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# Joint Deblending and Interpolation of Irregularly Sampled Blended Seismic Data Using the Focal Transformation

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## Summary

Simultaneous source shooting or blended acquisition, which allows a temporal overlap between shot records, has been proposed as a method for substantially reducing the acquisition cost and improving data quality (e.g., denser shooting/efficient wide-azimuth shooting). Deblending allowed by traditional processing steps is still the dominant way of dealing with blended data. However, most of the deblending algorithms only utilize the blended input data without aliasing. In addition, it will be more challenging if the aliasing blended data traces are irregularly sampled, resulting in the failure of some deblending algorithms. In this paper we investigated the interpolation problem of irregularly blended seismic data using the focal transformation. Synthetic data example demonstrates the validity of its application for joint deblending and interpolation of the irregularly blended data.

## Introduction

Simultaneous source shooting, also known as blending, has been proposed as a method for speeding up seismic acquisition with a denser spatial source sampling, which can save substantially on acquisition cost and increases data quality (Berkhout, 2008). To handle this blended data in next processing steps can be done via two routes. The first route is directly imaging of the blended data without source separation, where the crosstalk will be suppressed during the imaging step (Tang and Biondi, 2009). Currently, the second route, i.e., deblending followed by traditional processing steps, is still the dominant way of dealing with blended data. A number of deblending algorithms have been proposed in literature, including coherency-based filtering methods (Huo et al., 2012; Gan et al., 2016) and inversion-based methods using Radon transforms (Ibrahim and Sacchi, 2013), seislet transform Chen et al. (2014), focal transform (Kontakis and Verschuur, 2015) and curvelet transform (Wason et al., 2011).

In realistic marine surveys, the seismic data is often incomplete and/or irregularly sampled, which is introduced by cable feathering, field obstacles, economic constraints and/or bad traces. Also, for the 3D ocean bottom node (OBN) acquisition, the source boat may not have perfectly regular shooting patterns. In addition, the dataset will generally be undersampled in one or more dimensions. In this paper we will focus on the joint deblending and interpolation problem of irregularly blended seismic data using the focal transformation.

## Method and Theory

For the discussion in this work, a matrix-based operator notation is used to formulate the theory, which was introduced by Berkhout (1982), where bold capital symbols, e.g. $\mathbf{P}$, represent multi-dimensional data or operators for one frequency component. We begin by first reviewing deblending using double focal transformation, which can be regarded as a sparse inversion problem of a blended dataset $\mathbf{P}_{\text{bl}}$ (Kontakis and Verschuur, 2014):

$$\min_{\delta\mathbf{X}_1,\ldots,\delta\mathbf{X}_K} \left\{ \sum_t \sum_{k=1}^{K} ||\delta\hat{\mathbf{X}}_k||_S \right\} \text{ s.t. } \sum_\omega \left|\left| \mathbf{P}_{\text{bl}} - \sum_{k=1}^{K} \mathbf{W}_k^- \delta\mathbf{X}_k \mathbf{W}_k^+ \Gamma \right|\right|_F < \sigma, \Rightarrow \mathbf{P}_{\text{debl}} = \sum_{k=1}^{K} \mathbf{W}_k^- \delta\mathbf{X}_k \mathbf{W}_k^+, \tag{1}$$

where the deblended data $\mathbf{P}_{\text{debl}}$ is recovered by calculating the adjoint double focal transform. Here $K$ pairs of one-way extrapolation operators $\mathbf{W}_k^+$ and $\mathbf{W}_k^-$ are used. $\delta\mathbf{X}_k$ is $k$-th focal subdomain in frequency-space. $\mathbf{\Gamma}$ is the blending operator that applies the blending code to the unblended data (Berkhout, 2008). $\sigma$ represents the noise level in the data. All variables or operators are in the frequency domain, except when marked with a hat symbol, in which case they are in the time domain. The notations $||\mathbf{A}||_S$ and $||\mathbf{A}||_F$ for a matrix $\mathbf{A}$ with elements $A_{ij}$ are the sum norm and Frobenius norm, respectively, with $||\mathbf{A}||_S = \sum_{i,j} |A_{ij}|$ and $||\mathbf{A}||_F = \sqrt{\sum_{i,j} |A_{ij}|^2}$. Unlike other transforms, the main advantage of using the focal transform for deblending is that it is intimately linked to the physics of wavefield propagation and can utilize prior knowledge on the subsurface model.

