A seismic apparition experiment on towed streamer seismic data

Sergio Grion, Rob Light and Stuart Denny, Shearwater GeoServices

SUMMARY

This paper discusses a field test of seismic apparition, a simultaneous source technique for marine airgun sources that uses modulation to facilitate source separation. The first part of the paper focuses on the design of the modulation codes. The second part introduces a field test where a single line of 3D data was acquired using three two-string sources. This field test provides real data for testing current and future implementations of the seismic apparition method. In this paper we present initial separation results obtained after minimal pre-processing of the recorded data. Conclusions are drawn on the challenges and opportunities of towed-streamer seismic apparition for multi-source surveys.

Introduction

Seismic apparition (Sjøen Pedersen et al., 2016; Robertsson et al., 2016) uses regular periodic codes for blended source acquisition, in contrast with the more commonly used natural or artificial random dithers. The periodic codes act as modulation functions and facilitate isolation of the coded sources.

There are three main issues associated with the application of this method to marine streamer data acquired using airgun sources. First, phase modulation is not possible using airgun sources, and this limitation introduces singularities in the separation process. Second, noise that is not source-generated, like swell noise and tug noise, breaks the periodicity assumption that the method is based on, and results in separation artefacts; edited traces have a similar effect. Finally, for the case of n blended sources the aliasing frequency is reduced by a factor of $1/n$; where aliasing is present separation results will be degraded.

In the next sections, an analysis of separation singularities motivates the choice of modulation used for the field test, and initial separation results on field test data illustrate the benefits and challenges of this method.

Seismic apparition codes for airgun sources

Time modulation of an airgun source can be achieved by selectively applying a time delay to the guns in the array. Amplitude modulation of an airgun source can be achieved by deactivating certain source elements on selected shots to reduce peak source output. While amplitude modulation has an associated phase modulation due to tuning changes, an arbitrary phase modulation of an airgun source is not possible.

Figure 1 (left) shows the theoretical post-separation standard deviation for a time-modulation-only case. The standard deviations are normalized to the assumed prior standard deviation of the separated sources and expressed in percentage terms: a value of 100% means that separation is unreliable, since prior and posterior standard deviations are equivalent. The purple line indicates the level of standard deviation assumed for noise in the input data. The time delay used is τ=8ms, as for the synthetic example in Eggenberger et al. (2017). For this triple-source example, the starboard, central and port sources have periodicity three in terms of time delays on consecutive shot points: the starboard source has delays [τ,0,0,...]; the central source has delays [0,τ,0,...]; and the port source has delays [0,0,τ,...]. At each shot point one of the sources is always delayed, and the use of shifted codes for each source ensures equivalent post-separation standard deviations for the three sources. This is not guaranteed for a generic code. The instabilities in Figure 1 are due to the linear combination of the three sources appearing in each of the three signal-cone areas that the signal is modulated to, and

