# Increasing Towed Streamer Survey Efficiency

The theme of value generation from different acquisition technologies in a climate of cost-saving pressure challenges for new marine exploration and 4D seismic acquisition is shaping the agenda at the EAGE 'Marine Acquisition Workshop' which will be hosted in Oslo on August 22-24, 2018. In this paper I will review the incremental improvements in survey efficiency that have taken place over the last couple of decades, and the step-change improvements that have recently emerged with the industry-wide use of both physical and virtual multi-source configurations.

## Introduction

The towed streamer papers that are being presented at this workshop represents the continued evolution of themes that have been emerging for over a decade: the adoption of multi-sensor streamers by all the major service companies, survey design efforts to improve the resolution of shallow data during exploration programs, and an increasing focus upon the use of smaller and often compact air gun arrays.

In one sense, the latter ambition has been forced upon the service companies courtesy of their increasing use of between three and six active sources to improve cross-line spatial sampling rather than traditional dual-source shooting. With only six sub-arrays of air guns available on most seismic vessels, this means that modern source 'arrays' are no longer comprised of three sub-arrays being simultaneously fired, and are more likely to be built from one or two sub-arrays. One negative consequence of using a higher number of source arrays is that the inline spatial sampling and fold is compromised by comparison to dual-source shooting unless a smaller relative shot interval is used, and this leads to a higher shot record overlap between consecutive shots, or the routine acquisition of 'blended' data. So unsurprisingly, acquisition and processing methods to facilitate more robust separation of blended data also feature prominently in the technical program.

The most notable extension of the drive towards smaller air gun sources whilst developing fundamentally new ways to deal with blended shooting is the use of continuous wavefields; both on the source and receiver side. ***eSeismic*** fires individual air guns in rapid succession with randomized timing increments and makes no effort to deblend the recorded data. Undoubtedly, a key issue investigated at the Oslo workshop will be the question of whether compact air gun arrays provide sufficient deep signal penetration. In the eSeismic case the energy is integrated from all the source events when reconstructing pre-stack gathers, so the final data is equivalent to data acquired with large arrays of air guns fired simultaneously. From an operational perspective, some freedom from having to fire on a fixed shot grid is created, thereby providing an opportunity to sail the vessel faster with greater survey efficiency—the key theme of this paper.

I consider a few fundamental concepts below when attempting to increase the survey efficiency of towed streamer operations. This discussion includes a few relevant considerations for the geometry of the survey designs used, how these may impact signal processing and imaging, and how various acquisition and processing-imaging solutions could benefit the pursuit of higher survey efficiency.

## The Default Vessel Configuration and the Acquisition of Blended Shot Records

Figure 1 provides a schematic illustration of a conventional 3D towed streamer vessel configuration. Using the nomenclature of a common midpoint (CMP) occurring mid-way between every possible source and receiver surface coordinate, several CMP sublines are defined for the vessel configuration where (number of sublines) = (number of sources) x (number of streamers), and the 'near offset' for each subline is the minimum distance between the respective source and streamer that contribute that that subline. Figure 1 illustrates an example relationship between streamer 1 and source 1 that has CMPs with different source-receiver offsets distributed along subline 1. Long (2017b) demonstrates that simple geometric relationships can be found between the streamer separation L, the number of streamers N, the number of sources S, an integer k than is zero for the conventional deployment of sources between the innermost two streamers (increasing values of k correspond to the outermost two sources in a dual-source or triple-source configuration being placed outside the innermost two streamers with increasingly large lateral separation), and the following parameters:

| | |
|---|---|
| **Source Separation** | (k+1/S)L |
| **Subline Separation** | L/2S |
| **Sail Line Separation** | 0.5(N+k)L |

Note these relationships extend to higher numbers of sources being used too, but I restrict the discussion here to dual-source and triple-source shooting. For the example in Figure 1 where the number of streamers N = 10, the number of sources S = 2, and k = 0, a streamer separation of L = 100 m would have nominal source separation of 50 m, subline separation of 25 m, and sail line separation of 500 m. An acquisition calculator at [https://www.pgs.com/marine-acquisition/tools-and-techniques/acquisition-solutions/calculator/acquisition-calculator/](https://www.pgs.com/marine-acquisition/tools-and-techniques/acquisition-solutions/calculator/acquisition-calculator/) can be used to examine the interplay between these fundamental survey parameters. Figure 2 shows schematic diagrams for dual-source and triple-source shooting geometry.

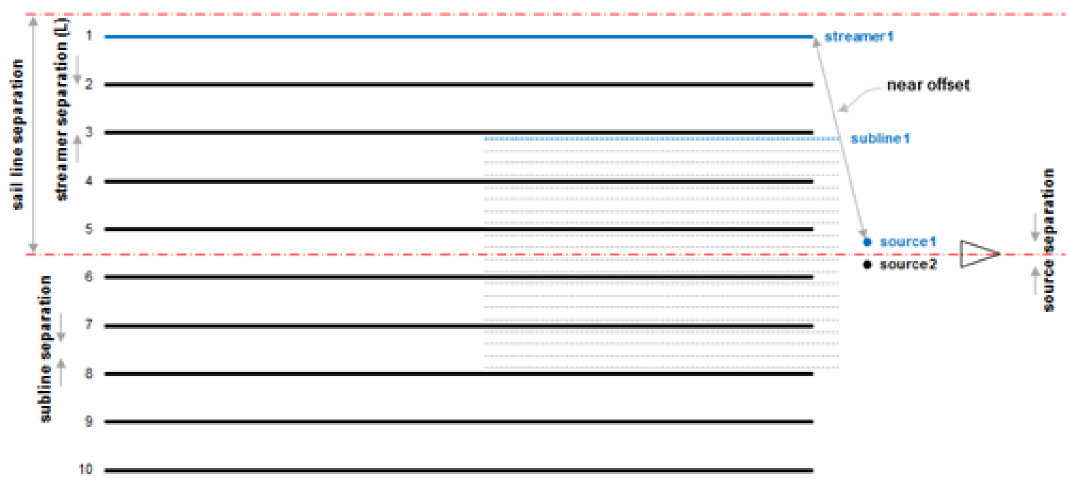


*Figure 1. Nominal towed streamer acquisition geometry for dual-source shooting with 10 streamers.*

