On the use of frequency-dependent repeatability metrics for evaluating wavefield reconstruction: a time-lapse perspective

Summary

The emergence of multisensor towed-marine streamers, with multichannel wavefield reconstruction, offers the prospect of true 3D processing, overcoming the spatial sampling constraint in the crossline direction associated with hydrophone-only acquisition. Time-lapse seismic data processing has developed a range of metrics to assess repeatability between different vintages and which can be used to assess the reconstruction quality of such algorithms. However, in most cases these metrics are applied in a frequency-independent fashion. With dealiased wavefield reconstruction being a core technique of multimeasurement seismic processing, such 4D metrics can be adapted to evaluate its performance in a frequency-dependent manner. Normalized root-mean-square and predictability metrics, defined in the frequency domain, provide tools to measure reconstruction quality. Our study of real data from the North Sea is tied to a time-lapse experiment investigating frequency-dependent repeatability on prestack gathers as well as 2D stacks. We also apply different configurations of the reconstruction algorithms to understand better the contribution of the individual measurements: pressure (P), the vertical (Z), and crossline (Y) accelerations. We find that multichannel reconstruction using all three input measurements considerably enhances repeatability against a measured benchmark in the higher frequency bands, both pre- and poststack on the total wavefield, with reconstruction using P and Y coming a close second.

Introduction

For successful time-lapse seismic, the non-repeatable noise floor must be minimized throughout the 4D processing workflow to ensure that the individual vintages match each other outside production-affected areas. Lacombe et al., (2011) show on a representative 4D processing example how this translates into an increase in repeatability after each major processing step applied. To monitor how repeatability improves throughout the 4D processing sequence, and also to benchmark different surveys in the context of time-lapse seismic, a range of 4D metrics can be employed. The most frequently used metrics are normalized root-mean-square (NRMS) and predictability (PRED) as described by Kragh and Christie (2002). Whereas the former metric is sensitive to amplitude differences, time shifts and phase rotations, the latter metric is driven by the similarity of the signals. Cantillo (2011) further introduced a signal-to-distortion ratio that has its roots in perturbation theory and can be utilized as a complementary metric to NRMS and PRED.

Recent advances in towed-marine multisensor acquisition as described by Robertsson et al. (2008) have mitigated the spatial aliasing associated with sparse crossline sampling by employing multichannel wavefield reconstruction algorithms (Özbek et al., 2010; Vassallo et al., 2010). The wavefield reconstruction challenge for such algorithms increases as we move towards higher frequencies where higher-order aliasing must be overcome. To evaluate reconstruction quality quantitatively, 4D metrics can be employed, as demonstrated by Eggenberger et al. (2011; 2012): a measured benchmark wavefield represents the baseline survey, while the reconstructed wavefield can be considered as the monitor survey. In such a context we do not expect any 4D effect in the subsurface and, hence, we can assess the potential of the reconstruction algorithm over all parts of the wavefield.

Most repeatability analyses, whether in time-lapse processing projects or in the context of wavefield reconstruction, have been evaluated using time-domain metrics. However, Grion et al. (2000) discussed a frequency-dependent approach to repeatability, using NRMS. In the following we will investigate, in the frequency domain, multimeasurement-enabled wavefield reconstruction using the generalized matching pursuit (GMP) method (Özbek et al., 2010) in various configurations, GMP(PZ), GMP(PY), and GMP(PYZ), using multisensor data from a recent North Sea acquisition. For our investigation we exclusively focus on the total, reghosted wavefield. First, we look into the frequency-dependent prestack repeatability of reconstructed shot gathers against an actual measured benchmark. Then, we examine the repeatability of the same data after stacking. In addition to GMP, a single-sensor wavefield reconstruction algorithm is employed to assess the uplift provided by the multichannel reconstruction algorithms and the individual input measurements.

Data acquisition

A repeated sail line was acquired during an experimental 3D trial in the North Sea, using six multimeasurement streamers to record P, Y, and Z. The spread was limited to an aperture of 500 m inline and 375 m crossline with a nominal cable separation of 75 m. The streamer tow depth was 22.5 m, whereas the source was positioned at a depth...
Frequency-dependent repeatability

of 6 m. The shotpoint interval was 25 m. Between two passes acquired over the same sail line, considerable receiver and source feathering was observed on some parts of the sail line. The frequency-dependent impact of non-repeatable receiver positioning between the two passes was evaluated to investigate the performance of the multimeasurement-based 3D wavefield reconstruction, pre- and poststack, as a function of reconstruction distance away from the benchmark cables, even though this performance includes the effects of non-repeatable source positioning, which could not be discounted or compensated for by receiver wavefield reconstruction.

