Variable-depth streamer acquisition: broadband data for imaging, post and pre-stack inversion

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SUMMARY

Variable-depth streamer acquisition is a broadband streamer acquisition technique where the depth profile of the streamer is optimized in order to ensure receiver ghost diversity, which in turn allows the deconvolution of the residual ghost at the imaging stage, pre-stack or post-stack. This technique allows the streamers to be towed at an average depth of several tens of 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. This variable-depth streamer acquisition and processing has been field-tested on a variety of locations, achieving bandwidth up to 6 octaves (2.5Hz -160 Hz). This broad bandwidth translates into improved results for the acoustic impedance inversion. The lack of low frequencies in conventional seismic data means that a low frequency model must be incorporated in the inversion process, obtained by interpolating low-passed filtered impedance logs between well locations. With variable-depth streamer data, high-resolution NMO-derived seismic velocities are used to define the low frequency model in a range 0-5Hz, while the reflectivity provides information from 2.5Hz. Variable-depth streamer data thus have the potential to fill the usual gap between the high frequencies of the seismic velocities and the low frequencies of the reflectivity, the 2.5-5 Hz octave being the overlapping zone. Pre-stack elastic inversion has also been performed, providing both impedance and Vp/Vs sections, proving the feasibility of pre-stack deghosting of variable-depth streamer data.

Key words: marine acquisition, broadband, deghosting, imaging, inversion.

INTRODUCTION

The traditional approach to receiver deghosting is to include the zero-offset receiver ghost into the far-field signature and to perform 1D deconvolution of the dataset at preprocessing stage. Δz being the depth of the streamer and c the water velocity, we have:

$$G(f) = 1 - e^{2j\pi 2\Delta z f/c} \qquad (1)$$

This traditional approach can be refined by taking into account the angle of propagation of the wavefield instead of assuming vertical propagation. The ghost takes the form:

$$G(f,k_x,k_y) = 1 - e^{2j\pi 2\Delta z\sqrt{f^2/c^2 - k_x^2 - k_y^2}} \qquad (2)$$

This approach raises two problems. The first one is that, while it is easy to take into account non vertical propagation in the inline direction x (parallel to the streamers), it is much more difficult to take into account the crossline direction y, due to the coarse y sampling that a multi-streamer acquisition performs. The second problem, is of a more fundamental nature: considering that the deghosting operator is variable, it should not be done as a preprocessing, but should be done after stack. It is a general principle in signal processing that any deconvolution of a redundant measurement with a variable wavelet should be done after stack. We will therefore investigate the possibility of performing the deghosting, not at pre-processing stage, but after stacking.

OPTIMAL STACKING WITH A VARIABLE WAVELETET

The optimal solution of the multichannel deconvolution problem:

$$T_n(f) = W_n(f)R(f) + E_n(f), n = 1,.., N \qquad (3)$$

is not the pre-stack deconvolution plus stack formula:

$$\hat{R}(f) = \frac{1}{N}\sum_{n=1}^{N}\frac{T_n(f)}{W_n(f)} \qquad (4)$$

but the least-squares formula:

$$\hat{R}(f) = \frac{\sum_{n=1}^{N}\overline{W_n(f)}T_n(f)}{\sum_{n=1}^{N}\left|W_n(f)\right|^2} \qquad (5)$$

which corresponds to matched filtering, stacking, and post-stack deconvolution. The only case where the pre-stack deconvolution is valid is when the wavelets $W_n(f)$ do not depend on n. The more diversity we have in our wavelets, the more advantage we have to use the least squares formula.

Equation (5) is written for a 1D wavelet. When considering the receiver ghost problem of a streamer acquisition, and in order to take into account all angle of propagation, including the crossline propagation, the multidimensional matched filtering can be realized by a "matched mirror migration". The matched mirror migration is defined as a migration in which the number of receivers is doubled by introducing for each receiver located at (x_r,y_r,z_r) and having recorded the data $d_r(t)$, a mirror receiver at the location $(x_r,y_r,-z_r)$ and consider that this mirror receiver has recorded the data $-d_r(t)$.

