

# ULTRA-HIGH DENSITY LAND NODAL SEISMIC – PROCESSING CHALLENGES AND REWARDS

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## Summary

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The desire for ultra-high density (UHD) seismic surveys is now becoming more achievable for future exploration and field development with the increasing availability of versatile nodal land systems. Acquisition geometry design using a higher density of sources as well as receivers considerably reduces the effects of spatial aliasing and also provides better subsurface illumination. By sampling the wavefield more densely, there are improved recordings of both signal and noise. This presents new opportunities for processing and imaging. We use a recent UHD nodal survey with nominal trace density approaching 200 times that of typical conventional cable-based surveys to discuss the challenges and rewards.

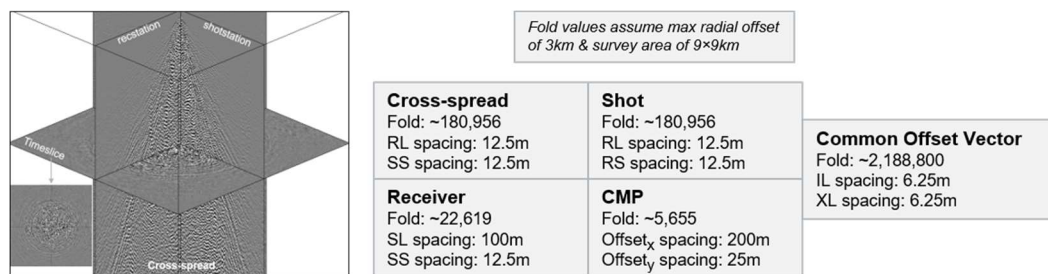
## Ultra-high density land nodal seismic – Processing challenges and rewards

### Introduction

Any advancement in land seismic exploration often involves a comparatively prolonged process due to the complexity of geographical environments, or diverse range of operational requirements and associated costs. Technologies such as simultaneous shooting (Bouska, 2008; Howe et al., 2008), broadband, ultra-high density (Ourabah et al., 2015a) and nodal systems (Manning et al., 2019), although widely acknowledged to be beneficial, are often not routinely implemented due mostly to the lack of practical expertise and economic constraints. Using a recent UHD nodal survey, our paper embraces all of these technologies and focuses on their respective processing challenges and rewards. These include sampling of signal and noise, data quality, processing domains and the near-surface; broadband, longer offsets and phase control; fast-track images, and seismic attributes.

### Processing challenges and results

The 9x9 km survey was a large-scale field trial (LSFT) of a new nimble nodal system (Ourabah and Crosby, 2020). The ultra-high density of 184 million traces/km<sup>2</sup> was achieved using a 12.5x12.5 m receiver carpet and 12.5x100 m shot carpet geometry layout (Figure 1).

