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Engineering Division

GROUND MOTION MEASUREMENTS AT THE 1 - 2 GeV SYNCHROTRON RADIATION SOURCE SITE

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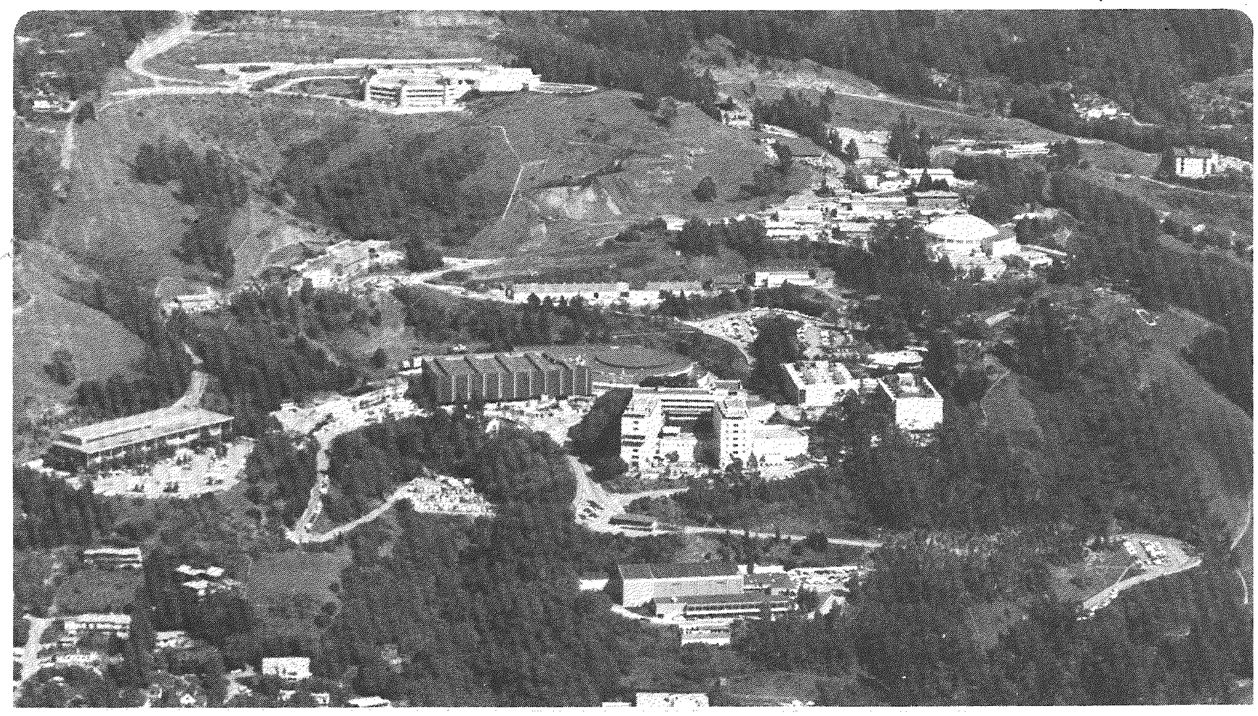

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ERRATUM

Note that in all figures which are labeled Displacement Response Vs Frequency ----------------, which have a vertical axis labeled FOURIER AMPLITUDE (CM), the value 10E-6 means ten to the minus six power and so on. (This applies to figures 7 through 20)

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Abstract

This report describes the technique for measuring ground motion at the site of the 1 - 2 GeV Synchrotron Radiation Source (Light Source) at Building 6. The results of ground motion measurements at the Light Source site are presented. As comparison, ground motion measurements were made at the Byerly Tunnel, the Bevatron, Blackberry Canyon, and SLAC at the Spear Ring.

The primary ground motion at the Light Source site is in a band from 10 to 30 Hz. This noise is 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. Ground motion at SLAC and the Bevatron is comparable to ground motions measured at the Building 6 Light Source site. The frequency signature of each site is very different.

Background

The Lawrence Berkeley Laboratory has proposed the construction of the 1 - 2 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.

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 = 0.144 mm and δ_y = 0.046 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 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 a five hertz are not 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 which 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 the attenuation of seismic waves in typical LBL soils. In addition one can determine whether the Bevatron has any effect on noise 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, which is a fixed property of the permanent magnet and coil, and is equal to the product of the flux density (tesla) and the length of the conductor (meters) in the magnetic field. The specifications of the AMF Geo Space GS-11D Subminiature Digiphone Geophones used are: natural undamped frequency = 4.5 Hz, generator constant = 50 volts/meter/sec, damping = 0.6 critical. The geophone package consists of three 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 high frequency geophones were amplified and filtered by band-pass filters which exclude frequencies below 0.2 Hz and frequencies above 50 Hz. 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 ± 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 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.

The Analysis Procedure

The digital data was read from the cassette digital recording into the LBL computer for analysis. A displacement response is calculated which represents a worst case calculation of the displacement of an object mounted at the site. The analysis procedure, shown in a logic diagram in Figure 5, 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 axes 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.

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 fixture with little damping at the site.

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:

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

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:

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

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 second's worth of data (about 400 sample points) was 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 ± 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). A simplified equation for motion for the geophone coil as a function of time for a steady sinusoidal ground motion is represented as follows: (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_0 with respect to a stationary point.

$$M(\omega) = \frac{x_0}{\delta} = \left[\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(2\,\frac{C}{C_0}\quad\frac{\omega}{\omega_0}\right)^2\right]^{-0.5} \qquad (3)$$

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_0 to the velocity of the geophone coil as follows for a given sinusoidal motion at ω.

$$V_0 = \omega\, x_0 \qquad (4a)$$

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

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

where V_0 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 should note that the NSAS program calculates $(1 - M(\omega))$ as a complex function. The form used here is a simplified form used for explanation.)

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 6. The case illustrated in Figure 6 has 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 result from integrating the velocity spectra, are shown in the final panel marked d.

For engineering studies, it is useful to convert displacement spectra into a <u>peak displacement response</u> 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 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_o, the displacement spectrum is multiplied by a magnification factor $M(\omega)$ given by Equation 3 for the given damping ratio C/C_o.

2) The displacement spectra modified by $M(\omega)$ are 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_o.

4) The process given in Steps 1 through 3 is repeated for the whole range of f_o from the minimum to maximum values. This yields the peak displacement response which is 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 computer can present the data to the user several different ways. The data which is presented in this report is presented only as a peak displacement response. The data is presented in graphical form in Figures 7 through 21. Figure 7 is a plot of data calculated for the Byerly Tunnel site at the U.C. Botanical Garden (see Figure 1). There are two graphs shown in Figure 7, a typical displacement response curve. The upper graph is a graph of the digitized data given as signal amplitude versus time. The letters and numbers above the plot indicate the channel number (NC-1 is a vertical channel; NC-2 and NC-3 are horizontal channels) and the starting time when the data was taken. 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 components were used to generate the peak displacement response.

The data on the lower graph in Figure 7 is presented in peak displacement response form over a range of frequencies from about 2 Hz to 100 Hz. The displacement response data is only good from 5 Hz to about 60 Hz unless a calibrated geophone is used. Below 5 Hz, the data is affected by the geophone frequency response which results in $1 - M(\omega)$ being small and in some cases even negative. If more than one geophone is used and the geophones are not calibrated, error will creep in due to uncertainties in the resonant frequency and the damping ratio. Calibration of the geophone and using the same geophone filter combination for all measurements greatly reduces this uncertainty error and moves the lower limit frequency down from 5 Hz to 2 Hz. Below 2 Hz the signal from the geophone is small. At frequencies above 50 Hz, the major source of error is the band-pass filter. The signal is reduced by an order of magnitude by the time one gets to 100 Hz. Between 50 and 100 Hz, the uncertainties in the band-pass filter will contribute to the measurement error. The peak displacement response was calculated using an assumed damping ratio of 0.02 in Figure 7 and all subsequent figures.

Results of Ground Motion Measurements

The results of the ground motion measurements in the form of peak displacement response are given in Table 1 and in Figures 7 through 20. The table summarizes the amplitude peaks at frequencies from 5 to 10 Hz (the data is not very good below 5 Hz) and from 10 Hz and above (peaks above 50 Hz are not very accurate because of the 50 Hz band-pass filter).

The low noise Byerly tunnel measurements (see Figure 7) indicate that equipment motions are 1.5 x 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 measurements made in Building 6 with all the equipment running were also made on July 6, 1983. The ground motion measurements were made at some of the locations shown in Figure 2 (in the Building 6 area) are presented in peak displacement response form in Figures 8 through 12. In most locations around Building 6, the peak response motions are around 4 x 10^{-8} m. (See Table 1 for many of the locations shown in Figure 2.) In most locations, the frequency peaks generally occur at 11 or 17 Hz. In most cases, vertical motion is the largest motion measured. Figure 8 shows the peak displacement response at Station 1, which has been chosen as a reference station. This station was close to the building crane support, close to the plank bridge, and on the side Building 6 facing the Bevatron.

Figures 9 and 10, which show the peak displacement response at stations 8 and 12, show similar ground motions to Station 1 (Figure 8). At both stations 8 and 12 the peak displacements occur at 11 Hz rather than 17 Hz. The Station 25 measurements, shown in Figure 11, were made in the basement of Building 80. These measurements show about a factor of 3 reduction of ground motion as one moves away from the noise sources in Building 6. Figure 12, which presents measurements at Station 30, shows the effect of moving close to one of the major noise sources (the 11 Hz Kinney pump noise). It is interesting to note that the upper parts of Building 80 are noisier than Station 25. This suggests that ground motion is magnified by the building structure.

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 13). 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 Hz and 60 Hz peak disappear entirely - see Figure 14). This suggests that the attenuation length for LBL soils at 15 Hz is of the order of 100 m or a little less. The ground motion due to the Bevatron has no measurable effect on ground motion in Building 6 (see Figures 8 and 15 for a comparison of peak displacement response with and without the Bevatron running).

The effects of two specific sources of noise in and around Building 6 were tested. A large LBL fire truck was run across a plank bridge outside of Building 6. The movement of the fire truck across the bridge increased ground motion over an order of magnitude for a short period of time (see Figure 16). The two cranes in Building 6 were also tested while ground motion was measured at Station 1. A peak displacement response of 1.7 x 10^{-6} m was measured when both cranes were running. (See Figure 17)

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 18 through 20. 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 may be limited.) The peaks are believed to be caused by the hydrogen compressors, and 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.

A comparison of Station 7 ground motion (Figure 18) with Station 3 (Figure 19) ground motion shows the effect of magnification of the SPEAR magnet support beams. Station 3 is mounted on a survey marker and it shows a peak displacement response which is a factor of 3 to 5 lower than the peak displacement response measured on the SPEAR magnet support beam (Station 7). A comparison of Station 7 ground motion (Figure 28) and Station 18 ground motion (Figure 20) shows that the compressor is the probable source of the 4.6 Hz noise. The compressor puts out considerable high frequency noise which is attenuated by SLAC soils.

Noise Sources at Building 6

The ground motion sources in the Building 6 area measured in July 1983 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 reciprocating ground motion 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 also 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 and 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 Test 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 not a significant ground motion source. The two backup reciprocating machines could be if they were running. There are two 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 compressors do not appear to be significant as far as ground motion for the Light Source is concerned.

