Beam Forming and Super-Grouping for Seismic Data Enhancement in 5D Domain

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Abstract. In this study, we have developed a novel seismic data enhancement approach along with its corresponding software implementation that enables comprehensive processing of data in the 5D domain. The primary objective of this development is to establish a robust and computationally efficient methodology capable of producing optimal data enhancement results. Our approach is fundamentally based on the integration of two key techniques: seismic data super-grouping and non-linear beamforming. While each of these techniques individually operates using two spatial coordinates and one time coordinate, it is important to note that complete seismic datasets actually contain four spatial coordinates. To address this dimensionality challenge, we have developed an innovative integration of these techniques that effectively accounts for all four spatial coordinates simultaneously, thereby providing a more comprehensive and robust solution. A significant portion of our research has focused on systematically investigating the most suitable data domains for optimal performance when applying super-grouping and beamforming in combination. Through this investigation, we have identified and characterized several effective domain configuration options. The primary domain configuration employs the cross-spread domain for beamforming operations while utilizing its orthogonal counterpart for super-grouping. An alternative important configuration option utilizes the offset domain for beamforming while employing the central point domain for super-grouping operations. Furthermore, we have developed optimal data sampling strategies that are specifically tailored to different data geometries. Additionally, we have implemented several significant optimizations that enhance the standard application of non-linear beamforming, improving both its efficiency and effectiveness. To complete this comprehensive development, we have created specialized software that implements our enhanced methodology. The performance and capabilities of both our algorithmic approach and its software implementation have been rigorously evaluated through extensive testing. These evaluations have included both synthetic datasets and real seismic data acquired from the Arabian Plate. The results of these tests conclusively demonstrate the proposed methodology's capabilities and effectiveness, validating its practical utility for seismic data enhancement applications.

Keywords: Beam forming · Super-grouping · 5D seismic data enhancement

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1 Introduction

In land seismic exploration, strong scattering caused by small- to medium-scale heterogeneities in the near-surface greatly degrades the quality of seismic images [1, 2]. Standard seismic time processing procedures—such as surface-consistent deconvolution, statics estimation, and velocity analysis—require reliable prestack signal data. However, their application in areas with complex near-surface conditions often yields unreliable results because the derived parameters are based on noise rather than signal. To address this issue, it is essential to significantly improve the signal in the prestack data before evaluating any processing parameters [3, 4].

Local stacking is one of the most powerful methods for data enhancement. For example, supergrouping adjacent traces in different domains after applying normal moveout (NMO) correction [5] has proven highly effective for enhancing reflections. Data-driven local stacking of neighboring traces can substantially improve signals of varying complexity. Existing methods based on this technique include common reflecting surface (CRS) stacking [6–10] and multifocusing [11–14]. One of the most effective data enhancement procedures involves local summation of the initial data along surfaces defined by locally coherent seismic events [15].

A developed version of this method employs an operator-oriented scheme to enhance the useful signal while suppressing regular and irregular noise [15]. In this approach, the wavefront of the useful signal is locally approximated by a second-order surface, which can be viewed as a Taylor series expansion of the seismic event arrival time around an arbitrary point. The expansion coefficients (local kinematic attributes) are estimated by maximizing the coherence measure (semblance) calculated along the second-order surface. A key feature of this scheme is that the most computationally intensive step—estimating these parameters—is performed on a sparse grid. Once the parameters are determined, the "signal gain" operator is defined, which involves summing adjacent traces along a two-dimensional hodograph.

Bakulin et al. [16] proposed nonlinear beamforming (NLBF) in the cross-spread domain—an approach for enhancing challenging prestack data acquired in modern 3D land seismic surveys. The advantages of the cross-spread domain for data enhancement are demonstrated with real-data examples, highlighting its signal-preservation and signal-enhancement properties.

In this study, we further develop the beamforming procedure by introducing a novel seismic data enhancement method and corresponding software designed to process data in the 5D domain. The primary goal is to deliver a robust and computationally efficient approach that enhances data with a high signal-to-noise ratio. We develop the corresponding software and evaluate the algorithm using both synthetic data and real seismic data from the Arabian Plate, demonstrating significant improvements.

2 5D Data Enhancement Method

The 5D seismic data enhancement method is founded upon two fundamental techniques: super-grouping of seismic data and beamforming (collectively referred to as SGBF 5D). While conventional seismic data contains four spatial dimensions (4D), these individual techniques each utilize only two spatial coordinates (2D) plus a time coordinate. Naturally, the number of available traces in the complete 4D domain significantly exceeds that in any 2D subset. To quantify this difference precisely, we have conducted a detailed investigation of typical acquisition geometries.

