Blasting Seismograph Comparison in Side-by-Side Blast Monitoring Tests

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Abstract

The Appalachian Blaster Certification Delegation initiated a study to compare the consistency of measurements from blasting seismographs. Six blasts were monitored at surface coal mines in West Virginia, Maryland, and Ohio. A total of seven different makes were deployed during the tests, with as many as seven models from five different manufacturers compared during any one blast. Great care was taken to bury the geophones in identical fashion. The variations in seismograph readings were compared to the International Society of Explosives Engineers' Performance Specifications for Blasting Seismographs. Between 4 and 125 Hertz, the ground vibration amplitudes should be within ±5% and airblast amplitudes should be ±1 decibel. For each of the three mutually perpendicular ground vibration channels and the acoustic channel, the median value of all the units was used as a baseline for comparison. The six blasts monitored had median peak particle velocities ranging from 0.42 to 3.47 inches per second (in/s) (10.7 – 88.1 mm/s) and median airblasts ranging from 124 to 135 decibels (dB). There were 46 seismograph recordings for the six blasts. Eighteen (39%) of the 46 maximum peak particle velocities varied more than ±5% from the median. A total of 138 (3 × 46) component particle velocities were recorded, with 50 (36%) of the readings varying more than ±5% from the median. For airblast comparison, 43 recordings were obtained, with seven (16%) varying more than ±1 dB of the median. Variances may be attributable to blasting seismograph differences, variations in field deployment, and relative locations of the geophones. Full waveform seismic and acoustic overlays for individual blasts showed encouraging conformity with some slight anomalies.

Introduction

Blasting seismographs are used in the blasting industry as a means of measuring ground vibration and airblast to establish compliance with regulations and to quantify the potential for blasting damage to structures. In the mid 1990s concerns about the accuracy of seismograph recordings were raised and the International Society of Explosive Engineers (ISEE) decided to take the leading role in establishing guidance. In 1995 the ISEE formed a Seismograph Standards Group within the Technical Committee to explore the development of seismograph standards for blasting operations. After drafting of Field Practices/User Responsibility and Seismograph Specifications standards, the ISEE moved the seismograph standards responsibility into the newly formed Blast Vibration and Seismograph Section in 1997. The Seismograph Standards and Practices Working Group was formed to establish uniform and technically appropriate standards for both seismograph performance specifications and how seismographs are used in the field. The intention was to improve the accuracy and consistency of ground vibration and airblast measurements. In 1999 the Field Practice Guidelines for Blasting Seismographs (FPGBS) were ratified by the ISEE as the society's first standard. Subsequently, the Performance Specifications for Blasting Seismographs (PSBS) were ratified in 2000. Together, these two standards promoted considerable improvement in the consistency and accuracy of blast vibration measurements. Standard setting was removed from the Blast Vibration and Seismograph Section when the ISEE Standards Committee was sanctioned in 2005. The most recent versions of the FPGBS and PSBS are 2009 and 2011, respectively.

Despite improvements in seismographs and greater consistency in field deployments, no published, peer-reviewed data are available for side-by-side comparisons of different seismograph makes and models in actual field blasting conditions, and many regulators have expressed concern about the degree of variance when placing their seismographs next to a blaster's seismograph. Those concerns prompted the Appalachian Blaster Certification Delegation (ABCD) in 2012 to initiate side-by-side comparison tests by monitoring surface coal mine blasts with as many as five different makes and seven different models of seismographs during any one blast. The ABCD is comprised of blasting regulators from Appalachian coal mining states that focus on more consistent application of blasting technology and regulations across the region, with special emphasis on comparing and improving blaster certification programs. The ABCD participants collectively deploy a variety of blasting seismograph makes and models in their home states to ensure compliance with ground vibration and airblast limits and investigate blasting complaints, and have no commercial affiliations with seismograph manufacturers or distributors. Therefore, it was logical for this group to initiate this study.

The objective of the testing was to deploy off-the-shelf, commonly available blasting seismographs in the field according to the ISEE FPGBS standards and compare the waveforms and peak amplitudes of the airblasts (air overpressures) and ground vibration particle velocities in the three component directions. Initially, the ABCD had no expectations, or hypothesis, about what the findings might show. But after the first of six field tests, the group decided to compare the results to the ISEE seismograph accuracy specifications, with the expectation that the recorded amplitudes would fall within the range of ±5% of the median value for the particle velocities and ±1 dB of the median for the airblast readings.

Field Test Locations and Blast Designs

The ABCD researchers conducted six side-by-side seismograph comparison tests in 2012 and 2013, at surface coal mines in three different states. Test 1 was near Beckley, WV; Tests 2 and 4 were near St. Clairsville, OH; Test 3 was near Frostburg, MD; Test 5 was near Pax, WV; and Test 6 was near E. Canton, OH. Locations were selected based on coordination with the mining and blasting companies, blast site accessibility, soil conditions favorable to geophone burial, and feasibility of geophone deployment at a distance that was likely to yield particle velocity and airblast amplitudes substantial enough for meaningful comparisons.

One blast was detonated for each of the six field tests. The six blasts can be generally characterized as moderate-scale, multi-row blasts in sedimentary rock above a coal seam. Blasthole diameters ranged from 6 ¾ in (17.1 cm) to 7 $^7/_8$ in. (20.0 cm). The hole depths, which were consistent within each blast, ranged from 30 to 86 feet (9 – 26 m). The holes were loaded with bulk ANFO or emulsion/ANFO blends. The Test 1 and Test 5 blasts were initiated with nonelectric detonators. The other four blasts were initiated electronically. The Test 3 blast utilized three separate explosive charges per hole, while all other blasts had a single column per hole. The Test 1 blast detonated two charges (holes) per delay (in less than 8 milliseconds), while the other blasts detonated one charge per delay. The maximum charge per delay ranged from 115 to 1,656 lbs (52 – 751 kg). All scaled distances to the geophone deployment sites were below 20 ft/lbs$^{1/2}$ (9 m/kg$^{1/2}$). Note that the ABCD researchers had no role in designing the blasts, but the specific blast parameters were not critical to the study. Further details about the six test site locations and blast design parameters may be found in the six individual summary reports that are available upon request.

Blasting Seismographs and Deployment

To each of the six test blast sites, the ABCD researchers brought one or more of the blasting seismographs routinely used by their agencies and available "off-the-shelf," along with a few seismographs that were borrowed from blasting industry users and consultants. Up to nine seismographs were deployed for the same blast. A total of seven different makes were represented during the tests, with as many as seven models from five different manufacturers compared during any one test. All units had external geophones and were shake-table and acoustic-chamber calibrated within the previous 12 months. Note that the researchers did not attempt to repeat identical makes/models and serial numbers throughout all six tests. This was simply impractical due to the many months between most tests and the unavailability of certain units that an agency might have installed at new complaint locations before the next test date. However, this was not considered to be critical to the objective of the study. Throughout this paper, references to seismographs have been coded as follows: the make (manufacturer) is represented by an upper-case letter, which is followed by a single number designating the model, and a lower-case letter designating the serial number (for example: C2a).

