High-resolution land seismic acquisition with Broadsweep

Tagir Galikeev[1*], Alexander Zhukov[2] and Ilya Korotkov[2] present a Vibroseis acquisition technology with real-time data feedback that adjusts sweep parameters to compensate for changing near-surface conditions while delivering broadband seismic data with high signal-to-noise ratio.

Introduction

Seismic acquisition techniques have steadily progressed over time to achieve higher productivity and greater data bandwidth. Vibroseis sources with new hydraulics and plate and chassis design (Bagaini, 2008; Wei, 2017) are able to generate sweeps between 1-2 Hz to 300-400 Hz (Wei, 2015). Receivers have graduated from complicated patterns to the single-point omnidirectional receiver. Trace density of surveys has increased to provide higher signal-to-noise ratio and homogeneous azimuthal and offset coverage.

Vibroseis is a controllable source and its amplitude and frequency characteristics can be manipulated to shape the signal of the desired amplitude and phase spectrum. This remarkable feature of the Vibroseis source, however, remains underutilized: most of the acquisitions are performed with linear sweeps or sweeps with a very mild degree of non-linearity in the frequency-time domain.

Increasing the bandwidth of seismic data has several advantages from reducing ambiguity in statics and velocity models during processing to more reliable seismic-to-well ties and seismic inversion results. The result is better reservoir characterization and reduced exploration risk. High quality data with increased signal-to-noise ratio provides for faster conventional interpretation as well as quantitative interpretation utilizing sophisticated multi-trace attributes, machine learning-based algorithms and azimuthal seismic anisotropy analysis (Curia et al., 2018).

We have developed a real-time adaptive Vibroseis acquisition technology utilizing a new controller hardware and software, which takes advantage of real-time data feedback and adjusts sweep parameters to compensate for changing near-surface conditions while delivering broadband seismic data with high signal-to-noise ratio. Electronic sweeps, signals from the inertial mass and baseplate are stored, and can be used during processing to further increase data quality. This autonomous system can be used with any vibrator and without any special hardware modifications.

The technology can be tuned for a particular reservoir interval to achieve maximum signal-to-noise ratio and resolution, which is further enhanced in processing. This targeted approach is especially beneficial for tight unconventional reservoirs for time-lapse hydraulic fracturing monitoring.

Theory

From early efforts of combi sweeps (Werner and Krey, 1979) to a more sophisticated shaped and HFVS sweeps (Krohn and Johnson, 2006) the seismic acquisition companies tried to take advantage of the fact that Vibroseis is a controllable source and its amplitude and phase spectrum can be shaped in a desirable way. Later, however, the industry changed direction towards higher productivity and fold increase and the more complex signals were left for the research side of the industry. The technology has been steadily progressing along with the

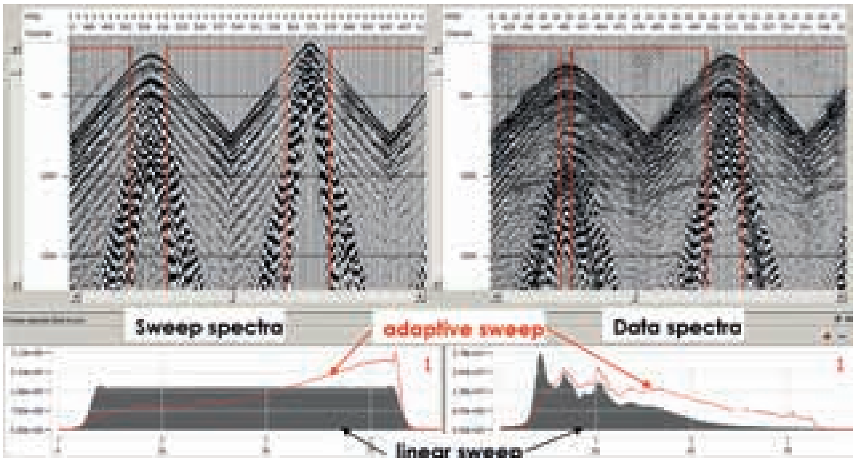

Figure 1 Computation of the optimal (adaptive) sweep.