2.1 Trace Statistics Analysis

Our analysis examines trace number statistics for single-sensor real data geometry [17, 18] (Fig. 1). The acquisition parameters are as follows: source grid spacing: dx_s =75 m, dy_s =12.5 m; receiver grid spacing: dx_r =12.5 m, dy_r = 150 m. In our terminology 4D geometry employs all four coordinates (x_s, x_r, y_s, y_r), 2D geometry fixes two coordinates (x_r, y_s) while varying the remaining two (x_r, y_s). The data enhancement procedure can be implemented in two distinct approaches: 2D Case - varying only two coordinates (x_r, y_s) within the aperture, and this is the implementation used in our developed code; 4D case - varying all four coordinates (x_s, x_r, y_s, y_r) within the aperture. We have computed and compared the number of traces within the aperture for both cases, examining how these values scale with aperture size (Fig. 2). Key observations include: in 4D approach 1000 traces require 125 m aperture, 10000 traces require 150 m aperture, 600 m aperture yields 1000000 traces; in 2D approach: 1000 traces require 200 m aperture, 10000 traces require 600 m aperture, 600 m aperture yields 10000 traces.

Our trace statistics analysis demonstrates that the 4D spatial domain provides substantially more traces (over tenfold) within a given aperture compared to the 2D spatial domain. This finding strongly supports the superiority of the 5D approach, which incorporates all four spatial coordinates (source and receiver) plus time, for seismic data enhancement applications. The 5D methodology offers two key advantages: potential for significantly higher signal-to-noise ratio in processed data; more comprehensive utilization of available seismic information. To fully realize these benefits, we have developed an innovative solution that combines both 2D techniques (beamforming and super-grouping) in a manner that effectively accounts for all four spatial coordinates. This integrated approach provides: more robust noise attenuation; better preservation of signal fidelity; improved resolution in the final processed data. The implementation maintains computational efficiency while delivering superior results compared to conventional 2D processing methods, particularly in challenging acquisition environments or when working with noisy datasets.

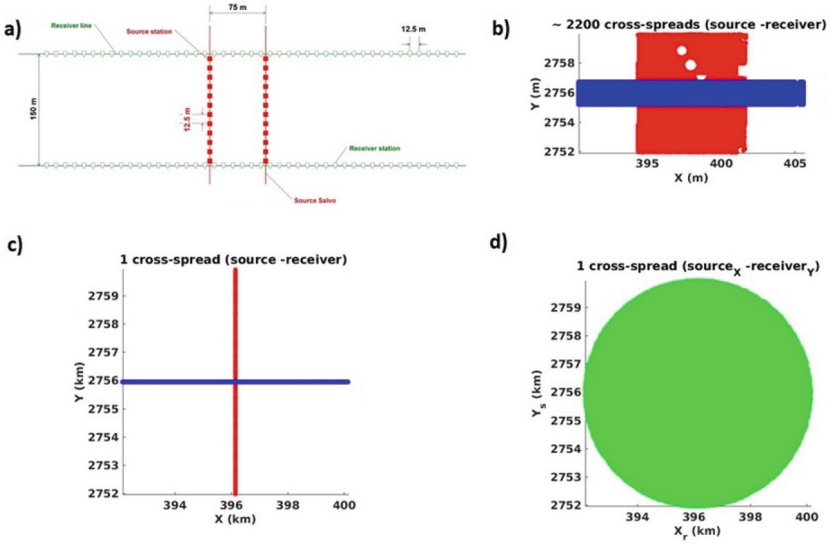

Fig. 1. Single sensor real data geometry: a) acquisition geometry; b) 4D source–receiver coordinates for ~2200 cross-spread gathers; c) 4D source–receiver coordinates for one cross-spread gather; d) 2D source_x–receiver_y coordinates for one cross-spread gather.

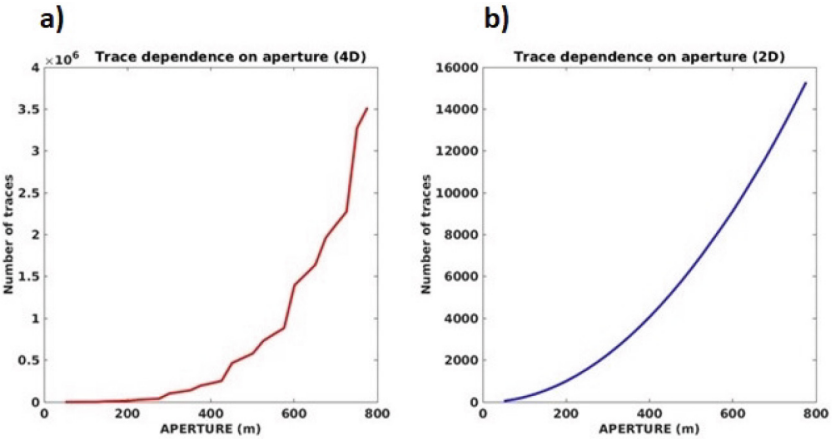

Fig. 2. Number of traces within aperture with respect to aperture size: a) 4D geometry; b) 2D geometry.

