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Linear Collider Collaboration Tech Notes

Stanford University

Stanford Linear Accelerator Center
Los Angeles County Metropolitan Transit Authority Vibration Study
Designs Guidelines Summary

Parsons
Pasadena, CA

For

Stanford Linear Accelerator Center
Stanford University
Stanford, CA

Abstract: The overall objectives of this project are to experimentally determine the vibration transmissibility in rock similar to that at SLAC's NLC site. Vibration transmissibility was measured at the location of the Los Angeles MTA's Metro Red Line tunnels near the Universal City Station in North Hollywood. Transmissibility was measured from surface-to-tunnel, along one tunnel, and tunnel-to-tunnel using both ambient (traffic and other cultural sources) and controlled vibration energy. Results will be used by SLAC to assess potential impacts of internal and external vibration sources on the operation of a proposed future linear accelerator.

GEOVision
geophysical services
a division of Blackhawk GeoServices

Stanford Linear Accelerator
Tunnel Vibration Measurements

Conducted at

MTA Universal Subway Station
North Hollywood, California

Revision 5

April 30, 2004

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Report Prepared for

Parsons

Pasadena, California

by

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INTRODUCTION

The overall objectives of this project are to experimentally determine the vibration transmissibility in rock similar to that at SLAC's NLC site. Vibration transmissibility was measured at the location of the Los Angeles MTA's Metro Red Line tunnels near the Universal City Station in North Hollywood. Transmissibility was measured from surface-to-tunnel, along one tunnel, and tunnel-to-tunnel using both ambient (traffic and other cultural sources) and controlled vibration energy. Results will be used by SLAC to assess potential impacts of internal and external vibration sources on the operation of a proposed future linear accelerator.

Project Team

The vibration measurements and analyses described herein were performed by staff of GeoVision Geophysical Services in partnership with Parsons Infrastructure. Field supervision and assistance were provided by Stanford Linear Accelerator. The Los Angeles Metropolitan Transit Authority (MTA) provided logistical support as well as access to their tunnels.

Schedule

Planning and preparation for this project were done in March and April, 2003. The actual field measurements were done between May 12-14, 2003. Analysis efforts were then done in late May and early June, 2003.

Report Scope

This report details the field vibration measurements and the analysis of the vibration data. Subsequent report sections discuss the Instrumentation, Test Procedure, Analysis and Results, and Summary and Conclusions. Most of the detailed data and results are included in the five appendices, one for each of Tests 1-5.

INSTRUMENTATION

Our basic instrumentation system consisted of the following components:

- Six low-frequency seismometers to sense vertical vibration velocity
- Cables to connect the sensors and the recorders
- Three high-resolution digital seismographic recorders
- Two PC field computers
- High-energy, low-frequency seismic source (accelerated weight drop)

Sensors were passive low-frequency seismometers, both Kinemetrics Model SS-1 and Geospace Model HS-1. These have frequency bandwidths from <3Hz to >100 Hz, and noise levels far less that one micro-inch/second.

These were augmented by 10-Hz Geospace Model GS-20DM geophones to cover the higher part of the frequency range. These sensors have a frequency bandwidth from 10 Hz to several hundred Hz.

Sensors were coupled to the floor of the tunnel or to the ground using gravity; this method is quite adequate for the low-level vibrations encountered, and is non-destructive.

Three digital recorders were used during the various tests. Two were Geometrics "Geode" digital seismographs, each with 24-channels of 18+-bit digital data resolution, and digital recording. One of these was set for low gain (gain=0dB=1) and the other for high gain 9gain= 24 or 36 dB). The third recorder was a Kinemetrics Model SSR-1 six-channel seismograph, with 16-bit resolution and higher gain (up to 1000) for use in the relatively quiet tunnel environment. All three recorders, and the sensor system, were powered by 12-volt batteries.

Our vibration source for the controlled-source testing was a Bison Model EWG accelerated weight drop seismic source. This has a 220-lb (100 kg) steel weight that is accelerated by large rubber bands in tension. It is commonly used for seismic reflection studies where the seismic energy must travel over several hundred to a few thousand feet. It produces low-frequency energy down to 10 Hz and below. The EWG system was modified from the usual gasoline engine power to 12-volt battery power to allow use in the subway tunnels (where gasoline is not allowed). A 500-g piezoelectric accelerometer was fixed to the EWG mass to measure the force impulse transmitted to the ground; a battery-powered signal conditioner/power supply was used for this sensor. Later, a 1/10 resistive divider was added to further reduce the accelerometer signal.

The sensors were calibrated prior to use, and the system was checked through a “huddle test” at Geovision on May 11. In this test, all the velocity sensors were mounted on a concrete floor in a huddle, and vibration from both ambient sources and from a sledgehammer were recorded.

Table 1 below presents the sensor calibration data. Figure 1 shows data from the huddle test; the close match of the data from all 1-Hz seismometers verifies that the channel calibrations are correct.

TABLE 1: Sensor Calibration Data

Designation	Type	Ser. No.	Sensitivity	Comments
10’A	SS-1	442	1780 mv/cm/s	4.7k Rd
10’B	GS-20DM	Na	190 mv/cm/s	nominal
100’A	GS-1	1178	3880 mv/cm/s	
100’B	GS-20DM	Na	190 mv/cm/s	nominal
200’A	GS-1	1177	3770 mv/cm/s	
200’B	GS-20DM	Na	190 mv/cm/s	nominal
300’A	GS-1	1179	3700 mv/cm/s	
300’B	GS-20DM	Na	190 mv/cm/s	nominal
500’A	GS-1	1180	4140 mv/cm/s	
500’B	GS-20DM	Na	190 mv/cm/s	nominal
Source A	SS-1	441	1750 mv/cm/s	4.7k Rd
Source B	GS-20DM	Na	190 mv/cm/s	nominal
Source C	Accelerometer		1.00mv/g	1/10 divider

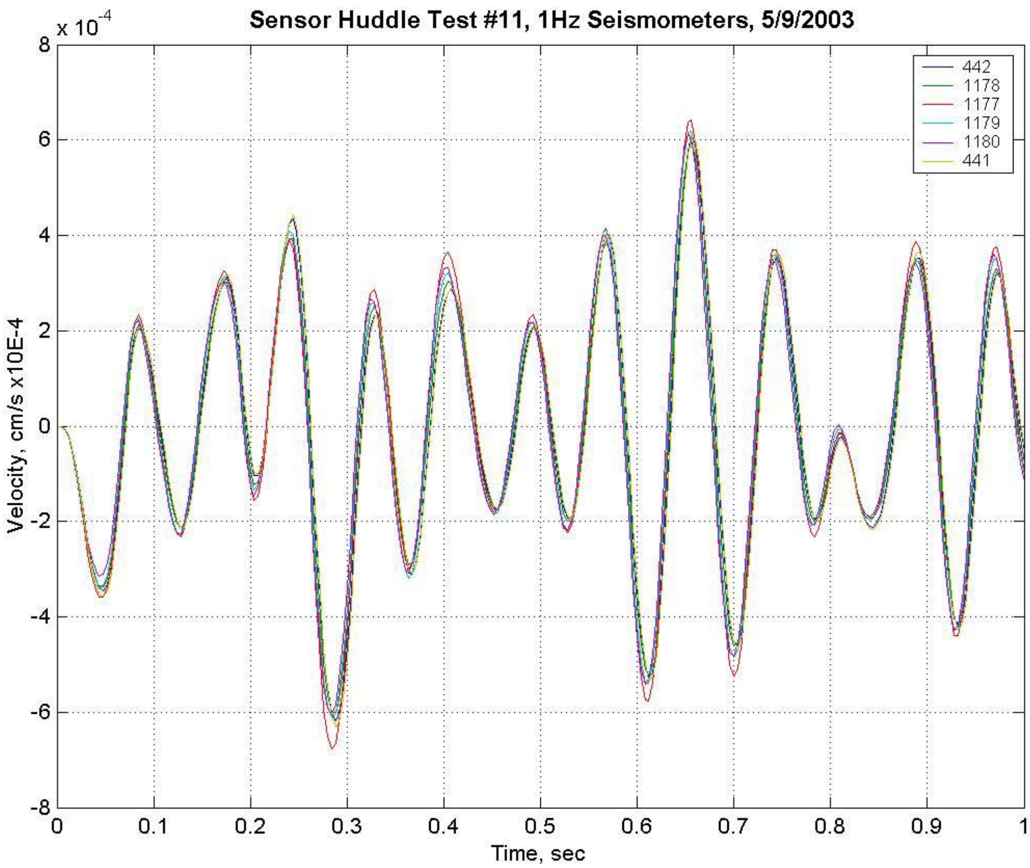


FIGURE 1: Segment of Huddle Test Ambient Vibration Data from the Six 1-Hz Seismometers

TEST PROCEDURE

Five different tests, denoted Tests 1-5, were done. The purpose of these five test types was to gather different vibration transmission information into, along, between, and out of the tunnels. Tests 1-5 were:

- Test No. 1 – Surface to the tunnel (Traffic source)
  Sensors on surface and in Tunnel A (“AL”)
- Test No. 2 – Surface to the tunnel (Controlled source)
  Controlled source on surface and sensors in Tunnel A
- Test No. 3 – Along the tunnel (Controlled source)
  Controlled source and sensors in Tunnel A
- Test No. 4 – Between the tunnel (Controlled source)
  Controlled source in Tunnel A and sensors in Tunnels A and B (“AR”)
- Test No. 5 – Tunnel-to-Surface (Train source)
  Uncontrolled source (trains) in Tunnel A and sensors on surface

The test procedure and schedule for each of these tests is described in the following subsections.

Test 1

Tests 1 and 5 were done at the same time, with one measurement system in the tunnels and one system on the surface directly above. The purpose of these two tests was to measure the transfer functions between the surface and the tunnel for both surface traffic vibration and for in-tunnel train vibrations.

On the early morning of May 14, after completion of Test 2 described below, the following instrumentation was installed in Cross-Passage 60 midway between Tunnel A (“AL”) and Tunnel B (“AR”) at tunnel reference location/station 758.00:

- Kinemetrics Model SS-1 1Hz seismometer, Serial Number 442 (vertical orientation)
- Kinemetrics Model SSR-1 digital recorder, Serial Number 253

The sensor was set on the concrete floor of the cross-passage and oriented vertically.

The digital recorder was set up to record 60 seconds of data at 1000 samples per second every half-hour from 0430 (4:30am PDT) to 1130. In between these fixed intervals, the recorder was in triggered mode to capture train passing events. This measurement system was left unattended and was retrieved in the evening of May 14 with the assistance of MTA staff.

The following instrumentation was set up on the surface directly above Cross-Passage 60 in the southeast corner of the MTA parking lot at the corner of Lankershim and Ventura:

- Kinemetrics Model SS-1 1Hz seismometer, Serial Number 441 (vertical orientation)
- Geometrics Model Geode digital recorder, Serial Number 3390
- PC notebook computer running Geometrics control software
- External trigger switch
- Car battery for power

The sensor was set on the asphalt and oriented vertically.

The recorder and computer were set up inside a car parked near the sensor. The recorder was set up for one channel at 1000 samples per second, and for high gain (36dB). The recorder was also set up for manual triggering by trigger switch.

This surface installation was manned by a Geovision engineer. Every half-hour between 0430 and 1130 the trigger switch was pushed and 60 seconds of data were recorded. These data were automatically downloaded to the computer. The measurement system was removed at noon.

Recorded data from the surface system were transferred to the analysis computer at the site prior to removal. Data from the tunnel system were downloaded from the SSR-1 digital recorder to the analysis computer on the evening of May 14 after retrieval.

This was the final test done. After removal of the in-tunnel instrumentation in the evening of May 14 by Geovision and MTA staff, it was confirmed that all instrumentation and equipment were removed from the site.

Test 2

The purpose of Test 2 was to measure the transmission of vibration from the ground surface to the tunnel. This was done using an active vibration source on the surface and an array of sensors in Tunnel A below the surface source.

On the night of May 13 the following equipment was temporarily installed in the mini-mall parking lot at the southwest corner of Lankershim and Ventura, directly across Ventura from the Test 1/5 surface sensor location:

- Bison Model EWG accelerated weight drop source
- PCB accelerometer on the 100-kg drop weight
- Kinemetrics Model SS-1 1Hz seismometer, Serial Number 441, vertical orientation, 20' from weight drop source
- Geospace Model GS-20DM 10Hz geophone, mounted on a concrete stepping stone and installed 20' from weight drop
- Geometrics Model Geode digital recorder, Serial Number 3463
- External trigger switch
- PC notebook computer
- Car battery for power

The weight drop source was set up at the corner of the parking lot in the small dirt patch under the corner sign post. The two vibration sensors were on the asphalt 20' to the northwest in the parking lot and were oriented to measure vertical vibration.

The digital recorder was set up for three channels, recording at 2000 samples per second per channel with a 10-second recording time. Table 1 below details the channel configuration.

Table 1: Channel Configuration for Test 2, Surface System

Channel	Sensor	Location	Orientation	Sensitivity
1	1Hz Seismometer, SS-1 #441	20' West of Weight Drop Source	Vertical	1750 mv/cm/s
2	10Hz Geophone, GS-20DM "Source"	20' West of Weight Drop Source	Vertical	190 mv/cm/s
3	Accelerometer, PCB	On 100-kg drop weight	Vertical	1.00 mv/g

After installation of the surface system, two Geovision engineers and one Stanford engineer remained to operate that system. The remaining Geovision and Parsons staff drove to the MTA Universal Station and met with MTA staff. Equipment was loaded onto the MTA rail vehicle and moved into Tunnel A at about 0115 on May 14.

In the early morning of May 14 the following equipment was set up in Tunnel A ("AL"):

- Four Geospace Model GS-1 1Hz seismometers
- Four Geospace Model GS-20DM 10Hz geophones
- Cables for the eight sensors
- Junction box for cable management
- Geometrics Model Geode digital recorder, Serial Number 3390
- PC notebook computer running Geometrics control software
- External trigger switch
- Car battery for power

The reference location in the Tunnel A, directly below the surface source, was at Station 756.50 in tunnel coordinates and was 150' from Cross-Passage 60. Sensors were installed on the concrete surface at the bottom of the tunnel at 0, 100, 200, and 300' from the reference location down the tunnel (toward Los Angeles, to the south). Data from these sensors were recorded on Channels 1-10 of the digital recorder as detailed in Table 2 below. The recorder was set up to record the 10 channels at 2000 samples per second per channel with a 10-second recording window.

It must be noted that the two measurement systems (surface and tunnel) were not synchronized, as cable connection between the two recorders was not possible. Recorder clocks were manually synchronized to within one second to insure that data could be roughly synchronized for identification.

The in-tunnel instrumentation was set up between 00130 and 0200. Radio communications between the tunnel and the surface was attempted unsuccessfully. An MTA telephone was then used to communicate with the Geovision engineers at the surface. They were instructed to activate the source at 1-minute intervals beginning at 0200, which they did.

Data from 13 weight drop blows were recorded between 0200 and 0212, both on the surface system and in the tunnel.

The systems were then removed from the tunnel and the surface. Data from both systems were transferred to the analysis computer.

Path lengths were calculated between the source and various receivers using the measured sensor positions and tunnel depths from MTA drawings. Table 3 provides the calculated path lengths for Test 2.

Table 2: Channel Configuration for Test 2, Tunnel System

Channel	Sensor	Location	Orientation	Sensitivity
1	none			
2	none			
3	1Hz Seismometer, GS-1 #1178	Tunnel A, 100' from Reference, Station 755.50	Vertical	3880 mv/cm/s
4	10Hz Geophone, GS-20DM	Tunnel A, 100' from Reference, Station 755.50	Vertical	190 mv/cm/s
5	1Hz Seismometer, GS-1 #1177	Tunnel A, 200' from Reference, Station 754.50	Vertical	3770 mv/cm/s
6	10Hz Geophone, GS-20DM	Tunnel A, 200' from Reference, Station 754.50	Vertical	190 mv/cm/s
7	1Hz Seismometer, GS-1 #1179	Tunnel A, 300' from Reference, Station 753.50	Vertical	3700 mv/cm/s
8	10Hz Geophone, GS-20DM	Tunnel A, 300' from Reference, Station 753.50	Vertical	190 mv/cm/s
9	1Hz Seismometer, GS-1 #1180	Tunnel A, 0' from Reference, Station 756.50	Vertical	4140 mv/cm/s
10	10Hz Geophone, GS-20DM	Tunnel A, 0' from Reference, Station 756.50	Vertical	190 mv/cm/s

Table 3: Calculated Source-Receiver Path Lengths for Test 2

MTA Tunnel Vibration Measurements
Source-Sensor Path Lengths

Test 2: Surface - Tunnel A ("AL")

Source Elevation=590' (from DWG C-032)
Tunnel Elevations from DWG C-033

		Units are Feet			
Channel	**Designation**	**Horizontal Distance**	**Elevation**	**Vertical Distance**	**Path Length**
S1	Surface Source +20	20	590	0	**20**
T1	Tunnel A +100'	100	502	88	**133**
T3	Tunnel A +200'	200	501	89	**219**
T5	Tunnel A +300'	300	499	91	**313**
T7	Tunnel A + 0'	0	503	87	**87**

Test 3

The purpose of Test 3 was to measure the transmission of vibration along the length of a tunnel. This was done using an active vibration source at the bottom of the Tunnel (Tunnel A, AL, Station 756.50) and an array of sensors along Tunnel A toward Los Angeles.

This was the first test done during this project. On the night of May 11 the field team (consisting of Robert Nigbor, Rodney Merrill, Brent Lawrence, and Andy Morehouse from Geovision; Paul MacCalden from Parsons; and Fred Asiri and Andrei Seryi from Stanford/SLAC) met at the MTA Universal Station and moved the equipment into the subway platform. The source and some equipment had been previously loaded onto an MTA rail-mounted pickup truck and transported to the MTA North Hollywood Station.

After a safety briefing, the team was met by MTA staff and the rail vehicle at 0100 on Monday morning May 12. The equipment and people were transported into the tunnel on the rail vehicle.

The following equipment was then temporarily installed in Tunnel A ("AL"):

- Bison Model EWG accelerated weight drop source
- PCB accelerometer on the 100-kg drop weight
- Two Kinemetrics Model SS-1 1Hz seismometer
- Four Geospace Model GS-1 1Hz seismometers
- Six Geospace Model GS-20DM 10Hz geophone, each mounted on a concrete stepping stone
- Two Geometrics Model Geode digital recorders
- Two cable junction boxes
- Cables
- External trigger switch
- PC notebook computer
- Car battery for power

The weight drop source was mounted on the hitch receiver of the rail vehicle and moved to the reference location (Station 756.50, 150’ south/east from Cross-Passage 60). The accelerometer was attached to the 100-kg drop weight.

Vibration sensor pairs (1Hz and 10Hz sensors) were then installed on the tunnel floor at distances of 10’, 20’, 100’, 200’, 300’, and 500’ from the source toward Los Angeles (to the south). Sensors were set on concrete stepping stones resting on the concrete at the bottom of the tunnel between the tracks. Cables were run from the sensors to the junction boxes, which were then connected to the digital recorder.

The digital recorder was set up for 13 channels, recording at 2000 samples per second per channel with a 10-second recording time. Table 4 below details the channel configuration.

Data were recorded for 10 weight drop blows using the low-gain recorder (Geode #3463, Gain=1) and then for 11 weight drop blows using the high-gain recorder (Geode #3390, Gain=24dB).

Data were then transferred to the analysis computer, and the system was removed by 0315.

Table 4: Channel Configuration for Test 3, Along Tunnel A

Channel	Sensor	Location	Orientation	Sensitivity
1	1Hz Seismometer, SS-1 #442	Tunnel A, 20' from Source, Station 756.30	Vertical	3880 mv/cm/s
2	10Hz Geophone, GS-20DM	Tunnel A, 20' from Source, Station 756.30	Vertical	190 mv/cm/s
3	1Hz Seismometer, GS-1 #1178	Tunnel A, 100' from Source, Station 755.50	Vertical	3880 mv/cm/s
4	10Hz Geophone, GS-20DM	Tunnel A, 100' from Source, Station 755.50	Vertical	190 mv/cm/s
5	1Hz Seismometer, GS-1 #1177	Tunnel A, 200' from Source, Station 754.50	Vertical	3770 mv/cm/s
6	10Hz Geophone, GS-20DM	Tunnel A, 200' from Source, Station 754.50	Vertical	190 mv/cm/s
7	1Hz Seismometer, GS-1 #1179	Tunnel A, 300' from Source, Station 753.50	Vertical	3700 mv/cm/s
8	10Hz Geophone, GS-20DM	Tunnel A, 300' from Source, Station 753.50	Vertical	190 mv/cm/s
9	1Hz Seismometer, GS-1 #1180	Tunnel A, 500' from Source, Station 751.50	Vertical	4140 mv/cm/s
10	10Hz Geophone, GS-20DM	Tunnel A, 0' from Source, Station 751.50	Vertical	190 mv/cm/s
11	1Hz Seismometer, SS-1 #441	Tunnel A, 10' from Source, Station 756.40	Vertical	1750 mv/cm/s
12	10Hz Geophone, GS-20DM "Source"	Tunnel A, 10' from Source, Station 756.40	Vertical	190 mv/cm/s
13	Accelerometer, PCB	On 100-kg drop weight	Vertical	1.00 mv/g

Test 4

The purpose of Test 4 was to measure the transmission of vibration between tunnels. This was done using an active vibration source at the bottom of the Tunnel (Tunnel A, AL, Station 757.25), an array of sensors along Tunnel A toward Los Angeles, and an array of sensors in Tunnel B ("AR") directly across from the Tunnel A array.

In the early morning of May 13, the equipment was again moved into Tunnel A after the last train. The following equipment was then temporarily installed in Tunnel A ("AL") and in Tunnel B ("AR"):

- Bison Model EWG accelerated weight drop source
- PCB accelerometer on the 100-kg drop weight
- Two Kinemetrics Model SS-1 1Hz seismometer
- Four Geospace Model GS-1 1Hz seismometers
- Six Geospace Model GS-20DM 10Hz geophone, mounted on a concrete stepping stones
- Two Geometrics Model Geode digital recorders
- Two cable junction boxes
- Cables
- External trigger switch
- PC notebook computer
- Car battery for power

The weight drop source was mounted on the hitch receiver of the rail vehicle and moved a new reference location 75' north of the Test 3 source location (Station 757.25, 75' south/east from Cross-Passage 60). The accelerometer was attached to the 100-kg drop weight.

Vibration sensor pairs (1Hz and 10Hz sensors) were then installed on the tunnel floor at along-tunnel distances of 17', 42.5', and 94.5' in Tunnel A and 0', 100', and 300' in Tunnel B. Sensors were set on concrete stepping stones resting on the concrete at the bottom of the tunnel between the tracks. Cables were run from the sensors to the junction boxes, which were then connected to the digital recorder. Cables from Tunnel B sensors were routed through Cross-Passage 60.

The digital recorder was set up for 13 channels, recording at 2000 samples per second per channel with a 10-second recording time. Table 5 below details the channel configuration.

Data were recorded for 11 weight drop blows using the low-gain recorder (Geode #3463, Gain=1) and then for 10 weight drop blows using the high-gain recorder (Geode #3390, Gain=36dB).

Data were then transferred to the analysis computer, and the system was removed by 0330. The source was manually removed from the rail vehicle and carried to the surface in the Universal Station, where it was mounted on a Geovision pickup truck for the Test 2 measurements the following morning.

Path lengths were calculated between the source and various receivers using the measured sensor positions and tunnel depths from MTA drawings. Table 6 provides the calculated path lengths for Test 4.

Table 5: Channel Configuration for Test 4, Between Tunnels

Channel	Sensor	Location	Orientation	Sensitivity
1	1Hz Seismometer, SS-1 #442	Tunnel A, 42.5' from Source, Station 756.83	Vertical	3880 mv/cm/s
2	10Hz Geophone, GS-20DM	Tunnel A, 42.5' from Source, Station 756.83	Vertical	190 mv/cm/s
3	1Hz Seismometer, GS-1 #1178	Tunnel A, 94.5' from Source, Station 756.31	Vertical	3880 mv/cm/s
4	10Hz Geophone, GS-20DM	Tunnel A, 94.5' from Source, Station 756.31	Vertical	190 mv/cm/s
5	1Hz Seismometer, GS-1 #1177	Tunnel B, 0' (along-tunnel) from Source, Station 757.25	Vertical	3770 mv/cm/s
6	10Hz Geophone, GS-20DM	Tunnel B, 0' (along-tunnel) from Source, Station 757.25	Vertical	190 mv/cm/s
7	1Hz Seismometer, GS-1 #1179	Tunnel B, 100' (along-tunnel) from Source, Station 756.25	Vertical	3700 mv/cm/s
8	10Hz Geophone, GS-20DM	Tunnel B, 100' (along-tunnel) from Source, Station 756.25	Vertical	190 mv/cm/s
9	1Hz Seismometer, GS-1 #1180	Tunnel B, 300' (along-tunnel) from Source, Station 754.25	Vertical	4140 mv/cm/s
10	10Hz Geophone, GS-20DM	Tunnel B, 300' (along-tunnel) from Source, Station 754.25	Vertical	190 mv/cm/s
11	1Hz Seismometer, SS-1 #441	Tunnel A, 17' from Source, Station 757.08	Vertical	1750 mv/cm/s
12	10Hz Geophone, GS-20DM "Source"	Tunnel A, 17' from Source, Station 757.08	Vertical	190 mv/cm/s
13	Accelerometer, PCB	On 100-kg drop weight	Vertical	1.00 mv/g

Table 6: Source-Receiver Path Lengths for Test 4

MTA Tunnel Vibration Measurements
Source-Sensor Path Lengths

Test 4: Tunnel A ("AL") - Tunnel B ("AR")

Tunnel Elevations from DWG C-033

		Units are Feet				
Channel	**Designation**	**Horizontal Distance**	**Tunnel Separation**	**Elevation**	**Vertical Distance**	**Path Length**
S	Source (no sensor)	0	0	503	0	**0**
1	Tunnel A +48'	48	0	502	1	**48**
3	Tunnel A +95'	95	0	502	1	**95**
5	Tunnel B + 0'	0	39	503	0	**39**
7	Tunnel B + 100'	100	39	502	1	**107**
9	Tunnel B + 300'	300	39	499	4	**303**
11	Tunnel A + 17'	17	0	503	0	**17**

Test 5

The purpose of Test 5 was to simultaneously measure surface and tunnel vibration from passing trains. This was done simultaneously with Test 1 as described above.

During the measurement period from 0430 to 1130 on May 14, data were recorded for 60 seconds every half-hour both in Cross-Passage 60 and in the MTA parking lot on Lankershim and Ventura directly above Cross-Passage 60. Vertical velocity was measured by a 1Hz seismometer at both locations.

Only one train passage was recorded during these 15 60-second intervals, at 0730. These data were used as Test 5 data.

In addition to this one train passage recorded both in-tunnel and on the surface, another 20-30 train passages were captured by the in-tunnel recorder while in triggered mode in-between the fixed recording intervals. These data were not analyzed but may be useful in the future.

DATA ANALYSIS AND RESULTS

Overview

Data from Tests 1-5 were reduced to a consistent format and then analyzed by Geovision staff. This report section describes the analysis procedure and results. Detailed plots of the data and analysis results are provided in Appendices A-E, corresponding to Tests 1-5.

