Broadband processing of linear streamer data

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Summary

Conventional marine seismic data is affected by the interference from ghosts on both the source and receiver sides. The natural diversity provided by propagation directions, depth variations and imperfect reflections at the sea surface means the notches are not as deep as they often appear after stack. For a flat streamer, the apparent time delay between the main signal and its ghost is angle dependent, and deterministic de-ghosting in the τ-p domain can reduce the effect of ghosts and retrieve the original wavelet spectrum. For a linearly-slanting streamer, further to the angle-dependant time shift a lateral separation occurs in the angle dimension. The amplitude and phase discrepancies around the notch frequencies caused by the variations in depths and effective refection coefficients can be reduced by using a stochastic search for the optimum set of de-ghosting parameters. A deconvolution process stabilized by averaging over a large number of traces in common–slowness panels may be used to address the remaining spectral defects.

Introduction

The frequency content and the temporal resolution of marine seismic data acquired using conventional streamer is affected by the interference from the reflections at the sea surface on both source and receiver sides. The interference by the slightly delayed reflections trailing the original source wavelet, called ghosts, can be either constructive or destructive for different wavelengths. The resulting wavelet may contain a number of notches in the amplitude spectrum, accompanied by drastic variations in the phase spectrum.

High resolution broadband seismic data may be acquired by reducing the ghosting effects in the acquisition stage. Suggested acquisition-based solutions include variable-depth streamer, or slanting cable, to tackle the receiver-side ghosting (Soubaras and Dowle, 2010), and dual-sensor streamers combined with random-depth sources (Tenghamn *et al*., 2007 and Carlson *et al*., 2007). A processing-based solution however, is highly cost effective for two reasons; it does not require any extra acquisition effort, and it is applicable to the existing legacy data library acquired by conventional flat cables (Baldock *et al*., 2012; Woodburn *et al*., 2012; Zhou *et. al*., 2012).

In this paper we present a processing-based broadband solution. Using a stochastic search for the best set of parameters, we apply a semi-deterministic stage of de-ghosting operations in the plane-wave domain. This can be complemented by a statistical stage including a carefully designed deconvolution operation, averaging over a large number of common-slowness traces, in order to address the remaining spectral defects including residual ghosts, side lobes and the bubble effect.

De-ghosting in the plane-wave domain

Our de-ghosting approach aims to acknowledge the fact that in conventional marine operations, the ghosting phenomenon is a function of the angle of propagation. Therefore, for a flat streamer, an appropriate de-ghosting can be performed in the f-k_x-k_y domain, or alternatively in the τ-p_x-p_y domain. After the transformation, all seismic events along a single slowness trace share a certain ray parameter p, and therefore the time delay t between the main signal and its ghost remains invariant along the τ axis. As shown schematically in Figure 1 for a source side ghost in a 2D plane, regarding a plane wave propagating with an angle of θ, we may write:

$$t = \frac{2d\cos\theta}{v}, \quad (1)$$

where d is source depth and v is water velocity. Since horizontal slowness, or ray parameter, may be defined as:

$$p = \frac{\sin\theta}{v}, \quad (2)$$

we can rewrite Equation (1) as:

$$t = \frac{2d\sqrt{1-p^2v^2}}{v}, \quad (3)$$

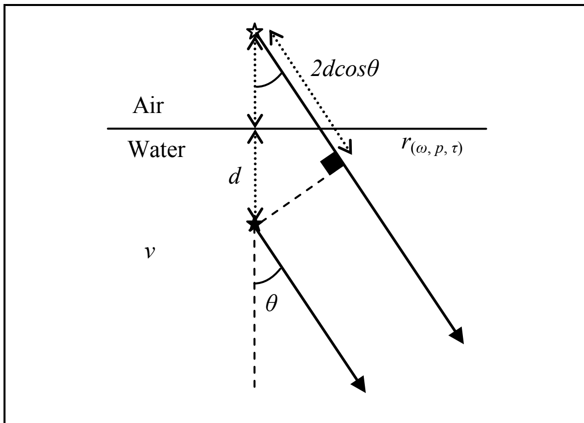

Figure 1: The time delay between a source signal and its ghost is angle dependent and uniform for a plane wave, i.e. along a slowness trace with a certain ray-parameter.

