Application of deghosting for spectral matching in OBS-streamer 4D processing

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Summary

Large spectral differences exist between streamer and ocean bottom seismometer (OBS) data, mostly due to different surface-related ghost effects – streamer data have both shot- and receiver-side ghosts, while OBS data have only the shot-side ghost. In a recent OBS-streamer time lapse study in deepwater Gulf of Mexico, we investigated three schemes of spectral matching between OBS and streamer data: conventional 1D matching of streamer to OBS, receiver deghosting of streamer data only, and full deghosting of both data sets. The study demonstrated the benefits of receiver deghosting on streamer data over 1D matching, particularly because it provided a better match between the streamer and OBS data before migration and an increased 4D signal-to-noise ratio (S/N) after migration. However, we found that shot deghosting on both surveys did not improve the 4D results; instead, the spectra of streamer and OBS, especially at lower frequencies, were more different after shot deghosting. Receiver deghosting alone on the streamer data gave the best 4D results among the three schemes.

Introduction

In recent years, OBS acquisition has gained popularity for imaging complex subsurface structures in close proximity to reservoirs because of its long offset and full azimuth coverage as well as flexible acquisition configurations that are not hindered by platform obstructions. In particular 4D seismic using OBS for both baseline and monitor surveys have been recognized as a superior approach for monitoring reservoir production and water injection due to the excellent repeatability of shot and receiver positions. For these reasons, many OBS surveys have been acquired on top of production (or discovery) fields in the Gulf of Mexico (GOM) and other parts of the world in the last few years (Beal et al., 2014). Many of these OBS acquisitions do not have OBS baseline surveys acquired prior to the production of the fields, and only towed streamer data are available as baseline surveys. Even though OBS and towed streamer are two very different acquisition systems and using them for 4D seemingly defies the golden rule of 4D seismic – namely, repeatability – clearly there is significant business impact to gain from a successful OBS-streamer 4D project.

The major challenge in OBS-streamer 4D processing comes from the receiver depth difference and the resulting difference in their ray paths and spectra. Much effort has been devoted to mitigate the effect of ray path differences with delicate pre-migration 4D trace co-selection (Lecerf et al., 2010; Haacke et al., 2013) or post-migration amplitude matching in the angle domain (Theriot et al., 2015). In our study we focus on compensating the spectral differences in OBS-streamer 4D processing.

Streamer and OBS data have large spectral variations stemming from differences in free-surface ghost effects. For OBS data, where the receivers are placed on the water bottom, the receiver-side ghost is the down-going wavefield. After up/down wavefield separation using hydrophone pressure data and vertical geophone data, the OBS up-going and down-going wavefields contain only the source-side ghost; this contrasts with surface streamer data that have both source- and receiver-side ghosts. Ghost notch frequency not only depends on the source (and receiver) depth, but also varies with the surface take-off, or incident, angle. Therefore, matching of OBS and streamer data is a challenging task in OBS-streamer 4D processing.

In theory, the best way to match the spectra of OBS and streamer data is to remove the free-surface ghost from the data. This became feasible with the rapid advancement of pre-migration deghosting methods in recent years (Wang et al., 2013, 2014). Pre-migration deghosting has been applied in 4D processing to achieve better spectral matching between baseline streamer data with flat-towed cables and monitor streamer survey data with variable depth cables (Hicks et al., 2014), where the receiver-side ghosts are very different due to different cable configurations. When two vintage surveys are acquired with the same type of acquisition (i.e. streamer-streamer, or OBS-OBS), and thus record nearly identical primary wavefields, 4D joint deghosting on both baseline and monitor surveys simultaneously is able to further minimize wavelet differences and provides better survey matching (Wang et al., 2015).

