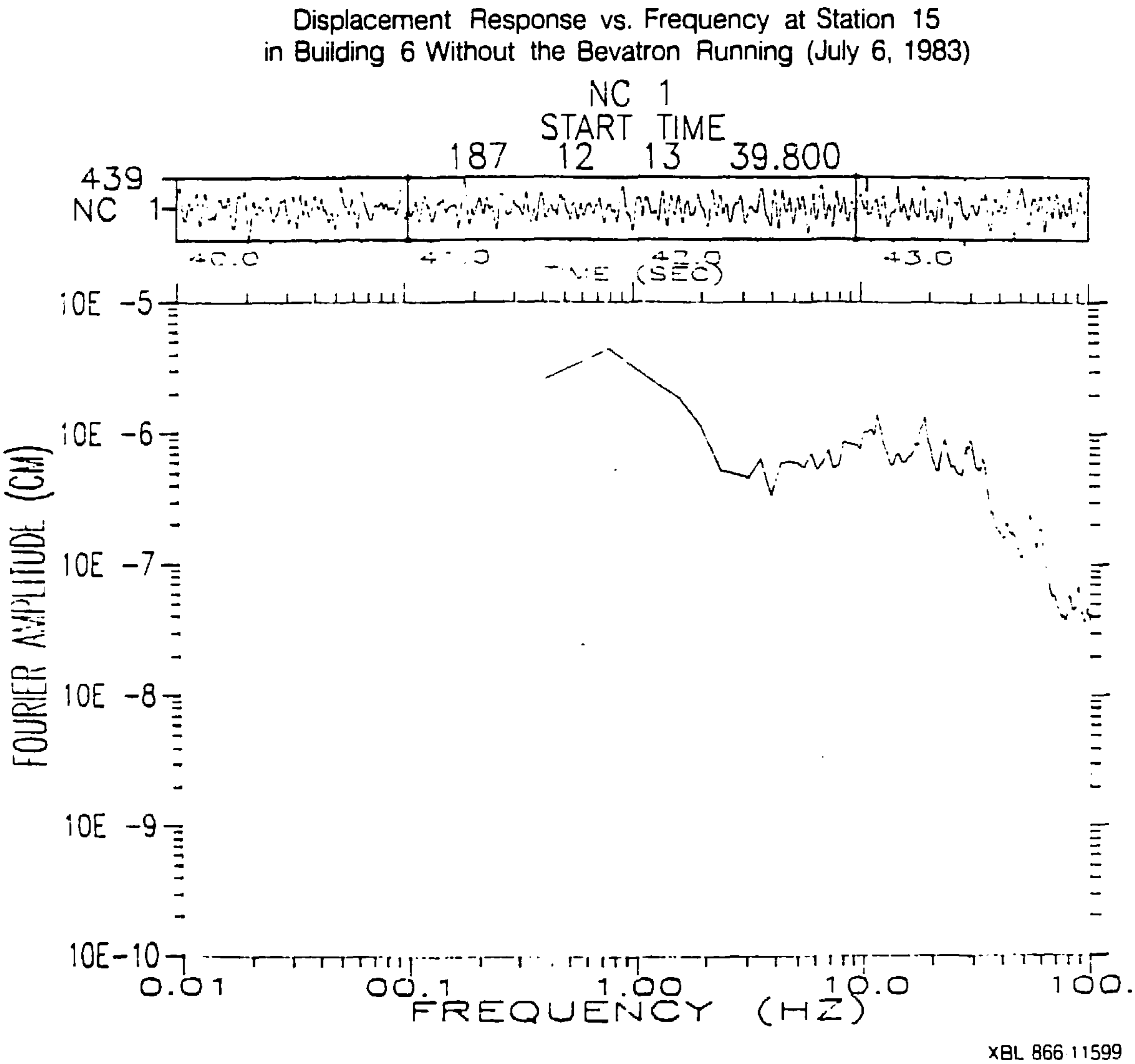


Figure 28. Displacement Response versus Frequency Measurements at Station 15 in Building 6. Note: This station is quieter than Station 14, and it has the characteristic one over frequency response typical of places in the building where motion from local sources is absent.

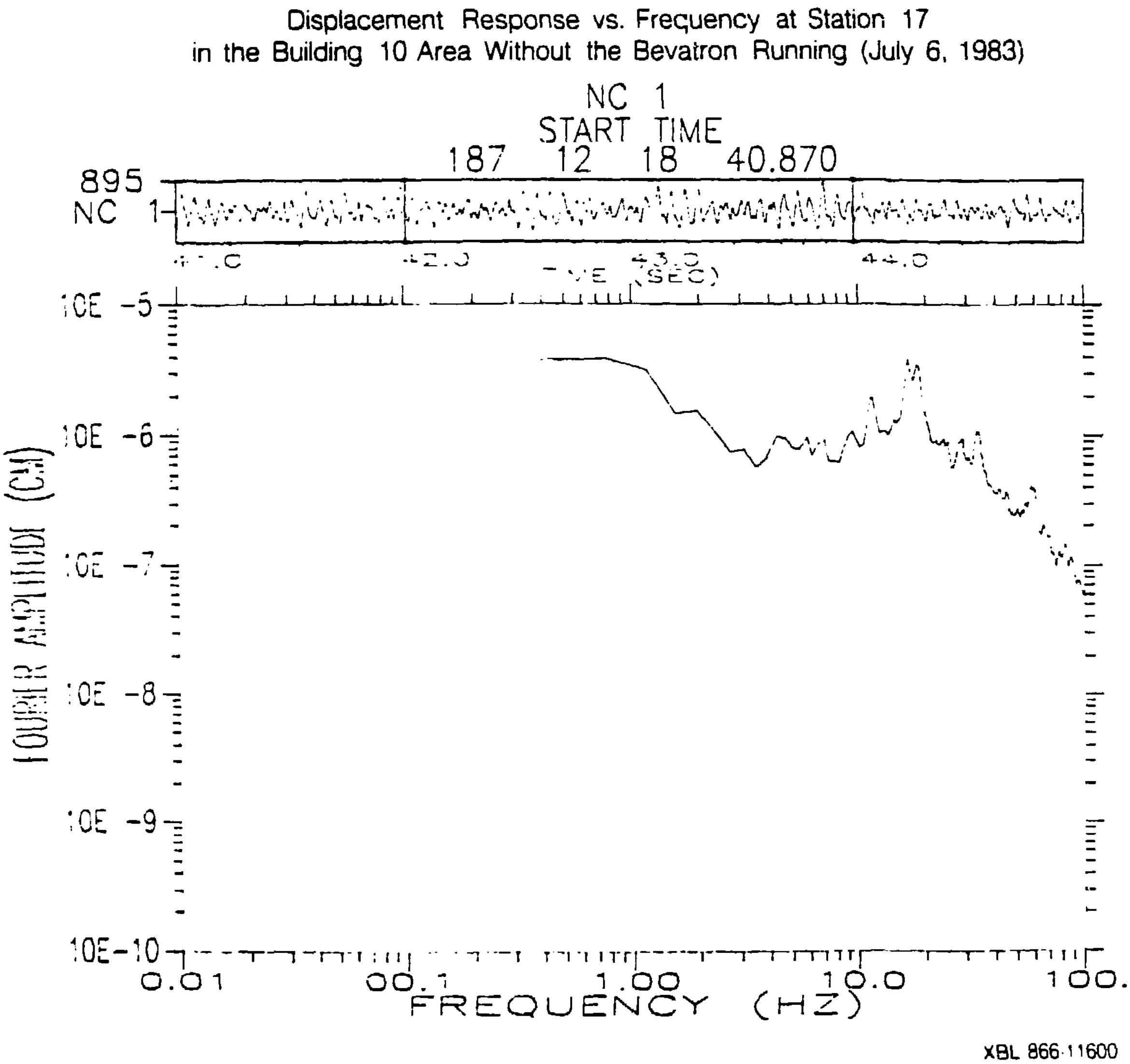


Figure 29. Displacement Response versus Frequency Measurements at Station 17 in the Building 10 Area. Note: This site is quieter than most of the Building 6 sites.

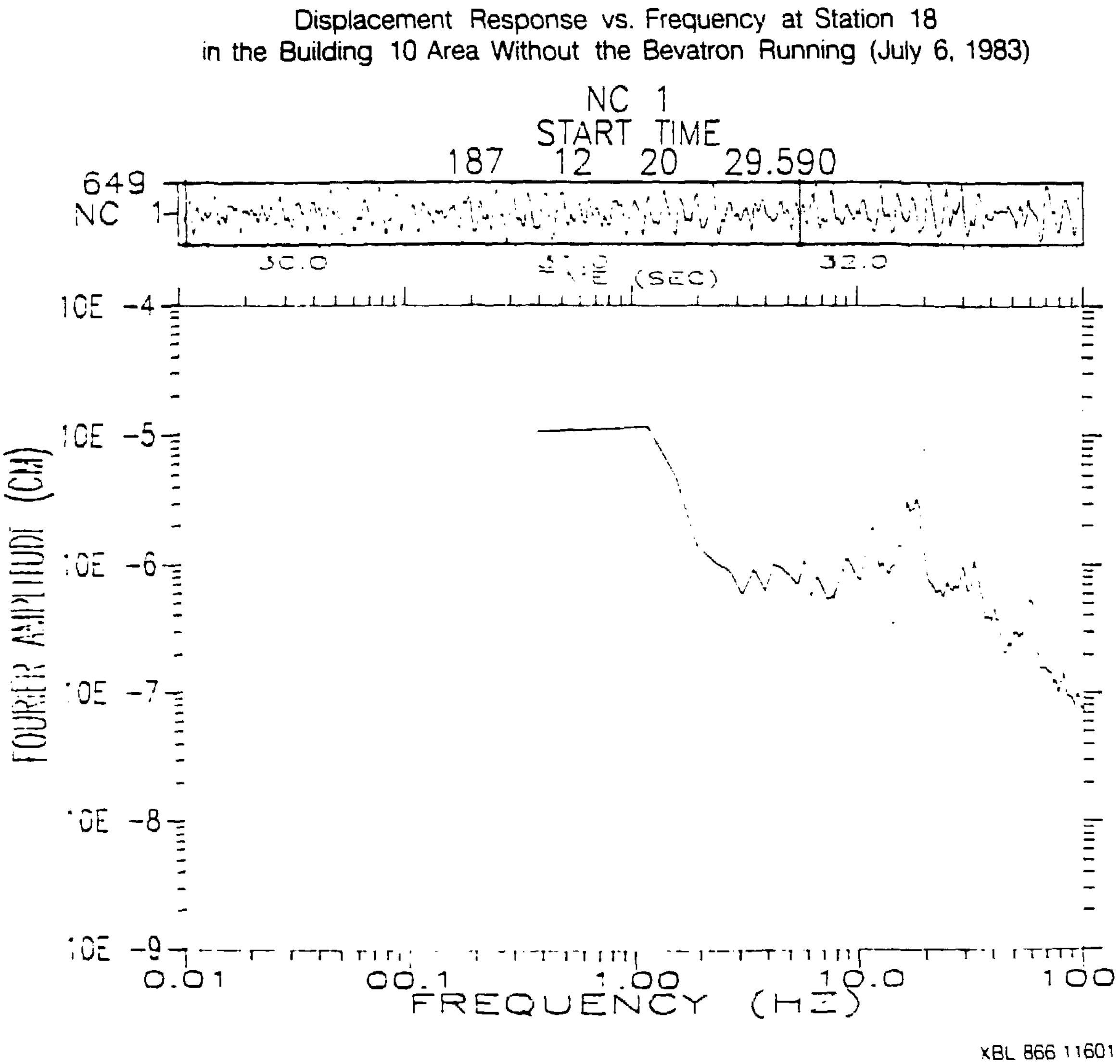
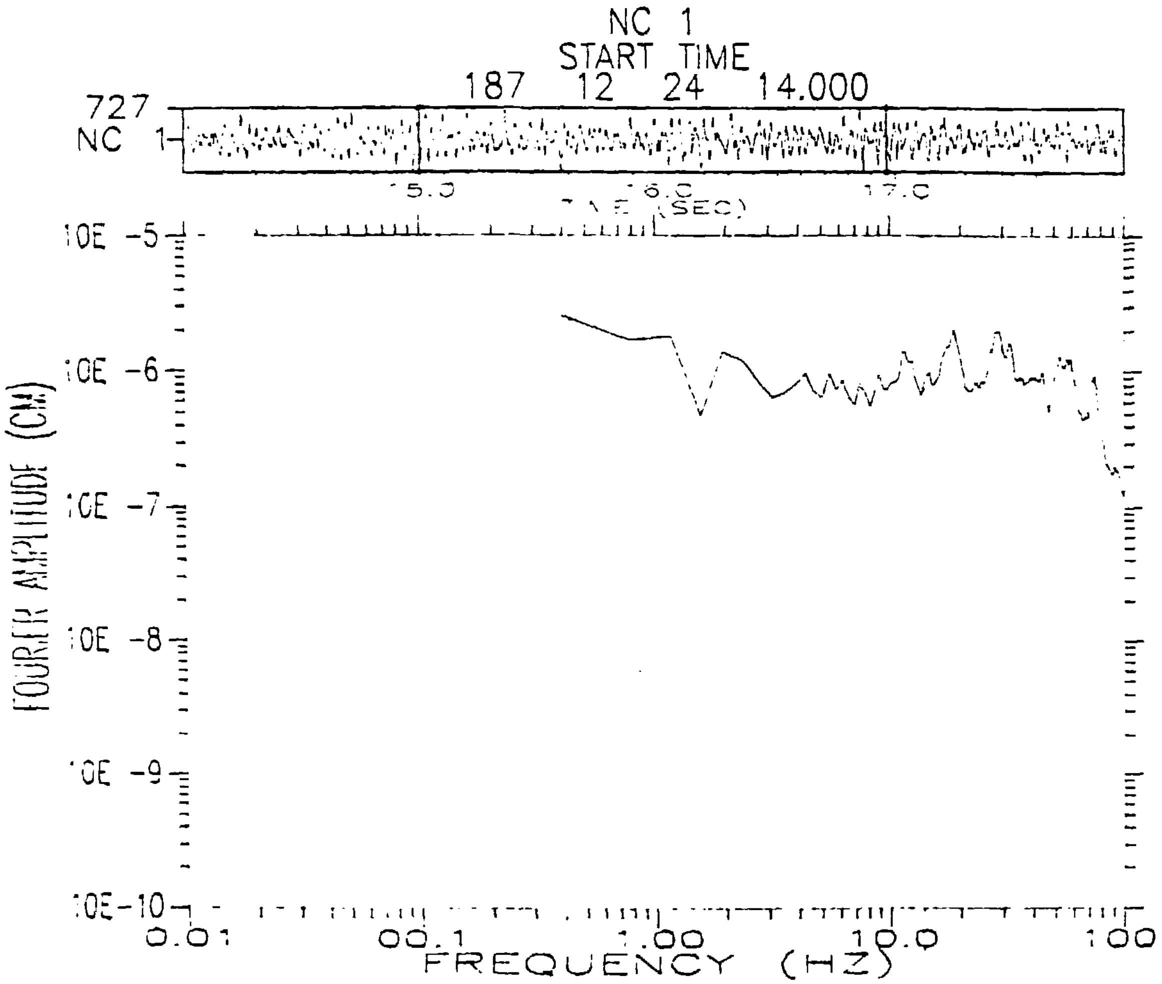


Figure 30. Displacement Response versus Frequency Measurements at Station 18 in the Building 10 Area. Note: This station is relatively quiet. There are some local sources of noise as evidenced by the high-frequency peak. The low-frequency peak below 4 Hz should be ignored.

Displacement Response vs. Frequency at Station 19
in the Building 10 Area Without the Bevatron Running (July 6, 1983)



XBL 866 11602

Figure 31. Displacement Response versus Frequency Measurement at Station 19 in the Building 10 Area. Note: This station is relatively quiet, but there are a lot of high frequency peaks suggesting there are a number of local sources of noise. (The exact location of Station 19 in Building 10 was lost, hence it is not shown in Figure 2. A log book entry shows Station 19 to be in the Building 10 area.)

