Field comparison of 3-C geophones and microphones to high-precision blasting sensors

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ABSTRACT

It is well known in seismic exploration that geophone amplitudes do not directly represent the actual magnitude of ground velocity. Certain applications of seismic data require knowledge of the exact magnitude of ground velocity (e.g. fracture characterization). A field test was undertaken during the summer of 2008 at the west end of the University of Calgary campus. Seven sensors were used for measuring particle velocity and pressure in the vicinity of the geophones. This experiment was unique in that two high-precision sensors designed for blast monitoring and engineering purposes (Blastmate®) were used as a reference. Amplitude analysis of particle velocity in three directions of motion was performed on uncorrelated Vibroseis and hammer data. Amplitude difference factors were obtained for each receiver gather between 0 - 52.5 m nominal offset for Vibroseis shots, and 0 - 25 m nominal offset for hammer shots relative to the Blastmate peak particle velocity (PPV) measurements. In all cases, the conventional geophone amplitudes were smaller than the calibrated geophone amplitudes. Vibroseis shots yielded amplitude difference factors of 6.42 and 2.82 for the vertical component of the ION spike geophone at 0m and 52.5 m nominal offset, respectively. The corresponding values for the radial and transverse components were 10.61, 2.85, 19.87 and 3.05, respectively. Hammer shots yielded 2.11 and 3.90 for the vertical component at 0 m and 25 m nominal offset. The corresponding values for the radial and transverse component were 3.89, 2.84, 6.04 and 3.01, respectively. The Oyo GS-3C geophone yielded similar results with actual values slightly smaller than the ION spike values due to their different sensitivities.

INTRODUCTION

Seismic exploration geophones are able to detect and measure the particle velocity of ground motion with amplitudes in the range of 0.00025 mm/s to 25 mm/s. They are capable of recording reliable seismic data in the 5 to 500 Hz range depending on the resonant and spurious frequencies of a specific type of geophone. The resonant frequencies, also known as geophone natural frequencies, determine the low-frequency limit of reliable seismic data. Most commercial geophones are manufactured with natural frequencies in the 5 to 50 Hz range and spurious frequencies from 250 Hz and above. Typical values of resonant and spurious frequencies for seismic exploration geophones are 10 Hz and 250 Hz, respectively.

It is well known in seismic exploration that geophone amplitudes do not directly represent the actual magnitude of ground velocity. According to geophone modelling results by Hons (2008), the geophone output is not exactly ground velocity. Instead, it is a mix of amplitudes and phase rotations that might be called the “geophone domain”. Although a geophone shows a fairly flat frequency response to ground velocity above the resonant frequency, it cannot be considered a “true velocity sensor” because low frequencies (below resonance) are recorded with small amplitudes relative to the amplitudes at high frequencies, and there are varying phase rotation up to 100 Hz or more (Hons, 2008).

Therefore, it is of interest to seismologists to compare different types and models of ground motion sensors to assess their benefits and drawbacks in terms of frequency response, phase distortion and operational limits. For instance, Hons (2008) has recently analyzed and compared the system response of conventional geophones to the system response of MEMS accelerometers both in laboratory and field tests. Despite their limitations for reliable low-frequency recordings, conventional coil geophones have been used as the standard sensors since the beginning of seismic exploration largely because they are self-powered, inexpensive and reliable. Although geophones with improved low-frequency response are commercially available, they are expensive, heavy and large, and consequently impractical for large-scale seismic acquisition. However, a common application of these geophones with improved low-frequency response is found in blast monitoring.

In this paper, we compare a calibrated 3-C geophone attached to a blast monitor system to two conventional 3-C geophones (i.e., 10 Hz resonant frequency) and evaluate their performances in terms of particle velocity amplitudes. To achieve this goal, a very short seismic line was deployed west of the University of Calgary campus during the summer of 2008 (Figure 1) which included two different seismic sources, three different geophones and four different microphones (Figure 2).

A microphone is a transducer that converts sound pressure into an electrical signal. Pressure data have been recorded in the past while acquiring seismic data by placing small microphones at each receiver station. Microphone data can be combined with geophone data for attenuation of air noise (see Alcudia and Stewart, in this Research Volume). The basic microphone design consists of a thin membrane which vibrates in response to an incident sound pressure. The vibration of the membrane in a microphone is the analog to the velocity of the coil with respect to the case in a geophone. In both cases, the output voltage is proportional to the motion of the sensing element from rest position relative to a reference point. A calibrated microphone, two studio microphones and a CREWES designed microphone were used in this experiment to evaluate the ability of a microphone to capture some of the energy transported by the low-frequency surface waves (<20 Hz down to 2 Hz).

TRANSDUCER SENSITIVITY

A typical transducer converts physical signals into electrical signals. The magnitude of the transducer output, usually given in volts (V), is determined by the conversion mechanism and a sensitivity factor. For instance, the voltage output from a geophone is directly proportional to the velocity of the coil with respect to the case, scaled by a sensitivity factor given in units of V/m/s. The geophone’s sensitivity depends upon the number of loops in the coil and the strength of the magnetic field. Conversion from volts to physical units for a geophone is given by

$$u = \frac{Vout}{10^{\frac{gain}{20}} \times 1000 \times sensitivity} \qquad (1),$$

where u is particle velocity in m/s, *Vout* is the sensor output in millivolts (mV), *gain* is the recording system gain given in dB, 1000 is a factor that converts from millivolts to volts and *sensitivity* is a factor given in V/m/s (Albert, 1993). Similarly, the equation to convert from volts to units of pressure in a microphone is given by

$$p = \frac{Vout}{10^{\frac{gain}{20}} \times 1000 \times sensitivity} \qquad (2),$$

where p is pressure in Pascal (Pa), *Vout* is the sensor output in mV, *gain* is the recording system gain given in dB, 1000 is a factor that converts to from millivolts to volts and *sensitivity* is a factor given in V/Pa (Albert, 1993).

FIG. 1. Location map of the test site located west of the University of Calgary Campus. The direction of the seismic line was northeast-southwest. Shot direction was southwest-northeast. The seven-sensor test pad was located at the northeast end (from Google maps).

INSTRUMENTATION

3-C geophones

Two types of 3-C exploration geophones were used in this field study. Twenty-two ION Spike 3-C geophones with SM-24 elements manufactured by Input/Output Inc. and a single Oyo 3-C geophone with GS-20DM elements manufactured by OyoGeospace. The first type has a long case, housing three geophone elements at its bottom. The second type has a large metal spike and a smaller secondary spike to provide a better geophone planting and levelling. These geophones have similar manufacturer's specifications with the actual values listed in Table 1. The string of geophones was connected to the Geode Ultra-Light Exploration Seismograph, a product of Geometrics, INC.

Table 1. Summary of geophone specifications (Hons, 2008; Instantel, 2001).

Sensor	Type	Natural frequency	Frequency response	Sensitivity	Damping
ION Spike 3-C	3-C	10 Hz	~10-240 Hz	20.5 V/m/s	0.69
OYO 3-C	3-C	10 Hz	~10-300 Hz	19.7 V/m/s	0.70
Calibrated 3-C geophone	3-C	Not specified	2-250 Hz	Not specified. Returns true amplitude	Not specified

Microphones

Three microphones from different manufacturers were used in this experiment. The APEX 435 is a wide-diaphragm condenser microphone with frequency response from 20-20 kHz and cardioid polar pattern (reception pattern). The EMC 8000 is an electret-condenser microphone with frequency response from 15-20 kHz and omnidirectional polar pattern. The CREWES prototype is based on a small Panasonic WM-54BT electret-condenser microphone. The first two microphones are commonly used for professional audio recording and need power from either a battery, a mixing desk or a microphone pre-amplifier in the form of "phantom" power (+48 V DC). In this case, a USB-powered audio/MIDI production device, the Digidesign Mbox2, was acquired and used for three main tasks: 1) to serve as the "phantom" power provider, 2) pre-amplification, and 3) redirection of its two available analog inputs to their analog outputs.

