Using Single-Sensor Acquisition and Processing Techniques to Acquire Lower-fold Exploration Data that can be Re-used for Reservoir Surveys

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Summary

The current method of acquiring land seismic data usually involves configuration of source and receiver arrays in a way designed to provide some measure of protection against coherent noise.

This approach has some drawbacks in that aliasing of the noise will occur if it is not sampled properly, leading to contamination of the data and a reduction in the signal-to-noise ratio.

The resulting acquisition data may be satisfactory for an exploration survey and structural interpretation, but may not be of sufficient quality to be used as part of a survey for reservoir characterization purposes.

This paper demonstrates how a custom-designed deployment with use of single-sensor acquisition and complementary processing techniques can provide prestack data with substantially higher signal-to-noise ratios and frequency content than conventionally acquired and processed data. It is illustrated how this superior prestack data maybe used to both acquire lower field effort exploration data and subsequently reused for seismic imaging throughout the lifecycle of the field.

Introduction

Single-sensor recording has been used since the start of the seismic industry in the early 1920s. As technology developed, it was feasible to reduce the size of the sensors and to record data received by more sensors at the same time. With the advent of digital recording and processing, use of receiver arrays began. These arrays are used to cancel out noise and both random and coherent ground roll. The effectiveness of these arrays is discussed by Newman and Mahoney (1973) and later authors.

Noise attenuation through the stack-array approach was developed as channel counts increased to around 96 channels per shot (Anstey, 1986). The key concept in the stack-array approach is to sample the ground roll symmetrically so that the stacking process removes the remnant ground roll. This process works for the 2D case, but is less successful for 3D acquisition due to an inadequate sampling of the ground roll because symmetry is lost in most common survey designs. Cancellation is no longer complete and can contribute to an acquisition footprint seen in the data.

In 1988, the 'hands-off' approach was proposed (Ongkiehong and Askin, 1988) which advocated the use of source and receiver arrays to act as antialias filters to suppress the short-wavelength noise and allow a coarser sampling of the remnant wavefield. These basic principles have been used throughout the 1990s and early 2000s as recording system channel counts have increased. With the advent of higher channel count acquisition systems, it is time to review the key assumptions that form the basis of land seismic acquisition.

It is generally agreed that the optimal 3D survey would sample all azimuths and all offsets evenly, where each source and receiver point are acquired at a predetermined spacing throughout the 3D survey area. This spacing is typically chosen to be closest to the Nyquist sampling required to sample diffraction tails or steeply dipping events. The spacing would typically be in the 25-m to 50-m range, and while sufficient for sampling the seismic signal, is too coarse to be able to sample the coherent noise typically generated by an explosive or vibroseis source. Spatial antialias filter protection against such noise is given by the combination of source and receiver arrays.

The inefficient attenuation of ground roll by source and receiver arrays is seen as a driver for higher channel count crews that can record higher-fold surveys. Put simply, fold is required to overcome the shortcomings of arrays used to attenuate coherent noise.

