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4D-ready marine seismic data

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Summary

A new concept for the acquisition of time-lapse, 4D-ready towed-streamer seismic data is introduced. Time-lapse (or 4D) seismic has emerged as a valuable technique for reservoir management. Several successful examples (*e.g.* Cooper *et al.*, 1999; Koster *et al.*, 2000) have demonstrated the potential of the 4D technique in understanding the dynamic behaviour of the reservoir and its potential use within a reservoir management workflow.

The requirements for repeatability and fidelity of the seismic data are significantly greater for 4D reservoir monitoring than for exploration surveys, because we are looking for relatively small changes in the reservoir's seismic response. 4D-ready towed-streamer data requires better control of the seismic source signature, streamer geometry and recorded signal fidelity to ensure data repeatability and the reduction of the acquisition footprint.

An integrated seismic data acquisition system is introduced where all these issues are addressed, ensuring the delivery of qualified, high-fidelity towed-streamer seismic data, ready for time-lapse reservoir monitoring.

Introduction

Reservoir monitoring using seismic data relies on there being a measurable time-lapse signal induced by reservoir changes. Typical objectives for a 4D seismic study would be to:

- Map fluid movements, pore fluid saturation changes and pressure changes;
- Identify un-swept oil and in-fill drilling opportunities;
- Identify flow units and flow barriers;
- Monitor performance of enhanced recovery programs;
- Quantify and constrain the spatial properties of the reservoir model.

Most time-lapse survey interpretations have been made for reservoirs with highly porous sands, where fluid replacement has a greater impact on the seismic response. The largest time-lapse signals are induced by the replacement of either oil or water with gas. The replacement of oil with water generally leads to a smaller time-lapse signal. Altering the pressure regime within the reservoir during production also induces time-lapse anomalies in seismic data. The time between surveys is another significant factor in defining a measurable time-lapse signal. The greater the period between surveys, the larger the time-lapse signal may become, as more fluid

replacement takes place during an extended period of production.

Figure 1 shows the time-lapse difference from two towed-streamer surveys acquired nine years apart. Those areas in the reservoir where most hydrocarbon production has occurred are clearly indicated by the bright colours in the difference plot.

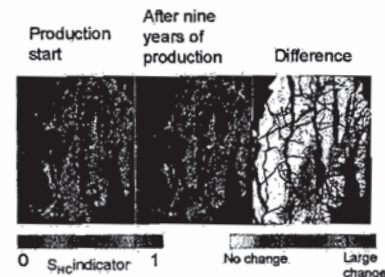


Figure 1: Time-lapse difference in a sandstone reservoir after nine years of production, showing produced oil and hydraulic barriers (after Sonneland *et al.*, 1996).

The characteristics of the time-lapse signal are therefore defined by the fluids, lithology, petrophysics and time elapsed between surveys. Like all signals, the time-lapse signal is only detectable if it is not masked by noise. One of the key sources of pseudo-random noise affecting marine seismic data quality is introduced by the perturbations affecting signal fidelity, as developed by Martin *et al.* (2000) and Ongkiehong & Huizer (1987).

The design criteria of the new marine acquisition system were defined through a rigorous analysis of the factors that limit the applicability of 3D seismic data for time-lapse studies. The significant perturbation factors have been addressed by new sensor and streamer technology; new source array technology; advances in navigation and positioning systems and new data analysis and processing techniques.

Sensitivity to perturbations

The design of the new acquisition system has been driven by our understanding of the factors that limit our ability to meet the objectives of a 4D study.

Our understanding of these limitations has been developed through detailed analysis of the sensitivity of seismic data and the time-lapse signal to the different perturbations that occur in towed-streamer seismic operations. The source of

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the perturbation may be internal or external. Examples of internal perturbations are hydrophone calibration variations and positioning error of each hydrophone with respect to the prescribed array design. External perturbations include environmental effects like the rough sea surface and tidal variations. We can divide the perturbations (internal and external) into:

1. Those that affect the received signal, such as sensor sensitivity variations, swell or rough-sea noise;
2. Those that affect the emitted source signature, such as shot-to-shot variation in the source array output and the effect of source array directivity;
3. Those that affect positioning accuracy and reliability, such as the use of compasses along the streamer and the effect of water velocity variations across the positioning network.

The sensitivity testing was performed for both modelled and real data cases, and culminated in a quantification of the impact of perturbations on seismic data quality, in terms of relative levels of noise behind the signal, or non-repeating noise. The specification criteria for the new acquisition system were therefore set to address the significant perturbations to the received signal, the emitted source signature and the accuracy and reliability of the positioning system.

