Report on Optimization of Seafloor Deployments for Permanent Reservoir Monitoring

DigiMon

Digital monitoring of CO_2 storage projects

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Scope

This report addresses how distributed fibre-optic sensing can be used for monitoring of CO2 storage processes, and more specifically how it compares to conventional seismic data. It focusses on shallow subsurface characterization (uppermost 100 m below seabed), and high resolution and high frequency seismic data. Our main conclusion is that distributed acoustic sensing in our experiment gives comparable results to those obtained from shallow seismic methods.

Revision

Version	Date	Change	Page
1.0	24.08.2021	First version	All
1.1	10.09.2021	Comments by NORCE	5, 6, 7, 10
1.2	17.09.2021	Comments by Mike Kendall	2,3,5,6,9,13,14
1.3	23.01.2023	Final version including reference to Q-article,, minor edits	

Document distribution

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1 Introduction

NTNU's role within WP1 is to compare conventional seismic and fibre optic sensors. For this purpose, a field test in the Trondheimsfjord in Norway was conducted. Furthermore, conventional seismic data, collected at the Oseberg oilfield and provided by Equinor, were analysed.

This research has so far resulted in one publication on “Distributed acoustic sensing (DAS) for near-surface imaging” (Taweesintananon et al. (2021)). The main results of this paper as well as further non-published findings are presented in section 2of this report. In addition to the DAS paper unpublished findings from the Oseberg will be presented in section 3.

2 Field Experiment in the Trondheimsfjord

In order to better understand the seismic reflection response recorded by DAS, a field test was conducted in the Trondheimsfjord in March 2020. Figure 1 shows the crew onboard the R/V Gunnerus and the layout of a seismic source and a hydrophone streamer towed behind the seismic vessel. A standard submarine telecommunication cable in the Trondheimsfjord was used to simultaneously acquire the DAS-data as the source vessel (Gunnerus) was sailing above the cable (Figure 2). The data acquisition parameters are described as follows:

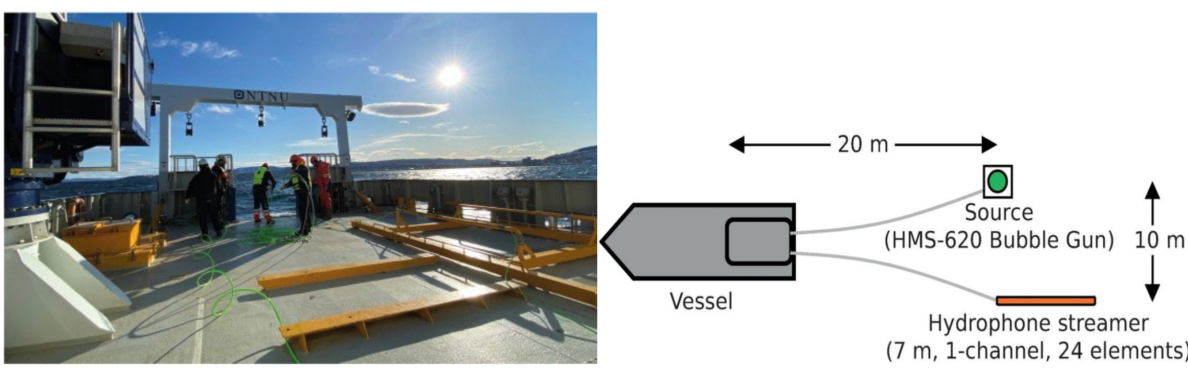


Figure 1: The crew in action on R/V Gunnerus (left) and its seismic acquisition layout (right).

- “HMS-620 BubbleGun” airgun (dominant frequency at 600 Hz).
- Conventional single-channel streamer (7 m long with 24 hydrophones).
- NTNU's research vessel, the R/V Gunnerus, to tow the seismic source and the hydrophone streamer, as shown in Figure 1.
- Several weights to perform weight-dropped tests.

- "OptoDAS" Interrogator provided by Alcatel Submarine Networks (ASN) (t_{sample} = 0.44 ms, 2.04 m channel spacing and 4.08 m gauge length were used as recommended parameters by ASN for a seismic survey).
- Sailing line along an existing submarine telecommunication cable (SMF-28 single-mode silica fibre) at the seabed linking between Trondheim harbour and Kvithylla on the other side of the fjord, as shown in Figure 2.