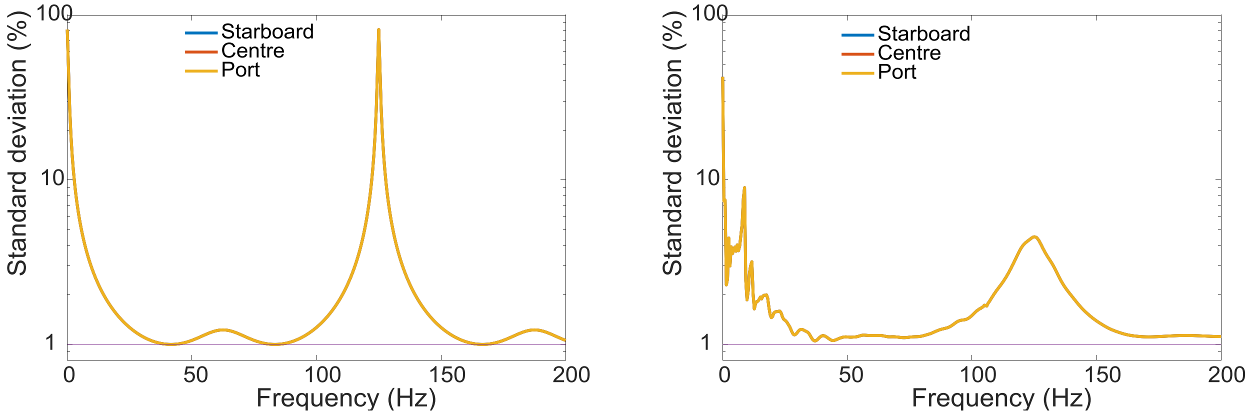

Figure 1 *Theoretical separation errors for starboard, centre and port sources in the case of time modulation only (left) and joint time and amplitude modulation (right). The errors are the same for the three sources. The periodic time delay is* τ *=8ms and instabilities occur every 1/* τ *=125Hz. With the addition of 3 dB of amplitude modulation the instability at 125 Hz is substantially reduced.*

determine the bandwidth over which signal is separable. More complex periodic timing codes can dramatically reduce the 125Hz instability in Figure 1, but for this first field experiment of the method a simple code was desirable. When amplitude modulation is associated with time modulation the 125Hz instability is substantially reduced (Figure 1, right). In this case, the amplitude modulation takes the form of periodically changing source volume from 2965in^3 to 2100in^3, creating a drop in peak output of 3dB. Time and amplitude modulation were applied simultaneously, so that when a source is delayed, it is also reduced in amplitude. Adding amplitude modulation reduces the destructive interference at 125 Hz.

The DC singularity of the separation process is equally strong with or without amplitude modulation. However it should be noted that in the case of single-boat multi-source surveys the close proximity of the three sources means that at low frequencies they act as a single source (see e.g. Bagaini et al. 2017) and do not require separation given the short time delays. Furthermore, when using the codes described earlier, the side signal cones generated by modulation have zero value in the presence of identical signals. For seismic apparition with two sources this can be easily verified starting from the modulation equations in Robertsson et al. (2016), and the extension to three sources is straightforward. Therefore, without any algorithmic adjustment, for the low frequencies separation is simply achieved by partitioning the recorded signal.

Field data examples

For several years the seismic exploration industry invested heavily in broadband streamer acquisition, testing various sensor configurations and streamer depth profiles. More recently, attention has turned to the source side, with blended and multi-source surveys meant to provide additional flexibility in terms of towing arrangements. Cost, resolution and environmental issues require a range of survey designs that go beyond the conventional flip-flop arrangement with three-string sources. In this context, in September 2017 Shearwater's *Polar Empress* acquired a number of test lines to evaluate various source configuration options, including one line to test seismic apparition with time modulation and one line with joint time and amplitude modulation. The modulation codes used were introduced in the previous section.

Figure 2 shows a common channel section of data acquired with time modulation (left) and the port, starboard and central separation results. For this display the data was down-sampled to 4ms and isolated in the bandwidth 2.5Hz to 110Hz to avoid the 125Hz singularity visible in Figure 1. No other pre-processing was applied to this data, apart from a 2.5Hz low cut to remove swell noise. At the 20km scale of these figures the data appears well separated. However noise stripes are visible: these are isolation artefacts due to the presence of un-modulated (i.e. not source-generated) noise and missed shots in the input data. These artefacts become more visible at later times (Figure 3).

