Vibration and air pressure monitoring of seismic sources

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ABSTRACT

Vibration monitoring of a seismic exploration program was conducted in the Nanton area, Alberta. Peak particle velocity (PPV) in three directions and peak air-overpressure (PSPL) were recorded by a vibration monitoring system. Dynamite blast monitoring suggested no damage could be caused to the water spring with a 1.6 km safe radius, since the recorded PPV indicated ground vibrations well below permissible levels and comparable to natural vibrations. The vertical and longitudinal channels both yielded PPV values of 0.0476 mm/s whereas the transverse channel yielded 0.0635 mm/s for a series of dynamite shots. The computed peak vector sum (PVS) was 0.0794 mm/s, which is smaller than the PVS obtained from natural vibrations monitoring (i.e., 0.0953 mm/s). Vibration monitoring results suggest that 3C measurements are required because the maximum ground motion could occur in any direction. Waveform analysis of ground motion and air vibration may reveal some interesting features in the data. For instance, the existence of harmonics in the recorded signals demonstrates that the transfer of energy from the vibrator to the earth is not perfect. Further analysis of the frequency harmonics may give additional information about the source-generated noise.

INTRODUCTION

Seismic operations are undertaken to satisfy exploration goals while respecting the environment. Monitoring of ground vibration and air-overpressure generated by seismic sources during land data acquisition is not a standard procedure. The standard methodology followed by most of the seismic contractors in Canada and worldwide is to apply safe offsets between the sources and facilities or infrastructure. This requires using standard charts whose values are collected empirically and rely on best practices around the world. Such charts are published by the International Association of Geophysical Contractors (IAGC), and in Canada, the Canadian Association of Geophysical Contractors (CAGC) plays the analog role (see Table 1). However, as suggested by Rappin et al. (2007), “the use of available standard reference charts is not optimal as it will define cautiously large safety distances usually too conservative. In addition, their use does not ensure that arguments or lawsuits can be avoided in case of damage”.

Rappin et al. (2007) proposed a monitoring methodology based on a calibration stage followed by real-time monitoring of ground vibrations during seismic operations. The early stage produces calibrated reference curves of the ground response to the seismic energy sent into the ground (i.e., either dynamite or vibroseis), quantitatively expressed in terms of the peak particle velocity (PPV). According to Rappin et al. (2007), these calibrated curves can be used to tune the safety distances to specific objects. Because PPV limit values are now known for sensitive areas, they can be used during seismic acquisition for real-time monitoring by means of 3-C geophones placed near the objects.

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The industrial and cultural impact of vibration monitoring approaches during seismic operations could be significant. On the one hand, seismic data quality can be improved as a function of reducing gaps in the fold. In addition, the calibrated curves of ground response could be presented as reference material in case of contention between the seismic contractor and complainant (Rappin et al., 2007). In other cases, measurement of PPV versus distance is legally accepted to prove that seismic operations are not causing damage to near objects (WorleyParson Komex, 2007). On the other hand, it might not be cost-prohibited since only a small additional crew or specialized contractor would be required. Vibration monitoring of seismic sources can be used to achieve an optimal tradeoff between seismic data quality, safety operations and environmental protection.

The aim of this paper is to describe the measurements and typical instrumentation involved in vibration monitoring. A case study is also presented of vibration monitoring during a seismic exploration program at Nanton, Alberta, in which dynamite and vibroseis sources were successfully monitored to protect the valuable water springs in the Nanton area.

Table 1. Stand-off distances applied by the CAGC.

Canada Oil and Gas Geophysical Operations Regulations (SOR/96-117)			
Facility	Stand-off distance		
	2 > kg dynamite	2 < kg dynamite < 4	Vibroseis
Dam	64 m	90 m	100 m
Oil or gas well	32 m	45 m	15 m
Pipeline	32 m	45 m	15 m
Structure with concrete base	64 m	90 m	50 m
Residence	64 m	90 m	50 m
Area of public congregation	64 m	90 m	50 m
Water well	64 m	90 m	100 m

IMPERFECT SEISMIC SOURCES

Ground vibrations and air-overpressure are direct consequences of using imperfect seismic sources for natural resources exploration. Gupta et al. (1988), in a study of ground and air vibration predictions generated by buried explosions, suggested that an explosion is an imperfect use of energy. When dynamite is detonated at a certain depth below the earth’s surface, approximately 20 to 30% of its energy is utilized in fragmenting the rock or other materials around. Part of the energy is not only transmitted through the earth in the form of seismic waves (i.e., used for seismic exploration) or vibrations, but also dissipated in the air, producing noise. Gupta et al. (1988) explained that the vertical vibration of the earth’s surface produces an equivalent particle velocity in the air, which results in air vibration of the same frequency as the seismic waves.

In the vibroseis case, it is well known that nearly two-thirds of the energy generated by a vibroseis truck is in the form of surface waves and the rest in the form of body waves (Oriard, 1994; Kalinski, 2007). However, one effective way of attenuating surface waves while at the same time enhancing body waves is by controlling the frequency spectrum of the sweep. When operating in an urban environments or hard-soil environments in general (e.g., roads, highways, gravel roads, etc.), the vibroseis source produces a significant amount of surface vibrations which could damage close structures. Oriard (1994) wrote: "If the vibrations can be felt and heard, it is quite common that many of the observers will regard the motion as potentially damaging to their houses, even though the vibrations may be below any reasonable threshold of damage". In such cases, vibration monitoring programs are very helpful to respond to damage claims.

INSTRUMENTATION AND MEASUREMENTS

A vibration monitoring program requires measurements of particle velocities in three directions because several features are responsible for the variation of these at a given distance. For instance, the geological and soil conditions, the type of seismic source, the type of waves, and the wavefield spreading geometry, affect the magnitude and direction of propagation of induced ground vibrations. Therefore, the strongest ground vibrations are expected to occur in any of the three directions (i.e., vertical, longitudinal, and transverse). In the case of air vibrations, these are transmitted through the air; hence, weather conditions replace geology as a principal variable (Sharp and Yule, 1998).

Typical instrumentation for vibration monitoring consists of a triaxial geophone, a microphone and the recording system, referred to as vibration monitor. This configuration is typical for peak particle velocity and air-overpressure measurements. However, other type 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.). The sampling frequencies are larger than those used in seismic data acquisition, therefore sampling frequencies in the range 1 kHz - 16 kHz are not uncommon.