Considering the large difference in acquisition configuration between OBS and streamer surveys, deghosting must be applied on individual data sets separately as well as using slightly different deghosting methods tailored to their particular acquisition geometries. In this case study, we compared three schemes of spectral matching between OBS and streamer data: Scheme 1 applied a traditional 1D matching filter designed from the near offset water bottom stack wavelet to match streamer data to OBS data; Scheme 2 applied receiver deghosting on the streamer data only; and Scheme 3 applied full deghosting on both surveys, i.e., source and receiver deghosting on streamer data and source deghosting on OBS data. We chose the OBS data set as the target to match since it had richer low frequencies due to the absence of the receiver ghost. Thus, we increased the low frequency in the streamer data instead of reducing it in the OBS data. This provided stronger low frequencies in the final 4D results, which was beneficial for subsalt 4D signals and later seismic inversion work.

Conger OBS and streamer surveys

The Conger and nearby Penn State reservoirs are located in Garden Banks, GOM and were discovered in 1998 and 1996, respectively. Both fields have gone through a long history of production since then. In 2013, an OBS survey was acquired with the aim to improve the structural image of the subsalt reservoirs. The OBS survey was full azimuth with a node spacing of 400 m and a shot spacing of 50 m at a nominal shot depth of 10 m. The water-bottom depth at the survey area where the OBS receivers were placed ranges from ~200 m to 700 m. During the course of the OBS imaging project, we co-processed a narrow azimuth (NAZ) streamer survey to facilitate OBS multiple attenuation and velocity model building. The NAZ survey was acquired in 1995, prior to production. It was shot along the east-west direction with a shot interval of 62.5 m and had three recording cables with a cable spacing of 160 m and a channel spacing of 12.5 m. The nominal shot and receiver depths of this NAZ survey were 7.5 m and 9 m, respectively. Clearly, these two surveys were very different, especially in the receiver depth and the azimuthal coverage. Yet, they were the only two available data sets readily in our hands that carry 4D information related to the reservoir changes. Therefore, despite the poor repeatability of these two surveys, we conducted a 4D study in order to extract any potential 4D value. A few specific processing steps were designed and tailored to this type of unconventional 4D processing. Among them, applying deghosting to facilitate spectral matching between OBS and NAZ surveys was one of the important steps.

Deghosting OBS and NAZ surveys

Deghosting was applied using a sparse TauP-based approach (Wang et al., 2013, 2014) that was equipped to handle spatially aliased marine seismic data and eliminate the angle-dependent ghost wavefield through iterative inversion. Due to the limited azimuthal coverage, the NAZ survey did not adequately sample the wavefield along the direction perpendicular to the cables. Therefore, we used a bootstrap approach in 2D TauP domain for the NAZ receiver and source deghosting (Wang et al., 2013). For the OBS data, with a full azimuth shot coverage and dense shot spacing, 3D TauP deghosting in the common receiver domain was a natural fit for source ghost removal (Wang et al., 2014). We applied a residual matching filter on the NAZ data after performing the receiver-only deghosting and full deghosting in order to compensate for minor spectral differences caused by factors such as source depth

