Pushing toward the low frequencies

Everyone agrees that broadband seismic sources and receivers are essential for improved imaging and resolution, but old habits sometimes prevent operators from taking full advantage of new technology and methods that can overcome limits previously viewed as fundamental.

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The use of seismic in structural imaging is well established. However, vertical resolution becomes increasingly difficult with increasing depth, especially when trying to image below high-velocity formations. A large improvement in the vertical resolution of surface seismic (say, one order of magnitude, from meters to decameters!) is viewed by oil companies as the most important step toward wider use of seismic in reservoir description. Differential absorption of higher frequencies along the travel path of the seismic signal hampers the ability to create and record a broadband spectrum, thus preventing seismic from filling this important need. Borehole seismic may improve the situation by shortening raypaths.

Extending the emitted and recorded bandwidth will help improve vertical resolution of surface seismic and exploration of deep targets. Enrichment of the reflected signal by using lower frequencies is critical for converted-wave recording and post-stack amplitude inversion. The rationale and supporting theory for this is described, along with new acquisition equipment that makes it possible to enhance low-frequency (below 10 Hz) seismic acquisition on land and offshore.

INTRODUCTION

Seismic data with dominant frequencies around 1-kHz and 1-m resolution have been recorded in cross-hole seismic acquisition.[1] However, the scarcity of wells with the appropriate geometry has limited the number of these surveys.

Vertical resolution (i.e., the ability to discriminate an event) depends on the S/N ratio and, generally, on higher signal frequency, F_{max}. However, in Fig. 1, it is shown that isolation of a reflected peak wavelet means that resolution also depends on relative bandwidth, as measured in octaves. The typical frequency range of surface seismic is between 10 Hz and 80 Hz. This represents three octaves, that is, three doublings of frequency (10–20/20–40/40–80 Hz), Fig. 2.

To gain resolution, it should be easier to add one octave by recording signal from 5 to 10 Hz than by recording it from 80 to 160 Hz. What has prevented the industry from using this opportunity?

First, we have not wanted to record low frequencies because they have a reputation for being easily contaminated by noise. Because of this, most seismic source and receiver technology is not designed to transmit or sense very low frequencies. Thus, low frequencies have been filtered out in the recording process to avoid losing dynamic range. This problem is solvable, but with some added cost, as this requires dense spatial sampling and high-fold coverage.

In addition, on land, when using a Vibroseis source, the creation of very low frequencies is often avoided due to the fear of surface and subsurface structural damage. Furthermore, most recording systems do not allow the specification of parameters that will properly sample all frequencies. For all of these reasons, low frequencies have not been focused on in source or recording systems, or in data processing. But recent advances in marine

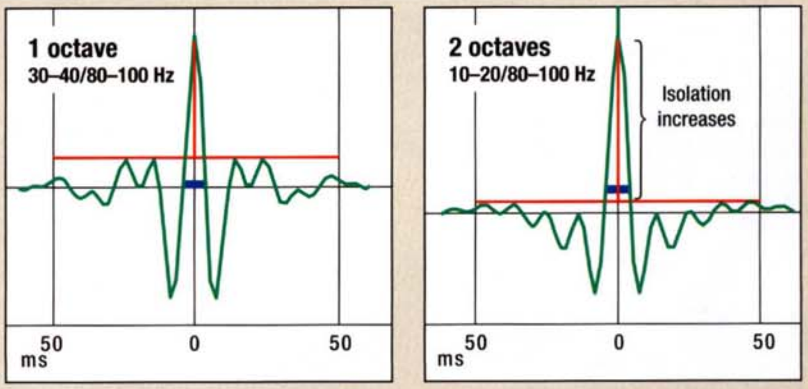

Fig. 1. Two aspects of resolution: Using a zero-phase Butterworth wavelet, the width of the central lobe is determined by F_{max} (identical for the two wavelets), but its isolation is related to relative bandwith, where n is the number of octaves: $2^n = F_{max}/F_{min}$.

