Global acquisition geometry optimization with 5D constraints using spectral gap

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Abstract

The necessity to acquire ultra-long offset ocean-bottom node (OBN) data is gaining momentum as a means to stabilize full-waveform inversion, especially for delineating the basement of salt structures. To reduce the acquisition cost, simultaneous acquisition is preferable, which requires a source separation framework during the processing stage to generate data as if acquired conventionally. The standard practice is to acquire data on a periodic temporal grid with a small-time dither, which results in sub-optimal randomization of interference noise in the data; thus, we need to carry out extra work to produce robust source separation results. To overcome this, we propose generating an optimal survey design using the spectral-gap-based rank minimization. The proposed technique is computationally efficient and uses realistic environmental and instrumental constraints to generate source and/or receiver locations, where the acquisition is constrained with random time dithers. Using both synthetic and real OBN data examples from the Gulf of Mexico, we demonstrate the efficacy of the proposed technology over the standard acquisition practices.

Introduction

Seismic data acquisition in the land and marine environment is expensive; thus, producing a cost-effective survey design is always a necessity. Moreover, due to environmental constraints, we need to maintain a separation between subsequent sources while acquiring data in inline or crossline directions. Recent advancements in simultaneous-source acquisition (SSA) have tremendously improved data acquisition efficiency (Beasley et al., 1998; Berkhout, 2008; Moore et al., 2008; Akerberg et al., 2008; Abma, 2010; Hays et al., 2014; Mosher et al., 2014). More recently, SSA has been used to acquire ultra-long offset data (~40 - 60 km) with ocean-bottom nodes (OBN). Although the simultaneous source design reduces the cost of surveys significantly, two key challenges remain. The first one is the separation of signal from different sources, also known as deblending, whose success relies upon the randomization of interference noise (also known as blending noise) in the time-space domain. The robustness of source separation heavily relies on the differentiation of coherent signal from the interference noise in a sparsity or low-rank-promoting transform domain. Here, low-rank-promoting transformation means a domain where underlying fully sampled seismic data exhibit low-rank characteristic, i.e., fast decay of the singular values. This differentiation is highly controlled by the survey design, which brings us to our second challenge. Often the survey design is sub-optimal; thus, different sources can either generate strong interference noise overlying the strong coherent signal, termed as a strong-over-strong phenomenon, or the strong interference noise on the weak coherent signal, termed as strong-over-weak phenomenon (Kumar et al., 2021). Optimizing the survey design to increase the randomization in interference noise is key to successful source separation. Here, we address the second challenge of producing an optimal survey design for simultaneous source acquisition following the principle of compressive sensing (Cand`es et al., 2005, 2006). Our method exploits the fact that dense seismic data exhibit sparse or low-rank structures in a transform domain. When we subsampled the underlying dense data, depending upon the sub-sampling pattern, data should exhibit less sparse or high-rank structure in the transform domain (Kumar et al., 2015). From a sampling perspective, this translates to improving the connectivity of edges of a bipartite graph; thus, a large spectral gap (i.e., the gap between the first and the second singular value), guarantees the optimal signal recovery using sparsity or rank minimization techniques under certain incoherence properties (Bhojanapalli and Jain (2014)). Here we propose a global optimization strategy to minimize the spectral gap to generate regular or irregular seismic survey design with random time dithers, i.e., optimizing off-the-grid sources and/or receivers' locations for seismic data acquisition.