For Tests 1 through 4 the geophones were buried approximately 6 in (15 cm) in cylindrical holes, in a linear array equidistant from the blast. The holes were spaced about 18 – 24 in (46 – 61 cm) apart (Figure 1; left photo). For Tests 5 and 6 the geophones were buried in a cluster about six inches apart in the same hole (Figure 1; right photo). Prodigious efforts were made to achieve firm and uniform compaction of the backfill soil around and above the geophones. For Tests 2 and 4 the spikes were removed from the geophones before burial due to hard soil conditions; for the other tests the geophones were first spiked to the bottom of the hole. Before burial, all geophone radial (longitudinal) channels were pointed in the same direction toward the blast by aligning them with a sighting pole near the blast site, and a leveling tool was used to level each unit. For the six test blasts, the distances from the linear array or cluster of geophones to the closest blasthole varied from 206 to 450 ft (63 – 137 m). For all tests, the seismographs were not interconnected in any manner, and each geophone independently measured the ground motion at the point where it was coupled to the ground.

For all tests, the microphones were covered with the foam windscreen provided by the manufacturer. For Test 5, all microphones were also loosely covered by a thin plastic bag to shield them from the rain that was expected that day.

Prior to each blast and subject to the limitations of the various models, the seismographs were programmed as follows:

- Seismic trigger levels were generally set at 0.05 in/s (1.3 mm/s).
- Acoustic trigger levels were generally set at 130 dB.
- Recording durations were generally set for 4 – 6 seconds.
- Sampling rates were either 1,000 or 1,024 samples per second.

For each test, an Ohio representative buried a geophone aligned at a 45° angle from the blast to gather information for a separate study. That geophone, from Test 6, can be seen in the photo on the right in Figure 1. For Tests 5 and 6 (the two cluster tests), a West Virginia representative included two geophones—from two identical seismograph models—that had been tightly strapped together, one on top of the other, before burial. These “stacked” geophones also can be seen in the photo on the right in Figure 1. While the stacked geophones were not officially part of this study, their readings merit some discussion that will appear in the last section of this paper.

Figure 1. Linear geophone deployment (left); Cluster geophone deployment (right).

Data Analysis Overview

Following each of the six test blasts, the ABCD analysts generated a data summary table, printed the full waveform records, transferred the digital data into Microsoft Excel, from which waveform overlays and bar charts were created, and generated a field test report. The data summary table for each field test is included in the Appendix. All six individual field test reports are available upon request.

To illustrate the analysis methods in detail, the results from Test 2 will be presented and discussed in the next sections: Test 2 Waveform Comparisons; Test 2 Ground Vibration Amplitudes; Test 2 Airblast Amplitudes; and Test 2 Summary Observations.

Test 2 Waveform Comparisons

Test 2 produced particle velocity and airblast data from nine different seismographs, including five different makes and seven different models. Digital data from each seismograph were downloaded and transferred to an Excel spreadsheet. Time histories (waveforms) for the airblast channel and each of the three ground motion channels were then plotted in graphical form. For comparison purposes the radial waveforms from all nine seismographs were overlaid on a single graph (Figure 2). The vertical, transverse and acoustic waveforms were plotted in the same fashion (Figures 3, 4 and 5). Because of different triggering points, the start times for the waveforms were adjusted to allow visual matching while overlaying the time histories. In some cases the polarity of a particular geophone channel was opposite from the rest. This was corrected in Excel by reversing that channel’s data from positive to negative.

On the radial channel (Figure 2), most of the waveforms compared favorably. The B1a, B1d, B1e, C1a, C2a, and E1a units recorded nearly identical waveforms. The A2a waveform strayed the most from the group, primarily in amplitude. The A1a and D1a waveforms exhibited a slight amplitude shift but tracked closely with each other throughout the event. Note that for all nine seismographs, the maximum peak particle velocity (PPV) occurred on the radial channel.

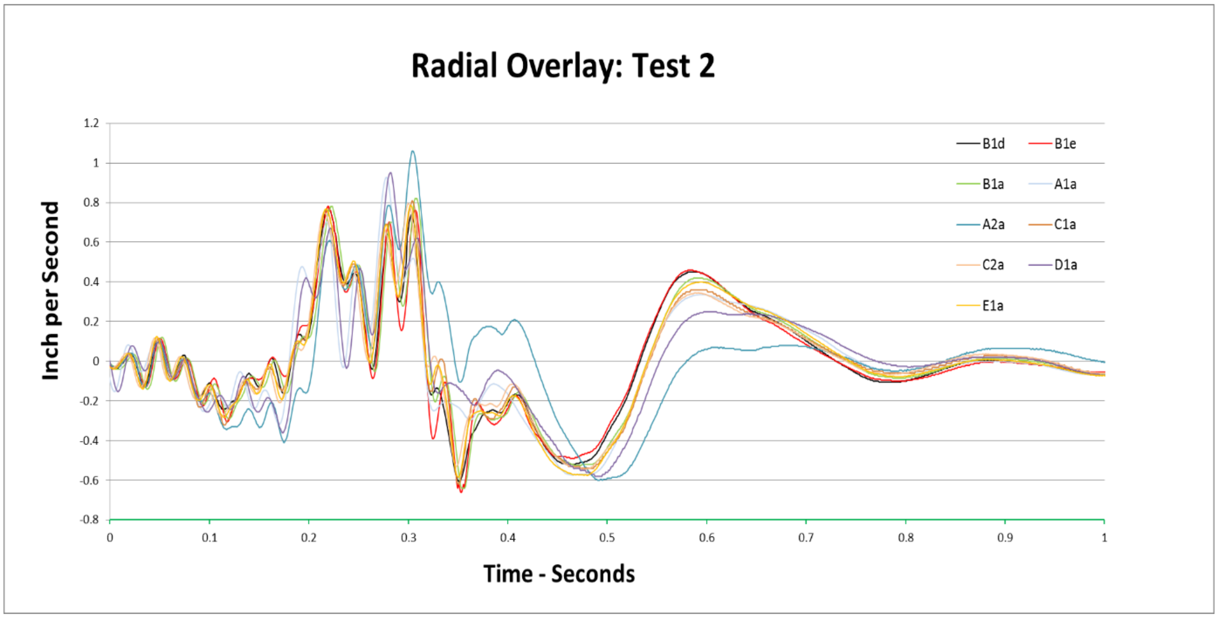


Figure 2. Radial waveforms from Test 2.

