Ground Motion Studies at SLAC

Chris Adolphsen
John Irwin
Gholam Mazaheri
Tim Slaton
Frank Zimmermann

- ❑ 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: $\rightarrow\leftarrow$

- 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.

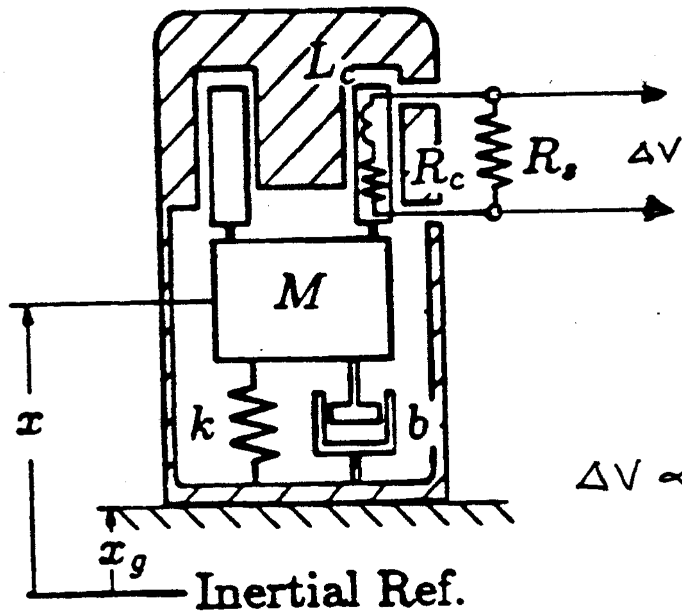
- Measurements of Vertical Motion:

  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.

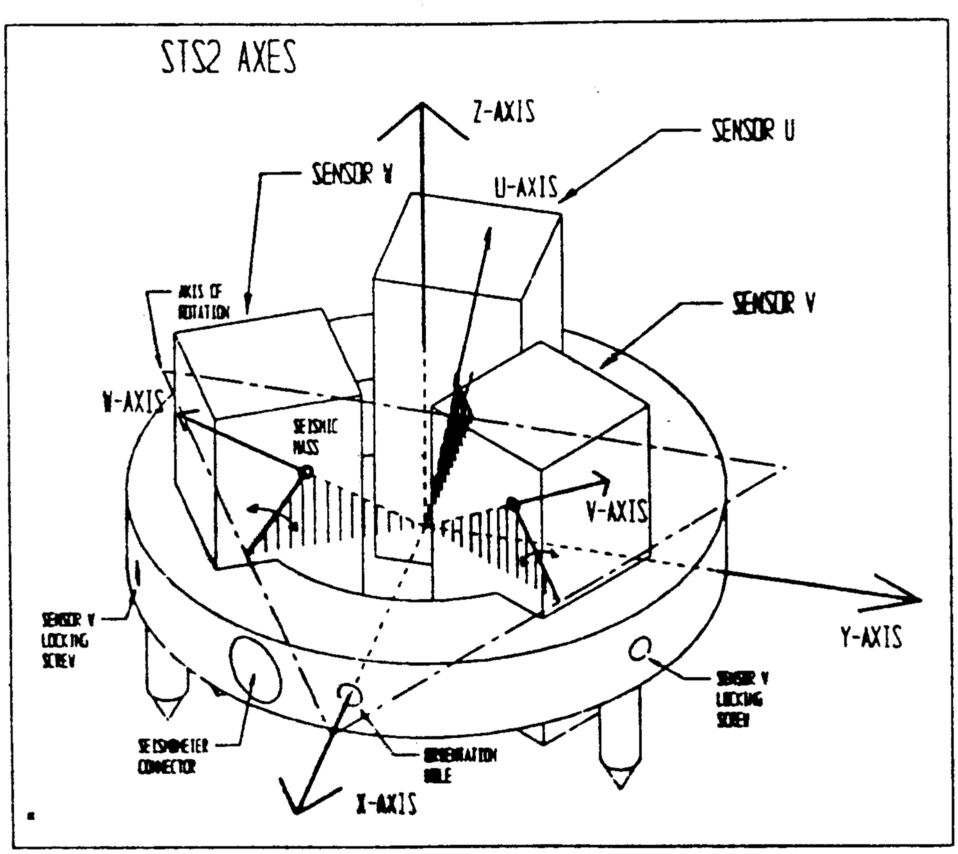
SEISMOMETERS



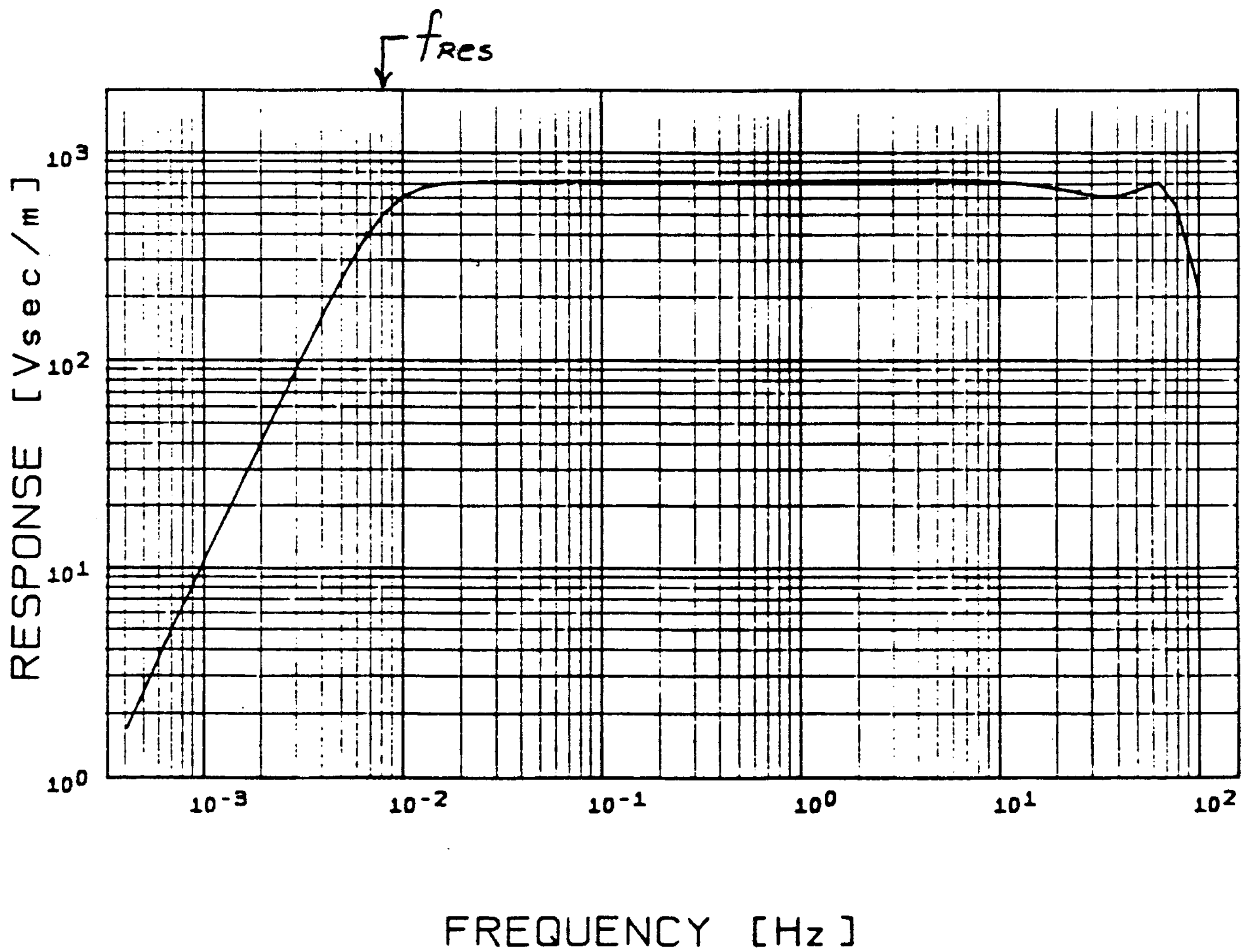
Ground Position $= x_g$

$$\Delta V \propto \dot{x}_g \text{ for } f \gg f_{res} = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$$