Microphone connections to the Geode Seismograph are accomplished by using conventional microphone XLR cables and special cables consisting of jack connectors on one end and single-pin geophone connectors on the other. The MBox2 analog inputs receive the analog microphone signals through the XLR cables and then they are internally routed to the analog outputs (Figure 4a). By plugging the jack connectors into the Mbox2 analog outputs, the microphones can be connected to any available channel in the Geode by simply plugging the single-pin connector into any takeout. The MBox2 has to be connected to a laptop through a USB port since the PC provides its power (Figure 4b). The MBox2 has pre-amplifier gain capabilities which can be applied to the analog inputs and routed to the available analog outputs. However, a disadvantage of the MBox2 is that the pre-amplifier gain control is knob-based and no legend is printed on the front panel. Microphone pre-amplifier gains were chosen so that the control knobs were fixed to the center position. The total gain applied to both microphones is a combination of the MBox2 gain and whatever gain is selected in the Geode Seismograph. Table 2 summarizes some relevant microphone specifications.

Calibrated sensors

Typical instrumentation for vibration monitoring consists of a calibrated 3-C geophone, a calibrated microphone and a portable recording system. Our monitor, the Blastmate III, includes one calibrated 3-C geophone and one calibrated microphone both with band-pass responses from 2-250 Hz. This configuration is typical for peak particle velocity (PPV) and air-overpressure (POP) measurements. The Blastmate geophone resolution, or minimum recordable amplitude, is 0.0159 mm/s. Its maximum amplitude is limited up to 254 mm/s. The minimum and maximum values for the calibrated microphone are 0.25 Pa and 500 Pa, respectively, which are equivalent to linear sound pressure levels (SPL) from 88 to 148 dB. The accuracy of the geophone is ±5% or 0.5 mm/s, whichever is larger between 4 and 125 Hz. Microphone accuracy is ±10% or ±1 dB also between 4 and 125 Hz. Other types of sensors could be used such as accelerometers or hydrophones, depending on the physical variable to be measured and the site environment (e.g., land, water, swamp, etc.). Sampling frequencies of the Blastmate III are faster than those typically used in seismic data acquisition with options in the range of 1.024 kHz to 16 kHz.

Table 2. Summary of microphone specifications (from owner's manual).

Sensor	Type	Frequency response	Sensitivity	Power source
Calibrated Microphone	Overpressure microphone	2-250 Hz	Not specified. Returns true amplitude	Blastmate II
CREWES Microphone	Electret- condenser	20 Hz-20 kHz	6 mV/Pa	9V battery
APEX 435 Microphone	Condenser	20 Hz-20 kHz	10 mV/Pa	Phantom (+48V)
EMC 8000 Microphone	Electret- condenser	15 Hz-20 kHz	1 mV/Pa	Phantom (+48V)

DATA ACQUISITION

The receiver line was deployed along a roadside and extended 52.5 m in the northeast-southwest direction. The uppermost layer in the near surface was mainly comprised of clay. Soils that are high in clay are sticky when wet, compact easily and stay in rough lumps when dry. There was also some vegetation extending to the west side of the receiver line (Figure 7). A number of ION Spike 3-C geophones were planted along the receiver line at a 2.5 m receiver spacing. Small 15 cm deep by 6 cm wide holes were drilled for each ION spike using a gas-powered handheld auger. The seven-sensor test station was located at the northeast-end of the line (Figure 3). The test station included an additional OyoGeospace 3-C geophone, an Instantel calibrated 3-C geophone, an Instantel calibrated microphone, an APEX 435 condenser microphone, an EMC 8000 electret condenser microphone and the CREWES microphone prototype. The calibrated sensors were attached to their own portable recorder (Blastmate III). All other sensors were connected to three Geode Ultra-Light Exploration Seismographs. The use of two different recorders imposed an inherent difference between the high-precision and conventional sensors, which was later minimized in data processing. Other logistics and recording issues are further explained below.

An IVI EnviroVibe (Figure 6) and a sledgehammer were used as seismic sources. Shot points were spaced every 2.5 m over a shot line parallel to the receiver line, nominally offset 2.0 m to the east. Each vibration point was centered and aligned to its corresponding receiver station. Following the vibe survey, the center of the vibrator's pad marks were used as the location for hammer shot points. The shooting direction for both sources was southwest-northeast with the first source point located at station 1, equivalent to a 52.5 m offset from the test station located at the northeast end. Each Geode was powered separately by a 12V battery and connected in series to a Panasonic Toughbook laptop through a special Ethernet cable. A total of 72 channels were available, 24 from each Geode, assigned as listed in Table 3. Color codes were used in the cables for connecting each geophone component and each microphone to a particular channel set (Figure 6). Station numbers, shot numbers and channel numbers for each Geode started at the southwest-end of the line. For example, channels 1, 25, 49, and shot 1 correspond to the geophone and source point at station 1, respectively; channels 2, 26, 50, and shot 2 correspond to the geophone and the source point at station 2, and so forth.

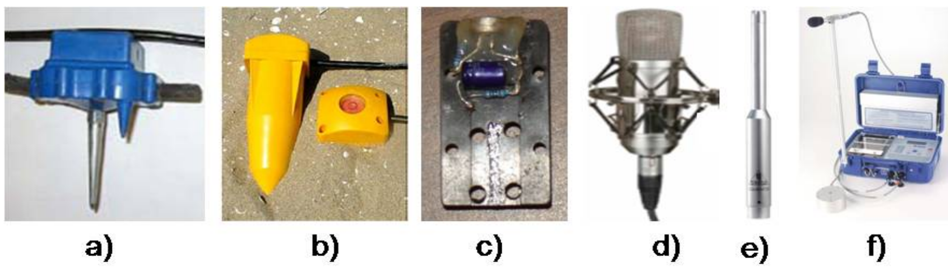


FIG. 2. Seven sensors were used in the test: a) OyoGeospace GS-3C geophone, b) Input/Output Spike 3C geophone, c) CREWES microphone prototype, d) APEX 435 condenser microphone, e) EMC8000 electret-condenser microphone, and f) Blastmate III unit with two calibrated sensors (3C geophone and microphone).

