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Ground Vibration Measurements at LHC Point 4</td></tr>
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1. ABSTRACT

Ground vibration was measured at LHC Point 4 during the winter shutdown in February 2012. This report contains the results, including power and coherence spectra.

2. PURPOSE

We plan to collect and analyze vibration data from representative collider halls to inform specifications for future linear colliders, such as ILC and CLIC. We are especially interested in vibration correlations between final focus lens locations.

The Point 4 experimental hall at LEP/LHC is about 140 m below grade. Its width is similar to the proposed ILC detector hall. Thus, it is expected that vibration correlations will be similar to those seen in ILC, and that this will help to inform design decisions for the ILC detector and final focus.

3. MASUREMENT LOCATION

We had planned to take measurements across the Point 4 experimental hall, with the sensors arranged symmetrically in the final focus tunnels at 1m, 5m, 10m, and 15m from the edge of the experimental hall. However, we were not allowed access to the hall or final focus tunnels due to problems regarding the tunnel access and lockup schedule.

We were able instead to make an abbreviated set of measurements in a utility tunnel at Point 4 on February 10, 2012 (area highlighted in red in Fig 1). We measured vertical vibrations between two sensors separated by 20 m and 30 m (Fig. 2).

4. INSTRUMENTATION AND MEASUREMENTS

Measurements were taken with a SLAC instrumentation system in February 2012. The vibration sensors were Sercel/Mark L4C geophones/seismometers, sensitive in the vertical direction. These are passive sensors with a suspended mass of 1 kg and a resonant frequency of about 1 Hz. Motion of the mass is detected with a permanent magnet and voice-coil pickup.

The signals were pre-amplified near the sensors using battery-operated preamplifiers. The inputs of the preamps are impedance-matched to the L4C sensors. The preamps have a voltage gain of 30x, and a two-pole critically coupled anti-alias filter at 400 Hz.

The analog signals from the preamps were passed through BNC cables and were sampled and digitized by a National Instruments NI-DAQ A-D card in a portable laptop computer. Sampling was done at 1024 Hz. Time series were typically 1024 sec in length.

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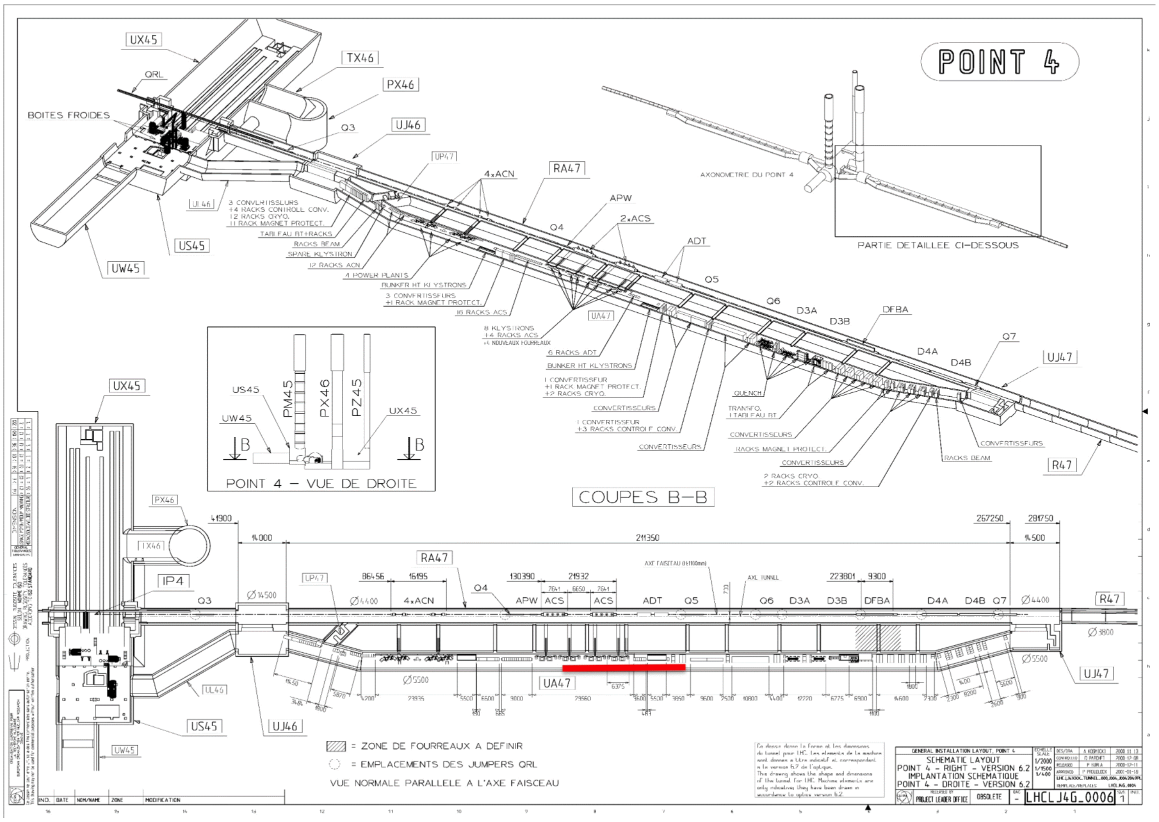

