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Highlights from the Third EAGE Marine Acquisition Workshop

A recent industry workshop in Oslo addressed the burning issues in marine seismic acquisition, including the benefits and challenges of ocean bottom seismic (OBS) methods; source solutions to emit richer low frequencies, improve spatial sampling, or reduce environmental impact; supporting the transition to new energy, notably with regards to carbon capture & storage (CCS); or sharing some thought-provoking applications to interplanetary exploration.

Introduction

The Third EAGE Workshop on Marine Acquisition held recently in Oslo discussed several developments in marine acquisition technology and its applications. Pre-event promotion acknowledged the impact in recent years of global disruptions, including the energy transition, upon seismic technology demand. Indeed, the strong familiarity of most talks presented, having already featured at other industry events in recent years, pointed to the lack of investment dollars into acquisition hardware R&D. Speaking from experience, disruptive technology development is expensive, high risk, and takes several years of incremental testing and validation to move from concept to commercial reality.

Platforms for ocean bottom seismic (OBS) acquisition do not represent a cheaper or more efficient solution to acquire 3D and 4D data in comparison to towed streamer methods. Instead, any motivation to apply such solutions is typically either driven by whatever 'additional' information value can be provided (and with a measurable value), such as converted wave data for better reservoir property insights, ultra-long offsets for deeper velocity model building, or by logistical considerations such as operations in shallow water or congested areas with significant infrastructure. Workshop presentations indeed showcased the value of relevant OBS seismic and narrated an industry focus upon finding pragmatic ways to reduce costs.

Alternative seismic source concepts have been floating around for several years and tend to be driven by the fear that one day air gun source arrays will no longer be allowed to operate in large regions deemed by regulators to be environmentally fragile, or a desire to emit richer low-frequency signals beneficial to Full Waveform Inversion (FWI) stability. Several relevant presentations described a variety of air gun, pneumatic and marine vibrator source concepts.

So-called New Energy pursuits such as offshore wind or marine mineral exploration are focused upon seafloor and near-seafloor properties and require high-resolution temporal and spatial sampling platforms to enable the recording of signal frequencies more than 1000 Hz. Carbon Capture and Storage (CCS) in marine aquifers and depleted reservoirs will have a greater focus upon overburden properties than traditional time-lapse 3D ('4D') monitoring of reservoir production and may also benefit from high-resolution acquisition platforms. Both OBS and ultra-high-resolution (UHR) methods suffer a shared dilemma of inefficient acquisition rates (in square kilometers of data acquired per day), so much R&D focus is upon means to improve efficiency.

Several presentations addressed survey design concepts relevant to CCS site screening and monitoring, including the opening keynote presentation by Jens Olav Paulsen (Equinor), titled "Marine seismic acquisition, moving forward in the energy transition", which also addressed hydrogen storage and nuclear waste disposal. A workshop course titled "Geophysical Monitoring of CO2 Storage" by Martin Landrø (NTNU) was also offered to workshop participants on the third day after the technical program concluded.

Many industry perspectives written in recent years identify a general shift to more infrastructure-led exploration and reservoir monitoring to improve asset recovery, which correspondingly points to more 4D surveys, hybrid streamer-OBS acquisition and site survey / geohazard identification. Commonalities were also observed with the aforementioned CCS pursuits.

The 'Beyond Marine Seismic' session also included an invited presentation titled "Seismic exploration on the Moon, Mars and beyond", also a popular theme at recent SEG (Society of Exploration Geophysicists) annual conferences. Planetary geophysics increasingly has commercial focus as technologies become feasible to mine precious resources on the Moon and asteroids.

Looking Deeper into OBS Acquisition

Three talks addressed OBS acquisition and imaging. A keynote presentation titled “Marine seismic acquisition, moving forward in the energy transition”, profiled how marine surveys are applied for various applications, including CCS, wind farm preparations, and nuclear and hydrogen storage planning. Although lower costs are always sought, caution was given against compromising on technical specifications. Source sizes tend to be low-volume air gun arrays, and multi-source shooting is increasingly applied to improve spatial sampling and shallow seismic image resolution. No abstract link is available.