The proposed method is inspired by the recent work of Zhang et al., 2022, 2023 where authors demonstrated a rank minimization framework to optimize on-the-grid survey design. The underlying idea is to evaluate the spectral gap of the sampling matrix organized in a domain where we expect seismic data to exhibit low-rank property. Here, we create a sampling matrix by assigning one at the locations where we acquire the data and zero at the locations where we are missing the data. Note that the computation of spectral gap involves performing singular value decomposition (SVD) over the sampling matrix. Even though the optimization framework generates optimal grid locations, one needs to project these locations on a periodic grid to evaluate the survey design. The sampling of the periodic grid depends upon the minimum interval between two subsequent sources among all possible sources present in the optimized design. For example, during the survey design, if the minimum sampling between two subsequent sources is 0.5 m, then the underlying periodic grid needs to be sampled at 0.5 m to evaluate the survey design. The design of denser sampling grid to compute spectral gap becomes computationally expensive when we are designing a survey over hundreds of kilometers of survey area. Apart from the computational burden, in practice, we face instrumental constraints, such as not being able to activate sources that are close to each other due to the limitation of the compressor, or not being able to change the distance between multiple air guns separated in the crossline direction situated on the same boat during the acquisition. We also see environmental constraints, i.e., restriction on the amount of energy generated at any point during acquisition; therefore, we are unable to activate multiple sources together.

Method

To overcome the computational burden of evaluating the survey design with the practical constraints, we propose to solve the following non-convex combinatorial optimization problem for off-the-grid subsampling mask $\mathbf{M} \in \{0,1\}^{n_s n_r}$:

$$\boldsymbol{\varphi}(\mathbf{M}) = \underset{\mathbf{M}}{\mathbf{minimize}} \frac{\boldsymbol{\sigma}_2(\boldsymbol{\mathcal{T}}\boldsymbol{\mathcal{N}}'\mathbf{M})}{\boldsymbol{\sigma}_1(\boldsymbol{\mathcal{T}}\boldsymbol{\mathcal{N}}'\mathbf{M})}$$

$$\textbf{subject to} \quad . \ (1)$$

$$\|\mathbf{M}\|_0 = \lfloor n_s x\, r \rfloor \, x \, \lfloor n_r x\, r \rfloor \cap \mathbf{M} \in (\mathcal{J} + \mathcal{D} \in \{-x_a, x_a\}^{n_s n_r} + \mathcal{E}_1 \in \{-x_{b1}, x_{b1}\}^{n_s n_r} + \mathcal{E}_2 \in \{-x_{b2}, x_{b2}\}^{n_s n_r}) \cap \mathbf{M} \in \{0,1\}^{n_s x\, n_r}$$

The underlying framework follows the fact that an optimal survey design exhibits a small spectral ratio (SR), which is the ratio of the first to second singular values (López et al. (2022)). As the ratio becomes smaller, the underlying design has larger spectral gaps, which means the underlying sampling design exhibits maximum randomization in the transform domain. Here, $n_s \in n_{sx} \, x \, n_{sy}$ is source locations, $n_r \in n_{rx} \, x \, n_{ry}$ is receiver locations along x and y-directions, respectively, and r represents the underlying subsampling ratio for sources and receivers. In equation (1), $\boldsymbol{\sigma}$ represents the singular value of the underlying mask $\mathbf{M}$ in the transform domain $(\boldsymbol{\mathcal{T}})$, where the data exhibit sparse or low-rank structure, $\boldsymbol{\mathcal{N}} \in \mathbb{C}^{n_{sub} \, x \, n_{sx} n_{sy} n_{rx} n_{ry}}$ represents a multidimensional, off-the-grid Fourier transform, which maps data from an unstructured subsampling grid to a dense periodic grid. The first reason behind using the off-the-grid Fourier transform is that the SR of the underlying grid does not change if evaluated in physical domain or Fourier domain, as the Fourier transform conserves energy and is orthogonal in nature. The second reason is that we need to form a matrix to estimate the singular values; it is impossible to construct a matrix using off-the-grid locations in the physical domain as compared to the wavenumber domain, where the off-the-grid Fourier operator generates a regular grid. If we want to construct a matrix in the physical domain obeying off-the-grid locations, we need to create a highly dense sampling grid as proposed in Zhang et al., 2022, 2023, which makes the evaluation of equation (1) computationally expensive.

