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Hunting High and Low in Marine Seismic Acquisition; Combining Wide-Tow Top Sources with Front Sources

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Summary

Placing marine sources on the top of the seismic streamer spread improves resolution and reservoir inversion in shallow and intermediate depth targets. This is due to the abundance of near offset data and high illumination compared to conventional marine seismic. A drawback of this top source solution is the lack of long offsets, which are important for deeper imaging and AVO. In this paper, we present a combined solution with sources on both the top and in the front of the spread. We deploy the front sources from the streamer vessel, while a separate dedicated source vessel is towing the widely separated top sources on top of the spread. With successful deblending of the different sources, this solution could give an operationally efficient solution to the seismic imaging and inversion problem, for both shallow and deep targets, and providing both high and low frequencies. We will present the acquisition concept and describe the deblending strategy, to address the common challenge to any multiple-source blended acquisition.

Introduction

Marine seismic acquisition with a source vessel operating over a streamer spread is illustrated in Figure 1 and was first introduced by Vinje et al. in 2017. Lundin Norway initiated the development and testing of the method designed to solve the imaging problems over the particular geological setting in the Loppa High Barents Sea with shallow targets within high-velocity Permian carbonates.

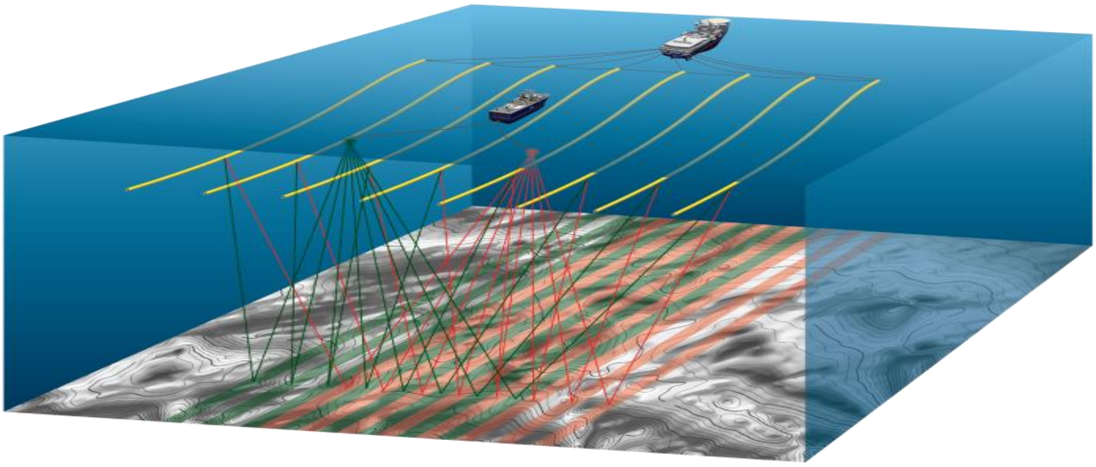

Figure 1: *Conceptual drawing of a source vessel operating over the streamer spread acquisition*

The solution involves two seismic vessels, a streamer vessel and a pure source vessel. The source vessel is located in the middle of the deep-towed spread with sources wide apart. This gives a split-spread seismic data set rich in near offset traces. These near-offset traces are recorded in the deep and quiet part of the cable, far away from the noisy front part of the cable and the swell noise from the water surface. This benefits the imaging and inversion, especially in the shallow part of the subsurface. This was clearly demonstrated in the full-scale top source acquisition over 2000 km^2 over Alta-Gotha in the Barents Sea in 2017 (Dhelie et al., 2018a) where a top source solution provided an excellent uplift with significantly higher resolution and better bandwidth than the previous vintage data. In this acquisition, three top sources were deployed with a 133 m crossline separation, which was the maximum achievable separation at that time. Later, up to six sources were tested (Dhelie et al., 2018b) and more recently, a much wider source tow was deployed for a small North Sea survey.
However, by putting the sources on the top of the spread, the maximum offset in the acquisition is reduced to half the value of a conventional marine seismic acquisition. For deeper targets, this will limit the reflection angle, which will affect the image quality, AVO and velocity estimation.

