Variable depth streamer deghosting using a linear Radon transform with a time domain sparsity constraint

Introduction

For a long time, the marine ghost problem was considered insoluble, and the best way forward was to deal with its effect on seismic data (Clarbout, 2004). Today, deghosting has become a standard step in the seismic processing sequence, and there exist many mature deghosting algorithms (e.g. Poole et al. 2018; Zhang et al. 2018). It is therefore fair to say that we have learnt how to effectively handle the marine ghost. However, development of new deghosting algorithms continues to be driven by both the adoption of novel algorithms (e.g. Sun and Verschuur, 2018; Vrolijk and Blacquiere, 2020) and modern acquisition types (e.g. Masoomzadeh et al., 2015).

One particularly challenging acquisition type is variable depth streamer acquisition, where receiver deghosting is further complicated by the following issues. First, at a greater streamer depth the ghost notches appear at lower frequencies and interfere with the desired signal’s bandwidth. Second, the varying receiver depths prevent the analytic prediction of ghost notches. Third, large receiver depth variations introduce significant changes in the ghost delay time. Fourth, aliasing issues arise due to the presence of diffractions and the acquisition in shallow waters. These issues can cause deghosting artefacts such as “ringing” near the apex or “stripes” at high p-values.

In this abstract, we present a high-quality deghosting algorithm that tackles these deghosting issues using a sparsity constrained solver rather than an iteratively reweighted least squares approach. Furthermore, our deghosting algorithm imposes a sparsity constraint in the time rather than the frequency domain, which results in a significant reduction of artefacts. These two changes to the current standard practice enable significant improvements in deghosting quality.

Here, we first describe our algorithm and demonstrate its performance using a synthetic data example for a variable depth streamer acquisition. Next, we apply our algorithm to field data from a recent acquisition in offshore Gabon. Finally, we conclude with a discussion and a few remarks.

Method

Our deghosting algorithm uses a linear Radon transform to create a ghost-free model at the sea surface. Following Poole et al. (2018), the forward modelling operator that links the data $d$ and the model $m$ can be defined as

\[
d(t, x, y) = Lm(\tau, p_x, p_y) = \sum_p FT^{-1} S L_{\tau p} FT m(\tau, p_x, p_y)
\]

\[
L_{\tau p} = L^y_{\tau p} + RL^p_{\tau p} = \exp\left(-i\omega(xp_x + yp_y - zp_z)\right) + R \exp\left(-i\omega(xp_x + yp_y + zp_z)\right).
\]

Here, $x$ and $y$ represent the source-receiver offset, $z$ represents the receiver depth, $\tau$ is the intercept time, $\omega$ is the angular frequency and $R$ is the sea surface reflection coefficient. The horizontal slownesses $p_x$ and $p_y$ are linked to the vertical slowness $p_z$ through the water velocity. Finally, the operator $FT$ denotes the 1D Fourier transform and the operator $S$ denotes the convolution with a source wavelet. The adjoint operator is defined in a similar fashion.

After defining the forward and adjoint operators, we can set up an inverse problem that minimizes the misfit between the modelled and observed data. To mitigate the ill-posedness of the inverse problem, we choose to introduce a time-domain sparsity constraint and solve the basis pursuit denoise problem:

\[
\min_m \|m\|_1 \text{ with respect to } \|Lm - d\|_2 \leq \sigma.
\]

Here, $\sigma$ is a user-defined noise level. To solve this problem, we deploy the SPGL1 solver (van den Berg and Friedlander, 2008; Sun and Verschuur, 2018).

Numerical example

To demonstrate the correctness of our algorithm, we created a 3D marine shot record using finite difference modelling. The receiver ghost was modelled using mirror receivers to create a shot gather without a source ghost. For modelling, we used a 25 Hz Ricker wavelet as source wavelet. The
underlying 2.5D velocity model varied smoothly with depth and the seismic reflections were created using sharp changes in density. We simulated an experiment with 12 cables, 564 channels per streamer, 12.5 m trace spacing and 100 m cable spacing. Near the source the receiver depth was 7 m and increased gradually to 50 m. To prepare the data for deghosting, we modelled and subtracted the direct arrival.

Using this synthetic dataset as input, we applied our algorithm to attenuate the receiver side ghost (Figure 1). Looking at the input data, we observe the increase in ghost delay times characteristic for slanted streamer acquisitions. After application of our deghosting algorithm, this ghost has been effectively attenuated. Examining the turning rays and wide-angle reflections, we observe a simplification of the wavefield. After deghosting, we recovered the 25 Hz Ricker wavelet used in modelling. Comparing the deghosted data with the ground truth yields a signal-to-noise ratio of 19 dB, which makes it comparable to other published methods (e.g. Vrolijk and Blacquière, 2020).

Field data example

To demonstrate the quality of our method, we apply it to a field dataset acquired offshore Gabon. The experiment used a variable depth streamer configuration with receiver depths varying from 7 m near the source to 50 m at the far end of the cable. Data were acquired using 12 streamers spaced 100 m apart with 564 channels each and a channel spacing of 12.5 m. To prepare the data for deghosting, we applied basic data pre-conditioning including low frequency noise attenuation (swell, cable strum, cross-feed, etc.) and source deghosting.

Figure 1 Receiver deghosting results of a synthetic 3D shot gather. Figures (a) and (c) show the input data for an outer and an inner cable. Figures (b) and (d) show the results after receiver deghosting.
Application of our deghosting algorithm shows that we can separate primary energy and ghosts for variable depth streamer data without compromising the reflected or the diffracted energy (Figure 2). After deghosting, no processing related artefacts such as “ringing” or “stripes” are apparent. Comparing the brute stacks for an inner cable before and after deghosting (Figure 3) shows an increase in usable bandwidth and effective receiver ghost attenuation. We note that for the stacked image the ghost notches are less pronounced due to the summation of traces with different ghost notches. Most importantly, the low frequency content has been boosted and the receiver ghost notch has been effectively filled in.

Discussion and conclusions

In this abstract, we have presented a novel implementation of a linear Radon transform based deghosting algorithm that imposes the sparsity constraint in the intercept time-slowness domain rather than the frequency-slowness domain. We have demonstrated the effectiveness of this algorithm using both synthetic and 3D field data. This algorithm has facilitated a great improvement in deghosting for different streamer configurations deployed at various water depths. Only deghosting in extremely shallow water remains challenging because the linearity assumption fails. In this scenario, a hyperbolic rather than a linear Radon transform may yield superior results (Poole et al., 2018; Sun and Verschuur, 2018). Most importantly, the time domain sparsity constraint has allowed us to reduce the deghosting artefacts related to variable depth streamer acquisition. This reduction can be understood intuitively, because seismic data are sparser in the time domain than in the frequency domain. Since a spike

\[\text{Figure 2} \text{ Field data from a variable depth streamer experiment acquired offshore Gabon. Figures (a-d) show common shot and common channel gathers before and after receiver deghosting. The red dashed lines mark the intersection of the common channel and the common shot gathers.}\]
translates into a flat spectrum, the temporal sparsity constraint favours a flatter spectrum. In addition, time domain solutions use the whole bandwidth of the seismic signal and can therefore outperform frequency domain solutions. Combined these recent developments have enabled a significant improvement in the quality of receiver side deghosting.

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References

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