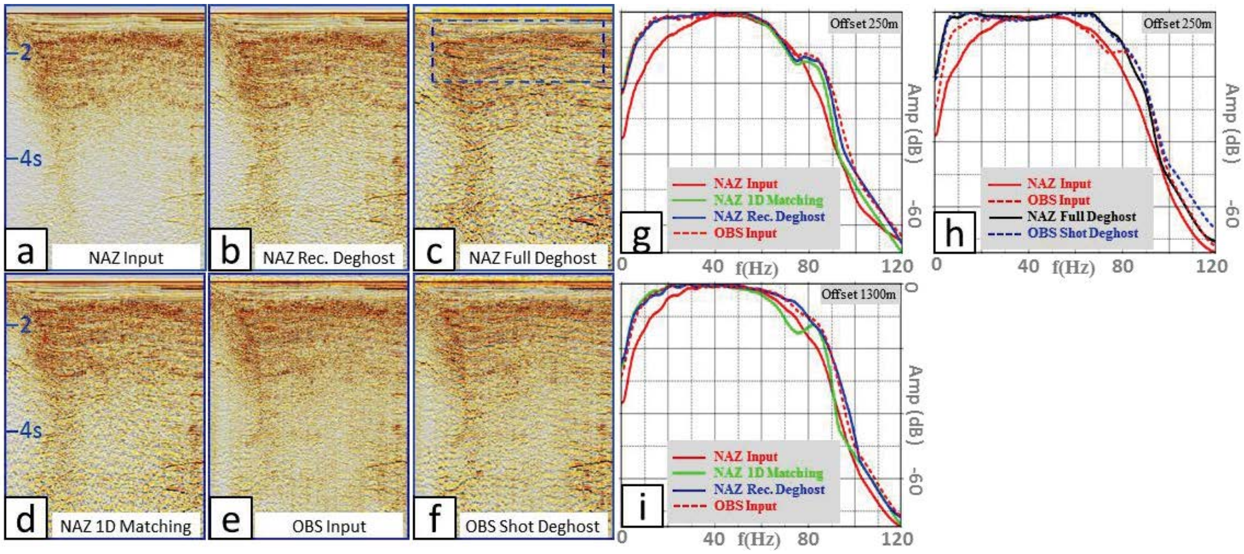

Figure 1: Common offset seismic sections at offset 250 m (a) NAZ input, (b) NAZ after receiver deghosting, (c) NAZ after full deghosting, (d) NAZ after 1D matching filter; and OBS down-going wavefield data at the equivalent offset (e) OBS input, (f) OBS after source deghosting. (g) and (h) show the normalized spectra comparisons at offset 250 m. The amplitude spectra are taken in the shallow region indicated by the blue dashed rectangle in (c). (i) shows the spectrum comparison at the same shallow region at offset 1300 m (seismic data not shown here) where the surface take-off angles or incident angles are further away from zero degrees than offset 250m. Notice that the water bottom has been aligned at 1 second for an easier comparison of NAZ and OBS data.

differences (10 m for OBS vs 7.5 m for NAZ), gun output differences, etc.

Results and discussion

Figures 1a - 1d show the NAZ data at different processing stages within the three Schemes: input, after application of a 1D matching filter, after receiver deghosting, and after source and receiver deghosting. We observed stronger low frequencies in the seismic data after application of the 1D matching filter, after receiver deghosting, and even more so after full deghosting on the NAZ data. We had similar observations with the OBS down-going wavefield data when comparing the input (Figure 1e) to OBS after source deghosting (Figure 1f). To examine how well the NAZ and OBS data matched after the different spectral matching schemes, we compared their amplitude spectra in a shallow window, highlighted by the rectangle in Figure 1c. In Figure 1g, we observe how the OBS input data had more low and high frequencies compared to the NAZ input data, due to the absence of the receiver-side ghost. At the near offset of 250 m, both the 1D matching filter and receiver deghosting on the NAZ data adequately compensated for this spectral difference and matched the NAZ spectrum to that of OBS. Similarly, we see in Figure 1h that the spectra of NAZ and OBS also matched well after OBS shot deghosting and NAZ full deghosting. However, when moving to a longer offset (1300 m) as shown in Figure 1i, where the surface take-off angles or incident angles deviated significantly from zero degrees, the 1D matching filter was not able to fully compensate for the spectral mismatch between the NAZ and OBS data. Receiver deghosting on the NAZ data was nonetheless able to closely match the spectra of the NAZ with the OBS. We attributed this to the deghosting process that considered the angle-dependent ghost effect.

The effect of improved spectral matching between OBS and NAZ after deghosting was also observed on the 4D difference after migration. Here we performed Kirchhoff migration of the NAZ and OBS down-going wavefields separately after 4D trace co-selection of NAZ and OBS data based on midpoint with a limit of shot-receiver distance (dS+dR) at 600 m. We examined the 4D difference between the NAZ and OBS after a few post-migration processing steps, including common angle stacking and 4D co-denoise (Huang et al., 2014). The 3D images of NAZ and OBS were very similar after 4D trace selection, as shown in Figures 2a and 2b. Strong 4D signals related to production at three different reservoirs (highlighted by the white arrows) were clearly observed on the 4D difference from spectral matching (Scheme 1) with a simple 1D matching filter on the NAZ data (Figure 2c). Reduced low and high frequency noise on the 4D difference from Scheme 2 (Figure 2d) was observed when compared to Scheme 1. We credited this improvement to better wavelet matching of NAZ and OBS after removing the receiver ghost from the NAZ data.

