Optimising 4D Seismic with Evolving Technology over 20 Years of Reservoir Monitoring of the Gullfaks Field, North Sea

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Summary

Seismic monitoring of the Gullfaks field has been in progress for over 20 years. Over that time changes in acquisition equipment and planning have led to improved 4D repeatability. In addition, upgrades in processing and imaging technology such as designature and demultiple have reduced 4D noise and consequently given us higher confidence in the interpretability of 4D signal. A monitor survey was acquired in 2016 with a multi-component streamer solution and thus led to a 4D time-lapse processing project including older vintage surveys. This paper summarises the various changes in acquisition over the years and shows that continuous improvement in acquisition design alongside backward compatibility, rather than strictly repeating acquisition parameters, pays off with better quality 4D results. Finally, some intermediate results from the latest processing show that even the best repeated surveys can benefit from reprocessing when compared with previous processing results.

Introduction

The Gullfaks field lies in block 34/10 in the northern part of the Norwegian North Sea. Production from Jurassic sandstone reservoir units consisting of the Brent, Cook and Statfjord formations started in 1986 and since 2012 the shallower reservoir units of the Shetland and Lista formations have been producing.

The Gullfaks asset has been running a successful seismic monitoring program since 1995 when a 4D survey was performed on a research basis, the conclusions of which resulted in the acquisition of the first full monitor survey in 1996. Since then 4D surveys have been acquired at regular intervals to monitor production in the reservoir.

During the 21 years of seismic monitoring on the Gullfaks field there have been a number of changes in acquisition systems and processing algorithms. This paper summarizes the various acquisition changes and also compares the latest processing technologies used in the current processing to the previous results.

Improvements in Seismic Acquisition

Including the original 3D seismic survey shot in 1985, there have been nine towed streamer surveys acquired on the Gullfaks field. Step changes in acquisition systems and survey design standards have resulted in geometries which fall into four separate phases of 4D monitoring which are summarized in Table 1. The vintages being processed in the latest seismic monitoring round are in bold.

Phase	1	2	3	4
Acquisition years	**1985**	1995, **1996**	1999, 2002, 2005	**2008, 2011, 2016**
Number of source arrays	1	2	2	2
Array separation (m)	-	50	50	50
Number of streamers	2	6	8	17
Streamer separation (m)	50	100	100	50
Overlapping sail-lines	No	No	Yes	Yes
Steerable streamers/sources	No	No	No	Yes

Table 1 *Summary of the four phases of towed-streamer acquisition over the Gullfaks field.*

The first phase comprises the first 3D survey in 1985, which serves as the baseline pre-production survey. The second phase includes the initial 4D monitor surveys of 1995 to 1996. These were essentially 3D surveys as the acquisition geometries were significantly different to the 1985 acquisition parameters. The three monitor surveys acquired between 1999 and 2005 are in phase three, and were planned to maximize repeatability, using overlapping streamers and planned pre-plots to reduce the impact of feathering. The latest phase (2008-2016) took advantage of a general increase in towing capacity available in the seismic industry to perform High Density 3D acquisition (HD3D) with a towed spread of 17 streamers at 50m spacing while still being backward compatible with the 1999-2005 vintages. The 17 cable acquisition introduces double fold and 20-25% relative improvement of NRMS compared to 100 m cable separation and was done primarily to enhance 4D processing results. In addition, the latest acquisition phase has steerable sources and streamers to further improve the 4D repeatability.

A common measure of repeatability in 4D monitoring surveys is dS+dR which is the sum of the difference in source and receiver positions between two vintages for a given trace pair. Figure 1 shows dS+dR maps between 2011-1985 (left), 2011-1996 (middle) and 2011-2008 (right) for a near offset class. These maps show a general improvement in dS+dR as the acquisition geometry gets progressively more repeated. The 1985-2011 map has a mean dS+dR of 100.48m, and shows a stripe pattern corresponding to the change in acquisition spread width. The 1996-2011 map has a mean dS+dR of 81.52m and while there isn't a distinct stripe pattern the areas of low dS+dR are only outside of the platform areas. The 2008-2011 map has a mean dS+dR of 18.95m and is clearly well repeated thoughout the survey area, even close to the platform holes.

