Successes and challenges in 3D interpolation and deghosting of single-component marine-streamer data  
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Summary

Combining deghosting with crossline interpolation enables genuinely 3D deghosting. I show that such a 3D algorithm outperforms an adaptive 2D algorithm on a complex synthetic example. A by-product of the joint interpolation and deghosting is an estimate of the upgoing seismic wavefield with dense crossline sampling. However, although samples at receiver locations have been effectively deghosted, inspection of the interpolation results in the f-x domain reveals strong artifacts at moderate and high frequencies. It is also possible to attempt to reconstruct data with dense crossline sampling with a pure interpolation operation. Results with like-for-like interpolators show that without the ghost model, the aliasing artifacts are even stronger still. We anticipate that the extra information provided by multicomponent streamer measurements would aid the interpolation process.

Introduction

If a hydrophone is situated below the surface of the ocean, it records both signals traveling from depth and their ghost reflections from the free surface. These ghost reflections cause a loss in frequency content through destructive interference and artifacts in seismic images; therefore, it is useful to attenuate their effects.

If the free surface is flat, the receiver is close to the free surface, and the local velocity is homogeneous, then the ghost effect can be modelled as a temporal convolution in the ray-parameter domain:

$$d_{\text{total}} = [\delta(0) - \delta(\Delta t)] \ast d_{\text{up}}$$  \hspace{1cm} (1)

where $\Delta t = 2z p_x = 2z \sqrt{p_0^2 - p_x^2 - p_y^2}$, $z$ is the depth of the receiver, $p_0$ is the reciprocal of the water velocity, and $p_x$ and $p_y$ are the inline and crossline ray parameters, respectively.

For sufficiently well-sampled data, we can perform a transform to the horizontal ray-parameter domain, and calculate the ghost operator explicitly. Usually, sampling is sufficient in the inline direction; however, data are usually sparsely sampled and aliased in the crossline direction.

To mitigate the problems of unknown crossline ray parameters, the industry has moved towards adaptive algorithms for single-streamer deghosting (e.g., Wang et al., 2013, Rickett et al., 2014). Although these work effectively much of the time, they can run into problems due to the nonlinearity of the estimation process, particularly in geologically complex areas.

Although crossline sampling is aliased, additional streamers clearly contain additional information that is useful for deghosting the wavefield. Özbek, et al. (2010) and Özbek, Vassallo et al. (2010) showed the advantages of jointly interpolating and deghosting seismic data simultaneously rather than sequentially.

For slanted-cable acquisition (Soubaras and Dowle, 2010; Moldoveanu et al., 2012), further difficulties arise in that the ghost model in equation 1 is no longer valid, and there is mixing between plane waves, a point also noted by Masoomsadeh et al. (2013).

In this paper, we test 3D joint-interpolation and deghosting of slanted marine-streamer data using a sparsity-constrained inversion using local plane-waves. For computational efficiency, the local plane-wave synthesis operator assumes the cables are locally straight and parallel; however, a correction is applied to compensate for dip along the cable, making the algorithm effective for slanted-streamer acquisition.

Method

Seismic data can be interpolated in the crossline direction by minimizing an objective function of the form

$$\chi = ||W[S m - d]||_2^2 + \lambda ||m||_1,$$

where $\mathbf{d}$ is the pressure recorded at the streamers, $\mathbf{S}$ is a basis synthesis operator, $\mathbf{m}$ is the set of coefficients, and $W$ is a data-conditioning operator. This is an example of the basis pursuit denoise problem (BPDN), which it can be effectively solved with a number of sparsity-promoting solvers.

For the examples presented here, the model space, $\mathbf{m}$, contains a five-dimensional set of local plane-wave coefficients, i.e., they are functions of $t$, $p_x$, $p_y$, and the window locations. The synthesis operator, $\mathbf{S}$, creates local plane-waves from these coefficients, samples the waves at streamer locations, and then merges them to produce a pressure wavefield for a full 3D shot gather. With this
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approach, the local plane waves work together to fit the data in a globally optimal sense.

The data-conditioning operator, \( W \), has an AGC-like formulation, so that it decreases the objective function’s sensitivity to very high amplitudes and increases its sensitivity to lower amplitude signals.

Once the model of the wavefield has been estimated, a densely sampled wavefield can be constructed. The L1 constraint on \( m \) promotes sparse solutions and enables the interpolation to work beyond conventional Nyquist sampling limits.

To jointly interpolate and deghost, a ghost operator, \( G \), that implements the convolution in equation 1, can be included in the forward-modeling operator:

\[
  x = \| W [ S G m - d ] \|_2^2 + \lambda \| m \|_1.
\]

Now the model that is constructed can be interpreted as a plane-wave representation of the upgoing wavefield. We can potentially use this wavefield for interpolation, deghosting, or both. For the deghosting application, we can model the downgoing wavefield and subtract it from the total data. This preserves energy in the data that does not survive the sparsity-constrained inversion. Unfortunately, this option is not available for the interpolation application.