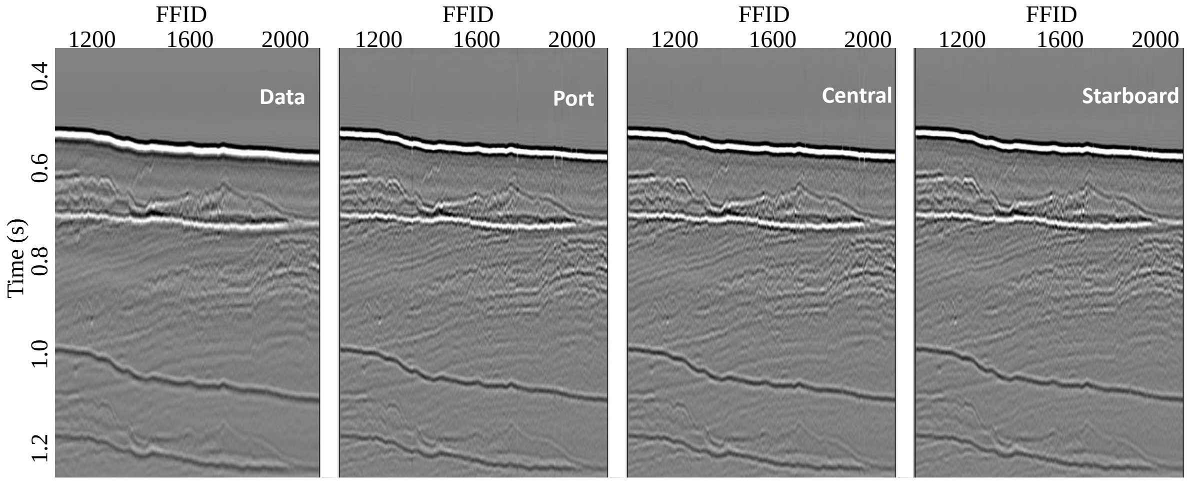

Figure 2 *Apparition common-channel data and separated port, central and starboard results, in the time range 0.4-1.2s.*

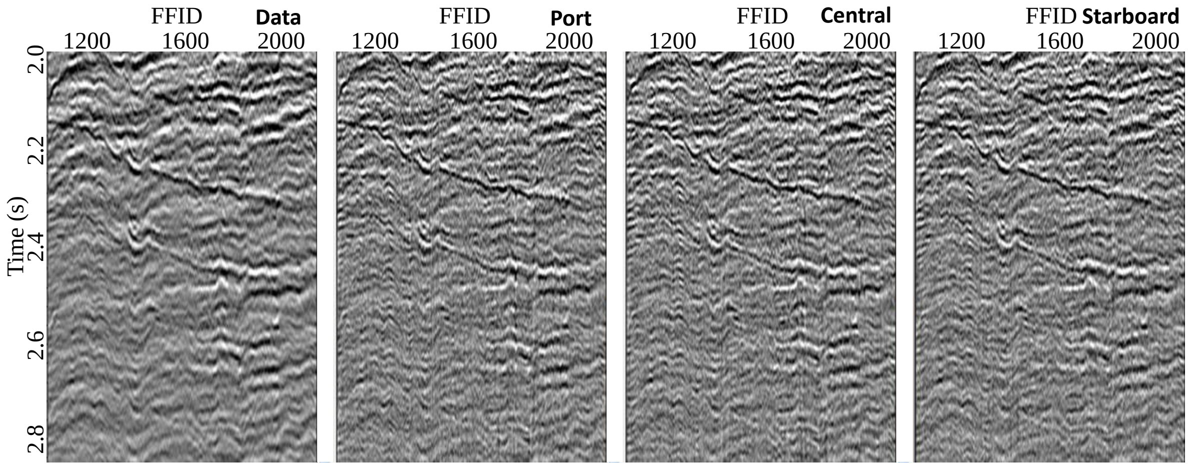

Figure 3 *Apparition common-channel data and separated port, central and starboard results, in the time range 2-2.8s.*