2.2 Super-Grouping and Beam Forming as a 5D Data Enhancement

From a technical perspective, 5D data enhancement can be effectively achieved through the implementation of super gathers. A super gather is created by combining several Common Depth Point (CDP) gathers into a single, more comprehensive gather. In our research, we have thoroughly investigated the most suitable data domains for the combined application of super-grouping and beamforming, presenting several viable options.

One primary configuration utilizes the cross-spread domain for beamforming operations while employing its orthogonal counterpart for super-grouping. Within the beamforming procedure in the cross-spread domain, we consider a second-order travel-time approximation in the 2D plane ($\boldsymbol{x_s}, \boldsymbol{y_r}$) around point ($\boldsymbol{x_{0s}}, \boldsymbol{y_{0r}}$):

$$\begin{aligned}\Delta t = t(x_s, x_r, y_s, y_r) - t(x_{0s}, x_{0r}, y_{0s}, y_{0r}) = A(x_s - x_{0s}) + B(y_r - y_{0r}) + \\ + C(x_s - x_{0s})(y_r - y_{0r}) + D(x_s - x_{0s})^2 + E(y_r - y_{0r})^2\end{aligned} \tag{1}$$

where coefficients ***A,B*** represent the wavefront dips, while coefficients ***C,D,E*** characterize the wavefront curvatures. However, when working with a CDP gather or a super-gather composed of multiple CDPs, the trace points ($\boldsymbol{x_r}, \boldsymbol{y_s}$) within such gathers are neither identical to each other nor equal to the parameter trace point ($\boldsymbol{x_{0r}}, \boldsymbol{y_{0s}}$). This observation implies that approximation (1) is incomplete for this scenario and should instead be considered in a 4D plane, thereby elevating the data enhancement process from 3D to 5D. To address this, we introduce the missing terms to approximation (1):

$$\begin{aligned}\Delta t = t(x_s, x_r, y_s, y_r) - t(x_{0s}, x_{0r}, y_{0s}, y_{0r}) = A(x_s - x_{0s}) + B(y_r - y_{0r}) + \\ + C(x_s - x_{0s})(y_r - y_{0r}) + D(x_s - x_{0s})^2 + E(y_r - y_{0r})^2 + \\ + A1(x_r - x_0r) + B1(y_s - y_0s) + D1(x_r - x_0r)^2 + E?1(y_s - y_0s)^2 \\ + C1(x_r - x_{0r})(y_s - y_{0s}) + C2(x_r - x_{0r})(y_r - y_{0r}) + C3(x_s - x_{0s})(y_s - y_{0s}) \\ + C4(x_r - x_{0r})(x_s - x_{0s}) + C5(y_s - y_{0s})(y_r - y_{0r})\end{aligned} \tag{2}$$

where coefficients ***A1,B1*** represent the wavefront dips in the domain orthogonal to the cross-spread domain, and coefficients ***D1,E1,C1,C2,C3,C4,C5*** characterize the corresponding wavefront curvatures. Implementing this complete travel-time approximation requires estimating nine additional parameters, which demands substantial computational resources. Alternatively, we can apply beamforming in this context and examine its implications for the complete travel-time approximation (2) in the 5D domain. This approach effectively reduces approximation (2) back to approximation (1), implying that the additional parameters (***A1,B1***, ***D1,E1,C1*** through ***C5***) are set to zero. This reduction means we perform summation in the orthogonal plane ($\boldsymbol{x_r}, \boldsymbol{y_s}$) using a horizontally flat approximation. When we consider how super-grouping operates, we recognize that it implicitly performs this operation in the orthogonal plane ($\boldsymbol{x_s}, \boldsymbol{y_r}$). Therefore, applying beamforming to a super-gather consists of two components: beamforming in the cross-spread domain; super-grouping in the domain orthogonal to the super-gather. This combined operation functions as a 5D data enhancement according to travel-time approximation (2), with parameters (***A,B,C,D,E***) being estimated while parameters (***A1,B1***, ***D1,E1,C1*** through ***C5***) are set to zero. We designate this integrated approach as Super Grouping Beam Forming (SGBF) 5D data enhancement.