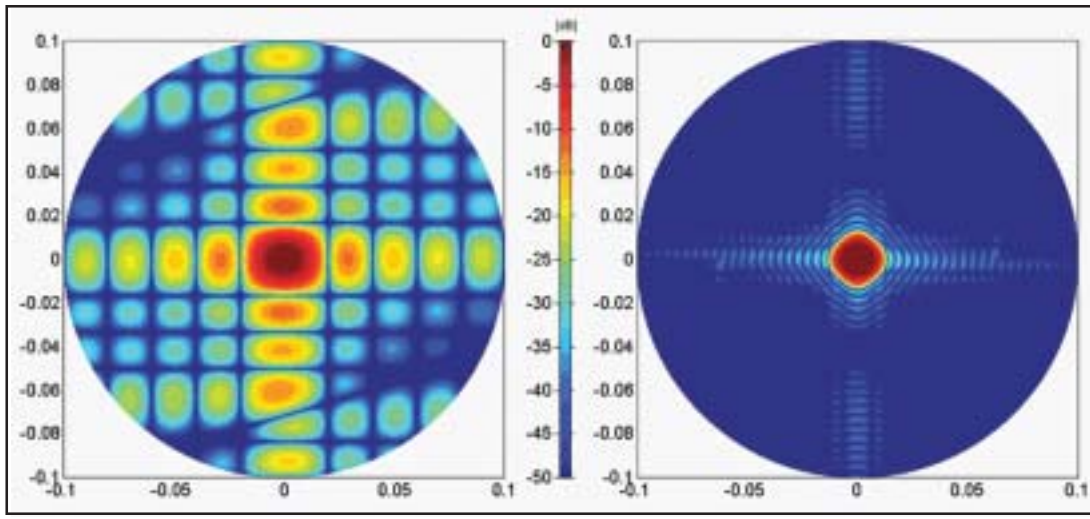

Fig. 1: Shows two FK plots from records 25 m from the receiver line; these plots show that the ground roll on the conventional dataset has not been sampled adequately, has been aliased, and is wrapping around into the signal band. The FK plot of the single-sensor data shows that the ground roll has been effectively removed and that any remaining dipping noise is unaliased, enabling it to be removed through additional processing.

Theory

The single-sensor acquisition and processing methodology developed to deal with the noise is to decompose orthogonal acquisition geometry into cross spreads, and to spatially repeat these within the acquisition area. The cross spreads provide single-fold subsets of the continuous wavefield, sampled finely enough to prevent aliasing of the coherent noise. This allows the effective application of 3D FKK techniques on the individual cross spreads. (Quigley, 2004)

The two diagrams in Figure 1 show the FKK spatial antialias filter response of the source/receiver array (left) and for the point-source/point-receiver digitally group formed (DGF) digital spatial antialias filter. An ideal spatial antialias filter would have a flat response within the spatial filter passband and complete rejection outside it. The ideal spatial antialias filter response would also be azimuthally isotropic; i.e. the array response is the same for energy arriving from all angles.

Figure 3: KxKy response plots for source/receiver arrays (left) and point-source/point-receiver combination digitally group formed (DGF) digital spatial antialias filter (right) as per Figure 2.

The antialias filter performance for conventional data acquisition is typically achieved by the convolution of source and receiver arrays, with some imperfect and azimuthally variable level of noise rejection in the filter stopband and an imperfect (non-flat) response in the passband. All remnant energy in the stopband will be aliased into the passband during acquisition and appear as noise on the seismic trace. The Q-Land acquisition technique allows the application of optimal digital spatial antialias filters designed using the alternating projections onto convex sets (APOCS) filter design technique (Özbek et al., 2004).

Cross-spread test

A comparison cross-spread test was conducted to

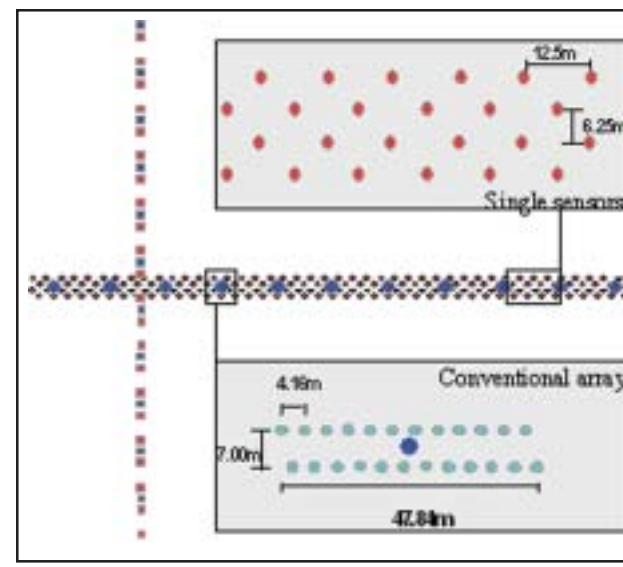

Fig. 2: Descriptive subset of the point-source/point-receiver (red) vs. conventional array (blue) comparison cross-spread test layout.

investigate the potential uplift in signal-to-noise ratio to be realized from single-sensor cross-spread recording over conventional recording with source and receiver arrays.