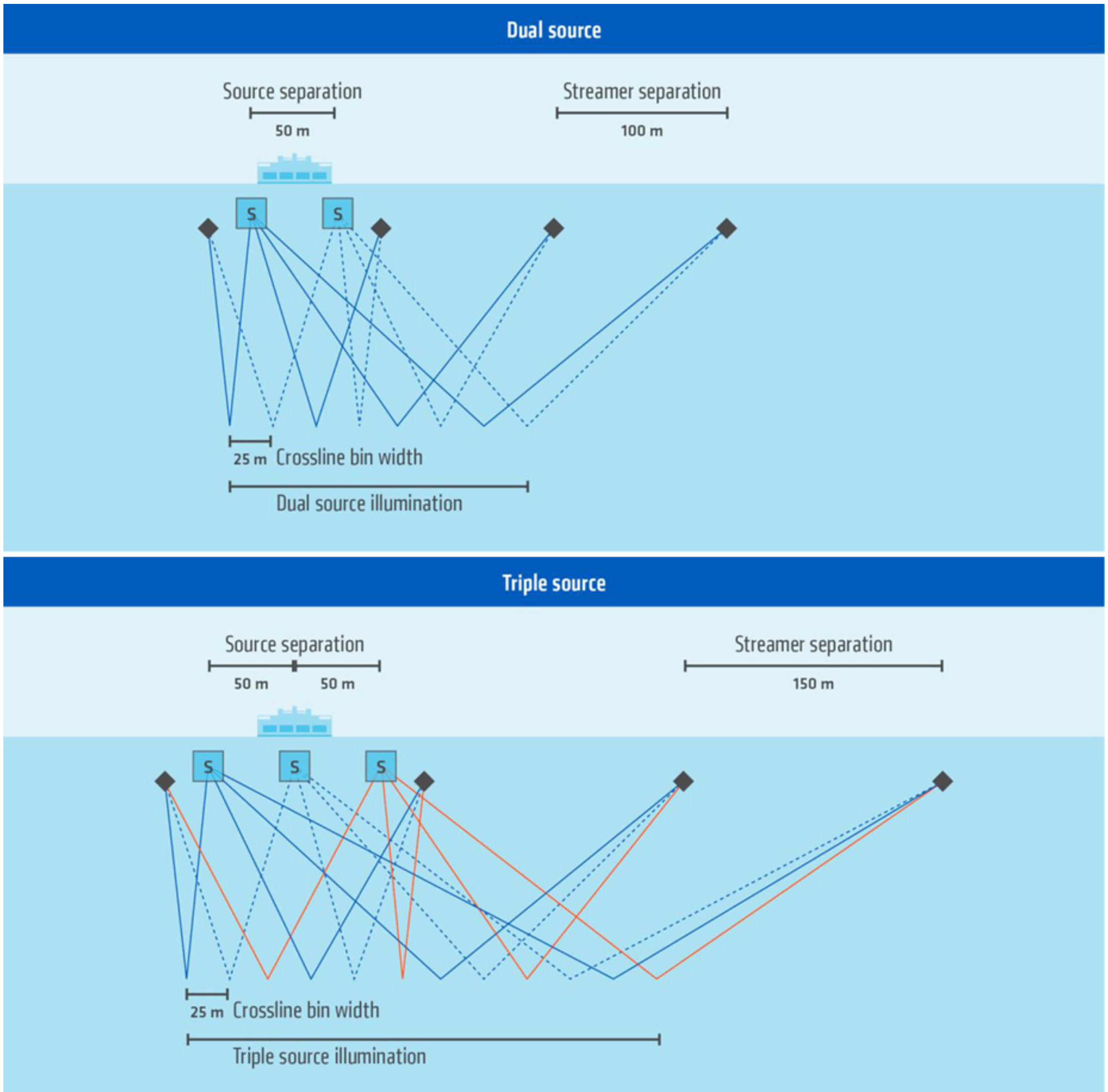


*Figure 2. Comparative cross-line schematic illustrations for dual-source (upper) and triple-source (lower) shooting being used to provide 25 m subline separation (CMP bin width).*

Conventional 3D towed streamer surveys acquire a series of semi-parallel sail lines until the entire survey area has been traversed, and the minimum CMP fold at all offsets at each subline location along each sail line meets pre-survey technical criterion.

It can be observed in Figure 1 that the near offset to most streamers is large. In practice, for nominally uniform geometry, every odd-numbered subline in Figure 1 will correspond to CMP traces for source 1, and every even-numbered subline will correspond to CMP traces for source 2. For dual-source shooting the sources are fired alternately so that the 'pop' interval between the same source being fired consecutively = S x the shot interval, i.e. twice the shot interval. Historically, the shooting template was designed to minimize interference between consecutive shots by using an appropriately large shot spacing (and thus time interval). However, decreased shot spacing (and receiver spacing) will translate to improved spatial resolution, so there is motivation to acquire shots more frequently. There is also motivation to record long records to image deep reflectors. If the record length exceeds the time interval between consecutive shots there will be overlapping shot gathers; commonly referred to nowadays as ‘blended’ or interfering shots, where the wavefields from consecutive shots are superimposed on each shot gather (refer to Figure 3). It follows that if the vessel speed increases but the spatial shot interval remains constant, the time interval between consecutive shots will decrease, and therefore the amount of shot overlap will increase. Similarly, if the time interval between consecutive shots is reduced, the amount of shot overlap will increase. A relevant example occurs when shooting changes from dual-source to triple-source: the spatial shot interval must decrease by one-third (e.g. from 18.75 m to 12.5 m) to preserve CMP fold and the frequency of pre-stack spatial sampling in the common offset, common receiver, and common midpoint domains. As a consequence, the degree of shot overlap observed in triple-source surveys is inevitably higher than when using dual-source shooting.