While solving equation (1) to find optimal unstructured grid locations, we impose a couple of constraints. The first one, i.e., $\lfloor n_s x\, r \rfloor \, x \, \lfloor n_r x\, r \rfloor$ imposes the fact that the outcome of the optimization problem should maintain the desired number of subsampling ratio r, where $\lfloor . \rfloor$ denotes the rounding off operation. The second constraint constitutes a couple of spatial sampling constraints, such as (i) the idea of jittered sampling (Hennenfent, & Herrmann (2008)), which is defined to control the gap size between the source-receiver locations during the survey design process; (ii) random dither spatial location $\mathcal{D}$ to incorporate off-the-grid randomness within $\pm x_a$ spatial distance from the underlying on-the-grid locations, where off-the-grid randomness could be inline or crossline; (iii) user-defined spatial location constraints, i.e., $\mathcal{E}_1$ and $\mathcal{E}_2$ to ensure that two sources along a sail line or two source lines next to each other in the field are never activated within spatial distance x_{b1} or x_{b2}, respectively; (iv) The third constraint ensures that the underlying mask is a binary mask with a value of either zero or one at each of the survey locations. Ultimately, the optimal survey design lies at the intersection of all these constraints. We can also add different constraints as we face different acquisition obstacles in equation (1). Note that, although equation (1) optimizes the survey design on spatial locations, given a boat speed, the same parameters can be optimized over acquisition time also. To solve equation (1), we use the simulating annealing (SA) algorithm (Kirkpatrick et al., 1983; Zhang et al., 2022), which can approximate the global optimum of a combinatorial optimization problem within a computational budget using probabilistic techniques. Figure 1a shows the sampling pattern where sources are activated on a periodic grid and Figure 1c shows its corresponding point-spread function representation in the Fourier-wavenumber (FK) domain. As evident, due to the periodic sampling, we observe aliasing artefacts in the FK-domain. Figure 1b shows the optimized survey design using the proposed methodology where blue dots show the new locations after optimization and Figure 1d shows the associated FK spectrum. As evident, randomization in the source locations turns aliasing into noise, thus stabilizing seismic data processing (Hennenfent et al., 2010).

Results

To demonstrate the benefits of the proposed methodology to create an off-the-grid survey design for simultaneous source acquisition, we evaluated it on both synthetic and real field data scenarios from the Gulf of Mexico. In both acquisition scenarios, we design the survey as consisting of a two-vessel acquisition, with three sources (i.e., triple source) on each vessel. The underlying sampling assumption for nodes is 1000 m by 1000 m, whereas the sources are acquired with 50-m by 100-m sampling in inline and crossline directions. Conventionally, three sources on each vessel are either activated approximately every 16.66 m in a flip-flop-flap manner or simultaneously in a flip-flip-flip manner with ±1 s of time dither. In flip-flip-flip acquisition, we also impose a constant time delay of ± 500 ms, which is applied between sources to ensure that multiple sources are not activated simultaneously in the field. We compare the flip-flop-flap and flip-flip-flip models with the optimized survey design using the proposed technology. We call flip-flop-flap model I, flip-flip-flip model II, and the optimized survey design model III in the rest of the paper. In this survey, a 2-km distance is maintained between vessels.

Figures 2a, 2b and 2c show the blended data generated using models I, II and III, respectively, using a complex synthetic model from the Gulf of Mexico. We can see that model I generates a strong-over-weak phenomenon (Figure 2a), where strong coherent noise overlies weak signal in the deeper time section, whereas model II generates a strong-over-strong phenomenon (Figure 2b), where strong coherent noise overlies strong signal in shallow time sections and weak coherent noise is imposed over weak signal in deeper time sections. Kumar et al. (2021) showed that models I and II result in the most difficult deblending tasks and describe how and why standard sparsity promotion-based deblending technologies may struggle in such scenarios. Moreover, the authors presented a novel multistage deblending solution based on prior information about the wavefield that can reduce the sensitivity to the shooting strategy and produce stable source-separation results. In this experiment, we want to compare the quality of source separation by comparing it to the ground truth and show how the improvement in survey design impacts the preservation of strong and/or weak coherent signal buried beneath the strong interference noise. Figure 2c shows that producing the optimal source location with the lowest spectral ratio makes a drastic difference in how the interference energy appears over the coherent signal of interest, i.e., the interference energy becomes randomized and no longer localized in the temporal-spatial window. Therefore, it increases the chances of producing an optimal source separation result. Figures 2d, 2e and 2f show the source separation results, whereas Figures 2g, 2h, 2i show the difference between ground truth and source separated data. We can clearly see the signal leakage generated by model I (Figure 2g) and II (Figure 2h), whereas the proposed survey design mitigates the signal leakage (Figure 2i).

