Bootstrapping invisible signals: prestack land data enhancement using nonlinear beamforming with local waveform corrections

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Summary

We present a method for enhancement of challenging prestack seismic data that preserves valuable local information such as residual statics, wavelet shape and frequency bandwidth. This information is encoded in the original data; but is often not easily extracted because of low signal-to-nose ratio (SNR). While enhancement methods based on local summation are very powerful to increase SNR, they inevitably smear and average such local information. The method proposed here attempts to alleviate these shortcomings by using efficient data-driven estimation of local traveltime signal trajectories and performing general waveform corrections before summation that compensate for differences in residual traveltimes, phases and amplitudes. The proposed method might lead to optimal processing of modern high-channel count and signal-sensor data and should enable extracting more usable information from the modern land seismic surveys.

Introduction

Modern dense land seismic datasets acquired with small arrays or single sensors often have poor signal-to-noise ratio. Every processing step that relies on pre-stack data is challenging in such a case because reflected signals are weak, irregular, and are hidden behind strong coherent and random noise. Conventional surface-consistent processing, residual static and velocity analysis require reliable pre-stack signal in the data. Their application to modern datasets often leads to unreliable results because the derived processing parameters are based on noise and not on signal. To extract maximum information from the dense high-channel data, one needs to suppress noise and to enhance signal in the pre-stack domain.

Different methods were proposed in the past to enhance prestack seismic data. Multi-dimensional data-driven stacking techniques such as common-reflection surface method (CRS) or multi-focusing (MF) have been widely used to enhance prestack gathers (Baykulov and Gajewski, 2009; Berkovitch et al., 2008; Curia et al., 2017). These methods assume a global trajectory of the reflection events, which may fail in complex geological conditions. Non-zero offset CRS and non-hyperbolic MF methods were proposed to avoid global hyperbolic approximations and to use local kinematic wavefield parameters (Zhang et al., 2001; Muller and Spinner 2010; Berkovitch et al., 2011, Buzlukov and Landa, 2013, Bakulin et al. 2017a). All multidimensional local data stacking techniques mentioned above can be considered as a realization of "delay-and-sum" beamforming. The general scheme implemented in these approaches can be decomposed into three stages: 1) estimation of local kinematical attributes (LKA) that describe local moveout of reflected waves (i.e. relative time delays of desired signals), 2) alignment of coherent arrivals in the ensemble with respect to corresponding event in the reference trace using obtained LKA attributes, and 3) stacking of moveout corrected traces to produce an output trace with increased signal-to-noise ratio. Usually, stage 2 is implemented implicitly during stage 3 when the signals are summed along local moveout surfaces. Ensembles of time-aligned traces usually are not constructed.

To get reliable prestack signal in the case of very noisy data large stacking apertures are often required. Apertures can reach hundreds of meters. Individual traces from such large stacking ensemble are recorded in different near-surface conditions. Such traces often have different local time-shifts and waveform variations. As a consequence, enhanced data

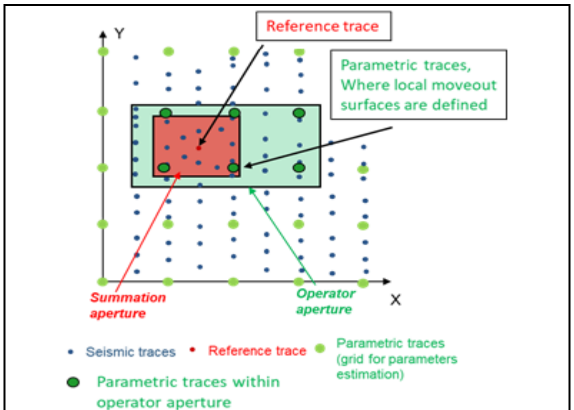

Figure 1. Explanation of the meaning of parametric traces and traces to be used for reference trace enhancement in operator oriented approach used in NLBF.

obtained during summation along the estimated average local traveltime surfaces may suffer from non-optimal stacking. This leads to suppression of higher frequencies of the desired signals and smearing of valuable information used to estimate residual statics and design deconvolution operators within the stacking aperture.

