Efficient prestack enhancement based on local stacking: finding optimal domain for modern 3D land seismic data

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Summary

Modern 3D land seismic data, acquired by small field arrays or single sensors, require some type of prestack enhancement based on local stacking to accumulate large enough signals for estimating time processing parameters. We demonstrate that the cross-spread domain provides the most suitable 2D domain with regular and dense trace distribution. Evaluating residual moveout after normal moveout (NMO) correction enables local estimation of reflection moveout, whereas summation along moveout in the cross-spread domain benefits from uniform trace density within the enhancement ensembles irrespective of offset, azimuth or fold. This is demonstrated on field data examples. Mixing of different azimuths is naturally avoided for anisotropy friendly processing.

Introduction

Land seismic data often have a low signal-to-noise ratio (SNR) due to near-surface complexity. Every processing step that relies on prestack data is challenging because reflections are weak, irregular, and hidden behind strong coherent and random noise. In addition, standard noise removal techniques are often unable to make target reflections visible. To facilitate early processing steps, data enhancement procedures based on "smart" multi-dimensional local stacking of neighboring traces may be very effective. Existing methods based on this technique include the Common-Reflection Surface (CRS) method (Baykulov and Gajewski, 2009; Buzlukov and Landa, 2013) and multifocusing (Berkovitch et al., 2009). The main idea of these approaches is to collect signals from neighboring traces along locally defined surfaces that describe local moveout of reflected waves. Parameters that describe these surfaces may be treated as local kinematic attributes (LKA) of reflected waves and should be assumed or estimated from the data. The usual way to define LKA mathematically is to use a second-order Taylor expansion of reflected traveltime surfaces in the vicinity of some reference point in the data space. The position of each trace within the whole 3D seismic data volume is characterized by four coordinates (two source and two receiver). Generally, a local second-order approximation of a wavefront in 4D acquisition space based on a Taylor expansion is expressed by 14 parameters (first and second derivatives corresponding to dips and curvatures of the wavefront in each direction). Currently, it is computationally impossible to estimate so many coefficients taking into account the huge volume of data to be processed. One practical simplification is to implement data enhancement within some 2D subsection of the 4D data volume. In this case, only five local kinematical parameters need to be estimated. Here we concentrate on the implementation aspect, which is vitally important for effective use of data enhancement procedures based on local stacking with huge modern 3D land seismic datasets. In what subdomain of the 4D seismic volume is it better to implement local stacking? First, we briefly discuss current trends in land 3D seismic acquisition design from the point of view of acquired trace density and data volume. Then we consider, in detail, a typical 3D land seismic dataset acquired in Saudi Arabia and analyze its geometry. We extract 2D gathers of different types, namely: 1) common-offset gathers, 2) CDP gathers, and 3) cross-spread gathers and demonstrate that the third option has significant advantages over other domains.

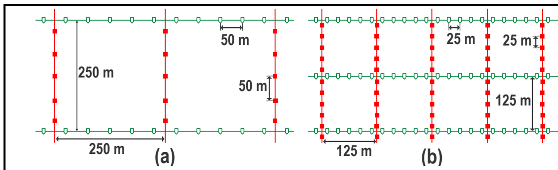

Figure 1. Examples of typical 3D land seismic acquisition geometries including (a) a low-density survey, and (b) a medium-density survey (see text and Figure 2 for classification).

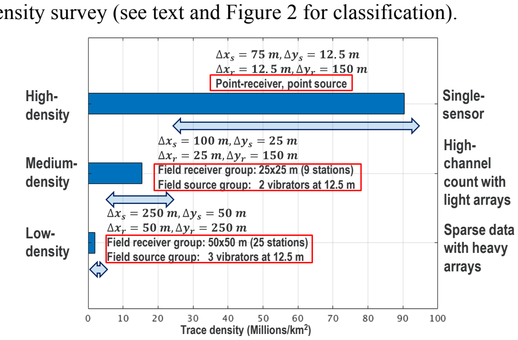

Figure 2. Land 3D seismic survey classification based on trace density illustrated with some typical acquisition parameters.