Control of receiver perturbations

The sensitivity analysis revealed that the two most significant perturbations to the received signal, under realistic acquisition conditions with conventional streamer systems were swell noise and sensor sensitivity.

Swell noise, and the noise induced in the streamer as a result of the sea-state is a major limiting factor in seismic data quality. Conventional analogue groups are designed to suppress swell noise, however a new technique for data-adaptive coherent noise attenuation (Özbek, 2000) delivers even greater noise suppression (an additional 6-12 dB) for densely spatially-sampled point-receiver data. The method works by searching for coherent low-frequency, low-velocity noise fields across groups of adjacent traces, then defines a suitable multi-channel filter to attenuate this noise while protecting the reflected signal data. Figure 2 shows a typical shot gather recorded with a conventional analogue group-forming streamer, in parallel with a point-receiver streamer and including digital group-forming using the data-adaptive coherent noise filter.

Different hydrophones in a group will have different sensitivities, depending on the design specification tolerance. (Newman & Mahoney, 1973). The response of the group will vary with the apparent wavenumber of the incident wave-front and is therefore not surface consistent. Individual sensor drop-outs are difficult to detect in

analogue groups, further affecting the calibration of the group response. These issues are addressed in the new point-receiver streamer by the use of hydrophones with a high manufacturing tolerance specification and a well-characterised ageing profile. In-sea calibration techniques can detect gross sensitivity variations and null responses are immediately obvious in the data as zero traces.

The impact of receiver motion on the recorded data has been considered and found to be a relevant factor for successful 4D imaging, particularly across adjacent opposing swaths in the same survey, and for the same swath acquired in opposing directions between the baseline and repeat survey. Combee (2000) proposes a pre-stack time-variant offset-interpolation filter for correcting the motion of the streamer, applied to the densely-sampled point-receiver data acquired by the new acquisition system.

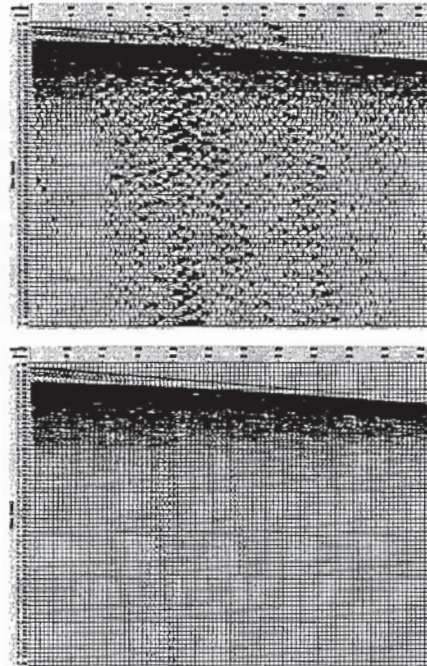


Figure 2: Comparison of shot-domain data recorded simultaneously on a conventional analogue group-forming streamer (Nessie 4, upper plot), and a point-receiver streamer (lower plot). The point-receiver data are displayed after digital group-forming using the data-adaptive coherent noise filter.

Control of source perturbations

The signature of an air-gun source array is known to vary from one shot to the next, depending on variations in the individual air-gun firing-times, air-gun chamber pressure and array geometry. The far-field signature of a source array can be measured using a far-field hydrophone, suspended some hundreds of meters below the source array, however this is impossible in continental-shelf seas. Furthermore, an inability to accurately position and locate

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the far-field hydrophone will reduce confidence in the validity of the far-field representation.

A method of estimating the far-field output of the source array is the Notional Source Method (Ziolkowski *et al.*, 1982, proprietary to Schlumberger). The method uses recordings of the acoustic pressure field made close to each air-gun (or air-gun cluster) and inverts for the effective source output. The Notional Source Method has been steadily refined since its first disclosure, and a recent algorithm development compensates for variations in the source array geometry by monitoring the position and azimuth of each sub-array using dGPS receivers mounted on the floats.

An extension of the method allows for source signature estimation in significantly shallower water depths, where the near-field hydrophones record the sea-bed reflections. Kragh *et al.* (2000) apply a linearly-constrained adaptive beam-forming filter, after Özbek (2000), to the near-field recordings to remove the up-going sea-bed reflection, then invoke the Notional Source Method in the usual manner.

It has long been known that non-flat sea-surfaces reflect the ghost arrival with a reflection coefficient other than -1. An approximate, empirical relationship exists between the sea-state (in terms of significant wave height) and an effective sea-surface reflection coefficient, which can be invoked in the estimation of the far-field signature. Laws & Kragh (2000) simulated realistic, moving rough-sea surfaces in order to quantify their effect on seismic data. A Kirchhoff method is used to compute the time-varying reflection response of the rough sea surface, and the authors show examples of the effect of this response on the emitted source signature and synthetic recorded data. For raw data, the spectral errors are typically 1-3 dB in amplitude and 10-20° in phase for a 2-4 m significant wave height sea. The errors in the final processed data depend on the stack fold, but typical errors for the same sea-states range from 5-10% (or more) RMS amplitude. Errors of these magnitudes can be significant for 4D seismic.