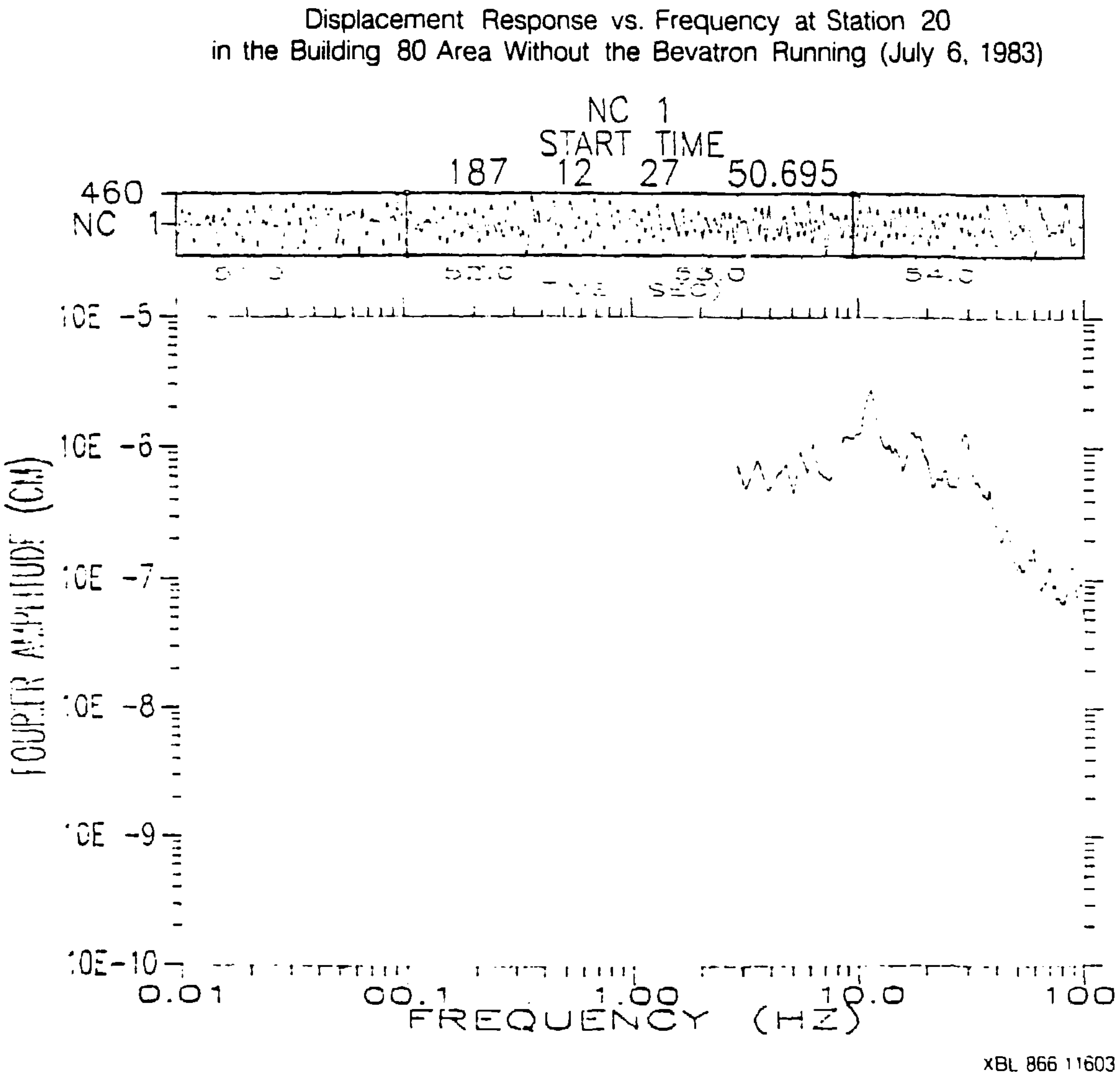
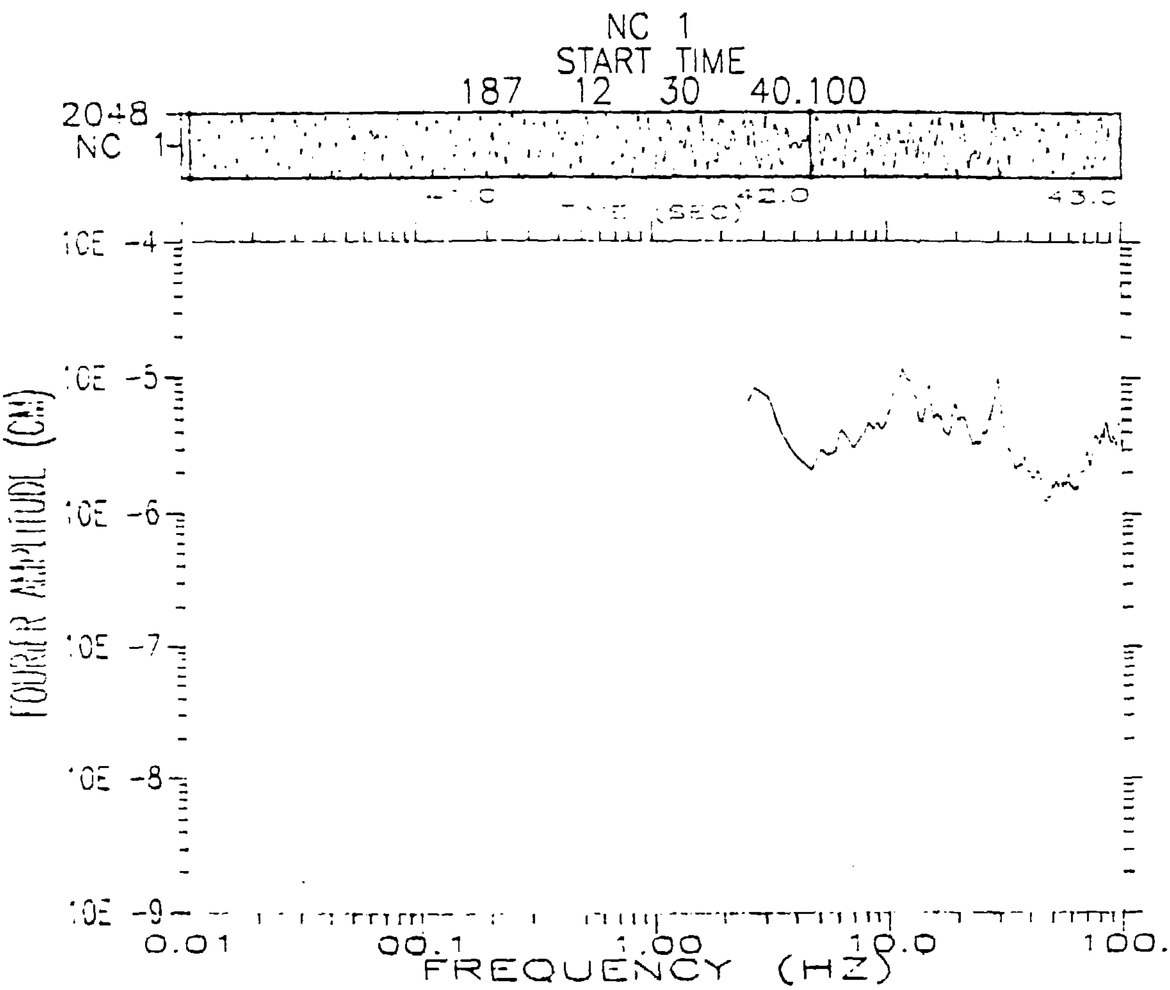


Figure 32. Displacement Response versus Frequency Measurements at Station 20 in the Building 80 Area. Note: The 11, 17 and 30 Hz peaks. The fall off at higher frequencies suggests that local sources of noise are some distance away.

Displacement Response vs. Frequency at Station 23
in the Building 80 Area Without the Bevatron Running (July 6, 1983)



XBL 866 11604

Figure 33. Displacement Response versus Frequency at Station 23 in Building 80. Note: There seems to be considerable local noise. (The exact location of Station 23 was lost, hence its location is not shown in the figure. Log book entries show Station 23 to be in Building 80.)

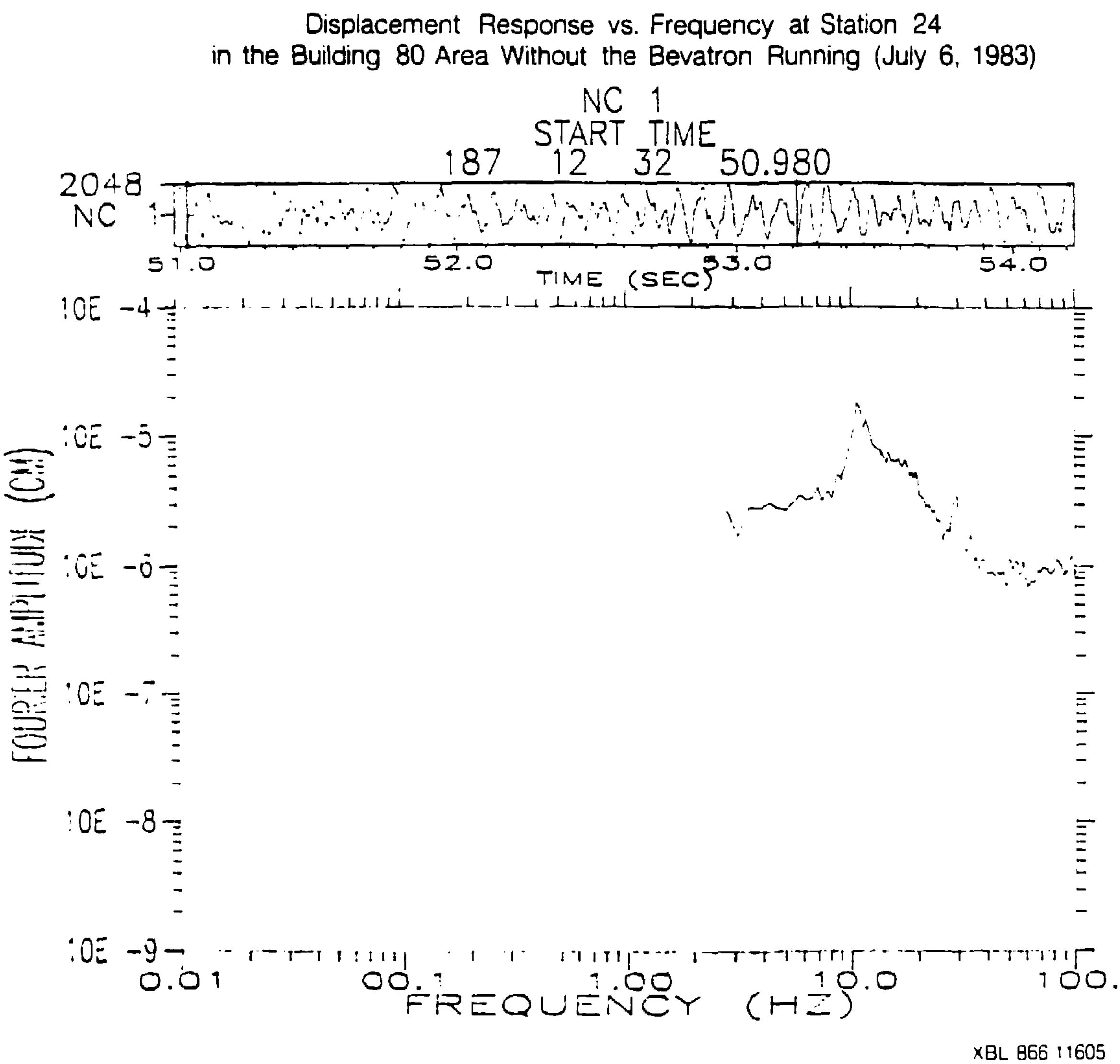


Figure 34. Displacement Response versus Frequency at Station 24 in the Building 80 Area. Note: There is a sharp 11 Hz from the 184-Inch Cyclotron vacuum pumps. Local sources in Building 80 are some distance away.

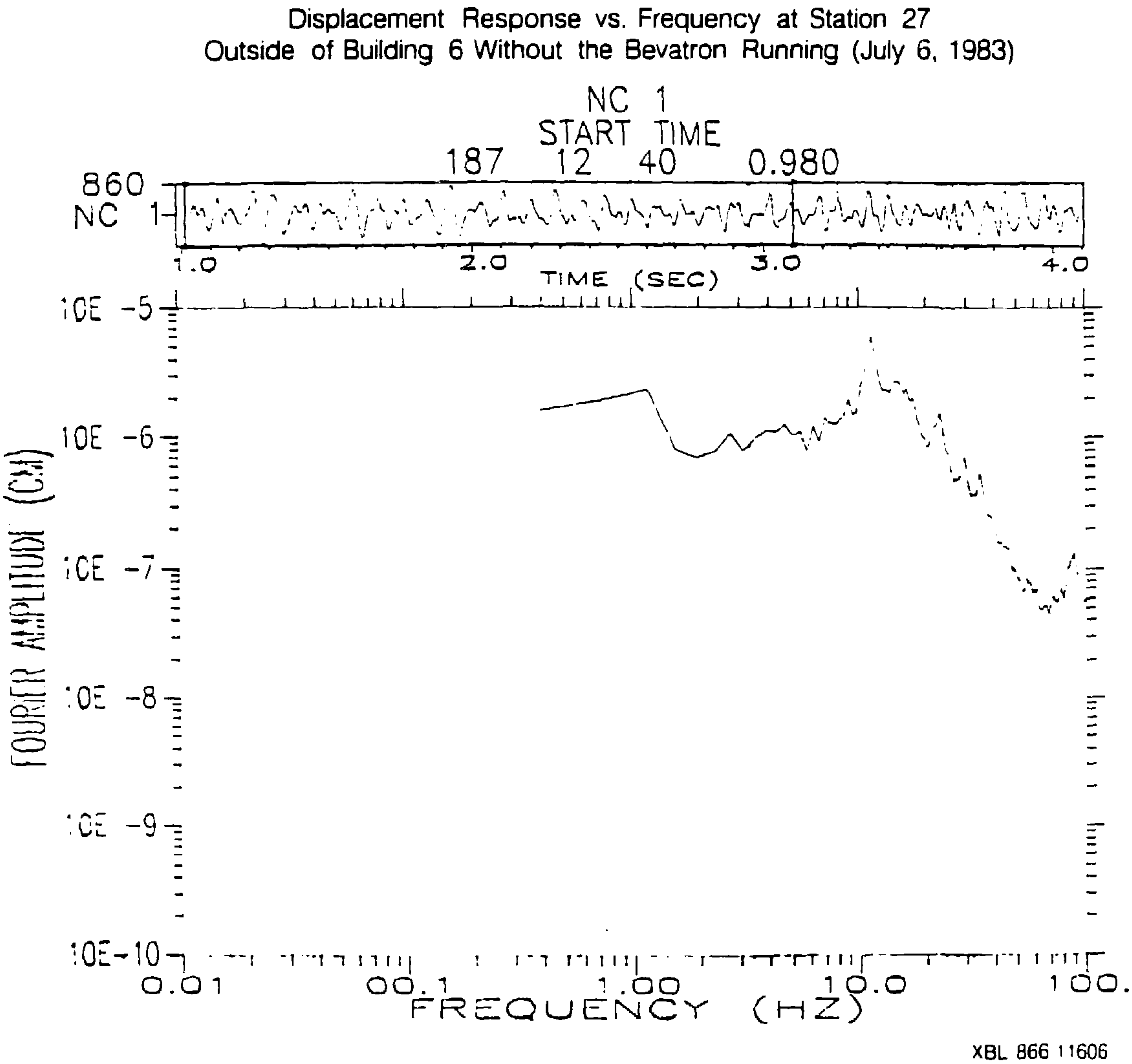
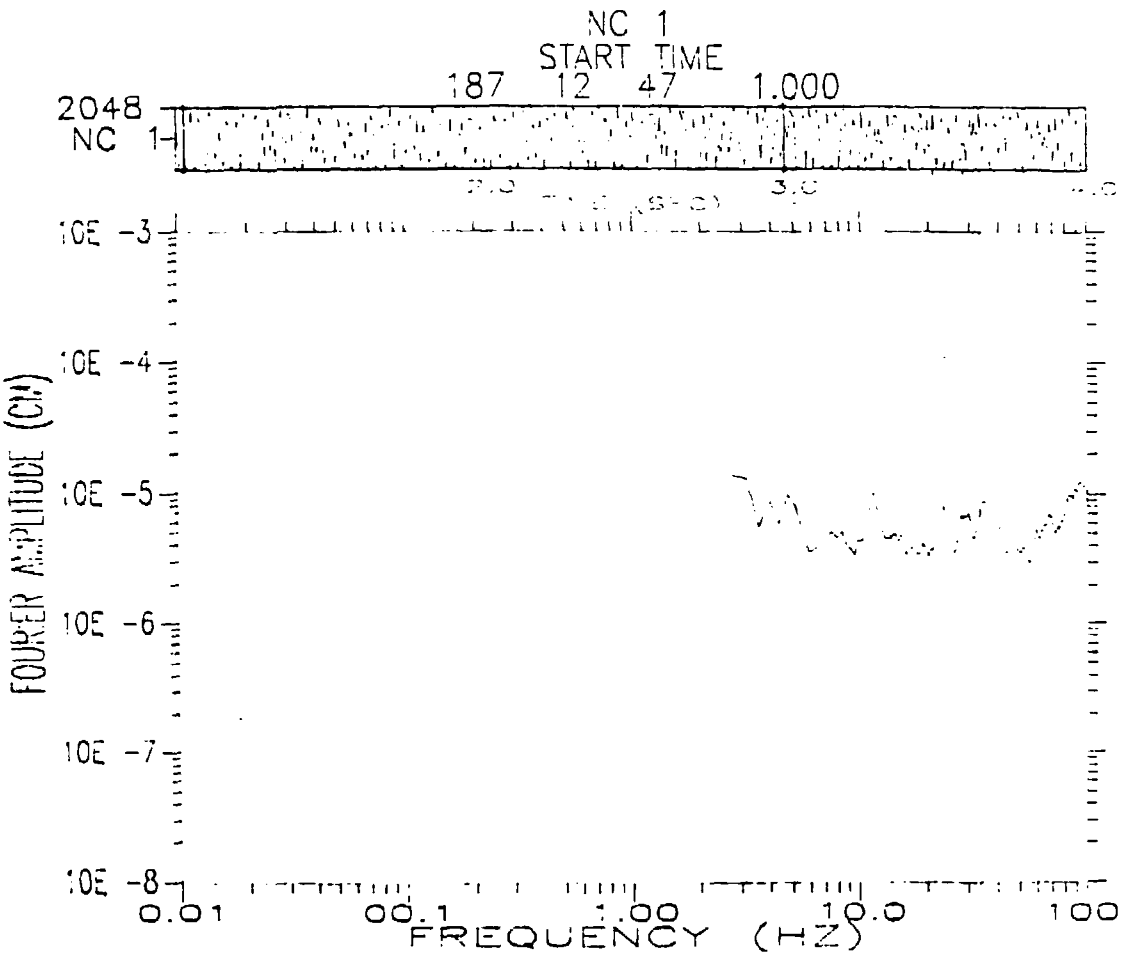


