A Marine Vibrator 3D Acquisition and Processing story

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Summary

In 2023, a first 3D survey using towed marine vibrators (MVs) was conducted over the Johan Sverdrup field in the North Sea. The survey, employing both low-band and high-band units, covered a broadband seismic frequency range from 3 to 150 Hz.
The incorporation of phase encoding effectively minimized residual sweep noise, eliminating the need for silent breaks between sweeps and achieving nearly 100% utilization.
An additional test confirmed robust low frequency signal emissions in the 2-8 Hz range, which is useful for Full Waveform Inversion (FWI) and imaging.
This survey was also the first time the entire acquisition system was tested, including towing, handling, positioning, control software, source signature measurements, and Quality Control (QC).
The dataset collected in this survey proved valuable for processing and imaging tests.
Processed MV data compared well with legacy airgun-based data, highlighting the potential of employing marine vibrators for large-scale broadband seismic surveys in both 3D and 4D settings.

Introduction

Driven by potential advantages in terms of both efficiency and reduced environmental footprint (Southall et al., 2019; Matthews et al., 2020), a new generation of marine vibrators (MVs) is being developed.
In this paper, we describe the first 3D field test of the BASS (Broadband Acoustic Source System) marine vibrator (MV), and the processing results.
The acquisition was performed in 2023 over the Equinor-operated Johan Sverdrup Permanent Reservoir Monitoring (PRM) system in the North Sea offshore Norway. The water depth in the area is around 120 meters. The Sverdrup field produces from a sandstone reservoir at a depth of around 1,900 meters.
The goal of the field test was to test the functionality of the newly developed MV system, and to compare the processed MV data with legacy airgun data from the same area.

Method - acquisition

The MV survey included several 2D test lines with two vibrators sweeping in parallel, two ultra-low-frequency lines using only a low-band (LB) unit, as well as a broadband 3D patch consisting of 30 neighboring source lines designed to provide a 3D migration aperture for imaging down to the reservoir level. The latter was acquired with a single vibrator in broadband mode. This allowed comparison of the MV data with legacy airgun-based data from the same field.
The towing speed was around 4.8 knots, similar to the speed used with airguns. A drone photo from the acquisition can be seen in **Error! Reference source not found.**.

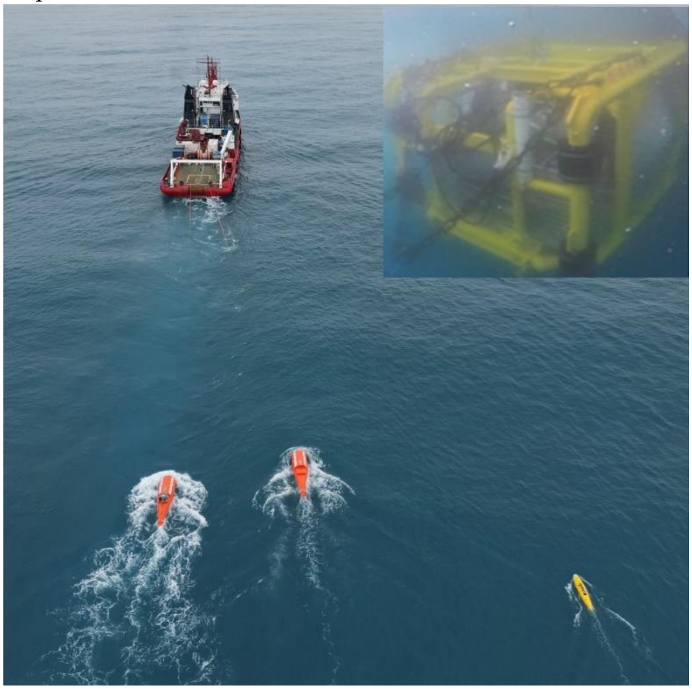

Figure 1. Drone photo showing the two MVs being towed (under the red floats). An underwater picture of one of the units is inserted in the top right corner. The yellow float is part of the door that pulls sideways ensuring a stable separation between the units.

The survey provided an opportunity to test the complete acquisition setup, including towing and handling, positioning, control software, source signature measurements, and quality control (QC). During the survey, we also tested several novel marine vibrator (MV) features: Firstly, the emitted energy was optimized by deploying each electrically powered and hydraulically driven vibrator at a depth appropriate to its emitted frequency range and ghost response. Accordingly, the LB vibrator was deployed at a depth of 15m, and the high-band (HB) unit was deployed at a shallow depth of 5m as suggested by Laws and Morice (1999). Such a bandwidth specialization is also valuable in the design of the units themselves since each was optimized for efficiency over the frequency range it emitted. Nevertheless, all the MVs can emit all frequencies if needed. The nominal acquisition setup used during the survey is illustrated in Figure 1, where one LB unit [3-25] Hz and one HB unit [25-150] Hz are towed. Together they formed a broadband [3-150] Hz source.