The stacked matched mirror image is the equivalent of the numerator of equation (5). What would be the equivalent of the division by the denominator? Spectral whitening by a zero-phase operator is a possible solution but it is not true amplitude, as a white reflectivity assumption has to be made. In order to have a true amplitude deghosting, we consider separately the two components of the matched mirror migration: the normal migration that migrates the receivers and the mirror migration that migrates the mirror receivers. The normal migration stacks coherently the primary events, the ghosts events being imperfectly stacked in such a way that the migration has a residual ghost wavelet that is causal. The mirror migration stacks coherently the ghosts events with their polarity reversed, in such a way that the primary events are imperfectly stacked in such a way that the mirror migration has a residual ghost wavelet that is anticausal. The proposed deghosting method uses this "binocular vision" of two images of the same reflectivity with a different viewpoint to extract the true amplitude deghosted migration, that would have been obtained by a conventional migration if the water-surface was non-reflective.

JOINT DECONVOLIUTION

The conventional deconvolution method, (Robinson and Treitel, 1964) can be stated as: given a trace d(t), find a minimum phase wavelet $a_{min}(t)$ and a reflectivity r(t) such as:

$$d(t) = a_{min}(t) * r(t) \tag{6}$$

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

It is a very reasonable assumption to consider a ghost wavelet as a minimum phase signal, or at least a marginally minimum phase signal. We can likewise consider that the mirror migration gives the same reflectivity as the migration but distorted by a ghost wavelet which is maximum phase. We can then consider the following problem:

Considering $d_1(t)$ and $d_2(t)$ two given signals, find a signal r(t), a normalized minimum phase operator of given length $g_{min}(t)$ (normalized meaning $g_{min}(0)=1$), and a maximum phase normalized operator of given length such as:

$$\begin{aligned} d_1(t) &= g_{min}(t) * r(t) \\ d_2(t) &= g_{\max}(t) * r(t) \end{aligned} \tag{7}$$

In an intuitive way, we can say that we have a binocular vision of the reflectivity r(t): one image, $d_1(t)$, the migration, is colored by a normalized minimum phase distortion, and the other, $d_2(t)$, the mirror migration, is colored by a normalized maximum phase distortion. We want to recover r(t) in true color, that is without distortion. Although the joint deconvolution problem as stated by equation (7) looks like the conventional deconvolution model stated by equation (6), it has totally different mathematical properties. It is a well-posed problem, which means it has a unique solution, even when the minimum phase and maximum phase properties are marginally respected (meaning the operators have perfect spectral notches) (Soubaras, 2010).

VARIABLE-DEPTH STREAMER

Although this deghosting method can be used with any kind of acquisition geometry, it is particularly adapted to acquisitions exhibiting pre-stack notch diversity. The pre-stack notch diversity prevents perfect notches being present on the post-stack data. One such acquisition is the slant streamer where the streamer depth increases linearly with depth. However, with current streamer lengths, such a configuration does not ensure sufficient notch diversity for shallow events, which do not use the whole length of the streamer. There is the need to optimize the depth profile in order to ensure diversity for all reflectors depths. After migration and mirror migration, the residual ghosts have no perfect notches (apart from frequency zero), so they can be estimated and deconvolved by joint deconvolution. Because this 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.

Such a variable-depth streamer acquisition was performed offshore West Africa. The processing flow consisted in source designature, surface-related multiple elimination, time-migration (normal and mirror), joint deconvolution. No spectral shaping was performed, so we can consider this section as being not only true amplitude but also true spectrum. The results is shown in Figure 2, with a bandwidth [2.5-150 Hz] as seen on Figure 4-a, plotted with a 0-160 Hz horizontal scale. The broadband nature of this image, both in low and high frequencies, together with its non-noisy nature, can be verified. Figure 1 is the conventional image obtained by processing a conventional acquisition performed along the same 2-D line just before the variable-depth acquisition and with the same equipment, and processed with a similar flow, apart from the receiver deghosting done by including the receiver ghost in the source designature instead of the joint deconvolution.

INVERSION RESULTS

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. Typically, low frequency information is obtained by interpolating low-passed filtered impedance logs between well locations, using interpreted horizons as a guide. If wells are sparse and the geology complex, the well-derived low frequency model may be inaccurate and yield biased inversion results. One option 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.

Variable-depth streamer data are ideally suited to recover these missing frequencies and reduce the need to build a low frequency inversion model from well data. Figure 3 shows in red the interval velocities derived from the high resolution V_{rms} field obtained during the processing of the variable-depth streamer data. The very good match with the well velocities shown in black can be verified, although the well information was not used to derive the red curve, which is derived solely from the V_{rms} field.

