Evaluation of a marine broadband slanted source

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Summary

Results are presented on the processing of a 2D test-line acquired with a standard versus a broadband source. To control for potential differences due to weather, water velocity and cable feathering, the data for both experimental source and reference source were acquired along the same sail line with each source fired alternately. The datasets were processed using essentially identical pre-stack time migration sequences and an assessment made of relative imaging quality and signal-to-noise ratio on stacks. It is found that despite efforts aimed at achieving comparable bandwidth from both sources, there is more noise present in the final section of the line acquired with standard source. This noise is visible in the spectrum centered on the standard source's ghost notch at 107 Hz, and takes the form of a reduction in the spatial coherence of the image.

Introduction

The seismic air-gun array is intrinsically a broadband source in the 2-200 Hz range but the proximity of the sea-surface causes interference between the direct and reflected waves resulting in peaks and notches in the spectrum, Figure 1. In practice, the notches limit the available energy but they are not perfect nulls and do contain signal that sits above the noise floor.

De-ghosting will recover lost bandwidth and improve the resolution and interpretability of the seismic section but the amount of signal recoverable from the notches depends on sea-state, noise level and scattering geometry i.e. diversity of ray parameters contributing to an image. The signal level also depends on the acquisition set-up – receiver cable depth, source array depth and internal configuration. This paper investigates the benefit of minimizing ghost interference by configuring the air-guns in the source array at different depths, in a slanted configuration. This diversifies the ghost notch frequency leading to a flatter spectrum, as shown in Figure 2 and, by appropriate timing of the guns, maintains a synchronized downward leading wave-front. While Parkes and Hegna (2011) and Siliqi et al. (2012) also make use of this source design principle, our study differs in the details of the processing. The standard source data we used as reference were processed up to the Nyquist frequency and not just up the first source ghost notch frequency.

2D marine seismic data were acquired over a 30km sail-line in the Norwegian North Sea to test the benefit offered when using a broadband source. A standard single-depth source array was shot alternately with the experimental, broadband array as a reference.

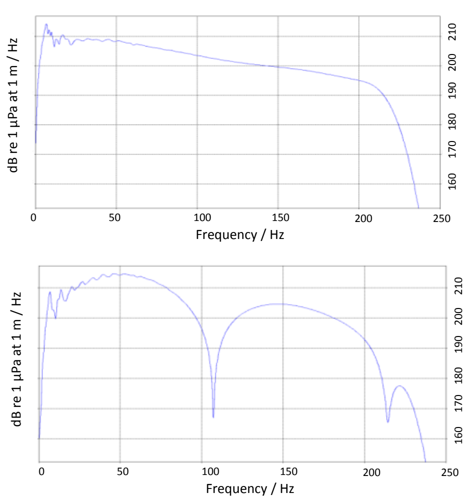

Figure 1 - Typical ghost-free source output spectrum for marine seismic air-gun array (top) and with ghost due to sea-surface with reflection coefficient R = -1 (bottom).

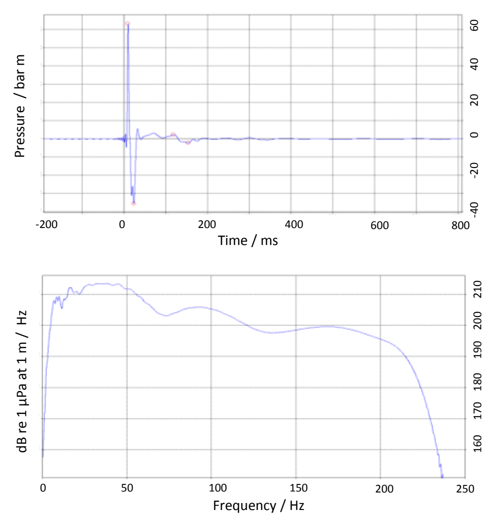

Figure 2 - Experimental broadband source modeled far-field signature (top) and corresponding spectrum with ghost (bottom).

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Acquisition and processing

The 2D line was acquired in the North Norwegian Sea in November 2013 in a 20 knot Northerly wind and 3m sea-state. The acquisition parameters are summarized below:

- 1709 shots at 18.75m spacing (854 standard source, 855 experimental source)
- 37.5m shot interval for processing (after separation of sources)
- Standard source at 7m depth, experimental source air-guns set at multiple depths
- 640 receiver channels at 12.5m spacing
- Streamer flat at 30m depth
- Near channel offset 150m, far channel offset 8137.5m
- 2ms sample rate
- Record length 7.5s

The standard and broadband source arrays comprised three strings and 28 guns in total, with guns ranging from 40 to 300 cubic inches. The air-guns in the standard array were all set at 7m with identical timing. For the slanted broadband source array the guns were set between 4.5 and 15.5m to diversify the source ghosts and achieve a flatter spectrum. These guns were fired with appropriate timings in the range 0.0 to 7.3ms to ensure that a coherent downward propagating source wavelet is generated.