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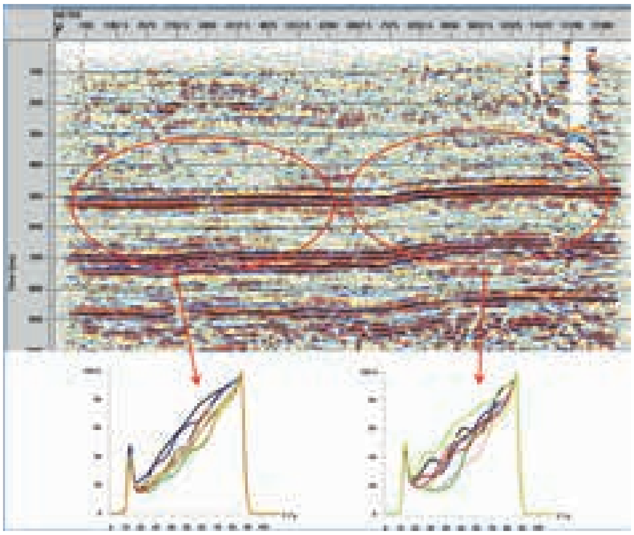

Figure 2 Power spectrum of the adaptive sweep shown for two distinct near-surface conditions: harvested wheat field (left) and marshy area (right).

technology of Vibroseis hardware, programmable boards, navigational and radio electronics, and implementation of slip sweep (Wams and Rozemond, 1998), shuffle sweep (Zhukov et al., 2017) and independent simultaneous sweeping (ISS) (Howe et al., 2009).

The system is a natural progression from the optimal sweep algorithm developed in the 1980s (Kolesov and Inozemtsev, 1988.) It utilizes the concept of the inverse amplitude spectrum (Figure 1). In that sense it is similar to the deconvolution concept, but performed during field acquisition to improve bandwidth and S/N of the recorded data and therefore used to increase the resolution of seismic data.

Figure 1 illustrates the main concept of the optimal/adaptive sweep computation with real time data feedback.

1. Data are acquired with linear sweep. Amplitude spectrum of the sweep is shown in grey on the bottom left of Figure 1.
2. Upper left side of Figure 1 shows data recorded with the linear sweep with selected analysis windows (red rectangles).
3. Bottom right shows the power spectrum of the acquired data with linear sweep in grey.
4. The inverse of the data power spectrum from (3) is computed and then recalculated into frequency-time dependency of the new adaptive sweep, which takes into account filtering properties of the Earth. With the help of Parseval theorem we can convert power spectrum into frequency-time dependency. Thus, we can generate a sweep signal with a given power spectrum. Its power spectrum is shown as a red line, bottom left of Figure 1. Adaptive sweep is naturally non-linear and will have a slower sweep rate (Hz/s) on mid-to-higher-frequencies to compensate for frequency loss at the higher end of the spectrum.
5. Red line in bottom right is the recorded data power spectrum with newly computed adaptive sweep. It has a flatter spectrum and higher frequency content, which translates into higher S/N ratio and higher resolution as illustrated in upper-right part of Figure 1.

The Broadsweep algorithm has been modified to accommodate the ‘one sweep per VP’ field acquisition. An adaptive part can be computed using the known non-linear sweep from the previous VP without initial linear sweep. Vibrator electronics coupled with a software solution allows one to select the proper parameters in real time during the field acquisition project and does not require preliminary custom sweep acquisition tests and calculations. Most of the limitations such as sweep start and end frequency as well as frequency rate will be dictated by the hydraulics of the given vibrator fleet.

Figure 2 illustrates how the rate of adaptation varies along the seismic line. Part of the seismic line went through the harvested wheat field (left side) and another part of the line crossed the marshy area (right side). The wheat field has a more homogeneous and dense near surface, which translates into smaller variability of the computed adaptive sweeps and their power spectra (bottom left). While adaptive sweeps in the marshy area vary significantly to compensate for highly variable near surface (bottom right). The final seismic section has similar amplitude-frequency characteristics, S/N ratio and resolution regardless of the changing near-surface conditions.

To implement the concept of complete control over the shape of the emitted geophysical signal along with the ability to control the amplitude spectrum of the sweep signal, which is carried out by frequency and amplitude modulation, it is necessary to introduce the phase delays into the sweep to compensate for the phase changes occurring due to propagation in the geological environment. For example, the phase dispersion of various frequencies during signal propagation in a medium is a well-studied phenomenon (Jacobson, 1987) and usually leads to an increase in the total duration of the reflected signal, which reduces the vertical resolution of the seismic survey. To compensate for phase dispersion during propagation, it is necessary to add reverse phase delays into the emitted signal. Such delays are calculated based on the amplitude spectrum of the reference sweep signal using the nonlinear absorption model of the medium (Strick, 1967; Futterman, 1962).

