Multisensor streamer recording and its implications for time-lapse seismic and repeatability

Kurt Eggengenber, Philip Christie, Dirk-Jan van Manen, and Massimiliano Vassallo, Schlumberger

Abstract

Effective time-lapse, or 4D, processing seeks to extract the 4D signature with minimal background noise to help understand reservoir behavior in the production phase and to optimize producer and injector well placement. Nonrepeatability of source and sensor positions in the presence of overburden heterogeneity limits our ability to repeat seismic data and to deliver 4D signals with low background noise levels. To compensate for imperfect receiver repositioning, wavefield-regularization techniques can enable wavefield matching on a grid common to both data vintages. Often there is a trade-off between reducing the receiver-positioning mismatch and crossline interpolation error from wavefield spatial aliasing. Through the use of towed multisensor marine seismic streamers that record collocated pressure (P) and acceleration measurements (Y and Z) and the application of a matching-pursuit interpolation technique, a 3D dealiased, reconstructed, and deghosted pressure wavefield can be obtained on a densely sampled grid that permits wavefield matching to prior positions in a highly effective way. From analysis on field multisensor streamer data, implications for time-lapse seismic and repeatability are investigated.

Introduction

The noise floor for marine time-lapse seismic acquisition is usually determined more by nonrepeatable recording of coherent wavefronts from one survey to the next and less by ambient noise. This can be because of variation in physical parameters such as water velocity or water-column thickness that affect the repeatability of multiples but also because of the inability to repeat the acquisition geometry with sufficient accuracy.

Usually, knowledge of where the sources and streamers were at a given shot instance is much more precise than the ability to control where they should have been. This implies that the operational ability to hold a predefined course for streamers and sources can be challenging even for systems with steerable devices (Brown and Paulsen, 2011). Normally, shot location is more easily repeatable than sensor location, even with steerable streamers. Four-dimensional processing therefore needs to include interpolation onto a common grid.

However, conventional data typically are sampled inadequately in the crossline direction, resulting in the leakage of aliased energy. It is now widely recognized that repeating source and receiver positions from the baseline survey is of utmost importance to minimize time-lapse background noise.

Landro (1999) also finds that overburden heterogeneity has a significant impact on repeatability from analysis of a varietygram of trace-to-trace differences against source-separation distance in a 3D VSP common-receiver gather. Landro (1999) asserts that for a homogeneous earth, shot location should not matter, and recorded traces should be the same after allowing for different path lengths. The fact that there were differences between traces, that the differences were a function of shot separation, and that the variance spatially correlated with shallow overburden heterogeneity supported the inference that overburden heterogeneity limits the ability to repeat time-lapse seismic data and to deliver 4D signals with low background noise levels. Calvert (2005), Smit et al. (2005), Misaghi et al. (2007), and Naess et al. (2007) further discuss this issue in detail.

Consequently, matching source-receiver pairs for different seismic data vintages becomes critical. It can require oversampled acquisition and/or reliance on wavefield interpolation to yield wavefields recorded at corresponding locations between two or more surveys.

Robertsson et al. (2008) introduce the concept of a multi-measurement or multisensor streamer that would measure not only scalar pressure wavefields but also vector wavefields of particle motion such as velocity or acceleration. Based on those additional measurements, Ozek et al. (2010) outline the theory for a signal-processing technique called generalized matching pursuit (GMP) that can realize joint wavefield reconstruction and deghosting in a 3D sense by finding basis functions that model simultaneously the recorded pressure wavefield and as many gradients as might be available. The spatially continuous basis functions allow wavefield reconstruction at any point within the streamer aperture up to and beyond twice the corresponding pressure-only crossline Nyquist wavenumber.