STRECKEISEN STS2



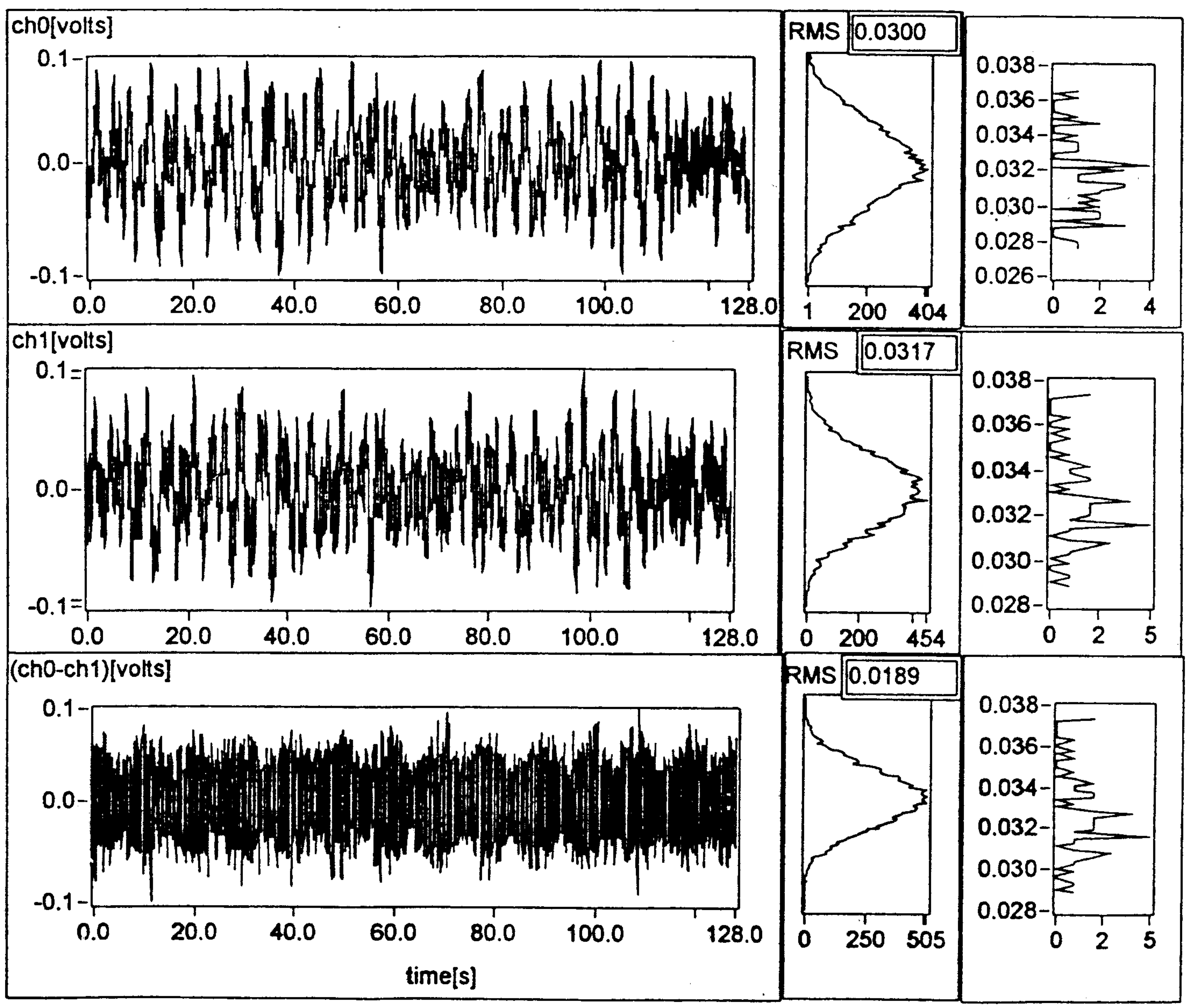
STS2 VELOCITY RESPONSE



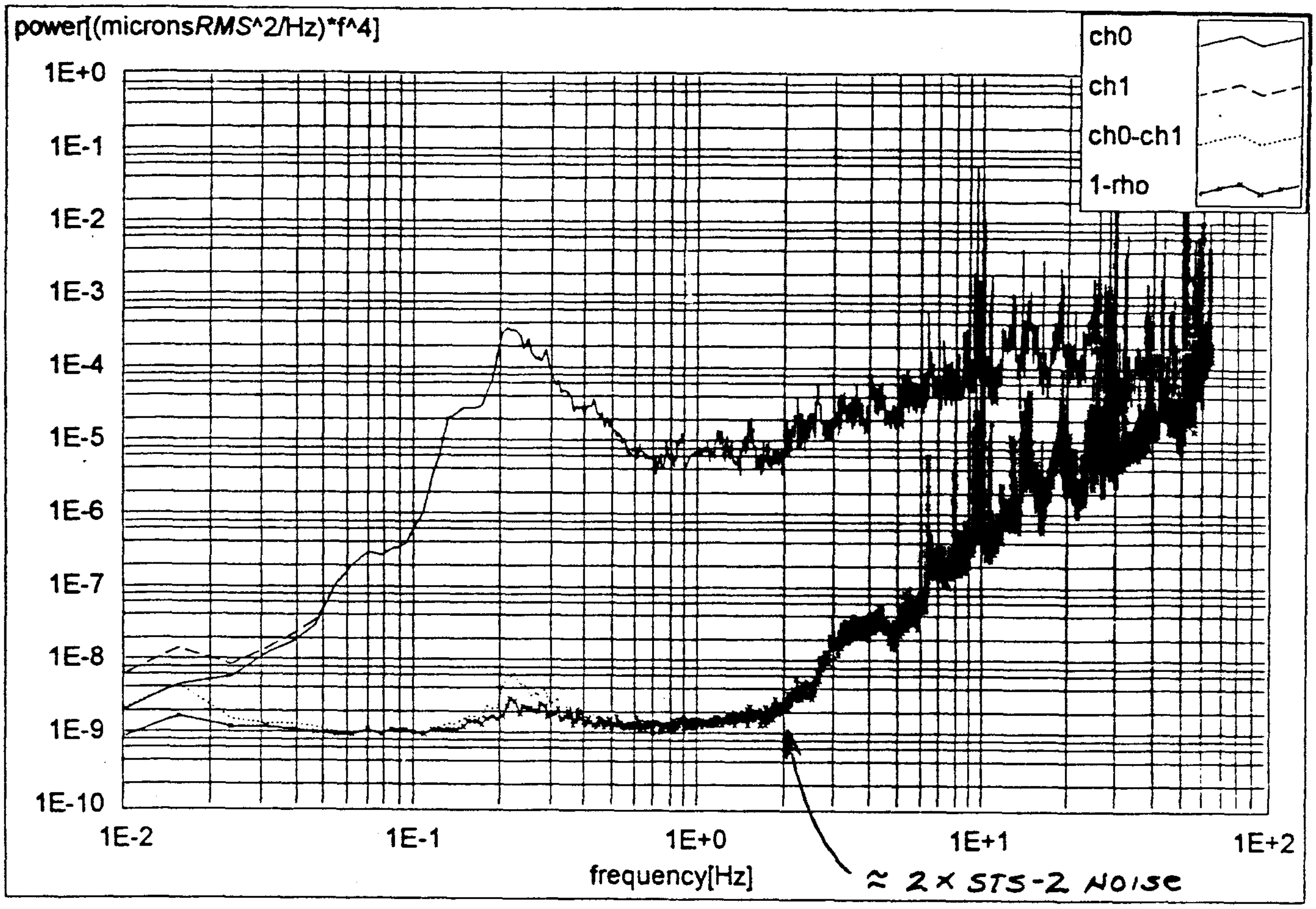
STS2 MEASUREMENTS

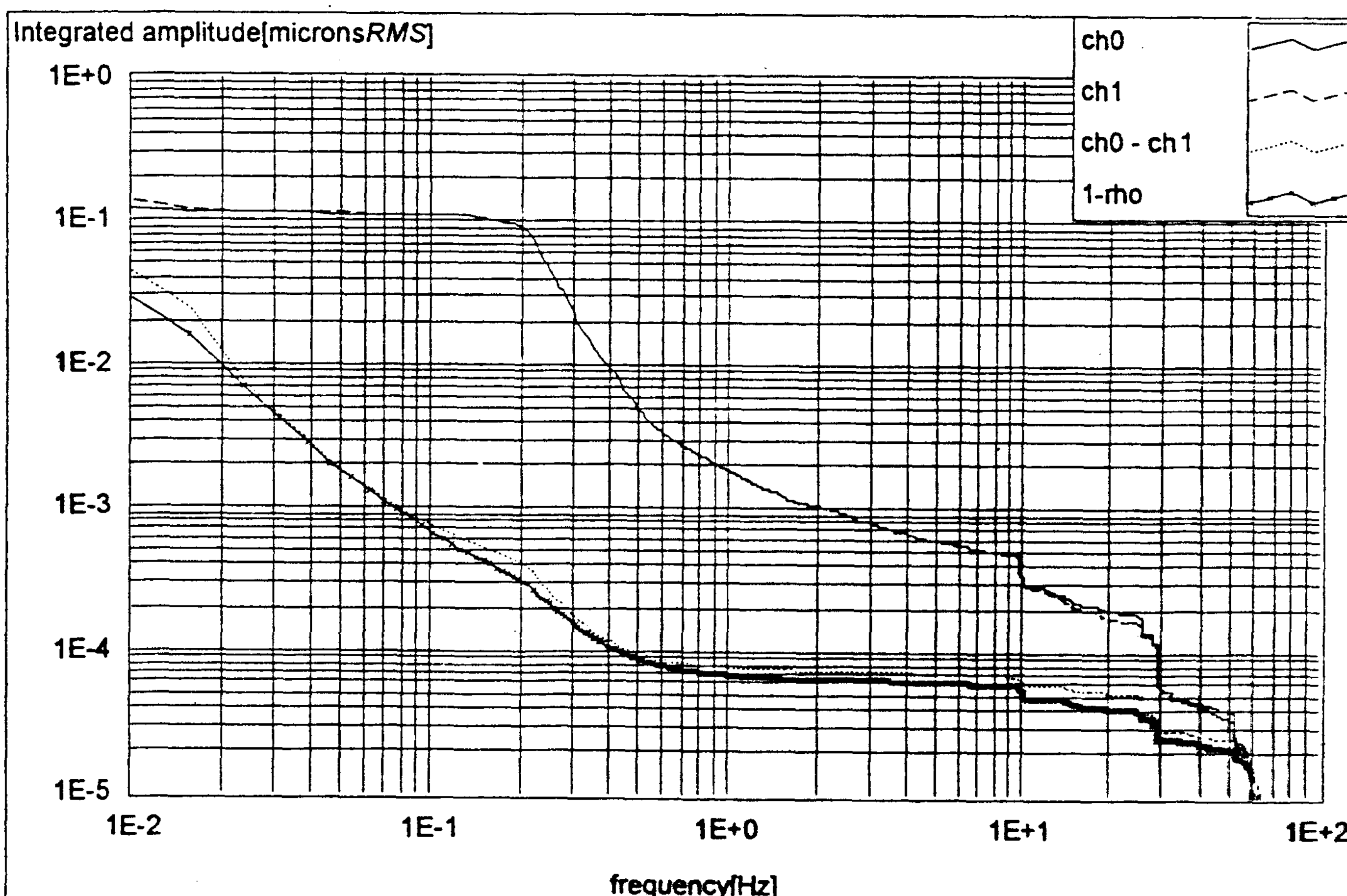
1) Amplify signals from two STS2's by 100 and connect to channel 0 (ch0) and channel (ch1) of a PC digitizer running with Labview.
2) Scan at 64 kHz, filter and decimate → 128 Hz effective scan rate.
3) Record data for 1.8 hours and divide into 50, 128 sec long samples.
4) Compute FFT of 50 samples using a cos-like windowing function.
5) Average power, $\langle ch0^2 \rangle$ and $\langle ch1^2 \rangle$, and cross power, $\langle ch0 \bullet ch1^* \rangle$ of 50 samples at each frequency. Do same for signal difference, ch0 - ch1.

