Maximizing quality and efficiency with wide-tow multi-source configurations

Martin Widmaier[1*], Carine Roalkvam[1], Julien Oukili[1] and Rune Tønnessen[1] present latest achievements in multi-sensor streamer acquisition with wide-tow sources and how these have optimized high-resolution imaging of the shallow subsurface.

Introduction

The need for cost-effective high-quality marine streamer seismic data has grown steadily over the last few years. The focus on near-field exploration and exploration in prolific basins very often requires improving or upgrading the seismic data existing in the area. Better spatial sampling, higher trace density, improved near offset coverage but also longer offsets and richer azimuth coverage are the typical design criteria for new seismic surveys over legacy seismic data. In addition, the emerging new energy markets express their demand for affordable fit-for-purpose 3D seismic data. Seismic applications are accurate imaging and characterization of the subsurface from a shallow seabed down to the reservoir level in carbon capture and storage (CCS), or regional mapping of the geology close to the seafloor for offshore mineral exploration. In most cases, near offset and spatial sampling requirements are the key cost drivers.

While seismic acquisition with large high-density streamer spreads has been common practice in high-resolution seismic exploration and 4D monitoring for many years, the potential of using wide-tow multi-source spreads has only been exploited recently (Widmaier et al., 2020). Wide-tow multi-source configurations provide denser crossline sampling and better coverage of the near offsets compared to standard seismic vessel configurations with source array set-ups in front of the central streamers. The combination of high-density streamer spreads with wide-tow multi-sources overcomes the traditional 3D seismic challenge of imaging the near surface in shallow or moderate water depths. The ultimate objective is to provide quality uplifts without compromising acquisition turnaround. In this article, we explain how the wide-tow multi-source concept was successfully applied during a 3D seismic survey in the western part of the Norwegian Barents Sea in 2020.

The wide-tow source concept

New strategies for high-resolution acquisition and imaging of shallow targets were introduced by Long (2017) and Widmaier et al. (2017). One of the key technical elements was the introduction of wide-tow sources, i.e., the distribution of multi-sources along the front of a streamer spread. The concept was launched as an alternative to the marine survey design method commonly used to improve near-offset coverage, i.e., the reduction of the streamer spread width to minimize the distance between the sources in the centre and the outermost streamers. Reducing the streamer spread width also means reducing the sail line separation, and consequently, lower survey efficiency and higher cost.

Widmaier et al. (2020) presented a series of case studies that illustrated how wide-tow sources enable higher streamer counts, and thus higher survey efficiency, without comprising the near offset coverage. Furthermore, the distribution of the nearest offsets can be significantly improved by spreading out the sources without sacrificing acquisition turnaround. Naturally, imaging workflows and seismic products benefit from modern data with rich near-offset coverage.

Wide-tow multi-source surveys in the Barents Sea 2020

The experience with wide-tow source surveys so far has mainly been based on triple source set-ups with an increased separation between the source arrays. Wide-tow triple sources were key survey design elements of innovative multi-azimuth programmes in the Viking Graben Offshore Norway in 2019 and 2020. Oukili et al. (2020) showed how the acquisition of rich near-offset data led to more accurate imaging of quaternary channels, gas-filled sand mounds and minor scours or plough-marks in the shallow part of the subsurface.

Building on the operational experience and the imaging success from the first wide-tow triple source projects, the natural next step was to increase the number of source arrays and the total source spread width. After the completion of a large multi-client 3D programme in the Barents Sea last year, additional sequences were acquired after a reconfiguration from a wide-tow triple source to an ultra-wide penta source set-up (Figure 1). The streamer spread and the corresponding nominal sail line separation of 450 m were kept constant in the main programme and the ultra-wide penta source extension project.