Data analysis methodology

Prior to the analysis step, the acquired data were preprocessed with a flow comprising single-sensor noise attenuation, receiver motion correction, and tidal statics, but with no dedicated 4D processing step involved. After shot-by-shot wavefield reconstruction on the second of the two passes using either GMP or interpolation by matching pursuit (IMAP), a hydrophone-only, single-channel interpolation algorithm (Özbek et al., 2009; Özdemir et al., 2008), we time-lapse binned the actual recorded data of the first pass against the reconstructed and reghosted data of the second pass on a shot-by-shot basis and then stacked the data for a particular cable. Alternative to the time-lapse binning, we also interpolated the reconstructed second pass data from a spatially non-aliased 6.25-m by 6.25-m grid onto the trace positions of the first pass using a standard sinc interpolator. Both methods, the time-lapse binning and the interpolation, exhibited very similar results. On the moveout-corrected prestack data and poststack data, we used an analysis window of 1.0 s – 2.5 s – corresponding to the target zone – to derive the frequency-dependent NRMS and PRED metrics.

Common midpoint gather comparison

In a first step, we examine prestack the GMP(PYZ) wavefield reconstruction on the reghosted second pass against the actual measurements from the first pass. To better understand the uplift achieved by the additional acceleration measurements, we also perform wavefield reconstruction using IMAP which uses prior information, as does GMP. Figure 1 shows the actual measured shots of cable 3 of the first pass, together with the corresponding differences from the reconstructed shots of the second pass. The traces of the 290-odd shots are reorganized in common midpoint (CMP) gathers and moveout corrected using a 1D velocity function. The two difference plots are characterized by varying 4D noise, depending on the preprocessing applied and with GMP(PYZ) producing considerably less 4D noise than its hydrophone-only counterpart, IMAP. The most prominent differences between the two solutions can be found in the reconstruction quality of the diffractions and the attenuation of the noise bands being related to the acquisition mispositioning. In a geologically meaningful analysis window of 1.0 s – 2.5 s, we then calculate the frequency-dependent NRMS and PRED metrics as shown in Figure 2.

Figure 1: CMP-sorted, non-stacked traces from cable 3 of the first pass for a full sail line are shown in panel a. Panels b and c show the difference between IMAP- and GMP(PYZ)-reconstructed second pass data interpolated back to the trace positions of the first pass. The top two frames show source and receiver mispositioning.

Figure 2: Panel a shows frequency-dependent NRMS for the IMAP reconstruction from Figure 1b using an analysis window of 1.0 s – 2.5 s. Panel b depicts analysis for GMP(PYZ) from Figure 1c. The bottom row shows frequency-dependent PRED with IMAP results in panel c and GMP(PYZ) in panel d.
Frequency-dependent repeatability

In the very low frequencies below 10 Hz, theoretically not subject to spatial aliasing with the given acquisition geometry, IMAP and GMP produce almost identical results as only the pressure component is used to reconstruct the wavefield. Also visible is the low-cut filter applied to the pressure data, generating vertical stripes on the NRMS panels around 1.5 Hz and below. Starting from around 10 Hz upwards, the data input to the reconstruction algorithms become increasingly spatially aliased. IMAP, despite its antialiasing-protection through the use of prior information, is no longer able to reconstruct correctly, whereas GMP(PYZ) draws uplift from the two additional measurements, Y and Z, to enhance the repeatability against the measured total pressure wavefield recordings of the first pass. The NRMS repeatability is proportional to the signal amplitude strength, (see also Figure 4), with a pronounced ghost-notch effect visible at around 35 Hz. PRED is less sensitive than NRMS to gain variations, but it also shows the impact of the ghost notch. Repeatabilities are well within expectations for such a prestack analysis early in the workflow and with the effects of source mispositioning still inherent to the data.