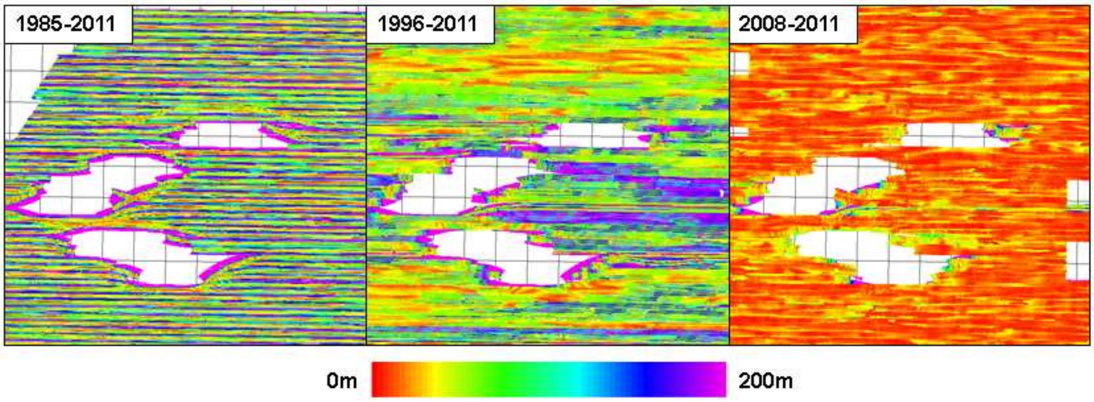

Figure 1 *Maps showing the difference in source and receiver positions between the 2011 vintage and 1985 (left), 1996 (middle) and 2008 (right). The maps clearly show the improvement in acquisition repeatability over the years.*

While the acquisition geometry and preplot for the latest (2016) monitor survey were the same as in 2008, there was one change which has the potential to improve the imaging further, that being an upgrade from conventional hydrophone-only streamers to multicomponent streamer technology. The use of pressure sensors together with particle velocity sensors in wavefield separation allows for deeper towing depths than hydrophone only acquisition, thereby reducing noise levels and increasing acquisition efficiency without compromising the bandwidth. In addition, the wavefield separation as presented by Söllner et al. (2008) offers the flexibility to output the upgoing wavefield (P-UP) for broadband processing and a reconstructed hydrophone dataset (H-REC) for 4D backward compatibility (Day et al. 2010). Therefore the 2016 survey sets a new milestone in the monitoring program and opens up for future broadband 4D seismic.

Improvements in Seismic Processing

The move to broadband acquisition has seen a need for an improvement in the handling of the low frequencies, especially during the designature processing step when trying to minimise the bubble effects. While not that noticeable in 3D imaging, any inaccuracies in designature manifests itself on 4D differences as low frequency ringing.

The 2016 processing used ghost-free hybrid signatures instead of purely modelled far field signatures. Generating these signatures involves using measured near field signatures to improve the low frequencies, combined with modelled near fields at high frequencies. These hybrid signatures are then matched to a zero-phased desired output based on the instrument response of the acquisition system. Alongside this the source and receiver ghosts are de-phased in 2D, accounting for the change in ghost notch with emergence angle.

In addition to adding 4D noise, residual bubble can have a knock on effect in the processing sequence. Tau-P deconvolution, long the workhorse of shallow-water marine towed streamer processing, can latch on to residual bubble alongside multiples when the water bottom is of a similar depth to the bubble period. This can result in different behavior in demultiple even though the same parameters have been used for each 4D survey, resulting in residual multiples left on the 4D difference. These in turn can affect any time shift calculations and so on.

The 2016 processing did not rely on Tau-P deconvolution and instead used fully 3D demultiple processes as described by Barnes et al. (2015), consisting of seabed convolutional 3D SRME and 3D wavefield extrapolation SRME which were simultaneously adaptive subtracted, followed by muted 3D SRME to remove longer period multiples.

One testing technique applied in the 2016 processing has been to try and set up a pre-migration processing sequence in advance of 2016 acquisition by running all testing on the 2008 and 2011 surveys. At the end of each of the denoise, demultiple and sail-line related time shift correction stages the two surveys were taken through 4D binning, regularization and migration to output a stack to compare against a fast track “reference sequence”. Figure 2 shows Normalised RMS Difference (NRMS) maps of the test migration stacks as the project progressed through the denoise (median NRMS 25%), demultiple (median NRMS 24.5%) and sail-line related statics (median NRMS 23.5%) stages of the project. As well as a general reduction in NRMS the maps also look less stripy, which is a result of applying the sail-line static corrections.

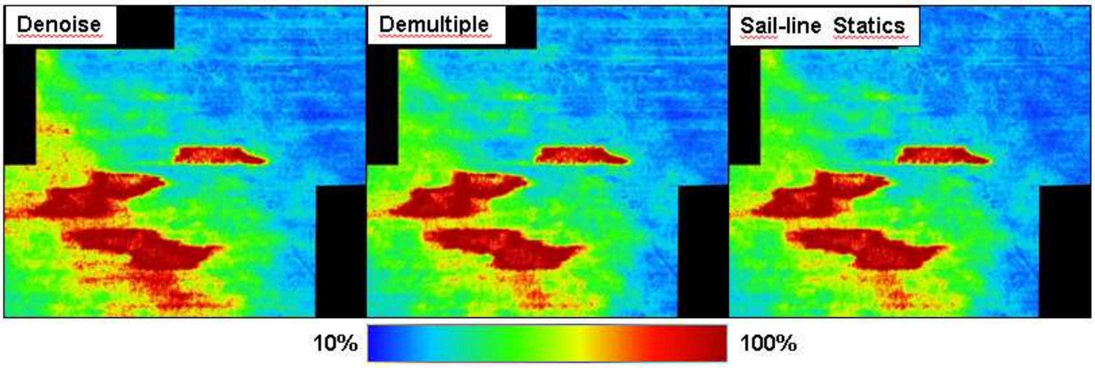

Figure 2 *NRMS maps at the denoise (left), demultiple (middle) and sail-line static corrections (right) stages of the project. Median NRMS values for these maps were 25% for denoise, 24.5% for demultiple and 23.5% for sail-line related statics.*

