Get to the Point – Seismic Data Acquisition for Full-wave Imaging

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Introduction

Since the earliest use of seismic data in hydrocarbon exploration, geophysicists have primarily concerned themselves with the apparent direction and speed with which the waves travelled through the earth. They effectively focused on the P-waves and treated the shear and near-surface waves as noise that need to be removed.

Full-wave imaging questions this conventional approach, as geophysicists now realise that a rock particle's behaviour when a seismic wave passes it reveals new information about the subsurface. This is in part due to the fact that the rock particles do not necessarily appear to move neither in the same direction nor with the same velocity as the passing wave.

Full-wave acquisition and processing is the next revolution in seismic imaging, as was 3-D seismic twenty years ago. Full-wave imaging is defined as:

- Faithfully recording the complete ground motion from all seismic signals, including source-generated noise,
- Accurately measuring anisotropy, both p-wave and s-wave modes and in terms of both amplitude and velocity,
- Obtaining an unaliased spatial sampling of the reservoir for a given dip, frequency and velocity,
- Recording the full bandwidth of frequencies that the earth will return.

Full-wave imaging is essential as seismic imaging to date, including conventional 3-D, has made basic assumptions about the nature of the recorded wave-field that limit our ability to sufficiently image reservoirs and their associated fluids for maximum economic impact. Because of these assumptions, we are faced with the fact that 3-D, as the technology is currently implemented, is beyond its first-generation success and is diminishing in its ability to add economic value. The diminishing usefulness of conventional 3-D data directly affects our ability to find and develop new economic reserves with acceptable risk. Perhaps more significantly, plans to extract additional hydrocarbons from existing fields suffer from the diminishing economic impact of current 3-D technology. The question is: what is missing?

A significant part of the answer lies in the adequate sampling of the full wave field. Full-wave imaging has the potential to take the interpreter to the next level of imaging quality by providing:

- Broader bandwidth, higher resolution images
- More accurate and reliable stack amplitudes and AVO
- Vp and Vs instead of Vp only
- A frequency link between velocity and the seismic bandwidth
- Symmetry in the recorded wave-field without the distortion imparted by current acquisition and processing practices
- The possibility of using some of the seismic signal previously considered as noise to contribute to the image and to the final interpretation (e.g. anisotropy, surface waves, and mode contamination)

Consequently, to reach that next level of reservoir imaging quality, the industry needs to overcome the geophysical assumptions made during the emergence of conventional 3-D techniques, namely isotropy, frequency band limitation, vertical emergent angle and the need to always attenuate noise in the field. However, the industry first required the enabling technology of high vector-fidelity, multi-component, digital receivers and efficient, high channel-count recording systems. Before the advent of these technologies, poor vector-fidelity and cumbersome field requirements made economic and technical success almost unobtainable.

Requirements for full wave

Full-wave recording requires at least six considerations. These are:

1. High-vector fidelity, multi-component, single-point sensors (to preserve the relative amplitudes between components thus allowing successful vector-oriented processing)
2. A wide-azimuth 3-D patch (to address the azimuthally-oriented component of amplitude and velocity anisotropy)

3. Offsets sufficiently long to allow allowing at least 45 degrees of reflection angle (noting that this angle is beyond the point where the assumption of a two-term velocity is necessarily valid and where the vertically oriented symmetry of anisotropy can become significant)
4. A sufficiently high channel count to accommodate nos.2 and 3 above, without spatially aliasing the target in either the p-wave or c-wave domains (noting that this consideration does not require the noise to be acquired in a spatially unaliased form or to have the target vastly over-sampled to address source-generated noise),
5. Point-source and point-receiver acquisition (to preserve as faithfully as possible the anisotropy, especially given the acquisition of the long offsets at widely varying azimuths and to accommodate no.6 below)
6. To faithfully record and preserve the maximum bandwidth of frequencies the earth will return, with special considerations given to the low frequencies (given the very deep targets now being explored where p-wave bandwidth is normally limited, given that converted-wave data is already band-limited and considering that high-resolution reservoir analysis using acoustic and elastic inversion normally requires a link between amplitude and velocity that normally does not exist in seismic data)

Of prime importance in full-wave acquisition is the enabling technology of the recording equipment. The technology foundations required for land full-wave imaging are high vector fidelity, three-component, single-point receivers such as VectorSeis® sensors, and high capacity land acquisition systems, such as Input/Output's System Four™, capable of supporting the high spatial receiver densities and large channel count operations required by wide-azimuth and long- offset recording. A significant corollary to the high-channel count and the sensor technology is the additional benefit of significantly improved operational efficiencies due to the incorporation of next-generation technologies in recording systems and single-point receivers (Tessman *et al*. 2004). This corollary mitigates the cost impact and potential safety issues of high-channel-count operations.