The spread consisted of 16 multi-sensor streamers of 7 km length towed with 56.25 m nominal separation, including three 10km-long streamer tails (Figure 2). This high-density streamer configuration with variable streamer lengths had already been successfully applied in the Barents Sea during 2018. The novel

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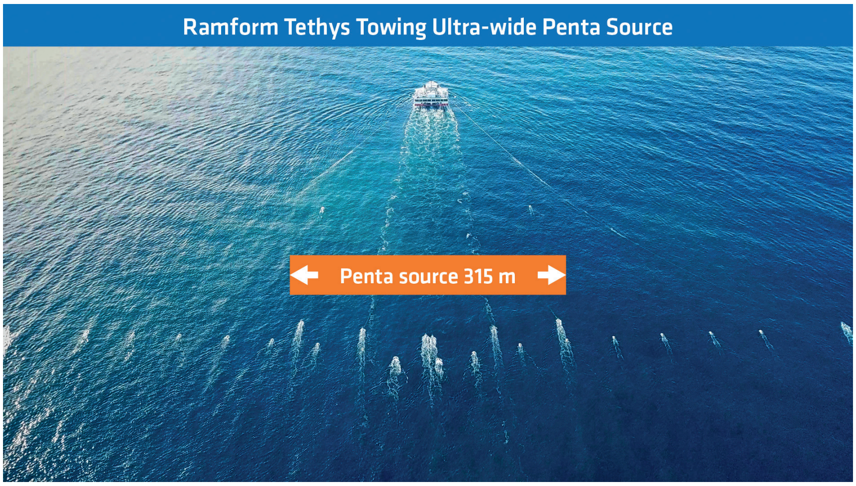

Figure 1 Drone photo showing Ramform Tethys during a seismic programme in the Barents Sea in 2020. The seismic vessel is towing an ultra-wide penta source with 78.75 m source separation and 315 m total source spread width. The source separation is larger than the streamer separation (56.25 m).

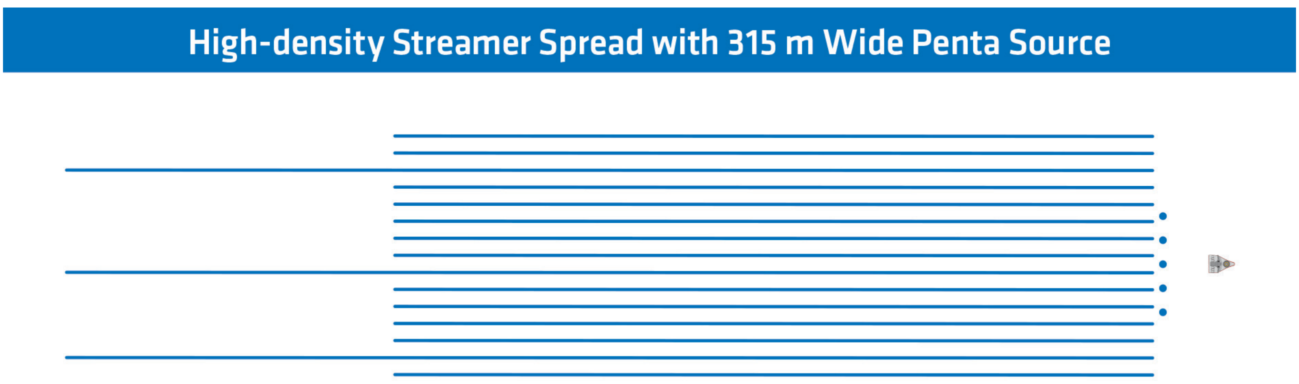

Figure 2 Schematic illustration of the vessel configuration with the 16 x 56.25 m x 7000 m deep-tow multi-sensor streamer spread. The set-up comprised 3 long streamer tails (10 km length) for refraction FWI velocity model building. The ultra-wide penta source was positioned in front of the streamer spread with an inline distance of ca. 65 m.

