Nonlinear beamforming for enhancing pre-stack data with challenging near surface or overburden

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Summary

Modern seismic data acquired with dense high-channel count acquisition systems are very challenging to process, especially in the presence of a complex near surface or overburden. To address this issue, we develop a nonlinear beamforming algorithm for pre-stack data enhancement that searches for nonlinear local coherent events in the data and performs partial summation along the estimated trajectories. Nonlinear beamforming shows excellent results when applied to synthetic as well as challenging land data acquired in an arid environment. Specifically, it enables more robust estimation of pre-stack parameters as well as better imaging.

Introduction

Modern land seismic data acquisition is moving from sparse grids of large source/receiver arrays to denser grids of smaller arrays or point-source, point-receiver systems. Large arrays were designed to attenuate ground-roll and back scattered noise with high apparent velocity and to increase overall signal-to-noise ratio (SNR). Decreasing the size of field arrays during acquisition in arid environments leads to dramatic degradation of SNR in the data. Theoretically, we are sampling the signal and noise better and expect to achieve improved imaging. Achieving this in practice with huge amounts of low SNR data proves to be very challenging. Conventional time processing tools such as surface-consistent scaling, statics correction, and deconvolution require reliable pre-stack signal in the data. Their application to the modern datasets acquired with small array sizes often leads to unreliable results because the derived operators are based on noise and not on signal. To extract the maximum value from dense high-channel acquisition, we need to enhance signal in the pre-stack data. Fortunately, densely sampled data gives us more flexibility than grouping geophones directly in the field. Promising enhancements of very challenging data were obtained recently by supergrouping (Bakulin et al., 2016), which locally sums nearby traces. Application of normal moveout (NMO) corrections prior to supergrouping allows handling of larger spatial separation between traces and preserves higher frequencies in the data. In the presence of a complex near surface or overburden, the assumption of global hyperbolic NMO may break down and a more sophisticated approach is desired that can estimate actual moveout directly from the data.

Buzlukov et al. (2010) and Buzlukov and Landa (2013) proposed an approach for enhancing pre-stack data based on searching for locally coherent events in the data and partial summation along the estimated trajectories. This can be considered as a delay-and-sum beamforming method. Unlike conventional beamforming (slant stack), the time-delay in this approach is a nonlinear function of distance. Further advances were achieved by Khaidukov et al. (2016). Building on this earlier work we introduce nonlinear beamforming for enhancing challenging pre-stack land seismic data with low signal-to-noise ratio caused by strong near-surface scattering.

Method

The data-enhancement procedure comprises a local summation of traces and can be written as:

$$u(x_0, h_0, t_0) = \sum_{(x,h)\in B_0} w(x,h)\, u\big(x, h, t_0 + \Delta t(x,h)\big), \qquad (1)$$

where $u(x,h,t)$ represents a trace with midpoint and offset coordinates, x and h, respectively. The coordinates of the output trace after the beamforming procedure are given by x_0, h_0. The summation is done over a local region B_0 around the output trace in CMP-offset plane along a trajectory with some moveout $\Delta t(x,h)$.

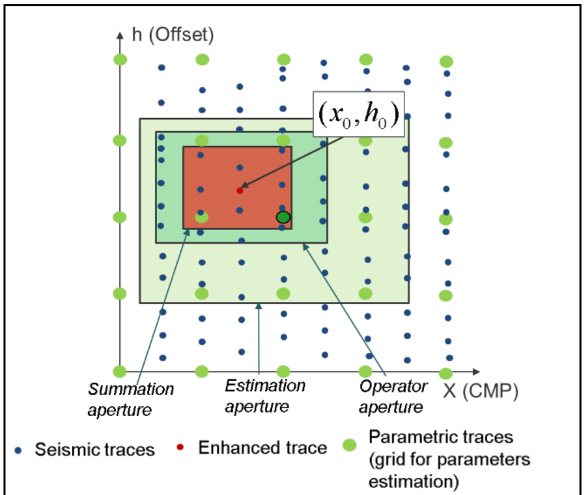

Figure 1: Geometry of the beamforming process.

The main assumption used here is that the wavefront can be locally approximated by a second-order surface as follows:

$$\Delta t = t(x,h) - t_0(x_0,h_0) = A\Delta x + B\Delta h + C\Delta x\Delta h + D\Delta x^2 + E\Delta h^2$$

where A,B,C,D,E are unknown beamforming coefficients and Δx, Δh represent shifts of the summed trace with respect to the output trace.

