Elevating 3D Ultra High Resolution processing and imaging for wind farm site characterisation

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Summary

This paper underscores the use of modern processing and imaging techniques to enhance 3D Ultra High Resolution (UHR) data, offering unparalleled subsurface resolution. After briefly outlining the P-Cable system used for acquisition, the abstract explores key challenges and their solutions.
Highlighted aspects include wavelet processing, sea-state statics, demultiple, 4D regularization, and migration. Advanced processing technologies, originally designed for conventional Oil & Gas seismic projects, have been successfully adapted and tailored to UHR data. The final 3D UHR data demonstrates substantial improvements in both vertical and spatial resolution compared to vintage 2D data, effectively capturing geological features as thin as a few decimeters and only a few meters wide.
These improvements are pivotal for constructing accurate ground models and identifying shallow geohazards in offshore wind projects. The showcased advanced processing technologies hold promise for significantly enhancing 3D data for offshore wind.

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Introduction

Acquisition and processing of 3D Ultra High Resolution (UHR) seismic is emerging as a favourable option for imaging the near surface to aid in wind farm site characterisation. The parameters and specifications for these types of surveys aim to optimise the shallow imaging and therefore require alternative processing workflows when compared to conventional 3D seismic. Data from a 3D UHR survey will be used to illustrate advances made in 3D UHR processing and imaging. This survey represents a significant milestone for the offshore wind industry as it is one of the first instances where 3D UHR seismic data have been extensively acquired.

The survey was conducted using a P-Cable system (MacGregor et al., 2022) consisting of 11 x 100 m streamers As the name suggests, the P-Cable system features a perpendicular cable (or cross cable) at the start of the spread. All streamers were connected to this cable separated by 6.25 m, ensuring excellent crossline sampling when coupled with a wide-tow triple source configuration (Widmaier et al., 2019). The acquisition bin size was 1.56 m x 1.04 m in subline and crossline directions respectively. Boomers served as seismic sources, positioned above the front of the streamer spread to minimize the radial distance to the first offset class. The temporal sampling interval of 0.25 milliseconds equates to a Nyquist frequency of 2000 Hz.

The survey layout was based on planned turbine locations and consisted of multiple 3D swathes, each 200 meters wide. The swathes were executed such that each of them covered a maximum number of turbine locations with their respective centre sail line. Six sail lines were required to cover each swath and three additional sail line passes along their respective centres were collected to increase hit count and allow a nominal bin size of 0.78 m x 1.04 m.

The sources were towed at an average depth of 0.3 m, therefore keeping the first non-zero notch of the source ghost above 1500 Hz, i.e. beyond the upper limit of the bandwidth provided by the boomers. The streamers were kept at depths between 1 m and 3 m. The processing sequence was specifically designed for UHR and leveraged cutting-edge technologies which have been tested and proven for the Oil and Gas industry. The main steps highlighted in this abstract have proved to be the most critical and challenging for this UHR project.

Wavelet processing and statics

Achieving a broadband wavelet in the early signal processing steps is critical to maximize resolution and the recovery of fine stratigraphic details and small-scale features. The wavelet processing consists of receiver-side and source-side deghosting, followed by designature including zero-phasing.

Removing the receiver ghosts posed a significant challenge due to the high frequency content in these data and the variations in receiver depth. Notably, the ghost period is influenced by the shape of the streamer, the shape of the sea surface, as well as the propagation angle. Even slight variations in receiver depth or sea state (waves) - in the order of a few decimetres - greatly impact the notch frequencies caused by the ghost in the amplitude spectrum. The variations are different along every streamer and every shot. Therefore, an inversion-based deghosting methodology was necessary, where the receiver depths are optimized in local time-slowness windows.

Source-side deghosting was less challenging since each boomer was suspended to a floating device, which naturally followed the sea surface, therefore keeping the depth close to the nominal 30 cm. Source notches were not observed within the signal bandwidth, meaning the actual source ghost event did not appear separated from the main event. The effect of removing the source ghost was therefore equivalent to a spectral shaping and a linear phase compensation.