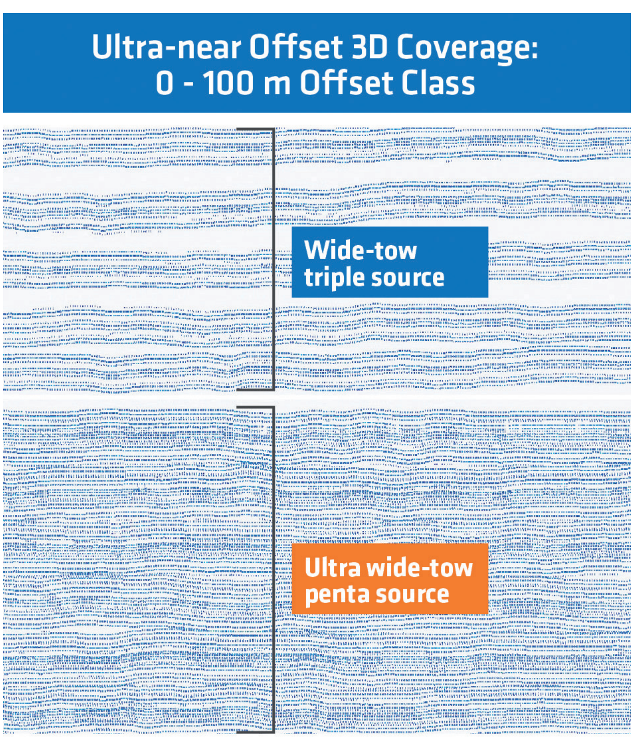

Figure 3 Near offset coverage map for the 0-100 m offset class as calculated from the navigation data. While the wide-tow triple source already provided good ultra-near offset coverage (top), the penta source solution delivered almost uniform near-offset sampling without the typical gaps at the sail line boundaries (bottom).

design delivered optimal wavefield sampling both for high resolution imaging and for refraction full waveform inversion (FWI) velocity model building (Naumann et al., 2019).

The separation between adjacent source arrays in the wide-tow triple source set up was 93.75 m, resulting in a total source spread width of 187.5 m. The nominal acquisition grid was 6.25 m x 9.375 m. The inline offset between the sources and the streamer front-end was as short as 65 m. In the ultra-wide penta source case (Figure 1), the separation between adjacent source arrays was 78.75 m, resulting in a total source spread width of 315 m. The corresponding acquisition bin size was 6.25 m x 5.625 m. This unique crossline bin size of 5.625 m was simply the result of not adjusting the streamer separation when changing from triple to penta source. A symmetric 6.25 m x 6.25 m grid size was used in processing. An overview of the streamer and source-related survey parameters before and after configuration is provided in Table 1.

Both wide-tow source solutions led to significantly enhanced near-offset coverage. Figure 3 compares the population of the offset class 0-100 m between the wide-tow triple source and the adjacent wide-tow penta source survey. The real navigation data from the two wide-tow multi-source surveys is used in the analysis. This nearest offset class is seldomly populated in traditional towed-streamer surveys with a narrow source set-up that is positioned in front of the two centre streamers. The

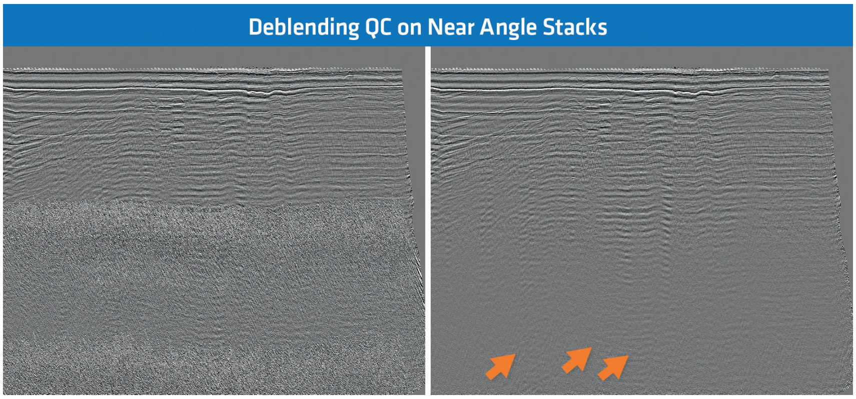

Figure 4 Comparison of near angle stacks before (left) and after deblending (right) from the ultra-wide penta source survey. The deblending provided high-quality clean results. Weak coherent signal has been recovered in the deeper part of the seismic data.

