Seabed permanent reservoir monitoring (PRM) – A valid 4D seismic technology for fields in the North Sea

Morten Eriksrud1 demonstrates the advantages of PRM using 4D technology, such as a significant uplift in image quality, and how this is leading to a broadening market for this technology in the North Sea.

4D seismic technology provides solutions for performing time-lapse repeat of 3D seismic surveys. Recorded (and processed) 4D data are used by reservoir engineers for monitoring reservoir performance changes during production and/or injection. 4D seismic provides unique insight into the pressure and saturation distributions away from the wells. Better understanding of the dynamic behaviour of the reservoir will lead to higher production, improved estimate of reserves and reduced drilling costs.

4D seismic surveys have been used as a reservoir monitoring tool for more than 20 years. Towed streamer seismic time-lapse has been the dominant 4D technology. It was introduced by Statoil in 1990 with a 4D pilot at the Oseberg field and was in 1995 followed by a full-field investigation and application on the Gullfaks field where the 4D technology proved to be an excellent enabler for improved reservoir management. Since then, 4D streamer data have been integrated into a multi-disciplinary increased oil recovery (IOR) effort aiming at recovering 70% of the in-place reserves from a structurally complex and heterogeneous reservoir sequence. 4D seismic at the Gullfaks field has contributed directly to more than 19 successful infill wells and generated a net present value of around $1 billion, while the total cost of the 4D seismic was estimated to be $60 million (Sandø et al., 2009).

Within 15 years of the first Gullfaks survey, Statoil operated more than 100 4D surveys in the North Sea. The application of 4D seismic has continued to evolve and today 4D streamer surveys are widely used also for fields in the Gulf of Mexico, West Africa, Brazil, Asia and Australia.

The main driver for applying 4D seismic on a producing field is increased oil recovery (IOR). Field recoveries have improved enormously in the past 20 years, but the worldwide average is still about 35%, which means that 65% is left in the ground. Major oil companies are targeting much higher values. Statoil has announced that it targets average recoveries of 60% on its fields in the North Sea. 4D seismic technology will play an important role in achieving this goal.

Another important driver today for 4D seismic is improved drilling efficiency. A third driver that might turn out to be important in the future is improved production safety and environmental protection. It might be that government authorities will require permanent monitoring systems installed in environmentally sensitive areas.

Seismic 4D data is capable of influencing field decisions throughout the field life. So far, it is mainly for mature fields which have passed the production plateau that 4D seismic has been implemented and really demonstrated its potential as a value-adding technology. However, information gathered from 4D seismic during early production stage could be essential in defining future depletion plans. At this early stage, it is important to understand the overall connectivity of the reservoir system in order to define well locations required to effectively drain the field. Later in the field life 4D seismic can be used to optimise infill drilling campaigns and EOR schemes to improve field recoveries.

4D data quality
The 4D seismic data is generated by subtracting data from two surveys (separated by time) to highlight dynamic changes in the reservoir between the two surveys. The quality of the resulting data is dependent on the changes in the elastic properties resulting from the changes in the reservoir between the two surveys and to what extent these changes can be detected by the seismic acquisition technology used to generate the data. Towed-streamer surveys are the far most common technology used to generate 4D data. Even though the towed-streamer technology has improved significantly over the past few years, limitations exist in the 4D data quality. Improved quality of the 4D data will basically require: (i) better imaging and (ii) higher repeatability.

Improved imaging is obtained by using ocean bottom seismic data which is acquired with long-offsets, full azimuths and multi-component receivers. In addition, the

---

1 Optoplan AS.
2 Corresponding Author, E-mail: Morten.eriksrud@optoplan.com
Most focus on PRM versus towed streamer has so far been on the difference in cost and cost structure, but not very much on the difference in the data quality, which is a more difficult issue to define. There is no doubt that PRM systems provide significant uplift in 4D image quality, but it is not straightforward to quantify this improvement with respect to streamer surveys. However, recent imaging data from the PRM system installed at the Ekofisk field in the North Sea, provide significant insight into 4D image quality aspects achievable with PRM. This will be further discussed. However, we will first describe the main value criteria of 4D technology and then finally briefly discuss the PRM marketplace as seen in the North Sea.