However, most of the deblending algorithms only solve this ill-posed inversion problem using blended input data without aliasing. In addition, it will be more challenging if the aliasing blended data traces are irregular sampled, resulting in the failure of some deblending algorithms. Fortunately, the extrapolation operators $\mathbf{W}_k^\pm$ could be written analytically, making the focal transform able to deal with the irregular shot and receiver sampling data by changing the $\mathbf{W}_k^\pm$ operators to the irregular locations. Although we can do the deblending process on the blended irregularly subsampled seismic data $\mathbf{P}_{\text{bl,us}}$ first and then use other methods to do the interpolation, it's straightforward to reconstruct the data after focal deblending by using one step adjoint double focal transform with regular $\widetilde{\mathbf{W}}_k^\pm$ operators, as follows:

$$\min_{\delta\mathbf{X}_1,\ldots,\delta\mathbf{X}_K} \left\{ \sum_t \sum_{k=1}^{K} ||\delta\hat{\mathbf{X}}_k||_S \right\} \text{ s.t. } \sum_\omega \left|\left| \mathbf{P}_{\text{bl,us}} - \sum_{k=1}^{K} \mathbf{W}_k^- \delta\mathbf{X}_k \mathbf{W}_k^+ \Gamma \right|\right|_F < \sigma, \Rightarrow \mathbf{P}_{\text{debl,us}} = \sum_{k=1}^{K} \mathbf{W}_k^- \delta\mathbf{X}_k \mathbf{W}_k^+, \, \mathbf{P}_{\text{rec}} = \sum_{k=1}^{K} \widetilde{\mathbf{W}}_k^- \delta\mathbf{X}_k \widetilde{\mathbf{W}}_k^+. \tag{2}$$

To quantitatively analyze the results, we use the following two expressions to evaluate the deblending and interpolation quality

$$Q_{\mathrm{debl}} = 10\log_{10}\left(\sum_{\omega}||\mathbf{P}_{\mathrm{ideal,us}}||_F^2 / \sum_{\omega}||\mathbf{P}_{\mathrm{ideal,us}} - \mathbf{P}_{\mathrm{debl,us}}||_F^2\right),\ Q_{\mathrm{rec}} = 10\log_{10}\left(\sum_{\omega}||\mathbf{P}_{\mathrm{ideal,dense}}||_F^2 / \sum_{\omega}||\mathbf{P}_{\mathrm{ideal,dense}} - \mathbf{P}_{\mathrm{rec}}||_F^2\right). \tag{3}$$

where $\mathbf{P}_{\mathrm{ideal,us}}$ is the unblended and undersampled data with aliasing. $Q_{\mathrm{rec}}$ is more focused on the final reconstruction quality comparing with the original densely sampled data $\mathbf{P}_{\mathrm{ideal,dense}}$, while $Q_{\mathrm{debl}}$ puts more emphasis on the deblending quality of the intermediate inversion process.

## Synthetic data example

A synthetic dataset was generated using finite difference modeling, using the velocity and density models shown in Figure 1(a) and 1(b), separately. Figure 2 illustrates its three common shot gathers with sources at different locations. This densely sampled dataset consists of 151 shots with a 20m spacing between source locations and 151 traces per shot. Then we placed several receivers at irregular locations and placed sources at the regular locations to model an irregularly sampled seismic dataset with aliasing as shown in Figure 3(a). The coarsely sampled dataset consists of 151 shots with 15 traces per shot (for the case of 90 % decimation). We can see the irregularity more clearly in the time slice gather at 1.52s in Figure 4(a).

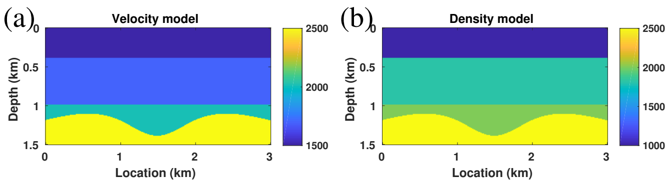


*Figure 1* *The velocity (a) and density (b) models used for creating the dataset shown in Figure 2.*

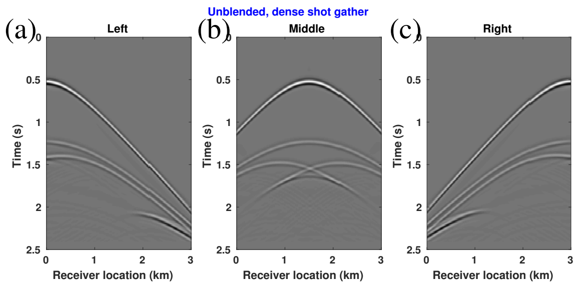


*Figure 2* *Unblended, densely sampled shot gathers with the source at (a) 0 km, (b) 1.5 km and (c) 3 km.*