The peak particle velocity (PPV) is the most accepted and used indicator of vibration levels. Most regulations and standards prescribe vibrations thresholds in terms of the PPV. For each recorded waveform, the maximum particle velocity over the total recorded time is regarded as the peak particle velocity (see Figure 1). This type of particle velocity must not be confused with the velocity with which the wave propagates through the medium (i.e., information of interest in seismic exploration).

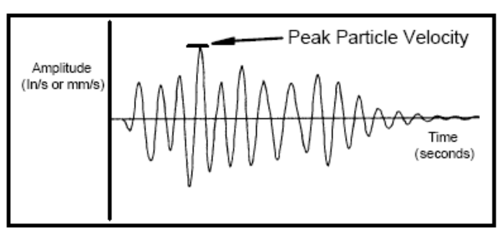

FIG. 1. Peak particle velocity definition (From Instantel, 2001).

The peak vector sum (PVS) is often preferred over the PPV because it reflects the effect of the other two components. Both have units of mm/s with slightly different magnitudes. In most blasting, the PVS occurs at about the same time as the PPV of one of the components, but the addition of the other two components increases its magnitude. In other words, the peak vector sum represents the resultant particle velocity magnitude. Recall that the magnitude of the resultant vector is always greater than the magnitude of its individual components. It is computed by squaring and summing the samples of each component at a time *t*, and then taking the square root of each sum. The maximum of theses sums is the peak vector sum and does not necessarily occur at the PPV of an individual waveform.

Air vibration is measured with a microphone whose output units are pressure (Pascals). Peak Sound Pressure Level (PSPL) is the analogous to PPV and determines the maximum overpressure. It if often referred to as air-overpressure because microphones measure pressure changes with respect to the atmospheric pressure level. This pressure amounts to roughly 100,000 Pa. Then, sound pressure is defined as the difference between the actual instantaneous pressure due to sound and the atmospheric pressure. Therefore, sound pressure has a much smaller value than the one corresponding to the atmospheric pressure.

The zero-crossing frequency (ZC frequency) is an approximation of the frequency of the peak particle velocity. It is computed by taking the inverse of the period between two consecutives zero crossings at the peak. It's an approximate measurement because the peak in a waveform may be the result of a band of frequency components.

REGULATIONS

The United States Bureau of Mines (UBSM) RI 8507 standard states that for frequencies between 3 and 10 Hz, the PPV should be kept below a threshold level of 13 mm/s to reduce the potential of damage. The threshold level increases with increasing frequency to 51 mm/s at 40 Hz and remains constant at 51 mm/s for frequencies above 40 Hz (Kalinski, 2007).

A CASE STUDY: NANTON, ALBERTA

WorleyParsons Komex was contracted by Compton Petroleum Corporation to conduct the vibration monitoring of a seismic exploration program in the area around Nanton, Alberta. The survey area was in the proximity close to water springs which are economically important for the Nanton community. There was a concern about the potential damage to the water springs caused by seismic activities. Therefore, the aim of the project was to monitor vibrations generated by vibroseis and dynamite sources. The recordings and their analysis are further discussed in a document prepared by WorleyParsons Komex (2007). However, we present and analyze some waveforms of peak particle velocity and air-overpressure recorded at the field.

The Vibroseis array consisted of four buggy-mounted Mertz model 8 vibrators. There were six sweeps (8-125 Hz) of 18s length each. Dynamite shots consisted of 2 kg of buried explosives in holes 15 m deep. The vibration monitor system was a Blasmate II developed by Instantel. It recorded four channels with a sampling rate of 1024 samples per second (1.024 kHz). The triaxial geophone and microphone both had bandpass responses from 2Hz to 250Hz.

The methodology consisted of two monitoring points. One monitor system was placed at the Nanton water spring for continuously recording ambient vibrations and the PPV for each of the shot points. The second vibration monitor was placed at a specific shot point from where all shots within a single seismic line were monitored. The methodology was repeated for all seismic lines in the survey. A 10 s waveform was recorded for a variety of distances between the fixed points and fired shot points. Figure 2 shows the monitoring area and vibration monitor setup.

FIG.2. Vibration monitor setup (left) and shooter ready to fire a source point (right).

Figure 3 shows an example of a vibration event report. This example corresponds to a vibration monitor placed 5m from one dynamite test shot at approximately 2.2 km of the Nanton water spring. The event report includes an informative section with the date and time of the acquisition, site location, file name, etc. The actual measurements are organized by sensor type. For the microphone, the peak sound pressure level (PSPL) in Pascal (Pa), the zero-crossing frequency in Hertz, the type of scale (linear or weighted), and sensor-check status are included. For the triaxial geophone, each component is checked and recorded independently. PPV (mm/s), ZC frequency (Hz), peak time (s), peak acceleration (g), peak displacement (mm) and peak vector sum (mm/s) are calculated for each channel. The waveforms are also plotted along with the sensor-check curves. Finally, recorded PPV values are plotted within a compliance reference chart. This reference is based on available vibration regulations, which are different from country to country. The report in Figure 3 uses U.S.A. USBM/OSMRE but other options can be chosen as reference. Note that monitoring of ground vibrations at 5m offset gives very high PPV in all three directions. The measured PPV values are 145 mm/s in the vertical direction, 113 mm/s in the longitudinal, and 40.1 mm/s in the transverse. The computed PVS is 145 mm/s at 5.001 seconds.

Figure 4 is an event report for the vibroseis shot point monitored at a distance of 5m. The vibroseis array moved in the south direction along a seismic line running north to south. The responses of the triaxial geophone and the microphone are quite different from those recorded for the dynamite case. Such responses were expected given the different nature and mechanism of energy transmission of the sources. An important feature in this event report is the magnitude of the PPV in the transverse component, which is greater than the PPV recorded in the vertical and longitudinal components. This facture is also observed with the monitor placed at 50 m from the vibroseis trucks.

