Advancements in Seismic Data Acquisition and Processing: The First Broadband 3D Marine Vibrator Survey in the North Sea

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Summary:

We present the results of the processing and imaging of marine vibrator (MV) alpha test data recently acquired at the Johan Sverdrup field in the North Sea. The alpha test includes a 3D survey using a single MV across a frequency spectrum of 3-150Hz and additional testing of several 2D source-lines using two MVs. Moreover, two ultra-low frequency (ULF) test lines were conducted over a 1-8Hz frequency range. The preliminary processing results of the 3D survey are on par with those derived from the legacy airgun array acquisition, thereby affirming the viability of employing MV technology on a large scale.

Introduction:

Recent discussions have highlighted various capabilities of the marine vibrator (MV), particularly in effective acquisition, optimised spatial wavefield sampling and reduced environmental effects, facilitated by its high-precision control over emitted signal (Laws et al., 2019). These give the possibilities for novel survey design (JafarGandomi et al., 2023, Wang et al., 2023). In recent years, several 2D field tests utilising different MV technologies with output frequencies below 100Hz have been conducted (Teyssandier & Sallas, 2019; Alfaro et al., 2023; Harnar Singh & Zawawi, 2023). This paper presents the first broadband (3-150Hz) 3D alpha-test of the MV, conducted in the summer of 2023 at the Johan Sverdrup field, approximately 140km west of Stavanger, Norway (JafarGandomi et al., 2024). The field, operated by Equinor ASA and its partners AkerBP ASA, TotalEnergies EP Norge AS, and Petoro AS, is located at a water depth of about 120 meters. In this paper, we focus on the 3D dataset. We will first briefly introduce the acquired data, followed by the key processing steps applied. The migration outcomes of the MV data will be compared with the image obtained from the legacy airgun array. Ultimately, the critical acquisition differences between the MV used for this test and the airgun array of the legacy survey will be discussed.

Data acquisition

During the alpha test, 3D data were acquired using a single MV, along with several test lines, including ultra-low frequency (ULF) lines, also using a single MV. Additionally, several test lines utilising two MVs were conducted using an array of two vibrators, one emitting a low-band sweep covering 3-25Hz and another emitting a high-band sweep within the 25-150Hz range. Two ULF test lines spanning 1-8Hz were similarly acquired using a single MV. This paper presents the initial processing results from the 3D survey. The processing of additional test lines is currently underway and will be detailed in future publications.

During the acquisition, the MV continuously emits sweeps. For the 3D test, each sweep is a 10-second non-linear up-sweep with phase modulation [0°, 90°, 0°, 90°, …]. This technique efficiently attenuates residual sweep noise (Laws et al., 2019). Given that the source is moving during the acquisition, the concept of a source point in airgun acquisitions does not apply to the MV scenario. Instead, source-point locations are associated with fixed predefined locations where the sweeps are activated. In this sense, the 10s sweep, with a vessel speed of 4.5 knots, achieves a nominal source spacing of 25m. The receiver spacing along the Permanent Reservoir Monitoring (PRM) cables is 50m, and the distance between neighbouring receiver lines varies between 200m and 400m.

Data processing

The main processing strategy is to transform the MV data, which is acquired by a continuously moving source, into a data acquired by an impulsive source. This approach ensures that the following processing sequence remains the same for MV and airgun data. In the initial stage of preprocessing, it is essential to construct the common receiver gathers from the recorded data based on the nominal source-point locations. Maintaining sufficient record length during this stage is critical due to the long source signature, which will require deconvolution in the following processing stage.

Accurate estimation of the notional source (NS) signature is essential for effective deconvolution (Telling et al., 2023; Wang et al., 2023). Accelerometers are mounted on both sides of the MV radiators, and near-field hydrophones (NFHs) are also attached to the MV. We have demonstrated that either sensor type can be used for NS estimation. We evaluated all options and found that the NS estimation using accelerometers closely aligns with results from estimated NS via joint inversion. We have used the accelerometers (ACCs) for NS estimation to optimise processing efficiency in this case.

We first applied deterministic component rotation and calibration to the P and Z components during processing. This was followed by an approximate trace-by-trace 1D deconvolution, which effectively removed the phase modulations employed in the field. This step is critical for facilitating data windowing and de-blending. However, source motion—a time and frequency-dependent effect—remains in the data and is then corrected simultaneously along with sweep deconvolution, de-ghosting, wavefield interpolation, de-blending, and re-datuming (JafarGandomi et al., 2023 and 2024).