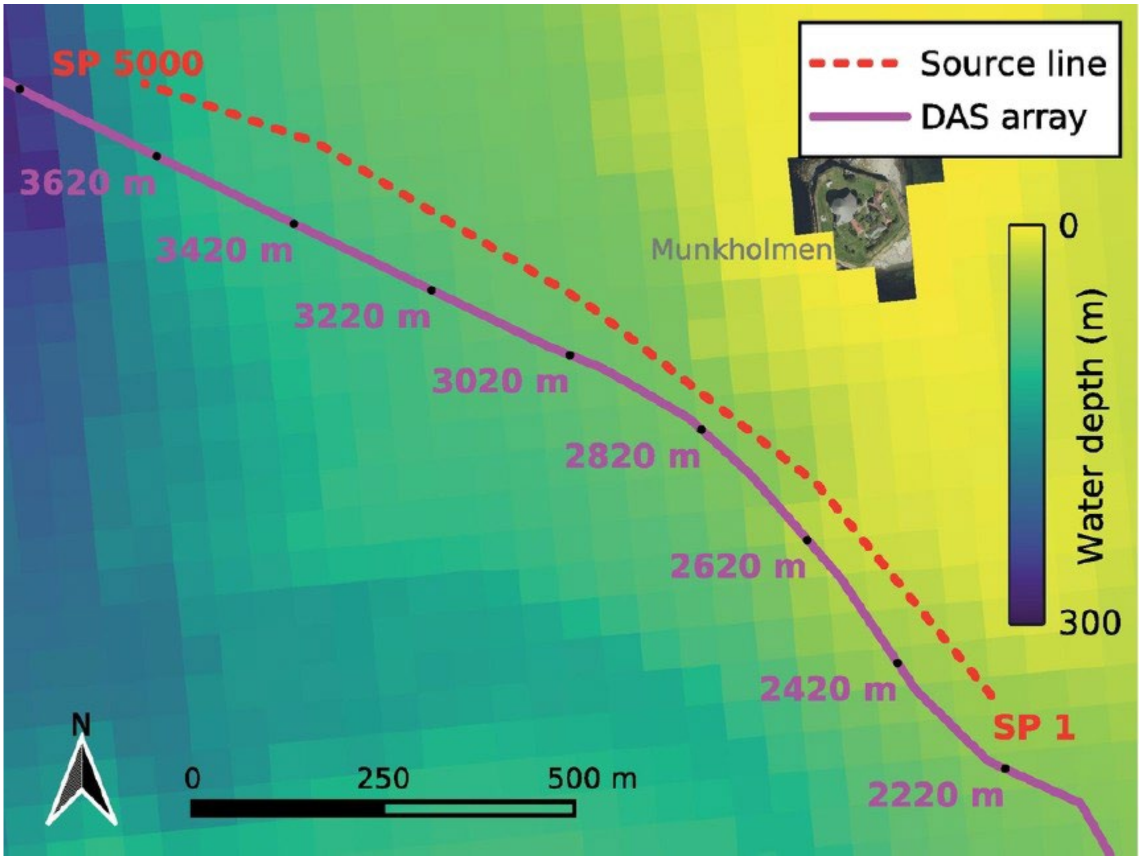


Figure 2: Map of the source positions (SP) and the submarine telecommunication cable for DAS data recording.

The OptoDAS interrogator recorded the seismic waves generated by the seismic source at about 0.6 m below the sea surface. Subsequently, the recorded data were analysed and processed to produce seismic images of the seafloor and the near-surface geologic structures. The detailed data processing is described in Taweesintananon, Landrø et al. (2021).

2.1 Comparison of Seismic Acquisition using Hydrophone and DAS

The main conclusions of this experiment are highlighted below. Please refer to Taweesintananon, Landrø et al. (2021) for details.

- The seismic images of the seafloor and the subsurface geologic structures produced from the streamer and DAS data are comparable, as shown in Figure 3.
- The images from the streamer and DAS data have a comparable signal-to-noise ratio, as shown in Figure 4.

- As shown by the DAS amplitude response analysis, using a seismic source with sufficiently large energy within the frequency range matching the spatial resolution of DAS controlled by DAS recording parameters (gauge length and pulse width) should yield an improved DAS image.
- The temporal resolution of DAS images can be increased by minimising the crossline offset between the seismic source and the DAS receiver cable, which is to reduce the effect of normal moveout (NMO) stretch prior to imaging.