Example of A 128 sec Sample (Δz = 100 m) RMS Hist of 50 RMS's

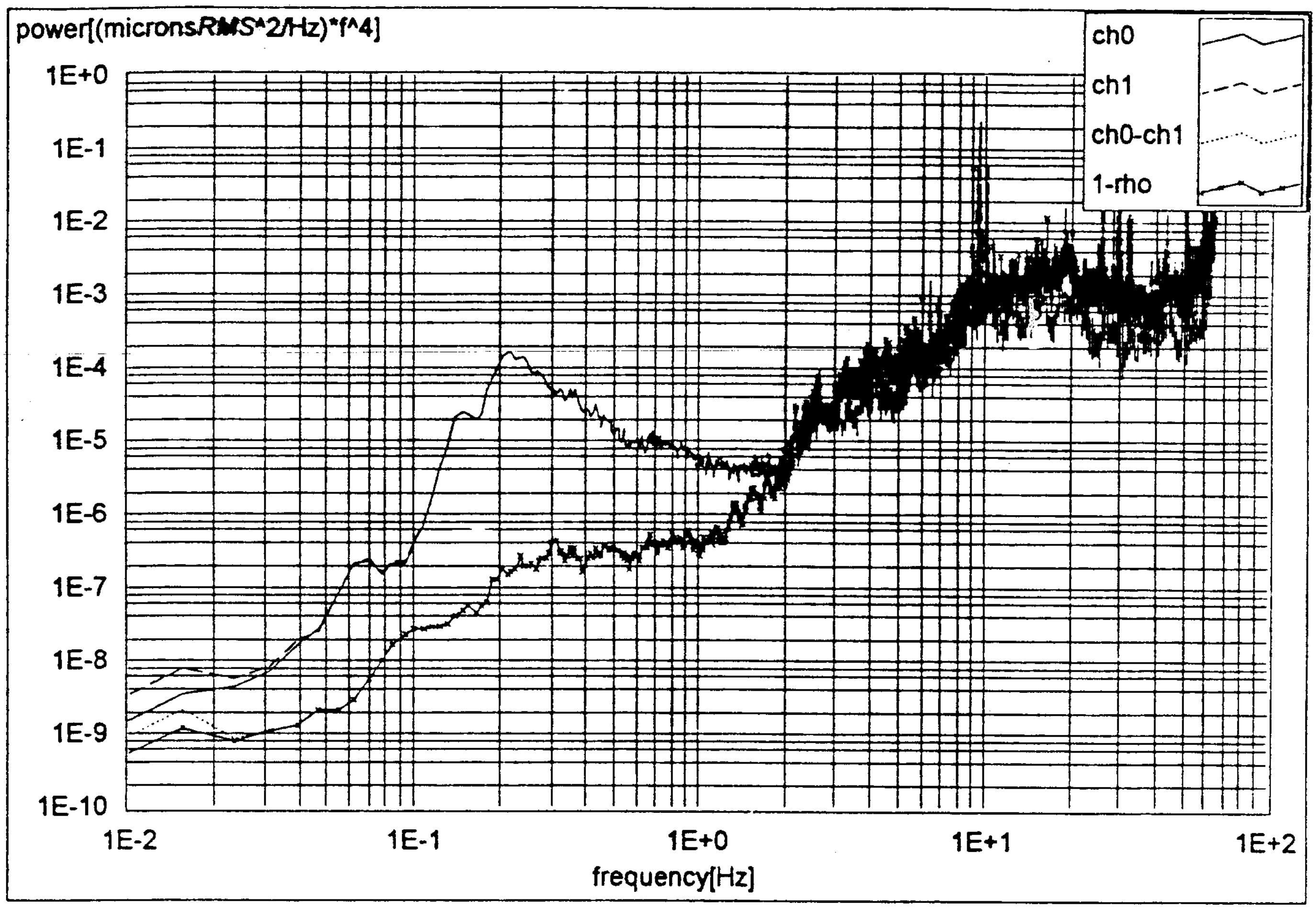


Spectra Measured at 2AM in LI04-8 : ΔZ = 0

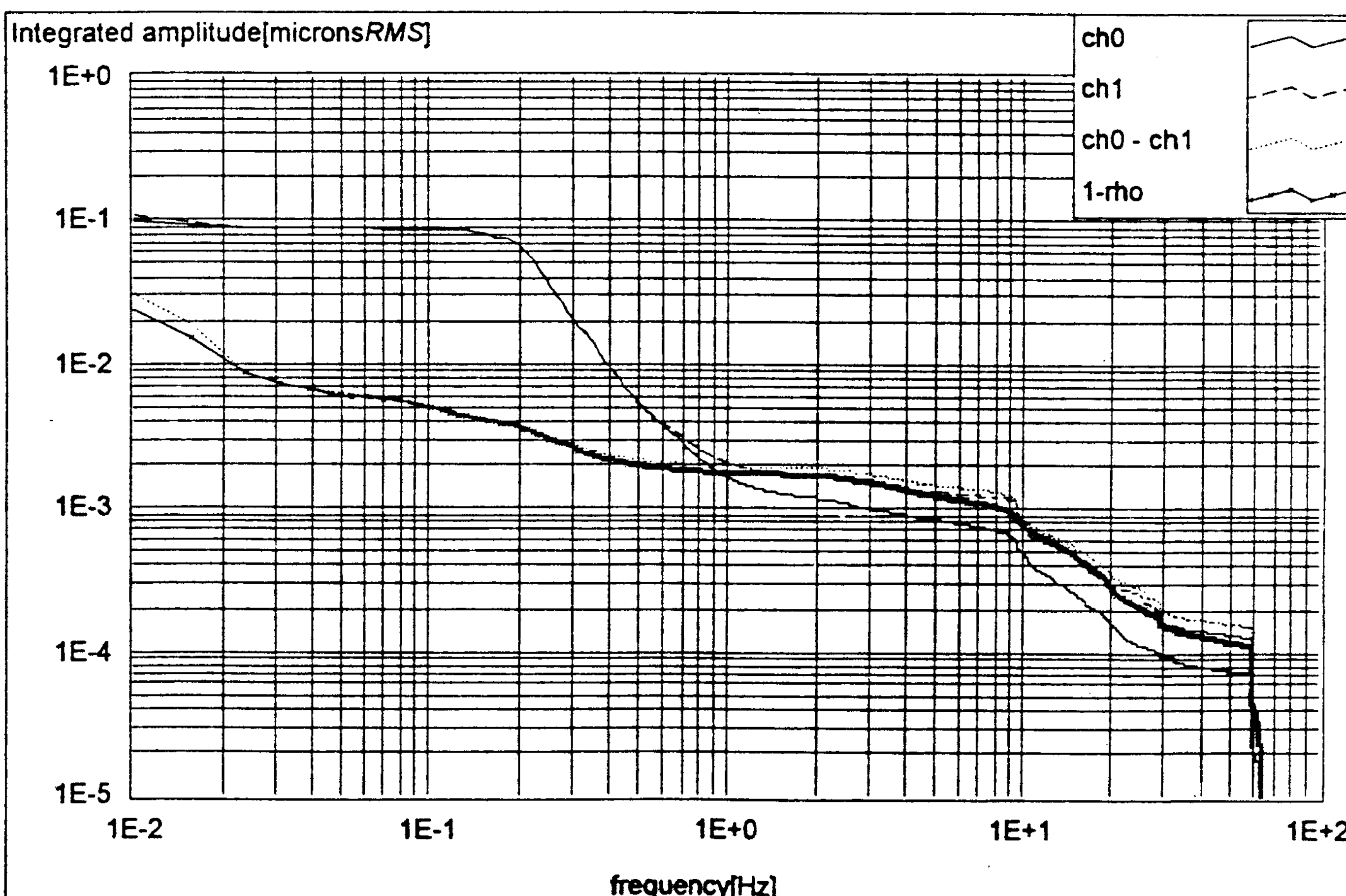




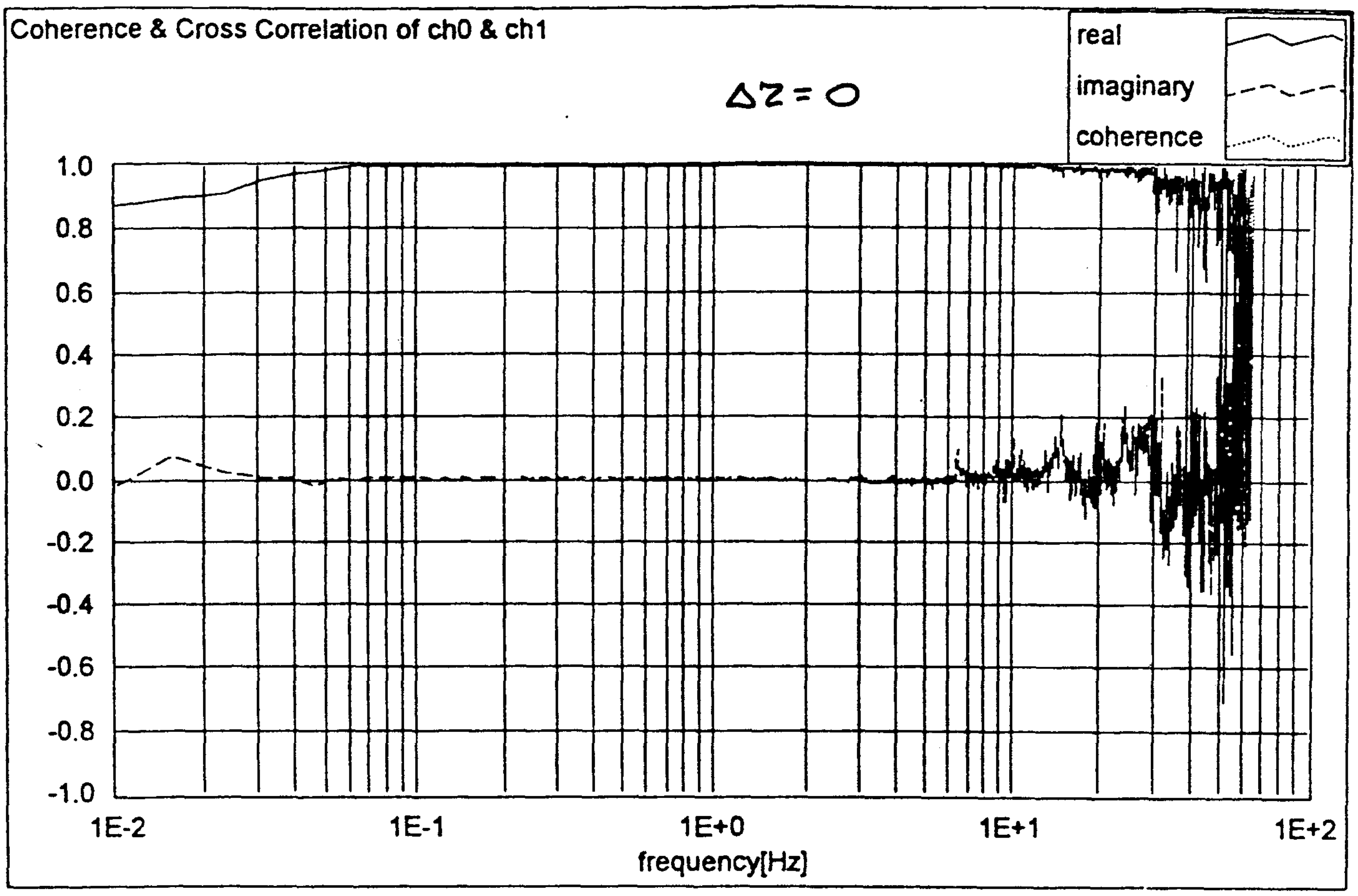
Δz = 100 m

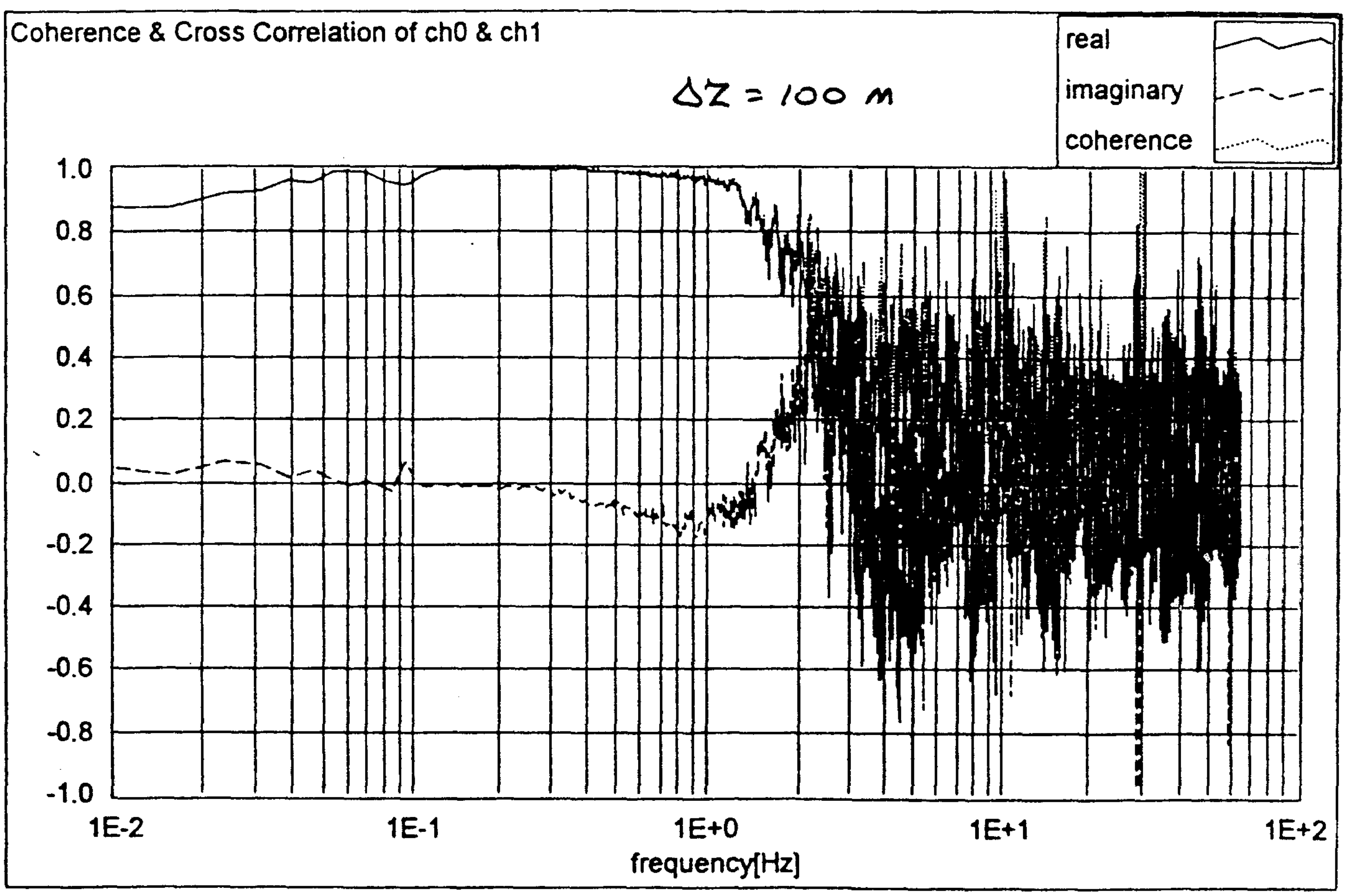


power[(micronsRMS^2/Hz)*f^4]
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]
ch0
ch1
ch0-ch1
1-rho

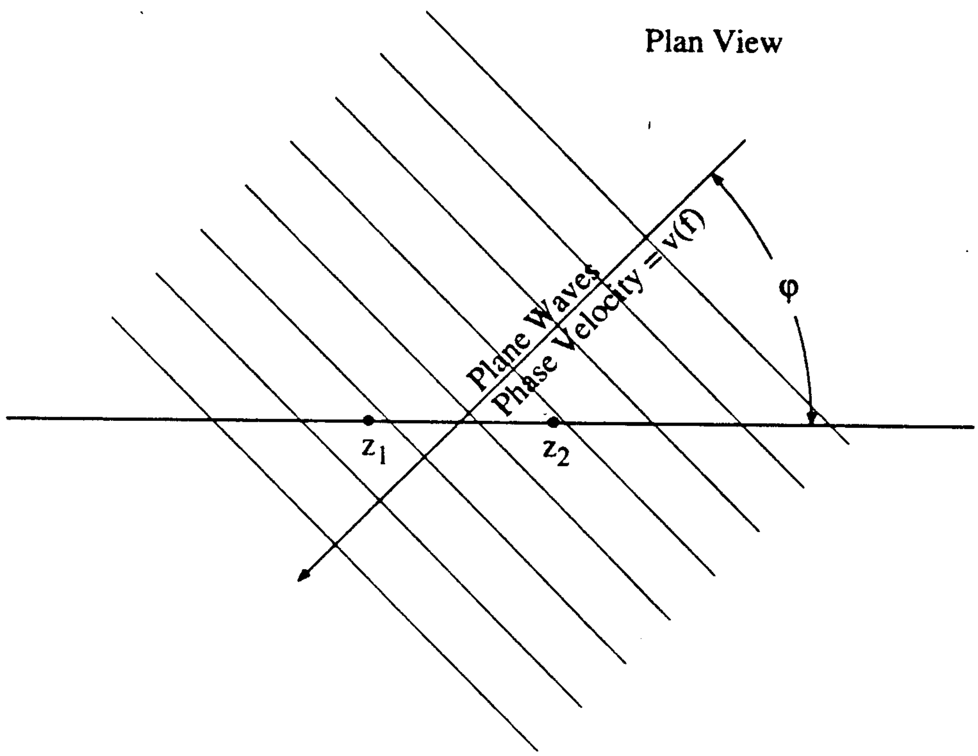


Integrated amplitude[micronsRMS]
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]
ch0
ch1
ch0 - ch1
1-rho


Coherence & Cross Correlation of ch0 & ch1
real
imaginary
coherence
ΔZ = 0
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]


Coherence & Cross Correlation of ch0 & ch1
real
imaginary
coherence
ΔZ = 100 m
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]

2D GROUND MOTION MODEL



Let $\tilde{y}_i(f)$ = Complex FT of vertical ground motion at z_i

$\Delta z = z_2 - z_1$

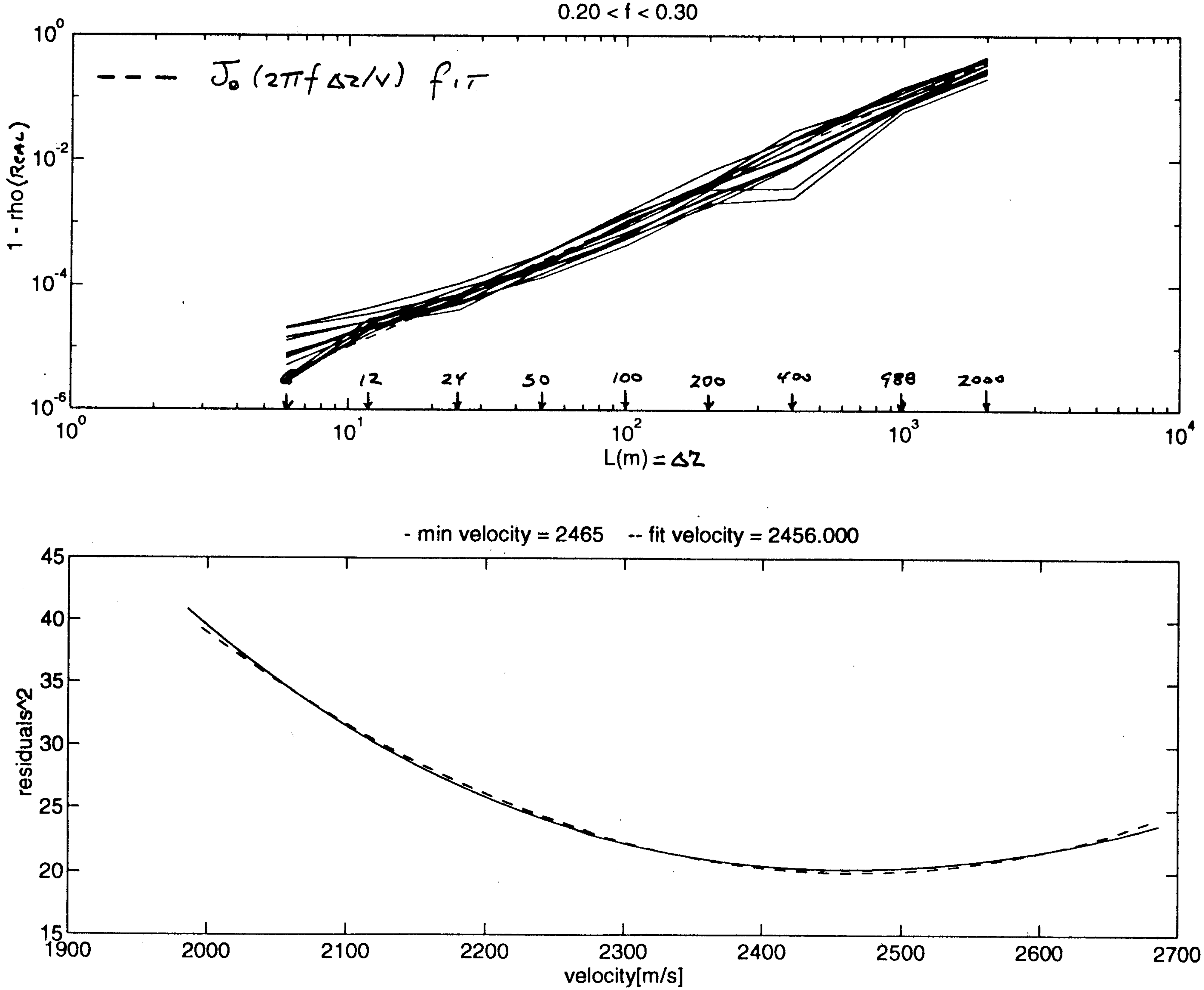
Then $\rho(f) \equiv \langle \tilde{y}_1 \cdot \tilde{y}_2^* \rangle_t \Big/ \sqrt{\langle \tilde{y}_1^2 \rangle_t \langle \tilde{y}_2^2 \rangle_t}$

