# Ekofisk life-of-field seismic: Operations and 4D processing

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## Abstract

In 2010, the world's largest optical permanent reservoir monitoring (PRM) system was installed in the southern part of the Norwegian North Sea at Ekofisk. The life-of-field seismic (LoFS) system consists of 3966 seabed multicomponent sensors along 200 km of mostly trenched fiber-optic seismic cables and covering about 60 km$^2$ of Ekofisk field. Seismic data are acquired via a topside recording unit and a containerized source operated on a supply vessel. Six vintages of data were acquired between the end of 2010 and fall 2013. Different aspects of seismic operations at Ekofisk include seismic source, recording system, data transfer, quality control, and processing. One of the key factors in achieving the full value of a PRM system is to handle such operations in a safe, integrated, and efficient manner to deliver high-quality seismic volumes for interpretation with rapid turnaround. Key aspects of the 4D processing sequence include robustness and optimal turnaround. Integration of the different operational phases of the LoFS project and integration of expertise between client and contractor play a key role in delivering clean, well-resolvable 4D signals and low residual 4D noise with NRMS as low as 5%. The high-quality data delivered by operations and processing are now routinely used in well planning and reservoir-management workflows.

## The Ekofisk field

Ekofisk is a giant chalk field containing approximately 6.7 billion stock tank barrels of oil (STBO) in the southern Norwegian North Sea. Ekofisk was discovered in 1969. Since the beginning of production, in 1971, the field has experienced significant compaction, caused by pressure depletion and water weakening resulting from water injection. This has led to seabed subsidence, requiring a spectacular jack-up of the platforms in 1987.

Four-dimensional seismic has played a significant role in understanding and characterizing compaction and production mechanisms and in assisting well planning by identifying unswept zones. In 1999, the first 4D monitor was acquired as a repeat survey of the first 3D streamer survey, acquired in 1989. Their joint processing revealed significant time shifts, as high as 20 ms at the top reservoir level, related to compaction. Since then, three more streamer surveys have been acquired, in 2003, 2006, and 2008 (Haugvaldstad et al., 2011). Top reservoir time shifts have been the most used 4D attribute as an indicator of reservoir compaction because they are sensitive to pressure depletion and water injection/weakening.

With more than 1 billion STBO to be produced and more than 80 wells to be drilled during a period of 15 years, a large number of 4D seismic surveys will be necessary to support the drilling program. In 2005, a value-of-information (VoI) study at Ekofisk (Folstad, 2011) concluded that installing a permanent seabed system would be a better seismic-monitoring strategy than continuing with towed-streamer surveys. Despite a larger initial investment, the permanent system was found to be the most economically viable solution. Its better 4D repeatability, caused by using fixed receivers, would result in increased production and cost savings from fewer redrills in the future development program. In 2008, based on its expected long-term reliability, ConocoPhillips selected an optical system for the Ekofisk LoFS project.

## Ekofisk PRM system and installation

The Ekofisk LoFS system consists of 200 km of seismic cables, an additional 40 km of connection cables, and a containerized recording system provided by Optoplan, a Sercel

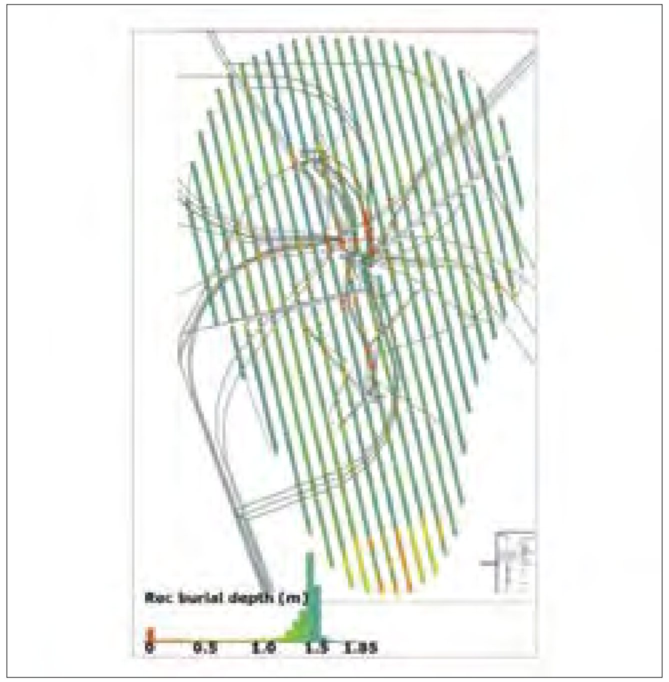


*Figure 1. The Ekofisk PRM receiver array of fiber-optic cables, color-coded by receiver-station burial depth.*