High fidelity, single-point, digital receivers

Three-component, high vector-fidelity, single-point receivers provide four significant benefits over conventional receiver arrays:

- Extremely accurate measurements of all ground motion - both seismic signal and noise
- No directional bias, making them ideal for recording azimuthal variations in seismic velocities and amplitudes (anisotropy)
- Freedom from intra-array statics, providing higher bandwidth, higher resolution seismic signals
- Easily deployed, better coupled, with lower weight and bulk for improved field operational efficiency

High vector-fidelity receivers are required for the complete and accurate measurement of ground motion. By measuring this motion on three orthogonal axes, these receivers provide information that describes the apparent ground motion at the instant each sample was recorded. New generation MEMS digital receivers (P. Maxwell *et al*. 2001) such as VectorSeis (Figure 1) fulfill these requirements. These sensors exhibit broad bandwidth, low distortion and tight sensitivity calibration, thereby contributing to the overarching term *vector fidelity*.

VectorSeis sensors are deployed as point receivers. The main reason for this is that single-point receivers lack directional bias; therefore they are uniquely suited for measuring the anisotropy of seismic signals both azimuthally and transversely. Figure 2a is a plot of recorded signal frequency (X axis), receiver array azimuth (Y axis), and attenuation (colour scale), showing the complete lack of directional frequency attenuation for point receivers when using point sources. Figure 2b shows significant frequency and azimuth-dependent attenuation effects for a 12-sensor array and point source, assuming the seismic signal emergent angle is non-vertical. Higher frequencies experience greater attenuation effects, thereby reducing the reliability of anisotropy measurements. These signal frequency components are not recoverable; they are lost forever, thus reducing the bandwidth and resolution of the seismic images and impairing the accuracy of anisotropy measurements.

Figure 1 VectorSeis vector receiver

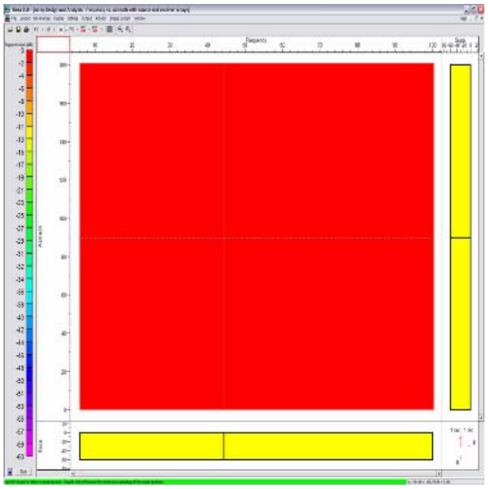

Figure 2a Azimuthal frequency attenuation effects for point receivers and point source.

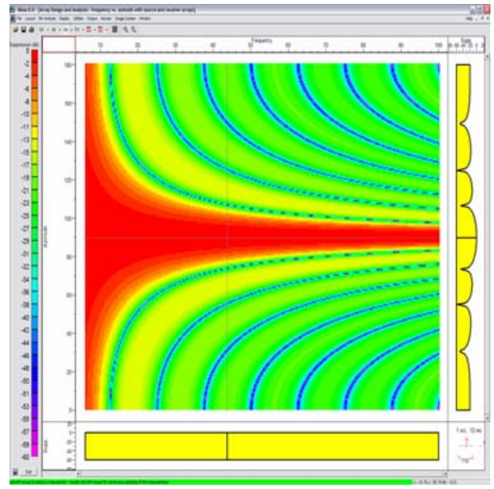

Figure 2b Azimuthal frequency attenuation effects for a 12-receiver array and point source.