On the vertical channel (Figure 3), waveforms from the B1a, B1d, B1e, C1a, C2a, A2a, and E1a units were nearly identical. The A1a and D1a waveforms closely tracked each other but exhibited a phase shift away from the other seven waveforms beginning around 0.4 seconds.

On the transverse channel (Figure 4), most of the waveforms compared favorably. The B1a, B1d, B1e, C1a, C2a, and E1a units had nearly identical waveforms. The A2a waveform strayed the most from the group, with a slight amplitude shift after 0.4 seconds. The A1a and D1a waveforms exhibited a slight amplitude and phase shift around 0.25 seconds, but tracked closely with each other throughout most of the event.

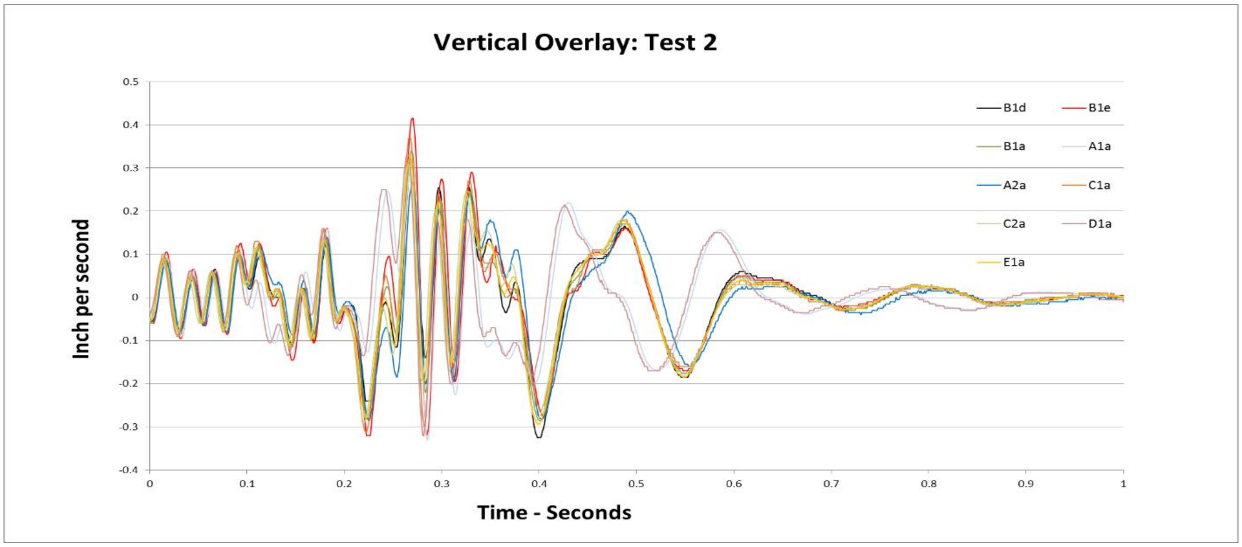


Figure 3. Vertical waveforms from Test 2.

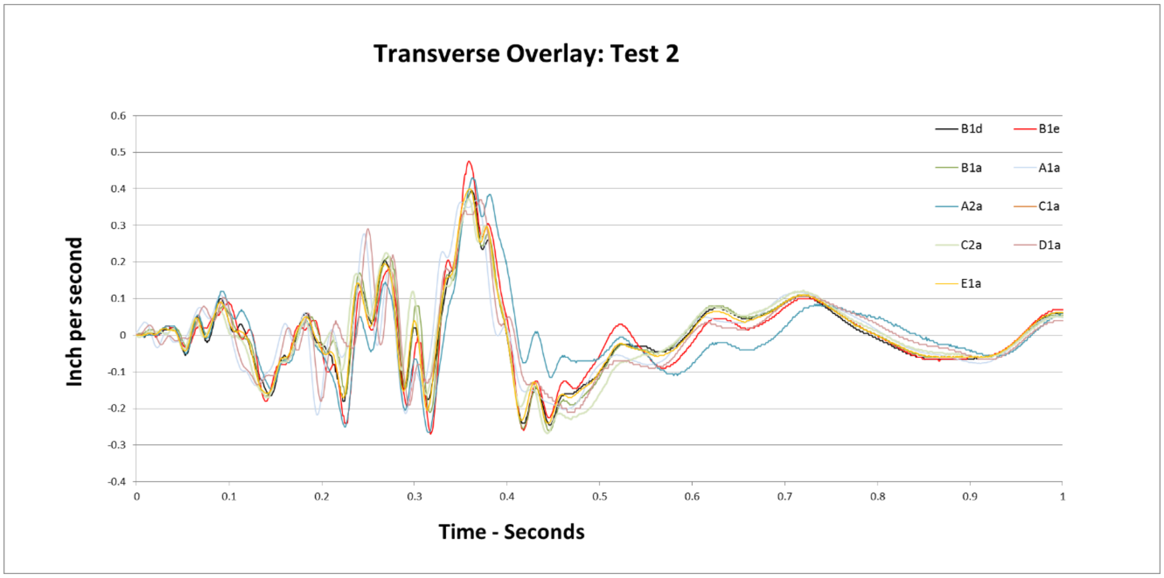


Figure 4. Transverse waveforms from Test 2.

The acoustic waveforms (Figure 5) compared favorably for all the units on the front end of the waveforms where the frequencies were higher. At around 0.65 seconds, the frequency of the event became low and the C1a and C2a waveforms began to stray from the group.

