Broadband processing of 3D towed streamer data: a critical analysis of 2D and 3D plane wave decomposition

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Summary

The ghost delay time is a function of the ray parameter. In the case of 3D data in the shallow water environment, the crossline component of the ray parameter is not negligible. However, the extent of offset increment in the crossline direction often results in severe spatial aliasing. Conventional interpolation techniques combined with the use of a high-resolution Radon transformation help reduce the aliasing effect. This combination facilitates a full 3D deghosting process, in which both inline and crossline components of the horizontal slowness are acknowledged.

Introduction

In recent years, the deghosting of conventional 2D marine seismic data has become a standard process. A number of techniques have been introduced for deghosting before, during, or after the migration process. A premigration bootstrap method was proposed by Wang and Peng (2012). Zhou et al. (2012) applied a deghosting process on conventional streamer data. Masoomzadeh et al. (2015) proposed a method of angle-dependent redatuming and deghosting for variable-depth streamer data, in the presence of an undulating sea surface.

For a 3D survey however, the common wisdom is to apply a 2D deghosting process to each gun-cable data set, either by acknowledging the actual irregular offsets, or by moving the data temporarily to a regular 2D grid, using a differential NMO correction or any alternative regularization technique. In other words, the common assumption is that the ray parameter has a negligible crossline component, i.e. $p_y \approx 0$.

This assumption however, is more likely to break down in the case of a wide-azimuth (WAZ) survey, especially in a shallow water environment. This is because the angle of incidence for a shallow event observed at the near-offset trace of a far cable can easily exceed the critical angle. In this instance, ignoring the crossline component of the horizontal slowness results in a miscalculation of the ghost delay time, which in turn could cause visible ringing at the shallow-near corner of the outer-cable deghosted data.

A more elaborate approach is to perform a 3D tau-p, i.e. tau-p_x-p_y transformation. However, conventional algorithms require a dense sampling in both inline and crossline directions. In a typical 3D marine survey, the offset spacing in the inline and crossline directions are 12.5 m and 75 m respectively, meaning that the recorded data is aliased. In other words, for a high slowness wavefront travelling with a velocity of 1500 m/s, in the inline direction, all temporal frequencies above 120 Hz, and in the crossline direction frequencies as low as 20 Hz are aliased. Wu et al. (2014) demonstrated the use of a progressive sparse tau-p inversion to overcome the aliasing issue caused by the lack of sampling in the crossline direction. In this paper we compare four alternative approaches, the first approach is to use a 2D transformation after a regularization, second is to apply a window-based 2D interpolation algorithm in both inline and crossline directions to populate a dense grid of traces, then use a fast tau-p algorithm in both directions. The third approach is to apply a high-resolution linear Radon algorithm in both directions successively. Finally we examine a hybrid of the two latter approaches, aiming to determine a preferred 3D deghosting work flow, in terms of both quality and computation time.

3D deghosting in the tau-p_x-p_y domain

A ghost function may be described as:

$$G = 1 + r_{(\omega,p)} e^{-i\omega t}, \qquad (1)$$

where ω is the angular frequency, p is the ray parameter or horizontal slowness, t is the ghost delay time and $r_{(\omega\ ,\ p)}$ is an effective reflection coefficient at the sea surface, given by the following empirical formula:

$$r_{(\omega,p)} = r_0\ \ (1-(pv)^2)^{\alpha}\ \ \ e^{-2(\frac{\omega h}{v})^2}. \qquad (2)$$

In this equation (modified after Kluver and Tabti, 2015), r_0 is an estimation of reflection coefficient in the case of $\omega=0$ and $p=0$, usually assumed as r_0 = -.95, v is the water velocity, α is a positive power often assumed as α =.5, and h is the wave height at surface.

In the case of 3D, the delay time can be expressed as:

$$t = 2d\sqrt{1/v^2 - (p_x^2 + p_y^2)}\,, \qquad (3)$$

where p_x and p_y represent the inline and crossline components of p. A full 3D deghosting operation may be achieved by applying the inverse of both source-side and receiver-side ghost functions, using the best knowledge of t and r. Plane-wave decomposition algorithms can be used to decompose a conventional 3D seismic shot gather into its p_x and p_y components. For this purpose we first apply tau-p_x

transformation along the inline direction, using offset-*x* component, then sort the results into the common-p_x panels before applying p_y transformation using offset-*y* component. In each of the latter passes, we have a chance to use either a fast tau-*p* transformation via the *f-k* domain, assuming regular offset increments, or a slant-stack approach, which is capable of handling irregular offset increments, as well as a least-squares and a high-resolution Radon algorithm. The latter is known to be computationally intensive, yet least sensitive to irregularities and large increments of offset.

