Source and streamer towing strategies for improved efficiency, spatial sampling and near offset coverage

Andrew Long[1*] presents a study of the fundamental relationships between cross-line source configurations and towed streamer survey efficiency and spatial sampling using a set of robust geometric relationships.

Introduction

Several towing concepts have arisen in recent years that break the convention of towing two source arrays between the innermost two streamers in a multi-streamer 3D configuration ('dual-source shooting'). Three 'arrays' of one or more sub-arrays were towed more than 20 years ago to improve cross-line spatial sampling, but inline spatial sampling and fold were compromised by inefficient recycling times on air gun compressors and limited recording lengths. Modern acquisition systems enable continuous recording, very short physical shot intervals, and up to six source arrays being deployed between the innermost two streamers; always with the ambition of improving cross-line spatial sampling.

I discuss two newer variations to these scenarios using either dual-source or triple-source shooting, although the principles may be expanded to more sources distributed in the cross-line direction: 1. Towing source arrays outside the innermost two streamers such that survey efficiency is improved courtesy of the nominal sail-line separation being increased. It is demonstrated that cross-line fold becomes irregular as source separation increases in the cross-line direction, so complementary processing methods may be required to reduce imaging artifacts. 2. Alternatively, if the sail-line separation is based on a conventional source towing scenario, some flexibility may be created in terms of near offset sampling.

Source separation and CMP bin width

Figure 1 shows a schematic source and streamer configuration with two sources and ten streamers. The nomenclature used defines the basic geometry wherein the source separation is based on the nominal streamer separation, and the streamer separation is divisible to a whole number by the subline separation.

For S sources (S = 2 or 3), a source separation that is an integer k multiple of the streamer separation L (i.e. kL) results in a nominal bin size equal to 1/S of the streamer separation, whereas towing each source array with a separation of (k + 1/S)L results in a nominal bin width equal to 1/2S of the streamer separation. For example, the improved cross-line spatial sampling of triple-source shooting enables 12 streamers at 150 m separation to have equivalent cross-line spatial sampling and sail line efficiency to 18 streamers at 100 m separation, but the inline shot spacing needs to be scaled by a factor of 2/S to retain comparable CMP fold and inline spatial sampling in pre-stack gathers. If the sources for both dual-source and triple-source shooting are between the innermost two streamers (k=0) the only cross-line difference between dual-source and triple-source shooting will be in terms of spatial sampling, and the nominal fold of each subline will be equal for all sublines in each sail line. When the sources for dual-source shooting or the outermost two sources for triple-source shooting are placed outside the innermost two streamers (k>0) the cross-line spatial sampling is unchanged, but the nominal subline fold becomes irregular. I

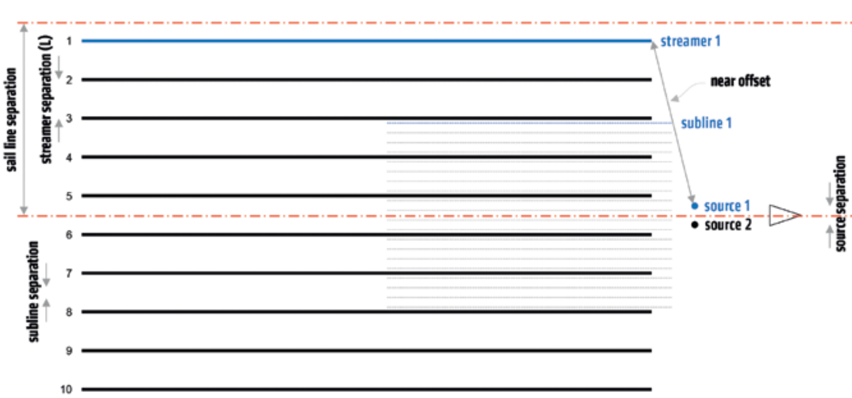

Figure 1 Schematic example for dual-source shooting. In the nomenclature used throughout this paper the number of sources, S, is 2 in this example, and the number of streamers, N, is 10. The near offset is shown for trace 1 of subline 1. Geometric relationships can be found between the subline separation, the sail line separation, and S, N, and the streamer separation, L.