We finally tested the optimized survey design by acquiring test data in the Gulf of Mexico. The survey consists of a similar configuration of sources as demonstrated in the synthetic study. For comparison purposes, we also acquired the data using flip-flop-flap design where we impose ±1 s of time dither. Figures 3a, 3b show the data acquired using flip-flop-flap and the optimized survey design generated using equation (1). As evident from Figure 3, we can randomize the interference noise by optimizing the source locations; thus overcoming the strong-over-weak phenomenon caused by the flip-flop-flap survey. Figures 4a, 4b show the source-separation results using the multi-stage iterative source separation with prior framework (Kamil et al., (2021); Kumar et al., (2023)) and Figures 4c, 4d show the interreference noise removed after source separation. The coherent signal after source separation using the optimized survey exhibits better signal-to-noise ratio (Figure 4b) as compared to the flip-flop-flap design (Figure 4a).

Conclusions

The success of the source separation technique relies on the fact that interference noise should appear random in nature in the transform domain. This becomes even more important when interested in the refracted and weaker reflection energy, especially in a salt environment. Current standard simultaneous acquisition generates sub-optimal interference randomization; thus, extra attention is needed during the source separation process. Here, we proposed a novel off-the-grid acquisition design using a rank minimization technique to generate the optimal acquisition geometry. The new design complements the existing or advanced source separation technique to predict robust signal models. Both synthetic and real data examples from the Gulf of Mexico demonstrate the potential of the proposed survey design technique compared to the standard practice of acquiring seismic data.

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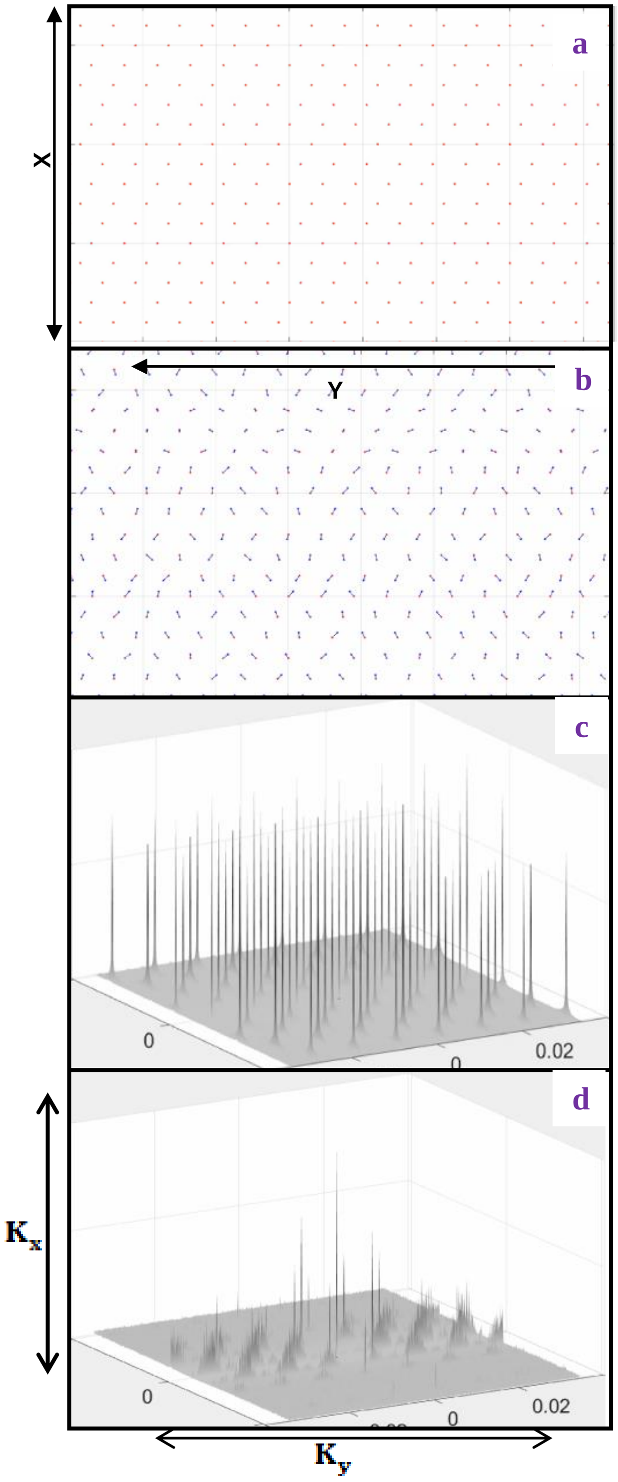