In the presence of complex geology, this technique can be applied to the shot gathers, aiming to deal with the receiver-side ghost, followed by a second pass in the common receiver-location gathers to address the source-side ghost, acknowledging small variation of source depths.

Real data example

We examine various transformation and deghosting approaches using a 3D shot gather acquired in the Rona Ridge area, West of the Shetland Isles on the North-Western European Continental Shelf. This shot gather is from a narrow-azimuth survey acquired with 12 streamers separated by 100 m, a receiver interval of 12.5 m, and a shot point interval of 18.75 m operated in a flip-flop style. The water depth in the survey area varies between ~ 100-600 m. The source and streamer depths were about 7 m and 18 m respectively. Although this is not a wide-azimuth data, the shallowness of the water bottom means the crossline slowness can be large enough to demonstrate the concept. Figure 1 shows a small subset of this shot gather.

Figure 2 contains displays of deghosted data both in the time-offset and in the tau-*p* domains, comparing four various 2D approximated approaches. First we use a fast tau-*p* transformation algorithm via the *f-k* domain, with the assumption of a regular offset increment, which loses its validity as the offset-*y* increases. Then we tried a primitive regularization approach, i.e. using a differential NMO correction to move from 3D to 2D offsets, as if relocating all cables into the central position. We also tried both slant-stack and high-resolution linear Radon algorithms, which both acknowledge the actual offset of every trace. It seems that the latter options, provide convincing results.

Figure 3 demonstrates deghosted data, using four different options for performing a full 3D tau-p_x-p_y transformation. Since the offset increment in both directions can be assumed fairly regular, both fast and slant-stack methods provide similar results, which is heavily aliased in the crossline direction, as one would expect.
We examined two ways of avoiding the aliasing effect. First we tried cable interpolation by using a Nonequidistant Discrete Fourier Transform (NDFT) to reduce the offset-*y* increment down to 25 m. Then we used a progressive high-resolution Radon transformation in the crossline direction, in which the sparseness weights were estimated using a nonaliased low-frequency range (e.g. 1-15 Hz), and were gently tapered at both edges. Finally, we examined a combination of the two latter options. Even a fast 3D approach is much slower than any of the 2D options shown in Figure 2, yet the use of high-resolution algorithm makes it extremely slower. Meanwhile, the end product does not demonstrate a significant improvement to justify the extra processing cost and effort.

Conclusions

Using a high-resolution 3D plane-wave decomposition, we apply a deghosting operation while acknowledging both inline and crossline components of the horizontal slowness. This computationally intensive approach is expected to provide a more accurate result than the 2D alternatives. In spite of heavy computation, this process remains affordable because a whole 3D shot gather could be deghosted at once. The final product shows reduced ringing on the shallow events of the outer cables.

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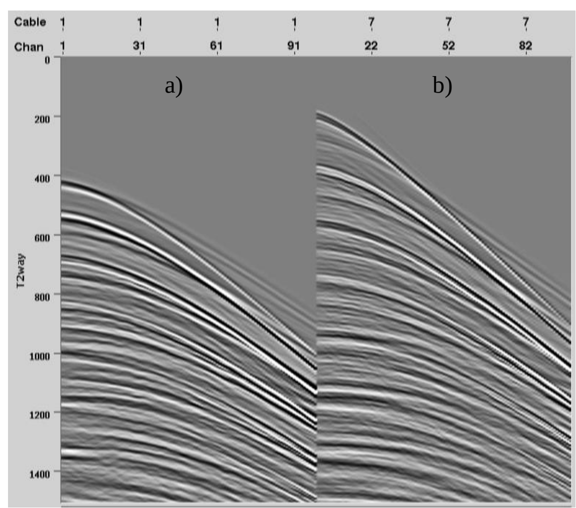

Figure 1: The shallow-near offset zone of a) an outer cable and b) an inner cable of a narrow-azimuth 3D shot gather from the West of Shetland, before deghosting.

