Broadband processing with calm and rough seas: observations from a North Sea survey.

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Summary

It is well known that rough seas cause higher levels of noise in marine seismic data, and that the noise level is higher for shallower streamer tows. It is also understood, although less well known, that the roughness of the sea surface induces time and space dependent variations in both receiver-side and source-side ghost reflections. Since broadband processing aims at the removal of ghost effects, it is important to assess the impact of these factors on broadband data quality. This paper reviews previous work related to these subjects and discusses two adjacent 3D seismic lines acquired in the central North Sea (Quad. 29/30), in calm and rough conditions respectively. The objective of this analysis is to draw qualitative and quantitative conclusions on broadband seismic data quality in rough and calm conditions.

Introduction

The effect of swell on seismic data quality decreases with streamer depth, and is a function of the swell spatial wavelength, with longer wavelengths having a greater effect at depth than shorter ones (Sheperd and McDonald, 2004). It is in general accepted that, in marine acquisitions, towing streamers deep reduces noise levels significantly, but at the same time introduces receiver ghost notches at frequencies within the normal usable bandwidth, although with the benefit of improved signal content at frequencies smaller than the ghost. Grion et al. 2001 evaluated a dual-pass over/under post-stack de-ghosting of conventional 3D streamer data acquired at different depths during different passes over the same line. The technique was successful in allowing deep tows and increased bandwidth, but this complicated acquisition technique did not become a commercial success.

The advent of dual-sensor streamers in 2007 strongly revived interest in deep tows and de-ghosting. Tabti et al. (2009) compare deep tow (15m) dual-sensor data with conventional data acquired at 8m depth. Dual sensor data delivers the expected resolution and SNR increase. Interestingly, the authors argue that the time-space variations of the receiver ghost due to rough sea conditions are the cause for ineffective de-ghosting of the conventional, hydrophone-only data at high frequencies.

The effect of a rough sea surface on seismic data has been investigated by several authors (e.g. Laws and Kragh 2004, Kragh and Laws 2006, Orji et al. 2012), with the conclusion that it can affect time-lapse (4D) signal. However, corrections for sea-surface roughness have not become standard in 3D processing. Furthermore, de-ghosting and imaging methods that make use of flat sea-surface assumptions have been proposed in recent years and were well received by the seismic exploration industry. Imaging methods that assume a flat sea surface include mirror imaging for ocean-bottom data (Grion et al. 2007) and its application to dual-sensor streamer data (Whitmore et al. 2010). The variable-depth post-stack de-ghosting method of Soubaras (2010) also makes use of mirror imaging, and therefore assumes a flat sea surface, and similarly for the multi-component streamer joint de-ghosting and wavefield reconstruction method of Özbek et al. (2010).

In this context, Williams and Pollatos (2012) point out that the key to successful de-ghosting of single component streamers lays in SNR, and that the coupling of modern low-noise equipment and deep tow depths should allow significant bandwidth increases even when using conventional equipment and a depth-invariant acquisition configuration. In this paper we further expand this analysis by considering two adjacent lines acquired in calm and rough conditions using solid streamers and a deep towing depth.

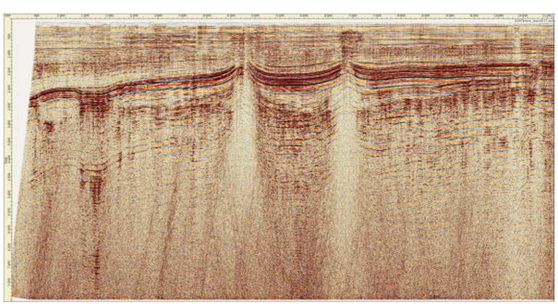

Figure 1: Brute stack of the calm-sea line

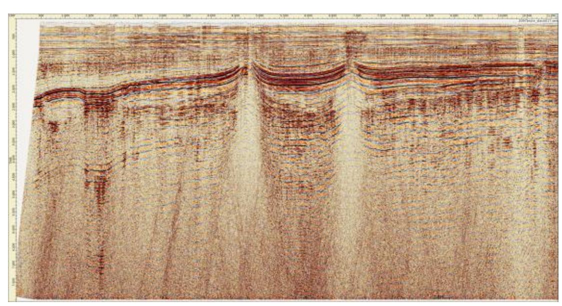

Figure 2: Brute stack of the rough-sea line (3.5-4m waves)