The beamforming weights $w(x,h)$ are used to preserve signal energy and to suppress noise. In the following examples we use a simple fold normalization, but more sophisticated approaches can be adopted. The beamforming coefficients have particular physical meaning in models of mild complexity. For example, the A and D coefficients correspond to slope and curvature of events in common-offset sections and are related to structural characteristics of the model. The B and E coefficients define slope and curvature of events in the common-midpoint domain and are related mostly to the model velocity. The mixed coefficient C combines the two domains. These coefficients are connected to a common-offset CRS operator (Zhang et al., 2001) and to a non-hyperbolic multi-focusing operator (Berkovitch et al., 2011) and in simplified cases can be derived through them. The optimal values of the beamforming coefficients are obtained by means of coherence analysis similar to CRS or multi-focusing techniques.

We follow a similar approach as in Hoecht et al. (2009) and first make a two-parameter scan of A and D, following another scan of B and E. Finally, we fix the estimated four coefficients and search for an optimal value for C. To avoid unwanted events and to improve search efficiency, we use a priori information from a preliminary stack section and stacking velocities available prior to data enhancement. This data is used as a guide during the parameter estimation process and the user defines how far the scanning parameters can deviate from this guide. To improve the results and efficiency of the search, we implement the operator-oriented approach proposed in Hoecht et al. (2009). According to it, the moveout coefficients are estimated on a coarse grid in the CMP-offset plane using all traces falling inside an estimation aperture (Figure 1). After the estimation step, we construct travel-time operators around all parametric traces. For each actual trace, the traces falling inside the summation aperture are summed up according to Equation (1). The summation operators are taken from the parametric traces falling inside the operator aperture around the actual trace. This approach allows us to bring signal in each sample from different estimated operators giving high fold and also partial resolution of the conflicting dips problem.

Synthetic data example

To demonstrate the benefits of partial summation along estimated coherent trajectories in comparison to simple grouping of traces, we use a synthetic example from Sigsbee model similar to one presented in Baykulov and Gajewski (2009).

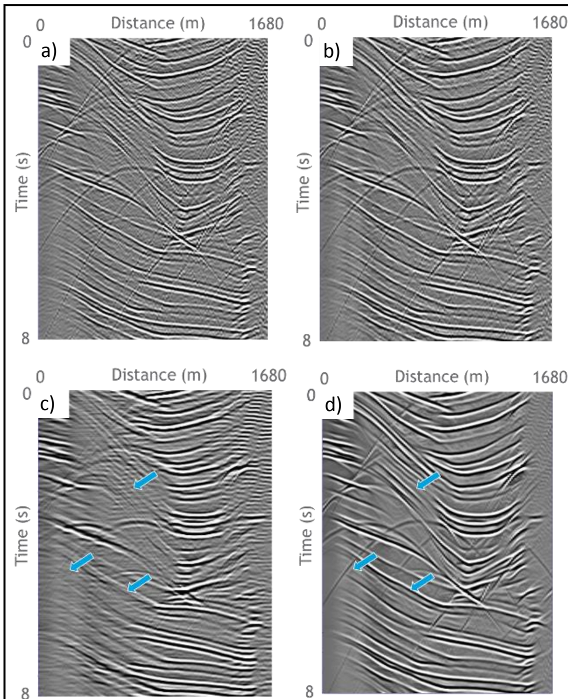

Figure 2: Synthetic data example showing a common offset gather after supergrouping (a) and nonlinear beamforming (b) using a 40m aperture; after supergrouping (c) and nonlinear beamforming (d) using a 150m aperture. Arrows show difference between simple partial stack and nonlinear beamforming.

Since the main interest here is to validate the ability of the method to preserve signal, a noise-free synthetic dataset is used. In Figure 2a we show a common-offset gather after supergrouping of traces inside an aperture with size of 60 m in both mid-point and offset directions. The result is almost identical to the original common-offset gather (not shown here). The nonlinear beamforming algorithm provides gather shown in Figure 2b. The coherent events are preserved while some slight incoherent features of the wavefield are treated as noise and are suppressed. The local summation with much larger aperture size of 300 m reveals big differences between the two approaches. As expected, supergrouping of traces suppresses steeply dipping events including strong diffractions with hyperbolic shapes. In contrast, nonlinear beamforming preserves most of the events despite a large summation aperture. Due to using an operator-oriented approach, the partial summation is also able to keep most of the conflicting dips in this example.

Real data examples

First, we apply nonlinear beamforming to a land seismic dataset from an area in Saudi Arabia with significant imaging challenges. This 3D data was acquired in an orthogonal layout with a 120 x 60 m shot grid and a 60 x 240 m receiver grid. We extract a single line from the full dataset to simulate a 2D survey.