After reading in the SEG-Y file the line was separated into the standard and test sequence. An outline of the processing steps applied to each sequence is provided below:

- Fourier regularization of bad shot/channel edits
- 1.5 Hz/18 dB low-cut filter applied
- F-X swell noise attenuation
- 2:1 channel interpolation, anti-alias k-filter and trace-drop back to 640 channels
- Linear noise attenuation using F-K dip filter
- De-convolution of bubble pulse and zero-phasing of wavelet
- Multiple attenuation by SWME, de-convolution and then muting after parabolic Radon transform on NMO-corrected CMP gathers using a 1 km velocity field
- Source and receiver de-ghosting
- Common offset binning
- F-X de-convolution
- Pre-stack time migration
- Residual multiple attenuation
- Stack, spectral shaping, residual de-noise - trace mix, F-K filter, and time-varying low-pass filters
- Amplitude, time and phase - matching of the two sections

Note that 2ms sampling was preserved, enabling processing up to 200 Hz. Source and receiver de-ghosting was directional and time-space variant, with operators derived using a combination of adaptive estimation and a-priori information on cable depth, source depth, water velocity and sea-surface reflection coefficient. The process also included statistical corrections for the minimization of any residual ghost energy. The in-line directivity of the slanted broadband source is compared to the standard for reference in Figure 3. The cross-line directivity for the broadband source is similar to the in-line function but with less pronounced minima with respect to the standard source. Source directivity is explicitly compensated for by directional de-convolution in the de-ghosting process.

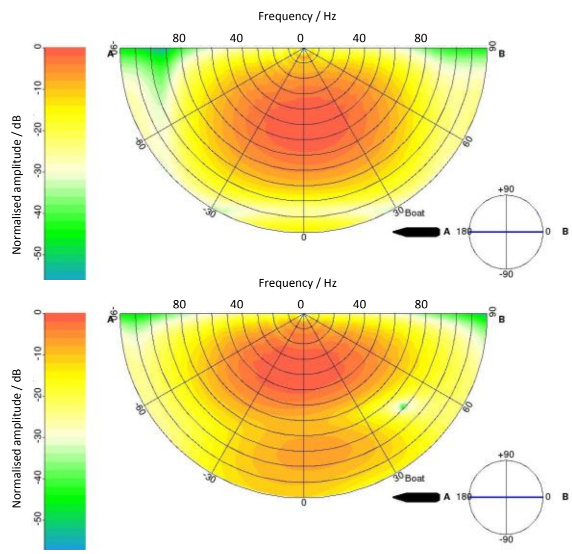

Figure 3 – Array directivity as a function of in-line angle for the standard (top) and broadband source (bottom).

After migration the standard and test gathers were stacked and residual noise attenuation and spectral shaping carried out. Wherever possible, the processing parameters for both sources were identical. As a final processing step, the broadband source image was matched to the standard one to remove residual bulk time, amplitude and phase shifts.

Results

Firstly, a comparison was made of the effect of processing the standard source data over the full available bandwidth 2-200Hz with processing only up to the first source notch 2-107 Hz. Figure 4 shows a shallow section of the data, where the greatest increase in resolution is expected. The arrows in the figure highlight some of the horizons that are resolved with full bandwidth available but which are not visible or poorly resolved for the band-limited case.

The fully-processed sections obtained with the broadband source and using the standard source, together with a difference section were then examined in detail. These sections are shown in Figure 5. Note that each line corresponds to adjacent imaging mid-points therefore the datasets are not identical, and are most dissimilar at the sea-floor – hence its prominence in the difference section. These two sections appear broadly comparable, from a structural imaging point of view.