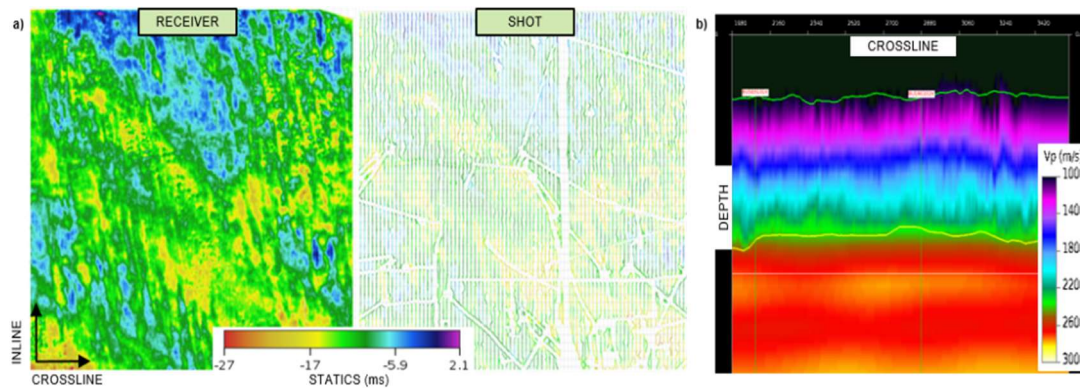


**Figure 1** Raw data and acquisition geometry, showing better sampling in respective domains.

Simultaneous shooting acquisition techniques have made UHD blended acquisition possible by increasing shot density in a very efficient manner. Compared to conventional surveys acquired using vibrator and geophone arrays, blended single sources and nodal receiver surveys typically involve less sensor and source effort, resulting in relatively weak signal, no ground roll cancellation and much more back-scattered noise (especially on near offsets). However, using the appropriate tools and taking advantage of the high trace density populating the different sorting domains, these issues can be addressed in processing. A denser carpet coverage of receivers and shots increases the spatial sampling of the recorded data, highly beneficial for linear noise attenuation (LNA). Most advanced algorithms published over the years incorporate superior modelling of the noise, mitigating the issues associated with additional de-aliasing processing, such as: interferometry-based surface wave removal (Chiffot et al., 2017), anti-leakage tau-p transform, usually combined with a primary reflection model (Le Meur et al., 2014). With the increased spatial sampling due to this dense acquisition, these techniques can be applied in a single, or several, domains (common shot, receiver and cross-spread), in combination with a simultaneous adaptive subtraction of their noise and signal models for improved results. For this survey, coherent noise was removed in the cross-spread and common mid point (CMP) domain, and incoherent noise was attenuated in the common offset vector (COV) domain. Overall, the full de-noise sequence was performed using proven conventional techniques and shown to be highly effective. The data also responded well to advanced guided de-noise approaches and specular imaging (using dip-angle gathers for attenuation prior to stacking), both providing equally good results.

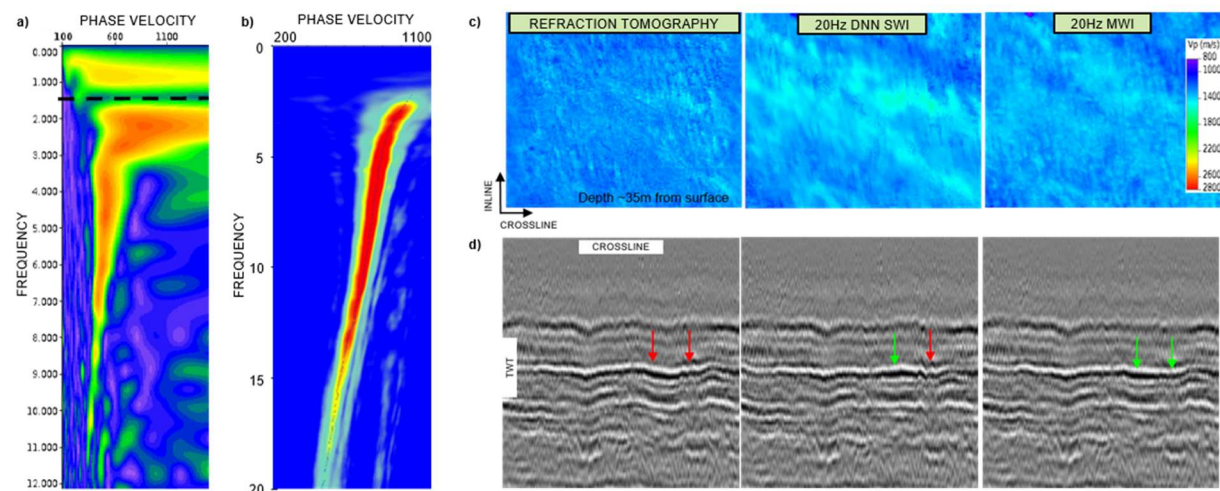
Similarly, surface-consistent solutions for amplitude, deconvolution and residual statics benefitted from the higher density of sources and receivers, allowing for robust offline pre-processing to further improve the signal-to-noise for the surface-consistent calculations. The better surface sampling meant that there was no need for the interpolation that is often used as a pre-conditioning step for some algorithms in order to minimise artefacts. For 5D processing, data regularisation was not necessary, and interpolation was limited to just filling in acquisition holes.

Another particular advantage of the denser receiver carpet was to help generate an exceptionally detailed model of the near-surface, important for ongoing field activities, statics corrections (Figure 2a) and velocity model building for depth imaging. For depth model building, the refraction tomography velocities were inserted into the shallow section, followed by reflection tomography (Figure 2b).