In this paper we propose an approach which attempts to alleviate these shortcomings. We introduce an additional module in the standard "delay-and-sum" scheme that performs general phase corrections for locally time-aligned ensembles of traces. This is based on the approach proposed

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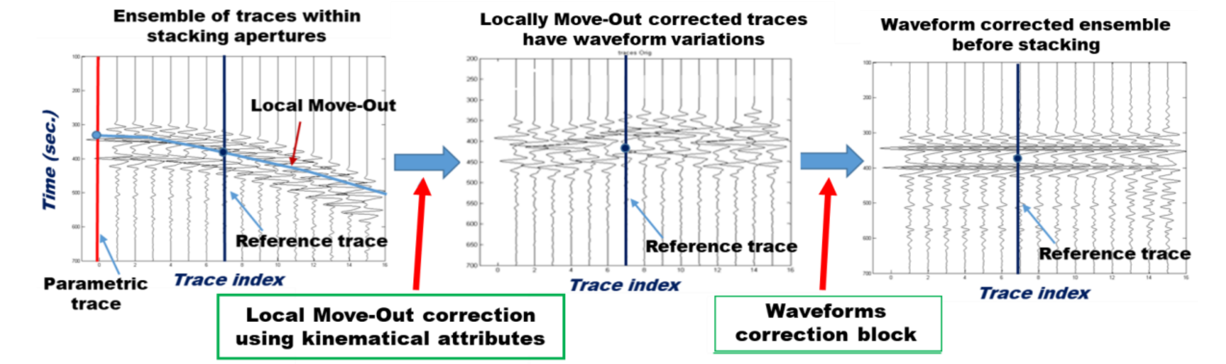

Figure 2. Explanation of the proposed method for single parametric trace. (left) Local move-out surface is constructed from the parametric trace using estimated kinematical attributes with respect to reference trace; (middle) Move-Out corrected ensemble of traces with residual static and waveform variations; (right) Waveform and static corrected ensemble of traces before summation

by Neklyudov et al. (2017) and comprises beamforming in the Short-Time Fourier Transform domain. We expect that such corrections allow to compensate for differences in residual traveltimes, phase and amplitude variations so summation will be performed more optimally.

Method

The basic requirements for the data enhancement procedure is an ability to handle the huge data volumes acquired by modern high-density land seismic acquisition. Note that for typical high-channel-count surveys acquired over an area of say 2,000 km^2, the size of the data can be around 150 terabytes, and for single-sensor surveys it can reach more than one petabyte. Therefore, efficiency and optimization are a must for any viable data enhancement technique. Based on our previous experience in enhancing 2D data (Bakulin et al., 2017a, 2018), we introduce nonlinear beamforming (NLBF), an approach for enhancing challenging 3D prestack data acquired with modern orthogonal land seismic surveys. We have adopted so called Operator Oriented (OO) scheme for data enhancement (Hoecht et al., 2009; Buzlukov and Landa, 2013). The main advantage of the OO scheme is the fact that the most computationally expensive stage of the algorithm (local kinematical attributes estimation) is performed using a sparse grid (see Figure 1).

The proposed approach consists of the following steps:

1) *Selecting the appropriate domain and sorting*. An important practical simplification is to implement data enhancement within some 2D subset of the 4D data volume. In this case, only five local kinematical parameters need to be estimated: two dips and two curvatures in each coordinate plane and one mixed derivative. For example, for 3D land data with orthogonal acquisition geometry an appropriate domain to perform the enhancement is a cross-spread domain (Bakulin et al., 2018). However, the proposed approach can be applied to other domains such as common-shot, common-offset, common-receiver domains and to more general multi-dimensional 3D or 4D subdomains of the whole prestack data cube.