Shooting on the top and in the front

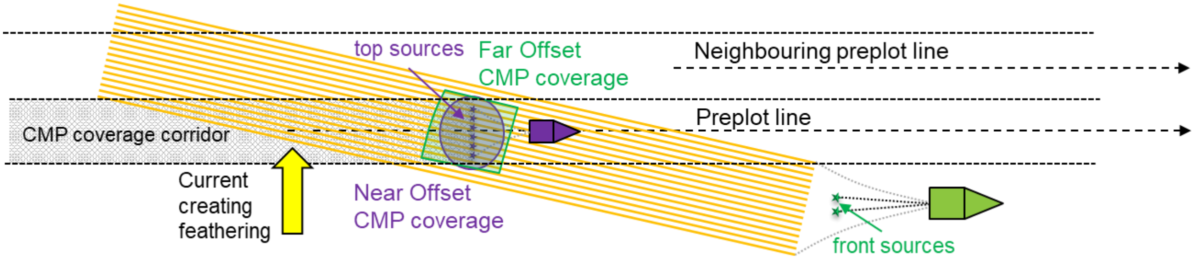

Figure 2: *Setup and steering strategy for the proposed solution with preplot coverage for near and far offsets.*

To mitigate the lack of far offsets in a pure top source solution, we propose a combined solution, with sources located both on top of, and in front of the spread. This solution still only involves two vessels, one pure source vessel, and one combined source/streamer vessel as shown in Figure 2.
The top sources are designed to take care of the shallow imaging while the front sources from the streamer/source vessel will provide the intermediate and long offsets to benefit deep imaging and full waveform inversion (FWI) as in a conventional marine seismic acquisition. As shown in Figure 2, the top sources will be shot along the pre-plot lines, while the streamer vessel will steer to keep the streamers directly underneath the top sources. This solution gives good CMP coverage for both near and far offsets even in the case of severe feathering as show in Figure 2, which is not the case for a conventional solution.

In Figure 2, the purple ellipse around the top sources represents their near-offset CMP coverage while the green rectangle is the CMP coverage of the farthest offsets of the front sources. Both of these will track the pre-plot CMP corridor around the preplot line. Figure 2 also illustrates that the number of top sources typically is large (from three to up to six) in order to maximise the shot sampling in the crossline direction of the survey. An optimally spread top source setup will create a uniformly sampled shot carpet over the survey area as shown in Figure 3 which is a benefit for processing and imaging. This uniform source configuration is typical for Ocean Bottom surveys but unique for a towed marine survey.
With a configuration as in Figure 3 where six sources are deployed from the source vessel with a separation between the outermost sources of more than 300 m, we are also able to achieve a sail line separation (and thus productivity) matching a conventional marine solution.

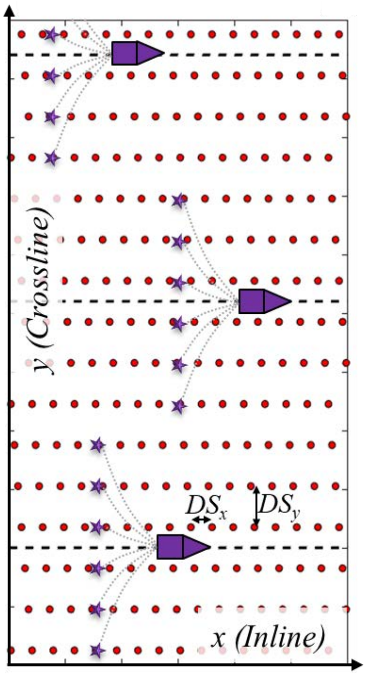

Figure 3: *The red circles are shot locations forming a uniform carpet of shot points over the survey*

