The first Broadband Marine 3D vibrator survey

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Summary

Recently, the first-ever 3D broadband survey utilizing towed marine vibrators (MVs) was successfully acquired over a North Sea permanent reservoir monitoring (PRM) system. Two vibrators were deployed, one low-band unit and one high-band unit, collectively covering the entire seismic frequency band from 3 to 150 Hz.

The implementation of phase encoding proved effective in efficiently reducing residual sweep noise. Consequently, a nearly 100% utilization rate was achieved, eliminating the need for a silent period between sweeps.

In an additional test, the survey demonstrated the emission of robust signals in the 1-8 Hz range, which holds significance for Full Waveform Inversion (FWI) applications and imaging.

The survey encompassed comprehensive testing and verification, including towing and handling, positioning, control software assessment, source signature measurements, and Quality Control (QC) measures, forming a holistic acquisition system.

In comparison to airgun-based sources, marine vibrators exhibited a notable decrease in peak pressure and out-of-band (high-frequency) noise pollution.

The processed MV data displayed favorable comparisons with legacy airgun-based data, highlighting the realistic potential of employing marine vibrators for large-scale acquisition of broadband seismic data.

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Introduction

The first generation of marine vibrators (MVs) were developed in the late 1960's and deployed commercially in the 1970s. According to Landrø and Amundsen, (2018), it was acknowledged that the acquired data was of decent quality but lacked low-frequency content. Furthermore, compared with airguns, these early vibrators were bulky, slow- and prone to failure. As a result, airgun-based sources held a dominant position in the marine seismic market for over 50 years.
However, today there are two new drivers for MV technology: improved survey efficiency/quality and a perceived reduced environmental impact. Geophysically, MVs offer precise control over signal spectrum and phase. This enables highly effective deblending, removal of residual sweep noise, and enhanced resolution or improved efficiency by an alternating sequence of monopole and dipole sweeps (Laws et al., 2019). Moreover, when properly designed, a MV can function as a powerful low-frequency (LF) source.

Environmentally, MVs present intriguing advantages over airgun-based sources. They are continuous (not impulsive) sources and are therefore inherently less impacting for the same emitted sound energy (Southall et al., 2019; Matthews et al., 2020). Also, because vibrators spread out the signal over time, the peak amplitude is reduced. In addition, they largely avoid the emission of energy outside the seismic frequency band of approximately 3 to 150 Hz. Finally, by tailoring the output signal to the noise levels in a survey area, it is possible to reduce the overall emitted energy without compromising the image Signal-to-Noise Ratio (SNR) (Jafargandomi et al., 2021).

This study describes the recent MV field test and 3D survey conducted using the BASS (Broadband Acoustic Source System) marine vibrator over the Johan Sverdrup Permanent Reservoir Monitoring (PRM) system in the North Sea. The goal of the field test was to validate the newly developed MV system by acquiring a 3D survey and processing both 2D and 3D seismic datasets and finally compare the processed MV data with legacy airgun data from the same area.

Method

The Johan Sverdrup oil field is situated in the North Sea, about 140 km west of Stavanger, Norway. It is operated by Equinor ASA, with partners AkerBP ASA, TotalEnergies EP Norge AS, and Petoro AS. The water depth in the area is around 120 meters. The field came online in 2019 and is producing from Upper Jurassic intra-Draupne sandstone at a depth of around 1,900 meters. In 2019 and 2020 a Permanent Reservoir Monitoring (PRM) system was installed. Since then, multiple vintages of 4D data using conventional towed airgun-based sources have been acquired.

In June and July 2023, we acquired data with a MV system over parts of the PRM system at Johan Sverdrup. Two vibrators were included in the test, one low-band (LB) vibrator [3-25] Hz and one high-band (HB) vibrator [25-150] Hz.

An A-frame on the stern of a vessel of opportunity was used for deployment and recovery. The MVs were powered electrically via the umbilicals and suspended below floats as illustrated in Figure 1.
The MV survey consisted of several 2D test lines with both vibrators sweeping in parallel, two ultra-low frequency lines, using only the LB unit, as well as a 3D patch consisting of 30 neighboring source lines designed to provide a 3D migration aperture for imaging down to the reservoir level of around 1,900 meters or around two-second two-way travel time. This allowed comparison of the MV data with legacy airgun-based data from the same field.