Figure 35. Displacement Response versus Frequency at Station 27 Outside of Building 6. Note: The 11 Hz peak is quite evident even though Station 27 is some distance from the 184-Inch Cyclotron kinney pumps.

Displacement Response vs. Frequency at Station 30 Outside the Building 6 Pump Room, Without the Bevatron Running (July 6, 1983)



XBL 864 11075

Figure 36. Displacement Response Measurements at Station 30 Outside of the Building 6 Pump Room. Note: There are strong 5.5 and 11 Hz peaks and lots of high frequency noise due to various motors and pumps nearby.

Displacement Respnse vs. Frequency at Station 25 in the Building 80 Basement Without the Bevatron Running (July 6, 1983)

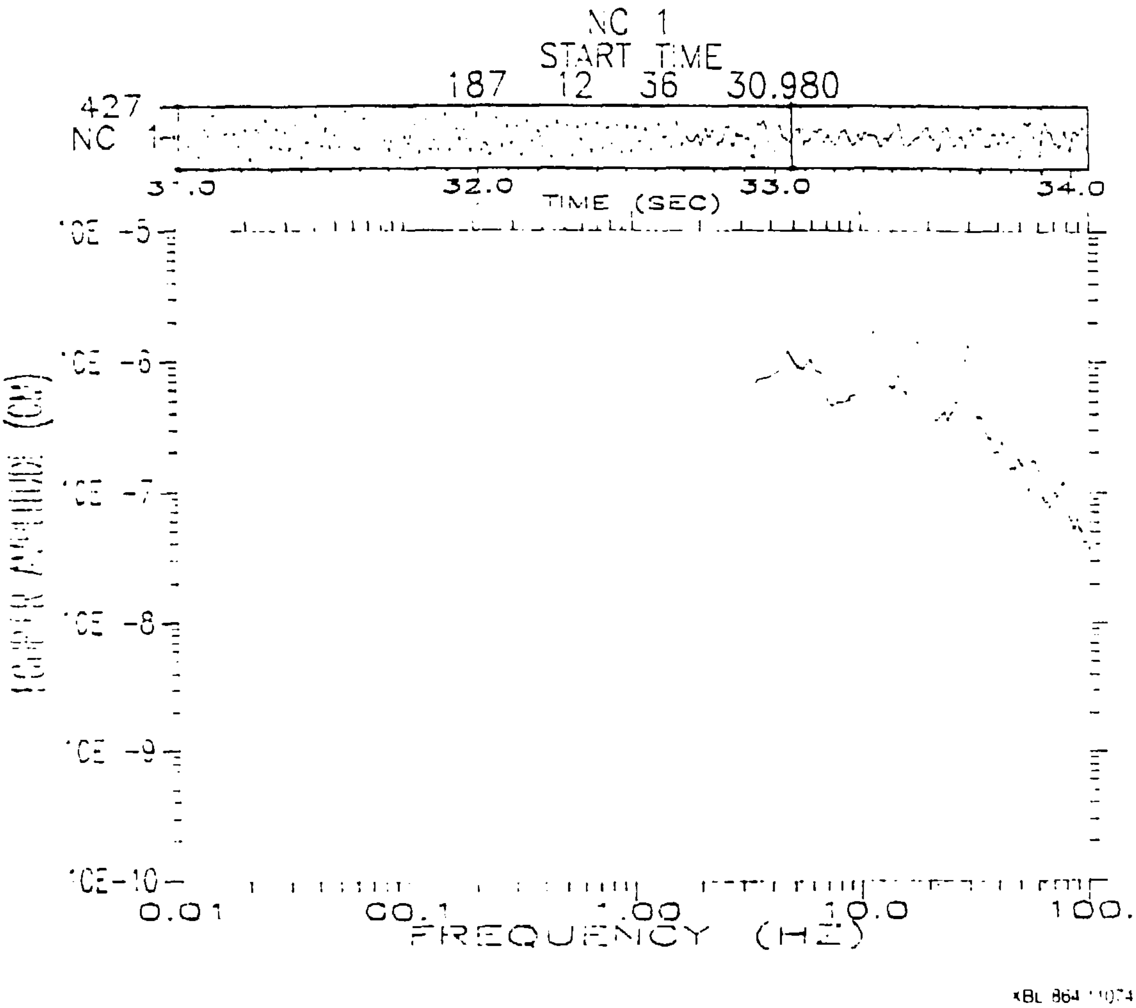


Figure 37. Displacement Response Measurements at Station 25 in the Basement of Building 80. Note: There is no magnification of ground motion by Building 80 in the basement. The peaks at 11, 17 and 30 Hz are evident. There is a fall off of the higher frequency motion because one is some distance from the source.

and 25 shows the effect of peak displacement response magnification by the structure of building 80. The displacement response peaks are 3 to 20 times higher at Station 23 and 24 as compared to Station 25 which is located on firm ground in the basement.

The measurements around Building 6 suggest that much of the noise generated in the building comes from the building. High frequency noise sources appear to be highly localized. Noise sources at 11 and 17 Hz appear to travel much farther than the higher frequency ground motions. Building 80 has distinct noise sources of its own, but these tend to be of relatively high frequency.

c) Bevatron Measurements and Its Effect on Building 6

The Bevatron produces its own noise signature which is dominated by the main motor generator set which produces peaks at 15, 30 and 60 Hz (see Figure 38). The motor generator set has a nominal speed of rotation of 900 RPM. The 15 Hz M.G. set noise is reduced a factor of three as one moves into Blackberry Canyon (the 30 and 60 Hz peaks disappear entirely - see Figure 39). This suggests that the attenuation length for LBL soils at 15 Hz is of the order of 100 m or a little less.[8] The attenuation length for 30 and 60 Hz waves is much shorter. This is consistent with what was seen in Building 6. The attenuation theory shown in the Appendix suggests that the attenuation length for a 30 Hz wave should be 45 - 50 m, and the attenuation length for a 60 Hz wave should be less than 25 m.

The theory for attenuation of seismic waves suggests that Bevatron noise should not be seen in the Building 6 area. A comparison of measurements at Station 1 in Building 6 with and without the Bevatron running is seen by comparing Figure 17 (July 6, 1983 measurements without the Bevatron on),

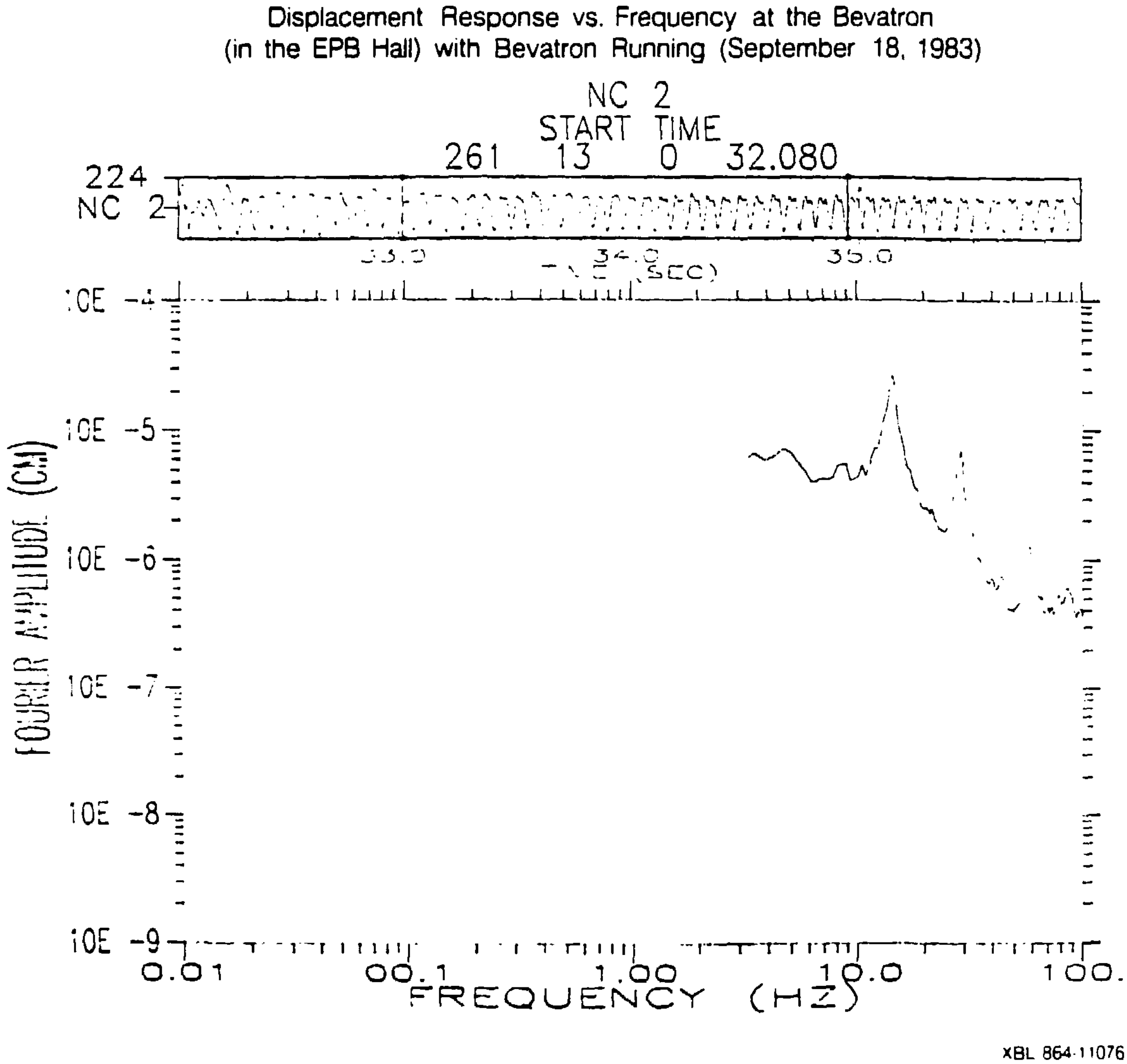
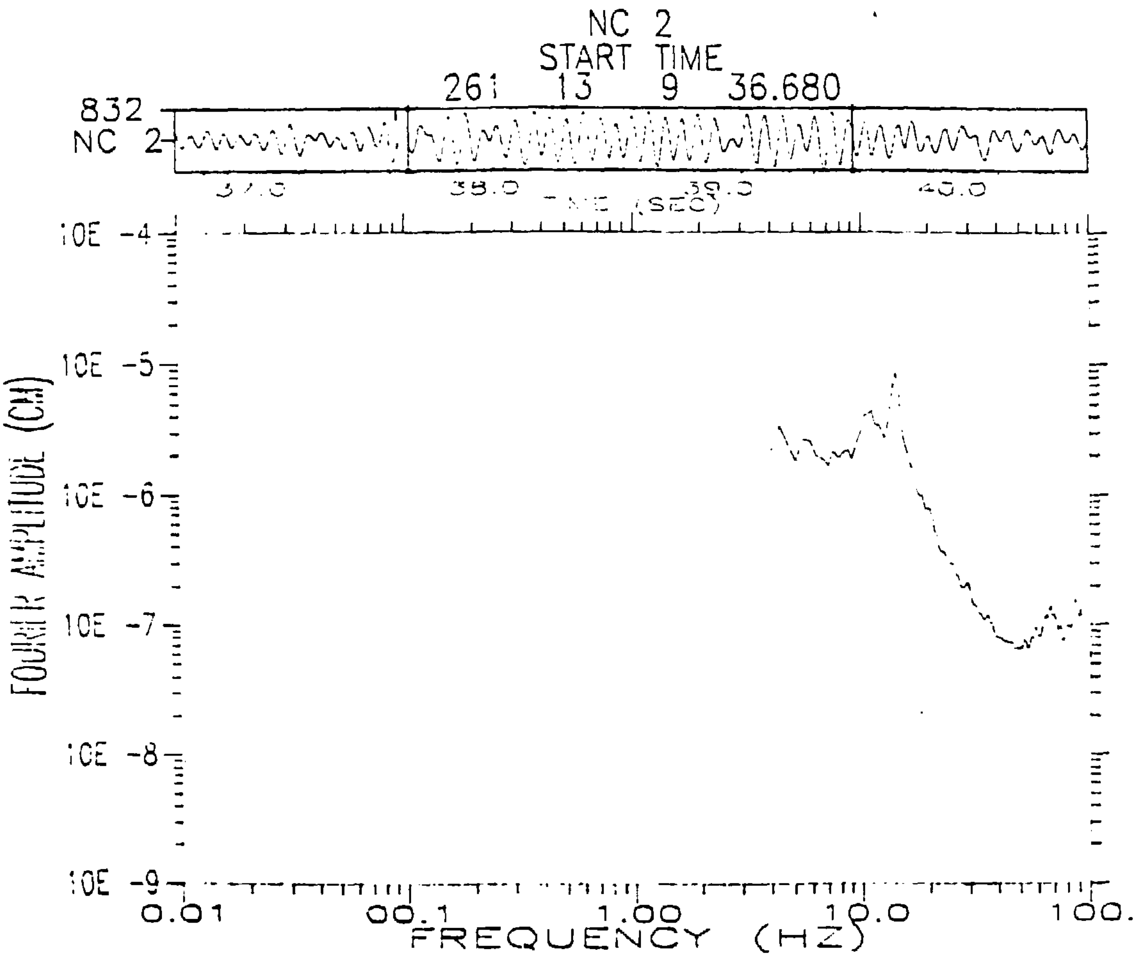


Figure 38. Displacement Response Measurements on Channel NC-2 (horizontal motion) in the Bevatron High Bay. Note: Bevatron ground motion is dominated by the motor generator set. See the 15, 30 and 60 Hz peaks. Compare this displacement response signal with Figure 10 which is for Channel NC-1 (vertical motion).