“Challenges and solutions in shallow and deep water ocean bottom seismic” by Claudio Bagaini (Schlumberger) attempted to manage expectations for data characteristics as a function of water depth and propose pragmatic compromises in data fidelity to improve survey efficiency. He defined ‘shallow’ water areas as being sensitive to multimodal and dispersive interface waves: either lower-frequency Scholte waves associated with a fluid-solid interface or higher-frequency guided waves often associated with post-critical energy and harder seafloor areas. The impact of temporal variations in the speed of sound in water is their criterion used to define the threshold between ‘medium’ and ‘deep’ waters. Shallow water surveys are challenged by inadequate (near) offset sampling and may benefit from hybrid survey designs complemented by short streamer arrays or innovative imaging solutions that can exploit the superior shallow illumination provided by surface multiples. Deep water surveys are challenged by water speed variations, positioning errors for deep receivers and clock drift.

With emphasis upon the potential value of converted (PS) waves for reservoir characterization and monitoring, “Time lapse 4D seismic – A success story from the Edvard Grieg field”, by Per Eivind Dhelie (Lundin Energy), drew upon experiences also published in the 2021 EAGE conference, the 2022 EAGE conference, and the M.Sc. Thesis published by Sima Daneshvar (who also co-authored the Best Paper presented on the same topic at the 2021 SEG conference). **Figure 1** below is from the 2021 EAGE conference and compares baseline data and the respective time-lapse signals for PP vs. PS data.

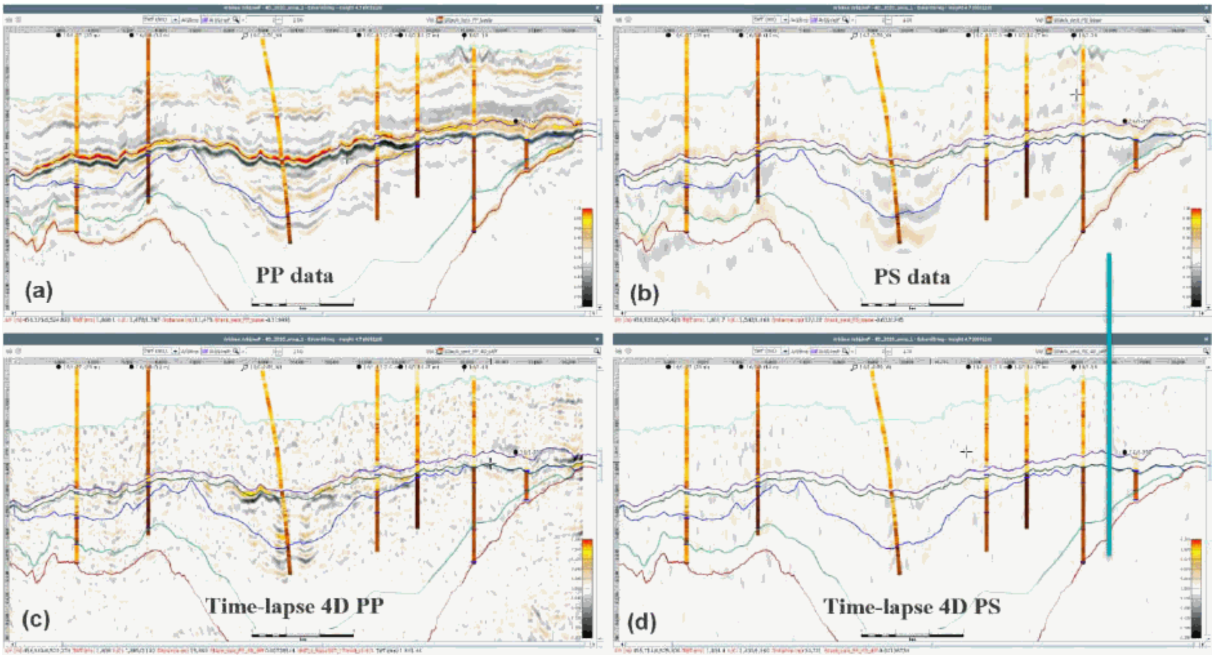

Figure 1: Full stacks generated from pre-stack OBS data over the Edvard Grieg field. The top row (a and b) shows the baseline PP and PS data, while the bottom row (c and d) are the corresponding time-lapse signals. From Dhelie et al. (2021).