Source signatures were estimated from the data on a shot-by-shot basis, since neither near-field measurements, nor catalogued notional signatures were available for the boomers that were employed. The method is based on high-order statistics as described by Bekara (2021). One of its advantages is that it does not require aligning to the water-bottom reflection, which is not trivial in the presence of sea surface statics. The designature process consisted of shaping each signature to a common broadband zero-phase wavelet, therefore removing variations between sources, from shot-to-shot and between sail

lines. The resolution was greatly enhanced, especially around the water bottom reflection as illustrated on Figure 1.
Clearer and sharper reflection peaks mean the statics computation becomes more accurate. The statics issue arises from the variations in the relative distance between the seabed and the sources/receivers. With a temporal sampling of 0.25 ms, even several centimetres can cause visible jitters in 3D common midpoint (CMP) gathers, causing a loss of the very high frequency information at the stacking stage. Variations up to several meters between adjacent traces in CMP domain were observed. Furthermore, the misalignments can negatively impact multidimensional processes, such as data regularization and migration. To compensate for those shifts, statics corrections were estimated using the water-bottom reflections against the demigrated bathymetry from the multibeam echosounder data (MBES) acquired simultaneously. Receiver depth values estimated during the deghosting step were also used to constrain the static corrections by decoupling the effects at sources and receivers. After the application of statics, the data is redatumed to the same reference datum as the bathymetry data.

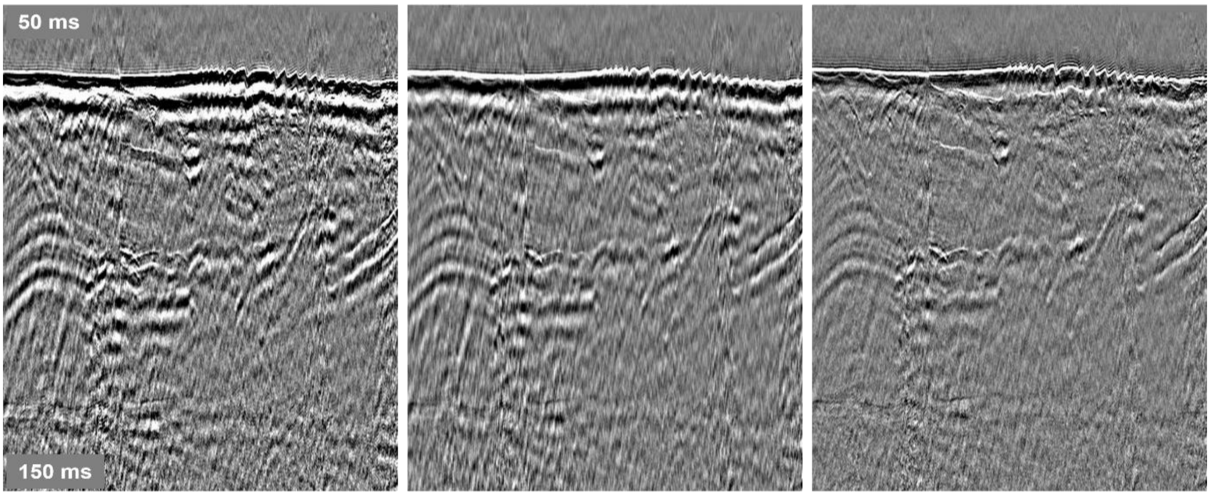

***Figure 1**. 3D unmigrated stacks after denoise (left), after deghost (centre), and after designature (right). Statics were applied at all steps for this comparison only.*

3D demultiple, 4D regularisation and migration

Demultiple is generally a significant step in seismic pre-processing where a combination of several methods are often required. Examples of both convolutional 3D SRME and 3D wave-equation multiple modelling (Barnes et al., 2015) are shown here to produce accurate multiple models which were simultaneously adapted and subtracted. The major challenge in the subtraction step was to compensate for sea surface statics. Multiples are further affected by free surface effects in a non-linear way compared to their corresponding primary events. The adaption process was tuned by allowing for larger time shift corrections in relatively larger windows.
As shown in Figure 2, the pre-migration demultiple was effective in removing both water bottom reverberations and pegleg multiples, also in noisy areas where weak primary signal is present.
Following the main demultiple stage and additional noise attenuation (not described here), 4D regularisation (x, y, time, offset), based on anti-alias anti-leakage Fourier transform (Schonewille et al., 2009), allowed the reconstruction of well-populated offset classes from 9 m to 100 m with an increment of 3.125 m before migration. As mentioned in the introduction the final regularisation bin size was 0.78 m x 1.04 m. The multidimensional nature of the method allows a high-fidelity reconstruction of the signal.
Finally, the 3D Kirchhoff Pre-Stack Time migration better positions and focuses the seismic wavefield, leading to improved interpretability and reliable attributes, as shown on Figure 3. Moreover, the processing workflow was designed to preserve the amplitude of seismic data, ensuring reliable quantitative interpretation.

Time migration velocity model building was performed in the migrated space with an initial model based on a vintage 2D interpolated velocity model. Residual move out (RMO) picking was performed on a 3 m x 3 m grid in an iterative fashion.

