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Full-fold, multi-source acquisition through shot isolation technology and its implications on productivity gains

K. Eggenberger^{1*}, J.O.A. Robertsson¹, F. Andersson¹, D.J. van Manen¹, R. Walker¹ and L. Amundsen² report on and discuss signal apparition enabled multi-source technology, supported with a synthetic data example from the Gulf of Mexico and an emulated real data example from the North Sea respectively.

Introduction

Shot isolation enabled full-fold, multi-source acquisition is achieved by applying the novel technology of signal apparition to the encoding and decoding of fully superimposed shot records from non-distance separated sources. The introduction of periodically varying shot-to-shot modulation functions for encoding injects energy at predetermined positions within distinct wavenumber ranges, which then enables a deterministic decoding of individual shots in data processing. We demonstrate the method for single vessel operations, first on a dual source configuration for seabed acquisition, extracted from the SEG Advanced Modeling Program (SEAM) Phase I dataset, and then extend the methodology to triple-sources through the use of an emulated marine real data example from the North Sea.

With shot isolation enabled multi-source acquisition being successfully applied in a marine and seabed seismic context, scope for significant productivity gains is created. Compared to established acquisition techniques, gains arise from the ability to acquire full-fold data in a shorter time frame without compromising the subsurface bin size. For marine seismic acquisition, this also implies that the number of towed streamers can be reduced,

giving leeway to additional strategic considerations on subjects such as capital expenditures and the optimization of vessel deployment plans.

Receiver-side vs source-side

Offshore seismic data acquisition costs are significant and enhanced acquisition productivity has therefore been a major driver behind the development of new technology. Such advances can be realized on the receiver side as well as on the source side. In the past, the receiver side has experienced the greatest focus with an ever-increasing number of streamers as well as longer streamers being towed. However, the incremental efficiency gain of every added streamer through a wider ‘paint brush’ diminishes with increasing streamer count (Figure 1). Furthermore, in recent times a flattening of the cumulative productivity has been observed. This is a consequence of the diminishing return in incremental productivity when simply adding a streamer to a spread which already contains a fairly high number of streamers and of the increased physical challenges when growing the crossline spread size.

In contrast, productivity on the source side has seen little change since the introduction of flip-flop sources to marine seismic acquisition in the mid-eighties (Hansen et al., 1989). Whereas flip-flop shooting brought efficiency gains through the doubling of subsurface lines acquired per sail line, it was also noted that the technique decreases the shot sampling in the sail direction because of the inability to separate shots fired simultaneously.

The simultaneous source technique was introduced to marine seismic acquisition two decades ago (e.g. Beasley et al., 1998). However, the commercial uptake has remained limited for towed marine seismic acquisition since the decoding of source responses has often proven challenging and since the value proposition for simultaneously shooting dual sources mainly concerns data quality improvements rather than savings in acquisition time. Driven by a desire to overcome the crossline-sampling limitation in marine seismic acquisition, multiple source acquisition has lately experienced an elevated interest where the introduction of additional sources in single

Figure 1 Incremental productivity gains per single streamer added as a function of the total number of streamers before adding one more streamer.

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Figure 2 Multi-source acquisition geometry with inline staggered source arrays using the 2D line from SEAM phase I. Every second shot of source 'B' is excited with a time delay of 16ms relative to source 'A'.

Figure 3 Common receiver gather in the x-t domain from the full-fold, dual-source acquisition geometry shown in Figure 2: a) modelled reference data, b) synthesized dual-source gather, c) isolated shot responses, d) difference between reference and isolated shots.

vessel operations enables a reduction in crossline bin sizes compared to a conventional dual source acquisition with the same streamer spacing. This increased crossline sampling comes at the expense of overlapping shot records. For example, dithered shots (up to ± 1 s) are excited every 5 s rather than every 10 s (Hager et al., 2015). For targets deeper than 4 s deblending is necessary (Hager et al., 2016).

Similarly, for seabed seismic acquisition the receiver count is continuously growing to cover bigger swathes acquired on tighter shot grids (Lewis et al., 2016). Traditionally, most of the innovation took place on the recording hardware side with new cable- and node-based solutions emerging over the years. Receiver handling is becoming increasingly automated (Hovland, 2016) and new receiver deployment techniques are further fuelling productivity (Hovland, 2016; King et al., 2016; Walker et al., 2013). However, this productivity gain is limited when receiver deployment and/or moving becomes unbalanced with the source effort. On the source side in the seabed case, productivity gains can be achieved by simultaneous multi-vessel acquisition. In such a type of acquisition, however, each source vessel still acquires data in sequential flip-flop mode and therefore forfeits gains that would come from full-fold acquisition and the introduction of multi-sources. Furthermore, the need to acquire in a distance and/or time separated mode to reduce the contamination of shot records with seismic interference (e.g. Nakayama et al., 2015) limits operational flexibility.