The front sources are designed for deeper imaging, which require larger gun volumes, but can tolerate sparser shot sampling. Therefore the number of front sources is smaller (e.g. *NS*=2), and they do not have to be spread out. Table 1 shows a comparison of a conventional setup and the combined top source / front source configuration with identical number of streamers, streamer separation and sail line separation. In Figure 4 we compare the distribution of traces in the offset and y position of the CMP for the conventional on the left and top + front shot to the right. Here we use signed offset;

$$offset = sign(x_{off})\sqrt{x_{off}^2 + y_{off}^2}\ ,$$

where $\langle x_{off}, y_{off} \rangle$ is the offset vector from source to receiver.
As shown in Figure 4 the conventional solution is lacking near-offset traces, especially in-between the sail lines where the smallest offset is around 400 m, which is the distance from the shot to the first receivers in the outermost streamer. In the proposed solution, the regular distribution of top sources (red stars) ensures much better coverage of near offsets (black dots) while the traces of the two front sources, indicated by the red dots, is similar to what we see in a conventional acquisition.

	Conventional	**Top shots + front shots**
# streamers @ separation	14 @ 60m	14 @ 60m
Sail line separation	420 m	420 m
# front sources and separation	2 @ 30 m	2 @ 30 m
Front source Inline shot point interval	37.5 m	44 m
# top sources / separation	-	6 @ 70 m (350 m spread)
Top Source Inline shot point interval	-	37.5 m
Streamer length	6000 m	6000 m

Table 1: *Comparing typical acquisition parameters of a conventional and a top source + front source used in Figure 4 and Figure 5 below.*

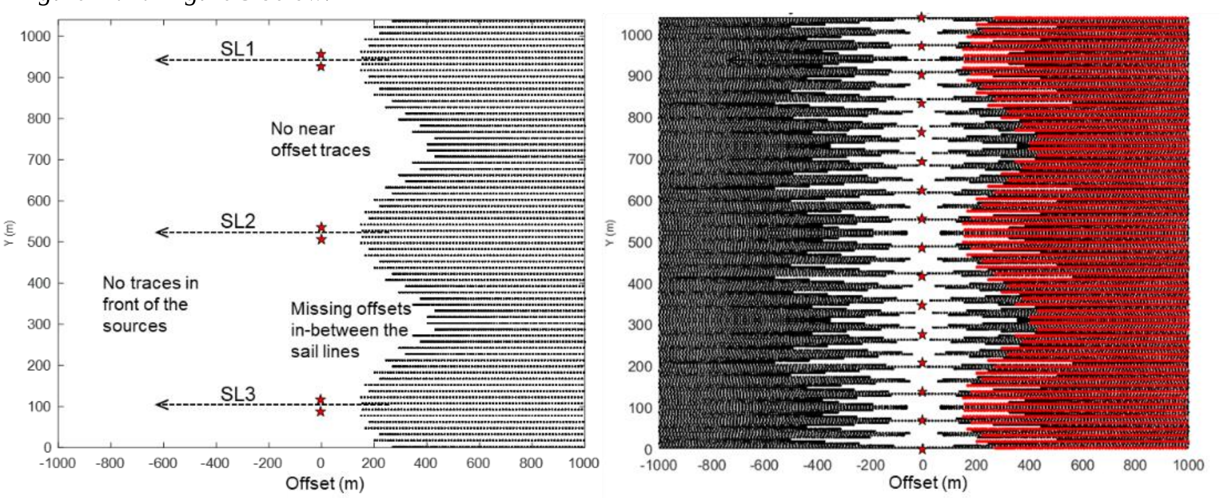

Figure 4: *Trace distribution in Offset/CMP-y domain for conventional (left) and the new top + front shot solution (right) with the survey parameters as given in Table 1.*

For the example in Figure 4 there are almost 8 times as many traces within a 1000 m max offset in the new solution compared to the conventional solution. The new solution gives a better near-offset coverage and generally a much higher trace density (number of traces per unit area), which is a great advantage for imaging shallow targets.

