# Time-jittered ocean bottom seismic acquisition

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## SUMMARY

Leveraging ideas from the field of compressed sensing, we show how simultaneous or blended acquisition can be setup as a – compressed sensing problem. This helps us to design a pragmatic *time-jittered* marine acquisition scheme where multiple source vessels sail across an ocean-bottom array firing airguns at – jittered source locations and instances in time, resulting in better spatial sampling, and speedup acquisition. Furthermore, we can significantly impact the reconstruction quality of conventional seismic data (from jittered data) and demonstrate successful recovery by sparsity promotion. In contrast to random (under)sampling, acquisition via jittered (under)sampling helps in controlling the maximum gap size, which is a practical requirement of wavefield reconstruction with localized sparsifying transforms. Results are illustrated with simulations of *time-jittered* marine acquisition, which translates to jittered source locations for a given speed of the source vessel, for two source vessels.

## INTRODUCTION

Constrained by the Nyquist sampling rate, the increasing sizes of the conventionally acquired marine seismic data volumes pose a fundamental shortcoming in the traditional sampling paradigm and make large area acquisition particularly expensive. Physical constraints on the speed of a source vessel during acquisition, on the minimal time interval between adjacent shots (to avoid overlaps), and on the minimal spatial shot sampling further aggravate the acquisition related costs. Several works in the seismic acquisition literature have explored the concept of simultaneous or blended source activation to account for these situations (Beasley et al., 1998; de Kok and Gillespie, 2002; Beasley, 2008; Berkhout, 2008; Hampson et al., 2008; Moldoveanu and Fealy, 2010).

For blended acquisition, the challenge is to estimate interference-free shot gathers (*deblending*) and recover small subtle late reflections that can be overlaid by interfering seismic responses from other shots. Stefani et al. (2007), Moore et al. (2008) and Akerberg et al. (2008) have observed that the interferences in blended data will appear noise-like in specific gather domains such as common-offset and common-receiver, turning the separation into a typical (random) noise removal procedure. Application to land acquisition is reported in Bagaini and Ji (2010). Subsequent processing techniques, which aim to remove noise-like source crosstalk, vary from vector-median filters (Huo et al., 2009) to inversion-type algorithms (Moore, 2010; Abma et al., 2010; Mahdad et al., 2011). In this paper, we show that this challenge can be effectively addressed through a combination of tailored multiple-source/blended acquisition design and curvelet-based sparsity-promoting recovery.

Recently, compressed sensing (CS, Donoho, 2006; Candès and Tao, 2006) has emerged as an alternate sampling paradigm in which randomized sub-Nyquist sampling is used to capture the structure of the data with the assumption that it is sparse or compressible in some transform domain. Seismic data consists of wavefronts that exhibit structure across different scales and amongst different directions. With the appropriate data transformation, we can capture this structure by a small number of significant transform coefficients resulting in a sparse representation of data. In our work, we rely on the CS literature to analyze a physically realizable *time-jittered* (multiple-source) marine acquisition scheme, and recover the canonical sequential single-source (interference-free/deblended) data by solving a sparsity-promoting problem (Mansour et al., 2012; Wason and Herrmann, 2012). Hence, we develop the relation between blended acquisition design and (curvelet-based) sparse recovery, within the CS framework.

The paper is organized as follows. First, we give a brief overview of compressed sensing. Next, we describe how *time-jittered* marine acquisition (in particular, ocean-bottom cable) can be setup as a CS problem. Finally, experimental results demostrate the successful implementation of the proposed sampling scheme and the sparsity-promoting recovery technique.

## COMPRESSED SENSING

Compressed sensing is a signal processing technique that allows a signal to be sampled at sub-Nyquist rate and reconstructs it (from relatively few measurements) by utilizing the prior knowledge that the signal is sparse or compressible in some transform domain, i.e., if only a small number $k$ of the transform coefficients are nonzero or if the signal can be well approximated by the $k$ largest-in-magnitude transform coefficients. For high resolution data represented by the $N$-dimensional vector $\mathbf{f}_0 \in \mathbb{R}^N$, which admits a sparse representation $\mathbf{x}_0 \in \mathbb{C}^P$ in some transform domain characterized by the operator $\mathbf{S} \in \mathbb{C}^{P\times N}$ with $P \geq N$, the sparse recovery problem involves solving an underdetermined system of equations