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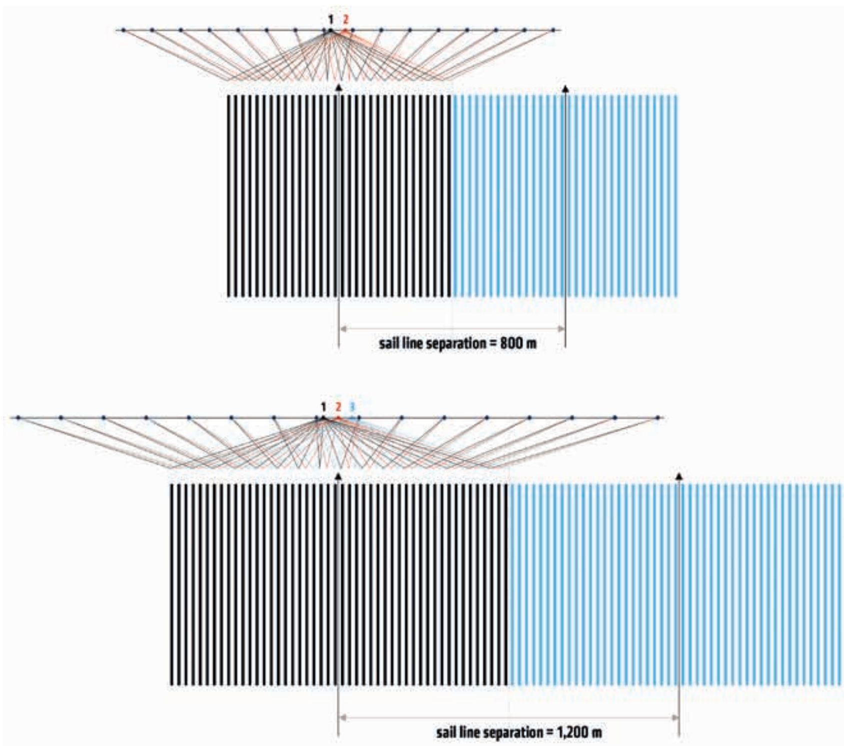

Figure 2 (upper) Cross-line ray path schematic for a conventional dual-source towing configuration with 16 streamers and overhead perspective of the sublines for two adjacent sail lines; (lower) Equivalent plot for triple-source shooting and a 50% increase in streamer separation. Sail line 1 in both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

illustrate how this can be predicted below, comment on how wider source towing can be used to improve sail line efficiency, and comment on how wider source towing can be used to improve near offset coverage for each subline.

Improved sail line efficiency

The upper panel in Figure 2 shows a 16 streamer configuration where the source separation is 0.5L, i.e. k=0 and S=2 (conventional dual-source shooting), and the subline separation is L/2S, i.e. L/4. The black lines on the left represent the sublines for the first sail line, the blue lines on the right represent the sublines for the second sail line, and the nominal sail line separation is 0.5(N+k)L, where N is the number of streamers. In the lower panel of Figure 2 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 a roughly comparable sail line efficiency and lower streamer inventory usage. The penalty is that the shot interval must be reduced by one-third to maintain equivalent CMP fold and equivalent trace separation in the common receiver, common offset, and common midpoint domains. Shorter shot intervals necessitate recording overlap, particularly when long records are desired. Separation of overlapping/blended shot gathers in signal processing inevitably have some cost to data fidelity, and residual shot energy from preceding shots can also create unwanted noise, particularly when the shot interval is short. Anecdotal estimates state that 18 seconds is required between consecutive shots to allow sufficient decay of shot energy (Martin Landrø, personal communication).

The upper panel of Figure 3 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), and the subline separation remains L/2S, i.e. 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 3 shows 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/2S, i.e. L/4. Following the principles observed in the upper panel of Figure 3, 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 centre source remains midway between the innermost two streamers but the outer two sources are increased in separation (e.g. Figure 4). 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.

Source separation	$\left(k+\frac{1}{S}\right)L$
Subline separation (bin width)	$\frac{L}{2S}$
Sail line separation	$0.5\left(N+k\right)L$
Total number of sublines per sail line	$S\left(N+k\right)$
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.

