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Variable Depth Streamer Acquisition: Enhancing interpretation with broadband marine seismic

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Summary

Variable-depth streamer acquisition is a solution for broadband marine seismic which utilizes a novel deghosting technique to remove the receiver ghost and extend the usable primary bandwidth up to six octaves. This technique benefits from towing streamers at depths of up to 50 meters, which, combined with the use of solid streamers, ensures the raw data has an exceptionally good signal-to-noise ratio, especially at low frequencies. We will demonstrate the benefits of technique to enhance seismic interpretation on images and on inversion results.

Introduction

This paper revisits the problem of receiver deghosting, and provides a method which uses hydrophones only to provide robust removal of the receiver ghost across the full bandwidth of the recorded primary energy.

A new deghosting algorithm is described, based on computing both a migration and a mirror migration and performing a joint deconvolution of the two, either post-stack where the method benefits from improved signal-to-noise, or on pre-stack image gathers. This method is true amplitude, as it is able to extract the true deghosted reflectivity, i.e. the reflectivity that would have been obtained had the water surface not been reflecting. We describe how this new technique provides a method of deghosting data acquired with a variable depth streamer geometry optimised to provide ghost notch diversity.

This variable-depth streamer acquisition and processing has been employed extensively for commercial 2D and 3D surveys and has also been tested successfully in a wide azimuth survey. It is operationally robust, is proven to extend the marine acquisition weather window and has been combined with fan-mode streamer acquisition to reduce infill and survey duration.

From our portfolio of results in a range of environmental and geological settings, we show examples from the UK Central North sea and make comparisons to modern conventional data in the area, focussing the benefits for interpretation and show other post-stack seismic inversion results.

Receiver Deghosting with Joint Deconvolution

Reflection energy from the subsurface is recorded by the receivers (direct arrival) before it continues upwards to the water surface, is reflected back and recorded as a “ghost” arrival at the receivers. It is the interference between the direct and ghost arrivals that cause the interference pattern (receiver ghost notches) we are familiar with in the amplitude spectrum of streamer data.

Conventional attempts to remove the receiver ghost are typically include the zero-offset receiver ghost in the far-field signature and perform a 1D deconvolution of the data at the preprocessing stage. From

Robinson and Treitel (1964), given a trace $d(t)$, we need to find a minimum phase wavelet $a_{min}(t)$ and a reflectivity $r(t)$ such that:

$$d(t) = a_{min}(t) * r(t) \tag{1}$$

This problem is mathematically ill-posed, so we must assume the reflectivity $r(t)$ is white.

Our approach to removing the receiver ghost is to address the problem using redundant information provided by the ghost itself. A migration and mirror migration can be performed, providing two different views of the reflectivity (Figure 1). Assuming that the ghost wavelet is a minimum phase signal and that the mirror migration gives the same reflectivity as the migration, but distorted by a ghost wavelet that is maximum phase, we can pose the problem as a joint deconvolution. This becomes the joint deconvolution of two signals, $d_1(t)$ and $d_2(t)$, to find a signal $r(t)$, a normalized minimum phase operator of given length $g_{min}(t)$ and a normalized maximum phase operator of given length $g_{max}(t)$ such that:

$$\begin{aligned} d_1(t) &= g_{min}(t) * r(t) \\ d_2(t) &= g_{max}(t) * r(t) \end{aligned} \tag{2}$$

In an intuitive way, we can say that we have a binocular vision of the reflectivity, $r(t)$, with the conventional migration image, $d_1(t)$, coloured by a normalized minimum phase distortion (residual receiver ghost), and the mirror migration image, $d_2(t)$, coloured by a normalized maximum phase distortion (residual or “de-focused” primaries).

Joint deconvolution recovers the reflectivity in true colour (i.e. without distortion). Although the joint deconvolution, equation (2), looks very similar to conventional deconvolution, equation (1), this is a well-posed problem, which means it has a unique solution, even when the minimum phase and maximum phase properties are marginally respected, i.e. the operators have perfect spectral notches (Soubaras, 2010). No assumption is needed regarding the amplitude spectrum of the reflectivity, which is arbitrary and unknown. The joint deconvolution can be performed in a least squares sense where there is noise in the data, and can also be performed in a multichannel manner, making it robust.