$$\mathbf{b} = \mathbf{A}\mathbf{x}_0, \tag{1}$$

where $\mathbf{b} \in \mathbb{C}^n$, $n \ll N \leq P$, represents the compressively sampled data of $n$ measurements, and $\mathbf{A} \in \mathbb{C}^{n\times P}$ represents the measurement matrix. We denote by $\mathbf{x}_0$ a sparse synthesis coefficient vector of $\mathbf{f}_0$. When $\mathbf{x}_0$ is strictly sparse (i.e., only $k < n$ nonzero entries in $\mathbf{x}_0$), sparsity-promoting recovery can be achieved by solving the $\ell_0$ minimization problem, which is a combinatorial problem and quickly becomes intractable as the dimension increases. Instead, the basis pursuit (BP) convex optimization problem

$$\tilde{\mathbf{x}} = \underset{\mathbf{x}\in\mathbb{C}^P}{\operatorname{argmin}} \|\mathbf{x}\|_1 \quad \text{subject to} \quad \mathbf{b} = \mathbf{A}\mathbf{x}, \tag{2}$$

can be used to recover $\tilde{\mathbf{x}}$, where $\tilde{\mathbf{x}}$ represents the estimate of $\mathbf{x}_0$, and the $\ell_1$ norm $\|\mathbf{x}\|_1$ is the sum of absolute values of the elements of a vector $\mathbf{x}$. The BP problem typically finds a sparse or (under some conditions) the sparsest solution that explains the measurements exactly. The matrix $\mathbf{A}$ can be composed of the product of a restriction operator (undersampling matrix) $\mathbf{R} \in \mathbb{R}^{n \times N}$, an $N \times N$ mixing matrix $\mathbf{M}$, and the sparsifying operator $\mathbf{S}$ such that $\mathbf{A} := \mathbf{RMS}^H$, here $^H$ denotes the Hermitian transpose. Consequently, the measurements $\mathbf{b}$ are given by $\mathbf{b} = \mathbf{Ax}_0 = \mathbf{RMf}_0$. A seismic line with $N_s$ sources, $N_r$ receivers, and $N_t$ time samples can be reshaped into an $N$ dimensional vector $\mathbf{f}$, where $N = N_s \times N_r \times N_t$. For simplicity, we assume that all sources see the same receivers, which makes our method applicable to marine acquisition with ocean-bottom cables or nodes (OBC or OBN). We wish to recover a sparse approximation $\tilde{\mathbf{f}}$ of the discretized wavefield $\mathbf{f}$ from measurements $\mathbf{b} = \mathbf{RMf}$ (jittered data). This is done by solving the BP sparsity-promoting program (Eq. 2), using the SPG$\ell_1$ solver (Berg and Friedlander, 2008), yielding $\tilde{\mathbf{f}} = \mathbf{S}^H \tilde{\mathbf{x}}$.

## TIME-JITTERED MARINE ACQUISITION

The success of CS hinges on randomization of the acquistion, since random undersampling renders coherent aliases (e.g., interferences due to overlapping shot records in blended acquisition) into harmless incoherent random noise, effectively turning the interpolation problem, which is also a deblending problem in our case, into a simple denoising problem (Hennenfent and Herrmann, 2008). Given limited control over the source signature of the airguns and their recharge time between shots (typically, a minimal time interval of 10.0s is required), the only way to invoke randomness is to work with sources that fire at random times that map to random shot locations for a given speed of the source vessel. Unfortunately, random sampling does not provide a control on the maximum gap size between adjacent measurements (Fig. 1), which is a practical requirement of wavefield reconstruction with localized sparsifying transforms such as curvelets. Jittered sampling, on the other hand, shares the benefits of random sampling and offers control on the maximum gap size (Fig. 1) (Hennenfent and Herrmann, 2008). Since we are still on the grid, this is a case of discrete jittering. A jittering parameter, dictated by the type of acquisition and parameters such as the minimum distance (and/or minimum recharge time for the airguns) required between adjacent shots, relates to how close and how far the jittered sampling point can be from the regular coarse grid, effectively controlling the maximum acquisition gap.

