SUMMARY

Recently introduced multi-sensor streamers measure particle motion as well as acoustic pressure. The generalized matching pursuit (GMP) algorithm applied to independent, coincident wavefield measurements allows dealiased signal reconstruction and is well suited to finite crossline sampling in marine data. GMP also allows receiver deghosting which broadens signal bandwidth. The performance of wavefield reconstruction and deghosting can be evaluated using time-lapse repeatability metrics if the reference signal is known. However, these metrics are usually calculated in the time domain making it difficult to evaluate reconstruction performance near spectral notches and at high frequency. We analyze time-lapse data acquired over the North Sea Forties Field by a commercial multi-sensor streamer. Using frequency-dependent normalized root mean square (NRMS) attributes we evaluate algorithm performance across the spectral bandwidth. We find that wavefield reconstruction can significantly improve data repeatability early in processing while later processes have a smaller impact, in contrast to repeatability of single measurement data, leading to a simpler and more time-lapse friendly workflow. A reduction in NRMS following GMP is retained throughout subsequent processing resulting in a final migration with improved repeatability over a broader bandwidth. This emphasizes the importance of multi-sensor acquisition for high quality wavefield reconstruction in time-lapse seismic.
Introduction

Marine time-lapse seismic requires very good wavefield repeatability between surveys which, in turn, demands excellent repeatability of the source and streamer positions from one survey to the other. Ideally we would interpolate the data to a common location to compensate for inevitable positioning differences. Furthermore, because of costs, towed streamer seismic data are subject to coarse crossline sampling which leads to signal aliasing. Therefore data preconditioning is required before subsequent 3D data processing, either to remove aliased energy or to interpolate data in the crossline direction. The first approach leads to poor crossline dip resolution in the final data volume. The latter approach relies on highly accurate interpolation techniques.

Single-component interpolation algorithms are based on the Shannon (1949) sampling theorem. Doubling the number of independent measurements reduces the required sampling rate for exact reconstruction to half the Nyquist rate (Linden and Abramson 1960). In particular, acquisition by a multi-sensor streamer (Robertsson et al. 2008) enables expansion of the crossline Nyquist wavenumber by a factor of three. Özbek et al. (2010) described a multi-sensor reconstruction technique, called generalized matching pursuit (GMP) that can realize joint wavefield reconstruction and deghosting in a 3D sense, and overcome higher order aliasing. In contrast to classical signal theory, it does not assume an infinite series of regularly sampled multichannel data, which makes it very practical for the finite crossline apertures in marine surveys. Previously published examples (Vassallo et al. 2010; Özbek et al. 2010) visually demonstrate the high quality performance of GMP in the presence of aliasing. Further quantitative analyses were performed by Eggenberger et al. (2012). That study used time-domain repeatability metrics: normalized root mean square (NRMS) and predictability (Kråg and Christie 2002), and was later augmented by a frequency-domain approach (Eggenberger et al. 2013). Those analyses used data from an experimental geometry in which the inline offset was restricted to 500 m, and necessitated a limited processing sequence. This paper analyses a production dataset from 3-km long streamers to further evaluate, both qualitatively and quantitatively, time- and frequency-dependent attributes following a time-lapse processing workflow. Furthermore, we make some first attempts to assess, in the frequency domain, 3D redatuming capability as well as wavefield reconstruction. In contrast to the Forties data analysis by Smith et al. (2013), which compared multi-sensor data to previous single-component surveys, this study compares repeated passes of the 2013 multi-sensor data. In doing so, we remove from the reconstruction process the potential impact of different acquisition platforms and configurations.

Data acquisition

Repeated sail lines were acquired over the Forties Field in the North Sea for time-lapse feasibility testing using eight multi-sensor streamers to record P, Y and Z components. The streamer length was 3 km. The nominal crossline cable separation was 75 m; however, two middle streamers were separated by 50 m. The streamer tow depth was 18 m, while two sources were towed at a depth of 5 m. The shot point interval was 12.5 m flip-flop. In this study the data from just one source were analysed. As two passes were recorded within a 2-day interval, no time-lapse signal was expected, and observed differences should be due only to acquisition non-repeatability. The average source positioning error was approximately 2.3 m between the passes. However, receiver feathering in excess of 20 m was observed for much of the line, which motivated us to reconstruct the data to common receiver positions to improve wavefield repeatability.