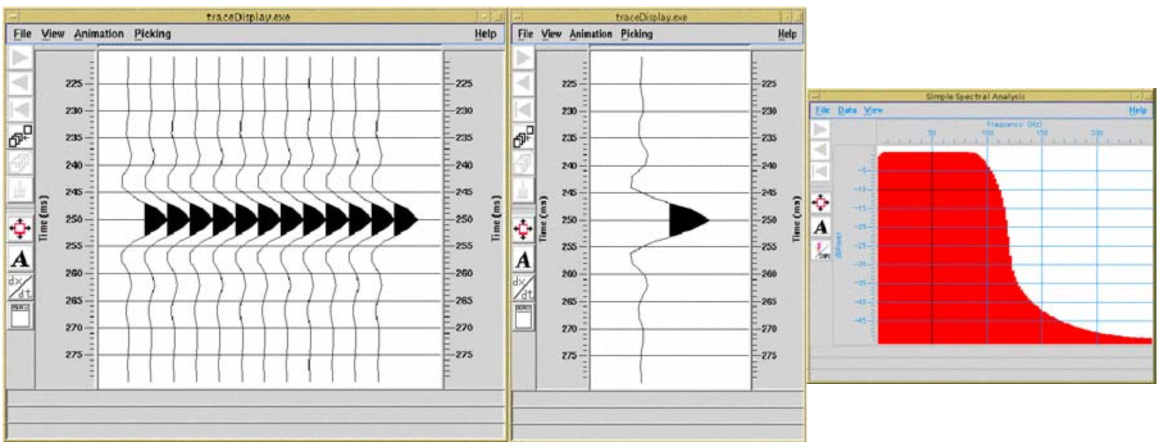

Figure 3a Synthetic example of frequency attenuation effects from intra-receiver array statics - base case, no statics effects.

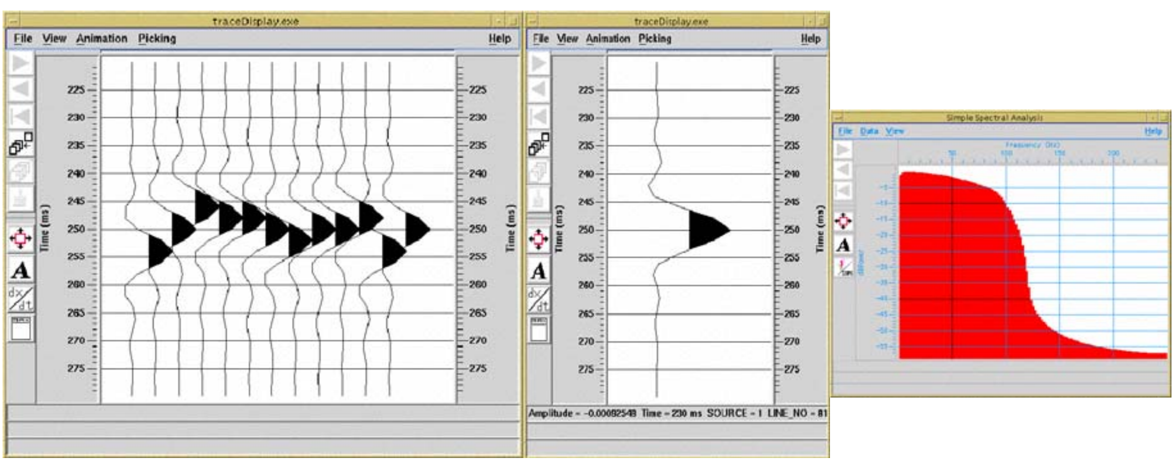

Figure 3b Synthetic example of frequency attenuation effects from intra-array statics - + / - 4 ms intra-array static shifts.

