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Broadband Processing of Variable-depth Streamer Data

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SUMMARY

The frequency of ghost notches is naturally diversified by random variations, both at the sea surface and in the streamer depth. A systematic diversity may be introduced by towing a streamer at variable depths. Regardless of the streamer shape, the recorded seismic data needs to be redatumed and deghosted with respect to both, angle of wave-front and individual source and receiver depths. We present a slowness-variant redatuming and deghosting method, applicable to data acquired by variable-depth streamers, and capable of handling offset increment irregularity. We utilize estimated elevations for redatuming, and fine-tuned depths for deghosting. The effectiveness of the presented method has been validated by application to field data acquired by various configurations including flat, slant, and curved streamers.

Introduction

Broadband seismic data is desirable for interpretation purposes. In a marine environment however, the spectrum of recorded seismic signal is governed by a number of factors including the interference of the ghost reflections. Attempts are made to improve both temporal and spatial resolution of seismic data in both acquisition and processing stages. Recent developments in the acquisition stage include dual-sensor streamers (Carlson et al., 2007), over-under streamers (Özdemir et al., 2008), variable-depth streamers (Soubaras, 2010) and multicomponent streamers measuring pressure and the gradient wavefields (Vassallo et al., 2013). In the processing stage a number of techniques have been introduced aiming to deghost the data either before, while, or after the migration process. A premigration deghosting method was proposed by Wang and Peng (2012). Zhou et al. (2012) applied a deghosting process on conventional streamer data. Masoomzadeh et al. (2013) proposed a method of angle-dependant redatuming and deghosting for slanted streamers, assuming a flat sea surface. Robertsson and Amundsen (2014) developed a finite-difference method for deghosting streamer data towed at arbitrary variable depths. In this paper we propose a method of redatuming and deghosting applicable to seismic data acquired by single-sensor variable-depth streamers, in presence of sea surface undulations.

In practice, neither the sea surface is flat nor do the receivers remain in predefined depths. As can be seen in Figure 1, the receiver depths are constantly changing, even during the listening period. This level of variation results in a 'natural' diversity of non-zero notch frequencies. This nearly random diversity means that the weak signals surviving the destructive ghost interference in the vicinity of the nominal notch frequencies may not survive the stacking process, due to the rapid variation of phase at the notches. Therefore, even after a successful prestack deghosting, the stacking process could introduce a secondary notch effect at those frequencies where the maximum phase discrepancy occurs. This secondary loss of signal can be observed more often on the shallow events where the primary and ghosts are almost parallel after the NMO correction. A more systematic notch diversity can be introduced by towing a streamer in different depths.

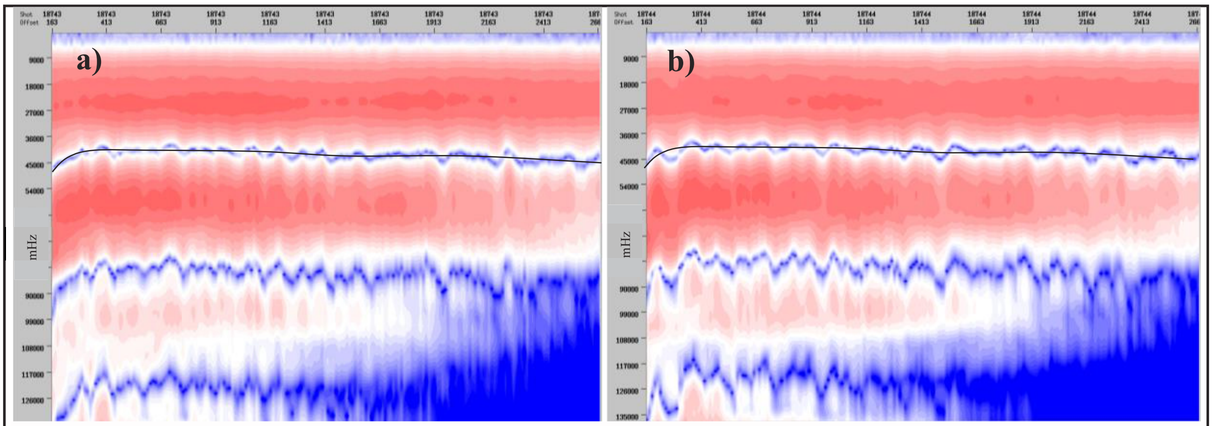

Figure 1 *a) Amplitude spectra of traces from a shot gather acquired at a nominal depth of 18 m, obtained after the water-bottom event is approximately isolated and NMO corrected. It can be seen that the notch frequency is inconsistent along the streamer length, due to the variation of the sea surface and the streamer shape. b) Amplitude spectra of the next shot gather, which present a completely different trajectory of notch frequencies compared to a). Local variations may be attributed to the surface undulations while the global feature (black curve) can represent the streamer shape.*