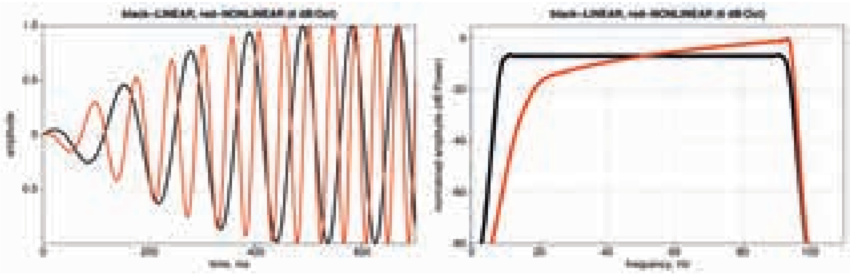

Figure 3 Linear and nonlinear (dB/Oct) sweep. First 700 ms of the sweeps are shown on the left and the amplitude spectra are on the right. Black is linear sweep and red is dB/Oct with 6dB/octave degree of nonlinearity.

Algorithms that implement nonlinear absorption compensation and phase dispersion are widely known as inverse Q-filtering. In cases when the waveform recorded in the medium is known, for example, based on the results of measuring the direct wave during VSP operations, a filter is constructed that is inverse to such signals. The amplitude spectrum of this inverse filter is used to calculate the nonlinear frequency modulated sweep and the phase spectrum is converted to time delays implemented at particular frequencies of the emitted sweep. Thus, deterministic accounting of the effects of signal propagation in the geological environment occurs.

When VSP data are not available, the phase spectrum can be constructed as a minimum phase equivalent. In this case, after the correlation of the recorded vibrogram with the reference signal, which do not contain such delays, a correlogram is obtained that is equivalent to the minimum phase pulse source, which corresponds to the convolutional model widely used in seismic data processing.

Adaptive sweeps increase the resolution of the acquired data (Figure 4), but still do not deliver the true broadband data of six frequency octaves as an industry standard. Boosting mid and high frequencies in a nonlinear sweep effectively redistributes energy from low frequencies into mid and high frequencies when compared to linear sweeps of the same length. Left side of Figure 3 demonstrates on the first 700 ms of the sweep that the nonlinear sweep goes through low frequencies quite quickly when compared to linear sweep, which results in lower low-frequency energy in the data as shown on the right side of Figure 3. Low frequencies are quite important for data resolution and reliable inversion results.

In order to achieve true broadband results, an adaptive sweep was enriched with low-dwell sweep on the low-frequency side. Adding low-dwell sweep allowed the boosting of low-frequency content while maintaining the demonstrated advantages of adaptive sweep.

Figure 5 shows a difference in characteristics for four different types of sweeps: linear, adaptive, low-dwell low-frequency and Broadsweep:

- Linear sweep has a linear frequency-time dependency and a constant vibrator force, which is reflected in the rectangular shape of the amplitude spectrum. The rest of the sweeps are nonlinear in nature.
- Adaptive sweep, in the same way as the conventional linear sweep, always works at full force, but has a nonlinear F-T dependence and boosts mid-to-high frequencies as evident from the spectrum plot.
- Low-dwell low-frequency sweep spends a considerable amount of sweep time on low frequency, but with a low force so as not to damage the hydraulics of the conventional vibrator. After that the force is ramped up and the sweep becomes linear. Low-dwell is essentially a linear sweep as reflected by the amplitude spectrum, where the low frequency rate on low frequencies (frequency modulation) is compensated by lower force (amplitude modulation).
- Broadsweep takes advantage of both low-dwell low-frequency and adaptive sweep to maintain the rectangluar-shaped spectrum of the recorded data for maximum S/N ratio and resolution.

The technology has a wide base of installations in Russia and China and works with a wide variety of conventional unmodified vibrators from Sercel, Inova, Geosvip, Bashneftegeofizika and Chinese manufacturers. Figure 6 demonstrates a comparison between Broadsweep and a conventional linear sweep of the same duration performed in China with a heavy Chinese-made vibrator. The linear sweep had frequencies of 8-90 Hz and Broadsweep 1.5-90 Hz. Both sweeps had a ten-second length. Bandpass panels show a central frequency of the filter and Broadsweep delivered six octaves of data formally qualifying the dataset as broadband, while the linear sweep delivered only three full-frequency octaves.