In marine and seabed acquisition, there exist various techniques for cost-effective acquisition. However, none of these deliver full-fold and full record length owing to compromises made in reducing or avoiding seismic interference from other

sources. Full-fold would be achieved if all sources on a vessel can be excited together all the time.

With receiver technologies pushed hard over the past decades, source-side technologies increasingly offer the greater potential for the next leap in productivity gains. Full-fold, multi-source acquisition represents a compelling value proposition but requires solving the challenge of accurate encoding. Shot isolation, based on the recently introduced technique of signal apparition (Robertsson et al., 2016) successfully addresses this challenge, as also illustrated by Eggenberger et al. (2016a) and Eggenberger et al. (2016b). In this work, we report on dual-source and triple-source synthesized data examples from the Gulf of Mexico and the North Sea respectively. The technology is extended to more than two sources and we discuss the gains that this is expected to have on productivity.

Signal apparition

The technique of signal apparition was introduced by Robertsson et al. (2016). Through the use of periodic shot-to-shot modulation functions for encoding, energy is partially injected (signal apparated) along the wavenumber axis in the frequency-wavenumber (f - k) domain to locations that would otherwise not be occupied by any signal. This apparition effect can also be considered as a maximization of dissimilarity of the energy in the f - k domain from the individual sources that contribute to the composite wavefield. Therefore, the technique not only works well for distant sources but also for sources that are next to each other and are activated together. From a perspective of productivity gains this is a particularly important area of application where other methods like simultaneous source acquisition have struggled. In the non-overlapping regions of the f - k domain, the individual shots

can be isolated using linear combinations of weighted versions of the data. Such shot isolation is optimal as it allows us to perfectly separate the wavefield within diamond-shaped regions in the spectral domain. Dithered simultaneous source methods, for example, can only recover a triangle shaped region of half of this size (Andersson et al., 2017). In case these diamond-shaped regions overlap towards the higher frequencies, unfolding (or dealiasing) these regions can be achieved by using a methodology such as the one presented by Andersson et al. (2016).

Dual-source example: SEAM Phase I

In a collaborative industrial research effort for large-scale geophysical numerical simulation projects, the SEG Advanced Modelling (SEAM) Programme was established. The projects are designed to provide the geosciences exploration community with earth models and simulated data that represent significant and relevant geophysical challenges to the petroleum resource industry. The Phase I project produced a highly complex deep-water subsalt 3D earth model which covers a region of $40 \times 35 \times 15$ km and includes a complex salt intrusive in a folded Tertiary basin, mimicking the geology in the Gulf of Mexico (Fehler and Keliher, 2011). From the elastic 3D modelling effort an East-West trending 2D line was made publicly available. The data are split-spread and consist of receivers at an interval of 25 m resulting in a total of 901 receivers per shot. There are 151 shots at an interval of 100 m. Traces represent the pressure recorded 15 m below the sea surface. Each trace contains 2001 samples at a 8 ms interval for a total length of 16 seconds.

Using reciprocity, we constructed a seabed-type acquisition configuration in which 901 source positions shoot into one single receiver. Two source arrays towed in-line with a 25m separation, are fired together every 50 m (Figure 2). Such a tow-configuration of sources enables data to be acquired

twice as fast by maintaining the shot point interval. For every second shot of source 'B' a small time delay of 16 ms is introduced. Figure 3a shows the reference data set as modelled by SEAM Phase I, whereas Figure 3b shows the data set as acquired with the simultaneous source geometry outlined in Figure 2. For display

