

Survey design for ultra-high resolution 3D seismic site characterization surveys

Introduction

Traditional 3D marine streamer seismic acquisition is designed for exploration surveys with relatively deep geological targets. As a result, configurations typically used only two closely spaced sources towed ahead at the centre of the streamer spread. While adequate for deep subsurface imaging, these setups provide coarse spatial sampling, and sparse source lines. Typically, large-volume source arrays are used. Langhammer and Bennion (2015) revisited acquisition designs and employed three sources. These triple-source configurations can improve shot sampling and produce smaller crossline bin sizes. However, in shallow water and for shallow targets—where dense near-offset coverage is essential for reliable imaging, AVO analysis, and efficient multiple suppression—such narrowly towed source configurations remain inadequate. Advanced acquisition configurations with multiple wide-tow sources have been presented by Widmaier et al. (2019). This technology can be leveraged for improving acquisition efficiency or enhancing image. By providing better near offset coverage, improved spatial sampling, and higher trace density, they are effective for imaging both shallow and deep targets.

The emergence of ultra-high resolution 3D seismic acquisition for offshore wind site characterization and high-density 3D for CCS container delineation has led to adapted wide-tow multi-source concept with uniform source lines, as described by Widmaier et al. (2023). These designs feature uniform source-line sampling, dense near-offset coverage, small bin sizes, high trace density, and compact, environmentally friendly sources. In this paper, we describe survey design considerations for these configurations, with an emphasis on offshore wind farm site characterization.

Wide tow multi-source configuration analysis

Assuming fixed acquisition efficiency, near-offset data quality can be enhanced by employing wide-tow multi-source configurations. Consider a hypothetical marine seismic survey targeting a shallow reservoir located approximately 1 km below the seafloor in a moderate water depth of about 200 m. The hypothetical acquisition system includes 10 streamers spaced 75 m apart, giving a 375 m sail-line separation. The streamer group interval is 12.5 m. With an average velocity of about 1850 m/s and a 50% stretch mute, the maximum useful offset for the target is approximately 1300 m, while the corresponding maximum useful offset at the seafloor is about 425 m. Table 1 summarizes the acquisition parameters for three source deployment modes: Narrow Dual Source (NDS), Narrow Triple Source (NTS), and Wide-Tow Triple Source (WTS). The table assumes identical shot-point intervals for all configurations and an omnidirectional unit-output source whose energy is distributed among the individual sources. This results in identical amplitude density per square kilometre (traces per square kilometre scaled by relative source strength). Figure 1 presents offset-distribution plots for three saillines (upper panels) and the corresponding offset-gap analyses (lower panels). The offset calculations assume zero inline offset; however, for visualization, the sources and receivers in the offset-distribution plots are shifted in the inline direction. The gap-analyses plots show, analysed in offset intervals equal to the channel spacing, all encountered gap sizes as horizontal ticks and the average of all gap sizes as dots. Minimum and maximum gap are connected by a vertical line for easy illustration of the gap size spread. The plots further show the small axis of the Fresnel zone ellipse for 100 Hz (blue dotted lines in the lower panels of Figure 1), calculated for 1200 m depth and a velocity of 1850 m/s, (Monk 2010). This curve indicates a representative maximum trace distance we might not want to exceed to be able to claim that we have sufficient information in the recorded data at target depth for high-quality data reconstruction onto a dense grid for imaging.

The traditional NDS configuration gives the largest crossline bin size, the largest source-line gap, and the longest firing interval (Table 1). As shown in Figures 1a and 1d, the very near offsets exhibit maximum crossline gaps exceeding 300 m. The average gap size decreases with increasing offset and approaches the nominal crossline bin size at the maximum minimum offset (Figure 1d). Figure 1d shows a large difference between minimum and maximum gap sizes over the entire near offset range. The maximum gap size is larger than the Fresnel zone radius for the first 250 m offset range. Near-offset

Acquisition configuration	# sources	Source separation (m)	Maximum source line gap (m)	Amplitude / source	Firing / pop interval (m)	Nominal inline / crossline bin size (m)	Nominal amplitude density [useful offset] /sqkm	Maximum minimum offset (m)
10 x 75m x 1300m NDS	2	37.5	337.5	0.5	18.75	6.25 / 18.75	73955	356
10 x 75m x 1300m NTS	3	25	325	0.33	12.5	6.25 / 12.5	73955	362
10 x 75m x 1300m WTS	3	125	125	0.33	12.5	6.25 / 12.5	73955	462

Table 1 Acquisition parameters for NDS, NTS, and WTS.