| Survey | Acquisition | Duration (days |
|---|---|---|
| LoFS1 | Nov. 2010–Jan. 2011 | 71 |
| LoFS2 | May–June 2011 | 33 |
| LoFS3 | Sept.–Nov. 2011 | 43 |
| LoFS4 | June–July 2012 | 38 |
| LoFS5 | March–April 2013 | 36 |
| LoFS6 | Sept.–Nov. 2013 | 56 |

*Table 1. Acquisition periods and durations of the first six LoFS surveys at Ekofisk field (including weather standby).*





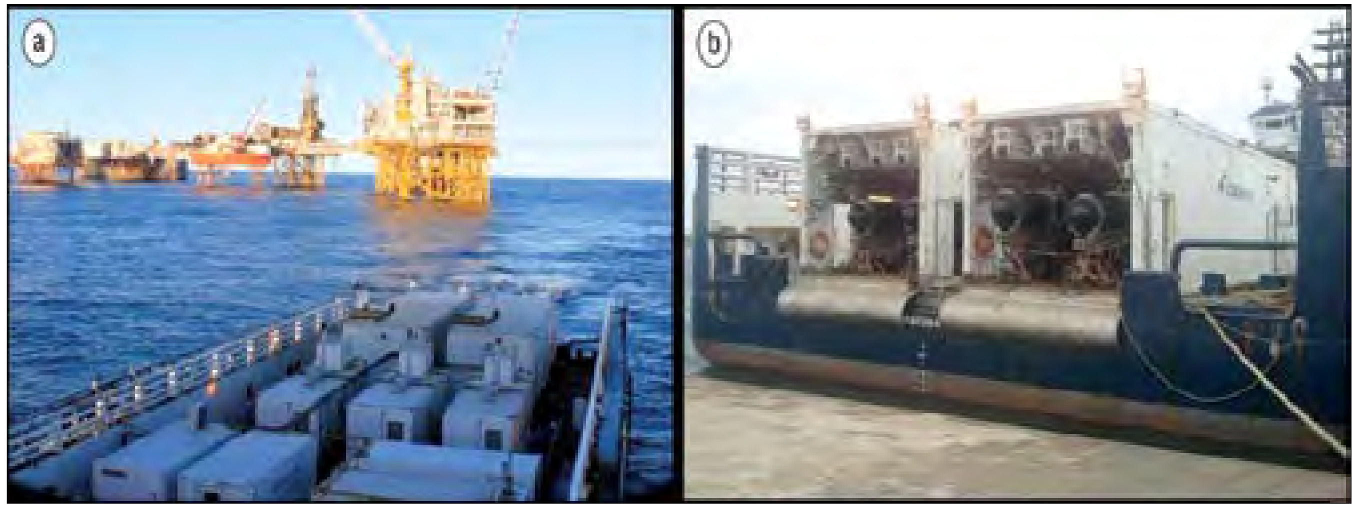


*Figure 2. (a) View of the back deck of the supply vessel, presenting the different containers used for seismic acquisition, shown here close to the main Ekofisk platform complex. (b) View of the rear of the vessel, showing both source containers with two subarrays in each.*

company (Figure 1). The seabed and topside system was installed in 2010. Cables were trenched at approximately 1.5 m below the seabed (70- to 80-m depth) using a jet-trenching remotely operated vehicle (ROV). For pipeline crossings, which created extra challenges during installation, cables were laid over pipelines and rock-dumped.

The receiver array consists of 24 cables spaced 300 m apart, for a total of 3966 four-component sensor stations (50-m receiver-station interval). Figure 1 shows the geometry of the receiver array, along with the numerous pipelines (in black). The orientation of the seismic array is identical to the azimuth of the streamer surveys so as to coprocess and link the two data types. The nominal shot grid is 25 m between shotpoints and 50 m between shot lines. Shots are acquired over 2 km beyond the limits of the receiver layout, giving approximately 143 km$^2$ of shot coverage.