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and extend it to 3D as:

$$t = \frac{2d\sqrt{1 - p_x^2 v^2 - p_y^2 v^2}}{v}, \quad (4)$$

where p_x and p_y represent ray-parameter components in the inline and cross-line directions. In the frequency domain, a spike followed by a ghost may be expressed as:

$$1 + r_{(\omega,\tau,p)} e^{i\omega t}, \quad (5)$$

where r is the negative reflection coefficient at the sea surface and ω is the angular frequency. A similar analysis is applicable to the receiver side as well. Therefore a full de-ghosting operation may be achieved by applying the inverse of both ghost functions with appropriate parameterization.

If the streamer is slanted by an angle of α, the source ghost remains unchanged. On the receiver side however, an up-going plane-wave and its down-going ghost appear with different ray-parameters, while the difference is angle dependent:

$$p_\alpha = \frac{\sin(\theta \pm \alpha)}{v} \approx p \pm \sqrt{1 - p^2 v^2}\,\frac{\sin\alpha}{v}, \quad (6)$$

in a variety of the plane-wave domain where the horizontal axis is θ rather than p, and the up-going and down-going wave-fields appear with a lateral separation of 2α (Figure 2).

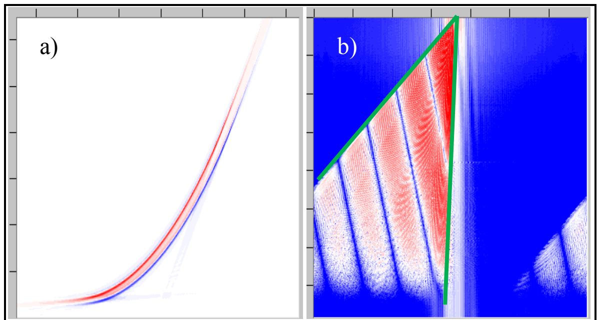

Figure 2: a) A synthetic event and its receiver-side ghost in the τ-θ domain assuming a linearly-slanting streamer towed at 5 m at near offset and 25 m at a far offset of about 5 km. b) Logarithm of amplitudes after a 2D Fourier transform applied to a). This angular (f-κ) transformation shows the position of dipping notches and facilitates deterministic de-ghosting. Near and far angular-offset traces are highlighted.