We assume that all receiver depths are known, either recorded at the time of acquisition, or estimated based on the information available in the recorded traces. For example, using the amplitude spectra shown in Figure 1, we can search for the lowest amplitude in the vicinity of estimated notch frequency to estimate the effective depth of individual receiver groups. These estimated depths are useful for the deghosting operation. For the redatuming purpose however, we consider smoothing those rapid variations attributed to the sea surface undulations, in order to estimate receiver elevations from the Mean Sea Level.

Method for redatuming and deghosting variable-depth streamer data

Beginning with a multichannel shot record in the time-offset domain, we first transform every trace into the frequency domain. Then for every temporal frequency sample we multiply either or both redatuming and deghosting operators, designed based on individual receiver depths, with a specific slowness in mind. Then we perform a slant-stacking process to obtain particular slowness traces for which those operations were reasonably accurate. After scanning over a range of required slownesses we perform an inverse transformation to obtain a processed wavefield back in the time-offset domain. Figures 2 and 3 schematically illustrate the redatuming and deghosting techniques respectively.

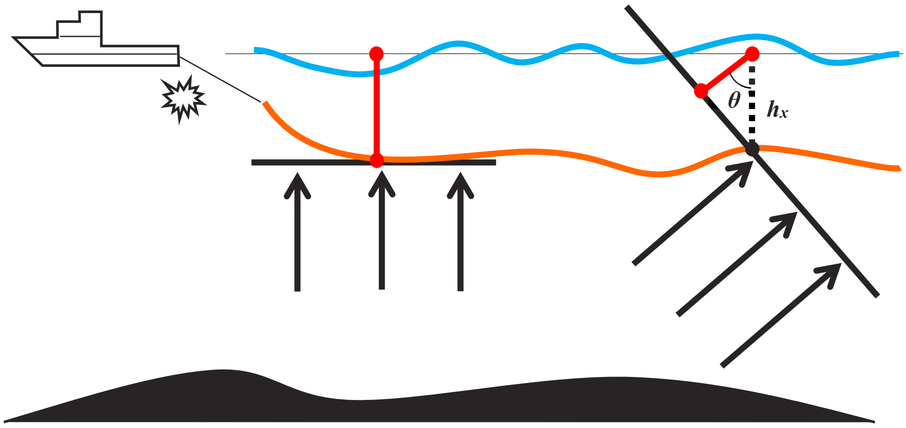

Figure 2 *Schematic diagram of redatuming seismic wavefields recorded by a curved streamer to the Mean Sea Level. A time shift of* $h_x \cos\theta / v_w$ *acknowledges both elevation of every individual receiver, and the angle of each plane-wave component. Every slowness trace is obtained via slant-stacking, after redatuming all contributing traces accordingly.*

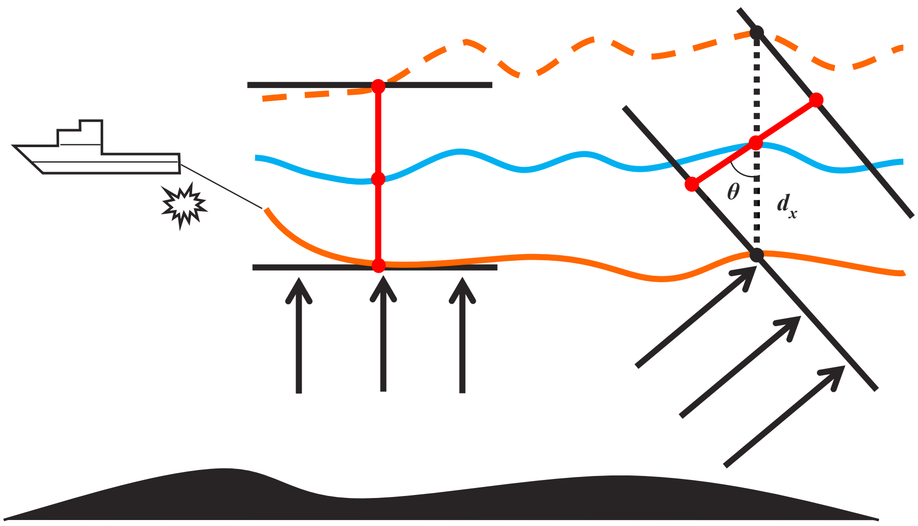

Figure 3 *Schematic diagram of deghosting seismic wavefields recorded by a curved streamer. A time delay of* $2d_x \cos\theta / v_w$ *takes into account both the depth of every individual receiver, and the angle of each plane-wave component. Every slowness trace is obtained via slant-stacking, after deghosting all contributing traces accordingly. The effect of the discrepancy in the angle of sea surface reflector is implicitly taken into account by using a frequency- and angle-dependant reflection coefficient at the sea surface.*