Kalinski (2007) suggested that the use of distance as the only criterion for selecting monitoring points is an oversimplification of the PPV field associated with vibroseis arrays. In fact, during the Nanton monitoring program there was a suspected zone of constructive interference (see Figure 5). A vibration monitor placed on a gravel road at a distance of 50m from the vibroseis array recorded a PSPL of 30.5 Pa (123.66 dB) with 2.5Hz dominant frequency, which is larger than the PSPL recorded at 5m offset along the same road (i.e., 19 Pa or 119 dB with 2.88Hz dominant frequency). However, the 5m offset microphone may have been shielded by the truck. On the other hand, there may be some sort of constructive interference occurred near the vibration monitor placed at 50m. Certainly, events of this magnitude may cause some disturbance to nearby humans, even though the dominant frequencies are in the infrasound band (i.e., not audible by humans) when vibroseis trucks operate in urban environments. Coupling phenomena at the air-earth interface provide a possible explanation for constructive interference. Air-coupled surface waves and ground-coupled airwaves may cause PPV or PSPL amplification as a result of resonance coupling at the air-earth interface. For further explanation on this phenomena please refer to Alcudia and Stewart (2007) in this research volume.

Figure 6 is an event report of a histogram recorded over 12.75 min at the water spring while shooting, with the closest dynamite shot at about 1.6 km. A histogram is computed by recording a number of time intervals. For each interval, the monitor calculates the maximum positive and negative peaks, the frequency of the largest peak, and one peak vector sum. For each channel, the maximum peak, its frequency, and the largest peak vector sum is calculated over the entire event. Figure 7 shows a histogram of natural vibrations recorded at the water spring few days before seismic activities started. Peak particle velocities in the vertical and longitudinal components are equal in both histograms despite they were recorded in different days. The PPV in the transverse component is slightly larger (i.e., 0.0794 mm/s) for the histogram of natural vibrations than the PPV for the histogram of shots (i.e., 0.0635 mm/s). This implies that ground vibrations induced by shooting did not reach the water spring. Moreover, peak sound pressure levels did increase a little while shooting, but this was largely attributable to other ambient vibrations. Therefore, the 1.6 km safe radius allowed seismic operations not to cause any potential damage to the water spring.

Time-frequency representations of the three ground motion components and the air vibration component induced by the vibroseis source were computed using the Gabor transform, a particular case of the windowed, short-time Fourier transform. This analysis revealed the harmonic distortion of the signals produced by the vibroseis source. The microphone output signal shows the fundamental frequency plus five high-order harmonics (see Figure 8). The ground motion signals show the fundamental frequency and only two high-order harmonics (see Figure 9, 10 and 11). For all cases, the high-order harmonics have low energy in comparison to the fundamental. However, the existence of harmonics in the recorded signals demonstrates that the transfer of energy from the vibrator to the earth is not perfect, and some of the energy is propagating as ground and air vibrations. Further analysis of the frequency harmonics may give additional information about the source-generated noise.

CONCLUSIONS

Vibration monitoring of seismic sources can contribute to achieve sustainable development, in particular when seismic operations are undertaken over sensitive and restricted areas. The monitoring results suggest that three components of ground motion need to be measured, since the PPV in the longitudinal and transverse components could be larger than the PPV measured in the vertical direction. Vibration measurements are fairly simple and straightforward in terms of peak values of particle velocity and air-overpressure. However, waveform analysis of ground motion and air vibration may reveal some interesting features in the data.

FUTURE RESEARCH

It has been suggested by Kalinski (2007) that the use of multiple vibroseis trucks creates the potential for complex PPV fields around the trucks. There is plenty of room for research in source-generated noise characterization. Noise is undesirable in seismic records but noise propagating at the surface in the form of ground and air vibrations is also environmentally important and deserves more attention. For instance, prediction of peak particle velocity and air-overpressure for dynamite and vibroseis are considered for future research.

If we think of a vibration monitoring system as a dual-sensor approach for land acquisition, the idea of using pressure and velocity, or pressure and acceleration for noise suppression is quite interesting. It could also be used for ground response modeling and analysis.

ACKNOWLEDGEMENTS

We would like to thank Compton Petroleum Corporation for providing the vibration monitoring data. A demo version of the Blasmate II software is available at the Instantel website, which generated the event reports presented in this paper. Hence, thanks to Instantel for such a facility. We would also like to thank CREWES sponsors and staff for their continuing support.

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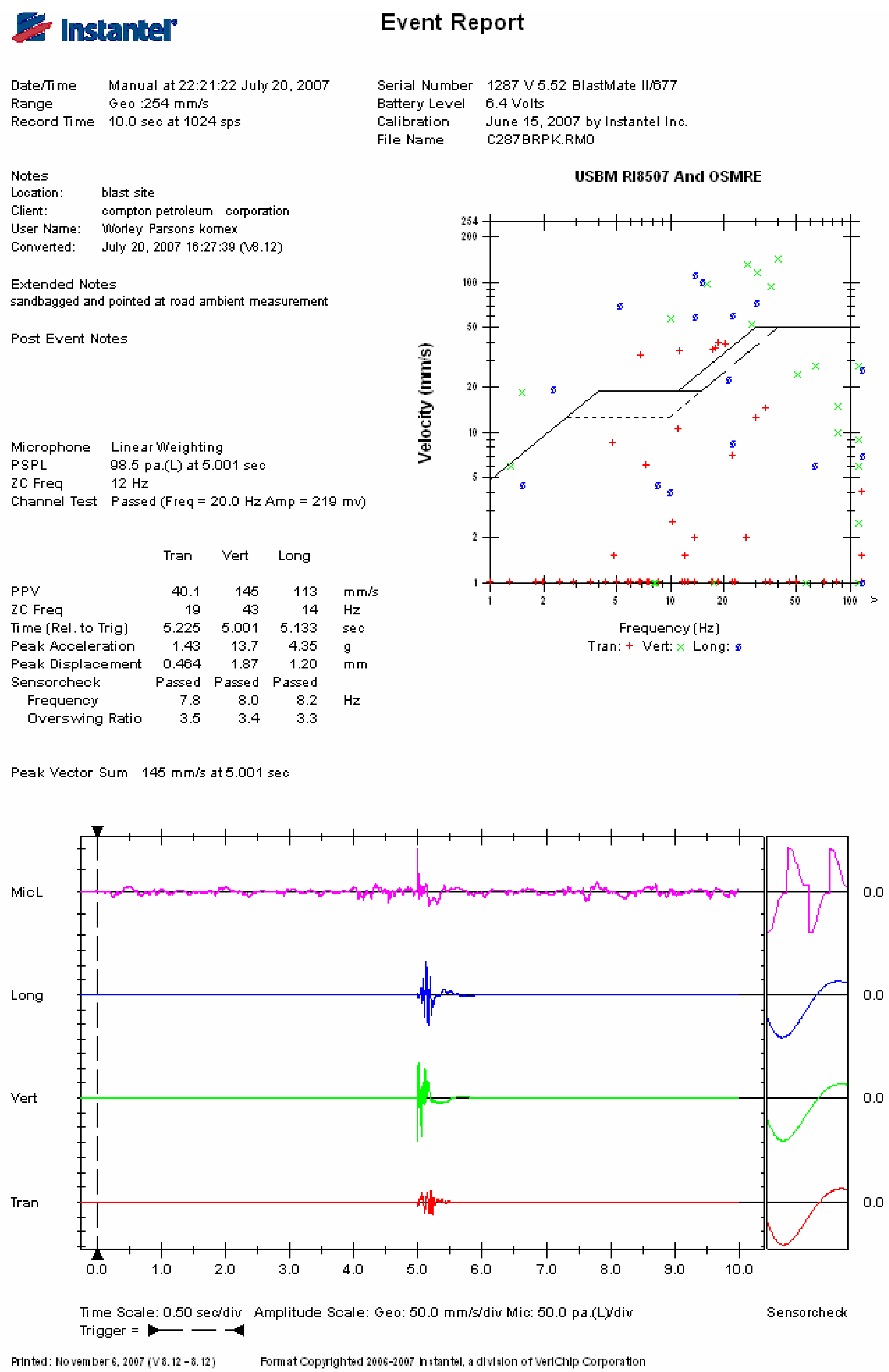