Displacement Response vs. Frequency in Blackberry Canyon with the Bevatron Running (September 18, 1983)



XBL 864 11077

Figure 39. Displacement Response Measurements in Blackberry Canyon. Note: The 15 Hz motor generator peak is evident. The 30 and 60 Hz peaks have decayed away. The high frequency noise may come from nearby transformer banks.

Figure 40 (September 18, 1983 with the Bevatron running) and Figure 41 (September 20, 1983 without the Bevatron running). When one compares Figure 17 with Figure 40, and Figure 41 with Figure 40, one might conclude that the Bevatron reduces noise in Building 6. This conclusion is not correct, because the Figure 40 measurements were made on a Sunday when a lot of equipment was turned off, but the Figure 17 and Figure 41 measurements were made on a weekday when everything was turned on. In any event, there is no evidence that the Bevatron has an appreciable affect on Building 6 ground motion. It is interesting to note that Figure 17 and Figure 41 are quite comparable, which suggests that the instrument calibration did not change in the 2 1/2 months between the measurements.

d) Specific Ground Motion Sources around Building 6

The effects of two specific sources of noise in and around Building 6 were tested on September 20, 1983. The reference measurements were made at Station 1 (see Figure 41). The first test was to measure the ground motion due to the LBL fire truck running across a plank bridge outside of Building 6. (This bridge was built to cover an excavation for pipe work outside the building.) The movement of the truck across the bridge increased the amplitude of the ground motion by an order of magnitude for a short period of time (see Figure 42). One can see that the amplitude is particularly high at 12 Hz when the truck is on the plank bridge (see the amplitude versus time curve above the main graph in Figure 42), but it is not so high when the truck just runs on the pavement. (Note: There is some clipping of the amplitude signals as the truck runs across the bridge.) This suggests that truck traffic on smooth pavement may be acceptable.

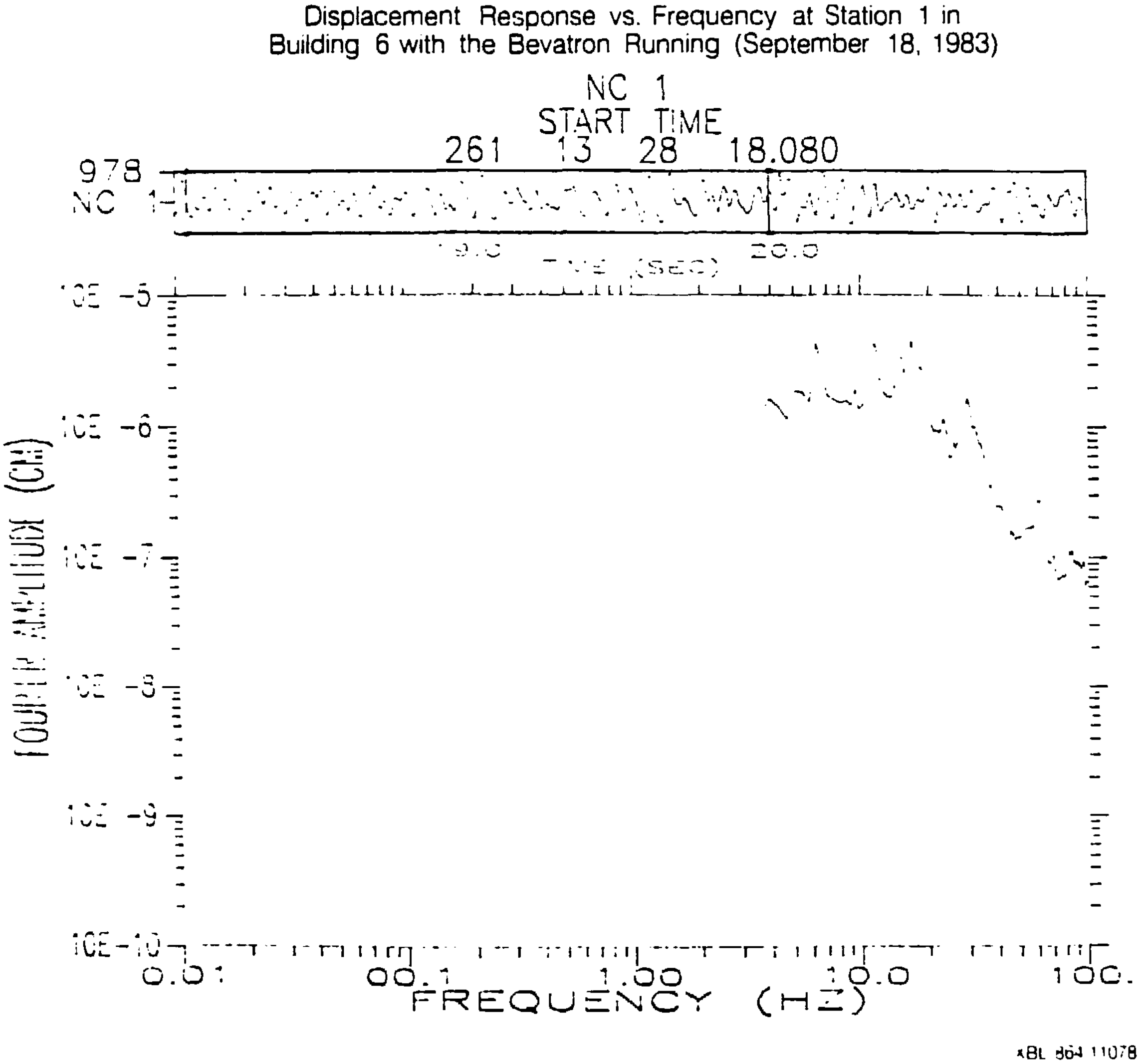


Figure 40. Displacement Response Measurements at Station 1 in Building 6 with the Bevatron Running. Note: The signal has a smaller amplitude than Figure 17. This measurement was made on a Sunday when some of the equipment in Building 6 was shut off. There are no measurable signals from the Bevatron. (This signal should be compared to Figure 13 which is a separate computer run of the same data. There is no difference in the data.)

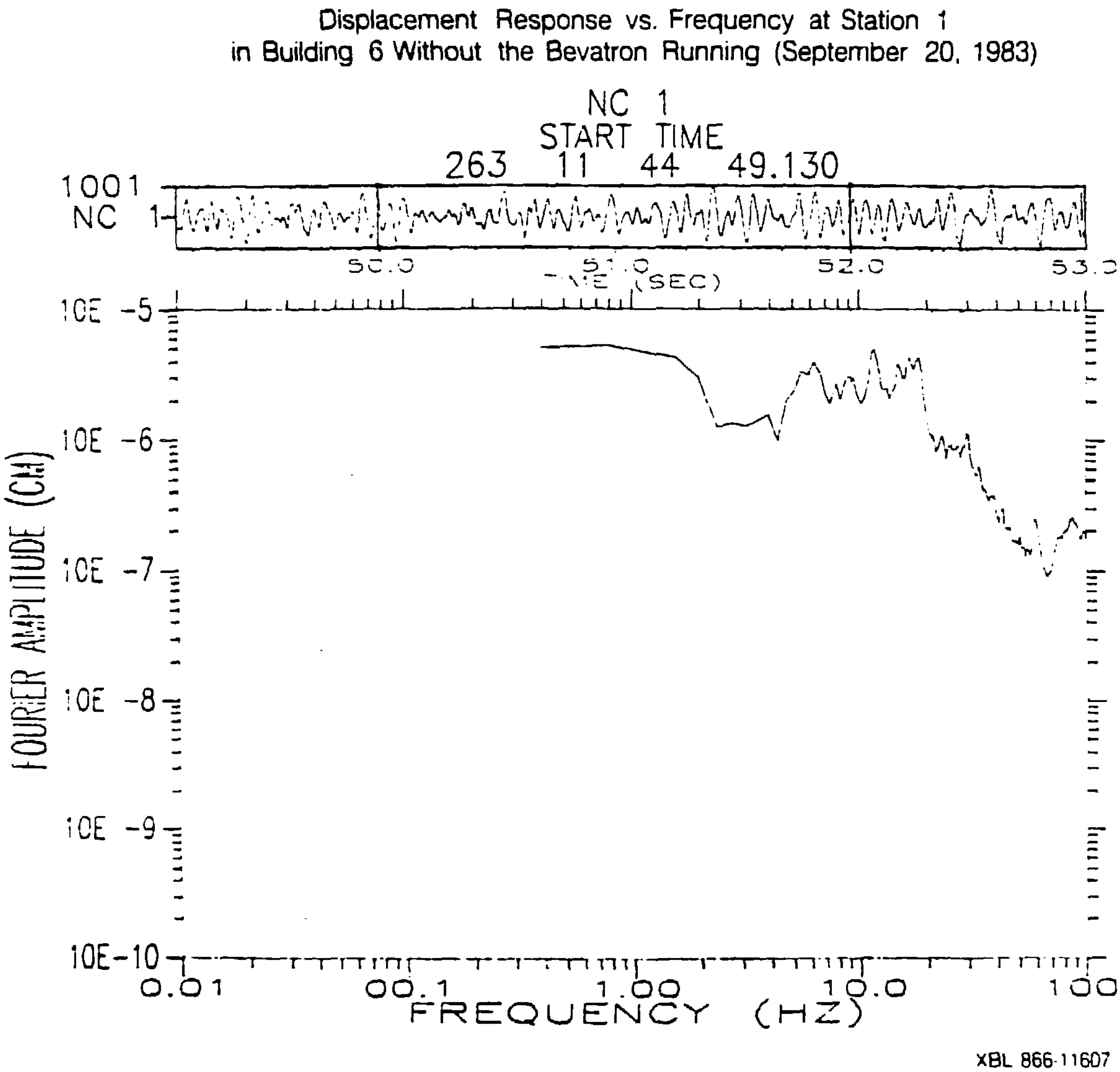


Figure 41. Displacement Response versus Frequency at Station 1 within Building 6. Note: This data was taken two days after the data presented in Figure 40. The Bevatron was not running, so this figure should be compared with Figure 17. The data in both figures was taken on busy days with nearly everything running in Building 6.

Displacement Response vs. Frequency at Station 1 in Building 6 with the Fire Truck Running across the Plank Bridge (September 20, 1983)

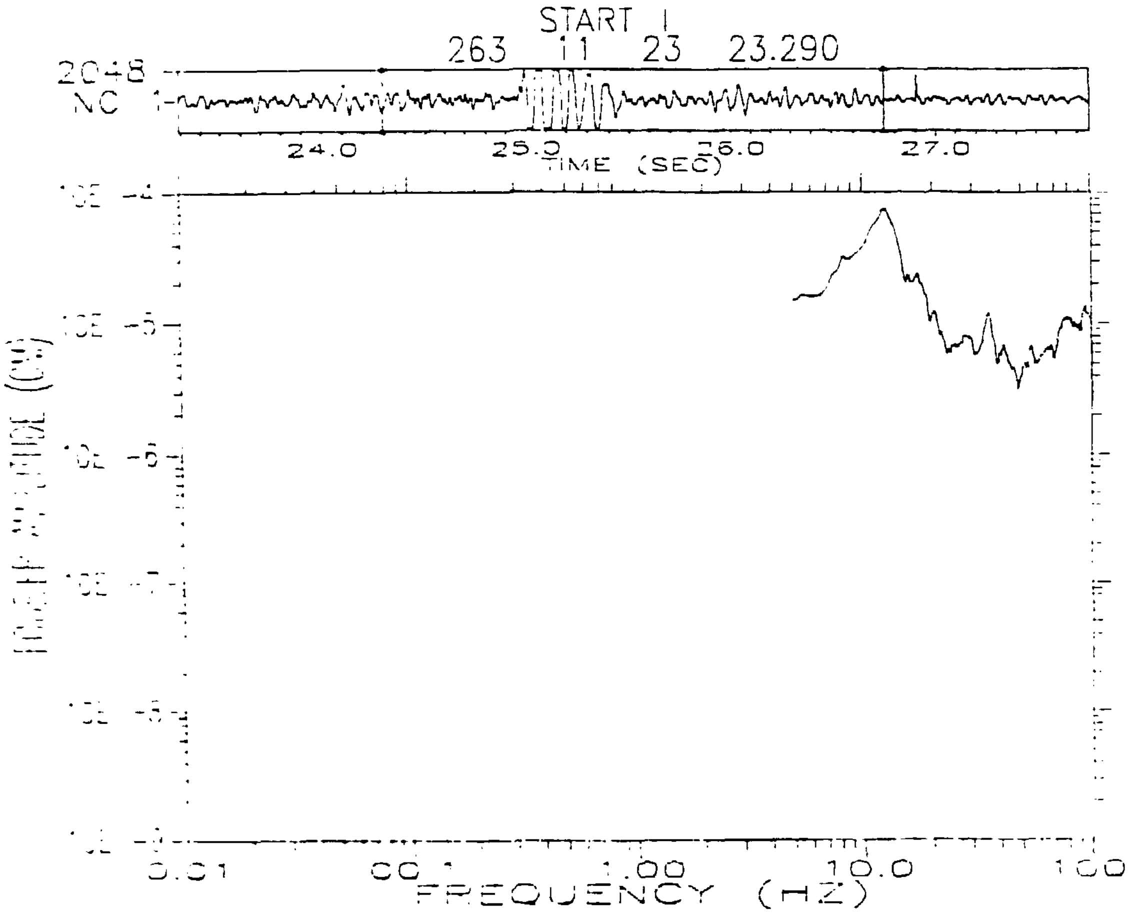


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Figure 42. Displacement Response Measurements at Station 1 in Building 6 when the LBL Fire Truck Runs Across a Plank Construction Bridge About 15 Meters from Station 1. Note: The highest peak occurs when the truck is on the plank bridge. Note: The signals are clipped slightly.

The two cranes in Building 6 were run separately and together; ground motion was measured at Station 1 in Building 6 (which is located quite close to one of the main support pillars for the crane). Figure 43 at Station 1 shows the affect of the secondary crane alone. There are pronounced peaks at 7 and 17 Hz of 4 to 6 x 10^{-7} m. The higher frequency noise falls off rapidly. When both cranes are operated simultaneously (see Figure 44) large spikes are generated, the largest of which is 1.7 x 10^{-6} m at 8 to 9 Hz. These are of an amplitude which might cause modestly noticeable effects to the Light Source electron beam. When both cranes are operated, there is a large amount of noise even at frequencies above 40 Hz. It appears that the cranes in Building 6 are a large source of ground motion over a wide range of frequencies from 5 to 40 Hz.

e) Measurements at SLAC

The measurements which were made at SLAC to compare with the Building 6 data were made on Sunday, August 28, 1983. They are shown in peak displacement response form in Figures 45 through 55. The amplitude of the peak displacement response for the SLAC measurements are of the same order as the peak displacement response amplitude calculated for the Building 6 measurements. The SLAC measurements show strong peaks at 4.6 or 6 Hz. (The 4.6 Hz peak is real, even though the accuracy of measurements at that frequency are limited.) The 4.6 Hz peak is believed to be caused by the hydrogen compressors operating at SLAC at that time. The SLAC ground motion is characterized by a strong horizontal component. The peak displacement response for frequencies above 10 Hz is lower at SLAC than that measured at Building 6. The attenuation distance for the 4.6 Hz compressor noise is expected to be of the order of 300 m.