**Value criteria of 4D technology**

The value of 4D seismic data results from information on dynamic reservoir properties that can positively influence reservoir decisions. This means that the value depends on two key factors: (i) the ability to provide useful information on dynamic reservoir properties and (ii) the ability to impact reservoir decisions in a positive way (Watts, 2012).

The first factor, i.e., the ability to provide useful information on dynamic reservoir properties, basically depends on:

- **a)** Rock/fluid properties - determining the strength of the seismic signal and the 4D response of the reservoir;
- **b)** 4D acquisition technology – determining to what extent a 4D response can be properly detected;
- **c)** frequency of surveys – determining the time resolution of the acquired 4D seismic data (with a quality dependent on the 4D acquisition technology).

The second factor, i.e., the ability to impact on reservoir decisions in a positive way, requires that:

- **d)** A number of reservoir decisions, which can be influenced, remain to be taken; i.e., infill wells to be drilled, intervention campaigns to be performed or other field investments to be made – one simple criteria could be that the field has sufficient volume of remaining reserves;
- **e)** 4D data will have to be delivered in time to impact field management decisions – depending on the processing turnaround;
- **f)** 4D data will have to be integrated with production data to ensure optimisation of decisions – depending on reservoir model updates.
Two of these value criteria relate directly to the reservoir characteristics. These are (a) the rock/fluid properties which determines the strength of the seismic signal changes and (d) the reservoir decisions to be taken, which to some extent will relate to the estimated remaining reserves of the reservoir (among other reservoir details). Figure 2 summarizes the various criteria related to the reservoir and 4D technology.

Another key criterion is the implementation of the processed 4D data and how these data are integrated with production data to improve the reservoir model for better prediction of the reservoir behaviour.

The rock and fluid properties determine the strength of the reflected seismic signal, which depends on impedance changes seen by the acoustic wave. 4D responses originate from changes in impedance (the product of velocity and density) caused by the depletion process.

Fluid properties as saturation, incompressibility and density, as well as pressure and temperature, will impact on the 4D response. In addition, the mineralogy and porosity of the reservoir rock will also influence the changes in elastic properties resulting from changes in fluid saturation and pressure. In principle both siliciclastic and carbonate rocks will provide some 4D response, although the clastic reservoirs have so far been considered to be the best candidates. However, expected 4D response from a reservoir needs to be compared with achievable data quality, i.e., the ability to detect small 4D responses. This ability is determined by the 4D technology. PRM has been considered to provide much better data quality than towed streamer, but just recently this data quality has been quantified by detailed results published from the first four shooting surveys on the PRM system installed at the Ekofisk field in the North Sea.

The installation of the fibre-optic system was successfully completed in October 2010 (Nakstad et al., 2011). The system consists of 200 km seismic cables (trenched at ~1.5 m below the seabed), an additional 40 km of backbone cables (also trenched) and a topside instrument in a dedicated container module at the platform deck. The seismic cables (24 in total), separated by 300 m, cover a seabed area of 60 km² at a water depth of 70-80 m. The cables contain close to 4000 four-component seismic stations (50 m separation along each cable). An illustration of the seabed cable layout is shown in Figure 5.

By the end of 2013 six seismic acquisition campaigns had been completed. The shotlines have been acquired parallel to the cable lines with 25 m between shotpoints and 50 m between shotlines. The shotlines extend the cable layout area and cover an area of 143 km². One survey includes approximately 120,000 shots. The source selected for the acquisitions is a containerized source including three sub-arrays of four gun clusters towed by stiff floats. The use of a supply vessel with a modern steering system enables a high source positioning repeatability. Close to 94% of the shots have been within 5 m of their pre-plot position during the four first surveys (Bertrand et al., 2013). During shooting the instrument is controlled from onshore and the generated SEGd files are transmitted near real-time via an optical fibre telecommunication link to a dedicated QC and processing centre located in ConocoPhillips offices in Stavanger. A key factor in designing this set-up has been to achieve a rapid turnaround to enable rapid reservoir

Characteristics of PRM system installed at Ekofisk

The PRM system installed at the Ekofisk field in the southern part of the North Sea was a technology breakthrough for fibre-optic sensing within the seismic industry (Erksrud, 2010). 4D towed streamer surveys were in extensive use at Ekofisk from 1999 to 2008 to help identify new drilling targets. In 2005 it was concluded that installing a permanent seabed system would be a better seismic monitoring strategy than continuing with towed-streamer surveys and ConocoPhillips decided to install a PRM system at Ekofisk (Folstad et al., 2011). A fibre optic system was selected as the best long-term solution to support the planned drilling programme and for fast delivery of high-quality 4D seismic products (Folstad et al., 2011).