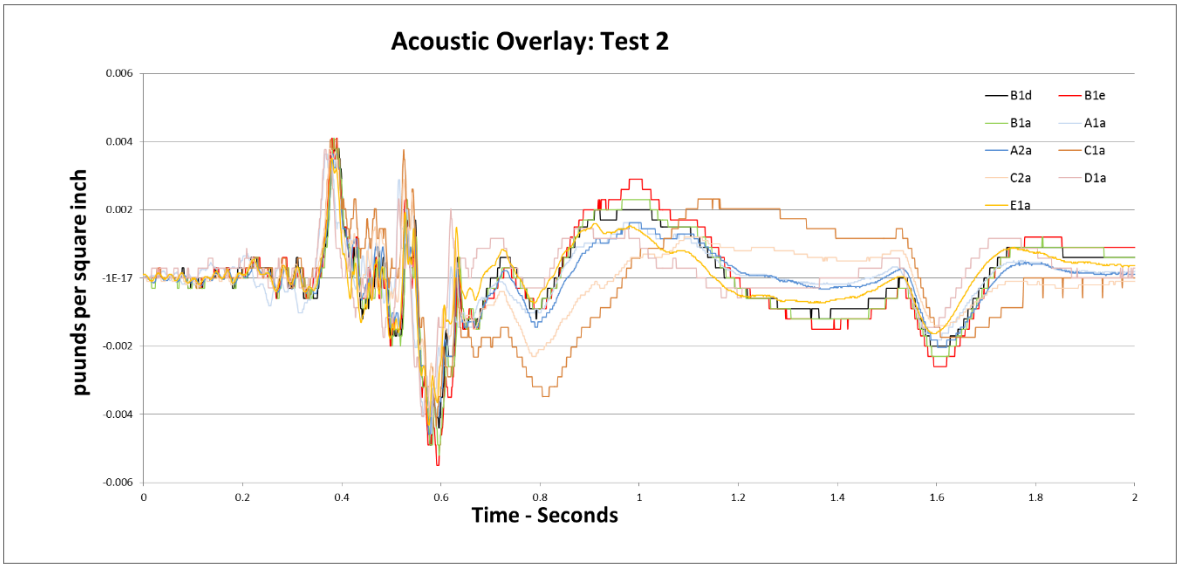
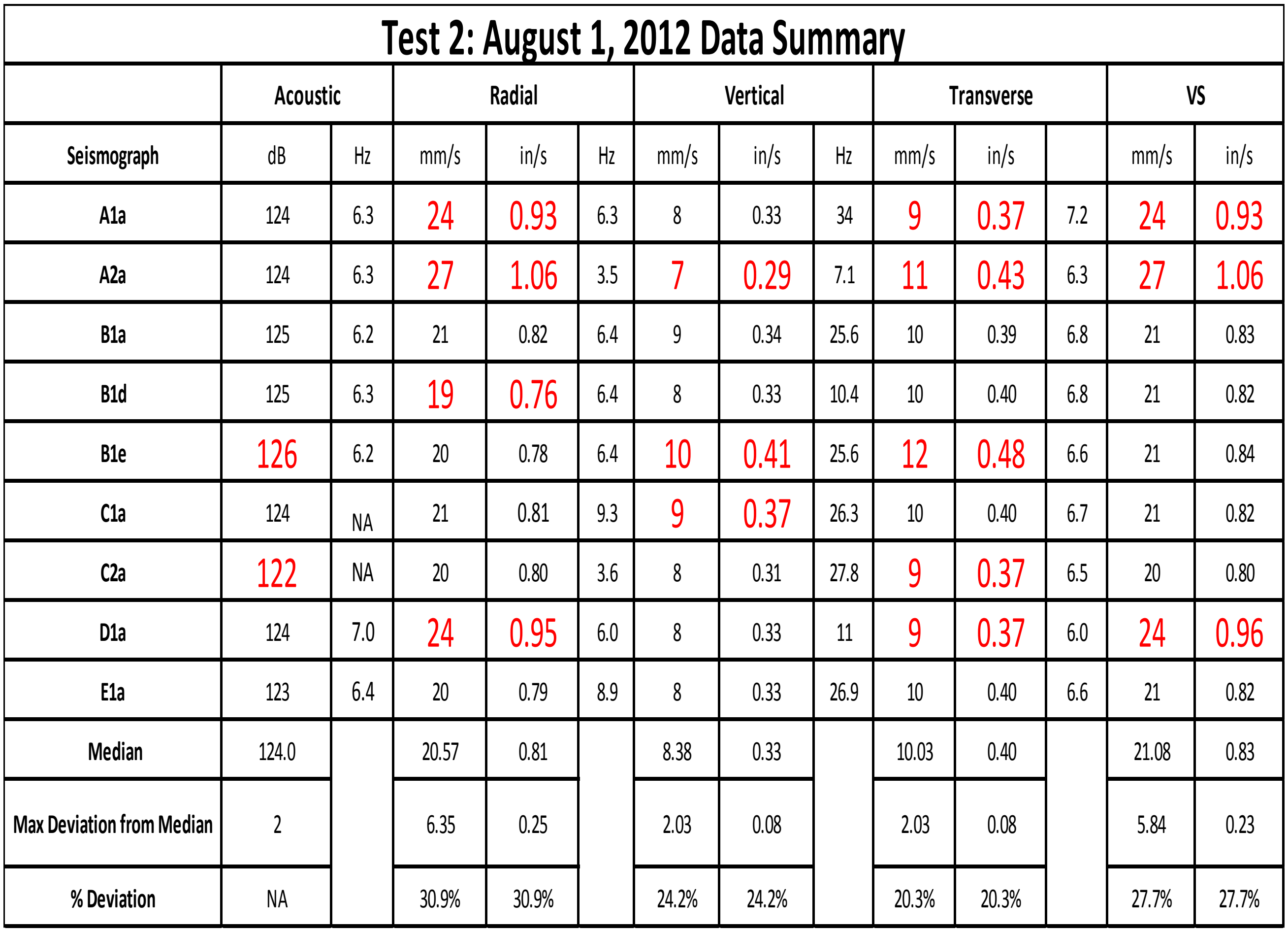


Figure 5. Acoustic waveforms from Test 2.

Test 2 Ground Vibration Amplitudes

For the second form of data evaluation, ABCD analysts compared the peak amplitudes on each channel of ground motion for all nine seismographs. Table 1 presents the PPV and associated zero-crossing frequencies for all units in Test 2. At the bottom of the table are the median, maximum deviation from the median (±), and maximum *percent* deviation from the median (±) for each channel. The ABCD analysts chose to use the median amplitude of each channel instead of the average to prevent skewing of data by a distant outlier, along with the assumption that an observed cluster of readings at or close to the median likely represents a truer model of the ground vibration amplitude in the vicinity of the geophones. The last column in Table 1 shows the peak vector sum (VS) particle velocity that was calculated from the set of component time histories for each seismograph. (Note that the peak vector sum is not the sum of the three component *peaks*, but is the highest vector sum calculated at any moment across the entire time history.)

Table 1. Test 2 data summary.