Data analysis

In the wavefield reconstruction process data from the first sail line pass were reconstructed onto the sensor positions of the second pass. The impact of receiver repositioning error between the passes was analyzed to evaluate the performance of the 3D wavefield reconstruction, pre- and post-stack. Post-stack data were analyzed in a 300-ms time window above the top of the reservoir horizon. The data were processed twice through the same sequence, except that GMP reconstruction was included in one of the routes. Prior to GMP, single-sensor noise attenuation, receiver motion correction, tidal
statics, and anomalous amplitude noise attenuation (AAA) were applied. After GMP, calibrated marine source (CMS) deconvolution, deterministic water-layer demultiple (DWD), and tau-p diffraction noise filtering were applied. Subsequently, the data were processed with expanded bin time-lapse binning, regularized with 3D azimuth moveout (AMO) and migrated with a pre-stack 2D Kirchhoff depth algorithm. Figure 1 shows post-stack line-average NRMS values measured after successive processing steps. Significant NRMS reduction is observed directly after application of GMP, and although later processes also reduce NRMS for the No-GMP route, the GMP route retains significantly lower NRMS values throughout the processing flow, including the final pre-stack depth migration. In practice it also means that the post-GMP processing workflow can be simplified, for example as source position error is small then time-lapse binning is not required. Also parameterization can be less aggressive and more time-lapse friendly, like in the tau-p filtering step.

Figure 2 shows the data after 2D Kirchhoff depth migration. Figure 3 shows stack differences between the two sail line passes, gained 6 dB in amplitude compared to the stack section. Panel 3a shows the data without GMP, panel 3b shows the data where GMP was applied to only one of the sail line passes, to reconstruct the data at the sensor positions of the other pass. Panel 3c represents the data after GMP on both passes for the purpose of simultaneous reconstruction and redatuming to 7 m tow depth: the first pass was reconstructed to generate up- and downgoing wavefields at the receiver positions of the second pass, while the second pass generated both wavefields at its own receiver positions. The wavefields were recombined after redatuming to 7 m. We analyzed redatumed data as this would be required to make a time-lapse comparison to vintage surveys where streamers were towed at 7 m. Panel 3a shows the highest level of non-repeatability. There is coherent noise present in the center of this panel, which originates from the platform leg reflection, aliased in the crossline direction. The stack differences in panels 3b and 3c, with GMP applied, show a better visual repeatability. No platform reflection artifact is observed, which indicates that this event has been reconstructed accurately at the targeted streamer position.

Figure 4 shows frequency-dependent NRMS histograms for the three examples above. The hotter the color (i.e. from blue to magenta), the more hits for a given NRMS bin. The data with GMP applied have a higher concentration of the histogram at lower NRMS values, which is marked by box 1 on panel 4b. In addition, we observe in box 2 an extension of the repeated frequency bandwidth toward receiver notch frequency marked by the horizontal dashed red line. Panel 4c shows the histogram for wavefield redatumed from 18 m to 7 m. The receiver notch is filled in a repeatable manner which is marked on the display with box 3. In that respect it indicates the power of the GMP algorithm for consistent receiver deghosting. The time-domain NRMS values for those 3 cases, 19%, 12% and 15%, imply that GMP improves time-domain repeatability, but redatuming to shallower depth offsets this improvement by increasing the high-frequency bandwidth. This effect can be explained by the change in the amplitude spectrum following redatuming and decreased signal level in the lower frequencies due to ghost notch repositioning. A greater increase in NRMS could be expected if the data, geometry corrected with GMP, had been directly acquired at 7 m, because of greater swell noise.

Conclusions

A multi-sensor towed marine streamer provides measurements which enable wavefield reconstruction at required detector positions. The analyses show GMP improves repeatability in both time- and frequency-domain attributes although we expect that using data from both flip-flop sources would reduce repeatability differences between both processing routes. It was observed that frequency-domain NRMS can detect redatuming-related amplitude spectrum changes. GMP filled in the receiver notch frequency zone in a repeatable manner, extending usable time-lapse frequency bandwidth. This confirmed that frequency-domain attributes like NRMS can add useful performance diagnostics. We also found that application of GMP significantly improves the repeatability at an early stage of the processing. This might help in earlier detection of any production related time-lapse effects, and in enabling more consistent and simpler, parallel processing of time-lapse surveys. We also observed that the overall reduction in NRMS in the GMP route is significantly greater than in the No-GMP route, which resulted in a better repeated final migration product.
**Figure 1** Evolution of post-stack NRMS after processors in No-GMP and GMP workflows. A large improvement in repeatability after GMP is seen, with lower NRMS values than those in the No-GMP route evident after each processor in the sequence.

**Figure 2** 2D PreSDM stack. Overlaid analysis window was used for quantitative analysis and additional qualitative visual evaluation in the reservoir window. Solid green line represents top Sele horizon.

**Figure 3** 2D PreSDM stack differences between repeated sail line passes. Overlaid windows used for quantitative analysis (top) and qualitative visual evaluation (bottom) in the reservoir window. Panels show results: a) without GMP applied; b) with GMP; c) with GMP after redatuming to 7 m depth. Panel a) shows highest level of residual non-repeatability, energy from poorly repeated platform leg reflection is visible. Panels b) and c) show improved repeatability, no platform reflection artifacts visible.

**Figure 4** Frequency-dependent NRMS histograms derived from the data shown in Figures 4: a) no reconstruction; b) GMP applied; c) GMP with redatuming to 7 m. GMP improved NRMS over usable frequency bandwidth. Additional redatuming filled in the receiver frequency notch zone in a repeatable manner.
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References