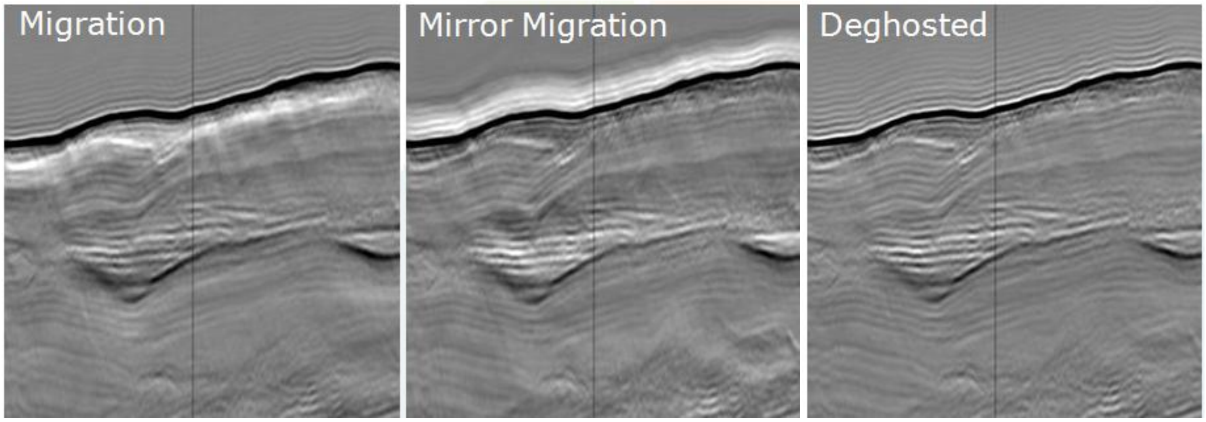

Figure 1: Migrated stack with residual ghost seen as white halo below water bottom (left), Mirror migration with residual primaries pre-cursor (centre) and deghosted result after joint deconvolution (right)

Variable Depth Streamer Acquisition

Although this deghosting method can be used with any kind of acquisition geometry, it is particularly suited to variable-depth acquisitions which maximise the receiver ghost notch diversity. This pre-stack notch diversity prevents perfect notches being present on the post-stack data. After migration and mirror migration, the residual ghosts have no perfect notches (apart from frequency zero), and so can be estimated and deconvolved using the joint deconvolution method. Since the deghosted image uses both the migration and the mirror migration, it benefits from ”fold doubling”, using both primary and ghost events to build the image.

Rather than using just a linear increase in streamer depth with offset (original slant streamer geometry) a custom profile is designed which has the general characteristics of a steep dipping front section and a gently dipping rear section (Figure 2). This optimised profile provides better receiver ghost diversity, particularly for shallow events, and can be tuned to provide the maximum possible bandwidth for a given geological setting and water depth.

This technique takes full advantage of towing solid streamers at what are currently considered as extreme depths (up to 50m), in order to benefit from the improved low-frequency response of the hydrophones and reduced sea-state noise. The flexibility means that the method can be used for a range of applications. The increase in penetration from the extension of the bandwidth at the low end benefits the imaging of deep targets and those below complex overburdens. Shallow targets (such as shallow drilling hazards) benefit from the total bandwidth available and recordable. Usable bandwidths between 2.5 and 160 Hz have been achieved with the technique, and when combined with source deghosting this has been extended to 200 Hz.