A further implementation of the Notional Source Method allows the estimation of far-field signatures at different azimuths and take-off angles. Spatially-extended air-gun arrays are typically tuned to optimise near-omni-directionality and far-field primary-to-bubble ratio. These metrics tend to trade-off with the spatial distribution of the different air-gun volumes, constrained by operational restrictions. Furthermore, the sea-surface reflection imposes a directivity response on the output of the source array. The directionality of a conventional air-gun array is most acute at long-offsets, for shallow targets and at high frequencies. The errors that this directionality imposes will be most evident in AVO analyses of shallow targets. The directional response of the source array, can be mitigated by a trace-by-trace deconvolution of source signatures

generated in the slowness domain from shot gathers in the intercept-slowness domain.

Control of positioning perturbations

Repeatability of the acquisition footprint is regarded as a key requirement for 4D surveys (Eiken *et al.*, 1999). Of the published 4D case studies, some of the most successful have been conducted using exacting repetition of the acquisition configurations between successive surveys, with:

- Identical streamer spread (number of streamers, type of streamer, cross-line separation and overall length). The same streamer depth;
- Identical source arrays (air-gun types, volumes and configuration) and number of sources and their depths;
- The same sail-lines and sail-directions along those sail lines and the repeat survey shot-points matched to those of the baseline survey.

Despite these efforts, it is not possible to replicate exactly the receiver positions from survey to survey, due to the effects of currents on streamer feathering. A technique has been proposed by Eiken *et al.* (1999) to reduce the effects of mis-matched receiver positions by interpolating CMP positions from the two vintages to a common grid. A grid regularisation technique has been implemented for use on data acquired with the new acquisition system.

Variations in the acquisition footprint from survey to survey depend on the positioning accuracies in a given survey. Relative positioning accuracy across the spread is determined by the combination of GPS nodes, acoustic range-finders and compasses, and the performance of the network solver. Cross-line accuracies are poorer than those in-line and present positioning systems have cross-line errors which can be as high as 12 m between acoustic nodes. A position error of 12 m is difficult to correct and will introduce significant noise in a 4D survey. Archer *et al.* (1999) studied the effects of positioning errors and Morice *et al.* (2000) analysed the impact on 3D imaging errors of both relative and absolute positioning errors as functions of dip and frequency. In broad terms, they suggest that a target accuracy of 2-3 m is required to reduce non-repeatable noise in a 4D signal to a level below other sources of error.

Integral to the new acquisition system is a new positioning and steering control system for towed-streamers, including integral streamer-mounted steering devices and an in-built fully-acoustic ranging system. Active lateral and vertical streamer control is achieved using a "steerable bird". These devices are inserted along the body of the streamer and consist of a unit containing sensors, electronics and actuators for the detachable wings. The total lateral force generated by the device allows the streamers to be steered up to 3° against the natural streamline. Computer

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simulations and offshore tests have shown that this is sufficient to give a high level of manoeuvrability. Streamers may be steered for optimal coverage, towing efficiency or minimal risk of tangling, and the streamers can be towed with cross-line separations of as little as 25 m with no significant risk of tangling. Closer streamer separations require more accurate positioning. This is achieved in the new system using full acoustic ranging with pulses recorded on the seismic hydrophones. Emitter and dedicated receiver nodes are placed every 300 m along the streamers to resolve the spread configuration to an accuracy of 2-3 m.

The streamer control devices have been designed to maximise hydrodynamic lift while minimising acoustic noise, and offshore tests have shown the devices to generate far less noise than conventional depth-control birds. Furthermore, the noise fields that are generated by the devices are readily attenuated by the data-adaptive coherent noise filter (Özbek, 2000) that is integral to the new digital point-receiver streamer.

Conclusions

4D-ready marine seismic data acquisition will minimise the impact of the acquisition footprint on time-lapse interpretations. Swell noise and pseudo-random noise introduced by perturbations in the seismic acquisition method, will be greatly reduced through the use of point-receiver recording. The accuracy of time-lapse interpretations will improve and allow the detection of weaker time-lapse signals. The period between monitoring surveys can be reduced, allowing greater control of reservoir management. Time-lapse reservoir monitoring, based on high fidelity towed-streamer seismic data acquisition, will be extended to a greater number of fields, and will become a standard tool for reservoir management.

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