Secondly, a new phase-encoding method was applied to consecutive sweeps, following a [0°, 90°, 0°, 90°...] pattern. This phase sequence, which cannot be implemented with airguns, shifts the residual sweep noise (RSN) energy in the frequency-wavenumber (f-k) receiver domain, making it easy to remove, as shown by Laws et al. (2019). This allowed continuous operation of the vibrators without needing significant silence or listening time between sweeps. Consequently, we used a 5 second (12.5 meter) flip-to-flip sweep-point-interval (SPI) with the high-band (HB) vibrator, and a 10 second (25 meter) SPI for the low-band (LB) vibrator. For the LB, this SPI is on par with conventional airgun-based surveys. The HB SPI exceeds what is typically used with an airgun arrays, because of the limitations in the gun-filling time and the need to allow the airgun residual shot noise (RSN) to decay.

Method - processing

On the processing side the strategy was first to convert the continuously emitting MV data to an equivalent impulsive source data at predefined source-point locations. Once this transformation is done, the remaining migration and processing steps are identical for both MV and airgun data.
The first stage in processing the recorded multicomponent data involves creating common-receiver gathers based on nominal source-point locations. At this point, it is important that the gathers have sufficient length to handle the extended source signature (the sweep), which must be deconvolved.
Accurate estimation of notional source (NS) signatures is essential for effective deconvolution (Telling et al., 2023). The MV has multiple accelerometers on the radiators and several near-field hydrophones (NFHs), all of which can be used to estimate NS signatures. Both the PRM P- and Z-components were processed, with deterministic rotations and calibrations applied to the data.
Initially, an approximate sweep deconvolution was performed on each trace as a 1D operation. This removes the phase encoding in each record, allowing for data windowing and the separation or removal of any remaining sweep noise. However, source motion, which varies with time and frequency, remains in the data.
After windowing, a global pilot sweep with the same frequency-time characteristics as the emitted sweep is convolved with the data. This is followed by joint corrections for source motion, free-surface ghost, interpolation, de-blending, and re-datuming to the desired level. Once the source motion has been corrected, the sweep can then be correctly deconvolved. All these processing steps occur in the common-receiver domain.

Results

In Figure 2 sample common receiver gathers from the PRM field are shown together with their corresponding frequency-wavenumber spectra. The MV data were acquired using one LB unit and one HB unit as described earlier, while the airgun data are from a conventional 1800in^3 source. Figure 2 demonstrates similarity between the MV and the legacy airgun gathers both in terms of character and details of events. Notice how the denser trace spacing on the HB MV data compared with the legacy airgun-based gather results in a smooth and continuous gather and reduces the spatial aliasing observed in the frequency-wavenumber domain.

Figure compares a 2D slice from a 3D PSDM volume of legacy airgun data and the new MV data. This MV volume was produced with only one vibrator unit. Consequently, the energy emitted was significantly reduced. Nevertheless, comparison of the MV and the airgun images shows strong similarity in both the character and detail of structures down to the base of target formations at around 2.5km. Furthermore, even the major dipping events extending to 4km are nicely imaged and can easily be tracked on both airgun and MV images. As a sidenote we mention that the MV data recordings contained strong seismic interference noise. The attenuation of this noise was a challenging task that required significant development and work. This leads us to Figure 4 which shows a 4D NRMS slice from the reservoir level. This image was produced by doing a global matching between the legacy airgun data and the new MV data, without any special 4D processing. We notice that the NRMS level in the central areas are down to around 10% (within a 0-200% scale), which is in line with what is typically seen in dedicated towed streamer 4Ds. This is therefore a strong indication that a carefully prepared and processed vibrator repeat survey on an airgun baseline should be feasible. The last image we show is in Figure 5. It shows a comparison from a test-line where we used one of the MVs for emitting ultra-low frequencies (ULF) in the [1-8] Hz range. By placing all the energy in this