The PRM system installed at the Ekofisk field in the southern part of the North Sea was a technology breakthrough for fibre-optic sensing within the seismic industry (Erksrud, 2010). 4D towed streamer surveys were in extensive use at Ekofisk from 1999 to 2008 to help identify new drilling targets. In 2005 it was concluded that installing a permanent seabed system would be a better seismic monitoring strategy than continuing with towed-streamer surveys and ConocoPhillips decided to install a PRM system at Ekofisk (Folstad et al., 2011). A fibre optic system was selected as the best long-term solution to support the planned drilling programme and for fast delivery of high-quality 4D seismic products (Folstad et al., 2011).
management response to the 4D observations. As a result, the 4D processing is now completed in less than four weeks from the last shot. This results in the opportunity to interpret 4D data with a short delay and assist in identifying production risks and prioritizing well interventions. The turnaround time impacts the value of 4D data for well operations and reservoir management when rapid changes might occur in the reservoir.

The 4D repeatability is mainly affected by repeatability of the sensor positions and the shot positions, but can also be impacted by various noise sources and potential variations in weather conditions. With stations trenched in the seabed, the sensor position error should be negligible compared with the shot position error (measured to be within +/- 5 m for the Ekofisk surveys). This is confirmed by an analysis of rotation angles (tilt angle of accelerometers). The angles have near perfect repeatability at Ekofisk (Hoeber et al., 2013).

Different types of noise might affect the recorded data. The main noise sources at the Ekofisk field are (i) strong backscattering noise caused by a large concrete tank (in the centre of the Ekofisk platform complex), (ii) low-frequency, low-velocity noise (Vz noise), (iii) seismic interference noise (from other seismic activities) and (iv) industrial noise (pile driving noise, vessel generated noise etc). The denoising approach used in the processing is removing a significant part of this noise (Buizard et al., 2013). In addition, 4D environmental corrections are included in the processing sequence. Tidal statistics and water velocity corrections derived from data measured during the acquisition have been used.

Other potential noise sources may originate from the acquisition equipment; ie instrument noise, cross-talk noise and signal transmission noise. Optical sensing systems have inherently very low noise characteristics, but still an optical denoising system is included in the Optowave system to remove optical noise from the recorded signals.

The 4D seismic data recorded with the PRM system at Ekofisk has shown remarkable repeatability. A median NRMS of 3.5% has been computed between the second and the third survey over a one-second window centered on the reservoir (Bertrand et al., 2013). Similar values (3-5%) have been reported for NRMS maps computed between the first four surveys (Buizard et al., 2013).
As a comparison, the best NRMS value achieved with streamer data at Ekofisk, and considered remarkable at that time, was around 12% (Haugvaldstad et al., 2011).

The excellent repeatability of the Ekofisk PRM system results in detectability of very small 4D signals. The main attributes used for 4D interpretation at the Ekofisk field are (i) time-shifts at top reservoir (overburden response to reservoir compaction), (ii) intra reservoir time-shifts, (iii) time-strain (derivative of the time-shifts) and (iv) amplitude changes (Lyngnes et al., 2013). Detectable time-shifts and amplitude changes have been quantified by ConocoPhillips (Bertrand et al., 2013). Amplitude changes in the order of 2-3% have been detected and interpreted. The detection level for time-shifts is as low as 200 µs and sometimes even lower levels have been detected for intra reservoir time-shifts. This precision would have been unachievable using streamer data. These reported data confirm the high image quality which can be achieved with fibre optic PRM systems.

