Evaluation of streamer apparition processing results

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SUMMARY

This paper presents the processing results for a field test of triple-source streamer apparition, a blending technique for marine airgun sources that uses periodic codes in contrast with the more commonly used natural or artificial random dithers. The paper discusses the processing steps taken and the issues encountered while processing apparition data. We also compare migrated results to similarly processed data from a conventionally acquired triple source line. Conclusions are drawn on the benefits and opportunities of towed-streamer apparition for multiple source marine surveys.

Introduction

In recent years a number of new source configurations and techniques have been developed, including blended and overlapping acquisition with three or more sources. These new designs have been driven by the need for lower costs, higher resolution and improved operational efficiency. Conventionally the separation of blended sources exploits the natural or artificial randomness in source firing times. Seismic data apparition (Sjøen Pedersen et al., 2016), relies instead on periodic codes which act as modulation functions and facilitate the isolation of the blended sources.

In this paper we discuss the broadband processing of triple-source apparition field data, where the three sources are activated almost simultaneously at each shot location, as opposed to the alternate locations of a flip-flop-flap acquisition. For this field test we use a modulation code where only one of the sources is delayed. The use of shifted codes for each shot point ensures equivalent post-separation error for the three sources (Grion et al., 2018a). Furthermore, with a time delay of 8ms, the separation instability occurs at 0Hz and 125Hz. The 125Hz instability is acceptable for 4ms broadband processing up to 80% of Nyquist (100Hz). The 0Hz instability can also be addressed as discussed in Grion et al, 2018a,b.

Processing of the field data

In September 2017 a reference triple-source line was acquired with 12 streamers 75m apart. The streamer depth profile was mildly slanted with the receiver depth ranging from 8m to 18m over the 6km streamers. Source separation was 25m cross-line, with 37.5m in-line between successive shot points for each source line. The apparition line was acquired with the same streamer spread and the same cross-line source separation but with 18.75m between successive shot points. Initial de-blending results obtained with minimal preprocessing were discussed in Grion et al., (2018a,b) and in the following we present substantial improvements.

With apparition blending, any non-source generated disturbance, such as swell or tug noise and edited traces, breaks the apparition periodicity and results in separation artefacts. Therefore a careful noise attenuation sequence was used to prepare the data for de-blending, Any residual noise was taken care in the de-blending by including time and space variant filtering while performing the apparition separation.

State-of-the-art broadband processing technology is included in the apparition processing sequence. Since three shots are acquired simultaneously, shot-record based broadband de-signature and de-ghosting are applied prior to the apparition de-blending, such that this processing cost is effectively reduced by one third. The reference line is processed with optimized shot-by-shot directional de-signature (Hargreaves et al. 2016) to remove any variations in the air-gun array signatures while the directional de-signature of the apparition line uses an average signature extracted from all the shots in the sail-line for reasons of simplicity, speed and robustness. Provided that the shot-by-shot variations are bandlimited within the signal apparition non-aliased regions, a full or residual de-signature could be applied after de-blending but this has not yet been applied. After de-signature, phase-shift receiver de-ghosting (Grion et al. 2016) removes any perturbations induced by receiver depth variations.

Figure 1 shows co-located outer-cable common-receiver gathers and their *f-k* spectra for the reference (a-b) and the apparition line before (c-d) and after (e-f) de-blending. Re-sampling from 2ms to 4ms was performed after 100 Hz low pass filtering. The reference triple-source line has a shot-point interval of 37.5m which results in aliasing at 20Hz for the events travelling in the water column (Figure 1b).While the apparition line has twice denser (18.75m) shot-sampling, seismic data apparition with three sources injects each modulated source to three wavenumber ranges and this reduces the nominal aliasing frequency at 40Hz by a factor of one third down to 13.33Hz. Where aliasing is present the separation results are compromised.

In an earlier attempt to de-blend apparition data, Grion et al. 2018a-b suggested separating apparition data by shot type (isolating shots with the same modulation code) before *f-x* interpolation. This allows de-aliasing in the common channel domain for each shot type. The three interpolation results were then joined, and apparition de-blending applied. After isolation, the interpolated traces were dropped to restore the original shot sampling. Interpolation methods which assume seismic data are decomposed into local plane waves rely on the un-aliased portion of the data to interpolate the portion where aliasing is present. By first separating the data by shot type we reduce the nominal aliasing frequency at 40Hz by a factor of one third down to 13.33Hz, therefore making the interpolation less accurate than if we could exploit the original sampling of the apparition data.