Despite using 72-geophone arrays and 5-vibrator source groups for noise attenuation, the raw data (Figure 3a) shows little evidence of reflections. To estimate the beamforming coefficients, we use an aperture size of 800 m. The operator and summation apertures are 400 m and 200 m in both midpoint and offset directions, respectively. The gather from the enhanced data clearly shows reflection events, which were previously obstructed by strong scattering noise caused

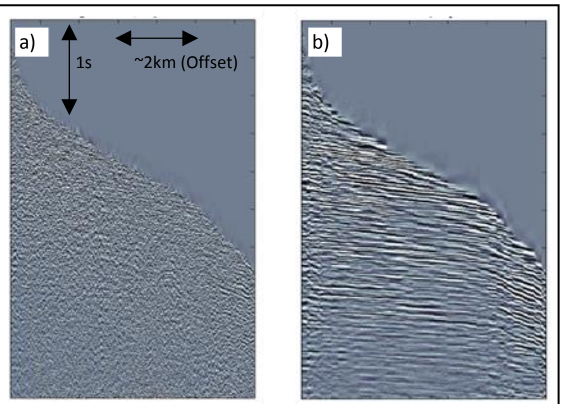

Figure 3: A 3D common-midpoint gather (a) before and (b) after nonlinear beamforming.

by a complex near surface (Figure 3b). The enhanced data can be used to derive better velocities or improved time processing parameters. Here, we simply compare the final stacks obtained from the data before and after enhancement (Figure 4). We observe a clear improvement in reflector continuity and strength especially in challenging zones.

In the next example, we apply nonlinear beamforming to a point-source, point-receiver 2D dataset from another area in Saudi Arabia. Both sources and receivers have 10 m inline sampling. Figure 5a shows an original common midpoint gather revealing an extreme degree of near-surface scattering which completely obscures the reflections. After applying NMO and supergrouping with receivers (Bakulin et al., 2016) we start to observe some hints of reflections (Figure 5b) albeit very weak. Nonlinear beamforming with a summation aperture of 300 m reveals much stronger, more coherent events. Figure 7 shows that a stack of data after nonlinear beamforming provides superior image quality compared to a stack of conventional supergrouped traces. We note that these stacks were constructed using identical velocities. We expect that the improvement in SNR of the pre-stack gathers should improve the velocity analysis, surface consistent processing, statics estimation and deliver even better final results. Figure 6 shows how velocity semblance panels are improved after the nonlinear beamforming compared to supergrouping result.

The initial velocity that was used as a guide is shown as a black line. In this example, the velocity and dip of events

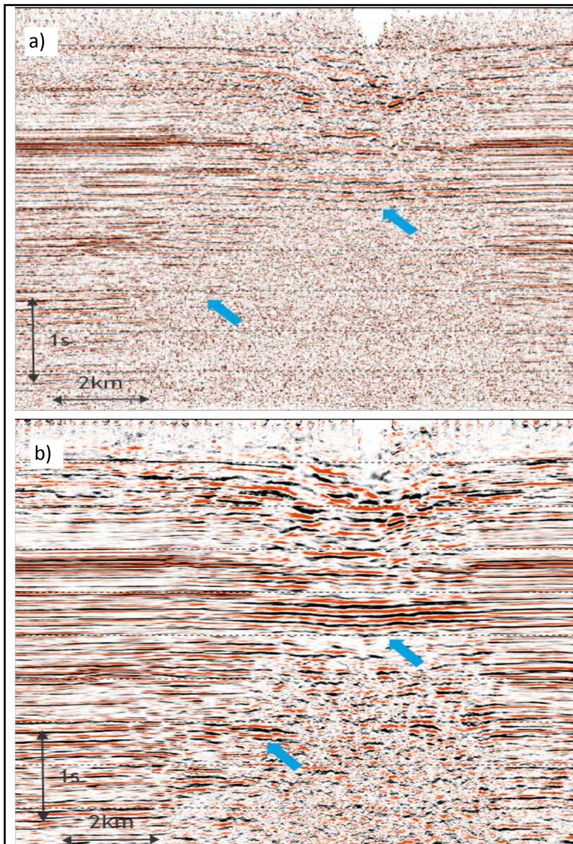

Figure 4: Stack sections from a 3D dataset (a) before and (b) after enhancement using nonlinear beam forming.

during the automatic coherency scan are perturbed up to 10%. Even though this was done locally for each point in CMP-offset section lying on 150x100 m grid, we observe a clear improvement in the quality of the semblance maxima now clustering around the guide velocity. This suggests that better velocities can be estimated using enhanced data. Nonlinear beamforming employs massive partial stacking from neighboring midpoint positions and reveals reflection events not visible in the original data. We also note that the