Data Reduction

Recorded data were in two binary formats. Data recorded by the Geode digital recorders were recorded in “SEG2” format, a standard format for geophysical data promoted by the Society for Exploration Geophysics. Data recorded by the SSR-1 recorder (Tests 1 and 5 Tunnel sensor only) were recorded in Kinemetrics’ proprietary “.SSR” format.

The Geode data were reduced to ASCII tab-delimited format using Geometrics’ “TAPE” program. With this program, subsets of channels and time intervals could be saved in ASCII format, with units of millivolts.

The SSR-1 data were also reduced to ASCII format using Kinemetrics’ proprietary programs CNVSSR and CDF2ASC. The output of this step was ASCII files with a 13-line header and data in columns. Data units are volts.

The ASCII data were then imported into the commercial MATLAB program (“Version 6.00 was used) using the MATLAB utility “DLMREAD”. Data were than scaled to engineering units using the appropriate calibration value for that channel/sensor combination. Seismometer channels were converted to units of cm/s. The accelerometer data from the source drop weight was converted to units of “g” and then to force units of “N” (Newton) by multiplying by the mass (100kg) and acceleration of gravity (F=ma=981 N/g * acceleration in g).

The controlled source data were further reduced to produce single time series connecting 10 weight drop source blows. The following steps were done to accomplish this:

- For each weight drop blow data file, identify the arrival time of the source pulse within the 10-second recorded data
- Extract a 1-second data segment of the time series matrix centered on the source pulse arrival
- Append the subsetted time series files to produce one time series file containing 10 source blows.
- Filter the data as described in the next section

Figure 1 below shows sample controlled source data, with 10 source blows stacked and low-pass filtering to remove noise.

Once in MATLAB, the reduced data were analyzed as described in the next section.

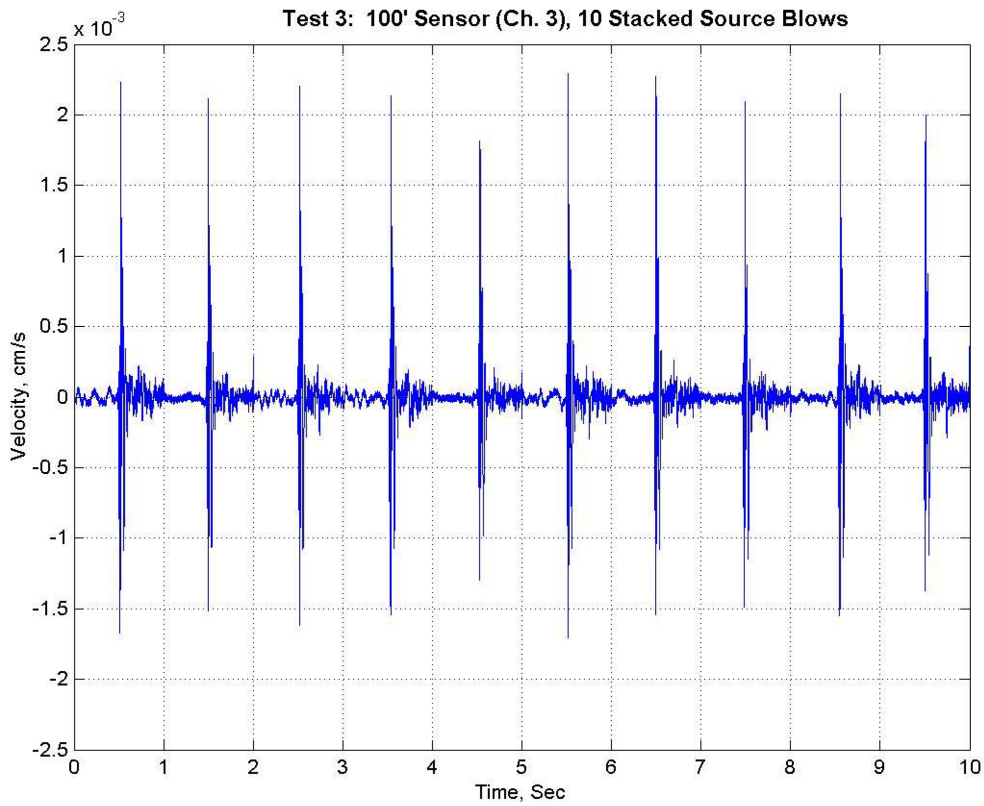


Figure 1: Sample Controlled Source Data Showing 10 Stacked Source Blows

Noise and Filtering

Much of the data, especially the in-tunnel data, were contaminated by noise. Strong AC power-related noise was observed inside the tunnel at 60 Hz and its integer multiples. This noise could have been electrical or vibration-induced, induced from the rails or from the many transformers present in the tunnel.

In addition, severe acoustic noise was observed in the data, especially in the 10-Hz geophone data.

Figure 2 shows a typical in-tunnel time series (unfiltered) from a 1-Hz seismometer 100' from the source. Figure 3 shows a spectrogram of this. Figure 4 shows a spectrogram of a typical 10Hz geophone signal. One can see the 60Hz multiples as lines constant over time and the acoustic noise arriving after the low-frequency vibration from the source.

After much effort to remove noise from the 10-Hz geophone data, it was decided to omit these data from further analysis. The signals are just too contaminated.

However, the 1Hz seismometer signals were cleaned up by performing low-pass filtering at 150 Hz using a bidirectional 4-pole Butterworth low-pass filter. Filtered data are of high quality in the frequency range of interest (1-120 Hz).

Filtering was done on all of the controlled-source data from both the accelerometer and from the 1Hz seismometer data.

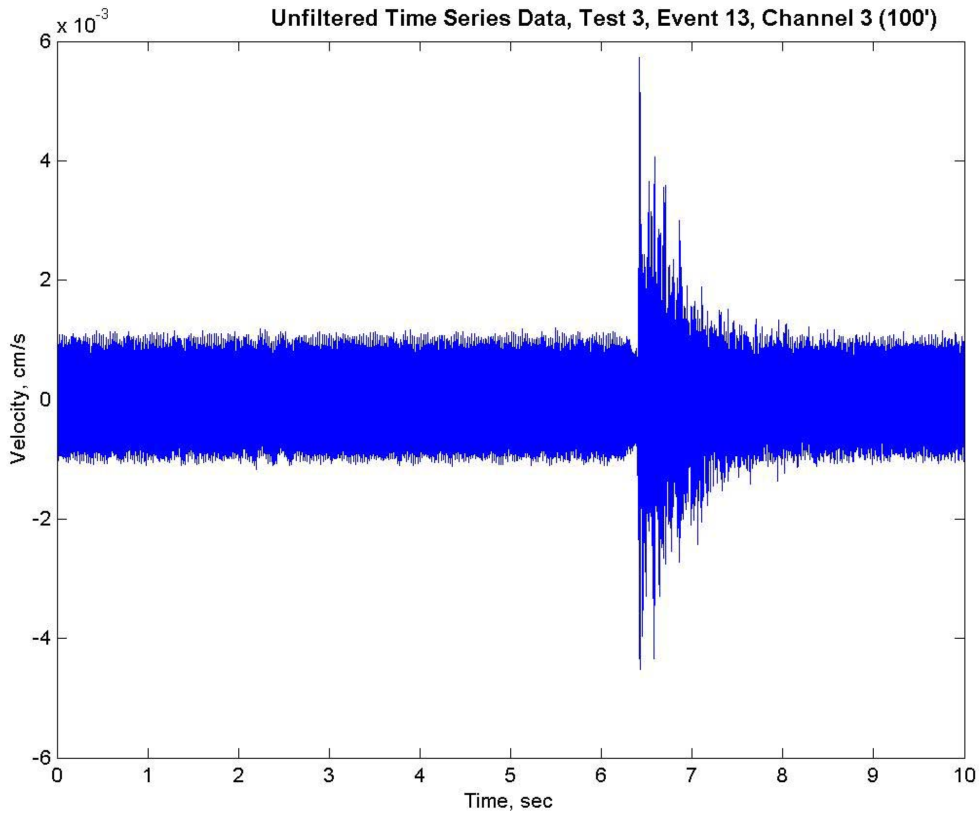


Figure 2: Sample In-Tunnel 1Hz Geophone Time Series

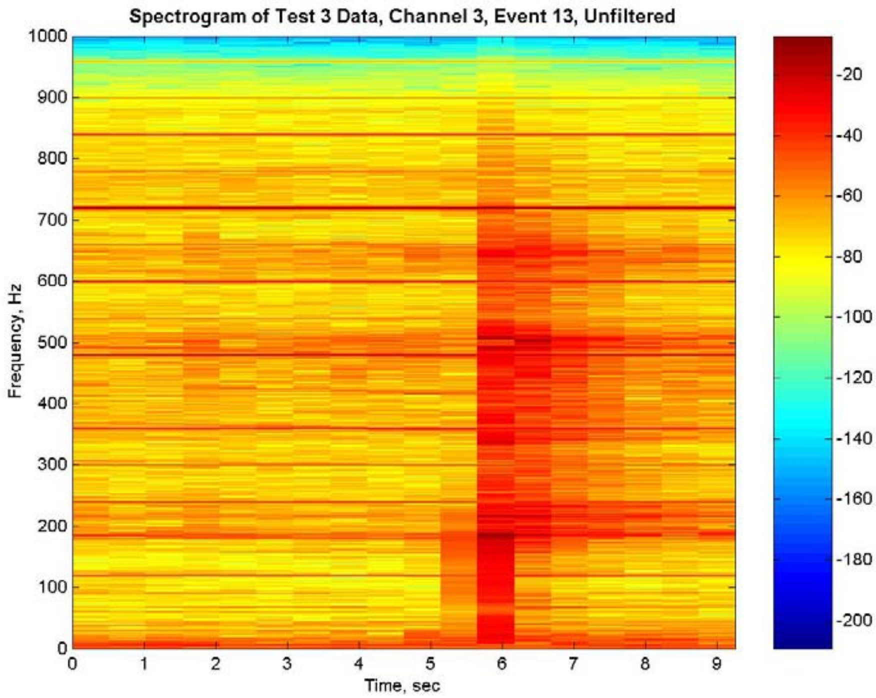


Figure 3: Spectrogram of Sample 1Hz Seismometer Data Showing 60n Hz Noise

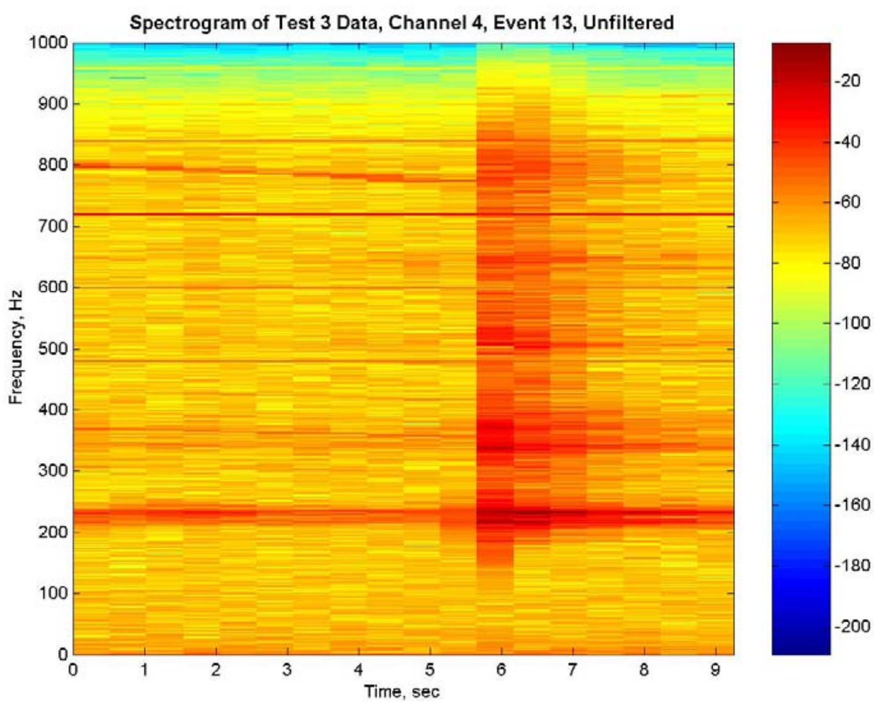


Figure 4: Spectrogram of Sample 10Hz Geophone Data Showing 60n Hz and Acoustic Noise

Test 1

Test 1 data were reduced to individual velocity time series scaled to cm/s as described above. Filtering was not needed for these data, as the measurement systems were away from the rail-borne noise and this was ambient data so there was no acoustic noise from the vibration source.

Unsynchronized time series from the surface and tunnel (Cross-Passage 60) were available from 15 60-second intervals spanning the time from 0430 to 1130 on May 14. All except the 0730 data set contained only ambient vibration data from freeway and other surface traffic.

Power spectra were calculated from the 60-second time series using Welch's Method as implemented by the PWELCH function in MATLAB. Appendix F contains further details of this calculation. The data sample rate was 1000 samples per second. In the calculations, a 1000-point FFT length with 500-point overlap and Hanning window was used.

Coherence was calculated using the COHERE function in MATLAB, also with 1000-point FFT, 500-point overlap, and Hanning window. Appendix F contains further details of this calculation. This coherence was low due to the distributed, uncorrelated nature of the traffic sources. So, the normal transfer function calculation method (cross spectrum/input autospectrum) was not valid. The transfer function (a measure of receiver/source transmissibility) was then estimated using the ratio of output to input power spectra.

Figure 5 below plots the calculated transfer functions for all 15 events. The 0730 data set that contains a train passage is the black outlier.

Further data and results are provided in Appendix A.

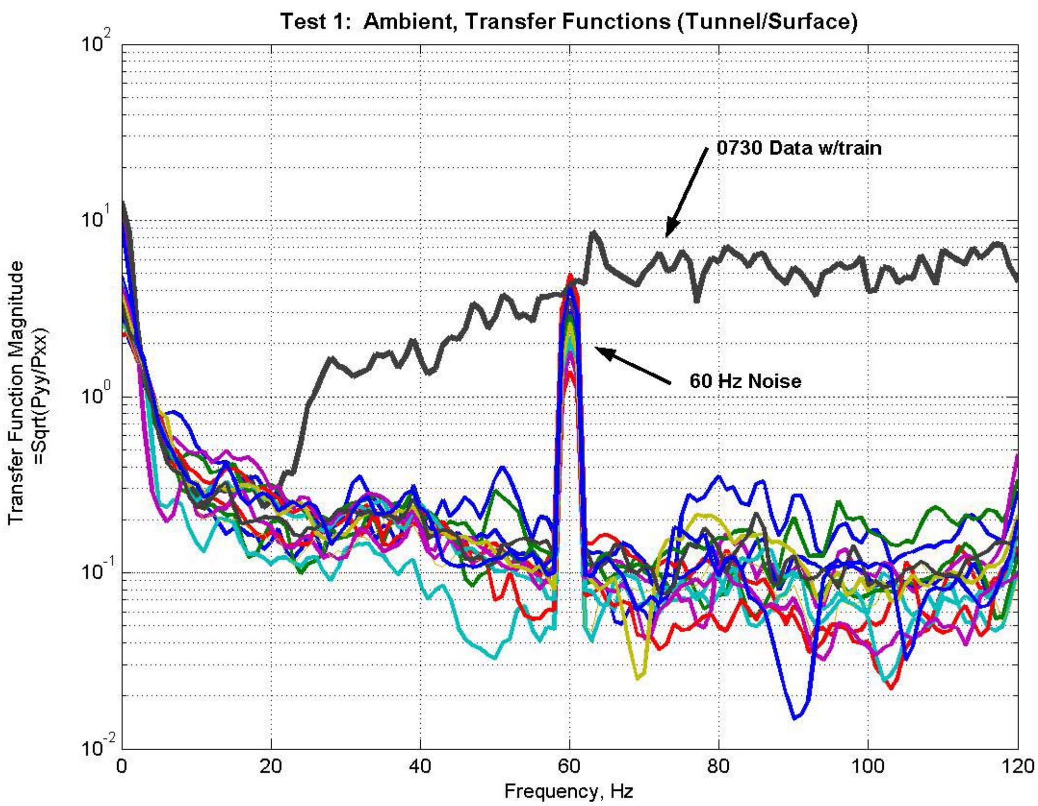


Figure 5: Calculated Transfer Functions for Test 1 (Ambient Traffic)

Test 2

Test 2 data were reduced to individual stacked (separate source blow data sets appended into one file) velocity time series scaled to cm/s as described above. Filtering was also done as described above. Only the 1-Hz seismometer data and the accelerometer data were used.

Power spectra were calculated from the 10 stacked 1-second time series using Welch's Method as implemented by the PWELCH function in MATLAB. The data sample rate was 2000 samples per second. In the calculations, a 2000-point FFT length with no overlap and Hanning window was used. The resulting averaged Power Spectra ("PSD) are then averages of the 10 discrete weight drop blows.

Coherence was calculated using the COHERE function in MATLAB, also with 2000-point FFT, no overlap, and Hanning window. The reference signal was the surface seismometer (for transfer function – velocity/velocity - measurement) and the source acceleration/force (for mobility – velocity/force - measurement). This coherence was low due to the unsynchronized recording of the reference and the tunnel sensors. So, the normal transfer function calculation method (cross spectrum/input autospectrum) was not valid. The transfer function (a measure of transmissibility) was then estimated using the ratio of output to input power spectra.

Figure 6 below plots the calculated transfer functions for the different locations in the tunnel. Figure 7 plots the mobilities for the different tunnel sensor locations.

Mobility, the frequency domain ratio of ground velocity at the receiver location to the source force, quantifies the relationship between the source force and the vibration at a specific location. It can, under ideal conditions, be used to estimate vibration from other sources. One must, however, consider important issues of source coupling and vibration transmission (wave types, etc.) when applying mobility to another type of vibration source.

Further data and results are provided in Appendix B.

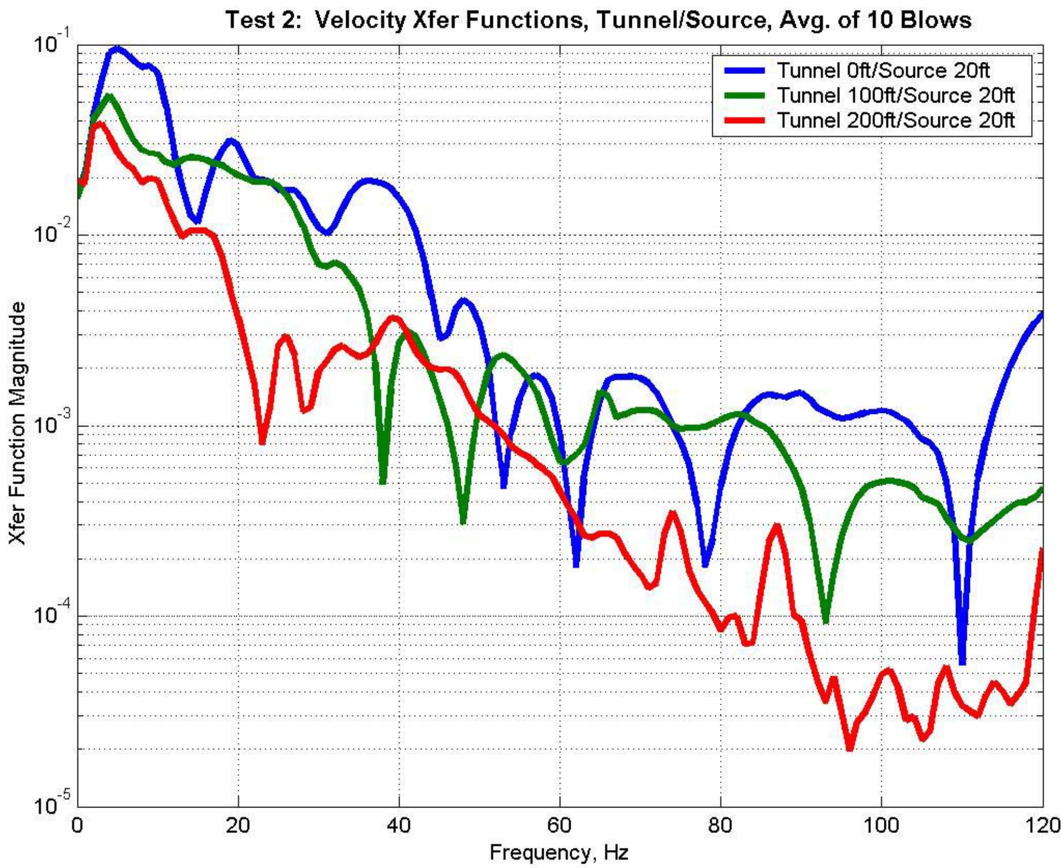


Figure 6: Test 2 Calculated Transfer Functions

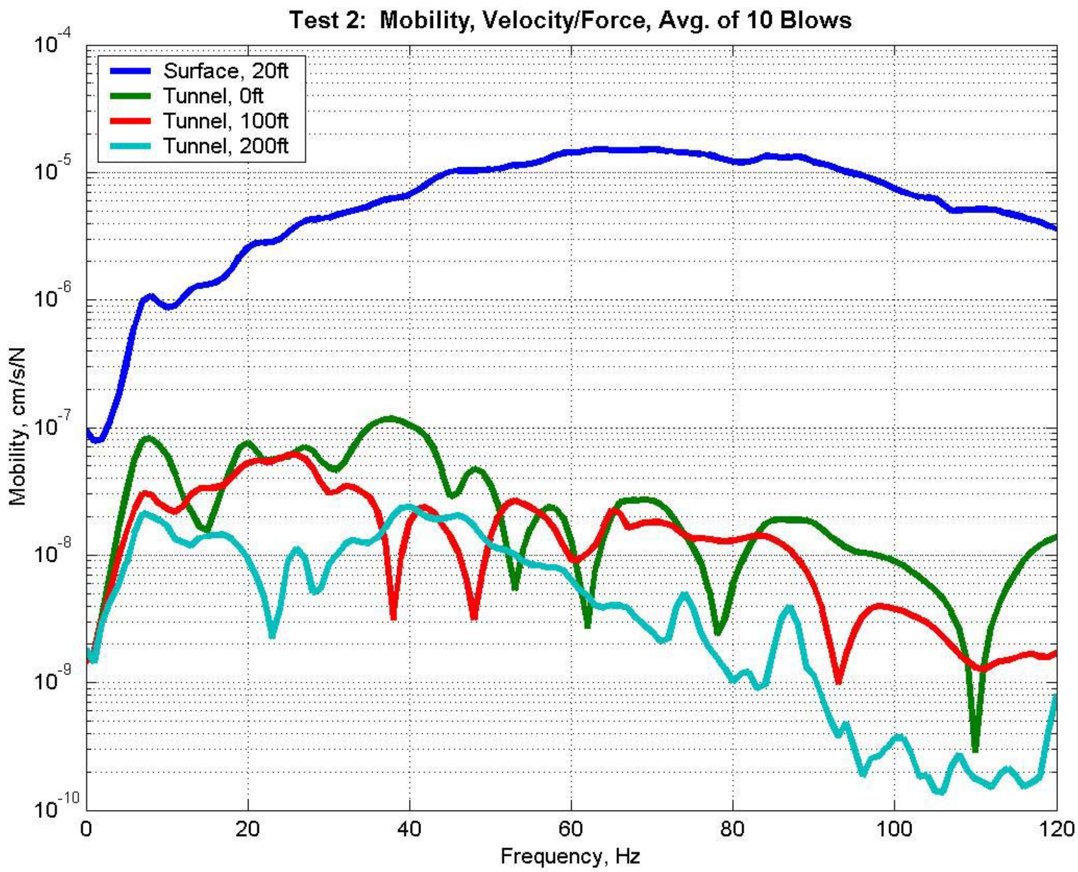


Figure 7: Test 2 Calculated Mobilities

Test 3

Test 3 data were reduced to individual stacked velocity time series scaled to cm/s as described above. Filtering was also done as described above. Only the 1-Hz seismometer data and the accelerometer data were used. All data were time-synchronized because a single recorder was used for these Tunnel A measurements.

Power spectra were calculated from the 10 stacked 1-second time series using Welch's Method as implemented by the PWELCH function in MATLAB (see Appendix F). The data sample rate was 2000 samples per second. In the calculations, a 2000-point FFT length with no overlap and Hanning window was used. The resulting averaged Power Spectra ("PSD) are then averages of the 10 discrete weight drop blows.

Coherence was calculated using the COHERE function in MATLAB (see Appendix F), also with 2000-point FFT, no overlap, and Hanning window. The reference signal was the 20' seismometer (for transfer function) and the source acceleration/force (for mobility). This coherence generally very high, getting a bit lower with distance (see the coherence plots in Appendix C). The normal transfer function calculation method (cross spectrum/input autospectrum) was therefore used. The TFE function within MATLAB was used, with 2000-point FFT, no overlap, and Hanning window. Appendix F contains further information about this calculation. Note that TFE calculates the transfer function in complex form, so the magnitude (absolute value) was used herein.

Figure 8 below plots the calculated transfer functions for the different locations in the tunnel. Figure 9 plots the mobilities for the different tunnel sensor locations.

Further data and results are provided in Appendix C.