Figure 1: Plan view of LHC Point 4. Vibration measurements were performed in the part of the utility tunnel highlighted in red.

Because the anti-aliasing filter has a fairly slow roll off, there may be some aliasing of signals near 500 Hz. But there should be essentially no aliasing in the critical low-frequency region (< 10 Hz). No 50 Hz power line harmonics can alias into this region with 1024 Hz sampling.

Each time series of 1024 sec was split into a number of short independent samples, either 128 samples of 8 seconds, or 256 samples of 4 seconds. Each short sample was passed through a Hanning window, an FFT was taken, and the results were averaged.

5. POWER SPECTRA

The power spectral density (PSD), *p(f)*, may be estimated by:

$$p(f) = \frac{1}{T}\left\langle \left| X(f) \right|^2 \right\rangle \qquad 1)$$

where *X(f)* is the Fourier transform of a time-dependent signal *x(t)*, and an average is taken over a number of independent time series, each of length *T* [1,2]. If *x(t)* is a measurement of ground position in units of meters, *p(f)* will have units of m^2/Hz.

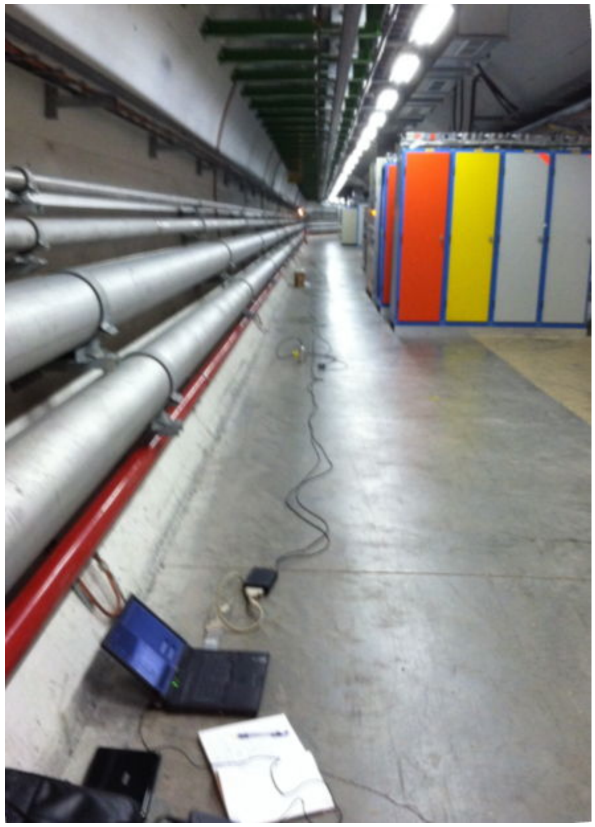

Figure 2: Vibration measurement system in utility tunnel at Point 4.