Acquisition configuration	# Sources	Source line separation (m)	Normalized efficiency (%)	Firing / pop interval (m)	Firing / pop interval (ms)	Vessel speed (knots)	Nominal inline / crossline bin size (m)	Nominal amplitude density [full offset] /sqkm	Maximum minimum offset (m)	Nominal amplitude density [max. min. offset] /sqkm
8 x 6m x 100m WPS	5	4.8	100	0.4	180	4.32	0.78125 / 0.6	53333333	31	16533333
10 x 5m x 100m WHS	6	4.2	104	0.33	150	4.32	0.78125 / 0.42	76807680	33	25346534
14 x 10m x 200m WPS	5	14	289	0.55	250	4.27	1.5625 / 1.0	23272727	93	10821818
14 x 12m x 200m WPS	5	16.8	347	0.55	250	4.27	1.5625 / 1.2	19393939	112	10860606

Table 2 Configuration parameters for ultra-high-resolution seismic surveys.

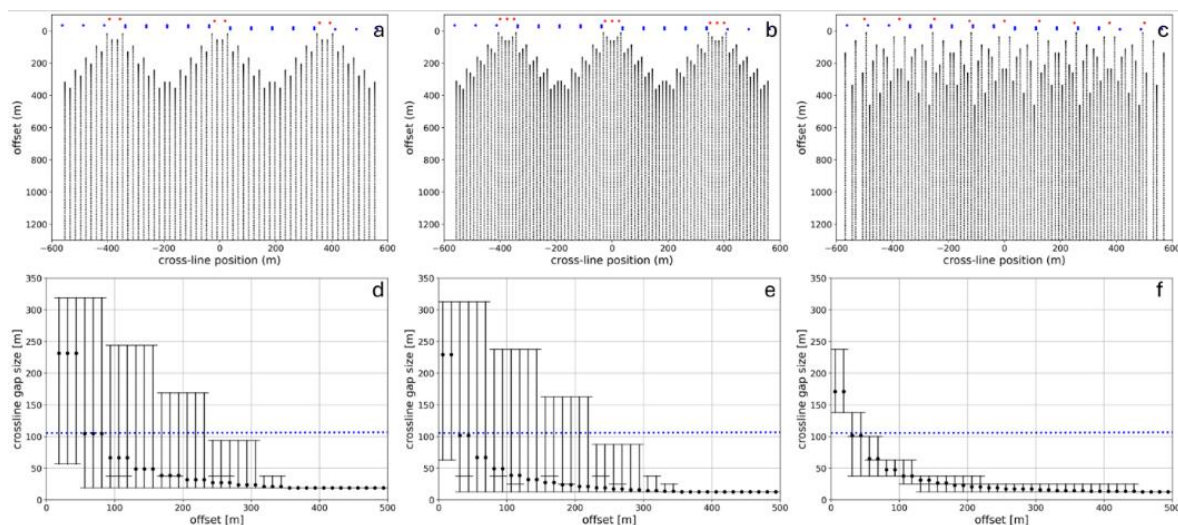


Figure 1 Offset distribution plots (top panels) and crossline gap analysis (lower panels) for NDS (a and d), NTS (b and e), and WTS (c and d). Red and blue dots indicate source and streamer locations. The offset Fresnel radius is shown in the lower panels by the blue dotted lines.

fold is concentrated at sailline centres, and the data contains little to no near-offset target information at sailline boundaries. This results in poor near-offset data regularization and strong acquisition footprint. The data likely requires an inner mute, removing the near-angle information essential for high-resolution shallow-target imaging and quantitative interpretation.

Deploying sources in NTS mode provides only marginal improvement over NDS (Table 1; Figures 1b and 1e). While the nominal crossline bin size is smaller, the crossline gap exhibits similar behaviour to NDS up to the maximum minimum offset. Consequently, NTS also lacks sufficient near-offset coverage with similar effects as described for NDS.