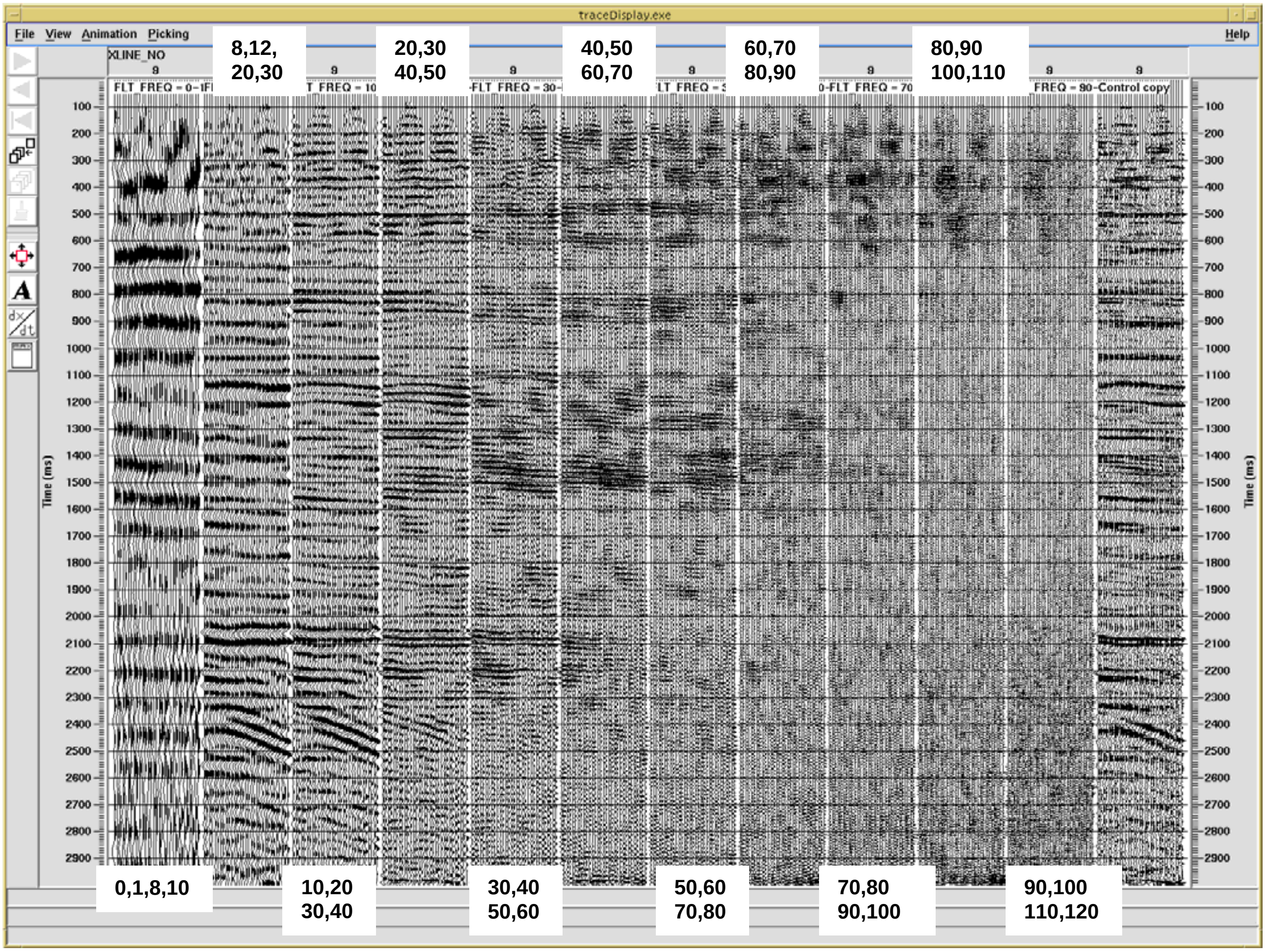

Figure 4 Frequency panel from a VectorSeis data-set illustrates the broad bandwidth capabilities of VectorSeis digital, full-wave receivers.

Survey design

To meet the requirements of all the six considerations for full-wave seismic imaging, careful, robust survey design is critical. Of primary importance is the acquisition of wide-azimuth, full-offset data i.e. seismic data that is sampled in every direction and represents the full range of offsets needed to accurately estimate the seismic velocities at the depths of geologic importance in the survey area. In a properly acquired wide-azimuth survey, the ratio between usable inline and crossline offsets sampled for each horizon of interest will be on the order of 1:1 (typically within the range of about 0.8:1 to 1.2:1). It is not sufficient that just the maximum inline and crossline offsets are comparable. It is important that the range of offsets in each direction is also well sampled. Such characteristics are most easily acquired with survey designs having source lines orthogonal to receiver lines, comparable source and receiver line spacings, and nearly square source-centred active receiver patches. Figure 9 illustrates narrow- and wide-azimuth recording patterns. Figure 10 shows the statistical distribution of offsets and azimuths for the same two designs. The narrow-azimuth design fails to capture long offset data in the crossline direction whilst the wide-azimuth design collects uniform offset distribution in every azimuth. As a general rule in full wave acquisition, the long offsets acquired in all directions should be in the order of twice the depth of the horizon of interest. This allows a more accurate estimation of the complete velocity field and better characterization of the amplitude variations with offset. The long offsets also provide the data for analyzing the apparent transversely anisotropic portion of the anisotropy. The caveat here is that if the transverse isotropy is not corrected for in processing, the data beyond an offset-to-depth ratio of one can be almost worthless.