Summary

Overall, the noise levels at LBL Building 6 are comparable to those at SLAC. In most of Building 6, the peak displacement response showed equipment motion amplitudes of less than 0.1 microns. At SLAC near SPEAR, the main noise problem appears to be the 4.6 to 6 Hz noise associated with the compressors at the hydrogen plant. This noise can be detected at every point on the SLAC site which was measured during the study. This noise also has the characteristic of having large amplitudes in the horizontal components. At Building 6 the noise sources appear to be more localized with the problem areas being on the east side of the building, closest to compressors and small pumps. The band of greatest noise is the 10 to 30 Hz range. The largest sources of this noise appears to be the vacuum pumps in Building 6. Most of the sources of ground motion which produce the pronounced peaks will be removed from Building 6 when the Light Source machine is built.

Ground motion from the Bevatron does not appear to be significant at Building 6, and therefore the Bevatron should not affect the Light Source. The biggest sources of ground motion in the Building 6 area will be heavy truck traffic in the region and ground motion associated with the operation of the Building 6 cranes.

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Table 1. 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 1. Summary of Ground Motion Measurements at Various Sites (cont.)

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
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 SPEAR ring	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.

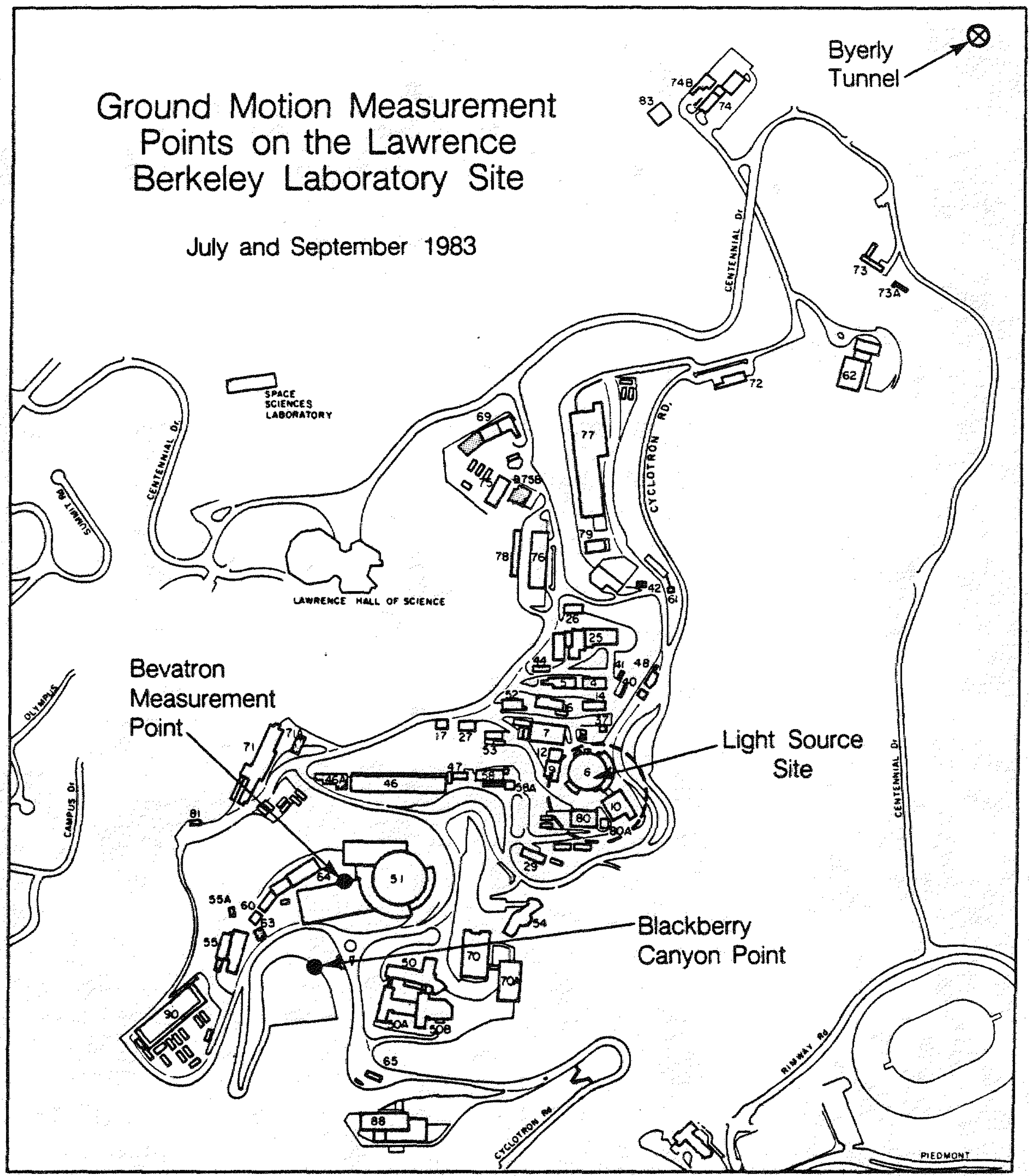

Figure 1. Ground Motion Measurement Points at LBL. (Note: The light source site contains 30 measurement points.)

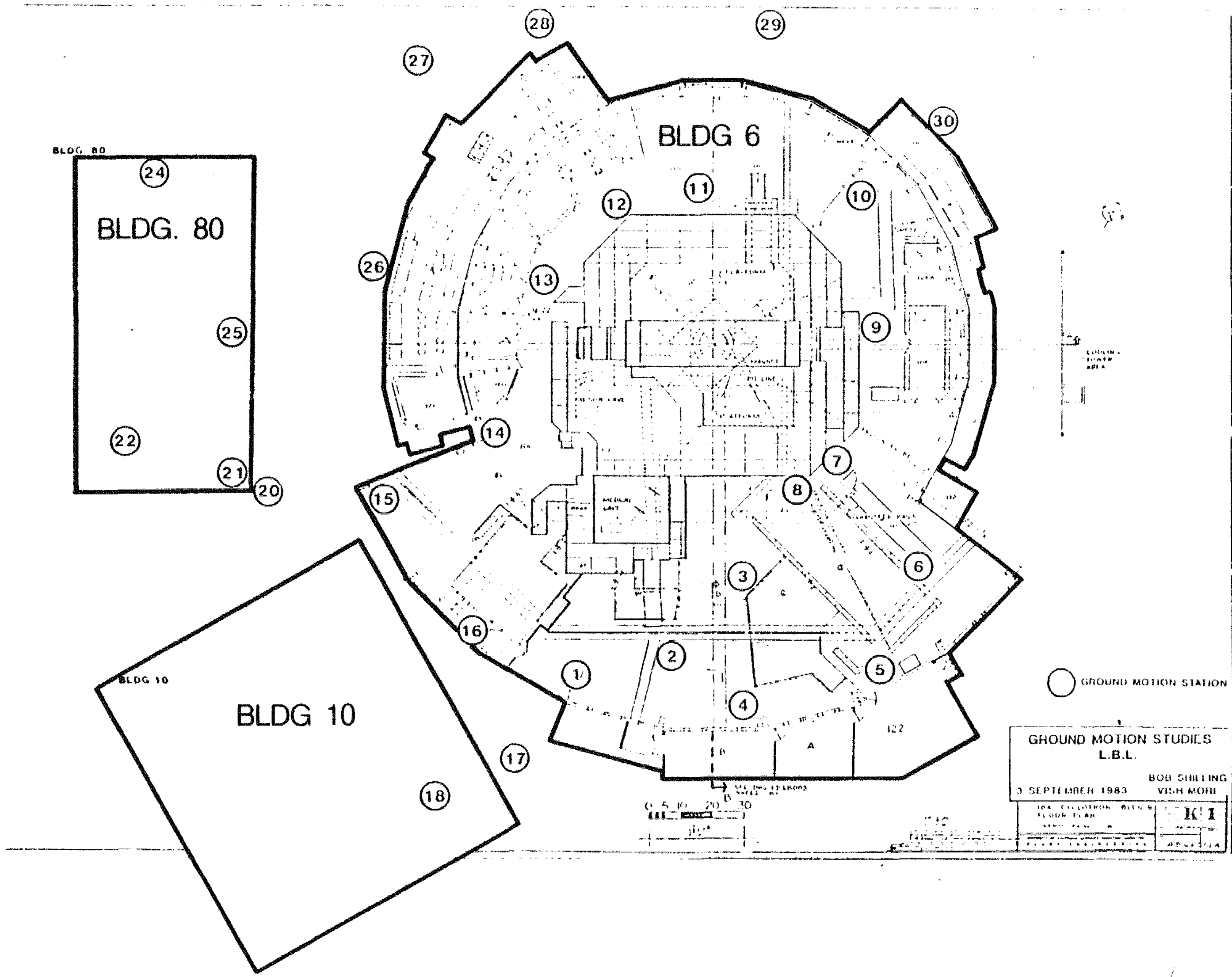

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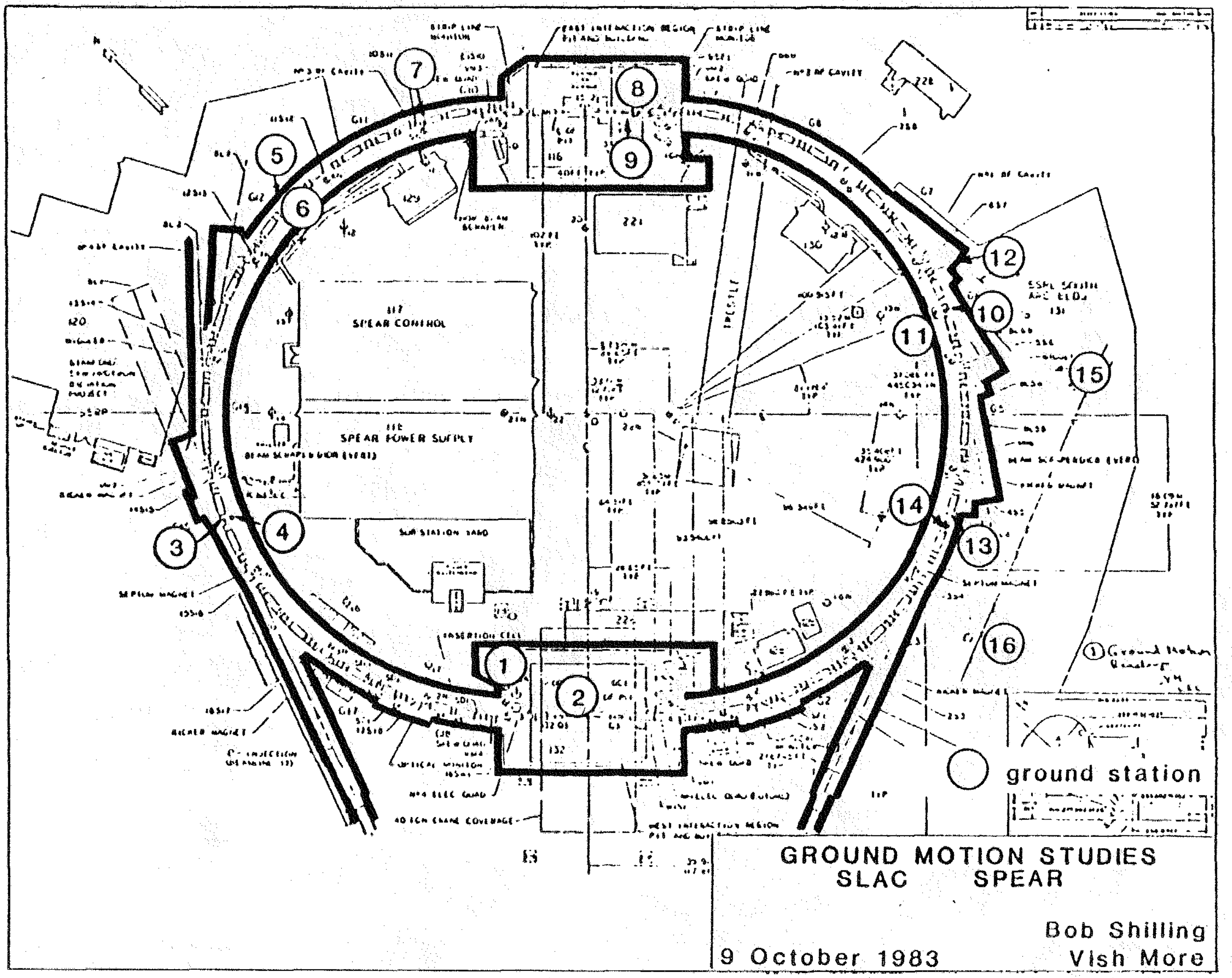
Figure 2. Ground Motion Measurement Stations Around Building 6 at LBL (the light source site).