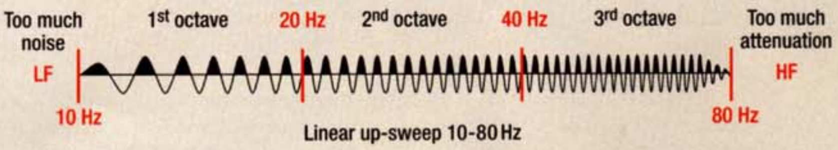

Fig. 2. Typical recorded seismic frequency content mostly contains 10 to 80 Hz.

and land acquisition equipment make it possible to emit and record broadband signal that includes low frequencies.

LAND SOURCES

Explosive sources are known to produce broadband signal, including low frequencies. However, little has been published to show the relationship between the type of explosive, the charge, its depth and the resulting frequency content. Crews often rely on rules of thumb (e.g., bigger and deeper charges create more low-frequency energy) that are more or less validated by field testing. As shown in Fig. 3, a recording of conventional charges used for seismic exploration (1–10 Kg at 10–30 m depth), using a broadband, digital accelerometer sensor, shows that most of the lower frequencies are concentrated in the surface noise (GR) and missing in the reflected signal (S_i).

An FK diagram on the whole shot point shows that the lower frequencies emitted (down to 2 Hz) are primarily ground-roll (GR). An amplitude spectrum of the reflected signal S_i shows that high and low frequencies are highly attenuated from a peak amplitude that occurs between 10 and 30 Hz. It seems that most of the explosive energy is used to produce fracturing, gas, heat, and surface waves. The transformation into elastic waves is highly dependent on borehole properties and on the nature of the explosive (speed, pressure and gas generation). Longer explosions, as provided by new dual-composition explosives specifically developed for seismic application, improve energy transfer into the formation. From analysis of the reflected signal, both low and high frequencies increase 12 dB, and peak amplitude is shifted toward lower frequencies.[2]

Vibrators offer the advantage of controlling the bandwidth and the emitted energy within each frequency range. Standard vibrator sweeps start at 10 Hz with a 0.5-s taper, or even at a higher frequency, when ground roll is severe or structural damage is possible. On most vibrator specifications, sweep capabilities start at 7 Hz but, generally, this is not at full drive and/or for a long duration. This restriction in the low-frequency start is related to the displacement D (stroke) of the vibrator mass M, limited by the available hydraulic flow.

$D = HPF/M\omega^2$, where $\omega = 2\pi f$. The displacement of the vibrator mass, necessary to produce low frequencies, increases with the high hydraulic peak force (HPF) of heavy vibrators, which can be more than 60,000 lbf.

The use of a bigger mass may limit the necessary displacement for low-frequency emission. In addition, a bigger mass improves the mass-to-baseplate weight ratio that limits the vibrator's ability to emit high frequencies.

For example, Sercel makes a heavy vibrator (97,350 lbf), the Nomad 90T, where the lowest sustainable frequency at 75% drive is 5 Hz. The stroke is 10 cm and the mass-to-baseplate ratio is 3.2 (7.1 T/2.2 T), which, to this author's knowledge, is the highest available. This vibrator design can enhance seismic resolution by producing a broadband sweep, including low and high frequencies that range 5 to 250 Hz, or close to six octaves. Its 90,000-lbf ground force is large enough to use as a point source.

MARINE SEISMIC

A standard airgun array (3 strings of 10 guns, 3,500 cu.in.) is band limited below 10 to 12 Hz. Its ability to produce lower frequencies may be improved by increasing the air pressure in the guns, Fig. 4a. For example, Sercel markets a G. GUN that is designed for standard use at a pressure of 207 bar (3,000 psi), which is higher than the typical gun pressure of 138 bar (2,000 psi).

The lowest frequency, F_{min}, of the emission also depends on the individual volume of the guns. The dominant bubble period, T_{bubble}, of a gun signature varies with the cube root of its volume. Thus, the dominant frequency of the signal that corresponds to the minimum frequency $F_{min} = 1/T_{bubble}$, decreases with increasing gun volume. As large guns are not easy to handle, it is possible to cluster identical guns to increase the bubble period. For a standard 2 x 250 cu. in. G. GUN parallel cluster, at 5-m depth and 3,000 psi, the dominant frequency is as low as 6 Hz, Fig. 4a.