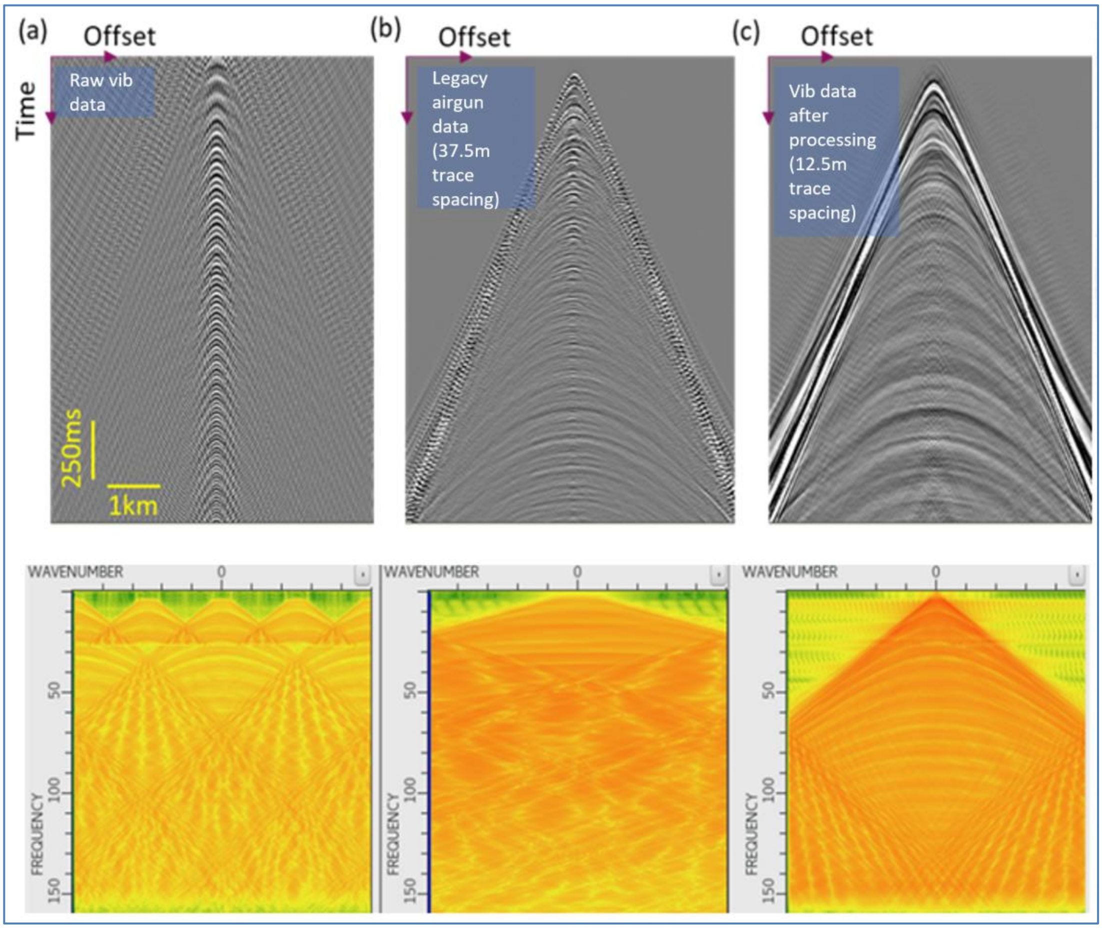

*Figure 2. Sample common-receiver-gathers from a) raw marine vibrator, b) raw legacy airgun-array, c) marine vibrator after de-ghosting, de-blending, re-datuming and source motion correction. Below are corresponding frequency-wavenumber spectra. The trace-spacing for a and c is 12.5m and for b 25m. Notice the reduction in aliasing in the frequency-wavenumber spectra for the MV data resulting from the 12.5m sampling. The range of wavenumber axes is up to ± 1/(2*trace spacing).*