Figure 1: (a) Periodic source locations (red dots) and (b) optimized source locations (blue dots) using the proposed technology. (c, d) Point spread function in the Fourier-wavenumber domain for the survey design shown in (a, b) respectively. Note that the green line in (c) represents the location of true signal in the Fourier-wavenumber domain.

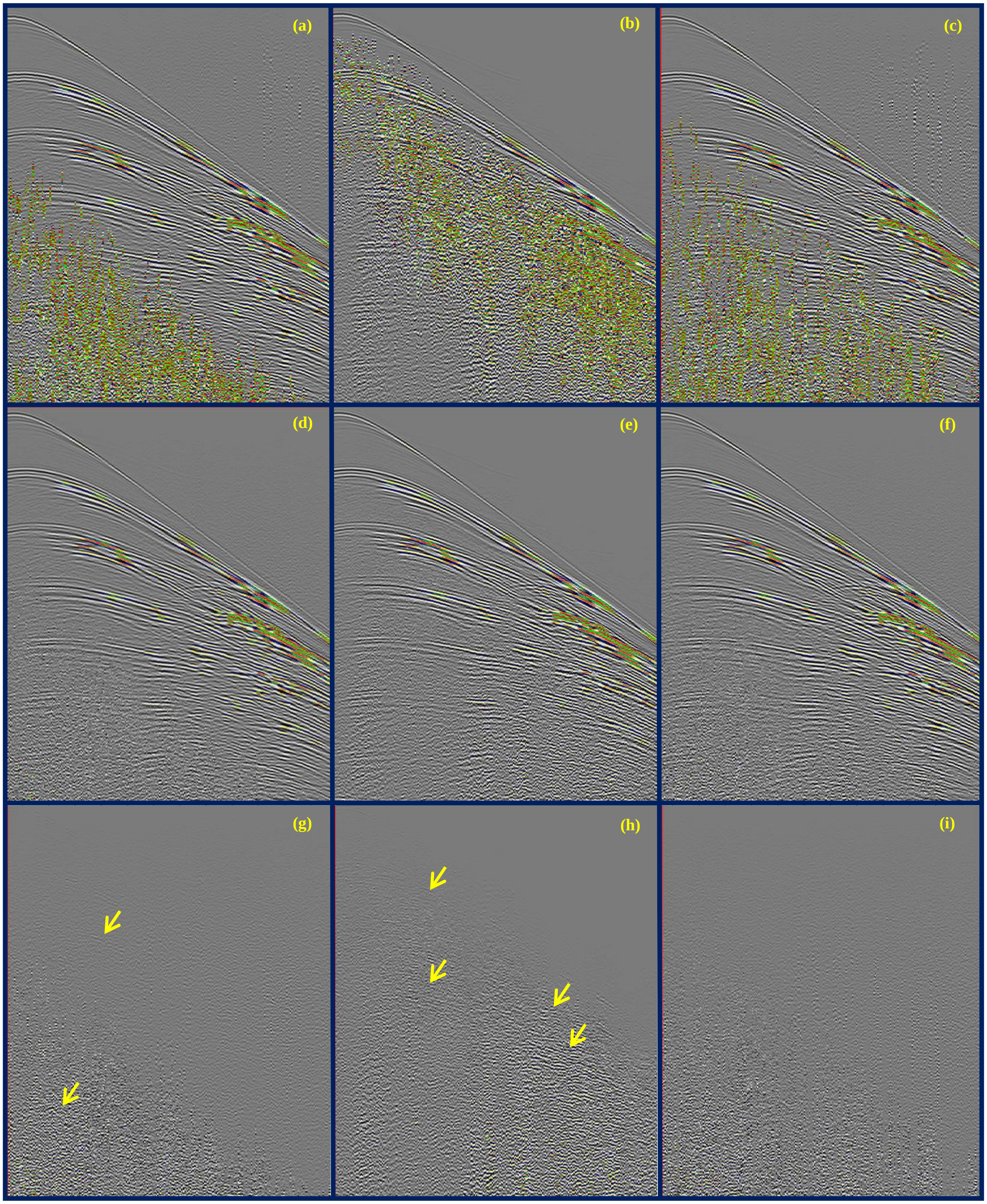

Figure 2: Survey design evaluation of the synthetic model generated using the Gulf