Key Acquisition Parameters	Barents Sea Main Program: Wide-tow Triple Source	Barents Sea Pilot: Ultra-wide Penta Source
Number of source arrays	3	5
Source separation	93.75 m (187.5 m total source spread)	78.75 m (315 m total source spread)
Source volume	3285 cu. in. (two sub arrays per source)	1225 cu. in. (one sub array per source)
Pop interval	12.5 m	7.5 m
Record length	continuous recording	continuous recording; clean record ca. 2.5s
Streamer type	multisensor	multisensor
Streamer configuration	16 x 56.25 m	16 x 56.25 m
Streamer length	13 x 7050 m and 3 x 10 050 m	13 x 7050 m and 3 x 10 050 m
Streamer tow depth	25 m (28-30 m for longer streamers)	25 m (28-30 m for longer streamers)
Inline offset	ca. 65 m	ca. 65 m
Bin size	6.25 m x 9.375 m	6.25 m x 5.625 m (proc. 6.25 m x 6.25 m)

Table 1 Comparison of the survey parameters before and after the reconfiguration from wide-tow triple source to ultra-wide penta source. Only the source-related parameters were changed (highlighted in the table). The streamer configuration and the corresponding nominal sail line separation of 450 m remained the same.

well-known consequences are imaging footprints, most obvious at shallow depths. While the wide-tow triple source provides an improved distribution of the nearest offsets, the ultra-wide penta source provides an almost uniform coverage for offsets smaller than 100 m. The typical lack-of-near-offset zones at sail line boundaries are not present. In summary, the step from a wide-tow triple to an ultra-wide penta source improved both the spatial sampling (i.e., the crossline bin size was reduced) and the coverage of the nearest offsets without compromising acquisition efficiency.

Blending and deblending

While the wide-tow geometry with five sources solved the traditional near-offset problem in the crossline direction, the shot sampling in inline direction needed to be addressed accordingly. The pop interval for the triple source part of the survey was 12.5 m. In order to achieve the same common mid-point (CMP) fold for the penta source, the pop interval was reduced to 7.5 m (Table 1). Consequently, sources had to be triggered ca. every 3 s for the penta source survey. Dithering of shot times was used to allow for optimal deblending in the pre-processing phase and enabled high-quality imaging for deeper exploration targets in the area. The deblending of overlapping shots was done with an iterative multi-domain method that simultaneously estimated the signal of all previous and subsequent shots present in the desired output record. Figure 4 shows a comparison of penta source data examples before and after deblending.

High-resolution imaging of the shallow subsurface

High-resolution imaging of the shallow subsurface is critical in the Barents Sea, both with shallow exploration targets and deeper geological structures in mind. The shallow subsurface can typically be characterized by a rough seabed with very high impedance contrasts, and with complex and strong reflectivity just beneath it. Imaging of the ultra-wide penta source data resulted in very high-resolution images of the near surface. Depth slices extracted just below the seabed are shown in Figure 5. The images are free from any acquisition footprint due the uniform near-offset coverage made possible by the wider tow of multi-sources.

The images show very good signal-to-noise ratio. Note that the penta source survey was acquired with relatively small source volumes of 1220 cu. in. per array, compared to the 3280 cu. in. in the triple source survey (Table 1). The latter is a common source

