Offshore injection and overburden surveillance using real-time passive seismic

S. Bussat1*, L.W. Bjerrum2, B.D.E. Dando3, E.V. Bergfjord2, K. Iranpour3 and V. Oye3 present the results of a caprock monitoring system at the Oseberg oil and gas field in the Norwegian North Sea.

In 2013 a seismic caprock monitoring system with 172 nodes was installed on the Oseberg oil and gas field in the Norwegian North Sea. It was specifically designed for active and passive seismic monitoring of a disposal injection well. The aim of the monitoring is for a safer operation with avoidance of leakages to the sea, and increased injection. Despite installation and yearly maintenance costs but owing to benefits in the operation of the injector, the system provides yearly savings of around $1.2 million. Currently, the system does most of the passive seismic analysis – microseismic and interferometry – in real time, and we present data examples from the last two years. Typical noise in the data (seismic shooting, platform generated noise and marine traffic) are removed and the signal-to-noise ratio is significantly improved, resulting in better detections and event location, especially for small microseismic events. Seismic interferometry is used to observe/detect changes in the water column and the shallow subsurface down to several hundred metres.

Several offshore hydrocarbon-bearing fields have experienced fractures in the overburden from injection into disposal wells, including leakage to the surface. Although injection procedures to avoid this are effective, they significantly limit the rates and pressures of the injection. To overcome this, a permanent offshore seismic monitoring system using both active and passive seismic methods has been developed. It was installed at the seabed of the North Sea Oseberg field in 2013 with the main aim to control caprock integrity and ensure safe injection, which makes the system unique.

The caprock monitoring system at Oseberg was developed in a joint industry project, supported by the Research Council of Norway. The system is installed with a ‘V’-shaped layout and consists of 172 four-component sensors, holding a hydrophone and three orthogonal Vectorseis sensors. The sensor spacing is 50 m on the outer legs and 25 m on the inner legs (Figure 1) and the seismic cable was trenched 1-2 m into the seabed at a water depth of 108 m. The system layout facilitates monitoring using both passive and active seismic methods. For real-time analysis, all recorded data are sent continuously onshore. Receiving real-time data speeds up 4D seismic processing projects. A 4D seismic base survey was acquired in 2014 prior to the injection start.

The availability of a disposal well for slop and cuttings saves more than $10 million per year for a single drilling rig. This is owing to the high expense of onshore disposal, the avoidance of drilling stoppages owing to bad weather (because of limited offshore storage capacity and no onshore transport possible) and therefore an earlier production start. For this reason, most fields operate disposal wells, which need to be monitored with a cost-effective system. Norwegian requirements demand the detection of leakages for manned installations within three hours. That can only be fulfilled with real-time monitoring, which is normally practised with downhole pressure gauges. Unfortunately, these measurements have not always been reliable enough for leakage detection; an additional passive seismic analysis supports the real-time monitoring. Despite installation and maintenance costs, a positive NPV (Net Present Value) of at least $1.2 million per year has been achieved. This is based on an extended lifetime of the disposal well owing to a better control of the

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waste pod (pathways of the injected fluids) and an increased injection rate and volume pending that the monitoring suggests no increased risks. An additional factor is the huge advantage of a safer operation and an improved reputation.

Figure 1 summarizes the caprock monitoring system. The Oseberg C-4A disposal well injects waste into a shale formation just below ‘sand 1’ at around 1500 m TVD, 900 m south of the platform. In the first phase, ‘sand 1’ will be filled until reduced permeability prevents further injections. During this phase, no strong events are expected, since we are conducting a matrix injection below fracture pressure. Afterwards, the shale above is expected to fracture up to ‘sand 2’. This is expected to produce, on average, significantly stronger events than the first phase. Finally, the Utsira sand will be targeted. Localization of microseismic events is needed to control the pathways of injection fluids and to avoid leakage to the sea. A 4D active seismic survey will be acquired as soon as the ‘sand 2’ is reached. The main monitoring is based on passive seismic, which we divide into microseismic and interferometry. Both methods are employed, using the same data and providing complementary subsurface information.

Modelling performed prior to the installation suggested that the sensor array could record signals from microseismic events with magnitudes of Mw-1 at a depth of 1500 m TVDSS. Microseismic location accuracy, efficient noise reduction schemes, economical deployment, and avoidance of seabed infrastructure, were considered in the array design. Cost-effectiveness was of primary importance during the system design, balancing the minimum array size with fulfillment of the system requirements.