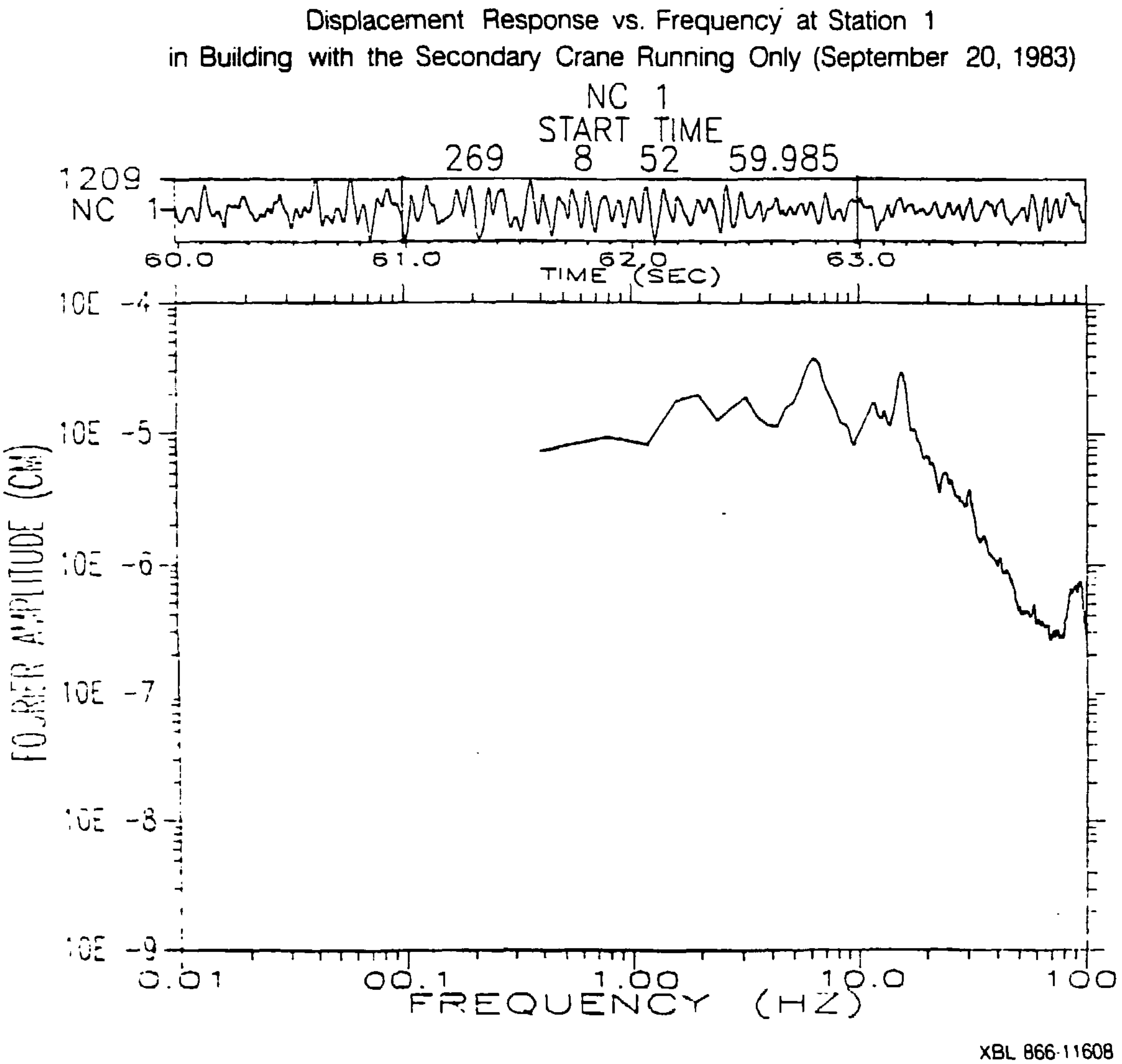
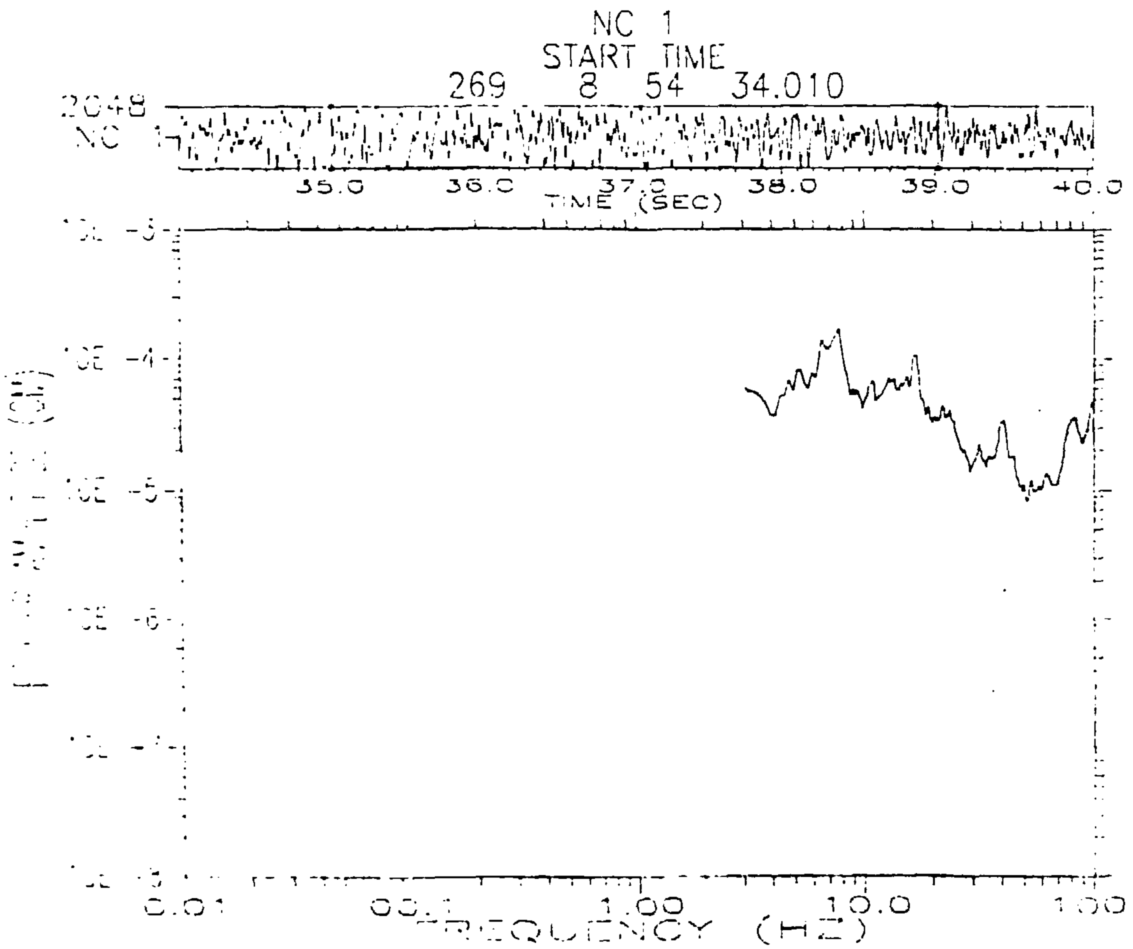


Figure 43. Displacement Response versus Frequency at Station 1 in Building 6 when the Secondary Crane is Running Only. Note: A peak at 17 Hz is visible, but this peak displacement is larger than a peak due to the stokes pumps. This figure should be compared to Figure 44.

Displacement Response vs. Frequency at Station 1 in Building 6
with both Building 6 Cranes Running (September 20, 1983)



XBL 864 11080

Figure 44. Displacement Response Measurements at Station 1 in Building 6 with Both Cranes Running. Note: Some peaks were clipped. The crane is a serious ground motion source.

Most of the SLAC measurements were taken around the SPEAR ring. The quietest areas around the SPEAR ring are in the pit at Station 2 (see Figure 45), on the floor around the SPEAR ring at Stations 4, 6 and 9 (see Figures 47, 48 and 51), on top of the survey marker at Station 7 (see Figure 49) and on top of the support pillar which supports the magnet beam at Station 8 (see Figure 50). These areas show peak displacement responses from 4×10^{-8} m to 10^{-7} m at frequencies in the 4 to 6 Hz range. Secondary peaks at 12 Hz occur, but beyond that the peak displacement response falls off with increasing frequency.

Measurements of peak displacement response on the magnet support beam at Stations 3 and 13 (see Figures 46 and 52) show a magnification of almost an order of magnitude at 4.6 Hz. The magnification is less than a factor of two at 20 Hz. The SPEAR magnet support beam appears to be undamped with a resonance at around 5 Hz.

A measurement was taken just outside the SPEAR ring at Station 15 (see Figure 53). The peak displacement response was comparable to measurements at Stations 1, 4, 6, 7, 8 and 9. Peak displacement response measurements on a nearby hillside (about 150 m from the SPEAR ring) show only a moderate reduction of the 4.6 Hz component, but there is a large reduction in the higher frequency components of the ground motion. (See Figure 54 for data from Station 17 on the nearby hill top.) Station 18 (see Figure 55) was located just outside the hydrogen compressor room in the SLAC experimental area. A peak displacement response of 7×10^{-7} m was measured at 4.6 Hz; a 9 to 10 Hz peak is also visible. At frequencies above 10 Hz there is considerable noise at the 10^{-7} m displacement response level. This is typical of ground motion measurements taken close to a source of ground motion.

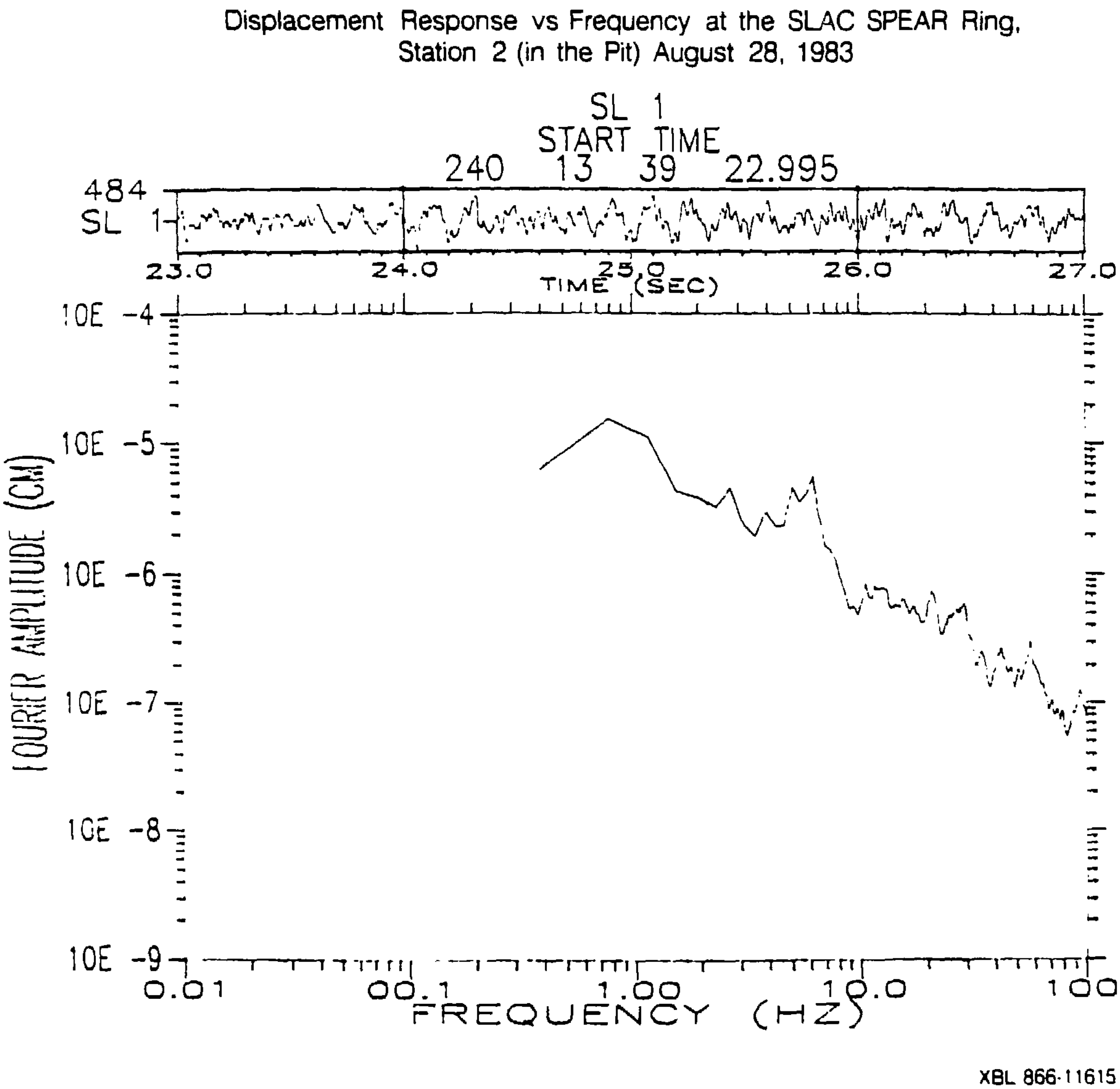
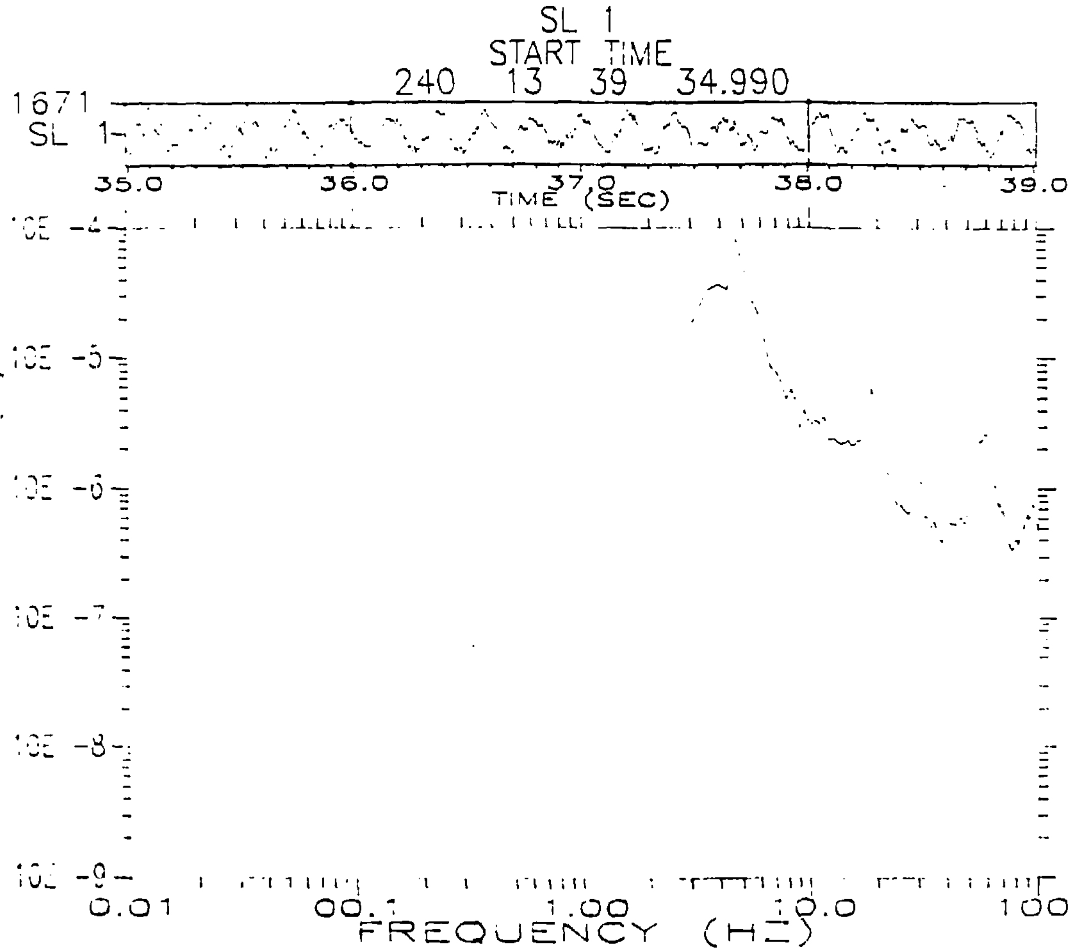


Figure 45. Displacement Response versus Frequency at Station 2 (in the pit) at SLAC. Note: There is a peak near 5 Hz. The peaks at frequencies below 4 Hz should be ignored.