**Figure 2** a) Near-surface representation from dense coverage of receiver and shot statics corrections, b) Zoom in of the near-surface extracted from the final PSDM velocity model.

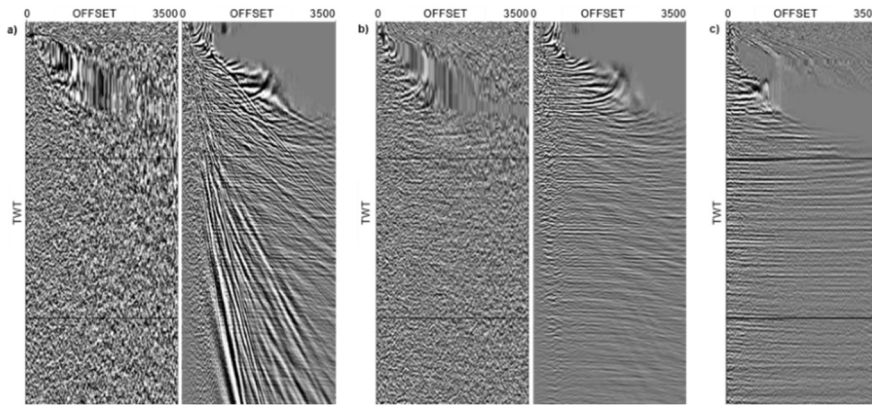
Additional testing was performed on the blended continuous records, which used an interferometry approach to build virtual shots containing ultra-low frequencies for the surface and refracted waves (Le Meur et al., 2020), as shown in Figure 3a. A new method for extending the surface-wave spectrum for dispersion curve picking was also introduced, to provide higher spectral and spatial resolution (Figure 3b). Subsequent dispersion-curve inversions through surface-wave inversion (SWI) incorporating a machine learning technique (deep neural network, DNN), and multi-wave inversion (MWI) including refraction picks, further enhanced the shallow velocity model (Figure 3c). As seen in Figure 3d, some of the distortion not corrected with refraction tomography statics (highlighted by the red arrows), were partially corrected with SWI statics (middle image), and improved further with MWI (green arrows).



**Figure 3** a) Dispersion curve with ultra-low frequencies, b) Dispersion curve with extended surface-wave spectrum, c) Velocity depth slice at 35 m from refraction tomography, SWI with extended bandwidth and MWI, d) Statics stacks for respective models.

A key challenge throughout, and particularly at the early stages of the workflow, is the quality control (QC) of each processing step, due to the low signal-to-noise ratio on the raw records. To overcome this challenge, pre-stack time migration was widely implemented to provide confidence at each stage. For example, to QC LNA on gathers, all discrete offsets were pre-stack migrated and super-binned to provide linear offset sampling (Figures 4a,b). An example of the final processed pre-stack depth migration (PSDM) CMP gather with significantly improved signal-to-ratio across all offsets is shown in Figure 4c. Post-stack time migration was performed to QC the full area. The impact of each process in the amplitude and frequency domains was also routinely evaluated for QC purposes.



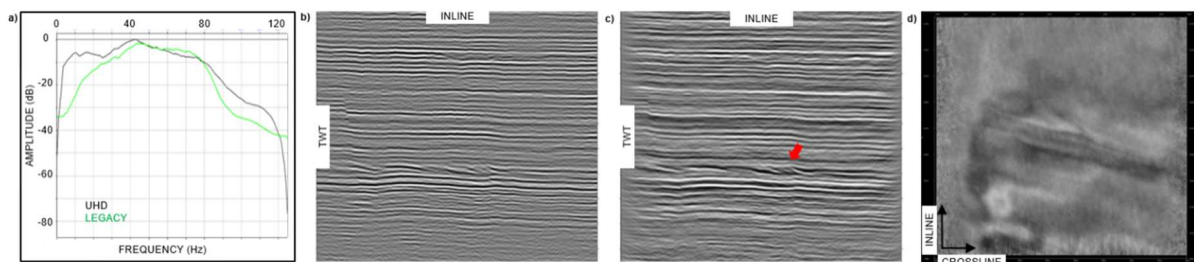


**Figure 4** a) Un-migrated (left) and migrated (right) CMP gathers prior to LNA, b) Corresponding gathers after LNA, c) Final PSDM CMP gather with a fold of 7200 (maximum offset 3500 m).