In this paper, we show results of the Oseberg caprock monitoring system, using both microseismic and interferometry. For better microseismic event identification and location, various noise suppression techniques are applied to the data to increase the signal-to-noise ratio (SNR). Furthermore, we show that by using the platform as a continuous seismic source we are able to detect small velocity changes in the water column and the shallow subsurface.

**Microseismic monitoring at Oseberg**

A real-time microseismic detection and localization algorithm using a semblance based imaging technique is implemented to analyse the passive seismic data from Oseberg. This algorithm detects most of the detectable microseismic events (~70%) in real-time with an immediate message to relevant personnel. Smaller events and those well hidden in the seismic noise, are not automatically detected. However, with additional noise removal techniques applied (currently in an ‘offline’ mode), the detection and localization improves.

In this study, we analyse 25 injections batches (240 hours in total) recorded during different campaigns in 2014/2015. In total 19 microseismic events from the area around the target injection well were detected and located (Figure 2). Furthermore, 10 perforation shots including from neighbouring wells, far outside the array, could also be detected. The different event types are categorized as drilling/completion related events; water and waste injection related events; and remote events. While the first category contains events from perforation shots and other well operations, the second and third categories consist of microseismic events correlating with the waste injection, accompanied by observed pressure drops in the injection well. The division of the second and third category is based on the event distance to the injection well, where the more distant events in category three can be interpreted as a fault reactivation, close to the injection zone (green dots in Figure 2).

For all the microseismic events, S-wave detection was most efficient, owing to their high amplitudes, while for most of the microseismic events, the P-wave amplitudes were too small relative to the noise for effective detection; this is in line with the findings of Witten et al. (2012). The S-wave velocity model was obtained based on inverted ambient noise surface waves and has velocities of approximately 1000 m/s at 1500 m depth, decreasing to approximately 200 m/s near the seabed, where Vp/Vs ratios of up to 9 were observed. Using a perforation shot and a strong microseismic event (with both P- and S-waves visible in the data) the P-wave velocity model was validated (statics of -4.7 to 5.8 ms were observed) and the shear wave velocity model was updated. After update of the S-wave velocity model, statics of ±30 ms were observed.

**Noise suppression for enhanced event detection**

The Oseberg monitoring system is the first offshore seismic recording system with a main purpose of monitoring for microseismic events. Onshore microseismic recording
systems are already numerous in the United States as a tool to monitor fracturing of tight rocks for gas and oil production, but the types of noise encountered onshore are in many ways different from noise that can be observed at the seabed, where a large amount of noise travels in the water column.

Events occurring at Oseberg at an injection depth of approximately 1500 m TVD have frequencies for P-waves of 20-60 Hz with a peak frequency at 50 Hz and 10-45 Hz for S-waves with a peak frequency at 25 Hz. Microseismic events from shallower depths are expected to have a higher maximum frequency owing to the shorter path to the seabed.

Various noise sources need to be removed to enhance the event detection. The noise signatures in the passive seismic data recorded at Oseberg can be characterized into four major types: microseisms, seismic interference, platform noise and marine traffic (Olofsson, 2010; Bjerrum et al., 2014). The microseisms are below 2 Hz, and do not interfere with the microseismic event detections. However, the microseisms contain energy, which can be used in ambient seismic noise studies (e.g. Bussat and Kugler, 2011; De Ridder and Biondi, 2015).

The strongest noise sources in the North Sea are seismic surveys ongoing for six months of the year, with seismic shots, called seismic interference (SI), contaminating the passive seismic data. Such surveys are seen at long distances, and several surveys are often ongoing simultaneously. SI covers a frequency range of about 10-100 Hz depending on the source used in the surveys.

The Oseberg C platform with its four steel legs coupled to the seabed is a strong noise source, which produces all types of seismic waves. For relevance to microseismic monitoring are the waves travelling through the water column (1500 m/s) and refracted waves with slightly higher velocities. Slowly propagating surface waves (Scholte and Love waves) with velocities down to 200 m/s (ground roll) are affecting the microseismic analysis only near the platform. These waves are strongly dispersive and have therefore a different propagation velocity for each frequency.

Finally, the frequency content of the noise from marine traffic affects a very broad frequency band from approximately 20 Hz upwards, although dominating above 50 Hz. This noise affects the data with long duration signals and can be strongly observed across the entire sensor array. The shape of the noise signature in the data is dependent on the ship distance and direction, hence, the noise signature changes over time.

