Adaptive multiscale processing of challenging 3D seismic data for first-break picking, FWI and imaging

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Summary

We propose an alternative way to achieve multi-shooting grids of low-, mid- and high-frequency sources of comparable signal-to-noise ratio using adaptive summation in processing and conventional high-productivity broadband acquisition. Splitting data into multiple frequency bands provides flexibility to apply variable apertures for enhancement based on local summation. We refer to this as Adaptive Multiscale Processing (AMP). Larger enhancement apertures acceptable for low frequencies enable to compensate for acquisition inefficiency of broadband sources in this range. At mid- and high-frequencies AMP efficiently suppresses near-surface scattering with a smaller enhancement aperture. We demonstrate that AMP can preserve the signal and deliver reliable first-break picks for tomography, waveforms for full-waveform inversion and data for imaging using field records that are otherwise too low signal-to-noise to be useful.

Introduction

Land seismic data is notorious for poor quality and variability of the waveforms. It is believed that full-waveform inversion (FWI) is a technique can give significant uplift. However, FWI places stringent requirements on the data quality. The majority of all FWI examples are obtained using relatively high quality marine data. To further exacerbate this challenge, FWI heavily relies on low frequencies 1-10 Hz that are more difficult to excite and record onshore. For instance, Pevzner et al. (2011) qualified signal-to-noise ratio (SNR) through repeat 4D observations and showed that low frequencies are characterized by reduced SNR and repeatability as compared to mid-band frequencies. Finally, as modern acquisition moves towards point sources and point receivers this can lead to further reduction of raw data quality. With this triple challenge in mind, it is no wonder the land FWI is lagging behind work on marine data. Radical solutions to the problem exist. Using a large number of vibrators in a group (Tonellot et al., 2015) helps but becomes prohibitively expensive to scale. Dispersed Source Arrays (Berkhout, 2012) advocate dedicated narrow-band sources. Low-frequency sources are slowly appearing offshore (Brenders et al., 2018) but not onshore. Is there another approach to solve this challenge that is less resource-intense but combines strong parts of modern high-channel acquisition and novel processing without placing an unreasonable burden on each? We intend to outline such an approach and demonstrate applications to some of the most challenging data in the world.

Back to basics with adaptive multiscale processing

The seismic industry is moving to point sources and point receivers, chasing higher bandwidth data. Figure 1 compares a gather from modern acquisition with a legacy version using larger arrays. While we come to discuss higher frequency at the end, first let us focus on low and mid frequencies required for FWI and first-break (FB) picking for initial model building. Figure 1a shows that signals at all frequencies are below any acceptable level for any straightforward processing. Nevertheless, legacy data shows that events may be hidden in the data. Leaving higher frequencies aside, we can amass significant signal and greatly suppress noise if we perform simple supergrouping (Bakulin et al., 2018a) as shown in Figure 2. First breaks and reflections become clearly visible. Supergrouping uncovers radially propagating signal on frequency panels at 4 Hz where only noise was seen after conventional single-sensor pre-processing. Supergrouping is another re-incarnation of array-forming albeit with moving averages, moveout and waveform corrections

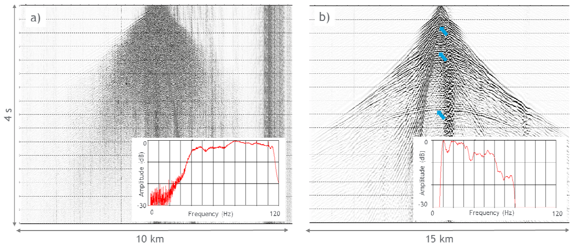

Figure 1. Comparison of two raw shot gathers including (a) from modern single-sensor acquisition and (b) from legacy acquisition with 72 geophones in a recording group. They illustrate a typical difference in data quality between two types of acquisition.