The design of the sampling operator $\mathbf{RM}$ is critical to the success of the recovery algorithm. We present a pragmatic marine acquisition scheme wherein the source vessels map the survey area while firing shots at jittered time-instances, which translate to jittered shot locations for a fixed speed of the source vessel. The top figure in Fig. 2 illustrates a conventional acquisition scheme where one source vessel carrying two airgun arrays fires every 20.0s (or 50.0m) travelling at about 5 knots ($\sim$2.5m/s) resulting in non-overlapping shot records. In time-jittered acquisition the airgun arrays fire at every 20.0s (or 50.0m) jittered time-instances (or shot locations), i.e., the minimum interval between the jittered times (or shots) is maintained at 10.0s (or 25.0m, a practical requirement) and the maximum interval is 30.0s (or 75.0m). The middle figure in Fig. 2 depicts this scenario resulting in overlapping shot records (Fig. 3(a)). A second source vessel comes in at a later time following the same principle. This corresponds to ($\eta =$) 2-time undersampled jittered acquisition grid for a conventional acquisition with non-overlapping shot records at every 25.0m. $\eta$ is the undersampling factor. Note that the source vessels travel at a constant speed during the time-jittered acquisition, i.e., they do *not* accelerate or decelerate while firing at jittered instances in time, which would render this scenario impractical.

With the same speed of the source vessel, if conventional acquisition could be carried out with a shot interval of 12.5m then acquisition on the 50.0m jittered grid would be a result of an undersampling factor of 4 (bottom figure in Fig. 2, and 3(d)). Hence, in order to recover data at finer source (and/or receiver) sampling intervals of 25.0m, 12.5m, etc., from the jittered data, the recovery problem becomes a joint deblending and interpolation problem. Since the undersampling is performed in the source-time domain, the sampling operator is defined as

$$\mathbf{RM} := [\mathbf{I} \otimes \mathbf{T}], \tag{3}$$

where $\otimes$ is the Kronecker product, $\mathbf{I}$ is an $N_r \times N_r$ identity matrix, and $\mathbf{T}$ is a combined jittered shot selector and time shifting operator. Taking the Kronecker product of $\mathbf{T}$ with $\mathbf{I}$ simply repeats the operation of $\mathbf{T}$ on every available receiver. Note, it is also possible to undersample the receiver axis or equivalently randomize/jitter positions of the ocean-bottom transducers (as in the case of OBN acquisition).

## EXPERIMENTAL RESULTS

We illustrate the performance of our time-jittered marine acquisition scheme on data generated from the BG compass model using the IWAVE software. Two sets of this data, one sampled at the source (and receiver) sampling of 25.0m and the other sampled at the source (and receiver) sampling of 12.5m, are used with $N_s = 129$ shots, $N_r = 129$ receivers and $N_t = 1024$ time samples. We recover the conventionally sampled seismic line (from the time-jittered data) via $\ell_1$ minimization using 2D curvelets Kroneckered with 1D wavelets as the sparsifying transform. It is well known that seismic data admit sparse representations by curvelets that capture "wavefront sets" efficiently (Smith, 1998; Candès and Demanet, 2005; Candès et al., 2006; Herrmann et al., 2008).

For the data with the source sampling of 25.0m, Fig. 3(a) displays 20 seconds of the jittered data volume where the regular coarse 50.0m grid is jittered using our jitter undersampling scheme (Fig. 1) resulting in overlapping shot records. The sparsity-promoting recovery results in a SNR of 23.6 dB, effectively deblending the jittered data and interpolating it to the finer 25.0m grid. Fig. 3(b) and 3(c) show one shot gather of the recovered seismic line and the corresponding residual, respectively. Similarly, for the data with the source sampling of 12.5m, jittering the 50.0m grid results in a 4-time undersampled jittered data volume, 20 seconds of which are shown in Fig. 3(d). One shot gather of the recovered seismic line (recovery of 17.0 dB) and the corresponding residual are displayed in Fig. 3(e) and 3(f), respectively. To demonstrate the effectiveness of our acquisition scheme and recovery algorithm, the displayed shot gathers were deliberately picked from the locations where none of the airguns fired. To quantify the cost savings associated with blended acquisition, Berkhout (2008) proposed two performance indicators: survey-time ratio

$$\text{STR} = \frac{\text{time of the conventional acquisition}}{\text{time of the blended acquisition}}, \quad (4)$$

and source-density ratio

$$\text{SDR} = \frac{\text{number of sources in the blended survey}}{\text{number of sources in the conventional survey}}. \quad (5)$$

If we wish to acquire 10.0s-long shot records at every 12.5m with no overlap, the speed of the source vessel would have to be *decreased* to 1.25m/s. Comparing this scenario with the jittered acquisition scheme (of overlapping shot records) presented here, we gain an acquisition-time speed up by a factor of 2 (STR). The SDR = 129/32 ≈ 4, where 129 is the number of sources in the blended survey (after recovery) and 32 is the number of sources in the conventional survey.