The Ekofisk PRM system is now routinely used for several different purposes including (i) optimization of new well locations and trajectories, (ii) suggestion and prioritization of well interventions as well as diagnosis of well mechanical issues and (iii) updating of reservoir model. In addition to reservoir applications, the data are used extensively for monitoring and surveillance of the impact of injection, production, compaction and subsidence of the overburden section at Ekofisk (Bertrand et al., 2013).

Different cases have been published by ConocoPhillips showing how the high fidelity 4D seismic attributes from the Ekofisk PRM have been used to mitigate the risk when drilling new wells (Lyngnes et al., 2013) and to impact on reservoir management, well interventions and production optimisation (Grandi et al., 2013 and Folstad et al., 2013). ConocoPhillips has also published results showing that multi-component processing enabled it to reduce significantly the extent of the seismic obscured area (SOA) for both the PP and PS data, as well as to improve data quality for interpretation of more subtle geological features (Bertrand et al., 2013)

The PRM market place (North Sea)
The PRM marketplace is currently moving slowly. The first commercial PRM system was installed at the Valhall field of BP in the North Sea in 2003 and the next full-scale system was installed at Ekofisk in 2010. Currently another two full-scale systems are being installed (2013-2014) in the North Sea at the Snorre and Grane fields operated by Statoil. In addition, a small system installed at the Claire field of BP (North Sea) in 2006 as a field test, has been used for repeated monitoring. Finally, two smaller systems have been installed in deep-water offshore Brazil for repeated monitoring; i.e., the Jubarte field of Petrobras in 2012 and the BC-10 of Shell in 2013. At the end of 2013 no decision is taken for new PRM installations.

The excellent repeatability of the Ekofisk PRM system results in detectability of very small 4D signals. The main attributes used for 4D interpretation at the Ekofisk field are (i) time-shifts at top reservoir (overburden response to reservoir compaction), (ii) intra reservoir time-shifts, (iii) time-strain (derivative of the time-shifts) and (iv) amplitude changes (Lyngnes et al., 2013). Detectable time-shifts and amplitude changes have been quantified by ConocoPhillips (Bertrand et al., 2013). Amplitude changes in the order of 2-3% have been detected and interpreted. The detection level for time-shifts is as low as 200 µs and sometimes even lower levels have been detected for intra reservoir time-shifts. This precision would have been unachievable using streamer data. These reported data confirm the high image quality which can be achieved with fibre optic PRM systems.

The Ekofisk PRM system is now routinely used for several different purposes including (i) optimization of new well locations and trajectories, (ii) suggestion and prioritization of well interventions as well as diagnosis of well mechanical issues and (iii) updating of reservoir model. In addition to reservoir applications, the data are used extensively for monitoring and surveillance of the impact of injection, production, compaction and subsidence of the overburden section at Ekofisk (Bertrand et al., 2013).

Different cases have been published by ConocoPhillips showing how the high fidelity 4D seismic attributes from the Ekofisk PRM have been used to mitigate the risk when drilling new wells (Lyngnes et al., 2013) and to impact on reservoir management, well interventions and production optimisation (Grandi et al., 2013 and Folstad et al., 2013). ConocoPhillips has also published results showing that multi-component processing enabled it to reduce significantly the extent of the seismic obscured area (SOA) for both the PP and PS data, as well as to improve data quality for interpretation of more subtle geological features (Bertrand et al., 2013)

The PRM market place (North Sea)
The PRM marketplace is currently moving slowly. The first commercial PRM system was installed at the Valhall field of BP in the North Sea in 2003 and the next full-scale system was installed at Ekofisk in 2010. Currently another two full-scale systems are being installed (2013-2014) in the North Sea at the Snorre and Grane fields operated by Statoil. In addition, a small system installed at the Claire field of BP (North Sea) in 2006 as a field test, has been used for repeated monitoring. Finally, two smaller systems have been installed in deep-water offshore Brazil for repeated monitoring; i.e., the Jubarte field of Petrobras in 2012 and the BC-10 of Shell in 2013. At the end of 2013 no decision is taken for new PRM installations.