Recognizing that super-grouping is inherently less precise than beamforming and is best suited for small apertures, we must consider alternative, more suitable operating domains for super-grouping. For super-gathers created from the nearest CDP gathers, the CDP domain emerges as the optimal choice for super-grouping due to the naturally small apertures resulting from the super-gather construction. This domain offers an additional advantage for horizontally layered geology, as the geological context perfectly justifies setting the additional parameters to zero. To demonstrate this mathematically,

let us examine 5D enhancement in the CDP-offset domain, defined by the following coordinates:

$$x_m = (x_r + x_s)/2, y_m = (y_r + y_s)/2; .h_x = (x_r - x_s), h_y = (y_r - y_s) \tag{3}$$

Analogous to our previous approach, we consider a second-order travel-time approximation in the 2D plane ($\boldsymbol{h_x}, \boldsymbol{h_y}$) around point ($\boldsymbol{h_{0x}}, \boldsymbol{h_{0y}}$):

$$\begin{aligned}\Delta t = t\big(h_x, h_y, x_m, y_m\big) - t\big(h_{0x}, h_{0y}, x_{0m}, y_{0m}\big) = A(h_x - h_{0x}) + B\big(h_y - h_{0y}\big) + \\ C(h_x - h_0x)\big(h_y - h_0y\big) + D(h_x - h_0x)^2 + E\big(h_y - h_0y\big)^2,\end{aligned} \tag{4}$$

where coefficients ***A,B*** represent wavefront dips, and ***C,D,E*** represent wavefront curvatures. Expanding this with the missing terms yields:

$$\begin{aligned}\Delta t = t\big(h_x, h_y, x_m, y_m\big) - t\big(h_{0x}, h_{0y}, x_{0m}, y_{0m}\big) = A(h_x - h_{0x}) + B\big(h_y - h_{0y}\big) + \\ + C(h_x - h_{0x})\big(h_y - h_{0y}\big) + D(h_x - h_{0x})^2 + E\big(h_y - h_{0y}\big)^2 + A1(x_m - x_{0m}) + \\ + B1(y_m - y_0m) + D1(x_m - x_0m)^2 + E1(y_m - y_0m)^2 + \\ + C1(x_m - x_{0m})(y_m - y_{0m}) + C2(x_m - x_{0m})\big(h_y - h_{0y}\big) + \\ + C3(h_m - h_{0m})(y_m - y_{0m}) + C4(x_m - x_{0m})\big(h_y - h_{0y}\big) + \\ + C5(y_m - y_{0m})\big(h_y - h_{0y}\big)\end{aligned} \tag{5}$$

where again the additional parameters (***A1,B1***, ***D1,E1,C1*** through ***C5***) are set to zero. This means we perform summation in the CDP plane ($\boldsymbol{x_m}, \boldsymbol{y_m}$) using a horizontally flat approximation. Since the super-gather is constructed from the nearest CDPs, this domain is particularly well-suited for super-grouping. Considering the geological context of the Arabian Plate, where reflectors are predominantly flat, this domain becomes an ideal candidate. Therefore, we also provide the option of SGBF 5D data enhancement in the CDP-offset domain.

2.3 Realization and Optimization of SGBF 5D Data Enhancement

When considering the theoretical context of SGBF 5D, there exists a clear and straightforward approach to implement the described method. The implementation requires taking the existing beamforming procedure and introducing specific modifications to enhance its functionality. First, we apply the beamforming procedure in both of the most effective domains for creating super-gathers, namely the cross-spread domain and the offset domain. To achieve this, we utilize the existing beamforming procedure in the cross-spread domain while simultaneously developing a new implementation for the offset domain. In these orthogonal domains, this approach results in simple stacking operations that do not require time corrections, which consequently means that super-grouping is automatically achieved within these domains. Additionally, as part of the SGBF 5D implementation, we introduce an optimization of the summation component within the beamforming procedure. This optimization involves eliminating unnecessary computations for new, unused traces within the enhanced super-gather, while retaining the computational processes only for the central CDP (Common Depth Point).

3 Numerical Investigations

3.1 Synthetic Data Set

In order to provide a feasibility study of the proposed and realized SGBF 5D, we create 3D synthetic data for realistic 3D acquisition geometry and for realistic 1D geological model, using analytic formulas and RMS velocities. The acquisition geometry simulates the standard acquisitions that are used in Saudi Aramco. The main acquisition parameters are taken with the following values: $\boldsymbol{dxs = 150\ m, dxr = 25\ m, dyr = 150\ m, dys = 25\ m}$. From that data we have created 1 central cdp gather, and 3 super gathers consisting of 3 by 3 cdp gathers, 5 by 5 cdp gathers, and 7 by 7 cdp gathers. At the end we add additive Gaussian noise with different level, i.e. 10% noise, and 100% noise.