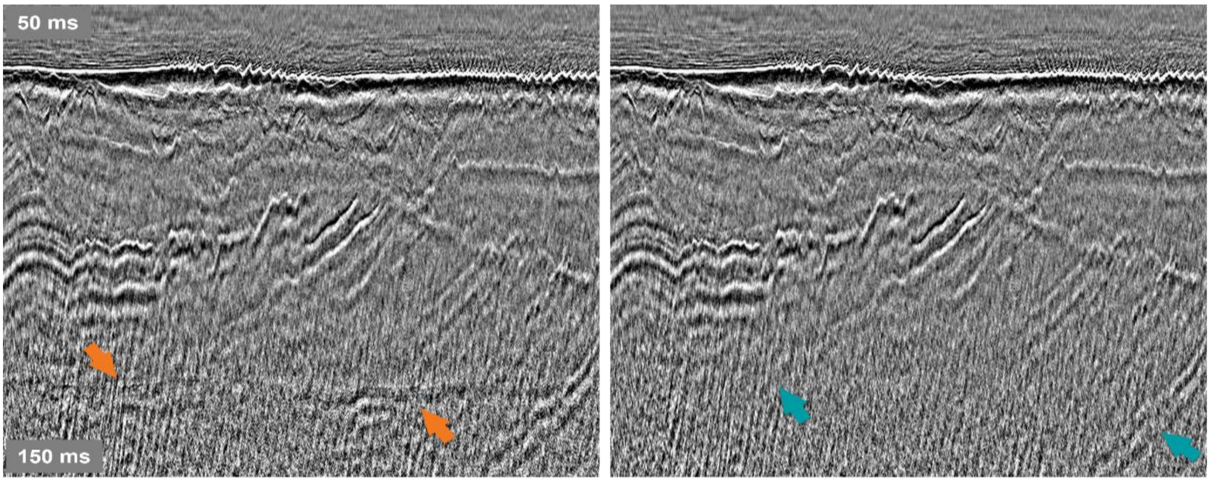

Figure 2. *3D post-stack migrated QC stacks, before (left) and after (right) demultiple. The orange arrows indicate the first water bottom multiple reverberation. The green arrows indicate deeper primaries of weak amplitudes, compared to the mutliple events.*

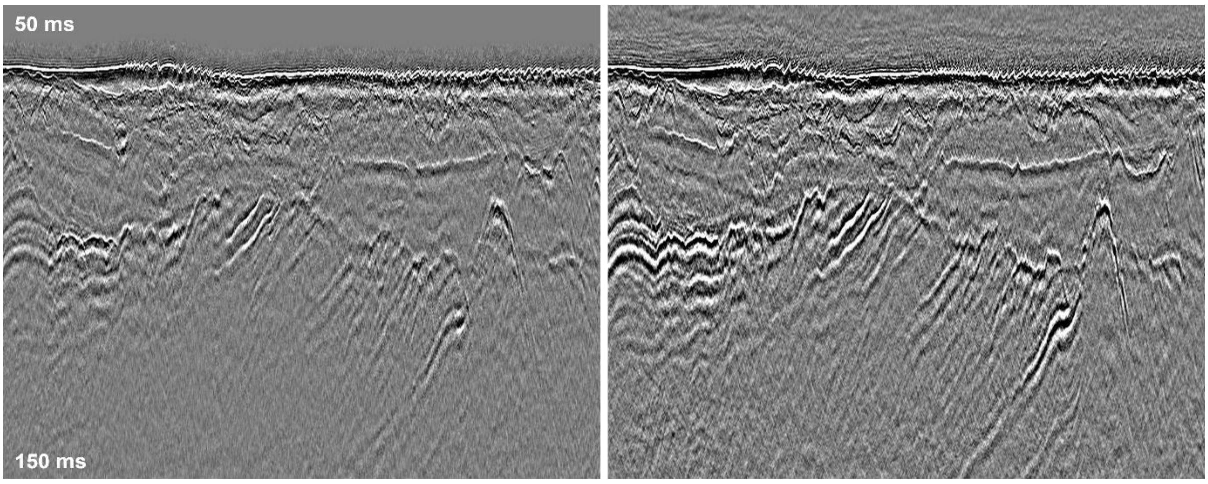

Figure 3. *Unmigrated stack after 4D regularisation (left) and migrated 3D stack (right).*

Final results

Some key objectives for 3D UHR surveys in relation to offshore wind are to provide high-quality geophysical data for constructing accurate ground models and identification of shallow geohazards. Figure 4 illustrates the considerable improvement in vertical and spatial resolution of the 3D data when compared to the vintage 2D, where remaining diffraction pattern are still visible in the migrated image. High-quality information in all directions (inline, crossline, time slice) are critical for tracking large- and small-scale geological features. Figure 5 illustrates the complexity of the near surface in different directions. The blue arrows highlight very small-scale features, of about a few meters in size, which could be boulders depending on the geological context. They can also be identified on the time slice, as increases in impedance contrast (black).