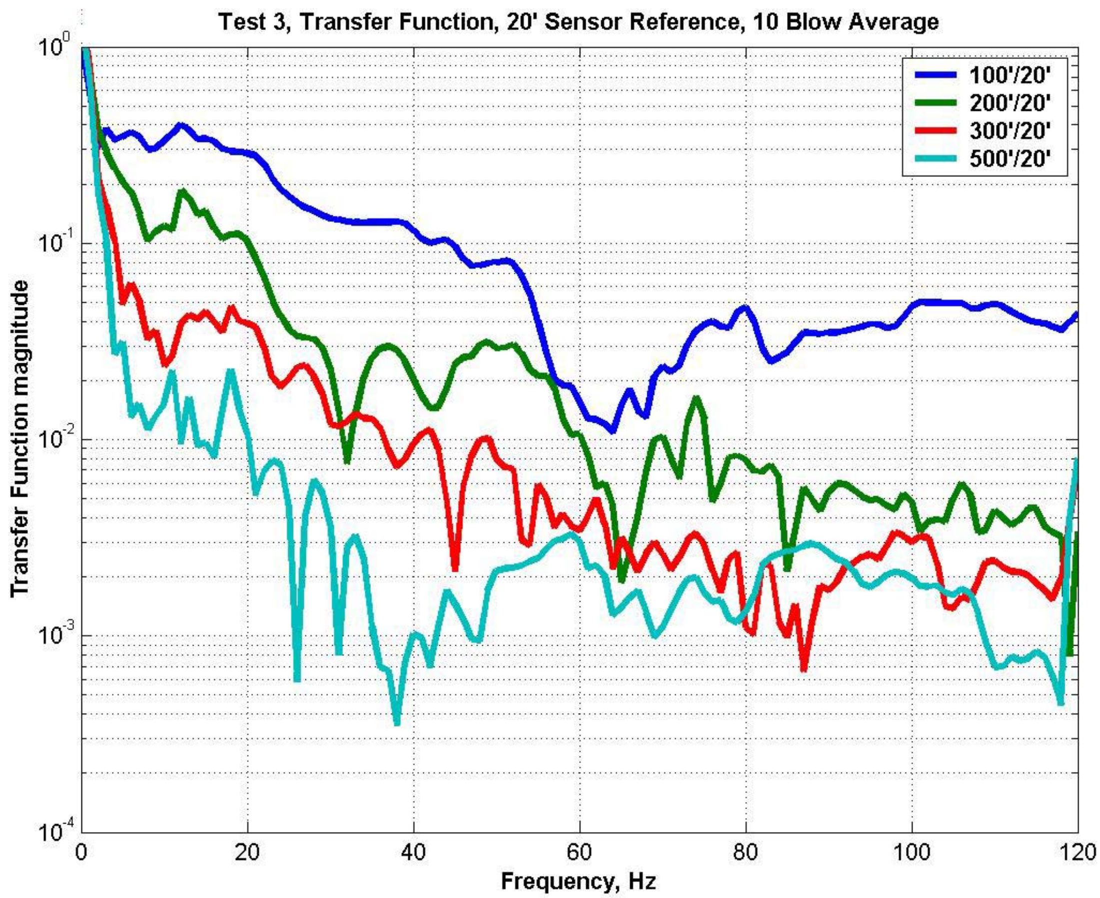


Figure 8: Test 3 Transfer Function Estimates

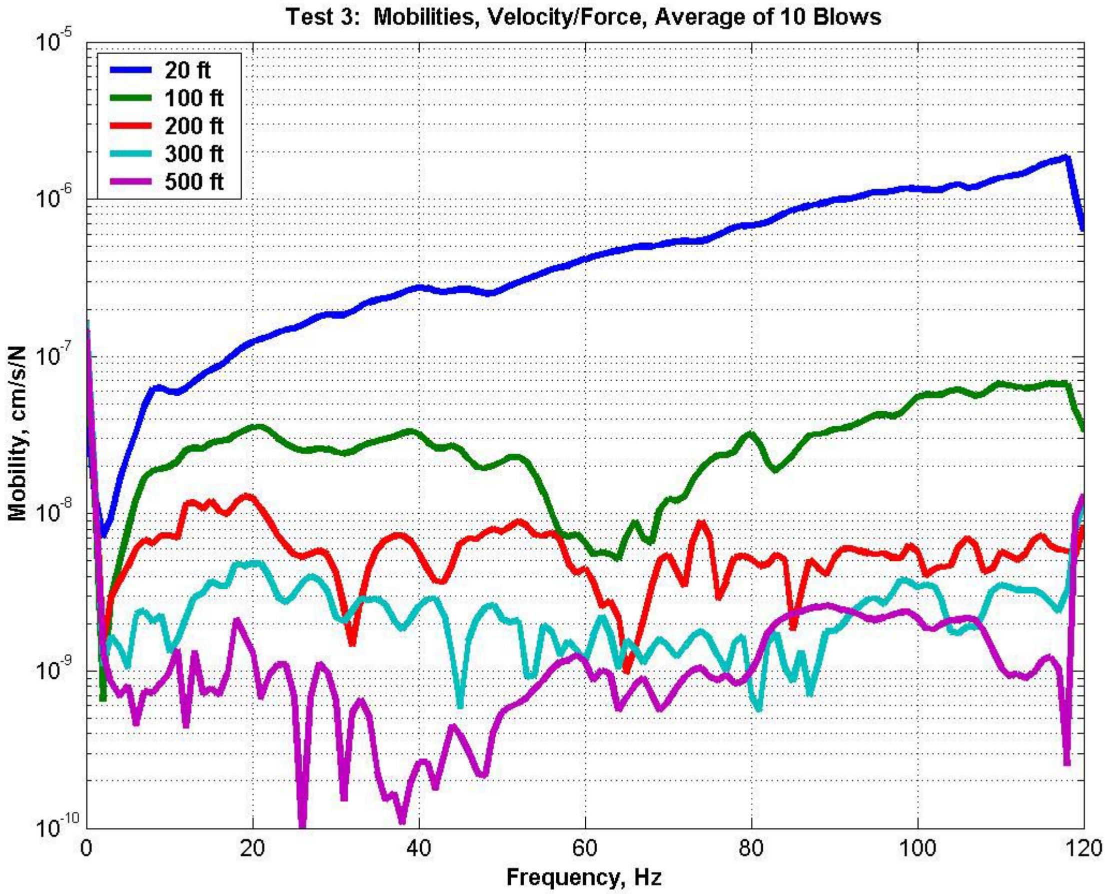


Figure 9: Test 3 Mobility Estimates

Test 4

Test 4 data were reduced to individual stacked velocity time series scaled to cm/s as described above. Filtering was also done as described above. Only the 1-Hz seismometer data and the accelerometer data were used. All data were time-synchronized because a single recorder was used for measurements.

In Test 4 the source accelerometer did not function during the tests, so no source force or mobility results are available.

Power spectra were calculated from the 10 stacked 1-second time series using Welch's Method as implemented by the PWELCH function in MATLAB. The data sample rate was 2000 samples per second. In the calculations, a 2000-point FFT length with no overlap and Hanning window was used. The resulting averaged Power Spectra ("PSD) are then averages of the 10 discrete weight drop blows.

Coherence was calculated using the COHERE function in MATLAB, also with 2000-point FFT, no overlap, and Hanning window. The reference signal for transfer function calculation was the 17' seismometer in Tunnel A. This coherence generally very high, getting a bit lower with distance (see the coherence plots in Appendix D). The normal transfer function calculation method (cross spectrum/input autospectrum) was therefore used. The TFE function within MATLAB was used, with 2000-point FFT, no overlap, and Hanning window.

Figure 10 below plots the calculated transfer functions for the different locations in the tunnels.

Further data and results are provided in Appendix D.

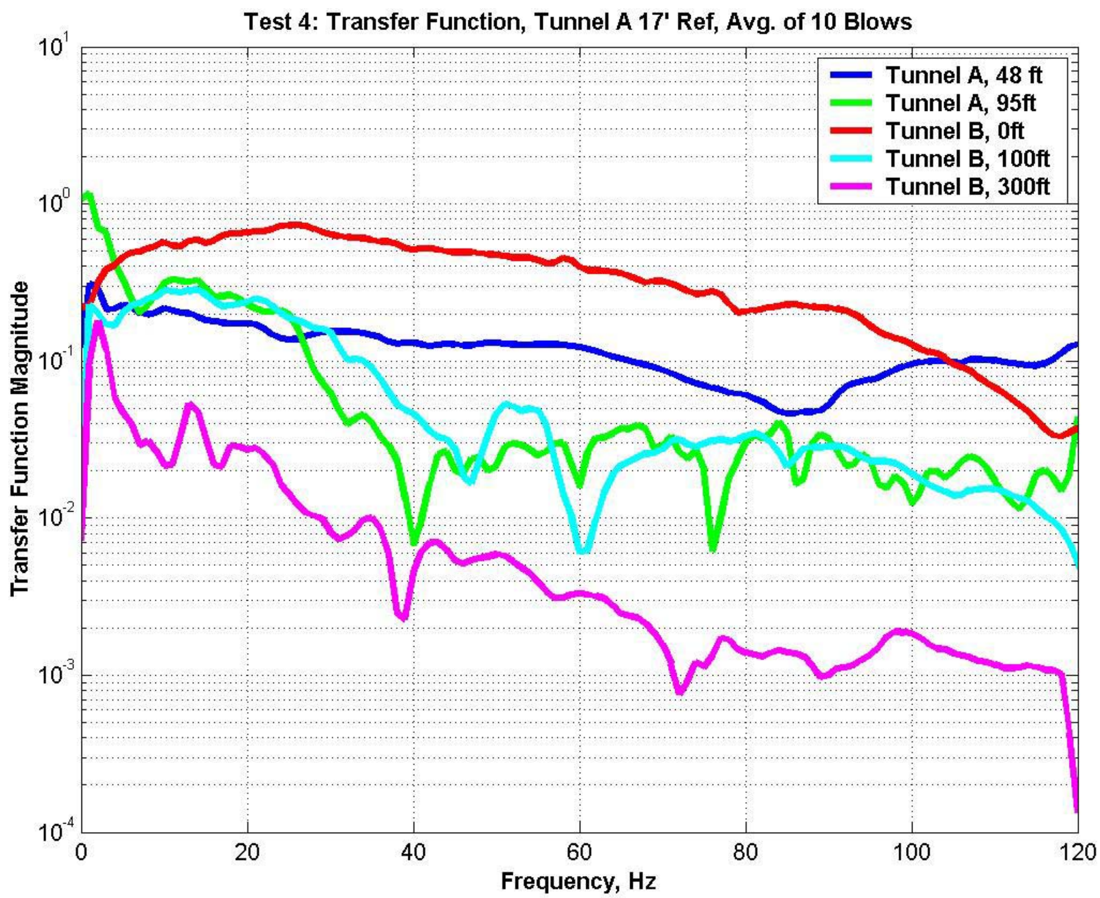


Figure 10: Test 4 Transfer Functions

Test 5

Test 5 data consist of the 0730 data set from Test 1, where a train passage can be clearly observed.

Test 5 data were reduced to individual velocity time series scaled to cm/s as described above. Filtering was not needed for these data, as the measurement systems were away from the rail-borne noise and this was ambient data so there was no acoustic noise. The first 10 seconds of data from this 60-second data set contained the train signature (see the spectrogram plots in Appendix E) and was extracted for further analysis of the surface/tunnel transfer function.

Power spectra were calculated from the 60-second time series using Welch's Method as implemented by the PWELCH function in MATLAB. The data sample rate was 1000 samples per second. In the calculations, a 1000-point FFT length with 500-point overlap and Hanning window was used.

The two 10-second time series (tunnel and surface) were aligned for maximum cross-correlation. Plots in Appendix E show this process.

Coherence was calculated using the COHERE function in MATLAB, also with 1000-point FFT, 500-point overlap, and Hanning window. Coherence was acceptable for the aligned recordings, so the normal transfer function calculation method (cross spectrum/input autospectrum) was considered valid. The alternate for transfer function calculation (ratio of autospectra) was also applied.

Figure 11 below plots the calculated surface/tunnel transfer functions and coherence for this train passage event. This is the transfer function or transmissibility between the tunnel and the surface for an in-tunnel source.

Further data and results are provided in Appendix E.

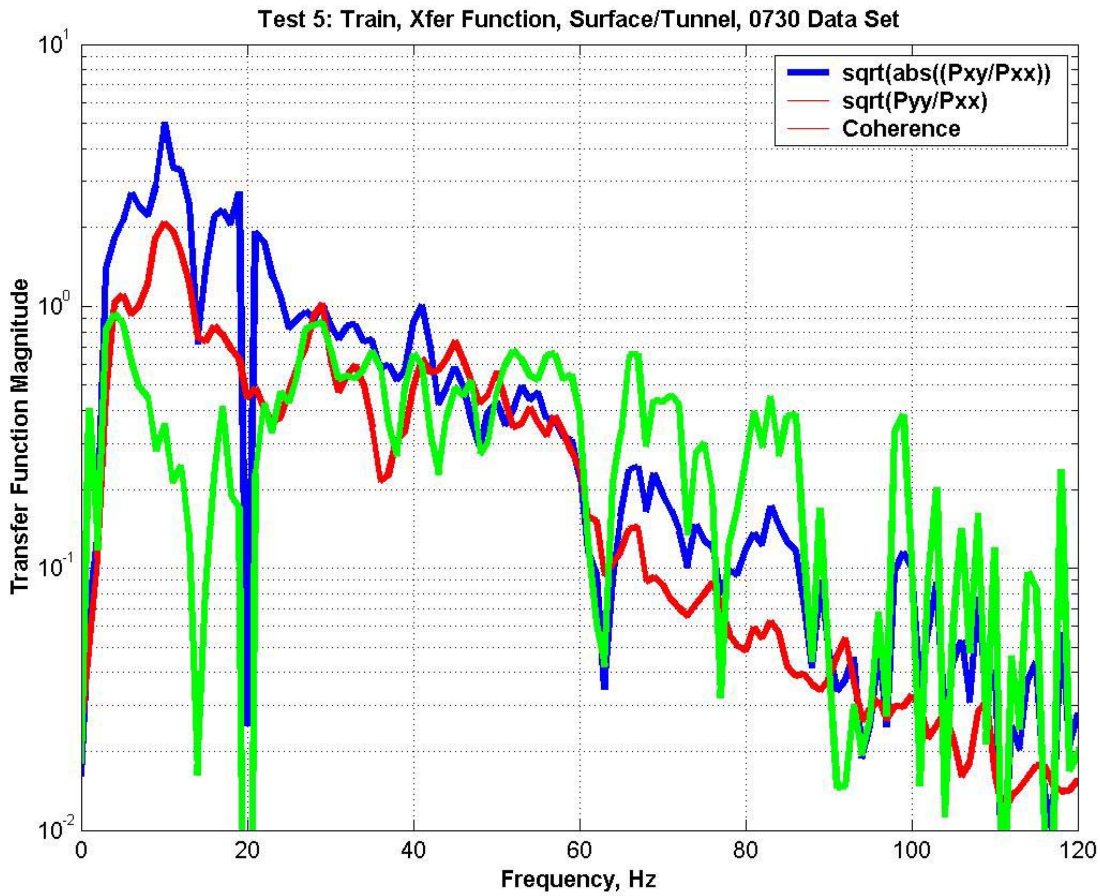


Figure 11: Test 5 Transfer Function for Surface/Tunnel with In-Tunnel Source

CONCLUSIONS

Data were successfully recorded for each of the component tests of this Tunnel Vibration Study. This included ambient (traffic) data for surface-to-tunnel, train-induced data for tunnel-to-surface, and controlled (weight drop blow) source data for surface-to-tunnel, along-tunnel, and tunnel-to-tunnel conditions.

These data were analyzed to estimate the transmissibility (velocity/velocity transfer function) of vibration as a function of frequency for sources on the surface, in the same tunnel, and in an adjacent tunnel. Data from the controlled source testing (surface-to-tunnel and along tunnel) were also analyzed to estimate mobility, the spectral ratio of the vibration response to the source force as a function of frequency and distance. Some of the data, including all of the 10Hz geophone data, contained high noise due to pickup of electrical noise and to acoustic coupling with the strong sound environment in the tunnel after a source blow. However, with filtering the transmissibilities and mobilities were accurately calculated between 3-120Hz.

Calculated surface-to-tunnel transfer functions for a surface source can be compared with this obtained for SLAC by Colin Gordon Associates in 2002. Table 7 compares results from Test 2 of this report with results from the 2002 Colin Gordon study. Figures 12-14 graphically compare the two independent transfer function measurements at 20, 30, and 60Hz. Agreement is good, especially considering that these two studies were done at different locations with different geologic conditions.

These results of this experimental evaluation of vibration propagation in the rock and tunnels of the MTA Red Line just south of the Universal Station can therefore be used with confidence in the design of SLAC's new facilities, allowing estimation of in-tunnel vibrations due to known sources on the surface, in the same tunnel, or in an adjacent tunnel.

Table 7: Comparison of Tunnel/Surface Transfer Functions, This Study and 2002 Colin Gordon Study

MTA Tunnel Vibration Measurements
Comparison of Geovision & Colin Gordon Results
Attenuation, Tunnel Receiver/Surface Source
Colin Gordon Data from Page 6 of 7 August 2002 Report (S1 Data)
Geovision Data from Test 2 Transfer Functions

		Attenuation/XFER Magnitude		
Data Source	Path Length, ft	20 Hz	30 Hz	60 Hz
Colin Gordon	130	0.0084	0.0120	0.0050
8/2002	134	0.0120	0.0140	0.0040
	162	0.0084	0.0060	0.0010
	233	0.0040	0.0020	0.0010
	289	0.0020	0.0009	0.0003
Geovision	87	0.0300	0.0110	0.0009
6/2003	133	0.0210	0.0070	0.0006
	219	0.0040	0.0020	0.0004

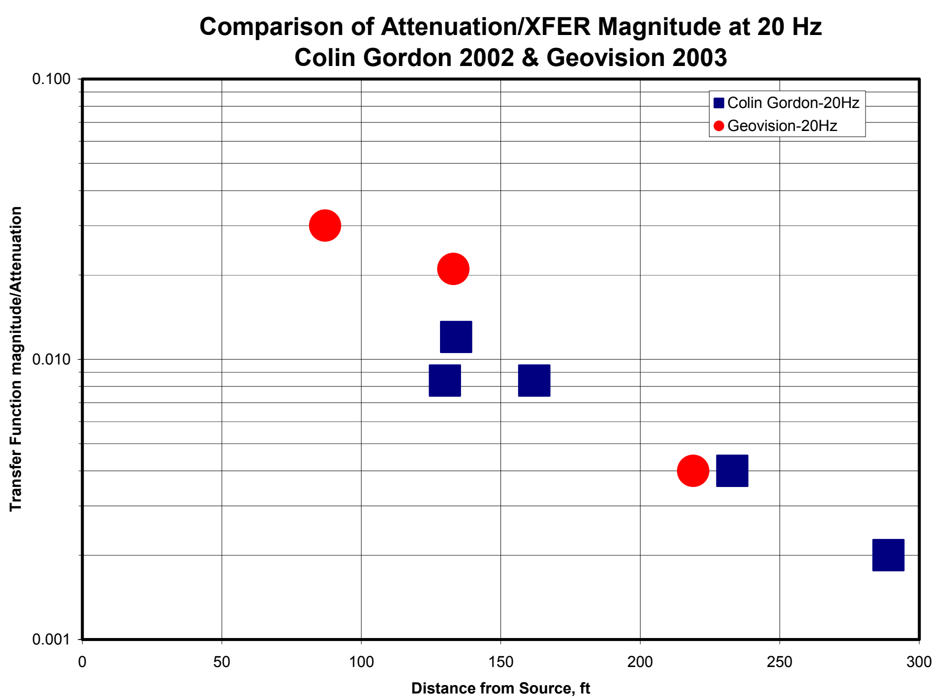


Figure 12: Comparison of Tunnel/Surface Transfer Functions at 20 Hz

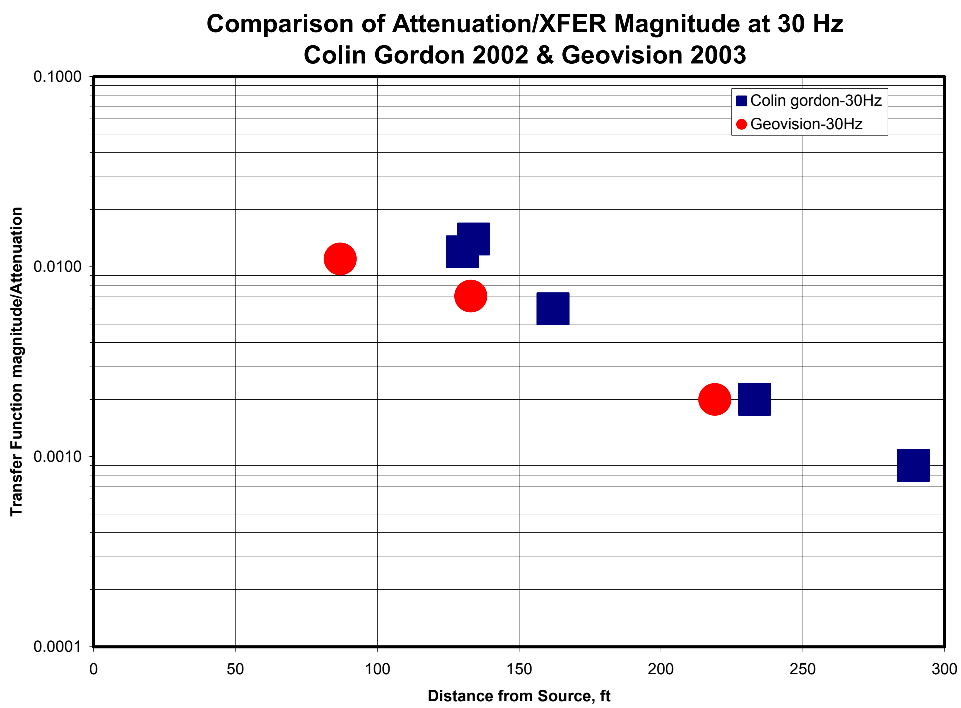


Figure 13: Comparison of Tunnel/Surface Transfer Functions at 30 Hz

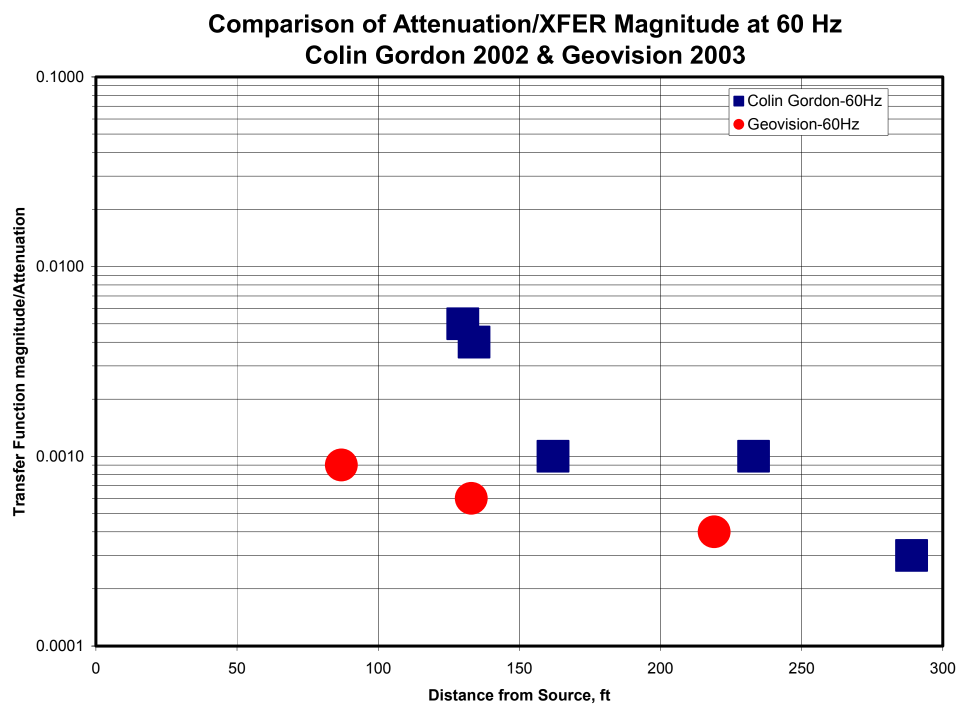
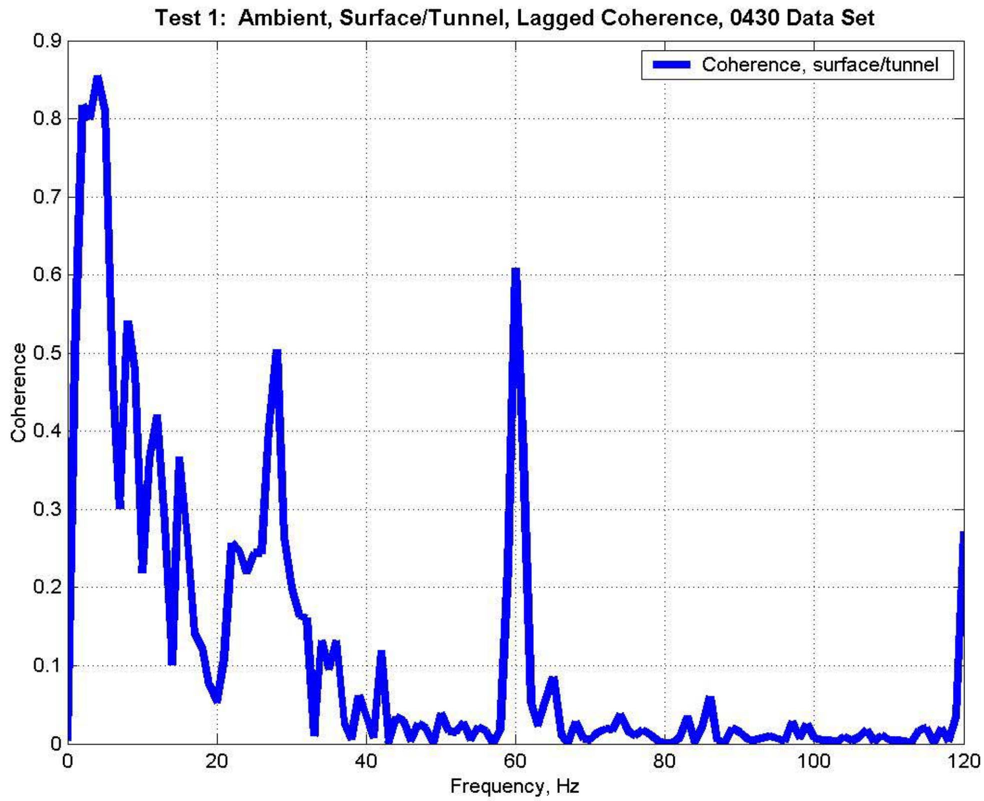
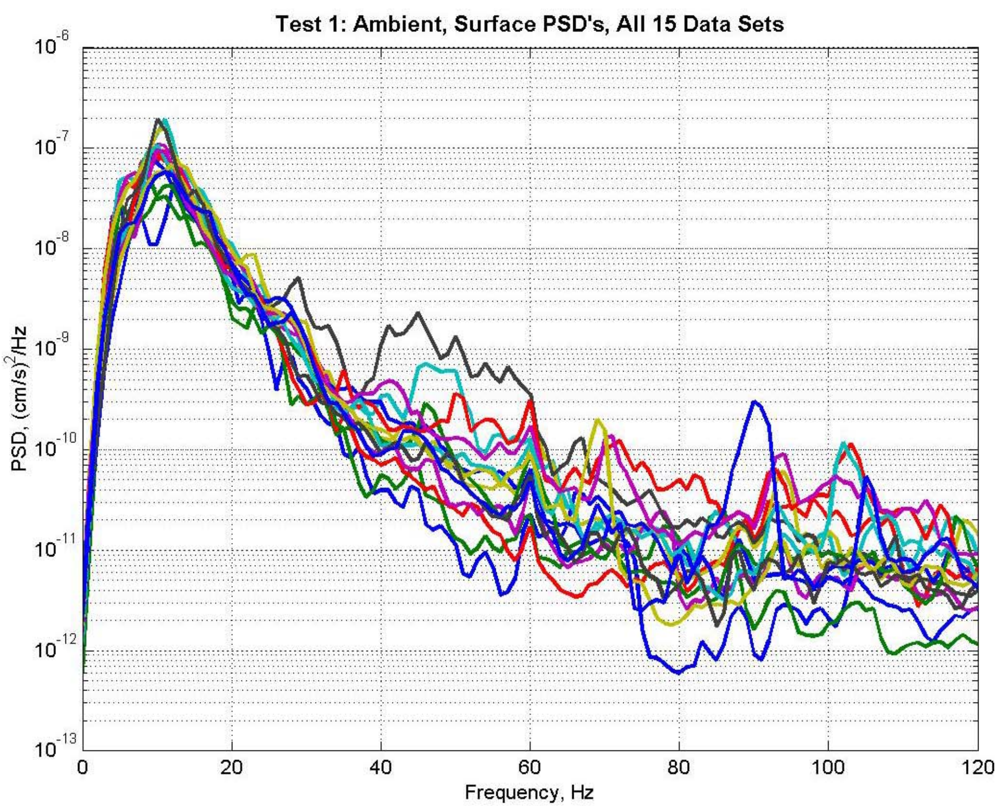
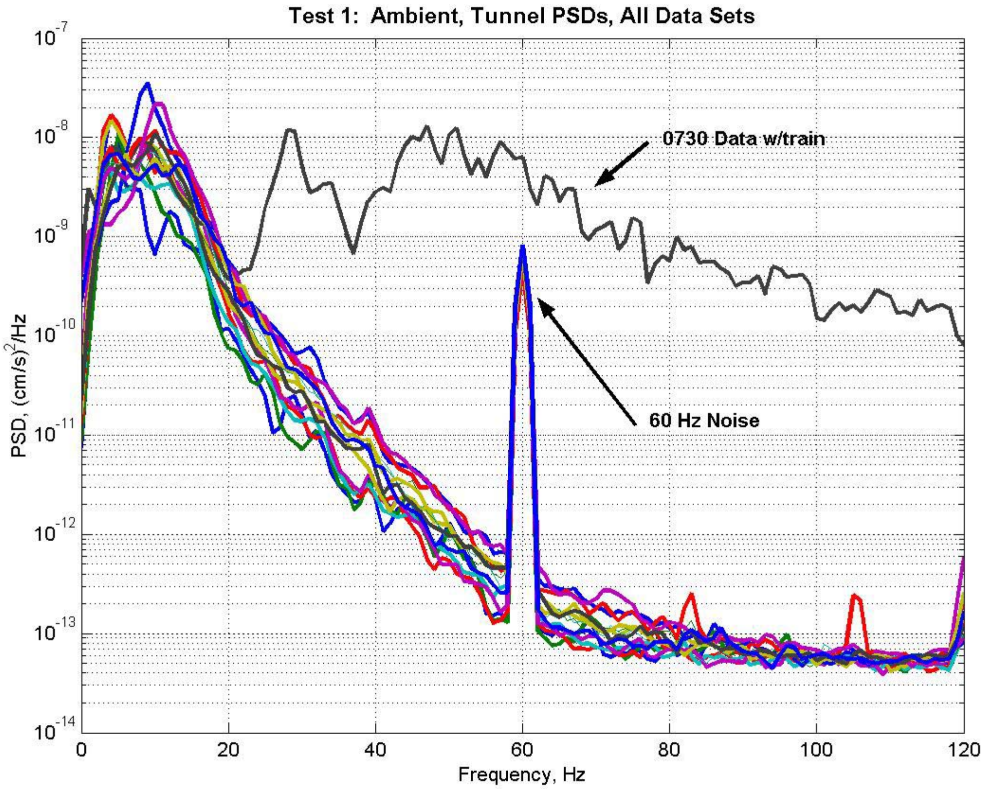


