Source and Propagation of the Predominant 1-50 Hz Seismic Signal From Off-Site at LIGO-Hanford

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Outline

1) Source of the Predominant Signal

2) Generation

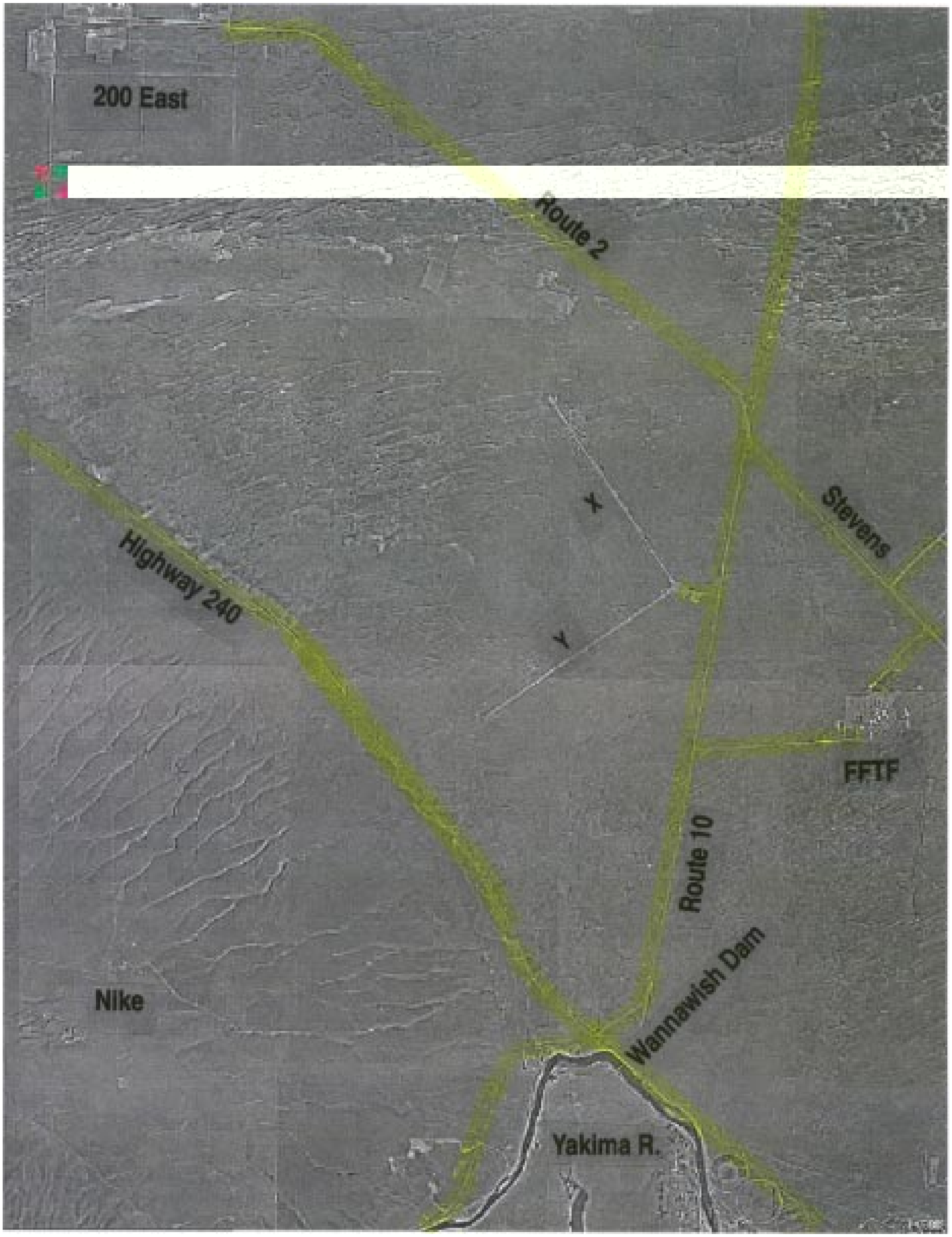
3) Propagation

A) Air or Ground?: Traffic, Airplanes and Helicopters

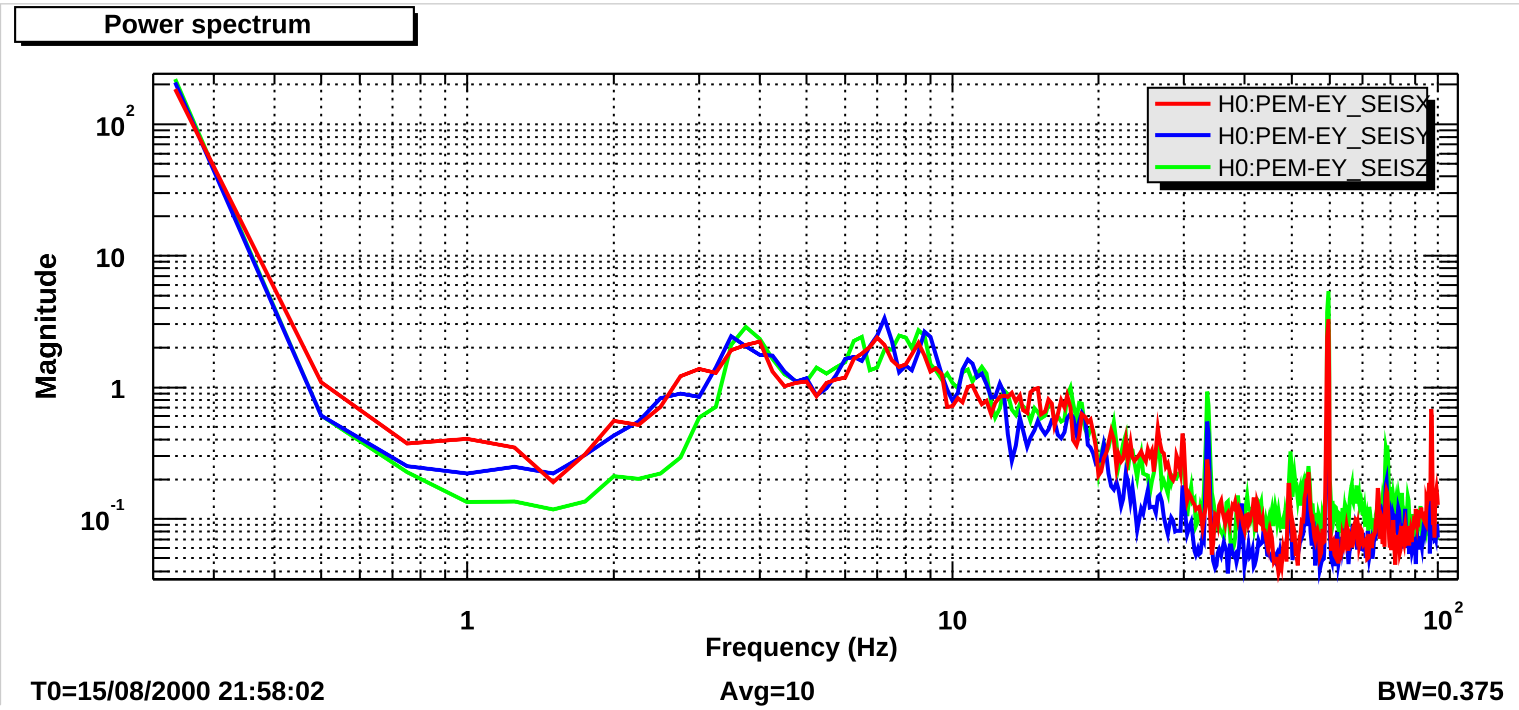
B) Velocity

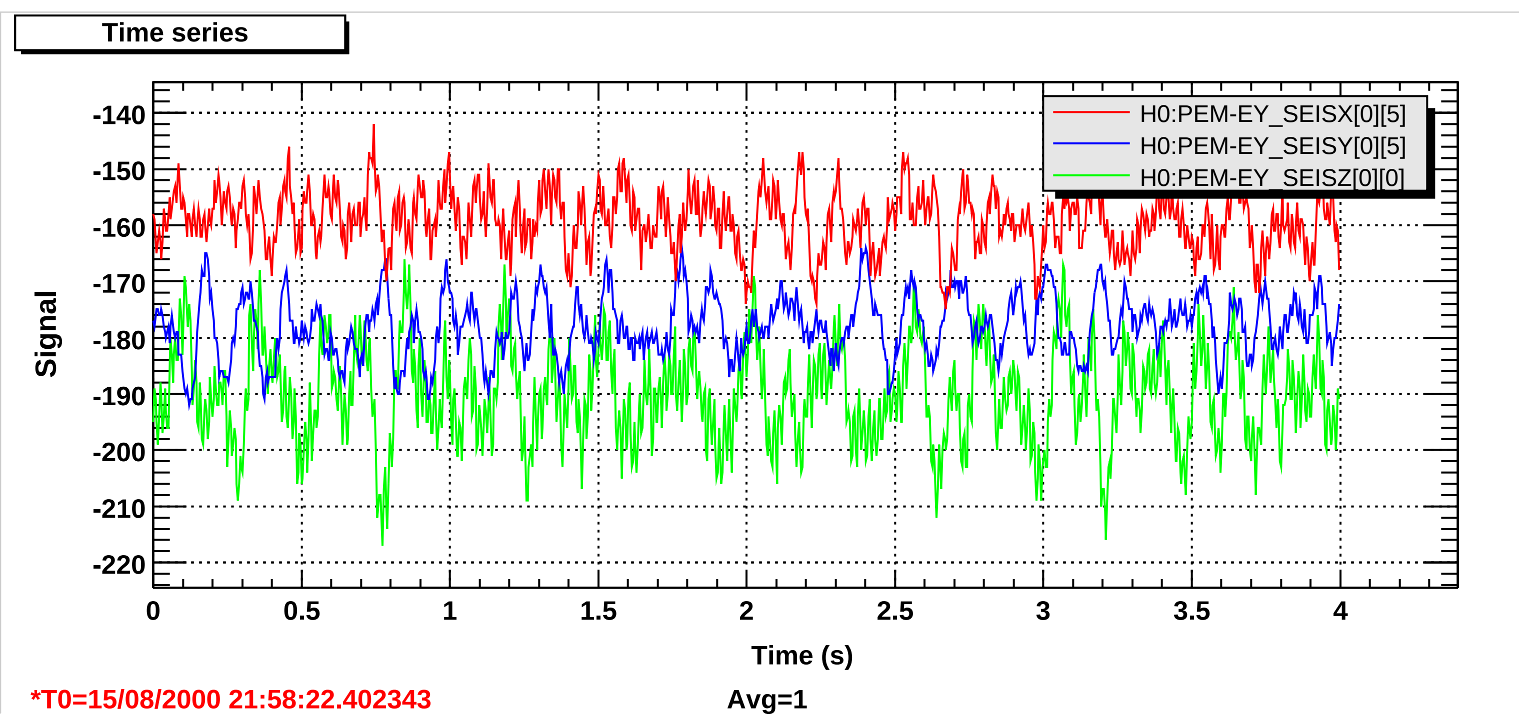
C) Q, anisotropy ratio, coherence etc.