The excellent repeatability of the Ekofisk PRM system results in detectability of very small 4D signals. The main attributes used for 4D interpretation at the Ekofisk field are (i) time-shifts at top reservoir (overburden response to reservoir compaction), (ii) intra reservoir time-shifts, (iii) time-strain (derivative of the time-shifts) and (iv) amplitude changes (Lyngnes et al., 2013). Detectable time-shifts and amplitude changes have been quantified by ConocoPhillips (Bertrand et al., 2013). Amplitude changes in the order of 2-3% have been detected and interpreted. The detection level for time-shifts is as low as 200 µs and sometimes even lower levels have been detected for intra reservoir time-shifts. This precision would have been unachievable using streamer data. These reported data confirm the high image quality which can be achieved with fibre optic PRM systems.

The Ekofisk PRM system is now routinely used for several different purposes including (i) optimization of new well locations and trajectories, (ii) suggestion and prioritization of well interventions as well as diagnosis of well mechanical issues and (iii) updating of reservoir model. In addition to reservoir applications, the data are used extensively for monitoring and surveillance of the impact of injection, production, compaction and subsidence of the overburden section at Ekofisk (Bertrand et al., 2013).

Different cases have been published by ConocoPhillips showing how the high fidelity 4D seismic attributes from the Ekofisk PRM have been used to mitigate the risk when drilling new wells (Lyngnes et al., 2013) and to impact on reservoir management, well interventions and production optimisation (Grandi et al., 2013 and Folstad et al., 2013). ConocoPhillips has also published results showing that multi-component processing enabled it to reduce significantly the extent of the seismic obscured area (SOA) for both the PP and PS data, as well as to improve data quality for interpretation of more subtle geological features (Bertrand et al., 2013)

The PRM market place (North Sea)
The PRM marketplace is currently moving slowly. The first commercial PRM system was installed at the Valhall field of BP in the North Sea in 2003 and the next full-scale system was installed at Ekofisk in 2010. Currently another two full-scale systems are being installed (2013-2014) in the North Sea at the Snorre and Grane fields operated by Statoil. In addition, a small system installed at the Claire field of BP (North Sea) in 2006 as a field test, has been used for repeated monitoring. Finally, two smaller systems have been installed in deep-water offshore Brazil for repeated monitoring; i.e., the Jubarte field of Petrobras in 2012 and the BC-10 of Shell in 2013. At the end of 2013 no decision is taken for new PRM installations.
Reservoir Monitoring

Several feasibility studies and evaluations for PRM installations at different fields have been made over the past few years. A strong focus seems to have been on the up-front cost structure with a PRM system and the need for justifying the return of investment. However, the cost of having a medium-sized PRM system installed in the North Sea is less than the cost of having a new well drilled (which might be in excess of $100 million in the North Sea). The financial impact of a PRM investment will be on increased oil recovery and reduced drilling cost. Statoil has announced that it expects that the PRM systems on Snorre and Grane will result in 30 million additional barrels of oil (Statoil, 2012). This number corresponds to 4-5% increased oil recovery at Snorre and Grane. Another approach is to evaluate how a PRM system can facilitate the infill drilling programme and estimate the corresponding cost impact on the drilling expenses. This approach seems to have been used by other operators of PRM. Anyway, infill drilling and increased oil recovery are strongly linked.

There seems to be some reluctance within the industry to acknowledge the value of PRM. Hopefully the Ekofisk results will bring a better understanding of the 4D image quality achievable with PRM and how this improved quality can produce business value for the field operators. The awareness of improved 4D image quality (combined with more frequent surveys) with PRM is now growing. The main challenge for PRM seems to be linked to the multi-disciplinary approach required to install and operate a PRM system; i.e.,

- The installation requires the skills and experience of the sub-surface group responsible for all subsea production equipment and infrastructure;
- Implementation of PRM requires good engineering solutions;
- The PRM recorded data (after seismic processing) needs to be ‘integrated’ with other reservoir monitoring data and production data.

This requires a structured co-operation between subsea engineers, reservoir and production engineers and geophysicists.