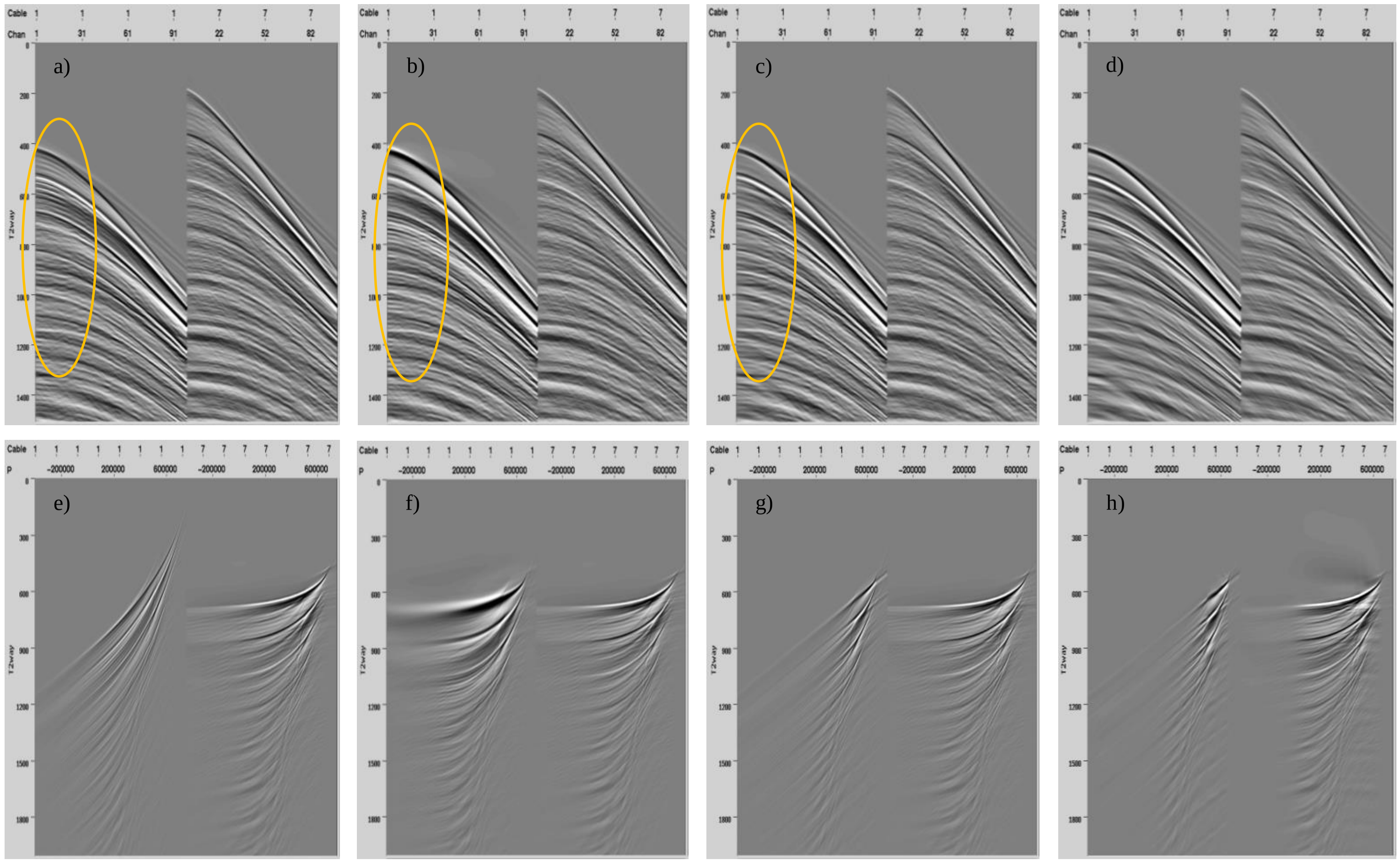

Figure 2: Deghosted data after using different 2D approximated approaches. a) A fast transformation algorithm is used, assuming a regular offset increment, which is not valid for the outer cable, meaning that the 3D effect is completely ignored, and therefore all slownesses are wrongly estimated and a visible ringing is introduced. b) A differential NMO correction is employed as a basic regularization approach, as if all cables are shifted to the zero-offset-*y* position. This improves the result to some extent, but this method is not accurate for all events. c) A slant-stack algorithm is used to acknowledge all actual offsets. This method performs a better deghosting but some smearing may occur at the near offset zone of the outer cables, due to a smaller offset increment. d) A high-resolution linear Radon transformation is applied in the inline direction, again acknowledging actual offsets. The deghosting result is convincing, although some high-slowness energy may seem to be less represented. e) as a) in the fast tau-*p* domain. f) as b) in the fast tau-*p* domain. g) as c) in the slant-stack domain. f) as d) in the hi-resolution linear Radon domain. Note that the inner cable result remains almost unchanged.