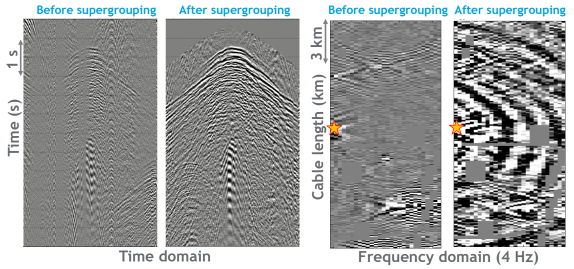

Figure 2. Supergrouping applied to 3D single-sensor land data (shot grid 12.5m x 75 m, receiver grid 75 m x 12.5 m)

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(Bakulin et al., 2018a; Neklyudov et al., 2017). As an industry, seismic processing has become averse to the idea of combining signals even where SNR is extremely low (Figure 1 and 2). To succeed in practical terms we need to: a) achieve sufficient SNR, and b) ensure that signal is preserved in the process. Let us address this at low- and mid-frequencies first. Figure 3 proves preservation of the signal at 6 Hz when we perform supergrouping using distributed 5x5 source array extracted from conventional acquisition. Bakulin at el. (2018b) showed similar examples for the mid- and high-frequency ranges in the case of depth imaging. Of course, the main motivation for enhancement techniques based on local summation is to increase SNR (Figure 2) while utilizing current dense broadband acquisition to reliably recover information. Clearly, different frequency bands will tolerate different levels of local summation. So we arrive at the idea of Adaptive Multiscale (multi-grid multi-band) Processing (AMP) where adaptive enhancement (based on local summation) tailored to each frequency band is applied with larger apertures/time windows for low frequencies and smaller apertures/time windows for high frequencies (Figure 4). With conventional acquisition and using moving averages, we can still output data with original dense sampling for each band (same grid). Alternatively, we can reduce the amount of overlap between groups/apertures and compress the data by outputting sparser grids for lower frequencies (multi-grid). In the latter case of AMP we achieve "multishooting grids" similar to the DSA concept (Berkhout, 2012), having higher frequency sources distributed more densely than low-frequency sources. However, AMP has achieved this goal using conventional orthogonal 3D acquisition and normal broadband sources such as vibroseis. We compensated acquisition deficiency of broadband sources at low frequency by applying large-aperture local summation in processing that amplified weak signal in this band. In essence, we decomposed data into frequency-dependent "atoms" using conventional broadband acquisition and then recomposed into appropriate-size "molecules" required for successful processing of each band. All frequency bands can be assembled at the end for broadband image. Regular distribution of broadband "atoms" (source/receiver grids) present in orthogonal 3D acquisition is fully exploited. Note that dense broadband acquisition gives us unlimited flexibility to design as many frequency bands as we desire or is required by the data, for example one for each octave.

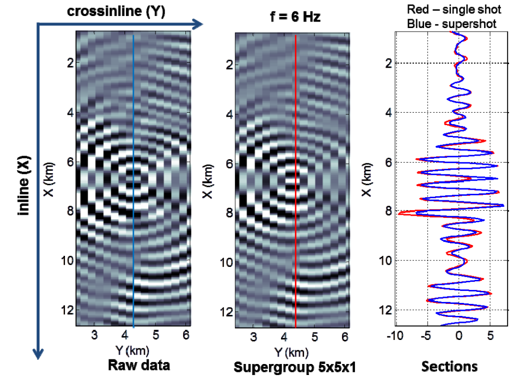

Figure 3. Frequency panels at 6 Hz for 3D SEG/EAGE Overthrust model. Observe equivalence of point source and supergrouped data combining 5x5=25 sources.

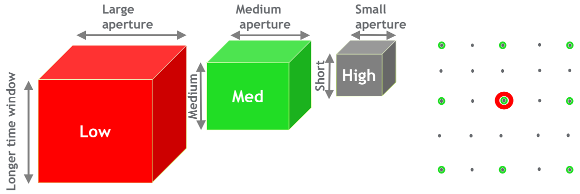

Figure 4. Sketch showing adaptive multiscale processing with increasing apertures/time windows for high, medium and low frequencies. To reduce significant overlapping, spatial grid density for grouped/enhanced data can be reduced accordingly.