Stack comparison

To be less subject to random noise, the individual reconstructed shot gathers are time-lapse binned against the first pass gathers and then stacked, using a representative 1D velocity function from the area. Figure 3 shows the total wavefield reference stack based on the actual pressure recordings from cable 3 of the first pass. The remaining five panels show plots of wavefield differences from the reference, using variously preprocessed data from the second pass: time-lapse binning only with no reconstruction, IMAP, and GMP with three different configurations: GMP(PZ), GMP(PY), and GMP(PYZ) with the latter showing qualitatively the least 4D noise, closely followed by GMP(PY). GMP(PY) corresponds to the multichannel interpolation by matching pursuit method (MIMAP), introduced by Vassallo et al. (2010). Figure 4 shows corresponding frequency-dependent NRMS repeatabilities derived in an analysis window of 1.0 s – 2.5 s. On all five solutions, the low-cut filter is visible below 1.5 Hz and all have similar NRMS values up to 10 Hz. However, from 10 Hz to higher frequencies, the repeatabilities of the time-lapse binning only, IMAP and GMP(PZ) solutions show a greater dependence on source and receiver mispositioning, whereas GMP(PY) and GMP(PYZ) show much less sensitivity to receiver mispositioning. Both of the latter fill in the high-frequency holes, with GMP(PYZ) doing a somewhat better job. In areas with a high receiver mispositioning exceeding 20 m in the middle of the sail line, the uplift provided by the Y and, to a lesser degree, the Z measurements is most noticeable, whereas in places with little receiver mispositioning, at the beginning and the end of the sail line, the uplift of multichannel reconstruction algorithms is much less pronounced. This is expected, as there is little compensation needed. As with the first analysis on the CMP gathers, wavefield reconstruction is not able to compensate for source mispositioning and, therefore, even a well reconstructed sail line like the one using GMP(PYZ) still shows some lateral repeatability variations.

Figure 3: 2D brute stack of cable 3, first pass in panel c. The other five panels show the difference from this stack, using variously preprocessed data from the second pass. a) Time-lapse binned second pass with no prior wavefield reconstruction. b) IMAP. c) GMP(PZ). d) GMP(PY). e) GMP(PYZ).

The minor noise leakage observed on the CMP gather repeatability analysis within the band of 10 Hz – 15 Hz is
no longer visible. The stacking process was able to attenuate it effectively and to hint at the uplift achieved by GMP in this frequency bandwidth also. Figure 4 further shows an amplitude spectrum that was derived from the reference stack volume displayed in Figure 3f. It becomes evident that the repeatability observed is also linked to the signal strength as a function of frequency.

This fits with observations made by Kragh and Christie (2002) on varying signal-to-noise ratios for time-domain NRMS values. The most pronounced feature represents the low signal-to-noise ratio ghost notch at around 35 Hz, corresponding to the tow depth of 22.5 m. GMP is able to enhance the repeatability within the ghost notch considerably and levels the NRMS values, along the sail line, closer to those observed at the beginning and end where both source and receiver repositioning are reasonably good.

Figure 5 shows frequency-dependent predictability in histograms for the five solutions: the cooler the colour, the more hits for a certain bin. At low noise levels, this metric is less sensitive to signal-to-noise ratio than NRMS. With increasing reconstruction sophistication, the variability in PRED is reduced and its values increase, representing an increase in repeatability against the measured benchmark. This is most pronounced at higher frequencies, starting at the ghost notch, but also can be observed in the lower-frequency bands. GMP(PYZ) exhibits the best repeatability across the full bandwidth closely followed by GMP(PY).

**Conclusions**

Multichannel wavefield reconstruction, enabled by multisensor towed-marine streamers, brings the potential to enhance the spatial bandwidth in the crossline direction, which is sparsely sampled. In a repeated sail line, we compared wavefield differences, characterized by NRMS and PRED, between unreconstructed reference data from pass 1 and variously reconstructed data from pass 2. We found that frequency-dependent repeatability is enhanced towards higher frequencies by the more sophisticated reconstructions, with the Y component playing the most important part. This is true for both pre- and poststack analyses on the total wavefield. A frequency-dependent view of repeatability, rather than the usual time-domain metrics, gives greater insight into the performance of dealiasing wavefield reconstruction. As with their time-domain counterparts, the complementary sensitivities of frequency-domain NRMS and PRED may also provide a valuable tool for wavefield reconstruction algorithm performance testing in general.
EDITED REFERENCES
Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2013 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES