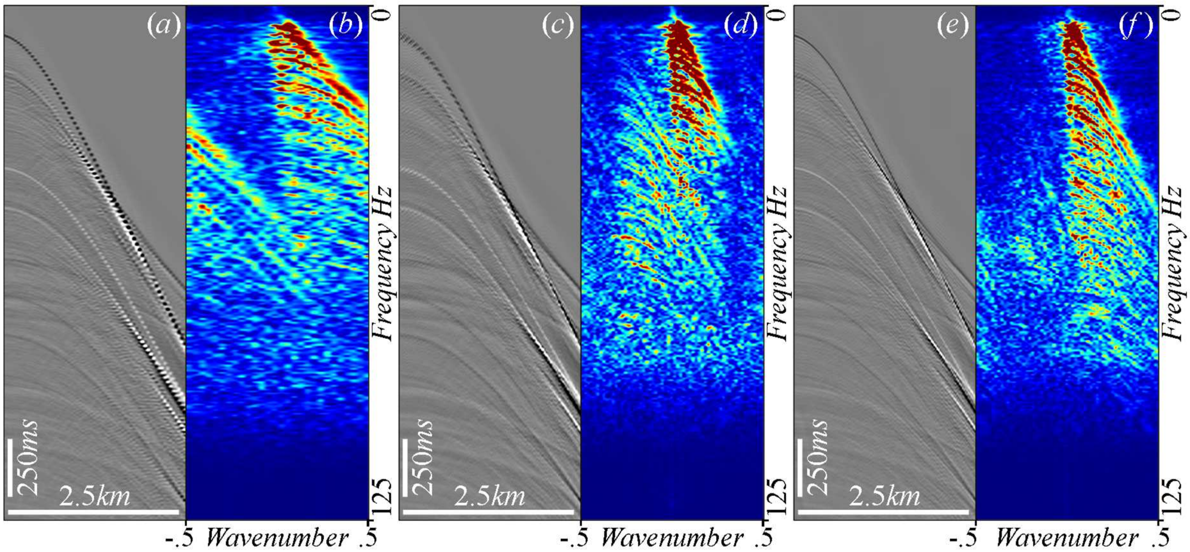

Figure 1 *Outer cable common receiver gathers and f-k spectra from the reference line (a-b) and the apparition line before (c-d) and after (e-f) de-blending. All data are de-signatured and de-ghosted. The wavenumber axis are normalized. The spatial Nyquist is 1/37.5*m^{-1} *for the reference line (b) and 1/18.75*m^{-1} *for the apparition line (d-f).*

Although counter-intuitive, it is in fact possible to interpolate the modulated apparition gathers directly without separating the data by shot type. It can be demonstrated that if the seismic data are composed of plane waves, an *n*-periodic shot code will inject *n* weighted replicas of each plane wave. Each replica will have a different apparent slope in the *f-k* domain: these slopes can then be estimated, for example, using an *f-x* prediction error filter with *n* times more coefficients. This allows a higher frequency range (up 40Hz) for de-aliasing when compared to the approach in Grion 2018a-b. Furthermore, this is an important advantage over conventional random dither blending schemes where interpolation and de-aliasing are not possible, neither on blended data nor on pseudo-deblended data.
Figures 1e-f shows the de-blended receiver gathers using the de-aliasing strategy outlined. Overall, the appearance of the separated result is comparable to that of the reference data. The periodic modulation pattern, clearly visible on the water-bottom reflection has been successfully demodulated (Figures 1c-e) as also confirmed by the disappearance of the interfering signal cones in the *f-k* spectra (d-f). Finally, the expected aliasing frequency of 40Hz at 18.75m shot spacing has been restored.