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

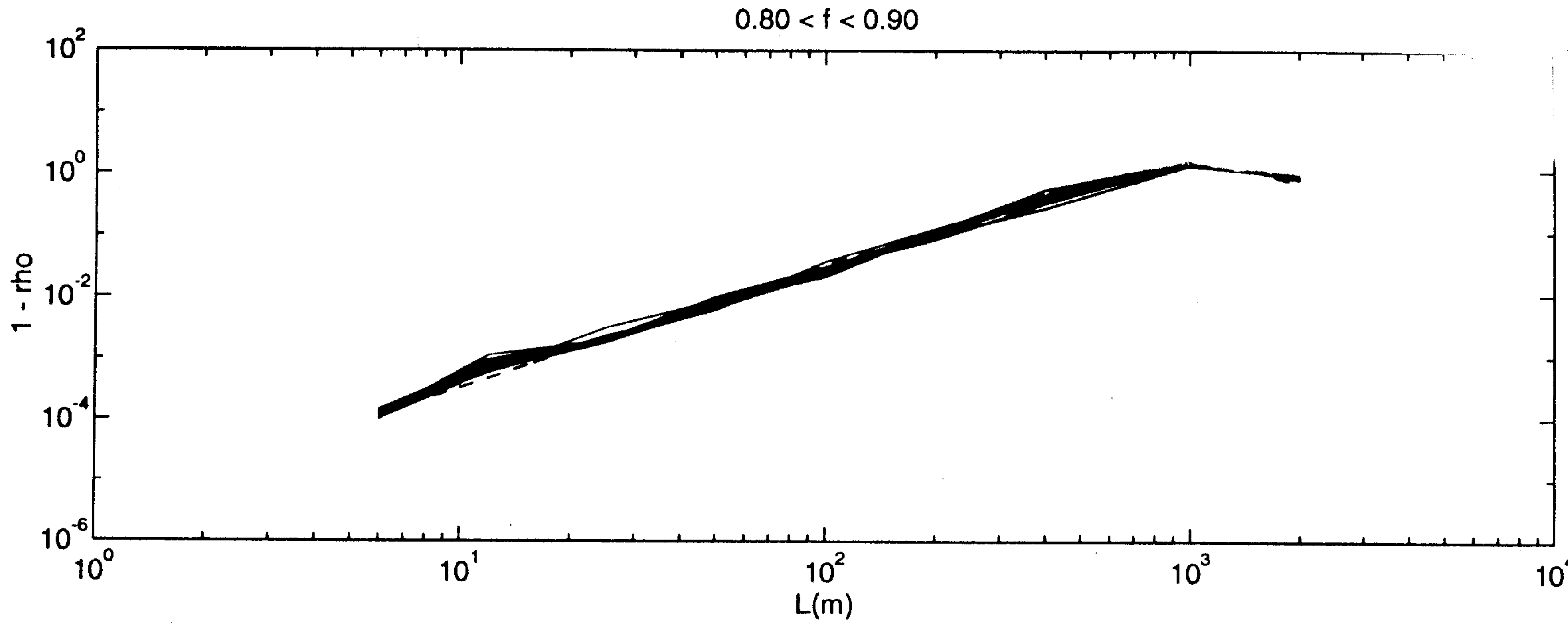
Now let wave direction be isotropic and average over φ:

$\rho(f) \to J_0(2\pi f \Delta z/v) + i0$

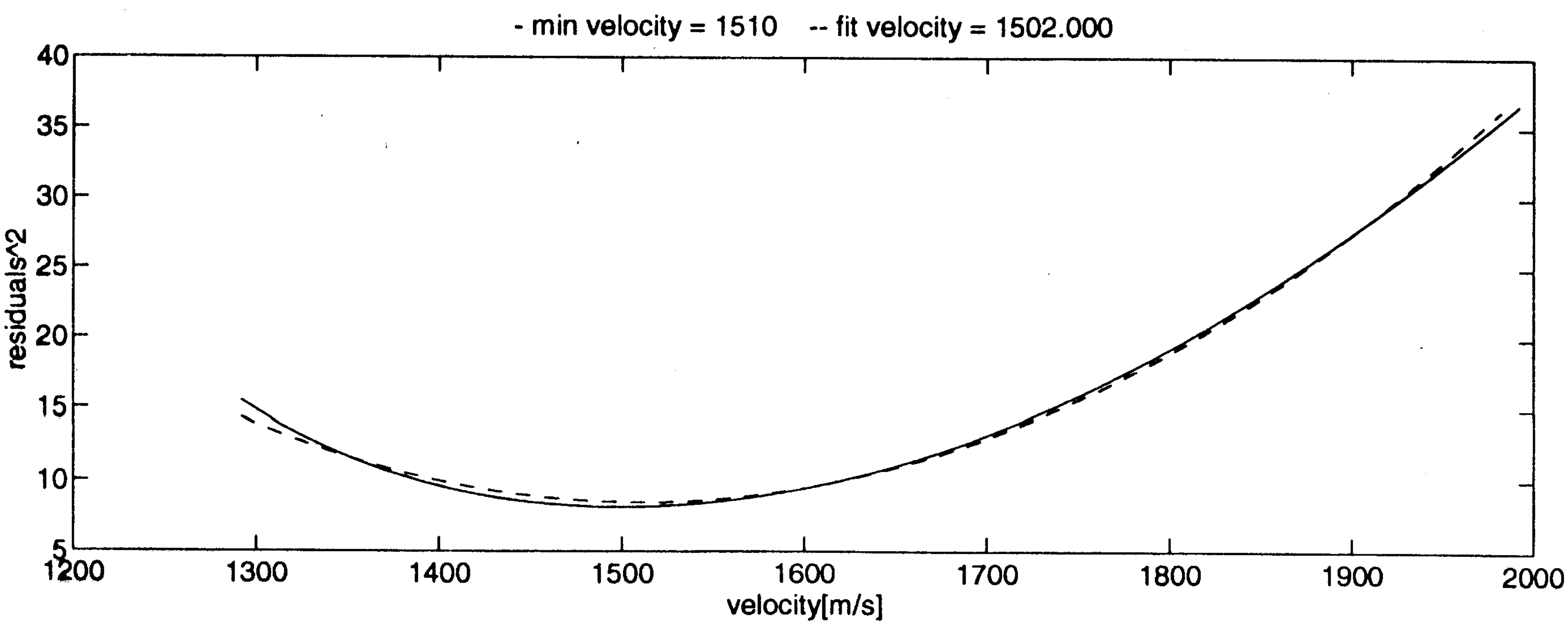
Fit measured $\mathrm{Re}[\rho(f)]$ -vs- Δz to J_0 dependence to find v(f).



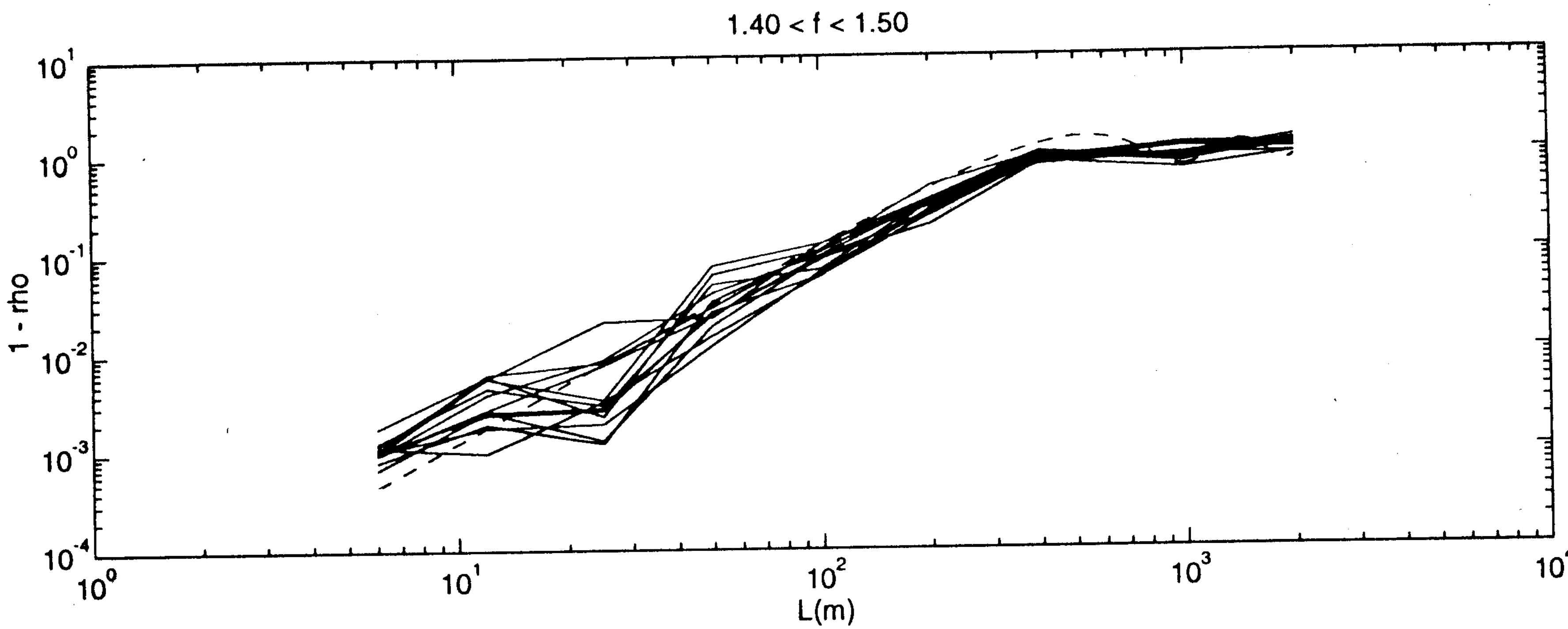
0.20 < f < 0.30
- - - $J_0(2\pi f \Delta z/v)$ fit
1 - rho(Real)
12
24
50
100
200
400
988
2000
L(m) = ΔZ
- min velocity = 2465 -- fit velocity = 2456.000
residuals^2
velocity[m/s]