The topside system contains the optical instrumentation, which sends the laser signal to the sensor stations (Nakstad et al., 2011). It also contains the recording system, which demodulates the optical signal and generates SEG-D seismic files. The topside equipment, which is in an instrumentation container on one of the Ekofisk platforms, can be turned on and operated remotely from shore. The full array is typically used during active seismic campaigns or for specific passive-monitoring purposes.

## Acquisition and QC

With two surveys of 40 to 50 days per year (Table 1) and a need to use the same source on each survey, an appropriate solution for Ekofisk LoFS acquisition is to use a containerized source operated from a platform supply vessel. The source system, provided by CGG, consists of source, compressor, and generator containers, all installed on the vessel's back deck (Figure 2). Fit-for-purpose equipment has been developed to minimize the time it takes to install the source system on the vessel shortly before a survey starts. The source includes three subarrays of four gun


*Figure 3. Shot-position error distribution for LoFS1-5. Solid lines show inline shot-position errors; dotted lines show crossline shot-position errors. Error distribution shows that 94% of shots are within 5 m of their preplot target positions.*

clusters towed by stiff floats. A spare subarray and other spare equipment (e.g., guns, compressor) are available in case of technical failure.

The use of a supply vessel with a modern steering system enables the high source-positioning repeatability required for PRM. For the first five LoFS surveys (Table 1), about 94% of the shots were within 5 m of their preplot positions (Figure 3). With this design, a change of vessel will not impact repeatability because the same source system is mounted throughout.

During operations, source headers (time stamps and navigation) are sent by satellite from the vessel to the recording system, where they are merged with raw seismic data. The generated SEG-D files are then sent near real time to the ConocoPhillips office in Stavanger, Norway, using a gigabit fiber-optic link. There, data are quality-controlled and processed in a dedicated center run by CGG, in which acquisition QC staff and processing personnel are colocated.

An efficient QC procedure has been established in which several attributes are generated in real time, allowing monitoring of the recording system, sensor response, noise levels, and various field activities. Figure 4 shows one of the QC plots generated in real time to monitor noise level. In this example, showing rms amplitude for one shot in the P-component for each sensor, strong seismic interference can be observed.

Constant communication between onshore and offshore QC personnel allows rapid and appropriate decisions to be made. Source behavior and positioning are monitored onboard the vessel. QC personnel collect all seismic and source QCs and generate end-of-line reports within a day for client line acceptance. Position data are then combined with seismic (nav-seis merge) and are passed to the processing specialists in the same office. In cases when strong or unusual types of noise are observed, lines can be fast-tracked through processing to help in deciding on potential reshooting.

## LoFS 4D processing

The design of the Ekofisk LoFS 4D processing sequence was guided by the need for robustness and efficiency. By the