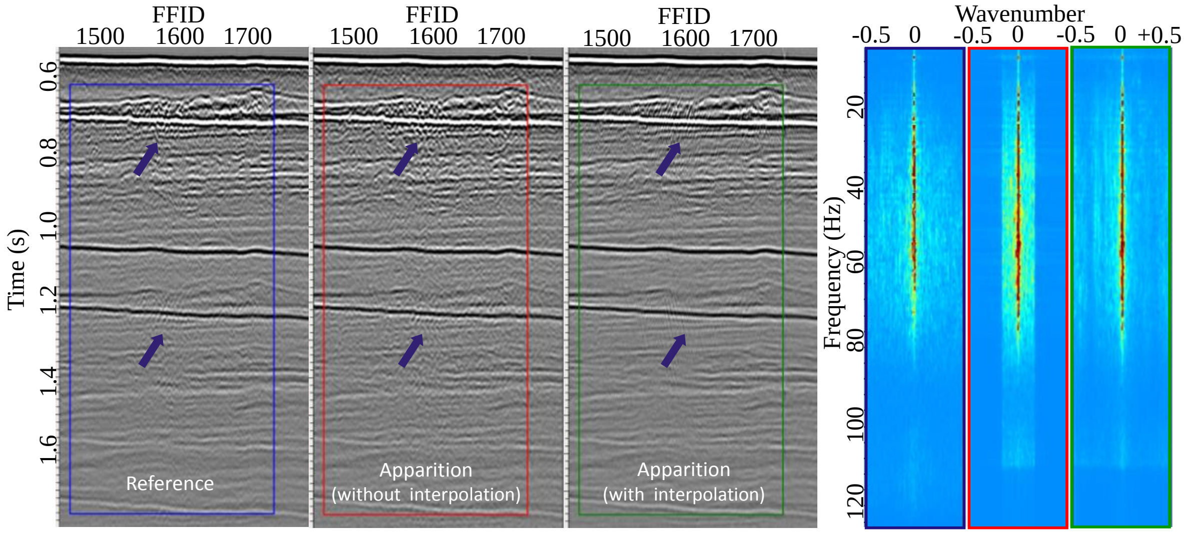

Figure 4 *A common-channel section for a reference dataset (left) is compared with sections for apparition results obtained without (centre) and with interpolation (right). The f-k displays on the far right correspond to these three datasets. The arrows point to areas where diffractions are present.*

Figure 4 shows apparition results compared to a reference dataset acquired with no interference from other sources. The common channel section on the left and the corresponding *f-k* display are from the central source of a triple-source line, with a shot point interval of 37.5m. Within this dataset, diffractions are aliased. The corresponding apparition result (centre) is for a line with time modulation, 18.75m shot sampling and no interpolation applied before isolation. While the shot sampling was denser for the apparition line, the isolation process suffers from aliasing at much lower frequencies than the reference line, and is also implicitly spatially band-limited. Overall, the appearance of the separated result is comparable to that of the reference data. However the noise level appears to be higher, due to separation artefacts. The apparition result with interpolation applied (right) shows improved diffraction definition and reduced noise level. This result was obtained by first interpolating the raw data by a factor of four individually for each shot point type ([τ,0,0], [0, τ,0] and [0,0, τ]), using the *f-x* method in common channels. The three interpolation results were then joined, and apparition isolation applied. After isolation, the interpolated traces were dropped to restore the original shot sampling.

Figure 5 shows the reference data on the left, and apparition results up to 200Hz in the centre and right. The apparition results were obtained after the interpolation described in the previous paragraph. With time modulation only, the 125Hz noise associated with separation instability is clearly visible