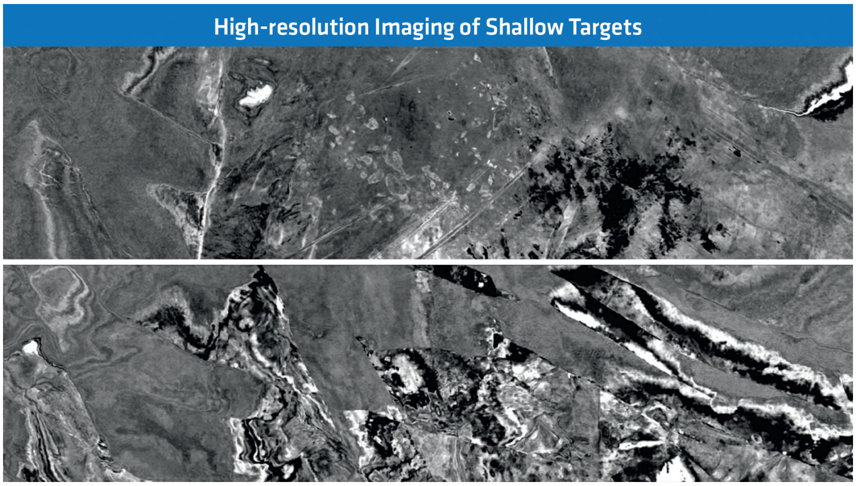

Figure 5 High resolution imaging results of the near-surface do not show any acquisition footprints typically caused by near-offset gaps at sail line boundaries. The depth slices shown are extracted from 410 m and 468 m below main sea level. Water depth ranges from 300 m to 400 m in the area. The surface dimensions of the depth slices are 21.9 km x 5.3 km. The ultra-wide penta source set up provided a natural processing bin size of 6.25m x 6.25m and uniform sampling of the ultra-near offsets.

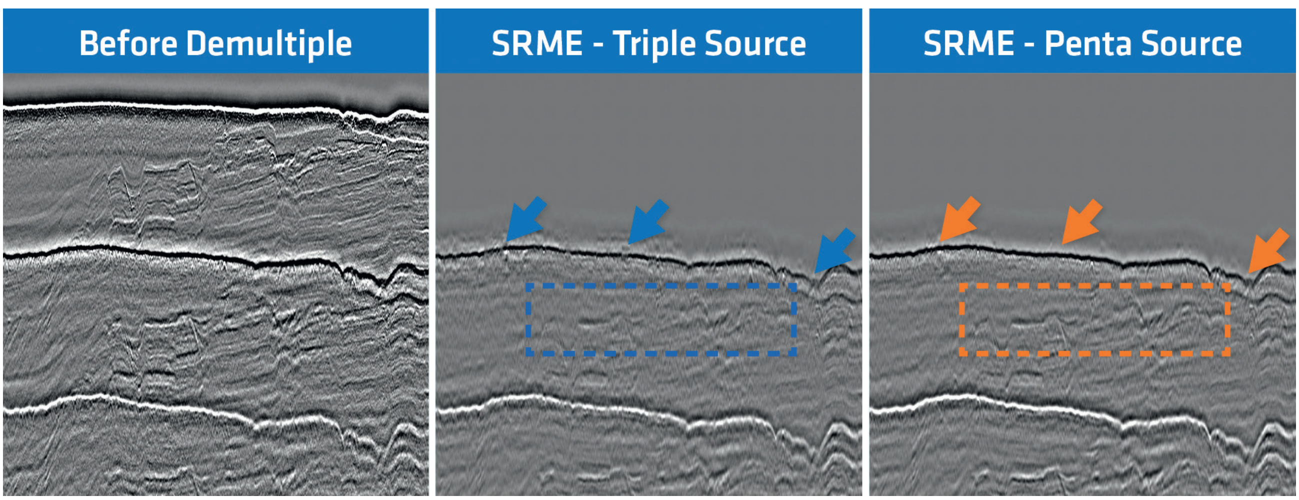

Figure 6 Near Trace QC of input data (left) and multiple models from SRME: utilizing only three sources (middle), and all five sources (right). The tests were run in realistic conditions using a large 3D swath covering the full aperture requirements for multiple predictions. Changing from three sources to five sources increases the trace density and the near offset information: both affecting the quality of the SRME output.

volume for triple source surveys. Consequently, the raw signal of the penta source data is weaker at the single trace level compared to standard seismic exploration data, but so is the shot generated noise. The increased shot effort and the high trace density combined with superior spatial sampling ensure a good signal-to-noise ratio, even for a source with reduced energy output.

The benefits are twofold since the added sampling, better source distribution and near-offset sampling also contribute to a more robust data pre-conditioning; for example, when predicting multiples via a Surface Related Multiple Elimination (SRME) workflow and performing data regularization prior to pre-stack Kirchhoff migration. Figure 6 illustrates what multiple models may be obtained from a realistic SRME run in a triple- and a penta source configuration. As expected, the penta source case shows higher accuracy and resolution, which means that simpler adaptive filters may be used for subtraction, and an overall better demultiple result can be achieved with less effort. Therefore, we anticipate that the increase in costs related to processing of a higher-density dataset is somewhat largely compensated by a reduction in the amount of testing and QC to be performed, as well as the use of more standardized workflows, i.e., with a potential for shorter turnaround.