## CONCLUSIONS

Time-jittered (blended) marine acquisition is an instance of compressed sensing, which shares the benefits of random sampling while offering control on the maximum acquisition gap size. The results vindicate the importance of randomness in the acquisition scheme, wherein the more random realizations we have in terms of the airgun firing times/shot locations (as shown here), and/or receiver locations, the more likely we are to hit more locations in the subsurface. The combination of randomized sampling and sparsity-promoting recovery technique will aid in improved deblending coupled with interpolation to finer and finer sampling grids, mitigating the acquisition related costs in the increasingly complicated regions of the Earth to produce images of desired resolution. Future work includes working with non-uniform sampling grids.


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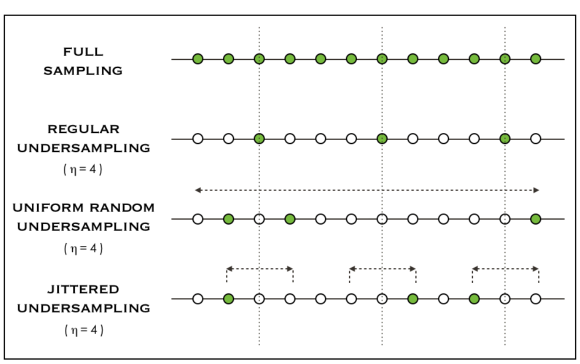


Figure 1: Schematic comparison between different undersampling schemes. $\eta$ is the undersampling factor. The vertical dashed lines define the regularly undersampled spatial grid.

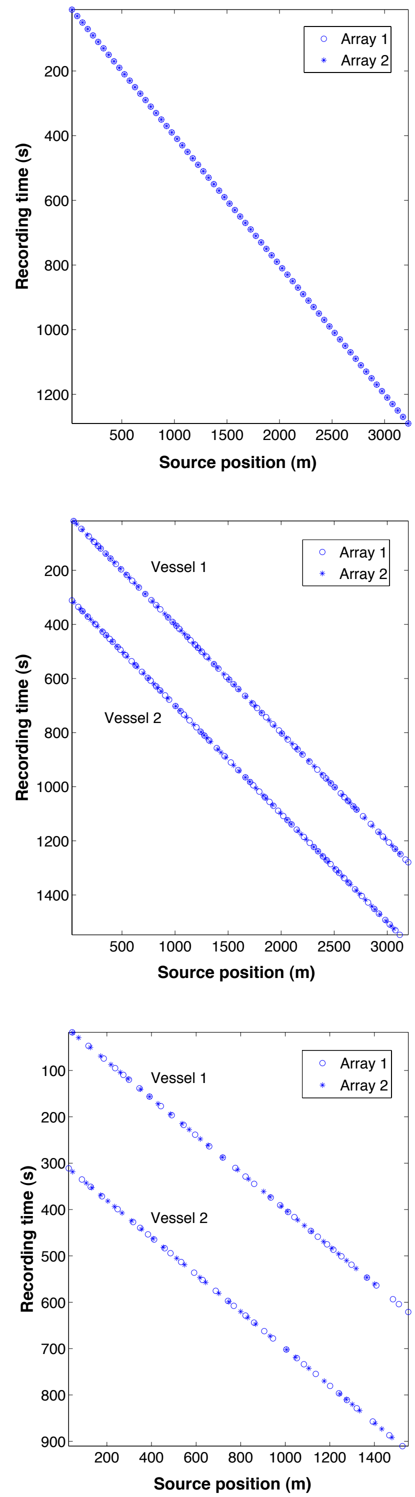


Figure 2: Top: Conventional marine acquisition with one source vessel and two airgun arrays. Time-jittered marine acquisition with two source vessels and two airgun arrays each; Center: with an undersampling factor of 2 (for data sampled at 25.0m); Bottom: with an undersampling factor of 4 (for data sampled at 12.5m).