The goal of this paper is to quantify the GMP-based wavefield-reconstruction fidelity on pre- and poststack data in different domains, using real data acquired during repeated passes in the North Sea. For quantification purposes, a witness (or benchmark) streamer recording the total pressure wavefield was employed as an actual measurement against which the wavefield-reconstruction quality was assessed. As a state-of-the-art, pressure-only reconstruction benchmark, the interpolation-by-matching-pursuit (IMAP) algorithm is used (Ozdemir et al., 2008; Ozbek et al., 2009) that also takes benefits of priors (Ozbe et al., 2012). The time-domain repeatability metrics used were normalized root-mean-square error (NRMS) and predictability (PRED), as defined by Kragh and Christie (2002), and their frequency-domain equivalents. This procedure also helps to distinguish the question of fidelity of the reconstruction from its repeatability.

Data acquisition

A repeated sail line was acquired during a mini-3D trial using six multimeasurement streamers that formed an active array of 500 m (inline) × 375 m (crossline) with a nominal streamer separation of 75 m and depth of 22.5 m. The source was positioned between Streamers 5 and 6 at a depth of 6 m (Figure 1a). The shot-point interval was 25 m. Strong currents in the area of acquisition introduced crossline source...
was established by time-lapse binning them for each platform individually between Pass 1 and Pass 2 and without any wavefield reconstruction involved (Figure 2a). After stacking the data, the NRMS value was computed between the two passes and plotted against the midpoint difference, which is a function of the source and receiver repositioning errors (Figure 3). A linear regression was then made through the cloud of NRMS data points. For small repositioning errors, in which small is somehow related to geologic variability and seismic wavelength, one would expect the NRMS mismatch in the repeated seismic wavefields to be linear in the repositioning error as a first-order approximation.

The acquisition also included three hydrophone-only production streamers for spread stability, and therefore, the same analysis was applied to the conventional data to provide benchmark results. Figure 3 presents NRMS as a function of midpoint error and a normalized histogram of the mispositioning of as much as 10 m and receiver mispositioning of as much as 20 m.

Data analysis

Prior to the analysis step, the acquired data for Passes 1 and 2 were preprocessed with a flow (Figure 1b) comprising preconditioning and multiscale noise attenuation (Özdemir et al., 2012). Receiver motion correction and tidal statics were then applied, although the latter correction was small. The Pass 2 data were then reconstructed onto a 6.25-m × 6.25-m surface grid, using either GMP with various inputs, GMP(PYZ), GMP(PY), and GMP(PZ), or pressure-only IMAP. The Pass 2 and Pass 1 data were compared after time-lapse binning to match midpoint locations and stacking with a common 1D velocity function.

Alternatively to the time-lapse binning, we also interpolated the reconstructed second-pass data from a spatially nonaliased 6.25-m × 6.25-m grid onto the trace positions of the first pass using a standard sinc interpolator. Both the time-lapse binning and the sinc interpolation exhibited very similar results. On the moveout-corrected prestack and poststack data, an analysis window of 1.0 s to 2.5 s was used—corresponding to the target zone—to derive the frequency-dependent NRMS and PRED metrics. After stacking, approximately 1160 traces were output with a midpoint spacing of 6.25 m to form a short section 7.25 km in length. The Pass 1 data went through a similar flow for repeatability evaluation, but in the comparisons to evaluate fidelity, no crossline reconstruction was carried out.

No signature compensation, multiple attenuation, or poststack processing was applied to the data before computing repeatability metrics. The purpose in this workflow was not to achieve the best possible 4D match but to provide a benchmark for evaluating the performance of the reconstructions. Because NRMS and, to a lesser degree, PRED are often used to define the similarity of two traces, we chose to apply the metric to estimate the trends of unreconstructed wavefield error with sensor repositioning error and to assess the reconstruction itself.

Whereas PRED is a measure of coherence between two signals, NRMS is sensitive to differences in gain, time shift, and phase between two traces, so it is a useful metric, in either time or frequency domains, to assess reconstruction performance relative to time-lapse wavefield mismatch resulting from repositioning errors. Other metrics, such as signal-to-distortion ratio (Cantillo, 2011), also could be useful but were not estimated in this analysis.