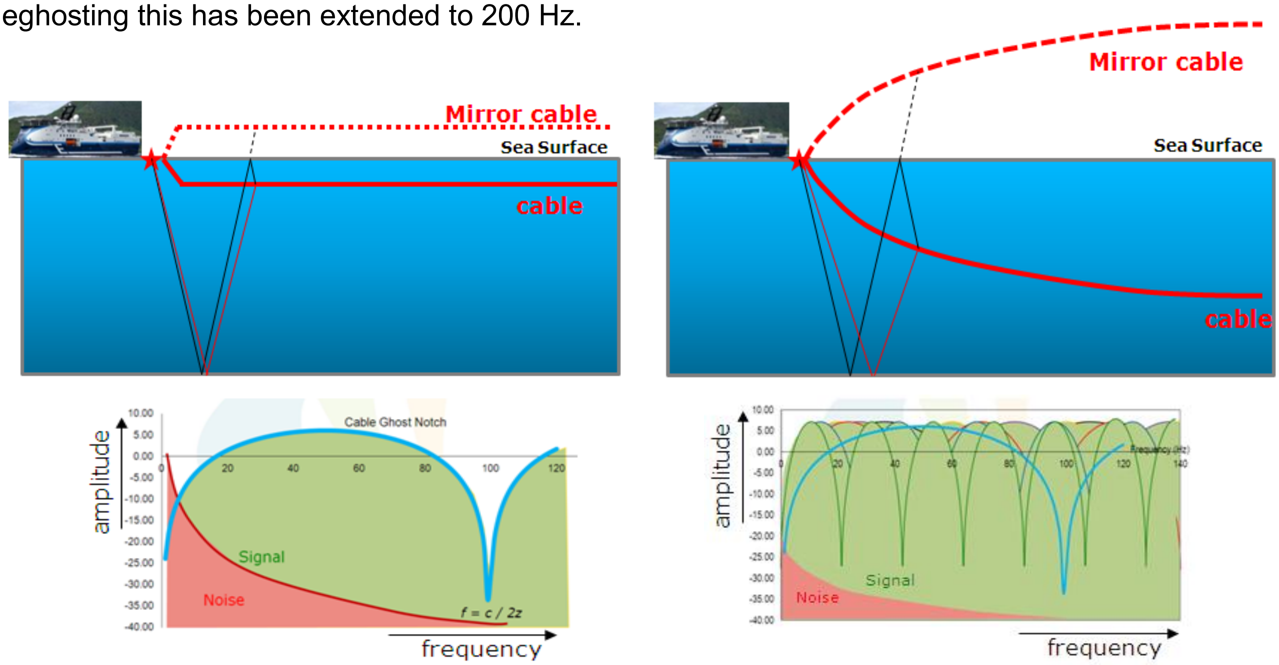

Figure 2: Comparison of schematic conventional (left) and variable depth (right) streamer profiles, and the amplitude spectra (below) which result from the interference from the receiver ghost. “Mirror cables” have been added to the schematic to illustrate the concept that conventional streamer acquisition uses a tuned array with a particular interference pattern (bottom left), the mirror cable representing the recording of the receiver ghost arrival. With variable depth streamer acquisition, the array is de-tuned with the ghost notch frequency varying with receiver depth. After summing the response along the cable, there is no discreet receiver notch and it is possible to access the full bandwidth. An addition benefit of deeper tow depths is that the noise from the water surface is reduced, as is shown in the schematic amplitude spectra, which is particularly important for the low frequencies.

Enhancing Interpretation

The broad bandwidth and increased low frequency content achieved with variable depth streamer acquisition and the novel deghosting scheme are very desirable characteristics for seismic data. They result in a sharp, clean wavelet with minimal sidelobes which makes it easier to resolve events (Figure 3) and interpret fine stratigraphic detail.

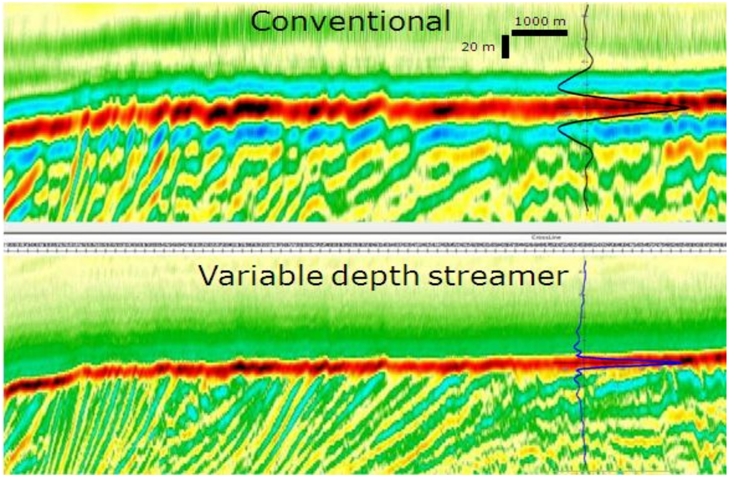

Figure 3: Water bottom and near-surface sediments imaged using conventional streamer acquisition (top) and variable depth streamer acquisition (bottom) in deep water offshore West Africa. The seismic wavelets extracted from the images are overlain on the water bottom reflector for reference. The resolvability of the dipping near-surface reflectors is greatly improved with the deghosted broadband variable depth streamer data. Data courtesy of Total, the Republic of Gabon and Cobalt.

The increased low frequency content has a surprisingly powerful effect on the seismic images, providing strong discrimination of layers and highlighting subtle acoustic impedance variations (which are visible on well log data) that may reflect equally subtle facies and fluid effects not revealed by conventional seismic.

