The fidelity of 3D wavefield reconstruction from a four-component marine streamer and its implications for time-lapse seismic measurements


Summary

It is well documented in time-lapse (or 4D) seismic literature that the non-repeatability of the acquisition geometry is the single-most important factor contributing to a residual noise floor for the 4D seismic signal from the reservoir. To compensate for imperfect receiver repositioning, wavefield regularization techniques can be applied to allow for wavefield matching common to both vintage surveys. Typically, a trade-off is made between reducing the receiver positioning mismatch and the imperfections introduced by wavefield spatial aliasing due to acquisition geometry and geology. Wavefield reconstruction techniques are at the core of this paper, however with a different underlying basis than that for conventional approaches. Through use of towed 3D four-component (4C) marine seismic streamers and the application of matching pursuit interpolation processing techniques, a 3D reconstructed and dehosted pressure wavefield can be obtained on a densely sampled grid that permits wavefield matching to vintage positions in an unprecedented, effective way, as recently demonstrated by Özbek et al. (2010). This paper focuses on quantifying the fidelity of the wavefield reconstruction and discusses the implications of such 4C acquisition and processing on 4D seismic measurements.

Based on data analysis from an experimental 3D-4C test, the findings from the assessment presented in this paper are three-fold: firstly, the pressure recordings of the new 3D-4C acquisition system are found to be fully comparable to that of the existing production, hydrophone-only counterpart, used as a benchmark. Hence, established 4D characteristics for the benchmark system remain valid for the pressure recording of the 4C system. Secondly, the uniformly sampled pressure cube, output by the multicomponent seismic wavefield reconstruction, compares favorably with the recorded and uninterpolated pressure benchmark, contributing to establishing the integrity of the reconstructed wavefield. Thirdly, the 3D-4C-enabled wavefield reconstruction is found to furnish superior performance as compared to a hydrophone-only state-of-the-art interpolator, in particular, in areas with significant cable feathering. Overall, we find this 4C seismic acquisition and processing approach to offer the prospect of significantly reducing the effects of receiver mispositioning, leading to marked improvements of the 4D results. The source mispositioning becomes the critical limiting factor on the acquisition side to ensure high seismic repeatability - a limitation, however, that can be addressed effectively through available source steering technology.

Introduction

Efficient time-lapse processing relies on extracting the 4D signature with minimal background noise to help optimize producer and injector well placement and understand reservoir behavior in the production phase. Landrø (1999) showed that overburden heterogeneity had a significant impact on 4D results as he observed a relationship between the similarities of traces recorded in a 3D VSP and their relative source locations. He argues that, for a homogeneous earth, it should not matter where the shot is located, and therefore, the recorded traces should be the same. The fact that there were trace differences, and that these differences were a function of the separation of the shot positions, gives a clear indication that overburden heterogeneity limits the ability to repeat time-lapse seismic data and to deliver 4D signals with low background noise levels. Calvert (2005), Misaghi et al. (2007), and Næss (2007) discuss this issue in detail. It is widely recognized that accurately repeating the source and receiver positions from the baseline survey is of utmost importance to minimize time-lapse background noise. However, depending upon currents, the operational ability to hold a predefined course for the cables and sources can be challenging, even for systems with steerable devices (Brown and Paulsen, 2011). Consequently, matching source-receiver pairs for different seismic snapshots becomes critical. It can require over-sampled acquisition and/or reliance on wavefield interpolation to yield wavefields recorded at corresponding locations between two or more surveys.

Robertsson et al. (2008) introduced the concept of a multicomponent streamer that would measure not only scalar pressure wavefields, but also vector wavefields of particle motion such as velocity or acceleration. Based on these additional measurements, Özbek et al. (2010, 2012) outlined the theory for a signal processing technique called generalised matching pursuit (GMP) that can realise joint wavefield reconstruction and deghosting in a 3D sense. This paper aims to quantify the GMP-based wavefield reconstruction fidelity on poststack data using real data acquired over repeat passes in the North Sea. For this purpose, the normalized root mean square (NRMS) and predictability metrics (Kragh and Christie, 2002) are used.
For quantification purposes, a “witness” cable recording the full pressure wavefield was employed as the benchmark. This procedure helps to distinguish the question of fidelity of the reconstruction from its repeatability that was addressed in a recent study by Eggenberger et al. (2012) on the same multicomponent seismic streamer data set. The latter study investigated several interpolation/reconstruction techniques and showed that good repeatability does not necessarily correspond to a correct reconstruction of the wavefield. This paper also aims to sketch the implications of our findings to 4D seismic data in general.