Calibration factors for scales in counts:
Seismometer: 0.076 μm/s per count
Microphone: 29 μPascals per count

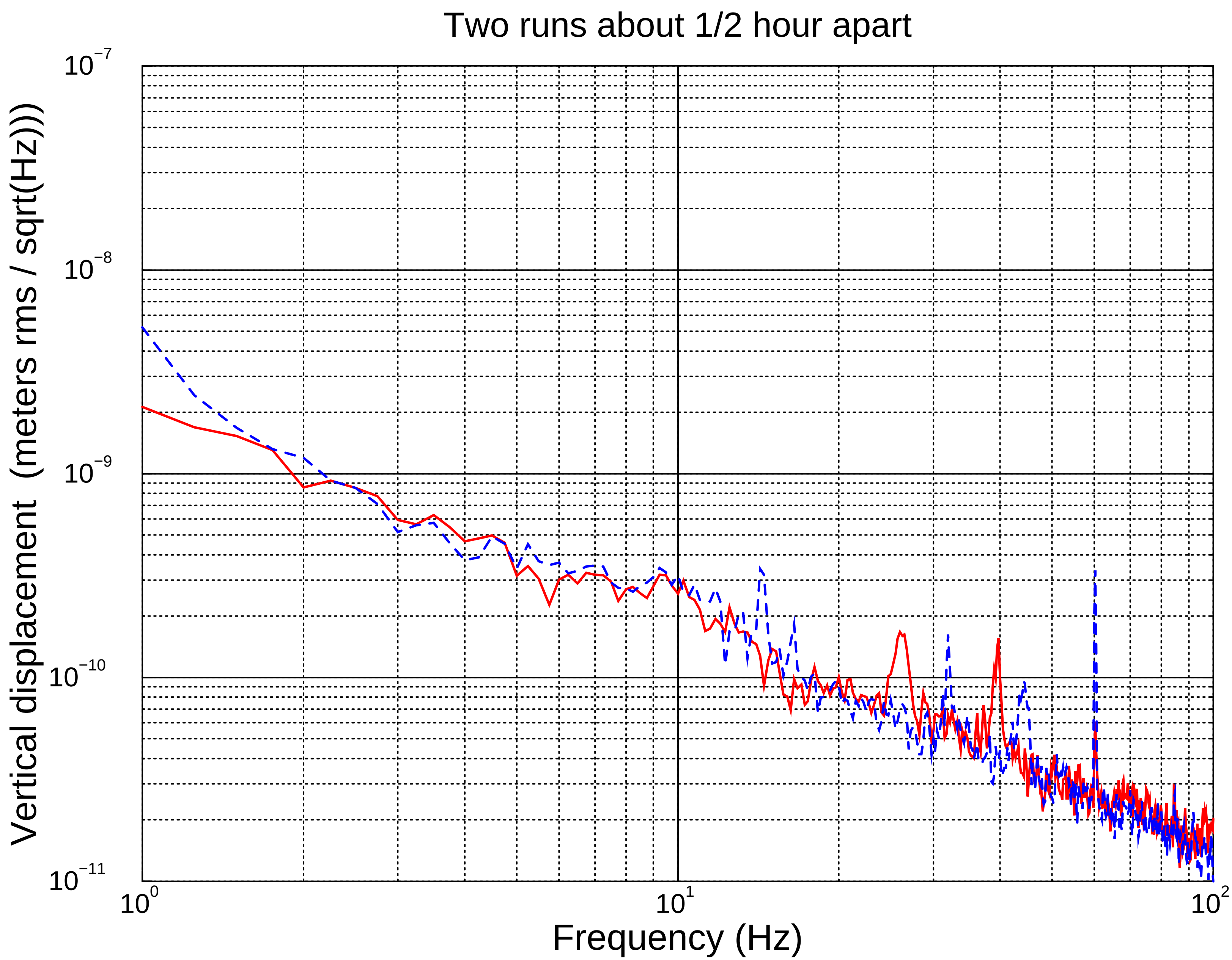


200 East
Route 2
Stevens
X
Highway 240
Y
FFTF
Route 10
Wannawish Dam
Nike
Yakima R.


Power spectrum
Magnitude
10^{2}
10
1
10^{-1}
1
10
10^{2}
Frequency (Hz)
H0:PEM-EY_SEISX
H0:PEM-EY_SEISY
H0:PEM-EY_SEISZ
T0=15/08/2000 21:58:02
Avg=10
BW=0.375


Time series
Signal
-140
-150
-160
-170
-180
-190
-200
-210
-220
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)
H0:PEM-EY_SEISX[0][5]
H0:PEM-EY_SEISY[0][5]
H0:PEM-EY_SEISZ[0][0]
*T0=15/08/2000 21:58:22.402343
Avg=1

X−end, No Vehicles Visible on Route 2



Generation of Traffic Seismic Signal

Tested Hypotheses:

1) Generation by the engine

2) Peak frequency given by the rotation frequency of the tire

3) Peak frequency given by the axel spacing and the velocity

Test vehicles: car (no longer available for photo) and this truck

Seismic Frequency from Axel Spacing

PREDICTED AND MEASURED SEISMIC PEAK FREQUENCIES (Hz)

EXPERIMENT	PREDICTED FROM TIRE CIRCUMFERENCE	PREDICTED FROM AXEL SPACING	MEASURED	NUMBER OF DRIVE-BYS
Car at 60 mph	6.9	10.0	9.75 $\pm$ 0.5	4
Truck at 60 mph	5.6	6.6	6.35 $\pm$ 0.1	5
Truck at 30 mph	2.8	3.3	3.82$\pm$ 0.4	7

Highway 240 is rough but not grooved.

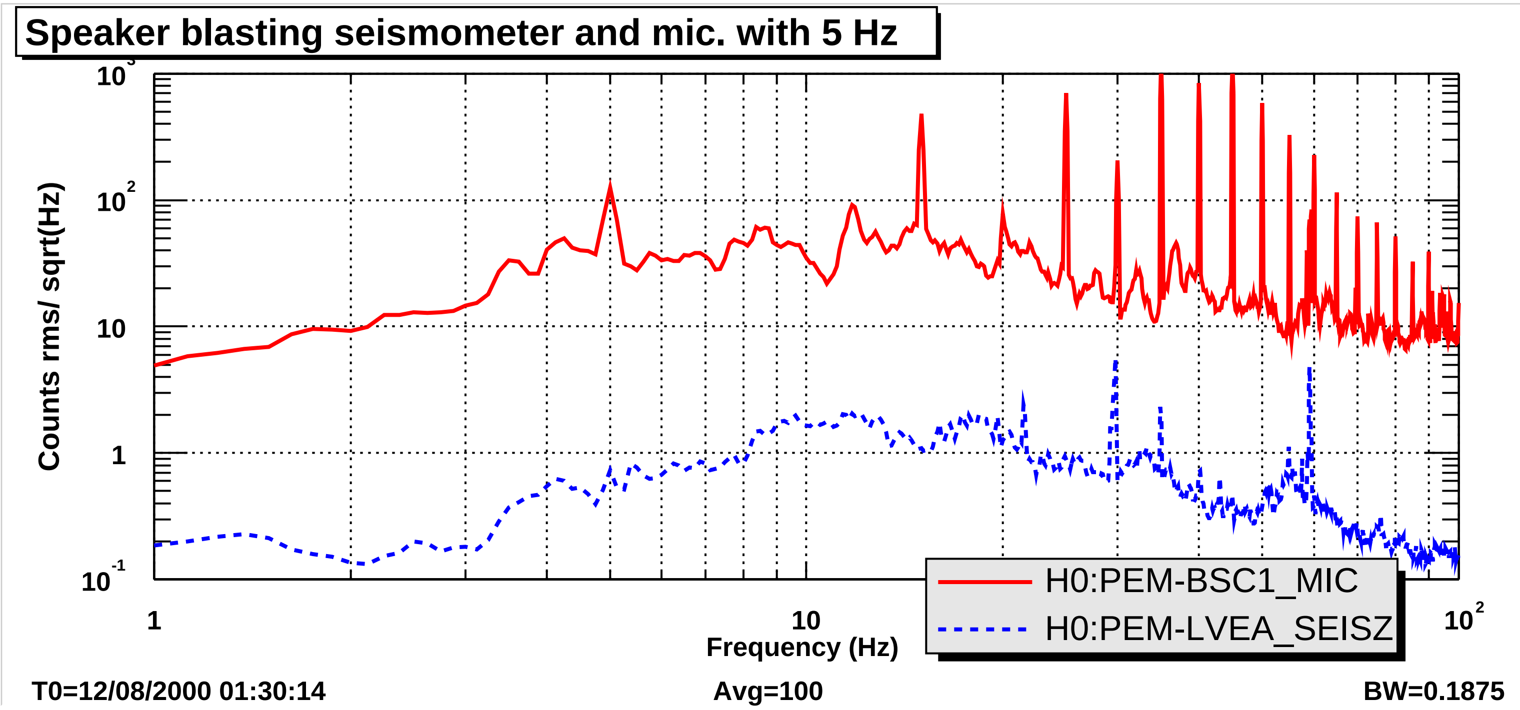
Considered Propagation Paths

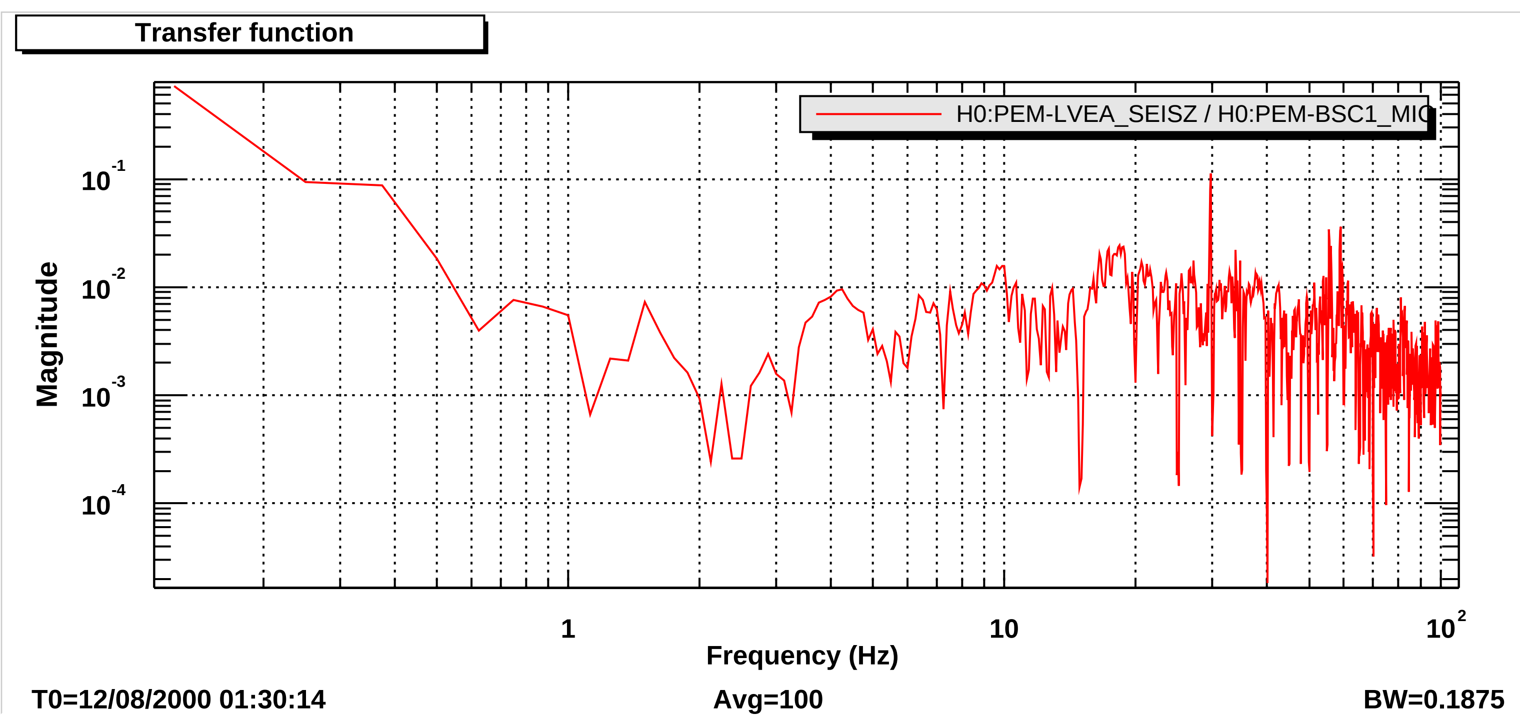
1) Acoustic signal from road traffic coupling directly to the seismometer