In order for each shot gather to be processed in a conventional manner the blended shots are deblended, and each shot gather contains only the wavefield energy from with the actuation of the source associated with that particular shot gather. Such processing efforts are generally acceptable as long as residual blended energy after deblending does not unacceptably contaminate image resolution and signal-to-noise ratio (SNR) at the target depths.

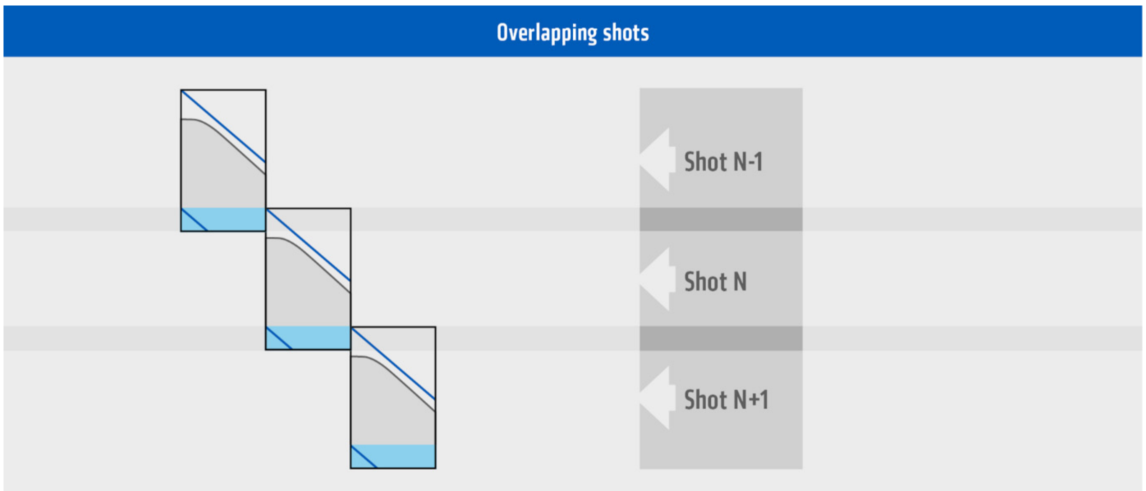


*Figure 3. Schematic illustration of overlapping consecutive shot gathers where the record length exceeds the time interval between consecutive shots. The early part of each shot gather overlaps and interferes with the later part of the preceding shot gather.*

As mentioned in my introduction, some 3D surveys now use as many as six sources (one sub-array per ‘source’), sometimes with air guns switched off that reduce the effective array length. A source array design which incorporates compact dimensions and proper tuning will minimize source directivity effects on high frequencies, as demonstrated by Ramsden et al. (2005) when used in partnership with the symmetric sampling criteria of Vermeer (1998). Of course, there is no smaller (or more environmentally-compliant) air gun source than firing one air gun at a time: the eSeismic principle discussed by Hegna et al. (2018) and Klüver et al. (2018). The potential benefits of eSeismic to survey efficiency are mentioned below, but this paper is otherwise limited to air guns being simultaneously fired as arrays.

## Options to Acquire Faster Surveys

The first-order way to improve ‘survey efficiency’ is simply to reduce the survey duration, as the overall cost is proportional to the number of days taken.

This can be achieved in three main ways:

**Use less sail lines, i.e. increase the nominal sail line separation**

- This has mainly been achieved over the past two decades by towing wider streamer spreads (more streamers and/or larger streamer separation: increasing N and/or L in Figure 1)
- More intelligent shooting plans where the sail line orientation is parallel to the longest axis of the survey, or is oriented to avoid obstructions such as platforms or shallow water, or is optimized to minimize the effects of variable currents upon streamer feathering, will all translate to less 'prime' sail lines and less 'infill' sail lines being required to compensate for unacceptable fold variations on some prime sail lines
- In recent years there has also been interest in increasing the lateral separation between the outermost sources (increasing k in Figure 1). This will in turn increase the nominal sail line separation, but as discussed briefly below, the cross-line fold for the sublines becomes non-uniform for each sail line

**Acquire each sail line with higher average vessel speed**

- As the hydrodynamic drag for laminar flow increases in proportion to the square of the water speed over an object being towed, it rapidly becomes inefficient in terms of required propulsion power and the associated fuel consumption to sail seismic vessels at speeds in excess of about 6 kn. Increased vessel speed with respect to the water translates to increased streamer drag-related tension and associated mechanical noise affecting each seismic sensor
- Increased vessel speed with respect to the water bottom translates to more frequent shooting and increased shot record overlap. As noted earlier, the contemporary practice is to pursue shot deblending during data processing—the success of which tends to vary between survey locations
- As noted, the eSeismic method makes no effort to pursue deblending, and potentially enables much higher vessel speed without impacting the recovery of stable pre-stack gathers in processing (Hegna et al., 2018; Klüver et al., 2018)

**Reduce the percentage of overall survey time taken for non-production downtime (excessive weather or sea state, technical problems, pre-survey technical specifications regarding acceptable noise thresholds, etc.)**