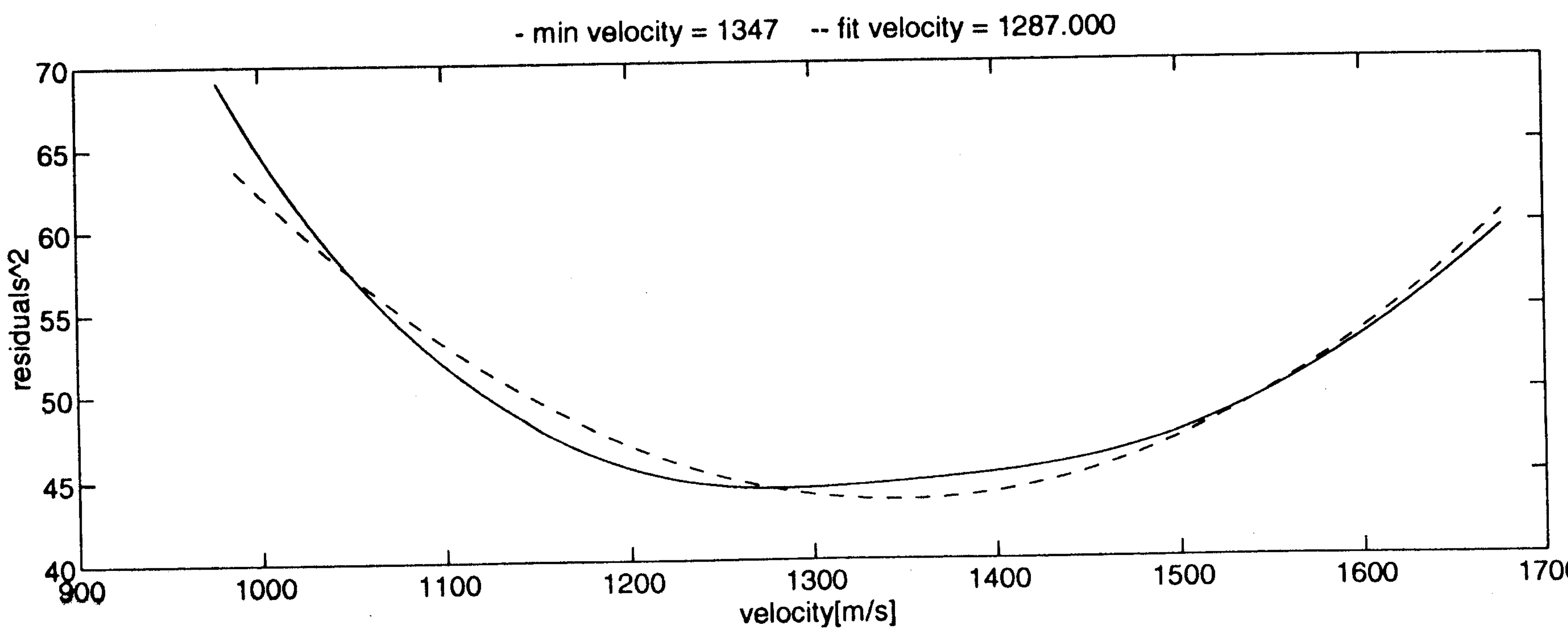


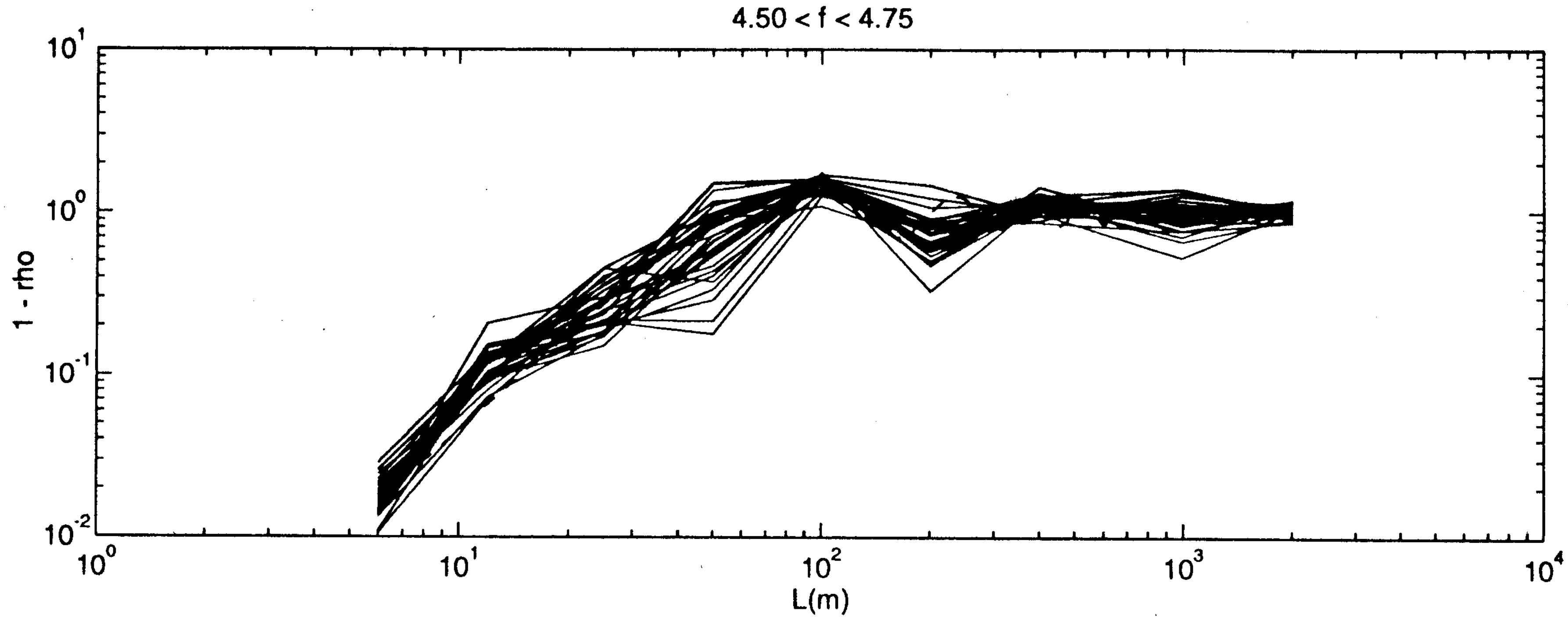
0.80 < f < 0.90
1 - rho
L(m)

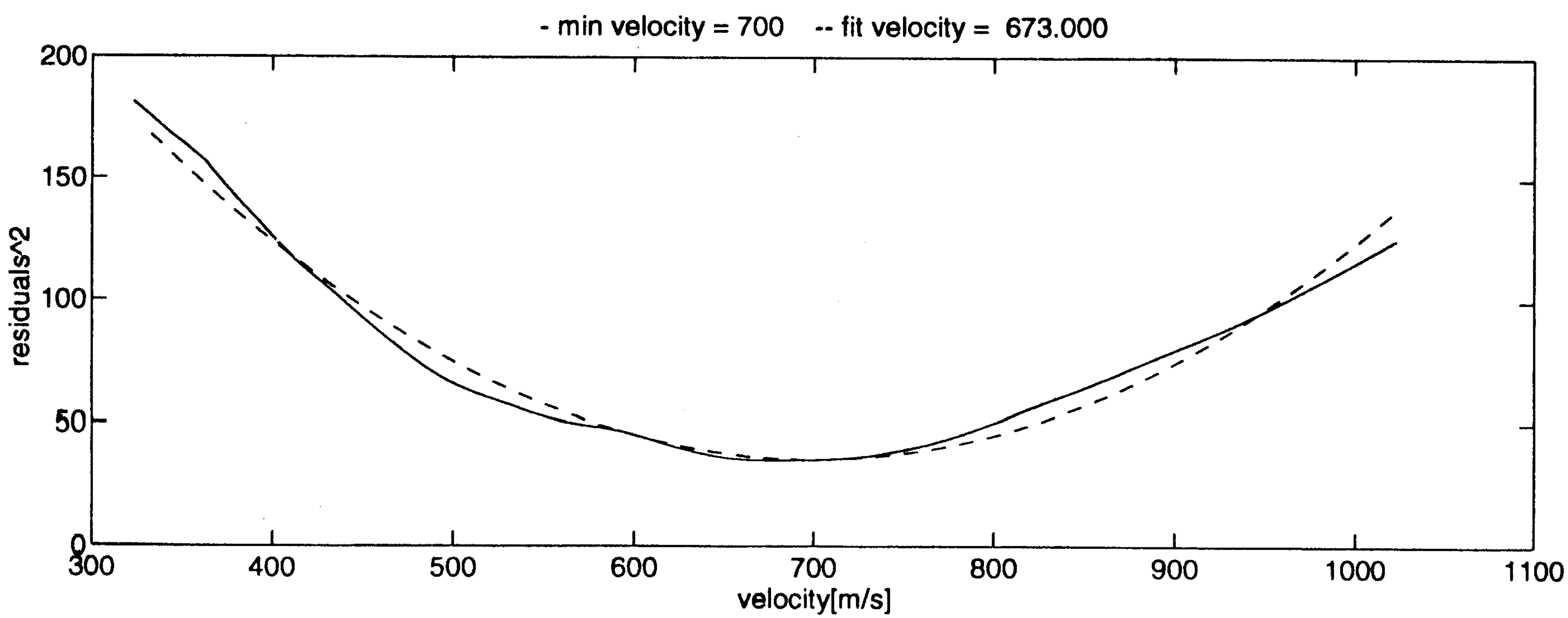


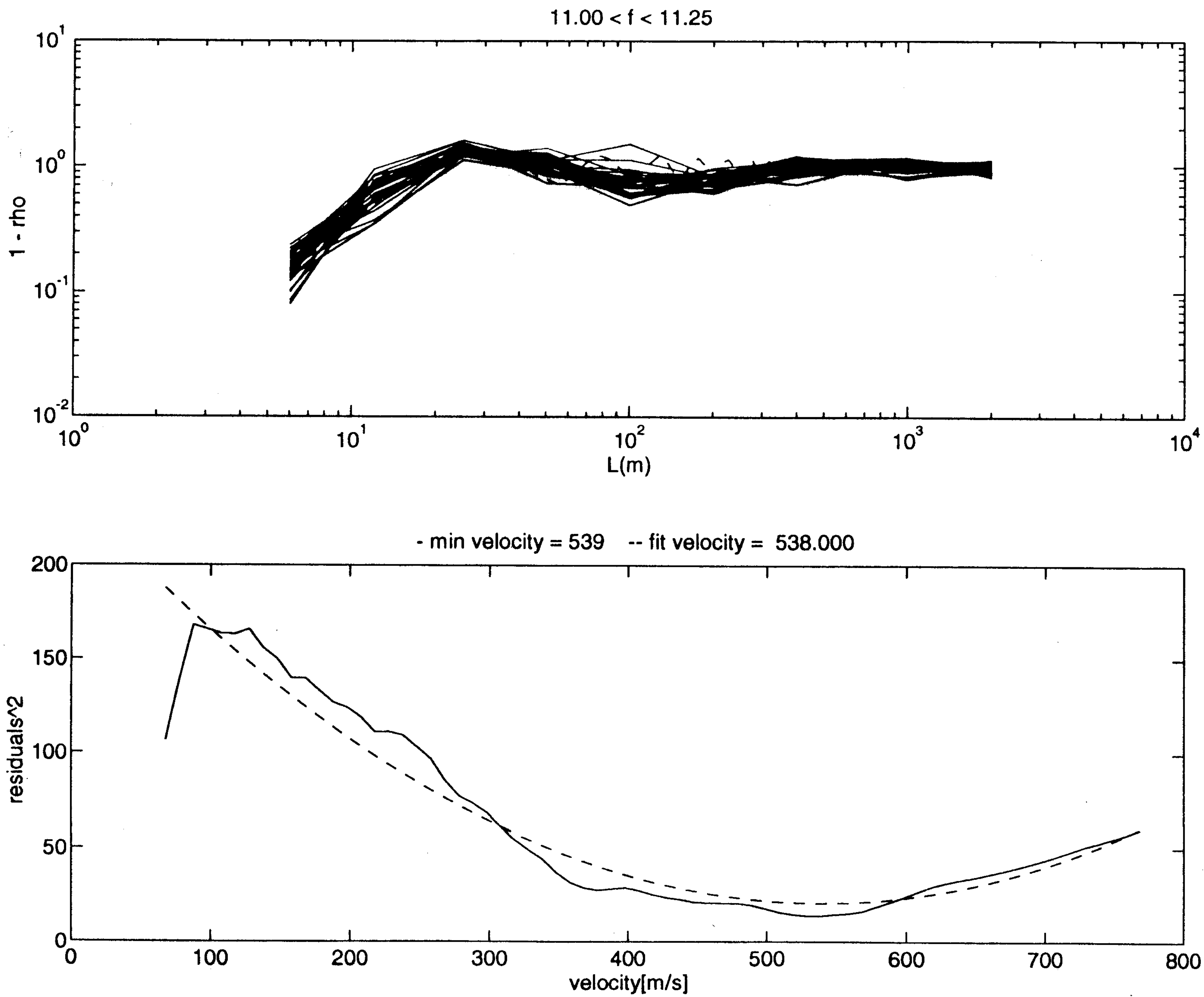
- min velocity = 1510 -- fit velocity = 1502.000
residuals^2
velocity[m/s]


1.40 < f < 1.50
1 - rho
L(m)

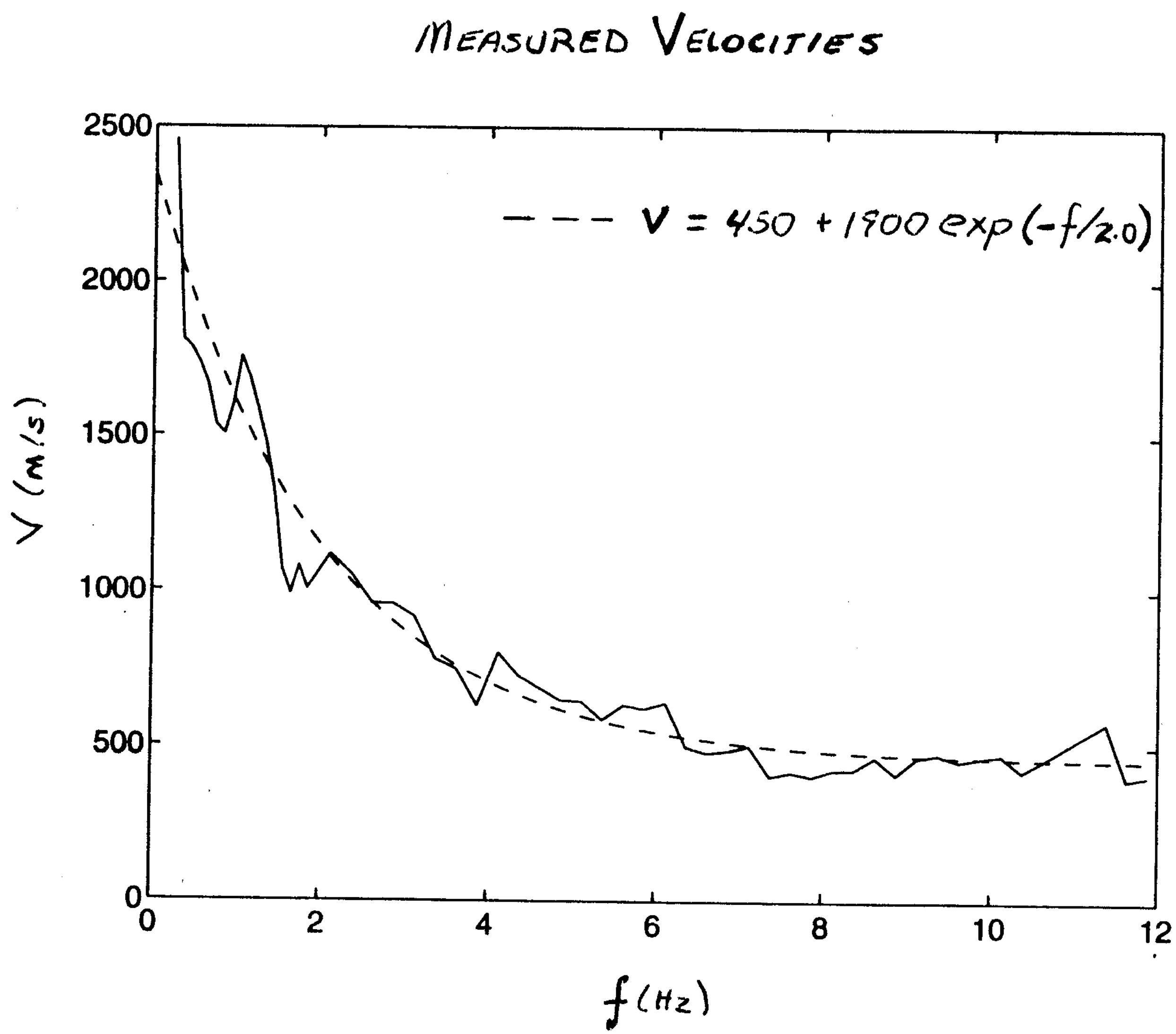

- min velocity = 1347 -- fit velocity = 1287.000
residuals^2
velocity[m/s]