The PSD and the integrated power for vibrations in the Point 4 utility tunnel with a separation of 30 m are shown in Fig. 3. The spectra for 20 m separation were quite similar.

The PSD spectra seen by the two sensors were nearly equal, as expected if ground vibration is predominantly due to remote rather than local sources. The vibration level was quite low, lower than any hall or tunnel measurements we have seen at SLAC. This was somewhat surprising, since the equipment in the tunnel produced audible noise.

The spectra show significant sharp spikes at 50 Hz and its harmonics (100, 200, 250, 300). This is not surprising with all of the electrical equipment in the tunnels. The large spike at ~480 Hz may be a 500 Hz harmonic aliased by the 1024 Hz sampling rate, but there is no evidence of aliasing below 400 Hz.

5. CROSS-POWER SPECTRA

The cross-power spectrum $p_{12}(f)$ may be estimated by:

$$p_{12}(f) = \frac{1}{T}\left\langle X_1^*(f) X_2(f) \right\rangle \qquad 2)$$

where $X_1(f)$ and $X_2(f)$ are Fourier transforms of the signals $x_1(t)$ and $x_2(t)$ at sensors 1 and 2.

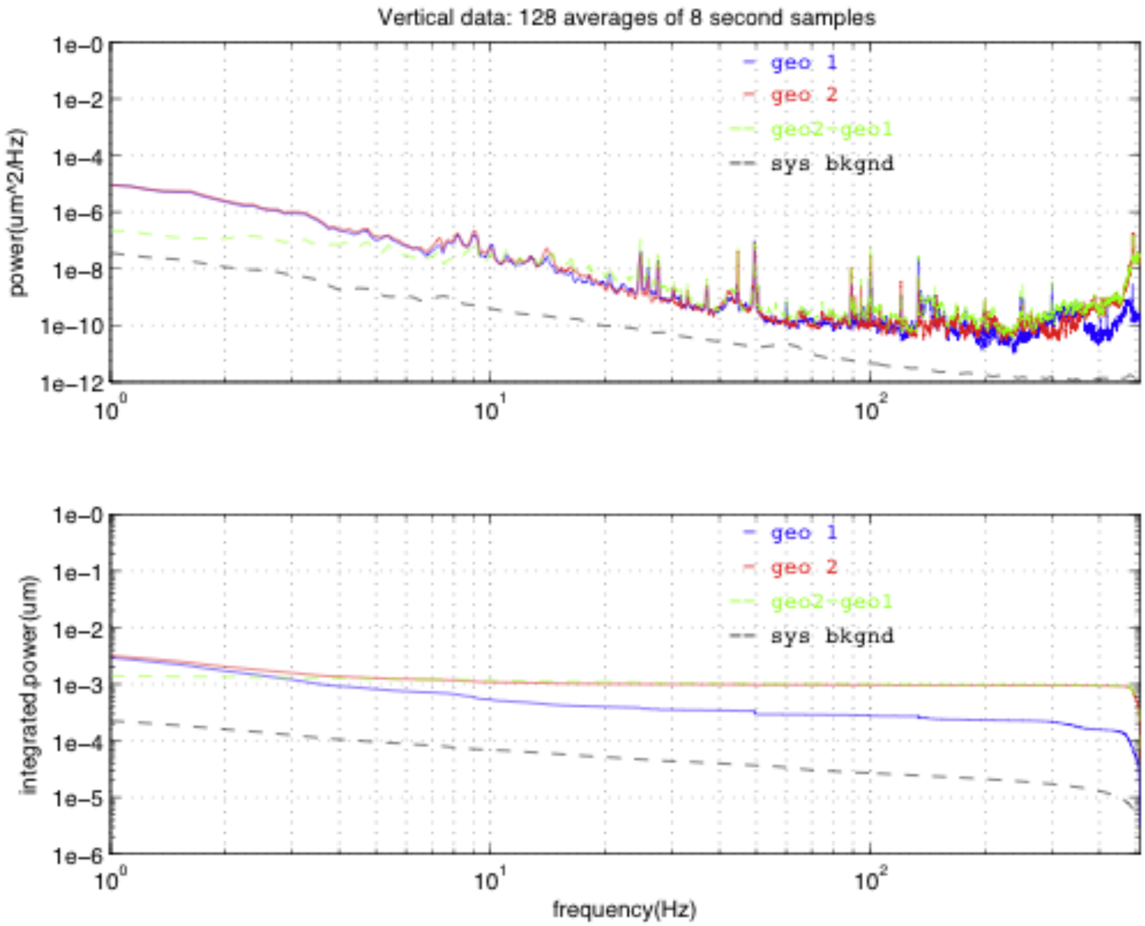

Figure 3: PSD of vertical vibrations, sensors 30m apart.

It is often more convenient to express the cross-power spectrum as a normalized quantity, the *correlation* $N_{12}(f)$:

$$N_{12}(f) = \frac{p_{12}(f)}{\sqrt{p_1(f)p_2(f)}} \qquad 3)$$

The measured correlation for vibrations in the Point 4 utility tunnel with a separation of 30 m are shown in Fig. 4, and for a separation of 20 m is shown in Fig. 5.

In general, the correlation is a complex quantity. However, if the characteristics of ground motion are not location-dependent, the imaginary part of the correlation will be zero [2]. This should hold when the ground properties are identical under each sensor, the ground does not absorb energy, and the sources of vibrations are very far away (so that their amplitude is the same at both sensors). As seen in Figs 4 and 5, though not identically zero, the imaginary part of the correlation is much smaller than the real part below about 10 Hz.

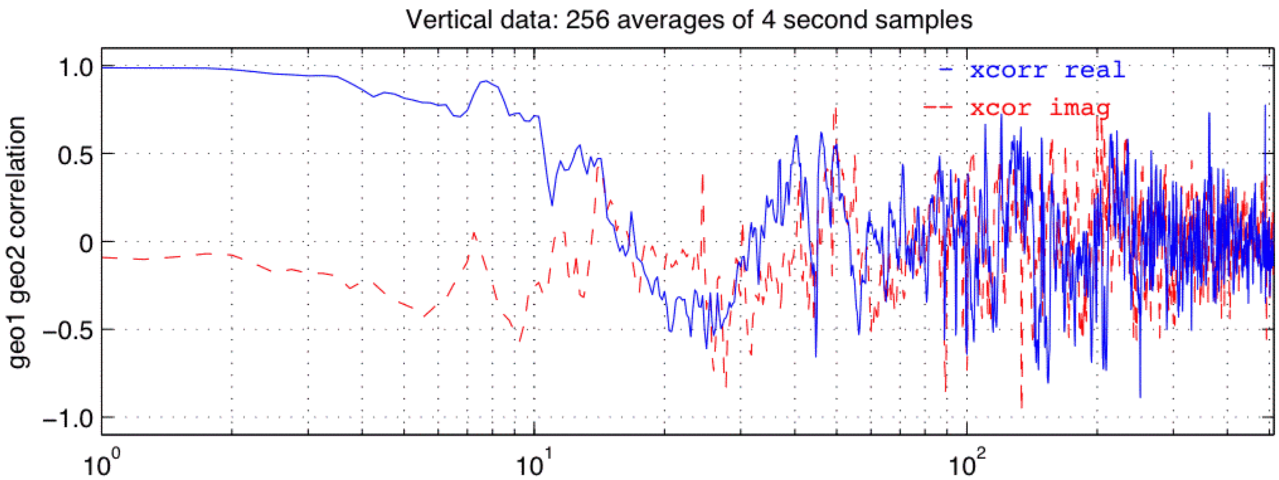

Figure 4: Real and imaginary parts of correlation, sensors 30m apart in Point 4 utility tunnel.