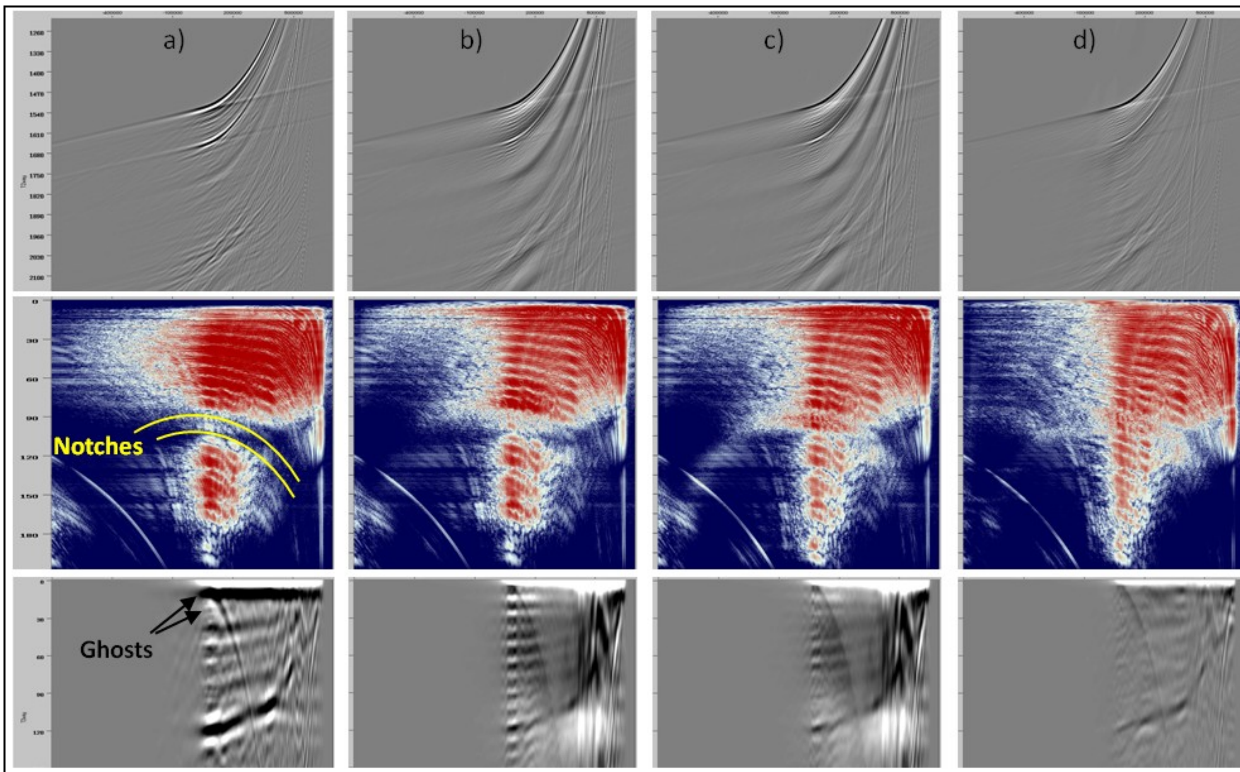

Figure 3: A shot gather in the τ-p domain (top), the logarithmic amplitude spectrum and the autocorrelation of each p-trace (middle and bottom): a) before de-ghosting, b) after de-ghosting with nominal parameters, c) after de-ghosting with optimized parameters, d) after complementary deconvolution to remove remaining spectral defects including residual ghosts and the bubble effect.

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Assuming a uniform distinction in both intercept-time and incidence-angle dimensions, a deterministic de-ghosting can be performed. Using a two-dimensional Fourier transform applied to data in the τ-θ domain, a ghost function can be expressed as:

$$1 + r_{(\omega,\tau,\theta,\kappa)} e^{i(\omega t + 2\kappa\alpha)}, \qquad (7)$$

where $\kappa = 2\pi/\bar{\lambda}$ is angular wave-number and $\bar{\lambda}$ is angular-wavelength.

It is important to use sufficiently accurate estimations of $r_{(\omega,\tau,p)}$ and t for each side to avoid ringing in the final product due to boosting the wrong frequencies. In a conventional marine operation, however, both source and receiver depths keep varying due to the weather conditions and acquisition limitations. The sea surface is not a perfect mirror (Williams and Pollatos, 2012) and reflection becomes increasingly imperfect for higher frequencies and ray parameters.

For a common-shot gather a certain source depth may be assumed, whereas a common-receiver gather with a fixed location does not exist. That is because each trace in a receiver gather is recorded by a different receiver, often in a different position. The variation of depths could leave a larger effect on the deeper events, because the same ray parameter may be received in a larger portion of the cable. Moreover, the signal-to-noise ratio is often lower in the deeper parts.

In order to improve the de-ghosting results, in practice we perform a stochastic search for the most appropriate set of parameters, including depths and frequency-dependent reflection coefficients on both sides. To address the effect of sea surface undulations and the variations in depths and signal-to-noise, we first perform a multi-gate search for optimum parameters and then we use empirical relations to define the effective value of r with respect to ω, τ and p, or θ and κ. Further improvements may be achieved by applying a multi-gate statistical deconvolution with a long-operator, designed by averaging over a large number of traces in all common-p or common-θ panels.