Modern trends in 3D land seismic data acquisition

A 3D seismic data volume can be treated as a 4D array of individual traces where the trace position is characterized by two source coordinates and two receiver coordinates at the surface. Typical orthogonal acquisition designs for land seismic surveys lead to unequal trace distribution along these coordinates. Usually, land data has dense trace distribution in two directions (inline direction for receivers and cross-line direction for shots) while the perpendicular directions (cross-line for receivers and inline for shots) are sampled much more coarsely (Figure 1). The following trends in

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modern land 3D seismic acquisition design can be highlighted: 1) the size of field shot/receiver arrays is rapidly decreasing and point-sensor surveys are becoming more popular, and 2) source and receiver spatial distributions become denser in both the inline and crossline directions. Figure 2 shows a simple schematic classification of 3D land seismic surveys based on trace density (Cooper, 2004), illustrated with some typical acquisition parameters representative of each category. Trace density has a direct effect on data volume. For instance, typical *low-density* dataset acquired over an area of 1000 km^2 may have a full data volume of 5 TB. *Medium-density* datasets (often referred to as high-channel count data), acquired using smaller source/receiver groups, for the same area may have a full volume of 80 terabytes. *High-density* datasets (single-sensor data for example) may reach full data volume of around 450 TB.

Basic requirements for data enhancement

Let us formulate the basic requirements for the data enhancement procedure based on local stacking. First of all, the procedure should be able to handle huge amounts of data within a reasonable computational time and hardware resources. Second, summation should be optimal meaning that the waveforms of the target arrivals in the ensemble to be stacked should be as similar as possible. The simplest way to satisfy this condition is to stack traces, which are close, both in the data space and physical space, i.e., (a) traces in the ensemble should have been recorded within similar excitation and registration conditions, and (b) reflected signals in the collected traces have followed similar travel-paths.

Analysis of different gather types for land 3D data enhancement

To fully appreciate the anatomy of modern 3D land seismic data, we consider a typical orthogonal low-density land 3D dataset acquired in Saudi Arabia using the geometry shown in Figure 1a. We identify several candidate 2D domains for enhancement and analyze their properties in detail. Our aim is to understand which 2D section of the 4D data-space is more suitable for application of data enhancement procedures based on “smart” local stacking. We analyze three scenarios. Scenario 1: common-offset gathers (COG), where the data space is defined by four coordinates, two of which are fixed (X_cdp, Y_cdp, offset=fixed, azimuth=fixed). Scenario 2: CDP-gathers with fixed CDP-bin crossline position, (X_cdp, Y_cdp=fixed, offset, azimuth=fixed). Scenario 3: cross-spread gathers (X_shot=fixed, Y_shot, X_rec, Y_rec=fixed).

For comparison, the following criteria are taken into account 1) azimuth preservation, 2) number of traces in each gather, 3) density and regularity of trace distribution, 4) behavior of reflection traveltimes in each domain, and 5) accessibility of gathers. *Azimuth preservation* means that only neighboring traces are used in LKA estimation and stacking stages and there is no trace mixing in the azimuthal direction. This is important because typical orthogonal 3D survey provides

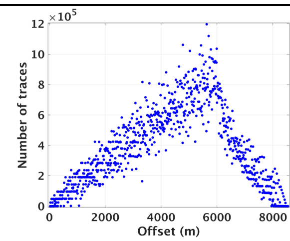

Figure 3. Offset distribution in the typical low-density 3D land seismic dataset with geometry from Figure 1a.

data with full azimuthal coverage. Any data enhancement procedure must preserve azimuthal information present in the original dataset which can be of great importance during anisotropic pre-stack processing and inversion. *Number of traces in each gather* means there should be sufficient data to perform estimation and summation. *Density and regularity of trace distribution* relies on dense and regular distribution of traces within the enhancement ensemble to increase the reliability of the LKA estimation stage. Likewise, local summation becomes more straightforward and leads to greater improvements in SNR when neighboring traces are accurately summed along local reflection moveout. *Behavior of reflection traveltimes in the chosen domain* affects how accurately the parameter searching can be performed. One needs to know how reflections behave in the chosen domain in order to organize an effective search procedure. Another consideration is that if local moveout of reflected arrivals may be well approximated using dips and curvatures varying within narrower intervals, it will significantly speed up parameter estimation. A*ccessibility of gathers* refers to how computationally intensive it is to form corresponding gathers from the entire data volume.

Application of smart stacking in the COG domain is typically considered in the literature either without (Buzlukov and Landa, 2013) or only partial azimuth preservation. The main reason for popularity of the common-offset domain is that the criteria (4) from above is easily satisfied. In both directions (X_cdp, Y_cdp), local moveout of reflected waves is similar within the whole section and may be reliably approximated as planar surfaces with dip and curvature varying in quite limited intervals. Let us analyze all three scenarios in a systematic manner using the selected criteria.