Conclusions

3D imaging of UHR seismic requires advanced processing technologies, many of which have been adapted from well-developed processes designed for conventional Oil & Gas seismic projects. The wavelet processing and statics issues are significant relative to the very fine sampling of the data. The potential of recovering very fine near surface detail is much greater with 3D UHR data compared to 2D UHR data. The processing technologies illustrated here could have a great impact in improving seismic designed for offshore wind projects.

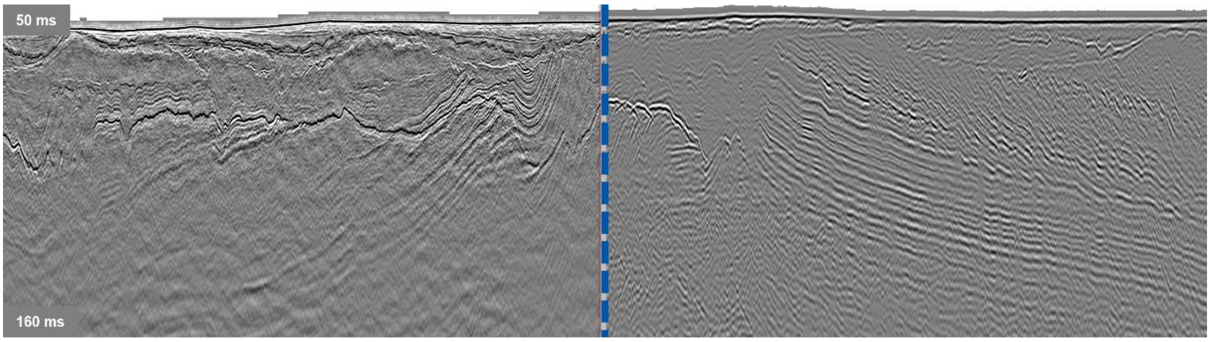

***Figure 4**. Composite line from the 3D UHR final stack (left) and 2D UHR final stack(right).*

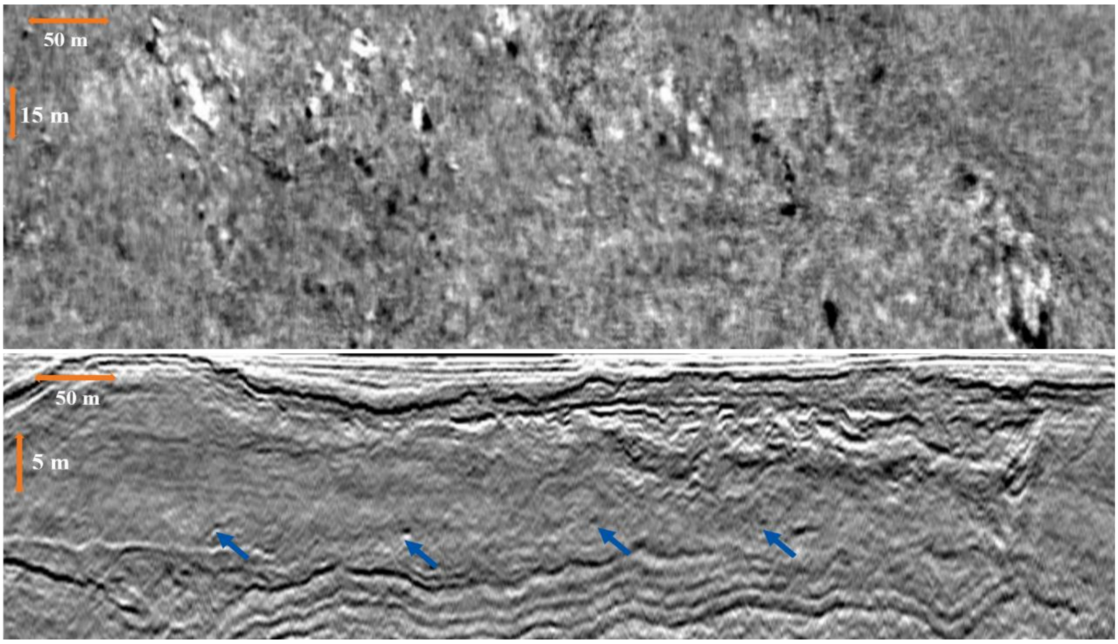

***Figure 5.** 3D final migration stack with inline (bottom) and shallow time slice (top) displays.*

Acknowledgements

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