Per Eivind shared an excellent history of the 4D monitoring since 2016, with a focus upon the evolution of how OBC (ocean bottom cable) surveys are being designed and exploited. Water depth for the Edvard Grieg field is about 110m. Originally drilled in 2007, first oil was produced in 2015, and current production of about 90 000 BBL per day is from 13 producer wells with pressure support from 4 injection wells. The first 4D OBC baseline survey in 2016 was acquired over existing 2008 OBC data. Monitor OBC surveys have since been acquired in 2018, 2020 and 2022. Notable changes in survey design include a growing focus upon converted wave (PS) events and PP-PS subsurface characterization, the use of small volume sources to enable better spatial sampling and faster shooting, shorter offsets, and the testing of various novel source concepts such as a deep-towed small 720 cu.in source to potentially enable weekly monitor surveys. The 2022 monitor survey used a wide-tow hexa-source configuration with uniform 25m source line separation synchronized with 150m sail line separation. Processing turnaround is now only a few days, with a future ambition of achieving weekly monitoring and near-continuous insights into subsurface production. Overall, it is estimated that the net investment in 4D seismic programs of $60m has been a major contributor to the forecasting of 50MMBL in increased 2P reserves, or about $3b revenue increase! Seismic imaging examples quite spectacularly showcase the oil movements, and guided the first infill well campaign in 2021, with a second infill campaign planned for 2023.

Best of Both Worlds with Hybrid Streamer and OBS Acquisition

"Hybrid seismic acquisition in the Barents Sea with streamers, free-drop nodes and 7 sources" also by Per Eivind Dhelie (Lundin Energy) discussed strategies to cost-effectively combine towed-streamer and OBS acquisition in a hybrid model. Their most successful such survey deployed almost 1 000 OBNs for the survey duration on a 1.2 x 1.2km grid and used a two-vessel operation to acquire both split-spread and long-offset streamer data. The Ramform Hyperion towed 18 x 8km streamers with 75m separation and one deep-tow large-volume source to enhance low-frequency signal content for FWI (full waveform inversion) model building. The Sanco Swift towed a world record hexa-source configuration with lateral distribution of 440m (refer also to **Figure 2**). Per Eivind discussed the strategy behind the survey design and highlighted the value of imaging the four complementary datasets acquired. Refer also to relevant papers in First Break, and both acquisition and imaging abstracts at the EAGE 2022 conference.