The shot generated seismic signal from active acquisition is usually the strongest source in the data, hence, active seismic data are less affected by surrounding noise sources than passive microseismic data. Furthermore, active seismic draws advantage of frequent shooting, allowing for processing techniques that attenuate incoherent noise between shot points, while keeping the coherent signal. In passive seismic noise attenuation, we aim to detect signals of such small amplitudes that they are often hidden in the noise on the recorded data. Understanding the characteristics of the signal and the different noise sources has been important when designing the noise suppression schemes. Different strategies and techniques have been applied to the data in order to suppress noise and reveal weak microseismic events. In the following pages, we present different solutions for efficient noise suppression.

**Suppression of seismic interference**

For suppression of SI we have tested two filters; one in the receiver domain (Eigenvector) and one filter in the shot domain (subspace). Repeated bursts of SI will appear similar on traces from the same receiver. In the presence of SI, a cross-correlation of consecutive traces from the same receiver is used to find the shot interval. Using that shot interval, consecutive shots from that receiver are aligned before noise removal methods are applied.

The Eigenvector filter is applied in the receiver domain, where a set of traces are considered as a matrix, which can be decomposed into sub-matrices. The 2D sum of all Eigenimages reconstructs the original data traces. The choice of which Eigenimages are used in reconstruction, allows the processor to include or exclude types of seismic events or noise (Jones and Levy, 1986). Seismic gathers before and after noise suppression with the Eigenvector filter and their difference are shown in Figure 3. The event in the data is a perforation shot in a nearby well, located significantly outside of the focus area of the Oseberg caprock monitoring
Suppression of noise from the platform

The Oseberg C caprock monitoring system is designed so that noise coming from the platform can be seen as linear events on the data. The four main lines in the sensor array (nodes 1-36, 46-87, 87-128 and 137-172) point towards the platform noise, facilitating the use of dip filters for attenuating the rig-generated noise. The platform-generated noise behaves linearly and the dips present in the data are depending on the propagating wave velocity. The waves in the water column travel at around 1500 m/s, and it is possible to attenuate the dipping noise by utilization of a Tau-P dip filter.

First, the aligned events are modelled using the Tau-P algorithm, and afterwards, they are subtracted from the data (e.g. Tatham et al., 1983; Yilmaz, 1987). Figure 5 shows an example where rig noise travelling in the water and a microseismic event arrives at the array simultaneously. The water-borne rig noise is attenuated with a Tau-P dip filter, while most of the microseismic energy remains in the processed data.

The dispersive ground roll affects mostly those stations closest to the platform. It has typically frequencies of less than 20 Hz and velocities between 200-1000 m/s (depending on frequency). A FX median filter is applied to remove this noise. The filter is similar to the time-frequency de-noising algorithm of Elboth et al. (2010), which was implemented for noise suppression of microseismic data by Blunda and Chambers (2013). The data are transformed to the time-frequency domain, and channels with significant energy
below 25 Hz are compared with the median of the unaffected channels. Amplitudes that exceed a given threshold are replaced with the median value from the unaffected channels, before they are transformed back to the time domain. Figure 6 shows an example of removal of the ground roll using an FX median filter. The event is a perforation shot in a

Figure 5 Example showing removal of noise originating from the platform using a Tau-P filter. Upper row shows seismic data as; before noise suppression, bandpass filtered 15-90 Hz (left); after noise suppression (middle); and difference between input and output (right). Lower row shows the stack function images before (left) and after (right) noise suppression. The event is a microseismic event, occurring in connection to the first injection phase in the monitored injection well.

Figure 6 Example showing removal of noise originating from the platform using a FX median filter. Upper row shows seismic data as: before noise suppression, bandpass filtered 10-50 Hz (left); after noise suppression (middle); and difference between input and output (right). Lower row shows the stack function images before (left) and after (right) noise suppression. The event is a perforation shot in a neighbouring well, located at approximately 2.65 km depth.
neighbouring well at 2650 m depth TVDSS, 1.5 km from the injection point of the monitored C4 well.

Spatial aliasing poses a problem when considering the platform generated noise. The waterborne noise from the Oseberg platform is spatial aliased from about 15 Hz for the outer legs with 50 m spacing, and from 30 Hz on the inner legs with 25 m spacing. The consequence is a larger risk of harming the signal during the noise processing. Concerning the ground roll, which propagates very slowly (down to 200 m/s), spatial aliasing already occurs at around 5 Hz for a receiver distance of 25 m. This poses problems for noise removal using simple dip filters as presented for the removal of seismic interference. However, the FX filter successfully manages to remove much of the ground roll.