Next, we start testing the developed code on the created data set. We choose rather small apertures for testing: $\mathbf{aper_sum_x = 150}\ \boldsymbol{m}$, $\mathbf{aper_sum_y = 150}\ \boldsymbol{m}$. We apply SGBF 5D using for the data with different noise level: 0%, 10%, 100%, and different number of gathers in super-gather: 1, 3 by 3, 5 by 5, 7 by 7, in the cross-spread domain (Fig. 3). Also, we apply SGBF 5D for the same data but in the offset domain (Fig. 4).

First of all, we should examine the results of data enhancement application when there is no noise present. Visual observation shows that for all super-gathers and in both domains (cross-spread and offset), the results of data enhancement appear appropriate - that is, nearly identical to the input data. This indicates that the data enhancement process does not distort or destroy the useful reflected signal. However, some minor differences do exist, which we will discuss later in greater detail.

Furthermore, visual inspection clearly demonstrates an improvement in data quality when comparing the enhanced data to the original noisy input data. This improvement is evident in both domains and is observable across nearly all super-gathers. Additionally, the visual analysis reveals that the quality of noise reduction improves as the number of gathers within each super-gather increases. This relationship holds true for both the cross-spread and offset domains. It is also visually apparent that for particularly noisy datasets, a greater number of gathers per super-gather is required to achieve satisfactory enhancement results, again applying equally to both domains.

However, these visual observations only provide qualitative assessments. To make more precise comparisons, especially in cases where visual differentiation is challenging, we conducted quantitative analysis by computing correlation coefficients between

the ideal data (known in our synthetic case) and the enhanced data obtained under various conditions. These conditions included different domains, varying noise levels, and differing numbers of gathers per super-gather. The resulting correlation coefficients (Table 1) not only confirm our visual observations but also establish the maximum achievable enhancement values (those obtained with noise-free input data).

The table reveals several important findings: For smaller super-gather configurations (specifically 1 gather and 3×3 gathers), the cross-spread domain yields the best achievable results. However, for larger configurations (5×5 and 7×7 gathers), the offset domain produces superior outcomes. This pattern persists when processing noisy data, with one crucial exception: when noise levels become excessive, smaller super-gather