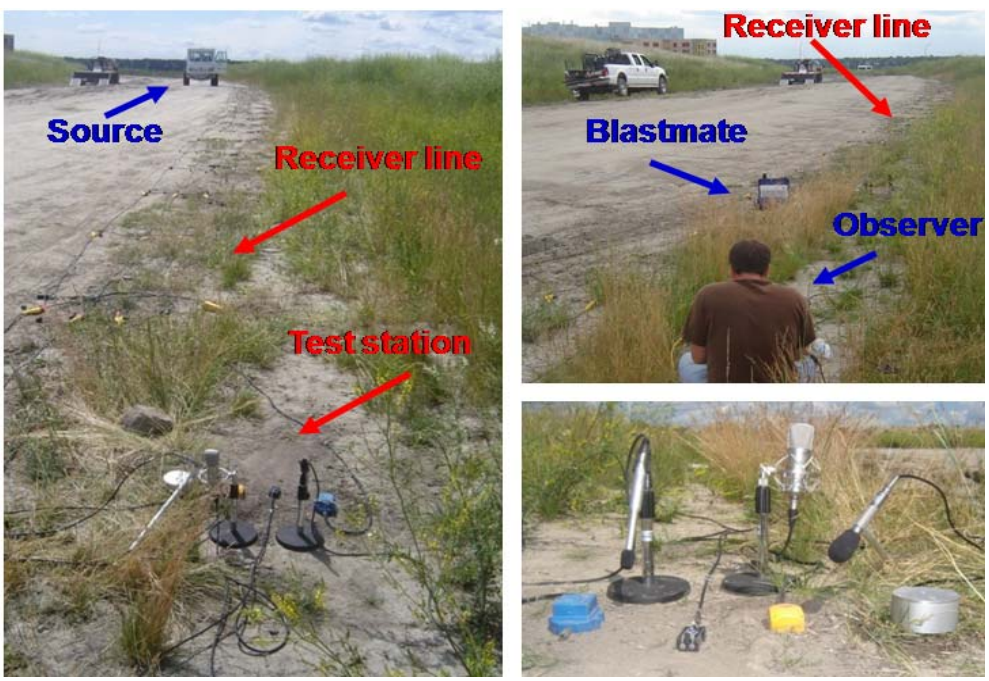
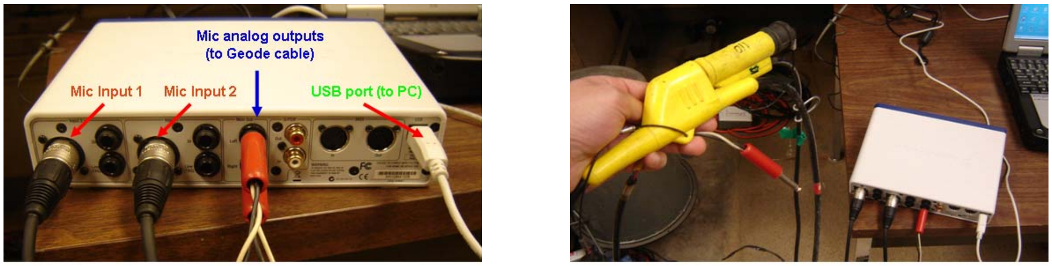


FIG. 3. Southwest view of the seismic line with the mini Vibe located at shot point one (left) and the seven-sensor test pad located at the northeast end (bottom right). The observer's computer was located about 3.5m north of the test station while the Blastmate monitor was located about 1 m east of the test station (top right) (Photos by first author).



a) b)

FIG. 4. Two studio microphones were connected to the analog inputs of a Digidesign MBox2 (left) using conventional microphone XLR cables. The MBox2 analog outputs were connected to the Geode receiver cable through special cables consisting of jack connectors on one end and single-pin geophone connectors on the other (right).

Table 3. GEODE channel assignation

Channel	Sensor component	Color code
1-20 and 22	Vertical / ION Spike 3-C	Red line
25-44 and 46	Radial / ION Spike 3-C	Green line
49-68 and 70	Transverse / ION Spike 3-C	Blue line
21	Vertical / OYO 3-C	Red line
45	Radial/ OYO 3-C	Green line
69	Transverse / OYO 3-C	Blue line
23	CREWES Microphone	Red line
47	APEX 435 Microphone	Green line
71	EMC 8000 Microphone	Blue line
24	Vibroseis sweep	Red line
48	OPEN	OPEN
72	OPEN	OPEN

The Vibroseis sweep was linear from 10-250 Hz over 10s with a 200 ms cosine taper. All sensors connected to the Geodes were sampled at 1ms. Listen time was set to 5 s due to a problem with time-zero. This problem could not be solved in the field and was attributable to either a trigger time delay in the cable connecting the VibePRO to the Geode trigger input, or to an unexpected time delay in the Geode response to the trigger signal. However, the sweep zero time was properly recorded at time-zero and cross-correlation of the pilot sweep with the raw data shows that the first breaks at the nearest offsets are very close to time-zero. Sledgehammer data was recorded without any problems over 1s at a sample rate of 1ms.

The Blastmate III is a self-triggered recorder. Recording starts only after an acoustic or seismic trigger level is reached. One can select a trigger source as either seismic, acoustic or both. To minimize the time difference between the Geode and Blastmate recordings, we selected a seismic trigger with the minimum level available (i.e., 0.127 mm/s). This level imposed a limitation on far-offsets recordings for the seismic sources used in this field study, especially sledgehammer recordings because hammer–induced vibrations are very low for a source located a few metres away. In fact, a first conclusion can be stated: sledgehammer shots do not generate PPVs greater than 0.127 mm/s at offsets greater than 25 m for soils such as dry clay. Recording times were 1s for hammer shots and 11s for Vibroseis shots. A sample rate of 1024 samples per second was selected for Blastmate recordings because this rate was the closest to standard rates used in seismic exploration (1 ms, 2 ms or 4 ms). In addition to the far-offsets limitation, the standard Blastmate III has limited storage capacity (300 one-second events at 1024 samples per second) and relative long wait-time between shots. Such limitations made the acquisition operations highly dependent on the Blastmate timing and reduced the number of monitored shots to less than 35. Increasing the sample rate would have increased the accuracy of the waveform recordings but reduced the storage capacity. Future experiments involving Blastmate recordings would require careful planning with regard to number of shots versus waveform accuracy, unless an extended memory is available.

Aliasing occurs when a high–frequency signal appears as an erroneous low frequency because the waveform was sampled at too low sampling rate. An anti-aliasing filter solves this problem by removing the high–frequencies before they can appear at lower frequencies. The BlastMate III standard sensors have anti-alias filters built into them to avoid this problem (Instantel, 2001).

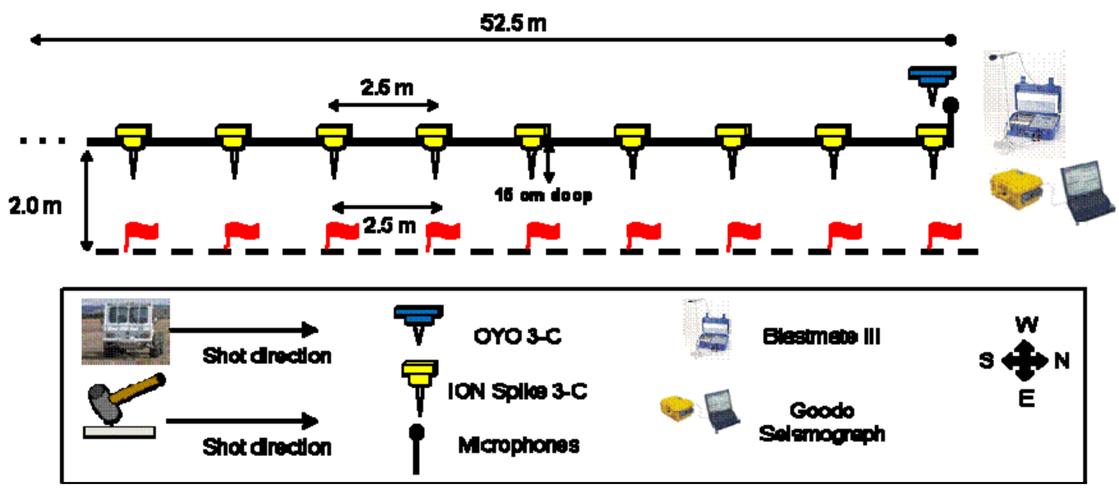


FIG. 5. Acquisition layout for shot and receiver lines.

FIG. 6. Geophone cable connections were facilitated by using color codes for each component (left). Each Geode recorded a full dataset of a particular geophone component. The mini EnviroVibe, owned by the University of Calgary, was used as one of two seismic sources (right).

FIG. 7. CREWES staff preparing equipment (left) and north view of test site (right). The receiver line was deployed along the vegetation boundary to allow trafficking on the road.