Data acquisition

A repeated sail line was acquired during a mini-3D trial using six 4C streamers forming an active spread of 500 m (inline) by 375 m (crossline) with a nominal cable separation of 75 m and a depth of 22.5 m. The source was positioned between Cables 5 and 6 at a depth of 6 m. The shot point interval was 25 m. Emphasis was put on repeating the source positions between the two sail lines, but existing strong currents in the area of acquisition introduced a source mispositioning up to 10 m, mostly in crossline, whereas the receiver mispositioning was observed to go up to 20 m. The data set examined exhibited areas of good source and receiver repeatability, but also areas where the source and receiver repeatability was subject to considerable mispositioning error. The receiver non-repeatability between the two passes is herein exploited to investigate the performance of the multicomponent-based 3D wavefield reconstruction as a function of reconstruction distance, away from the benchmark cables, albeit this performance carries with it the effects of source non-repeatability, which could not be discounted or compensated for.

Data analysis

Prior to the analysis step, the acquired data were preprocessed with a flow comprised of single-sensor noise attenuation, receiver motion correction, and tidal statics, but with no 4D processing step involved. The 4D analysis itself was performed on brute stacks with, as input, time-lapse binned shot gathers produced with or without wavefield reconstruction. In a first step, we set out to establish the non-repeatability level of the 3D-4C cables on the acquired data by time-lapse binning the pressure recordings of four cables of the repeat mini-3D-4C acquisition between Pass 1 and Pass 2 (Figure 1). After stacking the data, the NRMS was computed between the two passes and plotted against the delta midpoint which is a function of the delta source and delta receiver errors. Furthermore, a linear regression line was drawn through the cloud of NRMS data points. For small repositioning errors, where small relates in some way to geological variability and seismic wavelength, one would expect the NRMS mismatch in the repeated seismic wavefields to be linearly related to the repositioning error.

As the same acquisition effort also included three production (conventional pressure-only) cables, towed for the purpose of spread stability, the same analysis methodology was applied on the associated data so as to provide benchmark results. Figure 1 presents the NRMS as a function of delta midpoint error and normalized frequency of the NRMS residuals for the pressure recordings of the multicomponent towed-marine platform (left) and for a conventional, pressure-only acquisition platform (right). To account for the different populations of data samples between the two platforms, for each data point in the bottom row plots of Figure 1, the residual NRMS was taken against the linear regression line. Those differences were then binned and normalized by the overall number of data samples. It can be observed from Figure 1 that the pressure recordings of the two different acquisition platforms are similar as seen through the NRMS metric. Hence, established 4D characteristics for the benchmark conventional platform remain valid for the pressure recordings of the 4C platform.

In a second step, the multicomponent seismic joint interpolation and deghosting GMP algorithm was applied to the repeat sail line to provide a reconstructed wavefield on a 6.25 m by 6.25 m grid. Subsequently, the data were reghosted to create a uniformly sampled total pressure wavefield cube with the uninterpolated pressure recordings from the first pass acting as a reference. Strong currents introduced substantial mispositioning of receivers and the
source between the two sail line passes. The cable feathering (in Pass 2) allowed the investigation of the performance of the 4C-enabled GMP-based wavefield reconstruction for a variety of distances from the reference cables (in Pass 1).

Figure 2 shows a qualitative evaluation of the shot-based wavefield reconstruction for GMP as well as for P-only interpolation. The latter, based on interpolation using matching pursuit (IMAP) with priors, is a state-of-the-art single-component reconstruction algorithm (Özbek et al., 2009; Özdemir et al., 2008). Figure 2a depicts the brute stack of Cable 3 from the baseline whereas Figure 2b illustrates the 4D background noise when applying time-lapse binning on Cable 3 between Pass 1 and Pass 2. The residual energy on the difference plot in Figure 2b is seen to correlate well with source and receiver mispositioning. Figures 2c and 2d investigate use of increased sophistication in the interpolation. Figure 2c shows the 4D difference based on single-component (IMAP with priors) reconstruction. Compared to the unreconstructed time-lapsed binned solution (Figure 2b), an improvement is seen, but the main 4D noise features remain. A marked attenuation of the 4D noise is however attained when GMP is used as can be observed in Figure 2d. The noise levels are significantly reduced and a very weak, coherent

Figure 2: 2D Brute stack for a) baseline sail line of Cable 3, b) corresponding difference with the time-lapse binned monitor sail line, c) difference with the monitor sail line using interpolation by matching pursuit (IMAP) with priors, d) difference with the monitor sail line reconstructed using GMP with priors. The blue, dark green, magenta, and light green curves show the source, receiver, delta mid-point, and azimuthal mispositioning respectively. Black broken lines illustrate the analysis window.