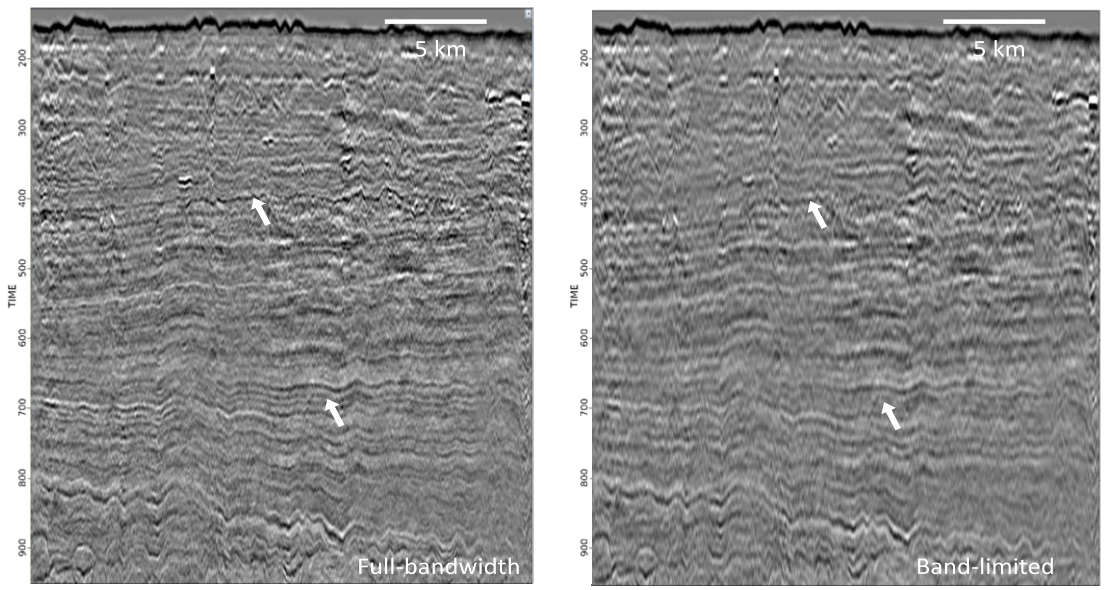

Figure 4 – Comparison between full-bandwidth processed section (left) and band-limited (by source ghost notch) section (right).

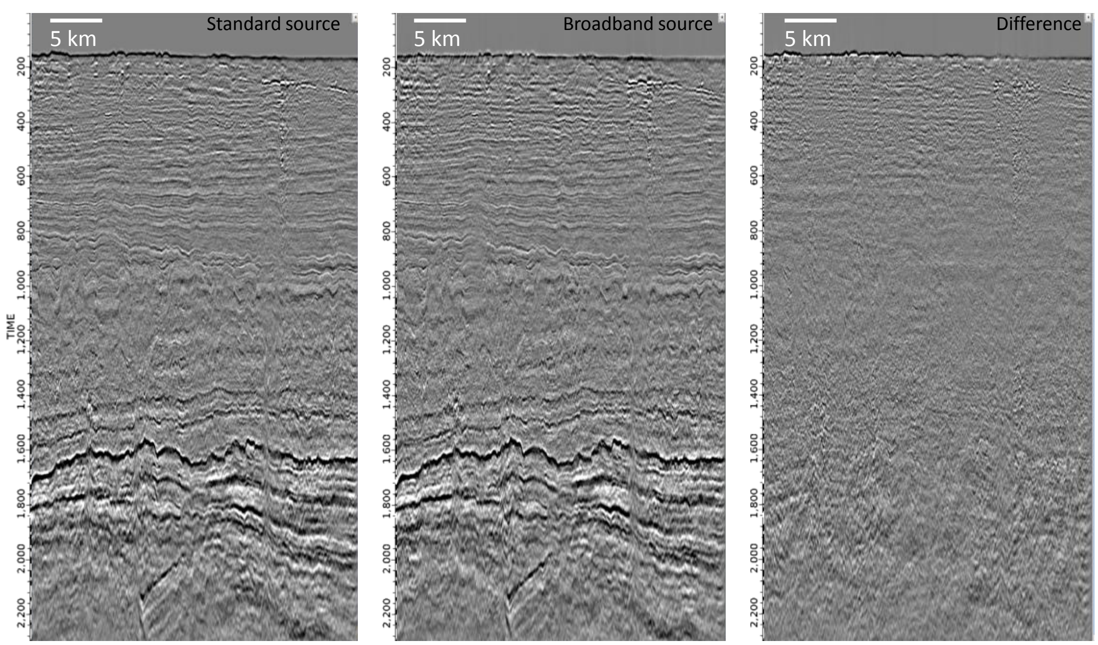

Figure 5 – Sections obtained using standard source (left), broadband source (centre) and difference (right).