So what about deeper targets? As mentioned above, the top source data will "run out of offsets" before the front sources since they are located in the middle of the spread. However, with the new solution, we will be able to maintain the trace density also for far offsets by the help of the front sources, as shown in Figure 5. Here we have used the survey parameters in Table 1 and show the ratio between the trace density of the new solution versus the conventional solution. We see that up to an offset of 3000 m (half the streamer length), there are about seven times as many traces per unit area in the new solution than in the conventional one. Above 3000 m, the ratio is 0.85, as the front sources are sparser (22 m shot point interval) than the sources in the conventional case (18.75 m shot point interval).

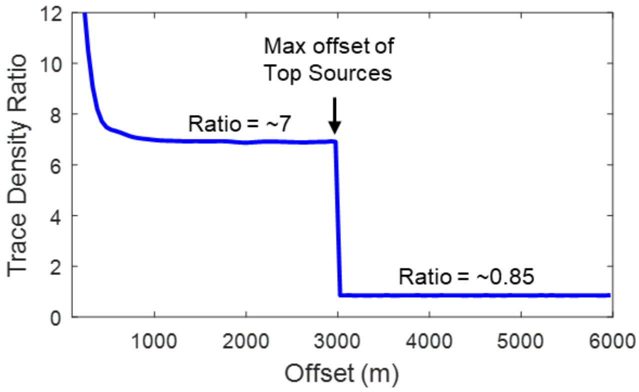

Figure 5: *Trace density ratio between the new and the conventional solution for a range of offsets.*

Deblending

With multiple sources firing sequentially, it is inevitable that we have to reduce the listening time interval in order to maintain an adequate minimum inline shot sampling for imaging (i.e. shot spacing in x direction).
In other words, the firing time between consecutive top shots will be short and given by the formula

$$DT = \frac{DS_x}{NS \cdot V} \ ,$$

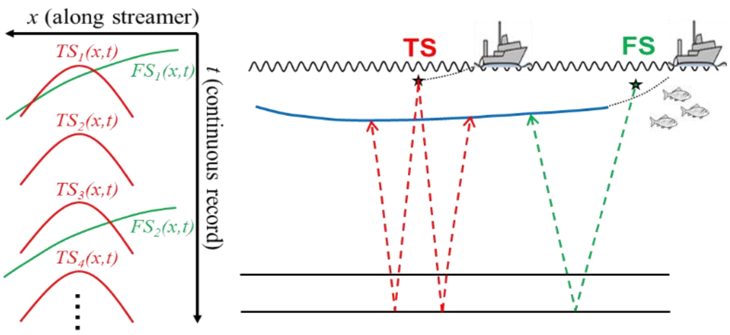

Figure 6: *Top sources in red and front sources in green in a continuous shot gather*

where *NS* is number of top sources, DS_x is inline shot separation and *V* is the source vessel speed. For a top source setup with *NS*=6, DS_x=37.5 m, and a typical vessel speed of *V*=2.3 m/s, we will have *DT*=2.7 s. Due to limitations in the compressor capacity and source inventory of the source vessels, this will lead to a relatively small source volume, typically around ~1000 cu.in . In a Barents Sea field trial, the result showed such a source volume is adequate enough to image down to 3sec of data (Dhelie et.al. 2018b).

However, there is a challenge that a shot gather will contain a blend of interfering energy from both top sources and front sources as shown schematically in Figure 6. The goal is to deblend the continuous record to end up with individual clean shot gathers. Depending on the signal to noise ratio, deblending may not recover all the signals perfectly. Therefore, it is important to design an optimal blending strategy so that we ensure that the signal at target level is recovered. We have tested various blending scenarios in the Barents Sea and the North Sea. One of these examples from the Barents Sea is shown in Figure 7 where the two left images show continuous recording along a central streamer before and after deblending of front sources from the top sources, and CMP stacks before and after deblending of the top sources on the two right plots. In this example, triple-source is used both in the front, and at the top.