XBL 864-11087

Figure 3. Ground Motion Measurement Stations Around SPEAR at SLAC.

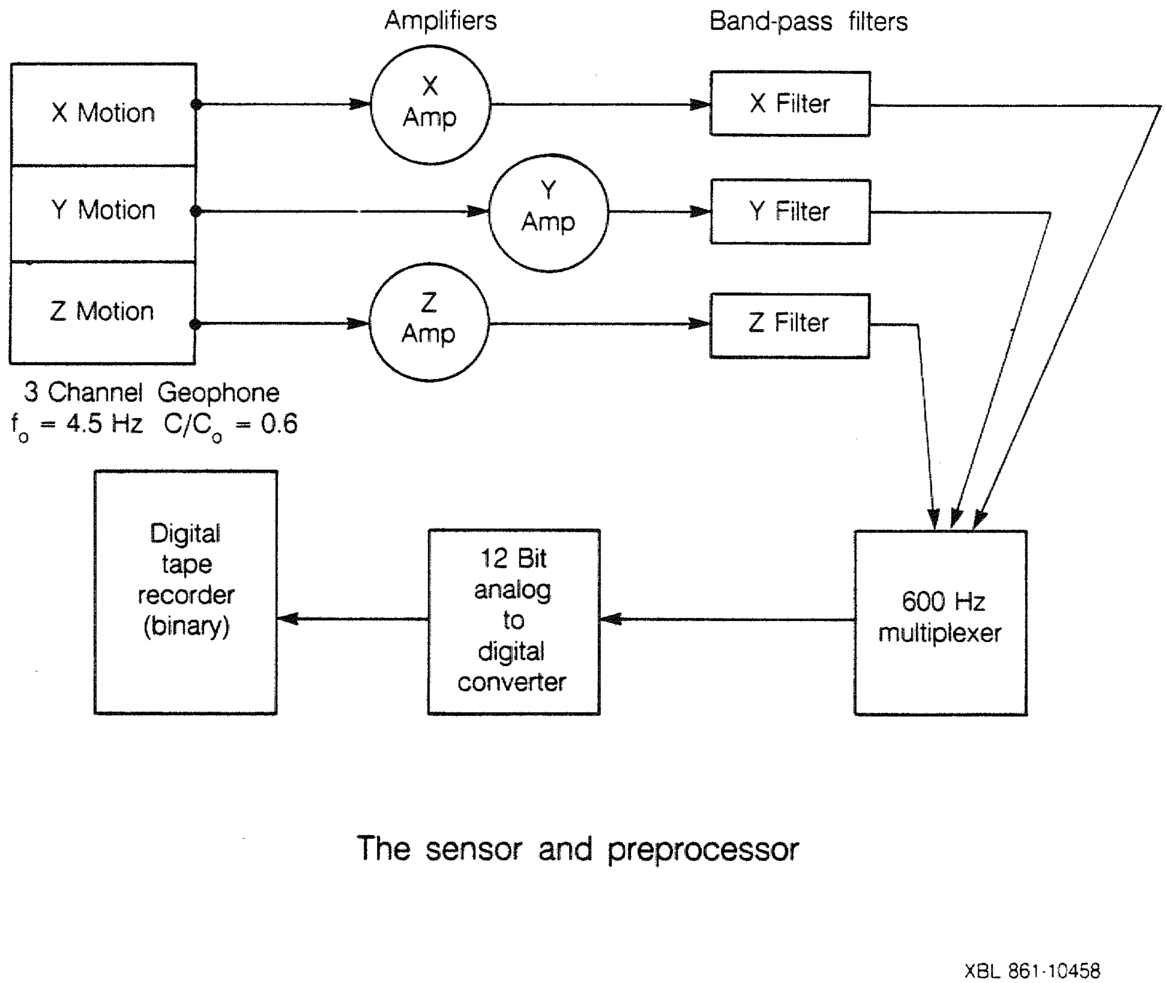


Figure 4. A Schematic Diagram of the Sensing System for the Ground Motion Measurement Apparatus.

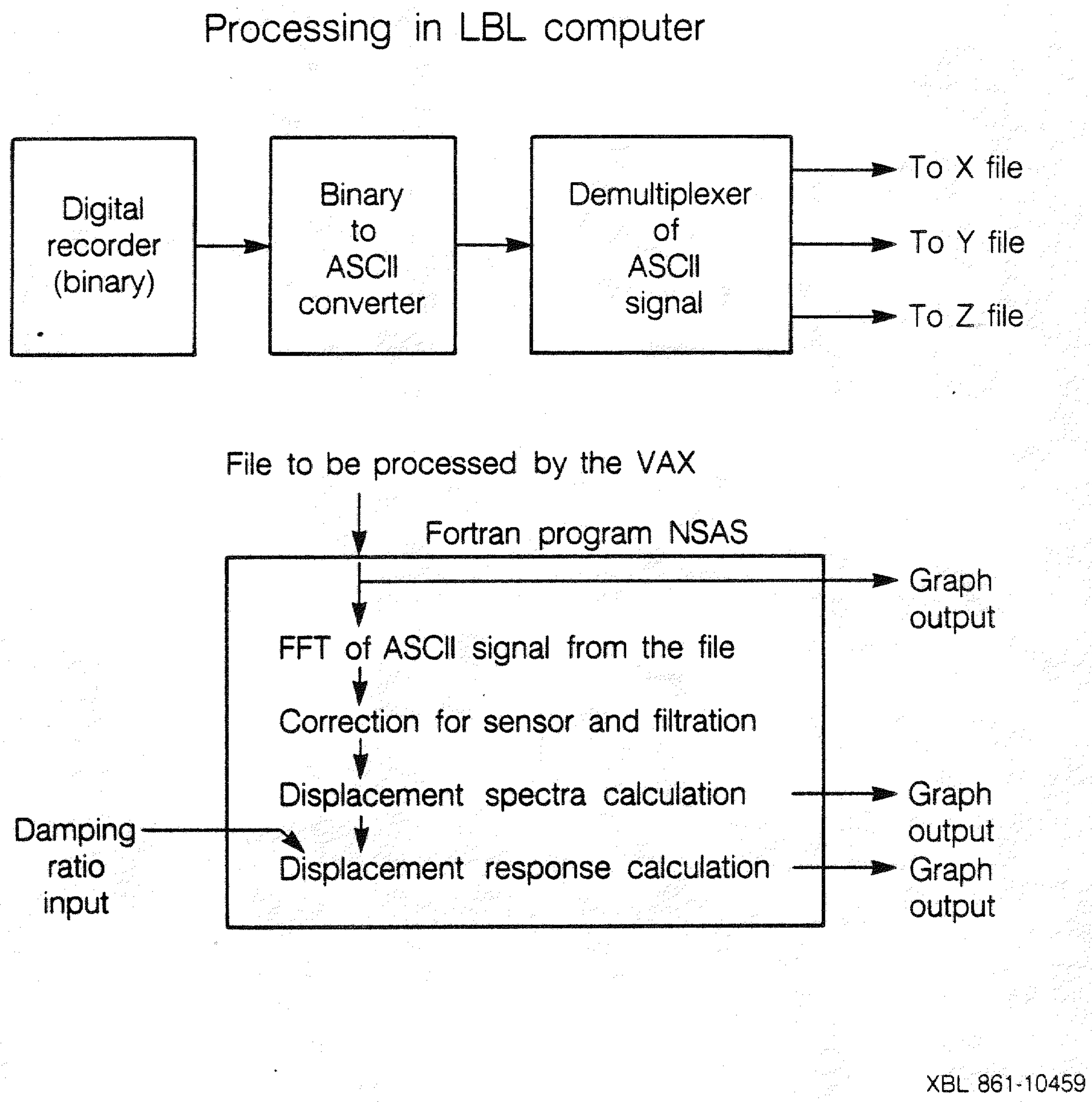


Figure 5. A Processing Schematic Diagram for Ground Motion Data Using the NSAS Computer Program.