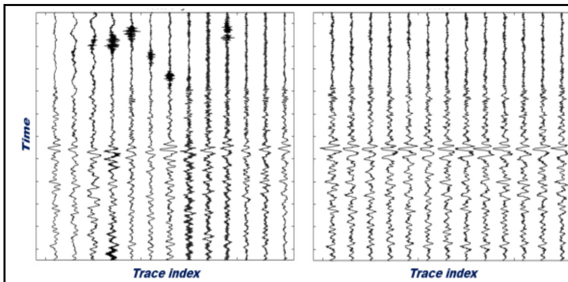

Figure 3. (Left) Ensemble of traces (fragment) after local moveout corrections. It is an input for waveform correction block; (Right) Ensemble of traces after waveform and amplitude correction before stack to produce an output trace.

2) *LKA calculation*. Local kinematical attributes are estimated for each multidimensional gather. They define local travel-time surfaces of reflected arrivals. The most straightforward way is to estimate these parameters at each trace in the data volume (in other words at each position of a reference trace). Considering the huge amount of data, this is very expensive. In the operator-oriented approach, kinematic parameters are estimated on a coarsely sampled regular grid, and then "opened" over the entire volume. Grid points where estimation is performed are referred as "parametric traces" (see Figure 1). Each "parametric trace" incorporates five kinematic parameters estimated at each time sample.

3) *Ensemble gathering and alignment*. For each actual trace to be enhanced (reference trace) an ensemble of neighboring traces is gathered. The number of traces in this ensemble is determined by user-defined stacking aperture. Local moveout corrections along the travel-time surfaces, which were estimated at the stage 2, are applied to all traces in the ensemble. As a result, moveout corrected ensemble of traces is obtained (Figure 2) and used as an input for next step.

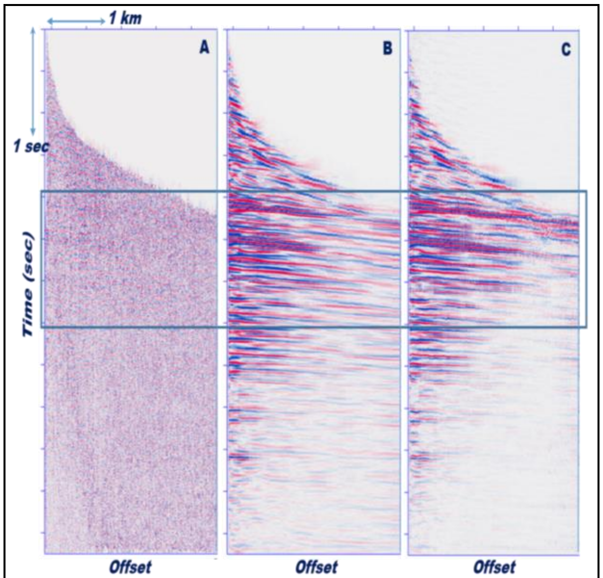

Figure 4. Real-data example: (A) Original data (CMP gather); (B) data after enhancement using NLBF without additional corrections; (C) data after enhancement using NLBF with additiaonal static and waveform corrections.

4) *Waveform corrections*. We apply a general waveform correction to each trace within each aligned ensemble to account for waveform variations within the ensemble. The correction is performed with respect to a reference trace or a pilot trace constructed on the base of a reference trace. More specifically, we utilize the approach presented by Neklyudov et al. (2017) where beamforming is performed in the Short-Time Fourier Transform domain. Corrections are independently applied for each frequency and thus can handle more complex variations of recorded signals than simple relative time shifts from trace to trace. Corrections are performed in a "locally surface-consistent" manner, meaning that waveforms variations of traces are calculated with respect to a given reference trace. In the current realization, reference trace is taken to be an actual trace from the middle of the ensemble where an enhanced trace is to be output. After this stage, all traces in the ensemble should be aligned and waveform corrected with respect to desired arrivals in the reference trace (Figure 3).