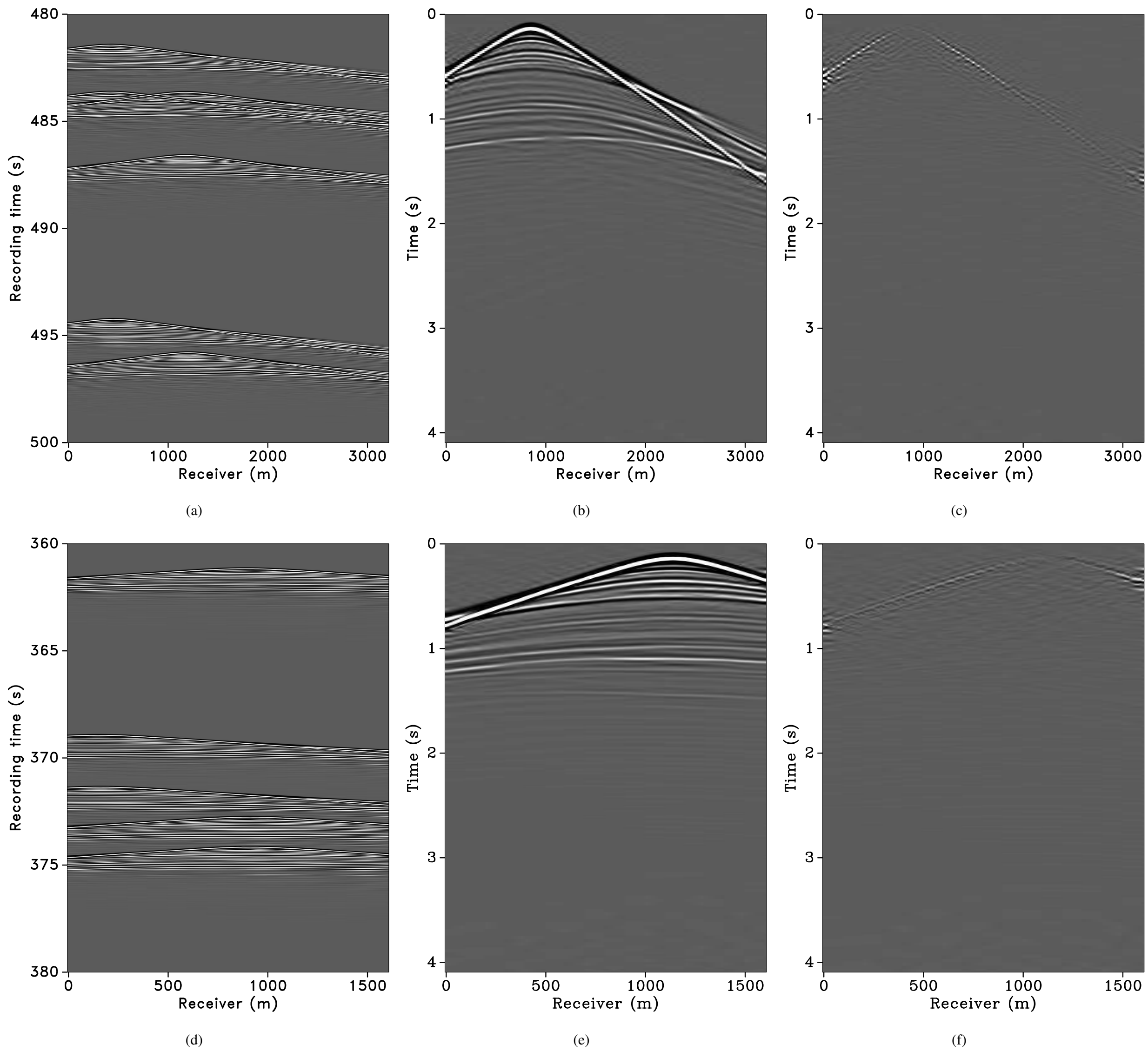


Figure 3: (a) Jittered marine data (showing only 20 seconds of the jittered data volume), (b) sparsity-promoting recovery (SNR = 23.6dB), and (c) residual for the data sampled at 25.0m. (d) Jittered marine data, (e) sparsity-promoting recovery (SNR = 17.0dB), and (f) residual for the data sampled at 12.5m.

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