Opportunistic 4D time-lapse using a regional non-repeated 4D monitor, an Ærfugl case study

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Summary

A MultiClient dataset has been used opportunistically for monitoring production of the Ærfugl gas field in the Norwegian Sea. Prior to a 2022 MultiClient survey, two dedicated 4D surveys were acquired, in 2005 and 2017 respectively. While the legacy 4D surveys (2005-2017) were optimized in terms of dual sources and streamer repeatability, the MultiClient dataset was acquired with larger sail line spacing and wide-towed triple-sources. The sail line azimuth was the only navigation feature in common. The non-repeatability of source and receiver geometry poses a significant challenge in resolving genuine 4D signal above the non-repeated noise floor. The results show that it was possible to retrieve a credible 4D signal consistent with the three vintages. However customized processes must be considered. Furthermore, continuous communication between geophysicists and interpreters is key for validating every processing/imaging step. In the light of the initial 4D results, it was decided to extend the area of interest to cover the full extent of Ærfugl field.

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Introduction

Standard 4D time-lapse acquisitions require extra planning, specialized navigation equipment and strict repeatability constraints for source and receivers. MultiClient (MC) acquisitions on the other hand are configured for covering extensive areas efficiently with relaxed positioning requirements. Combining both types of seismic surveys for a 4D project constitutes a technical challenge associated with uncertainties related to non-repeatability of source and receiver positions.
In this case study, an MC dataset have been used opportunistically for monitoring the production of a gas field in the Norwegian Sea.

The Ærfugl field is approximately 60 km long and 2-3 km wide, with a stratigraphic pinch-out to the East (Figure 1). A test producer P1 drilled in 2013 proved the presence of gas before start-up of the first regular producer in 2020. In total, 6 wells were set on production in the period 2019 to 2021. Prior to the 2022 MC survey, two conventional 4D surveys were acquired, in 2005 and 2017 respectively. Only minor water flooding effects were interpreted on the 2017 data, however as most of the production started after 2017, it was expected to see more 4D effects by using the MC 2022 dataset as monitor 2.

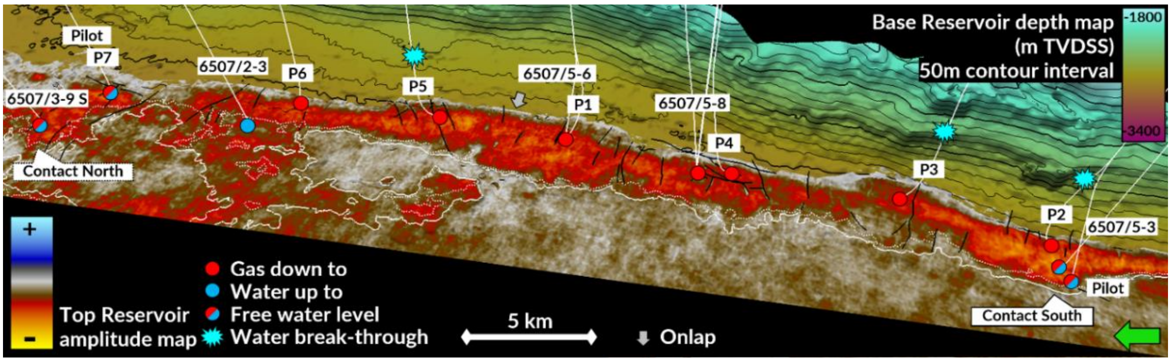

Figure 1 *Top Lysing depth map onlapping the base reservoir depth surface. The attribute map is minimum amplitude extracted from an AVO fluid volume where warm colours indicate gas presence. Wells are shown in white, annotated with fluid contact information. (Hjellbakk et al. 2023).*

Three Vintages Acquisition Geometry

The baseline dataset was acquired in 2005. Conventional shallow hydrophone streamers were used for this acquisition. The first monitor survey was acquired in 2017, using deep towed multi-sensor streamers. The survey was designed as a dedicated 4D acquisition aiming to repeat the baseline shot/receiver coordinates and using the identical dual source specifications.