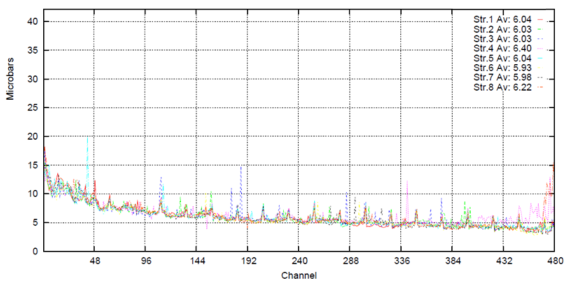

Figure 3: End-of-line noise records for the calm-sea line

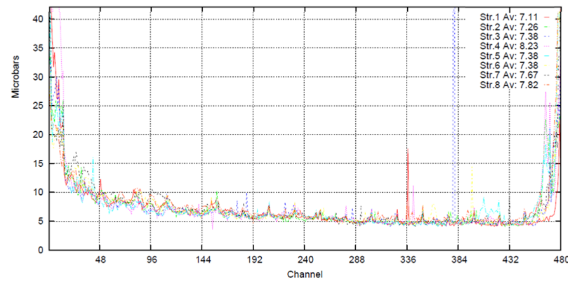

Figure 4: End-of-line noise records for the rough-sea line

Data acquisition and observer reports

Data acquisition took place in June 2012 in central North Sea blocks 29/30. The Artemis Arctic towed 8 hydrophone-only streamers, 75m apart and 6 km long. The streamer depth was 30m for all channels, and a 4300 cu. in. source array was towed at 6m. The shot point interval was 25m flip-flop, with 35m cross-line separation, while the receiver group interval was 12.5m.

For both the calm and rough lines objective of this study, the navigation heading was 181.2^{o}. The two lines are 900m apart, and 70km long. For the calm line acquired on June 20th, the wind strength was NE 4kts veering to E 8kts at the end of the line, with an observed wave height of 0m. For the rough line acquired on June 23rd, wind strength was SW 21kts at start-of-line, backing and decreasing to SE 4kts at end-of-line and the observed wave heights were NE 3.5m and SE4m, respectively.

Start-of-line noise records were taken while the streamers were still in turn, therefore showing noise levels partly due to drag, while end-of line records were taken with streamers in acquisition configuration and are more representative of actual noise levels. Due to the 30m streamer depth, despite the significantly different weather conditions noise levels are on average only 1.4µB higher for the rough sea line (7.53 µB) than for the calm sea one (6.09µB), as shown in Figure 3 and in Figure 4.

Data Analysis

The fast-track processing sequence was the same for both the calm and rough sea lines, and included swell noise attenuation, source and receiver-side tau-p deconvolution, radon demultiple, post-stack time migration and statistical de-ghosting. Finally, gap deconvolution and Q phase-only compensation were applied after de-ghosting to obtain the final stacked images.

Figure 5 shows a comparison between stacks of the de-ghosted calm and rough lines. It is striking that, besides the very different sea surface conditions at the time of acquisition, the two images are of comparable quality and show similar lateral coherency of events and level of detail. The amplitude spectra of the two datasets are shown in Figure 6 and confirm that they have similar bandwidth. Also shown in Figure 6 is the receiver ghost response for a 30m receiver depth at vertical incidence, under the assumption of a perfectly calm sea surface, as well as the amplitude spectra of the calm and rough stacks before de-ghosting. It is apparent that the data was successfully de-ghosted.