2) Acoustic signal coupling locally to the ground

3) Entire path through the ground

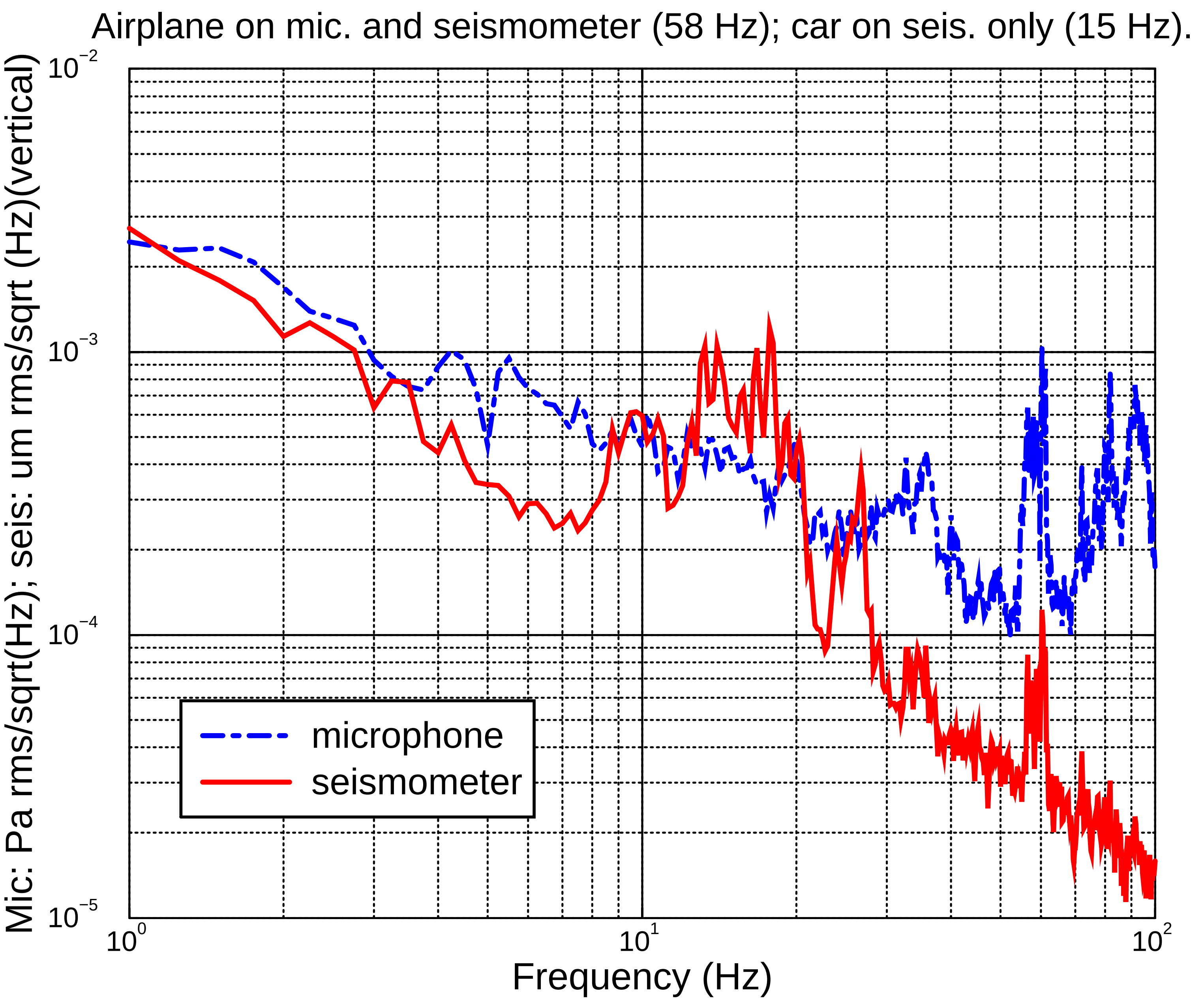

STAY CLEAR ZONE
KEEP OUT


Speaker blasting seismometer and mic. with 5 Hz
Counts rms/ sqrt(Hz)
10^3
10^2
10
1
10^-1
1
10
10^2
Frequency (Hz)
H0:PEM-BSC1_MIC
H0:PEM-LVEA_SEISZ
T0=12/08/2000 01:30:14
Avg=100
BW=0.1875

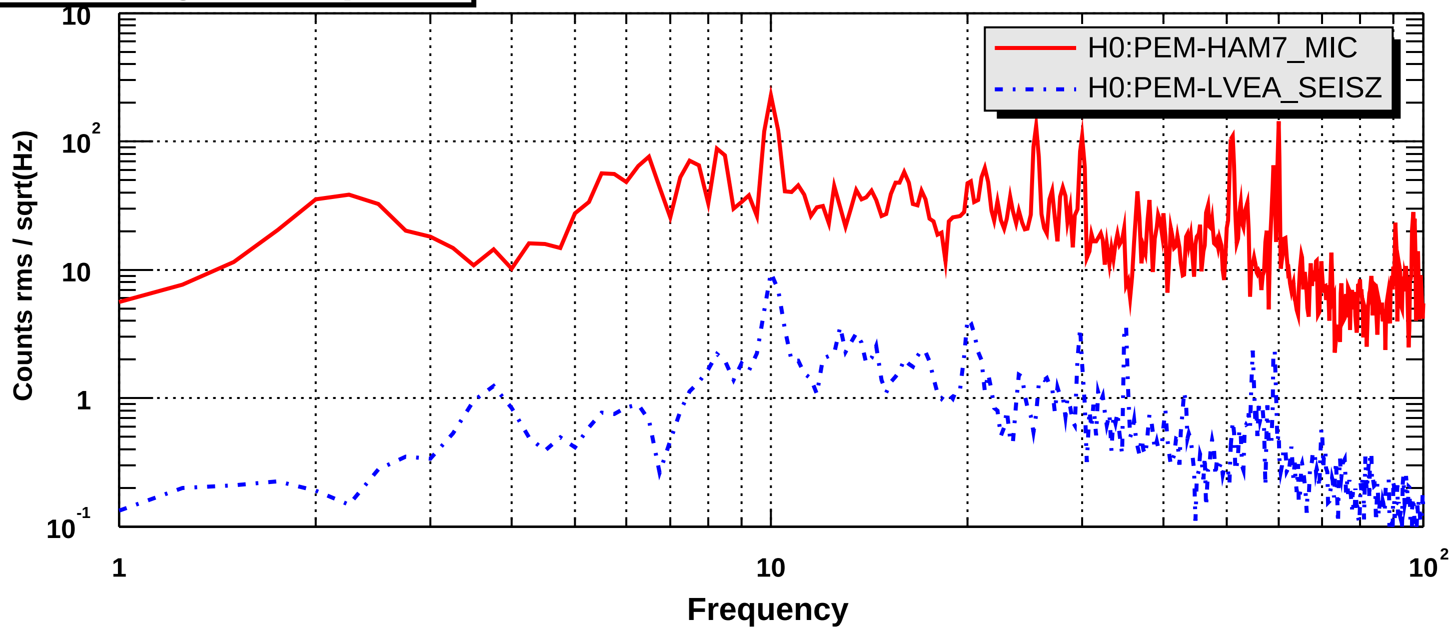

Transfer function
H0:PEM-LVEA_SEISZ / H0:PEM-BSC1_MIC
Magnitude
10^-1
10^-2
10^-3
10^-4
1
10
10^2
Frequency (Hz)
T0=12/08/2000 01:30:14
Avg=100
BW=0.1875

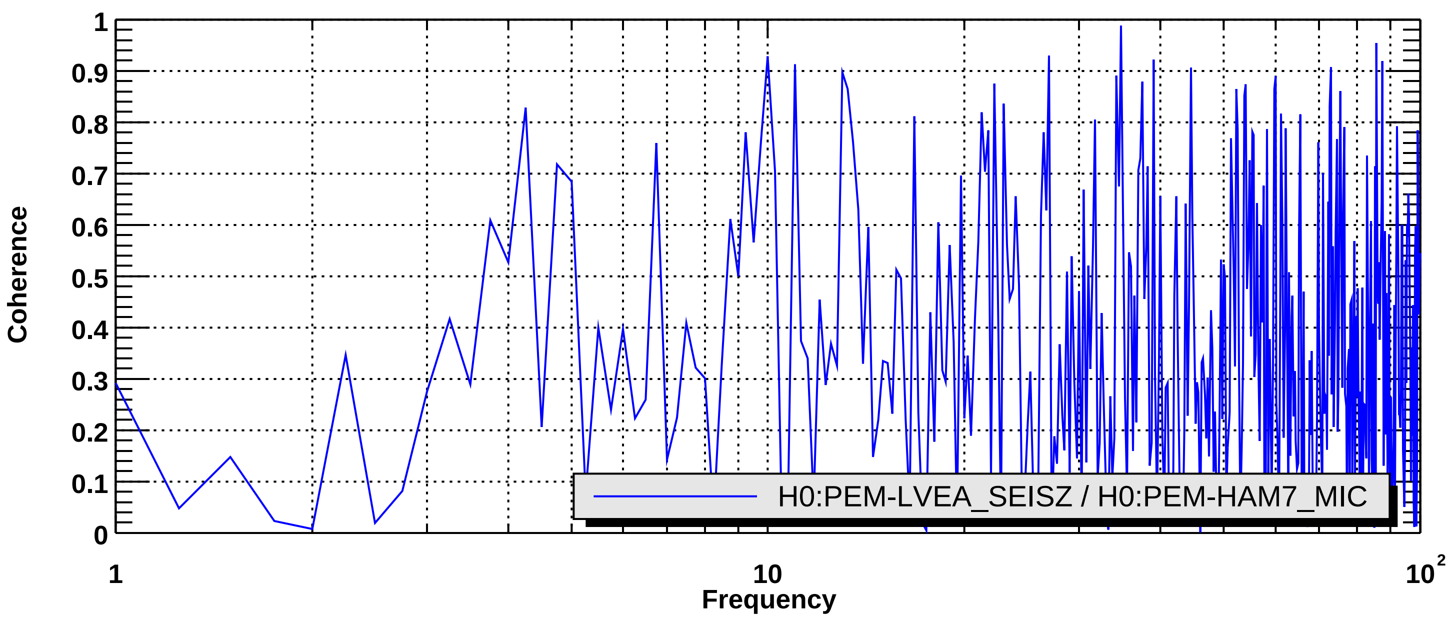
Seismometer Pits Near Y-End

Ground or Air Propagation?