Instantel

Event Report

Date/Time	Manual at 22:21:22 July 20, 2007
Range	Geo :254 mm/s
Record Time	10.0 sec at 1024 sps

Serial Number	1287 V 5.52 BlastMate II/677
Battery Level	6.4 Volts
Calibration	June 15, 2007 by Instantel Inc.
File Name	C287BRPK.RM0

Notes

Location:	blast site
Client:	compton petroleum corporation
User Name:	Worley Parsons komex
Converted:	July 20, 2007 16:27:39 (V8.12)

Extended Notes
sandbagged and pointed at road ambient measurement

Post Event Notes

Microphone	Linear Weighting
PSPL	98.5 pa.(L) at 5.001 sec
ZC Freq	12 Hz
Channel Test	Passed (Freq = 20.0 Hz Amp = 219 mv)

	Tran	Vert	Long	
PPV	40.1	145	113	mm/s
ZC Freq	19	43	14	Hz
Time (Rel. to Trig)	5.225	5.001	5.133	sec
Peak Acceleration	1.43	13.7	4.35	g
Peak Displacement	0.464	1.87	1.20	mm
Sensorcheck	Passed	Passed	Passed	
Frequency	7.8	8.0	8.2	Hz
Overswing Ratio	3.5	3.4	3.3	

Peak Vector Sum 145 mm/s at 5.001 sec

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FIG. 3. Vibration and air-overpressure monitoring of dynamite shot. The vibration monitor system was located 5 m distance from the explosion. The PPV occurred at 5.001 s in the vertical component. The PSPL also occurred at the same time. The PPV in the horizontal components occurred at slightly later times being smaller than the vertical PPV. Note that the vibrations at such small distance reach threshold levels.