- Towing the streamers deeper, as is conventional practice for GeoStreamer, reduces the recorded noise associated with sea swell as this noise decreases exponentially with increasing streamer depth (Lesnes et al., 2014; Widmaier et al., 2015)
- Creative ways to relax the implementation of noise thresholds will reduce technical downtime. For example, the use of automated barnacle cleaning devices proactively remove barnacle growth affecting streamers before they increase streamer drag and the associated mechanical noise to unacceptable levels. Alternatively, accepting 'high' noise levels in the field in the anticipation that denoising can be successfully applied after the survey is completed may allow vessel speed to be increased or re-shoots of affected sail lines to be avoided. Similarly, the use of intelligent infill criteria based upon survey-specific data quality metrics will typically reduce the amount of unnecessary infill sail lines being acquired
- Environmental regulations increasingly dictate how seismic surveys must operate within limited seasonal windows, stay outside sensitive marine parks, or operate with various low power and shutdown procedures when in the vicinity of various cetaceans. Source concepts that reduce such restrictions would improve survey efficiency. Indeed, the peak sound pressure level (SPL) and the sound exposure level (SEL) for individual air guns being fired is less than for arrays of air guns being fired, and the eSeismic methodology may therefore be able to operate in sensitive areas, whereas conventional air gun operations cannot (even when using compact arrays).

In the next two sections I attempt a brief snapshot of how the efficiency of towed streamer surveys has evolved over the past decade in the context of these considerations; both in terms of incremental improvements and in terms of some interesting innovations that are interesting departures from how surveys have historically been acquired.

## A Decade of Incremental Improvements in Survey Efficiency

Led by the development of the Ramform vessel platform, the number of long streamers towed by one vessel has increased from 4 in the early-1990s to 18 in 2016, and the Titan-class Ramform vessels have up to 22 streamer capacity. Over that same time the maximum streamer spread width has increased to about 1.8 km at the front end and several hundred meters more at the back end when streamer fanning is used to minimize infill requirements. A few years ago the industry returned to the use of triple-source shooting, a platform first used by PGS in the early 1990s, as triple-source shooting enables streamer separation (L in Figure 1) to be increased by 50% without changing the subline separation, by comparison to dual-source shooting (refer also to Figure 2), and one-third less streamers can be towed without affecting the nominal sail line separation. Survey efficiency can therefore sometimes be less exposed due to technical downtime, although the inline shot spacing must also be decreased by one-third to preserve CMP fold and the frequency of pre-stack spatial sampling in the common offset, common receiver, and common midpoint domains. The degree of shot overlap is consequently increased, and shot deblending solutions are required during data processing. It is also noted that 3D receiver sampling is compromised in the common shot domain when changing from dual-source to triple-source shooting, and this is relevant to image resolution and SNR when applying wave-theoretic migration solutions such as reverse time migration, separated wavefield imaging (SWIM), and full wavefield migration (FWM). Both SWIM and FWM (implemented as a least-squares formulation) have emerged in recent years as powerful solutions to optimize seismic image resolution and illumination at all depths and under all geological scenarios (Lu et al., 2015; Lu et al., 2018; Martin et al., 2018).

The multi-sensor GeoStreamer platform launched the marine ‘broadband revolution’ in 2007 (Carlson et al., 2007; Day et al., 2013), providing access to the separated wavefields: the up-going pressure (P-UP) and the down-going pressure (P-DWN). By removing the receiver-side ghost effects introduced by P-DWN into conventional hydrophone-only streamer data, GeoStreamer is able to be towed deep without any geophysical compromise. P-UP data is the optimal platform for quantitative interpretation (QI) and time-lapse 3D (4D) reservoir monitoring (Widmaier et al., 2015; Long, 2017a). As noted earlier, reduced exposure to weather and environmental downtime, coupled with the flexibility of being able to tow streamer depth profiles that reduce drag (Widmaier et al., 2015) enables increased survey efficiency with GeoStreamer operations. All major service companies followed the development of multi-sensor streamer platforms in recent years.

Robust solutions to remove receiver-side ghost effects were quickly followed by a variety of PGS innovations to reduce or remove source-side ghost effects in operationally efficient ways, thereby providing completely ghost-free data. Cambois et al. (2009) describe how multi-level source (MLS) arrays can be configured by firing sub-arrays of air guns at different depths at strategically incremental time intervals (typically 2 or 4 milliseconds depending upon the depth separation between sub-arrays), moving the source-side ghost notch frequency to twice its typical value, and partially removing ghost effects at both the low and high frequencies. The nominal shot interval is unaffected, in contrast to early industry deployments of ‘over-under’ source arrays fired at two different depths as independent source events with twice the conventional shot interval (e.g. Egan et al., 2007). The ability to preserve shot interval meant there was no compromise in CMP fold or the frequency of pre-stack spatial sampling in the common offset, common receiver, and common midpoint domains. Parkes and Hegna (2011) subsequently described how the combination of simultaneous shooting with sub-arrays at different depths enables full source-side deghosting, again without compromising shot interval or survey efficiency. Most recently, Hegna et al. (2018) and Klüver et al. (2018) introduced a methodology using continuous source wavefields from the randomized firing of individual air guns (or alternative source concepts) coupled with the use of continuous receiver wavefields during signal processing to deliver data that is fully deghosted, free of all acquisition system effects, and that may be efficiently acquired with a variety of new survey design concepts.

Aside from the fundamental vessel, streamer and source platforms described above, the availability of full source and streamer steering solutions, coupled with streamer fanning and intelligent shooting templates have collectively contributed to significant decreases in the infill percentages being acquired, as well as provide the optimal platform for highly repeatable 4D survey acquisition (Long, 2018). Whereas infill exceeding 30% was common a decade ago, less than 5% is common today in areas with mild current variations.