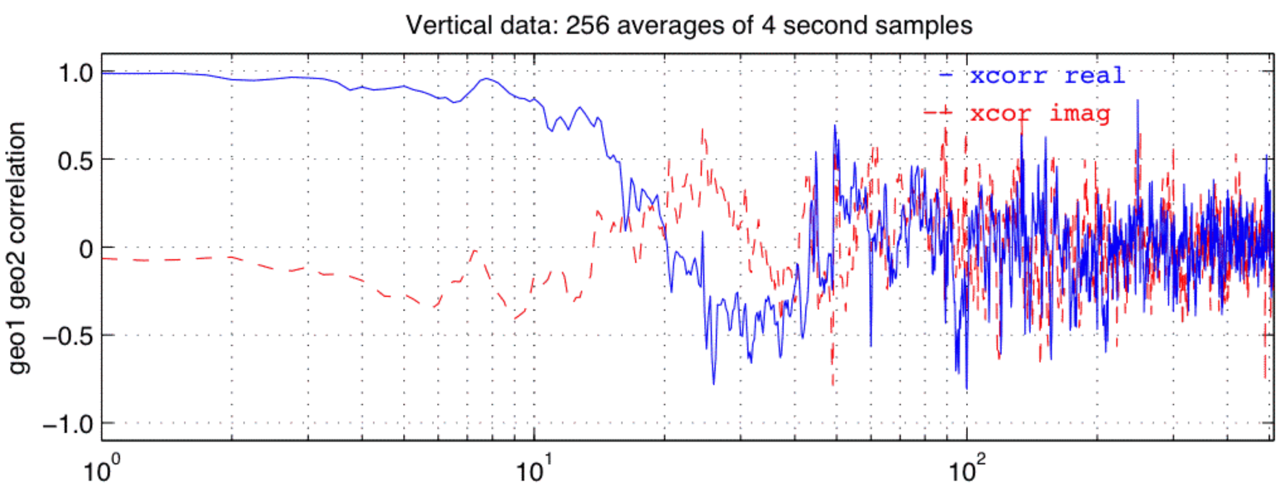

Figure 5: Real and imaginary parts of correlation, sensors 20m apart in Point 4 utility tunnel.

For distant vibration sources in line with the two sensors and with the above conditions met, the correlation will be [2]:

$$N_{12}(f) = \cos(\omega L/v) \qquad 4)$$

where L is the distance between the two sensors and v is the wave velocity. For vertical vibrations with two sensors separated horizontally, as here, v is the velocity of transverse or shear waves, often denoted as v_s or c_s.

For distant vibration sources in a horizontal plane and at random angles to the line joining the two sensors, the correlation will be given by a Bessel function [2]:

$$N_{12}(f) = J_0(\omega L/v) \qquad 5)$$

The real part of the measured correlations (Figs 4,5) can be fit with Eq. 5 to find the apparent shear wave velocity. We have passed the correlation data through a tenth-octave smoothing filter for better visualization. For 30 m separation, the apparent velocity is about 1330 m/s (Fig. 6). For 20 m, it is about 1150 m/s (Fig. 7). Averaging the two, we see an apparent shear wave velocity of about 1240 m/s at Point 4.