The effect of gun immersion on low-frequency content is not as straightforward as it is for high-cut frequency, which depends only on the spectral notch created by the surface ghost, Fig. 4b. This ghost has a destructive effect on the first bubble where the lower frequencies are concentrated.[3] Increasing the gun depth can shift the direct and ghost bubbles, which are of opposite polarity, potentially improving the amount of low-frequency energy. Independent of surface/notch effects, the bubble period decreases with depth due to greater hydrostatic pressure, that is, the corresponding

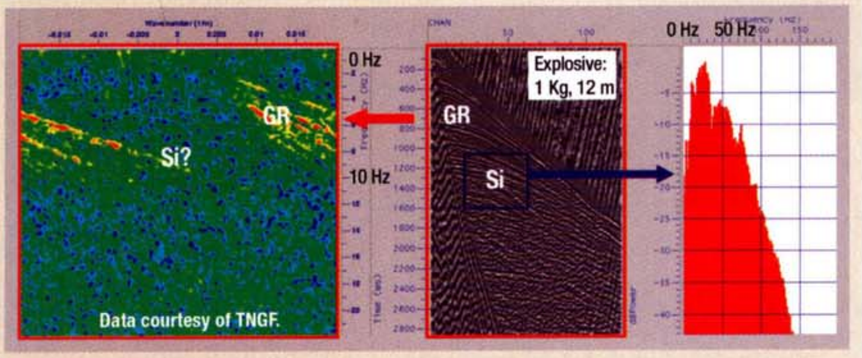

Fig. 3. Shot point (acceleration) recorded by the vertical component of digital sensors (center). FK spectrum (left) from the whole shot point (middle), including ground roll (GR) and reflections. Amplitude spectrum (right) from a small window within the reflected signal (S_i).

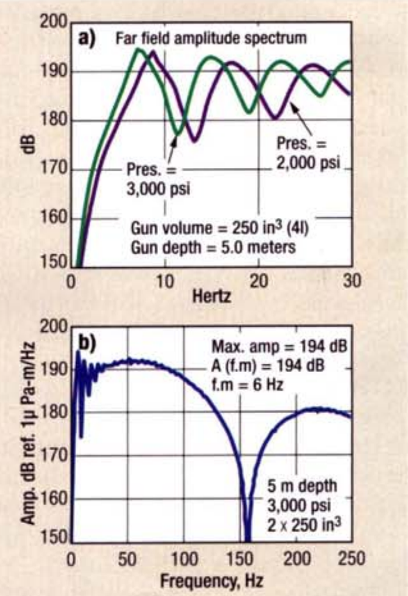

Fig. 4. 3,000-psi G. Gun parallel cluster far field amplitude spectrum and its variation with pressure (a). A notch due to the surface ghost occurs at 160 Hz when towing at 5 m(b).

dominant/minimum frequency increases rather than falls.[4]

On the streamer side, the depth below the sea surface has a pronounced effect on frequency; increased streamer depth will result in lower-frequency data, all else being equal. With the advent of steerable streamers (e.g., WesternGeco's Q marine), it is now possible to position the streamers in an over/under configuration, with the topmost streamer at 15 m and the lower streamer at 22.5 m. Steerability allows the two streamers to maintain that position laterally within 5 m. The net effect is a summation where the upper streamer preserves the high frequencies, while the lower streamer boosts the low frequencies.

A different way to enhance low-frequency signal content has been tested. It involves delaying the different guns of an array in order to synchronize bubbles.[5] This technique is a good way to improve low-frequency, but it is detrimental for the high-frequency content of the source. While it has proven useful for deep crustal and sub-basalt imaging, it lowers seismic resolution in sedimentary layers.

LOW-FREQUENCY ANALOG SENSORS

Coiled geophones are manufactured with resonant frequencies, F_R, that range from 2 Hz to 35 Hz. These depend on the spring/coil rigidity, K, and on the mass, M, of the magnet: $F_R = (K/M)^{1/2}/2\pi$. Since amplitude is attenuated below this resonant frequency at a rate of 12 dB/octave (Fig. 3), F_R is selected at 10 Hz or above to attenuate low-frequency surface noise. Lower resonant frequency geophones that use a larger mass are cumbersome, more expensive and they are more sensitive to tilt. They are seldom used in the field except for occasional refraction surveys.