System repeatability

In a first step, the nonrepeatability of the multisensor streamer and hydrophone-only streamer pressure recordings was established by time-lapse binning them for each platform individually between Pass 1 and Pass 2 and without any wavefield reconstruction involved (Figure 2a). After stacking the data, the NRMS value was computed between the two passes and plotted against the midpoint difference, which is a function of the source and receiver repositioning errors (Figure 3). A linear regression was then made through the cloud of NRMS data points. For small repositioning errors, in which small is somehow related to geologic variability and seismic wavelength, one would expect the NRMS mismatch in the repeated seismic wavefields to be linear in the repositioning error as a first-order approximation.

The acquisition also included three hydrophone-only production streamers for spread stability, and therefore, the same analysis was applied to the conventional data to provide benchmark results. Figure 3 presents NRMS as a function of midpoint error and a normalized histogram of the
NRMS regression residuals for the pressure recordings of the new multisensor streamers and the hydrophone-only production streamers. It is evident from Figure 3 that the pressure responses of the two acquisition platforms are very similar, as evaluated by NRMS regressions and residual histograms.

Wavefield-reconstruction fidelity against a measured benchmark

In a second step, the GMP algorithm was applied to the repeat sail line to provide a reconstructed and decomposed wavefield on a 6.25-m × 6.25-m surface grid into its up- and downgoing constituents. To allow a direct comparison to the witness Streamer 3 taken from the first pass (Figure 2b), the two wavefields were added together, reghosting the data by refilling the ghost notch to create a uniformly sampled total-pressure wavefield cube. The streamer feathering on Pass 2 allowed evaluation of the performance of GMP wavefield reconstruction for a variety of distances from the reference streamers (in Pass 1).

Figure 4 compares wavefield reconstruction by GMP using components P, Y, and Z and by IMAP. Figure 4a depicts the brute stack of Streamer 3 from the baseline. Figure 4b illustrates the 4D background noise when applying time-lapse binning between Streamer 3 of Pass 1 and the unreconstructed Pass 2 recordings. The residual energy on the difference plot in Figure 4b is seen to correlate well with source and receiver mispositioning.

Figures 4c and 4d illustrate the difference between single-channel and multichannel interpolation. Figure 4c shows the 4D difference after single-component reconstruction (IMAP with priors). An improvement is seen compared with Figure 4b, but the main 4D noise features remain. A much greater attenuation of the 4D noise is achieved when GMP is used (Figure 4d).

To quantify these results, 4D metrics were computed trace by trace on these brute-stack differences in the time window of 1.0 s to 2.5 s and are shown in Figure 5 as a function of trace inline position X. It shows NRMS between Pass 1 and Pass 2, where unreconstructed binning (green) is compared with IMAP (blue) and GMP (red) interpolations prior to time-lapse binning. In all three cases, Pass 1 recorded pressure is not interpolated and hence acts as a reference measurement.

Although both IMAP and GMP reconstructions are superior to simple time-lapse binning, GMP exhibits the best repeatability performance. The performance margin of GMP over IMAP is greater at inline positions where receiver mispositioning is large (see the top frame of Figure 5, which shows the source and receiver mispositioning). Where source mispositioning is large, the repeatability...
The performance of both GMP and IMAP decreases, as would be expected.

The same data sets were also analyzed in Figure 6, where NRMS is displayed as a function of interpolation distance for the three scenarios discussed above. The source mispositioning is wrapped into the color-coding as a result of time-lapse binning on the midpoint. The linear regressions, 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 flatten those curves further, leaving GMP output almost insensitive to receiver mispositioning for the given scenario. This indirectly confirms the wavefield-reconstruction fidelity because the comparison is made against an actual measured witness streamer.

Assuming equivalence between the level of 4D noise introduced for a given unit of source or receiver mispositioning, it is possible to quantitatively assess the quality of the reconstruction. The NRMS sensitivity to mispositioning without wavefield reconstruction involved is 1.8 NRMS % per meter. The ratio between receiver and source repositioning errors, averaged over the sail line, is 2.67.