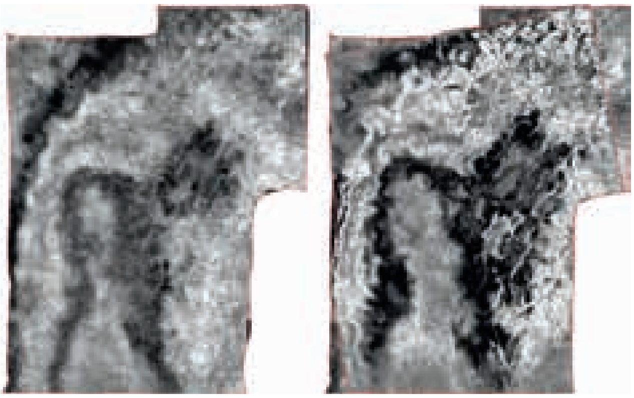

Figure 4 Time slices through the 3D volume at the reservoir level acquired with linear (left) and adaptive sweep (right). Same start and end frequencies for the sweep.

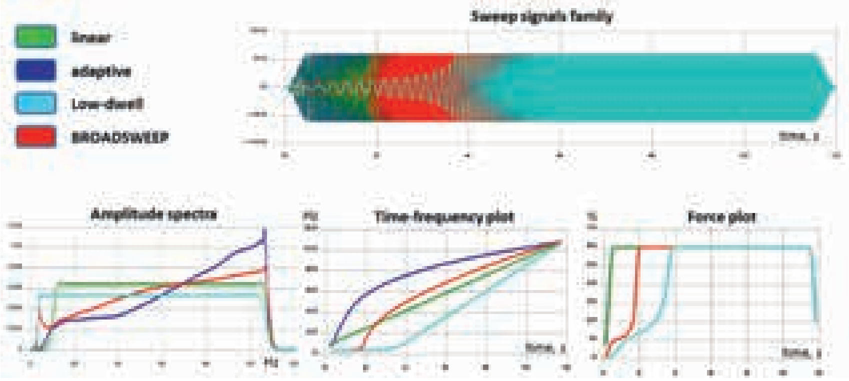

Figure 5 Different families of sweeps with their time, spectra, force and frequency-time representations.

Field examples

Two 3D field examples show the comparison between different types of sweeps (first example) and compare Broadsweep technology to the dynamite survey (second example).

The first field example is located in Orenburg area, Russia. A production 3D survey was shot with four different sweeps: linear, adaptive, low-dwell low-frequency and Broadsweep. Field acquisition parameters and source and receiver geometry are shown in Figure 7.

The project utilized conventional acquisition equipment on source and recording sides with Broadsweep vibrator controllers and a laptop housed in a recording truck with Broadsweep software. All four types of sweeps tested had a length of 12 seconds and the following frequency ranges:

- Linear: 8-110 Hz
- Adaptive 6-110 Hz
- Low-dwell: 3-110 Hz with low-dwell part 3-8 Hz
- Broadsweep: 3-110 Hz, with low-dwell part 3-8 Hz and adaptive part 8-110 Hz

Analysis of the acquired datasets was performed on all types of data from raw shot records through to intermediate stacks and final migrated stacks. The processing sequence was the same for all volumes acquired with four different sweeps with the statics solution and velocity field being exactly the same for all volumes. The generalized processing sequence consisted of:

- True amplitude recovery
- Refraction statics (several iterations)
- Velocity analysis
- Random noise attenuation
- Surface wave noise attenuation
- Surface-consistent amplitude corrections and deconvolution
- Pre-stack Kirchhoff time migration
- Post-stack processing

The value of utilizing Broadsweep is demonstrated by the acoustic inversion results illustrated in Figure 8. The area had two wells with sonic and density logs among others. The impedance curve computed from wells was compared to post-stack seismic sparse-spike inversion results for all four sweeps. The Broadsweep volume has the best seismic-to-well ties and the highest correlation between well impedance and seismic inversion results. The inversion algorithm converged to the true impedance model of the subsurface in the case of Broadsweep due to the broadband nature of the data acquired: the low frequency-guaranteed correct background impedance model and high frequencies helped with thin bed resolution.

A second example is from a recent 660 km^2 survey spanning land, transit zone and shallow waters of the Volga river, completed in 2018. Land data included two datasets: one acquired with Broadsweep and the second with dynamite. Survey geometry and dynamite charge parameters were selected according to the established acquisition practices in the area.