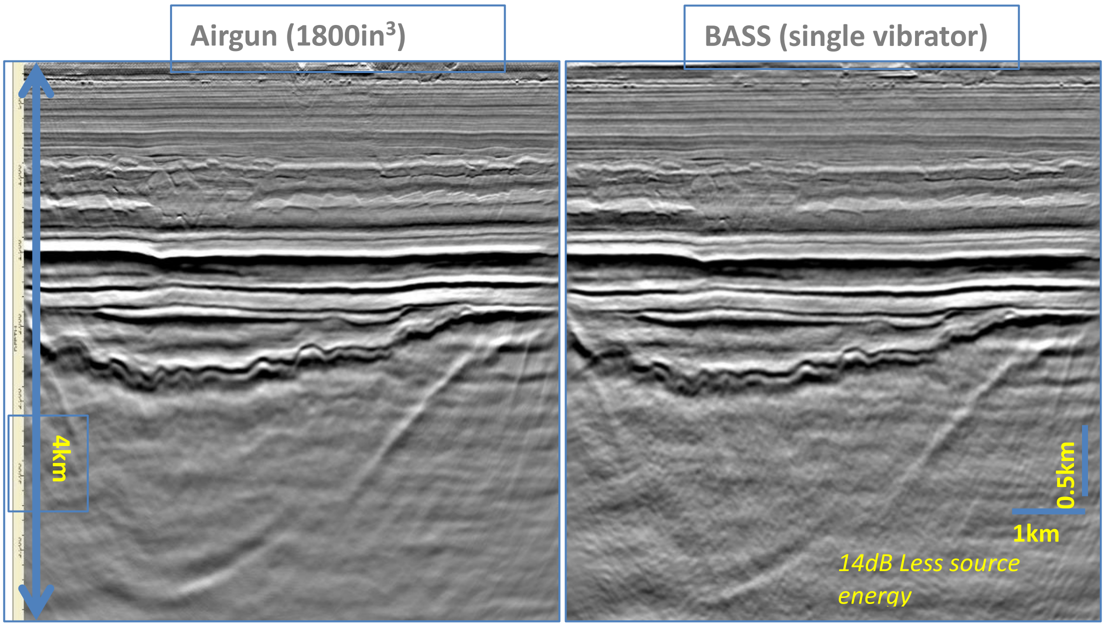

Figure 3. A 2D vertical slice from a 3D PSDM volume, comparing the marine vibrator data with legacy airgun data.

ULF range, we were able to get very good LF signals down to 1.8Hz which should be relevant for long offset acquisition and FWI.

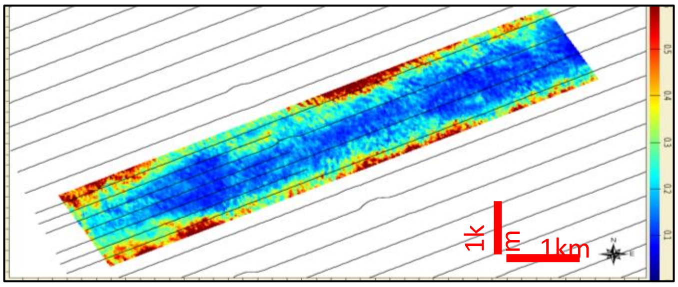

Figure 4. NRMS at the reservoir level between legacy airgun data and the MV data. The patch size is ~ [1.5 x 10] km.

Conclusions

The MV alpha test was successfully completed, including the acquisition of a 3D swath of data using a single vibrator unit covering frequencies from 3 to 150 Hz, as well as several test lines with a two-unit source array. Processing and imaging of these data produced images comparable to those from previous airgun array acquisitions, despite the MV emitting significantly less energy and having strong SI noise present in the data. We also show that the MV can emit valuable signal even below 2Hz and that a MV survey can realistically be used to repeat a baseline survey initially conducted with airguns.

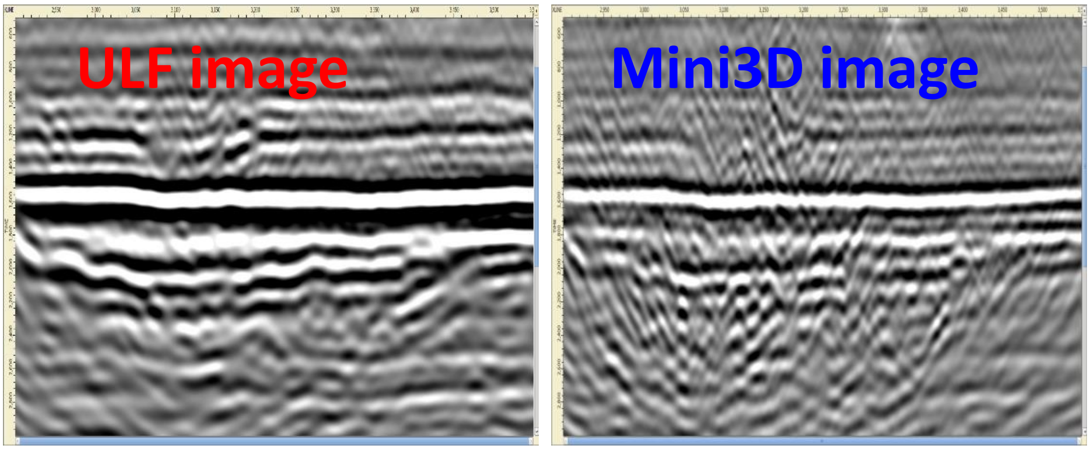

Figure 5. Left: ULF image in the [2-8] Hz range. Right: The corresponding [2-8] Hz image from the mini3D acquisition.

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