Example from the West of Shetland basin

We applied our broadband workflow to a dataset from the West of Shetland basin. Nominal depths were set to 7 m for

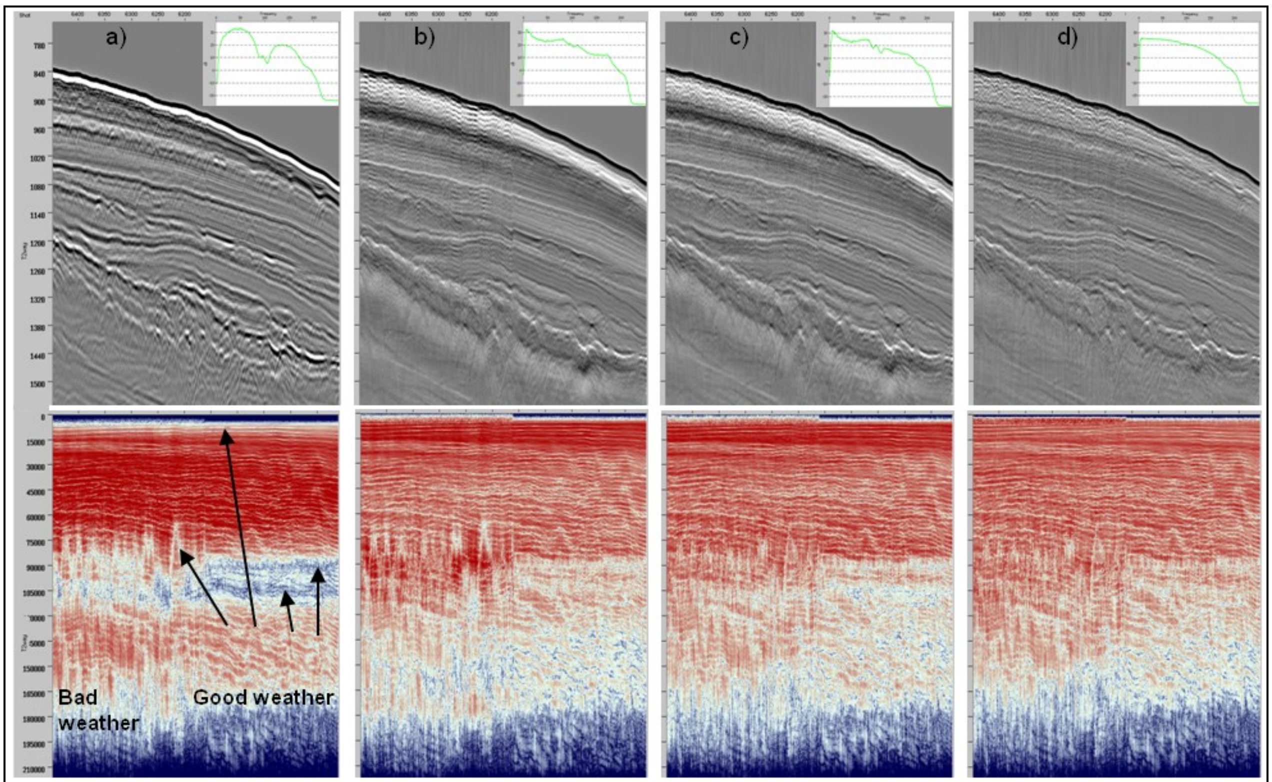

Figure 4: A common-p gather and its amplitude spectrum (top), the logarithmic amplitude spectrum (bottom): a) before de-ghosting, b) after de-ghosting with nominal parameters, c) after de-ghosting with optimized parameters, d) after complementary deconvolution to remove remaining spectral defects including residual ghosts and the bubble effect. Vertical axis on the amplitude spectra is frequency in Hz x10^3.

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the source and 9 m for the receiver. The actual depths, however, were different by up to 5 m in a bad weather condition. Figure 3 presents a τ-p transformed shot gather in time, frequency and autocorrelation views, before and after deterministic and semi-deterministic de-ghosting and after the complementary deconvolution process. Figure 4 shows a common-p gather in the same processing stages, and Figure 5 presents shallow and deep views of the time-migrated sections with and without our broadband workflow applied.

For a constant-depth cable, it is often sufficient to apply both source and receiver side de-ghosting operations to the transformed common-shot gathers. A linear transformation may tolerate limited variations of depth along the cable, and could even handle a linearly-shaped cable, but may struggle with large variation of cable depths. Moreover, a small and random variation of depths means the rapid phase changes expected around each notch could occur in a small range of frequencies. The phase discrepancy around the notch frequencies could cause the notches to appear much deeper than they are, mainly due to the cancellations during the stacking process. An accurate de-ghosting process however, helps in reducing both amplitude and phase issues initiated by the ghosts. This may include the phase of low-frequencies, which are of great importance for interpretation purposes.