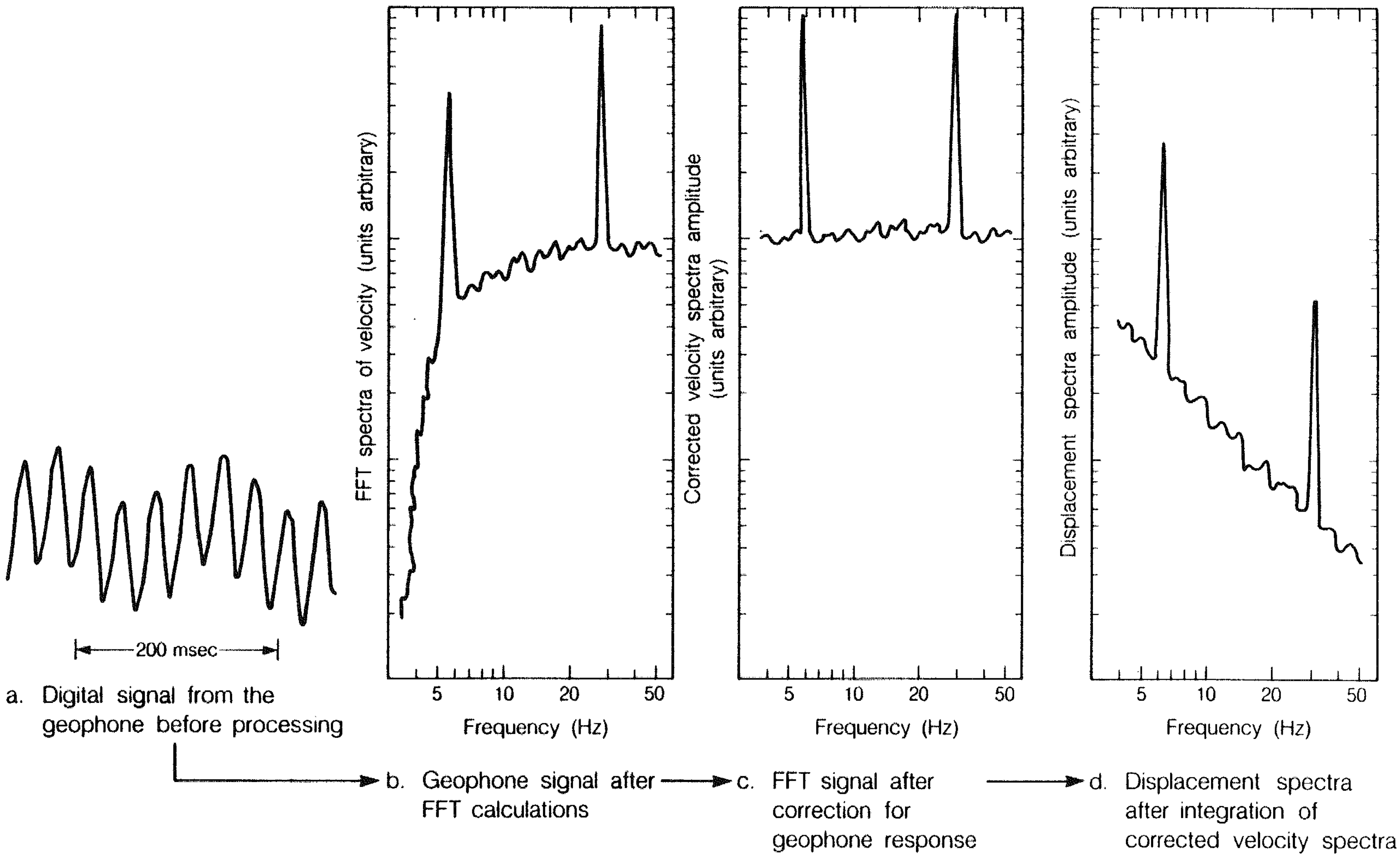


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Figure 6. The Ground Motion Data After Various Steps of its Processing by the NSAS Computer Program (a simulation).

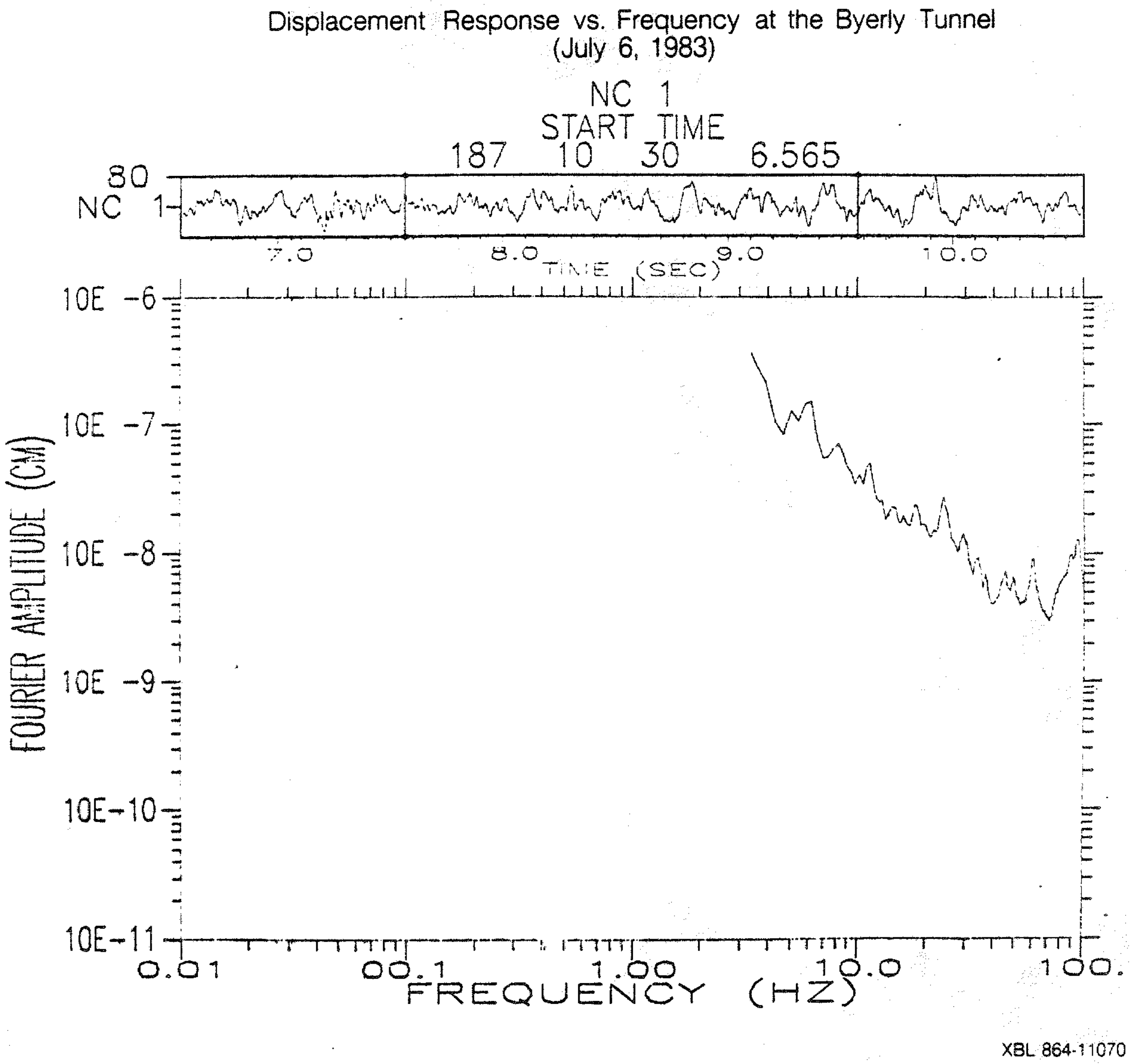


Figure 7. Displacement Response Measurements at the Byerly Tunnel. (Note: There is a characteristic displacement which goes as one over frequency. This is a typical quiet site.)

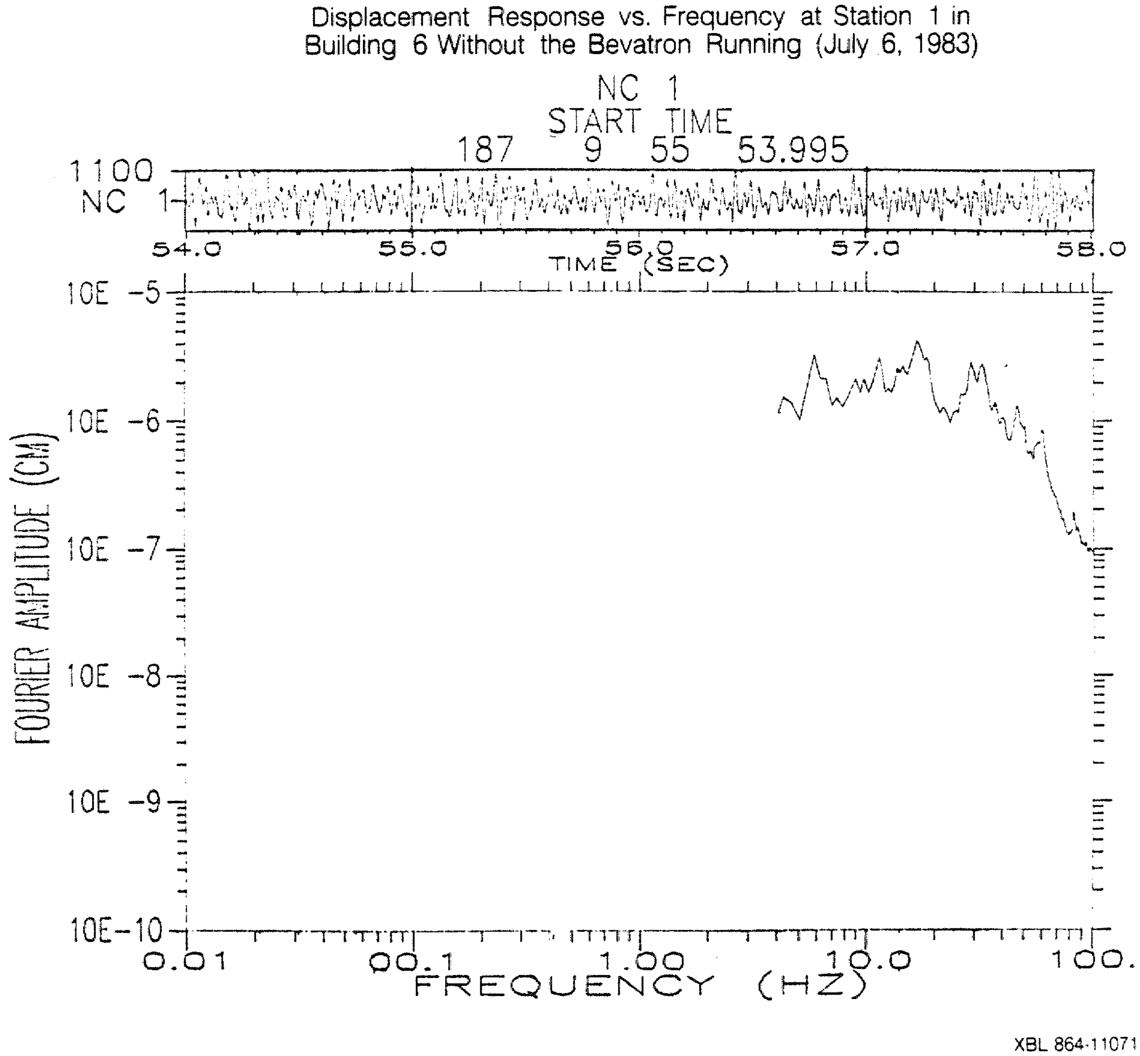


Figure 8. Displacement Response Measurements at Station 1 in Building 6. (Note: There are peaks at 5.5, 11, 17 and 30 Hz, which is characteristic of the Building 6 site.)