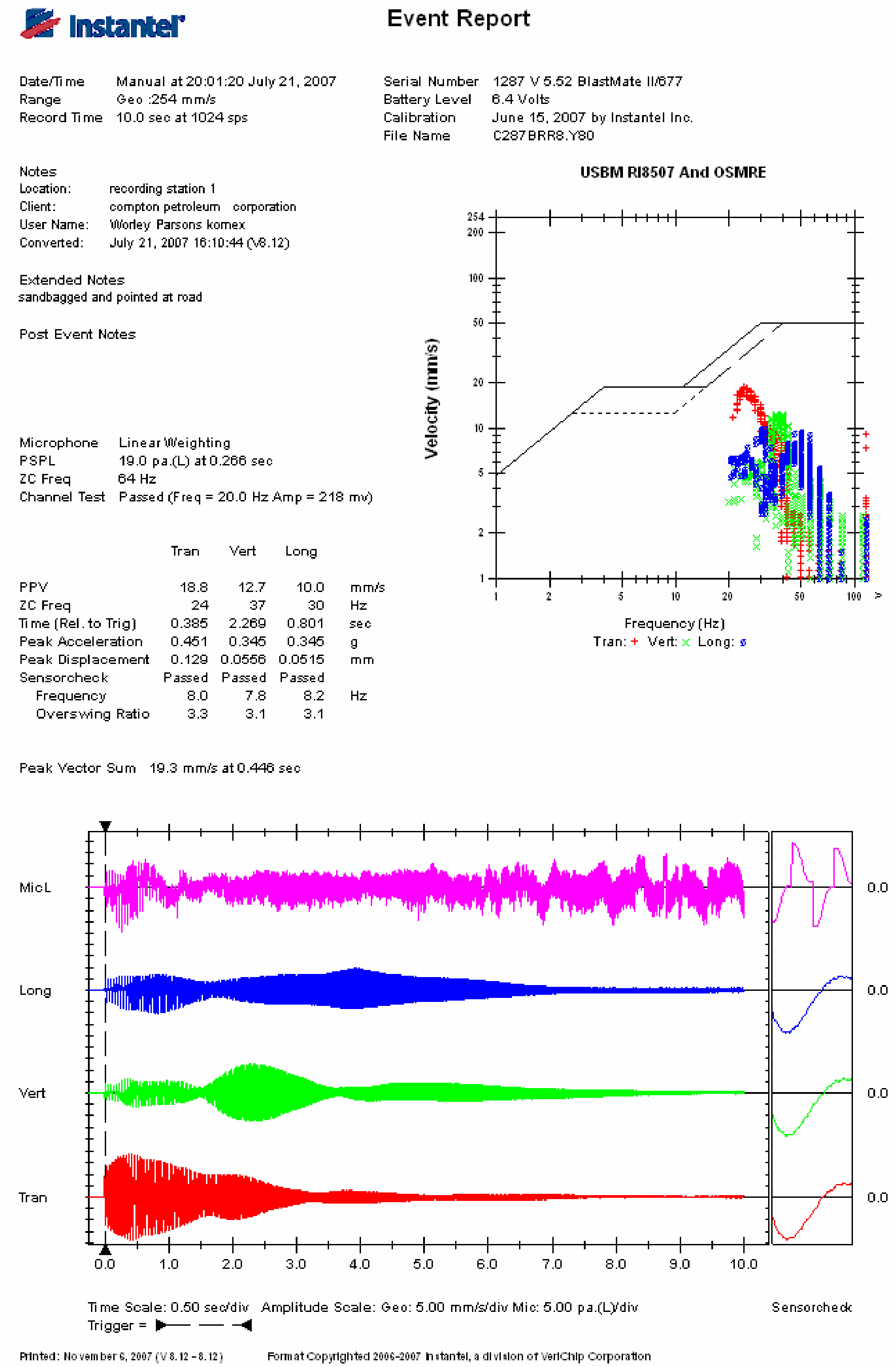
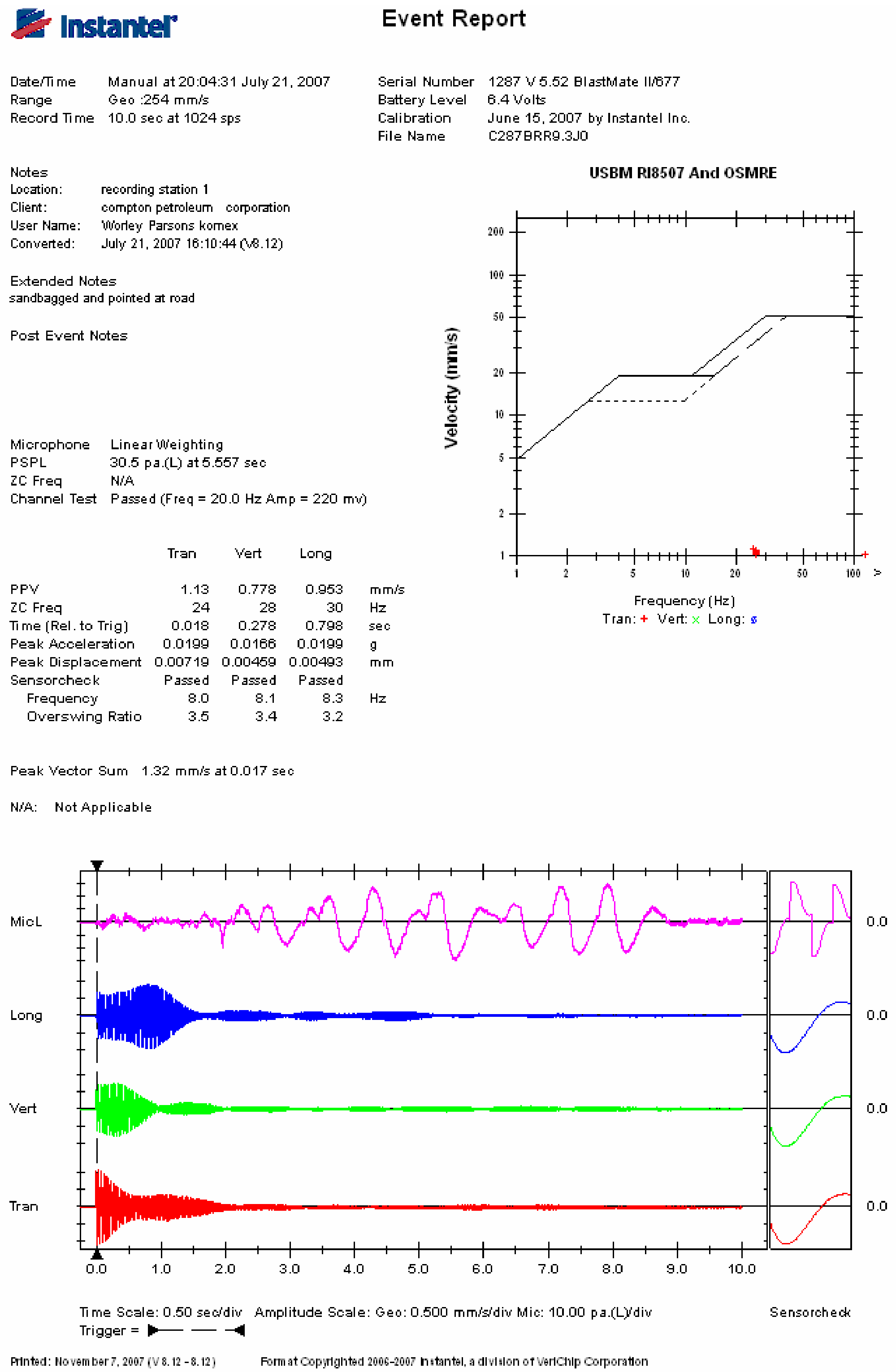


FIG. 4. Vibration and air-overpressure monitoring of vibroseis source. The vibration monitor system was located 5 m distance from the vibroseis array. The PPV occurred early in the transverse component, followed by the PPV on the longitudinal, and finally on the vertical. The PSPL was 19 Pa at 0.266 s. Note that none of the components reach a critical vibration level with respect to USBM and OSRME standards.



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Event Report

Date/Time	Manual at 20:04:31 July 21, 2007
Range	Geo :254 mm/s
Record Time	10.0 sec at 1024 sps

Serial Number	1287 V 5.52 BlastMate II/677
Battery Level	6.4 Volts
Calibration	June 15, 2007 by Instantel Inc.
File Name	C287BRR9.3J0

Notes

Location:	recording station 1
Client:	compton petroleum corporation
User Name:	Worley Parsons komex
Converted:	July 21, 2007 16:10:44 (V8.12)

Extended Notes
sandbagged and pointed at road

Post Event Notes

Microphone	Linear Weighting
PSPL	30.5 pa.(L) at 5.557 sec
ZC Freq	N/A
Channel Test	Passed (Freq = 20.0 Hz Amp = 220 mv)

	Tran	Vert	Long	
PPV	1.13	0.778	0.953	mm/s
ZC Freq	24	28	30	Hz
Time (Rel. to Trig)	0.018	0.278	0.798	sec
Peak Acceleration	0.0199	0.0166	0.0199	g
Peak Displacement	0.00719	0.00459	0.00493	mm
Sensorcheck	Passed	Passed	Passed	
Frequency	8.0	8.1	8.3	Hz
Overswing Ratio	3.5	3.4	3.2	

Peak Vector Sum 1.32 mm/s at 0.017 sec

N/A: Not Applicable

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FIG. 5. Vibration and air-overpressure monitoring of vibroseis. The vibration monitor was located 50 m distance from the vibroseis array. PPV for the three components are very small. However, the PSPL was 30.5 Pa at 5.557s. Most interesting is the microphone waveform with dominant low-frequency content.