Successful de-ghosting depends primarily on the SNR of the data in the frequency range of the ghost notches, and these are expected to be deeper in calm conditions than with a rough sea surface. The stacked images in Figure 5 have a nominal fold of 60. The question therefore arises whether a similarly successful de-ghosting would be achievable on a single channel section, which would have a nominal fold of 1, and therefore a lower SNR. Figure 7 compares a 275m offset section of the calm and rough lines. The processing sequence was the same used for the data in Figure 5. Analysis of the corresponding amplitude spectra in Figure 8 confirms similarity of bandwidth and successful de-ghosting for these 275m offset sections. It should be noted that in migrated images a nominal fold of 1 can still give rise to the stacking of contributions from different arrival angles in the presence of complex structures, and that complex structures are indeed present in this dataset. The receiver ghost notch appears only 2dB deeper for the calm line with respect to the rough one, due to this effect and to spectral averaging in the selected data window.

Conclusions

Analysis and comparison of broadband images acquired in calm and rough conditions in Quad 29/30 of the central North sea shows that for this dataset the sea surface state has negligible effects on data quality in the target area (0.8 to 2.8 seconds of two-way traveltime), meaning that the ability to interpret horizons and the visible spatial coherency of reflected events is similar for both datasets.

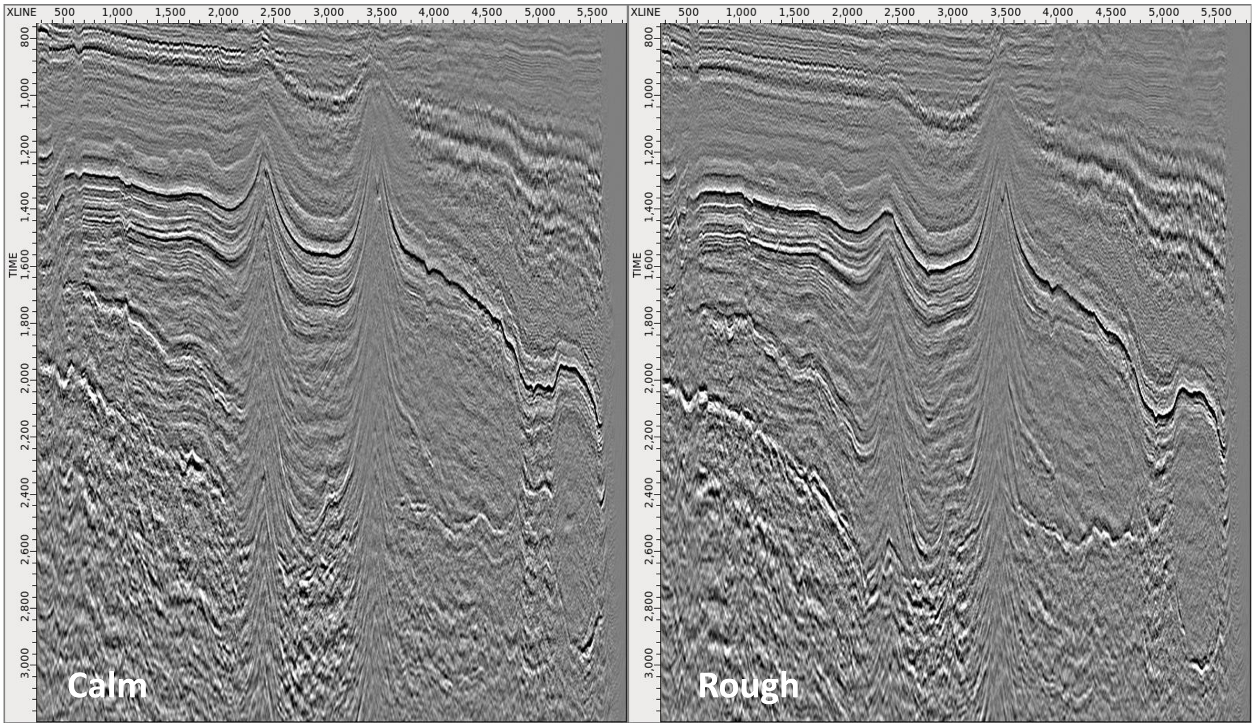