In order to quantify the benefits of the improved low frequency content on seismic inversion, we have performed comparative acoustic impedance (I_p) inversion tests using the West Africa conventional and variable-depth streamer data. Figure 4-a shows a comparison of the power spectra of the two datasets. The low frequency (0-5Hz) initial model was constructed from the seismic velocities of the variable-depth streamer data (Figure 4-b) and used to constrain both inversions. Log data from a well located near the seismic line were only used to validate the wavelets and the seismic velocities, and QC the inversion results. Figures 4-c and 4-d show respectively the absolute acoustic impedance profile estimated from the conventional and variable-depth streamer data. The two arrows displayed on the variable-depth streamer inversion results indicate the position of two thick sediment wedges whose shape is much better delineated than in the conventional data inversion. The impact of the additional low frequencies can be evaluated directly by subtracting the initial model from the inversion results, as shown in Figure 4-e and 4-f. The thick bands (100msec) of negative and positive relative impedances that are visible on the right hand side of Figure 4-f result directly from the low frequency bandwidth extension achieved with the variable-depth streamer data. In view of the structural complexity and absence of well data on the right hand side of the line, it would have been difficult to use standard well log extrapolation to recover the low frequency component missing in the conventional data inversion. The high frequency content of the variable-depth streamer data (Figure 4-a) is also expected to significantly enhance inversion quality for detailed reservoir characterization work. In the exploration example illustrated above, we chose to limit the high frequency content of the inversion by working in a relatively coarse (8 msec) layered framework adapted to the vertical resolution of conventional data processing.

CONCLUSIONS

We have described a new deghosting method that is not performed as a preprocessing stage, but at imaging stage to ensure the best signal-to-noise ratio. The method jointly deconvolves the migration and the mirror migration of the data. This deghosting method is true amplitude, retrieving from ghosted modeled data the migration of the unghosted modeled data. This deghosting method allows the processing of variable-depth streamer acquisitions. With such an acquisition and processing method, we have achieved a [2.5 Hz - 150 Hz] bandwidth on real data. Inversion results 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, the 2.5-5 Hz octave being the overlapping zone.

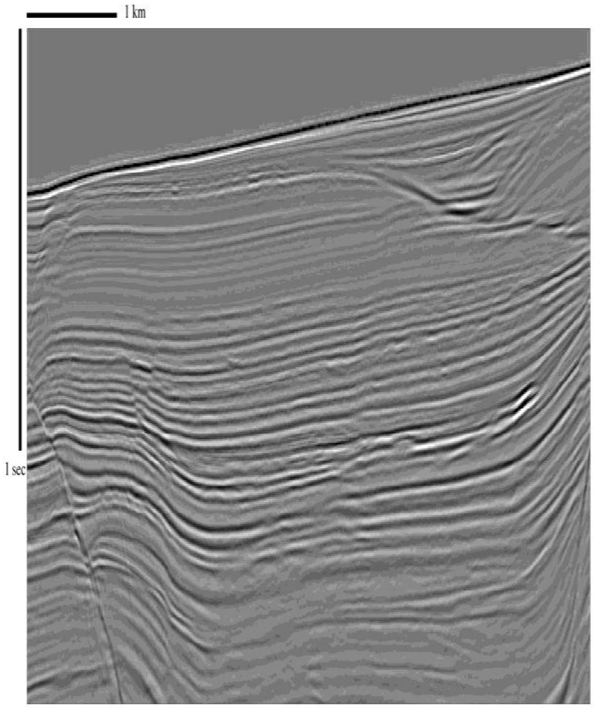

Figure 1. Conventional image.

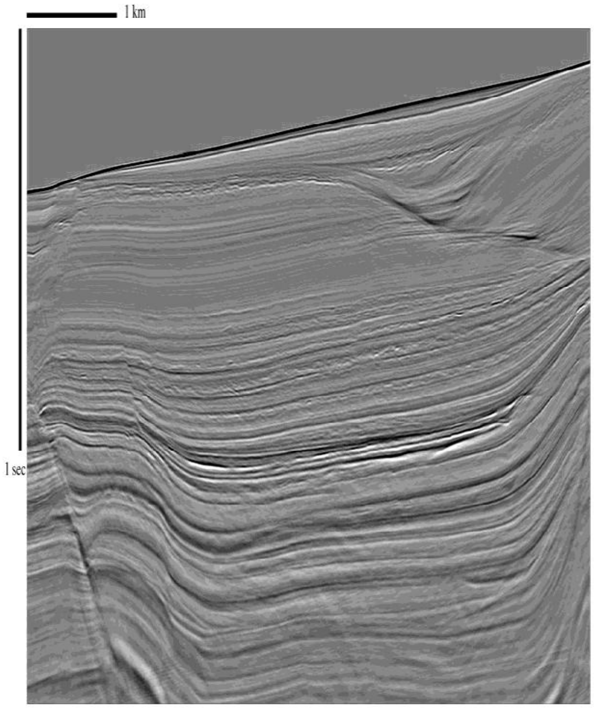

Figure 2. Variable-depth streamer image.