We split the deblending into two parts:

(i) **Deblending the front source data from the top source data.** The current way of doing this is by a workflow initially designed for seismic interference attenuation as described by Zhang and Wang (2015), in combination with additional random noise attenuation. In order to randomize the interference between top sources and front sources, we design the survey to make sure that the ratio of the shot point intervals of the front and top sources is not an integer value. For the surveys in Table 1, this ratio is 22/6.25 = 3.52 which is far from an integer. In addition, we add a pre-defined optimized dither of ±200-300 ms to each TS shot and ± 800ms for the FS.

(ii) **Deblending the individual shots in the top source data (TS_1, TS_2, etc. in Figure 6 above).** A hybrid approach has proven most effective so far. We first subtract a model of the direct arrival followed by a shallow event-picking step in tau-p domain. Finally, we employ an inversion algorithm combining 2D sparse tau-p transform and 2D HARCWT transform (Peng and Meng, 2016). We obtain event preservation by an adaptive subtraction in the complex wavelet domain.

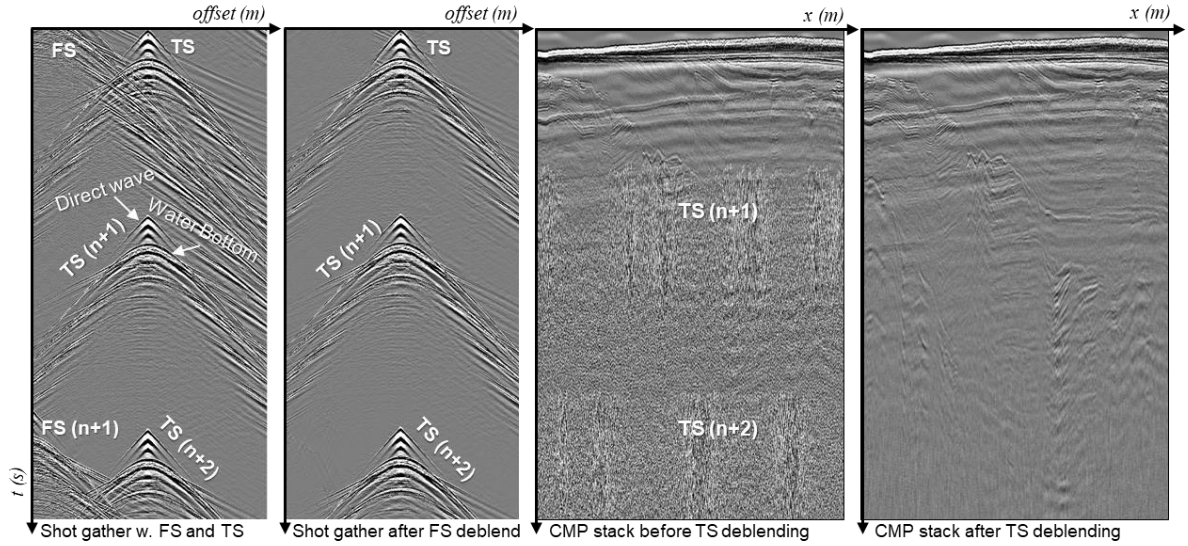

Figure 7: *Real data example from a 2017 Barents Sea test showing some stages in the deblending process with deblending part (i) (FS from TS) shown in the two left plots and part (ii) (TS from TS) to the right. The NMO stack to the right shows that most of the blending noise has been removed.*

Conclusions

We present a new marine acquisition solution combining widely separated sources deployed on the top of the seismic spread with sources in the front of the spread. The sources on the top of the spread are aiming to provide high resolution imaging of the shallow section and the sources in the front of the spread are for deeper imaging and full waveform inversion. The shallow section can also be used as site survey data. To mitigate the blending risk at deeper section, it is important to design the acquisition parameters based on the project priorities and the capability of the latest deblending technology. An effective deblending is required, which will split the data into the front shots and the top shots, which is processed jointly to produce high-quality images from the water bottom to the deeper targets. We expect the solution continue to evolve, as deblending is still an active research topic in the academia and the industry.

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