Other aspects of the full marine vibrator system were also tested and validated during the field test, including towing and handling, positioning, control software, source signature measurements, and QC (Quality Control) measures. It is essential to test and validate supporting systems like these to ensure the successful development of a fully commercial system.

During this survey two novel methods were used to optimize the emitted energy from our vibrators: Firstly, consecutive sweeps were phase encoded creating a [0°, 90°, 0°, 90°...] sequence. This phase sequence, which cannot be implemented with airguns, shifts the RSN (Residual Sweep Noise) energy in the f-k receiver domain making it easy to remove as shown by Laws et al., (2019). This allowed the vibrator to run continuously (100% duty cycle), without any need for a significant silence or listening time between sweeps.

Consequently, a 5 second (12.5 meter) sweep-point-interval (SPI) was maintained 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 achievable with airguns arrays, due to limitations in the gun-filling time and the need to allow the residual shot noise to decay. A short SPI is beneficial since it effectively reduces high-frequency spatial aliasing in the recorded data. Secondly, the emitted energy was optimized by deploying each vibrator at a depth appropriate to its emitted frequency range and ghost response; Accordingly, the LB vibrator was

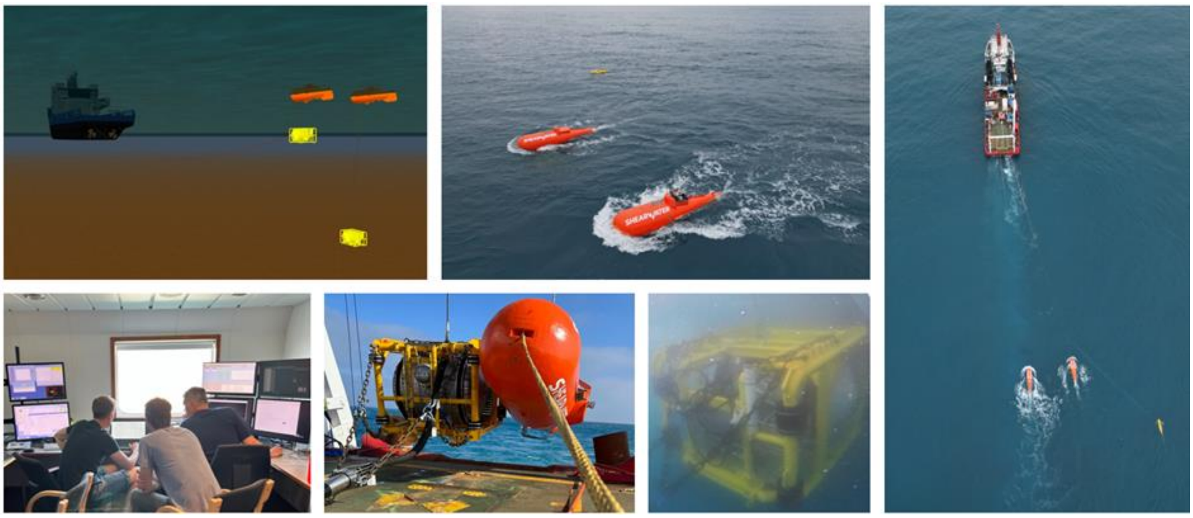

Figure 1. A collage of images and illustrations from the marine vibrator system Alpha test. In the nominal setup two vibrators were deployed (one deep tow LB unit, and one shallow tow HB unit.

deployed deep at 15m, and the HB unit was deployed shallow at 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 vibrators can emit all frequencies if needed. The nominal acquisition setup used during the survey is illustrated in the images in Figure 1, where one LB unit [3-25] Hz and one HB unit [25-150] Hz are shown.