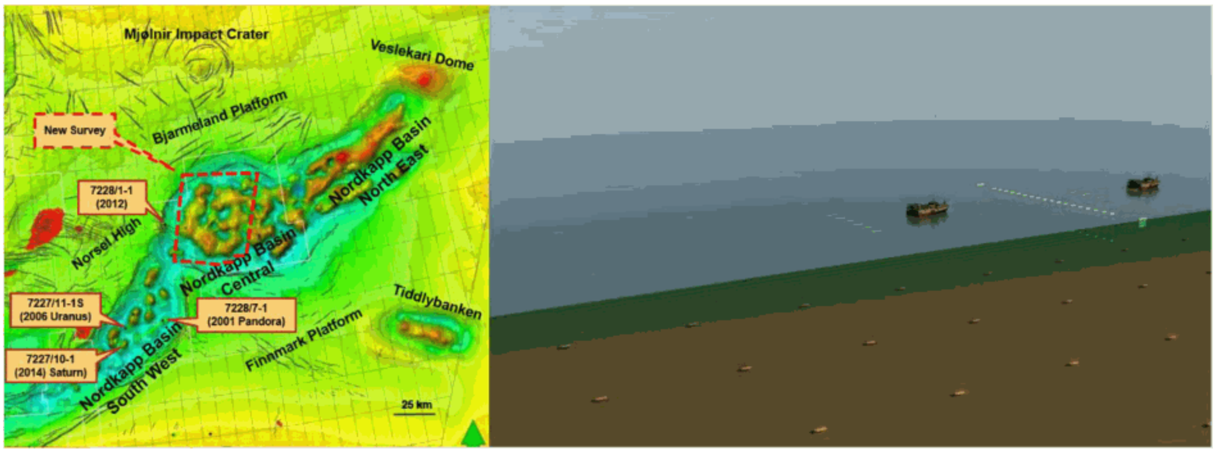

Figure 2: Location map (left) and schematic hybrid vessel and OBN geometry for the Nordkapp survey in the Barents Sea. From Dhelie et al. (2022).

"Optimization of operational costs when acquiring hybrid surveys with free-fall, self pop-up nodes" by Mellier et al. (Sercel and Ifremer) consider potential opportunities for free-fall seismometers in OBS surveys. They acknowledge that node-on-a-rope (NOAR) operations are limited to relatively shallow water and are not optimal for sparse deployment. Conversely, ocean bottom node (OBN) deployment by remotely operated vehicles (ROV) is well suited to deep waters, but very expensive. Features of their MicroOBS multisensor units were discussed, including the mechanisms for launch and recovery.

"OBN clock drift from an onshore processing point of view" was also presented by Paal Kristiansen (Schlumberger). No abstract link is available.

Looking into the Heavens

"Seismic exploration on the Moon, Mars and beyond", by Johan Robertsson (ETH Zűrich) was an updated version of a talk presented at the 2020 SEG conference. As shown in **Figure 3** from a 2018 publication in GEOPHYSICS, seismic experiments conducted during the Apollo missions to the Moon continue to provide a fertile laboratory to test novel signal processing concepts. For the seismic method to be applicable in future space expeditions, means need to be found to extract subsurface information from as little data as possible. **Figure 3** points to means by which measurements of the spatial gradients of the wavefield in addition to conventional geophone recordings can allow for detailed interpretation of seismic data with a minimum field effort.

Returning to earth, "Virtual receiver interferometry for offshore drill-bit seismic" by Alex Goertz (Octio), presented a novel interferometric method to reconstruct zero-offset VSP data from drill-bit variations passively recorded by OBN data placed near the drilling rig. A key element is that a wide-aperture array records finite-offset data with better signal-to-noise ratio (SNR) than would be measured at zero-offset, and these data can be used to reconstruct zero-offset data.

