Flexible surface multiple attenuation using the curvelet transform
Margaret Yu and Zhimei Yan*, WesternGeco

Summary

In this paper, we demonstrate that better primary preservation and effective surface multiple attenuation can be achieved by applying various iterative surface multiple attenuation approaches in different domains and in different areas. In areas where smaller moveout separation between primary and multiple exist, a conservative least-squares adaptive subtraction method is used to preserve primaries. The magnitude and phase thresholding approach in the complex curvelet transform domain is applied to other areas when local, more aggressive adjustments of the model traveltime or amplitude are required to effectively attenuate multiples and preserve primaries at the same time.

Introduction

The least-squares adaptive subtraction (LSAS) method (Verschuur and Berkhout, 1997), which designs one filter for all multiple reflection events within one local adaption window, cannot compensate for all local prediction errors and tends to leave a significant amount of residual multiple energy in the seismic data.

Hermann and Verschuur (2004) suggested an alternative approach to attenuate surface multiples in the curvelet domain through a nonlinear thresholding procedure. Due to the separation of primaries from multiples in the curvelet domain, and the sparseness of the curvelet coefficients, this method is very effective in adjusting local traveltimel or amplitude errors, and thus, can generate much cleaner images than the LSAS method. The Hermann and Verschuur approach is based on a real valued curvelet transform.

Neelamani et al. (2008a, 2008b, 2010) proposed an adaptive subtraction method that is based on a complex-valued curvelet transform (CCT) algorithm to attenuate multiple noises from seismic data. Compared with the real valued curvelet transform (Herrmann and Verschuur, 2004), the CCT coefficient magnitude is less sensitive to small time shifts (5 ms in 50-Hz data) and a direct translation exists between the permitted maximum kinematic time shift and the phase constraints. By limiting the magnitude and phase correction of the noise model in the CCT, the maximum range of amplitude and alignment adjustment can be strictly controlled. This makes the magnitude comparison between seismic and model more meaningful, and it also reduces the risk of matching multiples to primaries by the addition of the phase constraint.

Noise attenuation in the curvelet domain, however, is based on the assumption that primary and multiple energies are well separated in the curvelet domain. This is not always the case for real seismic data, where overlap of primary and multiple events is observed in localized areas. For this situation, there is a high risk of attenuating primary events. The LSAS approach, however, can preserve the primary very well if a sufficiently large adaption window is chosen. The overall model-to-multiple correlation for a large window tends to outweigh the model-to-primary correlation. While large windows preserve primaries better, they tend to reduce the attenuation of multiples and additional model matching is needed.

Here, we demonstrate that better primary preservation and effective surface multiple attenuation can be achieved by combining the traditional LSAS method with the flexible adaptive subtraction approach in the complex-value-based curvelet domain.

Methodology

Generalized surface multiple prediction (GSMP), a type of 3D SRME, (Dragoset et al., 2008) predicts surface multiples very well at mid to near offsets. Such surface multiples can generally be attenuated very effectively by the simple LSAS method in a common trace or offset domain. Due to the complexity of near-surface topography, the limitation of data availability, or insufficient aperture, surface multiple prediction at far offsets is more prone to errors than at mid to near offsets. Different localized traveltime or amplitude errors in the predicted multiples at far offsets cause the LSAS method to be less effective and commonly only sub-optimum results can be achieved. Radon demultiple is conventionally used to further attenuate the residual multiple energies, but this method tends to attenuate prismatic waves that are very important for imaging complex structures.

To preserve primary energy and attenuate the residual energy from the LSAS method, additional fine tuning of the multiple model is performed in the complex curvelet domain for areas where further attenuation of the residual multiple energy is required. Matching the model to the seismic data using amplitude thresholding, combined with a limited phase modification, allows the process to automatically become more aggressive where primaries do not overlap with multiples, and to become more conservative in areas where they do overlap. An additional advantage of performing residual multiple energy attenuation in the complex curvelet domain is that different
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attenuation parameters can be applied to different curvelet panels, depending on the residual energy level in that panel. The additional multiple attenuation in the curvelet domain further improves the multiple model by more closely matching the amplitude and phase of the multiple energy in the seismic data. When applied to shot gathers, the moveout differentiation of primary and multiple energy, at mid to far offsets, makes the parameterization fairly stable for a variety of data sets and areas within a data set.