of Mexico model. (a, b, c) Input blended, (d, e, f) source separated results and (g, h, i) difference between ground truth and source separated signal for model I, II and III respectively.

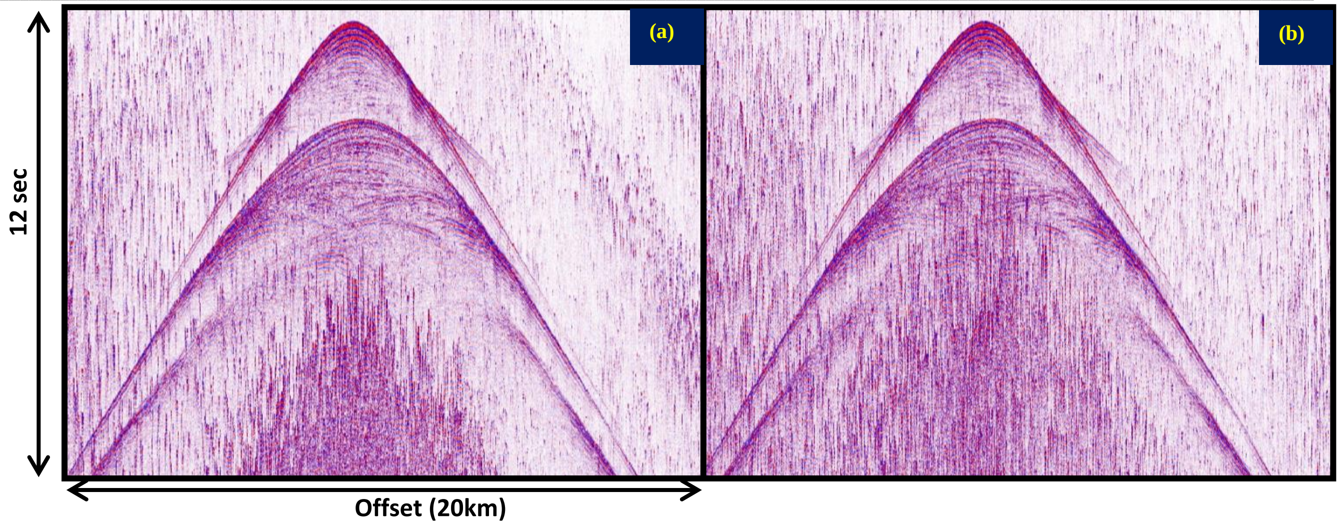

Figure 3: Real seismic data acquired in the Gulf of Mexico using (a) flip-flop-flap and (b) the proposed survey design. The proposed survey design randomizes the interference noise and overcomes the strong-over-weak phenomenon evident in (a).