Instantel® **Event Report**

Histogram Start Time	23:33:17 July 29, 2007	Serial Number	1287 V 5.52 BlastMate II/677
Histogram Finish Time	23:46:00 July 29, 2007	Battery Level	6.3 Volts
Number of Intervals	153 at 5 seconds	Calibration	June 15, 2007 by Instantel Inc.
Range	Geo :7.92 mm/s	File Name	C287BS6C.3H0
Sample Rate	1024sps		

Notes
Location: nanton sping2
Client: compton petroleum corporation
User Name: Worley Parsons komex
Converted: July 30, 2007 10:07:41 (V8.12)

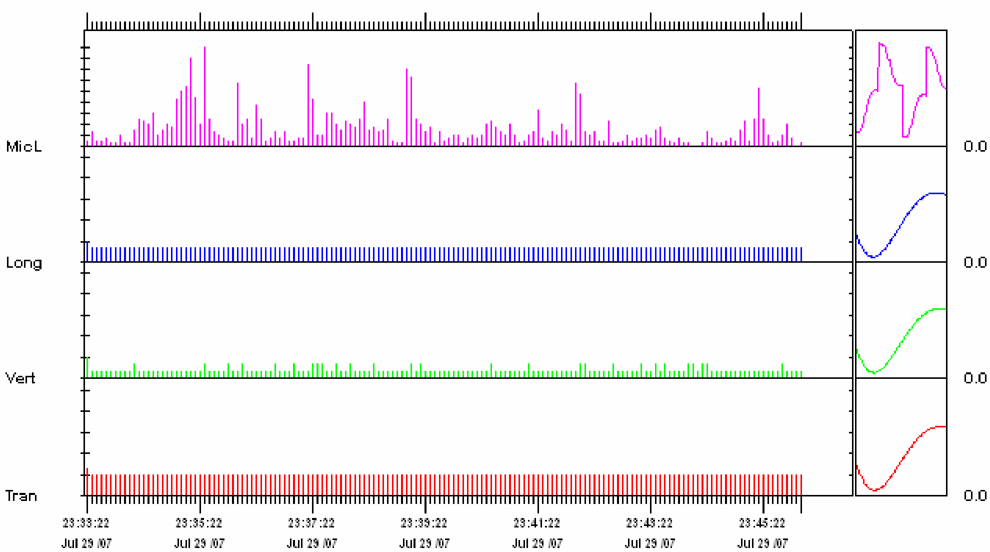
Extended Notes
sandbagged and pointed at line

Post Event Notes

Microphone Linear Weighting
PSPL 18.0 pa.(L) on July 29, 2007 at 23:35:27
ZC Freq 4.0 Hz
Channel Test Passed (Freq = 20.0 Hz Amp = 216 mv)

	Tran	Vert	Long	
PPV	0.0635	0.0476	0.0476	mm/s
ZC Freq	15	>100	>100	Hz
Date	Jul 29 /07	Jul 29 /07	Jul 29 /07	
Time	23:33:22	23:33:22	23:33:22	
Sensorcheck	Passed	Passed	Passed	
Frequency	7.8	8.0	8.3	Hz
Overswing Ratio	3.4	3.4	3.2	

Peak Vector Sum 0.0794 mm/s on July 29, 2007 at 23:33:22



Time Scale: 5 seconds /div Amplitude Scale: Geo: 0.0500 mm/s/div Mic: 2.00 pa.(L)/div Sensorcheck

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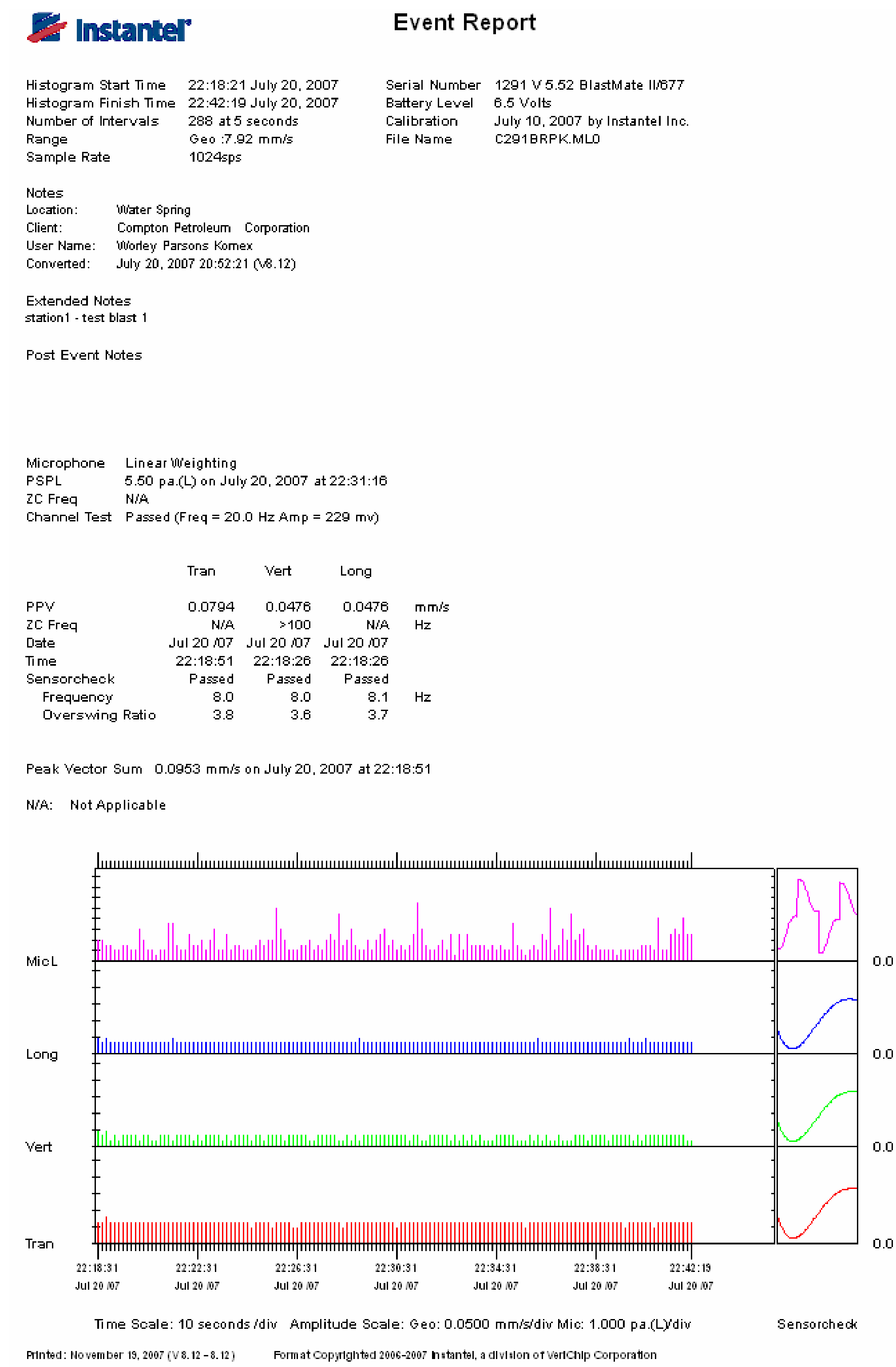
FIG. 6. Histogram recorded at the Nanton water spring for a series of dynamite shots. The nearest shot to the monitor station was at about 1.6 km.