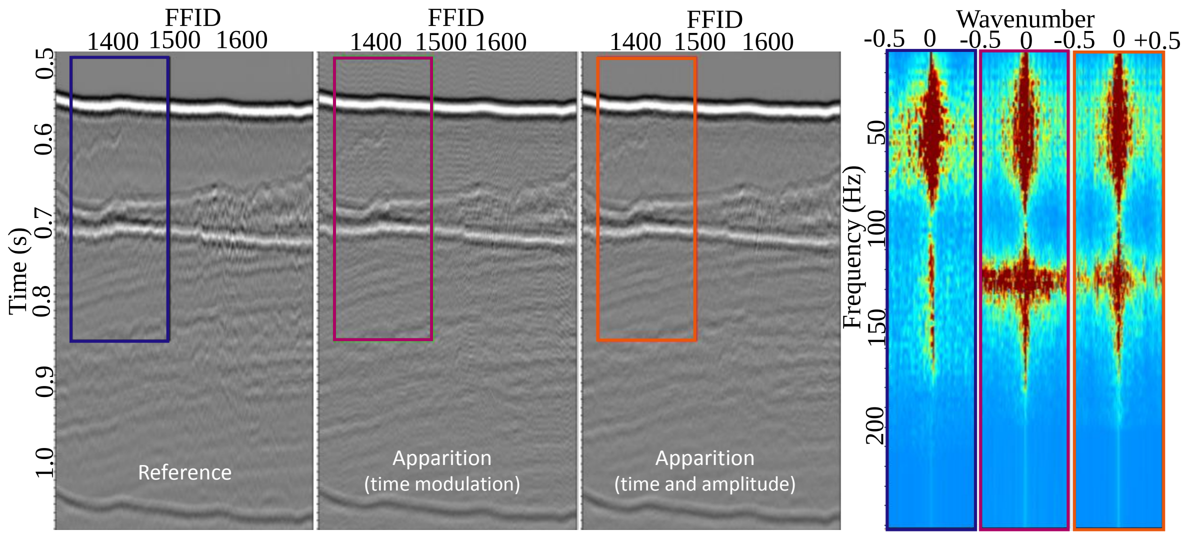

Figure 5 *A reference dataset (left section and left f-k spectrum) is compared to apparition results with time modulation only (centre section and f-k spectrum) and with both time and amplitude modulation (right section and f-k spectrum), in the frequency range 0-200Hz.*

both in the data and in the *f-k* spectrum. With joint time and amplitude modulation, the artefact is reduced (right).

Conclusions

Seismic apparition is a promising simultaneous source method. Before it is accepted for commercial application, several challenges will need to be overcome. As with any new technique, a key requirement is to demonstrate successful application on field data. The initial results obtained during the course of this study are encouraging and illustrate the challenges: noise levels are raised by the separation process, and need to be addressed by careful pre-processing; aliasing is an issue even when operating in common-channel gathers with relatively simple geology, and therefore careful data interpolation is needed; finally, for high resolution 2ms processing with frequencies up to 200Hz, simple time codes give rise to separation singularities within the signal bandwidth, and these need to be compensated for using more complex time modulation codes or joint time and amplitude modulation.

Acknowledgements

The authors are grateful to Wintershall Norge AS for permission to show the real data examples. The details of the seismic apparition method used for this study are discussed in UK Patent Application GB 2545390, applied for by Statoil Petroleum AS. We thank Shearwater's technical support staff, operations staff and the crew of the *Polar Empress* for their assistance acquiring the test data.

References

Bagaini, C., Moldoveanu, N., Moore, I. [2017] Marine seismic acquisition with phase-controllable sources. *79th EAGE Conference & Exhibition*, Extended Abstracts, Tu A4 02.

Eggenberger, K., Robertsson, J.O.A., Andersson F., van Manen D.J., Walker, R. [2017]. Full-fold, multi-source acquisition through short isolation technology and its implications on productivity gains. *First Break*, **35** (6), 105-111.

Sjøen Pedersen, Å., Amundsen, L., and Robertsson, J.O.A. [2016]. Wavefield signal apparition, Part II: Application to simultaneous sources and their separation. *78th EAGE Conference & Exhibition*, Extended Abstracts, We LHR2 06.

Robertsson, J.O.A., Amundsen, L., Sjøen Pedersen, Å. [2016]. Wavefield signal apparition part 1 theory. *78th EAGE Conference & Exhibition*, Extended Abstracts, We LHR2 05.