Test 2: August 1, 2012 Data Summary

	Acoustic		Radial			Vertical			Transverse			VS	
Seismograph	dB	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s		mm/s	in/s
A1a	124	6.3	24	0.93	6.3	8	0.33	34	9	0.37	7.2	24	0.93
A2a	124	6.3	27	1.06	3.5	7	0.29	7.1	11	0.43	6.3	27	1.06
B1a	125	6.2	21	0.82	6.4	9	0.34	25.6	10	0.39	6.8	21	0.83
B1d	125	6.3	19	0.76	6.4	8	0.33	10.4	10	0.40	6.8	21	0.82
B1e	126	6.2	20	0.78	6.4	10	0.41	25.6	12	0.48	6.6	21	0.84
C1a	124	NA	21	0.81	9.3	9	0.37	26.3	10	0.40	6.7	21	0.82
C2a	122	NA	20	0.80	3.6	8	0.31	27.8	9	0.37	6.5	20	0.80
D1a	124	7.0	24	0.95	6.0	8	0.33	11	9	0.37	6.0	24	0.96
E1a	123	6.4	20	0.79	8.9	8	0.33	26.9	10	0.40	6.6	21	0.82
Median	124.0		20.57	0.81		8.38	0.33		10.03	0.40		21.08	0.83
Max Deviation from Median	2		6.35	0.25		2.03	0.08		2.03	0.08		5.84	0.23
% Deviation	NA		30.9%	30.9%		24.2%	24.2%		20.3%	20.3%		27.7%	27.7%

The ISEE's PSBS recommends a ground vibration sensor response accuracy of ±5%, or ±0.02 in/s, whichever is larger, between 4 and 125 Hz. Therefore, in comparing the responses of multiple geophones of different seismographs to the same blast, the ABCD analysts decided it would be reasonable to expect the peak readings to vary by no more than ±5% of the median value, assuming that all geophones were coupled to the ground in an identical manner and in close proximity. The large red fonts in Table1 highlight the recordings that fell outside the ±5% expectation. As can be seen in all the frequency columns, zero-crossing frequencies were within the operating range specified by the ISEE standard.

The radial channel PPVs varied from 0.76 in/s (19 mm/s) to 1.06 in/s (27 mm/s), for a range of 0.30 in/s (8 mm/s). The median was 0.81 in/s (20.6 mm/s) and the maximum deviation was 0.25 in/s (6.4 mm/s), or 31% above the median (1.06 minus 0.81, divided by 0.81). Four of the nine PPVs fell outside ±5 % of the median. Figure 6 represents the data graphically in a bar chart. For the radial component, the median value is represented by a horizontal line at 0.81 in/s (20.6 mm/s), and the horizontal green-shaded zone shows the expected sensor range of 5% above and 5% below the median. In this case, that range is ±0.04 in/s (1.0 mm/s), derived by taking 5% of the median value of 0.81 in/s (20.6 mm/s).

The vertical channel PPVs varied from 0.29 in/s (7 mm/s) to 0.41 in/s (10 mm/s), for a range of 0.12 in/s (3 mm/s). The median was 0.33 in/s (8.4 mm/s) and the maximum deviation was 0.08 in/s (2.0 mm/s), or 24% above the median. Three of the nine PPVs fell outside ±5 % of the median (Figure 6).

The transverse channel PPVs varied from 0.37 in/s (9 mm/s) to 0.48 in/s (12 mm/s), for a range of 0.11 in/s (3 mm/s). The median was 0.40 in/s (10.0 mm/s) and the maximum deviation was 0.08 in/s (2.0 mm/s), or 20% above the median. Five of the nine PPVs fell outside ±5% of the median (Figure 6).

The ABCD analysts also compared the peak vector sums from the nine seismographs. The VS values varied from 0.80 in/s (20 mm/s) to 1.06 in/s (27 mm/s), for a range of 0.26 in/s (7 mm/s). The median was 0.83 in/s (21.1 mm/s) and the maximum deviation was 0.23 in/s (5.8 mm/s), or 28% above the median. Three of the nine VS values fell outside ±5% of the median. There was no significant difference in the median and maximum deviation from the median when comparing the VS data to the radial channel (where the maximum PPVs occurred).

In total, out of 27 component motions from the nine seismographs in Test 2, 12 PPVs fell outside ±5% of the median. The largest deviation from the median was 0.25 in/s (6.4 mm/s), or 31% above the median, on the radial channel where the maximum PPVs occurred.

Test 2 Airblast Amplitudes

Table 1 also presents the airblast amplitudes, in decibels (dB), and associated zero-crossing frequencies for all units in Test 2. The ABCD analysts chose to use the median amplitude of the acoustic channel instead of the average to prevent skewing of data by a distant outlier, along with the assumption that an observed cluster of readings at or close to the median likely represents a truer model of the air overpressure changes at the recording site. The ISEE's PSBS recommends an air overpressure microphone response accuracy of ±1 dB between 4 and 125 Hz. Therefore, in comparing the responses of multiple microphones of different seismographs to the same blast, the ABCD analysts decided it would be reasonable to expect the peak airblast readings to vary by no more than ±1 dB of the median value, assuming that all microphones were in close proximity and exhibited the same roll-off characteristics below 4 Hz (-3 dB at 2 Hz, per the ISEE PSBS). As can be seen in the airblast frequency column, the zero-crossing frequencies are within the operating range specified by the ISEE standard.

The airblast amplitudes varied from 122 dB to 126 dB, for a range of 4 dB. The median was 124 dB and two of the nine amplitudes fell outside ±1 dB of the median. In Figure 6, the horizontal green-shaded zone represents the expected microphone range of 1 dB above and 1 dB below the median value of 124 dB.