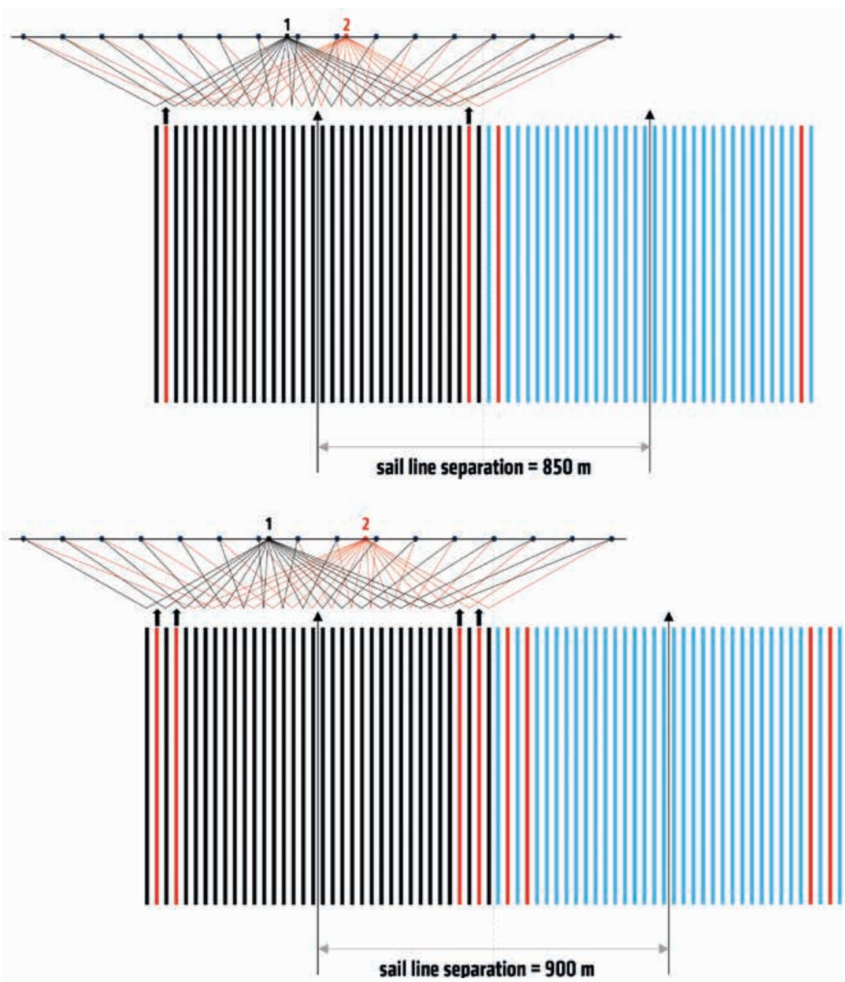

Figure 3 (upper) Cross-line ray path schematic for a wide source towing with two sources (source separation = 1.5 x streamer separation) configuration with 16 streamers and overhead perspective of the sublines for two adjacent sail lines; (lower) Equivalent plot for source separation = 2.5 x streamer 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.

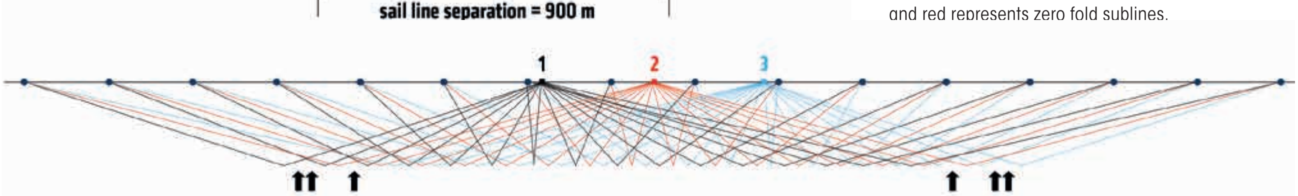

Figure 4 Cross-line ray path schematic for a wide source towing with three sources (source separation = 1.5 x streamer separation) configuration with 16 streamers. Note the larger fold gap at outer sublines by comparison to the upper panel of Figure 3.