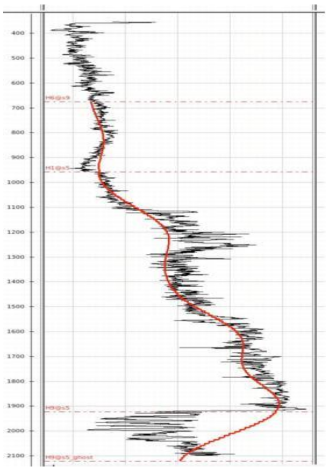

Figure 3. Black: Velocity from well data. Red: Interval velocity computed from the V_{rms} velocities of the variable-depth streamer data.

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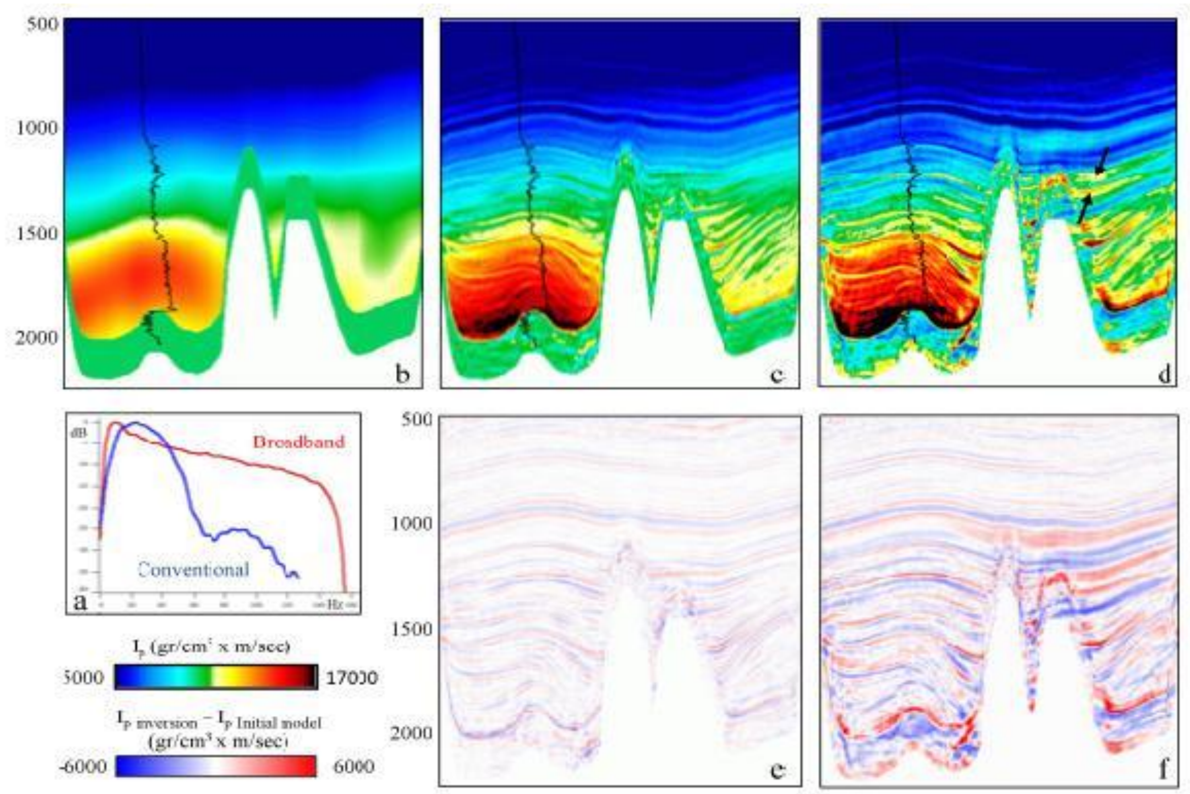

Figure 4. Acoustic inversion results.
a) Spectra of conventional and variable-depth streamer data.
b) Initial model.
c) Conventional data inversion.
d) Variable-depth streamer data inversion.
e) ΔI_p between conventional inversion and initial model
f) ΔI_p between variable-depth streamer data inversion and initial model