Displacement Response vs. Frequency at the SLAC SPEAR Ring,
Station 3 (on the Magnet Support Beam) August 28, 1983



XBL 864 11082

Figure 46. Displacement Response Measurements at Station 3 on the Magnet Beam at the SLAC-SPEAR Ring. Note: The magnet beam magnifies the ground motion about a factor of 3.

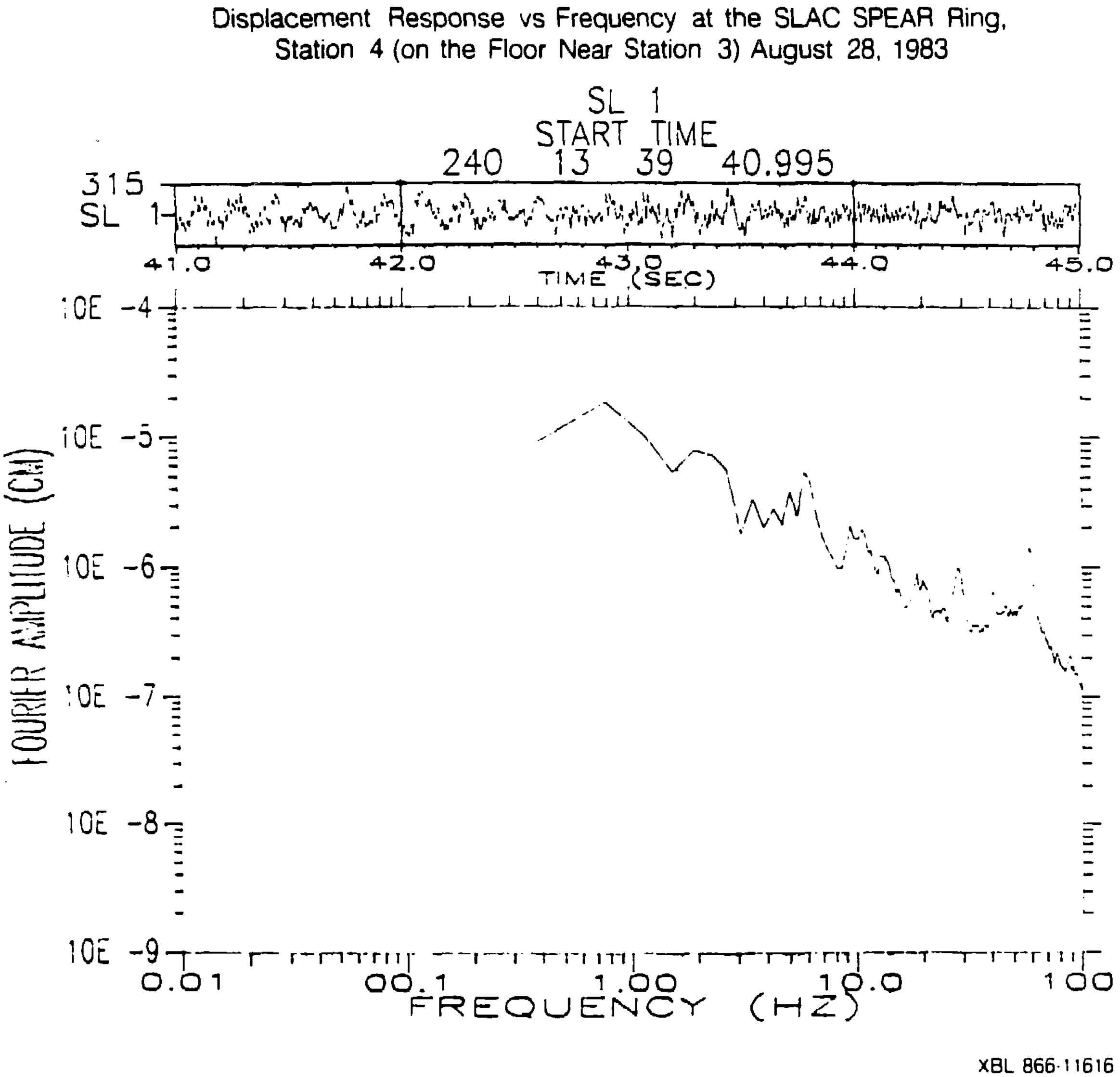


Figure 47. Displacement Response versus Frequency at Station 4 at SLAC. Note: Station 4 is quite close to Station 3. The peaks are a factor of three lower than peaks at the same frequency shown in Figure 46.

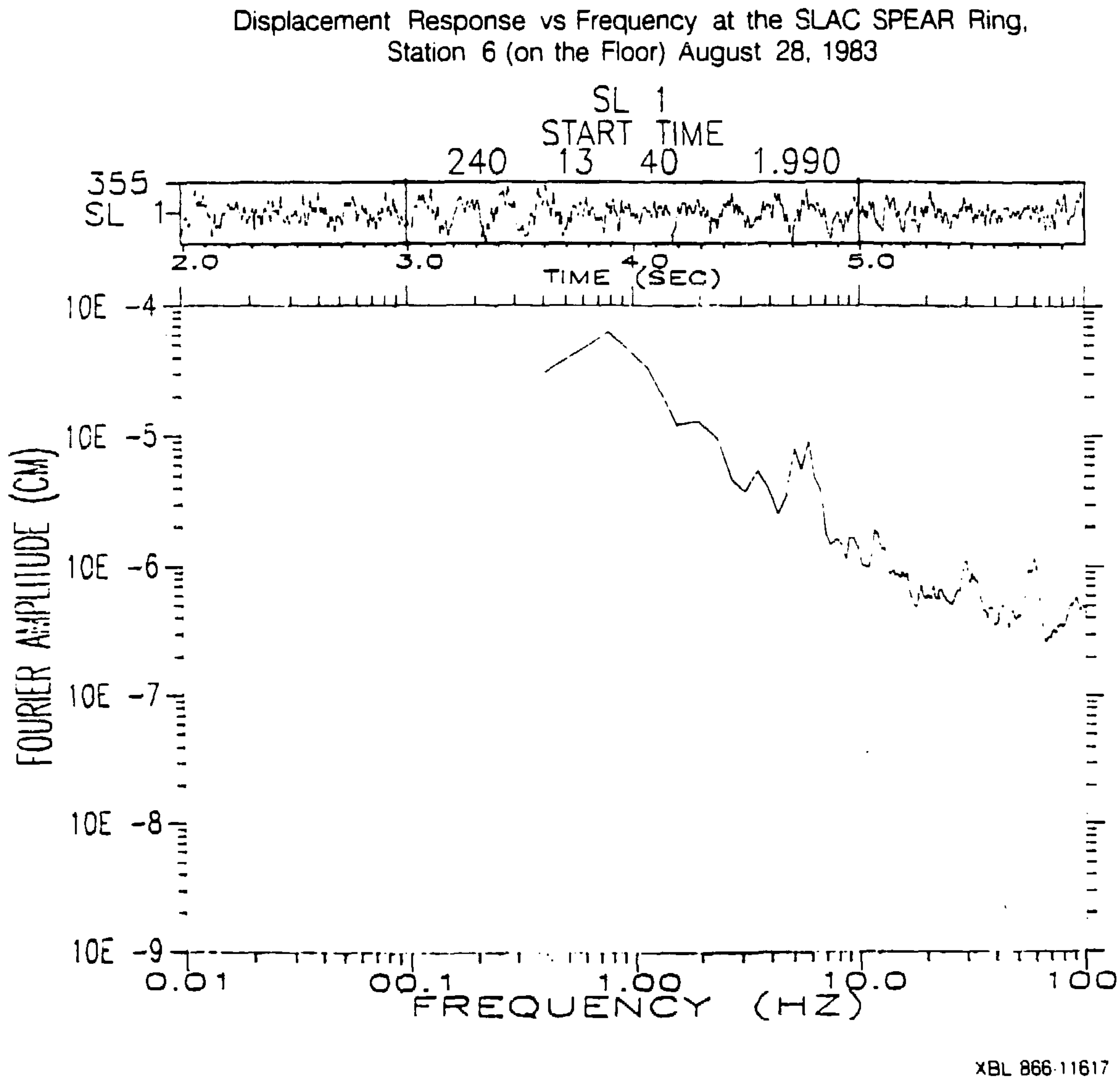


Figure 48. Displacement Response versus Frequency at Station 6 at SLAC. Note: This figure should be compared with Figures 45, 47, 49, 50 and 51.

Displacement Response vs. Frequency at the SLAC SPEAR Ring, Station 7 (on the Survey Monument) August 28, 1983

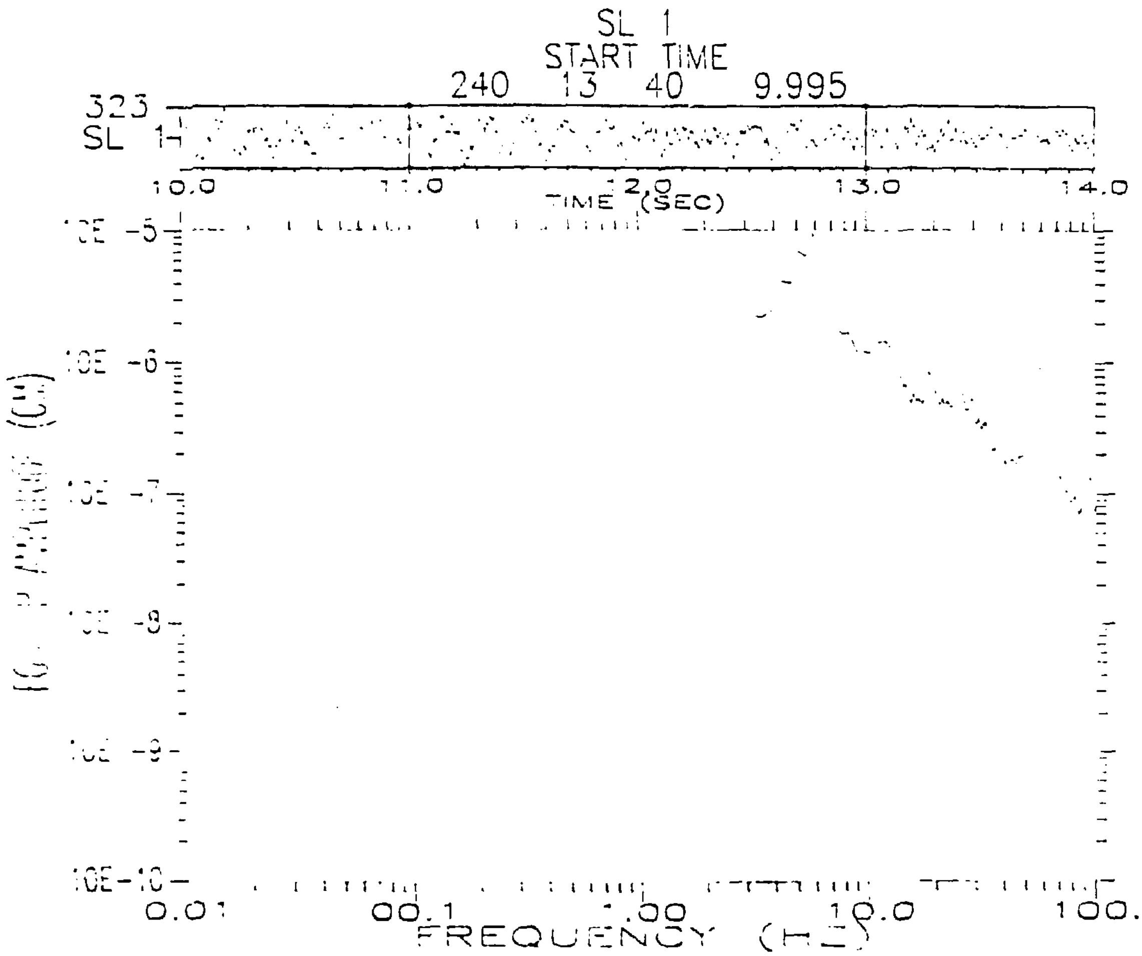
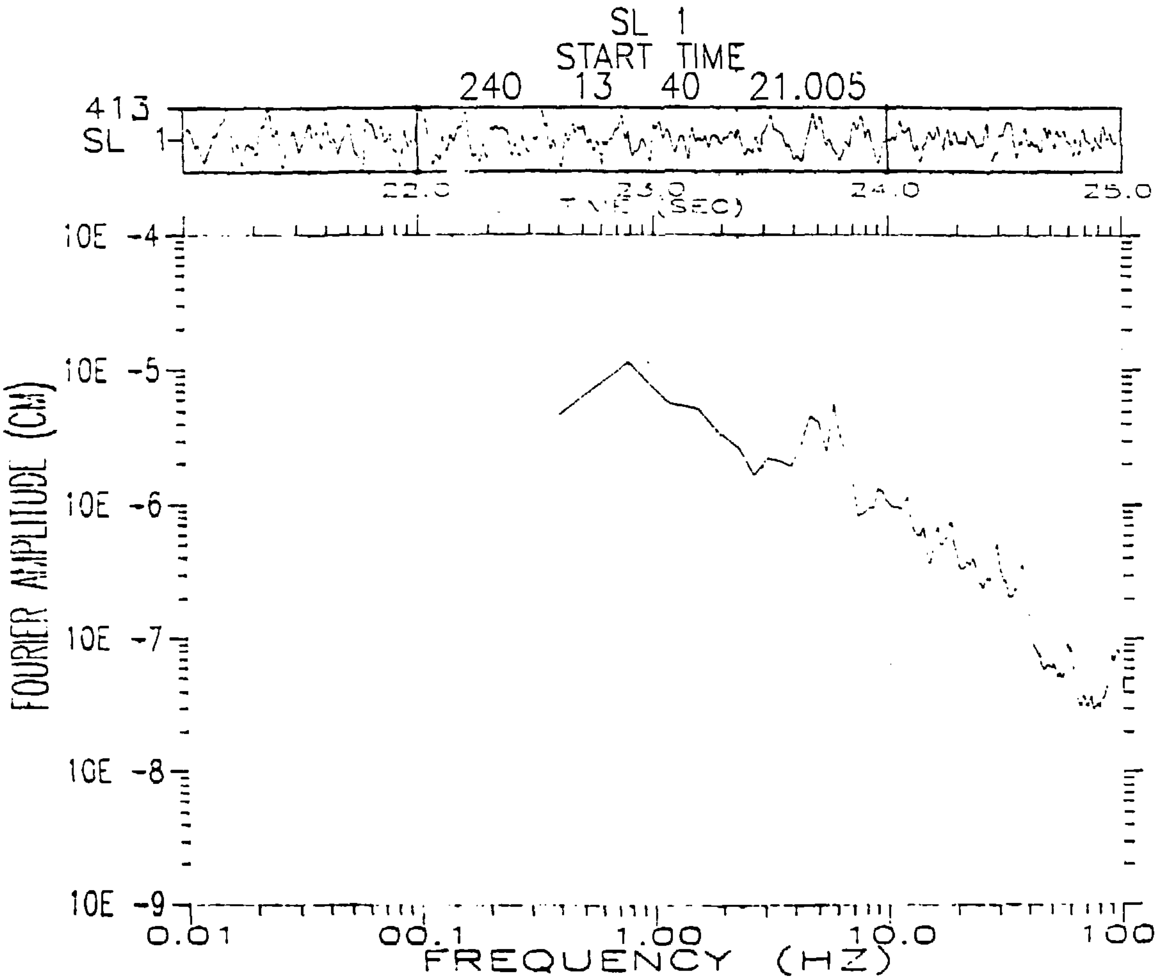


Figure 49. Displacement Response Measurements at Station 7 at the Survey Monument at the SLAC-SPEAR Ring. Note: The 4.6 Hz compressor peak is visible.