If GMP could address all the receiver mispositioning, the NRMS sensitivity would then translate into a slope of about 0.67 NRMS % per meter, dividing the original 1.8 NRMS % per meter by the ratio of 2.67. This is consistent with the observed NRMS sensitivity to the original repositioning error after GMP reconstruction. Because only Pass 2 data are reconstructed and compared with unreconstructed Pass 1 data, that observation suggests that the reconstruction error introduced by GMP is low compared with the time-lapse errors.

Repeatability and its implications for reconstruction fidelity

The data analysis performed so far has shown that GMP using P, Y, and Z as input, denoted GMP(PYZ), reconstructs the wavefield accurately against an actual measured benchmark, whereas the pressure-only, single-component algorithm IMAP is significantly less accurate. In a subsequent experiment, the wavefield reconstruction was applied to both passes, as shown in Figure 2c, and the data were reconstructed in the shot domain onto a 6.25-m × 6.25-m surface grid. The reconstruction on both passes was done by GMP(PYZ) or by IMAP, respectively.

Figure 7 shows time slices at 3.5 s of repeated shot-domain wavefields reconstructed from six crossline samples using IMAP (Figure 7a) and GMP(PYZ) (Figure 7b). The shotpoint is characterized by relatively low mispositioning errors. A diffraction with high spatial wavenumber and dip propagating within the time slice is visible, highlighted by green arrows. It becomes evident that these events are clearly reconstructed in the snapshots by GMP(PYZ) but are missed completely by IMAP, introducing aliased events.

Furthermore, the spatial frequency content, which adds to the fine-scale detail of the wavefield, is reduced compared with the GMP(PYZ) counterparts. However, if the NRMS is calculated from the Pass 1 and Pass 2 data after the two reconstructions, it turns out that IMAP produces considerably better repeatability than GMP(PYZ), despite being unable to reconstruct the diffracted part of the wavefield.

An explanation can be found in the sensitivity of NRMS to the bandwidth of the signal. As reported by Kragh and Christie (2002), a high-cut filter applied to time-lapse data will reduce the NRMS value. In the case of little acquisition mispositioning, as with the shot shown in Figure 7, IMAP produces consistent
results as a function of interpolation distance on both passes. IMAP also acts as a nondeliberate high-cut filter by reducing the frequency content in the spatial domain because it cannot overcome higher-order aliasing despite the use of priors.

A second shot gather, analyzed in Figure 8, has considerable receiver mispositioning but almost no source mispositioning. The time slice at 2 s shows features similar to those shown in Figure 7, with steeply dipping crossline energy reconstructed using GMP(PYZ) but missed by IMAP, which considerably simplifies the wavefield.

As shown in Figure 8, however, the repeatability improvements obtained by applying IMAP are compensated for by the inconsistency of the wavefield reconstruction as a function of interpolation distance, which was introduced by the original receiver mispositioning. Hence, GMP(PYZ) produces somewhat better repeatability. To consolidate the situation, Figure 9 displays the NRMS values for each individual time slice for both shots.

Figure 10 compares stacked data reconstructed between two physical input streamers for both passes using IMAP and GMP(PYZ). Consistent with the time slices shown in Figures 7 and 8, IMAP fails to reconstruct the aliased high-dip diffractions. Furthermore, residual energy can be seen correlating with higher-amplitude reflections in the stacked sections.

From the difference between GMP(PYZ) and IMAP Pass 1 data (top right in Figure 10), IMAP’s shortcomings become evident. However, if the 4D difference is taken between the IMAP-reconstructed wavefields of Pass 1 and Pass 2, the error appears smaller and less coherent and even suggests good repeatability, supporting what we already have shown on the analysis of shot-gather time slices.

These findings imply that good repeatability does not necessarily correspond to wavefield fidelity, and it can be achieved as long as the processes applied act in a consistent manner. To better account for this situation, the ability to reconstruct the high-wavenumber components of the wavefield must be included when deriving repeatability metrics in the context of time-lapse seismic. One potential avenue is discussed in the following, using frequency-dependent metrics.