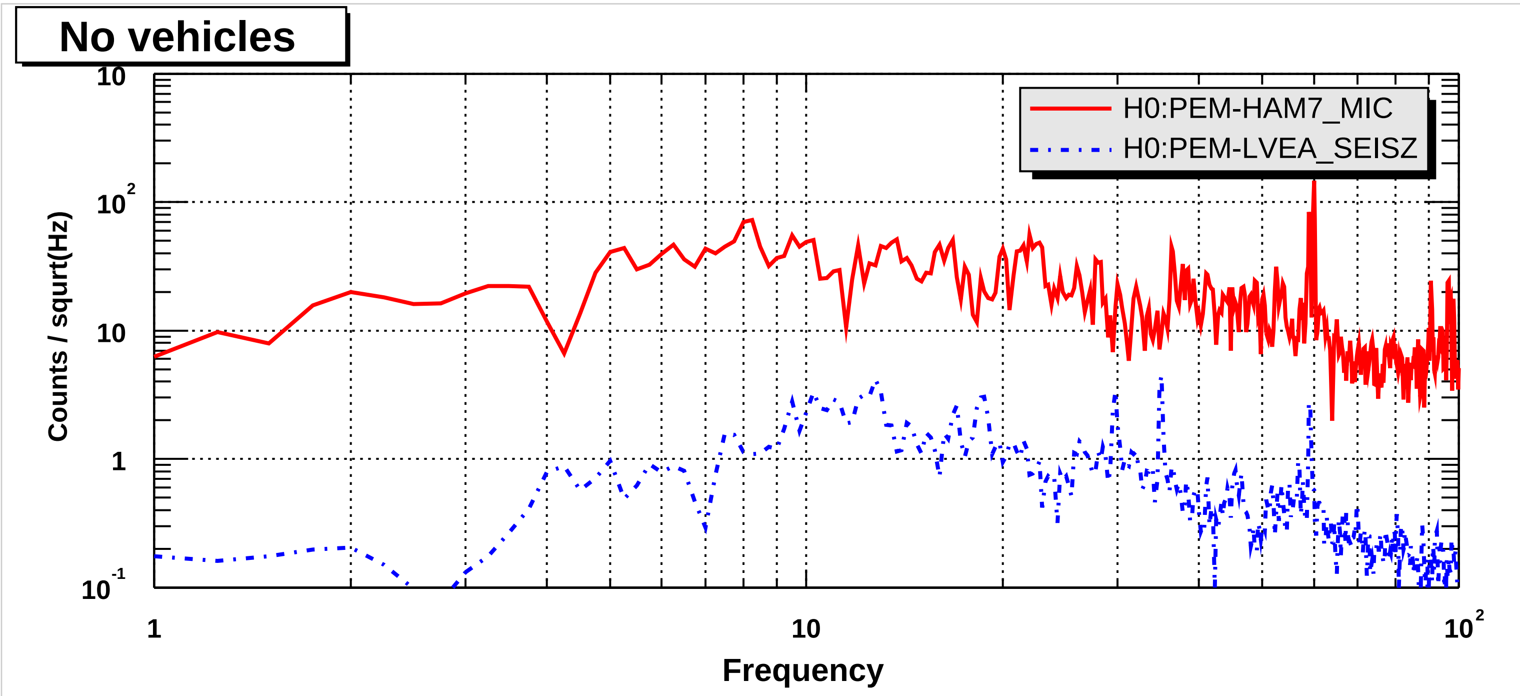


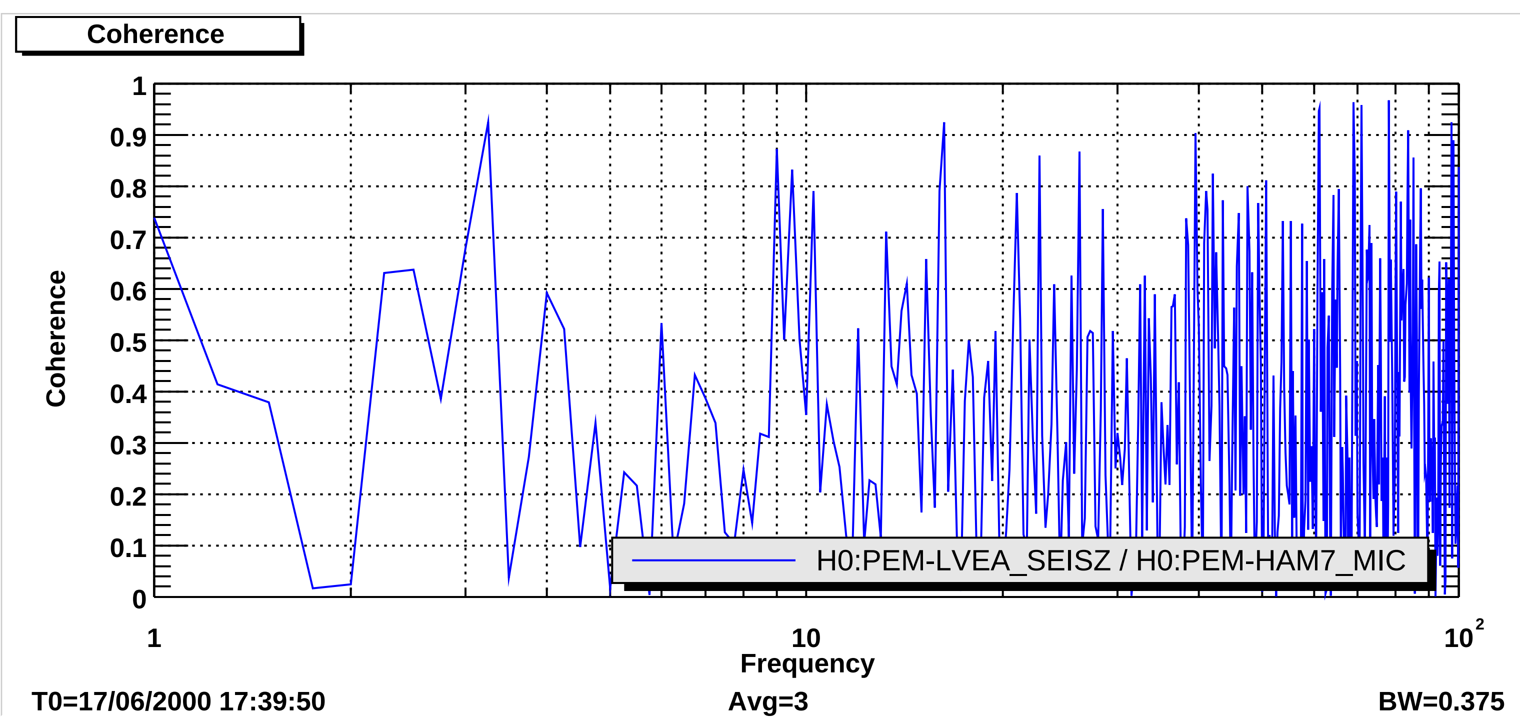
Passing helicopter

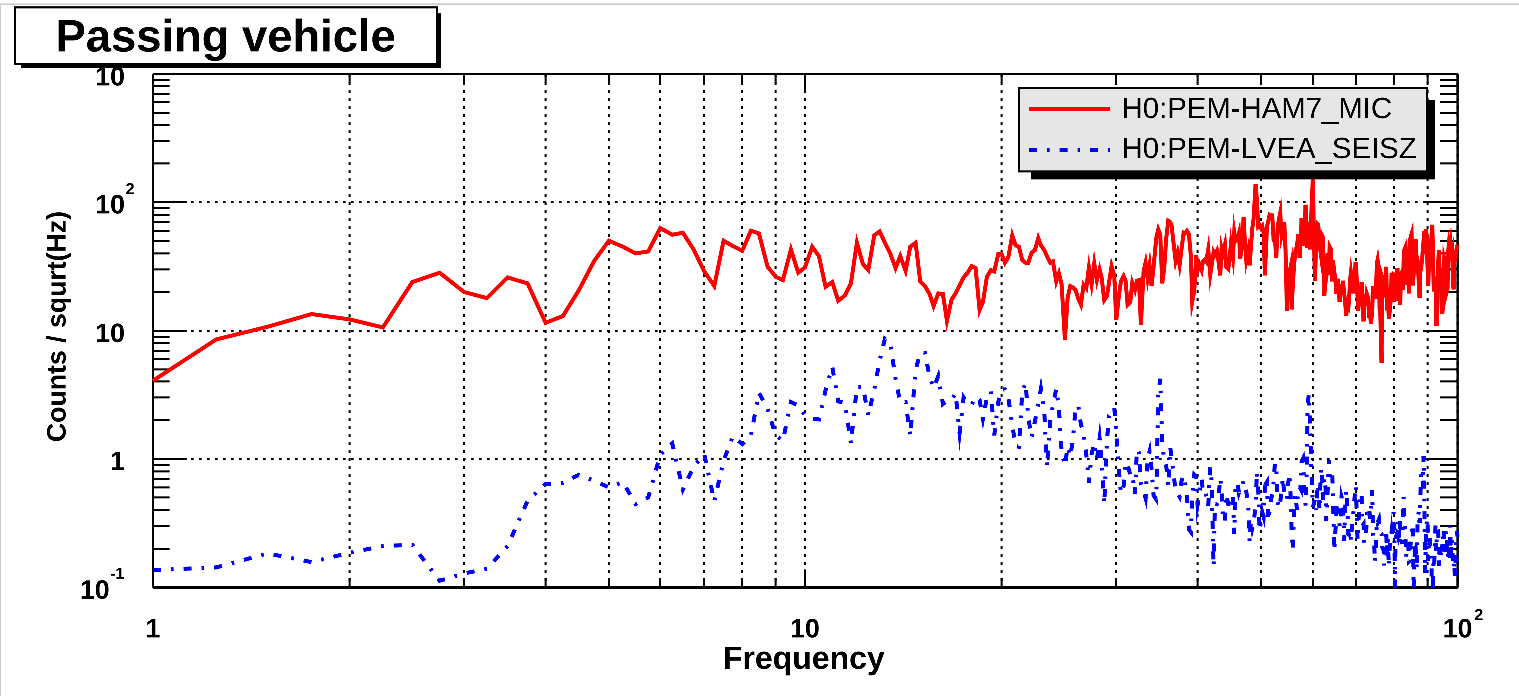


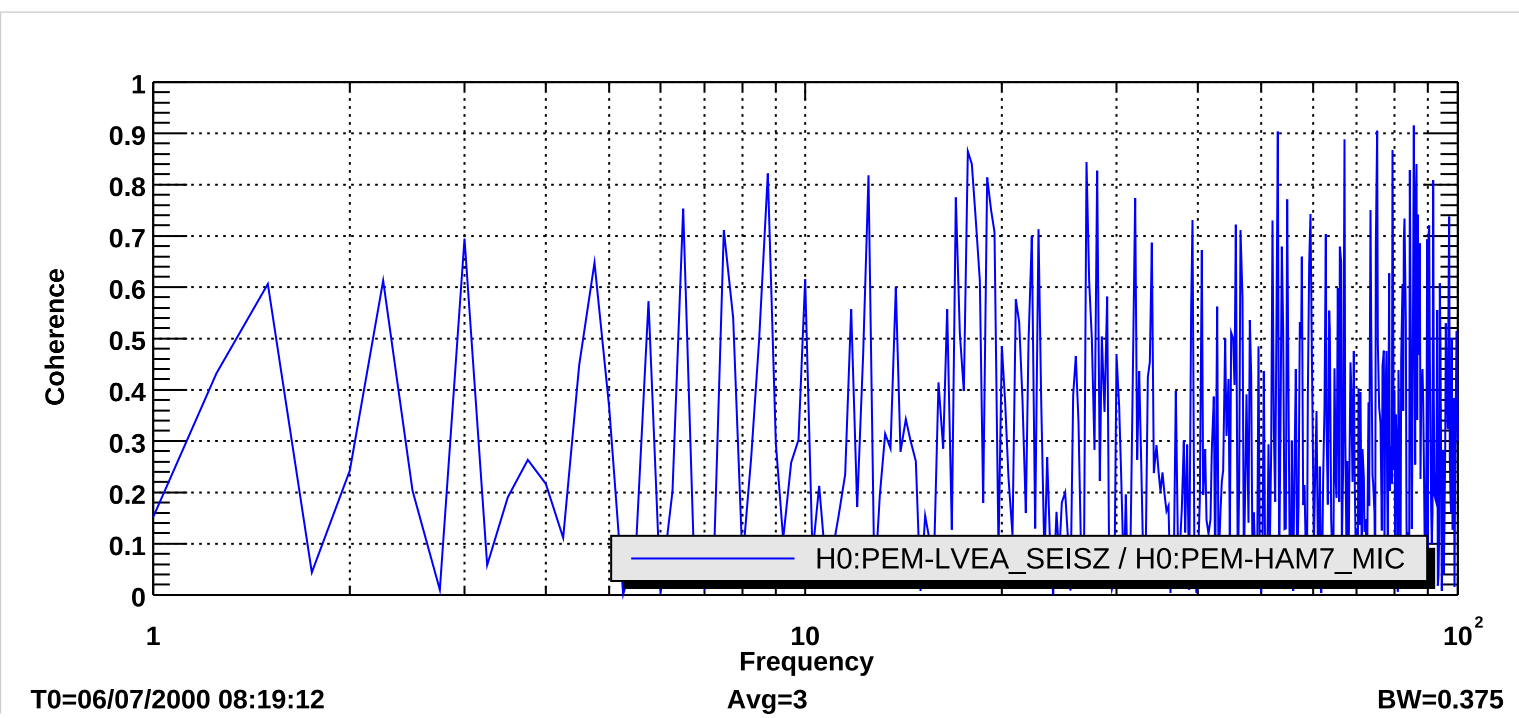


T0=17/06/2000 19:14:42 Avg=3 BW=0.375


No vehicles
H0:PEM-HAM7_MIC
H0:PEM-LVEA_SEISZ
Counts / squrt(Hz)
Frequency


Coherence
H0:PEM-LVEA_SEISZ / H0:PEM-HAM7_MIC
Coherence
Frequency
T0=17/06/2000 17:39:50
Avg=3
BW=0.375


Passing vehicle
H0:PEM-HAM7_MIC
H0:PEM-LVEA_SEISZ
Counts / squrt(Hz)
Frequency


H0:PEM-LVEA_SEISZ / H0:PEM-HAM7_MIC
Coherence
Frequency
T0=06/07/2000 08:19:12
Avg=3
BW=0.375

Ball Park Estimates of Ground Displacement

Using Boussinesq's (1885) solution for depression of an elastic half-space under a rigid and circular flat punch (DC!):

$$d = \frac{1 - \sigma^2}{2E}\frac{F}{a}$$

where d is the displacement, F is the total load on the punch, a is the radius of the punch, σ is Poisson's ratio and E is Young's modulus.

σ: 0.32 (from Skagit Report via Hughes and Thorne)

E: 0.35 giga Pascals (calculated from shear and pressure wave velocities in the Skagit Report and assuming a density of 1.8 gm/cm^2)

Ground depression from airplane acoustic pressure:

Assume airplane at 1000 m, a is the radius of the circular region beneath with phase variation of less than 1/3 cycle. Measured pressure amplitude: 1 x 10^{-3} Pa (at 58 Hz) :

Calculated depression: 0.25 nm

Measured rms displacement amplitude at 58 Hz: 0.1 nm

Ground depression from truck acoustic pressure:

Acoustic pressure measured at 50 m: 4 x 10^{-3} Pa (10 Hz - corrected for microphone rolloff). At 2000 m (assuming 1/r): 1 x 10^{4}Pa. Assume 2a is $\lambda/3$, and $\lambda = 45$ m.

Calculated depression: 0.003 nm

Typical rms amplitude at Y-end for large truck: 3 nm

Summary of Evidence against Acoustic Paths

1) Evidence against acoustic signal from road traffic coupling directly to the seismometer:

a) Speaker blasting seismometer experiment.
b) Increased acoustic insulation reduces sound level but not seismometer signal.

2) Evidence against local acoustic coupling to the ground- path.

a) For similar amplitude seismic signals, the local acoustic signal from road traffic is much lower than that from airplanes and a helicopter.
b) Simple model suggests that the acoustic signal from road traffic is about 3 orders of magnitude to small.

LEAVES

3) Entire path through the ground

Seismometer Pits Near Y-End

Maximum Propagation Velocity

Maxima in HP35670A cross correlations between signals from two seismometers were used to calculate arrival time differences.

Periodicities in the cross correlations indicated signal peaks of 4 - 12 Hz.