Conclusions

Conventional marine seismic data is affected by the ghost effects. Fortunately the notches are not as deep as they were thought to be. Owing to the imperfect reflection at the sea surface, and the natural notch diversity provided by the limited variations in the source and receiver depths, and more importantly, by the angle dependency of the delay times, the signal to noise ratio is often large enough to provide valid signal in a broad range of frequencies.

Semi-deterministic de-ghosting in the plane-wave domain, preferably followed by a deconvolution utilising large-scale statistics in the common-slowness panels, can effectively remove the ghosts, together with other spectral defects. It is crucial to use an accurate set of parameters for both source and receiver sides, including the effective delay times for each ray parameter, and the effective reflection coefficients for each frequency, ray parameter and intercept-time zone.

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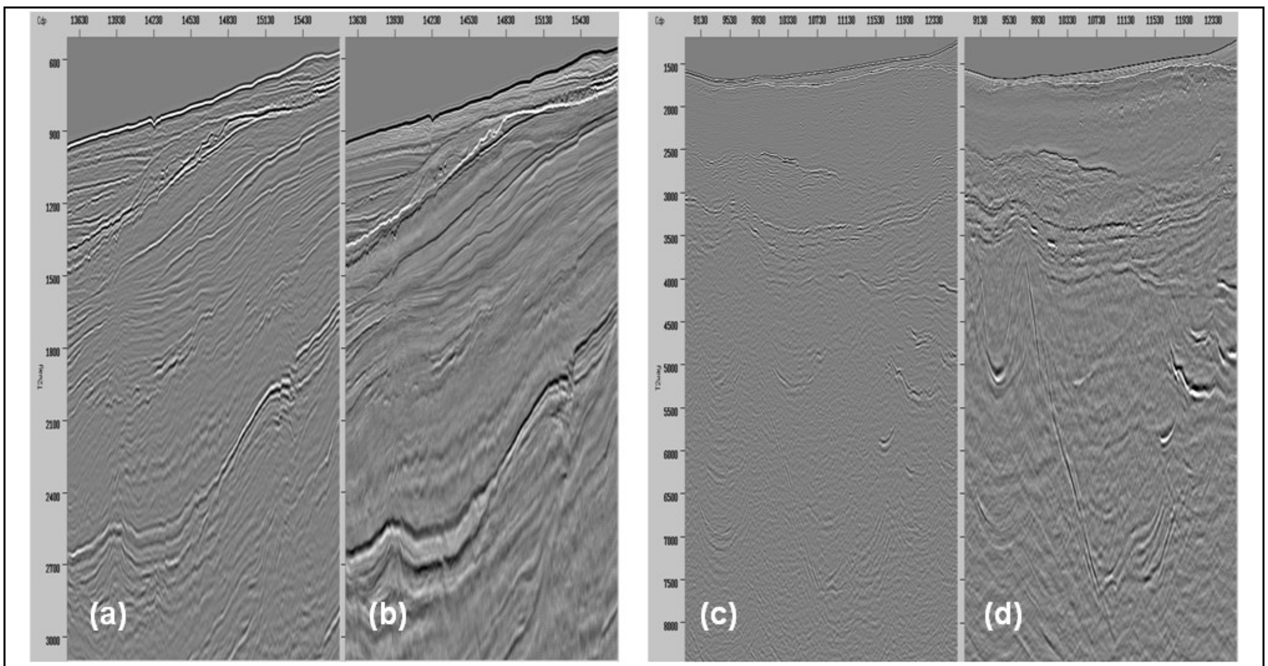

Figure 5: A 2D profile from the West of Shetland basin with and without application of de-ghosting in the τ-p domain, deconvolution in common-p and zero-phasing: a) and b) in a shallow zone, c) and d) in a deep zone. Note the improvement in resolution and also the enhancement achieved by exploiting the contribution from retrieved frequencies. Interpretable low-frequency signal is made available down to around 2 Hz.

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EDITED REFERENCES

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