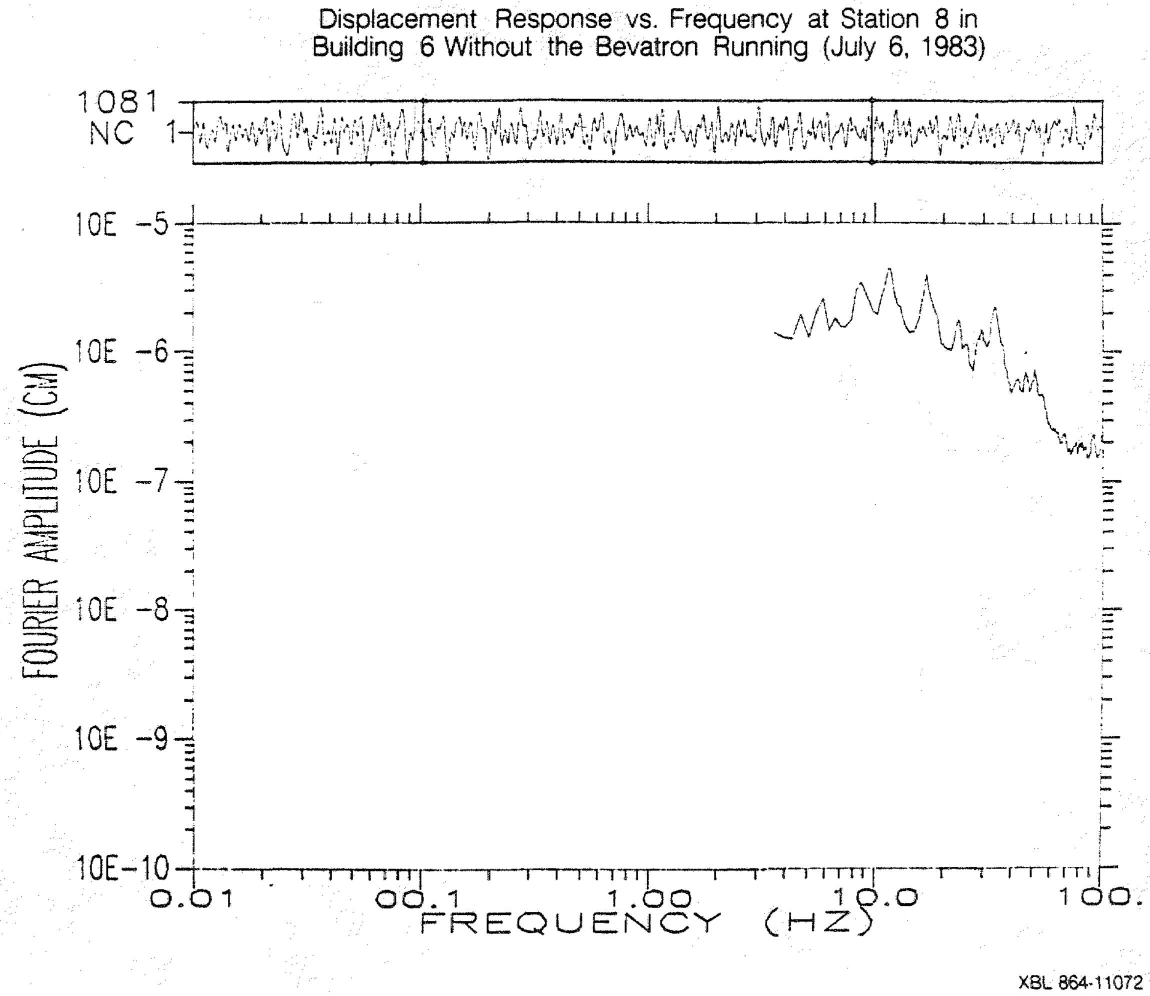
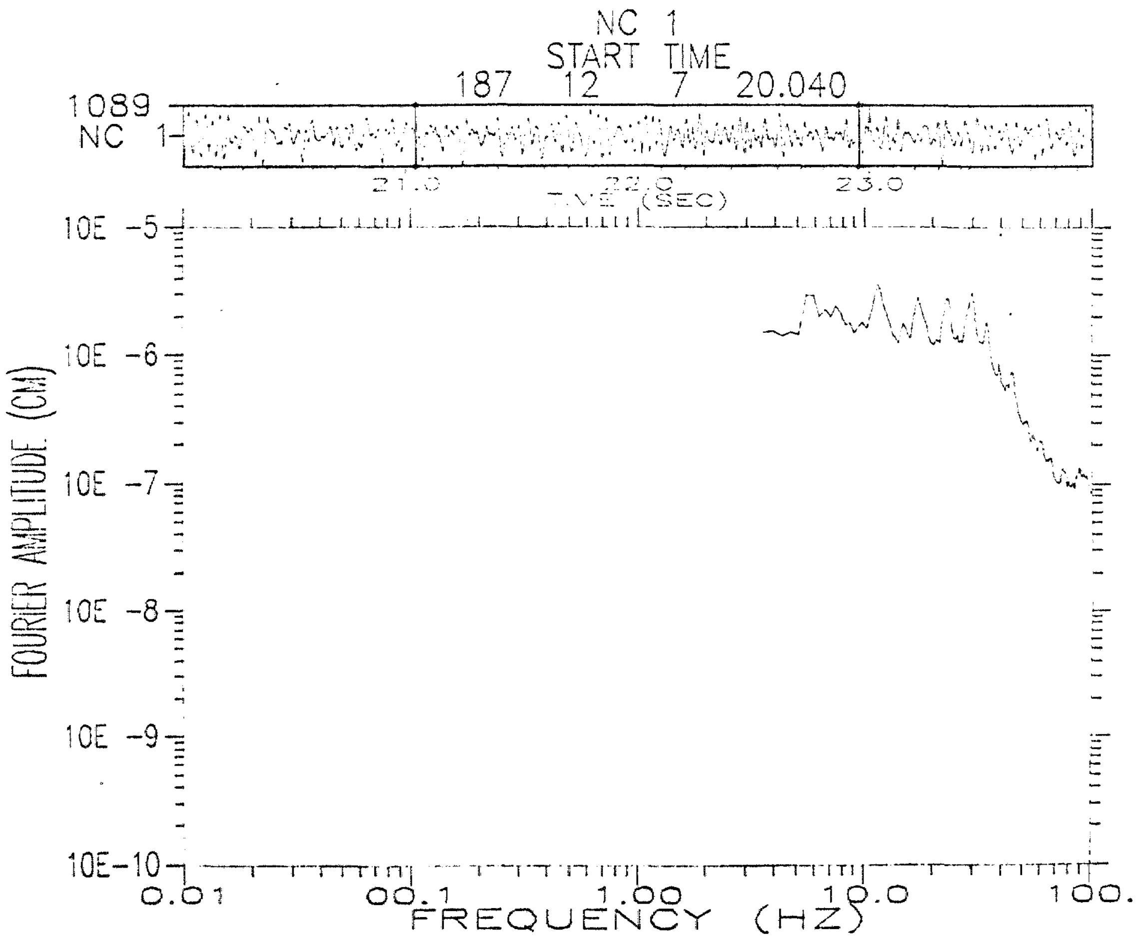


Figure 9. Displacement Response Measurements at Station 8 in Building 6 (note: the dominant 11 and 17 Hz peaks).

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



XBL 864-11073

Figure 10. Displacement Response Measurements at Station 12 in Building 6 (note: The 11,17, 22 and 30 Hz peaks).

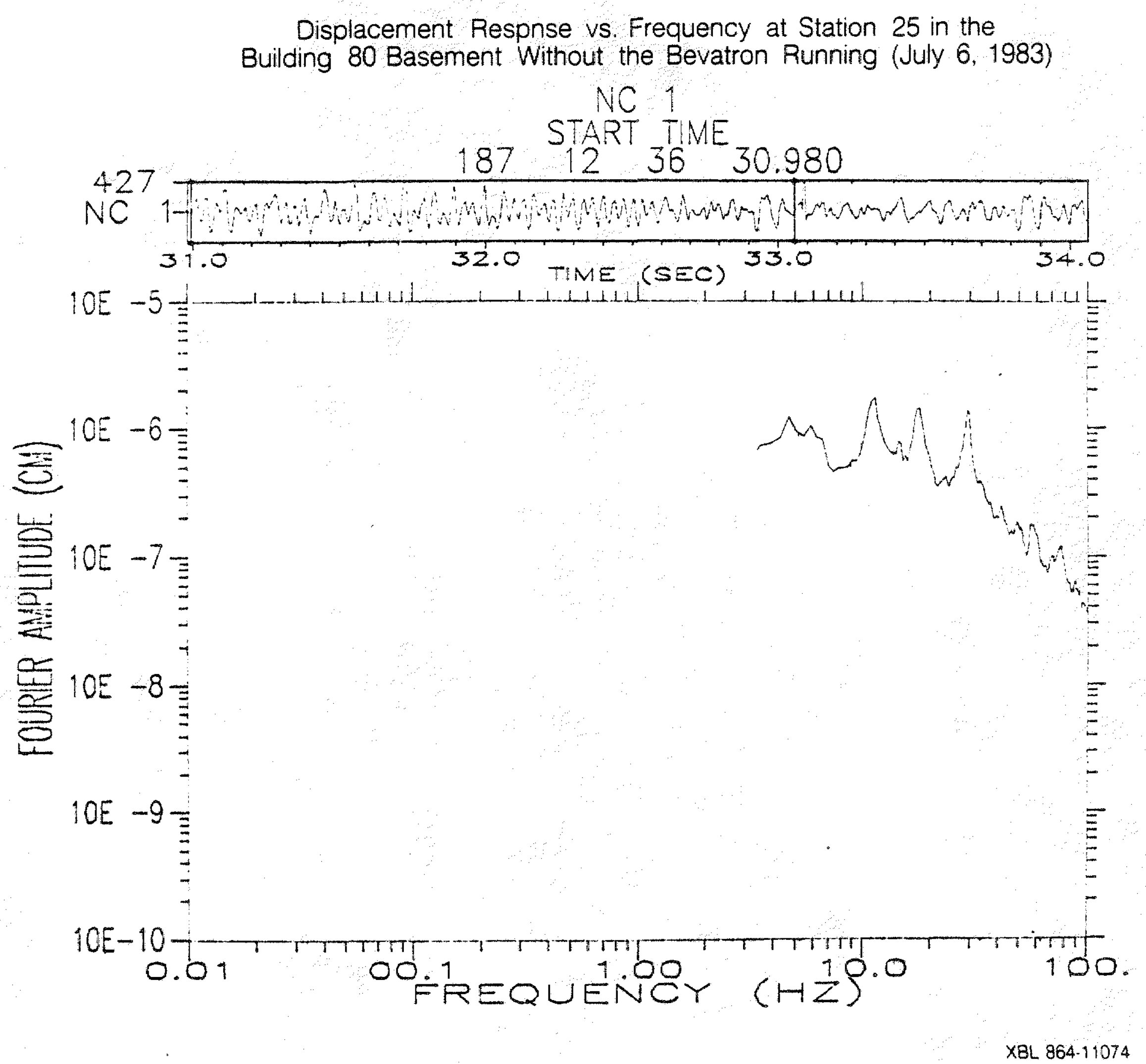
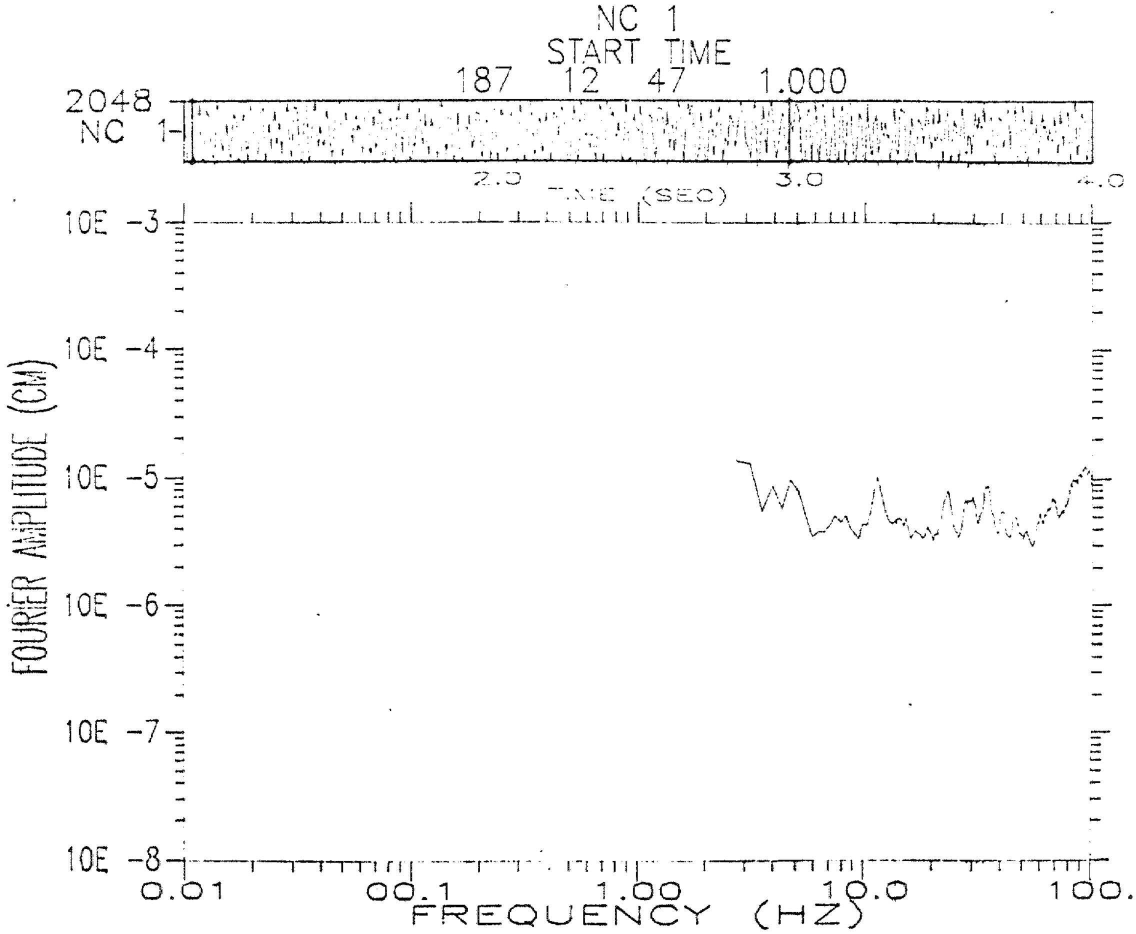