It is currently considered within the industry that 4D seismic is viable for fields with remaining oil reserves of 40-50 million barrels of oil and above. In the North Sea 4D seismic has been utilized for fields with less than 30 million barrels in remaining oil reserves. Close to 75% of Statoil’s producing fields in the North Sea use 4D technology today (Statoil, 2012). This means that, in theory, nearly all fields in the North Sea with remaining oil reserves of at least 50 million barrels of oil could represent a potential PRM market in the North Sea. There are about 30 fields in production in the Norwegian sector of the North Sea with the official (governmental) number of remaining oil reserves in excess of 50 million barrels of oil. Four of these fields have already decided to use PRM and most of the remaining fields could benefit from PRM. How large the real PRM market will be in the North Sea, in competition with towed streamers, will be determined by the 4D strategy of the field operators.

In addition to producing fields, new field discoveries are also candidates for PRM. There is some ongoing activity on evaluating whether PRM should be included in new field developments. Availability of 4D seismic data during the early production phase of a field development can be crucial for updates of the depletion and reservoir management plan.

Several new field discoveries in the Norwegian sector of the North Sea (and Barents Sea) have been made over the past few years. Close to 20 of these new discoveries have oil reserves in excess of 50 million barrels of oil and they should in principle be candidates for PRM. By far the largest of these recent discoveries in the North Sea is the Johan Sverdrup field with estimated reserves so far close to two billion barrels.

Conclusion
The data recorded by the fibre-optic PRM system at Ekofisk (and recently published by ConocoPhillips) demonstrate

<table>
<thead>
<tr>
<th>Field</th>
<th>Operator</th>
<th>Installation</th>
<th>Seismic cable</th>
<th>Sensor coverage</th>
<th>Water depth</th>
<th>Number of surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valhall</td>
<td>BP</td>
<td>2003</td>
<td>120 km</td>
<td>45 km²</td>
<td>70 m</td>
<td>16</td>
</tr>
<tr>
<td>Clair</td>
<td>BP</td>
<td>2006</td>
<td>45 km</td>
<td>11 km²</td>
<td>140 m</td>
<td>5</td>
</tr>
<tr>
<td>Ekofisk</td>
<td>ConocoPhillips</td>
<td>2010</td>
<td>200 km</td>
<td>60 km²</td>
<td>75 m</td>
<td>6</td>
</tr>
<tr>
<td>Snorre</td>
<td>Statoil</td>
<td>2013-14</td>
<td>480 km</td>
<td>190 km²</td>
<td>325 m</td>
<td>-</td>
</tr>
<tr>
<td>Grane</td>
<td>Statoil</td>
<td>2014</td>
<td>180 km</td>
<td>50 km²</td>
<td>130 m</td>
<td>-</td>
</tr>
<tr>
<td>Jubarte</td>
<td>Petrobras</td>
<td>2012</td>
<td>36 km</td>
<td>9 km²</td>
<td>1250 m</td>
<td>2</td>
</tr>
<tr>
<td>BC-10</td>
<td>Shell</td>
<td>2013</td>
<td>95 km</td>
<td>36 km²</td>
<td>1650 m</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1 PRM systems installed in the North Sea and offshore Brazil.
remarkable high-fidelity 4D seismic attributes which have been shown to efficiently assist well planning and critical reservoir management decisions. The outstanding seismic repeatability with clean 4D signals and low residual 4D noise delivered by the Ekofisk PRM project (equipment, acquisition and processing) indicates that PRM can provide sufficient 4D detectability even at fields with poor fluid response.

So far, the main (full scale) PRM systems have been installed or are being installed at fields in the North Sea (Norwegian sector). These first fields all have remaining oil reserves in excess of 200 million barrels, but it is expected that nearly all fields in the North Sea with reserves in excess of 50 million barrels might benefit from the characteristics of PRM systems. Furthermore, 4D seismic is now starting to be included in the early phases of field development plans and this might broaden the future PRM market in the North Sea by including new field discoveries.

References
Eriksrud, M. [2010] Towards the optical seismic era in reservoir monitoring. First Break, 28(6), 103-111.
Lyngnes, B., Landa, H., Ringen, K. and Haller, N. [2013] Life of Field Seismic at Ekofisk – utilizing 4D seismic for evaluating well target. 75th EAGE Conference & Exhibition, Extended Abstracts, We 1209.
Grandi, A., Lyngnes, B. and Haller, N. [2013] Reservoir management through frequent seismic monitoring at Ekofisk field. 75th EAGE Conference & Exhibition, Extended Abstracts, Th 1409.