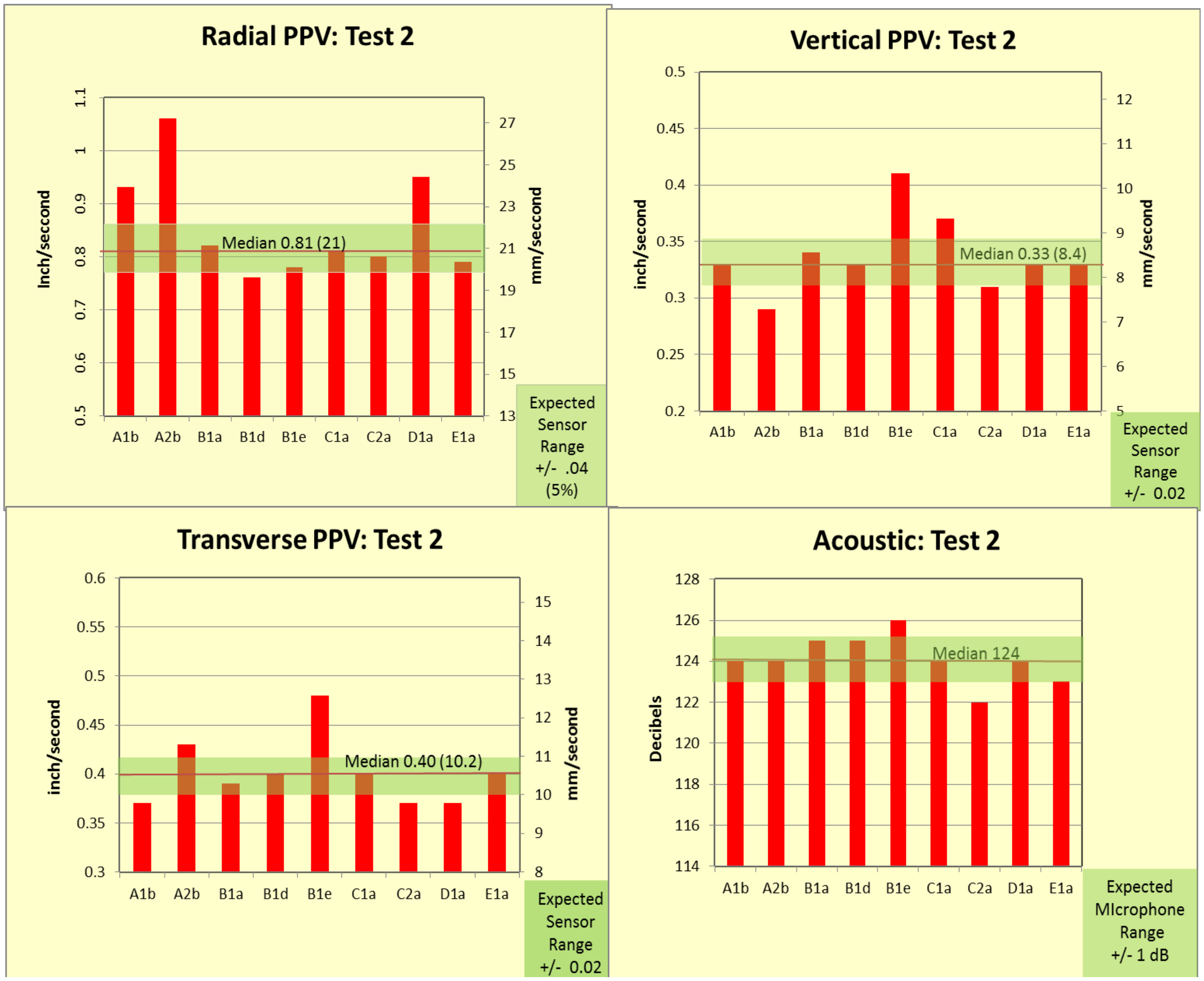


Figure 6. Expected sensor range charts for Test 2 data.

Test 2 Summary Observations

Test 2 was chosen to illustrate the analysis methods used to evaluate all six field tests because:

- it utilized as many or more seismographs (9), makes (5) and models (7) as any other test;
- the waveforms exhibited characteristics similar to those from the other tests;
- the percent variability in peak particle velocity amplitudes was higher than observed in the other tests; and
- the maximum PPVs ranged *above and below* a common regulatory vibration limit.

Below are summary observations for Test 2:

- The time- and polarity-adjusted waveform overlays for the three ground motion components showed good conformity among most seismographs; however, waveforms from a few units showed some anomalous phase and amplitude shifts. Note that other field tests yielded similar waveform conformity, as well as similar but random anomalies.

- The time- and polarity-adjusted waveform overlays for the acoustic channel showed good conformity among most seismographs, especially at higher frequencies. At lower frequencies, waveforms from a few units showed slight phase and amplitude shifts. Note that other field tests yielded similar acoustic waveform conformity for most units.
- The maximum PPVs occurred on the radial channel for all nine seismographs.
- The radial channel PPVs varied from 0.76 in/s (19 mm/s) to 1.06 in/s (27 mm/s), with a median of 0.81 in/s (20.6 mm/s). The maximum deviation was 0.25 in/s (6.4 mm/s), or 31% above the median.
- If a compliance structure with a commonly used regulatory limit of 1.0 in/s (25.4 mm/s) had been at the Test 2 recording site, one unit's reading (1.06 in/s, or 27 mm/s) would have exceeded the limit, while the other eight units would have recorded compliant readings.
- Four of the nine maximum PPVs fell outside ±5% of the median.
- Of the 27 component motions from the nine seismographs in Test 2, 12 PPVs fell outside ±5% of the median.
- A peak vector sum analysis showed variability that was highly similar to the maximum PPVs on the radial channel.
- The airblast amplitudes varied from 122 dB to 126 dB, with a median of 124 dB. Two of the nine airblast amplitudes fell outside ±1 dB of the median.

Summary of Results from All Six Field Tests

Table 2 presents the key parameters and significant data for the maximum PPV and airblast channels for all six field tests. Observations from the data in Table 2 can be summarized as follows:

- The maximum PPVs occurred on the radial channel for Tests 1 through 5, and on the transverse channel for Test 6.
- The recording sites for Tests 1, 3 and 6 produced moderately high ground vibration frequencies, while Tests 2, 4 and 5 produced moderately low frequencies.
- Of the 46 maximum PPV readings recorded during all six tests, 18, or 39%, fell outside the expected range of ±5% of the median PPV; 11 were above the range and seven were below
- The greatest deviation *above* the median PPV was 31%, in Test 2; the greatest deviation *below* the median PPV was 20%, in Test 5.
- In Tests 1, 2 and 4, the larger percent deviation was *above* the median PPV; in Tests 3, 5 and 6, the larger percent deviation was *below* the median PPV.
- No distinct PPV deviation patterns emerged in relation to ground frequencies, PPV amplitudes, or geophone arrangement (linear vs. cluster).
- For airblast, the peak frequencies were mostly under 10 Hz, the notable exception being Test 5 where all peaks occurred at 47 Hz.
- Of the 43 airblast readings from all six tests, seven, or 16%, fell outside the expected range of ±1 dB; two were above the range and five were below. (Note that for three of the 46 seismographs deployed, the airblast data were excluded per the footnotes under the summary tables in the Appendix for Tests 1, 3 and 5.)
- For airblast, the greatest deviation *above* the median was 2 dB, in Tests 2 and 6; the greatest deviation *below* the median was 10 dB, in Test 6. Excluding the single airblast reading in Test 6 that was 10 dB down, the greatest deviation below the median would then be 3 dB, in Tests 5 and 6.

Table 2. Summary of data from all six field tests.