Figure 5: Broadband post-stack time migrated images of the calm and rough sea lines. Inspection of the two images reveals similar data quality despite the very different weather conditions. The subsurface structure in the two images is similar but not identical, as the two lines are 900m apart.

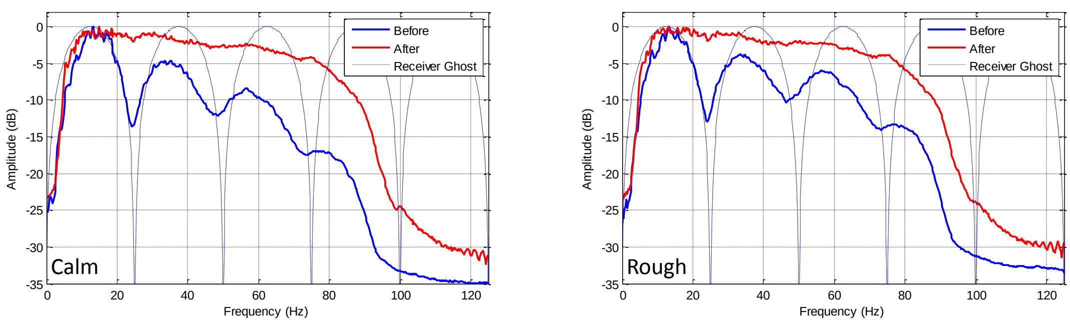

Figure 6: Average amplitude spectra of the calm and rough line stacks, before and after de-ghosting. The corresponding de-ghosted data is shown in Figure 5. Before de-ghosting, the receiver notches are slightly deeper (1.5dB) for the calm sea line.

After statistical de-ghosting, the achieved bandwidth is in the range 10 to 80 Hz for both the calm and rough sea lines, and both on a common offset section (275m) and on a full stack with a nominal fold of 60. The level of detail in the post-stack migrated images appears comparable regardless of the sea surface conditions at the time of acquisition.

It is suggested that the reason behind these results rests with the high SNR of the data, acquired with solid streamers at 30m depth and therefore only weakly sensitive to swell, and to the robustness of the commonly used flat-sea surface assumption.

Various authors have discussed the impact of sea-surface roughness on the quality of time-lapse (4D) seismic signal. These considerations are outside the scope of this work but do indeed need to be further addressed and understood to perfect the knowledge of the inter-relation between rough seas and seismic data quality. It is reasonable to assume, as suggested by previous authors, that sea surface roughness