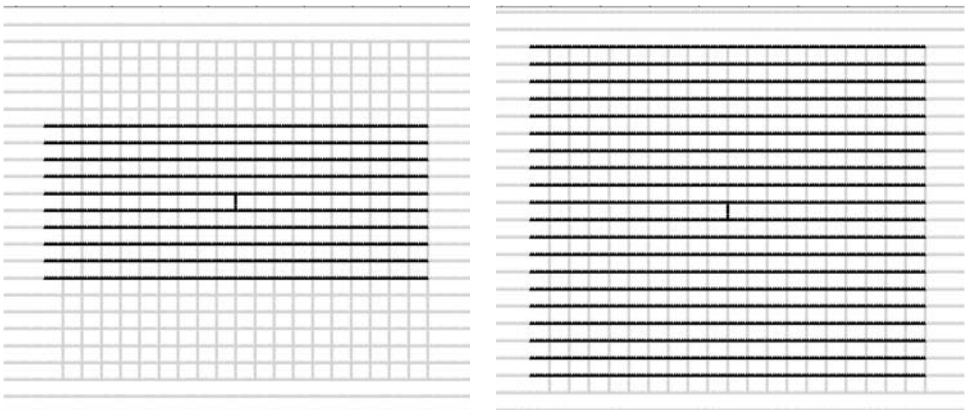

Figure 9 Narrow-azimuth survey design (left) with an inline to crossline offset ratio of about 2:1 is compared to a well-sampled wide-azimuth survey design (right) with an inline to crossline offset ratio of about 1.2:1*.*

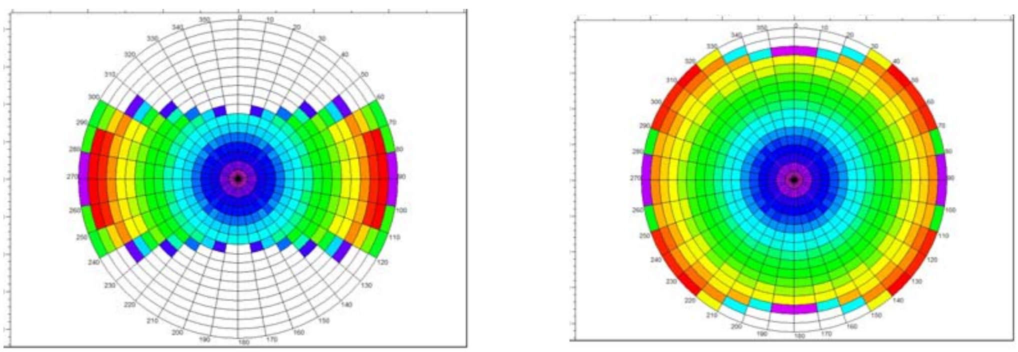

Figure 10 Offset-azimuth rose plots for narrow-azimuth (left) and wide-azimuth (right) survey designs. Radial wedges represent azimuthal sections (clockwise with north at the top) and concentric rings represent offset increasing from the centre outward. In both designs, inline offsets (east-west) are very well sampled. Crossline offsets are also very well sampled in the wide-azimuth design, but poorly sampled in the narrow-azimuth design.

For robust full-wave seismic acquisition, spatial sampling is also very important. Nyquist anti-aliasing spatial sampling criteria are usually used to predict the subsurface sampling interval (bin size) required to adequately image the subsurface horizons based on seismic velocity, frequency content and signal dip. This constrains the surface spacing for both source and receiver stations. However, S-waves and converted (PS) waves propagate at substantially slower velocities than P-waves, generally requiring finer spatial sampling. In a true full-wave seismic acquisition design, all components are acquired simultaneously, so the slower S-wave velocities should generally be used to compute the subsurface bin size and surface station spacings for imaging, meaning that the P-wave data will generally be over-sampled. Figure 11 illustrates the asymmetry of PS reflection data. Because of this shift of PS reflection points toward receivers and the fact that S-waves travel disproportionately slower in shallow unconsolidated sediments, it is very important in full-wave survey designs for the receiver line spacings to be kept relatively small, especially for shallow reflection horizons.