In the summer of 2022, PGS was acquiring a MC program for Norwegian Sea. The project was extended to the North-East to cover the Ærfugl field and use the new dataset for 4D time-lapse purposes. The acquisition azimuth was altered by 6 degrees compared to the optimal 3D survey design to match the azimuth of the baseline survey. All other parameters were kept the same as for the MC acquisition. The 2022 acquisition is different from the other two surveys as it is features wide-tow triple sources, denser trace coverage, larger streamer spread and shorter inline near offsets. Figure 2a describes the different acquisition designs involved. Figure 2b shows how well repeated shot and receiver locations were in 2017. In this example two additional outer cables offer increased redundancy because the inner cables from the monitor dataset overlay the baseline exactly. On the other hand, it’s very difficult to find anything in common between 2005 and 2022 shot/receiver positions.

Seismic sources for 2005 and 2017 acquisitions were the same: 2 sources, 5085 cu.in. each, 6 m. depth, 37.5 m. source separation. The 2022 survey was however acquired with 3 sources, with a volume of 3280 cu.in. each, 7 m depth and source separation of 125 m. (250 m. total). The source set-up discrepancy was one of the 4D challenges for this reservoir monitoring project.

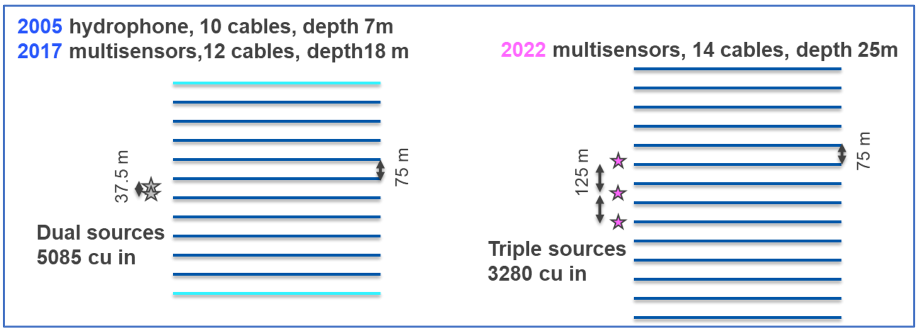

Figure 2a *Acquisition design scheme for the three surveys.*

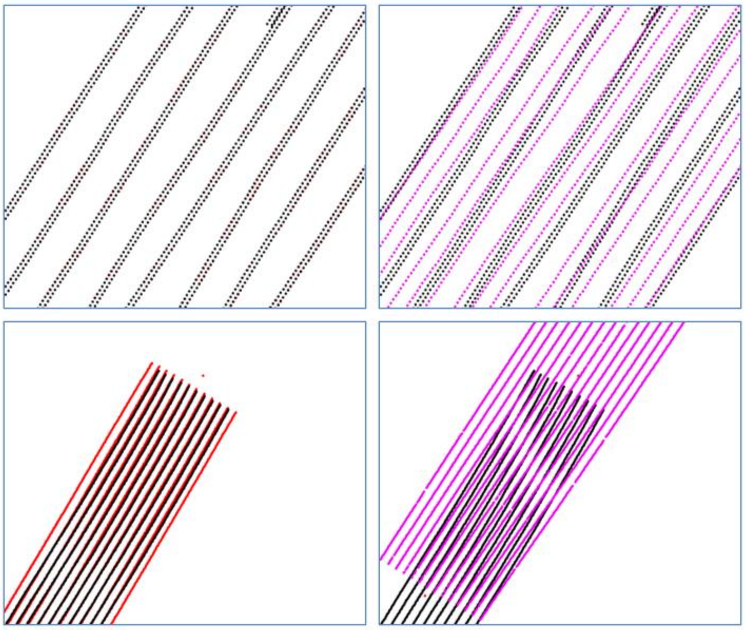

Figure 2b: *Source and receiver positions (top and bottom respectively). 2005 (black) vs 2017 (red) repeated dual sources (left), dual sources 2005 (black) vs wide towed triple sources 2022 (purple), non-repeated (right). Note that the 2022 MC dataset was acquired mostly in the opposite direction.*

