Tu_R01_05

Shallow Water Surface Related Multiple Attenuation Using Multi-Sailline 3D Deconvolution Imaging

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Summary

Surface related demultiple continues to be a major challenge in shallow water environments. While multiples generated by the water-bottom reflection can often be adequately attenuated with targeted demultiple approaches, multiple reflections from other shallow events can be more challenging to remove. Deconvolution can help to mitigate this problem, but applications are generally limited to 2D or work on one sailline at a time. We describe a 3D multi-sailline deconvolution-like approach that uses surface datum deghosted data to derive a multiple prediction operator in the image domain using one-way wavefield extrapolation operators. Synthetic and real data results show how the method may predict multiples from shallow multiple generators and may outperform targeted demultiple approaches.

Introduction

Many methods to predict surface related multiples are based on convolving data with an estimate of primaries. The most well-known of these approaches is Surface Related Multiple Elimination (SRME) (Berkhout and Verschuur, 1997). Practical implementations of SRME typically use the recorded data itself as an initial substitute for primaries. This strategy is not without complication, however, the resulting multiple model normally being adaptively subtracted from the input data to address inaccuracies relating to source wavelet squaring and cross-talk between multiples. An analogous approach based on one-way wavefield extrapolation is also available, following Pica et al. (2005).

In shallow water settings where the multiple generator has not been adequately recorded for SRME, targeted multiple prediction algorithms relating to a reflector of known depth have been described for wave-extrapolation and Kirchhoff Green's function extrapolation by Wiggins (1988) and Wang et al. (2011), respectively. Gapped deconvolution methods offer an alternative to targeted approaches, where multiple generators within an active operator length are derived from the periodicity of the multiples themselves. 1D deconvolution in the $\tau - p$ domain (Alam and Austin, 1981) was used for many years before being superseded by 2D deconvolution (Biersteker, 2001), and 3D implementations (Poole, 2017). The relative amplitude consistency between different orders of multiple may be improved by using second order correction terms (Backus, 1959). This strategy has been modified for several applications, including $\tau - p$ deconvolution (Lokshtanov, 1993), partial SRME (Hugonnet, 2002), and Green's function multiple modelling (Cooper et al., 2015).

We describe a multi-sailline 3D gapped deconvolution approach driven by one-way wavefield extrapolation. Results are given for synthetic and real data examples in a shallow water setting.

Methodology

Based on Pica et al. (2005), multiples generated by imaged primaries may be modelled using a one-way wave equation extrapolation scheme. For towed streamer data, the method is typically applied to surface datum, deghosted shot gathers. The approach begins by extrapolating the data to a given depth in the subsurface, after which it is scaled by the primary image to produce a reflecting wavefield. This reflecting wavefield is then extrapolated back up to the receivers. The approach is repeated for all depths in the image. This may be described mathematically as follows:

$$m(t,x,y) = F^{-1}\Phi(f,x,y,z)D_{\Phi}(f,x,y,z)r(x,y,z). \qquad (1)$$

In this formulation, D_{Φ} is the input data after extrapolation to all depths in the subsurface (*x*, *y*, *z*). After scaling by the primary image, r, the operator Φ extrapolates these reflecting wavefields back to the surface. This is repeated for all temporal frequencies, *f*, following which the wavefield is reverse Fourier transformed to the time domain, t, with operator F^{-1}. The resulting wavefield is a prediction of the multiples, m. The approach is illustrated in Figure 1. The primary models the first order multiple, the first order multiple models the second order multiple, and so on.

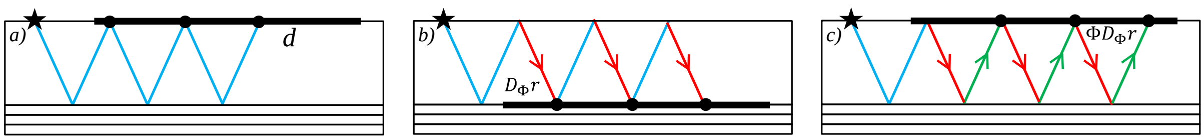

Figure 1 *Illustration of linear operators involved in one-way extrapolation-based multiple modelling. a) Input data; dots correspond to primary, first order, and second order multiple arrivals for a given ray, b) After extrapolation (red) into the subsurface and scaling by the reflectivity, and c) Reflecting wavefield extrapolated (green) back to the receivers.*

One-way extrapolation may be implemented in several ways. Examples include phase shift, phase shift plus interpolation, finite difference, and Fourier finite difference. For more information on one-way extrapolation see Biondi (2006). To avoid problems with spatial aliasing, input data can be interpolated between streamers prior to wavefield extrapolation.