The rest of the processing sequence consists of conventional steps: SRME de-multiple, linear and parabolic radon filtering, midpoint centring and offset-binning have been applied to both the reference and apparition line. Figures 2a-b and figures 3a-b show the pre-stack time migrated images and gathers for the reference and apparition line respectively. Overall the image and gathers show comparable quality. The signal-to-noise ratio is also comparable as illustrated by the good agreement of the average spectra for the shallow and deep parts of the migrated images (Figure 2g). Furthermore, the apparition line has been matched to the reference line using a global least-squares filter calculated for the entire image. The difference between reference and matched apparition images is shown in Figure 2c. Figures 2d-e show the first 2000ms close-up of the migrated sections and their matched difference (Figure 2f). A repeatability analysis (Ronen et al., 2000) has been conducted to compare the shallow migrated apparition data to the reference data. The average NRMS value of corresponding traces is 0.25 in the time domain, in line with the expected 4D streamer repeatability discussed in Ronen et al., 2000. The frequency dependent NRMS histogram (Figure 2h) in the overburden shows values at or below 0.25 in the band 7-40Hz.

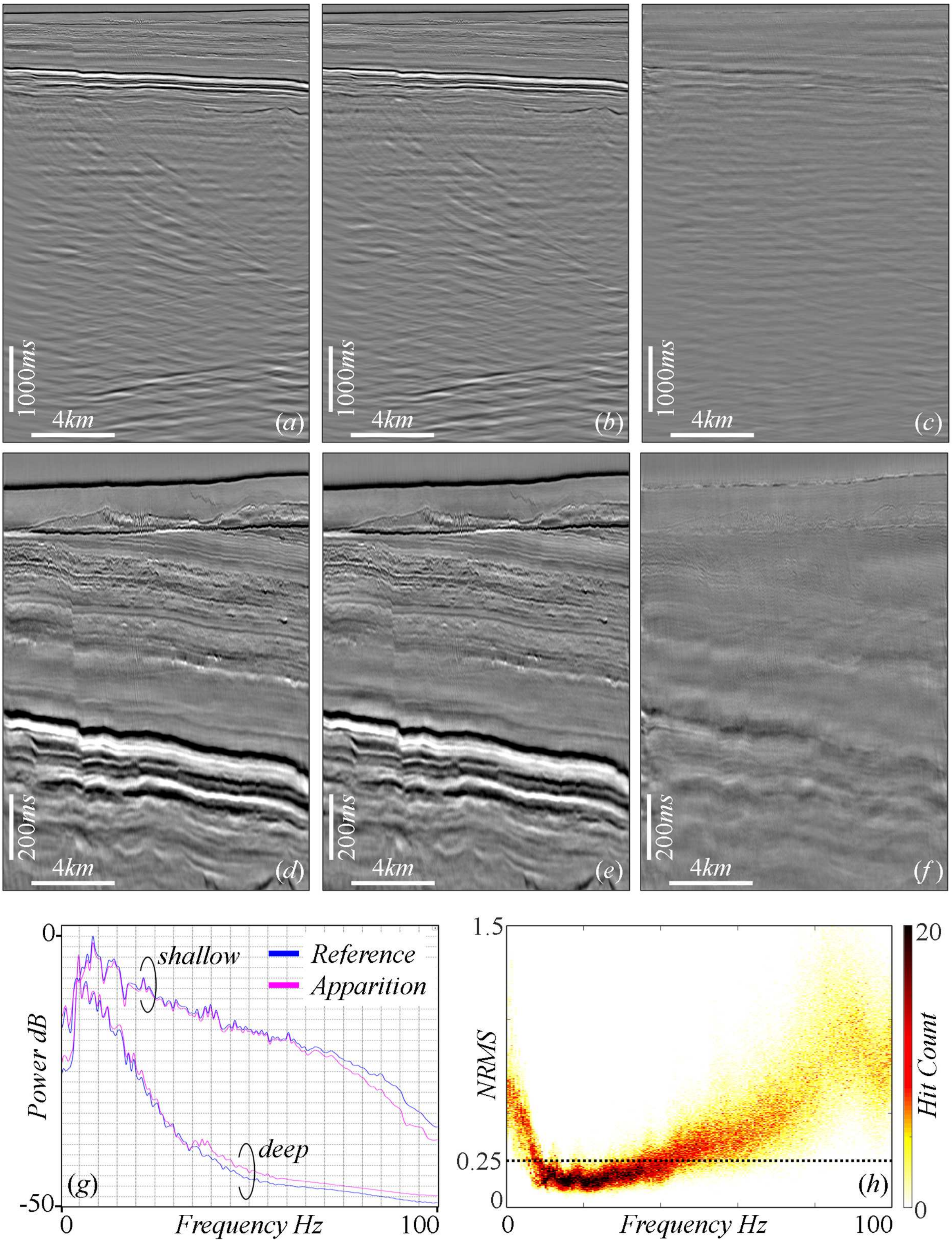

Figure 2 *Pre-stack time migrated images for the reference and the apparition line (a-b) and a close-up of the first 2000ms (d-e). The apparition line has been matched to the reference line using a global least-squares filter calculated for the entire image. Matched difference for the full stack image (c) and shallow close-up (f). The average spectrum (g) for the shallow and deep part of the migrated image show good agreement between the reference and the apparition line. The frequency dependent NRMS panel (h) calculated in the overburden shows repeatability values at or below 0.25 in the band 7-40Hz.*

