Advanced 3D Seismic Acquisition Solutions for Hydrocarbon Exploration, CCS Development, and Offshore Wind Site Surveys

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Abstract

Advanced towing configurations which combine distributed multi-sources with dense multisensor streamer spreads have been frequently used for hydrocarbon exploration in recent years. These acquisition solutions enable accurate imaging from very shallow targets and geohazards to deep geological structures in a cost-effective manner. The improved near offset coverage and the dense spatial sampling provided by the wide-tow multi-source configurations enable subsurface imaging with temporal and spatial resolution in the meter-range. The same survey design principles can be applied to near-surface high-resolution or ultra-high-resolution studies such as carbon capture and storage (CCS) site characterization or offshore wind farm 3D site surveying.

Typical site survey seismic technologies are based on hydrophone-only streamers that are towed a few meters below the sea surface. While shallow tow mitigates the receiver ghost problem at high frequencies, the operations are exposed to weather related downtime. With multisensor streamers, the receiver ghost problem is solved by combining pressure and particle motion recordings. This means the streamers can be towed deeper.

In this paper, modern acquisition configurations are revisited, and it is shown how the same concepts have recently been used to design and acquire the first larger CCS development surveys as well as ultra-high resolution 3D site surveys for offshore wind farms.

Introduction

The demand for high quality marine streamer seismic with rich near offset coverage 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 existing seismic data 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. In addition, the emerging new energy markets require cost-efficient high-resolution or even ultra-high resolution 3D seismic data.

Typical applications are imaging of the subsurface from a shallow seabed down to the reservoir level for CO2 storage sites, mapping of the shallow geological structures for seabed mineral exploration, or site surveys for future offshore wind farms. In most cases, near offset and dense spatial sampling requirements are the key cost drivers.

New and innovative strategies for acquisition and imaging of shallow targets have been exploited by Widmaier et al. (2019, 2020, and 2021). The key technical solution was the introduction of wide-tow multi-sources, i.e., the distribution of multiple sources along the front of a streamer spread. The combination of wide-tow multi-sources with high-density streamer spreads overcomes the traditional 3D seismic challenge of imaging the near surface in shallow or moderate water depths.

We have so far acquired 15 commercial seismic programs with this advanced method including wide-tow triple-, quad-, penta- and hexa-source configurations. Several new projects are ongoing. In some cases, source-over-the spread solutions were deployed to enable close-to-zero offset coverage for ultra-shallow targets.

While the method has initially been developed and used for hydrocarbon exploration, it has recently been adopted for CCS development related marine 3D seismic acquisition projects as well as ultra-high resolution 3D site surveys for offshore wind farm locations.

Method

The wide-tow multi-source 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 center and the outermost streamers.

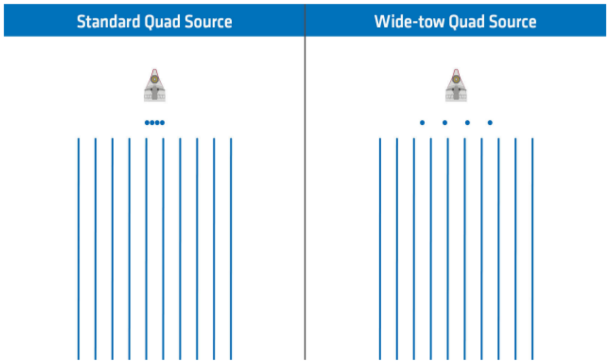

Figure 1 - *High-density streamer configurations of 10 streamers combined with a standard quad-source set-up (left) and a wide-tow quad-source set-up (right). The wide-tow source separation is 62.5 m, resulting in a total source spread with of 187.5 m. The resulting improved near offset separation is shown in Figure 2.*