We describe a 3D multi-sailline deconvolution-like approach based on solving Equation 1 as a least squares problem. The approach aims to find the multiple generator image, r, which is responsible for transforming data into multiples. We substitute the data itself for the multiples, m, and define a minimum image depth to avoid the trivial solution of a spike at zero-depth; this strategy is analogous to the use of a deconvolution gap. The approach has some similarities with separated wavefield imaging (Whitmore et al., 2010), the difference being that we input a single deghosted wavefield, and that conjugate gradients least squares inversion is used instead of a deconvolution imaging condition.

Equation 1 may be modified to include data domain sparseness weights, *S*. These may give preferential weighting to the inversion for data inside the mute zone, within the live trace length, and may also be used to constrain the multiple prediction to the location of recorded input traces:

$$m(t,x,y) = S(t,x,y)F^{-1}\Phi(f,x,y,z)D_{\Phi}(f,x,y,z)r(x,y,z). \tag{2}$$

The water-column depth and/or velocity can be changed on a shot-by-shot basis to overcome issues relating to water-column statics or striping. As the wavefield extrapolation is only on the receiver-side, the resulting multiple model will contain inaccuracies relating to source-side only multiples. However, in areas where the source and receiver multiple timing is similar, the method may be iterated to improve the amplitude consistency of the multiple prediction, for example following Poole (2017). To capture moveout errors relating to incorrect velocities, as well as modelling amplitude variations with offset, the method may be modified to use an extended imaging domain, for example sub-surface offsets or time-shift gathers (Sava and Fomel, 2006). Model domain sparseness weights may be added, for example to constrain the reflectivity to resemble known reflector depths. This may be by using sparseness at the depth of the water-bottom, or by using the envelope of a primary image.

Once the multiple generator image has been found, it is used to predict multiples through application of Equation 1. The resulting multiples may then be subtracted from the input data.

Synthetic example

The synthetic example is based on a towed streamer acquisition from a shallow water environment including a gas body. The reflectivity model is given in Figure 2a. The reflectivity was demigrated to model shot gather primary data, Figure 2c. The primary data was used as a down-going wavefield to iteratively model several orders of multiple using wave equation extrapolations, Figures 2d, 2e, and 2f. The primary and multiple datasets were summed to simulate recorded data, Figure 2g, which was then input to the described method, resulting in the multiple generator image of Figure 2b. The multiple generator image closely resembles the input reflectivity (Figure 2a) used to generate the input data. The input data and the multiple generator image were used to derive a multiple prediction, Figure 2h. Straight subtraction of the multiple prediction from the input data resulted in the data of Figure 2i. A targeted receiver-side multiple model based on the water-bottom generator produced the model shown in Figure 2j. We observe residual multiples in the corresponding demultiple result of Figure 2k; some of these multiples were not modelled by this approach as they were generated by the gas body (red arrow), others relate to partial multiple suppression as only receiver-side water-layer multiples were modelled (black arrow).

