Ground Motion Studies at SLAC

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- Seismometer Measurements
- Ground Motion Model
- Effect on Beam Motion in the NLC
INTRODUCTION

• Why is Ground Motion a Concern for the NLC:

  Ground motion will move the quadrupole magnets, 
  which will steer the beams, 
  which will cause them to miss at the IP: →←

• Scale of Problem:

  Motion slower than 0.1 Hz will be heavily suppressed 
  by trajectory feedback loops. 
  Motion faster than ≈ 60 Hz is generally not large 
  enough to have a significant effect. 
  Want uncorrelated vertical rms motion to be < 10 nm 
  for most quads and < 1 nm at the final doublet. 
  For f > 0.1 Hz, vertical ground motion ≈ few hundred 
  nm but it is correlated over long distances.

• Measurements of Vertical Motion:

  Two seismometers were used so both power and 
  correlation spectra could be measured. 
  Both were placed on the floor of the SLAC linac tunnel: 
  one at Sector 4 and other 0 to 2 km downstream. 
  Measurements were made at 2 AM during a period 
  when most power and cooling systems were off.
Seismometers

Ground Position = \( x_g \)

\[ \Delta V \propto x_g \quad \text{for} \quad f \gg f_{res} = \frac{1}{2\pi} \sqrt{\frac{k}{M}} \]

Streckeisen STS2

STS2 Axes

- Z-axis
- U-axis
- V-axis
- Sensor U
- Sensor V
- Sensor W
- Axis of Rotation
- Geometric Center
- V-axis
- X-axis
- Y-axis
- Sensor Y Locking Screw
- Sensor W Locking Screw
- Inertial Reference
STS2 VELOCITY RESPONSE

\[ \sqrt{f_{res}} \]

RESPONSE \([V_{sec}/m]\)  

FREQUENCY \([Hz]\)
STS2 MEASUREMENTS

1) Amplify signals from two STS2's by 100 and connect to channel 0 (ch0) and channel (ch1) of a PC digitizer running with Labview.

2) Scan at 64 kHz, filter and decimate → 128 Hz effective scan rate.

3) Record data for 1.8 hours and divide into 50, 128 sec long samples.

4) Compute FFT of 50 samples using a cos-like windowing function.

5) Average power, ⟨ch0²⟩ and ⟨ch1²⟩, and cross power, ⟨ch0 • ch1*⟩ of 50 samples at each frequency. Do same for signal difference, ch0 - ch1.

Example of a 128 sec sample (d2 = 100 m)

RMS

Hist of 50 RMS's
Spectra measured at 2AM in LTOY-8 : $\Delta Z = 0$

\[ \text{power}[(\text{microns RMS}^2/\text{Hz})^{1/4}] \]

\[ \begin{array}{c}
1 \times 10^0 \\
1 \times 10^{-1} \\
1 \times 10^{-2} \\
1 \times 10^{-3} \\
1 \times 10^{-4} \\
1 \times 10^{-5} \\
1 \times 10^{-6} \\
1 \times 10^{-7} \\
1 \times 10^{-8} \\
1 \times 10^{-9} \\
1 \times 10^{-10} \\
\end{array} \]

\[ \begin{array}{c}
1 \times 10^{-2} \\
1 \times 10^{-1} \\
1 \times 10^{0} \\
1 \times 10^{1} \\
1 \times 10^{2} \\
\end{array} \]

\[ \text{frequency [Hz]} \]

\[ \approx 2 \times \text{STS-2 Noise} \]

Integrated amplitude [microns RMS]

\[ \begin{array}{c}
1 \times 10^0 \\
1 \times 10^{-1} \\
1 \times 10^{-2} \\
1 \times 10^{-3} \\
1 \times 10^{-4} \\
1 \times 10^{-5} \\
\end{array} \]

\[ \begin{array}{c}
1 \times 10^{-2} \\
1 \times 10^{-1} \\
1 \times 10^{0} \\
1 \times 10^{1} \\
1 \times 10^{2} \\
\end{array} \]

\[ \text{frequency [Hz]} \]
Let \( \tilde{y}_i(f) \) = Complex FT of vertical ground motion at \( z_i \)

\[ \Delta z = z_2 - z_1 \]