Piezoelectric hydrophones, as used in marine streamers, have a low-frequency roll-off, beginning at 3 Hz, with an attenuation of 6 dB/octave, down to 0 Hz (DC). Therefore, these hydrophones can record low frequencies, limitations being more on the source side. Hydrophone capabilities may be extended below 0.5 Hz, with the drawback of more electric and swell noise. Such hydrophones are able to measure wave height, a parameter used to de-ghost seismic data.[6]

DIGITAL ACCELEROMETERS

New MEMS-based digital accelerometers have been developed over the past few years for the seismic industry. They offer a broadband linear phase and amplitude response that extends from 0 to more than 500 Hz, Fig. 5. These accelerometers make it possible to record frequencies below 10 Hz without attenuation, including direct current, which is related to gravity acceleration. This gravity vector is a useful reference for sensitivity control and tilt measurements.

The flatness and stability of the phase response compared to a geophone seem to be an important advantage in recording low frequencies. However, a geophone can be compensated in processing for its low-frequency attenuation, assuming this attenuation (and the corresponding resonant frequency) is stable. Used with arrays designed to attenuate the surface noise, the geophone also displays better signal-to-noise than the digital accelerometers in the low-frequency range. Probably the most interesting feature of a MEMS-based sensor is its lower distortion (–90 dB compared to –62 dB for the geophone) that helps preserve low-frequency signal by resisting interference from the strong harmonics of the surface noise.

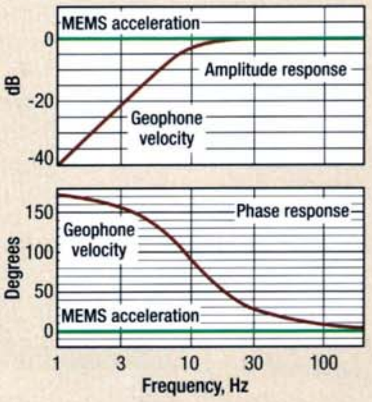

Fig. 5. Phase and amplitude response of a MEMS-based accelerometer compared to a 10-Hz geophone.

APPLICATIONS

The suitability of surface seismic for deep target exploration, say, below 5,000 m, is limited by attenuation and scattering of the wavefront. Due to their ability to carry more energy deeper into the subsurface with less attenuation and scattering, low frequencies are less affected by these propagation effects. Another limitation is the ability to reconstruct the true raypath and to properly gather traces reflected by the same Common Reflection Point. That ability decreases with increasing depth and associated subsurface complexities. Low frequencies with a larger Fresnel zone and apparent frequency are less sensitive to these imperfections and easier to stack. For example, it has been demonstrated that low frequencies are the key for imaging sedimentary layers below high velocity bodies like basaltic flow, Fig. 6.[7,8,12]