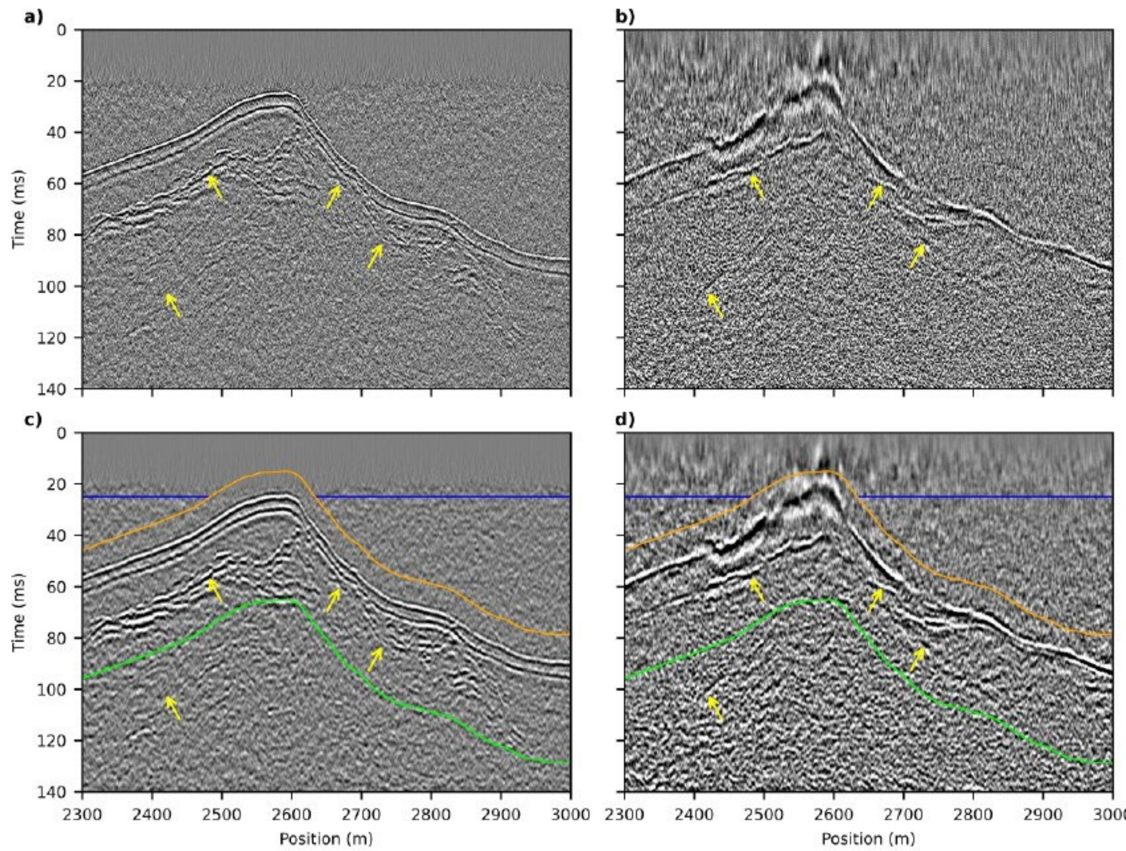


Figure 3: Poststack time migrated seismic images from different data sets: (a) the reference image from the towed single-channel streamer with a 24-element hydrophone array of 7 m active length, (b) the image from seabed DAS with 4 m gauge length, (c) the image of (a) with additional signal enhancement applied, and (d) the image of (b) with the same enhancement applied. The seismic events associated with the water bottom and subsurface reflections are present in both images. Subsurface reflections in the DAS image are highlighted by yellow arrows to ease the comparison to the reference image. The horizontal axis is the distance along the cable. The horizons plotted in (c) and (d) define the signal and noise windows for computing the S/N and spectrum in Figure 4. Signal window is defined between orange and green horizons, whereas noise window is defined between blue and orange horizons. Note that the DAS image represents the image at a different position from the streamer data since their receiver positions are different.