Figure 2 shows raw shot gathers recorded on the PRM system from the nominal acquisition setup. As expected, (not shown here), the sweep-to-sweep repeatability of the vibrators was excellent, and harmonic distortion was well controlled. As one of the first steps in in the processing sequence, the recorded raw vibrator data needs to be deconvolved using the sweep signal that was emitted by the

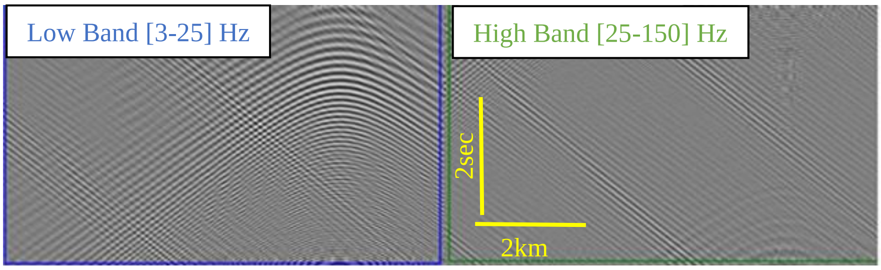

***Figure 2.** Raw vibrator data recorded on the PRM system. The 'straight' lines in the gathers are seismic interference from an airgun-based survey ~35km away.*

vibrators to form 'normal' looking seismic data. This deconvolution step requires an accurate source characterization, which is enabled by accelerometers and near-field hydrophones mounted on or near the vibrator itself.

Several 2D lines were acquired with both units sweeping in parallel. The main 3D survey was conducted using only the HB vibrator operating in the full [3-150] Hz range. Compared to the legacy 1800cu.in airgun array, having only one or two vibrators means that we emit significant less energy in the seismic band. This is likely to reduce the image SNR. Furthermore, the acquisition was conducted during the busy North Sea summer and strong seismic interference was experienced from two airgun-based surveys conducted ~35 and ~50 km away. This added noise resulted in a further reduction in SNR Despite this, the imaging results were excellent, as shown in JafarGandomi et al. (2024).

Results

Several 2D test lines and a 3D dataset were successfully acquired, processed, and compared with legacy airgun-based data. Figure 3 compares a sample common receiver gather from the MV test at various stages with the corresponding legacy airgun gather. This MV data was acquired using one LB unit towed at 15m depth and one HB unit towed at 5m depth. Both units were operating simultaneously emitting 10s sweep and 5s sweep, respectively. Figure 3a and 3b show the raw MV and airgun gathers, respectively and Figure 3c depicts the MV gather after 1D sweep-by-sweep deconvolution. Figure 3d shows the processed gather, including de-ghosting, re-datuming, de-blending and source-motion correction. Corresponding frequency-wavenumber spectra are shown in Figures 3e-3h.
Figure 3 demonstrates a great similarity between the MV, and the legacy airgun gathers both in terms of character and details of events. However, notice how the denser trace spacing on the HB MV data compared to the legacy airgun-based gather results in a smooth and continuous data gather and reduces the spatial aliasing observed in the frequency-wavenumber domain. Further details on the processing and imaging of these data are provided in JafarGandomi et al. (2024).