Figure 3: NRMS is displayed in b) as a function of inline position X. The colour coding is as follows: red = GMP, blue = IMAP, green = non-reconstructed and time-lapse binned pressure recordings. Frame a) depicts the receiver and source mispositioning for Cable 3. Frame c) illustrates the data from b) in histogram form, whereas d) shows the repeatabilities as a cross-plot of NRMS and predictability (PRED).

acquisition-related residual is unveiled, being a function of the source mispositioning inherent to the data. To quantify further these results, 4D repeatability metrics were derived in Figure 3, trace-by-trace, on the brute stack differences displayed in Figure 2 as a function of trace inline position X. The analysis window for NRMS and predictability
(PRED) corresponds to a shallow target area of 1 s – 2.5 s. Figure 3b shows NRMS as a function of inline position X for Pass 1 and Pass 2 where the uninterpolated approach (green curve) is compared with IMAP (blue curve) and GMP (red curve) interpolations prior to time-lapse binning. In all three cases, Pass 1 recorded pressure is uninterpolated, and hence, acts as a reference or benchmark. While both IMAP and GMP reconstruction techniques are seen to be superior to the approach where no regularization was attempted, GMP exhibits the best repeatability performance. The enhanced performance of GMP relative to that of IMAP is more pronounced at inline positions where receiver mispositioning is large (see Figure 3a, which shows the source and receiver mispositioning). Where source mispositioning is large, the repeatability performance of GMP decreases and so does that of IMAP. It can be observed that where the source mispositioning is small, the GMP non-repeatability tends towards a level of 20% NRMS, reminiscent of the findings by Kragh and Christie (2002) in the Gulf of Mexico and also found by the regression lines in Figure 1. This provides further evidence of GMP’s capabilities to efficiently address the non-repeatability induced by receiver mispositioning. Figure 3c takes the data points from Figure 3b and displays them in the form of a histogram, outlining the enhanced reduction of NRMS values when utilizing the 4C data and GMP for 4D interpolation purposes. Figure 3d cross-plots the NRMS and PRED of corresponding stacked traces. Again, the repeatability measured against the unreconstructed Pass 1 wavefield greatly benefits from GMP. The same data sets were also analyzed in Figure 4 where NRMS is displayed as a function of interpolation distance for the 3 scenarios discussed. The source mispositioning is wrapped into the colour coding due to time-lapse binning on delta midpoints. The linear regression curves, plotted through the data clouds become flatter with increasing sophistication of the interpolation applied, demonstrating the repeatability-enhancing effect of GMP. Better source steering is likely to further flatten those curves, leaving GMP output almost insensitive to receiver mispositioning whilst preserving the wavefield fidelity.

Conclusions

Time-lapse seismic measurements, due to their nature of acquiring two time-distinct 3D wavefields, are subject to source and receiver mispositioning. Previous work showed that these irregularities can introduce considerable 4D noise as a function of overburden heterogeneity. In this study of a data set acquired with multicomponent streamers that measure the pressure wavefield and its gradients, we show that the limitations of receiver mispositioning can be largely addressed with use of the recently introduced joint 3D interpolation and deghosting GMP technique. GMP uses the pressure wavefield and its gradients to reconstruct the wavefield onto a fine grid that permits interpolation to any vintage position within the receiver aperture. Acquisition-induced non-repeatability in such a 4D context can then be further reduced by source steering. Further, we show that GMP preserves the fidelity of the wavefield and its full bandwidth. Applied multicomponent processing also significantly outperforms state-of-the-art single-component wavefield reconstruction algorithms. This finding is significant as it illustrates the capabilities of multicomponent streamer wavefield reconstruction against a measured, unreconstructed benchmark for a challenging range of reconstruction distances following considerable cable feathering. As the availability of 3D-4C towed-marine seismic data is recent, it was also demonstrated that the pressure recordings of the 3D-4C experimental system employed possess the same sensitivity against receiver and source deviations in the context of time-lapse seismic measurements as do current production systems.

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EDITED REFERENCES

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