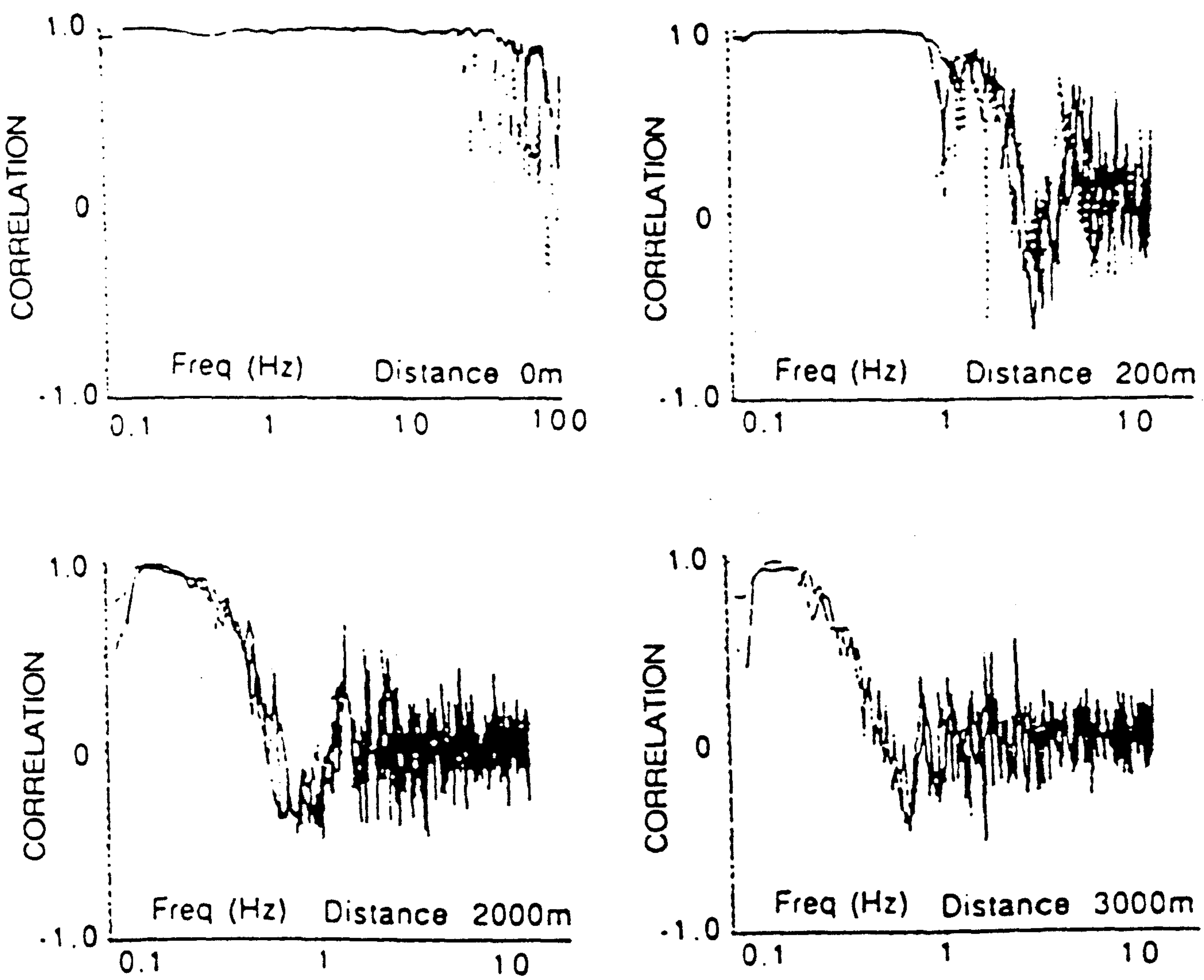

4.50 < f < 4.75
1 - rho
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3
10^4
L(m)


- min velocity = 700 -- fit velocity = 673.000
residuals^2
200
150
100
50
0
300
400
500
600
700
800
900
1000
1100
velocity[m/s]



11.00 < f < 11.25
1 - rho
L(m)
- min velocity = 539 -- fit velocity = 538.000
residuals^2
velocity[m/s]


MEASURED VELOCITIES
V = 450 + 1900 exp(-f/2.0)
V (m/s)
2500
2000
1500
1000
500
0
0
2
4
6
8
10
12
f (Hz)

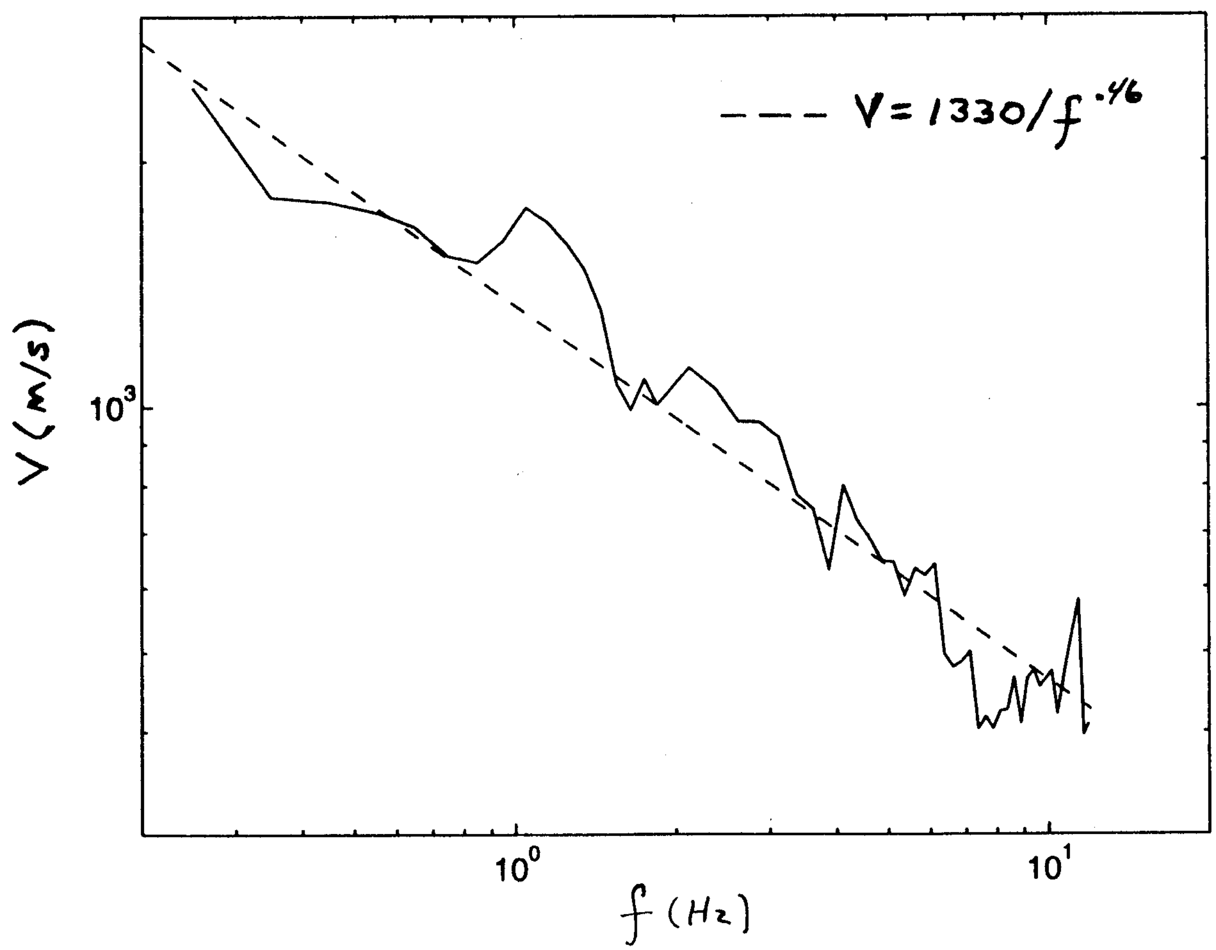


Correlation spectra for vertical vibrations

MEASURED IN THE LEP TUNNEL

POWER LAW FIT

V (KM/S) AT ρ (REAL) = 0 : $\begin{cases} 1.6\ \Delta Z^{.32} & \text{(SLC)} \\ 2.1\ \Delta Z^{.30} & \text{(LEP)} \end{cases}$ for ΔZ in KM