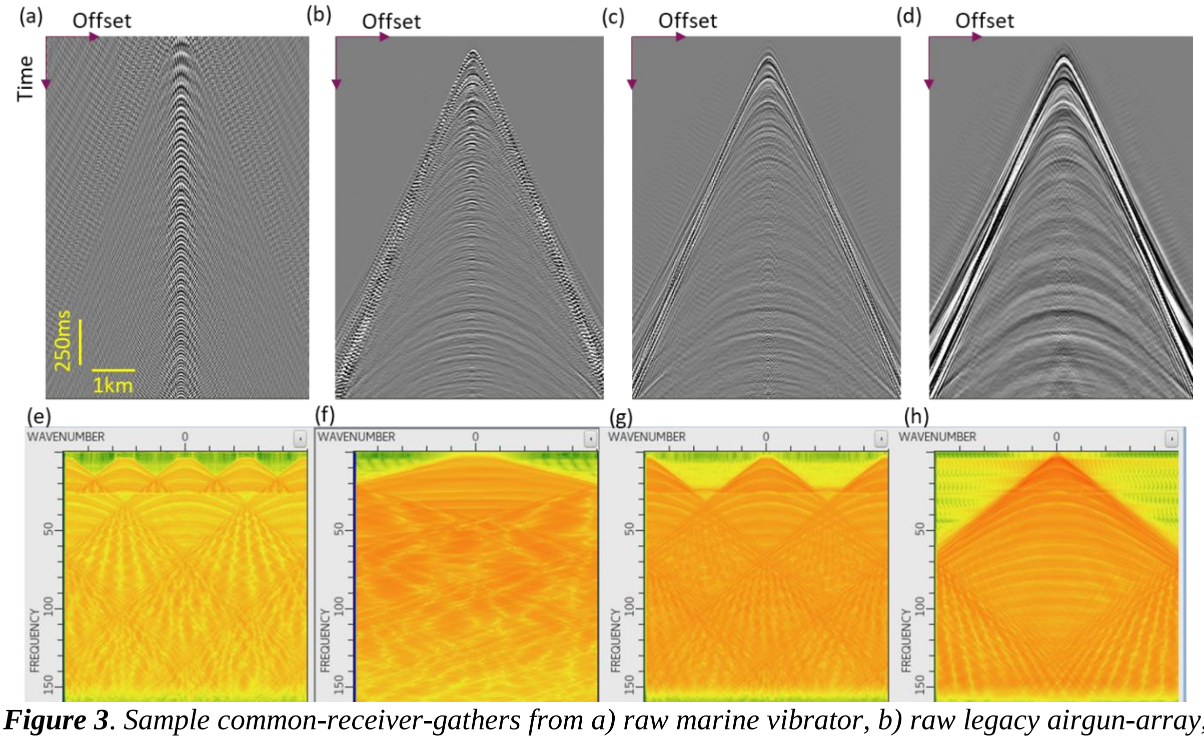

***Figure 3**. Sample common-receiver-gathers from a) raw marine vibrator, b) raw legacy airgun-array, c) marine vibrator after 1D sweep deconvolution and d) marine vibrator after de-ghosting, de-blending, re-datuming and source motion correction. e-h are corresponding frequency-wavenumber spectra. The trace spacing for a, c and d is 12.5m and for b 25m. Notice how the MV data in e, g and h limit the HB energy above 150 Hz.*

As an additional test, two low-frequency (LF) lines [1-8] Hz were acquired with the LB vibrator towed at 15m depth. In Figure 4 we have used this data to model the acoustic output from 3 vibrators towed at 25m depth and doing a 10sec sweep. The emitted energy is then compared with the measured notional source energy from one pop of a conventional 3110 cu.in airgun array towed at 6m. In this case, the

vibrators were able to emit significantly more energy in the 1-4 Hz range than the airguns. At 2Hz the difference is almost 10dB. This illustrates how vibrators allow for optimal generation of energy where it is wanted and the ability to tailor sweeps to given imaging requirements.
This mode of operation is interesting in connection with so-called FWI surveys, where the combination of long offsets and sparse receiver grid is used to build up a regional velocity model. With a MV, these types of surveys can be conducted without emitting any signal above, for example 10 Hz, which could lower the environmental footprint.

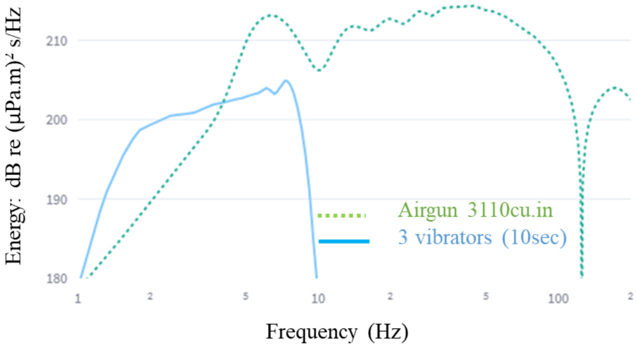

Figure 4. Comparing the notional source energy spectrum of a single airgun pop from a 3010cu.in airgun array towed at 6m depth, with the modelled (based on real measurements) notional source energy from a 10 sec [1-8] Hz sweep conducted with 3 vibrators towed at 25m depth. (Such a vibrator setup will have towing complexity comparable to an airgun array.)

Conclusions
We have successfully acquired and processed the first broadband 3D survey with a full marine vibrator (MV) system. The acquisition was set up to optimize the energy output from the vibrators to allow for imaging of a typical North Sea reservoir. Furthermore, it allowed us to test the entire system, including towing and handling, positioning, control software and QC. The resulting MV seismic data compares well with legacy airgun-based data, despite a much lower level of energy emitted by the MV. The results confirm that the MV-system is a viable alternative to airgun-based sources.

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