Figure 14: Comparison of Tunnel/Surface Transfer Functions at 60 Hz

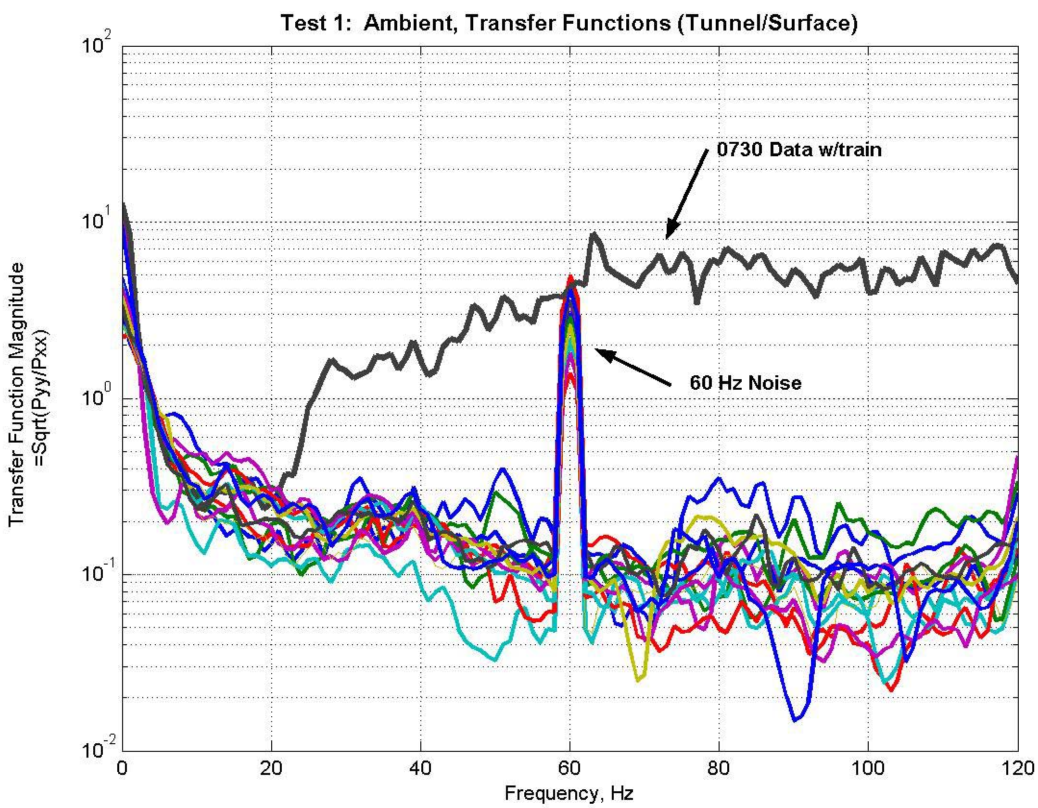
APPENDIX A: TEST 1 DATA PLOTS


Test 1: Ambient, Surface/Tunnel, Lagged Coherence, 0430 Data Set
Coherence, surface/tunnel
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
20
40
60
80
100
120


Test 1: Ambient, Surface PSD's, All 15 Data Sets
PSD, (cm/s)^2/Hz
Frequency, Hz
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
0
20
40
60
80
100
120

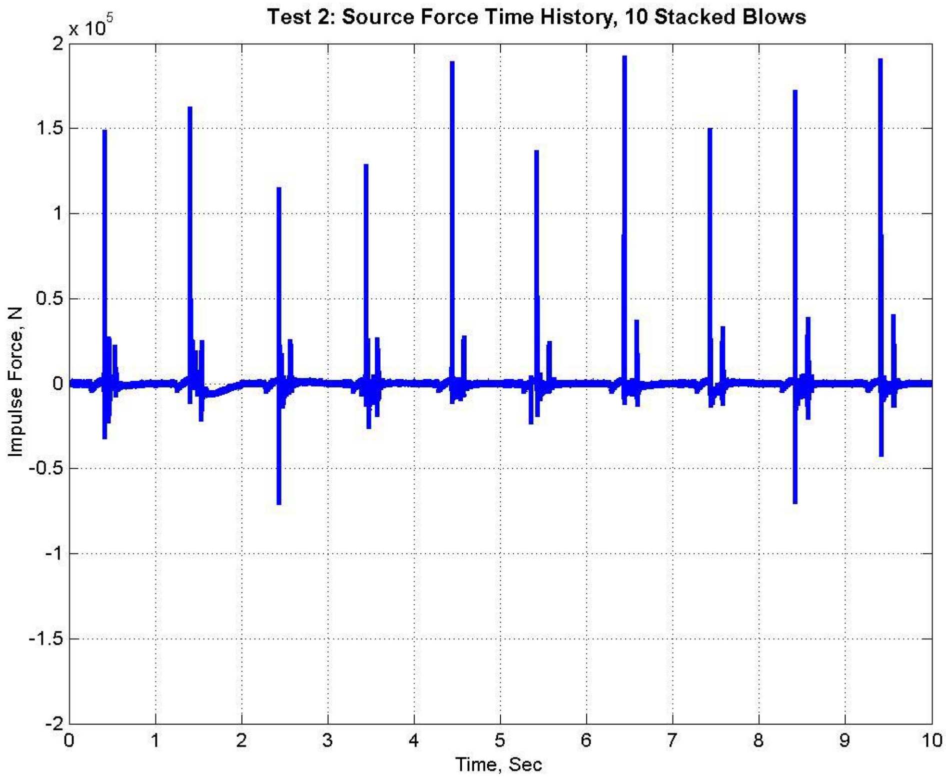


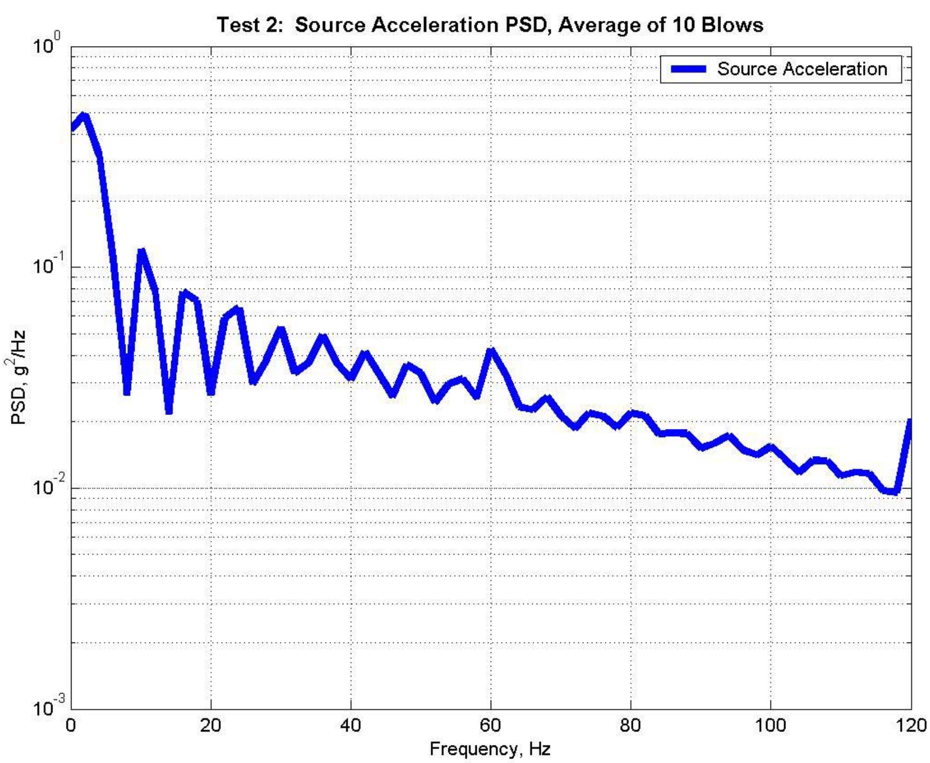
Test 1: Ambient, Tunnel PSDs, All Data Sets
PSD, (cm/s)^2/Hz
Frequency, Hz
0730 Data w/train
60 Hz Noise



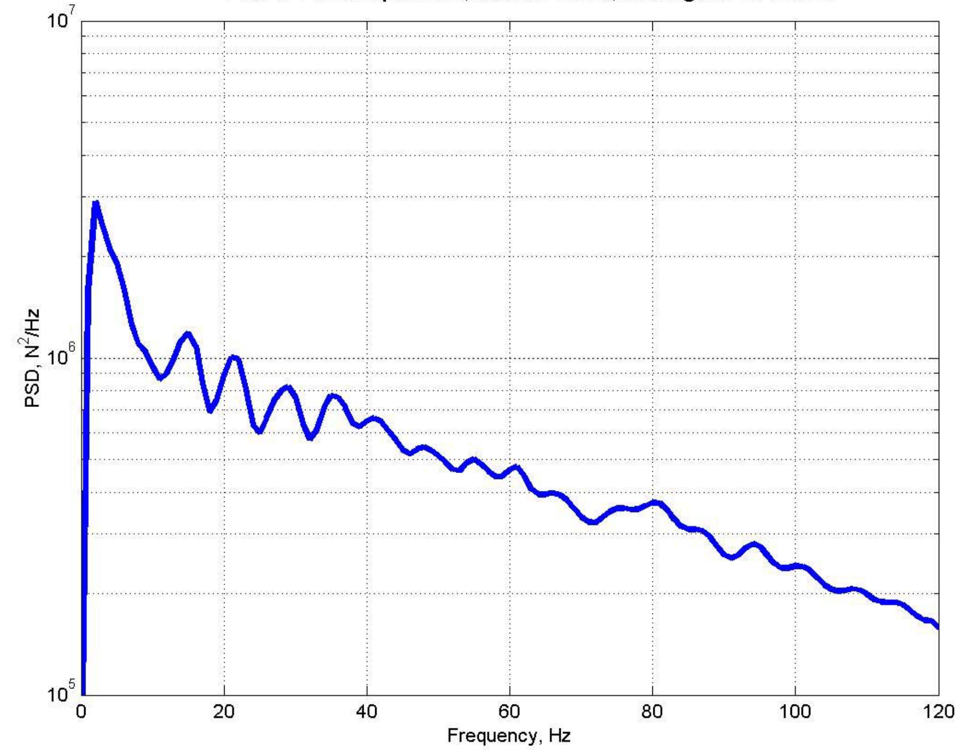
Test 1: Ambient, Transfer Functions (Tunnel/Surface)
Transfer Function Magnitude =Sqrt(Pyy/Pxx)
Frequency, Hz
0730 Data w/train
60 Hz Noise

APPENDIX B: TEST 2 DATA PLOTS

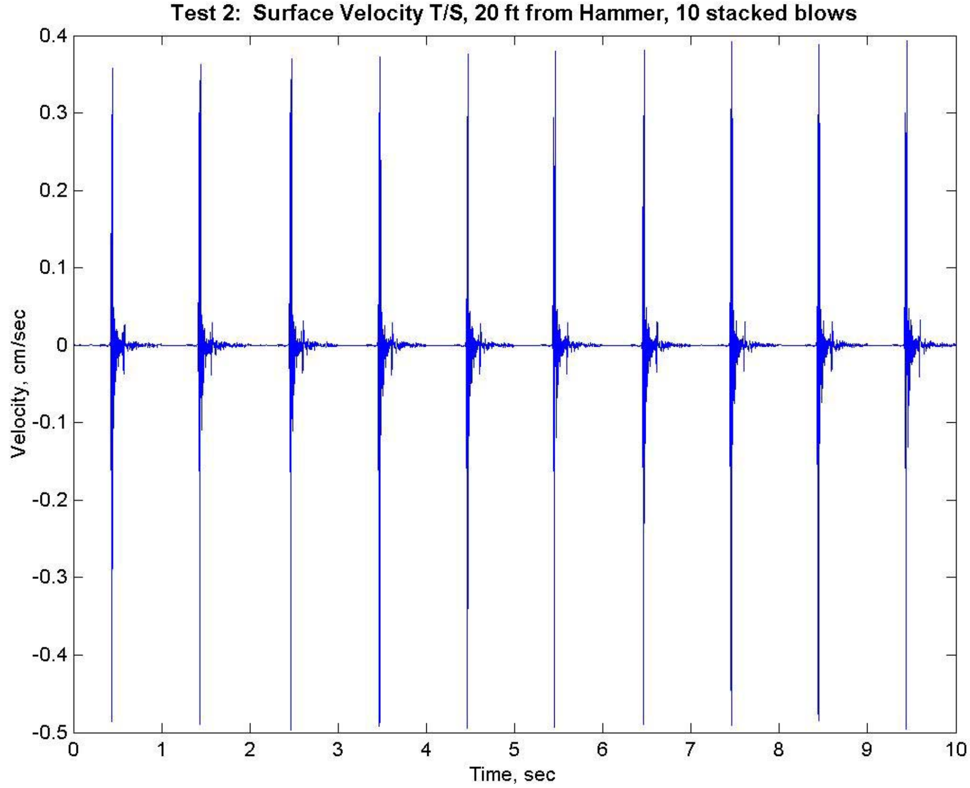

Test 2: Source Force Time History, 10 Stacked Blows
x 10^5
Impulse Force, N
Time, Sec

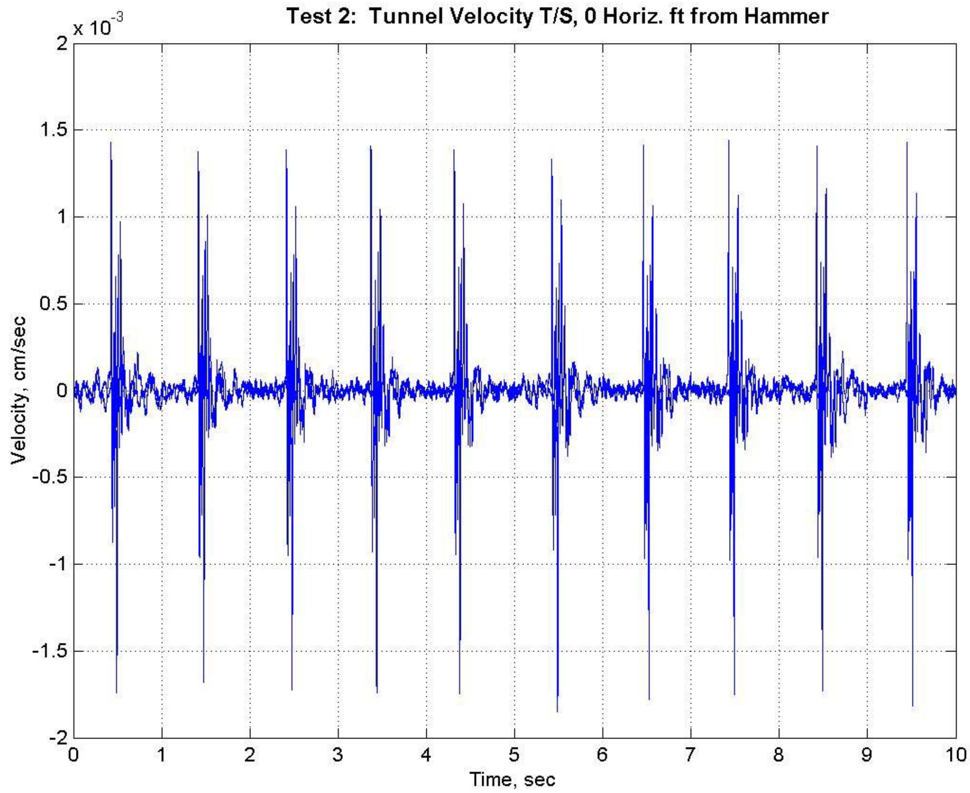

Test 2: Source Acceleration PSD, Average of 10 Blows
Source Acceleration
PSD, g^2/Hz
Frequency, Hz

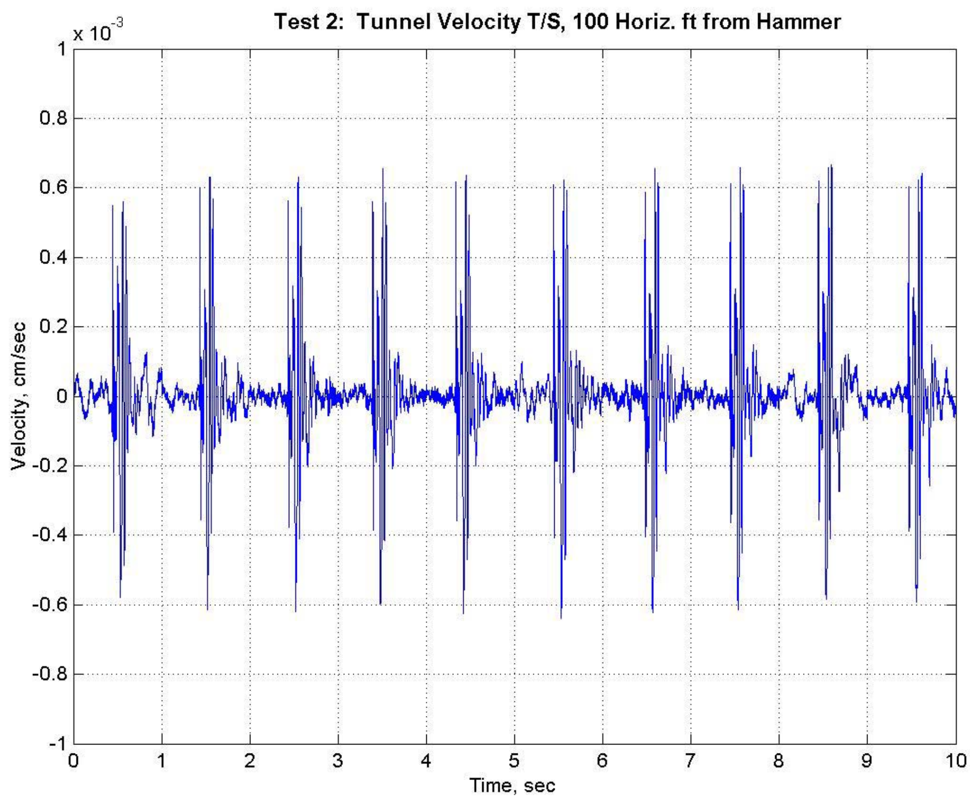
Test2: Power Spectrum, Source Force, Average of 10 Blows

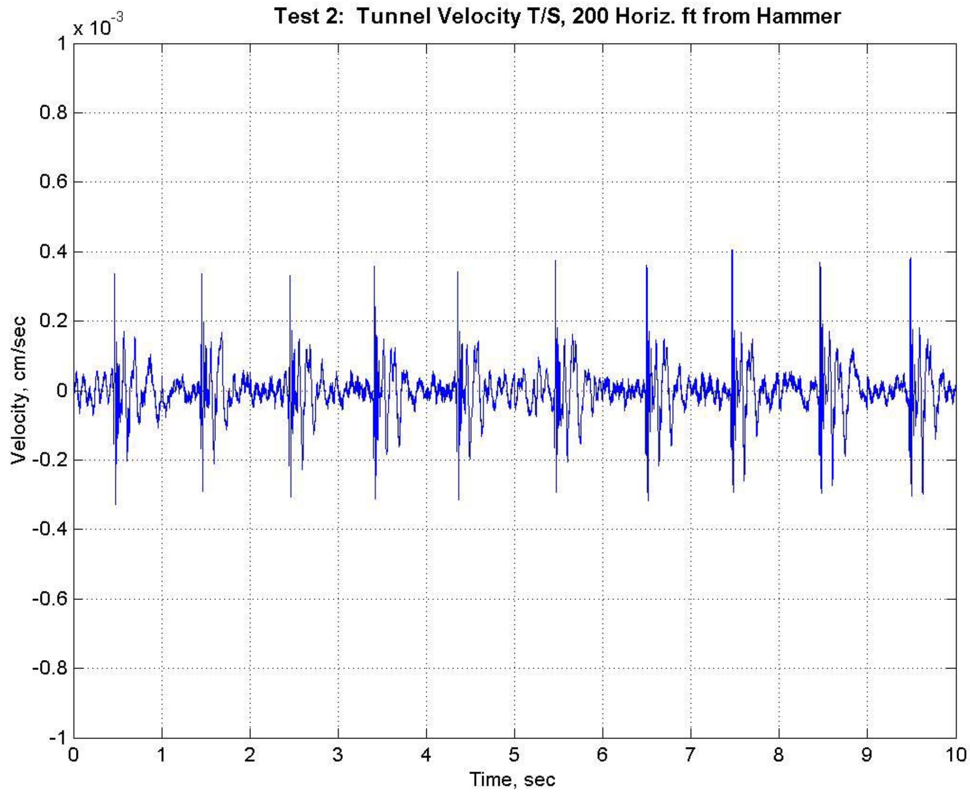


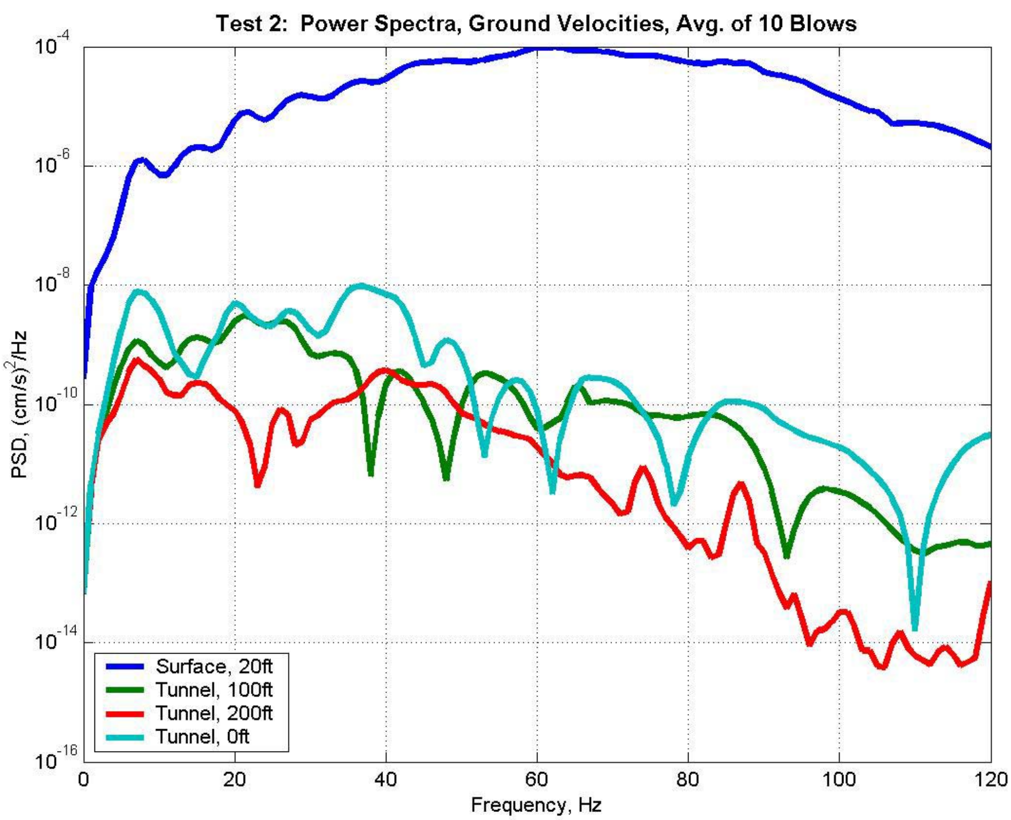
Test 2: Surface Velocity T/S, 20 ft from Hammer, 10 stacked blows