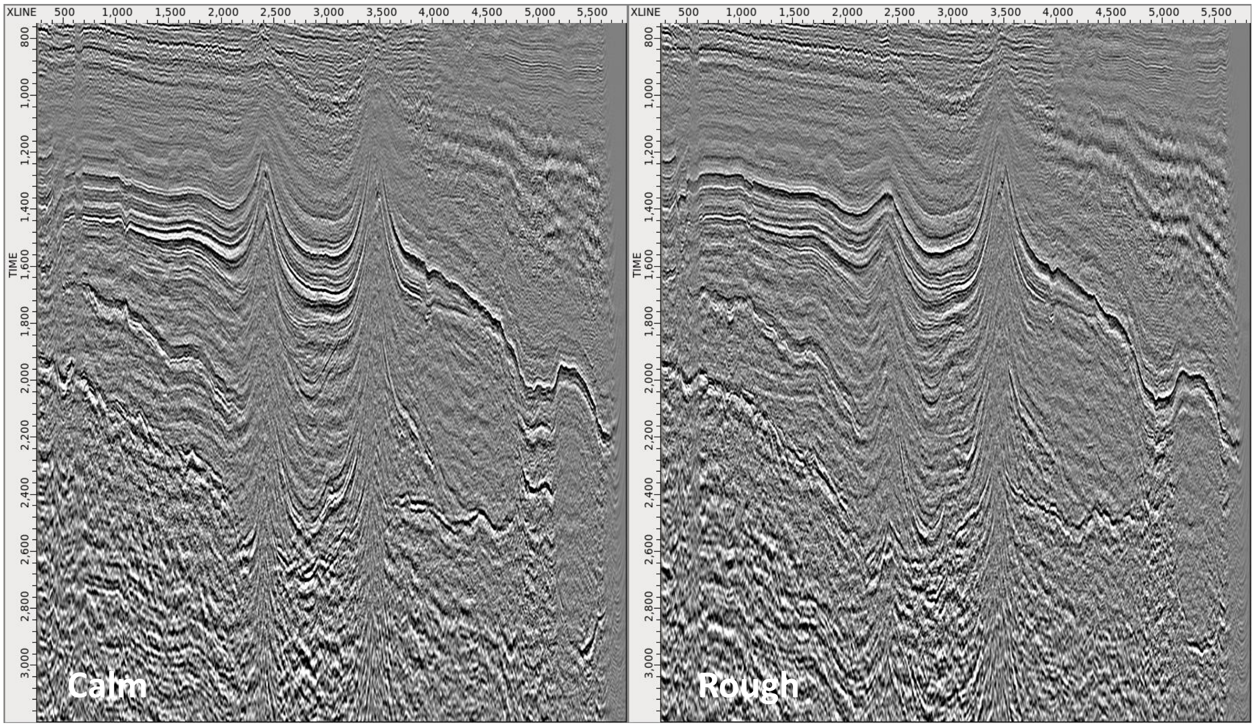

Figure 7: Broadband near-channel (275m offset) time migrated images of the calm and rough sea lines. Similarly to the full stack images, data quality appears comparable.

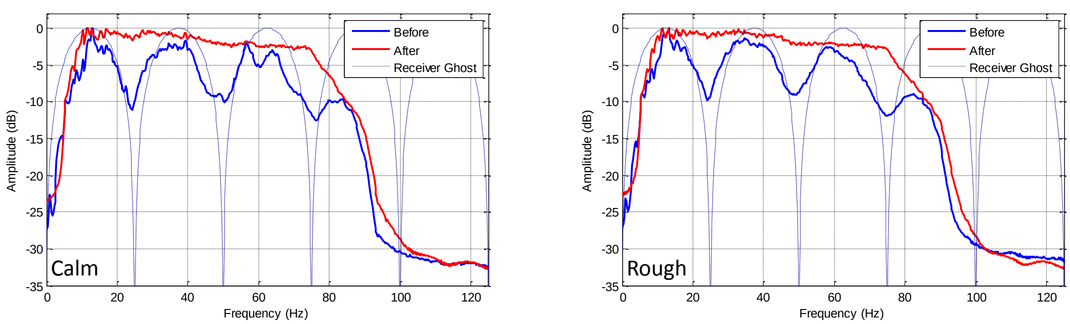

Figure 8: Average amplitude spectra of the calm and rough lines (275m offset), before and after de-ghosting. The corresponding de-ghosted data is shown in Figure 7

has increasing effects as frequency increases. In the frequency range available I nthe target interval during this study, these effects were not observed, and 4D differencing was not possible because of the spatial distance between the two lines (900m).

Recent years have seen the advent of various processing methods that assume a flat sea surface and a frequency-independent reflection coefficient for mirror imaging, de-ghosting and wavefield reconstruction. Observations on the data presented in this paper confirm the validity of these assumptions in the context of structural subsurface imaging at typical target depths.

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