The test was carried out by a crew that was acquiring data using source and receiver arrays. The cross spread was laid out as detailed in Figure 2 with the single-sensor locations overlaying the conventional receiver array (large dot denotes the center of gravity of the array). The length of receiver line was 12.8 km with 257 channels of conventional and 4096 single-sensor channels deployed.

The source locations are denoted by the vertical line of light red (point-source locations) and dark blue (conventional source array) squares. The length of the source line was 8.25 km. The source and receiver array parameters were the production parameters in use by the crew at the time. A detailed survey design process determined the optimum point-source/point-receiver parameters required to achieve the objectives (Table 1).

Table 1: Source and receiver parameters

Source Array	**Point Source**
50-m VP interval (CoG)	25-m VP interval
4 Vibrators (linear array of 45 m)	4 vibrators (boxed)
4 x 12-s sweep (12.5m move-up)	1 x 12-s sweep
Sweep frequency: 8-84 Hz	Sweep 6-72 Hz
Receiver Array	**Point receivers**
50-m interval (CoG)	Inline 12.5-m staggered
50-m array length	Crossline 6.25 m
24 geophones/group	Single sensors

The amplitude spectra show a peak at 48 Hz on the array data, which is due to high line pickup. This is effectively removed during the DGF process on the point-receiver data, thus removing more noise effects while enhancing the signal. This translates to a broadening of the bandwidth and a greater separation of signal and noise on the single-sensor data.

The raw array data have had no additional processing applied compared to the point-receiver data that have had airwave attenuation, high-line removal, intra-array statics, and a 3D FKK APOCS-designed filter applied as part of the DGF process. The ability to attenuate noise and correct for perturbations at the individual sensor level greatly enhances the ability to reduce noise and enhance signal. From this comparison test it was shown that point-source/point-receiver data, recorded with half the source effort and a lower upper sweep frequency, can deliver data with a higher effective frequency content and with greater signal-to-noise separation than the equivalent conventional data recorded with source and receiver arrays

Data example

The example shown above is related to the prestack domain. However, most analysis on surface seismic data is performed post stack. The stacking process, whether a straight summation or a more complex weighted summation such as used in the prestack migration algorithms, is a very powerful mechanism to improve the signal-to-noise ratio. However, any irregularities in the acquisition geometry can lead to a severe footprint, as the noise cancellation will not be uniform. This irregularity can be reduced by applying spatial filters in the poststack domain at the expense of spatial resolution. It is postulated that single-sensor data can improve the spatial resolution as the data input into the (complex) stacking process have less coherent noise, allowing recording of lower-effort surveys compared to some current surveys recorded with arrays. To illustrate this, a decimation/interleaving test was performed on the Minagish point-source/point-receiver dataset, acquired with the Kuwait Oil Company in 2004. This was a high-resolution dataset with source and receiver line spacing of 200 m, obtained after interleaving two datasets with 200-m source-line spacing and 400-m receiver-line spacing. The single-sensor spacing was 4 m to adequately sample the coherent noise in the area. The data were acquired in an orthogonal geometry and then decomposed into individual cross spreads. As the noise attenuation was performed on these individual cross spreads, the main factor governing the trace density was the source and receiver line spacing. This dataset was reprocessed at various schemes to show how these high-quality data could be reused to build a dataset of reservoir quality.

Figure 4 shows the various stages of this simulation. Each of the datasets, as processed, followed a similar processing flow including spiking deconvolution prestack and prestack time migration.

The left panel shows a decimated dataset from one pass of the 3D volume obtained by dropping every other receiver line and three out every four source lines to simulate a very sparse, low-fold 3D survey. No a-priori information from the full survey was used, and new statics and velocity solutions were derived and used to process the data through to final stack following a prestack time migration processing flow.