4D Processing

Several case studies of opportunistic 4D projects using a non-repeated dataset can be found in the literature. Those were mostly conducted for reservoirs with a strong 4D signal. For example, on the Sleipner carbon capture and storage project, eclectic acquisitions have been used for monitoring the CO2 plume (Wierzchowska et al. 2021). More challenging examples include ocean bottom node vs streamer acquisition 4D projects (Detomo et al. 2012). In the Ærfugl case the 4D signal was expected to be very weak, small amplitude difference and time-shifts less than 1ms.

For this opportunistic 4D project, special care has been taken during the processing of the signal calibration, receiver de-ghosting, de-multiple and denoise. All 3 datasets were re-processed together from raw data to ensure the best repeatability in terms of processing sequences and algorithms.
In addition to the 4D noise related to acquisition geometry discrepancy, one of the 4D processing challenges was to reduce the impact of the multiples. The reservoir target reflection is practically invisible before demultiple/denoise (Figure 3) and the 4D signal was only observable post-migration (on a full stack). Although these data are not located in very shallow water, multiples present a significant challenge. The water bottom two-way travel time is around 500ms and relatively hard, generating strong multiple reflections. The water bottom is highly rugose in some areas, which

generates complex diffracted multiples. Various multiple models were generated for each vintage and the adaptive subtraction parametrization was directly validated using 4D difference optimization.

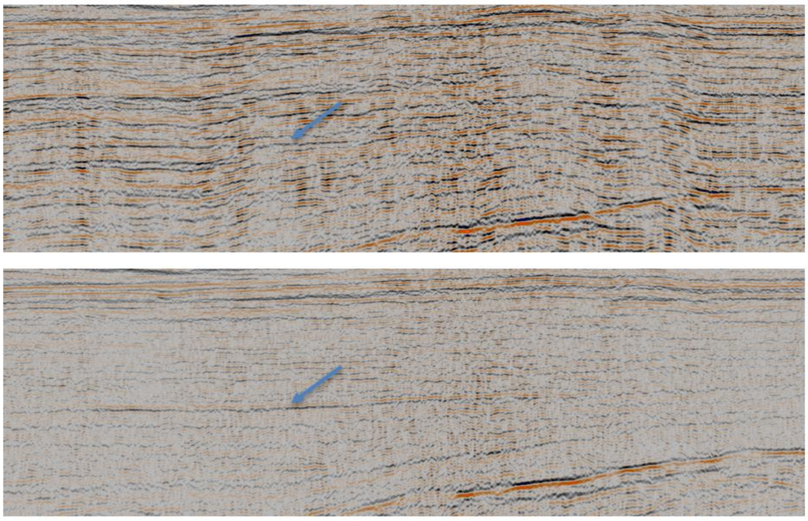

Figure 3: *3D QC full angle stack. Monitor dataset 2022. Before demultiple (top), after demultiple (bottom). An arrow indicates the target reservoir reflection.*

To compensate for the lack of repeatability of the second monitor survey, a pairwise 4D binning approach was chosen to give the optimum repeatability result for this multi-vintage 4D project (Brain et al., 2013). Different grids and different 4D binning strategies were tested. An expanded binning strategy on 18.75x12.5 m. grid has been chosen keeping multiple traces per bin. It was essential to preserve a maximum number of traces belonging to each survey to optimize the constructive interference in the migration stack process and reduce the 4D noise. The maximum sum of source and receiver errors (dSdR) at near offsets for the repeated surveys was 100m, whereas for the non-repeated pairs the maximum dSdR approaches 500m.

The data in this area are particularly noisy at the Lysing formation. The target reflection is very weak and there is little reflectivity around it, giving low signal-to-noise ratio. Both 4D and 3D noise represents a significant processing challenge. Application of a harsh denoise filter at the pre-migration stage was required. Another 4D denoise technique, called co-denoise, was beneficial in this case. The procedure uses combined datasets to design and apply frequency-domain predictive filters to attenuate random noise and preserve the 4D signal. The noise which is coherent only on one dataset will appear random in the combined version and then can be attenuated by a denoise procedure.