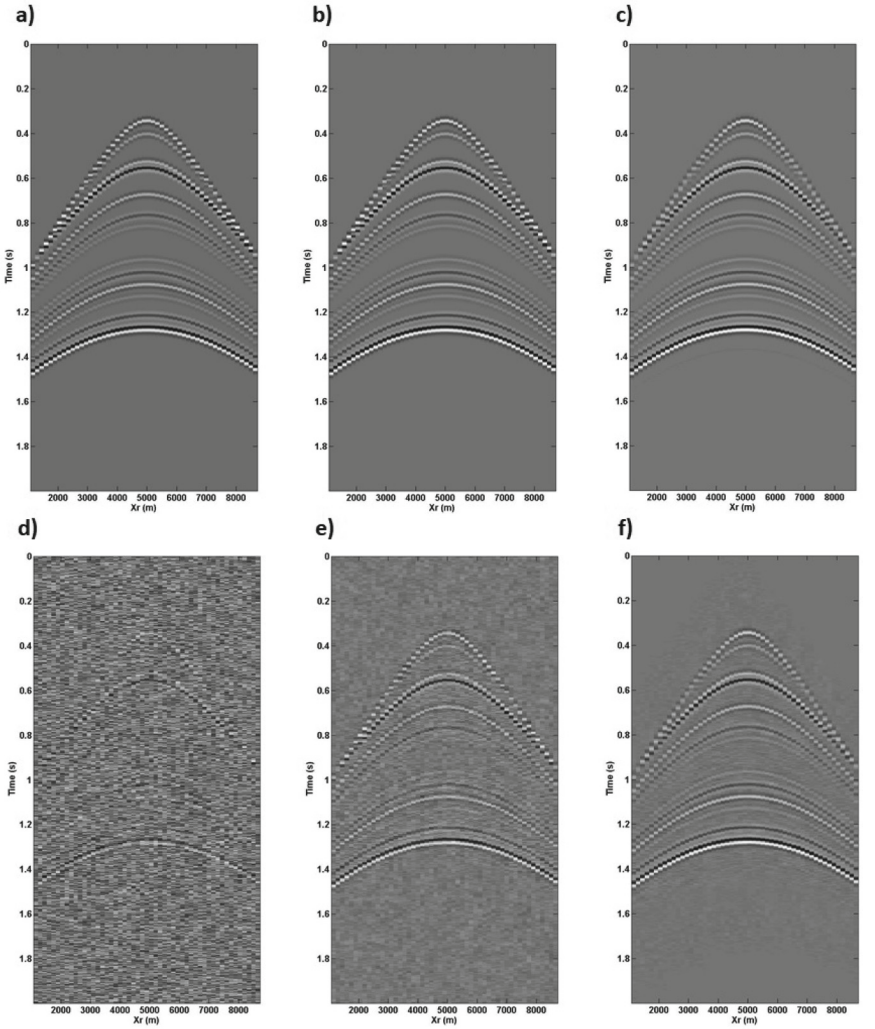

Fig. 3. (a) The input data without noise; (b) the data after 5D enhancement of 3 by 3 supergather in crosspread domain; (c) the data after 5D enhancement of 7 by 7 supergather in crosspread domain; (d) input data with 100% noise; (e) the noise data after 5D enhancement of 3 by 3 supergather in crosspread domain; (f) the noise data after 5D enhancement of 7 by 7 supergather in crosspread domain.

configurations prove inadequate, resulting in unacceptably low correlation coefficients. In such cases, larger super-gathers become necessary to achieve proper enhancement. Furthermore, when working with significantly noisy data, the offset domain - a new option in SGBF 5D - should be selected to obtain optimal results. These empirical findings align perfectly with the theoretical framework described earlier.

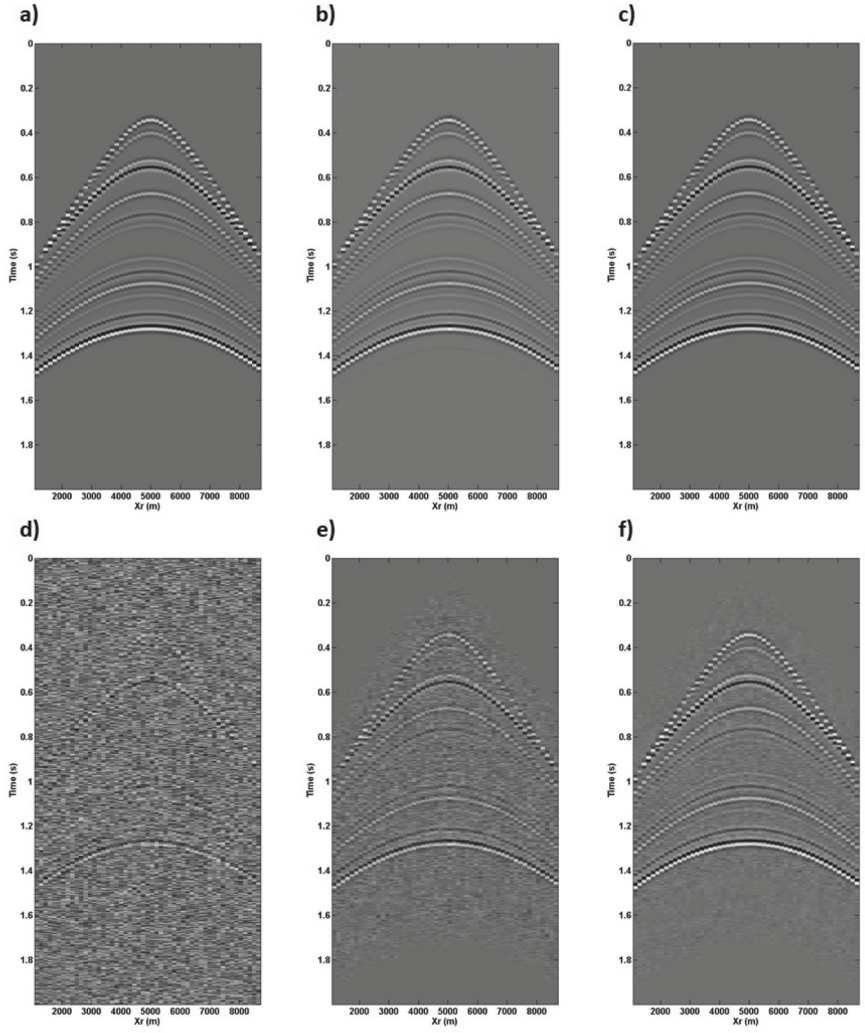

Fig. 4. (a) The input data without noise; (b) the data after 5D enhancement of 3 by 3 supergather in cdp-offset domain; (c) the data after 5D enhancement of 7 by 7 supergather in cdp-offset domain; (d) input data with 100% noise; (e) the noise data after 5D enhancement of 3 by 3 supergather in cdp-offset domain; (f) the noise data after 5D enhancement of 7 by 7 supergather in cdp-offset domain.