purpose, the amplitudes are clipped. Since the number of traces is half of the reference data but with two source events recorded instead of one, the energy on each trace is higher than that of a corresponding trace in the reference data set. The small time delays on every second shot of source 'B' do not produce any visible effect in the x - t domain at this scale. The isolated shot responses are depicted in Figure 3c which appear close to identical to the reference data in Figure 3a. This is confirmed by the difference plot between these two data sets in Figure 3d where the observed residual is minimal. The quality of shot isolation is particularly encouraging given the complexity of the synthetic SEAM Phase I data that contain a high degree of conflicting dips. The corresponding f - k domain representations can be found in Figure 4. The reference data set is shown in Figure 4a. In Figure 4b, which illustrates the recording from the geometry outlined in Figure 2, the periodic time delays in the common receiver gather cause parts of the wavefield to generate a signal apparition to a cone centred at the Nyquist wavenumber k_N in addition to the one centred at k_0 . This introduces a maximum of dissimilarity in the characteristics of the individual energy distributions which can be exploited for shot isolation. Shot isolation, the separation of energy attributed to individual sources, is achieved through the use of signal apparition and a dealiasing methodology as described in Andersson et al. (2016). Figure 4c shows isolated shot responses and Figure 4d shows corresponding difference with the reference data set. Again, the residual energy is minimal with the potential to further attenuate the spurious energy observed outside of the signal cone.

Triple-source example: Viking Graben, North Sea

A single-vessel towed marine geometry with triple-sources firing in full-fold mode is considered next. An openly available real 2D data set from the Northern part of the Viking Graben in the North Sea (Keys and Foster, 1998) was used to emulate the geometry in Figure 5. The original data were acquired using a single array of airguns and a single streamer comprising of 120 channels evenly spaced by 25 m in a water depth of roughly 350 m. The shot spacing is 25 m with a total of 1001 shot points. The time sampling interval is 4 ms with a trace length of 6 s. The nominal

Figure 4 Common receiver gather in the f - k domain from the full-fold, dual-source acquisition geometry shown in Figure 2: a) modelled reference data, b) synthesized dual-source gather, c) isolated shot responses, d) difference between reference and isolated shots.

cable depth is 10 m and the depth of the airgun array is 6 m. Since the Viking Graben data set is limited to a single 2D line we chose to partition the original sail line into three parts and associate each part with a hypothetical subsurface line generated by one of the three source arrays in the emulated full-fold source acquisition (Figure 5). This represents a case where the resulting

Figure 5 Emulated towed marine seismic triple-source acquisition geometry. The shot interval is 25 m. A time-shift modulation function of 8 ms was applied as indicated by the white stars.

variability between neighbouring subsurface lines is high and therefore, any signal leakage will show up more prominently. A time-shift modulation function T of 8 ms was selected to encode the triple-sources. For shots from source ‘A’ an encoding sequence of $[T, 0, 0, T, 0, 0, \dots]$ was applied whereas for source ‘B’ the sequence used was $[0, T, 0, 0, T, 0, \dots]$ and for source ‘C’ the sequence incorporated was $[0, 0, T, 0, 0, T, \dots]$.

Since apparent velocities of the reflections from sub-horizontal layers in a common offset gather (COG) tend to infinity and since signal apparition can be applied in any domain of choice which preserves the periodic modulation from trace to trace, the synthesized data are here sorted into the common offset domain for wavefield decoding. However, it is worthwhile to note that events with steep time dips can still exist. In fact, in COGs the slowest possible marine seismic events, e.g. diffractions occurring near the seabed, can have an apparent velocity that approaches half the water velocity. The modulation function selected for the triple-source example injects parts of the energy from all sources in different combinations into signal bounded regions around $k = 0$, $k = -(2k_N/3)$ and $k = +(2k_N/3)$ such that contributions from all three sources are equidistantly separated in the wavenumber direction, avoiding overlap toward the higher frequencies as

Figure 6 Evaluation of shot isolation: On a single COG with a) synthesized triple-source gathers, b/e) data isolated by signal apparition, c/f) non-synthesized benchmark data, d/g) corresponding difference. On brute stacks with h) data isolated by signal apparition, i) non-synthesized benchmark data, j) corresponding difference.

Figure 7 Example multi-source configurations for seabed acquisition to shoot a survey faster and to double the number of unique raypaths recorded to full-fold.

Figure 8 Single vessel multi-source example for marine acquisition with no tow-width constraint: a) represents a conventional flip-flop acquisition with six streamers, separated by 100 m, b) a triple-source acquisition with six streamers separated by 150 m, c) quad-source acquisition with six streamers, separated by 200 m. With no tow-width constraints the subsurface coverage for a single vessel pass can be significantly enhanced for the triple-source and the quad-source implementation by a factor 1.5 and 2 respectively. In addition, the joint activation of sources allows us to double the number of unique raypaths recorded to full-fold.

much as possible (Figure 6a). The f - k representation of the three cones shows that most of the energy resides in or around a few wavenumbers. For the triple-source presented here the data were sorted and immediately isolated in COGs which are generally less aliased. However, the data ideally undergoes purpose-built dealiased-isolation as presented by Andersson et al. (2016) to further handle aliased energy.