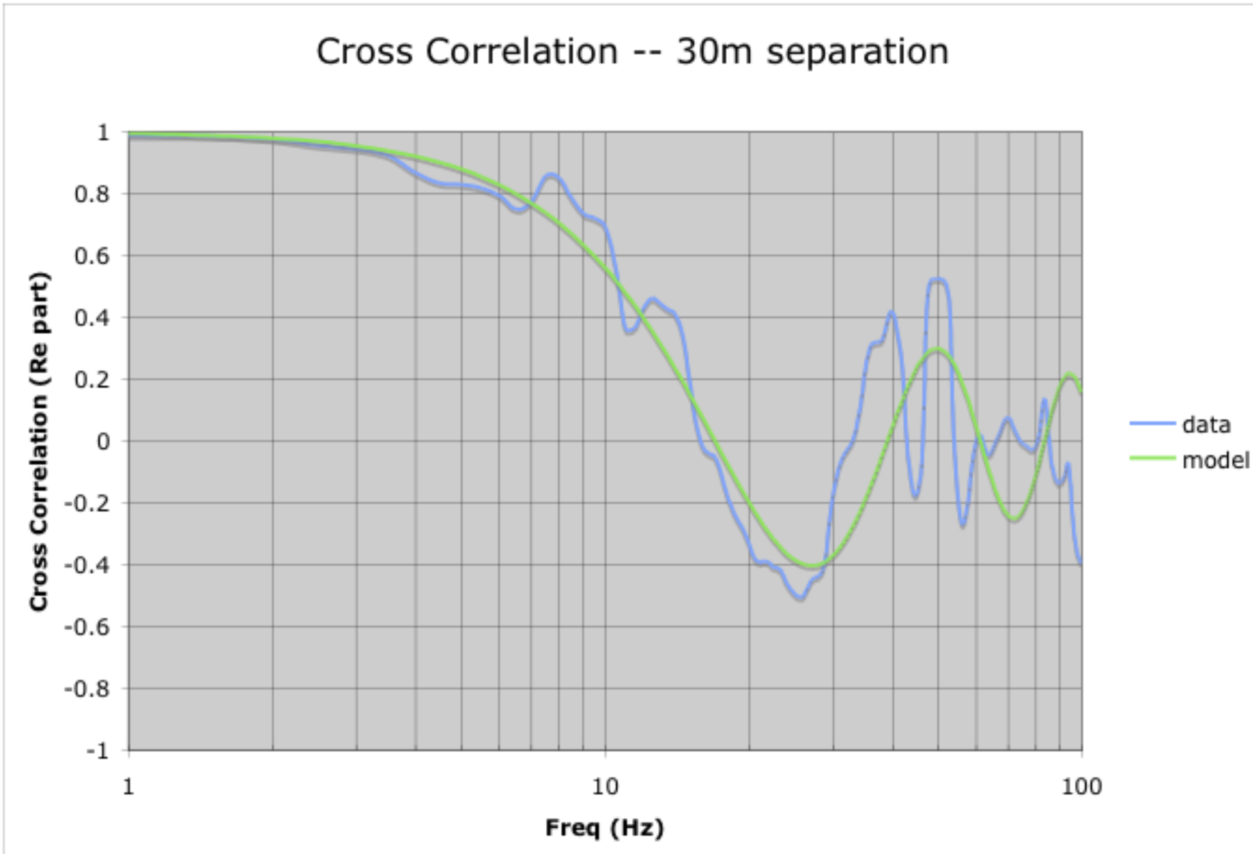

Figure 6: Real part of measured correlation and single-parameter Bessel function fit. Fit yields a velocity of 1330 m/s.

This fit can be improved slightly by adding a proportion of in-line noise sources to uniformly distributed noise sources, i.e., by adding a proportion of Eq. 4 to Eq. 5. However, the apparent velocity is only slightly changed (less than 10%) by this approach.

6. DISCUSSION

The Bessel function of Eq. 5 provides a good fit to the data, at least through the first zero of the Bessel function. The fitted shear velocity is seen to increase with sensor separation. A slight increase is to be expected, because soil is dispersive. Shear velocity increases with depth, due to the increase in pressure which increases the shear modulus of the soil. Lower frequency ground waves extend deeper into the soil, thus have a higher average velocity [3]. Larger separation between sensors emphasizes lower frequencies, so should give a larger effective shear velocity.