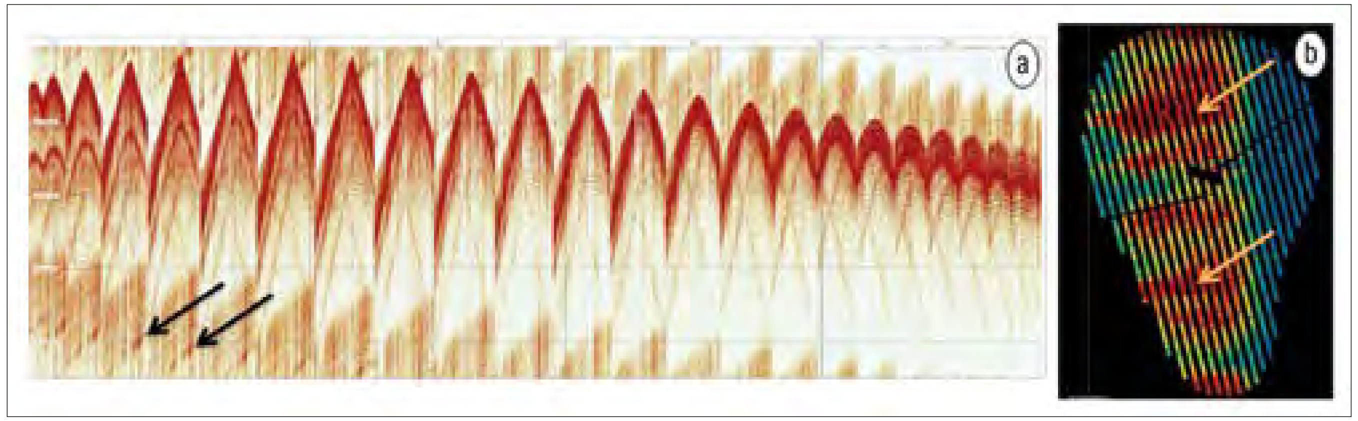


***Figure 4.*** *Example of real-time QC plots. (a) Hydrophone component of a single shot gather for all 24 cables. Black arrows indicate seismic interference. (b) Map of rms amplitude computed for each receiver (last 500 ms of the record), also highlighting the presence of seismic interference (orange arrows).*

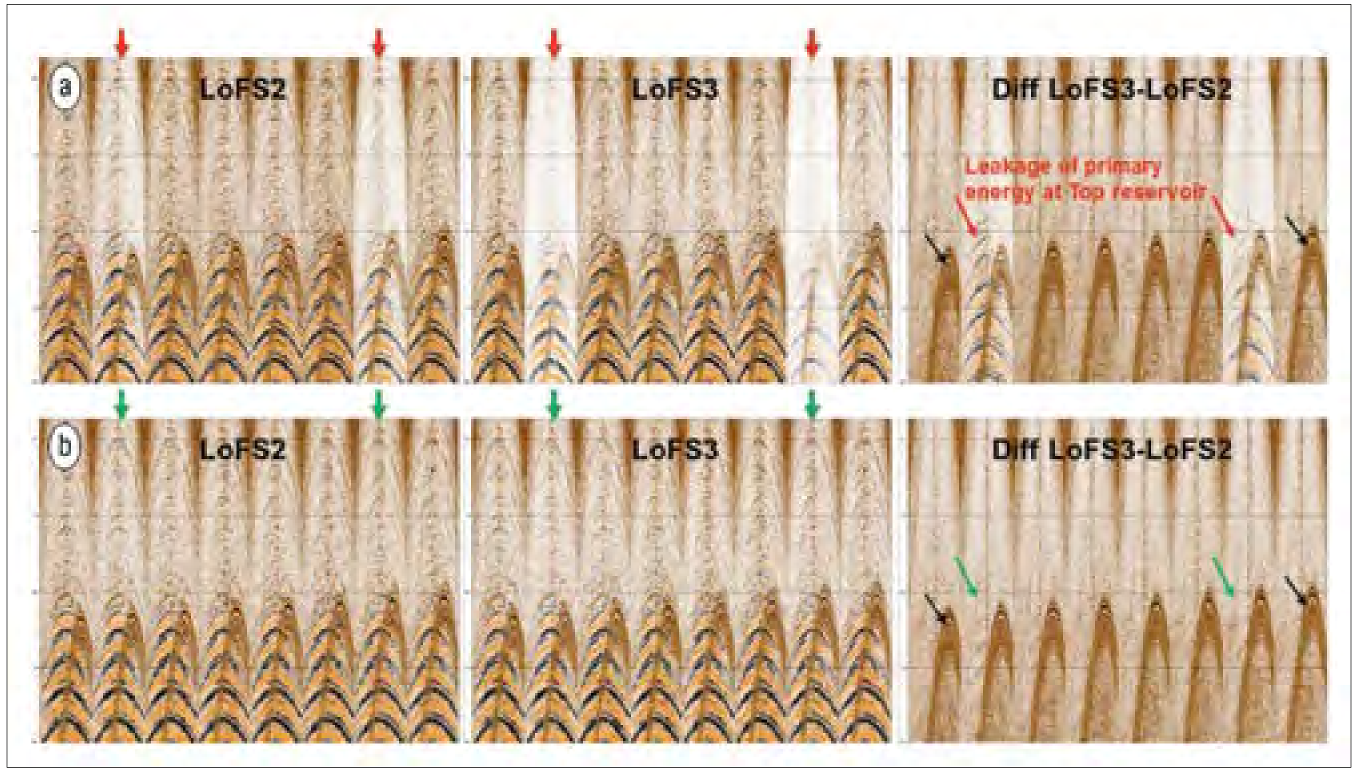


***Figure 5.*** *Pressure-recording harmonization. Eight consecutive 2D receivers are displayed from LoFS2 (left), LoFS3 (middle), and 4D difference (right) (a) before and (b) after mitigation. After corrections, variations across gathers have been removed (red and green arrows indicate the two affected hydrophones). The strong noise seen on the 4D difference (also present after mitigation and indicated by black arrows) comes from the energy reflected from the Ekofisk tank at the center of the platform complex. This noise (particularly multiple energy) is not repeatable because of change in water velocity between vintages.*