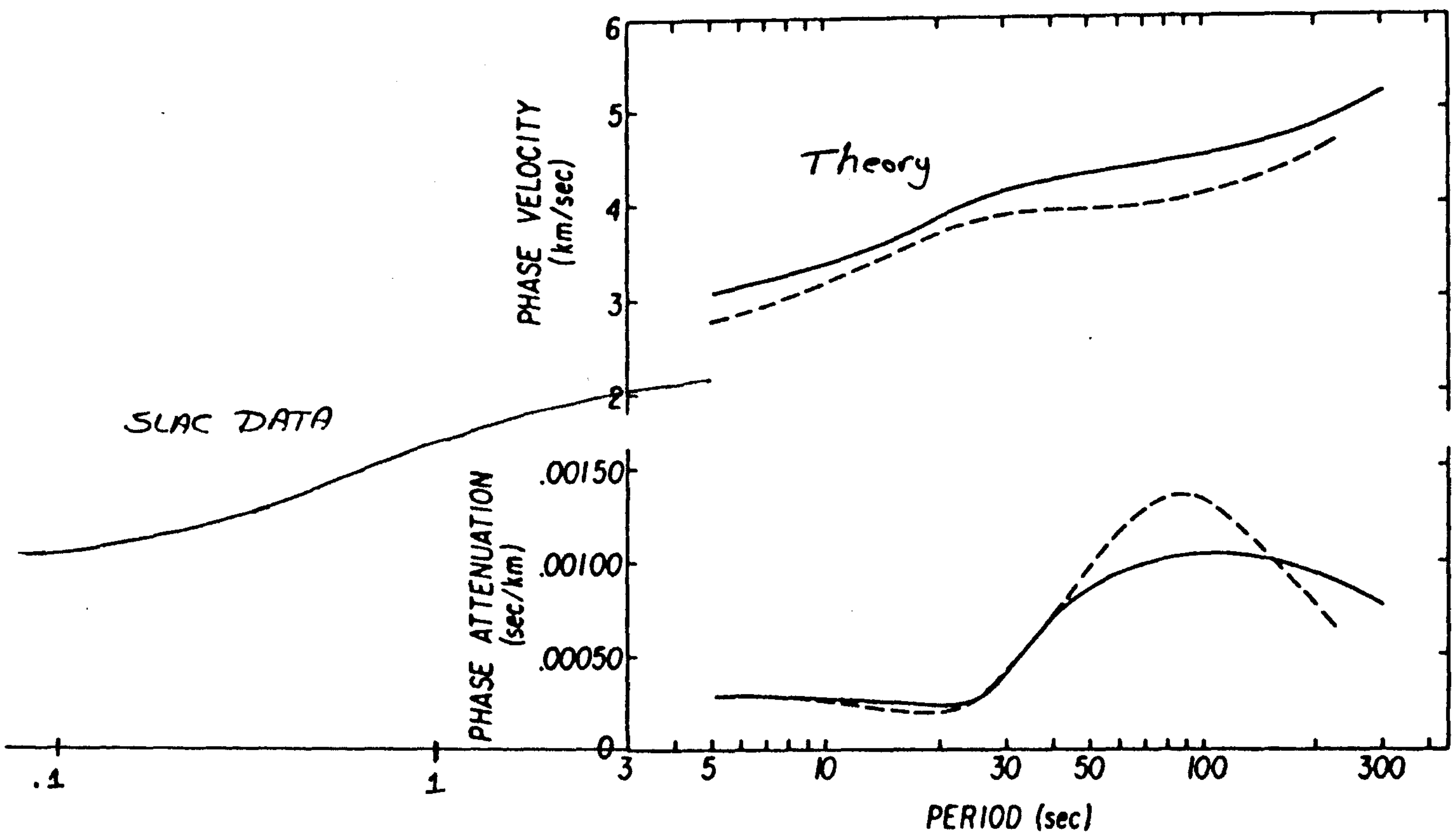
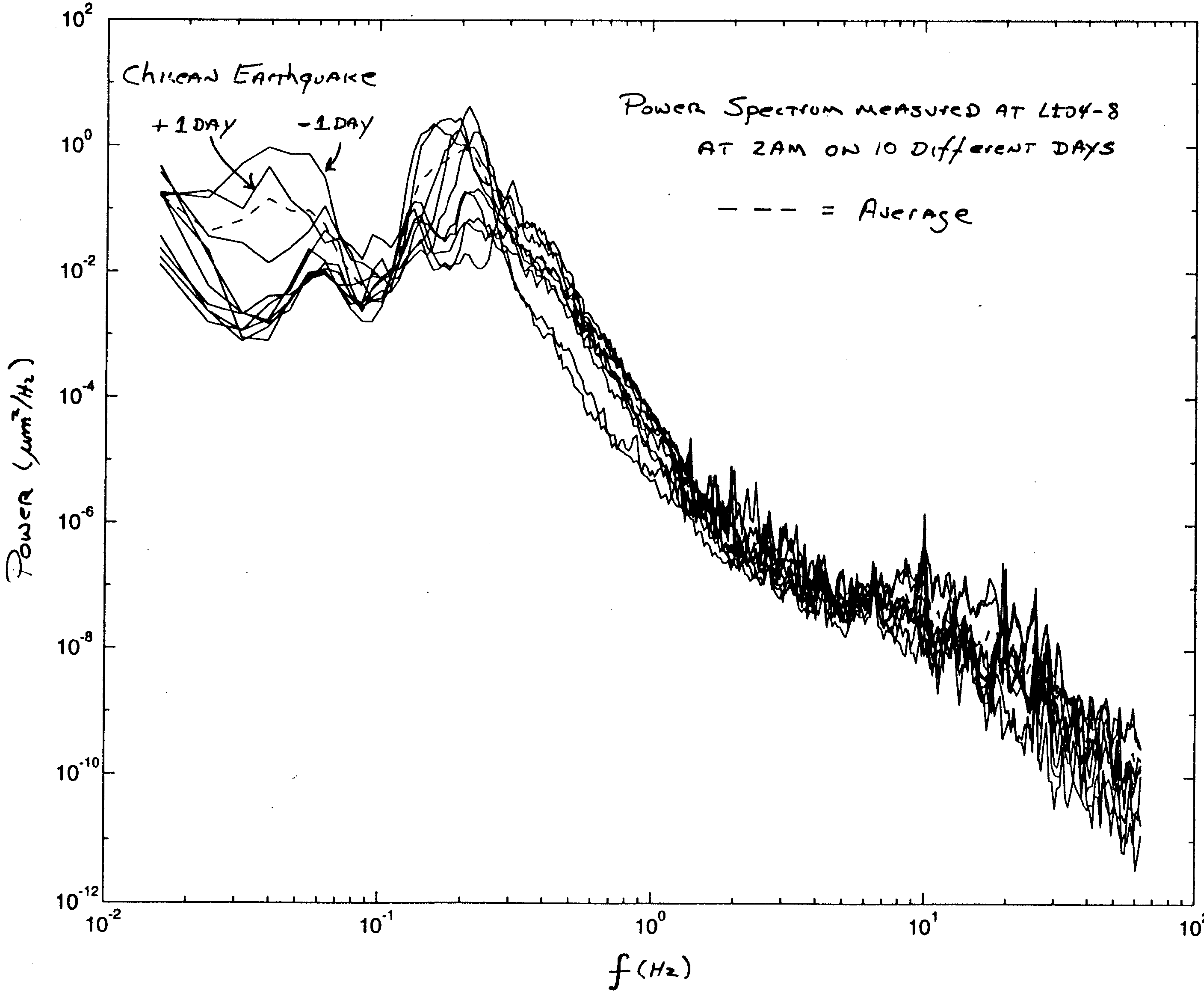
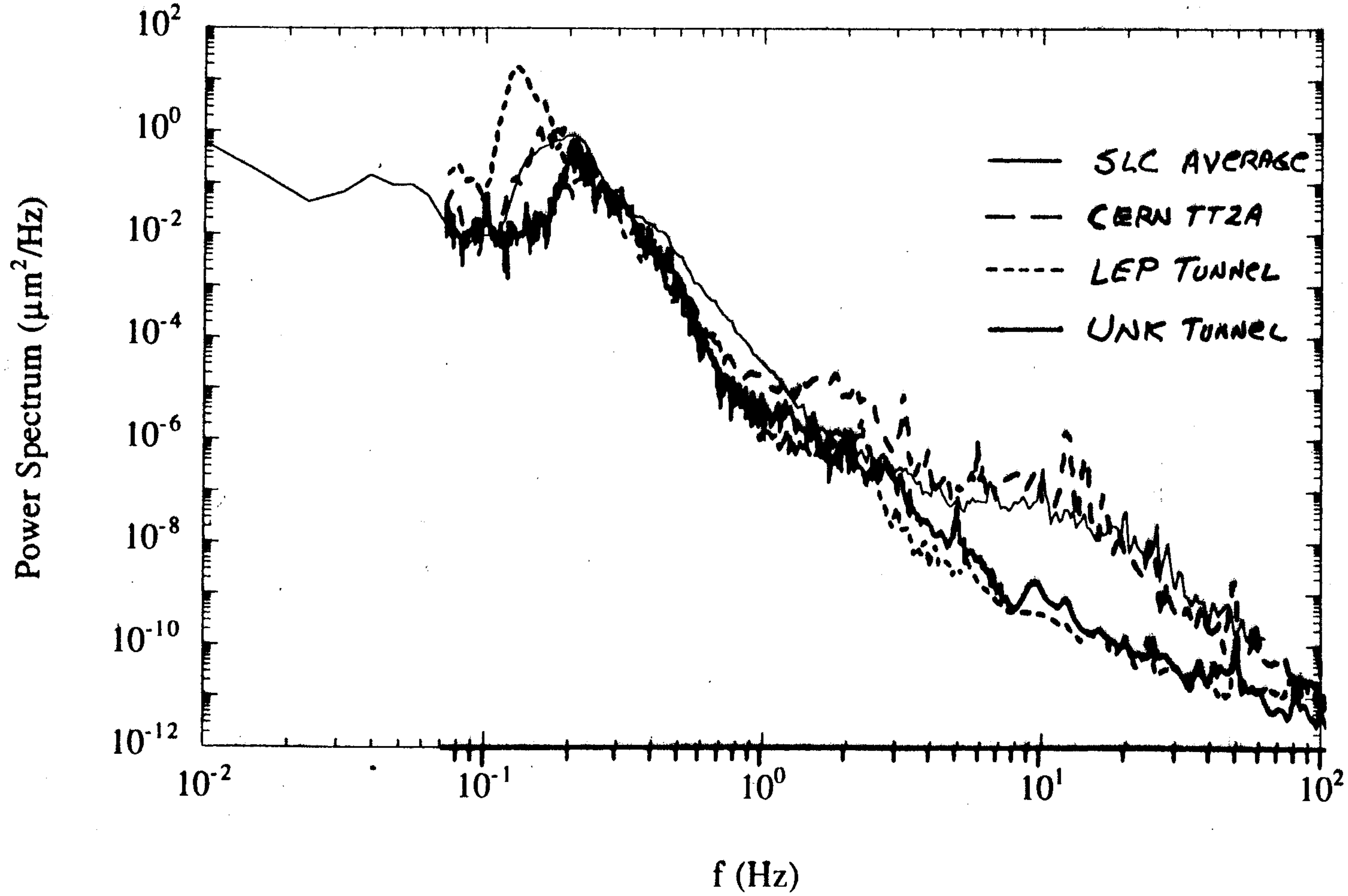


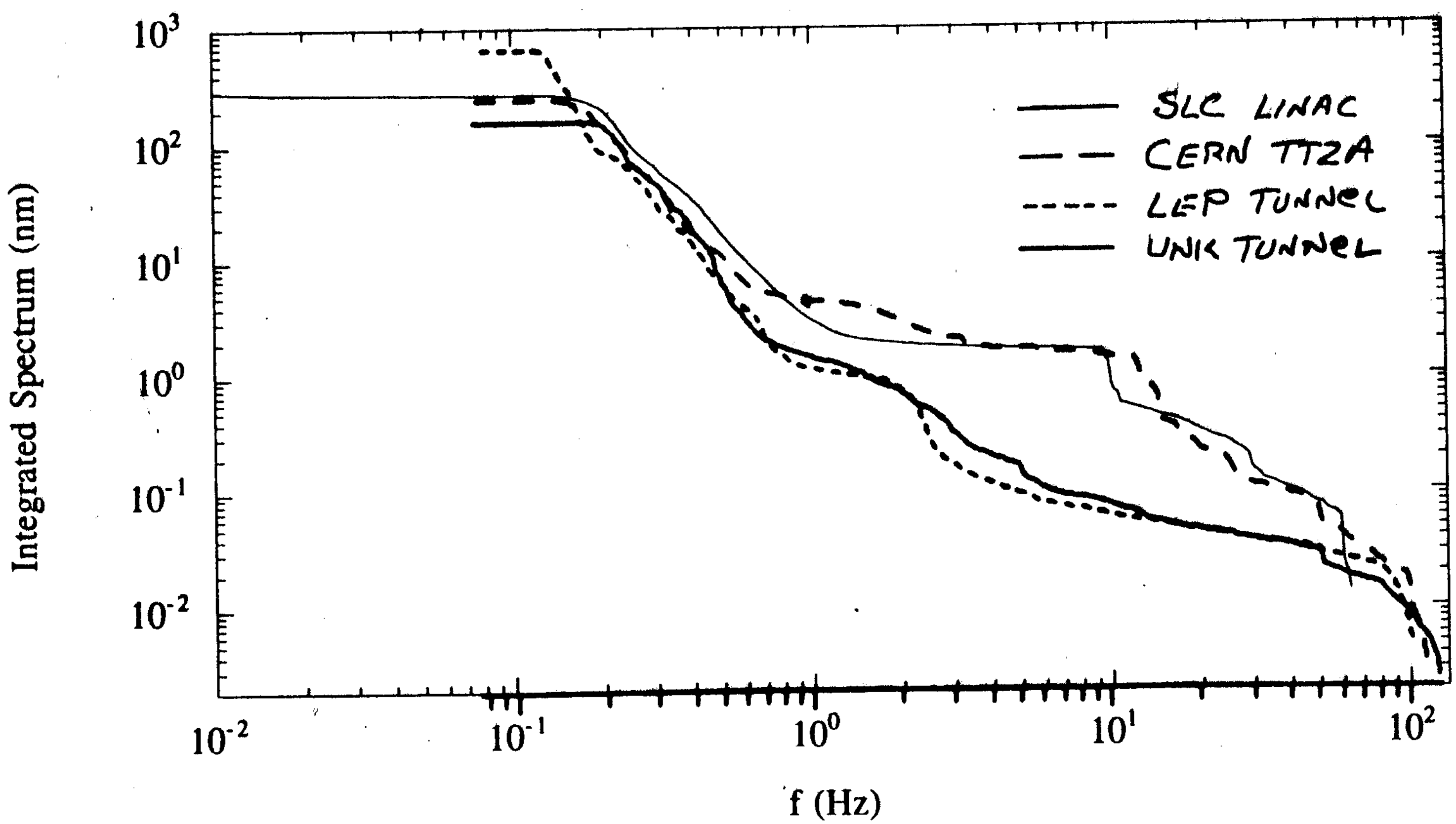
FIG. 18. Dispersion and attentuation of fundamental mode Love (—) and Rayleigh (- - -) waves for the (flat) anelastic "continental structure" given in Table XV.



Chilean Earthquake
+1 DAY
-1 DAY
Power Spectrum measured at LE04-8
at 2AM on 10 Different Days
- - - = Average
Power (μm²/Hz)
f (Hz)
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-2
10^-1
10^0
10^1
10^2



Power Spectrum (μm²/Hz)
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-2
10^-1
10^0
10^1
10^2
f (Hz)
SLC AVERAGE
CERN TT2A
LEP TUNNEL
UNK TUNNEL



SLC LINAC
CERN TT2A
LEP TUNNEL
UNK TUNNEL
Integrated Spectrum (nm)
f (Hz)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^0
10^1
10^2