In a first step, we investigate the shot isolation result on a single common near offset gather. 6b-d show the f - k representations, whereas Figures 6e-g depict corresponding x - t plots. Figures 6b and 6e show the isolated data for all three sources and Figures 6c and 6f the non-synthesized reference data. Corresponding differences are shown in Figures 6d and 6g. The isolation works well with only a small residual observed and with little leakage correlated with geology. After having applied the isolation to all 120 COGs, the full data set was sorted to CMPs, moveout corrected using a 1D velocity function, and stacked. Whereas Figure 6h depicts the stack of the isolated data, Figure 6i shows the reference stack using the non-synthesized, reference data. The corresponding difference between the stacks is shown in Figure 6j. The difference shown in Figure 6j only contains a small amount of residual energy, attributed to steeply dipping events that cannot be accurately isolated by the sorting into COGs and would require a more sophisticated isolation workflow as for example described by Andersson et al. (2016). Nevertheless, these results are quite encouraging and

demonstrate the potential of signal apparition for shot isolation enabled full-fold, multi-source acquisition.

Productivity gains

The results from the dual- and triple-source examples outline a new dimension of productivity gains where a single vessel now can utilize its source capability to the maximum. In Figure 7 we illustrate how seabed seismic data can be acquired with productivity gains using a single vessel set up, while honouring a possible legacy shot grid. Let us assume the seabed legacy data were acquired in a flip-flop configuration with alternating shots every 25 m. The in-line shot spacing is 50 m and source sail lines are separated by 100 m. Such a survey geometry suggests multi-source acquisition configurations such as triple-source or quad-source for productivity gains. In the quad-source example the sources can be staggered in crossline, separated by 50m each (Figure 7a) which allows the acquisition of two adjacent source sail lines in one pass. The activation of all four sources together in Figure 7a not only reduces the acquisition time up by a factor of 2, but also enables acquiring twice as many shot points compared to conventional flip-flop acquisition, translating into full-fold data and therefore further benefiting the data quality. Figure 7b depicts a triple source acquisition geometry that can generate time savings of a factor 1.5. The operational feasibility of a wide source tow was demonstrated by Brice et al. (2015) who suggested that even a crossline separation of 250 m is possible.

Figure 9 Single vessel multi-source example for marine acquisition with tow-width constraint: a) represents a conventional 14-streamer acquisition with flop-flop shooting sources, b) shows a quad-source acquisition configuration with the same maximum tow width but with only eight streamers deployed. The exact same subsurface lines are acquired and owing to the joint activation of the sources, the unique raypath density is increased at minimum by a factor of 2 to full-fold.

For towed marine seismic acquisition two productivity gain scenarios are considered: a tow-width limited scenario and a scenario where tow-width is no constraint. Starting with the latter, Figure 8 illustrates how productivity gains can be obtained by adding additional sources. Keeping the crossline bin size for example at 25 m, the sources are kept 50 m apart and the streamer separation increases according to the number of sources employed. Figure 8a represents the base case with a dual-source shooting in sequential flip-flop mode. Resulting subsurface lines are indicated in blue. Adding a third source as shown in Figure 8b then enables widening of the ‘paint brush’ by a factor of 1.5. Furthermore, the multi-source acquisition results in an increase in the number of shot points by a factor of 2, thus resulting in a doubling of unique raypaths recorded along a particular subsurface line (red, dashed lines), translating into full-fold that benefits data quality in addition to the efficiency gains. Figure 8c shows the corresponding quad-source example which enables acquiring twice as many shot points in a survey time only half of what it would take in the base case.

Given the scenario where the base case is a tow-width limited 14 * 100 m-separation streamer acquisition with flip-flop shooting sources (Figure 9a), the introduction of additional sources will not allow an increase of the streamer crossline spread when keeping the numbers of streamers the same. However, it is possible instead to ‘drop’ streamers and still maintain the maximum tow width. Figure 9b shows a quad-source example where the 1300 m crossline tow width and the 25 m crossline bin size with the identical subsurface line positions as recorded in the base case are maintained. For this example, six streamers of 8 km length each were dropped and the streamer separation of the outer three streamers was increased to 200 m. It is also worth noting that the width of the ‘paint brush’ widens when additional sources are introduced, even for the tow-width limited case. The quad-source example in Figure 9b shows that compared to the base line two more subsurface lines are acquired by each vessel pass. This is a result of the increased multi-source source aperture due to the two additional sources. However, above all, adding sources thus allows us to significantly reduce risk exposure and capital expenditure for in-sea equipment whilst enhancing operational flexibility at the same time.