Figure 11. Displacement Response Measurements at Station 25 in the basement of Building 80. (Note: There is no magnification of ground motion by Building 80 in the basement. The peaks at 11, 17 and 30 Hz are evident. There is a fall off of the higher frequency motion because one is some distance from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

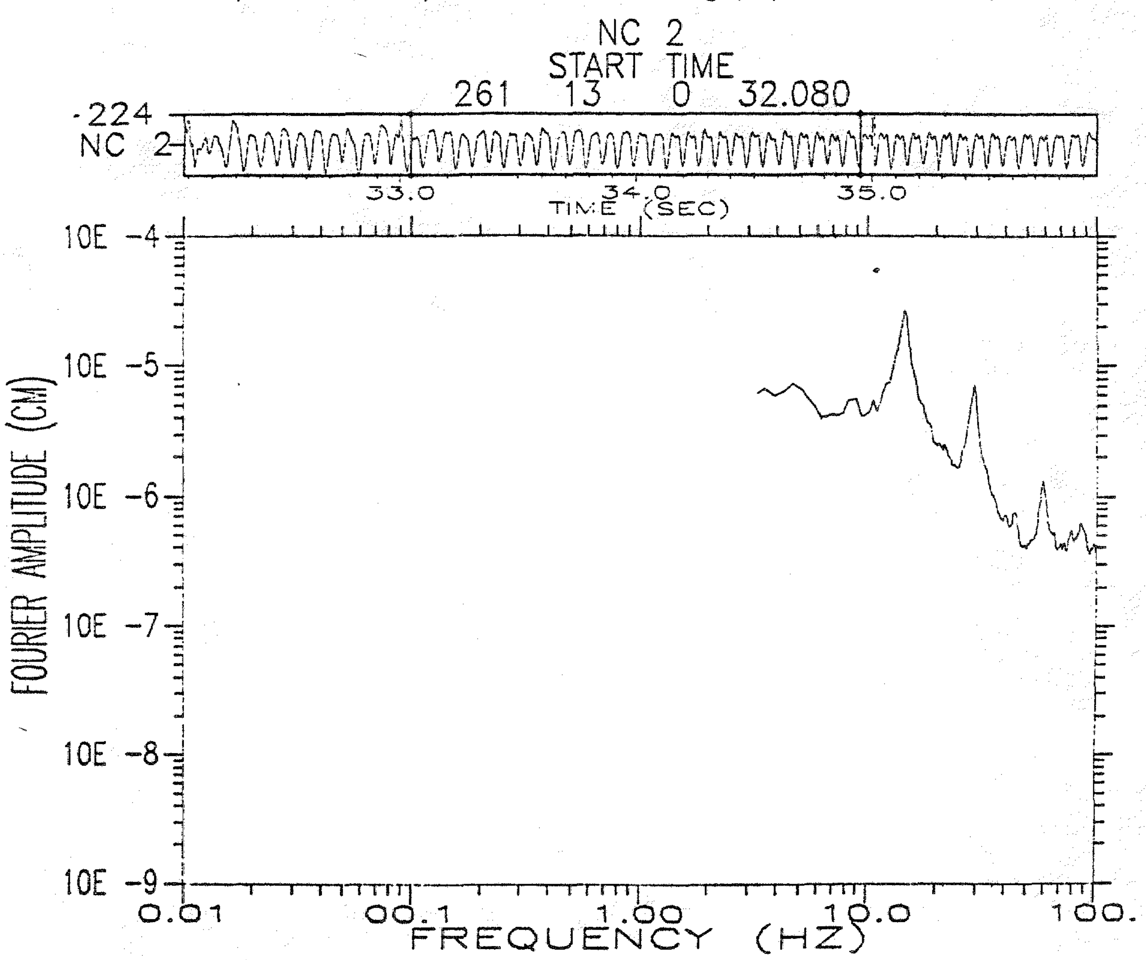
Displacement Response vs. Frequency at Station 30 Outside the Building 6 Pump Room, Without the Bevatron Running (July 6, 1983)



XBL 864-11075

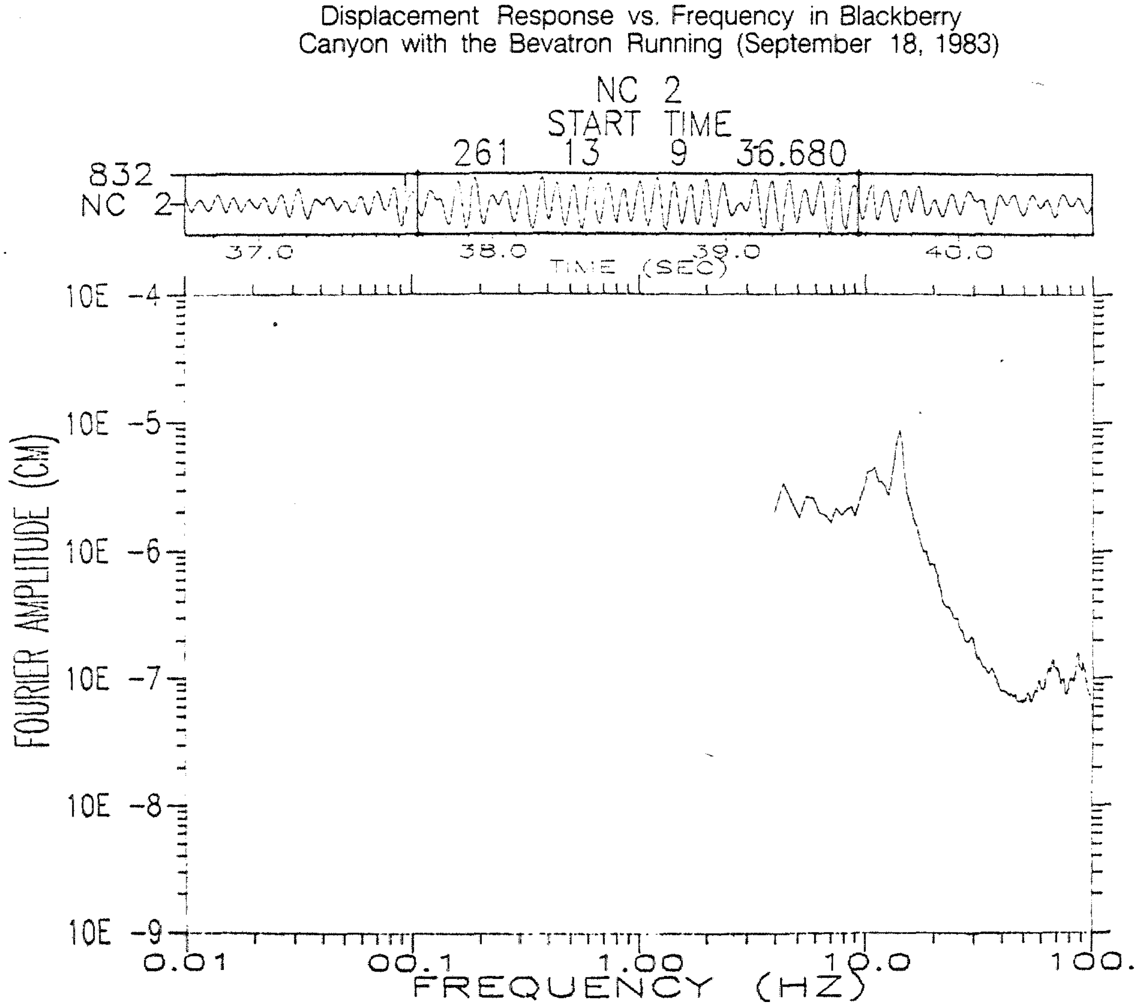
Figure 12. Displacement Response Measurements at Station 30 Outside of the Building 6 Pump Room. (Note: There are strong 5.5 and 11 Hz peaks and lots of high frequency noise due to various motors and pumps nearby.)