However, further deghosting on both surveys in Scheme 3 (Figure 2e) introduced slightly more low-frequency 4D noise instead of further improving the results. This was

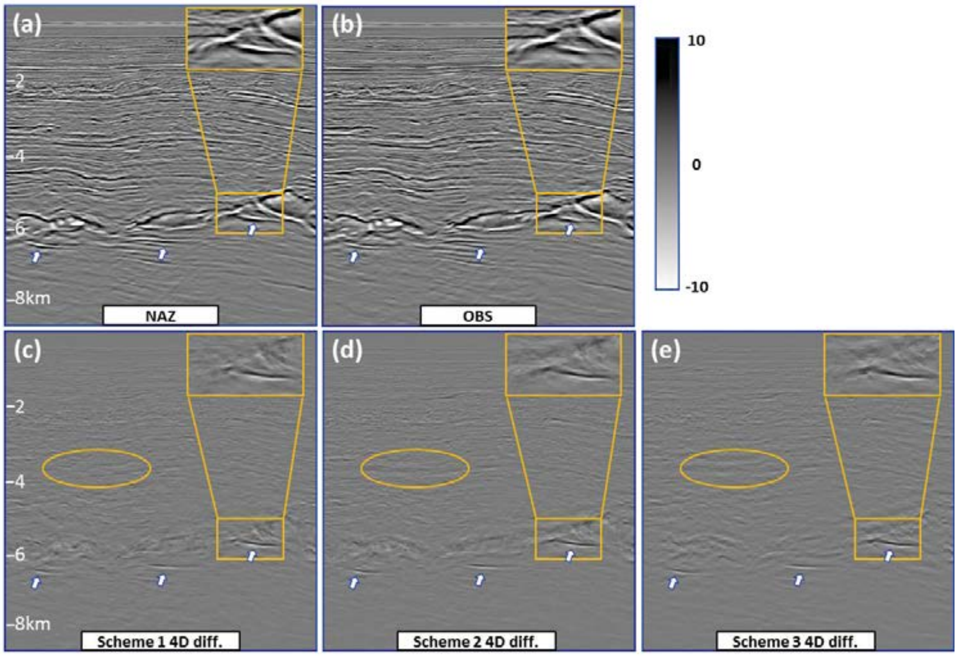

Figure 2: Kirchhoff stacks after post-migration processing of (a) NAZ and (b) OBS from Scheme 2, and 4D difference of OBS and NAZ at different matching schemes: (c) Scheme 1 - NAZ with 1D matching filter, (d) Scheme 2 - NAZ receiver deghosting, and (e) Scheme 3 - full deghosting on both surveys. The rectangular zoom-in sections highlight the Penn State reservoir.