## Recent Advances in Source Geometry Concepts and Improved Survey Efficiency

Continuous recording coupled with advances in shot deblending technology have also facilitated more efficient acquisition with blended sources. A particularly interesting example is the compressed seismic imaging (CSI) methodology published by Mosher et al. (2017) and Li et al. (2017). The strategic use of non-uniform streamer separation and non-uniform shooting interval, coupled with the sparse inversion principles of compressive sensing, enabled highly blended data acquired with nominally coarse 3D spatial sampling to be reconstructed during data processing with dense and uniform 3D spatial sampling. This survey method is operationally efficient from the perspective that the acquisition effort required to acquire the equivalent spatial sampling without data reconstruction would be prohibitively expensive. A notable challenge to towed streamer implementations of CSI is that the sources and receivers are physically coupled to the same vessel, limiting the flexibility in how they may be configured. In contrast, the sources and receivers are physically decoupled for both land 3D and ocean bottom seismic 3D surveys, and significant efficiency gains have been demonstrated using the CSI methodology (Mosher et al., 2017). Note that shot deblending is required as a component of the CSI methodology.

As noted earlier, placing both sources outside the innermost two streamers for dual-source shooting, or placing the outer two sources outside the innermost two streamers for triple-source shooting (using $k > 0$ in Figure 1), will increase the nominal sail line separation (i.e. survey efficiency increases) but at the cost of non-uniform subline fold in the cross-line direction (Long, 2017b). The upper panel in Figure 4 shows a 16 streamer configuration. The black lines on the left represent the sublines for the first sail line, and the blue lines on the right represent the sublines for the second sail line. In the lower panel of Figure 4 the number of sources has been increased by 50% ($S = 3$), the number of sublines has increased by 50%, the streamer separation has been increased by 50%, and as a consequence the subline separation is unchanged but the nominal sail line separation and therefore the 'sail line efficiency' has been increased by 50%. If the vessel is capable of towing a 50% wider streamer spread it follows that this sail line efficiency can be realized, otherwise the number of streamers can be reduced to yield an achievable spread width that nevertheless has roughly comparable sail line efficiency and lower streamer inventory usage.

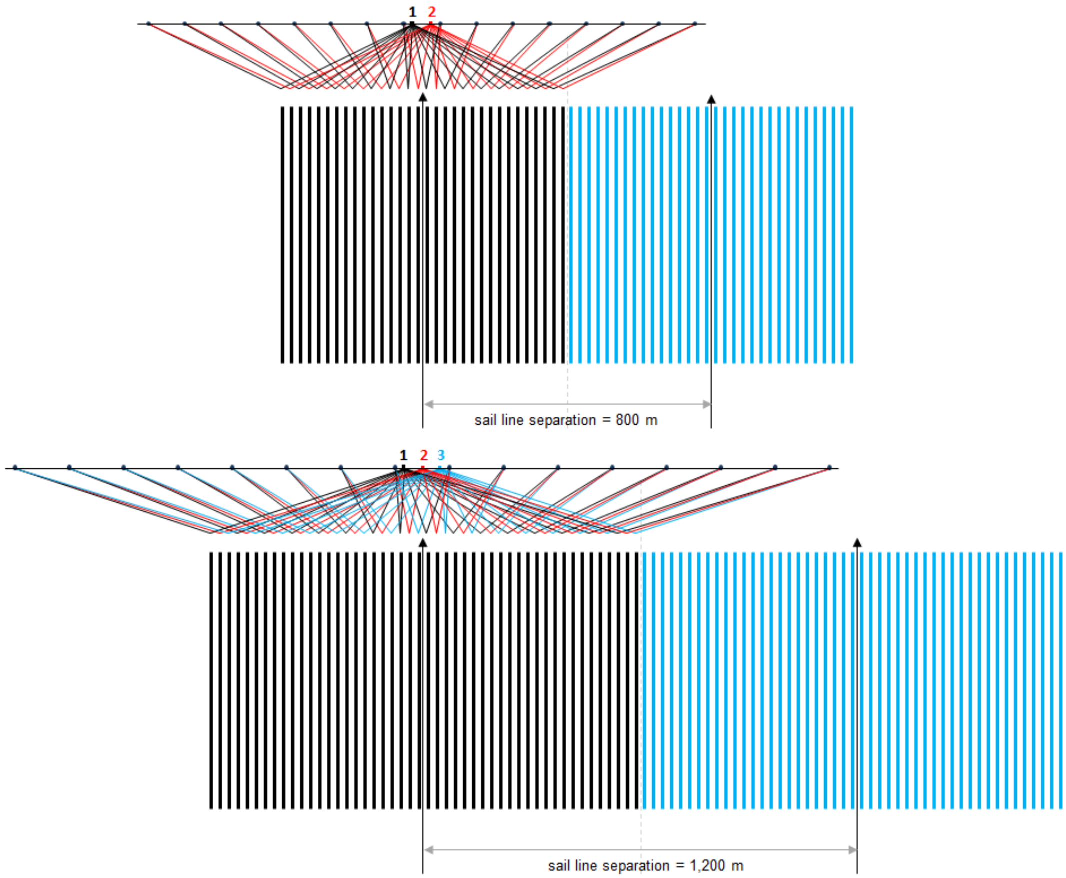


*Figure 4. (upper) Cross-line ray path schematic for a conventional dual-source towing configuration with 16 streamers and overhead perspective of the sublines for two adjacent sail lines; (lower) Equivalent plot for triple-source shooting and a 50% increase in streamer separation. Sail line 1 in both scenarios is represented by black sublines, and sail line 2 is represented by blue sublines.*

The upper panel of Figure 5 shows the same 16 streamer configuration where the source separation is now 1.5L, i.e. k = 1 and S = 2 (dual-source shooting with the sources placed outside the innermost two streamers). The subline separation remains L/4. Note, however, that the nominal number of sublines for each sail line increases from SN (in this case 32) to SN + Sk, i.e. 34, and the nominal sail line separation has correspondingly increased by 0.5kL. The number of nominal fold sublines remains unchanged, but Sk sublines have zero fold for each sail line (the red lines), assuming no streamer fanning is used and the shooting geometry is perfectly uniform. If this zero fold subline can be addressed by some form of regularization/reconstruction in processing, the nominal sail line separation can be increased from 0.5NL to 0.5(N + 1)L. In other words, for dual-source shooting, the nominal sail line separation increases by half of the increase in the source separation if the zero fold sublines can be accommodated in processing.