VIBROSEIS DATA

3-C geophones

The natural domain for a direct sensor comparison is the receiver domain. Receiver gathers for each conventional geophone and each of its ground velocity components are shown in Figure 8. The data were cross-correlated with the vibrator sweep and windowed to 400 ms to assist in the identification of seismic events. An AGC of 250 ms was applied before windowing the data for display purposes only. None of the amplitude analysis was performed using amplitude-corrected data. A valid reason for limiting our data in time was the presence of strong harmonic distortion after 500 ms, caused primarily by the non-linear coupling of the vibrator to the ground (which produces higher harmonics) and the proximity of the shot points to the geophones. After all, we expected no deep seismic reflections to be recorded in such a short line from such small source offsets. Seismic data recorded with the Oyo 3C have stronger air blast contamination than seismic data recorded with the ION Spike. As expected, the ION Spike data were less affected by the propagating sound wave in the surface because the ION Spike was mostly buried and its geophone elements were located at the bottom of its case. On the other hand, the Oyo 3C case was exposed and prone to a direct impact of surface ambient noise. Ambient temperature during acquisition was about 20° C and the sky was partly cloudy. At these conditions, the speed of sound in dry air is close to 343 m/s. Note that the air blast looks stronger at the far offsets (first shots) because the first breaks at the near offsets are strong enough to overwhelm the acoustic wave arrivals. However, if a high-pass filter is applied to these data, then the air blast becomes the predominant event across the receiver gather.

A total of 22 Vibroseis shots were simultaneously recorded with the Blastmate and Geode Seismographs. Amplitude analysis was performed on uncorrelated traces only because we were unable to compute cross-correlations of the Blastmate data with the Vibroseis sweep correctly. Therefore, the “correlated” Blastmate data were not suitable for comparative analysis. Table 6 lists the Blastmate PPV, POP and peak displacement measurements per shot. Although they are closely related, peak displacement does not necessarily occur at the PPV of the event (Instantel, 2001). Table 6 also includes the nominal offset and velocity component that triggered the Blastmate recording. Note that the Blastmate measurements show amplitude decay with increasing distance. For example, PPV values measured in the transverse direction decayed from 36.7 mm/s to

0.206 mm/s in a range of 52.5 m. Similarly, PPV in the vertical direction decayed from 10.8 mm/s to 0.222 mm/s and PPV in the radial direction from 18.2 mm/s to 0.302 mm/s. According to these measurements, a second conclusion can be stated: vibrations generated by the IVI EnviroVibe at offsets less than 52.5m are greater than 0.127 mm/s for soils such as dry clay.

Equation (1) was applied to each component of ground velocity as recorded from conventional geophones (i.e., each receiver gather) to determine the relative particle velocity amplitudes in physical units. Then, peak particle velocity (PPV) was found for each trace and compared to the Blastmate PPV measurements. A single difference factor was obtained per trace by dividing each Blastmate PPV measurement by the trace PPV. Table 4 contains factors of amplitude difference relative to the Blastmate geophone for Vibroseis shots.

These values represent a measure of the difference in amplitude between a conventional and a calibrated geophone, assuming that the PPV in both geophones occurs at the same event. The nearest-shot column in Table 4 contains amplitude difference factors for a shot point located 2.0 m nominal offset and 90-degree azimuth (in the cross-line direction). For this shot, the difference in amplitude of the transverse geophone relative to the Blastmate geophones was very large (19.87 for the ION spike and 18.43 for the Oyo 3C) because the vibration levels were so high (36.7 mm/s) that the conventional geophone amplitudes clipped. The other two components were also clipped as result of high vibration levels. As we will see later in the analysis of hammer data, for relative low PPV levels, these factors oscillate between 4 and 6. The ION spike PPV in the vertical direction was only 2.82 times smaller than the reference PPV for a 52.5 m source offset. Values between the ION spike and Oyo 3C differ a little due to their different sensitivities.

Table 4. Scaling factors for multicomponent seismic data relative to Blastmate data for Vibroseis shots.

Sensor component	Nearest shot	Farthest shot	Max. in receiver gather	Min. in receiver gather	Mean
Vertical / ION Spike 3C	6.42	2.82	6.42	2.57	3.18
Radial / ION Spike 3C	10.61	2.85	10.61	2.57	3.63
Transverse / ION Spike 3C	19.87	3.05	19.87	2.74	4.18
Vertical / OYO 3C	5.78	2.84	6.15	2.28	2.98
Radial/ OYO 3C	10.32	2.95	10.32	2.43	3.57
Transverse / OYO 3C	18.43	2.53	18.43	2.17	3.63

Average amplitude spectra were obtained for each uncorrelated receiver gather, including the Blastmate data. An average spectrum was obtained by averaging the 1D Fourier transform amplitude spectra computed for each trace in the receiver gather. Figure 10 shows average amplitude spectra for each component of particle velocity with the amplitude scale given in dB (referenced to the maximum amplitude on each spectrum). Note that the frequency responses of both conventional geophones are very similar to the frequency response of the calibrated geophone from about 15 Hz up to 80

Hz. As expected, the frequency response of conventional geophones at frequencies below resonance (i.e., 10 Hz) was not optimal (-40 dB).

Microphones

Figure 11 shows average amplitude spectra for each uncorrelated microphone output. A 5-260 Hz band-pass filter was applied to the data before the computations to reduce any low-frequency bias. Recall that the frequency response for most microphones is fairly good from 20 Hz-20 kHz (i.e., humans' audible band), but we are interested in their performance at frequencies down to 10 Hz and how they compare to the Blastmate calibrated microphone. Microphone responses are very similar from about 30 Hz to 260 Hz (filter cut-off frequency), especially at high frequencies, which correspond to times when the sound coming from the vibrator's baseplate is very loud. Note that all microphone responses (including the Blastmate microphone) start decaying at about 30 Hz. This looks more like a frequency notch in the CREWES and APEX 432 microphones. Power-line noise at 60 Hz introduced a spike in all microphone responses.

Alcudia and Stewart (2008) pointed out that the Vibroseis-generated airwave is a sweep-like waveform because its frequency content varies according to the frequency content of the Vibroseis sweep. This observation was made after transforming the uncorrelated output of a microphone and the pilot sweep into the time-frequency domain (i.e., the Gabor transform domain). The cross-correlation of a microphone signal with the pilot sweep results in a "pseudo-autocorrelation" of the microphone signal. In fact, the correlated microphone traces in either a shot or receiver gather are "pseudo-autocorrelations" with times of maximum amplitude given by the arrival times of the sound wave into the receivers. For instance, Figure 12 shows three receiver gathers for the un-calibrated microphones. Note that the highest amplitudes represent the amplitudes of maximum correlation due to the sound wave. Average amplitude spectra were also computed and plotted in Figure 12. The studio microphones have very similar response in the entire frequency range except for frequencies less than 30 Hz. This suggests that all microphones responded very different to frequencies where the ground roll is usually dominant. However, we cannot confirm that the recorded low-frequencies are due to ground roll because the pressure data in time do not show any coherent low-frequency event across the receiver gather.

SLEDGEHAMMER DATA

3-C geophones

Similarly to Vibroseis results, the OYO 3C geophone recorded noisier seismic data than the ION Spike. Only 11 out of 22 shots were simultaneously recorded with the Blastmate and the Geode Seismograph because particle velocity amplitudes of hammer shots beyond 25 m were very small. Such small amplitudes are well below the calibrated geophone resolution, which is the lowest measurable amplitude (i.e., 0.0159 mm/s). Factors of amplitude difference between conventional and calibrated geophone amplitudes were found following the same methodology used for Vibroseis data. Table 5 shows maximum, minimum and mean values of these factors for each receiver gather. Note that the longest offsets (25 m) correspond to trace 1 and the nearest offsets (2 m) correspond to trace 11 for all receiver gathers. According to these results, the particle velocity magnitude in the vertical direction as recorded by the IONspike is 2.11 times smaller than the true magnitude as recorded by the Blastmate. The mean value for the full receiver gather of vertical particle velocity is 2.97.