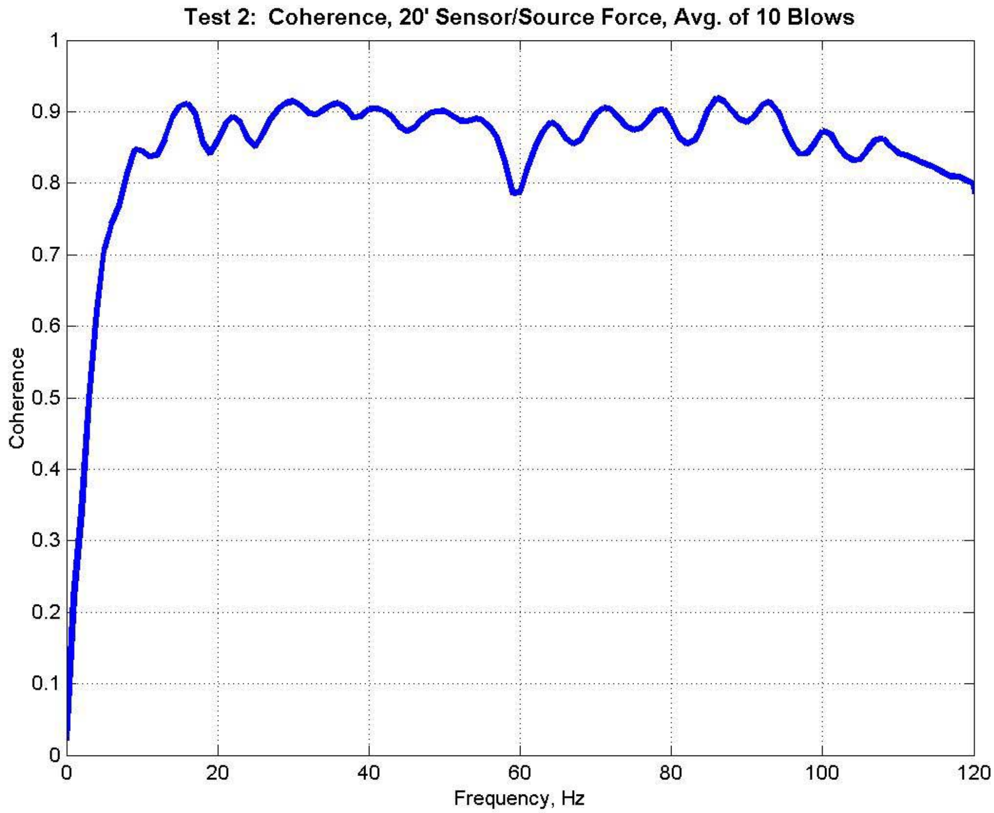


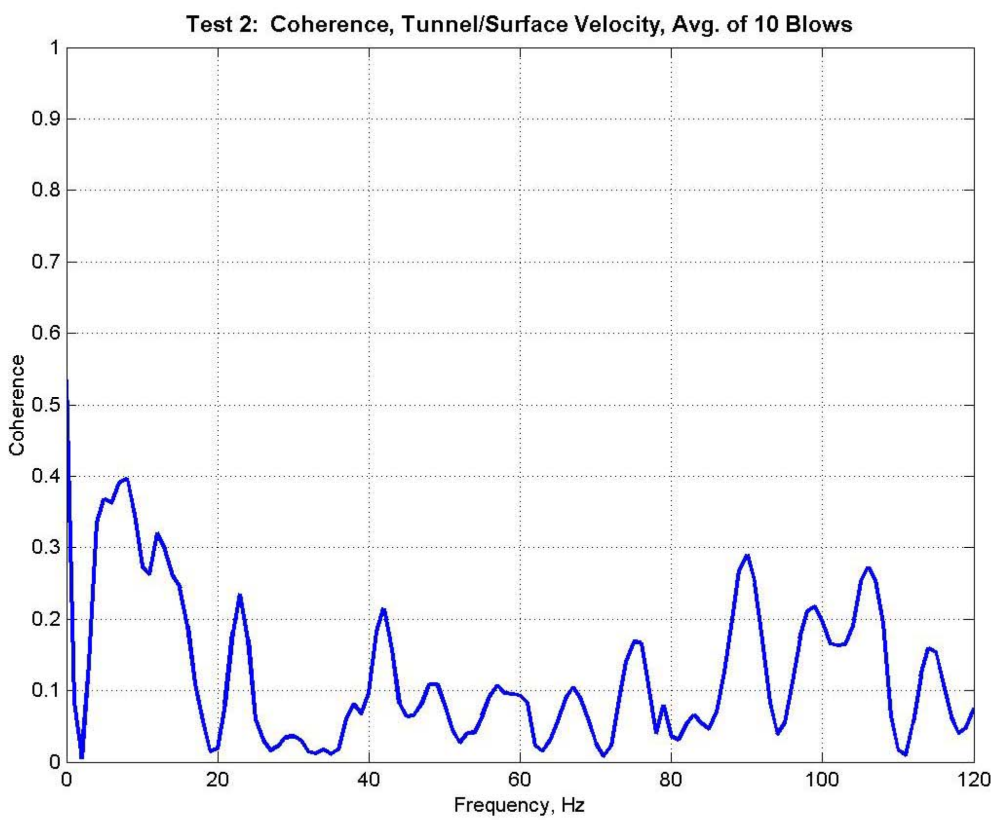

Test 2: Tunnel Velocity T/S, 0 Horiz. ft from Hammer
x 10^-3
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Velocity, cm/sec
0
1
2
3
4
5
6
7
8
9
10
Time, sec

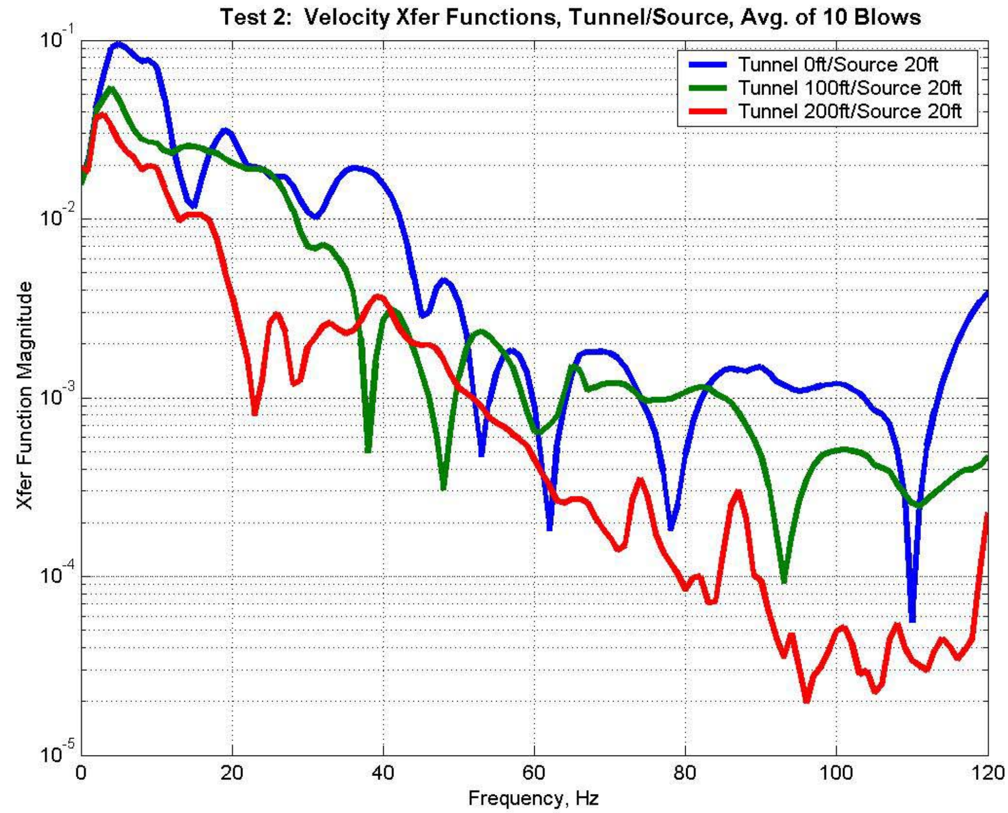

Test 2: Tunnel Velocity T/S, 100 Horiz. ft from Hammer
x 10^-3
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Velocity, cm/sec
0
1
2
3
4
5
6
7
8
9
10
Time, sec

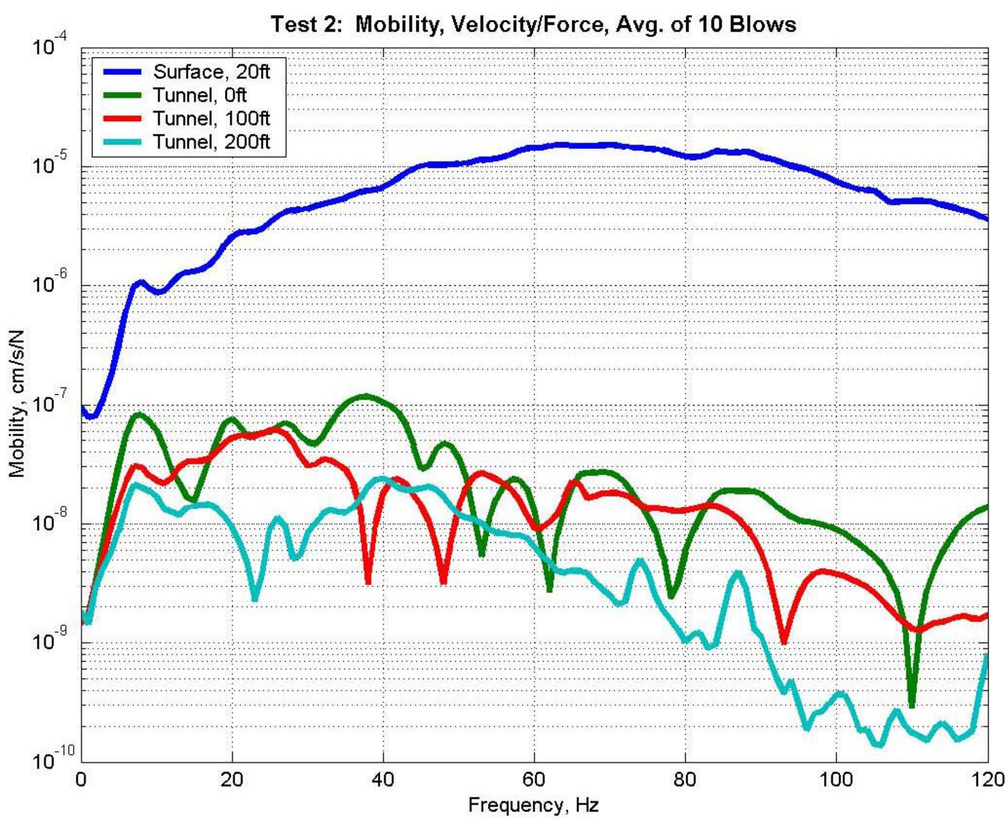

Test 2: Tunnel Velocity T/S, 200 Horiz. ft from Hammer
x 10^-3
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Velocity, cm/sec
0
1
2
3
4
5
6
7
8
9
10
Time, sec


Test 2: Power Spectra, Ground Velocities, Avg. of 10 Blows
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
PSD, (cm/s)^2/Hz
0
20
40
60
80
100
120
Frequency, Hz
Surface, 20ft
Tunnel, 100ft
Tunnel, 200ft
Tunnel, 0ft

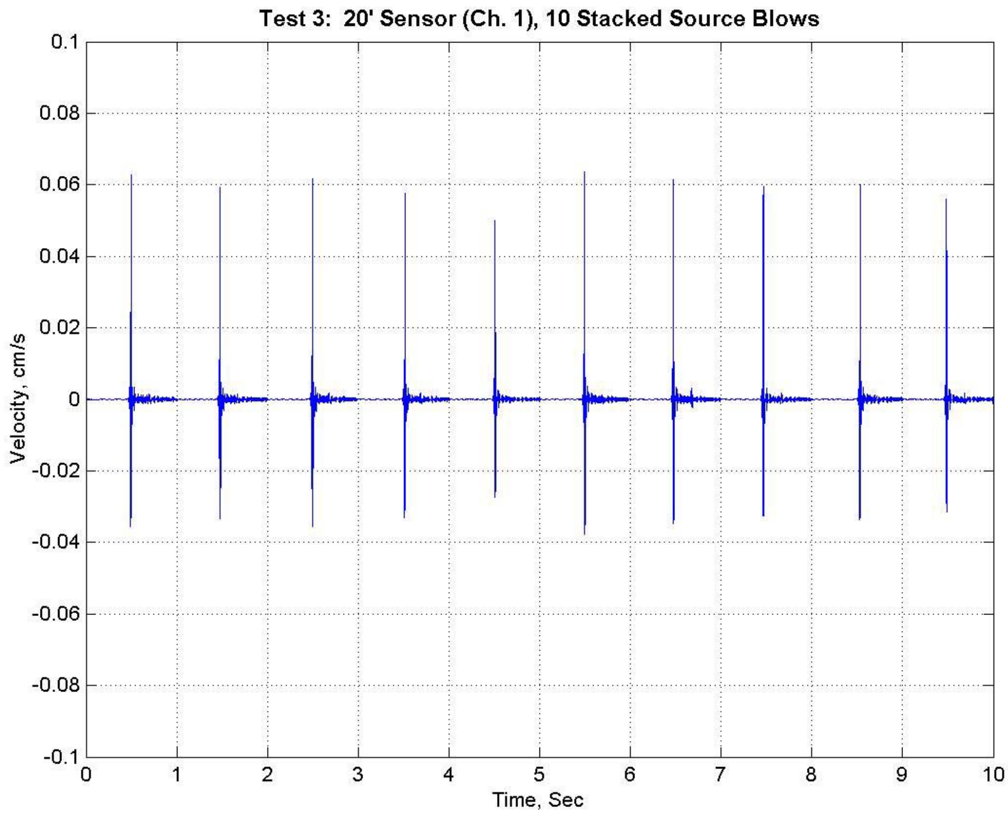

Test 2: Coherence, 20' Sensor/Source Force, Avg. of 10 Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
40
60
80
100
120

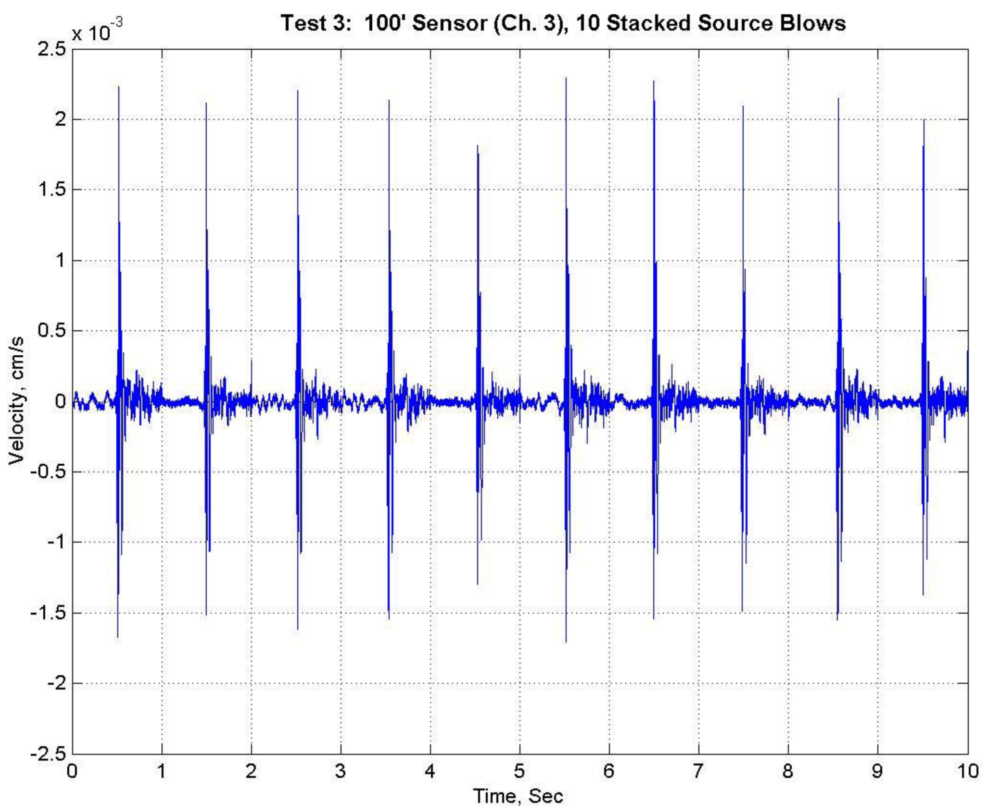

Test 2: Coherence, Tunnel/Surface Velocity, Avg. of 10 Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
40
60
80
100
120

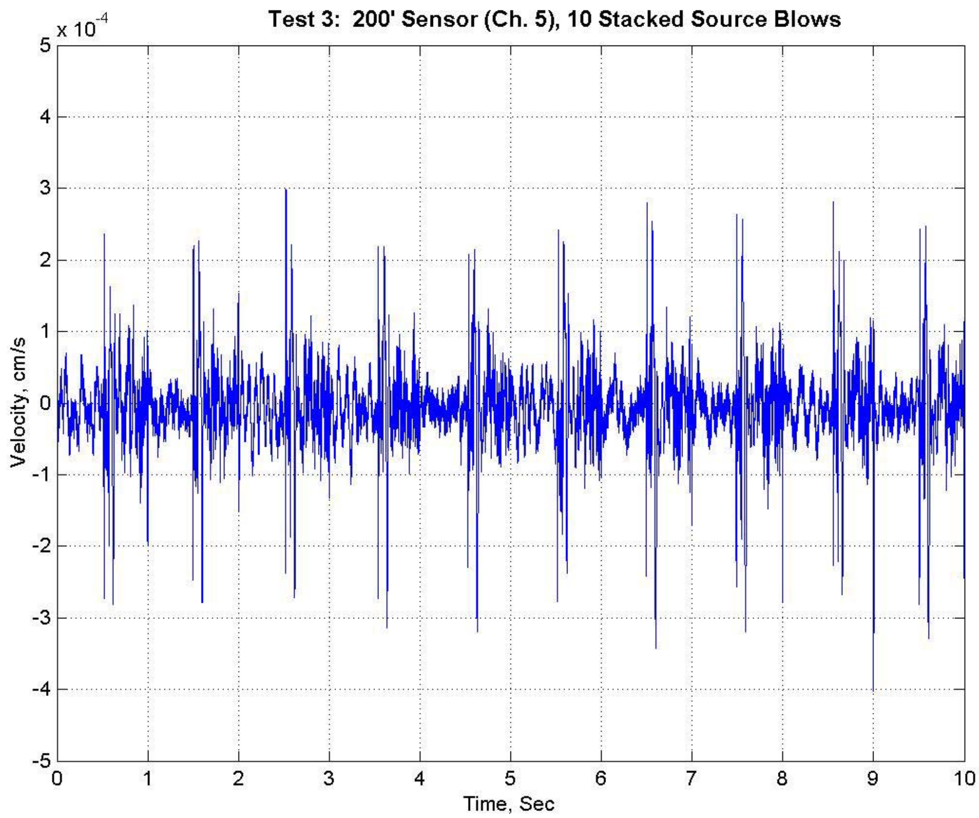

Test 2: Velocity Xfer Functions, Tunnel/Source, Avg. of 10 Blows
Tunnel 0ft/Source 20ft
Tunnel 100ft/Source 20ft
Tunnel 200ft/Source 20ft
Xfer Function Magnitude
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
20
40
60
80
100
120
Frequency, Hz


Test 2: Mobility, Velocity/Force, Avg. of 10 Blows
Surface, 20ft
Tunnel, 0ft
Tunnel, 100ft
Tunnel, 200ft
Mobility, cm/s/N
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
20
40
60
80
100
120
Frequency, Hz

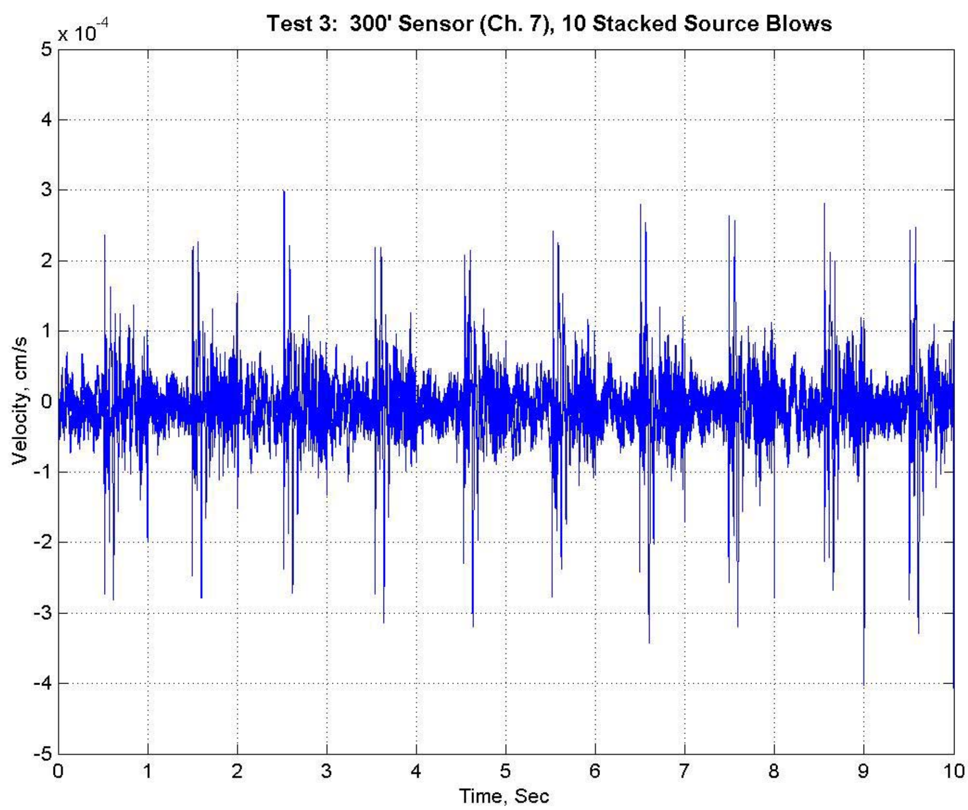
APPENDIX C: TEST 3 DATA PLOTS


Test 3: 20' Sensor (Ch. 1), 10 Stacked Source Blows
Velocity, cm/s
Time, Sec
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
0
1
2
3
4
5
6
7
8
9
10

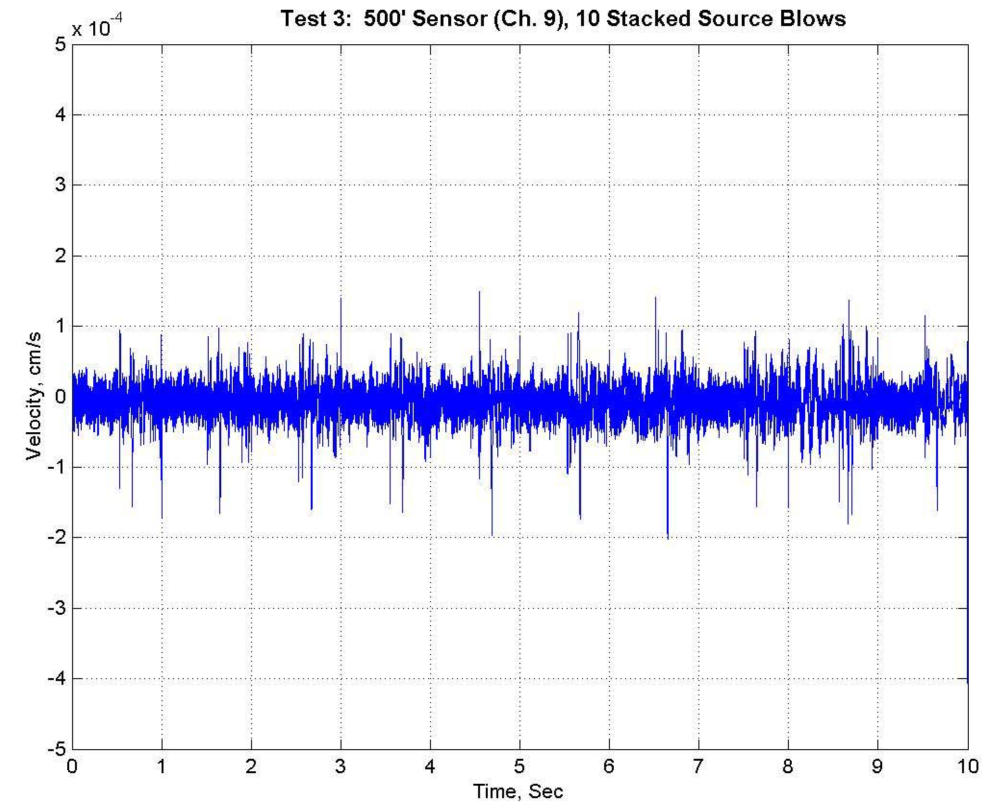

Test 3: 100' Sensor (Ch. 3), 10 Stacked Source Blows
x 10^-3
Velocity, cm/s
Time, Sec
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
1
2
3
4
5
6
7
8
9
10

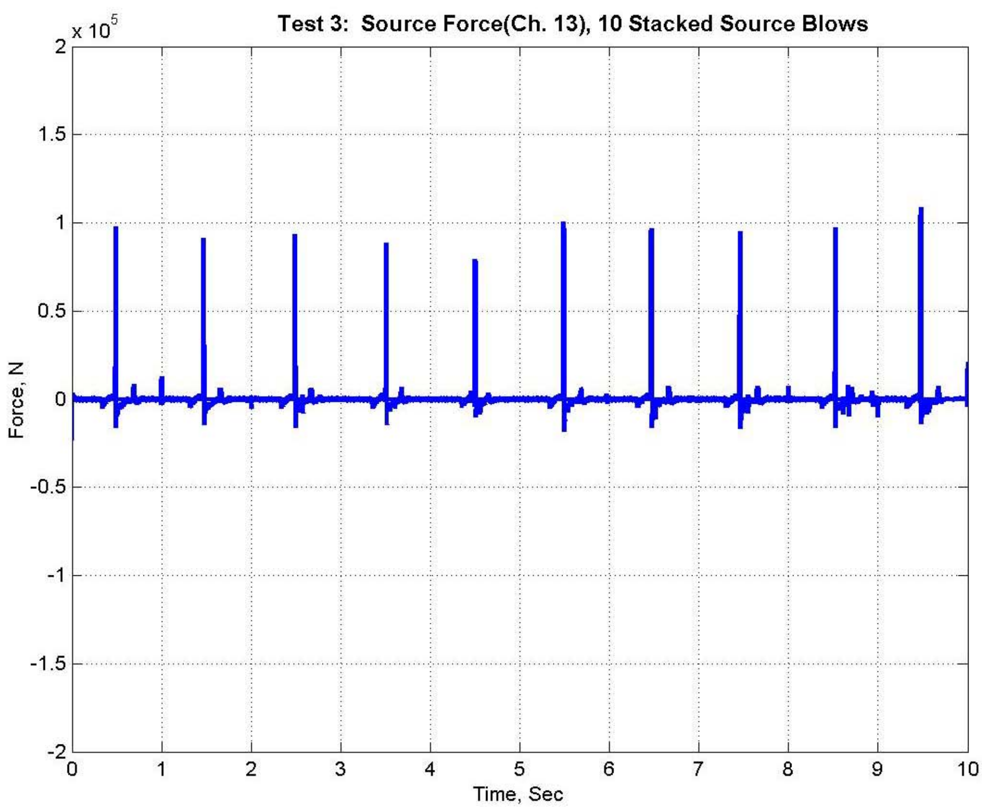


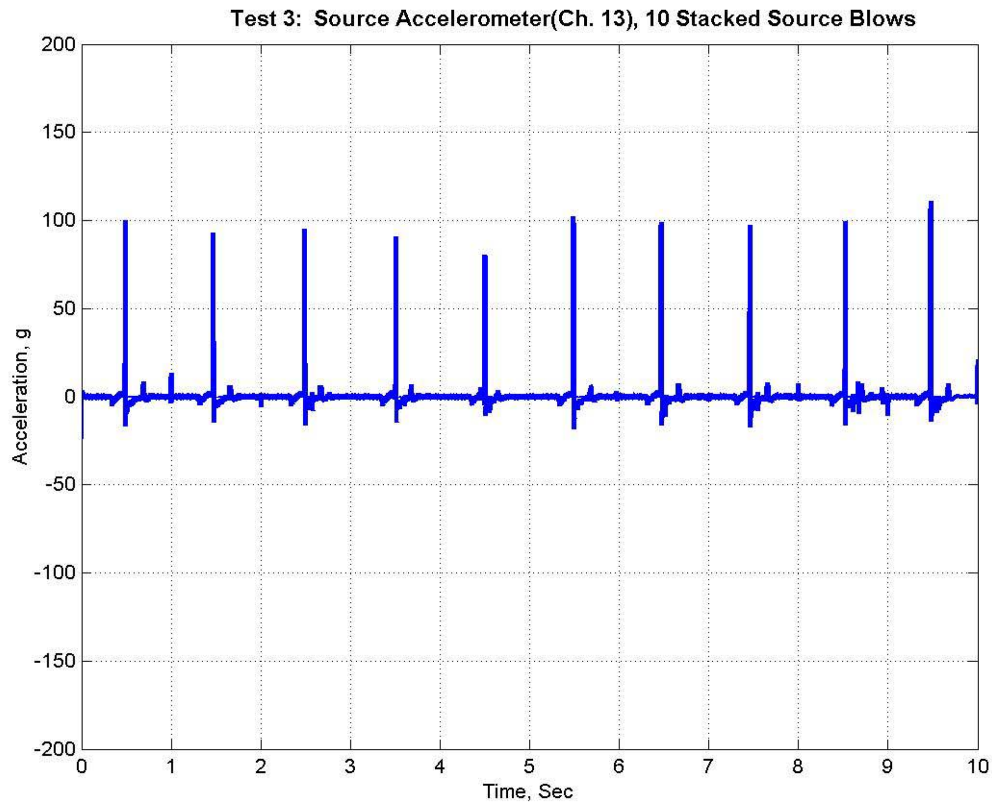
Test 3: 200' Sensor (Ch. 5), 10 Stacked Source Blows
x 10^-4
Velocity, cm/s
Time, Sec