Displacement Response vs Frequency at the SLAC SPEAR Ring, Station 8 (on top of Support Pillar) August 28, 1983



XBL 866 11618

Figure 50. Displacement Response versus Frequency at Station 8 at the SLAC-SPEAR Ring. Note: There is a peak at around 5 Hz due to the SLAC compressor. The peaks below 4 Hz should be ignored.

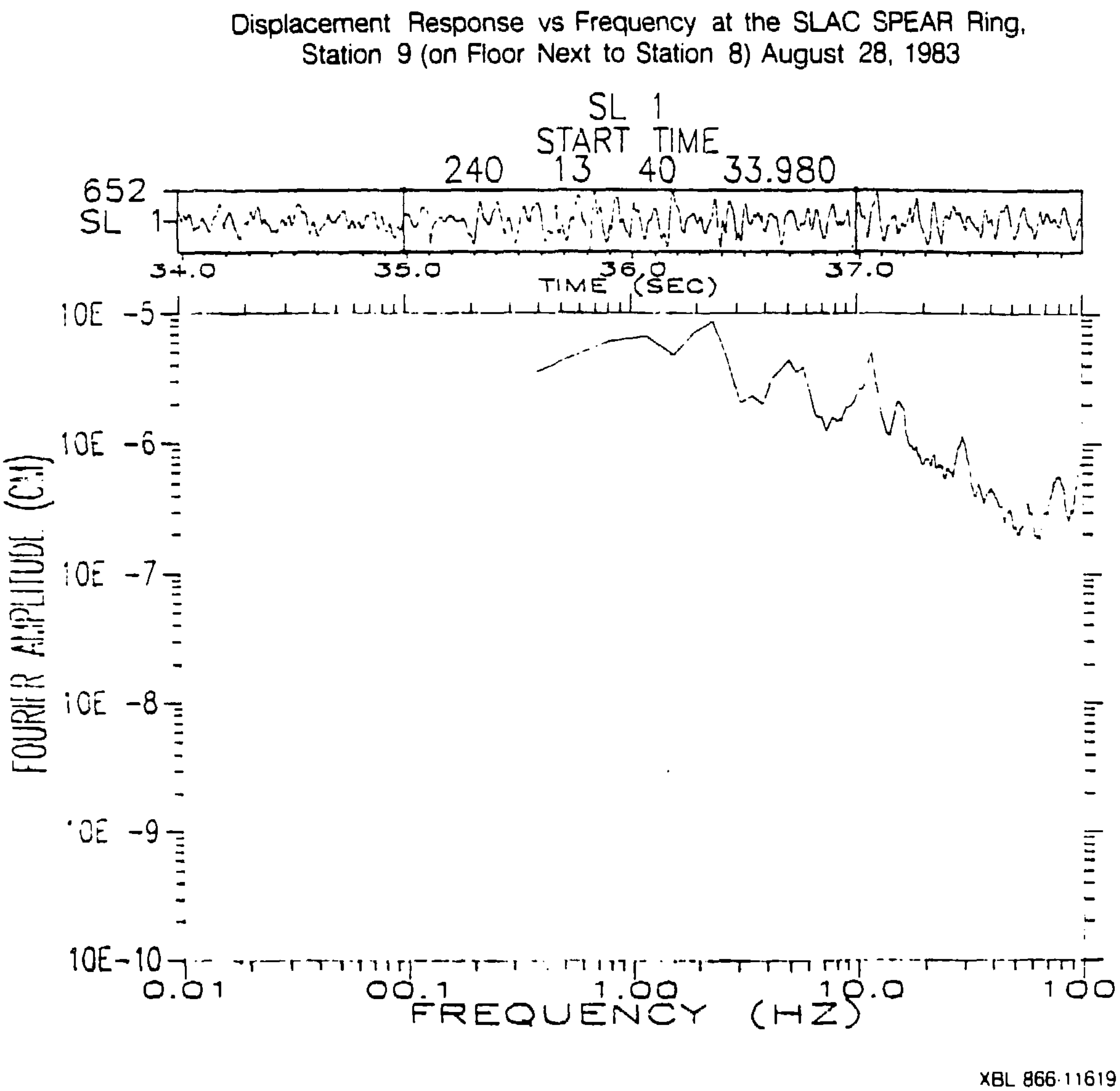
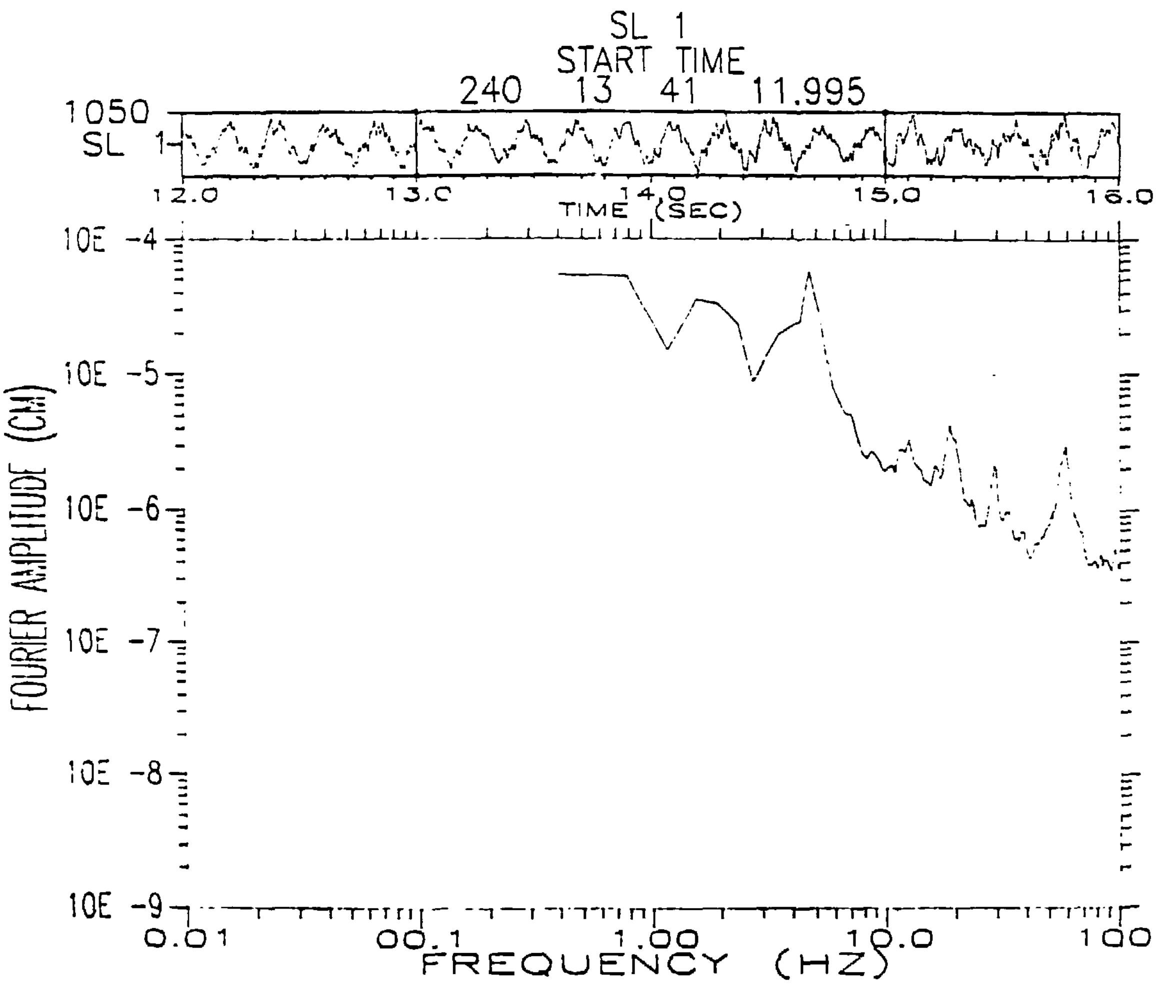


Figure 51. Displacement Response versus Frequency at Station 9 at the SLAC-SPEAR Ring. Note: This data is comparable to a number of stations shown in Figures 45, 47, 48, 49 and 50.

Displacement Response vs Frequency at the SLAC SPEAR Ring, Station 13 (on the Magnet Support Beam) August 28, 1983



XBL 866 11620

Figure 52. Displacement Response versus Frequency Measurements at Station 13 at the SLAC-SPEAR Ring. Note: This station is on the magnet support beam which magnifies the peak near 5 Hz. This figure should be compared with Station 3 in Figure 46.

Displacement Response vs Frequency at the SLAC SPEAR Ring, Station 15 (Outside the Shielding Wall) August 28, 1983

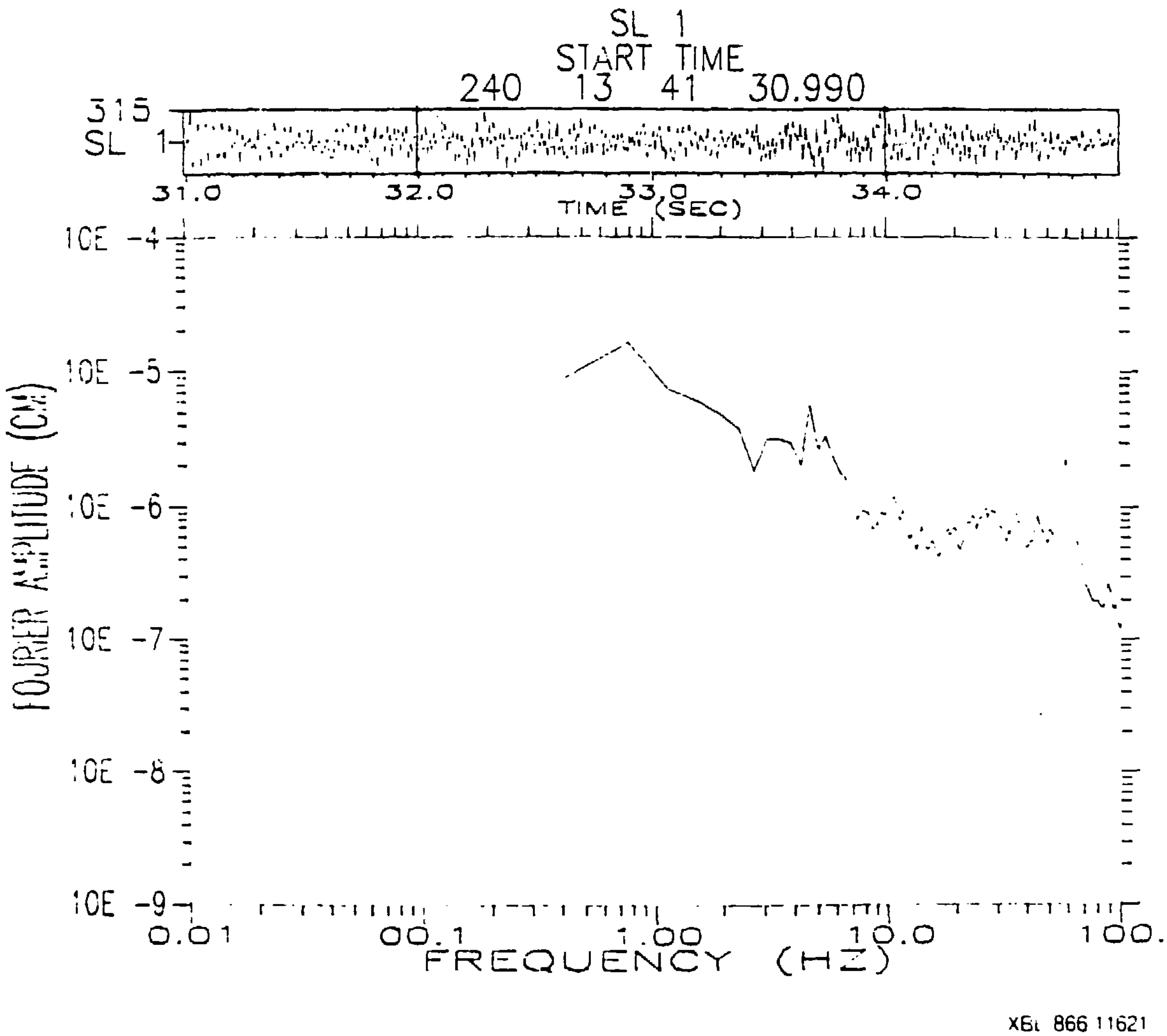


Figure 53. Displacement Response versus Frequency Measurements at Station 15 Outside the Shielding Wall at tne SLAC-SPEAR Ring. Note: This figure should be compared to Figures 45, 47, 48, 49, 50 and 51.

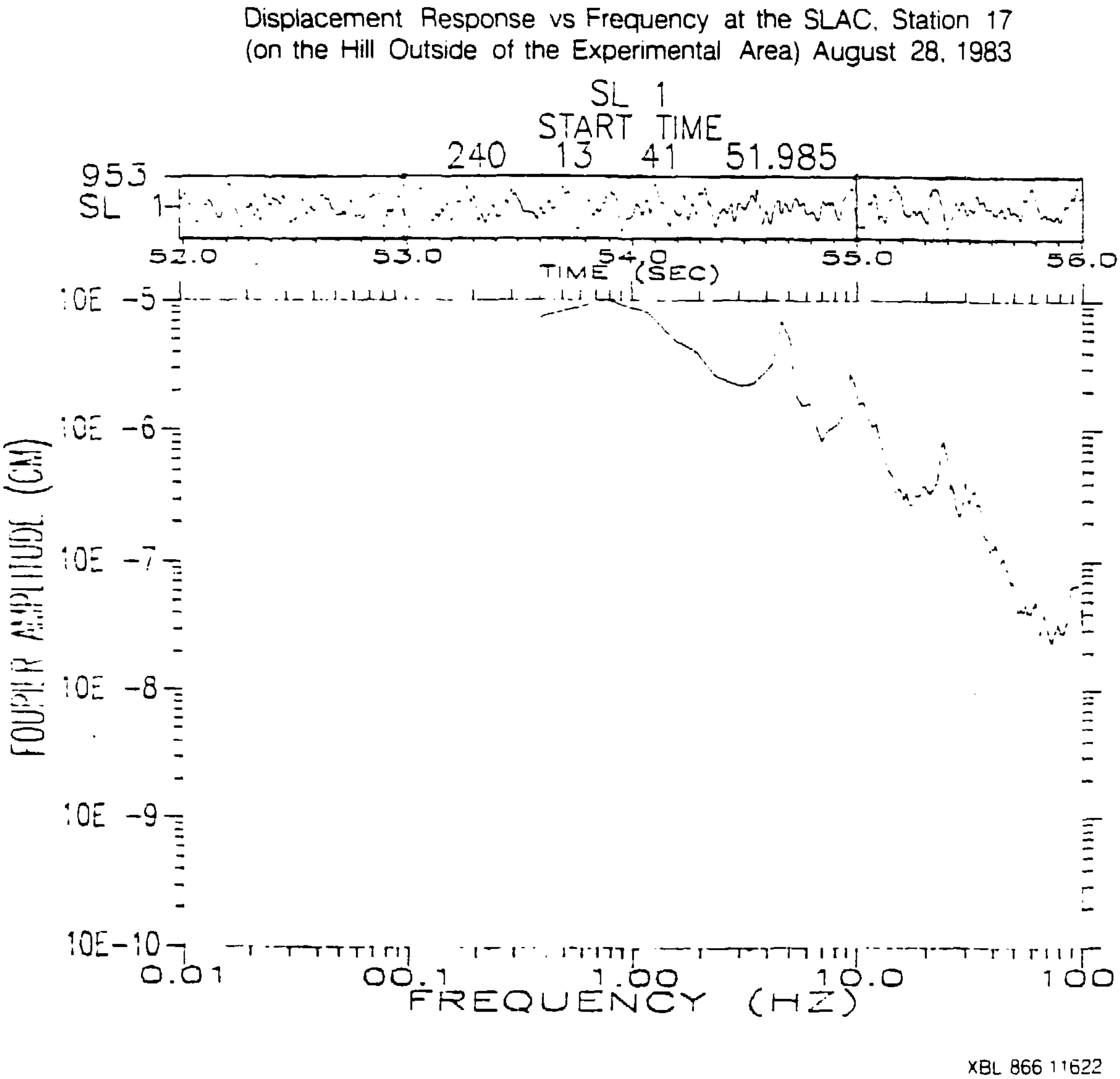


Figure 54. Displacement Response versus Frequency Measurements at Station 17 on the Hill Outside the SLAC Experimental Area. Note: Higher local noise sources are attenuated. The 4.6 Hz peak is quite visible. This figure should be compared with Figures 45, 53 and 55.