In conventional seismic acquisition, geophone arrays are used to attenuate ground roll and other surface noise, requiring the data to be acquired with small station spacings. This allows the noise to be removed in processing without aliasing. New high-fidelity, single-point, three-component digital receivers, such as VectorSeis sensors, record the full seismic wavefield in a single sensor package and have a uniform response in all directions and at all orientations. A major benefit of this technology is simultaneous and independent recording of seismic reflection signals and source-generated ground roll noise, allowing surveys to be designed for reflection imaging quality rather than for noise suppression. Because vector filtering techniques for ground-roll removal are applied as single-trace, post-acquisition processes and are totally independent of acquisition geometry, ground-roll noise aliasing is eliminated as a survey design criteria. Thus it is not necessary to design surveys for the spatial aliasing condition of ground roll, nor are receiver arrays required to physically filter ground roll.

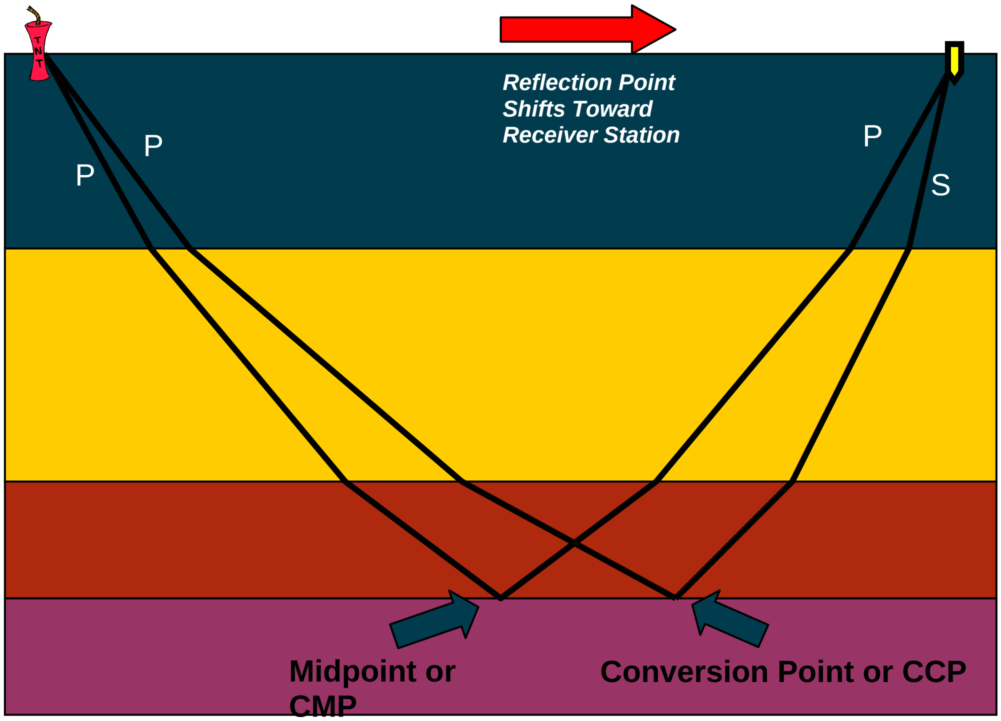

Figure 11 P-wave reflection data are recorded with a P-wave source and vertically-oriented P-wave receivers. In flat-lying layers, the P-wave reflection point is midway between the source and receiver. PS-wave reflection data are recorded with a P-wave source and horizontally-oriented S-wave receivers. Since the up-going reflected PS wave travels at the slower S-wave velocities, Snell's Law dictates that the reflection point for PS waves is shifted toward the receiver station.

Vector-filtering techniques

Vector filtering is a coherent noise attenuation method that leverages digital, full-wave information. The method uses differences between the noise and signal recorded on each of the three receiver components to isolate and attenuate unwanted noise. An example of this type of noise attenuation is the removal of ground roll from the vertical trace data (Figures 5a, 5b).

As experience with vector filtering methods has grown, not only has the process been successful in removing ground roll from vertical traces, but the process also successfully removes Love and Raleigh wave contamination from rotated horizontal data (Figures 6a, 6b). This application helped isolate converted wave signal from surface noise trains and has proven useful for converted wave processing.