Most blended acquisitions use a larger geometry spread with longer offsets recorded over an entire swath/zipper. Together with a high-fidelity vibroseis source, this is likely to provide a broader bandwidth (starting at low frequency 1-2 Hz), suitable for advanced broadband processing such as full waveform inversion (FWI) imaging. On this survey, the final results were considered to be broadband with nearly 20 Hz more at low, and 10 Hz at high end of the spectrum (also with better resolution and lower noise) compared to the legacy data (Figure 5a). Hence overall, even though the legacy source-receiver array survey was acquired with a higher effort, using more sensors and sources, the nodal survey results are superior (Figures 5b,c).

Besides continuous recording of the seismic data, extended field metadata such as the GPS times and ground forces were also included as part of the de-blending workflow. Deterministic matching of the times and derived source signatures allowed accurate phase control of the recorded data, as confirmed by well tie analysis.

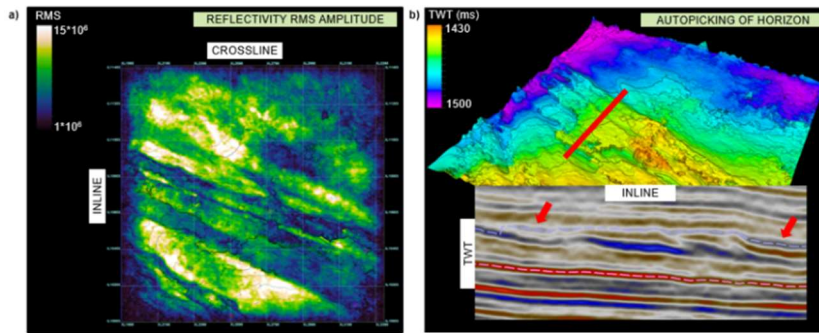
Another key benefit of UHD data is the useable quality of any fast-track stack, readily produced at any stage, with minimal processing. For this survey, subtle geological features (clinoforms) were clearly visible on an initial post-stack migration with refraction statics, preliminary velocity field, scaling, but no de-noise was applied (Figure 5d).



**Figure 5** a) Amplitude spectra in green for Legacy, in black for UHD, b) Crossline for Legacy data and c) UHD data with location of main clinoform highlighted by the red arrow, d) Timeslice showing the imaging of main clinoform with fast track processing.

Besides the higher resolution obtained from the seismic imaging of ultra-high density data, the increased sampling in azimuth and offset, consisting of 7200 COVs for this survey, also provided significant improvements in the resolution of seismic attributes (Figures 6a,b). This is in general beneficial for subsurface interpretation and reservoir characterization (Ourabah et al., 2015b).

Ongoing improvements in high performance computing (HPC), Big Data technologies and the optimisation of software algorithms help to better manage the turnaround of increasingly large datasets (e.g. 15 billion traces for this 9x9 km survey). These include efficient sorting between different domains, extensive testing ability and usage of highly-intensive processes (e.g. pre-stack time migration QC of de-noise data, specular imaging).



**Figure 6** a) Reflectivity RMS amplitude extracted at horizon from final PSDM volume, showing high definition of each clinoform and high amplitude fidelity, b) Auto-picked horizon and zoom in on the main clinoform, showing again good resolution of the main structures. Arrows indicate picked horizon.

## Conclusions

We have highlighted some positive and encouraging early insights into processing using the latest ultra-high density nimble node survey and available land seismic technologies. Without requiring wholly new techniques to be developed, we have shown that UHD blended point source and nodal point receiver acquisition can deliver a superior image compared to traditional unblended source arrays and cabled receiver arrays, including such surveys with higher effort (using more sensors and sources). There is still more to be explored, particularly in the areas of internal multiple attenuation, advanced depth workflow (FWI imaging), and machine learning. By meeting the processing challenges posed by UHD surveys, we believe the demonstrated improvements in seismic imaging results shown here will continue the drive to even higher, ultra-UHD, surveys in the future.

## Acknowledgements

The authors would like to thank BP, STRYDE, ADNOC, and CGG for their permission to publish this paper. We acknowledge the work of our colleagues from CGG Crawley Subsurface Imaging team.

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