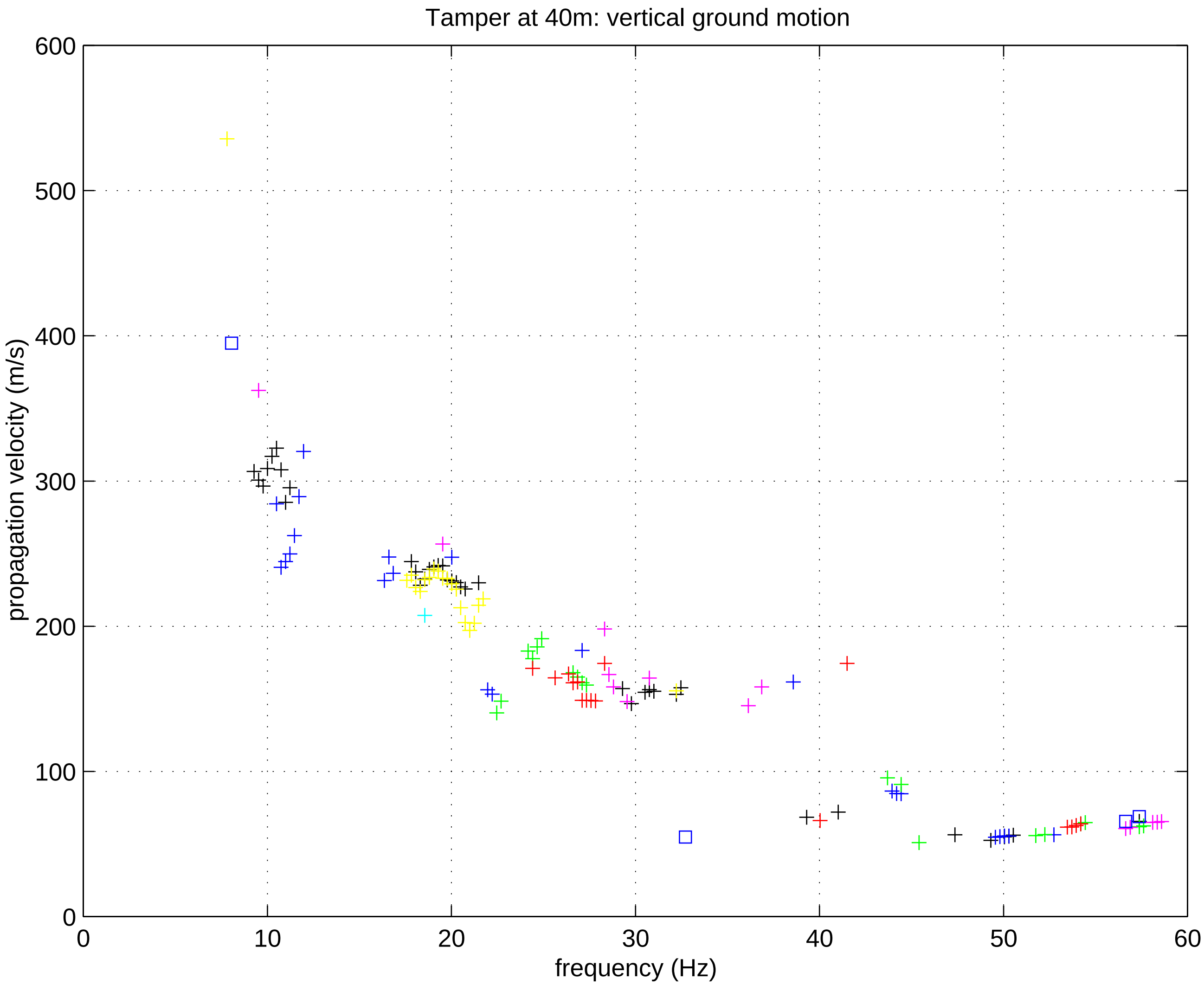
The spacing of the seismometers was used to calculate a maximum signal velocity (actual signal velocity only if they were pointed directly at the source).

Seismometer pairs were pointed roughly toward highway 240; 14 measurements were made with 4 different seismometer setups near Y-end, giving:

492 ± 62 m/s

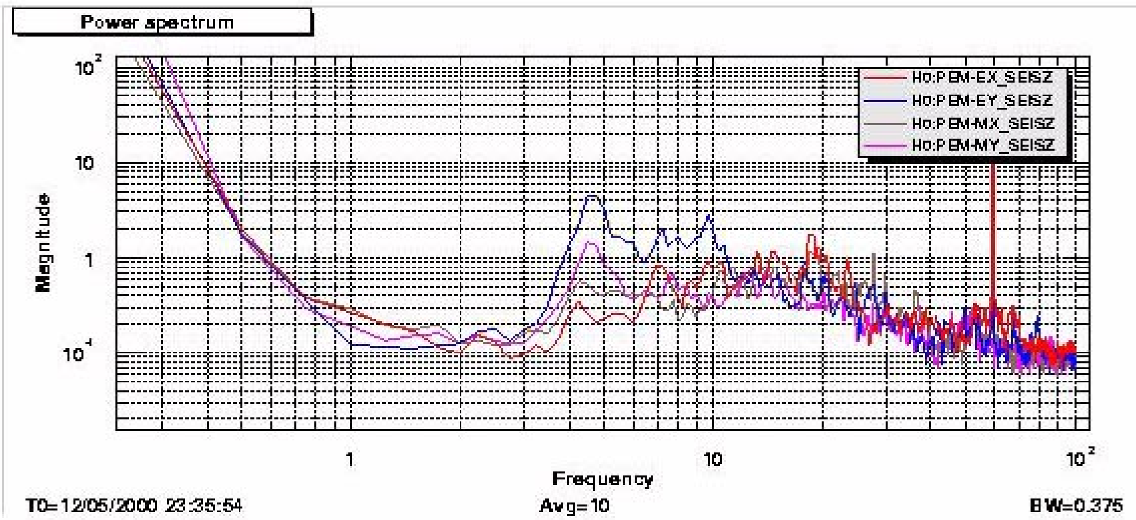
Estimated minimum velocity: 426 m/s (pointing off by 30 degrees).

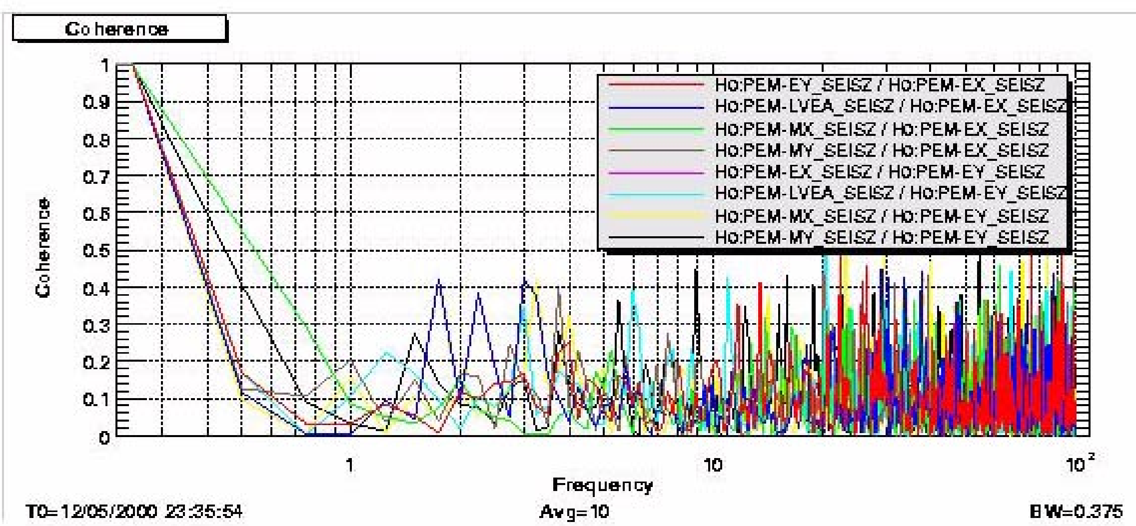
Dispersion Relation Near Y-End for Signals Generated By Two Compacter Types:



Tamper at 40m: vertical ground motion
propagation velocity (m/s)
frequency (Hz)
0
100
200
300
400
500
600
0
10
20
30
40
50
60