Vector filtering techniques also show promise for removing other types of semi-coherent noise such as back-scattered noise produced by near-surface point refractors and discontinuities (geologic or topographic).

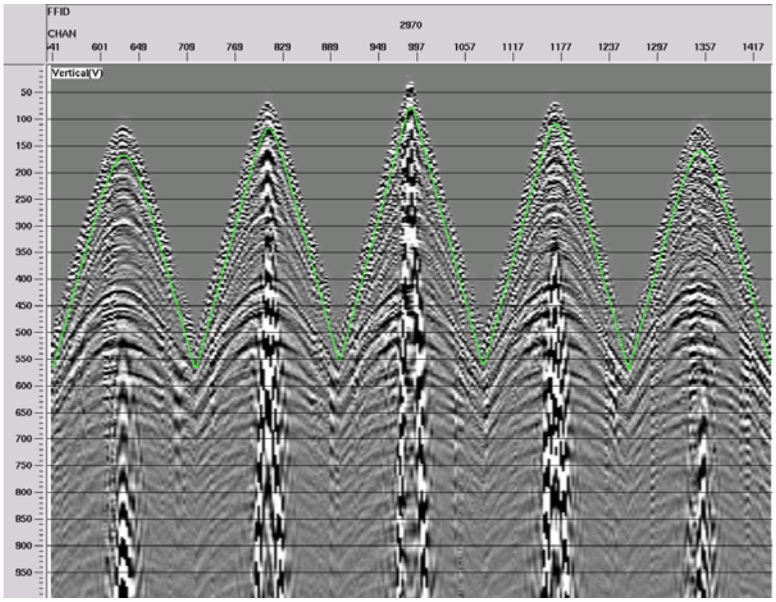

Figure 5a Raw VectorSeis record contaminated with aliased ground roll. After Vector Filtering and signal processing (Figure 5b), aliased ground roll is successfully attenuated.

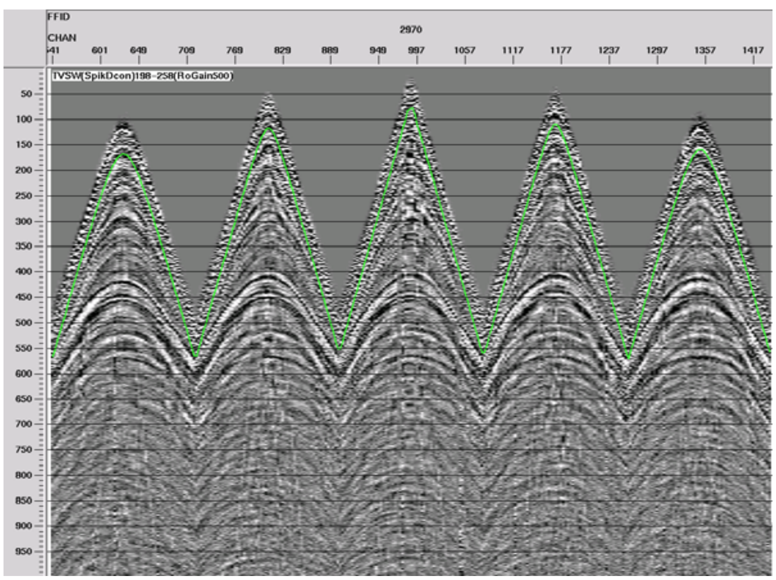

Figure 5b Same VectorSeis record as in Figure 5a but with aliased ground roll successfully attenuated with Vector Filtering and signal processing.