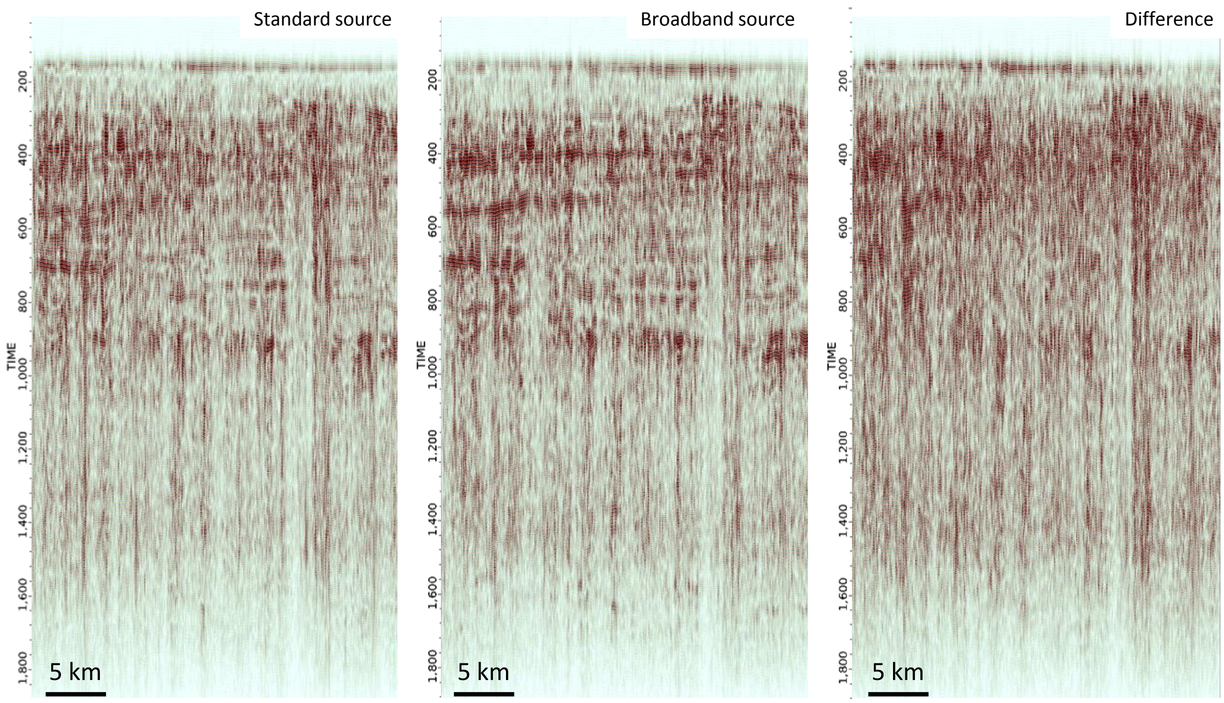

Figure 6 - Standard source (left), broadband source (centre) and difference section (right) in narrow-band 104-110 Hz.

To focus on where the greatest difference between the sections is expected, we band-passed the data using a notch filter defined by low-cut 104Hz at 72dB/octave and high-cut 110Hz at 48dB/octave. These sections are shown in Figure 6, which highlights the improvement in SNR obtained from the broadband source data. As expected, the difference section, after close matching of the two datasets, is dominated by noise.

Discussion

The first point to note from Figure 4 is that there is clear benefit, particularly for two-way travel times up to 1500ms, in recovering the bandwidth beyond the standard source first ghost notch and processing up to 200Hz. This advantage, in terms of higher resolution holds for the standard source and for a broadband source. The images clearly show horizons in the shallow section that are resolved with the full available bandwidth and that are simply not there using the conventional approach of cutting at or just below the frequency of first source ghost notch.

The second point, which is best illustrated by Figure 6, is that the signal to noise ratio after source de-ghosting is higher for the broadband source when compared with the standard source, which improves the overall imaging. The figure shows that the signal, in the form of coherent energy that follows geological horizons, is present for both source types but the lateral coherency is higher for the broadband source. This difference is most apparent around 107 Hz i.e. in the band where the first notch appears due to the source ghost.

Conclusions

The data comparison subject of this study demonstrates that there are advantages in extending conventional source bandwidth through processing, and that additional benefits exist when using a broadband source. For the dataset used in this study, these benefits are most evident at the ghost notch of the standard source.

Acknowledgements

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