Inherent challenges of randomized shooting strategies on deblending and a robust multistage prior based solution

Introduction
Simultaneous-source acquisition has become a well-established method to improve 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, the technique has been combined with ocean-bottom nodal (OBN) acquisition technologies to target full-azimuth ultra-long offsets (~40 - 60 km) that are rich in low frequencies (Salgadoe et al., 2020). Even though the simultaneous-source design brings down the cost of surveys significantly, the separation of signal from different sources, also known as deblending, is a challenging problem. The robustness of the source separation framework to separate the coherent signal from the interference noise relies heavily on the following factors: (i) number of sources firing at any point in time; (ii) firing delay between different sources; (iii) the randomness of time dithering; (iv) the directivity pattern of the wavefield recorded by a receiver from all sources firing at once. These factors implicitly dictate the level of interference noise (also known as blending noise) in the time-space domain, which lie on top of both the strong and weak coherent signals in the shallow and the deeper part of the seismic record. For example, the firing delay between different sources can either generate strong interference noise overlying the strong coherent signal, termed as strong-over-strong phenomenon, or the strong interference noise on the weak coherent signal, termed as a strong-over-weak phenomenon. Moreover, the randomness in time dithering impacts the local distribution of the interference noise. Controlling these impediments is an essential requirement for the success of any deblending framework, especially when dealing with sparse OBN ultra-long-offset surveys. Here, we first show how different simultaneous shooting strategies result in different challenges for deblending. We also show which shooting strategies result in the most difficult deblending tasks and describe how and why standard sparsity promotion based deblending technologies may struggle in such scenarios. We then present a novel multistage deblending solution based on prior information about the wavefield that can reduce the sensitivity to the shooting strategy. Such prior information about the seismic signal helps differentiate the coherent signal and the interference noise in the sparsity domain (Kamil et al., 2021). Finally, we show the effectiveness of the multistage source separation with prior framework on two different randomized shooting strategies designed for sparse OBN ultra-long-offset acquisitions.

Flip-flip vs. flip-flop-flap shooting
The two simultaneous-source acquisition surveys studied here are deep-water (500 – 1700 m) ultra-long-offset (~40 – 60 km) OBN surveys acquired in the Gulf of Mexico. The nodes are deployed in a staggered grid of 1000 m by 1000 m, whereas the sources are acquired with 50 m by 100 m sampling steps. Hereafter, we term the two surveys as A and B, respectively. In Survey A (Figure 1a), data are acquired with two sources, each on three vessels, where one source on each vessel fires approximately every 20 s, and the second source on the same vessel fires at nearly the same time. Survey B (Figure 2a) is a two-vessel acquisition, with three sources (i.e. triple source) on each vessel, where each source on the same vessel fires every 20 s, while the other two sources on the same vessel fire every 6.67 s thereafter, sequentially. In both surveys, a 2 km distance was maintained between vessels and a time-dither of ±1 s was applied. Due to the shooting pattern, Surveys A and B belong to the categories of flip-flip (Figure 1a) and flip-flop-flap (Figure 2a) acquisition, respectively. Also, in both surveys, all vessels acquired their assigned source lines independently of each other.

In Survey A, due to the flip-flip nature of the dual source on each vessel, the strongest interference from the same vessel occurs around the direct arrival, whereas the interference from the other two vessels appears randomly and is well distributed across the time-space domain (Figure 1b). Moreover, the strong interference noise appears on top of the strong coherent signal (strong-over-strong) and the weak interference noise appears on the weak coherent signal (weak-over-weak). Despite controlling the firing delay between sources, along with the randomness in the dithers, the data exhibit self-interference at ~20 s below the direct arrival, where the interference noise exhibits coherency. As compared to the flip-flip shooting, in Survey B, the flip-flop-flap shooting pattern introduces many challenges, such as: (i) the interference noise from the other two sources on the same vessel appears in a compressed hyperbolic region periodically every ~6.67 s (Figure 2b), and the self-interference noise from the same source appears every ~20 s; (ii) the interference noise from the other vessel is not randomly distributed, and, therefore, creates coherent patches of interference noise throughout the record. These types of
interference noise patterns from the same and/or different vessels are known as the strong-over-weak phenomenon.

The strong-over-strong, weak-over-weak, strong-over-weak, and the coherent self-interference nature of the blending noise determines how challenging the source separation problem is, especially when the separation framework solely relies upon the coherency criteria (Moore et al., 2008; Abma et al., 2012). In particular, for the strong-over-weak scenario, the dynamic range of the interference noise is very high compared to the signal, and thus the well-spread strong interference in the transformed domain remains stronger than the signal and makes the signal unperceivable. Therefore, the likelihood of picking the wrong coherent noise component instead of the weak signal buried beneath it at very early iterations of the source separation process is highly likely. Even if the signal is recognizable in the sparsity-promoting domain, its coefficients in the transform domain are still damaged in amplitude and phase by spread components of the random interference. This will challenge the coherency-based source separation process and its ability to preserve the weak coherent signal with a satisfactory signal-to-noise ratio. Moreover, due to the above reasons, the source separation problem becomes even more challenging in the deeper time sections.