5) *Summation*. Corrected traces are summed within each ensemble to obtain an output trace. Output traces from each auxiliary ensembles that correspond to different parametric traces are summed after residual static and phase corrections to produce a final output trace with increased signal-to-noise ratio. Residual statics, waveforms and higher frequencies in the enhanced trace are better preserved due to optimized summation of input traces.

Stages 3 - 5 are repeated for each trace in the considered multidimensional subvolume.

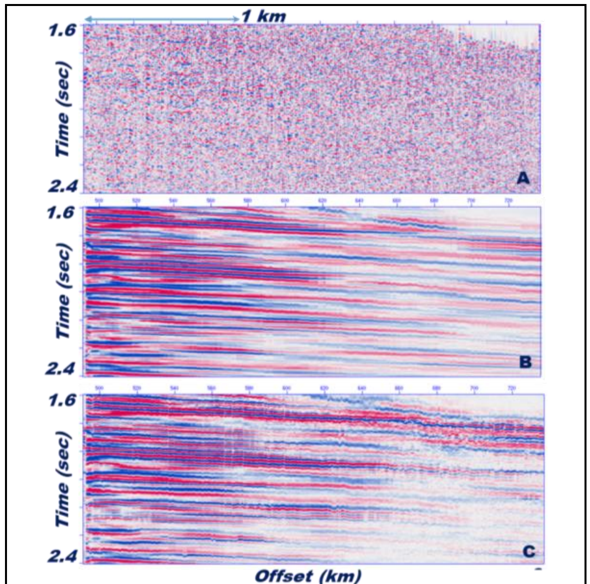

Figure 5. Zoom of Figure 4 in a time window 1.6-2.4 sec: (A) Original data (CMP gather); (B) data after enhancement using NLBF without additional corrections; (C) data after enhancement using NLBF with additional waveform corrections.

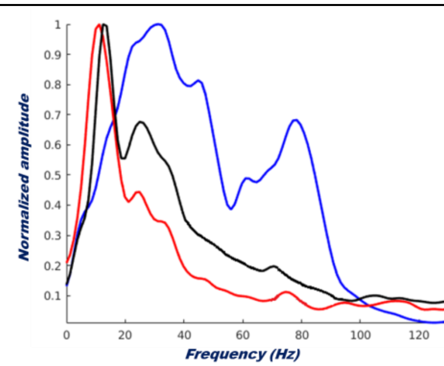

Figure 6. Comparison of avereged amplitude spectra calculated in the time window [1.6, 2.4] sec at far offset (2,800) m: processed original data (blue); data after NLBF enhancement (red); data after NLBF + STFT BF based waveform corrections (black).

Real data example

An example of a common-midpoint (CMP) gather from a challenging 3D land dataset acquired in a desert environment is shown in Figure 4. The input data have been already passed through a standard processing flow and is ready for velocity analysis and imaging. As one can see in Figure 4A, prestack signal is very weak and there are no visible reflections in the gather. Figure 4B shows the same CMP gather after NLBF data enhancement with summation apertures of 200m x 200m in the CMP and offset directions.