second monitor acquisition (LoFS3), turnaround needed to be reduced to one month after the last shot without loss of 4D resolution. Dedicated modules and solutions were developed for processing LoFS data using expertise across divisions and via joint workshops at key stages.

With fixed sensors, the high degree of acquisition repeatability on Ekofisk is ideal for repeat processing. The processing flow has been optimized on the base survey and first monitor survey and is now applied to each new LoFS monitor vintage with a minimum of change.

To achieve the required turnaround, a processing flow with few switches between data domains is required. This minimizes the time spent waiting for full data apertures required for subsequent processing steps. Shot-domain processing on the Ekofisk project starts immediately after each line is acquired. On completion of acquisition, full 3D receiver gathers are produced. True 3D processing, which optimally addresses the 3D nature of the LoFS acquisition, is then applied. After that, data are sorted to the common-offset domain for Kirchhoff migration. Some of the key elements of the 4D processing sequence are described below in more detail.

### *Shot-domain processing*

Shot-domain processing is initiated as soon as nav-seis merged data are available to the processing team, typically half a day after a sail line is acquired.

Key steps of shot-domain processing include:

- Pressure-recording harmonization: During analysis of LoFS1 data, we observed that the pressure response for some sensor stations had varied between prime and reshoot lines. Laboratory and field tests suggested an impaired pressure-transfer mechanism in the area of the hydrophone chamber (Nakstad et al., 2013). Close collaboration between contractor and operator personnel enabled a satisfactory processing mitigation to be developed. Although the number of affected sensor stations increased over time, detailed analysis shows that mitigated data are of comparable quality to unaffected data. Figure 5 shows a series of neighboring 2D receivers gathers before (Figure 5a) and after (Figure 5b) mitigation.
- 3C rotation and PZ summation: Parameters and operators were established during processing of the first LoFS survey and were unchanged for subsequent monitors. QC showed that this gives best 4D repeatability. The PZ summation consists of the following three-step procedure (Soubaras, 1996): (1) calibration of geophones (cross-ghosting technique); (2) separation of up- and down-going wavefields by summing the hydrophones and the calibrated geophones (ghost elimination); (3) application of a source-side depeg-leg which amounts to a surface-consistent gapped deconvolution in the receiver domain.
- Denoise 1 (Figure 6): $V_z$ noise, coherent on receiver gathers, is a low-frequency, low-velocity noise affecting the vertical component. It is removed on shot gathers,