Probable Truck on Highway 240





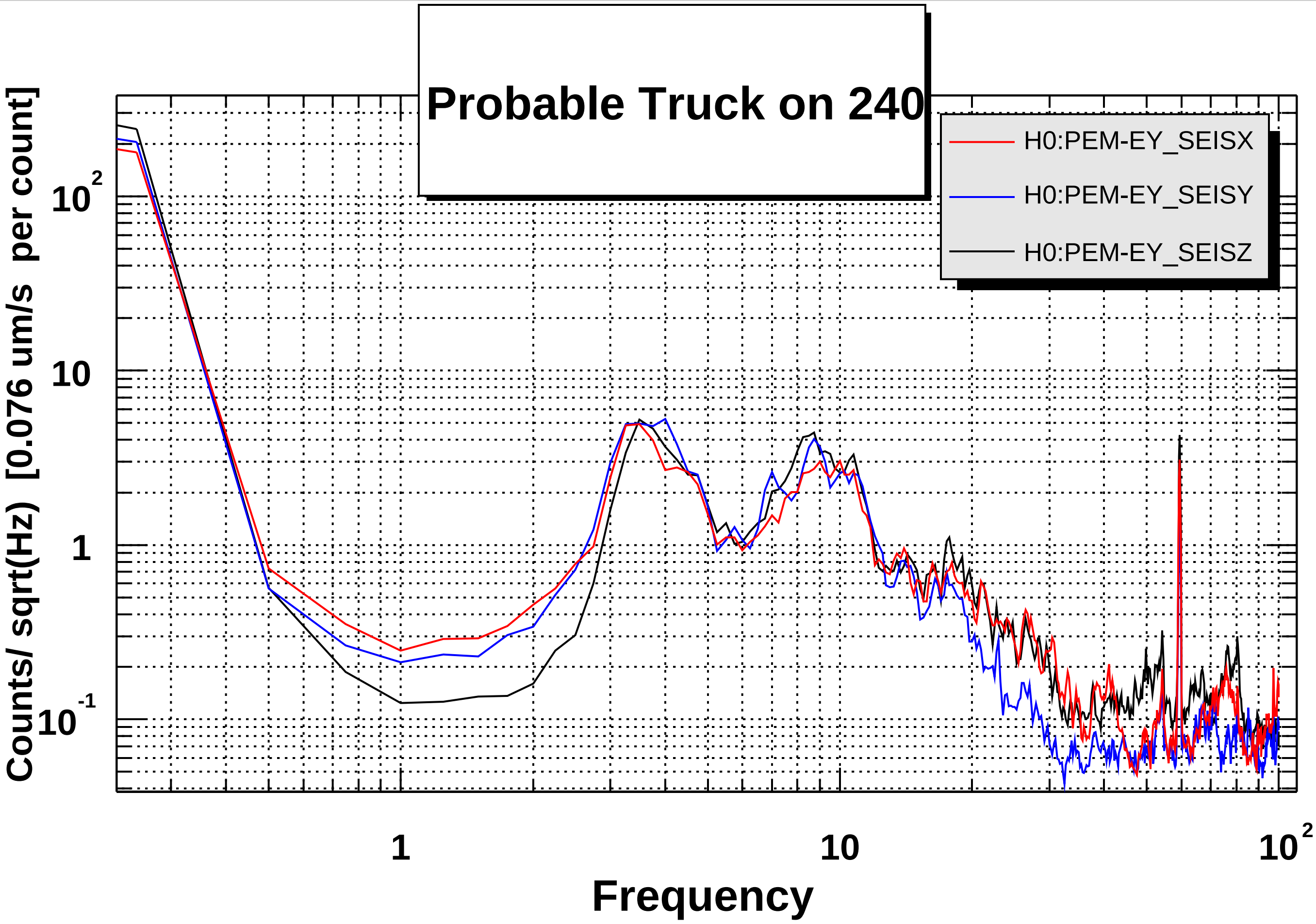
Q

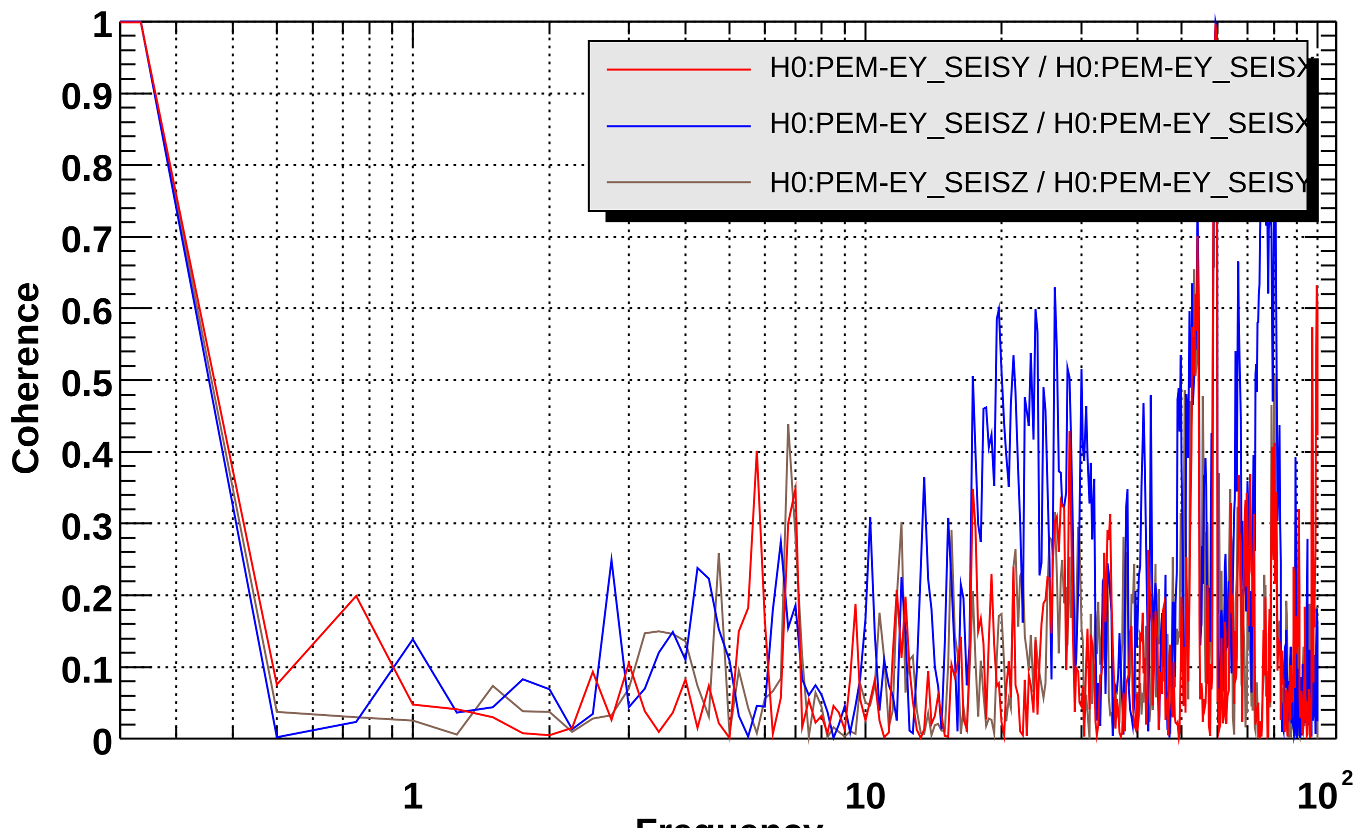
Calculted from amplitudes at Mid and End-Y. Assumed trucks on 240 at an average distance of 2000 m from End-Y for 100s periods around signal maximum.

$$\frac{A_{mid}}{A_{end}} = \sqrt{\frac{R_{end}}{R_{mid}}}e^{-\pi(R_{mid} - R_{end})/Q\lambda}$$

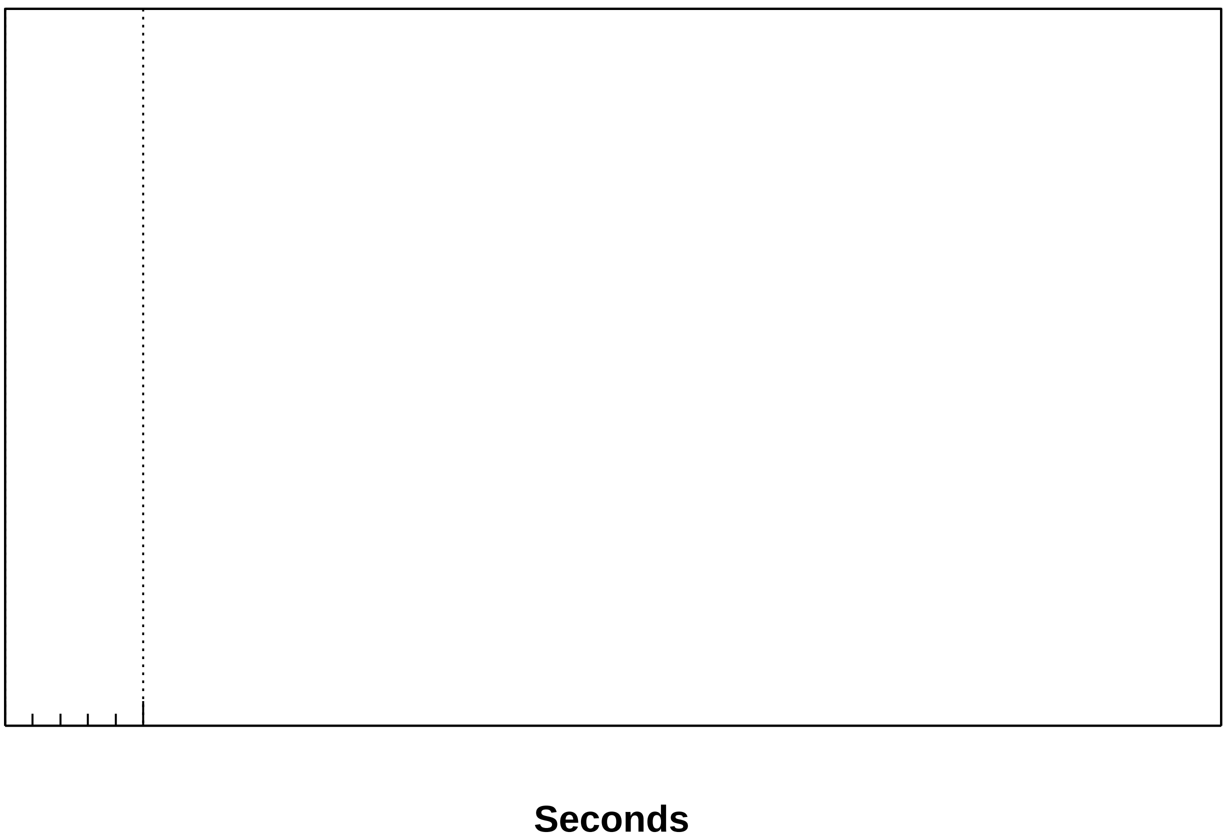
For 7 trucks, peaks at 4.4 - 6 Hz:

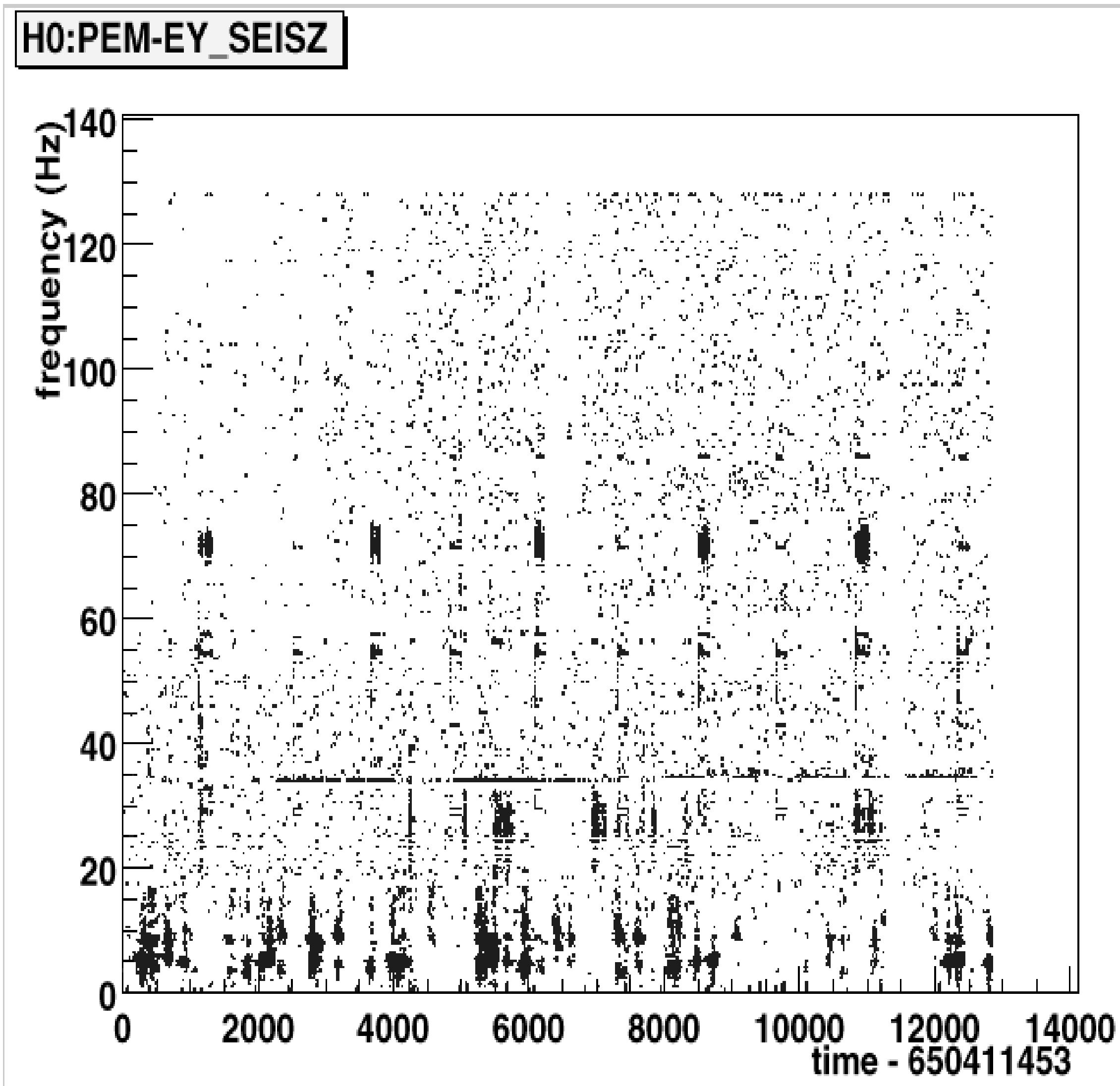
Q = 68 $\pm$ 12



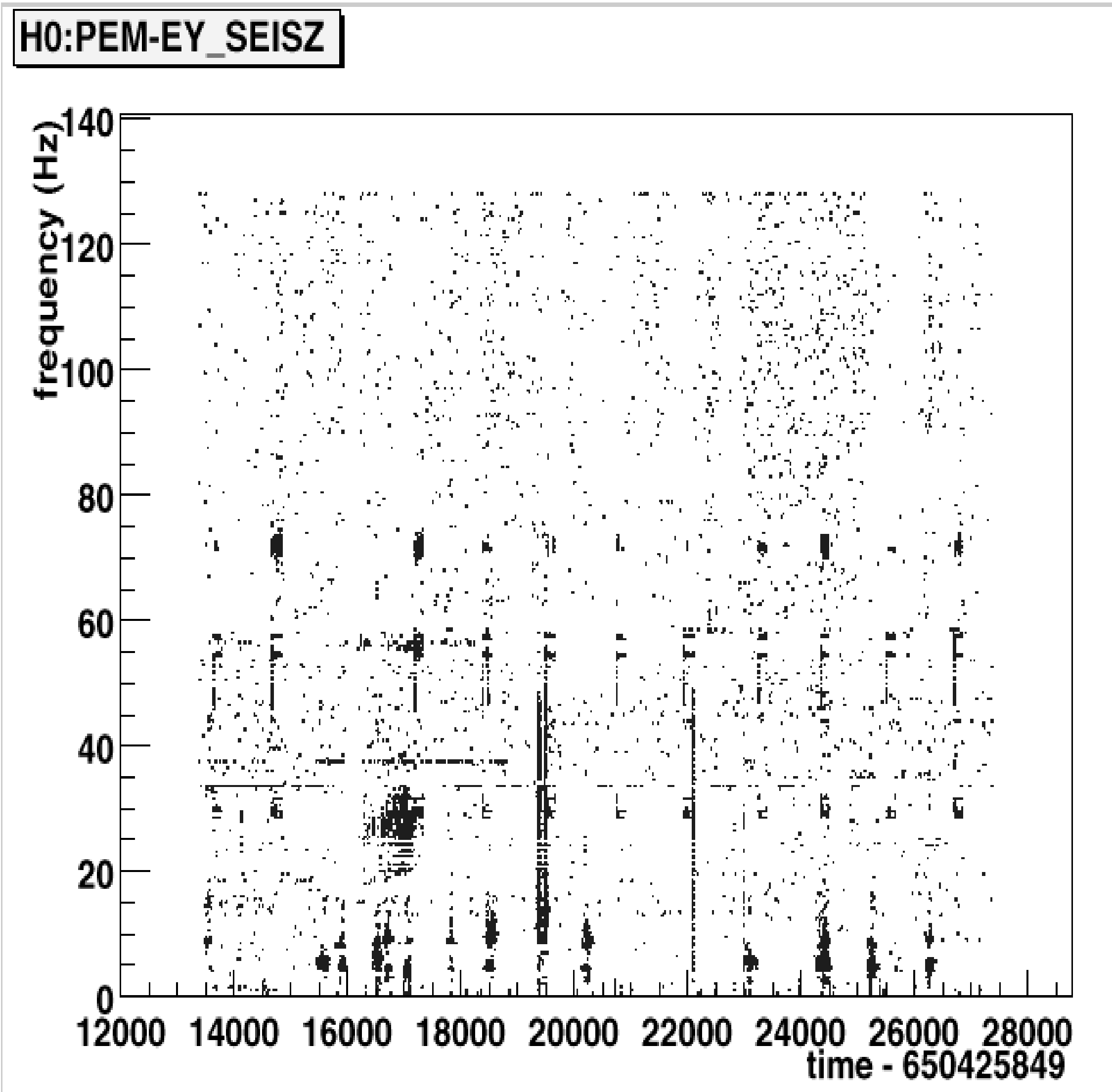


T0=12/07/2000 16:37:35 Avg=25 BW=0.375


Seconds



H0:PEM-EY_SEISZ
frequency (Hz)
140
120
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
12000
14000
time - 650411453


H0:PEM-EY_SEISZ
frequency (Hz)
140
120
100
80
60
40
20
0
12000
14000
16000
18000
20000
22000
24000
26000
28000
time - 650425849

Summary

1) The largest semi-continuous off-site seismic signal in the 1-50 Hz band is produced by traffic on the surrounding roads.