Instantel®

Event Report

Histogram Start Time	22:18:21 July 20, 2007	Serial Number	1291 V 5.52 BlastMate II/677
Histogram Finish Time	22:42:19 July 20, 2007	Battery Level	6.5 Volts
Number of Intervals	288 at 5 seconds	Calibration	July 10, 2007 by Instantel Inc.
Range	Geo :7.92 mm/s	File Name	C291BRPK.ML0
Sample Rate	1024sps		

Notes
Location: Water Spring
Client: Compton Petroleum Corporation
User Name: Worley Parsons Komex
Converted: July 20, 2007 20:52:21 (V8.12)

Extended Notes
station1 - test blast 1

Post Event Notes

Microphone Linear Weighting
PSPL 5.50 pa.(L) on July 20, 2007 at 22:31:16
ZC Freq N/A
Channel Test Passed (Freq = 20.0 Hz Amp = 229 mv)

	Tran	Vert	Long	
PPV	0.0794	0.0476	0.0476	mm/s
ZC Freq	N/A	>100	N/A	Hz
Date	Jul 20 /07	Jul 20 /07	Jul 20 /07	
Time	22:18:51	22:18:26	22:18:26	
Sensorcheck	Passed	Passed	Passed	
Frequency	8.0	8.0	8.1	Hz
Overswing Ratio	3.8	3.6	3.7	

Peak Vector Sum 0.0953 mm/s on July 20, 2007 at 22:18:51

N/A: Not Applicable

Time Scale: 10 seconds /div Amplitude Scale: Geo: 0.0500 mm/s/div Mic: 1.000 pa.(L)/div Sensorcheck

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FIG. 7. Histogram of natural vibrations recorded at the Nanton water spring nine days before shooting.

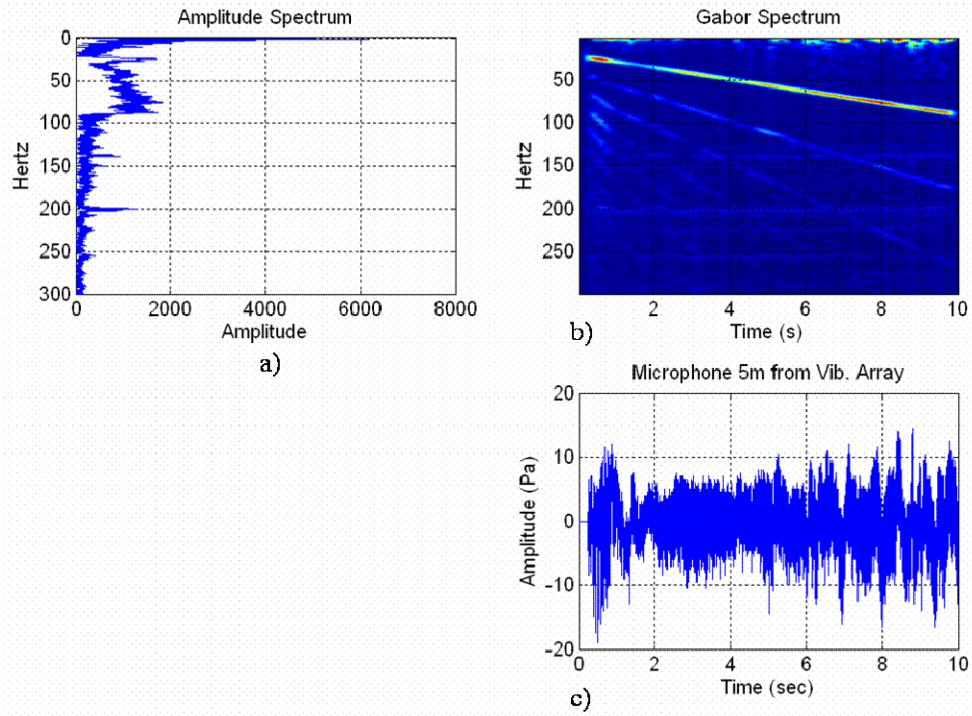

FIG. 8. a) Amplitude spectrum, b) Gabor transform in the time-frequency space, and c) time domain representation of the microphone record. Note that there exist high-order harmonics in the signal.