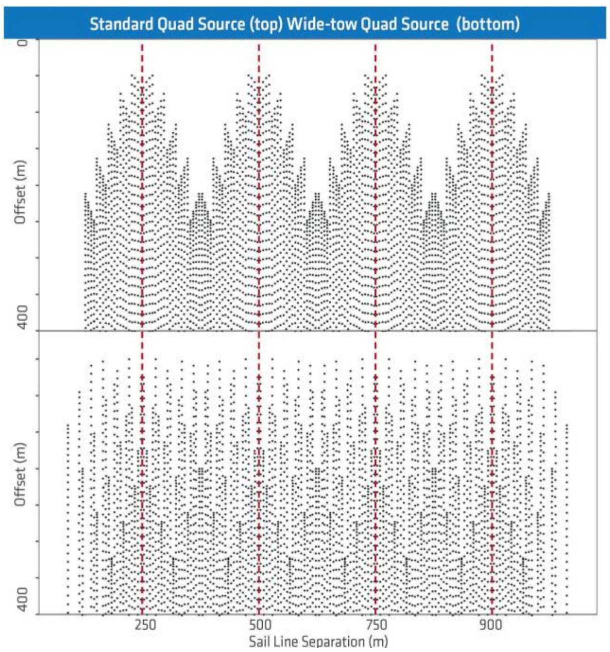

Figure 2 - *Near-offset distribution for a quad-source configuration with 12.5 m standard source separation (top) and 62.5 m wide source separation (bottom). The streamer separation is 50 m in both examples. The red dashed lines indicate the centre of each sail line. CMP-X positions are along the x-axis, and source-receiver offsets are along the y-axis. The wide source configuration provides an improved near offset coverage.*

Figure 1 illustrates the concept for a quad-source configuration in front of a streamer spread with 50 m streamer separation. The source separation for the standard narrow source tow is 12.5 m, and for the wide-tow alternative it is increased to 62.5 m. Furthermore, if the sail line separation is made a function of the source geometry (4 x 62.5 m, i.e., 250 m), the lateral source line spacing (62.5 m) becomes regular for the entire survey area. The regular dense source line spacing in combination with the high-density streamer spread provides significantly improved near-offset coverage (Figure 2). In addition to the improved near-offset sampling, this configuration provides a symmetrical bin size of as little as 6.25 m x 6.25 m. This concept can be extended to higher source count configurations and even denser streamer spacing.

High-resolution exploration survey with wide-tow penta-source

The wide-tow multi-source method was used in an exploration survey in the Barents Sea in 2020 (Widmaier et al., 2020). A high-density multisensor 16-streamer spread was combined with a wide-tow penta source (Figure 3 and Figure 4). The separation between adjacent source arrays was 78.75 m, resulting in a total source spread width of 315 m. The inline offset between the sources and the streamer front-end was as short as 65 m.

The multisensor streamer spread consisted of 16 multisensor streamers of 7 km length towed with 56.25 m nominal separation, including three 10km-long streamer tails (Figure 3). This high-density streamer configuration with variable streamer lengths had already been successfully applied in the Barents Sea during 2018. The novel design delivered optimal wavefield sampling both

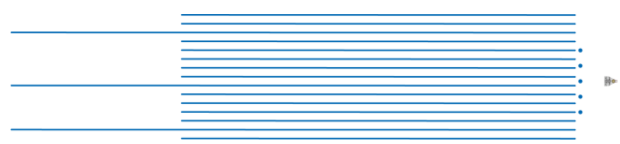

Figure 3 - *Schematic illustration of the vessel configuration with the 16 x 56.25 m x 7000 m deep-tow multisensor streamer spread. The set-up comprised 3 long streamer tails (10 km length) for refraction FWI velocity model building. The ultra-wide penta source was positioned in front of the streamer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