2) Seismic motion from trucks can be greater than 10 nm at the nearest stations. Motions from cars are usually less than 1 nm.

3) Experiments with site vehicles suggest that the seismic frequency is given by the velocity and axel spacing of the vehicle.

4) Data and a simple model indicate that propagation is not acoustic with local coupling to the ground or directly to the seismometer.

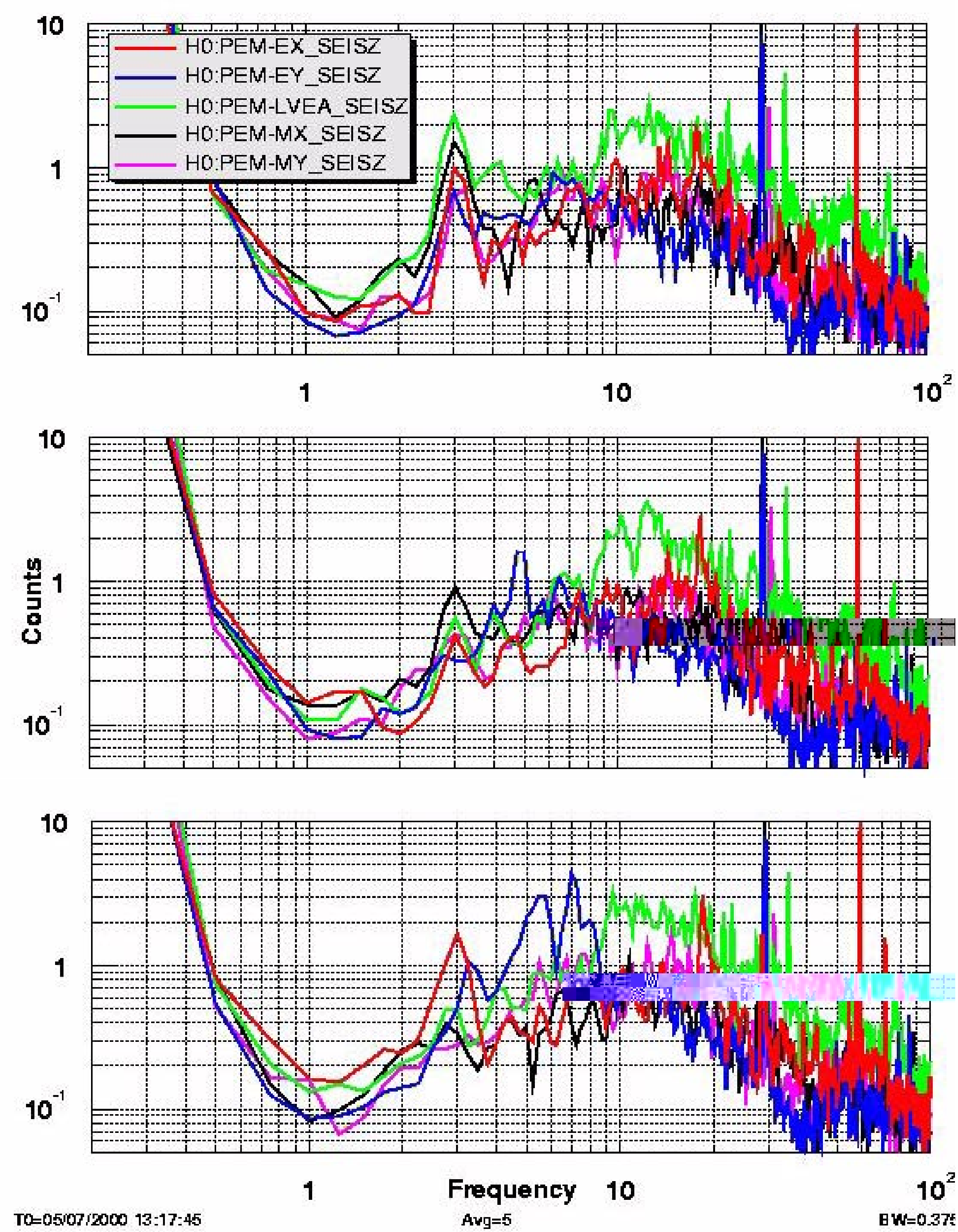
5) Signal propagation velocities are under 492±62 m/s and probably greater than 425 m/s (8 Hz average peak).

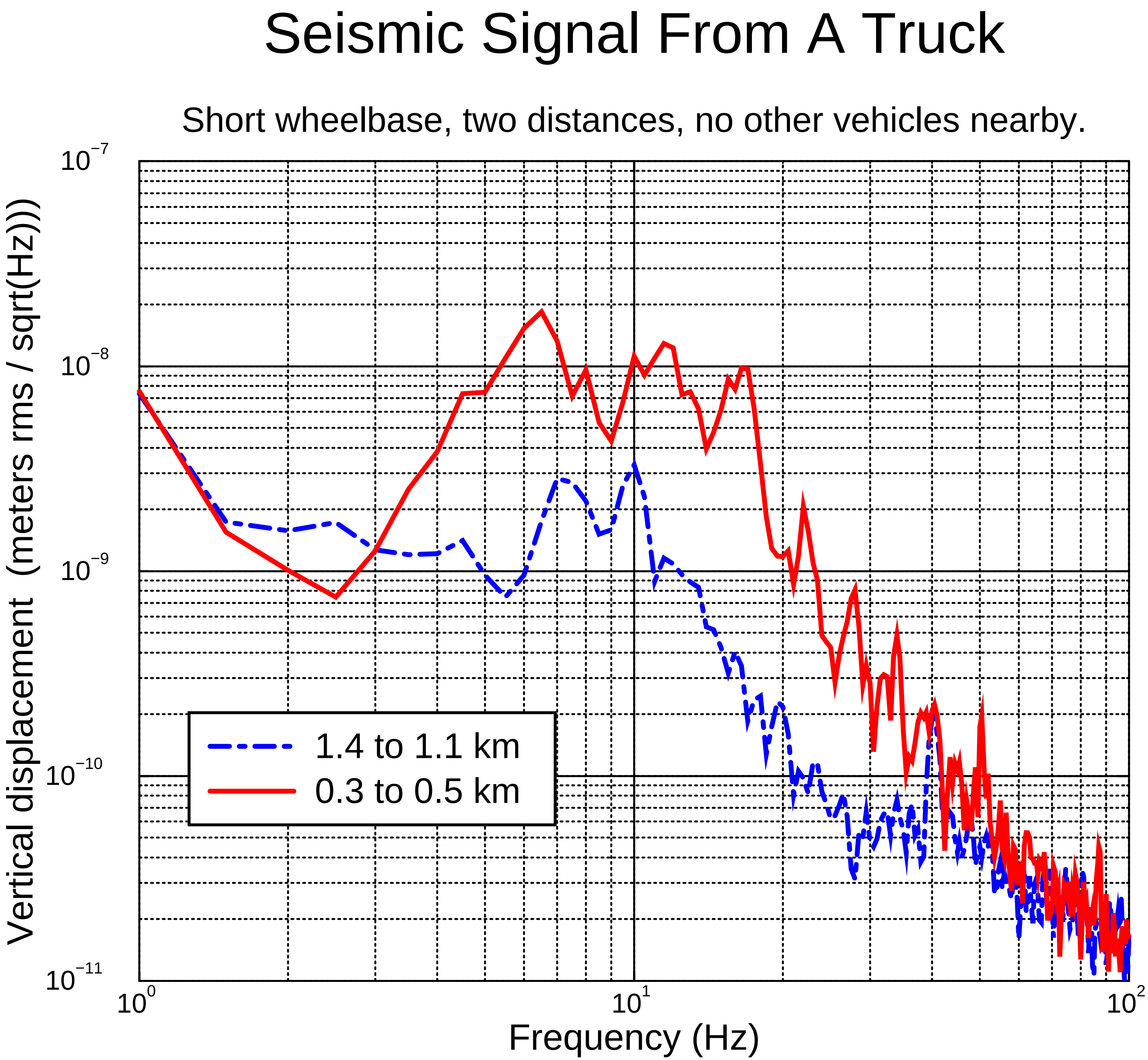
6) Tamper signals travel at about 300 m/s at 10 Hz and about 75 m/s at 50 Hz.

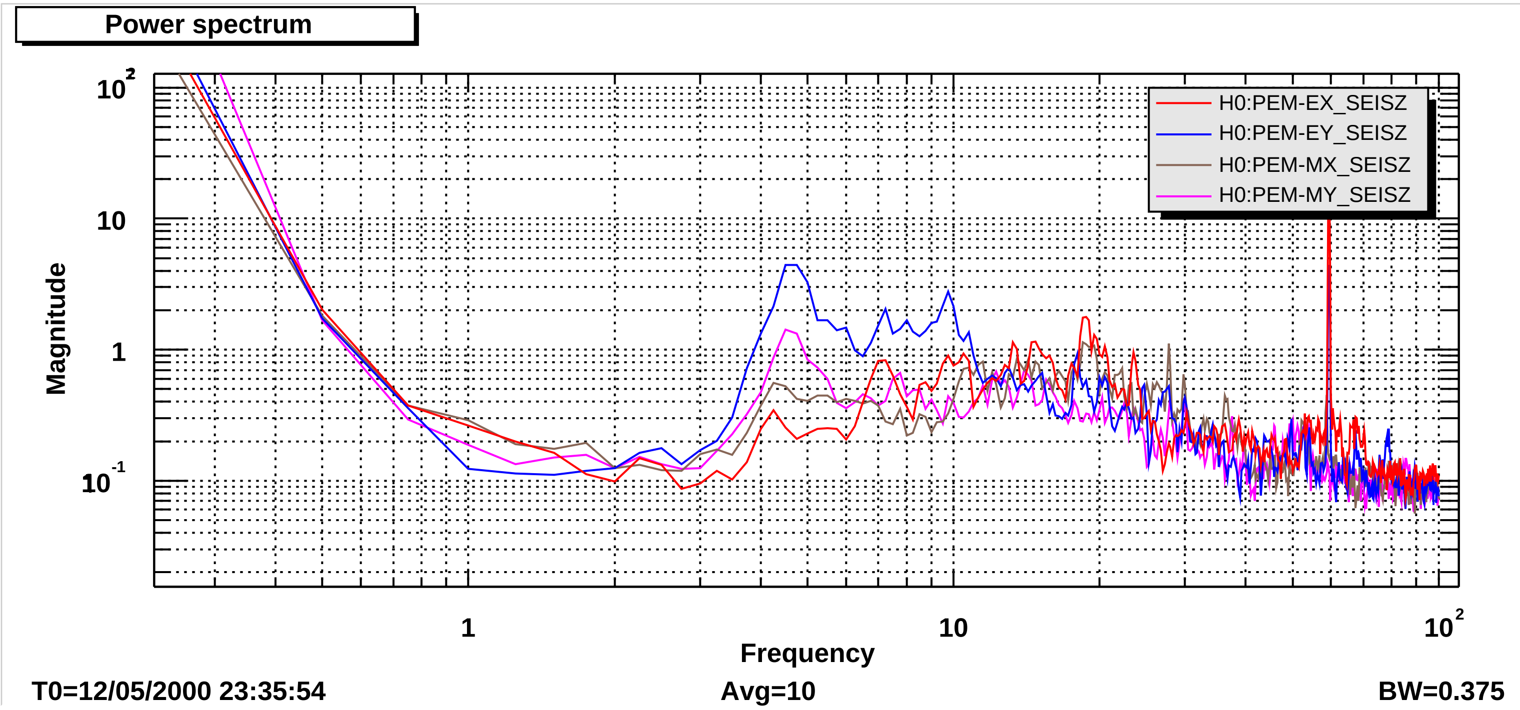
7) Q for seven trucks in the 4.4 - 6 Hz range was 68 ±12.