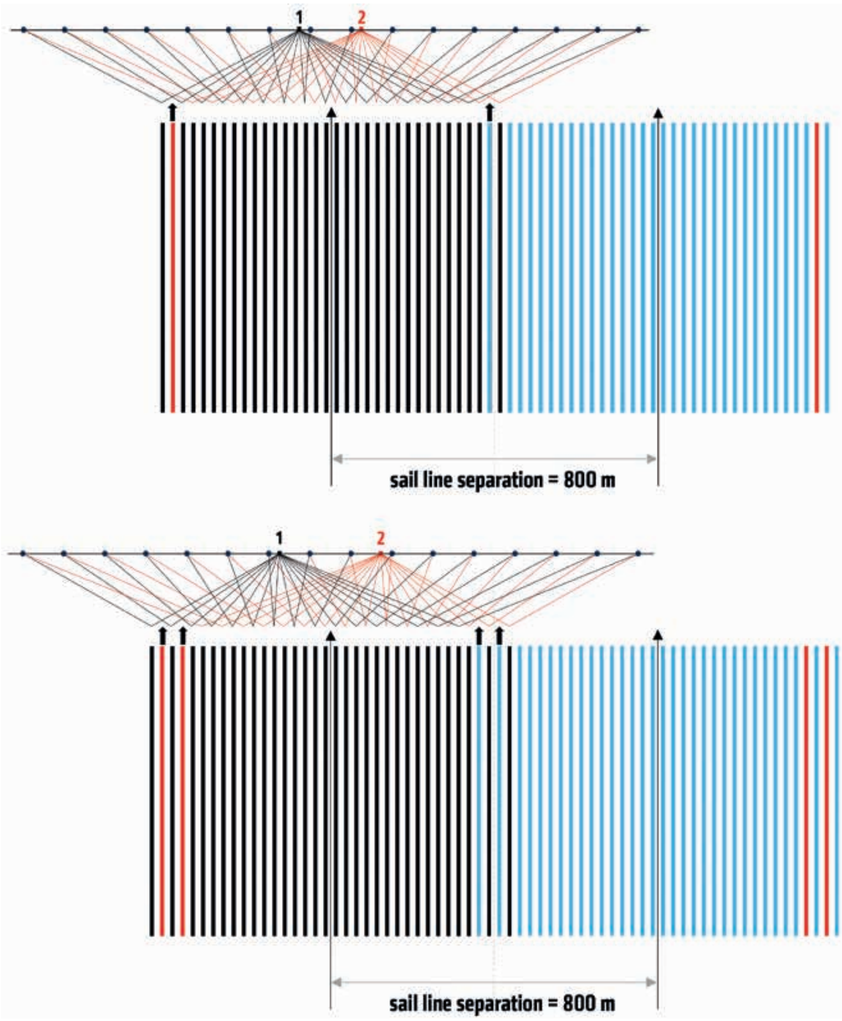

Figure 5 (upper) Cross-line ray path schematic for a wide source towing with two sources (source separation = 1.5 x streamer separation) configuration with 16 streamers and overhead perspective of the sublines for two adjacent sail lines. Sail line separation is the same as for conventional dual-source 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 2.

Mitigation of zero fold CMP sublines

Continuing the simplistic assumptions of no streamer fanning being used and that the shooting geometry is perfectly uniform, it is 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 5. 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 5 is the configuration in the upper panel of Figure 3 with nominal sail line separation reduced back to 0.5NL, and the lower panel of Figure 5 is the configuration in the lower panel of Figure 3 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.

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 2 while maintaining (relatively) uniform CMP fold on all sublines. This issue will be addressed within a future paper.

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 3 to 5, and interpolation/reconstruction in processing may yield uniform CMP fold for all offsets and all sublines.

Conclusions

I have illustrated the fundamental relationships between source configurations and towed streamer survey efficiency and spatial sampling for the 'conventional' scenario where all source arrays are towed between the innermost two streamers, and then for the scenarios of increasingly large source separations and sources being towed outside the innermost two streamers. 'Sail line efficiency' increases with increasing source separation if a predictable pattern of zero fold sublines centered around the sail line boundaries can be accommodated in signal processing and imaging. The number of zero fold sublines increases with increasing source separation. Alternatively, if the sail line separation is not adjusted, being based upon the nominal sail line separation for 'conventional' source towing, the zero fold sublines are mitigated by the finite fold contributions from the sublines of the adjacent sail lines in an interleaved manner. Sail line efficiency is therefore not changed, but the near offset distribution will be changed for each subline.

Acknowledgements

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