The combination of the sharp wavelet with minimal sidelobes and low frequencies which provide layer discrimination make broadband variable depth streamer data particularly attractive from an interpretation point of view, as illustrated in Figure 4 using a channel feature from the UK Central North Sea as an example.

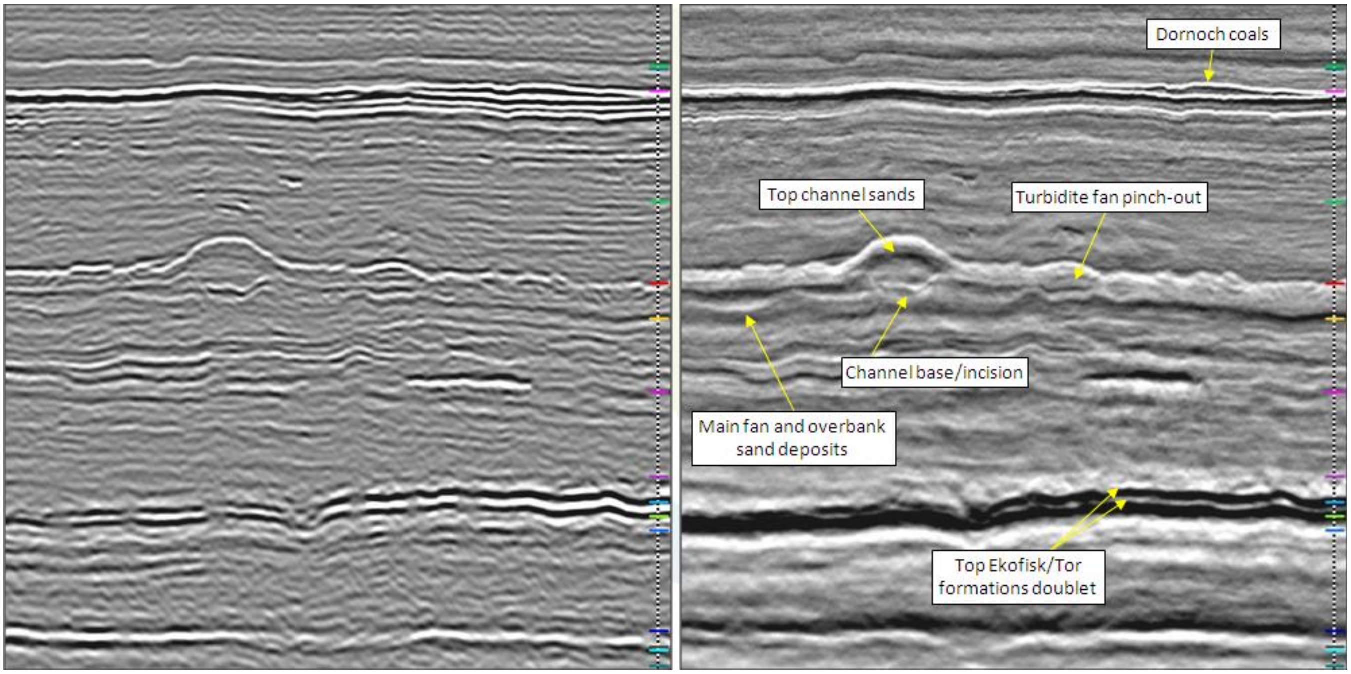

Figure 4: Conventional 3D (left) and variable depth streamer 3D acquisition (right) images from the UK Central North Sea. The clean broadband wavelet makes it easier to interpret specific horizons and clearly discern closely spaced events such as the top Ekofisk and Tor reflections. In terms of the interpreting the channel sands in the central part of the image, the low frequencies clearly map the softer shale horizon (pale grey) containing the sand channel, whilst the incised base and overbank deposits of the channel stand out very clearly on the broadband image. The polarity convention is that an increase in acoustic impedance is represented by a positive black peak. Formation tops are marked on the well on the right hand side of the sections.

More Quantitative Seismic Inversion

Variable-depth streamer data provide significant benefits for seismic inversion workflows, especially in terms of low frequency bandwidth extension. The lack of low frequencies in conventional seismic data means that a low frequency model must be incorporated in the inversion process in order to recover absolute impedance values. Usually, the low-frequency information is obtained by interpolating low-passed filtered impedance logs between well locations, using interpreted horizons as a guide. If the wells are sparse and the geology complex, the low frequency model derived from the wells may be inaccurate and yield biased inversion results.