**A way forward using frequency-dependent repeatability metrics**

Using the same methodology illustrated in Figure 2b, prestack frequency-dependent repeatability was first examined to better understand the uplift achieved by the additional acceleration measurements in contrast to pressure-only reconstruction. The traces of about 290 shots were reorganized into common-midpoint (CMP) gathers and were
moveout-corrected using 1D velocity function.

The two time-lapse difference plots shown in Figure 11 are characterized by varying levels of 4D noise, depending on the preprocessing applied, with GMP(PYZ) producing considerably less 4D noise than its pressure-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 related to acquisition mispositioning.

Using the same analysis window of 1.0 s to 2.5 s, the frequency-dependent NRMS and PRED metrics were calculated on a trace-by-trace basis and are displayed in Figure 12. The vertical axis relates to frequency, whereas the horizontal axis corresponds to trace inline position. 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 because only the pressure component is used to reconstruct the wavefield.

Also visible is the impact of the low-cut filter applied to the pressure data on the NRMS panels at about 1.5 Hz and lower. At frequencies above about 10 Hz, the data input to the reconstruction algorithms becomes increasingly aliased spatially. IMAP, despite its antialiasing protection through the use of priors, is no longer able to reconstruct correctly, whereas GMP(PYZ) gains 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 15 below), with a pronounced ghost-notch effect visible at about 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.

![Figure 7. Time slices at 3.5 s through Pass 1 and Pass 2 wavefields from a well-repeated Shot A, with little receiver and source mispositioning, reconstructed from six crossline samples with (a) IMAP and (b) GMP(PYZ). All wavefields are displayed on a rectangular output grid of 6.25 m × 6.25 m covering 500 m inline and 375 m crossline. A crossline diffraction, missed by IMAP, is well reconstructed by GMP(PYZ).](image)

![Figure 8. Time slice at 2 s through the wavefields from a repeated Shot B, with no source mispositioning but considerable receiver mispositioning, reconstructed from six crossline samples with (a) IMAP and (b) GMP(PYZ). All wavefields are displayed on a rectangular output grid of 6.25 m × 6.25 m covering 500 m inline and 375 m crossline. A crossline diffraction, missed by IMAP, is well reconstructed by GMP(PYZ).](image)

![Figure 9. For the two shots analyzed in Figures 7 and 8, NRMS was calculated for all the time slices down to 4-s two-way traveltime. The black curve indicates the difference between IMAP and GMP(PYZ) reconstructions. It becomes evident that when reconstructed wavefields are compared against each other, a good repeatability does not necessarily correspond to wavefield-reconstruction fidelity.](image)
These time-lapse binned shot gathers are then stacked, using a representative 1D velocity function from the area, which enhances the signal-to-noise ratio considerably. Figure 13a shows the total-wavefield reference stack based on the actual pressure recordings from Streamer 3 of Pass 1.

Figure 13b through Figure 13f show plots of wavefield differences from the reference, using variously preprocessed data from Pass 2: time-lapse binning only with no reconstruction; IMAP; and GMP with three inputs, GMP(PZ), GMP(PY), and GMP(PYZ), with the latter showing qualitatively the least 4D noise, closely followed by GMP(PY), hinting at the importance of the Y component. GMP(PY) corresponds to the multichannel interpolation by the matching-pursuit method (MIMAP), introduced by Vassallo et al. (2010).

Figure 14 shows frequency-dependent predictability histograms for the five solutions. Predictability was derived for each stacked CMP gather in a frequency-dependent manner and then stacked up across all the approximately 1160 realizations, in which the cooler colors (blue) indicate more hits for a certain bin. This metric tends to be less sensitive to signal-to-noise ratio than NRMS is.

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, above 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).