Figure 1: Synthetic tests of deghosting application. (a) Slanted-streamer input data; (b) results of 2D deghosting; (c) results of 3D deghosting; (d) flat-streamer synthetic data modeled without ghost; (e) error in 2D deghosting; (f) error in 3D deghosting; (g) f-x spectrum of (a); (h) f-x spectrum of (e); (i) f-x spectrum of (f).
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Slanted cables
With slanted-cable acquisition, the ghost model in equation 1 is not strictly valid, and an upgoing plane wave with an apparent \( p_x \) in the frame of the streamer will have a different \( p_x \) after reflecting from the free surface. For an upgoing wave, whose incidence angle projected into the plane of the streamer is \( \theta \), we have

\[
p_x = p_0 \sin \theta.
\]

If the streamer dip is small \((\phi \ll 1)\), the perturbation in the inline ray parameter is given by

\[
\Delta p_x = 2 \phi \frac{\partial p_x}{\partial \theta} \bigg|_{p_y} = 2 \phi p_0 \cos \theta.
\]

For a cable dipping at 0.5°, this will result in a shift of 1.7% of \( p_0 \) for vertical propagation, which is likely to be of similar magnitude as \( \Delta p_x \). Fortunately, the \( \tau \)-invariant lateral shift in \( p_x \) given by above, can be incorporated into the ghost model at effectively no additional cost.

Examples

Synthetic tests
The algorithm was tested on a 3D finite-difference synthetic shot gather generated over the SEAM model (Fehler and Keliher, 2011). The input data were modeled to 60 Hz without a free surface, but the effect of the ghost was simulated by the method of images. The receiver depth varied in a linear fashion from 25 m at the near offsets to 42 m at the far offsets to simulate a slanted-cable acquisition. As a reference, a second simulation was completed without the ghost effects and with a flat cable at 25-m depth.

Figure 1 compares the effectiveness the 3D joint interpolation and deghosting algorithm presented here with the adaptive 2D algorithm described by Rickett et al. (2014) for deghosting and redatuming the synthetic data. It is apparent that the errors for the 3D algorithm are significantly reduced compared to the 2D algorithm. Figure 2 shows the shows how the input data are aliased in the crossline direction, and the effectiveness of a portion of data recorded on a single streamer, and compares the results of the 2D adaptive and 3D deghosting algorithms.

Field data tests
We compared the different flavors of the 3D algorithm on a field dataset acquired in the Gulf of Mexico. The survey had a helical acquisition geometry (Moldoveanu and Kapoor, 2009), and the cables were slanted with receiver depths of 12 m at the front of the spread and 40 m farthest from the towing vessel (Moldoveanu et al., 2012). The shot analyzed in Figures 3 and 4 was acquired crossline to the receiver spread at an offset of about 12 km.

Figure 3a shows the heavily aliased input data. It is apparently well reconstructed by the interpolation and joint interpolation/deghosting algorithms in Figures 3b-3c. However, these plots are misleading as severe striping can be seen in the f-x panels in Figure 4, particularly above 40 Hz. The striping is worse if the interpolation does not use the information provided by the ghost model.

Conclusions

In the synthetic data tests presented here, a genuinely 3D deghosting algorithm that included crossline interpolation outperformed an adaptive 2D algorithm by making use of the additional information provided by multi-streamer measurements. With such alias-tolerant interpolators, it is possible to attempt to interpolate heavily aliased single-component marine-streamer seismic data in the crossline direction. However, although results may appear good in some domains, close inspection of results in other domains (e.g., f-x) reveals artifacts. These artifacts in interpolated results are reduced, but still present, if the extra information provided by the ghost operator is included in the forward-modeling process. It is anticipated that they would be reduced further if extra information was available through a multi-component streamer system.

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Figure 3: Crossline interpolation of slanted cable field data: (a) input data, (b) interpolation only, (c) total-wavefield from joint interpolation and deghosting, (d) up-going wavefield from joint interpolation and deghosting interpolation and deghosting, and (e) residual from joint interpolation and deghosting.

Figure 4: F-x spectra from Figure 3 in dB: (a) input data, (b) interpolation only, (c) total-wavefield from joint interpolation and deghosting, (d) up-going wavefield from joint interpolation and deghosting, and (e) residual from joint interpolation and deghosting. Location of streamers is shown in (b) to highlight interpolation artifacts.
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References


Fehler, M. and Keliher, P. J., 2011. SEAM Phase 1: Challenges of subsalt imaging in Tertiary basins, with emphasis on deepwater Gulf of Mexico: SEG.


EDITED REFERENCES
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REFERENCES
Fehler, M. and P. J. Keliher, 2011, SEAM Phase 1: Challenges of subsalt imaging in Tertiary basins, with emphasis on deepwater Gulf of Mexico: SEG.


Moldoveanu, N., and J. Kapoor, 2009, What is the next step after WAZ for exploration in the Gulf of Mexico?: Presented at the 79th Annual International Meeting, SEG.

Moldoveanu, N., N. Seymour, D. J. van Manen, and P. Caprioli, 2012, Broadband seismic methods for towed-streamer acquisition: Presented at the 74th Annual International Conference and Exhibition, EAGE.