The typical solution is to use NMO-derived seismic velocities to define the background low frequency model. However, while the seismic velocities provide information at very low frequencies (~0-4 Hz), they are not usually suitable to infill the missing frequencies in the range of 4-10 Hz. With variable-depth streamer data, these “missing frequencies” are present, reducing the need to build a low frequency inversion model from well data.

In our post stack inversion example one well has been excluded from the initial model-building and used as a blind well to compare with the results from the inversion of both conventional and variable-depth streamer data (Figure 5). The low frequencies provided by the variable-depth streamer data allowed the inversion to “escape” from the initial model and achieve a much better prediction of the absolute acoustic impedance at the blind well (Figures 5 and 6).

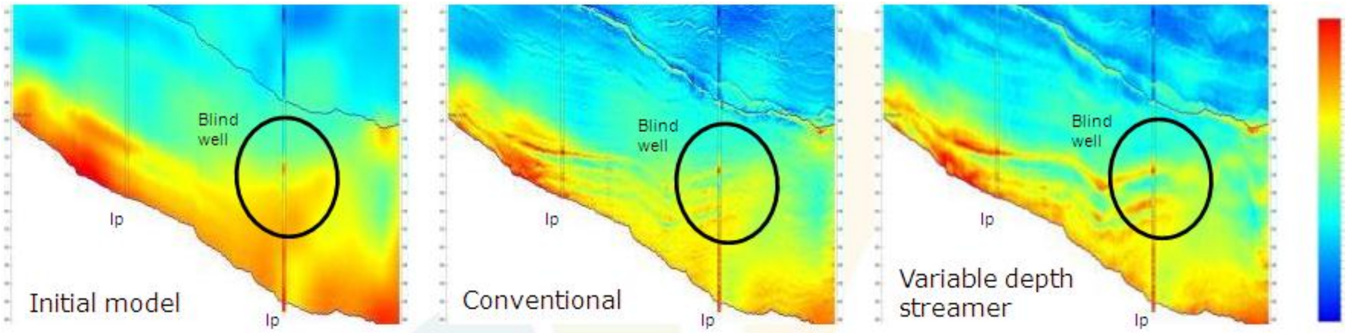

Figure 5: Initial P-impedance model (left) constructed using NMO-derived seismic velocities and the left-hand well only. The broadband variable depth streamer data provide a much better match with the blind well in terms of absolute P-impedance values.

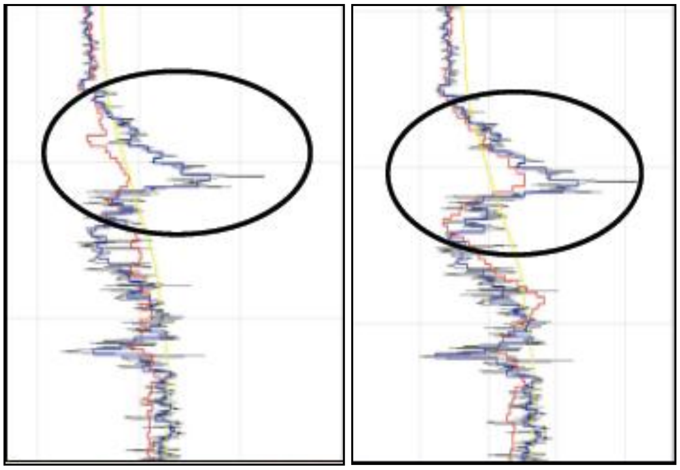

Figure 6: Conventional (left) and variable depth streamer (right) post-stack inversion P-impedance (Ip) results plotted at the blind well. The initial model is shown in yellow, the inversion results in red, the well log (Ip) in black and an upscaled version in blue. Inversion of the broadband variable depth streamer data results in a better well tie, while the conventional result is trapped near to the initial Ip model.

Conclusions

We have described a variable depth streamer acquisition technique and a new deghosting method that yields broadband seismic data. The data is characterised by a broad bandwidth (6 octaves has been achieved), a clean wavelet with minimal sidelobes and strong low-frequency content (down to 2.5 Hz).

The data has been proven to make seismic interpretation more intuitive and detailed by making it easier to resolve events and discriminate layers and subtle variations within layers.

Inversion results have been shown to benefit from this enhanced bandwidth. In particular, variable-depth streamer data seems to have the potential to fill the usual gap between the high frequencies of the seismic velocities and the low frequencies of the reflectivity, to produce more quantitative estimates of reservoir properties and reliable well ties.

Acknowledgements

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