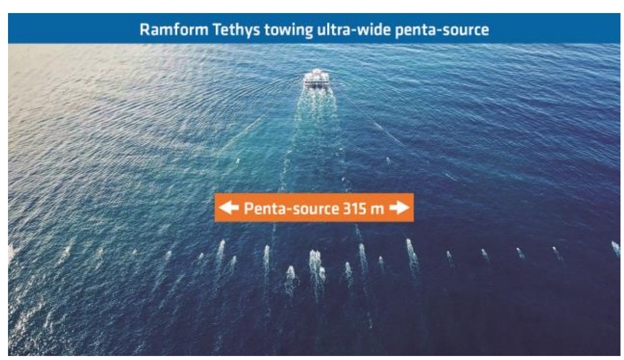

Figure 4 - *Drone photo showing Ramform Tethys during a seismic programme in the Barents Sea in 2020. The seismic vessel is towing an ultra-wide penta source with 78.75 m source separation and 315 m total source spread width. The source separation is larger than the streamer separation (56.25 m).*

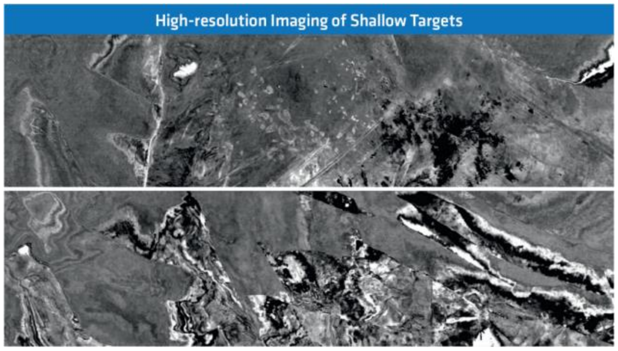

Figure 5 - *High resolution imaging results of the near-surface do not show any acquisition footprints typically caused by near-offset gaps at sail line boundaries. The depth slices shown are extracted from 410 m (top) and 468 m (bottom) below main sea level. Water depth ranges from 300 m to 400 m in 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.*

for high resolution imaging and for refraction full waveform inversion (FWI) velocity model building (Naumann et al., 2019).

The acquisition configuration enabled a bin size of 6.25 m x 6.25 m which is an ideal starting point for high resolution imaging. At the same time, the sail line separation of 450m kept cost and turnaround at reasonable levels. The tow depth of the multisensor streamers was 25m and thus the survey could be acquired with minimal exposure to weather related downtime and without rough sea surfaces effecting seismic data quality. With multisensor streamers, the receiver ghost problem is solved at all frequencies by combining pressure and particle motion recordings and thus the deeper tow does not limit the spectral bandwidth.

Imaging of the ultra-wide penta source data resulted in very high-resolution images of the near surface. Two depth slices extracted just below the seabed are shown in Figure 5. The images are free from any acquisition footprint due to the uniform near-offset coverage made possible by the wider tow of multiple sources.

CCS high resolution baseline survey with wide-tow quad source

The wide-tow quad source configuration shown in Figure 1 was the starting point for a novel high-resolution survey over three CCS structures in the Southern North Sea (Cooper, 2022) that we designed and acquired for the Northern Endurance Partnership (operated by BP) in 2022. One of the objectives was accurate imaging and characterization of the geological formations above the CO_2 storage reservoirs. Seismic modelling indicated that imaging of the near subsurface in the shallow water environment requires uniform coverage of near offsets down to the 30m-60m range. While the wider tow of the quad source enabled near offset coverage in crossline direction (Figure 2), it was still a challenge to meet the nearest offset needs given the typical towing solution with sources 65m in front of the spread. The inline offset challenge could be solved by moving the sources over the front ends of the streamers. Again, deep tow of multisensor streamers were key for broadband acquisition and to ensure high efficiency also under rougher weather conditions. Figure 6 shows the Ramform Hyperion operating with the innovative towing solution during the Northern Endurance project.