Along with checking how the attributes were progressing through the processing sequence, the migrated test stacks could also be compared to the final products from previous processing projects. This allowed for constant feedback from clients on processing decisions and confidence that the more modern processing algorithms were working to remove more 4D noise while preserving 4D signal. Figure 3 shows 4D difference sections of 2011-2008 data processed in 2011 (left, final processing) and 2016 (right, from one of the “reference sequence” tests). While there are imaging differences due to the older processing being PSTM and the new PSDM, the main differences are due to improved designature and debubble. The green arrow points to an event indicating production effects. Here the latest processing shows improved standout from the 4D noise. The black arrows show areas with residual bubble present, along with “unexplainable” 4D effects which are now removed due to the improved demultiple. In addition to comparing 4D difference sections, the NRMS was also calculated for the two datasets. The data processed in 2011 has a median NRMS of 25.7% while the 2016 processing has a median of 23.5%. As the latest processing is still to have post-migration Radon demultiple, denoise and 4D global matching applied we would expect the NRMS to lower further by around 5 percentage points based on past experience in the area.

Taken together, the 4D differences and the NRMS values show that the improved processing sequence reduces 4D noise and improves confidence in the 4D results, even for two surveys with the well repeated acquisition of 2008 and 2011.

Further improvement to the processing sequence could be the approach taken by Fahimuddin et al. (2016), which involved full (amplitude and phase) deghosting the conventional base and monitor surveys and processing them alongside the upgoing wavefield from multicomponent towed-streamer acquisition.

Conclusions

The Gullfaks seismic monitoring program has made successful use of available acquisition and processing to make improvements to both repeatability and the 4D image. We have shown in this paper that each new vintage successfully improves the 4D quality without compromising repeatability with previous surveys and that reprocessing gives great benefit to the interpretability of 4D seismic. Finally, employing up-to-date acquisition and processing technologies, including broadband solutions, sets a path towards future high resolution 4D projects.

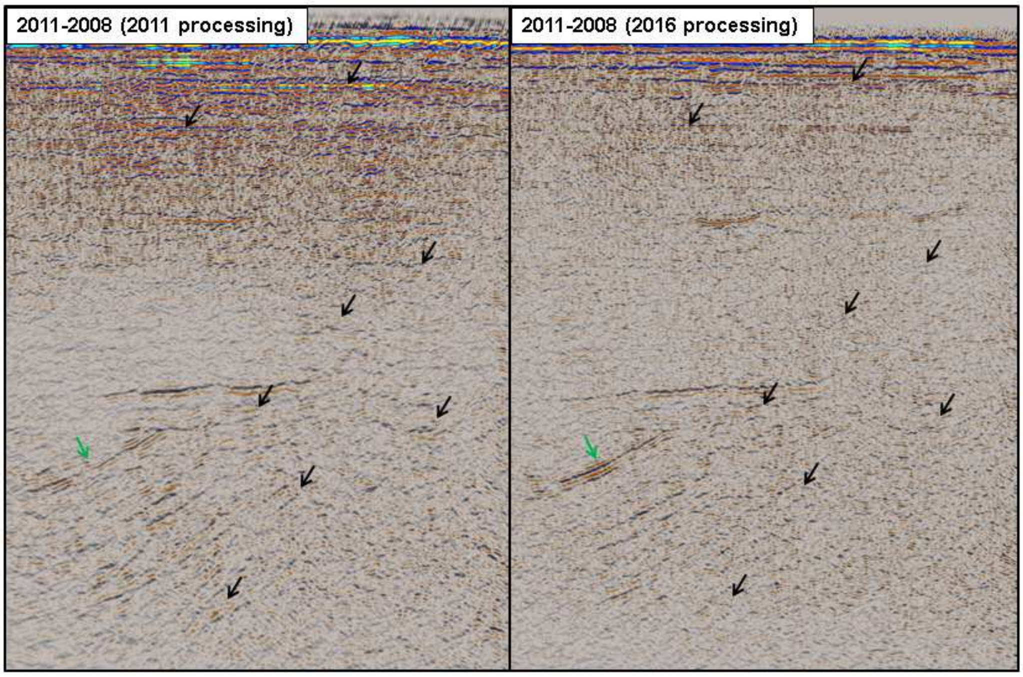

Figure 3 *4D difference sections between the 2011 and 2008 vintages showing the reduction in 4D noise for data processed in 2016 compared to 2011.*

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