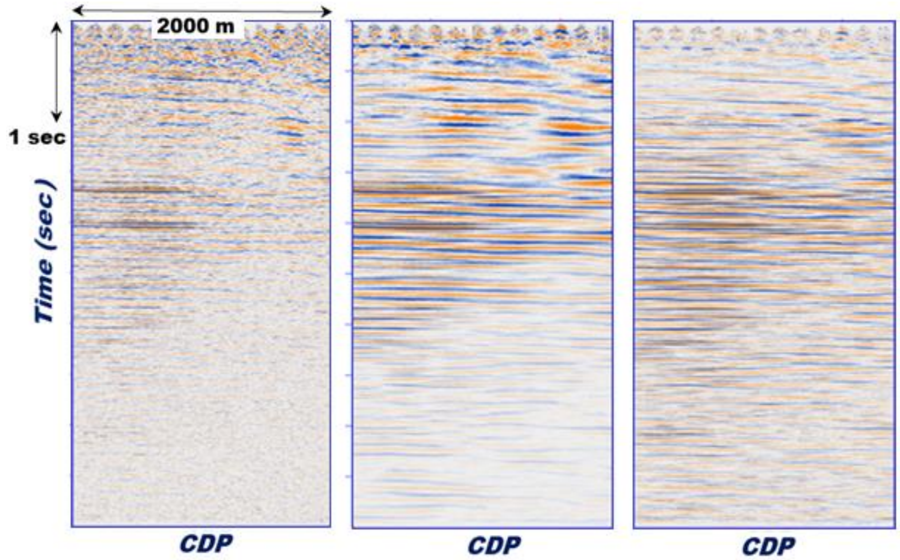

Figure 7. Fragments of stack sections with original and enhanced data: (Left) stack section obtained with original data; (Middle) stack obtined after NLBF data enhancement; (Right) stack after NLBF data enhancement with additional waveform corrections using the described method.

Approximately 300 neighbouring traces are used in the local summation to enhance each original trace in this case. As one can see, after the enhancement the reflections are easily recognizable along the entire offset range. However, high-frequency content of the signal is reduced due to sub-optimal stacking. The reflections are strong but become overly smoothed. In contrast, things are changed when we apply the proposed approach where NLBF data enhancement procedure is done together with intermediate waveform corrections (Figure 5). In this case, reflections are still visible in the entire offset range but are resolved with more spatial and temporal details. Sharp time shifts between neighbouring traces become clearly distinguishable (Figure 5). This confirms that the original input data still contain some residual statics in the gather which was unresolved due to low signal-to-noise ratio. The remaining residual statics can be successfully estimated now by applying the standard algorithms to the enhanced dataset. Computed amplitude spectra validate that introduced corrections led to preservation of higher frequencies in the data (Figure 6).

Comparison of stacks reveals that while both NLBF images have better event continuity in the challenging data area on the right, the image using waveform-corrected data possesses finer spatial and temporal details (Figure 7). The fact that higher frequencies are appearing after stacking (Figure 8, black) suggest that we gained additional signal on prestack records (Figure 5 and 6) that coherently added up during the imaging step. We conclude that NLBF with waveform corrections provides significant uplift in pre-stack and post-stack images obtained with challenging data.

Conclusions

We propose a new approach for enhancing challenging prestack seismic data that compensates and preserves local

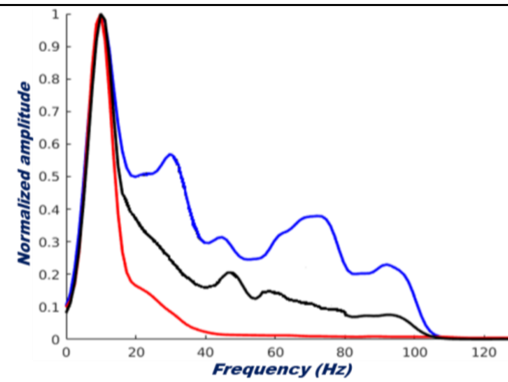

Figure 8. Comparison of avereged amplitude spectra calculated in the time window [1.6, 2.4] sec of the stack sections Figure 7: stack with original data (blue); stack using data after NLBF enhancement (red); stack using data after NLBF + additional waveform corrections (black).

travel-time shifts and waveform variations in the enhanced data. This information is of great importance for estimating reliable processing parameters such as residual statics corrections, deconvolution operators, stacking velocities and amplitude scalars. The reliable estimation of such parameters and their usage is an essential step of the Enhance – Estimate – Image approach (Bakulin et al., 2017b) for processing of modern dense land seismic data in order to get better seismic images of the subsurface as well as improved prestack gathers for inversion. The proposed method might lead to significant advances in processing of modern high-channel-count and signal-sensor data and should enable extracting more usable information from the current and future land seismic surveys.

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