For imaging of deeper targets, the dense 6.25 m x 6.25 m acquisition and processing bin size is usually not a geophysical requirement. The grid increments can be increased. The larger processing bin size results in higher fold, and thus preserves good signal-to-noise ratio also for imaging of deeper structures. Full integrity processing for the penta source and adjacent triple source survey is continuing and expected to complete very soon. Final imaging results will allow quantitative analysis and comparisons of image and velocity model quality from shallow to large depths.

Source towing challenges and performance

Sources in standard dual or triple source configurations are typically connected by a separation rope. To enlarge the distance between source arrays, the separation ropes should be removed. Without ropes, the control of the source position must be supported by a source steering system. The forces required to spread out and steer the sources can be generated by deflectors. Deflector-based source steering has been successfully used in 4D seismic surveys for many years to optimize source repeatability for single and (narrow tow) dual source arrays, and the available force depends on the size and shape of the deflector wings. For wide-tow sources, the steering capacity must be balanced between separation control and the forces needed to get the sources out to the desired lateral positions. In addition to the extra forces that are needed to achieve a wider source separation, higher hydrodynamic forces must be dealt with as source umbilicals are pulled at a much larger angle than usual through water.

The ultra-wide penta source configuration piloted last year comprised only one sub array for the sources S1, S2, S4, and S5. The centre source S3, however, was configured with two sub arrays as visible in Figure 1. This specific solution for the centre source was chosen for practical reasons as arrays pull slightly to the side. Connecting two sub arrays to one array was the easiest way to stabilize position control for the source array in the centre. The set-up for the centre source array also enabled the opportunity of emitting more source energy for every 5th shot. The stronger signal comes with benefits for refraction FWI as offsets up to 10 km were acquired.

The source separation statistics for the ultra-wide penta source pilot are shown in Figure 7. The graph shows the average separation between adjacent source arrays (i.e., separation between S1 and S2, S2 and S3, etc.) per acquisition sequence. After initial set-up challenges during the first sequence and corresponding adjustments, the source separations converged rapidly to a mean separation of just below 80 m. This is slightly above the nominal source separation of 78.5 m that was simulated in planning. The source separations between the inner sources remained very stable for the entire project (Figure 7). The outer arrays showed some minor undulations, but standard deviations of only about 1 m were observed for the source separations per acquisition sequence.

New energy seismic applications

Combining wide-tow multi-source spreads with high-density multi-sensor streamer configurations enable accurate imaging from very shallow targets and geohazards to deep geological structures. The novel configuration that was piloted in the Barents Sea in 2020 (Figure 2) was designed for hydrocarbon exploration. The same survey design principles can be applied to specialized near-surface high-resolution 3D studies such as CCS site characterization, deep-sea mineral exploration, or offshore wind farm site surveying. Of course, less streamer inventory is required for these applications. Near offset, long offset, and 3D spatial sampling requirements will depend on water depth and resolution requirements. Dense streamer spreads with short cables can be complemented with longer tails if refracted waves are analysed as part of the geophysical studies, and if velocity building or quantitative interpretation (QI) requires access to longer offsets. The wide-tow sources ensure improved or even uniform sampling of the near offsets in crossline direction. As near-surface seismic or seabed mapping frequently requires recording of seismic data

Average Source Separation between Adjacent Source Arrays per Acquisition Sequence