Then \[ \rho(f) = \frac{\langle \tilde{y}_1 \cdot \tilde{y}_2^* \rangle}{\sqrt{\langle \tilde{y}_1^2 \rangle \langle \tilde{y}_2^2 \rangle}} \]

\[ = \cos(2\pi f \Delta z \cos(\varphi)/v) + i \sin(2\pi f \Delta z \cos(\varphi)/v) \]

Now let wave direction be isotropic and average over \( \varphi \):

\[ \rho(f) \rightarrow J_0(2\pi f \Delta z/v) + i 0 \]

Fit measured \( \text{Re}[\rho(f)] \) -vs- \( \Delta z \) to \( J_0 \) dependence to find \( v(f) \).
$0.80 < f < 0.90$

$1 - \rho$

$10^0$ to $10^4$

$L(m)$

- min velocity = 1510
-- fit velocity = 1502.000

residuals$/\sqrt{2}$

1200 to 2000

velocity [m/s]
**MEASURED VELOCITIES**

\[
V = 450 + 1900 \exp \left( -f/2.0 \right)
\]
Correlation spectra for vertical vibrations

*Measured in the LEP tunnel*
Power Law Fit

\[ V(\text{km/s}) \propto \beta(\text{Refl.}) = 0 : \begin{cases} 1.6 \Delta z^{-3.2} \quad (\text{SLC}) \\ 2.1 \Delta z^{-3.0} \quad (\text{LEP}) \end{cases} \text{ for } \Delta z \text{ in km} \]

--- \( V = 1330/f^{0.46} \)

\( V(\text{m/s}) \)

\( f(\text{Hz}) \)

\( 10^3 \)

\( 10^0 \)

\( 10^1 \)
FIG. 18. Dispersion and attenuation of fundamental mode Love (—) and Rayleigh (---) waves for the (flat) anelastic "continental structure" given in Table XV.
Chilean Earthquake

Power Spectrum measured at LIDY-8
at 2 AM on 10 different days

--- = Average
Figure 22:
Comparison of power spectral densities of slow ground motion (vertical), measured in accelerator sites (HMB - DESY, NSK - Budker INP, KEK) and in geophysics labs (GAR, QCN, ZUR (see comments in text))
EFFECT ON LUMINOSITY

Sensitivity and Integrated Motion:

For wave-like motion at frequency \( f \),

\[
\frac{\Delta \mathcal{L}}{\mathcal{L}} \propto \sum_{i,j} g_i g_j J_0(2\pi f \Delta z_{i,j}/\nu)
\]

where \( g_i = \) Quad \( i \) to IP lattice transfer function

Factor in \{ Trajectory feedback response \} and compute \{ Limits due to STS 2 resolution \}

Sensitivity \( \equiv \) RMS Motion \( \rightarrow \frac{\Delta \mathcal{L}}{\mathcal{L}} = 1.5 \% \)

Integrated \( (f > 0.01 \text{ Hz}) \) luminosity loss:

\[
\frac{\Delta \mathcal{L}}{\mathcal{L}} = 1.5 \% \int \frac{P(f)}{\text{Sensitivity}^2(f)} \, df = 0.13 \%
\]
SLC TRAJECTORY FEEDBACK

Diagram showing the flow of electrons (e\(^-\)) through correctors, micro-processor, and BPMs.

Graph showing Betatron Amplitude Attenuation (60 Hz Sampling Rate) versus Frequency (Hz) with measurements and theory plotted.
Minimum Value of $1 - \rho$ Measurable
due to STS-2 Noise

\[ 1 - \rho \text{ for } \Delta z = 0 = \frac{\text{Noise Power}}{\text{Total Power}} \]
Quad and Ground Motion in the FFB

Integrated Vertical Ground Motion (nm)

- Top of Quad
- On the Floor
- Difference

Frequency (Hz)