The processed P- and Z-components have been used for up-down wavefield separation and deconvolution (UDD). These processed gathers underwent migration using Kirchhoff pre-stack depth migration. For comparison, legacy airgun data from a triple-source airgun ($1800in^3$) was processed in parallel and underwent the same migration process. The aperture for the legacy data was specifically tailored to replicate that of the MV acquisition, with no modifications or synchronisation applied to either dataset.

Figures 1a and 1b illustrate the migrated UDD results from the legacy airgun and MV acquisitions, respectively. Detailed inspection of these images in the middle and deeper parts of the section reveals comparable image quality. The comparison between the MV and airgun images reveals a strong resemblance in the character and detail of geological structures down to the base of target formations at approximately 2.5km depth.

Processing of the ultra-low frequency (ULF) data is ongoing, with initial evaluations indicating significant signals even below 2Hz. Further imaging and inversion efforts for this ULF data are currently underway.

Discussions

Although Figure 1 demonstrates a good similarity between the images from the airgun and MV acquisitions, it is important to note that the energy emitted by the MV was significantly lower than that of the corresponding airgun array. Specifically, the MV's emission was approximately 14.1 dB re uPa^2.m^2.s lower than the legacy airgun, according to far-field signature calculations for vertical incidence over a 10-second record. This equates to one sweep emission with MV (25m sweep spacing) and two airgun-array shots (12.5m source spacing).

This difference in emitted energy affects the signal-to-noise ratio, particularly in deeper areas, as shown in Figure 1b. Moreover, a distinct difference between the MV and legacy airgun acquisitions was the presence of strong seismic interference (SI) from an airgun acquisition conducted around 35km away during the MV acquisition, which was absent in the legacy data. Efforts to mitigate this interference are in progress, with promising preliminary results, although these were not incorporated into the preliminary processing results presented here. Despite these challenges, the processed images from the MV are comparable to those from the SI-free legacy images. Future research will continue to investigate the impact of SI on different source types, i.e. impulsive sources interfering with continuous sweeping.

Conclusions

The broadband 3D MV Alpha test was successfully completed, covering 3-150Hz. These data's preliminary processing and imaging demonstrate that the images are comparable to those obtained from the legacy airgun array acquisition. The objectives were achieved despite the presence of seismic interference (SI) noise in the MV data and the lower energy levels emitted by the MV compared to the airgun. The full processing of this data is ongoing, and additional results will be presented in the near future.

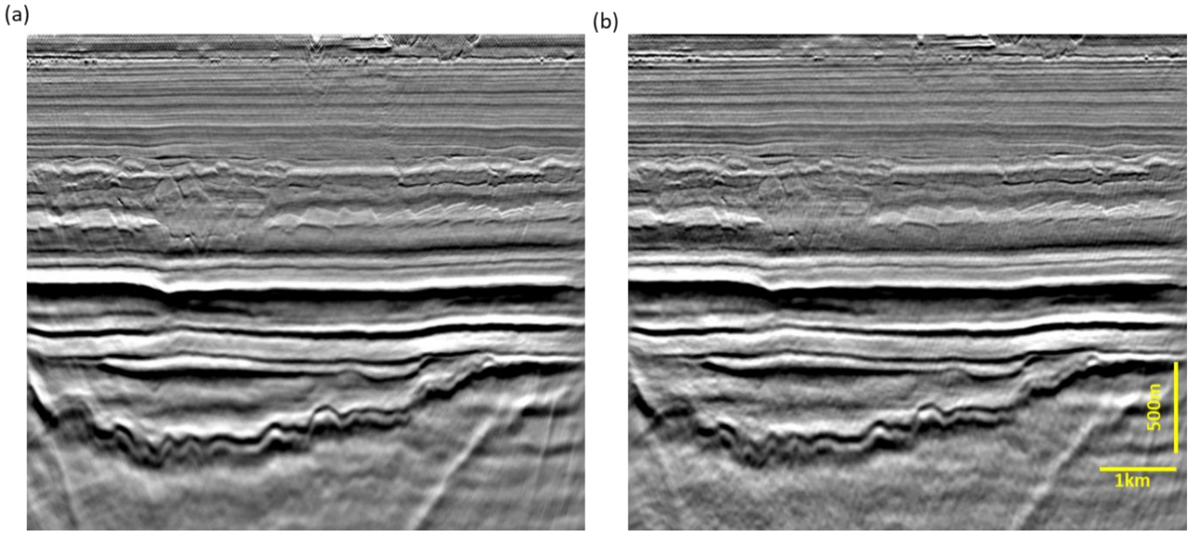

Figure 1. *Pre-stack depth migrated images of the UDD results for a) legacy airgun acquisition and b) for the 3D swath of MV.*

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