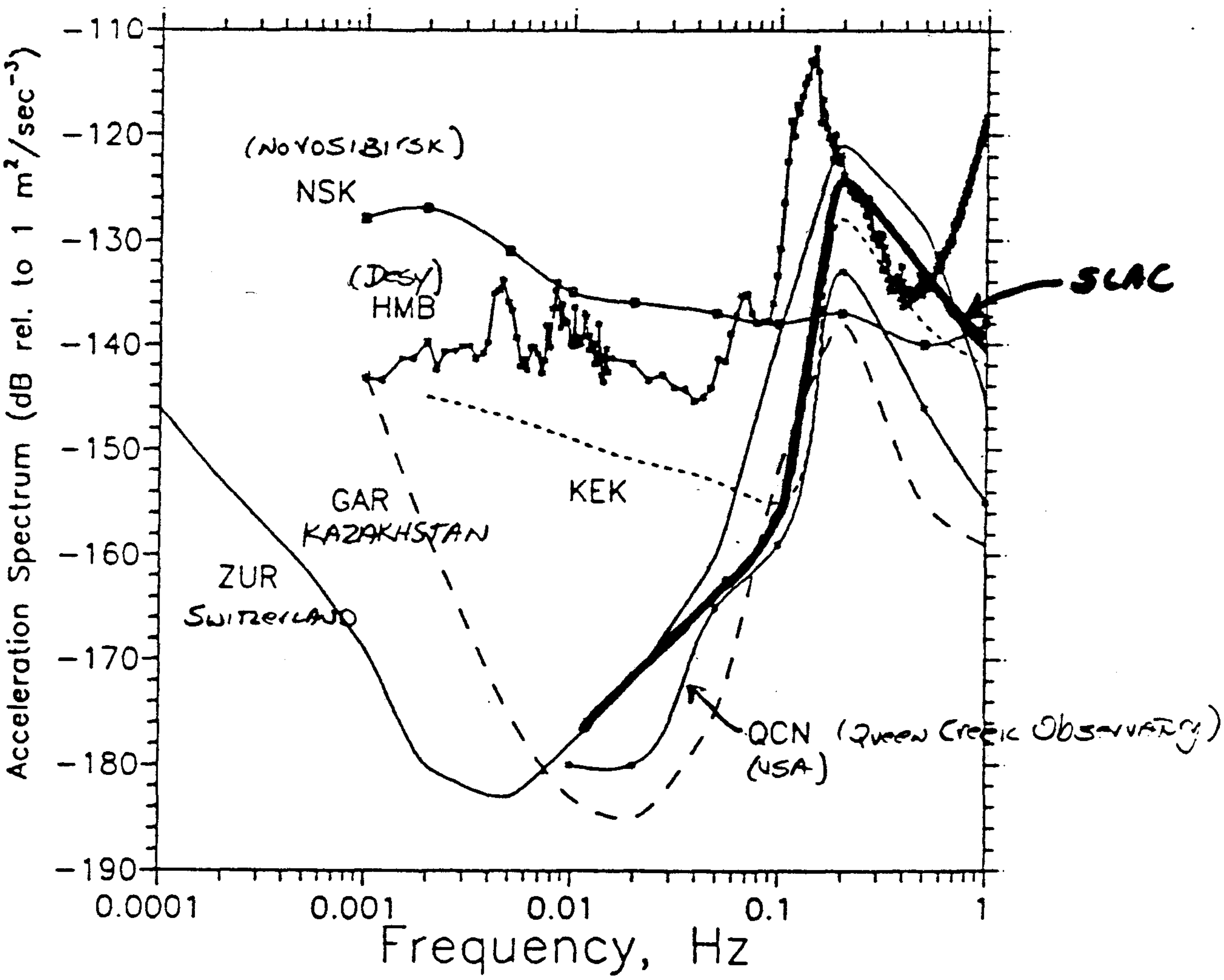


Figure 22:
Comparison of power spectral densities of slow ground motion (vertical), measured in accelerator sites (HMB - DESY, NSK - Budker INP, KEK) and in geophysics labs (GAR, QCN, ZUR (see comments in text))

EFFECT ON LUMINOSITY

Sensitivity and Integrated Motion:

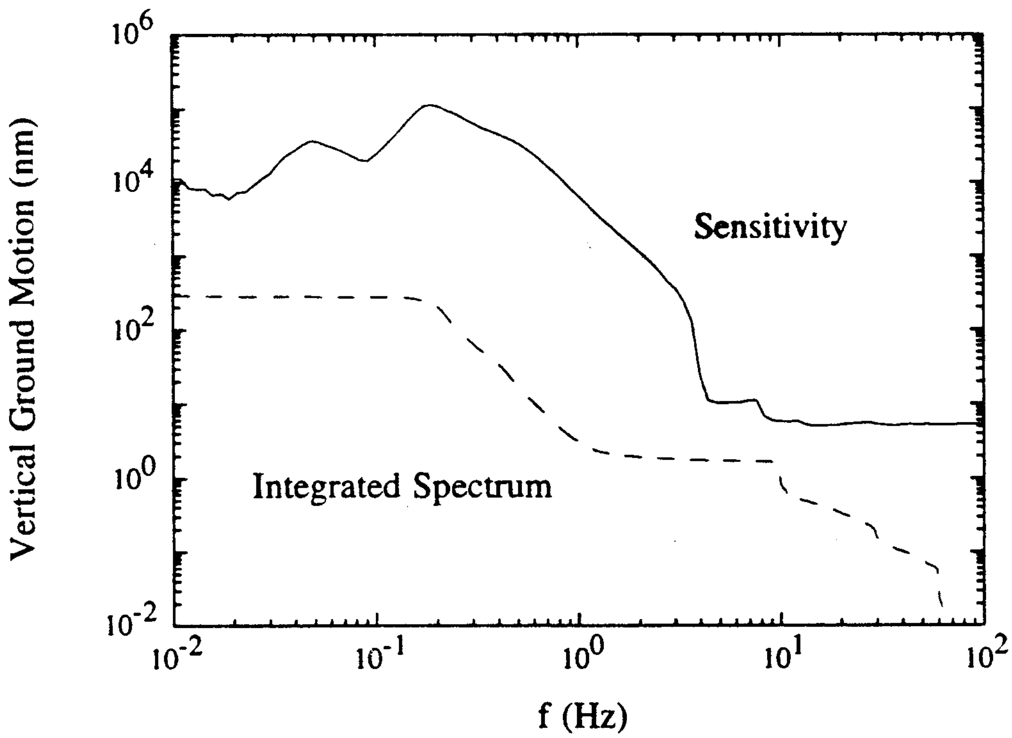
For wave-like motion at frequency = f,

$$\Delta\mathcal{L}/\mathcal{L} \propto \sum_{i,j} g_i\, g_j\, J_0(2\pi f \Delta z_{i,j}/v)$$

where g_i = Quad i to IP lattice transfer function

$$\text{Factor in} \begin{Bmatrix} \text{Trajectory feedback response} \\ \text{Limits due to STS 2 resolution} \end{Bmatrix} \text{and compute}$$

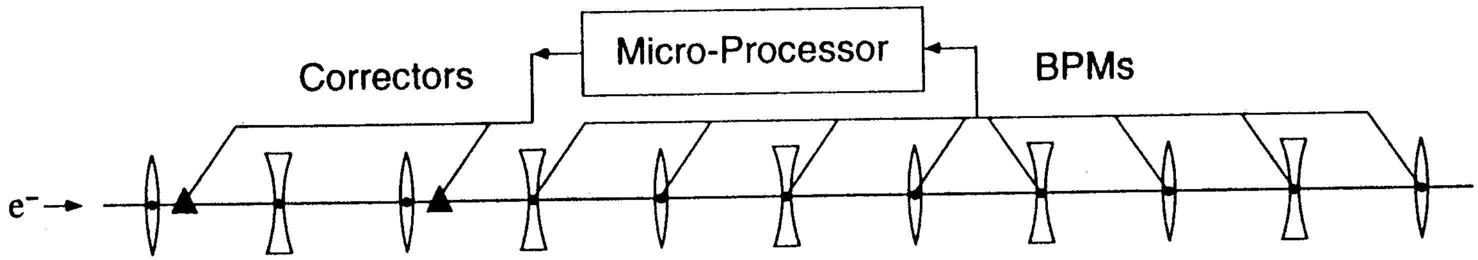
$$\text{Sensitivity} \equiv \text{RMS Motion} \rightarrow \Delta\mathcal{L}/\mathcal{L} = 1.5\,\%$$

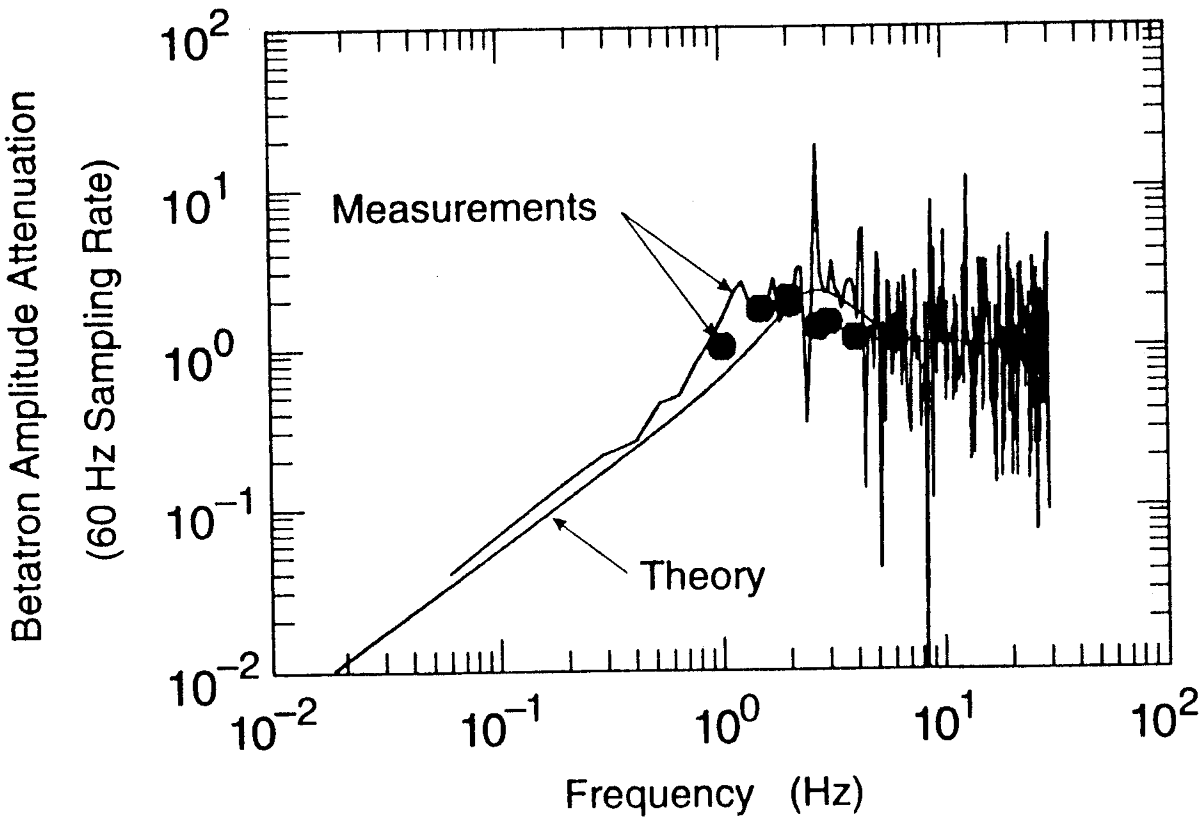


Integrated (f > .01 Hz) luminosity loss:

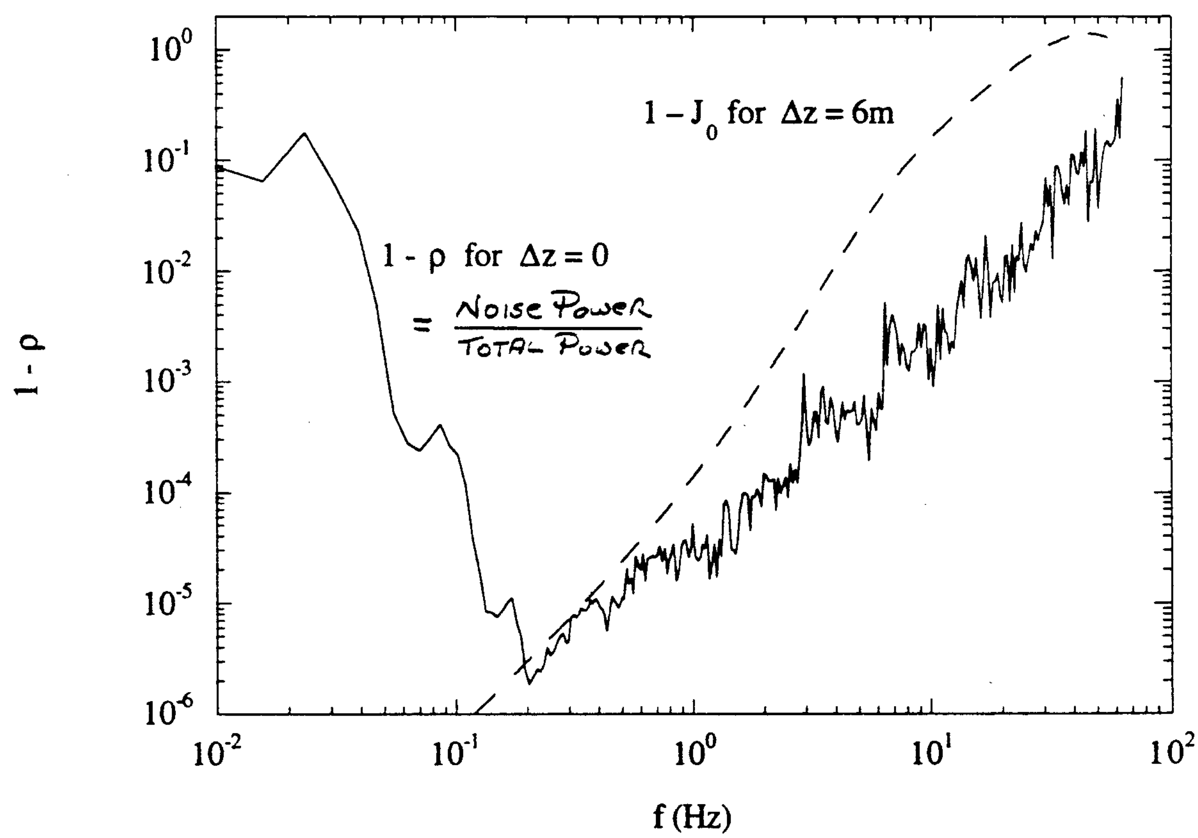
$$\Delta\mathcal{L}/\mathcal{L} = 1.5\,\% \int P(f)/\text{Sensitivity}^2(f)\, df \;=\; 0.13\%$$

SLC TRAJECTORY FEEDBACK





Minimum Value of 1- ρ Measurable
due to STS-2 Noise



QUAD + GROUND MOTION IN THE FFTB