We deblended Surveys A and B using a current sparsity promotion technology (Moore et al., 2008; Abma et al., 2012). Results are shown in Figures 1c and 1d (Survey A) and Figures 2c and 2d (Survey B). On the flip-flop acquisition (A), the source separation achieves good results (Figure 1c), preserving strong coherent energy and removing the associated incoherent interference noise; yet, the difference section (Figure 1d) shows the leakage of both the strong and weak coherent energy. On the flip-flop-flap acquisition (B), deblending still preserves strong coherent energy in the shallow areas where interference noise is minimal, however, the separation attenuates the weak energy in the deeper parts (Figures 2c and 2d) where the interference noise is coherent in nature. This example exhibits the weakness of a coherency-based source separation framework to distinguish between weak coherent signal and the strong coherent noise, because it picks the wrong coherent noise components at early iterations, causing removal of the weak energy.

\[ \text{Figure 1 (a) Flip-flop shooting design, and (b) observed blended common receiver gather subsection.} \]

\[ \text{Source separation results using (c) single-stage without priors, (e) multistage with priors framework, and (d, f) are the corresponding difference between the input and deblended results. Here, the symbols V1, V2, and V3 represent the three source vessels, and S1 and S2 are the two sources on each vessel.} \]
Addressing the limitations
To preserve the coherent signal buried beneath the strong interference noise, we must impose extra constraints while implementing any coherency-based source separation framework. Therefore, we present a novel multistage iterative source separation with priors (MS-ISSP) technique: the underlying idea is to combine information about the wavefield propagation with a sparsity-promoting transform domain such that the signal of interest buried beneath the high-energy interference noise gets a sparser representation in the transformed domain and exhibits stronger coherency, while the interference signal becomes more incoherent and random. To do so, we solve the following sparsity promotion based formulation:

$$\min_{\mathbf{u}} ||\mathbf{SPu}||_1 \quad \text{subject to} \quad \frac{1}{2}||\mathbf{b} - \mathbf{Gu}||_2^2 \leq \epsilon,$$

where $||\mathbf{r}||_1$ is the sum of absolute values of the components in the vector $\mathbf{r}$, $\epsilon$ is the noise level up to which we want to fit the least-squares misfit, the vectors $\mathbf{b}, \mathbf{u}$ are the observed blended and the predicted debledged data, $\mathbf{G}$ is the blending matrix, $\mathbf{S}$ is the sparsity-promoting transform domain, and the operator $\mathbf{P}$ encompasses various suites of prior information, which enhances the sparsity of the signal in the transform domain. To solve equation 1, we use the fast-iterative soft thresholding algorithm (FISTA) (Beck and Teboulle, 2009) where, at each iteration, we update the vector $\mathbf{u}$ as follows:

$$\mathbf{u}_i = \mathbf{P}^H \mathbf{S}^H \left( \mathbf{R}_i (\mathbf{SP}(\mathbf{u}_{i-1} + \alpha_i \mathbf{P}^T \mathbf{b} - \mathbf{Gu}_{i-1})) \right),$$

where $\mathbf{R}$ is the exponential shrinkage operator (Yang and Fomel, 2015), $\alpha_i, \lambda$ are the step-length and thresholding values at iteration $i$, and the symbols $(.)^T, (.)^H$ represent the matrix transpose and conjugate transpose, respectively. For more details about the FISTA solver, interested readers are encouraged to read work by Beck and Teboulle (2009). One of the key components of the iterative process to solve equation 1 is a multistage with prior strategy, where multistage helps in progressively modelling the different modes of seismic signal at different stages of the deblending (starting with the strongest signal), generating different levels and/or amplitudes of interference noise. Furthermore, incorporating various techniques based on our prior understanding about the nature of seismic such as moveout enhances the sparsity of the signal in the transform domain (Kamil et al., 2021). In summary, the multistage deblending process is facilitated by using different moveout information as priors at different stages. In this process, we first separate the direct arrival energy and the associated interference noise. We then separate the reflection, refraction energy, and the corresponding interference noise. Finally, we solve equation 1 to deal with the remnant seismic coherent events, such as diffraction energy. For each stage, the $\epsilon$ value is derived using a data-driven strategy, which automatically identifies the stopping criteria for equation 1, the solution of which converges in a fewer number of iterations at each stage, which makes MS-ISSP an economically viable solution. Please note that solving equation 1 in a single stage with $\mathbf{P} = \mathbf{I}$ is equivalent to the standard deblending mentioned in the previous section.

Experiments and results
We evaluate the performance of the proposed multistage iterative source separation with priors framework on a node gather extracted from Surveys A (Figure 1b) and B (Figure 2b). Figures 1c and 1d and 2c and 2d show results of the standard sparsity promotion deblending technology. As mentioned earlier, the weak signal gets damaged in flip-flop-flap Survey B, as most energy in the areas affected by strong interference is attenuated during deblending. Results of multistage source separation with priors are shown in Figures 1e and 1f (Survey A) and 2e and 2f (Survey B). While the presented advanced technology improves the results in both surveys, it is evident that the flip-flop-flap acquisition is the one where we see the substantial uplift in the preservation of the weak coherent energy, as the deblended signal is more continuous also in the deep regions affected by strong-on-weak interference, which were almost completely attenuated in Figure 2c.

Conclusions
Various aspects of survey design have a profound impact on how the strong interference noise appears on the coherent signal of interest. It is imperative to choose a shooting strategy that facilitates the deblending by minimizing the likelihood of strong interference on weak signal. Typically, a flip-flap acquisition is an effective strategy for OBN/marine multisource surveys because strong and/or weak interference noise appears randomly and is well distributed over the coherent signal of interest. In fact, for acquisition scenarios like flip-flop-flap, the standard source separation frameworks struggle to fully preserve the weak coherent signal that is buried under very strong, somewhat coherent, and random interference noise. Therefore, we proposed a more advanced deblending technology that can mitigate
the impact of strong-on-weak interference occurring in flip-flop-flap surveys: such a solution is based on the use of prior information in a multistage framework.

Figure 2 (a) Flip-flop-flap shooting design, and (b) observed blended common receiver gather subsection. Source separation results using (c) single-stage without priors, (e) multistage with priors framework, and (d, f) are the corresponding difference between the input and deblended results. Here the symbols V1 and V2 represent the two source vessels, and S1, S2, and S3 are the three sources on each vessel.

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References