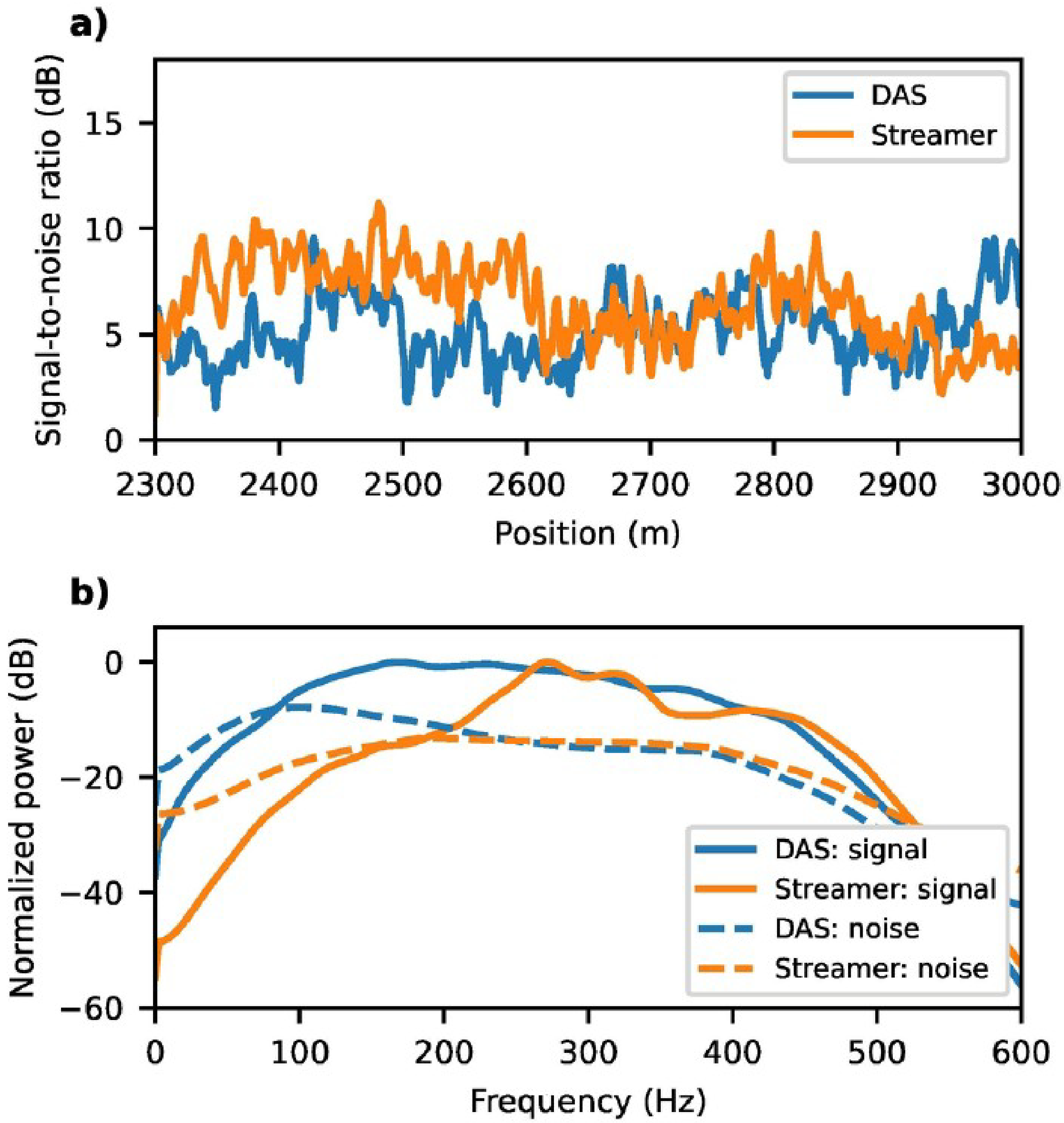


Figure 4: QC plots corresponding to the seismic images from DAS (blue) and towed streamer (orange) with additional signal enhancement applied as shown in Figure 3: (a) S/N at different seismic traces, and (b) normalised amplitude spectra within the signal and noise windows. Signal window is defined between orange and green horizons, whereas noise window is defined between the blue and orange horizons in Figure 3.

2.2 Drop Test

In order to study the detection capabilities of DAS for surface waves propagating along the seafloor, weights were dropped vertically at a position close to the fibre. In the data, one weight drop signal was identified and analysed.

The weight drop created a clear signal, peaking at 10 Hz and ringing for 1 s, as visible in Figure 5. The distance between the weight and the cable is unknown since there are uncertainties related to both the cable and vessel position. Because the exact position and time of the weight-dropped source is unknown, the conclusion of this study has not been finalised.