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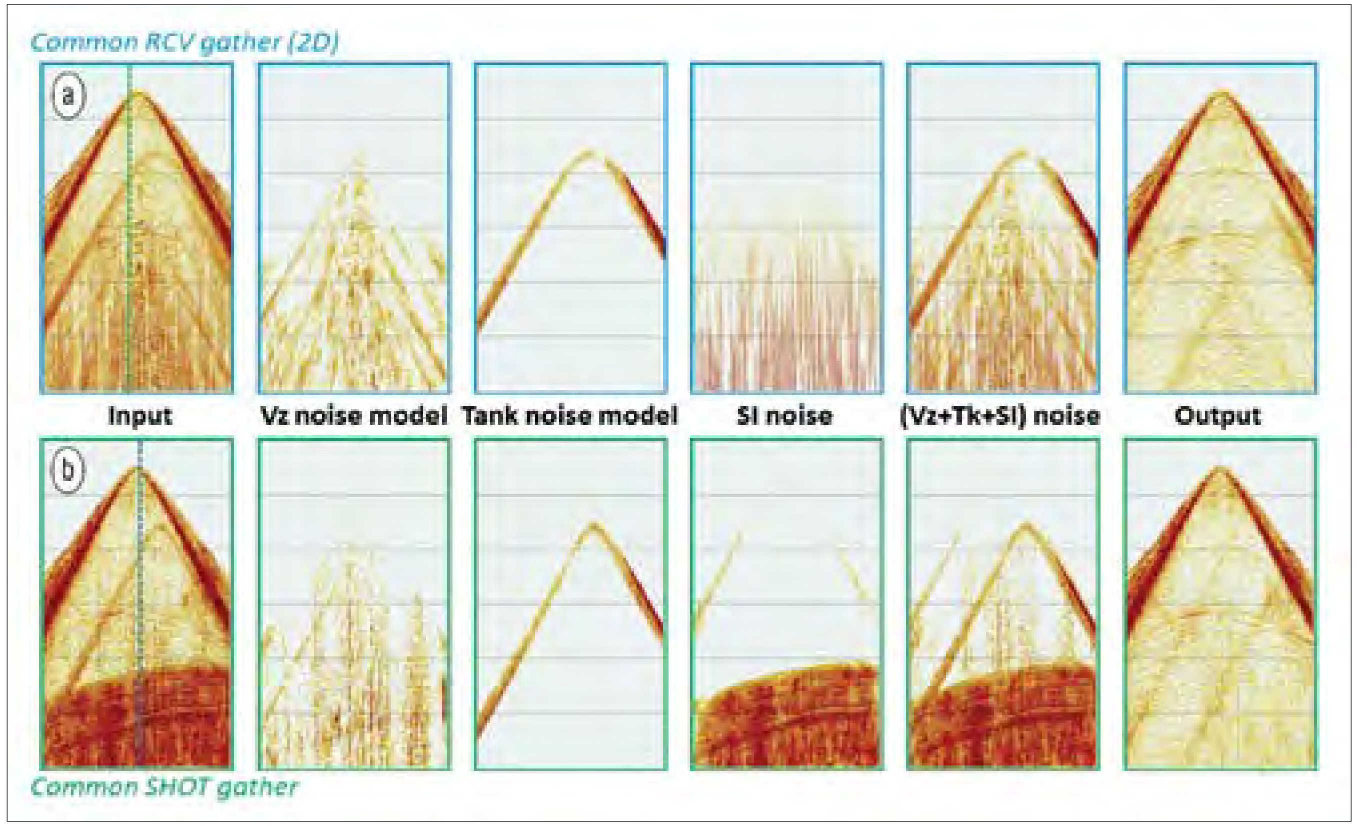


***Figure 6.*** *Denoise performed in the sail-line domain. (a) A typical 2D receiver gather and (b) common shot gather. The green dotted line (a) indicates locations of the displayed shotpoint. The blue dotted line (b) indicates locations of the displayed receiver. From left to right: gather before denoise; $V_Z$ noise model; tank noise model; SI noise model; full noise model; denoised gather.*

where it is incoherent, by using *f-x* projection filtering. The large concrete tank (100-m diameter) which stands in the center of the Ekofisk platform complex is a source of strong backscattering noise affecting all sail lines. Tank noise is removed in the 2D receiver domain by applying high-resolution linear Radon filter after tank-noise flattening with water velocity. Another source of noise is seismic interference (SI) from other crews shooting in the Ekofisk area, recorded on several occasions during LoFS surveys. This noise is removed by *f-x* prediction filtering. At the end of shot processing, the now significantly reduced data volume is transferred to CGG's computer hub in the UK for the more computer-intensive part of the processing sequence.

*3D receiver-domain processing*

After sorting the data into 3D receiver gathers, the following key processes are applied:

- Denoise 2: Within a 3D receiver gather sorted in the crossline direction, the nonrepeatable noise generated by vessels (and platforms) operating constantly in the Ekofisk area is randomized and can be removed by *f-x* projection filtering.
- 4D environmental corrections: Tidal statics and water-velocity corrections are derived from data measured during acquisition. These corrections are relatively small given the shallow water (70 to 80 m).
- Three-dimensional tau-$p_x$-$p_y$ deconvolution is then applied after interpolating shots down to 12.5 m to reduce spatial aliasing. A mute is also applied in the tau-$p_x$-$p_y$ domain.
- Four-dimensional trace editing is performed instead of the more usual 4D binning, which is suitable only for 4D parallel processing (not repeat processing). A small number of traces is rejected based on a geometric criterion fixed for all surveys and based on a threshold for $\Delta_{source}$, the distance between actual and preplot shot coordinates. This correction affects mainly traces around obstructions.
- Data regularization with missing trace restoration (midpoint regularization in the 3D receiver domain) ensures identical number and position of traces on every vintage.