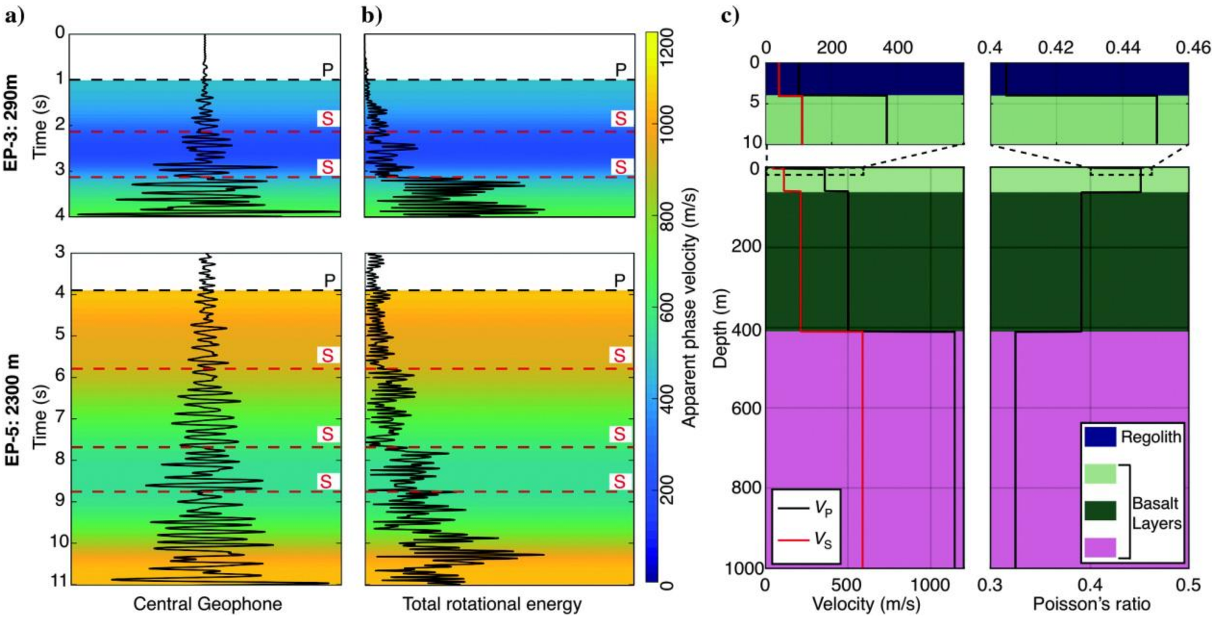

Figure 3: Analysis of the Apollo 17 active-seismic data using wavefield gradients as an additional observable (after Schmelzbach et al., 2018; Figure 9). In the left panels, example seismic data are shown for two explosive sources recorded by the central geophone of a star-like geophone array deployed on the lunar surface. The middle panel shows array-derived estimates of the energy in rotational ground-motion. The identification of S-waves yielded the shallow seismic velocity model of the lunar crust shown on the right.

A Lot of Air: Low-Frequency Air Gun and Pneumatic Source Concepts

"On long offsets and low frequencies", by Fons ten Kroode (Magseis Fairfield) kicked off a collection of solutions and concepts presented in recent years. Various experiences with sparse OBN surveys in the gulf of Mexico were described, with an emphasis upon ultra-long offsets for deep FWI model building in salt provinces. No abstract link is available.

Two presentations addressed the generation of higher amplitude low frequencies using traditional air guns with unconventional deployments, and one presentation addressed a high-volume, low-pressure pneumatic source concept.

"Improved low frequency output from seismic air guns by firing at shallow depths?" by Martin Landrø (NTNU) revisited high-volume (600 cu.in), shallow-depth air-gun tests published several years ago. Analysis of hydrophone recordings concludes that a mechanism to generate a single low-frequency spectral peak is preferable to bubble-tuned source output with several spectral notches. "Enhancing low-frequencies in airgun arrays" by Susanne Rentsch et al. (Shearwater) achieve up to 95% increase in effective bubble volume for a three-string array by configuring traditional air guns into a "hypercluster" arrangement. The net energy of the emitted source wavefield is distributed over a larger frequency range. Results shown suggest about 12 dB amplitude improvement at 4 Hz for a (large) 6000 cu.in 'tuned' array vs. a 5085 cu.in 'standard' array, although a notch at 7 Hz is also observed.

These comparisons also allude to the necessarily large volumes of air required to enhance low-frequency output. "New low frequency seismic source—tuning the bandwidth for subsurface penetration and reducing high frequency content" by Julien Large (Sercel) revisit 2020/2021 tests of the Tuned Pulse Source (TPS) high-volume low-pressure pneumatic source. By comparison to a conventional 5 100 cu.in air-gun array fired at 2000 psi, the 26 500 cu.in TPS operated at 1000 psi appears to generate 15-20 dB stronger amplitudes at the resonance frequency of 2.6 to 2.8 Hz. The higher amplitude output of the TPS decays more rapidly than observed from traditional arrays, and with reference to the sound exposure level (SEL) modelling presented by Robert Laws mentioned later, the

TPS output falls below the ambient noise floor for frequencies > 1500 Hz. Soon to be sold commercially as a 28 000 cu.in solution, the TPS will expectably have a much longer recycle time than traditional arrays and target FWI-related benefits.