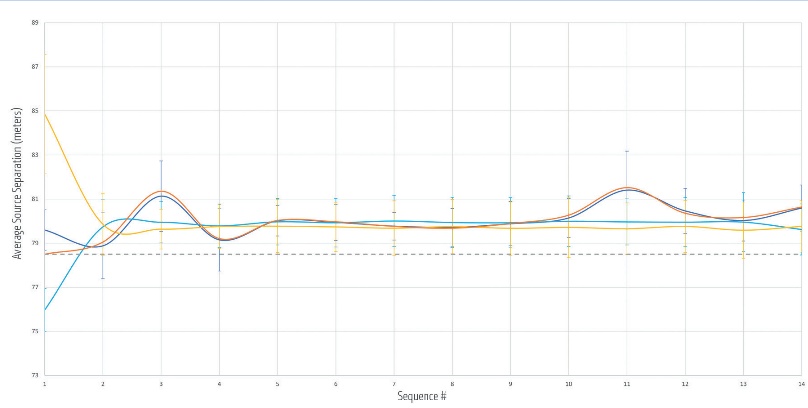

Figure 7 Average source separation between adjacent source arrays from acquisition sequences for the ultra-wide penta source pilot in 2020. Standard deviations are overlaid. The nominal wide-tow source separation was 78.5 m. After adjustments were made, the source separations were rather stable throughout the survey, despite the demanding configuration.

Sanco Swift Towing Ultra-wide Hexa Source

Figure 8 Source vessel (Sanco Swift) towing an ultra-wide Hexa source. The source configuration is 6 x 87.5 m. The record-breaking source spread was towed in a tandem source-over-streamer operation behind a streamer vessel, and over a sparse grid with ocean bottom nodes.

with close-to-zero offset, the inline distance between sources and streamers can be minimized by moving the sources over the front end of the streamer spread.

The sail line separation would still be several hundred metres and thus the survey efficiency would be comparable to that used for hydrocarbon applications. Another potential benefit comes from the deep towing of multi-sensor streamers. Typical site survey and near-surface seismic technologies are based on hydrophone-only streamers that are towed very shallow, i.e., only a few metres below the sea surface. While the shallow tow mitigates the receiver ghost problem at high frequencies (but at the expense of weaker low frequencies), the operations are exposed to weather downtime and poor data quality. With multi-sensor streamers, the receiver ghost problem is solved at all frequencies by combining pressure and particle motion recordings. This means the streamers are towed deep (e.g., at 25 m) and rough sea surface effects are avoided, which results in an increased operational weather window.

Ultra-wide hexa source survey 2021

As discussed above, it is relatively straightforward to scale down the seismic vessel configuration with the penta source (Figure 2) for applications in the new energy market. Upscaling the vessel configuration to increase efficiency while maintaining quality is, however, more challenging. Source spread widths significantly larger than the 315 m achieved last year cannot be achieved with current technology: towing and handling complexity increases with the number of streamers and sources towed from the same vessel. Decoupling the sources from the streamers is the low hanging fruit. Operating multi-sources from a dedicated source vessel allows for more flexible source towing solutions, and thus enables larger source spreads. An ultra-wide hexa source with 437.5 m total source spread and 87.5 m source separation (Figure 8) was deployed by a source vessel during an exploration survey for Lundin and partners in the Barents Sea this year (Dhelie et al., 2021). The source vessel operated on top of a massive, high-density multi-sensor streamer spread (18 x 75 m x 8000 m), and simultaneously over a sparse grid of ocean bottom nodes. The record-breaking wide-tow multi source configuration came with a nominal bin size of 6.25 m x 6.25 m, an (almost) uniform high trace density in the close-to-zero offsets class, and boosted the acquisition turnaround by allowing a sail line separation of 600 m.

Conclusions

Wide-tow multi-sources enable cost effective acquisition of seismic data with good coverage of the nearest offsets and dense spatial sampling. A novel marine seismic survey was acquired by combining a dense multi-sensor streamer spread with an ultra-wide penta source in the Barents Sea in 2020. Processing of the high-resolution seismic data delivered high-quality images of shallow targets just below the seabed without the acquisition footprint typically caused by lack of near offsets. Although the survey was acquired with relatively small source volumes, the high trace density and good spatial sampling ensured excellent signal-to-noise ratio. The ultra-wide penta source with 315 m total source spread width remains the widest multi-source set up towed by a streamer vessel on a commercial project to date. Despite the challenging source configuration, source position control performed well, and the source separations were stable throughout the pilot survey. Wide-tow multi-source solutions are also applicable to the energy transition market, especially for seismic imaging and characterization of the shallow subsurface.

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