Table 5. Scaling factors for multicomponent seismic data relative to Blastmate data for hammer shots.

Sensor component	Nearest shot	Farthest shot	Max. in receiver gather	Min. in receiver gather	Mean
Vertical / ION Spike 3C	2.11	3.90	3.90	2.11	2.97
Radial / ION Spike 3C	3.89	2.84	3.89	2.43	3.05
Transverse / ION Spike 3C	6.04	3.01	6.04	2.87	3.62
Vertical / OYO 3C	2.05	2.27	2.56	1.42	1.98
Radial/ OYO 3C	2.95	2.68	3.43	1.51	2.45
Transverse / OYO 3-C	4.02	1.77	4.02	1.15	2.11

Microphones

A 2-250 Hz band-pass filter was initially applied to the data (top left and top right in Figure 14). Note that the frequency response of the EMC 8000 microphone is very close to the Blastmate calibrated microphone for the entire frequency band, as in the Vibroseis data. However, the average spectra of the CREWES prototype and the APEX 435 microphone are biased by very low frequencies (<15 Hz). By applying a second band-pass filter to attenuate frequencies less than 10 Hz, the average spectra are partially corrected (centre left and centre right in Figure 15). By applying a third filter to attenuate frequencies less than 15 Hz, the average spectra are closer to the Blastmate microphone response (bottom left and bottom right in Figure 15). This suggests that frequencies below 20 Hz are not reliable except for the Blastmate microphone and EMC 8000.

CONCLUSIONS

Particle velocity and pressure data from seven different sensors were acquired in a test site located at the west end of the University of Calgary campus. Geophones and microphone outputs were sorted into receiver gathers and used to compute average amplitude spectra. Amplitude differences between conventional and calibrated geophone data can be found by taking the PPV of each trace recorded with conventional geophones, converting it to physical units, and dividing each Blastmate PPV measurements by the trace PPV. For hammer shots, the maximum and minimum amplitude difference between the calibrated and ION spike vertical geophone were 3.90 and 2.11, respectively. Mean factors for the ION spike and OYO geophones were between 1.98 and 3.62 for all particle velocity components and all hammer shots. Vibroseis uncorrelated data gave mean values between 2.98 and 4.18 for all particle velocity components. Dynamite shots would be very helpful for future work since PPV’s are much larger than PPV’s from Vibroseis and sledgehammer shots. Another advantage of using dynamite would be the recording of far offsets.

Pressure data recorded with three un-calibrated microphones and a single calibrated microphone suggested that some low-frequency acoustic energy (< 25 Hz) was recorded during this experiment. All microphones responded quite similar at frequencies where the airwave is stronger (higher frequencies). However, they responded quite different at lower frequencies, where the ground-roll is usually dominant. Unfortunately, we cannot conclude that this energy is due to low-frequency ground-roll because the microphone responses at frequencies below 30 Hz are quite different from shot to shot. Therefore, the low-frequency events displayed in time do not show any coherence across the microphone receiver gathers. Further signal analysis of these datasets is under research.

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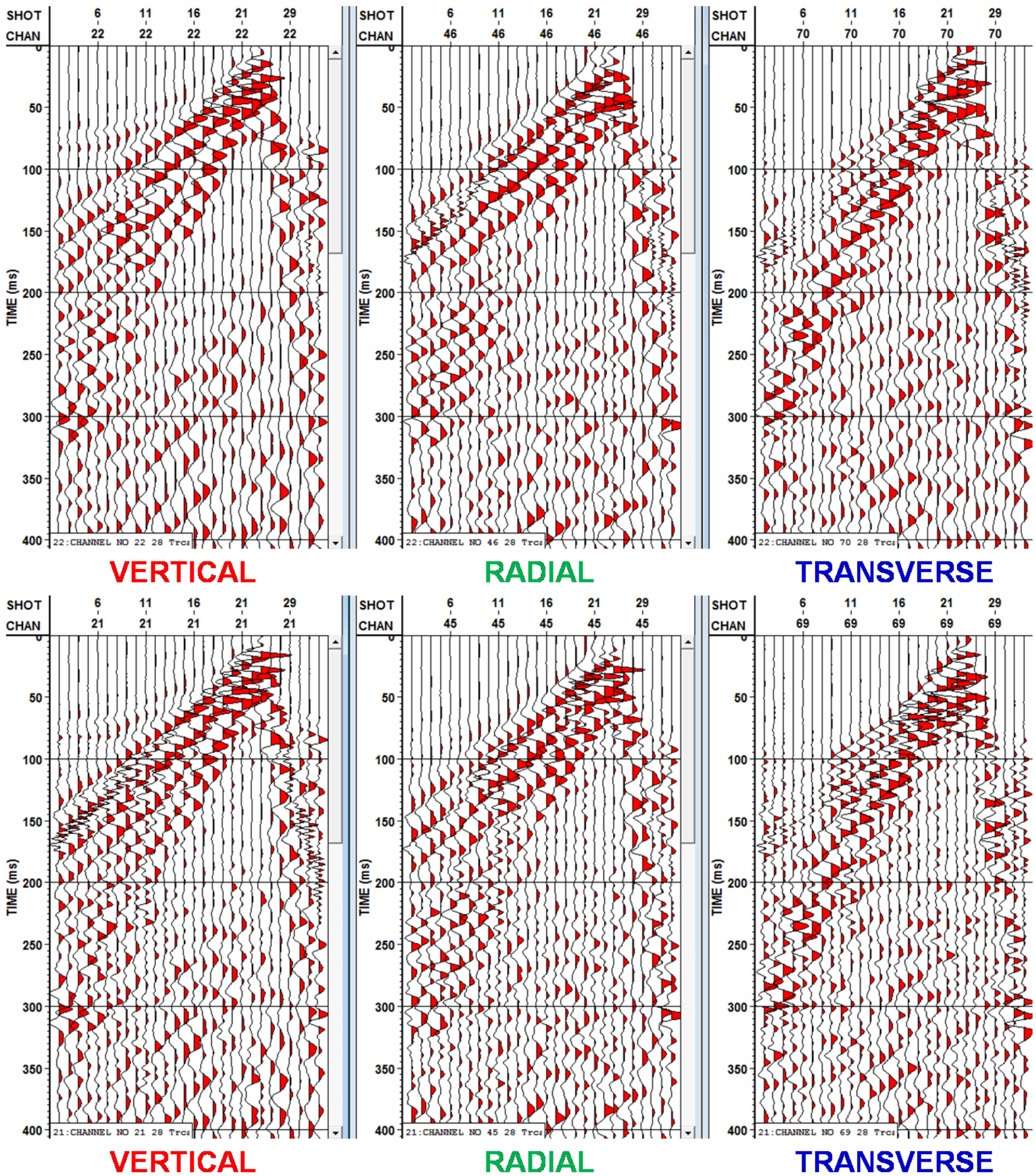

FIG. 8. Vibroseis data separated by component and sorted into receiver gathers. The top dataset is a receiver gather recorded from the ION Spike geophone. The bottom dataset is a receiver gather recorded from the OYO geophone at the test station.