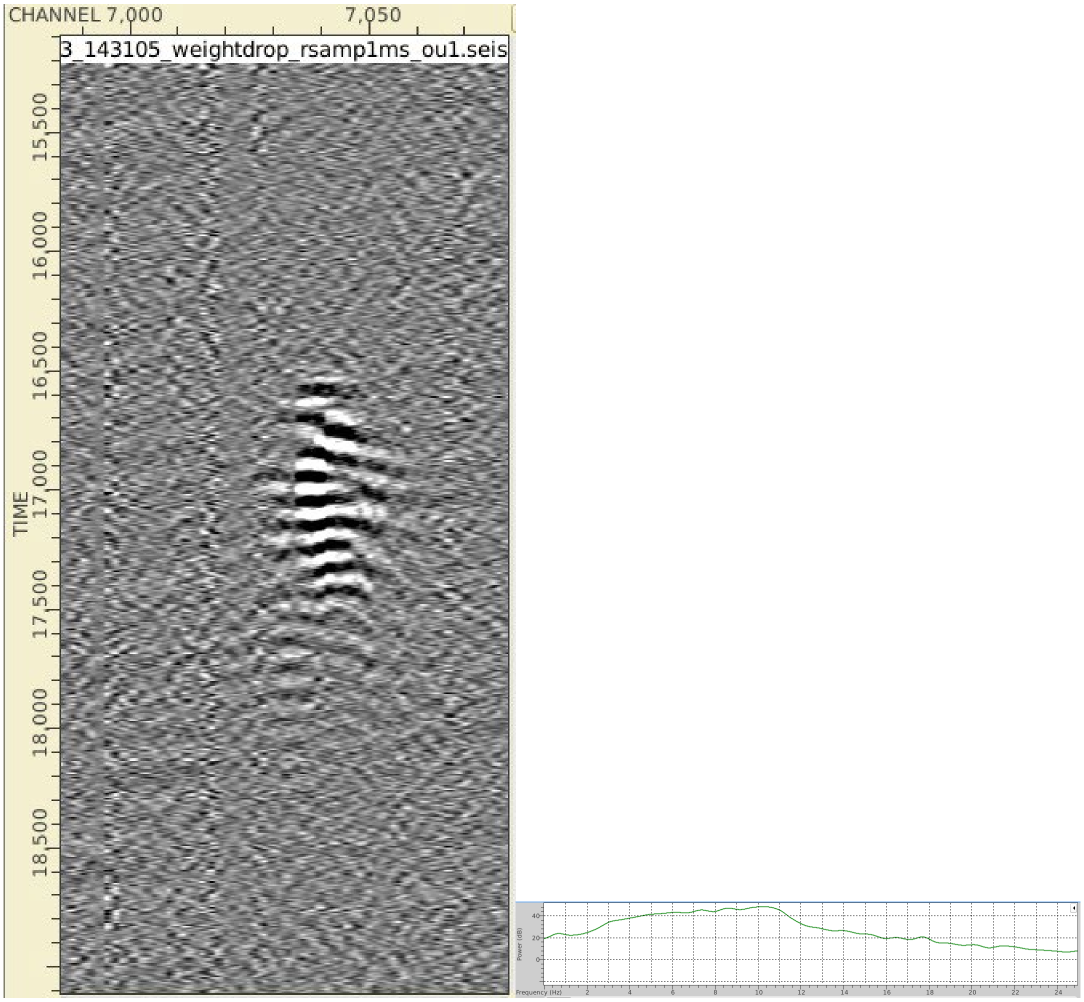


Figure 5: Seismic traces (left) and amplitude spectrum of the weight drop test (right).

2.3 Recording of Ship Noise

Another finding of interest in the DAS data set are the continuous signals of two ships, presumably the Hurtigruten leaving Trondheim harbour and an unknown ship close to the car ferry that commutes across the fjord. The signal of Hurtigruten in shallow water (75 m) in Figure 6 (left) is visible over a range of 0.25 km whereas the signal of the car ferry in deep water (500 m) in Figure 6 (right) is clearly visible over a range of 2.5 km. Striking for both signals is that the amplitude does decay but not fade to zero at the apex.

We aim to use these signals recorded by DAS for travel time inversion to determine the presumably unknown source position and time. A case study with synthetic data was successfully demonstrated using our algorithm. The implementation of this algorithm to the real ship signals in our DAS data is ongoing. We hope the results can be shown in near future.

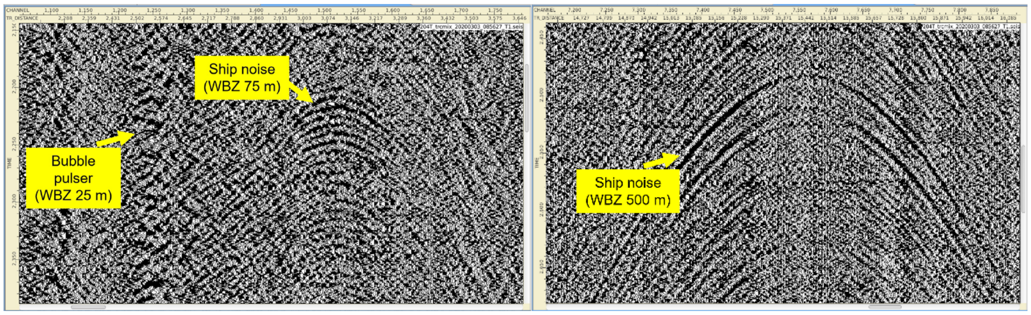


Figure 6: Seismic traces measured at the ocean bottom (WBZ stands for water bottom depth) of the mailboat Hurtigruten close to Trondheim harbour (left), and a ship close to the car ferry that connects Flakk and Rørvik on the two banks of the fjord (right).