Discussion

Further to the tow-width constrained example presented in the previous section, assuming a cost of \$500,000 per streamer km, a reduction of 14 streamers to 8 streamers translates into capital expenditure savings of ca. \$24 million. Furthermore,

having 48 km fewer streamers in the water will not only reduce operational risk exposure but will also considerably reduce drag and therefore allow less powerful vessels to tow an acquisition configuration that normally would be reserved to high-end vessels only. This further suggests that a cheaper and smaller vessel can efficiently compete with more expensive and bigger vessels and therefore could reduce or defer the need for vessel or fleet upgrades. The main cost for towed marine operations are the vessels themselves. On the one hand, this gives rise to strategic considerations and options where for instance a larger fleet of lower cost-base vessels enabled by shot isolation acquisition can be more globally deployed than what would be possible with only a small fleet of high-end vessels focusing on individual seismic provinces. On the other hand, high-end vessels can utilize freed-up bollard pull capacity after increasing steamer separation by adding additional streamers for a wider overall tow width. This would have been possible in the past too, but at the expense of increasing the crossline bin size. With full-fold multi-source acquisition, however, this limitation goes away and high-end vessels can efficiently play their power advantage.

So far, the focus has been on using shot isolation to enable higher productivity and lower cost in a general seismic environment. However, in addition to exploration-type surveys, source isolation also offers a compelling advantage for development and production-type surveys. Today, such surveys are almost universally limited to single source (in order to achieve the necessary fold and in-line source density) and 50 m streamer separation, this being a practical minimum for operational reasons. The availability of shot isolation provides options to provide high fold, high quality and dense cross-line sampling while operating with fewer streamers at, say 100 m.

Full-fold multi-source acquisition may put a higher demand on source compressor capacity. However, seismic surveys tend to be overshot so that smaller source volumes, for instance by a reduction from three sub-array sources to two sub-array sources, in most cases is sufficient to obtain equivalent image quality (Kragh et al., 2012) while remaining within the compressor and sub-array capacity of most source vessels. Should source compressor capacity remain an operational bottleneck in fully exploiting the benefits that can come with signal apparition, shot-to-shot amplitude modulation functions (A) with a reduced volume instead of time modulation functions (T) can be used.

Whereas the dealising in the triple-source example presented is deliberately kept minimal to data sorted into the common offset

domain (possible in the presence of a simple sub-surface geology), the dual-source example underwent a purpose-built shot isolation workflow that unwraps aliased parts of the spectrum outside the exactly isolated diamond-shaped regions in f - k space. Pedersen et al. (2017) investigate the suitability of such dealiasing-enabled signal apparition on a first field test data from the North Sea and find that the shot isolation yields 4D grade seismic data. Hence, the productivity benefits discussed are equally applicable for time-lapse seismic reservoir monitoring. The shot isolation within the non-aliased, diamond shaped region in the f - k domain is deterministic and represents a unique advantage over alternative source separation methods (Andersson et al., 2017). Since signal apparition enabled shot isolation allows us to acquire full-fold multi-source, this diamond shaped area can be enlarged so that it entirely covers the typical frequency interval for time-lapse analysis. Increased inline sampling will further benefit the shot isolation as the non-aliased, diamond-shaped region grows. This solution would not incur additional risk to overlapping shooting, but would further enhance productivity.

Conclusions

We have demonstrated on dual- and triple-source synthesized data that the method of signal apparition enables full-fold multi-source acquisition where sources can be towed close together to deliver full-fold data with minimal residuals after shot isolation. This advance promises a significant increase in marine and seabed acquisition productivity, including 4D, where in a shorter period of time more data can be acquired without compromising the subsurface bin size that leads to full-fold. The method can be generalized to even higher numbers of sources. Such full-fold multi-source acquisition allows for more versatile strategic planning where capital and operating expenditures can be optimized. In particular, this applies to marine seismic acquisition where the number of streamers towed can be reduced significantly while still maintaining the original crossline subsurface bin size and coverage. As a consequence, the need for vessel upgrades to tow wider spreads is reduced with freed up bollard pull and substantial in-sea equipment savings which is particularly appealing when operating in a market with limited streamer capacity available.

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