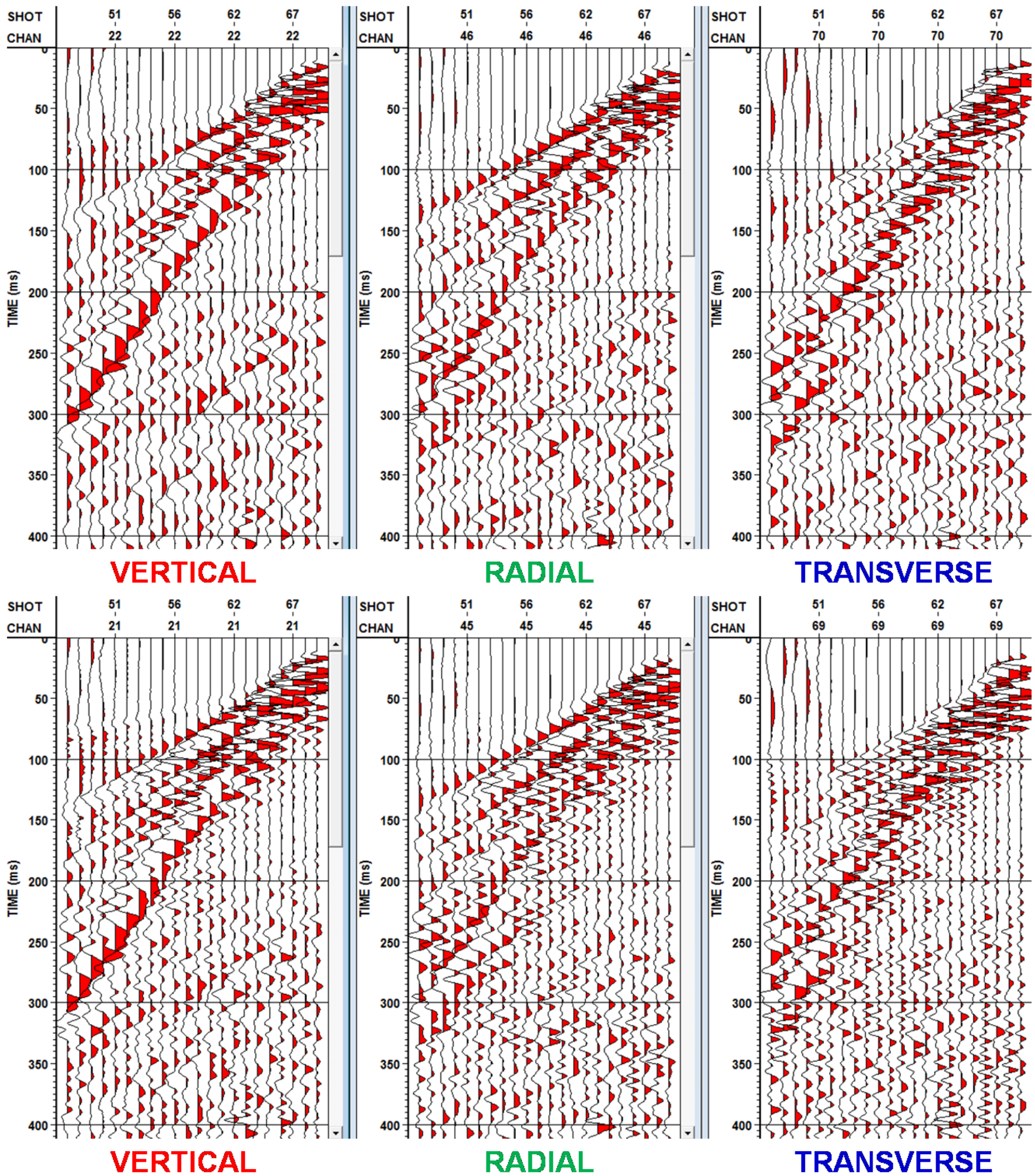

FIG. 9. Hammer data separated by component and sorted in receiver gathers. The top dataset is a receiver gather recorded from the ION Spike geophone. The bottom dataset is a receiver gather recorded from the OYO geophone at the test station.

Table 6. Blastmate data from Vibroseis shots.

Nominal Offset (m)	Trigger	Tran Peak (mm/s)	Vert Peak (mm/s)	Long Peak (mm/s)	Mic Peak (pa./dB)	Tran Disp. (mm)	Vert Disp. (mm)	Long Disp. (mm)
52.5	Long	0.206	0.222	0.302	1.00L	0.00088	0.00086	0.00128
50	Long	0.254	0.206	0.365	1.25L	0.00102	0.00099	0.0014
47.5	Long	0.286	0.222	0.286	1.25L	0.00103	0.0009	0.00102
45	Vert	0.317	0.19	0.413	1.00L	0.00093	0.00095	0.00121
42.5	Long	0.46	0.238	0.476	1.25L	0.00178	0.00094	0.0015
40	Long	0.651	0.27	0.397	1.75L	0.00274	0.00131	0.00168
37.5	Long	0.413	0.302	0.429	1.50L	0.00165	0.00115	0.00174
35	Vert	0.476	0.27	0.54	1.50L	0.00184	0.00115	0.00223
32.5	Long	0.571	0.381	0.556	1.25L	0.00243	0.00174	0.0021
30	Long	0.746	0.746	1	1.25L	0.00253	0.00285	0.00391
27.5	Long	0.762	0.778	1.32	1.75L	0.00228	0.00315	0.00522
25	Long	1	0.762	1.67	2.25L	0.00327	0.0029	0.00774
22.5	Tran	0.127	0.143	0.143	1.00L	0.00047	0.00104	0.00101
20	Vert	1.56	1.17	2.27	2.00L	0.00488	0.00385	0.00939
17.5	Vert	2.11	1.52	3.29	1.75L	0.00675	0.00671	0.0122
15	Long	1.17	1.68	2.87	3.00L	0.00407	0.00664	0.00957
12.5	Vert	2.37	2.38	4.05	4.00L	0.00588	0.00819	0.0123
10	Long	2.22	3.94	4.29	3.75L	0.00705	0.0127	0.0149
7.5	Long	2.41	4.24	4.46	6.50L	0.00819	0.0112	0.0182
5	Long	6.02	5.64	11.8	6.50L	0.0193	0.0147	0.0393
2.5	Tran	16.3	10.7	15.8	7.50L	0.0528	0.025	0.05
0	Tran	36.7	10.8	18.2	16.0L	0.103	0.0288	0.479

Table 7. Blastmate data from hammer shots

Nominal Offset (m)	Trigger	Tran Peak (mm/s)	Vert Peak (mm/s)	Long Peak (mm/s)	Mic Peak (pa./dB)	Tran Disp. (mm)	Vert Disp. (mm)	Long Disp. (mm)
25	Long	0.0952	0.0635	0.127	0.500L	0.00022	0.00016	0.00034
22.5	Long	0.127	0.0794	0.127	0.500L	0.00031	0.00039	0.00039
20	Long	0.238	0.111	0.175	<0.500L	0.00052	0.0004	0.00051
17.5	Long	0.159	0.159	0.206	0.500L	0.00036	0.00053	0.00066
15	Long	0.27	0.206	0.302	<0.500L	0.00052	0.00079	0.00102
12.5	Long	0.238	0.238	0.381	0.500L	0.0005	0.00065	0.00106
10	Vert	0.524	0.492	0.746	0.500L	0.00076	0.00129	0.0017
7.5	Vert	0.365	0.841	0.667	0.750L	0.00079	0.00179	0.00148
5	Vert	1.51	1.43	2.95	1.00L	0.00274	0.00315	0.00554
2.5	Vert	2.81	1.59	4.41	2.00L	0.00608	0.00359	0.00962
0	Vert	7.38	2.27	4.24	2.50L	0.0126	0.00567	0.00651