Figure 15 depicts corresponding frequency-dependent NRMS repeatabilities derived in the same analysis window as before. The lateral banding of high repeatabilities can be traced back to varying signal-to-noise ratio, as indicated by the amplitude spectrum shown on the far right-hand side, derived from the reference stack within the target window. Similar to the shot-gather analysis, on all five solutions, the low-cut filter is visible below 1.5 Hz, and all have similar NRMS values of as much as 10 Hz.

However, from 10 Hz to higher frequencies, the repeatabilities of time-lapse binning only, IMAP, and GMP(PZ) solutions show 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 measurement and, to a lesser degree, the Z measurement is most noticeable. In places with little receiver mispositioning, at the beginning and end of the sail line, for example, the uplift of multichannel reconstruction algorithms is much less pronounced. This is expected because little compensation is needed. As with the first analysis on the CMP gathers, wavefield reconstruction cannot compensate for source mispositioning, and even a well-reconstructed sail line such as the one using GMP(PYZ) still shows some lateral repeatability variations.

Another pronounced feature in the NRMS spectrum represents the lower signal-to-noise ratio ghost notch at about 35 Hz, corresponding to the tow depth of 22.5 m. GMP enhances the repeatability within this frequency region considerably by overcoming aliasing and equalizes 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. The minor noise leakage observed on the CMP-gather repeatability analysis in the band of 10 Hz to 15 Hz is no longer visible. The stacking process attenuates it effectively and hints at the uplift achieved by GMP in this frequency bandwidth.
Frequency-dependent repeatabilities can be used to optimize parameter settings for wavefield reconstruction such as relative weighting of the contributions of pressure and acceleration data to reconstruction, as described by Özbek et al. (2010). Overall repeatability can be maximized frequency by frequency in a time-lapse setting. The measure of repeatability against an actual measured benchmark is a direct indicator of reconstruction fidelity. In a case in which such a benchmark comparison cannot be made, repeatability metrics should be calibrated or weighted against the amplitude spectrum of the actual recorded data. Pattern-recognition methods could be particularly useful in that case.

Conclusions

Time-lapse seismic, because of its nature of acquiring two or more time-distinct 3D wavefields over heterogeneous geology, is vulnerable to source and receiver mispositioning. Previous work has shown that irregularities can introduce considerable 4D noise in proportion to overburden heterogeneity. In this study of a
data set acquired with multisensor streamers that measure the pressure wavefield and its gradients, we show in a qualitative and quantitative manner that the uniformly sampled pressure cube, output by multimeasurement seismic wavefield reconstruction, compares favorably with the recorded pressure benchmark. This helps to establish the integrity of the reconstructed wavefield. We have shown that the crossline acceleration component $Y$ is the key enabling factor.

Overall, we have found that multisensor seismic acquisition and processing offer the prospect of significantly reducing the effects of receiver mispositioning, leading to marked improvements in the 4D results. Source mispositioning then becomes the critical limiting factor on the acquisition side to assure high seismic repeatability. This limitation, however, can be addressed largely through source steering.

As part of this analysis, pressure recordings of the novel acquisition system were found to be comparable to those of its existing hydrophone-only production counterpart, used as a benchmark, sampling a given geology with the same repeatability. Furthermore, we have shown that single-component wavefield-reconstruction algorithms can still produce good repeatability, despite not being able to reconstruct the wavefield in an accurate manner, as long as the process applied produces consistent results. Essentially, this means that an aliased reconstruction will repeat well if the interpolation distance is similar for both two time-lapse snapshots.

This leaves the conclusion that for evaluation of both wavefield repeatability and fidelity, the validity of the reconstructed wavenumber spectrum must somehow be assessed. The ideal scenario is always to have a witness streamer to check reconstructed wavefields with measured wavefields. However, this might not always be possible for economic or towing and handling reasons. Therefore, an approach using frequency-dependent repeatability metrics can offer an alternative tool to evaluate the performance of different reconstruction algorithms in individual frequency bands and can be used to optimize parameter selection also. More work needs to be done to investigate those opportunities, but we expect that frequency-dependent repeatability metrics will prove to be useful.

References


Corresponding author: KEggenberger@slb.com