Strikingly, broadband processing of data with multiple separate frequency bands remains a significant challenge. While elements of octave-based processing start to appear (Retailleau et al., 2014), such workflows require serious development to replace conventional broadband processing approaches using a single frequency range. Workflows for FWI and first-break picking were chosen to demonstrate the power of the new approach.

Expanding toolbox and OBN long-offset field example

While supergrouping without any moveout corrections works well for very low frequencies, summing higher frequencies requires knowing signal trajectories. In reflection processing, supergouping is normally done after normal moveout correction (Bakulin et al., 2018a). Where one would find them for data shown in Figure 1a and 2 with unresolved statics, velocity and waveform variations? Using global NMO trajectories is just one initial approach. What do we do to find signal trajectories for first breaks? To resolve this challenge, we add nonlinear beamforming (NLBF) to our enhancement toolbox (Bakulin et al., 2018b). NLBF searches for hidden local trajectories (Figure 5) and then sums along them. For first-break picking we have to open up the search interval. Figure 5 shows relatively well-behaved ocean-bottom node data in the low-frequency band (5-10 Hz). However, FWI demands large offsets and clearly conventional pre-processing fails to deliver reliable first breaks beyond 8 km offset. In essence, conventional processing can be likened to trying small "high-frequency" apertures (Figure 4) to achieve good SNR for low- to mid-frequencies. While this is straightforward for data from Figure 1b with large field arrays, it is no longer possible with modern land datasets using small arrays or point sensors and in fact even higher-quality marine data from Figure 5. Furthermore, economics as well as environmental reasons do not motivate our industry to create stronger sources so learning to assemble reliable signals from reduced-quality "atoms" is a new skill we should perfect. In Figure 5 conventional approaches only allowed picking 0-8 km offsets, with only 35% of the picks acceptable for inversion. In contrast, after AMP with NLBF using a 500x500 m aperture, we were able to expand the useful offset range to 0-20 km with 60% acceptable picks.

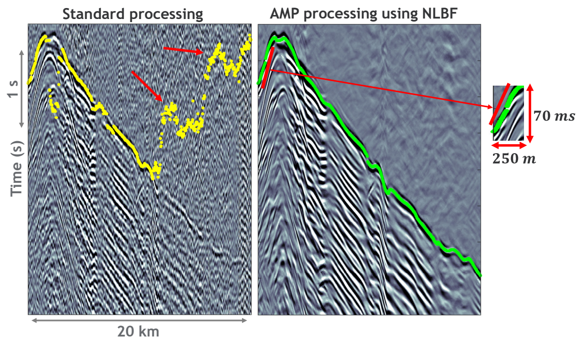

Figure 5. Demonstration of AMP using NLBF to enhance and pick first breaks on mid-frequency data using 500x500 m aperture for FWI initial model building.

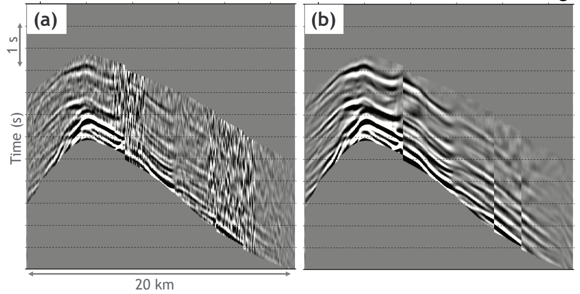

Figure 6. Low-frequency waveforms using standard processing (a) and AMP processing (b) with 500x500 m aperture for FWI (shown 0.5-10 Hz band for display only).

This is a clear demonstration of AMP capabilities as applied to low- to mid- frequency range data and enabled reliable FB picking for initial velocity model building. Using FB picks as a guide and applying NLBF, we were able to recover reliable waveforms for low-frequency FWI all the way to maximum offset of 20 km (Figure 6). Excellent results were obtained with FWI after AMP preconditioning as reported by Kim et al. (2019).