8) Seismic signals were about equal on all 3 axes.

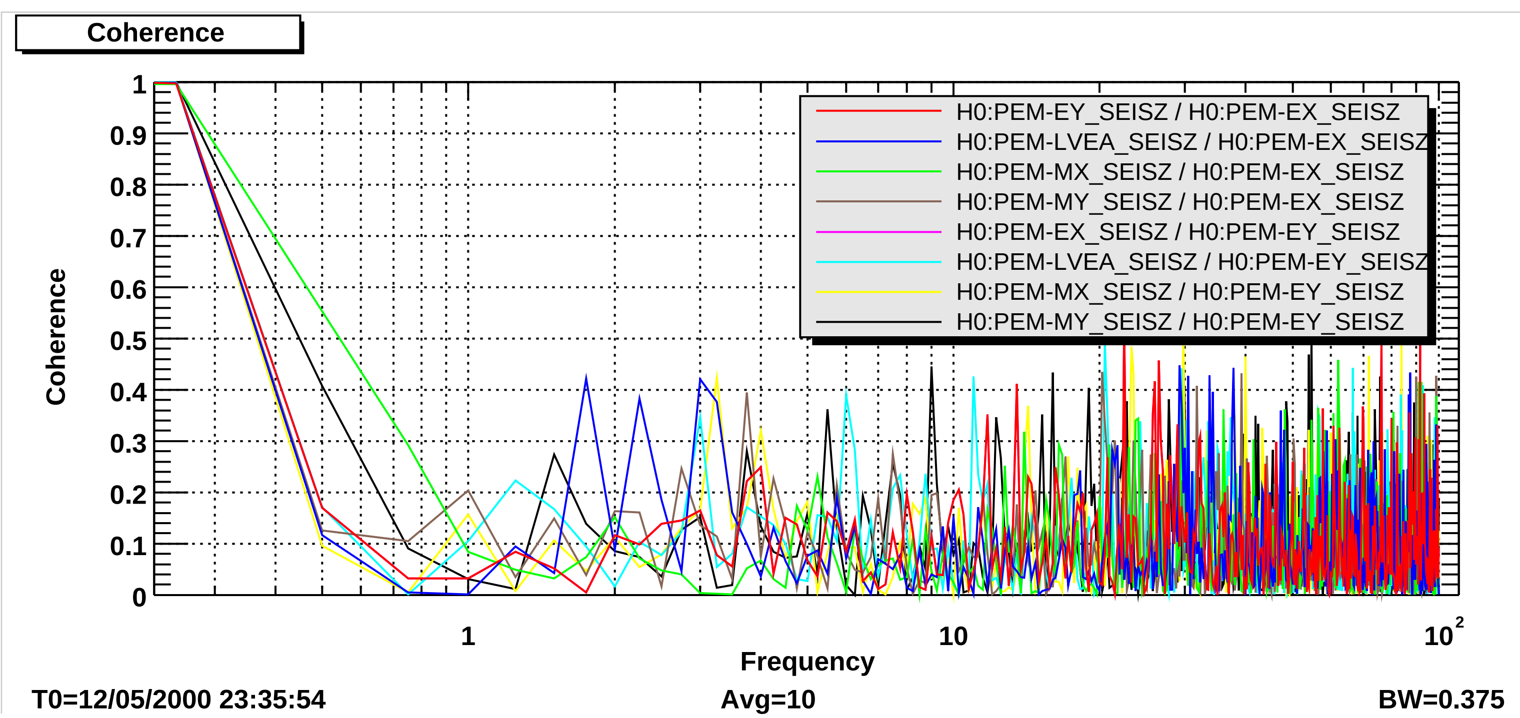
Probable Truck Progressing North on Route 2



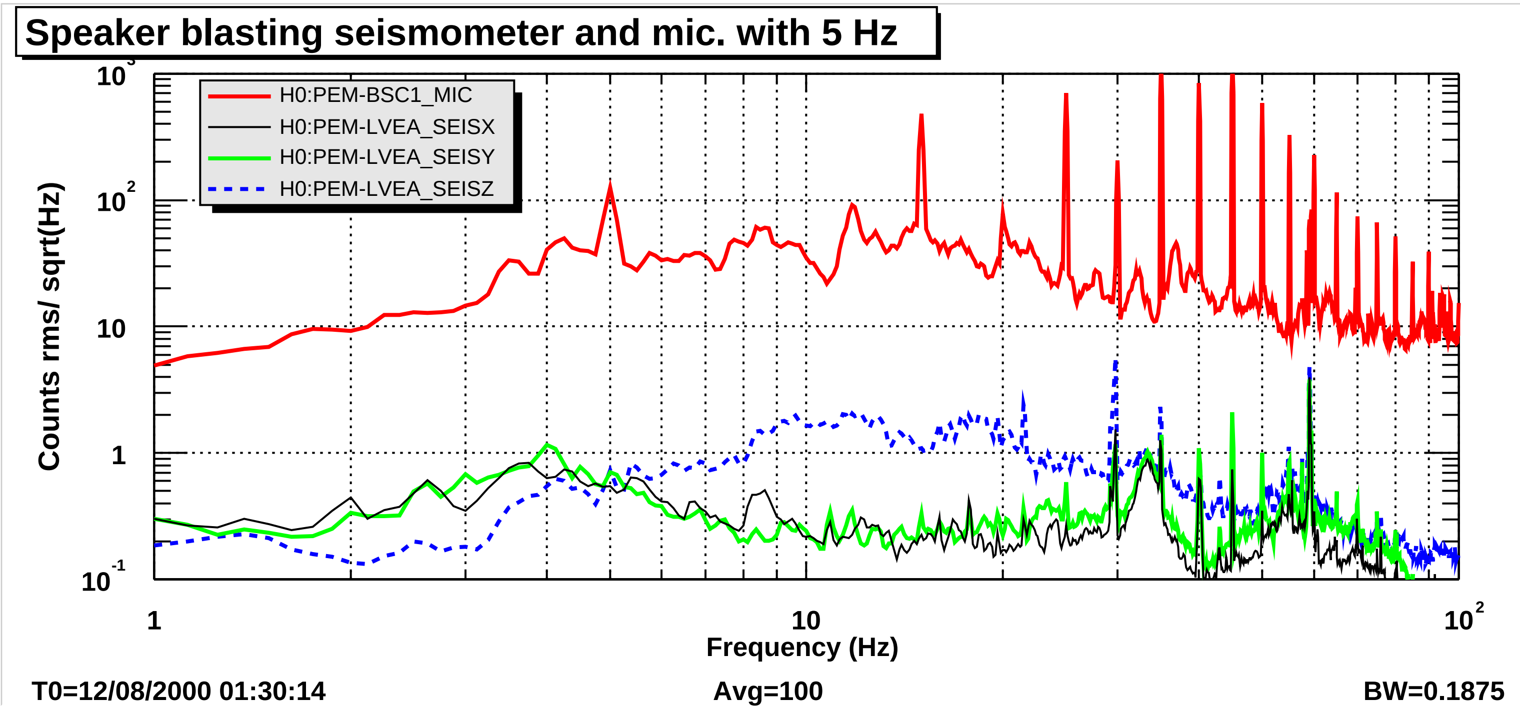

Seismic Signal From A Truck
Short wheelbase, two distances, no other vehicles nearby.
Vertical displacement (meters rms / sqrt(Hz)))
Frequency (Hz)
1.4 to 1.1 km
0.3 to 0.5 km

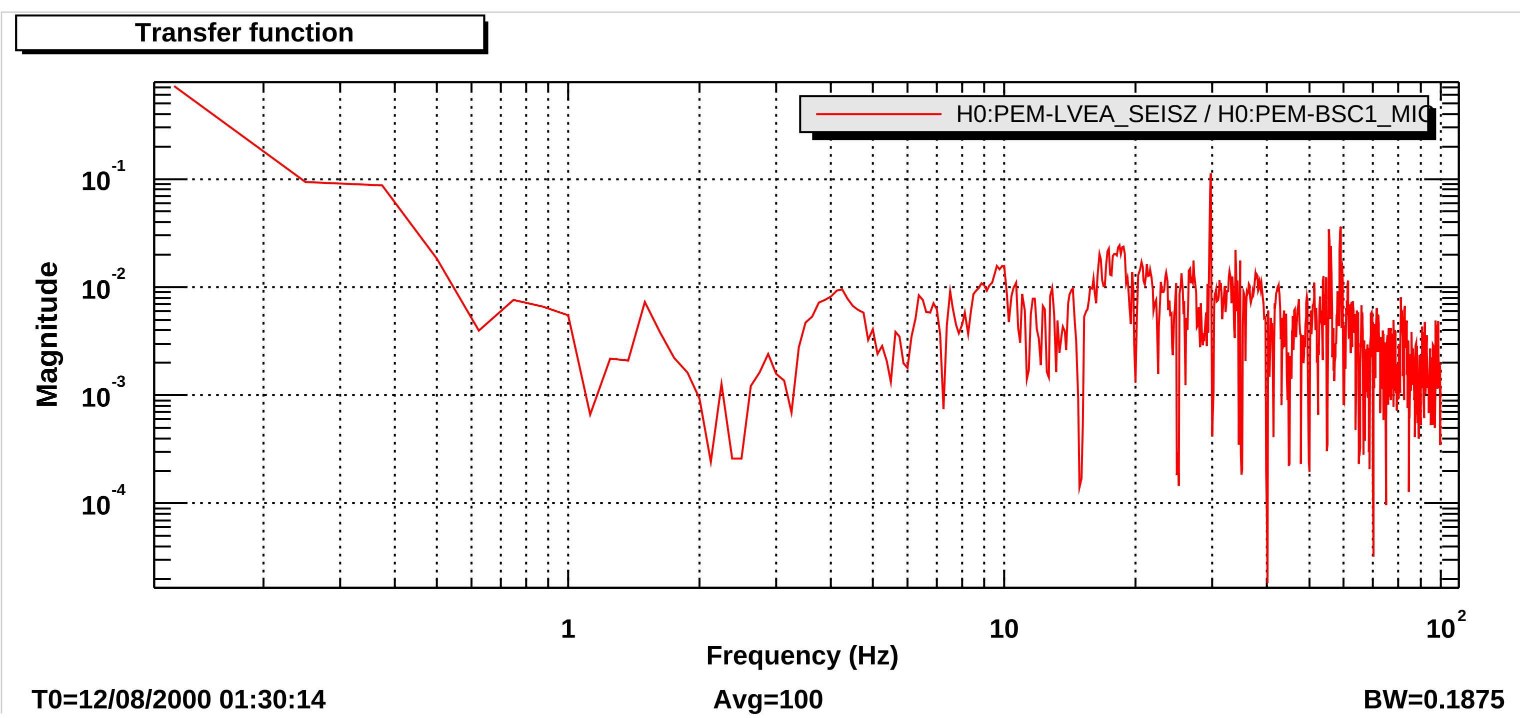


Power spectrum
Magnitude
Frequency
H0:PEM-EX_SEISZ
H0:PEM-EY_SEISZ
H0:PEM-MX_SEISZ
H0:PEM-MY_SEISZ
T0=12/05/2000 23:35:54
Avg=10
BW=0.375



Coherence
Coherence
Frequency
H0:PEM-EY_SEISZ / H0:PEM-EX_SEISZ
H0:PEM-LVEA_SEISZ / H0:PEM-EX_SEISZ
H0:PEM-MX_SEISZ / H0:PEM-EX_SEISZ
H0:PEM-MY_SEISZ / H0:PEM-EX_SEISZ
H0:PEM-EX_SEISZ / H0:PEM-EY_SEISZ
H0:PEM-LVEA_SEISZ / H0:PEM-EY_SEISZ
H0:PEM-MX_SEISZ / H0:PEM-EY_SEISZ
H0:PEM-MY_SEISZ / H0:PEM-EY_SEISZ
T0=12/05/2000 23:35:54
Avg=10
BW=0.375


Speaker blasting seismometer and mic. with 5 Hz
H0:PEM-BSC1_MIC
H0:PEM-LVEA_SEISX
H0:PEM-LVEA_SEISY
H0:PEM-LVEA_SEISZ
Counts rms/ sqrt(Hz)
Frequency (Hz)
T0=12/08/2000 01:30:14
Avg=100
BW=0.1875


Transfer function
H0:PEM-LVEA_SEISZ / H0:PEM-BSC1_MIC
Magnitude
Frequency (Hz)
T0=12/08/2000 01:30:14
Avg=100
BW=0.1875