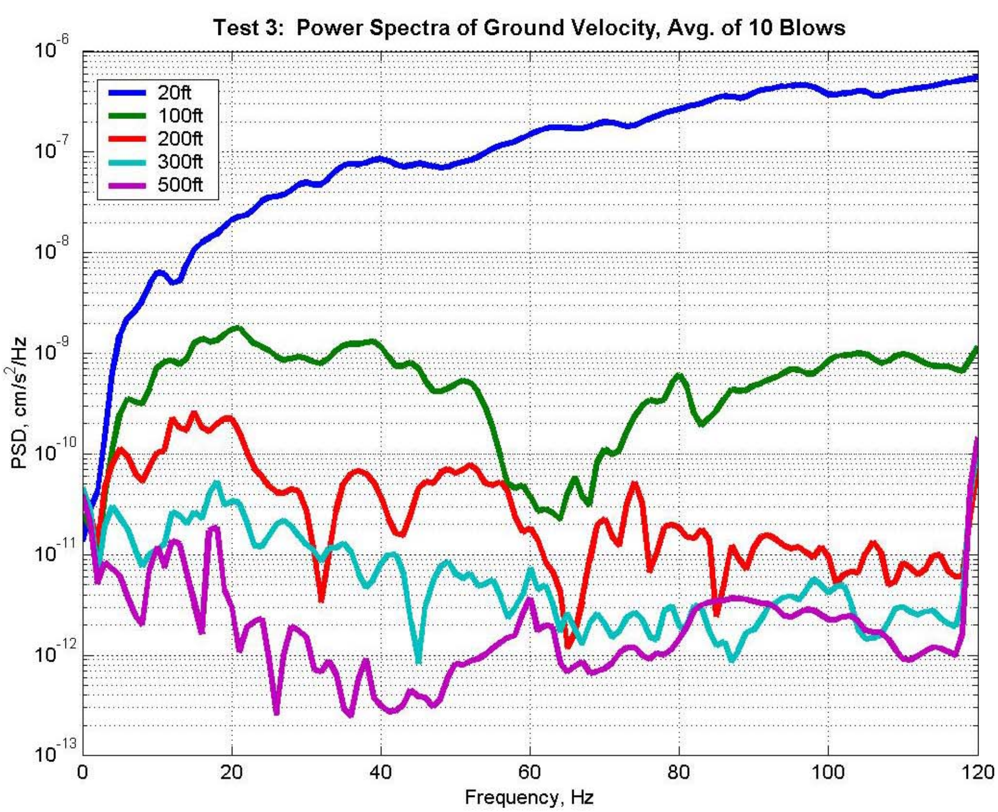
Test 3: 300' Sensor (Ch. 7), 10 Stacked Source Blows
x 10^-4
Velocity, cm/s
Time, Sec


Test 3: 500' Sensor (Ch. 9), 10 Stacked Source Blows
x 10^-4
Velocity, cm/s
Time, Sec
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
1
2
3
4
5
6
7
8
9
10

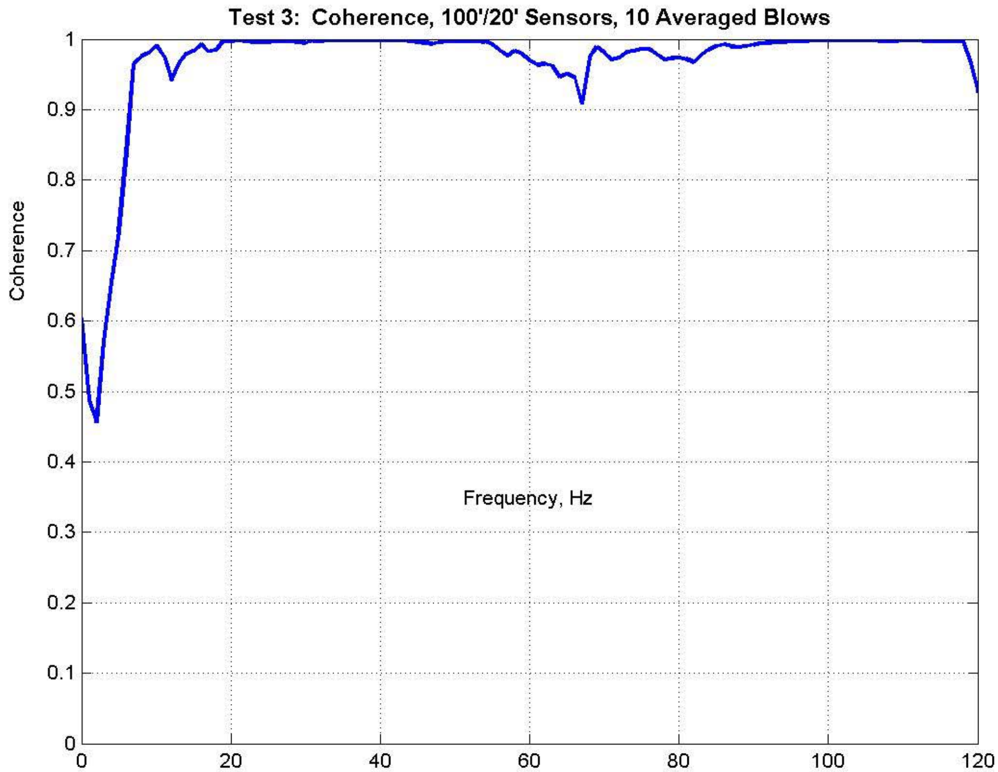

Test 3: Source Force(Ch. 13), 10 Stacked Source Blows
x 10^5
Force, N
Time, Sec
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
4
5
6
7
8
9
10

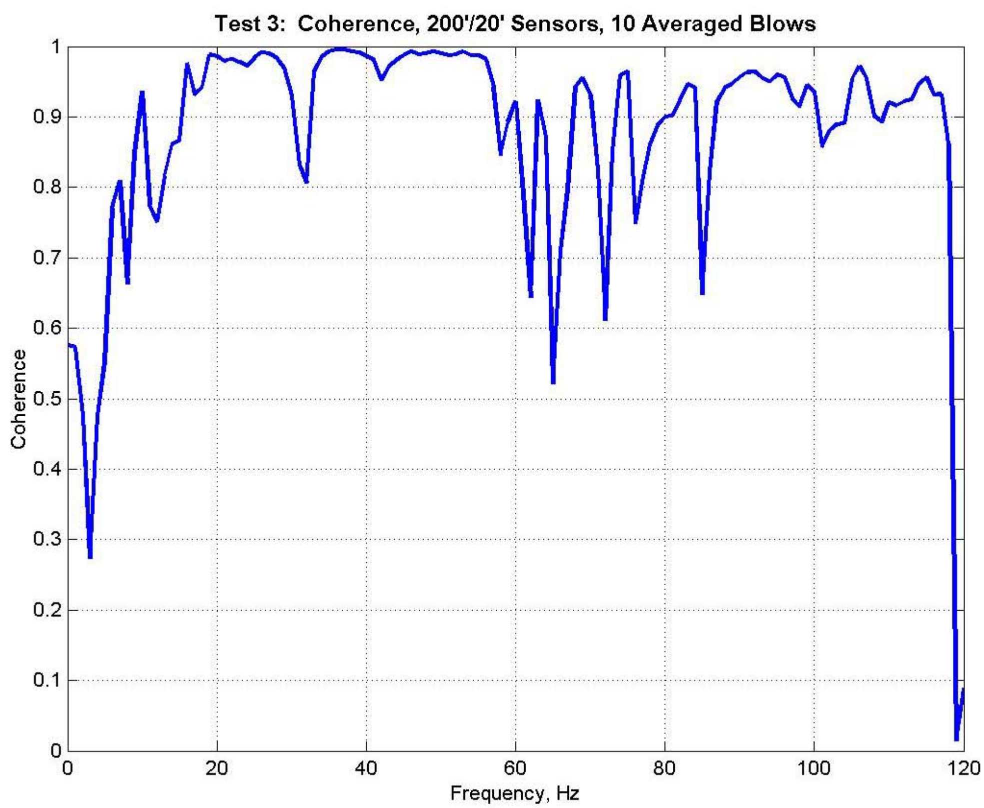


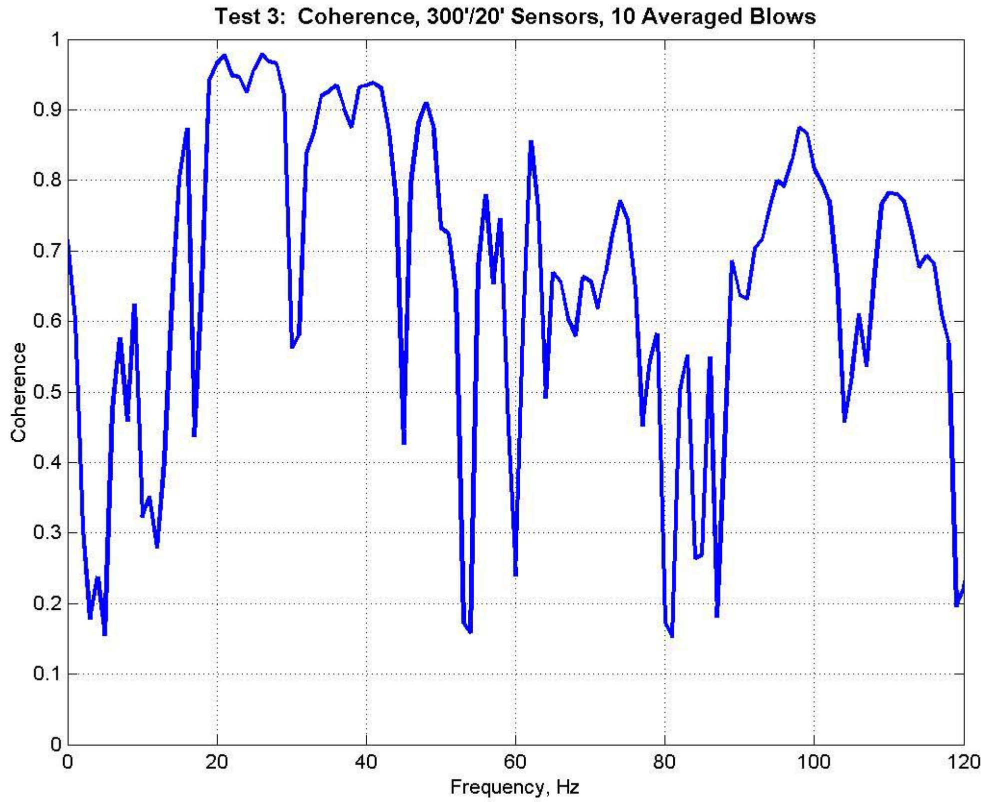
Test 3: Source Accelerometer(Ch. 13), 10 Stacked Source Blows
Acceleration, g
Time, Sec

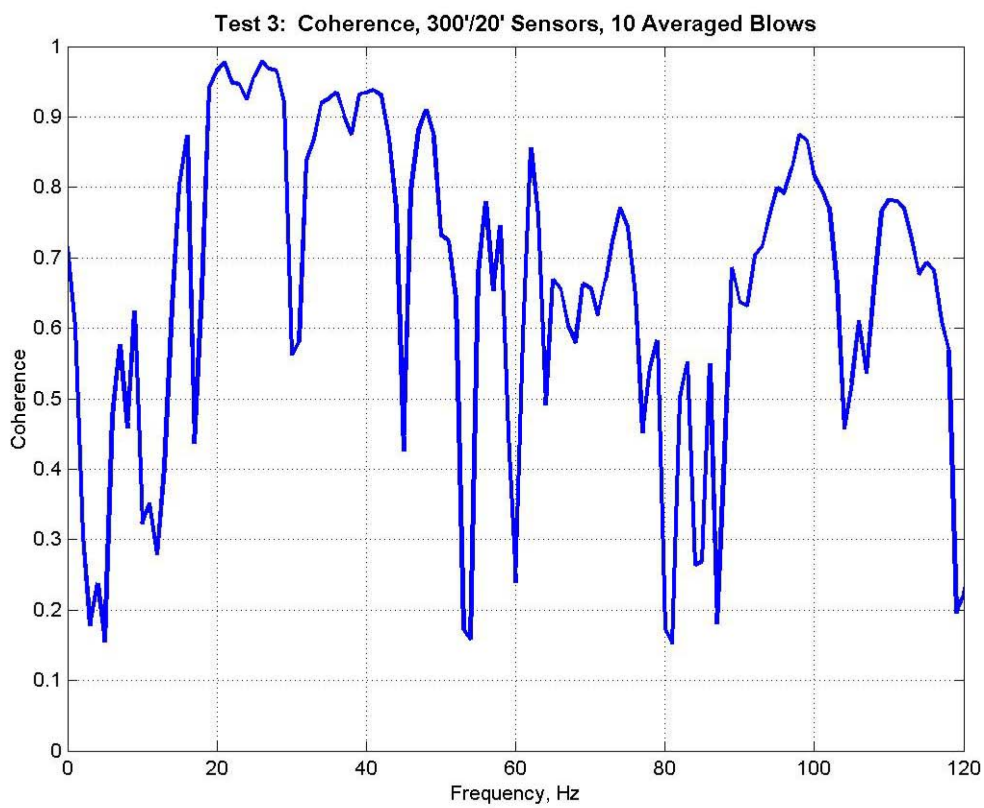


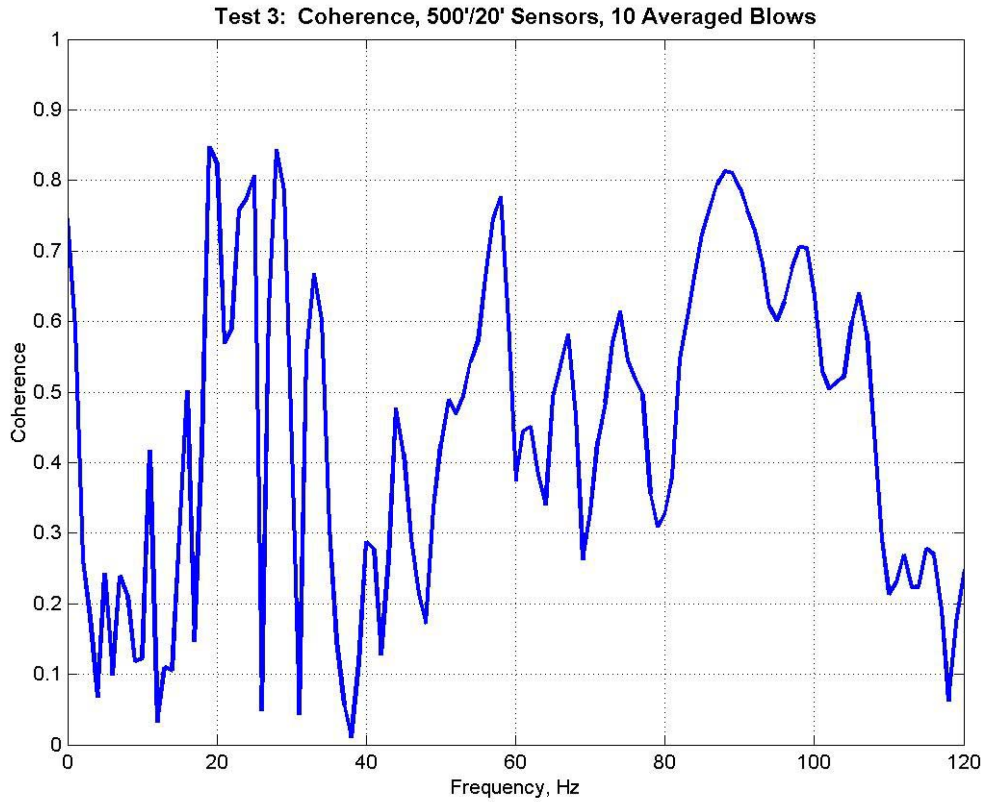
Test 3: Power Spectra of Ground Velocity, Avg. of 10 Blows
20ft
100ft
200ft
300ft
500ft
PSD, cm/s²/Hz
Frequency, Hz

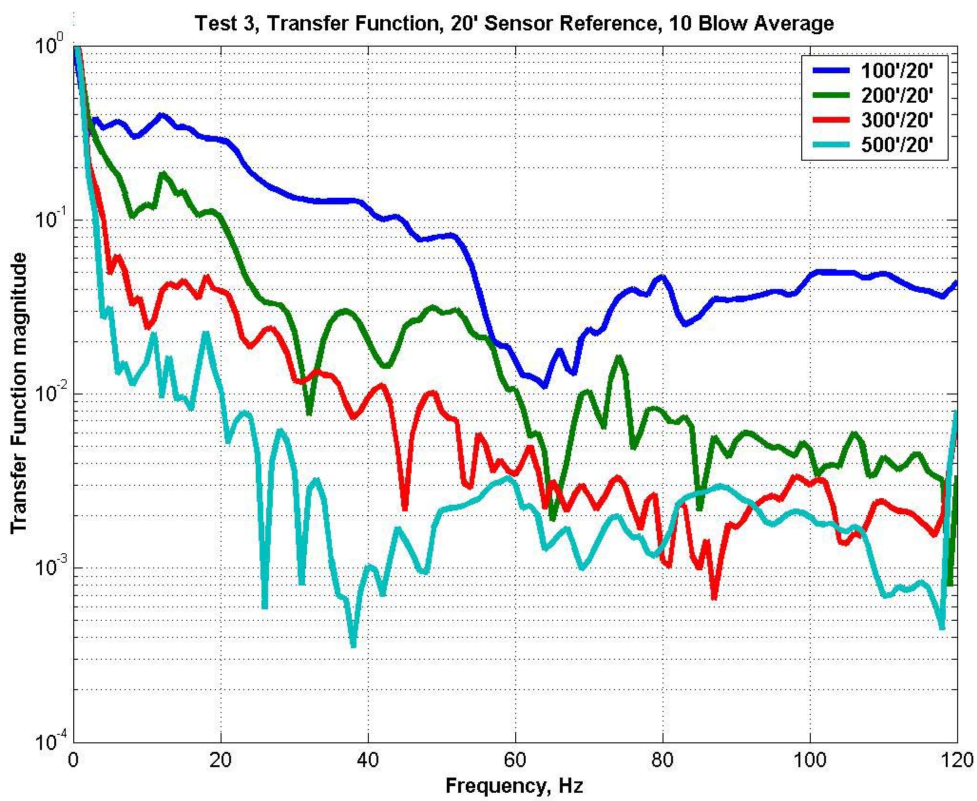

Test 3: Coherence, 100'/20' Sensors, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120

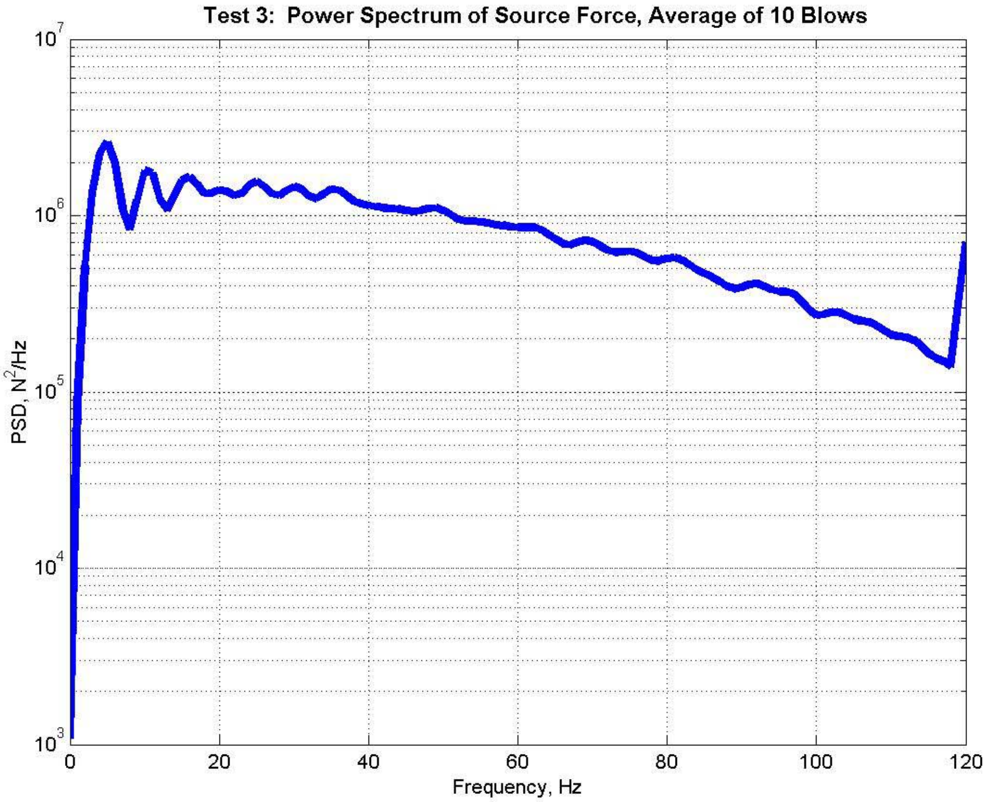

Test 3: Coherence, 200'/20' Sensors, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120


Test 3: Coherence, 300'/20' Sensors, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
40
60
80
100
120

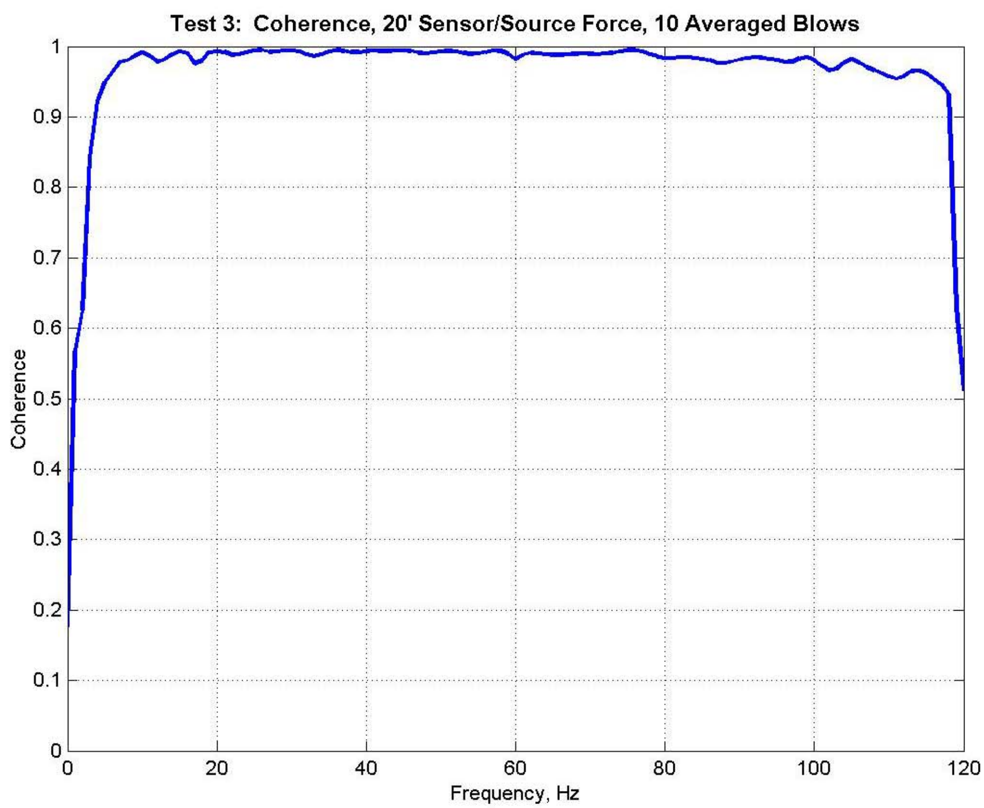

Test 3: Coherence, 300'/20' Sensors, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
40
60
80
100
120


Test 3: Coherence, 500'/20' Sensors, 10 Averaged Blows
Coherence
Frequency, Hz

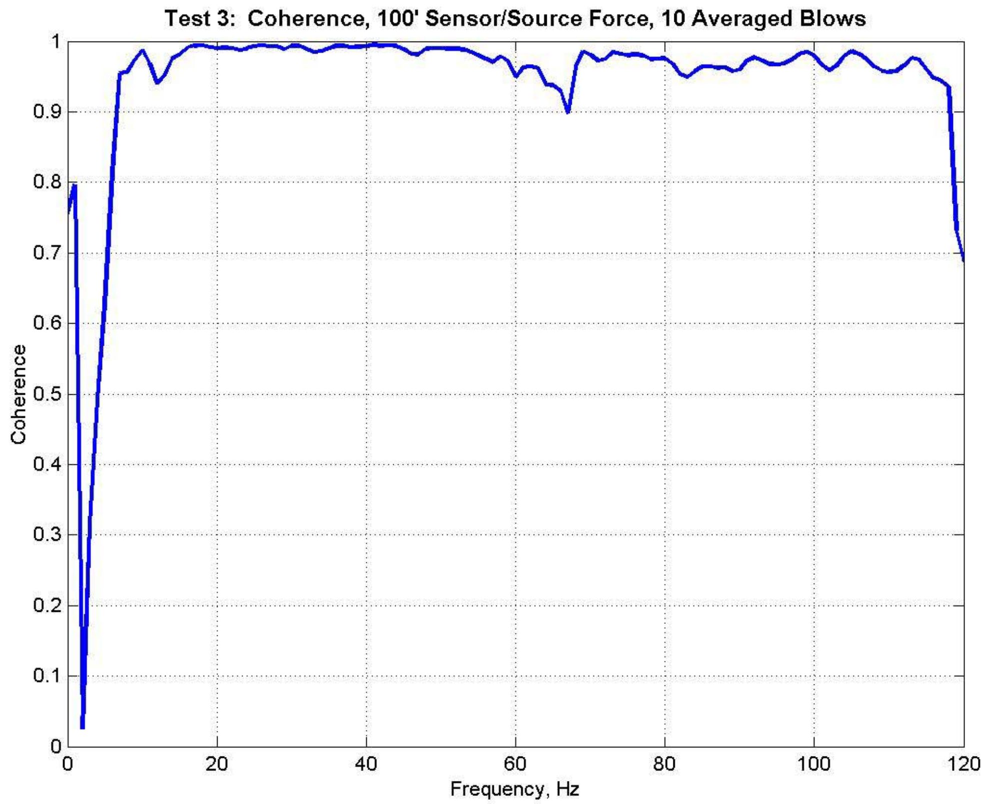

Test 3, Transfer Function, 20' Sensor Reference, 10 Blow Average
100'/20'
200'/20'
300'/20'
500'/20'
Transfer Function magnitude
Frequency, Hz