Figure 6 - *Ramform Hyperion acquiring a high-resolution CCS development survey for the Northern Endurance Partnership offshore UK in 2022. The configuration consisted of 11 multisensor streamers with 50 m separation and a wide-tow quad source that was towed over the front end of the streamer spread. The resulting nominal acquisition bin size was 6.25 m x 6.25 m.*

Ultra-high resolution 3D site surveys for offshore wind farms

The wide-tow multi-source survey design principles as discussed above for high resolution hydrocarbon and CCS surveys are also applicable to ultra-high resolution 3D surveys for offshore wind farm sites. Ultra-high resolution seismic is required to map the sea floor and image the shallowest part of the sub surface (e.g., upper 100m). Characterization of the near surface around potential locations for wind turbines, identification of shallow geohazards, and boulder detection are amongst the key objectives.

Thus, configurations must be scaled down to meet temporal and spatial resolution requirements. I.e., the wavefield must be sampled at higher sampling rate temporally and much denser spatially. The P-cable system, originally developed by Sverre Planke and Christian Berndt (Planke & Berndt, 2003), has recently been adopted for applications in the energy transition (MacGregor et al, 2022). In the P-cable system, short streamers (typically 50-100m long) are towed from a cross cable. For ultra-high-resolution applications, sparker or boomer sources are used, and temporal sampling rates are at 0.125-0.25 msec.

In contrast to multisensor streamers referred to in the previous sections, ultra-high-resolution systems such as the P-cable are towed at very shallow depths to emphasize the high frequency content in the recorded date. The shallow tow depth increases the weather exposure of ultra-high-resolution seismic surveys. Also, de-ghosting becomes a more critical step compared to multi-sensor streamers.

Examples of combing P-cable configurations with wide-tow multi-sources are shown in Figure 7 and Figure 8. In the first example (Figure 7), 10 short streamers with a separation of 6.25 m are combined with a wide-tow triple source. The resulting nominal acquisition bin size is circa 1 m and the sail line separation is 31.25 m. The second example (Figure 8) is a more efficient configuration. The number of streamers is increased to 14 and the streamer separation to 12.5 m. The source solution comprises a wide-tow quad source. The configuration has a nominal sail line separation of 87.5 m, and an (effective) crossline bin size in the range of 1.5 m to 3 m, depending on near-offset sampling requirements, i.e., efficiency has been gained while spatial sampling has been relaxed.

Figure 7 *– High integrity ultra-high resolution P-cable configuration with a 10 x 6.25 m x 100 m streamer spread and a wide-tow triple source.*

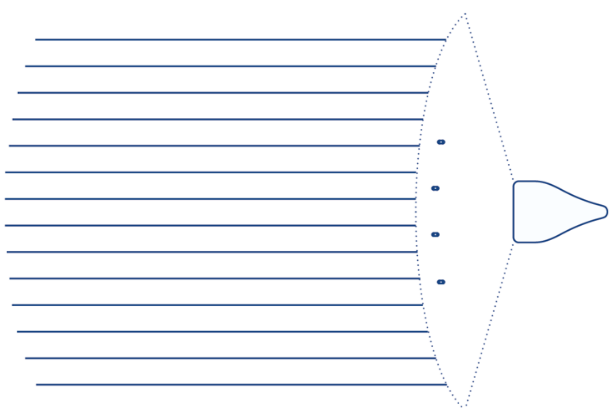

Figure 8 - *P-cable configuration with a 14 x 12.5 m x 100 m streamer spread and a wide-tow quad source.*

Conclusions

Wide-tow multi-sources enable cost effective acquisition of high-quality 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.

The same survey design principles can be applied to specialized near-surface high-resolution 3D studies such as CCS site characterization, or offshore wind farm site surveying. As near-surface seismic or seabed mapping in shallow water requires recording of seismic data 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 as demonstrated in novel quad source acquisition over the Northern Endurance CCS structures. We have also outlined how a scaled configuration (P-cable) can deliver ultra-high resolution seismic of 1m spatial sampling.

Acknowledgments

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