After this additional fine tuning of the multiple model in the curvelet domain, the improved multiple model is adaptively subtracted from the original seismic data. By doing this, we avoid introducing artifacts into the seismic data during the forward and inverse curvelet transform process. Using this method, we not only attenuate most of surface multiples for all offsets, but also preserve the primary and prismatic events.

Data examples

This methodology was applied to more than 1,200 blocks of deepwater data at the Gulf of Mexico Outer Continental Shelf. The improved data quality enhanced the depth imaging for both prestack Kirchhoff depth migration and Reverse Time Migration. This approach has significantly simplified the salt interpretation in areas where multiples has previously conflicted with primaries, especially in Gulf of Mexico subsalt plays.

The following data examples are from Gulf of Mexico.

- Figure 1 shows common midpoints gathers (CMPs) input where the presence of high-amplitude multiples severely mask the underlying primary energy.
- Figure 2 shows the same set of CMPs as from Figure 1 that resulted from this flexible method where primary events are uncovered from beneath significant multiple energy.
- Figure 3 shows the same set of CMPs from above that resulted from a simple LSAS where visible level of residual multiple energies still remained.
- Figure 4 shows the GSMP-predicted multiple model in CMPs. A type of quality control product that was used to verify whether primary is preserved or not when compared with Figures 1 and 2.
- Figures 5 and 7 show strong multiple energy on both shallower and deeper stacks before multiple attenuation. Arrows in Figure 7 point to areas where primary energy has been masked by strong multiple.
- Figures 6 and 8 show that surface multiple energy has been effectively attenuated on both shallower and deeper stacks after the application of flexible surface multiple attenuation. Arrows in Figure 8 point to areas where primary energy was unmasked and preserved.
- Figures 9 and 10 show shots before and after flexible surface multiple attenuation, as well as their predicted multiple model in Figure 11. Primary energy at a deeper section is preserved in Figure 10. Figure 12 shows the effectiveness of flexible surface multiple attenuation method when compared to the predicted model in Figure 11.

Conclusions

A combination of a least-squares adaptive subtraction and an iterative, flexible curvelet adaptive subtraction method has greatly improved multiple attenuation within marine seismic data. The resultant cleaner seismic data will, consequently, generate better seismic images for interpretation, especially for complex salt structures in the Gulf of Mexico.

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Figures 1 and 2 show the following data examples from Gulf of Mexico.

- Figure 1: Common-midpoint gathers prior to multiple attenuation. (Courtesy of WesternGeco)
- Figure 2: Common-midpoint gathers after multiple attenuation. (Courtesy of WesternGeco)
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Figure 3: Common-midpoint gathers after simple LSAS multiple attenuation. (Courtesy of WesternGeco)

Figure 4: GSMP predicted multiple model sorted in common-midpoint gathers. (Courtesy of WesternGeco)

Figure 5: Shallower stack section prior to multiple attenuation. (Courtesy of WesternGeco)

Figure 6: Shallower stack section after flexible surface multiple attenuation. (Courtesy of WesternGeco)

Figure 7: Deeper stack section prior to multiple attenuation. (Courtesy of WesternGeco)

Figure 8: Deeper stack section after flexible surface multiple attenuation. (Courtesy of WesternGeco)
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Figure 9: Shots prior to multiple attenuation. (Courtesy of WesternGeco)

Figure 10: Shots after flexible surface multiple attenuation. All primary energy at deeper section is preserved. (Courtesy of WesternGeco)

Figure 11: GSMP predicted multiple model shots. (Courtesy of WesternGeco)

Figure 12: Difference shots between Figures 9 and 10. This figure shows the effectiveness of flexible surface multiple attenuation method when compared to the predicted model in Figure 11. (Courtesy of WesternGeco)
EDITED REFERENCES
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REFERENCES