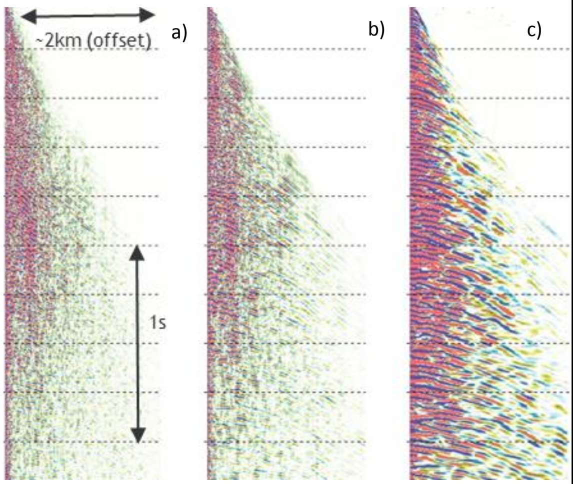

Figure 5: Common-midpoint gathers for original data (a), data after 1x7 supergrouping (b), and data after nonlinear beamforming (c).

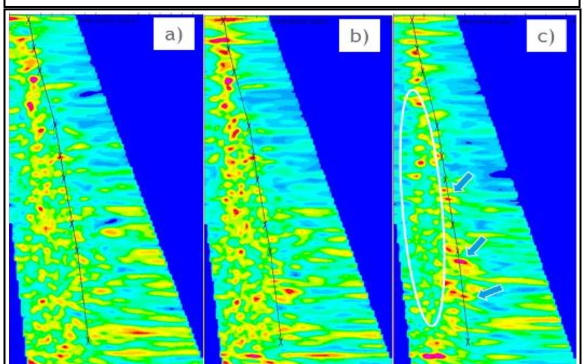

Figure 6: Velocity semblance panels for (a) original data, (b) data after supergrouping, and (c) data after nonlinear beamforming. Black line shows the guide velocity function used during the beamforming process. White ellipse indicates a zone of suppressed multiples.

beamforming also partially suppresses multiples (white ellipse in Figure 6c).

Conclusions

We apply nonlinear beamforming to challenging land seismic data corrupted by strong scattering noise caused by a complex near surface. The approach estimates local nonlinear coherent events in the data and performs partial summation along them. The approach is free from the classical hyperbolic assumptions and is based on a general local second-order approximation of travel-times. Preliminary stack sections and stacking velocities are used as guides thus allowing to suppress unwanted events such as backscattered noise and multiples and enhance reflection events. In the current study, beamforming weights are chosen in a simplified manner. More comprehensive approaches might be used to improve signal-to-noise ratio and to correct for local statics and waveform variations. The enhanced data should provide significant benefits for many stages of the processing flow. We expect that nonlinear beamforming might lead to a breakthrough in rocessing of modern high-channel count and signal-sensor data and should enable extracting the maximum usable information especially in the presence of a complex near surface or overburden.

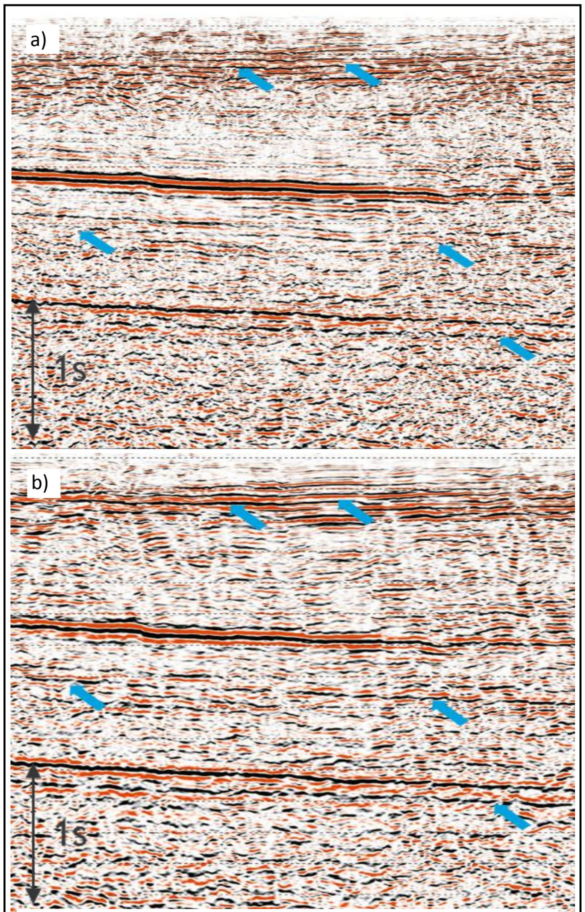

Figure 7: Stack sections of 2D point-source, point-receiver data obtained with (top) 1x7 supergrouping and (bottom) using nonlinear beamforming.

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited 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.

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