Displacement Response vs. Frequency at the Bevatron
(in the EPB Hall) with Bevatron Running (September 18, 1983)



XBL 864-11076

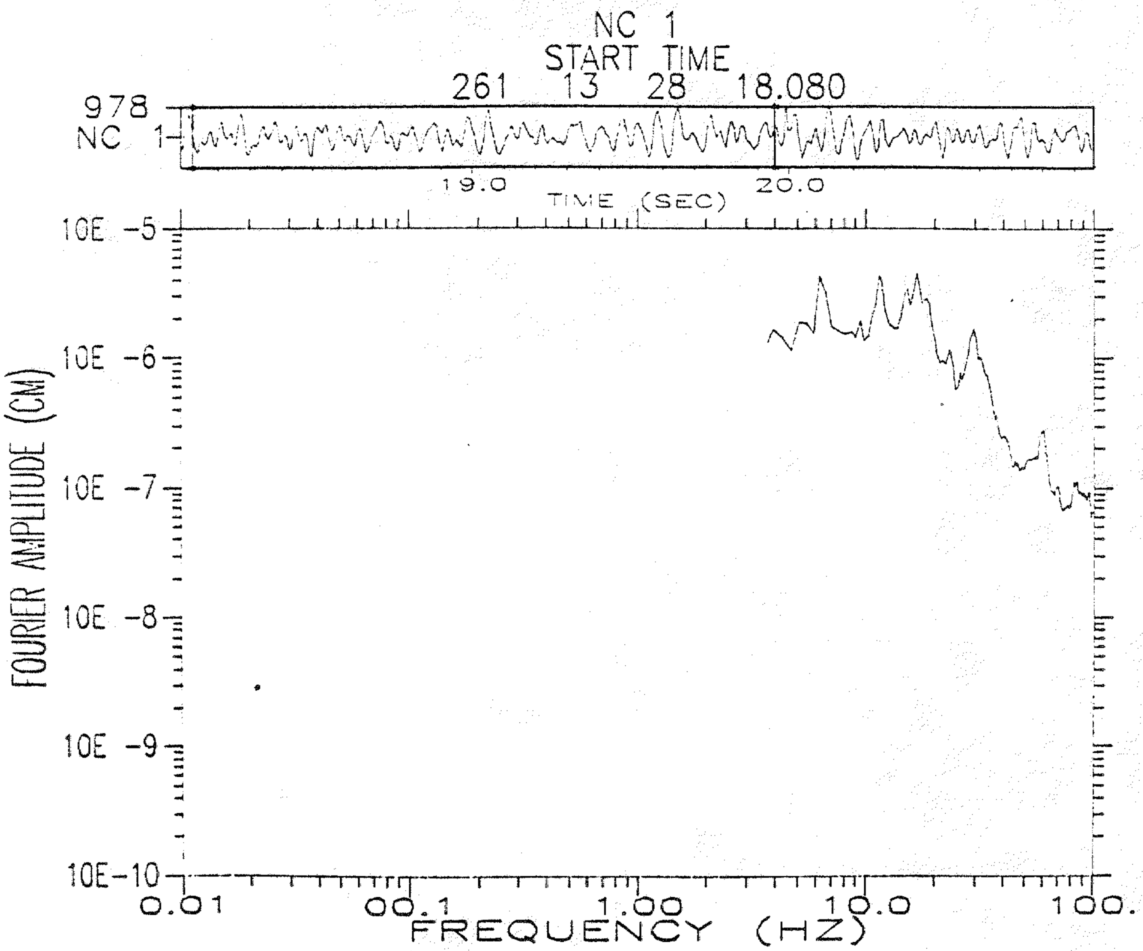
Figure 13. Displacement Response Measurements in the Bevatron High Bay. (Note: Bevatron ground motion is dominated by the motor generator set. See the 15, 30 and 60 Hz peaks.)



XBL 864-11077

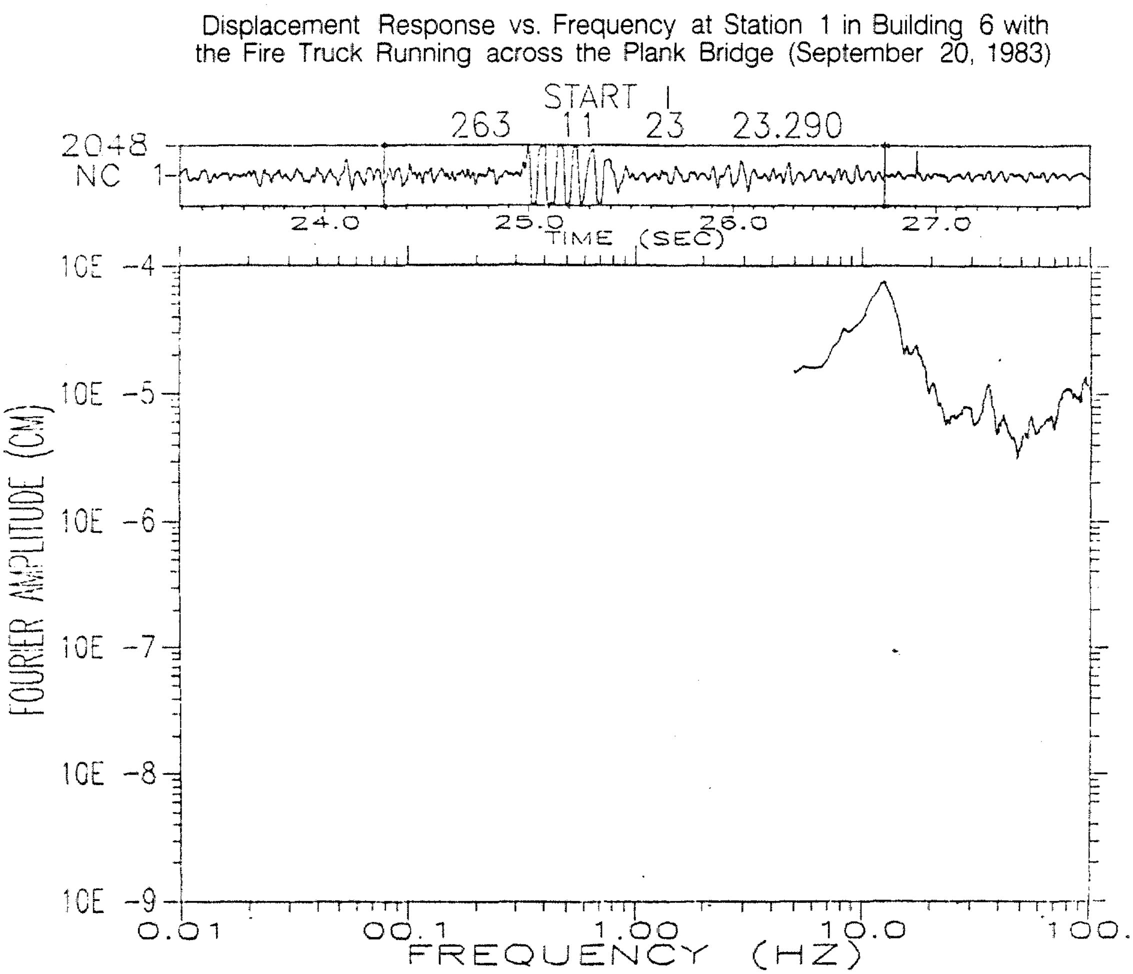
Figure 14. Displacement Response Measurements in Blackberry Canyon. (Note: The 15 Hz motor generator peak is evident. The 30 and 60 Hz peaks have decayed away. The high frequency noise may come from nearby transformer banks.)

Displacement Response vs. Frequency at Station 1 in
Building 6 with the Bevatron Running (September 18, 1983)



XBL 864-11078

Figure 15. Displacement Response Measurements at Station 1 in Building 6 with the Bevatron Running. (Note: The signal has a smaller amplitude than Figure 8. 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.)



XBL 864-11069

Figure 16. Displacement Response Measurements at Station 1 in Building 6 when an 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, and the signals are clipped slightly.)

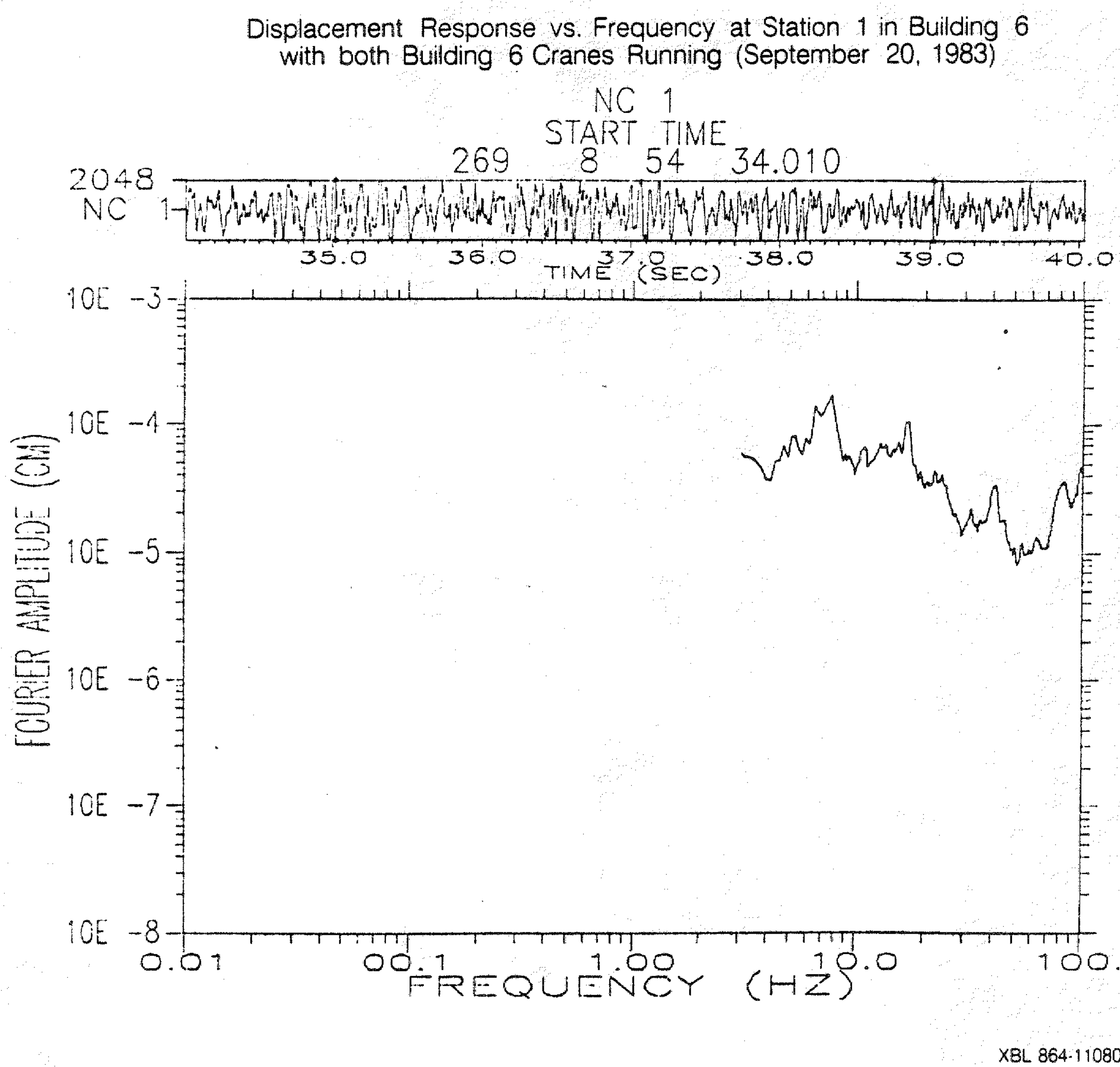


Figure 17. **Displacement Response Measurements at Station 1 in Building 6 with Both Cranes Running. (Note: Some peaks were clipped. The crane is a serious ground motion source.)**