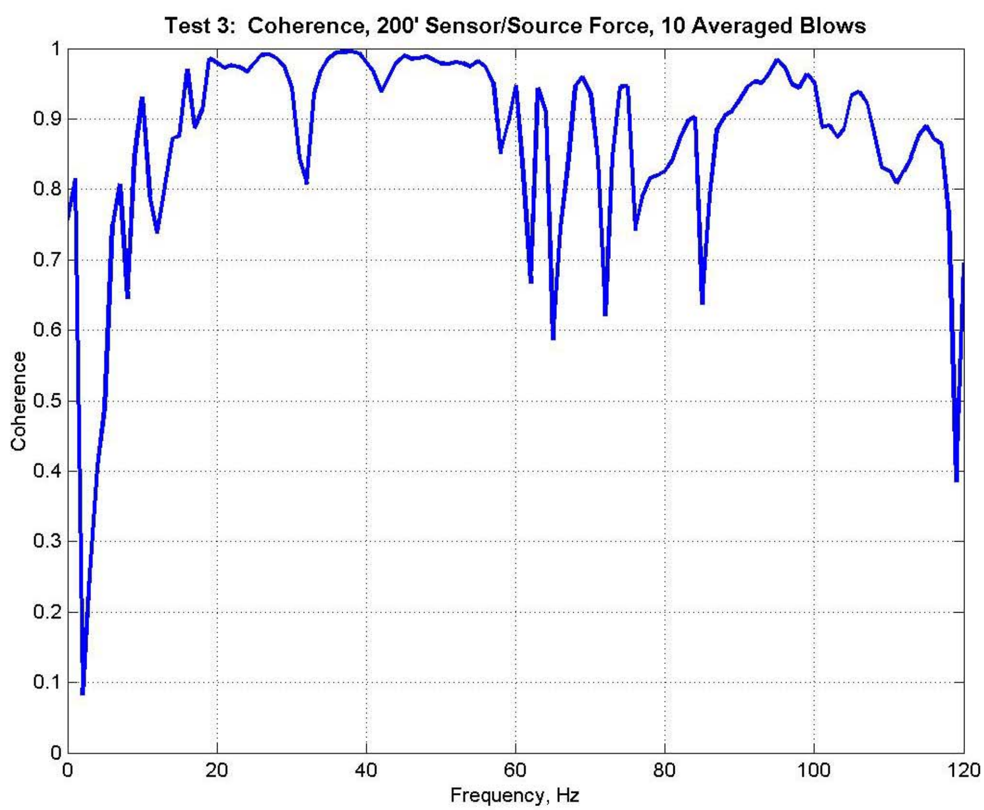


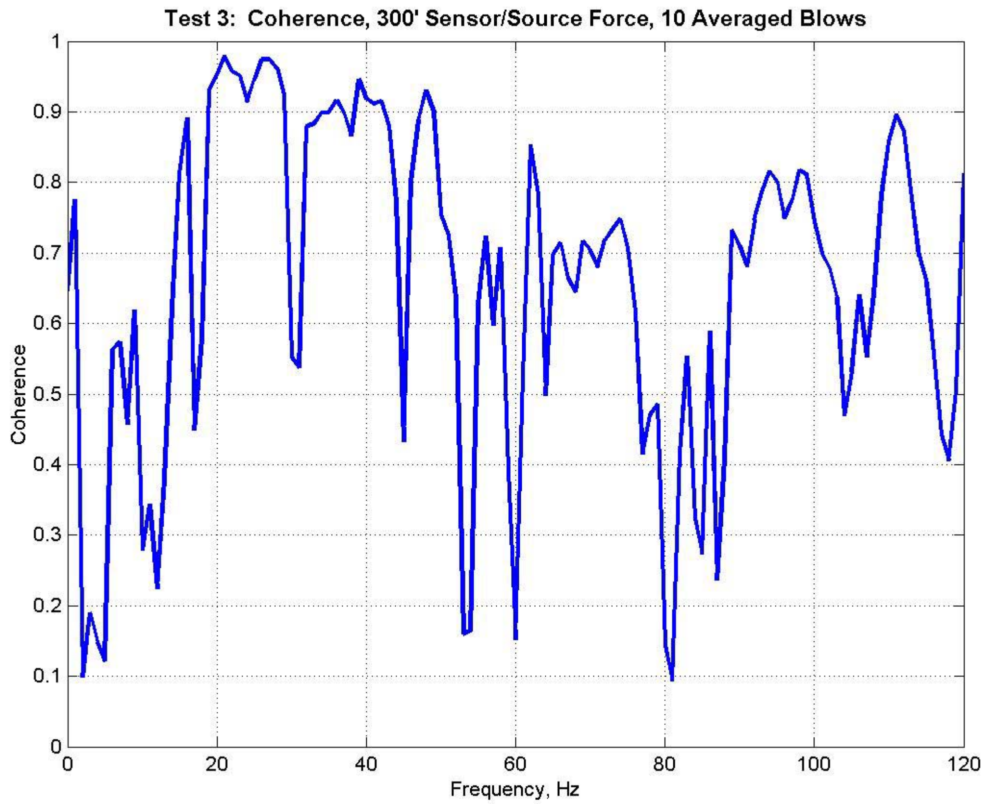
Test 3: Power Spectrum of Source Force, Average of 10 Blows
PSD, N^2/Hz
Frequency, Hz

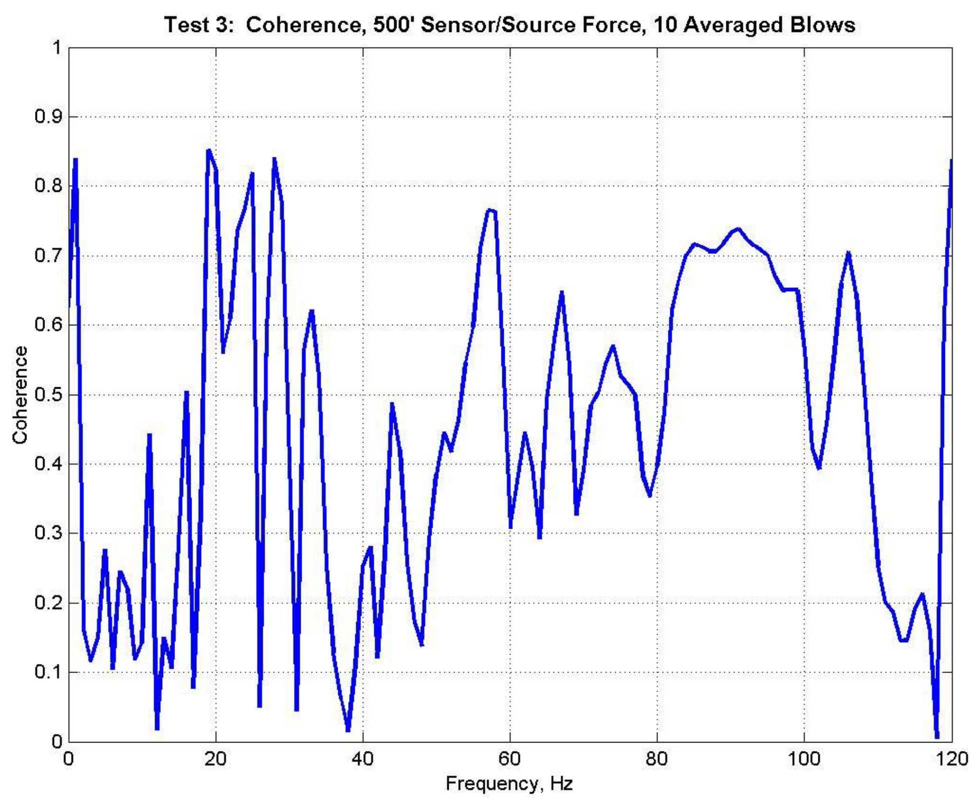


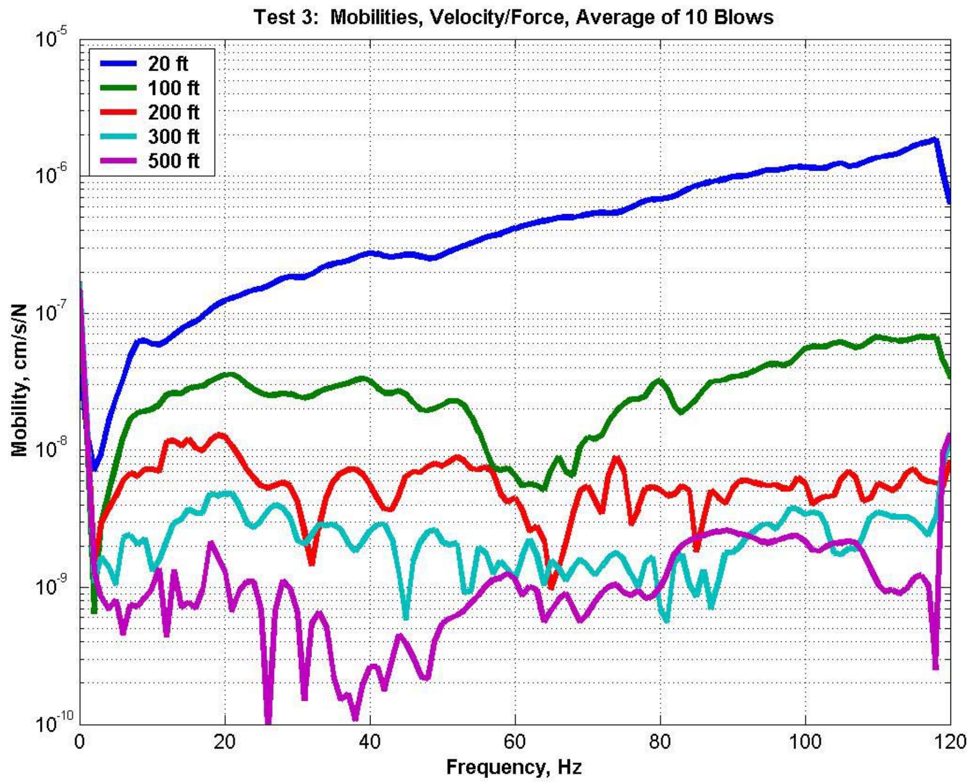
Test 3: Coherence, 20' Sensor/Source Force, 10 Averaged Blows
Coherence
Frequency, Hz


Test 3: Coherence, 100' Sensor/Source Force, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120


Test 3: Coherence, 200' Sensor/Source Force, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120

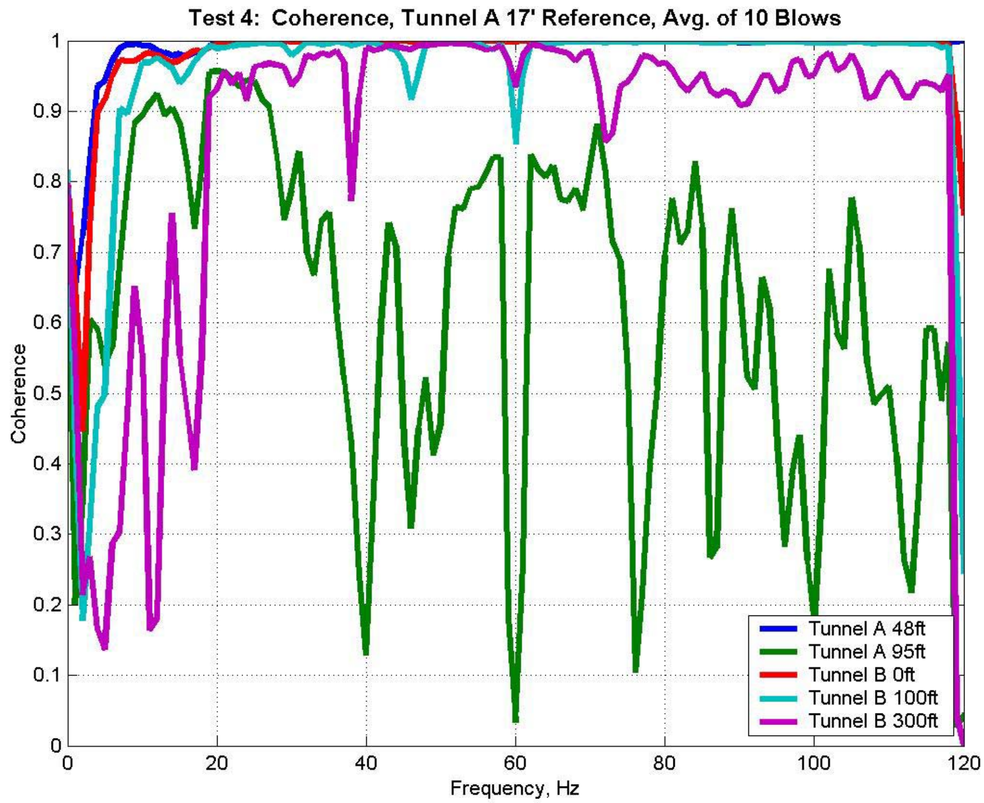

Test 3: Coherence, 300' Sensor/Source Force, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120

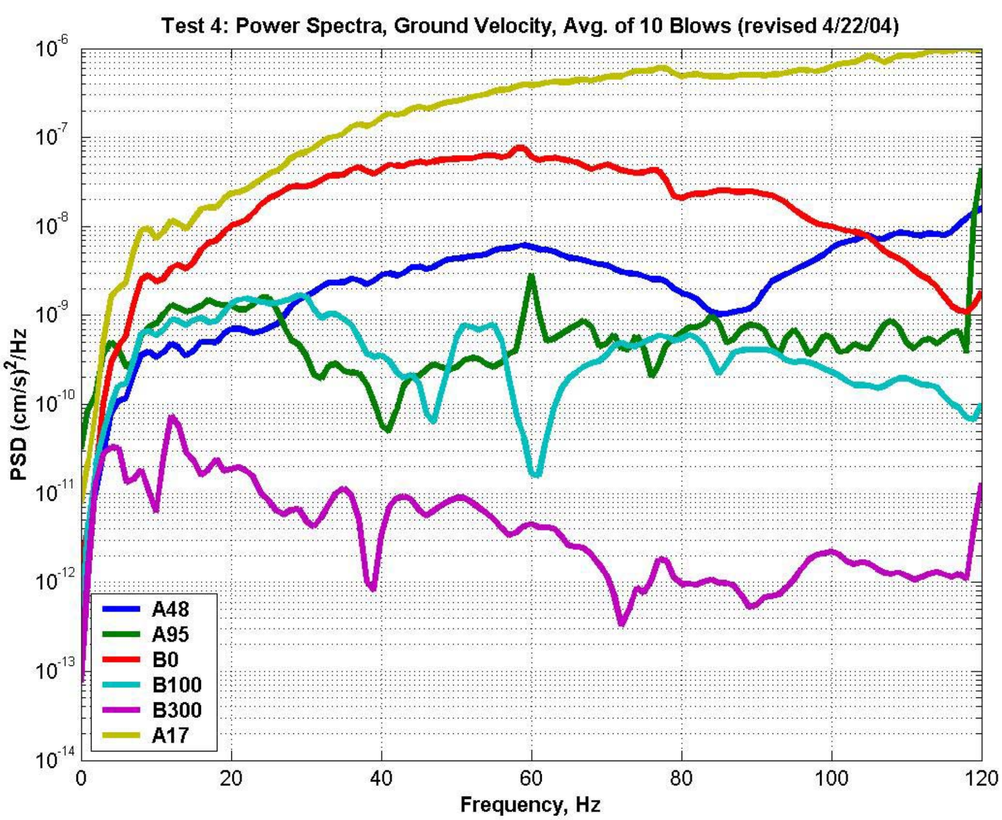

Test 3: Coherence, 500' Sensor/Source Force, 10 Averaged Blows
Coherence
Frequency, Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120

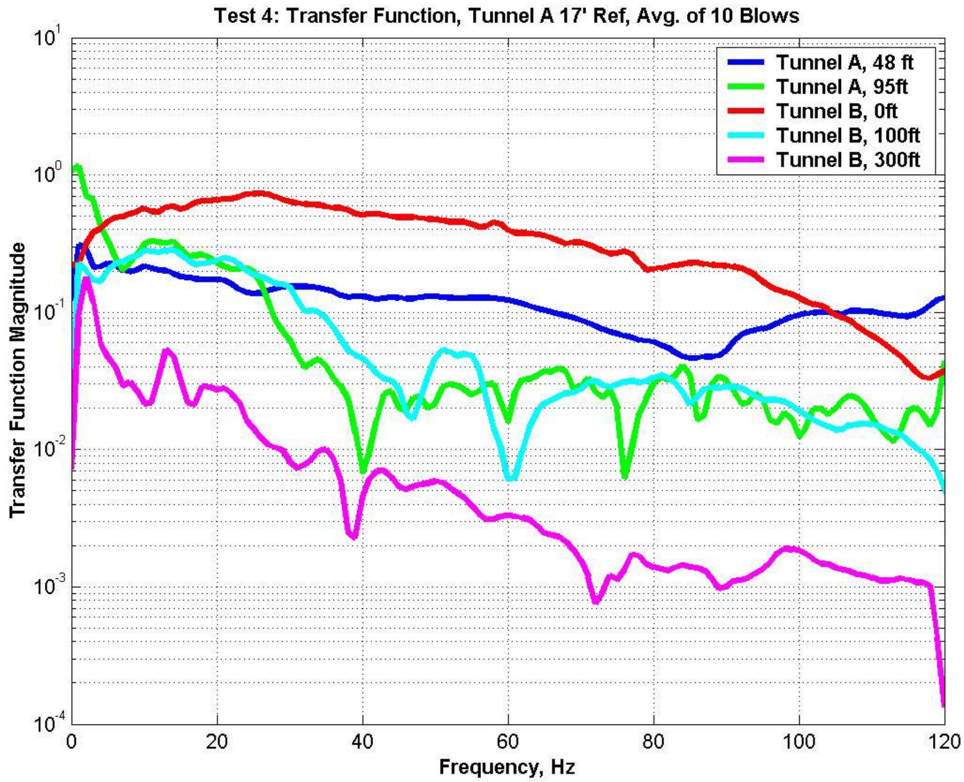


Test 3: Mobilities, Velocity/Force, Average of 10 Blows
20 ft
100 ft
200 ft
300 ft
500 ft
Mobility, cm/s/N
Frequency, Hz
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
20
40
60
80
100
120

APPENDIX D: TEST 4 DATA PLOTS

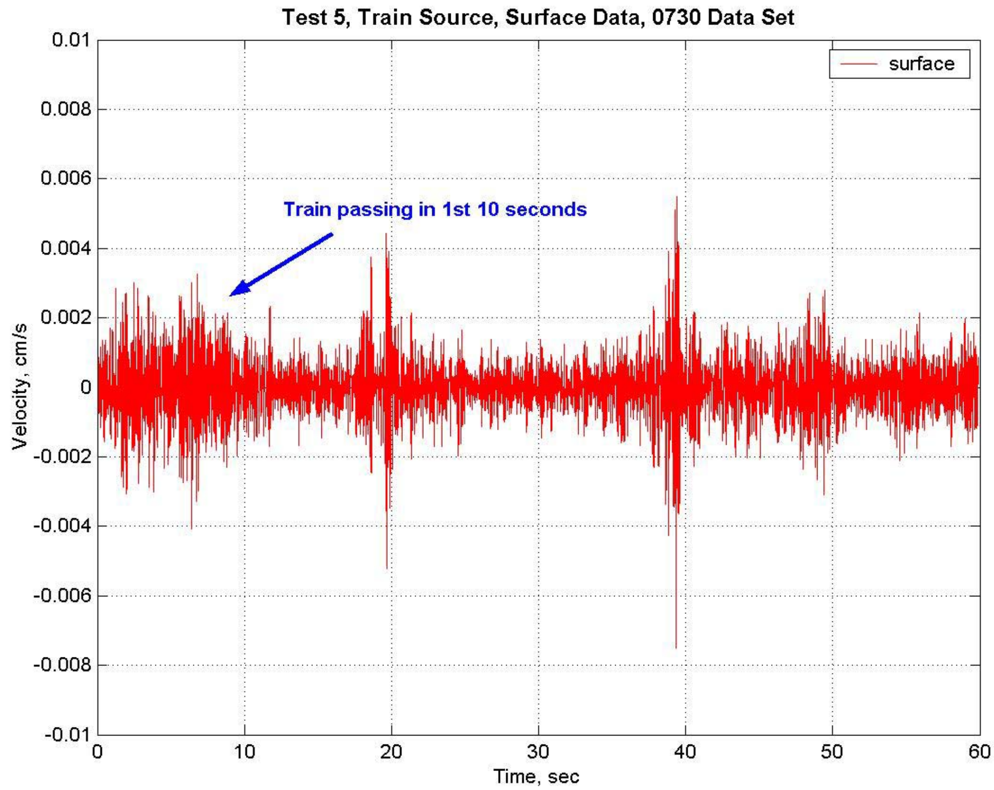

Test 4: Coherence, Tunnel A 17' Reference, Avg. of 10 Blows
Coherence
Frequency, Hz
Tunnel A 48ft
Tunnel A 95ft
Tunnel B 0ft
Tunnel B 100ft
Tunnel B 300ft

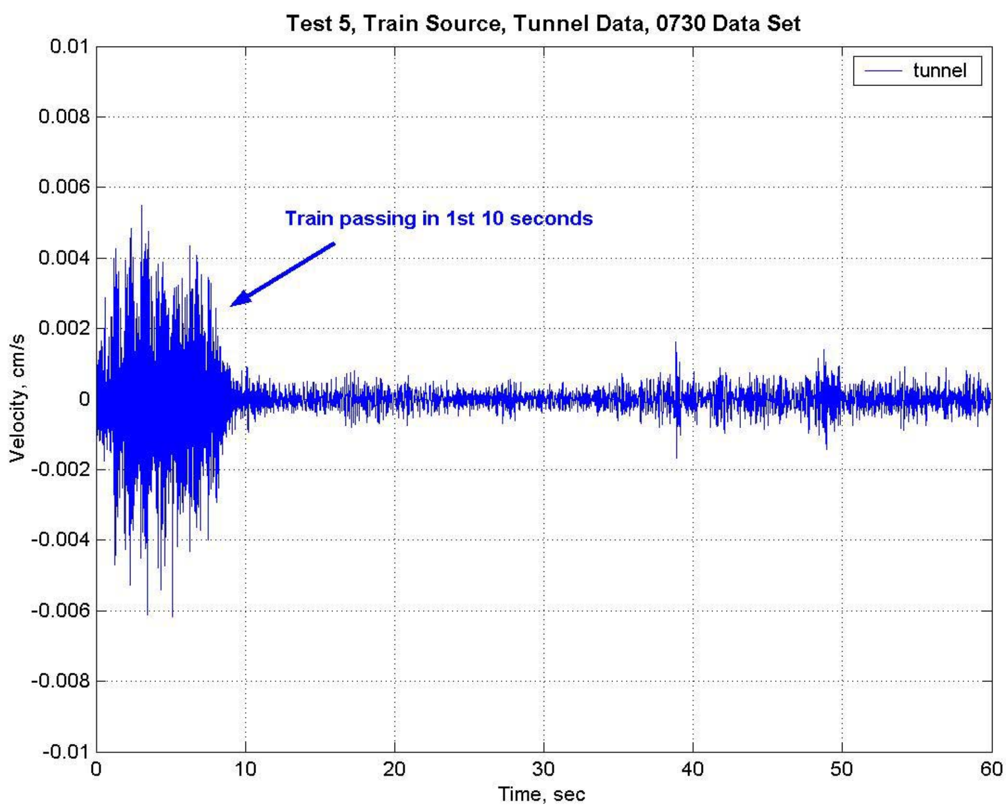

Test 4: Power Spectra, Ground Velocity, Avg. of 10 Blows (revised 4/22/04)
PSD (cm/s)²/Hz
Frequency, Hz
A48
A95
B0
B100
B300
A17

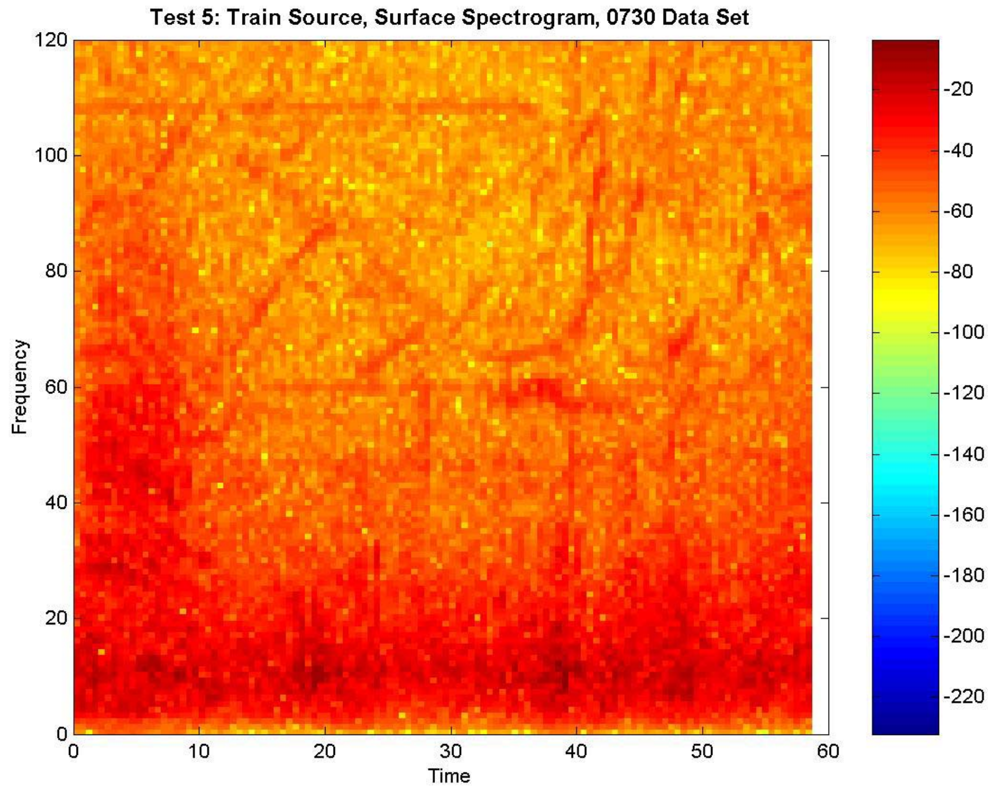


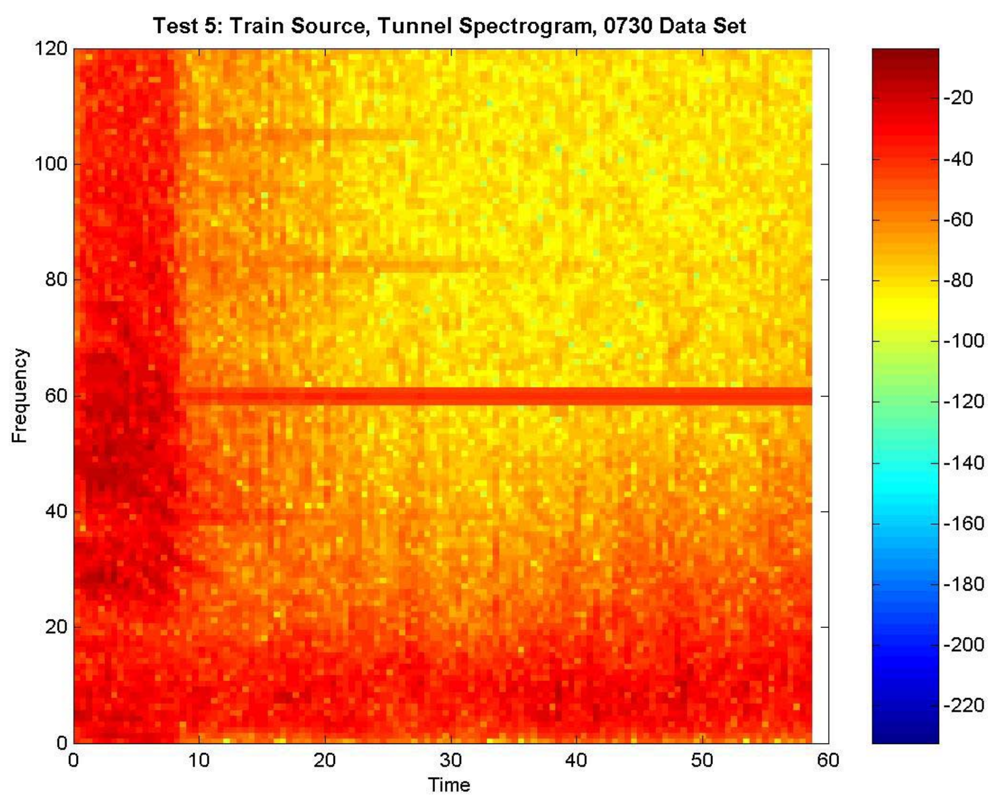
Test 4: Transfer Function, Tunnel A 17' Ref, Avg. of 10 Blows
Tunnel A, 48 ft
Tunnel A, 95ft
Tunnel B, 0ft
Tunnel B, 100ft
Tunnel B, 300ft
Transfer Function Magnitude
Frequency, Hz