When Less is More: Received Sound Levels and the Environment

“Blind and deaf? What does the increased noise levels in the ocean mean for marine organisms?”, by Jűrgen Weissenberger (Equinor) provided an interesting overview of a complex topic that remains open for debate (no available abstract link), and “Less impact is better”, by Xander Campman (Shell) discussed various published low-volume air gun source experiences (no available abstract link).

“Low-volume Apparition Sources: source trials from the Bass Strait” by Simon Redfearn (Shearwater) tested three ‘small’ air-gun source volumes and an apparition-enabled broadband processing flow to investigate whether lower volume apparition sources may be practical in environmentally sensitive areas. Although only 2D examples were shown, the Apparition method also offers an (untested) opportunity for better crossline spatial sampling. It was noted that Apparition deblending noise sensitivity is higher at low frequencies and may therefore be potentially more detrimental for the low-volume sources tested.

A relevant poster presentation by Robert Laws (Havakustik) titled “Unbiased hydrophone position errors can lead to biased estimates of SEL” ran a Monte-Carlo simulation of a hydrophone position being used to monitor sound exposure level (SEL). A normal distribution with a standard deviation of only 0.5m yield up to 15 dB overestimation in the 1 000 to 5 000 Hz range, i.e., well outside the frequency range relevant to seismic imaging, but relevant to marine fauna, nevertheless. Diminished sound levels above 1000 Hz, by comparison to air guns, is also touted sometimes as a motivation to pursue towed marine vibrators (discussed below).

Improved Near-Surface Imaging and High Spatial Sampling with Better Source Deployments

“High-resolution quad source acquisition over three CCS structures in the Southern North Sea”, by Charles Cooper (bp) described various bp experience with wide-tow multi-source shooting and dense streamer spreads. No abstract link is available.

“Recent advances and lessons learned with wide-tow multi-sources in marine streamer seismic” by Roalkvam et al. (PGS) presented the maturation of operational capabilities behind 10 wide-tow multi-source surveys. Up to six sources can be towed over a lateral distribution of up to 440m, improving near-offset distribution, improved crossline spatial sampling and near-surface imaging resolution whilst enabling highly efficient streamer operations without historical ‘acquisition footprint’ artifacts in crossline images.

Where near-seafloor imaging is required with frequencies of several hundred hertz or more, ultra-high-resolution (UHR) methods are required to record the seismic data with small temporal sampling rates (0.25 or 0.5 ms) and small CMP bin dimensions (as small as 1 x 1m has been tested by bp and the P-Cable system). Correspondingly, “Towards cost efficient CCS monitoring” by Sandrine David (Magseis Fairfield) discussed Extended High Resolution (XHR) acquisition with dense arrays short streamers for CCS applications, and also considered potential strategies for more cost-effective OBN acquisition wherever towed-streamer operations may be impractical. Note that bp also considered high-density ocean bottom cable (HDOBC) acquisition over the Clair field in the previous EAGE Marine Acquisition Workshop.

Much focus upon marine seismic survey efficiency will occur as massive wind farm site preparations and marine minerals exploration are pursued in coming years. Complementary seismic imaging methods were not really featured at this workshop, but given the volumes of relevant 3D towed-streamer data libraries around the world, much scope exists to high-grade shallow resolution for wind farm, marine minerals, and CCS applications…

Marine Vibrators Still Not Making an Impact

Three presentations addressed marine vibrator designs either in various stages of testing or in conceptual form only. The two ‘mature’ designs in testing represent a ‘last man standing’ situation after three decades of testing by related parties…

“Development of the MVJIP Marine Vibrator: What's next?” by Stephen Secker et al.(TotalEnergies) focused upon Integrated Projector Node (IPN) design that arose from the Marine Vibrator Joint industry Project (MVJIP). Developed by General Dynamics Applied Physical Sciences (GDAPS) since 2013, the IPN generates 5-100 Hz output with an electromagnetic piston-driven membrane (refer to **Figure 4**). A complementary Autonomous Source

Vehicle (ASV), a shallow-draft small catamaran with ~7-day endurance, is also being developed to deploy two IPNs in both shallow and deep water. The first real data test is planned for late-2022.