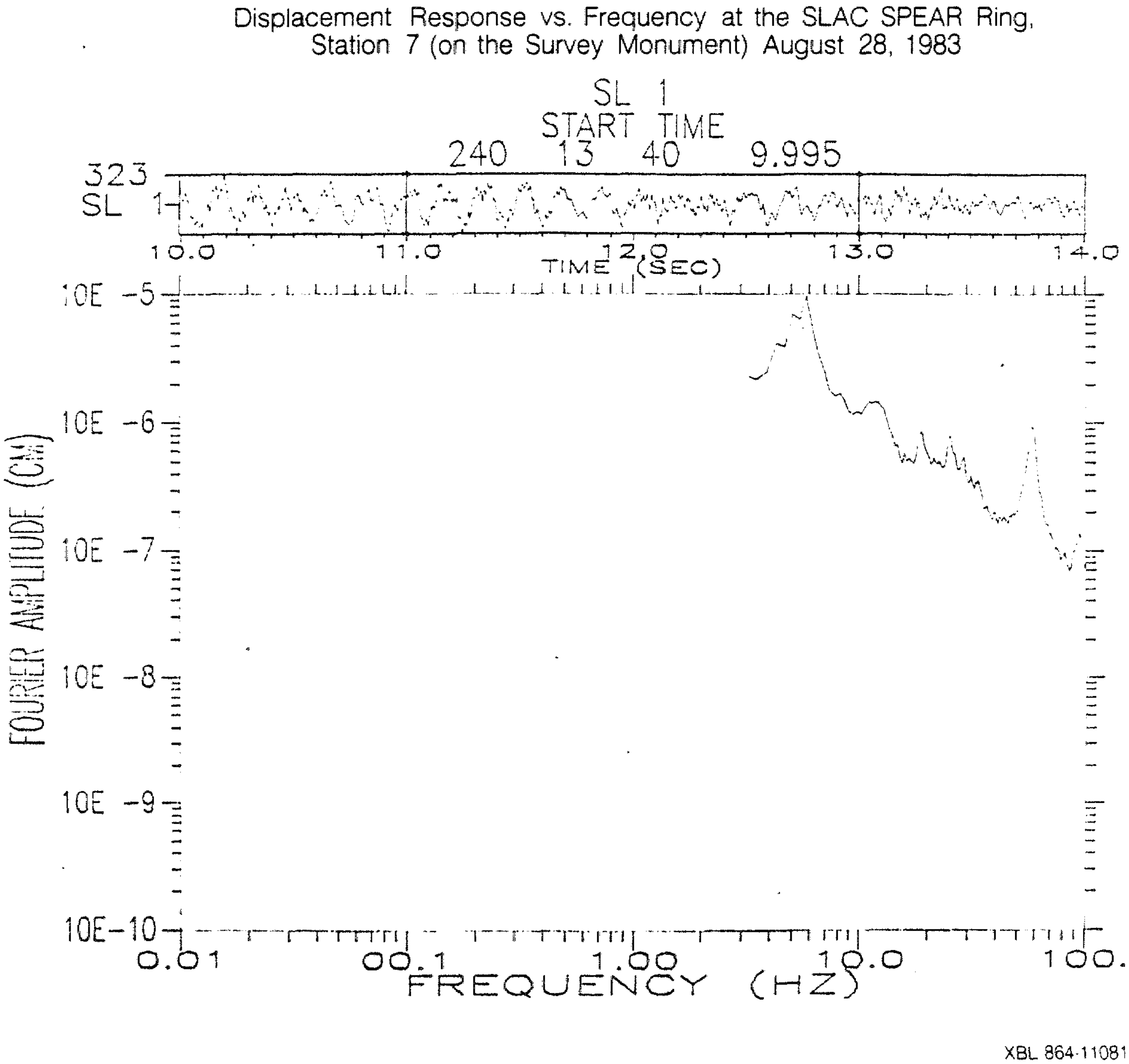


Figure 18. Displacement Response Measurements at Station 7 at the Survey Monument at the SLAC-SPEAR Ring. (Note: The 4.6 Hz compressor peak is visible.)

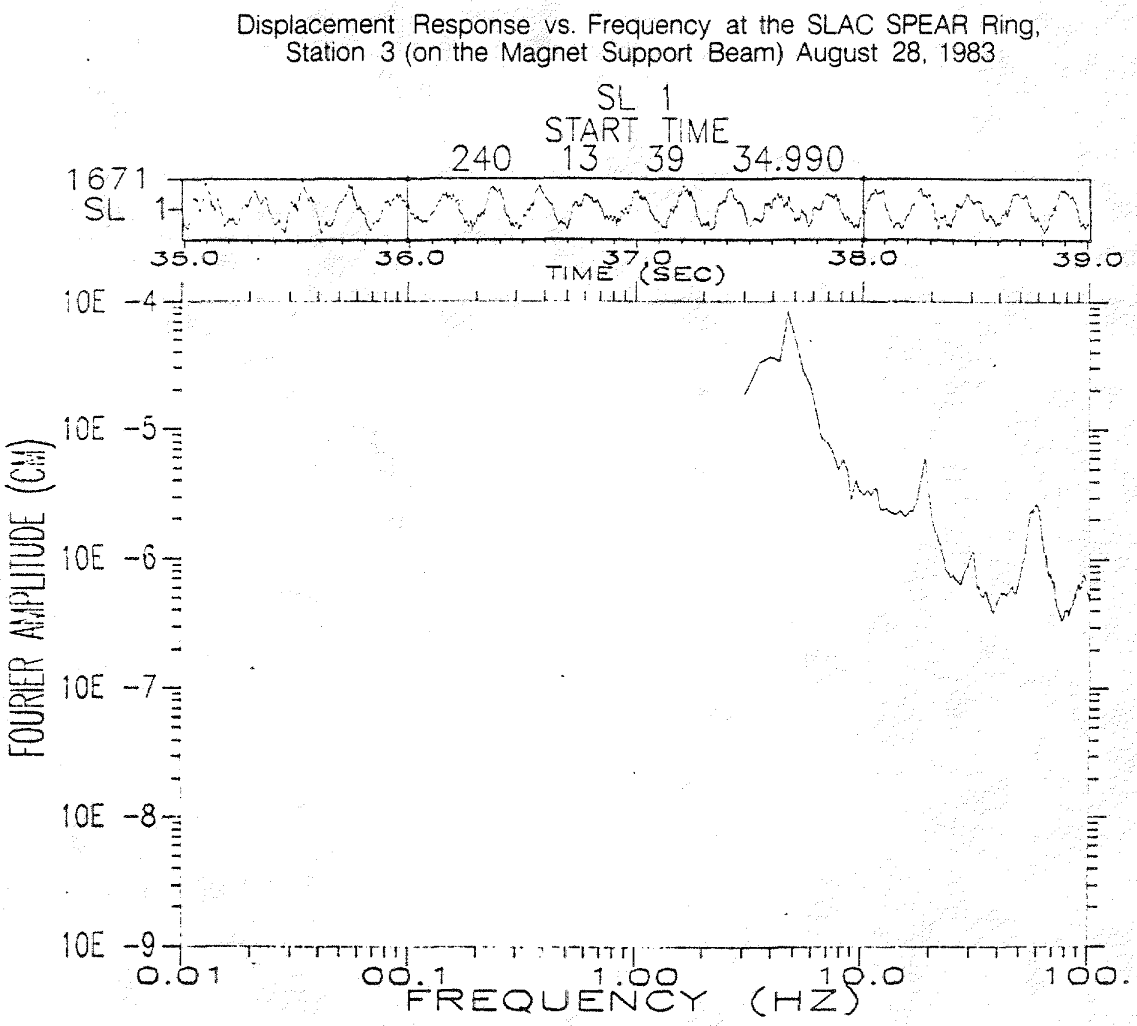
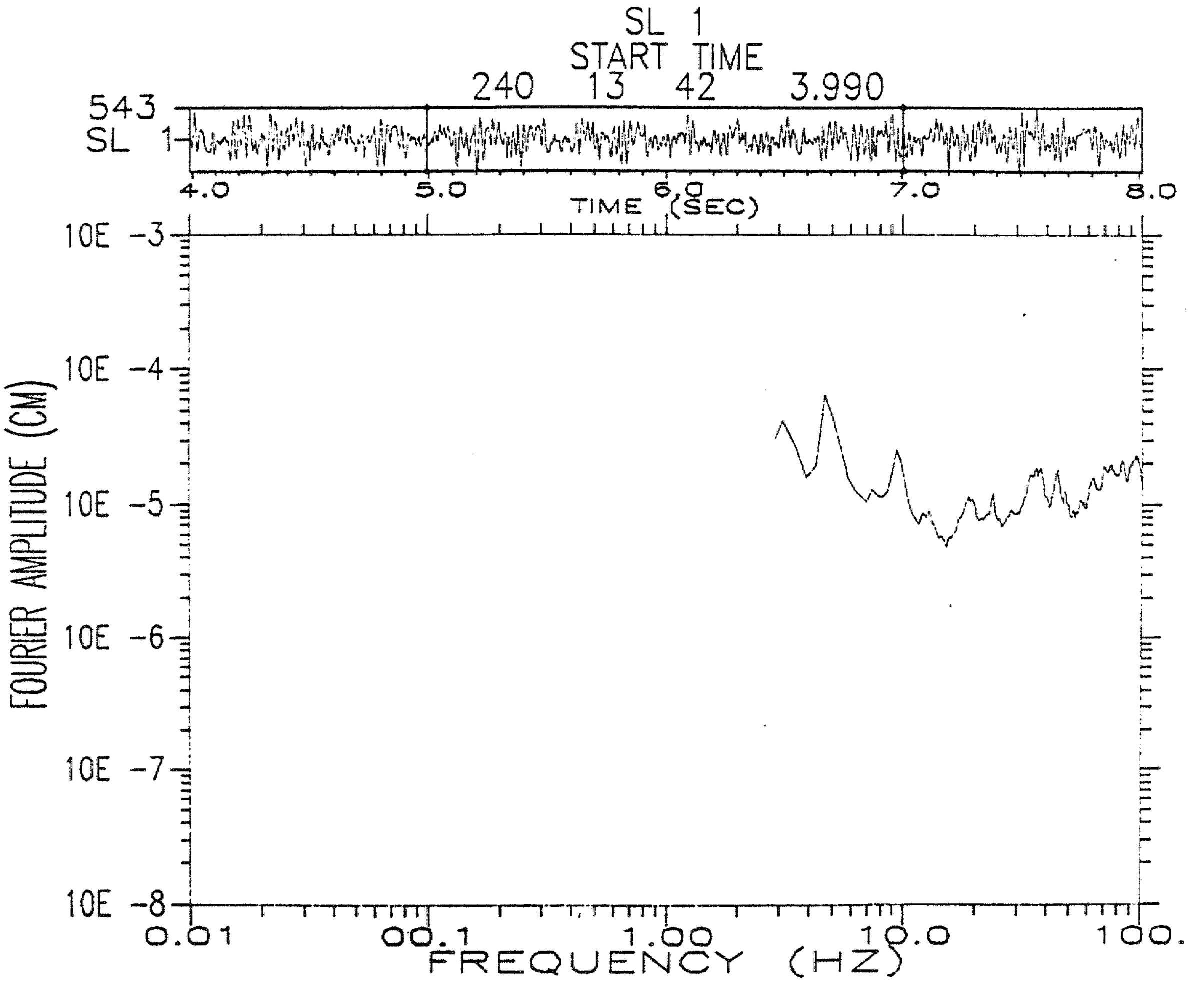


Figure 19. Displacement Response Measurements at Station 3 on the Magnet Beam at the SLAC-SPEAR Ring. (Note: The magnet beam magnifies the ground motion by about a factor of 3.)

Displacement Response vs. Frequency Outside the SLAC Compressor House (August 28, 1983)



XBL 864-11083

Figure 20. Displacement Response Measurements at Station 18 Outside 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 Hz and 9 Hz.)