The results for the repeated 2005 v 2017 datasets gave a Normalised Root Mean Square (NRMS) values in the target interval of 10%. NRMS values for non-repeated pairs, involving 2022 dataset, were 13% for 2017 v 2022 and 15% for 2005 v 2022. Overall, the level of 4D noise is higher on non-repeated datasets, which was expected as repeating shot/receiver coordinates and sources set-up will always give a lower 4D noise level. The level of 4D noise on non-repeated datasets was however low enough to reveal an interpretable 4D signal. Another observation is that 2022 dataset has a 2 percentage points better match against 2017 than against 2005. This might be explained by the fact that in 2017 deep tow multi-sensor streamers were utilized, as was the case in 2022. Meanwhile, during 2005 a single-hydrophone shallow cables were used.

The final 4D products show both hardening and softening effects, increase and decrease in acoustic impedance between baseline and monitors respectively (Figure 4). The hardening is interpreted as a combination of pressure decline and water replacing gas. This agrees with modelled 4D response (Figure 4e), where a weak hardening due to pressure decline can be seen at the well, combined with a stronger hardening down-flank, related to water movement. Softening effects are interpreted as an increase in gas saturation below the initial gas-water contact. The increase in gas saturation could come from gas out of solution in the aquifer or local gas expansion as the pressure in the reservoir is decreasing. The 4D effects are close to the noise level in the data, but the availability of multiple monitors enables the interpreter to link the 4D effects between the different production periods and build confidence in the visible signal.

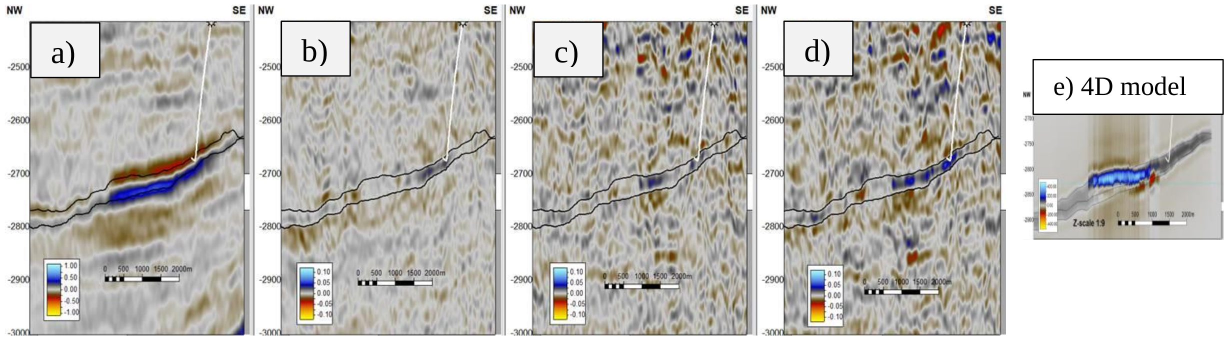

Figure 4 *Crossline section, a) 2005 3D stack b) 4D difference 2017-2005 c) 4D difference 2022-2017 d) 4D difference 2022-2005 e) the feasibility 4D model 2022-2005.*

Conclusions

This case study shows that MC datasets can be used in an opportunistic way for better understanding the reservoir production in a time-lapse project. In this case, it was possible to retrieve an interpretable 4D signal even if the MC acquisition was only repeating the sail line shooting direction. Customized processes and special care must be considered for such project for handling inherent discrepancy in 4D signal-to-noise. Furthermore, continuous communication between geophysicists and 4D interpreters is key for validating every processing/imaging step. In the light of the initial 4D results of the study, it was decided to extend the area of interest from 500 sq.km. to 1000 sq.km. to cover the full extent of Ærfugl field.

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