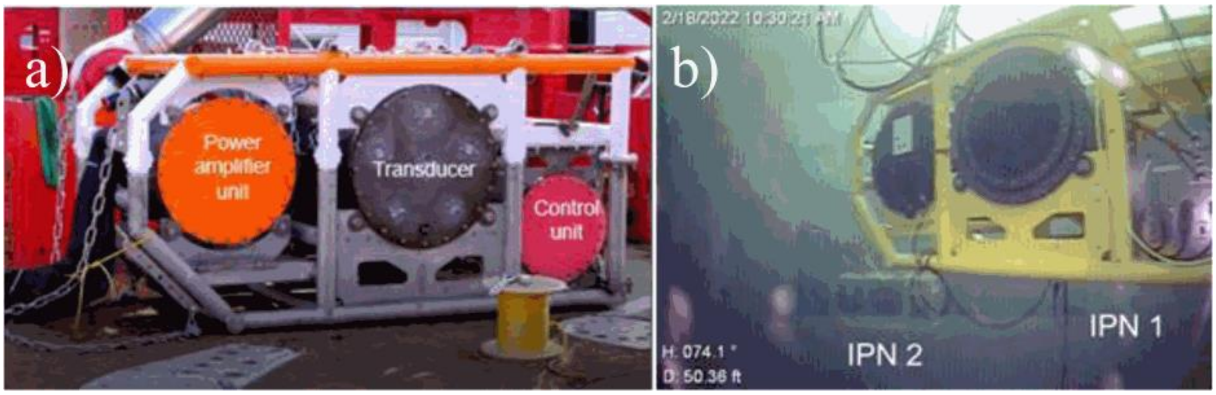

Figure 4: a) Tow Test conducted in October 2021 in the Baltic Sea using two dummy IPN marine vibrators; and b) Testing of two IPN marine vibrators in Seneca Lake February 2022. From Alfaro et al. (2022).

"New marine seismic acquisition equipment" by Thomas Elboth (Shearwater) included discussion of the Broadband Acoustic Seismic Source (BASS) development that is sponsored by Equinor (refer also to **Figure 5**). Like the IPN development thus far, the first real data testing is planned for late 2022.

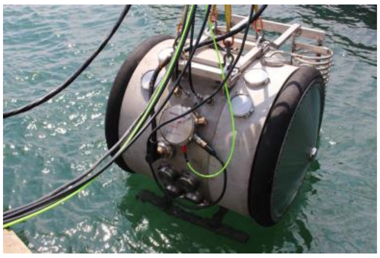

Figure 5: BASS marine vibrator in testing. From Hart Energy (2020).

In "A very low frequency marine vibrator", Rune Tenghamn presented a conceptual and novel source concept that consists of a horizontal plate suspended below a shallow-draft vessel (**Figure 6**). This concept represents a dipole source, in contrast to the other monopole MV sources presented. Linear motors would generate vertical movement of ±0.1m, and it was claimed that 190 dB re 1 µP sound pressure level (SPL) output should be possible over a (low) frequency range of 2-5 Hz.