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Date	5-30-12	8-1-12	10-4-12	11-8-12	5-30-13	10-31-13
Location	Beckley, WV	St. Clairsville, OH	Frostburg, MD	St. Clairsville, OH	Pax, WV	E. Canton, OH
Distance from Blast ft. (m.)	450 (137)	420 (128)	206 (63)	407 (124)	200 (61)	232 (71)
Max. Charge weight per Delay lbs. (kg.)	722 (328)	1064 (484)	115 (52)	1656 (753)	181 (82)	213 (97)
Geophone Arrangement	Linear in separate holes	Linear in separate holes	Linear in separate holes	Linear in separate holes	Cluster in single hole	Cluster in single hole
No. of Units	7	9	9	5	8	8
Maximum PPV Channel	Radial	Radial	Radial	Radial	Radial	Transverse
PPV Frequency Range (Hz)	16 – 20	4 – 9	23 – 27	5 – 6	7 – 9	21 – 23
Maximum PPV in/s (mm/s)	0.45 (11.4)	1.06 (27)	0.73 (19)	1.88 (48)	3.88 (99)	0.81 (21)
Lowest PPV in/s (mm/s)	0.40 (10.2)	0.76 (19)	0.62 (16)	1.64 (42)	2.78 (71)	0.67 (17)
Median PPV in/s (mm/s)	0.42 (10.7)	0.81 (21)	0.68 (17)	1.67 (43)	3.47 (88)	0.78 (20)
Maximum % Deviation Above Median	7	31	7	13	12	4
Maximum % Deviation Below Median	5	6	9	2	20	14
No. of Units Outside +/- 5% of Median	1 (above)	4 (3 above; 1 below)	4 (2 above; 2 below)	2 (both above)	6 (3 above; 3 below)	1 (below)
No. of Viable Microphones	6	9	8	5	7	8
Frequency Range (Hz)	2 – 3	6 – 7	6 – 9	2 – 27	47	2 – 6
Highest Airblast (dB)	132	126	125	128	136	135
Lowest Airblast (dB)	129	122	123	126	132	123
Median Airblast (dB)	131	124	124	127	135	133
Max. Decibels Above Median	1	2	1	1	1	2
Max. Decibels Below Median	2	2	1	1	3	10
No. of Units Outside +/- 1 dB of Median	1 (below)	2 (one above; one below)	0	0	1 (below)	3 (one above; two below)

The data summary tables that appear in the Appendix—one table for each of the six field tests—provide additional observations, including the following:

- For every field test, the maximum PPV occurred on the same channel for every seismograph in that test.
- Of the 138 component (radial, vertical and transverse) PPVs recorded during the six field tests, 50, or 36%, fell outside the expected range of ±5% of the median values; 29 were above the range and 21 were below.
- Of the 46 peak vector sums calculated for all six field tests, 12, or 26%, fell outside of ±5% of the median VS.
- The greatest variability in PPV readings, in terms of the spread of the readings and the number of PPVs out of the expected range, occurred during the first cluster test (Test 5). Contributing factors might have included the spongy forest soil conditions and the median PPV of 3.47 in/s (88.5 mm/s), which was significantly higher than the medians for the other five tests.

Conclusions/Discussion/Future Research

When blasting regulators compared different blasting seismographs in six side-by-side blast monitoring tests, using makes and models that were routinely deployed by their agencies or borrowed from industry users and consultants, they expected the PPVs to vary by no more than ±5% of the median, and the airblast amplitudes to vary by no more than ±1 dB of the median. Those expectations were based on seismograph performance specifications published by the ISEE. But despite meticulous seismograph deployment procedures, a significant number of PPV and airblast readings fell outside the expected range. Of the 46 maximum PPVs recorded during the six tests, 18, or 39%, fell outside the expected range; 11 were above the range and seven were below. The maximum deviation above the median was 31%; the maximum deviation below the median was 20%. Of the 43 airblast readings from the six tests, seven, or 16%, fell outside the expected range of ±1 dB; two were above the range and five were below. The greatest airblast deviation *above* the median was 2 dB; the greatest deviation *below* the median was a single reading of 10 dB down, with all other readings no more than 3 dB down.

The variability in readings can be significant from a compliance standpoint, as observed in one test where the median PPV for nine seismographs was 0.81 in/s (20.6 mm/s), the highest PPV of 1.06 in/s (27.0 mm/s) was 31% above the median and exceeded a common regulatory limit of 1.0 in/s (25.5 mm/s), and the other eight readings were all below that limit. In another test, the median airblast amplitude for eight seismographs was 133 dB, the highest airblast reading was 135 dB and exceeded a common regulatory limit of 133 dB, and two other readings of 134 dB also exceeded that limit. The above examples suggest that blasters should be aware of the potential variability in seismograph readings and design their blasts in a conservative fashion. This also reinforces the need to practice good field installation and geophone coupling procedures to minimize variability that might be introduced by the seismograph operator.

No distinct PPV deviation patterns emerged in relation to ground frequencies, PPV amplitudes, or geophone arrangement (linear in separate holes vs. clustered in a single hole). However, this could be due to the small sample size (six test blasts, four with linear arrays and two with clusters).

This study did not identify the source of the variability observed in the PPV and airblast amplitudes. On the manufacturing side, contributing factors might include the seismograph's hardware and embedded software, shake-table and acoustic-chamber calibration methods, and differences in geophone shape, size, density and frequency response. On the field deployment side, contributing factors might include soil variations across the linear arrays (in four tests), variability of wavefronts across the linear arrays at relatively small distances from the blast sites, and relative locations of the geophones in the two single-hole cluster tests. It is noteworthy that for the two cluster tests, a West Virginia representative included two extra geophones—from two identical seismograph models—that had been tightly strapped together, one on top of the other, before burial. In the first cluster test, the stacked geophones produced *identical* PPVs of 3.76 in/s (95 mm/s), which were about 8% above the median. In the second cluster test, the stacked geophones produced nearly identical PPVs of 0.76 in/s (19 mm/s) and 0.78 in/s (20 mm/s), both of which were clustered at the median value of 0.78 in/s (20 mm/s). Those results, while limited by the small sample size, suggest that the relative locations of individual geophones within the same hole might have been a significant factor for the variability observed in the two cluster tests. But it could also mean there were significant factors on the manufacturing side between different makes and models.

Future laboratory and field research should be designed to identify and quantify the factors contributing to the variability of the PPV and airblast amplitudes observed in this study. If significant factors are found to be related to seismograph design and calibration methods, the manufacturers and service providers can make improvements. If significant factors are related to field deployments, new field practice guidelines and better training for seismograph operators would be indicated. In both circumstances, the ISEE standards could be updated accordingly.

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Appendix – Summary tables for each field test (six).

In the seismograph column, the make (manufacturer) is represented by an upper-case letter, which is followed by a single number designating the model, and a lower-case letter for the serial number.