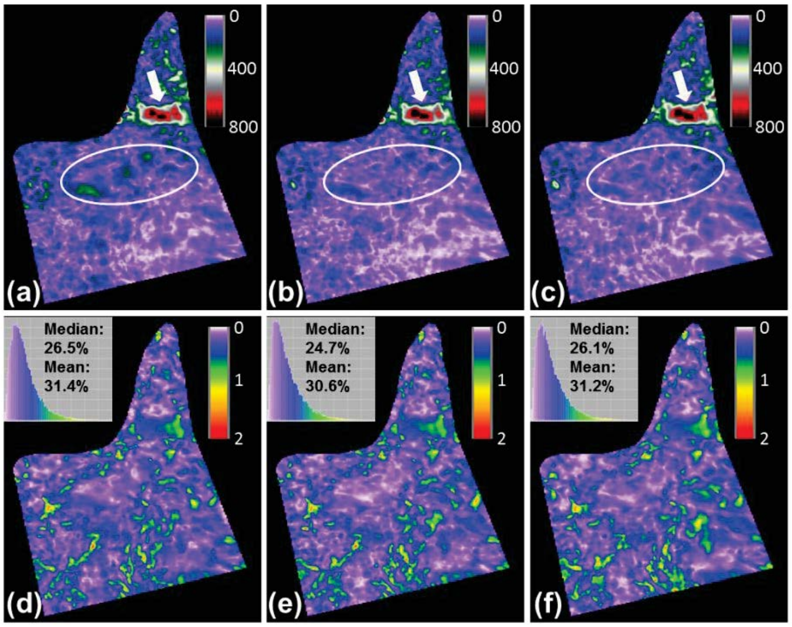

Figure 3: 4D RMS and NRMS maps at the Penn State target horizon after different spectral matching schemes: 4D RMS (a) Scheme 1 - NAZ with 1D matching filter, (b) Scheme 2 - NAZ receiver deghosting, and (c) Scheme 3 - after full deghosting on both surveys; and NRMS (d) Scheme 1, (e) Scheme 2, and (f) Scheme 3. Both RMS and NRMS are extracted from the Penn State target horizon with a window of +/- 50 m. White arrows on the RMS maps indicate the area of real 4D changes, while white ellipses denote the areas with reduced background noise after NAZ receiver deghosting. Insets in (d), (e) and (f) show the corresponding distributions of NRMS values.

mainly due to the uncertainty related to source deghosting in the streamer data. Accurate source deghosting requires a common receiver gather that has a stationary receiver position and dense shot sampling, which is the case for OBS data but not for streamer data. This small inaccuracy in streamer shot deghosting is usually hard to observe in 3D imaging, but can be noticeable in 4D seismic.

Similar patterns of 4D S/N among the three schemes were also observed on the 4D RMS and NRMS (Grion et al., 2000, Christie et al., 2002) maps at the Penn State reservoir. As highlighted by the white ellipses, relatively high background noise in areas with no real 4D changes in Scheme 1 (Figure 3a) was attenuated in both Scheme 2 (Figure 3b) and Scheme 3 (Figure 3c). Meanwhile, the real 4D changes, as highlighted by the white arrows, were enhanced in both Schemes 2 and 3 compared to Scheme 1. Clearer improvements in the 4D S/N from Scheme 2 were observed on the NRMS maps, where the median NRMS value was reduced by 1.8%, from 26.5% in Scheme 1 (Figure 3d) to 24.7% in Scheme 2 (Figure 3e). Scheme 3 (Figure 3f) only reduced the median NRMS error by 0.4% from Scheme 1. Overall, Scheme 2 spectral matching with receiver deghosting on NAZ gave the best 4D S/N.

Conclusions and discussions

We investigated three spectral matching schemes for OBS and streamer 4D processing: Scheme 1, 1D matching of streamer data to OBS; Scheme 2, receiver deghosting of streamer data; and Scheme 3, full deghosting of both surveys. Clear subsalt 4D signals were observed in this area in all three cases, even though the OBS and streamer surveys were poorly repeated. Compared to 1D matching, receiver deghosting of the streamer data removed the angle-dependent ghost effect, providing a better match of OBS and streamer data and, therefore, a better 4D S/N.

We did not find improvements on the 4D results after further source deghosting on both surveys; instead, more low frequency 4D noise was introduced. The main reason was probably the uncertainty associated with the source deghosting of the NAZ data. Accurate source deghosting requires obtaining source-side take-off angles through use of TauP or FK transforms in a stationary receiver gather with dense shot sampling, which is not available in towed streamer surveys. Often the receiver-side incident angle is used to approximate the source-side take-off angle during source deghosting in streamer data. Though the small inaccuracy relating to this approximation is often difficult to observe in 3D imaging, 4D seismic is a more sensitive measurement.

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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