*Offset-domain and postmigration processing*

The data are subsequently sorted into 50-m offset classes prior to Kirchhoff prestack depth migration. The P-velocity model used for migration comes from the comprehensive velocity-model-building workflow using full-waveform inversion and joint PP-PS tomography described in Bertrand et al. (2013). Using those updated velocities significantly improves imaging in the seismically obscured area (SOA). After migration, the prestack part of the processing consists of RMO and Radon demultiple processing. We then perform *Q* compensation and dip-consistent filtering on the stacked data. The final full-offset stack is delivered within the targeted one-month turnaround. Other than a small bulk time shift, no further 4D spectral matching is applied.





### 4D processing results

The LoFS 4D seismic data have remarkable repeatability with extremely low NRMS values, on the order of 4% to 5% (Figure 7), allowing much smaller 4D effects to be detected on Ekofisk than before. As a comparison, the best NRMS achieved with streamer data at Ekofisk, considered remarkable at the time, was about 12% (Haugvaldstad et al., 2011). NRMS is computed after warping of the baseline survey to account for subsidence. We currently consider that time shifts as low as 200 µs (sometimes less) and amplitude changes on the order of 2% to 3% can be detected.

Outside the SOA in the center of a field, where a gas cloud prevents optimal imaging, clean and well-delineated 4D signals can be observed at injector and producer wells operating between the LoFS surveys. Figure 8 shows an example of the high-quality 4D signal highlighting amplitude changes at a new producer well. The small amplitude change (less than 5%), corresponding to an acoustic-impedance change of approximately 3%, is

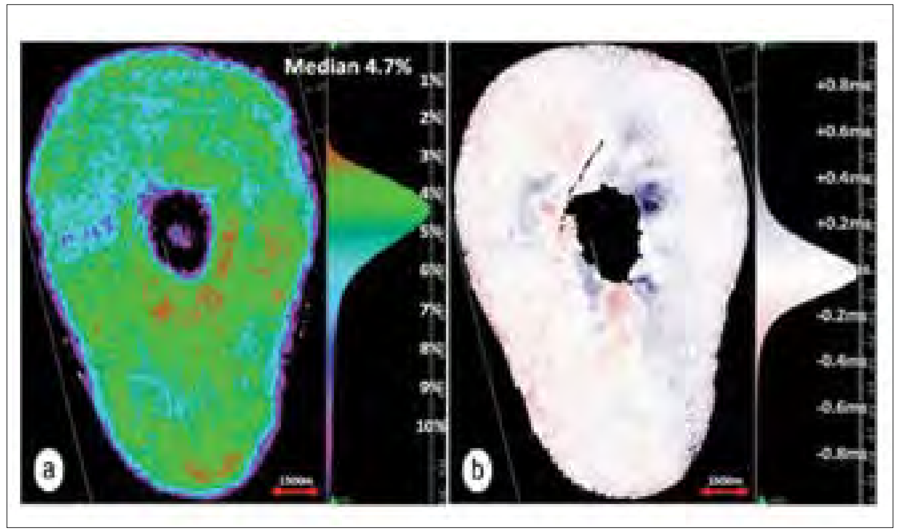


***Figure 7.*** *(a) LoFS2/LoFS3 NRMS map computed on final stacks in a 2500- to 3500-ms window. (b) Time shift at top reservoir. LoFS2 and LoFS3 were acquired 4.5 months apart. The area in black at the center of the field is seismically obscured because of an overburden gas cloud.*

interpreted as having been caused by gas exsolution resulting from pressure depletion in the area of this producer. That is confirmed by a large gas-oil ratio measured at the well.

LoFS seismic results are now routinely used for many purposes, including optimization of new well locations and trajectories (Lyngnes et al., 2013), suggestion and prioritization of well interventions, diagnosis of well mechanical issues (Grandi et al., 2013), and updating of the 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 on the overburden.

## Conclusions

The world's largest optical permanent reservoir monitoring system, using nearly 4000 seabed multicomponent sensors, was installed at Ekofisk in 2010. The aim of this PRM project is the frequent rapid delivery of high-quality time-lapse monitoring images to optimize various field-development aspects at Ekofisk. Six life-of-field seismic surveys have been acquired to date.