**Suppression of noise from marine traffic**

To remove the marine traffic noise from the data, a slowness projection filter (e.g. see Leaney, 1990) is used. Neighbouring traces are cross-correlated to align the noise and construct a noise model from which the dominant slowness values are removed. The model describes a wave front of a corresponding moveout for data on each arm of the array, looping over all the frequencies involved. Finally, the noise model is subtracted from the original data. A slowness projection filter example from a water injection event is shown in Figure 7. The event arrival is not visible in the data prior to noise reduction, where the ‘chevron-shaped’ marine noise is dominating. Furthermore, coherent stacking energy is not observed before noise removal, whereas the energy stacks with a clear maximum after the noise reduction is performed.

**Overburden monitoring by utilizing anthropogenic ambient noise**

The behaviour of possible leakages to the shallow subsurface (<500 m below the seafloor) and further to the sea is unknown. No publications describe microseismic events from these depths and leakages could emerge from stealthy pressure-ups of shallow layers. To avoid overlooking these cross-flows or leakages we perform a complementary analysis to the microseismic event detection. The seismic interferometry processing is added to the surveillance system in order to detect changes in water column and subsurface. This way, we obtain additional subsurface information by using the same input data twice.

There are two categories of ambient noise sources: natural sources (originating from weather, mainly below 2 Hz) and anthropogenic sources (seismic interference, vessels, platform noise, mainly above 2 Hz). Seismologists use interferometry with natural sources mainly in a global or regional setting (e.g. Benson et al., 2007), while some reservoir geophysicists have used the method already for hydrocarbon reservoirs (e.g. De Ridder and Biondi, 2015; Bussat and Kugler, 2011). In both cases, surface waves, originating from natural sources at low frequencies (<2 Hz) are used to probe the subsurface...
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down to several kilometres. However, this approach lacks the high frequencies of the anthropogenic ambient noise, which especially provide strong sensitivity to the shallow sediments and the water column. The main requirement for obtaining accurate results from interferometric processing is an equal distribution of noise sources. This is approximately given for the natural sources in the marine environment, but not for the anthropogenic sources. In this study, the lack of distributed sources are handled as follows: first, we achieve high precision in relative time-lapse changes instead of trying to obtain accurate absolute velocity information, and second, we use the site-stable Oseberg C platform as a continuous noise source.

The long signal from the platform is comparable with the long sweep emitted by a vibroseis source, and the processing is performed similarly. The following processing steps are applied to calculate the virtual shot gather (VSG) shown in Figure 8 (right): 1) the noise data are 10 Hz low-pass filtered. 2) the closest receiver to the platform is defined as a virtual source. 3) five minutes of noise data from that receiver are cross-correlated with the same five minutes of noise from all other receivers, creating a VSG representing five minutes of the noise data. 4) apply final spectral whitening in the frequency range of interest, 12 consecutive VSGs are stacked to improve the S/N ratio (see Groos et al., 2012, for a comprehensive discussion of different processing schemes). The virtual shot gather is now analogous to a shot gather with a seismic source at the receiver closest to the platform. A new virtual shot gather is obtained continuously every hour, resulting in 24 vintages per day. We focus our time-lapse analysis on the acoustic-guided waves (water multiples) to monitor the water column, and on the refracted waves and Scholte waves to detect changes down to a several hundred metres of the subsurface.

Figure 9a shows the modes of the acoustic-guided wave from the virtual shot gather (linear move-out corrected with 1480 m/s, dithering in the data is due to the offset sorting and varying water depths), and the calculated time-shift compared to a record six hours later (Figure 9b). It is clear that the time-shift is increasing from mode to mode. A modelling study reveals, that the observed time shifts are related to the tides (see also Bussat, 2015). In contrast to the time-shift increase from mode to mode (Figure 9b and Figure 9c), a change in water velocities (e.g. owing to a hydrocarbon leakage into the sea) would be represented as a time-shift increase with offset (Figure 9d). Note, that even a small velocity change from 1490 to 1480 m/s produces large time-shifts of up to 20 ms. This behaviour is used to distinguish between tidal changes, water-velocity changes and changes in seafloor velocities (refracted waves). Shear-wave velocity and density changes in the seafloor cannot be detected by the analysis of acoustic guided waves.