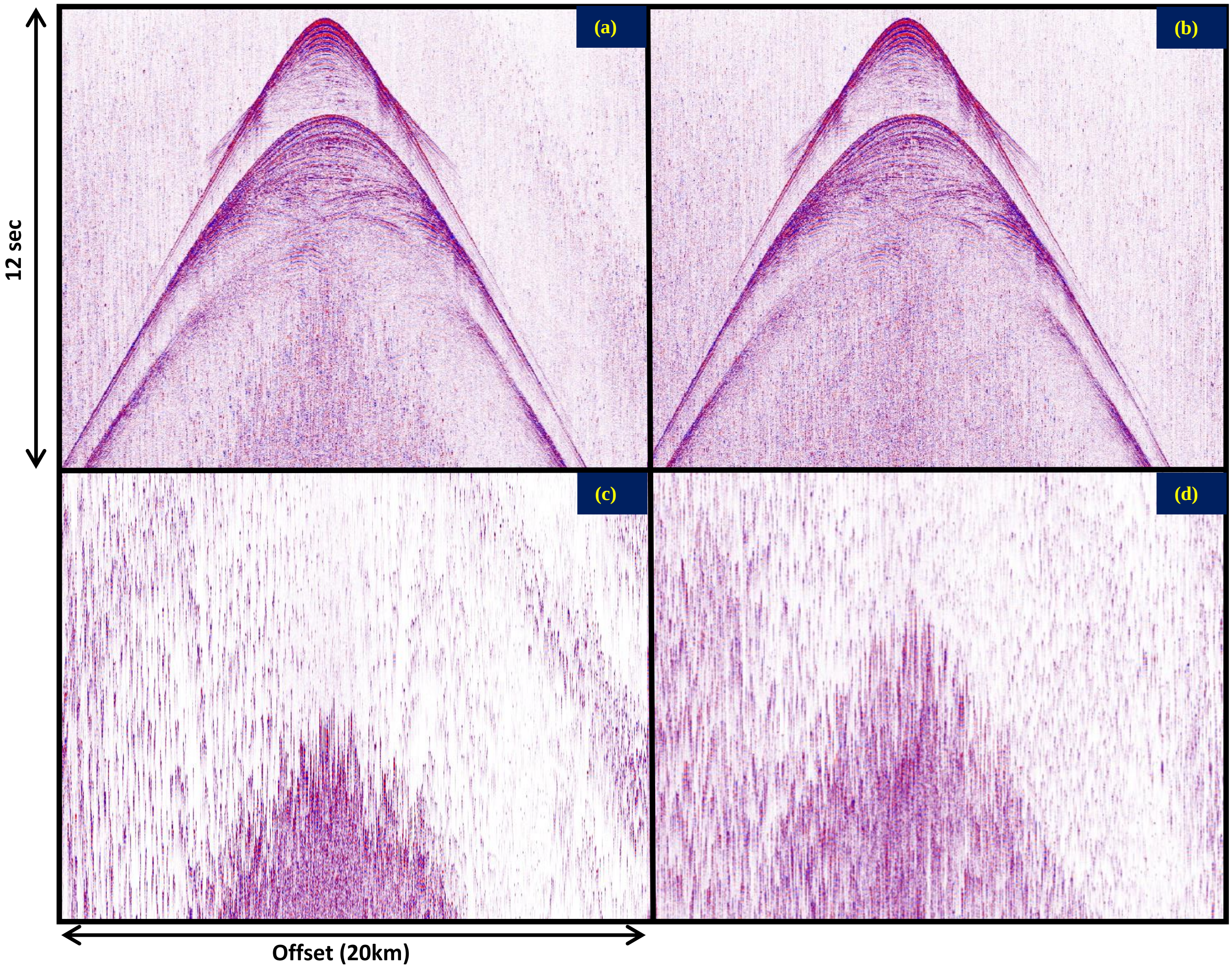

Figure 4: Source separation results on the real seismic data acquired in the Gulf of Mexico using (a) flip-flop-flap and (b) the proposed survey design. (c, d) Modeled interference noise after source separation for (a, b) respectively. As seen, the proposed survey design provides a better signal-to-noise ratio after separation.