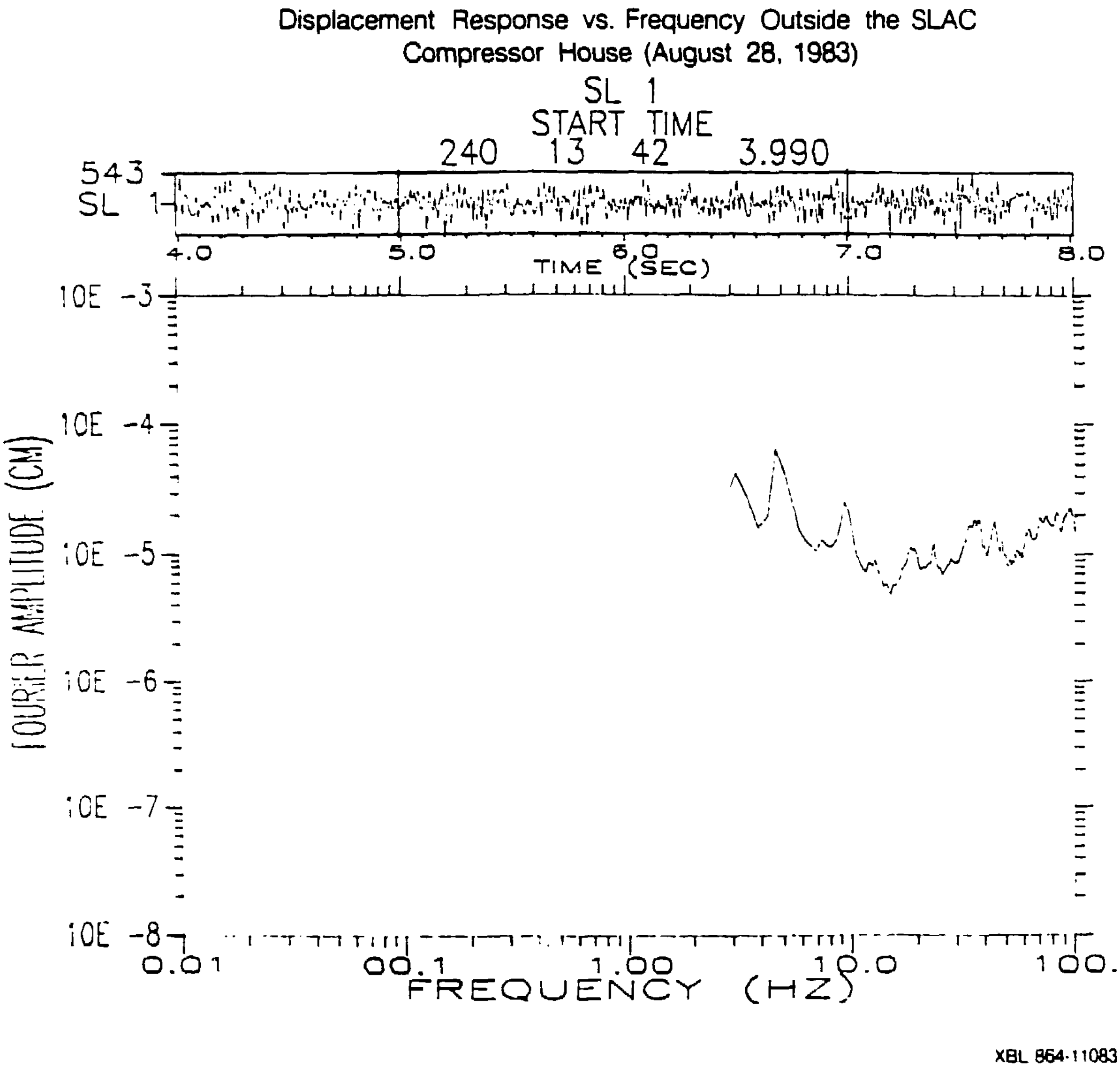


Figure 55. Displacement Response Measurements at Station 18 Outside of the Compressor House at SLAC. Note: There are strong peaks even at high frequencies due to motor and pump noise. The dominant peaks are at 4.6 and 9 Hz.

Noise Sources at Building 6

The primary noise sources in the Building 6 area in July 1983 are summarized in Table 3. The noise sources can be divided into rotary and reciprocating. The large Kinney vacuum pumps are examples of the latter, and the large 1500 HP water pump for the neutral beam facility is an example of the former.

The worst offending reciprocating noise sources appear to be the 184-inch Cyclotron Kinney pumps and some large Stokes pumps associated with the neutral beam facility. The rotational speed of most Kinney pumps is about 5 - 6 RPS. The large pumps have two vaned lobes which rotate at twice the pump speed so there is a general 11 Hz vibration associated with these pumps. The vibration is in general in a vertical direction. The Stokes pump rotation speed is 8 to 9 RPS, and the reciprocating frequency for these pumps is dominantly 16 to 17 Hz predominantly in the vertical direction.

Rotary noise sources include the 184-inch Cyclotron M.G. set, pumps for cooling towers next to Building 6, the large 1500 HP pump for cooling the neutral beam facility and the neutral beam facility refrigerator screw compressor. The 184-inch Cyclotron M.G. set has a characteristic frequency of about 20 Hz. The 184-inch Cyclotron M.G. set is very smooth in its operation. Most of the motors in Building 6 and adjacent buildings are 29 to 30 Hz motors. The exceptions are the 60 Hz drives on the 1500 HP cooling water pump for the neutral beam facility and the 400 HP screw compressor for the helium refrigerator for the neutral beam facility. The rotary sources in and about Building 6 do not significantly cause the measured ground motion.

The compressors in Building 37 were investigated as a possible source for ground motion in Building 6. The compressor which is primarily in use in Building 37 is a 1000 SCFM screw compressor which rotates at 30 Hz. This is

Table 3. Major Ground Motion Sources in the Building 6 Area

Noise Source	Freq (Hz)	Type of Motion	Importance of Noise Source	Will the Source be Present
184-inch Cyclotron Kinney Pumps	11	Reciprocating	Very Important	No
Neutral Beam Facility Stokes Pump	17	Reciprocating	Very Important	No
Cooling Tower Pumps (Small Motors)	30	Rotary	Not Important	Some Yes
1500 HP for Cooling Neutral Beam Facility	60	Rotary	Not Important	No
400 Helium Screw Compressor	60	Rotary	Not Important	Yes
184-inch Cyclotron Motor Generator	20	Rotary	Possibly Important	No
Building 37, 1000 SCFM Screw Compressor	30	Rotary	Probably Not Important	Yes
Building 37, 400 SCFM Reciprocating Compressor Electric Drive	6.7	Reciprocating	Important when Operating	Yes
Building 37, Standby Diesel Compressor	6.7	Reciprocating	Not Important On Only During Power Failure	Yes
Small Pumps and Motors in Building 6	?	?	Probably Not Important	Most Gone
Small Pumps and Motors in Buildings 10 and 80	?	?	Not Important	Yes
Building 6 Cranes	?	?	Very Important	Yes
Vehicular Traffic	?	?	Can Be Important	Yes

not a significant ground motion source. The two backup reciprocating machines are 400 CFM vertical piston compressors which have a characteristic frequency of 6.7 Hz. One is electric, the other is a standby diesel unit. The diesel unit probably has other frequencies of noise. The Building 37 primary compressor does not appear to be significant as far as ground motion for the Light Source is concerned, but the backup units might be.

The 11 Hz noise from the 184-inch Cyclotron Kinney vacuum pumps is probably the dominant noise measured at stations 7, 8, 12, 13, 14 and 30, and it is important for peaks in measurements at stations 1, 2, 5, 6, 9, 11, 15 and 27, as well as some of the stations in Buildings 10 and 80. The 17 Hz Stokes pump noise is dominant in measurements at stations 1, 2, 5, 9 and 17, and it is an important peak in noise measured at stations 6, 7 and 8. The low frequency noise (probably vacuum pumps) in Buildings 10 and 80 may be, at least in part, of local origin. Vacuum pumps in those buildings tend to be movable, so it is difficult to trace the source of those types of local noise. Stations which show large amplitude high frequency noise are usually close to a noise source. Such stations in the Building 6 area are Stations 6, 9, 11, 13, 19, 23 and 30.

The velocity of surface waves in the soils in the neighborhood of Building 6 ranges from 500 to 900 meters per second. The greatest affects of ground motion will occur when the wave length of a ground motion wave is near the betatron wave length in either the radial or vertical directions. The horizontal betatron wave length of 13.8 m is most affected by ground motions ranging in frequency from 36 to 65 Hz. The vertical betatron wave length of 24.1 m is most affected by ground motions with a range of frequencies from 21 to 37 Hz.

Conclusions and Recommendations

One can draw a number of conclusions and make a number of recommendations from the ground motion measurements made at LBL and SLAC during the summer and fall of 1983. The following conclusions and recommendations can be drawn from the LBL ground motion measurements.

1) Peak Displacement Response Spectra. Most of the results are presented as "peak displacement response spectra". The response amplitude presented is the peak displacement (zero-to-peak) that an actual resonant structure (one degree of freedom with damping coefficient of 2%) would undergo when subjected to the same ground motion as measured. Thus, if the Ring had a magnet stand with a resonant frequency of say 20 Hz and a damping coefficient of 2%, then one enters the spectra abscissa at 20 Hz and reads the ordinate to find the "actual" peak displacement that would occur due to the measured ground motion. The spectra are valid for frequencies from about 5 to 60 Hz. Values below 5 Hz and above 60 Hz are subject to question.

2) "Quiet" Spectrum. The ground motion spectrum measured at the Byerly tunnel, a "quiet" location, agrees closely with that measured at many other quiet locations throughout the world. Thus, the measured results are credible.

3) Building 6 Background Measurements. Measurements taken at 30 locations within and around Building 6 give spectra with peak displacement responses of less than 0.2 μm. Equipment that was operating during these measurements include that associated with normal operation of the 184-inch Cyclotron and the Neutral Beam

Engineering Test Facility (NBETF), both in Building 6, and LBL's primary air compressor in adjacent Building 37. This amplitude of 0.2 μm is unlikely to affect the photon beams of the Light Source.

4) Bevatron. Although 15 Hz (900 RPM) ground motion caused by the Bevatron motor-generator was significant in the immediate vicinity of the Bevatron, the amplitudes (< 0.05 μm) measured in the Building 6 vicinity were not significant compared to the background motion described above.

5) Vehicular Traffic. An LBL fire truck running over a temporary plank bridge immediately outside of Building 6 produced a transient peak displacement amplitude of approximately 1 μm which could produce some modest wavering of the Light Source photon beams (by a fraction of their beam size) but should promptly return to normal. Examination of the ground motion raw data suggests that the fire truck rolling on smooth pavement may not significantly affect the photon beams. This limited data suggests the desirability of smooth pavement adjacent to Building 6 as well as the possibility, but not certainty, that heavy vehicular traffic immediately adjacent to Building 6 may need to be controlled.

6. Cranes in Building 6. Operation of the two cranes in Building 6, both separately and together, produced peak displacement amplitudes of 0.4 to 1.8 μm which is enough to modestly waver the Light Source photon beams during crane motion. This suggests that crane operation, particularly for heavy loads, may need to be curtailed during sensitive photon experiments or alternatively that sensitive photon data acquisition might need to be suspended during crane operation.

7. Air Compressors; Building 37. Ground motion from the primary air compressor in Building 37 is acceptable. Further measurements of the ground motion produced by the two backup air compressors would be needed to assess whether their motion would be acceptable or not.

8. Measurements at SLAC. Ground motion measurements conducted at SLAC indicate peak displacement amplitudes that are generally comparable to those at LBL, with amplitudes below 10 Hz being somewhat greater and those above 10 Hz being somewhat lower.

9. Light Source Support Stands. The peak displacement response spectra at Building 6 indicate that structural stands with damping coefficient of at least 2% should produce acceptable displacements except in the case of major man-made ground motion sources, such as nearby cranes and trucks. Incorporating damping greater than 2% could be beneficial. In the unlikely event that damping of less than 2% were considered, then the peak displacement responses should be recalculated.

10. Light Source Mechanical Equipment. Most of the mechanical equipment associated with the 184-inch Cyclotron and the NBETF that were operational during these measurements will be removed prior to completion of the Light Source, which should reduce the peak displacement amplitudes. However, new equipment (e.g. mechanical vacuum pumps, refrigeration compressors, ventilation blowers) will be installed as part of the Light Source facility. Procedures should be considered for evaluating all such new equipment for their ground motion implications prior to their incorporation into the facility. In some cases, vibration isolators at the new equipment may be appropriate.

11. Water Flow Noise. Water turbulence in flow channels of components, such as magnets, can induce vibrational movements of the components. This was not addressed in this study, but a future study could address whether such vibrations might or might not be of significance.

The general conclusion that one can draw from the ground motion measurements is that the Building 6 site is favorable for the construction of a high-quality synchrotron Light Source. The potential problem sources for ground motion are local in nature. These can be dealt with on an individual basis by isolation of the source or restrictions in operation which can be lived with.

Acknowledgments

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Appendix

Attenuation of Surface Waves

This section describes the frictional attenuation function for surface waves. The exponential equation given here is empirical. The mechanism for frictional attenuation is not well understood for such complex structures such as surface soils of the earth and various rock layers.

The attenuation function for surface waves can be presented in the following empirical form:

$$A = A_0 e^{-\pi f t^*} \qquad \text{-A1-}$$

where A is the wave amplitude with frictional attenuation, A_0 is the wave amplitude without frictional attenuation, f is the frequency of the wave and t* is a time function which has the following form:

$$t^* = \frac{x}{cQ} \qquad \text{-A2-}$$

where x is the distance from the source, c is the wave velocity through the medium and Q is an attenuation function which is like an inverse damping ratio.

The functions c and Q are functions of the medium carrying the waves. Surface soils such as those around LBL will have rather low values of Q (Q can vary from 4 - 8) and wave velocity (c can vary from 500 to 1,000 meters per second). The deep rock of the earth, which might carry waves caused by ocean waves breaking on a distant shore, can have Q as high as 100 and wave velocities in the range of 3,500 to 6,000 meters per second. Table A1 illustrates the calculation of attenuation distance for the surface soils near the Bevatron and for deep rocks in the earth.

From Table A1, one can see that the approximate one over e attenuation distance for 15 Hz Bevatron power supply waves is about 90 m. The 30 Hz component of the Bevatron wave has a one over e attenuation distance which is about 45 m. As a contrast, the calculated one over e attenuation distance for surface waves generated by ocean swells breaking on a distant shore with a frequency of 0.16 Hz (these surface waves travel through deep crust rocks and a portion of the earth's mantle) is about 1,000 km. Even in the center of the United States, the 0.16 Hz surface waves will be quite evident.

Table A1. Calculation of Attenuation Distance (Three Cases)

	Case A LBL Soils at Bevatron	Case B LBL Soils at Bevatron	Case C Deep Rock of Earth
Distance X (m)	90	90	10^6
Frequency (Hz)	15	30	0.16
Wave Velocity (ms^{-1})	800	800	5,000
Attenuation Function Q	5	5	100
A/A_0 Ratio	0.35	0.12	0.35
Attenuation Distance (m)	~90	~45	$\sim10^6$