To observe velocity and density changes of the shallow sediments down to a few hundred metres below the seafloor, we analyse time-lapse changes in the recorded surface waves (ground roll). The surface waves (Scholte and Love waves) are extremely sensitive to shear-wave velocity changes and therefore to pore-pressure changes as they would occur during cross-flows of leakages. Figure 10 shows a simple example, where we have used the Love wave to detect subsurface changes. The interferometric processing is done for the crossline components of two nodes. One node acts as the virtual source, while the other node records the signal. This way, we are probing the subsurface between these nodes. In the example, we obtain a trace for every hour (ten days in total) which is deconvolved with a background dispersion to gather the signal around 0 seconds. As time passes, we
expect a stable signal, related to no subsurface changes, as seen within the first 30 hours in Figure 10a. However, after 30 hours the constant arrival is interrupted by an abrupt change in arrival time for the higher frequency part of the signal, as shown in Figure 10c. We observed a time-shift of up to 100 ms within only 4 hours (2% velocity decrease), which demonstrates the sensitivity of this method. The sudden velocity decrease is owing to the thixotropic behaviour of the sediments, which are affected by the waves on the sea surface. Figure 10b shows a strong correlation of the significant wave height with the observed time-shift. The shallow sediments become more liquid owing to the continuous pressure change originating from high waves on the sea surface. Analysing the dispersive behaviour of the Scholte and Love waves at the seafloor reveals that the velocity change occurs only within the upper 50 m and not deeper. A leakage from the subsurface towards the seafloor would be first visible at lower frequencies (deep layers) before it is visible for the higher frequencies (shallow layers). Therefore, it might be possible to detect leakages with this method, before the leak reaches the seafloor.

Discussion and Conclusions
The Oseberg system demonstrates a functional passive seismic monitoring tool for injection wells and caprock integrity surveillance. Despite installation and maintenance costs, a yearly saving of around $1.2 million is achieved, and the field operates even safer than before owing to the better control of the injected waste pod. Despite the high noise level owing to active seismic surveys, and the platform-generated noise, around 70% of the events have been detected in real-time. More events are detected after advanced noise suppression has been performed. All microseismic events can be related to injection activity or reactivation of a nearby fault. Furthermore, we observe perforation shots, which are located well outside and much deeper than the focus area of the caprock monitoring system.

Different noise suppression methods have been tested and applied in order to ensure better event detection. The seismic interference can be attenuated with an Eigenvector filter applied in the receiver domain, or a subspace filter applied in the shot domain. Both filters show good results, where the Eigenvector filter successfully removes noise without removing any of the seismic signal, and the subspace filter efficiently removes both the seismic interference together with other noise signatures. Despite removal of some of the seismic signal, the event is easily detectable and locates very well after the subspace filter has been applied. The strong surface wave energy from the Oseberg C platform has been successfully attenuated with an FX filter, whereas the water-borne noise from the platform is removed with a Tau-P dip filter. Finally, a slowness projection filter successfully removes marine traffic noise. Significant improvements in the stack images highlight the effectiveness of the applied noise suppression methods and their support for better detection and localization. Noise suppression must be applied very carefully to not risk destroying the microseismic signal. All methods for noise removal in this study are designed for single types of noise (noise with one dip) and in practice need to be applied in combination when more than one noise source is present in the data. For the concept of robust real-time monitoring, noise reduction should be applied in real-time, such that the complete event catalogue is available. This will lower the risk related to operation and provide value for the operator.

We perform a seismic interferometric processing, where acoustic-guided waves, refracted waves and surface waves (Scholte and Love waves) are extracted for every hour of recorded passive seismic data. By observing time-lapse changes of these waves we might detect variations within the water column (e.g. hydrocarbon leakages to the sea) and within the first several hundred metres below the seafloor. Before an injection fluid reaches the sea, it will increase the pore pressure in the subsurface (shear wave velocity reduction) and as such can be detected by the time-lapse analysis of the ambient noise surface waves, such that mitigation measures can be initiated.

The presented monitoring system is on its way to be established on further fields in the North Sea. In this respect, further techniques will be implemented in the real-time analysis.

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Applications are invited for two two-year full-time Oil and Gas Authority (OGA) Post-Doctoral Research Associate (PDRA) positions to be based in the Department of Geology & Petroleum Geology at The University of Aberdeen and in the Centre for Exploration Geoscience, in the School of Energy, Geoscience, Infrastructure & Society at Heriot-Watt University (HWU).

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Further particulars can be obtained from and applications made via the following URL links.

**Aberdeen University:** Rockall project: [https://www.abdn.ac.uk/jobs/](https://www.abdn.ac.uk/jobs/) Informal enquiries should be directed to:

Dr Nick Schofield (email: n.schofield@abdn.ac.uk)

**Heriot-Watt University:** Mid North Sea High project: [http://www.hw.ac.uk/about/careers/job-opportunities.htm](http://www.hw.ac.uk/about/careers/job-opportunities.htm). Informal enquiries should be directed to:

Professor John Underhill (email: J.R.Underhill@hw.ac.uk)

Closing Date for applications: 17:00 BST August 1st 2016

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