3 Oseberg Data

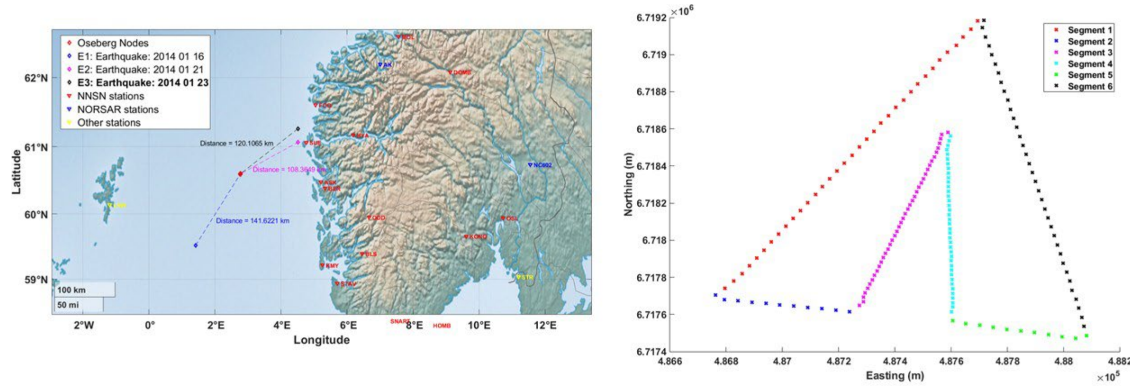
3.1 Introduction to Oseberg PRM

The Oseberg Permanent Reservoir Monitoring (PRM) system is a caprock monitoring system containing 172 4-component nodes. Each node consists of one hydrophone and three orthogonal geophone MEME accelerometers (recording [Pa] and [g], respectively). The system was initially designed for active and passive seismic monitoring of a disposal well. For our analysis, we have used the PRM system to analyse three separate North Sea earthquakes.

The 172 4-component nodes were installed 1-2 meters into the seabed at a water depth of 107 meters in a 'V'-shape with varying sensor spacing (see Figure 7 (b)). The outer arm (nodes 1-46 and 127-172) had a spacing of 50 meters, while the inner arm (nodes 47-126) had a spacing of 25 meters. We have access to data from January 2014 recorded with a sampling frequency of 500 Hz.

In total three earthquakes were detected during the recording period, 2014.01.16 17:09:31 (E1), 2014.01.21 06:39:03 (E2), and 2014.01.24 04:32:49 (E3) (see Figure 7(a)). Initially, we computed spectrograms (see Figure 8 for a stereotypical earthquake spectrogram) for the entire month to see if we found additional earthquakes to the ones reported by the National Norwegian Seismic Network (NNSN) but were unsuccessful. However, we detected and have clear signals from the three earthquakes that NNSN reported (E1-E3, Figure 9), which have been further analyzed here.

Note that only a selection of plots will be shown here as these are ongoing analyses that will be published later.



(a) (b)

Figure 7: (a) Shows the position of the three earthquakes, the location of the Oseberg nodes and the various seismometers in the vicinity of the North Sea operated by NNSN, NORSAR, and others. (b) Shows the lay-out of the Oseberg Node. The different linear segments have been separated into different colours. These were used in various steps of the different analyses.

3.2 Velocity Models and Relocation

We started our analysis by relocating the three earthquakes using the 172 nodes and compare the relocation to the locations reported by NNSN. In order to obtain a relocation, we need three different tools. Firstly, we needed a velocity model that represents the subsurface. We created a simple 1D model (dependency with depth) using a local acoustic well log from well 30/6-1 and combined it with the global velocity model generally used by NNSN. Figure 10(a)-(d) shows how the velocity model, (a) shows the acoustic log overlaid by its smoothed version, (b) shows the smoothed log combined with the global layered velocity model, the smoothed version of (b) is plotted together with the layered global velocity model in (c), while the smoothed and layered version of the global velocity model is shown in (d). Secondly, we need to estimate the travel time from source to receivers through this velocity model. This was done through a ray tracing algorithm. Thirdly, we need a robust inversion algorithm. We tried both a 'linearized location' algorithm and a conventional 'grid search' algorithm.

Furthermore, we have started a velocity analysis using the velocity model mentioned above as the initial step. The idea is to take advantage of the linear layout of the different segments making up the 'V'-shape of the PRM system (as depicted in Figure 7(b)). We use the ray tracing algorithm to predict the delays of observed seismic signals. This delay will be compared to the delay obtained by cross-correlating the nodes' P- and S-wave signal parts on the different segments. Doing this for all receivers, we should be able to improve the velocity model to fit the observation we make on the nodes. The analysis of this is ongoing.