In case the offset increment is regular, we may accelerate the technique by using Fourier transformation instead of slant-stacking, in which case, instead of creating a pair of p-traces we create a pair of k-traces in each iteration. In practice we can use the Fast Fourier Transformation (FFT) algorithm to quickly calculate a full range of k-traces, retaining those traces for which the performed operation is reasonably accurate. Further speed up is achieved by dividing the input gather into a number of overlapping subpanels. We apply a square root of cosine taper to the edges of each subpanel before application of the main process, and reapply similar tapering afterwards, before merging the processed subpanels back into a full gather. 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.

Examples

Figure 4 shows the results of application to synthetic data generated by assuming both a parabolic and a sinusoidal streamer shape. It can be observed that the gap time between the primaries and ghosts varies as a function of both offset and horizontal slowness. After redatuming and deghosting, as expected, both experiments converge to similar results.

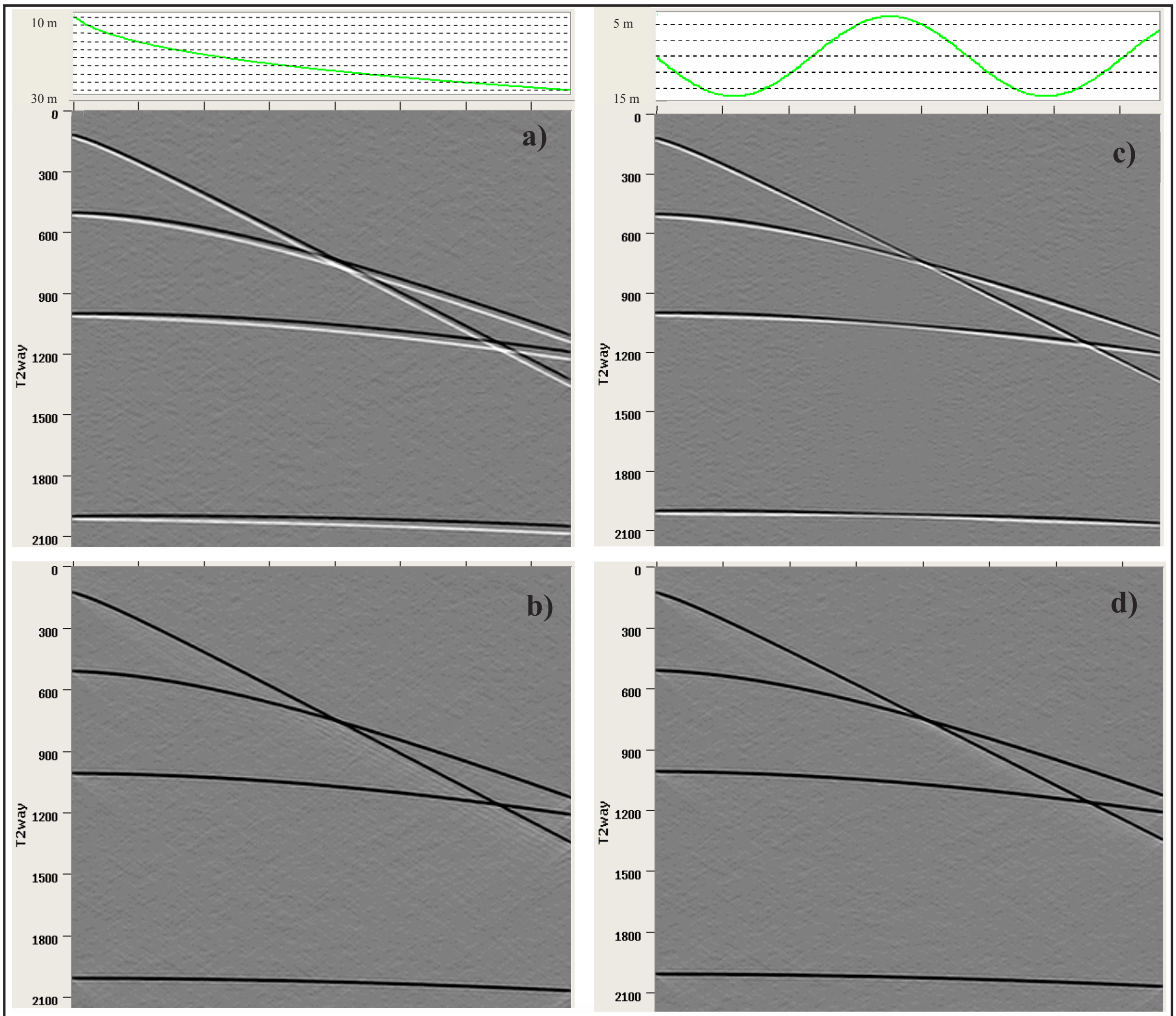

Figure 4 *a) A synthetic shot gather conformed of four events associated with their receiver side ghosts generated assuming a parabolic streamer shape. b) After redatuming and deghosting while acknowledging the depth of every individual receiver. c) A synthetic shot gather generated assuming a sinusoidal streamer shape. d) After redatuming and deghosting. Note that b) and d) are quite similar as expected.*