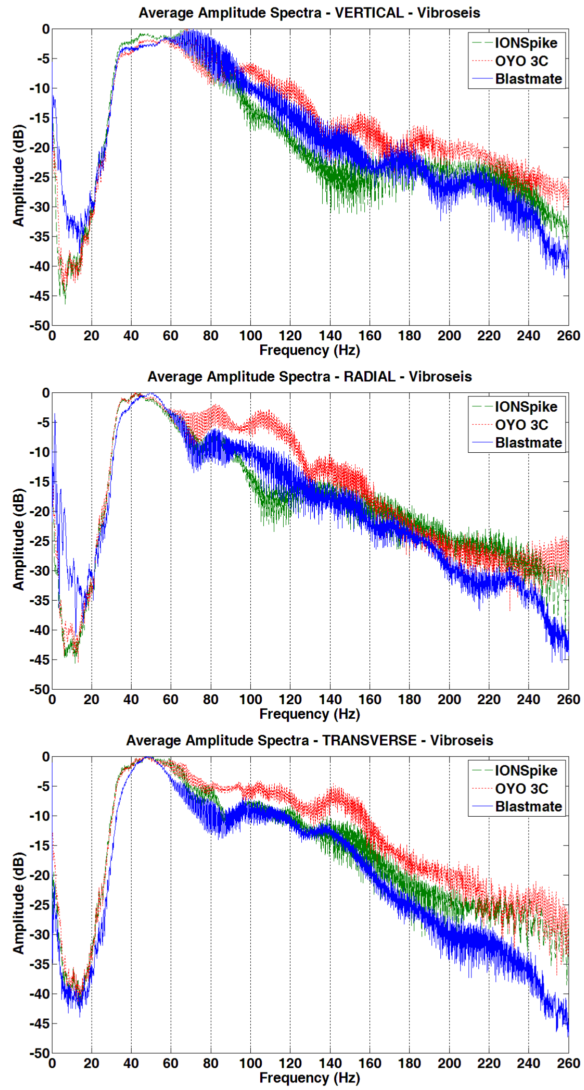

FIG. 10. Amplitude spectra average of geophone data. A 2-260 Hz band-pass filter was applied to these data.

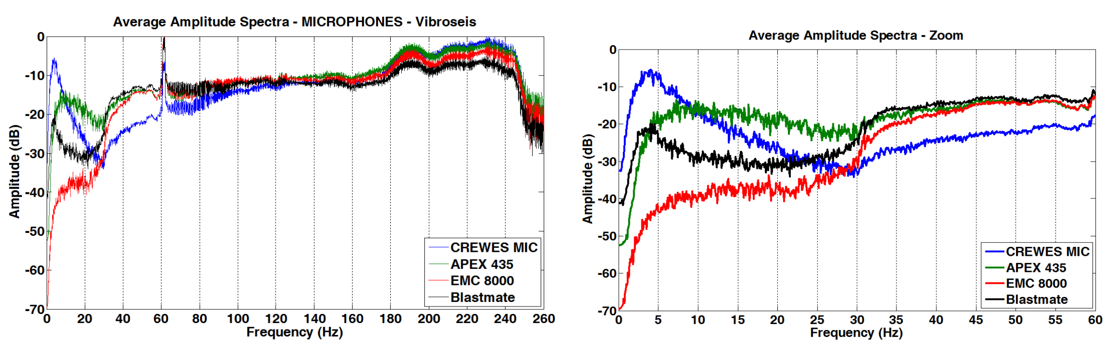

FIG. 11. Amplitude spectra average of microphone data. A 5-260 Hz band-pass filter was applied to uncorrelated data. Note that all microphone responses (including the Blastmate microphone) have a frequency notch at about 30 Hz.

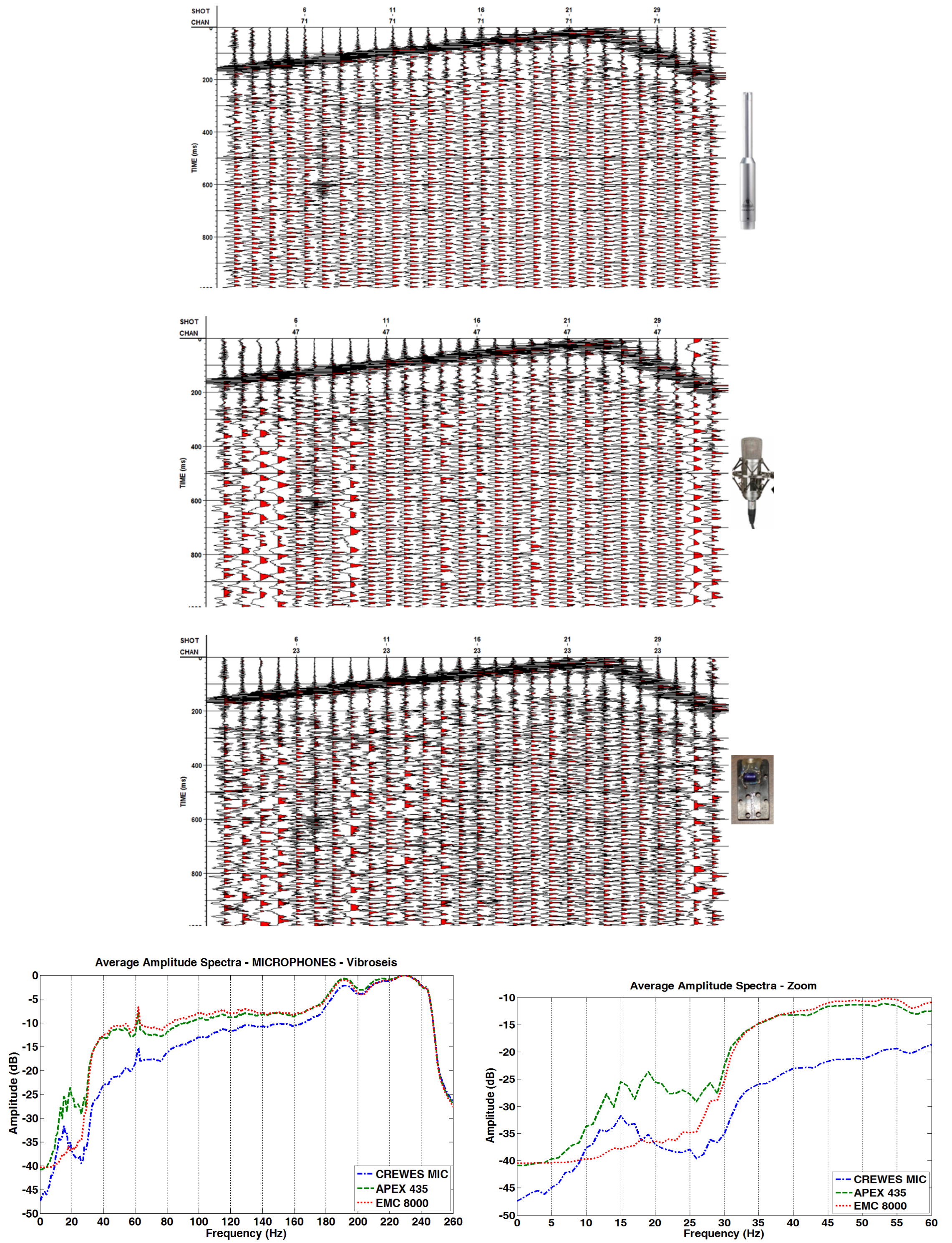

FIG. 12. Pressure data recorded from APEX435 (top), CREWES prototype (centre) and EMC 8000 (bottom) microphones for all Vibroseis shots at 2.5m interval. VP's 23 to 32 were spaced every 10 m. Data were cross-correlated with the pilot sweep. AGC of 250 ms was applied to data for display only. The average of amplitude spectra is also show at the bottom. Note that all microphone responses are identical at high-frequencies, where the air blast is dominant.