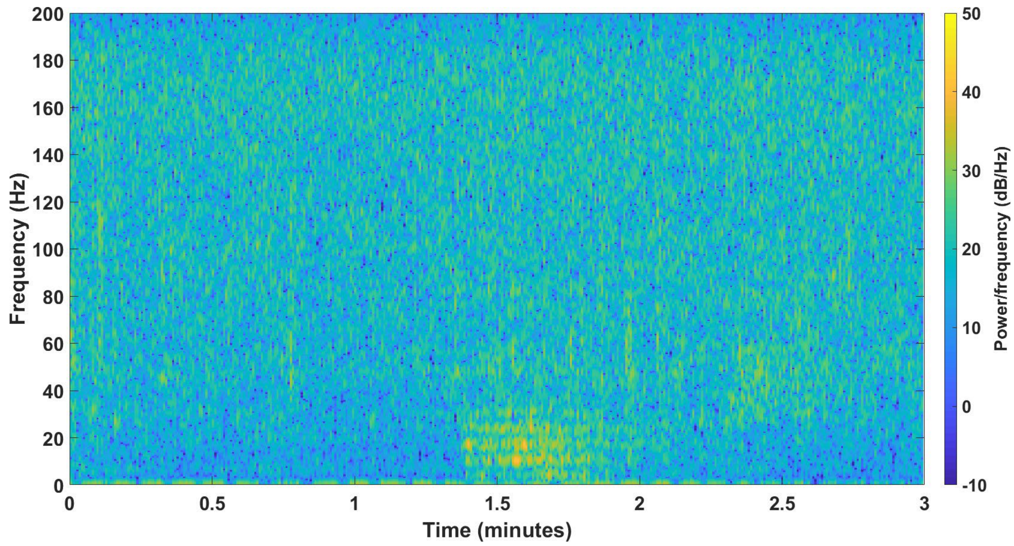


Figure 8: (a) Shows the position of the three earthquakes, the location of the Oseberg nodes and the various seismometers in the vicinity of the North Sea operated by NNSN, NORSAR, and others. (b) Shows the lay-out of the Oseberg Node. The different linear segments have been separated into different colours. These were used in various steps of the different analyses.

3.3 Q-estimation

Another interesting use of the Oseberg nodes is to estimate Q-values for each node. In order to get a reliable estimation, we need to execute various pre-processing steps. The first is to remove various noise sources in the data, for example, the noise emitted by Oseberg C north of the array and swell noise from the ocean. A second process is to remove notches created by multiples in the data. The ray-tracing algorithm also estimates the travel distance and time from source to receiver, similar to the relocation procedure. The analysis is finalized and will be published in 2023 (Rørstadbotnen and Landrø, 2023).

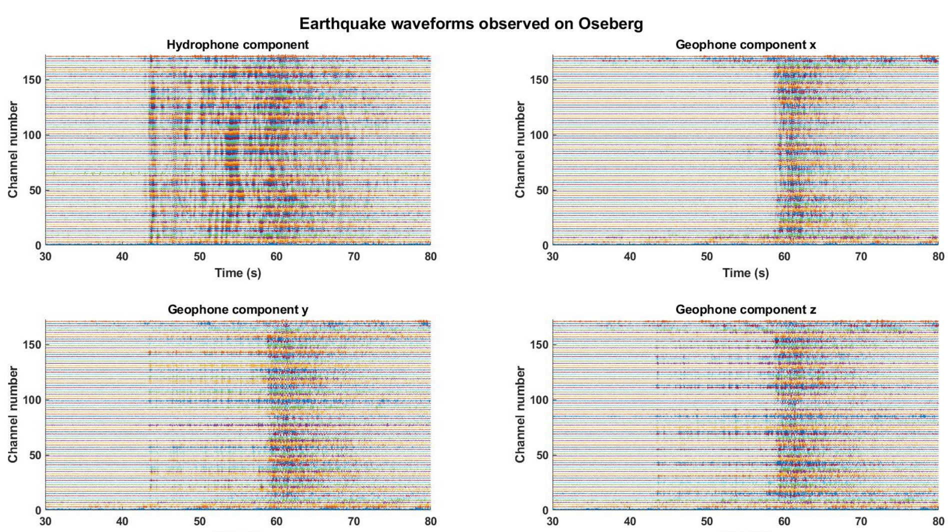


Figure 9: Waveform observed on the Oseberg nodes. Every second node from node 1 to node 172 are shown. We can clearly see how the hydrophone records the earthquake differently than the

geophones. For example, the pressure wave arrival (first arrival) is much more prominent on the hydrophone data than the geophone data. On the other side, the geophone records the shear wave arrival much clearer than the hydrophone.