Common-offset gathers with azimuthal binning (scenario 1)

Figure 3 shows very uneven trace distribution with respect to offset in the entire dataset (azimuth dependency was not taken into account in this figure). The number of traces in the short-offset (< 2000 m) and far-offset (>6000 m) ranges

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is much smaller than in the "intermediate" range. As a result, the corresponding common-offset gathers will vary dramatically in trace density. Figure 4 compares trace distribution inside fixed 1x1 km surface tiles for 500 m and 5000 m offset. In both cases, trace distribution is quite irregular. As expected from Figure 3, COG for short offsets (Figure 4a) consists of a small number of sparsely sampled traces. Therefore, it is hard to expect reliable results from data enhancement in this case. For the long offset COG (Figure 4b), the number of points is sufficiently large, however its irregular distribution in the plane would result in variable quality of LKA estimation and summation. The distributions presented in Figure 4 have been taken from the full-fold areas with most regular organization of the recorded traces. If we approach the edges of the acquisition area, the number of traces in COGs will decrease considerably. In this example, azimuthal binning in the 0-45^{o} range have been used. COGs constructed without taking into account azimuth would have much denser trace distribution, but the general trends mentioned above would remain the same.

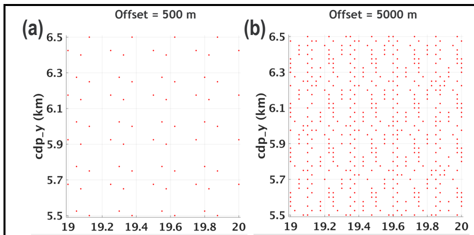

Figure 4: Trace distribution for two COGs (azimuthal binning in the range [0-45] deg. has been applied) showing (a) offset=500 m, and (b) offset=5000 m. (Data enhancement scenario 1)

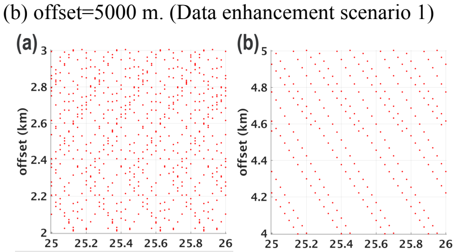

Figure 5: Trace distribution in CDP gathers (X_cdp, offset) with azimuthal binning [0-45] deg including (a) a surface tile from the full-fold area covering offset range 2-3 km, and (b) at tile from an area with less fold. (Data enhancement scenario 2)

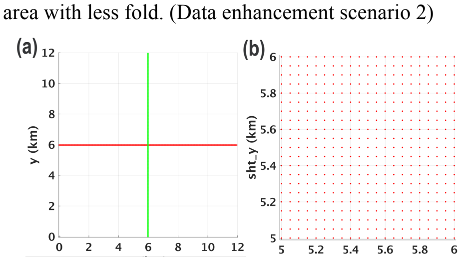

Figure 6: Cross-spread geometry examples including (a) a layout taken from a typical low-density dataset, and (b) a 1x1 km surface tile with trace distribution (in the plane X_rec,Y_shot). Coordinates Y_rec, X_shot are fixed. (Data enhancement scenario 3)

In summary, traces in COGs have a very predictable and favorable local moveout behavior, allowing effective constraints for the LKA searching intervals. COGs have significant disadvantages: (1) azimuth preservation is difficult (many additional sorting and storing efforts are needed); (2) ensemble trace density varies considerably with offset where for near and far offsets, the trace density may become insufficient for robust data enhancement; and (3) trace distribution is always very irregular.

CDP gathers with azimuthal binning (scenario 2)

Scenario 2 is considered in the domain characterized by coordinates (X_cdp, offset) keeping Y_cdp and azimuth ranges fixed. Here a set of CDP gathers is taken along one inline direction. During parameter estimation, we are clearly looking for segments of hyperbolas guided by initial stacking velocities. Such local moveout behavior is not as favorable as in Scenario 1. Indeed, in CDP gathers, hyperbolic moveout in the offset direction exists together with planar moveout in the X_cdp direction. Dip and curvature of hyperbolas varies significantly along the gathers. Therefore intervals of parameter estimation should be wide enough or offset-dependent. This fact considerably reduces the effectiveness of any moveout estimation scheme. To constrain search intervals in the offset direction, preliminary NMO corrections may be applied before data enhancement, which may compensate for the disadvantage mentioned above. Figure 5 shows similar trace distributions for inline CDP gathers. For areas with full fold and offset ranges [2-3 km], trace distribution is quite irregular (Figure 5a). Despite the good overall trace density, there are still some local gaps remaining. The situation is much worse (Figure 5b) when one approaches an area with less fold (usually corresponding to the edges of the survey). Trace distribution for this case is very sparse and greatly inhibits reliable data enhancement.