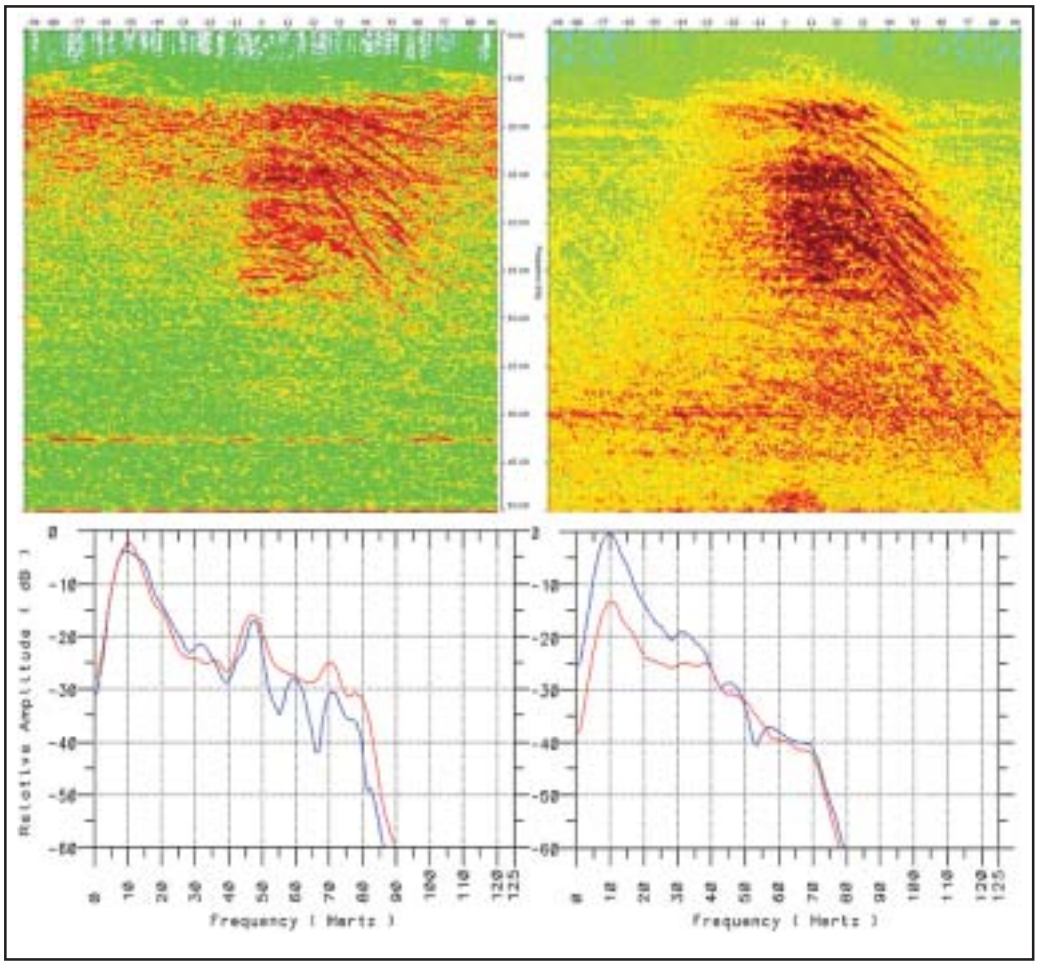

Fig. 3: FK plots of raw array data (left) vs. DGF point-source/point-receiver data (right). Below is the amplitude spectra comparison centered on the target at 2000 ms and after an FKK has been applied. Cross spectral estimate for signal is in blue, noise in red

The middle panel shows the results of one pass of acquisition with every other source line dropped to produce a dataset of 400-m x 400-m source and receiver spacing. The velocity and statics solutions derived from the previous stage were used and refined in this stage.

The right panel shows the interleaving of two 200-m x 400-m datasets to give a 200-m x 200-m dataset.

The poststack whitening sequence applied to each dataset was optimized based on the inherent signal-to-noise characteristics of the stack. For the coarse 800-m x 800-m grid, no whitening poststack was applied, as any poststack whitening resulted in introduction of high-frequency noise into the stack. For the 400-m x 400-m stack, spectral whitening was used, providing a bandwidth similar to legacy data. For the 200-m x 200-m fold dataset, spectrally constrained wavelet shaping was applied, resulting in a much broader bandwidth. The results of this last dataset were published by Shabrawi et al. (2004). Comparing these datasets, it can be concluded that fold reduces the noise floor in the seismic data, allowing application of much more rigorous whitening techniques. This should improve the reliability of the data interpretation.