The lower panel of Figure 5 shows the same 16 streamer configuration where the source separation is now 2.5L, i.e. k = 2 and S = 2 (dual-source shooting with the sources placed outside the innermost two streamers), and again the subline separation remains L/4. Following the principles observed in the upper panel of Figure 4, the nominal number of sublines for each sail line increases to 36, the nominal sail line separation has increased by another 0.5L, and there are 2k (i.e. 4) zero fold sublines. This pattern will continue until the sources are placed outside the outermost two streamers in the spread such that k = N, the source separation is (N + 0.5)L, there are 4N sublines, half of which are zero fold (so the effective subline separation has doubled), and the nominal sail line separation is NL, i.e. sail line efficiency is twice that for conventional dual-source shooting with the sources towed between the innermost two streamers. These same principles also apply to triple-source shooting (S = 3) where the center source remains mid-way between the innermost two streamers but the outer two sources are increased in separation (Long, 2017b). In such scenarios there will be various pairs of adjacent zero fold sublines incurred as the outer source separation increases, and the increase in nominal sail line separation is half the increase in outer source separation. Table 1 summarizes the geometric relationships discussed here, assuming in all scenarios that the acquisition geometry is uniform and streamers are parallel with no feathering.

Overall, we see that sail line efficiency for dual-source and triple-source shooting varies between '1' (conventional configuration) and '2' (outer sources towed outside the outermost streamers); in other words, sail line efficiency can be doubled if the (outer) sources are moved outside the streamer spread. This has logistical challenges discussed later, and effectively doubles the subline separation. A solution to the compromised cross-line spatial sampling is to tow either dual-source arrays outside the streamer spread with L/2 separation in the case of S = 2 (four sources in total), or triple-source arrays outside the streamer spread with L/3 separation in the case of S = 3 (nine sources in total). Such considerations would inevitably involve significant shot blending due to the necessity for short shot intervals.

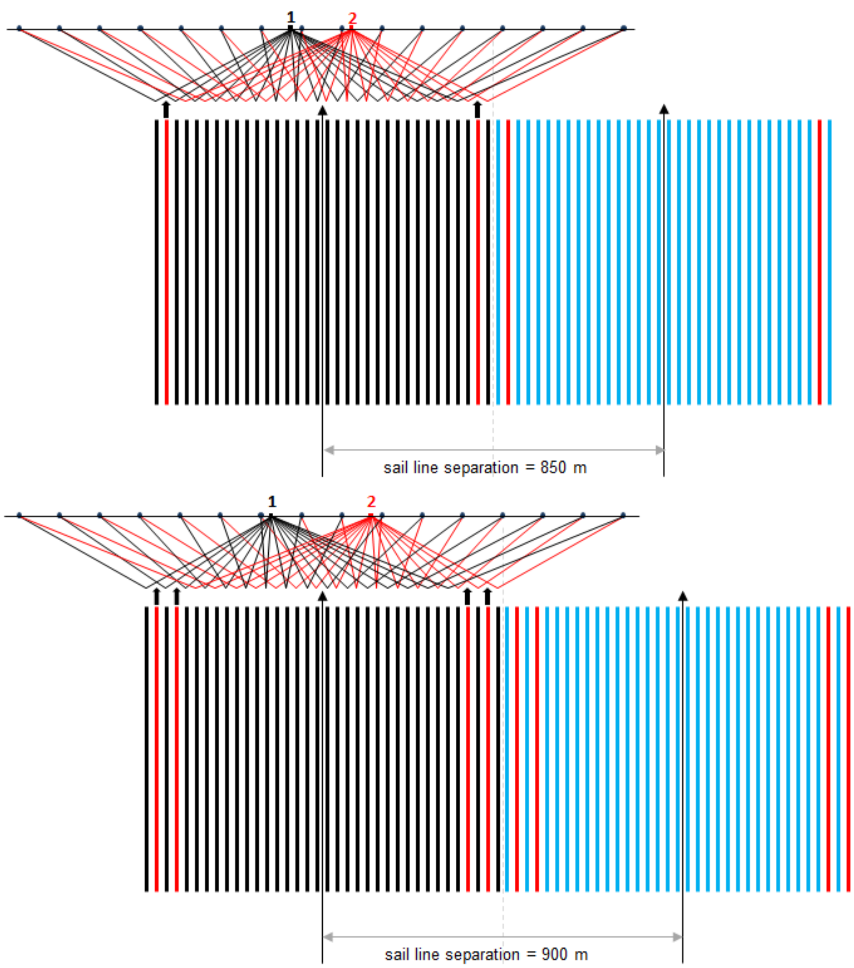


*Figure 5. (upper) Cross-line ray path schematic for a wide source towing with two sources (source separation = 1.5 x streamer separation) configuration with 16 streamers and overhead perspective of the sublines for two adjacent sail lines; (lower) Equivalent plot for source separation = 2.5 x streamer separation. Sail line 1 in both scenarios is represented by black sublines, sail line 2 is represented by blue sublines, and red represents zero fold sublines.*

| | |
|---|---|
| **Source Separation** | (k+ 1/S)L |
| **Subline Separation** | L/2S |
| **Sail Line Separation** | 0.5(N+k)L |
| **Total Number of Sublines per Sail Line** | S(N+k) |
| **Number of Zero Fold Sublines per Sail Line** | Sk |

*Table 1. Relationships between geometric parameters for towed streamer acquisition with two or more sources. L = streamer separation, N = number of streamers, S = number of sources, k is an integer. Refer also to Figure 1.*

Continuing the simplistic assumptions of no streamer fanning being used and that the shooting geometry is perfectly uniform, it can be shown that retaining the nominal sail line separation of k = 0 for each source separation scenario will yield nominally uniform CMP fold everywhere, but the sublines around each sail line boundary will alternately correspond to each sail line as illustrated in the upper and lower panels of Figure 6. In other words, the sublines overlap in a manner at each sail line boundary that 'cancels' the zero fold sublines. The upper panel of Figure 6 is the configuration in the upper panel of Figure 5 with nominal sail line separation reduced back to 0.5NL, and the lower panel of Figure 6 is the configuration in the lower panel of Figure 5 with nominal sail line separation reduced back to 0.5NL. Note that the source-receiver azimuth will vary in an alternating manner in this 'overlap' region as adjacent sublines correspond to source locations from different sail lines, and irregular streamer and sail line geometry will affect CMP fold uniformity too.