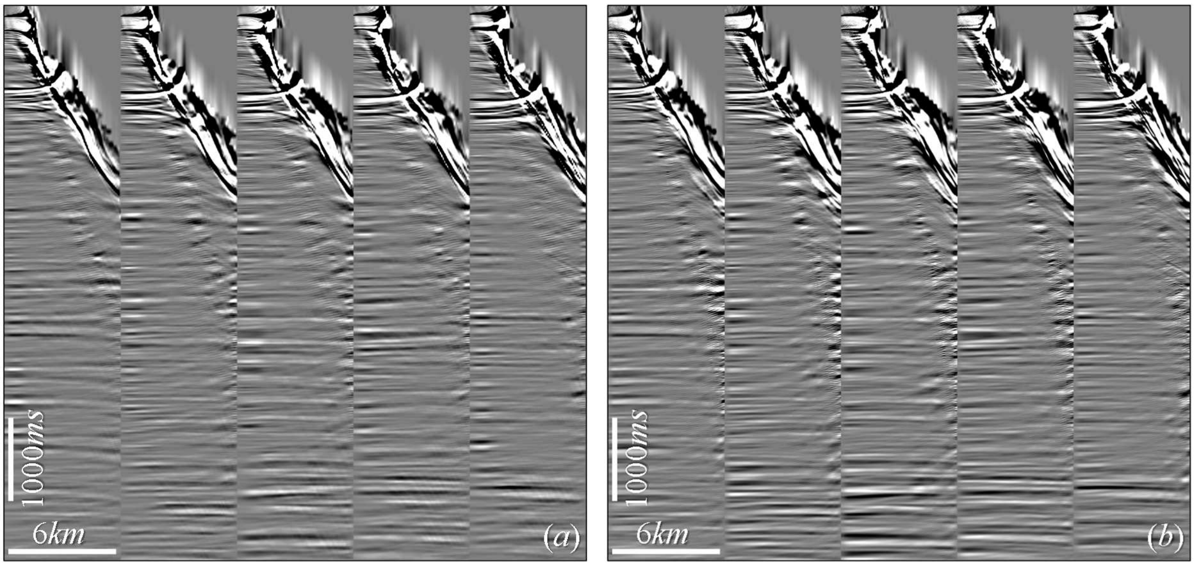

Figure 3 *Time migrated common image gathers for the reference (a) and the apparition line (b)*

Conclusions

The processing results presented here confirm the promise of seismic data apparition as a simultaneous source acquisition and processing method which allows the nearly instantaneous acquisition of multiple shots. This approach can further increase productivity, efficiency and quality compared to commonly used natural or artificial random-dither blending schemes. Provided that the data are well-sampled the apparition modulation theory provides a better posed solution to the de-blending inverse problem. When aliasing is present, interpolation is necessary to avoid the degradation of the separation results. Processing and analysis of early seismic data apparition test data continue to show encouraging results. The good agreement between reference and apparition data shown here reinforces the conclusion that apparition is suitable for structural imaging. Additionally, our NRMS analysis shows acceptable repeatability between the reference and apparition data sets. This suggests that apparition may also be compatible with reservoir monitoring and 4D processing. We speculate that more investigation on the: de-signature of apparition data, a more sophisticated interpolation algorithm, and possibly more complex time and amplitude modulation schemes for apparition will further improve the results presented here.

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