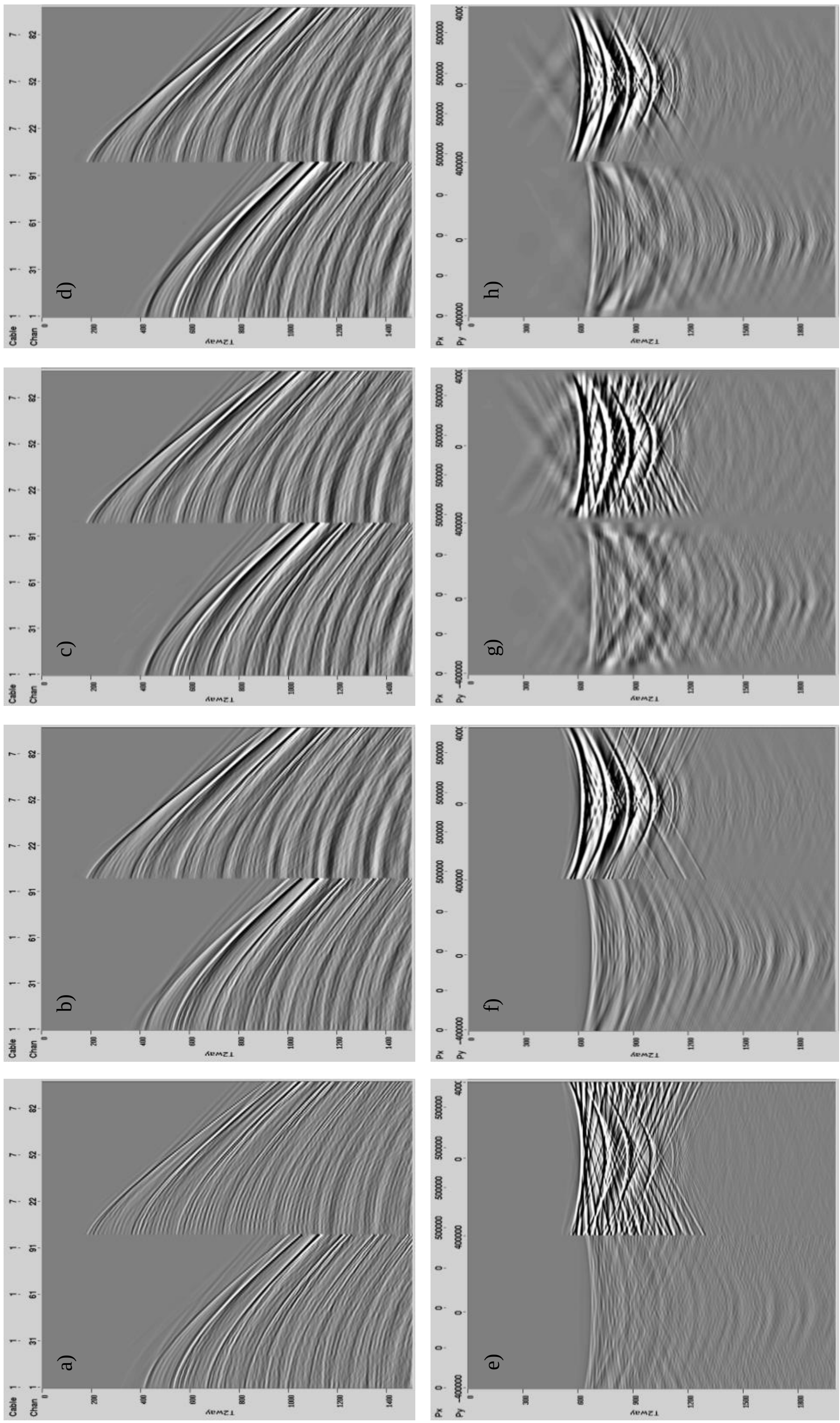

Figure 3: Deghosted data after using different 3D approaches. a) A fast transformation algorithm is used in both inline and crossline directions, assuming regular offset increments. The quality of the data is degraded due to a heavy aliasing effect, especially in the crossline direction. b) A cable interpolation method is employed to reduce the offset-*y* increment down to 25 m, while increasing the number of cables from 12 to 45. This interpolation helps reduce the aliasing effect significantly, yet the far cables may be prone to some edge effects, because no extrapolation and tapering is applied in the crossline direction. c) A high-resolution linear Radon transformation is used in the crossline direction only. This method also reduces the aliasing effect significantly. d) A hybrid of both interpolation and high-resolution techniques are used. This combination helps further reduction of the aliasing effect. e-f) as a-b) in the fast tau-p_x-p_y domain (only two panels of $p_x = 0$ and $p_x = 500{,}000$ ns/m are represented). g-h) as c-d) in the tau-p_x-p_y domain, in which a fast transformation is performed in the inline direction before a high-resolution Radon transformation in applied in the crossline direction.

EDITED REFERENCES

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