FB picking on land 3D single-sensor data

Marine data is still relatively good data compared to onshore seismic. Single-sensor data (Figures 7a and 8a) from different lines/cables shows quite poor SNR. Blue dots show FB picks obtained with a conventional workflow. Generally, the data pre-processing assumes a certain minimum SNR that is simply not available in this data (Figure 8b). Implementing NLBF focused on mid-frequencies, we are able to obtain much more consistent picks (red). Figure 9 shows a summary of the picks verifying that AMP recovers meaningful picks in the 2200-4000 m range, that were impossible to obtain otherwise.

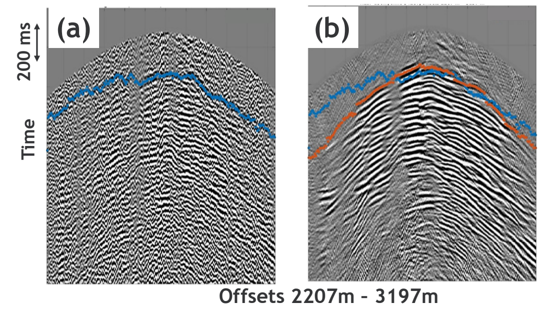

Figure 7. Shot gathers without (a) and with AMP (b) for a near receiver line.

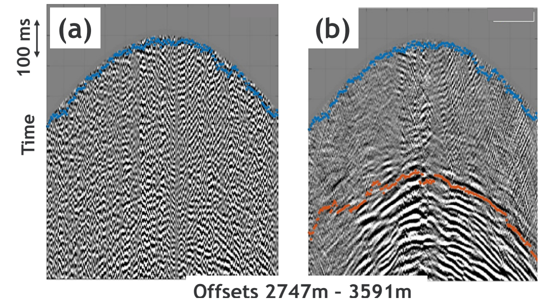

Figure 8. Same as Figure 7 but for a far receiver line.

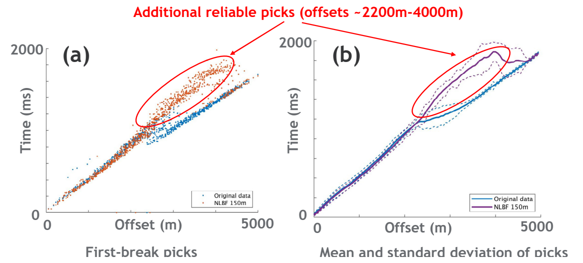

Figure 9. Summary of the FB obtained using standard (a) and new (b) approach with AMP.

FWI on 2D land data with field arrays

Even field arrays cannot reliably guarantee signal if complex near-surface scattering is present. Figures 10 and 11 show 2D land data acquired with 72-geophone groups and five vibrator field arrays. In challenging onshore areas, the AMP approach becomes a must to precondition the data in both time and frequency domain for reliable FWI.

Does AMP have a role for final imaging?

While everybody agrees that data shown here requires significant out-of-the-box processing, using the locally

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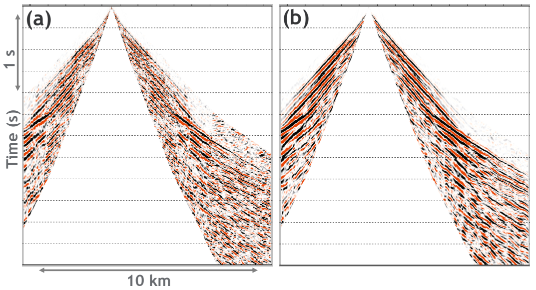

Figure 10. Early arrivals prepared for FWI before (a) and after (b) AMP processing with NLBF.