Additionally, we compared computational times across the various scenarios described above. The complete set of computational times for different scenarios is presented (Table 2). Of particular importance is the comparison between optimized SGBF 5D and non-optimized processing. The results demonstrate that the optimization provides computational acceleration of the summation process by a factor of 2 to 7, depending on the operation domain, number of OPM threads, and number of CDPs in

Table 1. Correlation coefficient between ideal data and data after SGBF 5D application with different noise level, different super-gathers and two different domains: cross-spread and offset.

	Noise 0%			Noise 10% 6.2 dB			Noise 100% -8.6 dB	
	Cross-spread	Offset		Cross-spread	Offset		Cross-spread	Offset
1 by 1	0.999	0.975	1 by 1	0.925	0.937	1 by 1	0.236	0.321
3 by 3	0.997	0.986	3 by 3	0.993	0.982	3 by 3	0.783	0.738
5 by 5	0.982	0.996	5 by 5	0.982	0.994	5 by 5	0.919	0.884
7 by 7	0.950	0.998	7 by 7	0.950	0.997	7 by 7	0.917	0.939

the super-gather. Another noteworthy observation is that when using the optimization, computational times become similar between the offset and cross-spread domains.

Table 2. Computational times of SGBF 5D application when optimization of summation is turned on and turned off with different super-gathers and two different domains: cross-spread and offset (38 OMP threads, different number of OMP provides different speed up, the same tests on 1 OMP threads provides speed up to 7 times).

	Without optimization			With optimization	
	Cross-spread	Offset		Cross-spread	Offset
1 by 1	1 s	3 s	1 by 1	1 s	3 s
3 by 3	9 s	6 s	3 by 3	3 s	5 s
5 by 5	36 s	20 s	5 by 5	9 s	9 s
7 by 7	108 s	48 s	7 by 7	26 s	18 s

3.2 Real Data Example

Finally, we present test results obtained from real seismic data acquired in the Arabian Plate, which demonstrate both the capabilities and effectiveness of our developed approach and its corresponding software implementation. The acquisition system parameters for this survey were as follows: shot spacing along the x-direction was 75 m; shot spacing along the y-direction was 25 m; receiver spacing along the x-direction was 25 m; receiver spacing along the y-direction was 75 m; with a CDP grid resolution of 12.5 m by 12.5 m. The dataset contains numerous different types of noise, making it particularly challenging to identify and trace reflected wave events (Fig. 5). We have applied our developed SGBF 5D methodology to process various super-gather configurations across different domains. In general terms, these real-data results provide clear confirmation of the conclusions we previously drew from synthetic data tests. More specifically, we have demonstrated significant improvements in signal-to-noise ratio through the application of SGBF 5D, even when using relatively small apertures in the CDP super-grouping domain (Fig. 5). These results strongly indicate the considerable

potential of our proposed approach for enhancing seismic data quality. Additionally, we would like to emphasize that this methodology shows promising potential for application in robust signal-to-noise ratio estimation [19, 20], particularly when dealing with challenging seismic datasets.

4 Conclusions

We have developed a novel seismic data enhancement approach along with its corresponding software implementation that enables comprehensive processing of data in the 5D domain. This innovative methodology combines two powerful techniques: seismic data super-grouping and non-linear beamforming. By integrating these complementary techniques, we have created a robust solution that effectively accounts for all four spatial coordinates simultaneously. Our research has systematically investigated the most suitable data domains for optimal performance when applying super-grouping and beamforming in combination.

The cross-spread domain has been identified as the optimal choice for beamforming operations due to its superior effectiveness when working with two spatial coordinates. However, it should be noted that super-grouping, being inherently less precise than beamforming, demonstrates better performance when applied with smaller apertures. This fundamental difference has led us to consider alternative domains that may be more appropriate for super-grouping applications. Specifically, when creating super-gathers from the nearest CDP gathers, the CDP domain emerges as clearly the most effective operating domain for super-grouping, primarily because the construction of super-gathers in this domain naturally results in very small apertures. Another significant configuration we have examined employs the offset domain for beamforming while utilizing the central point domain for super-grouping operations. Based on comprehensive analysis of data geometry, we have developed optimal data sampling strategies for various scenarios. Furthermore, we have implemented several key optimizations to enhance the standard application of non-linear beamforming.