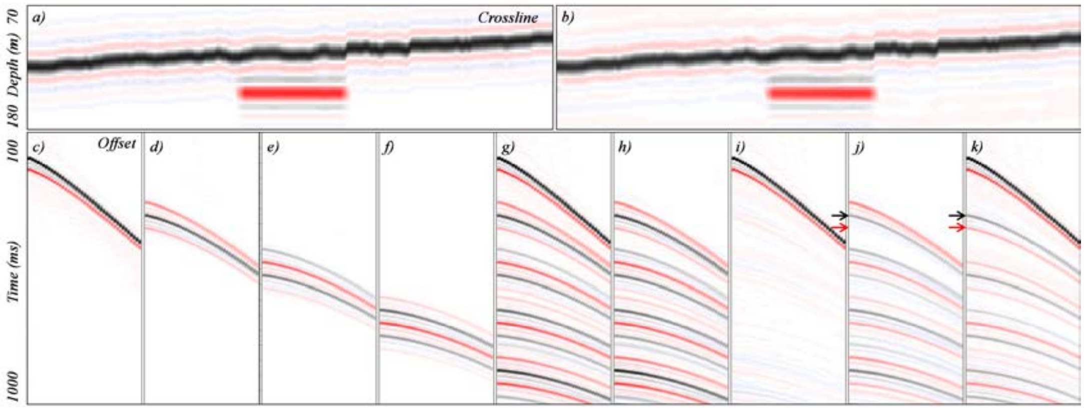

Figure 2 *Synthetic data example. a) Input reflectivity, b) Inverted reflectivity, c) Modelled primary, d) Modelled first order multiple, e) Modelled second order multiple, f) Modelled third order multiple, g) Summation of primary and all multiple orders, h) Multiple model from described method, i) Multiple attenuation using described method, j) Receiver side water-bottom peg-leg multiple model, and k) Multiple attenuation using receiver side water-bottom peg-leg multiple model.*

Real data examples

The first real data example comes from a towed streamer acquisition in the Norwegian North Sea. This area has a ~300 m water depth and several shallow gas bodies. An input stack is given in Figure 3a. The recorded data was input to the proposed method, resulting in the multiple generator image of Figures 3f (inline) and 3g (depth slice). These results appear similar to an image of primaries, but it should be remembered that this is an image of the multiple periodicity. A targeted multiple prediction corresponding to the water-bottom reflection (following Cooper et al., 2015) is given in Figure 3b. While the multiple prediction captures the complexity of the water layer peg-leg multiples, it does not predict the deeper peg-leg multiples from the gas. The multiple prediction from the described method is given in Figure 3c. Adaptive subtractions for the water-bottom targeted method and the described method are given in Figures 3d and 3e respectively. It is clear that the described method has predicted multiples corresponding to the gas bodies, giving a more effective demultiple result.

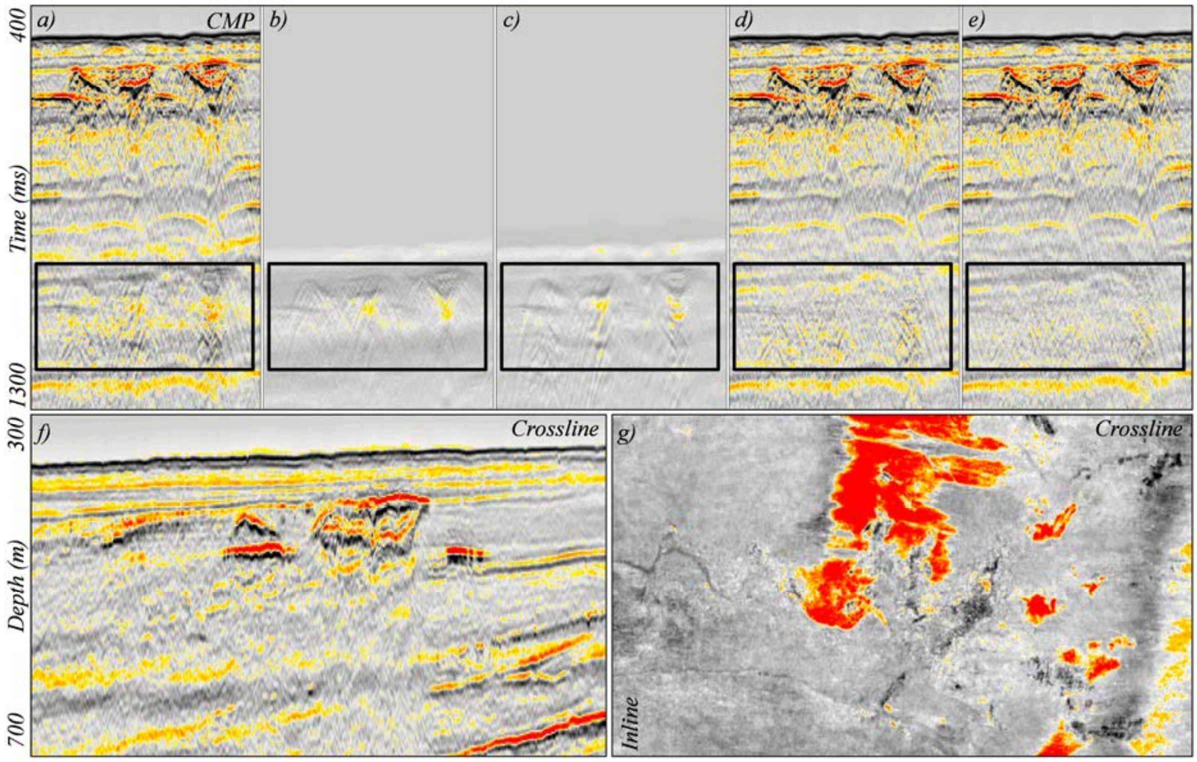

***Figure** 3 Norwegian North Sea real data example. a) Input stack, b) Multiple model for water-bottom targeted multiples, c) Multiple model for described method, d) Demultiple corresponding to water-bottom targeted multiples, e) Demultiple corresponding to described method, f) Inline from the derived reflectivity image, and g) Depth slice at 450 m from the derived reflectivity image.*