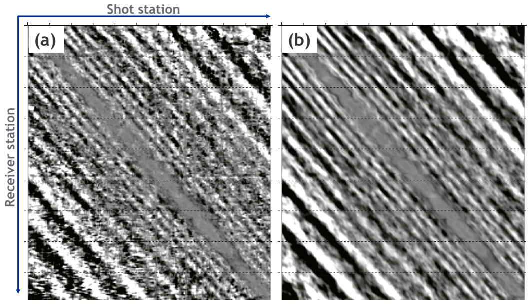

Figure 11. Same as Figure 10 for frequency panels at 6 Hz.

summed/grouped data for final imaging is still frowned upon. Our view is that for data below a certain minimum SNR this should be an acceptable practice. Figure 12 shows images from 3D single-sensor land example imaged without and with AMP-type processing with NLBF using a 500x500 m aperture. We claim that image variability observed on Figure 12a has nothing to do with geology and simply an imprint of near-surface scattering. The naïve expectation that final migration is the ultimate noise removal tool is not supported by imaging results in Figure 12a. In practice, we end up doing smoothing with post-stack filters, whereas AMP with NLBF achieves this with a more versatile pre-stack approach preserving discernable prestack signal details. Another strong evidence that pre-stack enhancement advocated by AMP is not achieved by simple final migration comes from 4D seismic applications on land (Bakulin et al., 2016) where it was shown that AMP can greatly enhance repeatability of the final stacks to a level not achieved by conventional pre-stack migration. Antileakage Fourier transform interpolation is an alternative ensemble-based technique that is often used as part of data enhancement flows for imaging (Qin et al., 2018). Interestingly, for the same 4D data, this approach was unable to deliver better repeatability on final stacks even though during early steps interpolation gathers look higher SNR (Smith et al., 2019). Our explanation is that interpolation of both signal and noise (Qin et al., 2018) with the objective to remove un-aliased noise, simply cannot preserve the signal fidelity in the presence of dominant noise. Reduced 4D compliance of interpolation suggests that part of the reconstructed "signal" becomes manufactured from noise. In contrast, AMP processing with enhancement solely focused on the signal trajectories (no noise interpolation) withstands stronger levels of noise and delivers the best signal fidelity as judged by 4D compliance or repeatability of the signal.

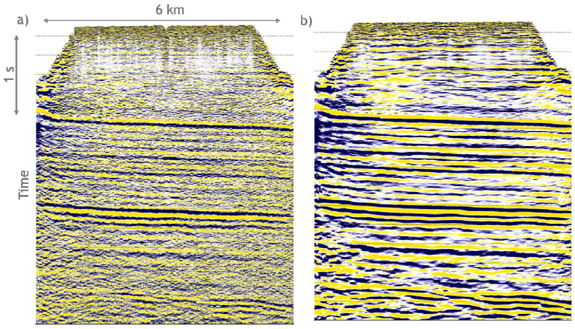

Figure 12. Stack section from 3D single-sensor survey without (a) and with (b) application of AMP with NLBF.

Conclusions

We outline an alternative approach addressing processing challenges of modern high-channel count 3D seismic data with smaller field arrays and broadband sources. This approach does not require new acquisition. Instead it tries to diagnose weak points of existing acquisition and address them using novel processing remedy. This led us to Adaptive Multiscale Processing that comprises of several local pre-stack signal summation approaches such as for example supergrouping and nonlinear beamforming. Splitting the data into multiple frequency bands, similar to DSA, provides us with flexibility to apply larger summation apertures for enhancing lower frequencies that demand them most, and adjust to smaller apertures at higher frequencies. At low frequencies, this allows to overcome the weakness of broadband sources (acquisition matter), whereas at medium and high frequencies it purges near-surface backscattered noise (geological issue). We showed several marine and land examples involving first-break picking and FWI that would be rendered completely useless without AMP. We further speculated that AMP could be carried all the way to imaging for challenging data, supported with exploration and 4D examples. We believe that AMP has a role for imaging, provided we can verify preservation of the signal. While it would be great to acquire pre-stack field data with high enough SNR that final migration would remove all remaining noise, the reality is very far from that and AMP offers way forward with what we have. AMP is a natural extension of Enhance-Estimate-Image approach (Bakulin and Erickson, 2017) that recognizes a need and power for frequency-dependent signal enhancement.

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