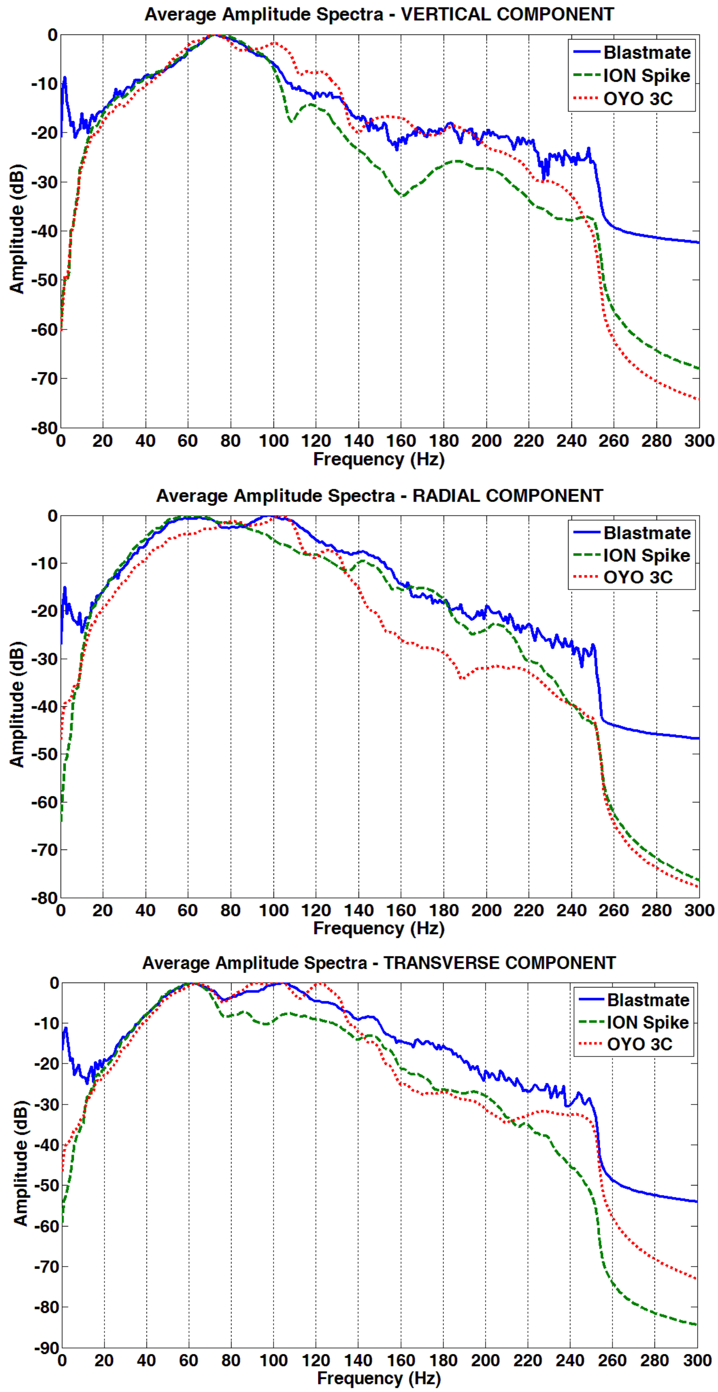

FIG. 13. Average amplitude spectra for each component of ground velocity for hammer shots. The average amplitude spectra for vertical components (top) in the 12 Hz to 90 Hz are very well matched to Blastmate data (in blue). Average spectra for radial components (middle) are well matched from 10 Hz up to 80 Hz. Average spectra for transverse components (bottom) are well matched from 12 Hz up to 85 Hz. In general, the spectra for all components start to diverge from Blastmate data above 90 Hz. Note the strong low-frequency response of the calibrated geophone at frequencies down to 2 Hz.

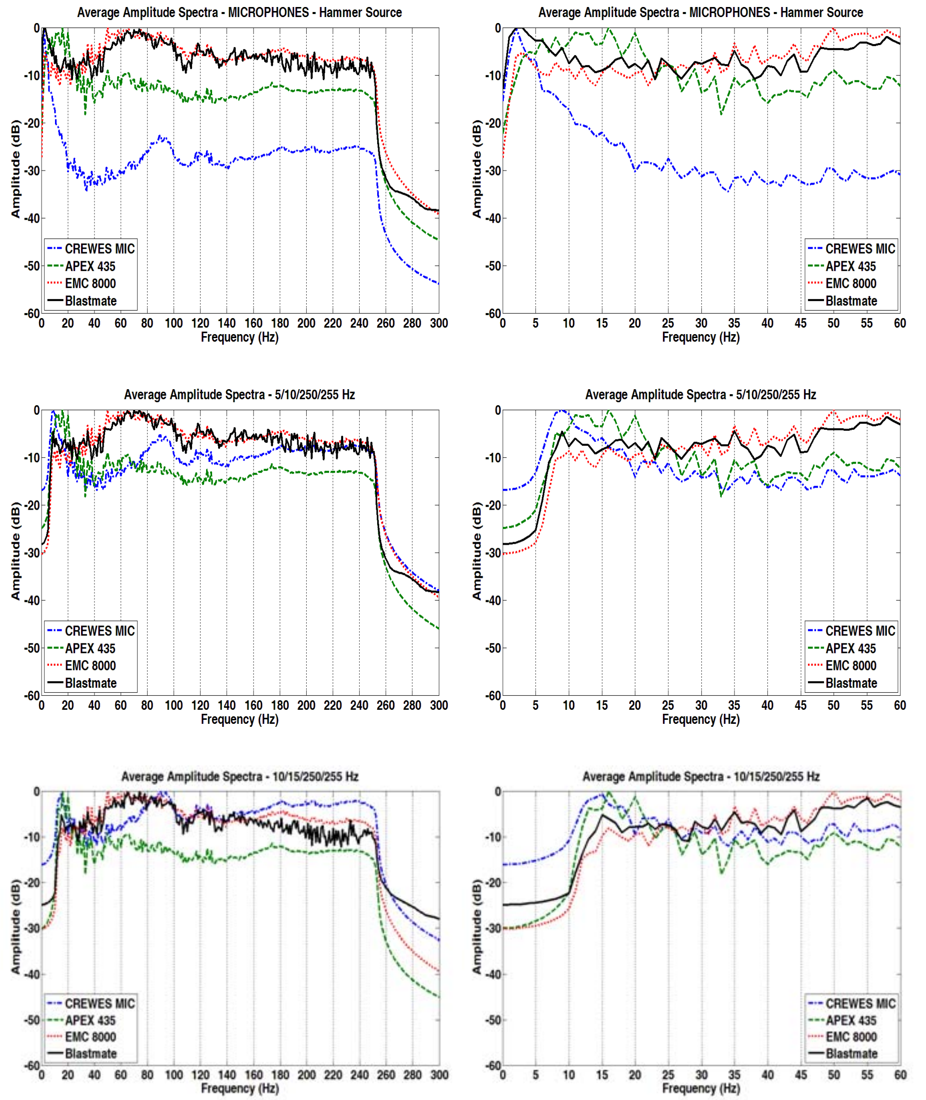

FIG. 15. Average amplitude spectra of microphone data. 11 hammer shots were used for these computations. A band-pass filter (0-2-250-255 Hz) was initially applied to the data (top left and top right). Note that the frequency response of the EMC 8000 microphone (in red) is very close to the Blastmate calibrated microphone (in black) for the entire frequency band. By applying a second band-pass filter to attenuate frequencies less than 15 Hz, the average spectra of the CREWES prototype (dashed blue) and the APEX 435 microphone (green) were partially corrected (bottom left and bottom right).