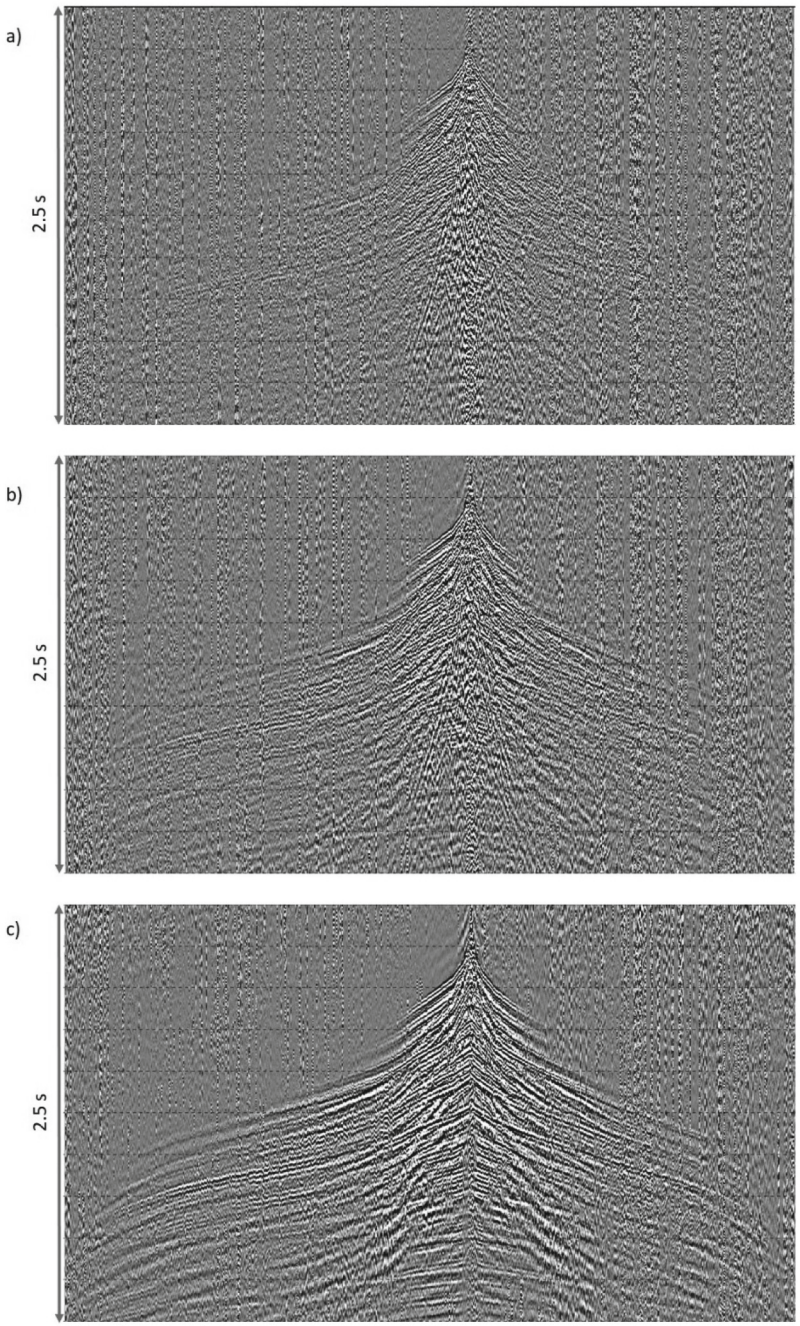

Fig. 5. CDP gather: (a) original data; (b) data after SGBF 5D, super-grouping in CDP domain (25 m by 25 m), beam forming in offset domain; (c) data after SGBF 5D, super-grouping in CDP domain (125 m by 125 m), beam forming in offset domain.

The SGBF 5D methodology has been thoroughly developed and rigorously tested using both synthetic gathers and real seismic data in both cross-spread and offset domains. Our optimized version of SGBF 5D demonstrates remarkable computational efficiency, achieving acceleration of the summation process by approximately 2–7 times, depending on three critical factors: the operation domain being used, the number of OPM threads employed, and the number of CDPs included in the super-gather. Extensive numerical testing has yielded several important findings regarding optimal configurations. The results indicate that the method potentially delivers the best performance when processing 3×3 super-gathers in the cross-spread domain, while for larger 5×5 and 7×7 super-gathers, the offset domain proves superior. More specifically, the numerical results demonstrate that appropriate enhancement results can be achieved for 3×3 and 5×5 super-gathers in both cross-spread and offset domains when processing data with low noise levels and using small apertures (150 m). Similarly, for datasets with moderate noise levels while maintaining small apertures (150 m), satisfactory results are obtained with 5×5 and 7×7 super-gathers in both domains. These empirically derived conclusions provide valuable practical guidance for initial implementation of the SGBF 5D methodology in real-world applications.

Based on the comprehensive results presented throughout this paper, we conclusively demonstrate that our developed approach, which synergistically combines beamforming and super-grouping techniques, represents a significant advancement in seismic data processing. This new 5D data enhancement tool successfully handles all spatial data coordinates while consistently delivering the best achievable processing results under various conditions.

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