Cross-spread gather (scenario 3)

Finally, we consider the case of the cross-spread domain (CSD). Cross-spreads are widely used in modern land 3D orthogonal data processing, mainly as a domain for effective noise removal. For 3D orthogonal shooting geometries (Figure 1), the cross-spread has the densest and most regular sampling in both directions. Figure 6 shows the corresponding trace distribution away from the edges of the survey. Physical proximity of the traces within the ensemble guarantees similar azimuths without any additional binning. Even at the survey edges trace distribution remains regular (Figure 7). Large gaps without traces may be avoided so that they will not affect the enhancement. The only disadvantage of the CSD is the considerable variability of local moveout within a gather. By definition, a single cross-spread gather consists of traces taken from many neighboring areal common-shot/common-receiver gathers. It usually contains "near-distance shot" and "far-distance shot" lines. Behavior

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of reflected arrivals in these cases is quite different. In both cases, moveout should be something like "hyperbolas" but with complicated behavior of dip and curvature. Moveout of reflected waves in the CSD is not as predictable as in common-offset or in CDP domains. This disadvantage can be mitigated if one applies preliminary NMO corrections before enhancement. The main idea is to make the reflection events more or less flat and estimate residual moveout, rather than absolute moveout.

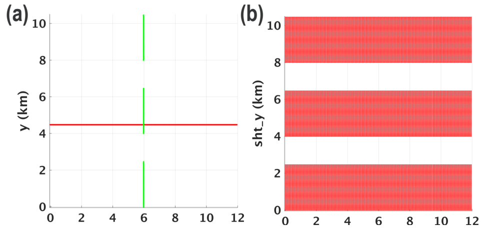

Figure 7: Acquisition geometry showing (a) a cross-spread layout taken from the edge of typical 3D low-density dataset, and (b) the full trace distribution in the X_rec,Y_shot plane. (Data enhancement scenario 3)

After careful analysis of the three scenarios we conclude that the CSD after NMO is the most appropriate domain for effective data enhancement based on local stacking. The ability to have natural azimuth preservation in combination with dense and regular trace distribution outweighs the difficulty caused by more complex moveout behavior, especially if this problem is mitigated by the simple trick of performing preliminary NMO correction.

Real data example of 3D data enhancement

To demonstrate the efficiency of "local-stack-based" data enhancement in the cross-spread domain, we use a cross-spread gather taken from a high-channel count dataset acquired with 23,000 active channels and geometry shown in Figure 1b. Small field arrays of nine receivers and two vibrators were used, but do not appear sufficient to suppress the noise and reveal coherent reflections, even after heavy noise suppression (Figure 8a). We apply two different enhancement approaches in the cross-spread domain and use the same stacking aperture. Supergrouping performs summation along global NMO surfaces (Bakulin et al., 2018) and naturally gives a more hyperbolic appearance (Figure 8b). In contrast, nonlinear beamforming estimates local summation surfaces from the data itself (Bakulin et al., 2017) and gives a less hyperbolic appearance (Figure 8c) that could be expected if some statics and waveform variations are still to be corrected for during early processing stages. In both cases, data enhancement procedures reveal coherent reflection events that are geologically plausible for this area. Enhancement appears uniform from small to large offsets and from center to the edge of the survey as expected of the cross-spread domain.

Conclusions

We analyze the problem of prestack data enhancement based on local stacking for realistic 3D land seismic acquisition geometries used in the industry. We demonstrate that the cross-spread domain provides the most suitable 2D domain with densest and most regular sampling of traces. Complexity of the reflection moveout in the cross-spread domain is mitigated by applying approximate NMO corrections and reducing the problem to estimation of only local residual moveout for fragments of reflected events. Uniform and dense sampling leads to consistent quality of enhancement for different offsets or locations with respect to the edges of the survey. Field data from Saudi Arabia support these conclusions and demonstrate absolute necessity of data enhancement for modern 3D land seismic data with light field arrays.

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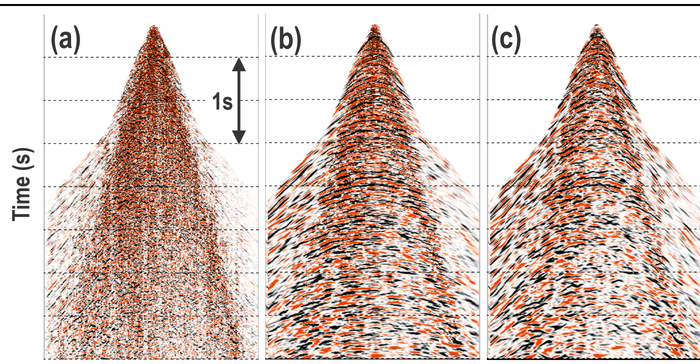

Figure 8: Field data example showing (a) a common-shot taken from a single cross-spread of a medium-density dataset after noise attenuation, (b) after supergrouping and (c) after nonlinear beamforming, both performed in the cross-spread domain. A stacking aperture of 400 m is used for both.

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