This paper describes the main operational aspects of the PRM system and the 4D processing and imaging of the P-wave data. Efficient operations are a key part of a PRM system. Involvement of a single contractor group enables good coordination between different project phases and has facilitated its realization, reduced processing turnaround, and enabled timely mitigation of any arising issues.

A robust 4D processing sequence has been established and optimized, allowing us to run rapid repeat 4D processing when a new monitor survey is acquired and to deliver 4D images within four weeks of the end of acquisition. Residual 4D noise for the LoFS data is significantly lower, down to 5%, than what is achievable with towed-streamer acquisitions. Time shifts on the order of 200 μs and acoustic-impedance changes on the order of 3% to 4% are clearly delineated on final 4D difference data.

LoFS seismic results are now used in many aspects of field management at Ekofisk such as well planning or reservoir model calibration. TLE

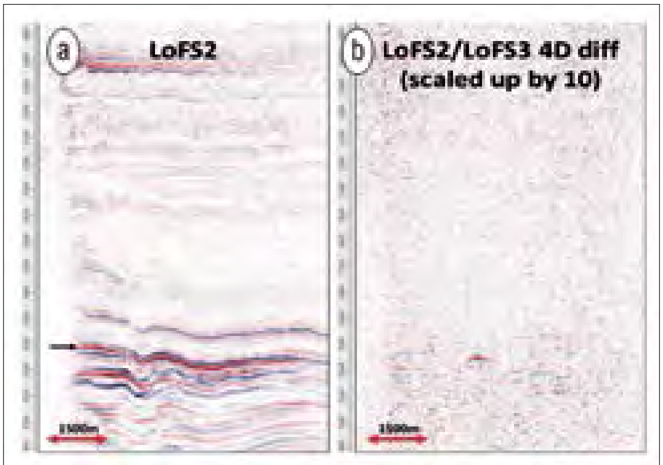


***Figure 8.*** *(a) LoFS2 and (b)LoFS2/LoFS3 4D difference scaled by a factor of 10. The arrow shows the location of the top reservoir. The SOA is visible on the left side of each panel.*


### References

Bertrand, A., T. Hellmann, C. Henstock, B. Lyngnes, S. Buizard, G. Oexnevad, and N. Haller, 2013, Wide-azimuth PP/PS depth imaging at Ekofisk using full waveform inversion: 75th Conference and Exhibition, EAGE, Extended Abstracts, http://dx.doi.org/10.3997/2214-4609.20130064.

Folstad, P. G., H. Haugvalstad, and G. Jeangeot, 2011, Ekofisk PRM —The technical case for this brand new installation: EAGE Workshop on Permanent Reservoir Monitoring (PRM)—Using Seismic Data.

Grandi, A., B. Lyngnes, and N. Haller, 2013, Reservoir management through frequent seismic monitoring at Ekofisk field: 75th Conference and Exhibition, EAGE, Extended Abstracts, http://dx.doi.org/.10.3997/2214-4609.20130175.

Haugvaldstad, H., B. Lyngnes, P. Smith, and A. Thompson, 2011, Ekofisk time-lapse seismic—A continuous process of improvement: First Break, **29**, no. 9, 113–120.

Lyngnes, B., H. Landa, K. Ringen, and N. Haller, 2013, Life of field seismic at Ekofisk: Utilizing 4D seismic for evaluating well target: 75th Conference and Exhibition, EAGE, Extended Abstracts.

Nakstad, H., J. Langhammer, and M. Eriksrud, 2011, Permanent reservoir monitoring technology breakthrough in the North Sea: 73rd Conference and Exhibition, EAGE, Extended Abstracts.

Nakstad, H., M. Eriksrud, and S. Valla, 2013, Pressure recordings at Ekofisk—Experience and route forward: Second EAGE Workshop on Permanent Reservoir Monitoring (PRM) — Current and Future Trends, http://dx.doi.org/10.3997/2214-4609.20131311.

Soubaras, R., 1996, Ocean-bottom hydrophone and geophone processing: 66th Annual International Meeting, SEG, Expanded Abstracts, http://dx.doi.org/0.1190/1.1826611.


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