The second example comes from a towed streamer acquisition in the Central North Sea with 100 m water depth. This shallow water environment created a reverberating curtain of multiples through the target section as seen by a migration of the input data shown in Figure 4a. The multiple generator image output from the described method imaged the water-bottom and some shallow channels, as shown in the inline section, Figure 4d, and the depth slice, Figure 4e. Depth migrated demultiple results stretched to time for water-bottom targeted demultiple (following Cooper et al., 2015) and the described approach are given in Figures 4b and 4c respectively. As highlighted by the arrows, the migration after the described approach exhibits a lower level of residual multiple than the targeted approach, highlighting the benefits of the described method.

Conclusions

We have described a 3D multi-sailline deconvolution-like approach for attenuating surface related multiples in shallow water settings. The approach uses surface datum deghosted data as input to a one-way wave equation extrapolation approach to derive the prediction operator directly in the image domain. The image is subsequently used to predict and attenuate multiples. Synthetic and real data examples have shown the benefit of this method over targeted demultiple approaches.

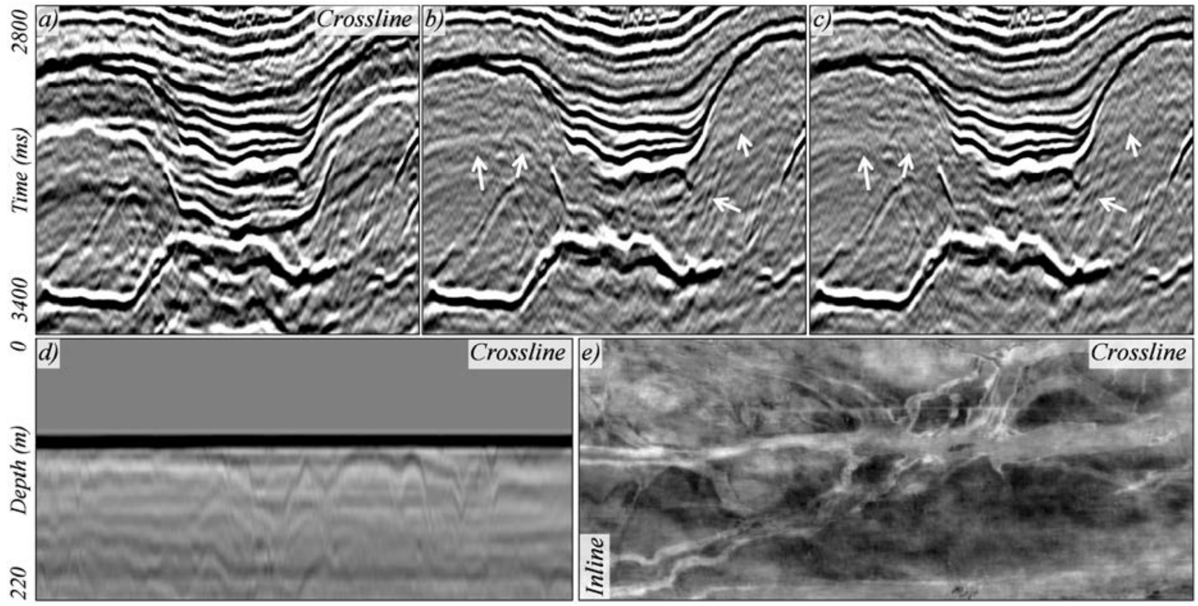

***Figure 4** Central North Sea real data example. a) Input migration, b) Water-bottom targeted demultiple migration, c) Described method demultiple migration, d) Inline from multiple generator image, and e) Depth slice at 115 m from the multiple generator image.*

Acknowledgements

We thank CGG Multi-Client & New Ventures for permission to show the North Viking Graben and Cornerstone data examples, CGG Subsurface Imaging for processing the data, and James Cooper in help preparing this paper.

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