Figure 5 shows a shot gather acquired by a variable-depth streamer, which was deviated from its expected linear trajectory due to some practical limitations. In this case the deghosting process using a τ-θ approach (Masoomzadeh et. al., 2013) created some ringing, due to the violation of the linear shape assumption. The new method however, demonstrated impressive capability to overcome this situation.

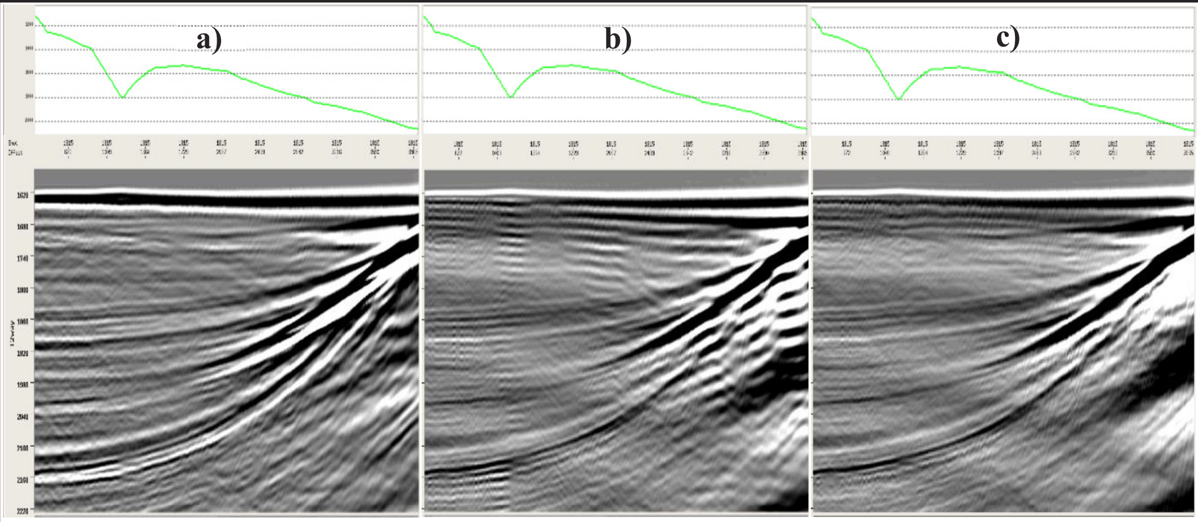

Figure 5 *A shot gather acquired by a variable-depth streamer, which was intented to be straight, a) before deghosting, b) after deghosting by assuming a linear streamer shape, resulting in some ringing effect due to inaccurate deghosting. c) After deghosting while acknowledging individual receiver depths (green curve), showing noticeable reduction in the ringing effect.*

Conclusions

We present a method for both redatuming and deghosting for marine seismic data acquired by single-sensor variable-depth streamers. This method is capable of handling irregular absolute-offset increment, often associated with the lateral offset of outer streamers in a 3D wide-azimuth survey. Accurate redatuming means we virtually move all sources and receivers to the Mean Sea Level. Therefore, conventional processing techniques historically designed for flat streamer data, including many demultiple techniques, velocity analysis and NMO correction, remain valid and applicable. Regardless of the streamer shape, using a measured or estimated depth for every receiver group improves the deghosting outcome, meanwhile, fine tuning those depths can result in further enhancements.

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