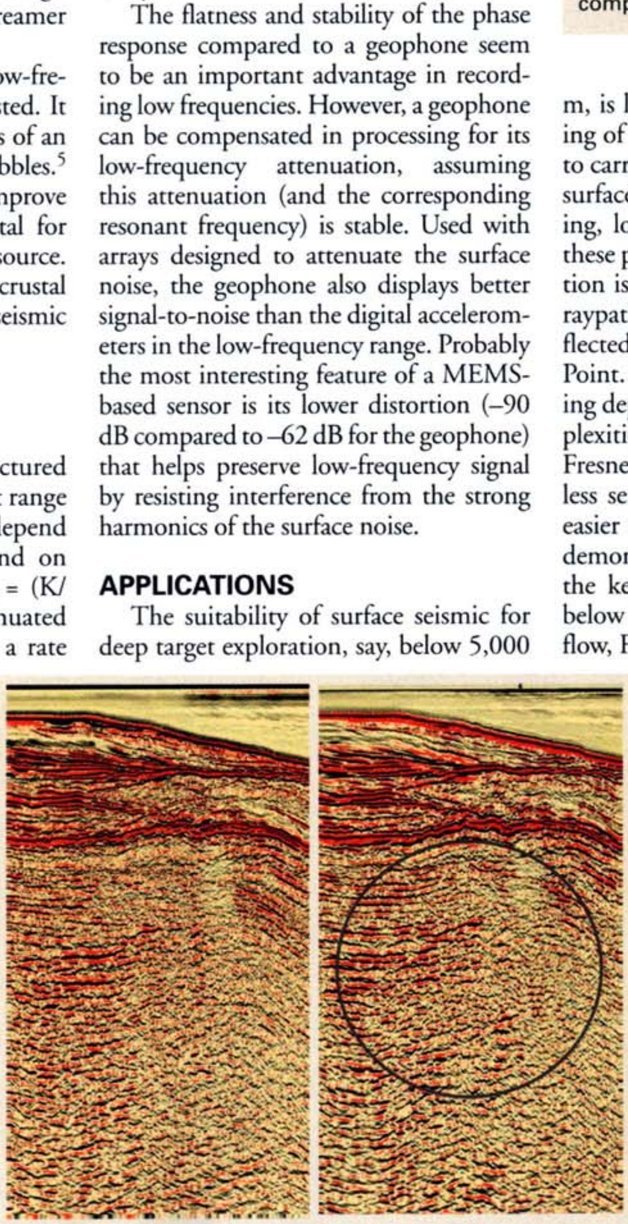

Fig. 6. Conventional seismic data (left) and results from specialized, low-frequency BLAST source (right). The low-frequency source data contain much more information on these deep, sub-basalt structures. Data courtesy of the BLAST group: Statoil, Anadarko, Enterprise, Phillips Petroleum, Veba Oil and Veritas DGC.[12]

Post-stack amplitude inversion is the transformation of seismic reflectivity into acoustic impedance at each seismic trace.[10] Since low frequencies are missing in the seismic data, an a-priori model of the low-frequency variations should be derived from the well data correlation. This model will guide the inversion in the seismic frequency range. The result of this inversion is fine-layered impedance traces that contain both low-frequency variation from well data and medium frequencies from seismic data.

These acoustic impedances are used for interpolation of well properties correlated with seismic, such as porosity, shaliness and gas content. However, the model-driven inversion result is only as accurate as the a-priori model allows. By incorporating more low frequencies into seismic data, the reliance on such interpretive a-priori modeling should decrease and, therefore, the overall accuracy of the inversion results should improve. This is even more relevant for deep targets, where well data becomes sparse.

Converted wave (PS) sections display a lack of high and low frequencies compared to PP waves recorded by the same receivers. This is not related to the P to S conversion itself, which preserves the frequency content. Rather, it is due to the lower velocity and then shorter wavelength of shear waves, which are more attenuated during propagation. Therefore, to preserve the bandwidth and associated resolution of converted waves, emitting more low frequencies should improve imaging even more than for a conventional P wave survey.[9]

The frequency dependence of reflectivity is related to fluid saturation. The difference in acoustic response between water-saturated and gas-saturated porous rock is greater at lower frequencies, as shifts in amplitude and time increase. This shows the interest of recording low frequencies for seismic monitoring (4D).[11]

CONCLUSION

Successfully recording low frequencies and improving vertical resolution is not yet common practice. For this to become a standard activity, many obstacles must be overcome. The steepest one is the surface noise that contaminates low frequencies. Solving this requires dense spatial sampling and high-fold coverage. But once that decision is made, the ability to recover and record broadband data, properly sampled, is a reality using today's recording systems, which are capable of handling very large channel counts effectively. It is also important to realize that standard processing modules are not often designed to preserve low frequencies due to hidden low-cut filters and to short filtering operators.

Improved vertical resolution of both PP and PS data will facilitate exploration of deep targets and seismic-to-well correlation through amplitude inversion. By contributing more efficiently to reservoir description, seismic should be able to confirm its future as a cost-effective tool to enhance oil and gas production.

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