Land acquisition used 400 grammes of dynamite in one borehole at depths of 9-31 m below the low velocity layer. Broadsweep was designed for six frequency octaves and swept from 3 to 96 Hz with the low-dwell part 3-8 Hz and the adaptive part 8-96 Hz. Acquisition hardware included conventional Sercel NOMAD 65 vibrators and Geospace GS-20DX receivers in groups of 12 spread over 25 m. The survey was designed as a high-density wide-azimuth survey with a CDP bin size of 25 m and with the maximum fold of 324.

An integral part of the system are accelerometers mounted on main vibrator components for feedback. Feedback signals

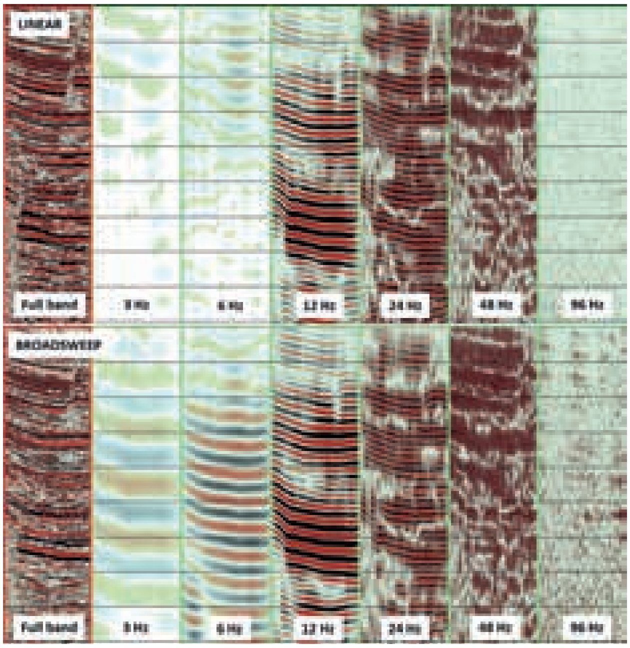

Figure 6 Comparison of conventional linear weep (top) with Broadsweep (bottom).

Receiver line distance, m	300
Source line distance, m	300
Receiver distance, m	50
Source distance, m	50
Active channels per line	120
Number of receiver lines	20
Maximum source-receiver offset, m	4207
Receiver type	GS 20-DX
Vibroseis truck	NOMAD 65
Force, %	60
Sources in group	3-4
Sweep length+listen, ms	12000+6000

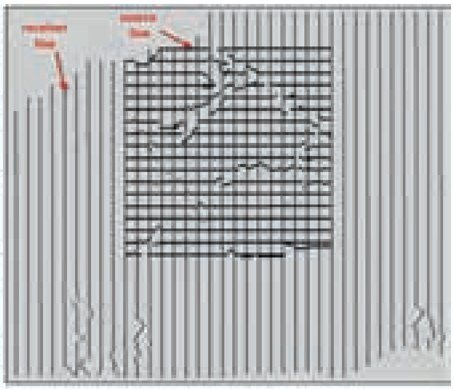

Figure 7 Field acquisition parameters. Exactly the same field geometry was shot four times with four different sweeps: linear, adaptive, low-dwell low-frequency and Broadsweep.

recorded during every sweep from inertial mass and baseplate are further used in a number of applications in data processing and baseplate coupling analysis. Figure 9 shows a vibrator source layout with sensor locations and real feedback signals recorded during field observations.

Field records were processed according to a single standard graph, which included the static corrections computed from the uphole survey, amplitude recovery, noise suppression, deconvolution, and prestack time migration. A comparison of images obtained with dynamite and Broadsweep is shown in Figure 10. The Broadsweep section is characterized by the richer frequency content and broadband look of the data with better fault definition (red arrows), horizon continuation, and better interpretability. Lack of frequencies in the 10-15 Hz range on dynamite data was successfully healed by the adaptive part of the Broadsweep as shown in the spectral graph. The horizon marked by the yellow arrow has a much better definition in the subsalt area on the Broadsweep section. Spectral plots indicate higher frequency content on Broadsweep data in the 40-100 Hz range.