Test 1: May 30, 2012 Summary table

	Acoustic		Radial			Vertical			Transverse			VS	
Seismograph	dB	Hz	mm/s	ips	Hz	mm/s	ips	Hz	mm/s	ips	Hz	mm/s	ips
A1a	*129	2	11	0.45	18	8	0.30	22	5	0.21	13	12	0.48
A2a	130	3	11	0.43	16	8	0.30	26	8	0.31	16	12	0.48
B1a	132	2	10	0.40	19	8	0.31	26	6	0.24	12	12	0.47
B1b	132	3	11	0.43	18	8	0.30	26	6	0.24	11	11	0.45
B1c	131	3	11	0.42	20	7	0.28	27	6	0.25	12	12	0.46
C1a	131	NA	10	0.40	19	8	0.30	25	7	0.27	11	11	0.45
C2a	129	NA	10	0.41	18	7	0.29	25	7	0.26	11	11	0.42
Median	131.0		10.67	0.42		7.62	0.30		6.22	0.25		11.68	0.46
Max Deviation from Median	-2		0.76	0.03		-0.51	-0.02		1.52	0.06		-1.02	-0.04
% Deviation	NA		7.1%	7.1%		-6.7%	-6.7%		24.5%	24.5%		-8.7%	-8.7%

* Timed out just before peak airblast arrived

Test 2: August 1, 2012 Data Summary

	Acoustic		Radial			Vertical			Transverse			VS	
Seismograph	dB	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s		mm/s	in/s
A1a	124	6.3	24	0.93	6.3	8	0.33	34	9	0.37	7.2	24	0.93
A2a	124	6.3	27	1.06	3.5	7	0.29	7.1	11	0.43	6.3	27	1.06
B1a	125	6.2	21	0.82	6.4	9	0.34	25.6	10	0.39	6.8	21	0.83
B1d	125	6.3	19	0.76	6.4	8	0.33	10.4	10	0.40	6.8	21	0.82
B1e	126	6.2	20	0.78	6.4	10	0.41	25.6	12	0.48	6.6	21	0.84
C1a	124	NA	21	0.81	9.3	9	0.37	26.3	10	0.40	6.7	21	0.82
C2a	122	NA	20	0.80	3.6	8	0.31	27.8	9	0.37	6.5	20	0.80
D1a	124	7.0	24	0.95	6.0	8	0.33	11	9	0.37	6.0	24	0.96
E1a	123	6.4	20	0.79	8.9	8	0.33	26.9	10	0.40	6.6	21	0.82
Median	124.0		20.57	0.81		8.38	0.33		10.03	0.40		21.08	0.83
Max Deviation from Median	2		6.35	0.25		2.03	0.08		2.03	0.08		5.84	0.23
% Deviation	NA		30.9%	30.9%		24.2%	24.2%		20.3%	20.3%		27.7%	27.7%

Test 3: October 4, 2012 Data Summary

	Acoustic		Radial			Vertical			Transverse			VS	
Seismograph	dB	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s
A1b	123	7	16	0.62	303	12	0.47	21	15	0.60	23	18	0.70
A2b	123	6	17	0.68	24	13	0.50	20	16	0.62	15	19	0.75
B1a	125	6	18	0.70	23	12	0.47	20	14	0.54	14	19	0.75
B1b	125	6	17	0.65	24	12	0.47	18	14	0.56	14	18	0.71
B1c	*	0	17	0.67	27	15	0.60	37	17	0.65	13	20	0.78
C1a	124	NA	18	0.72	25	12	0.49	14	16	0.64	33	20	0.79
C2a	123	NA	17	0.68	23	13	0.52	19	14	0.55	31	20	0.78
D1a	124	9	16	0.63	24	13	0.50	20	13	0.53	13	17	0.68
E1a	124	8	19	0.73	24	13	0.52	21	15	0.58	13	20	0.79
Median	124.0		17.15	0.68		12.70	0.50		14.73	0.58		19.05	0.75
Max Deviation from Median	1		-1.40	-0.06		2.54	0.10		1.78	0.07		-1.78	-0.07
% Deviation	NA		-8.1%	-8.1%		20.0%	20.0%		12.1%	12.1%		-9.3%	-9.3%

* Malfunction

Test 4: November 8, 2012 Data Summary

	Acoustic		Radial			Vertical			Transverse			VS	
Seismograph	dB	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s
B1f	128.0	1.7	46	1.80	6	28	1.09	15	29	1.16	15	47	1.86
C1a	127.0	NA	42	1.64	6.1	22	0.88	15	25	0.99	12	43	1.68
C2a	126.0	NA	42	1.64	6.2	24	0.94	15	24	0.95	6.6	44	1.73
D1a	126.0	27	48	1.88	5	23	0.90	16	25	1.00	16	50	1.98
E1a	127.0	24.3	42	1.67	6.1	23	0.92	6.6	25	0.99	15.5	43	1.70
Median	127.0		42.42	1.67		23.37	0.92		25.15	0.99		43.94	1.73
Max Deviation from Median	1		5.33	0.21		4.32	0.17		4.32	0.17		6.35	0.25
% Deviation	NA		12.6%	12.6%		18.5%	18.5%		17.2%	17.2%		14.5%	14.5%

Test 5: May 30, 2013 Data Summary

	Acoustic		Radial			Vertical			Transverse			VS	
Seismograph	dB	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	1n/s
B1g	136.0	47	94	3.72	9	51	2.00	17	48	1.88	9	95	3.75
B1b	136.0	47	99	3.88	9	59	2.32	16	48	1.88	9	100	3.94
C1a	134.0	NA	91	3.60	9	47	1.84	16	44	1.74	9	92	3.64
C2a	135.0	NA	97	3.83	9	54	2.13	16	50	1.96	9	98	3.86
D1b	116*	2	82	3.24	7	48	1.88	17	51	2.00	9	83	3.25
A2b	135.0	47	78	3.06	47	44	1.72	18	51	2.01	10	79	3.11
A1b	135	47	85	3.34	7	54	2.13	14	48	1.88	9	85	3.34
F1a	132	NA	71	2.78	8	49	1.93	9	40	1.59	6	80	3.14
Median	135.0		88.14	3.47		49.91	1.97		47.75	1.88		88.65	3.49
Max Deviation from Median	-3		-17.53	-0.69		8.89	0.35		-7.37	-0.29		11.43	0.45
% Deviation	NA		-19.9%	-19.9%		17.8%	17.8%		-15.4%	-15.4%		12.9%	12.9%

Test 6: October 31, 2013 Data Summary

	Acoustic		Radial			Vertical			Transverse			VS	
Seismograph	dB	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s	Hz	mm/s	in/s
B1h	134	3	12	0.49	26	7	0.26	21	19	0.76	22	21	0.81
B1e	134	2	13	0.51	24	7	0.27	20	20	0.78	22	21	0.84
B1i	130	6	13	0.51	26	7	0.27	20	20	0.79	22	21	0.82
C1a	133	NA	13	0.50	25	7	0.27	20	21	0.81	22	21	0.81
C2a	133	NA	13	0.49	23	7	0.26	20	21	0.81	22	21	0.84
D1c	133	3	14	0.54	12	8	0.33	19	17	0.67	23	20	0.80
F1a	123	NA	12	0.49	12	7	0.26	30	20	0.77	21	22	0.86
G1a	135	NA	13	0.51	25	7	0.29	20	20	0.79	23	21	0.84
Median	133		12.76	0.50		6.79	0.27		19.89	0.78		21.11	0.83
Max Deviation from Median	-10.0		0.95	0.04		1.59	0.06		-2.87	-0.11		0.74	0.03
% Deviation	NA		7.5%	7.5%		23.4%	23.4%		-14.4%	-14.4%		3.5%	3.5%