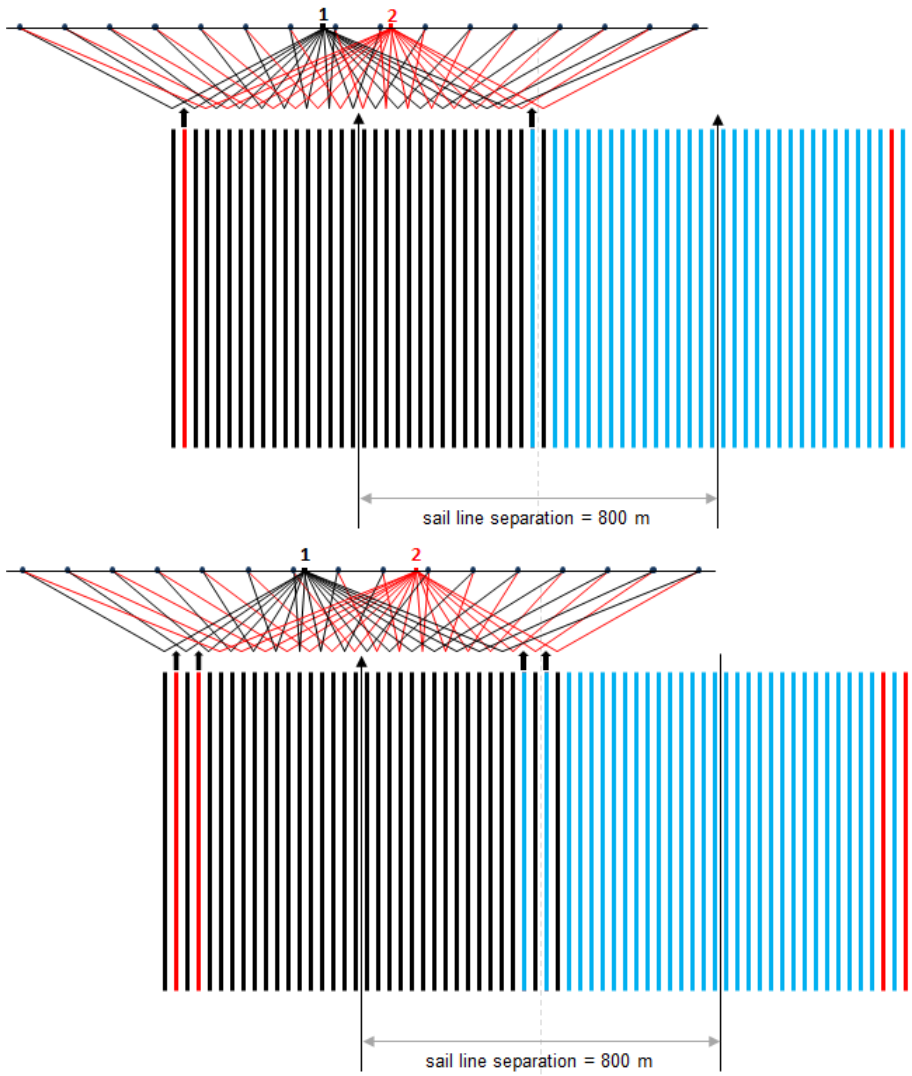


*Figure 6. (upper) Cross-line ray path schematic for a wide source towing with two sources (source separation = 1.5 x streamer separation) configuration with 16 streamers and overhead perspective of the sublines for two adjacent sail lines. Sail line separation is the same as for conventional dual-source shooting; (lower) Equivalent plot for source separation = 2.5 x streamer separation. Again, sail line separation is the same as for conventional dual-source shooting. Sail line 1 in both scenarios is represented by black sublines, sail line 2 is represented by blue sublines, and red represents zero fold sublines. Note in both scenarios that there are no longer zero fold sublines at each sail line boundary. Compare to the upper panel of Figure 4.*

So why 'undo the efficiency gain' by reducing sail line separation? The answer is that near offset coverage for each subline can be improved by comparison to the upper panel of Figure 4 whilst maintaining (relatively) uniform CMP fold on all sublines. Widmaier et al. (2017) demonstrate how a combination of wide-tow triple-source shooting, dense streamer separation, and the outer streamers pulled forward to be in line with the sources can significantly improve the uniformity of the near offset distribution for all sublines, and survey can be efficiently acquired with only one vessel (refer also to this). In practice, the use of streamer fanning and natural variations in streamer and sail line geometry will probably result in finite fold in each subline shown as having 'zero fold' in the schematic illustrations of Figures 5 and 6, but interpolation/reconstruction in processing would yield reasonably uniform CMP fold for all offsets and all sublines.

Overall, it is evident in this long section that an acceptance of non-uniform acquisition geometry is inevitable when considering the use of wider source towing, when pursuing applications of compressive sensing, or when using continuous wavefield methods. In every scenario discussed to this point, the sources and streamers are all physically coupled to the same vessel. As discussed in the next section, the use of ‘dispersed sources’ in acquisition or the use of ‘virtual sources’ in seismic imaging provide opportunities to introduce significant flexibility into how marine surveys are designed, and how further efficiency gains might be achieved.