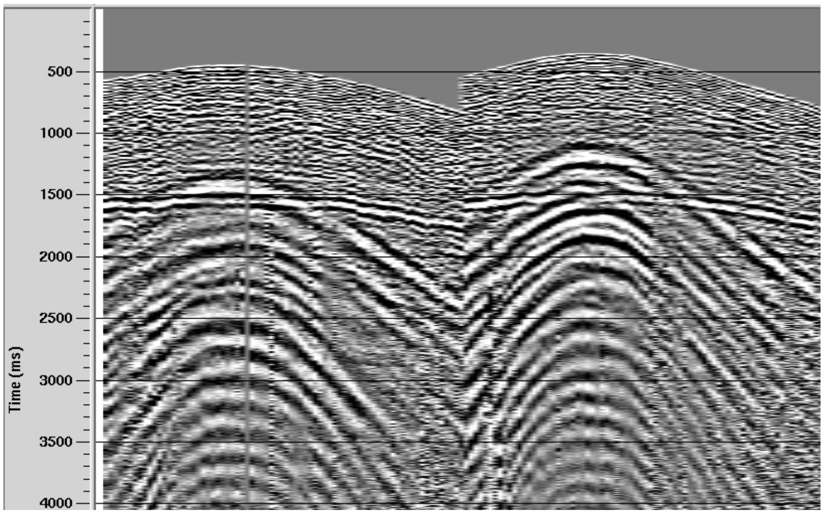

Figure 6a Raw VectorSeis radial record contaminated with ground roll. Vector Filtering techniques can attenuate direction noise from radial components.

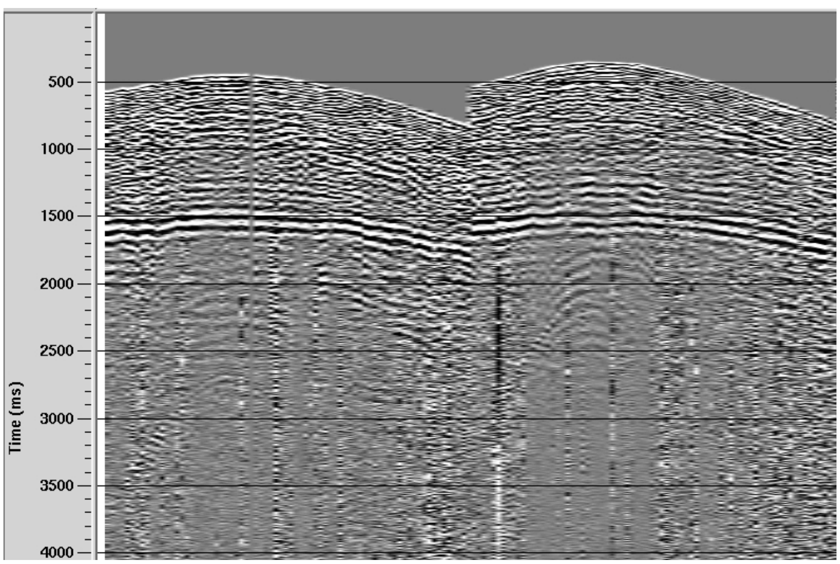

Figure 6b VectorSeis radial record post Vector Filtering. Ground roll has been successfully attenuated, leaving a clean record for further processing.

High capacity, high channel count systems

Full-wave acquisition techniques for improved P and S-wave images require high capacity, high channel count systems that can efficiently acquire, transfer and record large amounts of data (Mougenot, 2004). In addition, full-wave survey designs with adequate wide-azimuth sampling at target depths require a large number of deployed receiver stations. When combined with three-component sensors, the required system channel count can easily exceed 10,000. An additional factor is that full-wave acquisition requires longer listen times as S-wave velocities are lower than P-wave velocities.

Large spreads and active receiver patches must be managed efficiently to minimize power consumption and to carry out a variety of QC parameters in real time. Coupled with these demanding data handling, efficiency and QC requirements is the need for lightweight, easily deployed equipment that is sufficiently robust to operate reliably in harsh field environments.

Modern recording systems such as System Four address these full-wave imaging requirements. Fiber-optic cross-lines capable of high data transmission rates; fast, reliable network telemetry architectures and power delivery systems that self-heal in redundant deployment enable cost-effective full-wave acquisition. Parallel network architectures coupled with buffering and handshaking protocols ensure that there is a path for seismic data to get back to the recorder, even when severe cable disruption occurs.

Conclusions

Over the last 50 years, seismic imaging advances have occurred in a number of technological waves, each resulting in improved exploration successes and better hydrocarbon reservoir characterizations resulting from clearer seismic images. This latest imaging revolution, full-wave imaging, together with the technologies that make it possible, delivers high-quality seismic images to oil companies and operational benefits to contractors. With high-fidelity, three-component, single-point receivers and wide-azimuth surveys, full-wave imaging delivers improved resolution, more efficient noise suppression and higher quality seismic images that ultimately improve our geological and geophysical understanding of oil and gas reservoirs.

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