The WTS exemplifies wide-tow multi-source deployment. As shown in Table 1 and Figures 1c and 1f, it has the smallest maximum near offset crossline gaps and uniform source-line separation. In Figure 1f, the average gap size is the same as for the NTS configuration (except for the first 25 m offset range), illustrating the distribution of acquired fold in the crossline direction, but the variation between minimum and maximum gap size is significantly reduced. The maximum gap stays below the Fresnel zone radius at target down to about 50-75 m offset. This facilitates high quality near-offset data regularization as the recorded data contain the necessary information at all crossline locations. This reduces inner muting to about 75 m, compared to 250-300 m for NDS and NTS. With these inner mutes, for the target in our scenario, WTS recovers a minimum angle as small as 2.4°, versus about 9° for NDS

and NTS. After inner muting, WTS retains 350 m of offset with evenly distributed traces for seafloor imaging, substantially reducing acquisition footprint effects. The increased trace density achieved with triple source configurations (NTS and WTS) allows deployment of smaller sources that produce less sound pressure level per shot but still provide the same amplitude density as NDS for the same total source output (Table 1). Alternatively, NTS and WTS can reduce their source output, thereby lowering their environmental footprint.

The near hyperbolic behaviour towards near offsets for the average gap size indicates that achieving minor improvements in very near offsets incurs increasingly high costs. In theory, the ultimate 3D offset distribution—with the best spatial resolution—would have the smallest crossline bin size at all offsets (or flat average gap curve with zero gap size spread), as achieved in single source, single streamer acquisition. This is unrealistic for cost-efficient 3D acquisition. Carefully designed wide-tow multi-source configurations can effectively approach this ideal, as illustrated in Figures 1c and 1f.

Ultra-high-resolution 3D seismic for offshore wind farm site characterization

With high demand for renewable energy, wind turbines are increasingly deployed from shallow to deeper waters. Water depth and sediment composition dictate the foundation type and, consequently, the imaging depth required in seismic surveys. Depending on local geology, identifying geohazards and deriving geotechnical parameters from multi-physics data is essential, with 3D seismic data serving as a critical component. 3D seismic site surveys can begin with exploratory acquisition over a large area, followed by a targeted appraisal survey. Depending on the objectives—boulder detection, soil unitization, or both—tailor-made seismic solutions are designed. Shallow-water sites with abundant boulders typically benefit from very dense acquisition geometries, while deeper-water sites are suited for more cost-effective acquisition. The denser configurations with very narrow mini-streamer spreads provide dense spatial sampling. Corridor-type survey layouts may be used to reduce costs. Wider configurations with relaxed spatial sampling are more efficient and can cover full 3D survey areas.

Figure 2 shows two very dense ultra-high-resolution configurations designed for 25 m water depth: 8 × 6 m Wide Penta Source (WPS) and 10 × 5 m Wide Hexa Source (WHS). The channel spacing is 1.5625 m. The offset-distribution plots are color-coded by seafloor reflection angles. The offset corresponding to 45°, roughly the maximum useful offset for a flat reflector with a 50% stretch mute, is indicated. Although WPS and WHS have similar efficiency, WHS achieves ~44% higher trace density due to two additional streamers and an extra source (Table 2). There is no relative source strength adjustment as for the configurations in Table 1; sparker source strength is considered independent of the number of sources deployed. Gap analysis shows similar distributions for both configurations (Figures 2c and 2d), indicating comparable spatial resolution, though the flatter WHS curve suggests slightly better achievable resolution. Maximum gap sizes stay below the Fresnel zone radius for 1800 Hz at the water-bottom to well below 5 m offset. This is a significant contribution to successful near-offset interpolation and regularization. Interpolation of near-offset gaps is also improved for WHS, which has ~53% higher trace density up to the maximum minimum offset compared to WPS (Table 2; Figures 2c and 2d). However, at the same shot-point intervals and identical vessel speed, WHS yields a shortened clean record length. All solutions follow the uniform-source-line design shown in Figure 1c.