## Dispersed Sources versus Virtual Sources

Multi-vessel configurations that use one or more dedicated source vessels are already established for wide-azimuth (WAZ) and rich-azimuth (RAZ) surveys. The design of such surveys has primarily focused upon achieving a large range of source-receiver azimuths for all offsets that is as uniform as possible throughout the survey area. Dual-coil and quad-coil shooting are examples where the overall survey offset-azimuth distribution is well populated but the distribution various considerably over a scale less than the diameter of each coil.

Sources may be deployed with greater flexibility if they are towed by vessels that are independent of the vessel towing the streamer spread, or not limited by the length and weight restrictions of traditional air gun umbilicals. The latter consideration alludes in particular to towed marine vibrators (MVs), which in principle require only a modest electrical power supply to operate. Independent source vessels are currently expensive because they must be large enough to contain large air compressors for air gun operations and a full crew. If compact and autonomous source vessels could be developed this would significantly reduce overall survey costs, as well as create opportunities for several such source vessels to be simultaneously deployed around or over the streamer spread. Small vessels imply either small air compressor capability and the use of compact air gun arrays, or again, the use of MVs. In either case, several sources operating simultaneously will inevitably record highly blended shot gathers.

Alternatively to physically dispersed sources, most likely to be only a few in number anyway, is the use of virtual sources through the application of separated wavefield imaging (SWIM). Access to the separated wavefields; P-UP and P-DWN, enables every receiver in a multi-sensor streamer spread to be used as a virtual source, extending the spatial imaging extent for each sail line from the subline distribution (half of the cross-line receiver extent) to the full streamer spread extent. An established benefit is that the cross-line acquisition footprint can be mitigated due to the overlap between the streamers of each adjacent sail line (e.g. Figure 7), and LS-FWM mitigates cross-talk noise and extends the benefits of SWIM (which exploits the illumination from multiples) to large depths, and with the complementary illumination of primary reflections and multiples (Lu et al., 2018).

Opportunities therefore exist to increase the nominal sail line separation without changing the source-streamer configuration from the ‘conventional’ setup, or as a minimum, avoid the acquisition of any infill lines.

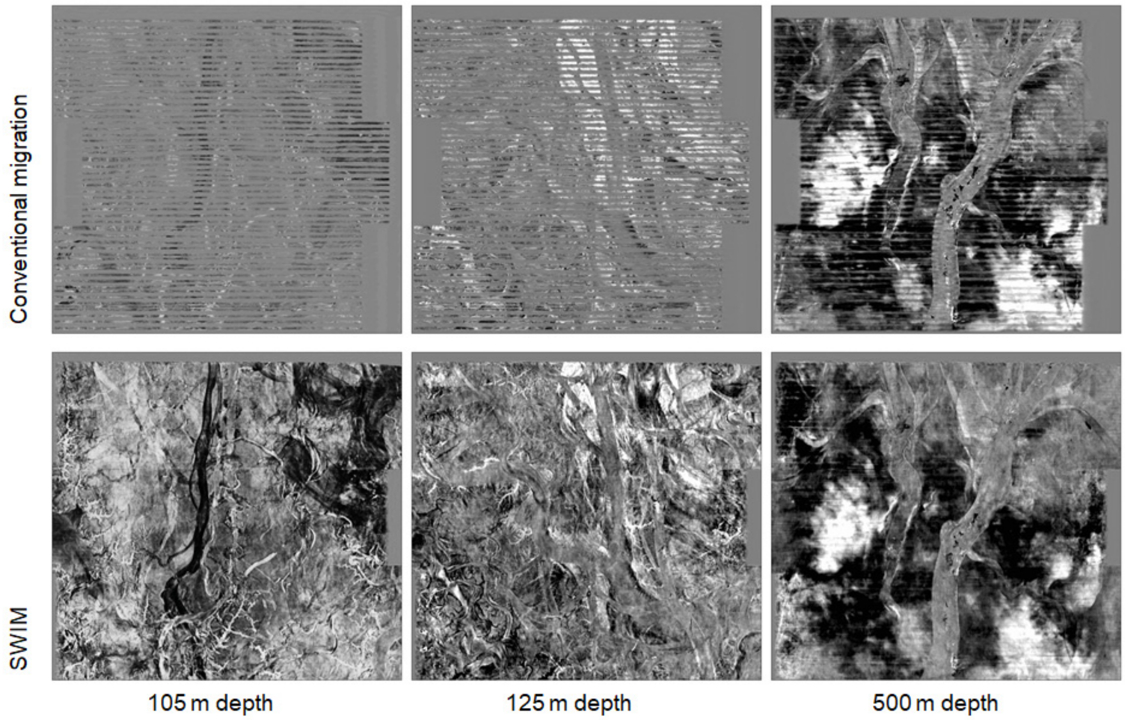


*Figure 7. Shallow depth slices comparing conventional migration (upper row) vs. SWIM (lower row) applied to multi-sensor GeoStreamer data.*

## Summary

As towed streamer survey designs move beyond uniform spreads of many streamers to more innovative designs used in the pursuit of higher survey efficiency it is inevitable that the associated CMP geometry will be non-uniform at various survey scales. Examples include adaptations of compressive sensing, wider towing of source arrays, or the pursuit of dispersed source arrays. Customized processing and imaging workflows and solutions will obviously be a necessary complement to each such survey design. The ambition to tow dispersed sources will be facilitated if source concepts can be developed that enable the use of compact sources—preferably not reliant upon large air compressors. It is also evident that the acquisition of highly blended shots is inevitable in the drive for greater survey efficiency, and solutions that can either deblend highly complex blended data or that can simply use such data without deblending (i.e. eSeismic), will be highly advantageous.

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