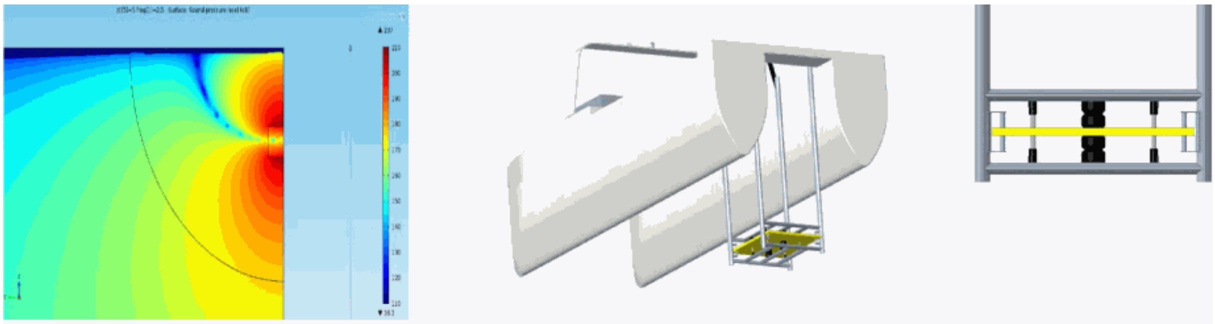

Figure 6: (left) A finite element simulation of a dipole source 5 m from the surface, where the upgoing wave is contributing to the downgoing wave to improve the far-field acoustic output.; and (right) An artist view of how the source could be installed on a small vessel. The vibrating plate is lowered down to a desired depth (for example 5m) and the plate is set in an oscillated motion. From Tenghamn and Mattsson (2022).

Various conceptual survey designs for marine vibrator operations have been proposed over the years, wherein several MV units operate simultaneously with different source wavefield bandwidth (e.g., so-called 'dispersed' source arrays). In a poster presentation titled "Investigation into methods for interpolating missing frequencies in seismic data", Samuel Tuppen (ETH Zűrich) showed how a convolutional neural network (CNN) and sparse solver approach might predict missing amplitude and phase from marine vibrator data acquired as discontinuous frequency bands. This presentation also reminds us that many signal processing and imaging challenges lie ahead for any MV consumers, and years of experience will expectably be necessary to mature the technology.

New Energy Applications: Combining the Best of Everything at Lower Cost?

"Application of seismic in near surface / shallow environments for the foundational studies of wind farms" by Sanket Bhattacharya (Fugro) discussing the rapidly growing market for offshore wind farms. From 35GW in 2020 to an ambition of 2 000GW in 2050 to help meet Net Zero goals, much work is planned. Obvious shallow sub-seafloor hazards for infrastructure installation include shallow faults, buried channels, localized gas pockets, and boulders. Denser spatial sampling than is normally possible with conventional towed-streamer acquisition is necessary for shallow imaging, coupled with small sample rates and high source frequencies. Survey design priority is given to the target source frequency (often > 1 000 Hz) and the other survey parameters are designed appropriately. No abstract link is available.

"Towards cost effective CCS monitoring", by Sandrine David (Magseis Fairfield) described short streamer configurations with CMP bin dimensions of 1.5625 x 6.25m, corresponding to 75m streamer lengths, 12.5m separation, and 3.125m receiver interval. No abstract link is available.

Finally, "Innovative reservoir monitoring technologies" by Mark Thompson (Equinor) compared Permanent Reservoir Monitoring (PRM) features and benefits to short-streamer ultra-high-resolution (UHR) acquisition and considered the potential relevance of Distributed Acoustic Sensing (DAS) fiber-optics for PRM applications. No abstract link is available.

Summary

The most significant change in marine seismic focus in recent years has been the growing focus upon near-surface resolution for CCS containment monitoring, wind farm preparations, seafloor minerals exploration, and nuclear waste disposal. Correspondingly, a 'new frontier' is created that will try to overcome low daily acquisition rates for surveys that potentially could be very large. Perhaps the interplanetary exploration talk came closest to articulating the true challenge: How can the industry extract the necessary subsurface information from as little data as possible? It will be interesting next time to hear the experiences of many more UHR surveys.

Time will also tell whether marine vibrators reach commerciality, and if so, what plethora of data processing and imaging challenges are encountered.

In many ways, the third installment of this workshop reinforced the fact that new acquisition technology breakthroughs require significant capital investment and time to escape the feasibility stage. Let us hope that the industry climate supports a growth in innovation, and the fourth installment shows that perseverance pays off for those who have been testing a few concepts for many years now.

Acknowledgements

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