In prior measurements in the LEP tunnel at 200 m separation the real part of the correlation crosses zero at 2.5-3 Hz, and measurements at 2000m the real part of the correlation crosses zero at about

0.4 Hz [4]. In our current measurements at 20 m separation the real part of the correlation crosses zero at abut 20 Hz. Scaling the velocity fit of Fig. 7 (~1200 m/s for 20 m separation), we find that the effective shear velocity at 200 m separation is about 1500 m/s, and at 2000 m separation is about 2500 m/s. The current measurements seem to be consistent with these prior measurements.

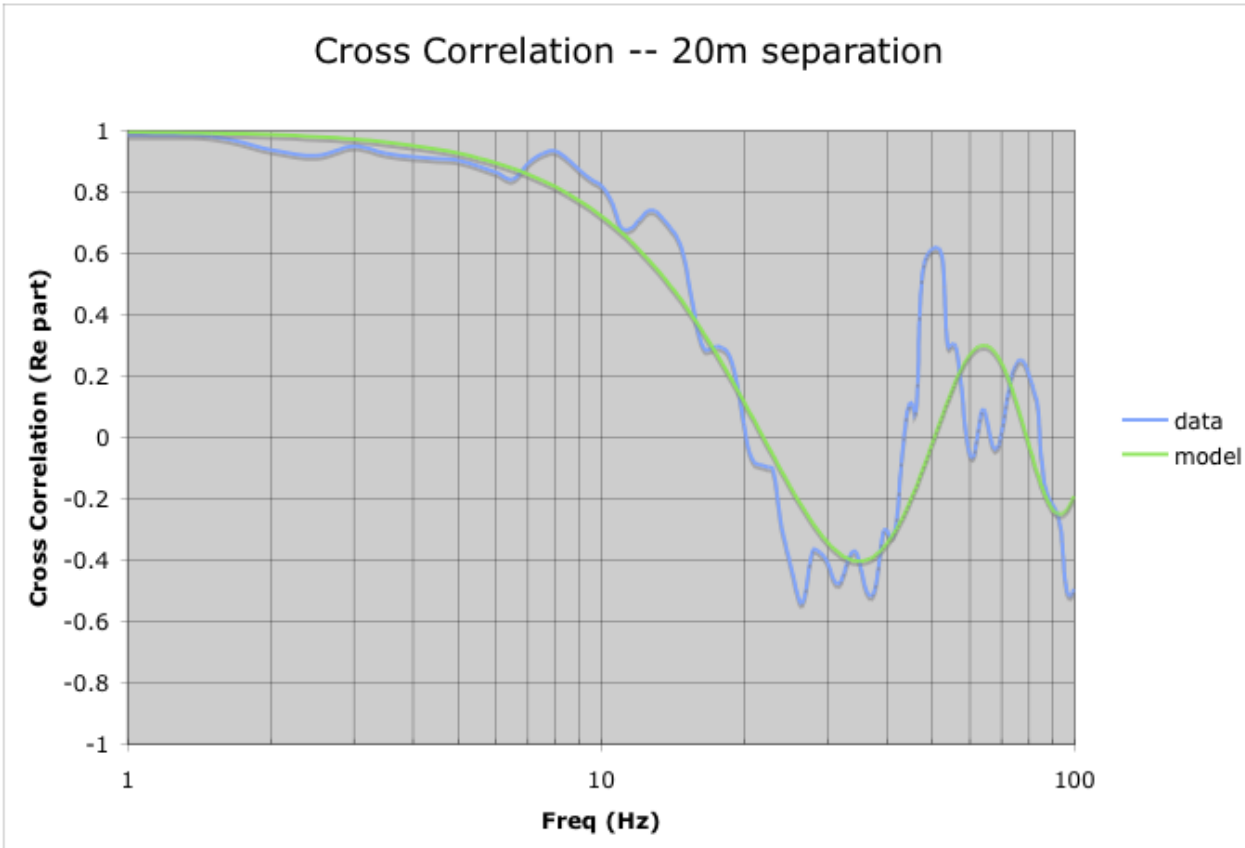

Figure 7: Real part of measured correlation and single-parameter Bessel function fit. Fit yields a velocity of 1150 m/s.

7. REFERENCES

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