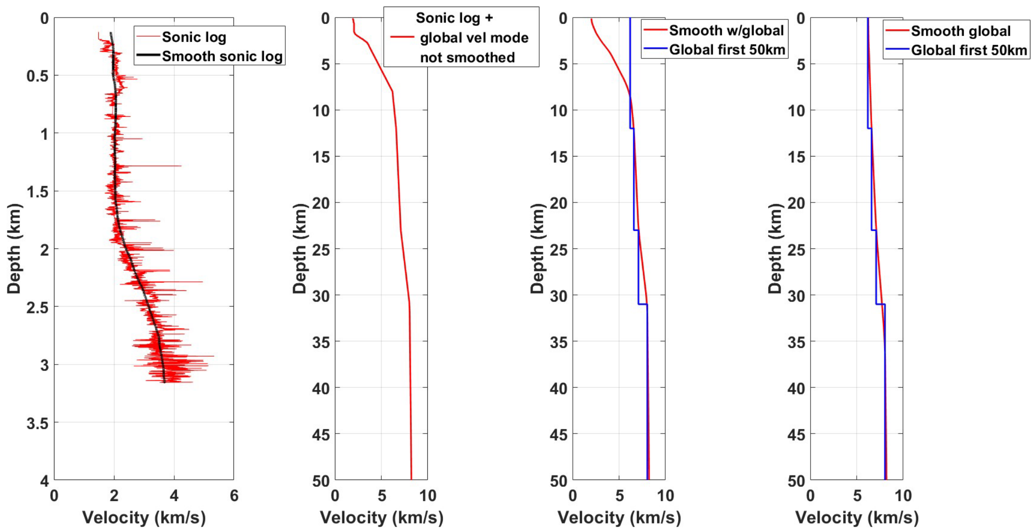


Figure 10: (a) Shows the sonic log (red) overlaid by its smooth version (black). (b) sonic log combined with the global velocity mode, a linear transition zone from the end of the sonic log $\simeq$~3.2 km to the velocity on 8 km in the global velocity model has been included. (c) The smoothed version of (b) (blue) is plotted together with the global velocity mode (red). (d) Smooth (red) and layered velocity (blue) representation of the global model.

4 Conclusion

4.1 Trondheimsfjorden

The field experiment in the Trondheimsfjord demonstrated that:

- DAS data generated in an active seismic survey with a standard submarine telecommunication cable as a receiver enables it to image the subsurface.
- the DAS image can be derived from the direct wave and subsurface reflections.
- the image quality can be improved by using sufficiently large source energy in an appropriate frequency range.
- the image resolution scales reciprocally proportional with the crossline offset between seismic source and DAS cable.

To our knowledge, this is the first time that the capability of DAS data, from a horizontal fibre, for subsurface imaging is demonstrated. Thereby it increases the Technology Readiness Level (TRL) of this sub-application of DAS to TRL 5 which requires validation in a real space environment.

4.2 Oseberg PRM

The analysis on the Oseberg PRM system shows that:

- we can clearly observe earthquakes with M_L as low as 2, and most likely lower.
- we are checking if we can use the aperture of the nodes to relocate the earthquake epicentre.
- we are trying to take advantage of the layout and number of receivers to improve a local velocity model of the area.
- It is possible to estimate average Q-values for the sedimentary layers at Oseberg by comparing the attenuation properties between seismic waves propagating in bed rock only (to the Bergen seismometer and waves propagating through the sediments at Oseberg (Rørstadbotnen and Landrø, 2023).

5 Outlook

The next scheduled field test will be a horizontal fibre parallel to a conventional geophysical monitoring system (geo- or hydrophones). Either a low and high frequency source or a broadband source will be used. At this time, NTNU is going to use its own interrogator such that all data can be shared with the DigiMon partners. The aim of this test is to study:

- the near and far field response of the DAS system to P-waves.
- whether DAS is capable to record a normal incidence P-wave on a straight cable.
- whether a polarity flip in the DAS response can be observed for an incident P-wave.

6 Bibliography

Taweesintananon, K., et al.,2021, Distributed acoustic sensing for near-surface imaging using submarine telecommunication cable: a case study in the Trondheimsfjord, Norway, Geophysics 86, B303-B320.

Rørstadbotnen, R. and M. Landrø, 2023, Average Qp and Qs estimation in marine sediments using a dense receiver array, Geophysics 88, 1-15.