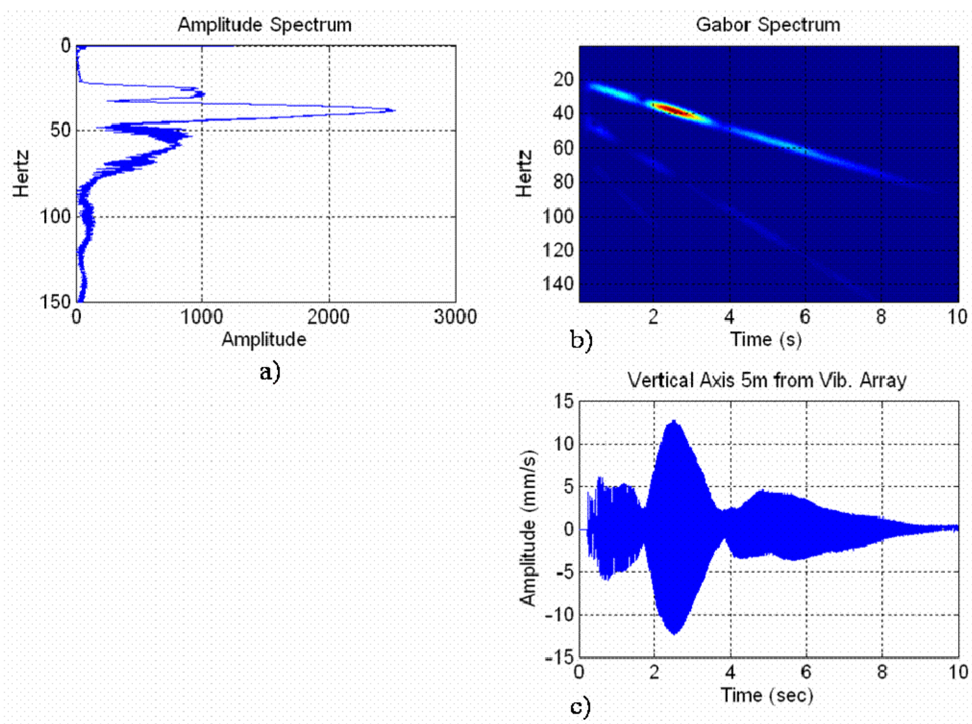

FIG. 9. a) Amplitude spectrum, b) Gabor transform in the time-frequency space, and c) time domain representation of the geophone vertical component. Note there are two high-order frequency harmonics.

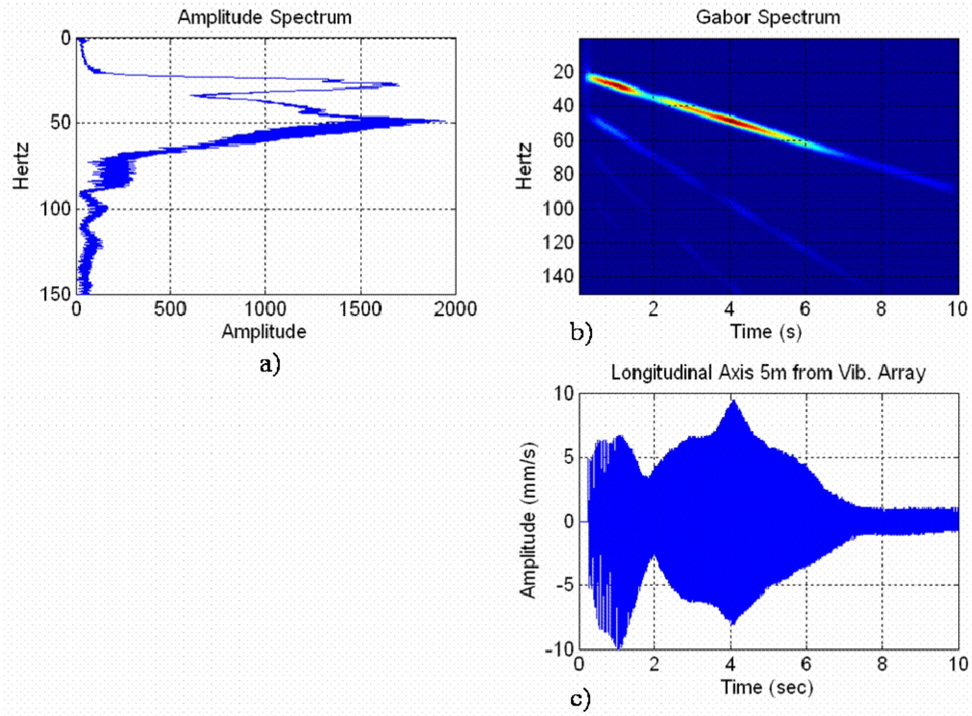

FIG. 10. a) Amplitude spectrum, b) Gabor transform in the time-frequency space, and c) time domain representation of the geophone longitudinal component. Note there are two high-order frequency harmonics.

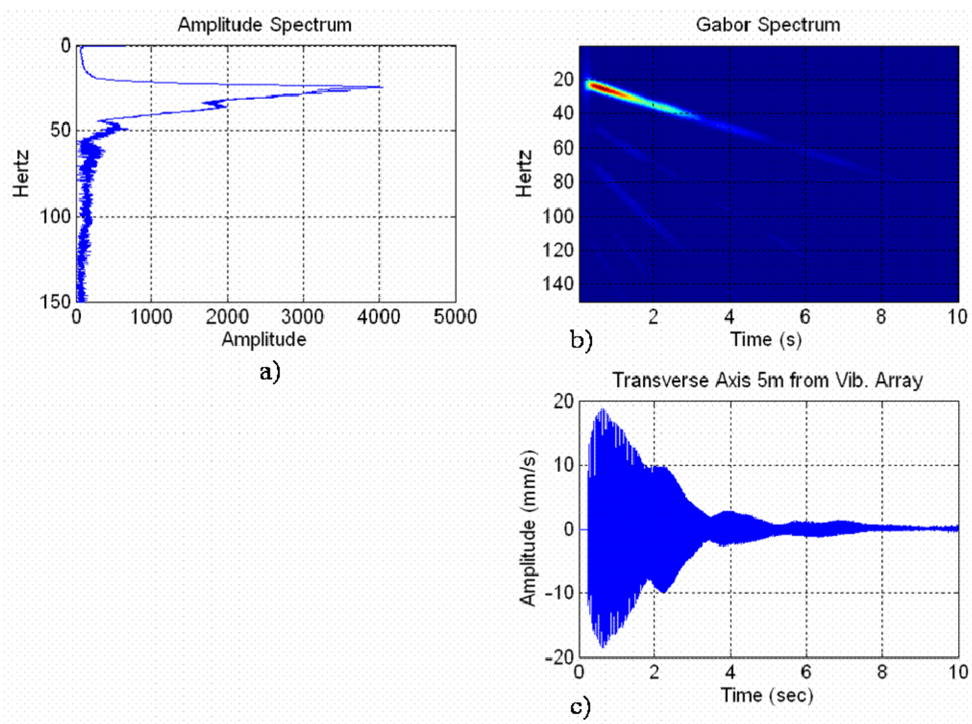

FIG. 11. a) Amplitude spectrum, b) Gabor transform in the time-frequency space, and c) time domain representation of the geophone transverse component. Note there are two high-order frequency harmonics.