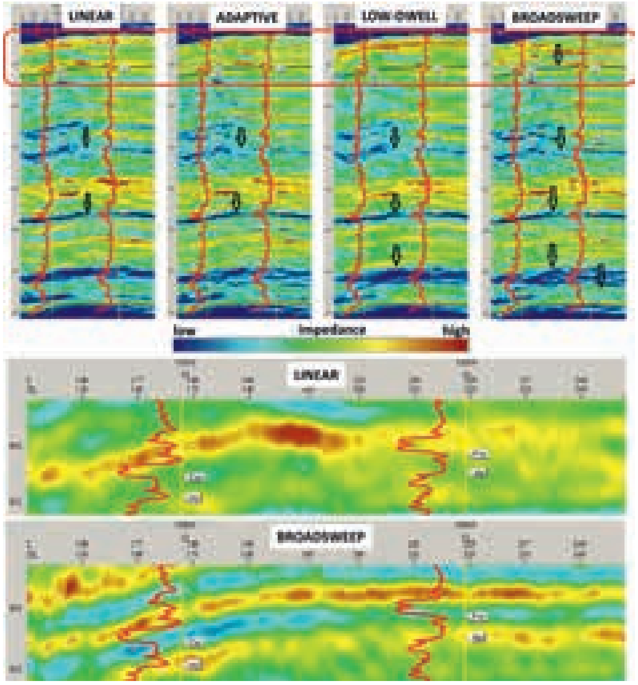

Figure 8 Acoustic impedance for four types of sweeps (top) and bottom shows a zoom of the same impedance section for linear and Broadsweep. Overlaid well impedance curves demonstrate excellent correlation with Broadsweep dataset.

Conclusions

Broadsweep takes advantage of the Vibroseis as a controllable source and can compute a sweep signal with pre-shaped amplitude and phase spectrum to deliver maximum S/N ratio and resolution in field data utilizing real-time data feedback.

Technology has steadily progressed over 20 years from just algorithmic and software application to a full expert solution for broadband land field acquisition. The system consists of innovative vibrator control electronics capable of generating conventional library sweeps and proprietary nonlinear sweeps delivering six frequency octaves of data, and a software performing real-time data analysis for sweep adjustment due to changing near-surface conditions. Data acquired with the technology are characterized by higher S/N ratio, higher resolution and broad frequency content ensuring a less ambiguous interpretation and inversion solution converging to a true subsurface reflectivity model. The technology does not require any additional time during acquisition and has been used successfully in production projects for the past several years.

In addition to conventional oil and gas exploration, where the technology has been already utilized by several acquisition companies on multiple projects, it can be used for unconventional exploration and active surface seismic fracking monitoring for further stimulated rock volume analysis and fracking efficiency. Reservoir-driven acquisition of 4D seismic data is also an area where the system can compensate for seasonal near-surface changes and deliver the same spectral characteristics.

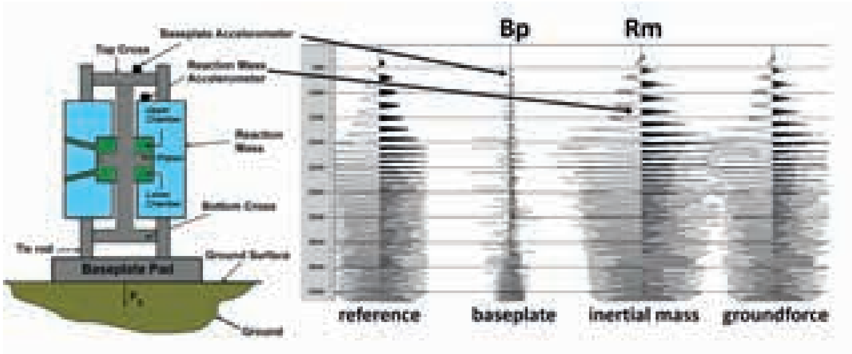

Figure 9 Broadsweep system sensor location and recorded signals.

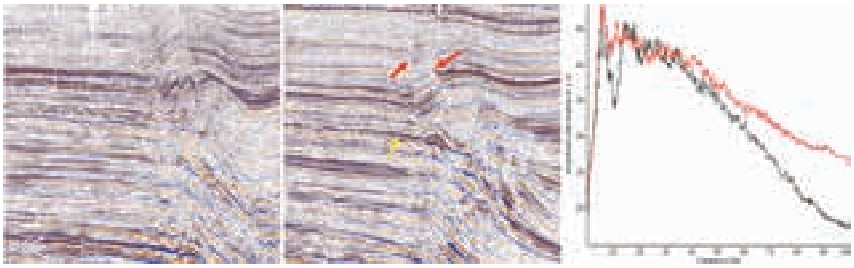

Figure 10 Comparison of dynamite data (left section) and Broadsweep dataset (middle section). Right graph illustrates amplitude spectra of dynamite (black) and Broadsweep (red) data.

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