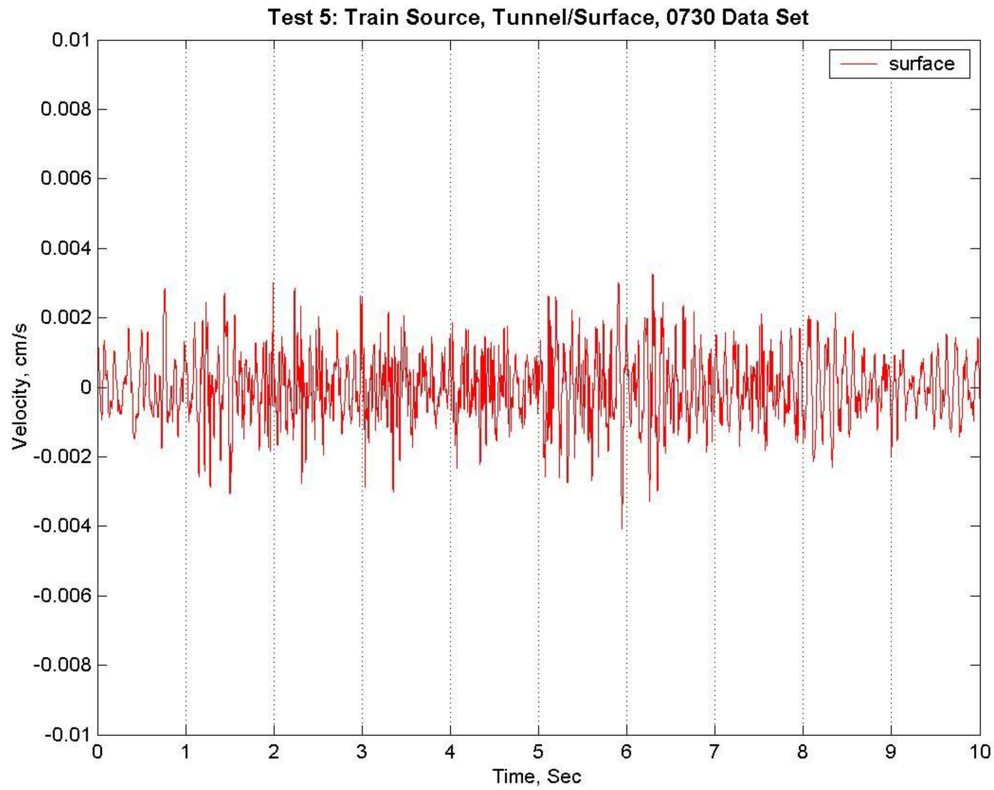
APPENDIX E: TEST 5 DATA PLOTS


Test 5, Train Source, Surface Data, 0730 Data Set
surface
Train passing in 1st 10 seconds
Velocity, cm/s
Time, sec
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
0
10
20
30
40
50
60

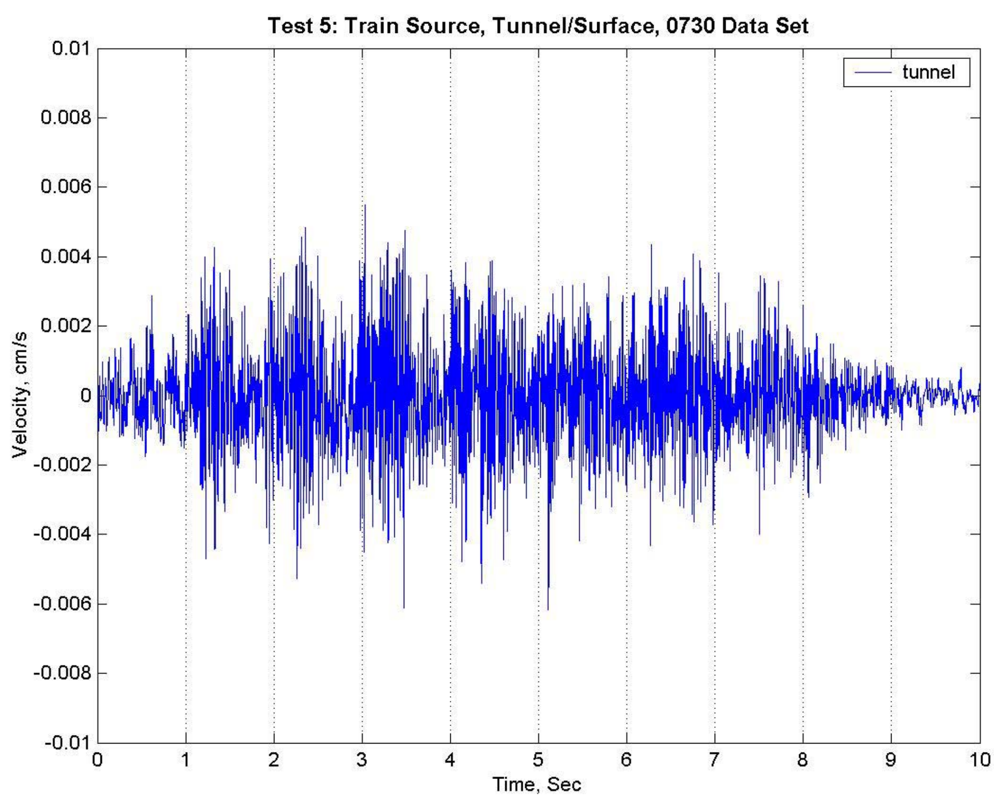

Test 5, Train Source, Tunnel Data, 0730 Data Set
tunnel
Train passing in 1st 10 seconds
Velocity, cm/s
Time, sec
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
0
10
20
30
40
50
60


Test 5: Train Source, Surface Spectrogram, 0730 Data Set
Frequency
Time
0
10
20
30
40
50
60
0
20
40
60
80
100
120
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220

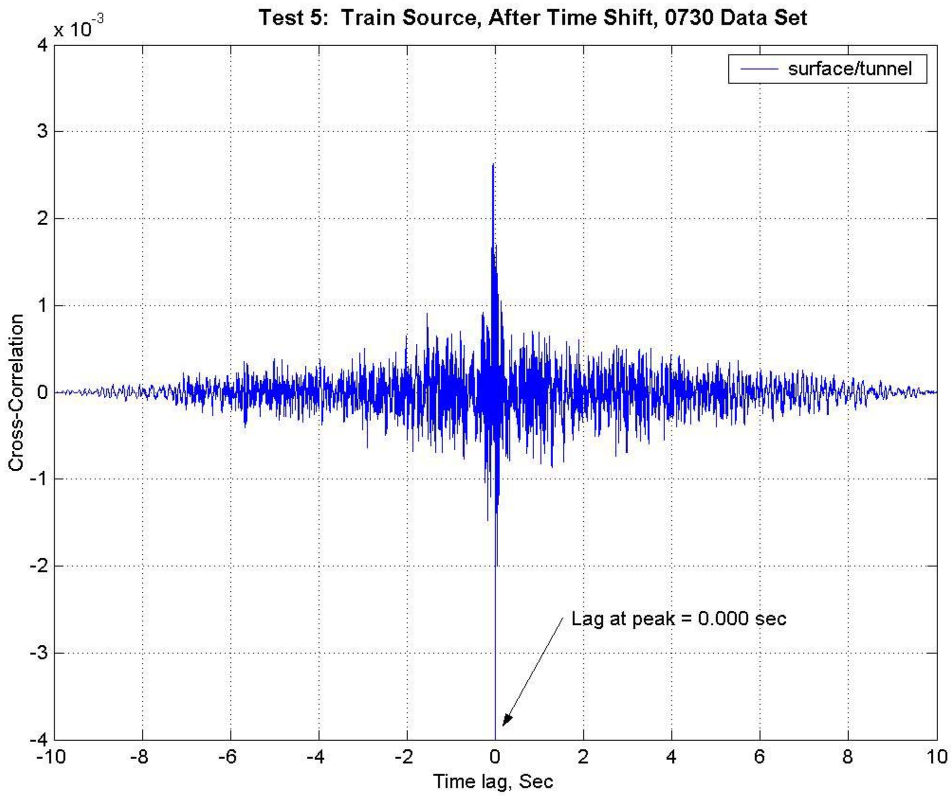

Test 5: Train Source, Tunnel Spectrogram, 0730 Data Set
Frequency
Time
0
10
20
30
40
50
60
0
20
40
60
80
100
120
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220

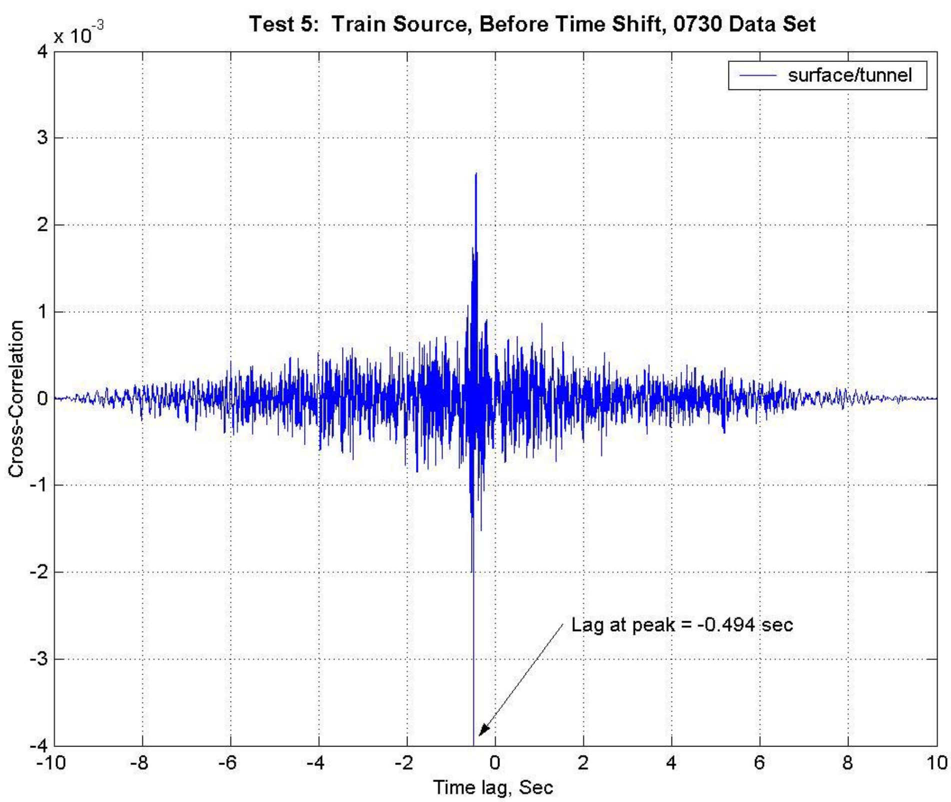


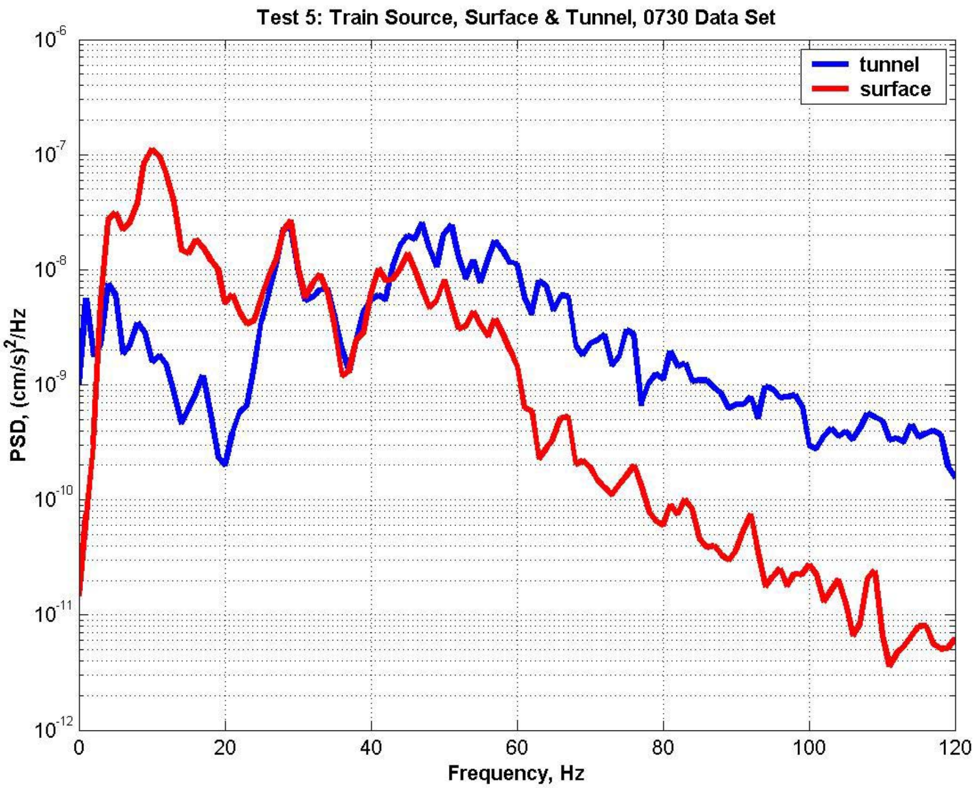
Test 5: Train Source, Tunnel/Surface, 0730 Data Set
surface
Velocity, cm/s
Time, Sec
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
0 1 2 3 4 5 6 7 8 9 10

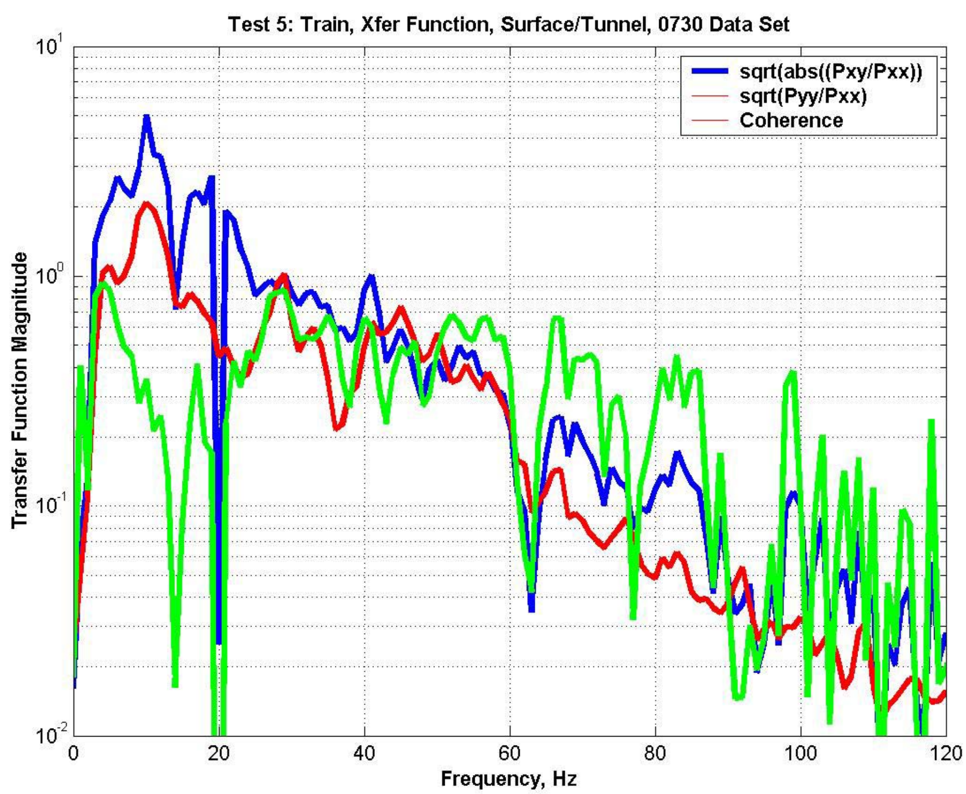


Test 5: Train Source, Tunnel/Surface, 0730 Data Set
tunnel
Velocity, cm/s
Time, Sec
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
0 1 2 3 4 5 6 7 8 9 10


Test 5: Train Source, After Time Shift, 0730 Data Set
x 10-3
4
3
2
1
0
-1
-2
-3
-4
Cross-Correlation
surface/tunnel
Lag at peak = 0.000 sec
-10
-8
-6
-4
-2
0
2
4
6
8
10
Time lag, Sec


Test 5: Train Source, Before Time Shift, 0730 Data Set
x 10-3
4
3
2
1
0
-1
-2
-3
-4
Cross-Correlation
surface/tunnel
Lag at peak = -0.494 sec
-10
-8
-6
-4
-2
0
2
4
6
8
10
Time lag, Sec


Test 5: Train Source, Surface & Tunnel, 0730 Data Set
tunnel
surface
PSD, (cm/s)^2/Hz
Frequency, Hz
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
0
20
40
60
80
100
120


Test 5: Train, Xfer Function, Surface/Tunnel, 0730 Data Set
sqrt(abs((Pxy/Pxx))
sqrt(Pyy/Pxx)
Coherence
Transfer Function Magnitude
Frequency, Hz
10^1
10^0
10^-1
10^-2
0
20
40
60
80
100
120

APPENDIX F: ANALYSIS DETAILS

This appendix includes descriptions of the MATLAB functions PWELCH, COHERE, and TFE. These were used in the analyses described herein for calculation of power spectral densities, coherence, and transfer function, respectively.

PWELCH: PSD calculation

```
PWELCH Power Spectral Density estimate via Welch's method.
Pxx = PWELCH(X) returns the Power Spectral Density (PSD) estimate,
Pxx, of a discrete-time signal vector X using Welch's averaged,
modified periodogram method.  By default, X is divided into eight
sections with 50% overlap, each section is windowed with a Hamming
window and eight modified periodograms are computed and averaged.

If the length of X is such that it cannot be divided exactly into
eight sections with 50% overlap, X will be truncated accordingly.

Pxx is the distribution of power per unit frequency. For real signals,
PWELCH returns the one-sided PSD by default; for complex signals, it
returns the two-sided PSD.  Note that a one-sided PSD contains the
total power of the input signal.

Pxx = PWELCH(X,WINDOW), when WINDOW is a vector, divides X into
overlapping sections of length equal to the length of WINDOW, and then
windows each section with the vector specified in WINDOW.  If WINDOW is
an integer, X is divided into sections of length equal to that integer
value, and a Hamming window of equal length is used.  If the length of
X is such that it cannot be divided exactly into integer number of
sections with 50% overlap, X will be truncated accordingly.  If WINDOW
is omitted or specified as empty, a default window is used to obtain
eight sections of X.

Pxx = PWELCH(X,WINDOW,NOVERLAP) uses NOVERLAP samples of overlap from
section to section.  NOVERLAP must be an integer smaller than the WINDOW
if WINDOW is an integer.  NOVERLAP must be an integer smaller than the
length of WINDOW if WINDOW is a vector.  If NOVERLAP is omitted or
specified as empty, the default value is used to obtain a 50% overlap.

[Pxx,W] = PWELCH(X,WINDOW,NOVERLAP,NFFT) specifies the number of FFT
points used to calculate the PSD estimate.  For real X, Pxx has length
(NFFT/2+1) if NFFT is even, and (NFFT+1)/2 if NFFT is odd.  For complex
X, Pxx always has length NFFT.  If NFFT is specified as empty, the
default NFFT -the maximum of 256 or the next power of two
greater than the length of each section of X- is used.

W is the vector of normalized frequencies at which the PSD is
estimated.  W has units of rad/sample.  For real signals, W spans the
interval [0,Pi] when NFFT is even and [0,Pi) when NFFT is odd.  For
complex signals, W always spans the interval [0,2*Pi).

[Pxx,F] = PWELCH(X,WINDOW,NOVERLAP,NFFT,Fs) returns a PSD computed as
```

```
a function of physical frequency (Hz).  Fs is the sampling frequency
specified in Hz.  If Fs is empty, it defaults to 1 Hz.

F is the vector of frequencies at which the PSD is estimated and has
units of Hz.  For real signals, F spans the interval [0,Fs/2] when NFFT
is even and [0,Fs/2) when NFFT is odd.  For complex signals, F always
spans the interval [0,Fs).

[...] = PWELCH(...,'twosided') returns a two-sided PSD of a real signal
X. In this case, Pxx will have length NFFT and will be computed  over
the interval [0,2*Pi) if Fs is not specified and over the interval
[0,Fs) if Fs is specified.  Alternatively, the string 'twosided' can be
replaced with the string 'onesided' for a real signal X.  This would
result in the default behavior.  The string 'twosided' or 'onesided'
may be placed in any position in the input argument list after NOVERLAP.

PWELCH(...) with no output arguments by default plots the PSD
estimate in dB per unit frequency in the current figure window.

EXAMPLE:
Fs = 1000;   t = 0:1/Fs:.296;
x = cos(2*pi*t*200)+randn(size(t));  % A cosine of 200Hz plus noise
pwelch(x,[],[],[],Fs,'twosided'); % Uses default window, overlap & NFFT.

See also PERIODOGRAM, PCOV, PMCOV, PBURG, PYULEAR, PEIG, PMTM, PMUSIC
and PSDPLOT.
```

COHERE: Coherence calculation

```
COHERE Coherence function estimate.

Cxy = COHERE(X,Y,NFFT,Fs,WINDOW) estimates the coherence of X and Y
using Welch's averaged periodogram method.  Coherence is a function
of frequency with values between 0 and 1 that indicate how well the
input X corresponds to the output Y at each frequency.  X and Y are
divided into overlapping sections, each of which is detrended, then
windowed by the WINDOW parameter, then zero-padded to length NFFT.
The magnitude squared of the length NFFT DFTs of the sections of X and
the sections of Y are averaged to form Pxx and Pyy, the Power Spectral
Densities of X and Y respectively. The products of the length NFFT DFTs
of the sections of X and Y are averaged to form Pxy, the Cross Spectral
Density of X and Y. The coherence Cxy is given by
    Cxy = (abs(Pxy).^2)./(Pxx.*Pyy)
Cxy has length NFFT/2+1 for NFFT even, (NFFT+1)/2 for NFFT odd, or NFFT
if X or Y is complex. If you specify a scalar for WINDOW, a Hanning
window of that length is used.  Fs is the sampling frequency which does
not effect the cross spectrum estimate but is used for scaling of plots.

[Cxy,F] = COHERE(X,Y,NFFT,Fs,WINDOW,NOVERLAP) returns a vector of freq-
uencies the same size as Cxy at which the coherence is computed, and
overlaps the sections of X and Y by NOVERLAP samples.

COHERE(X,Y,...,DFLAG), where DFLAG can be 'linear', 'mean' or 'none',
specifies a detrending mode for the prewindowed sections of X and Y.
DFLAG can take the place of any parameter in the parameter list
```

```
(besides X and Y) as long as it is last, e.g. COHERE(X,Y,'mean');

COHERE with no output arguments plots the coherence in the current
figure window.

The default values for the parameters are NFFT = 256 (or LENGTH(X),
whichever is smaller), NOVERLAP = 0, WINDOW = HANNING(NFFT), Fs = 2,
P = .95, and DFLAG = 'none'.  You can obtain a default parameter by
leaving it off or inserting an empty matrix [], e.g.
COHERE(X,Y,[],10000).

See also PSD, CSD, TFE.
ETFE, SPA, and ARX in the Identification Toolbox.
```

TFE: Transfer function calculation

```
TFE Transfer Function Estimate.
Txy = TFE(X,Y,NFFT,Fs,WINDOW) estimates the transfer function of the
system with input X and output Y using Welch's averaged periodogram
method.  X and Y are divided into overlapping sections, each of which
is detrended, then windowed by the WINDOW parameter, then zero-padded
to length NFFT.  The magnitude squared of the length NFFT DFTs of the
sections of X are averaged to form Pxx, the Power Spectral Density of X.
The products of the length NFFT DFTs of the sections of X and Y are
averaged to form Pxy, the Cross Spectral Density of X and Y.  Txy
is the quotient of Pxy and Pxx; it has length NFFT/2+1 for NFFT even,
(NFFT+1)/2 for NFFT odd, or NFFT if X or Y is complex. If you specify
a scalar for WINDOW, a Hanning window of that length is used.  Fs is
the sampling frequency which does not effect the transfer function
estimate but is used for scaling of plots.

[Txy,F] = TFE(X,Y,NFFT,Fs,WINDOW,NOVERLAP) returns a vector of freq-
uencies the same size as Txy at which the transfer function is
estimated, and overlaps the sections of X and Y by NOVERLAP samples.

TFE(X,Y,...,DFLAG), where DFLAG can be 'linear', 'mean' or 'none',
specifies a detrending mode for the prewindowed sections of X and Y.
DFLAG can take the place of any parameter in the parameter list
(besides X and Y) as long as it is last, e.g. TFE(X,Y,'mean');

TFE with no output arguments plots the transfer function estimate in
the current figure window.

The default values for the parameters are NFFT = 256 (or LENGTH(X),
whichever is smaller), NOVERLAP = 0, WINDOW = HANNING(NFFT), Fs = 2,
P = .95, and DFLAG = 'none'.  You can obtain a default parameter by
leaving it off or inserting an empty matrix [], e.g. TFE(X,Y,[],10000).

See also PSD, CSD, COHERE
ETFE, SPA, and ARX in the Identification Toolbox.
```