Figures 3a and 3b show two configurations with higher acquisition efficiency. Both utilise 14 streamers and a wide penta source. Option 2 (14 × 12 m WPS) with 12 m streamer separation is 20% more efficient than Option 1 (14 × 10 m WPS). Conversely, Option 1 provides ~20% higher amplitude density, better sampling, and a smaller minimum offset. Crossline gap analysis shows that Option 1 will likely deliver better image quality (see Figures 3c and 3d). The more efficient configurations are designed to meet slightly relaxed resolution requirements compared to the denser configurations, indicated by the approx. 6 m Fresnel radius at 1000 Hz for 45 m water depth.

Comparing the average gap size curves for all four configurations illustrates their clear difference for near offset coverage. Nevertheless, each configuration remains well-suited for its intended survey objectives. Well-designed configurations that ensure adequate target sampling in relation to physical

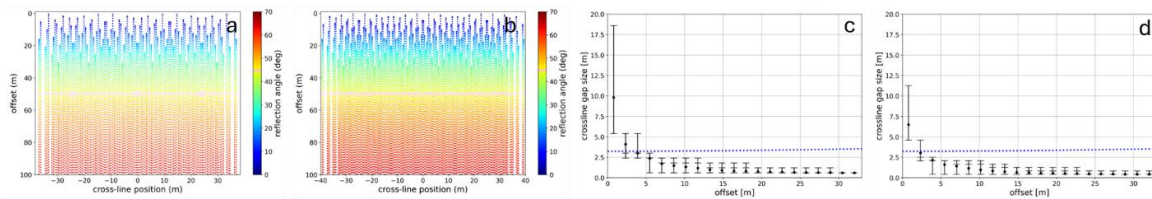


Figure 2 Offset distribution plots (left panels) and crossline gap analysis (right panels) for very dense seismic acquisition solutions: 8 x 6 m WPS (a and c), and 10 x 5 m WPS (b and d).

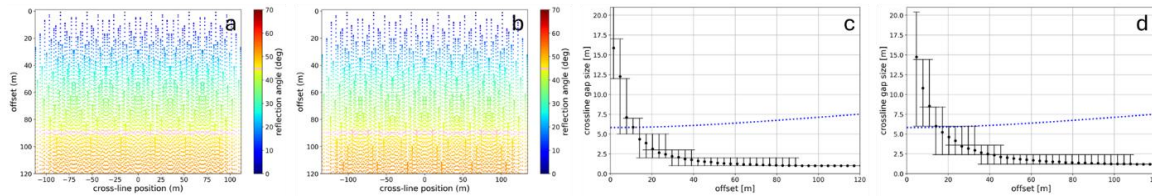


Figure 3 Offset distribution plots (left panels) and crossline gap analysis (right panels) for more efficient acquisition solutions: 14 x 10 m WPS (a and c), and 14 x 12 m WPS (b and d).

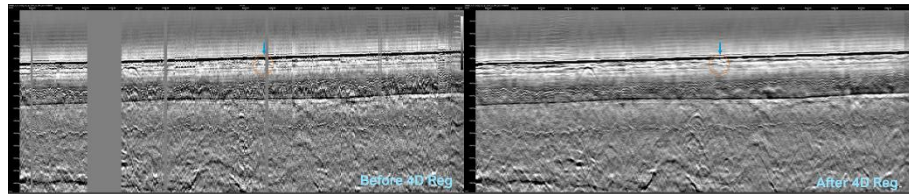


Figure 4 Very near offset stack from 8 x 6m WPS before (left) and after (right) regularization.

constraints (Fresnel zone sizes) facilitate effective reconstruction of data in near-offset gaps during processing. This is illustrated in Figure 4 which shows a near-offset example with well-interpolated results. The data was acquired with the 8 x 6 m WPS configuration described above.

Conclusions

Traditional narrow tow source configurations lack sufficient near-offset sampling to allow high quality 3D imaging of the shallow subsurface. Wide-tow multi source solutions even out near-offset sampling and enable fit for purpose image quality and more cost-effective acquisition. Site characterization surveys for offshore wind focus on the shallow subsurface from seabed to about 100 m below, often in very shallow water environments. Meeting Fresnel zone-based sampling criteria in a cost-effective way is challenging. We have outlined how modern ultra-high resolution 3D seismic solutions for offshore wind can be designed to meet sampling and resolution requirements with high acquisition efficiency. The validity of the approach has been demonstrated in numerous case studies (e.g., Caselitz et al., 2025).

References

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