Conclusions

With the advent of high channel count recording systems and the development of processing algorithms to complement them, it is time to reevaluate the basic assumptions used in designing a 3D survey. With the lower noise floor available from single-sensor acquisition and processing, and the ability to correct for perturbations within the group, fold and array design are no longer the dominant

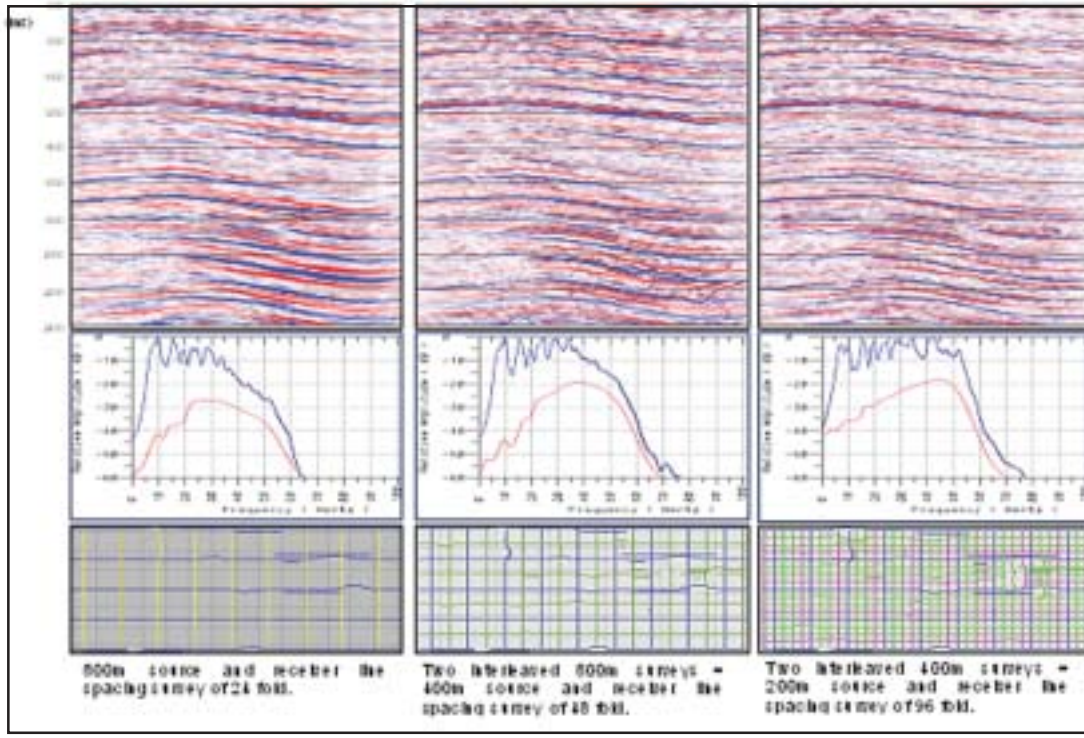

Fig. 4: Results of the interleaving processing tests showing improvements to stack data (top panels) and frequency content (middle panels) for each interleaving geometry scheme (lower panel).

factors in improving signal-to-noise ratio.

Rather, sensor spacing and the requirement to adequately sample the coherent noise become the main drivers in designing the receiver geometry. On the source side, as it is now possible to recover the signal more faithfully, the source effort can also be reevaluated, providing the possibility to record shorter single sweeps with a better sampling of the wavefield. With the removal of coherent noise, the true earth transfer function and improved statics and velocity solutions can be determined, allowing for improved spatial and temporal resolution.

These design considerations now offer the possibility of acquiring point-source/point-receiver surveys with a lower field effort (which could be lower fold and/or lower source effort) than equivalent surveys using source and receiver arrays. These data with better fidelity, signal-to-noise ratio, and bandwidth, acquired at the exploration phase, can also be reused at subsequent stages throughout the development cycle of an asset, provided that the final objectives have been designed in at the exploration phase.

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