To test the algorithm (2), a blending operator $\mathbf{\Gamma}$ and its adjoint $\mathbf{\Gamma}^{\mathrm{H}}$ are applied to the aliasing data (Figure 3a). The pseudo-deblended shot gather and its time slice gather are shown in Figure 3(d) and 4(d), respectively. The blending process combines two sources with random time delays from 0.1s to 0.5s. The deblended and interpolated common shot gather are shown in Figure 3(b) and 3(c). The difference profile (amplified 5 times) between the original coarsely sampled (Figure 3a) and deblended shot gather in Figure 3(e) is small enough to be ignored, demonstrating a successful deblending result with $Q_{\mathrm{debl}} = 25.28dB$. The deblending error (amplified by a factor 5) in the time slice gather (Figure 4) between Figure 4(a) and 4(b) also shows the good separation. When looking at the error profile between the original densely sampled shot gather (Figure 2a) and the interpolated shot gather (Figure 3c), as well as its time slice gather in Figure 4(f), it seems that the reconstruction error is a little big after being amplified by a factor 5, especially at the first hyperbolic event. Please note that we only use very few irregularly sampled traces (10 % used) to do the interpolation on the regular grid. In spite of this difficulty, we still get a satisfactory interpolation result (Figure 4c) with the quality factor $Q_{\mathrm{rec}}$ = 10 dB.

## Discussion

We also test this method with different percentages of decimated traces (irregularly sampled). The deblending quality (red line) and interpolation quality (blue line) are shown in Figure 5(a). It is imme-

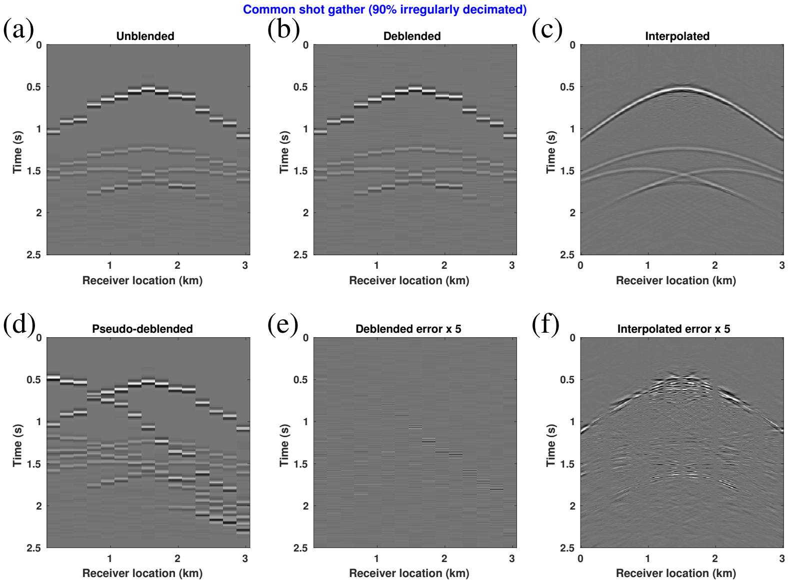


***Figure 3*** *Deblended and interpolated results in the common shot domain: (a) the coarsely sampled shot gather, (b) the deblended shot gather, (c) the interpolated shot gather, (d) the pseudo-deblended shot gather, (e) the difference between Figure 3(a) and 3(b), amplified by a factor 5, (f) the difference between Figure 2(b) and 3(c), amplified by a factor 5.*

diately obvious that the more traces we use, the more satisfactory deblended and interpolated results we get, but with more cost in data acquisition. Figure 5(b) shows the deblending quality curve of the irregularly sampled data (red line), which is slightly better than that of the regularly sampled data (blue line) when available data percentage is less than 40%.

Here we only present the interpolation result of the irregularly blended seismic data with irregularly sampled traces compared to the original, dense and regularly sampled data. According to the compressive sensing (CS) theory, it can be recovered when combining a prior knowledge is used with some suitable transforms (Donoho, 2006). However, the deblending and interpolation quality curve (Figure 5c) of the irregularly sampled blended data (red line) is slightly lower when comparing that of the regularly sampled data (blue line) using the same available percentage ($<40\%$) of the full data. So it is remarkable that for this case - using the focal transform - not much difference is observed when using regularly or irregularly sampled data, which is against the common idea of compressive sensing. For the examples in the paper, the source locations are regularly and densely placed at the surface. A next step in this research is to investigate the situation that the sources are also placed at some coarse and irregular locations.

## Conclusion

In this paper, we extended the focal deblending method to aliasing blended seismic data with irregular subsampling. The results on synthetic data demonstrate that it is possible to do the interpolation towards a regular grid using the same focal subdomains by changing the focal operators to the regular locations. This could economize a way for the future blended acquisition by using fewer measurement to reduce the survey cost while still getting a good imaging result.

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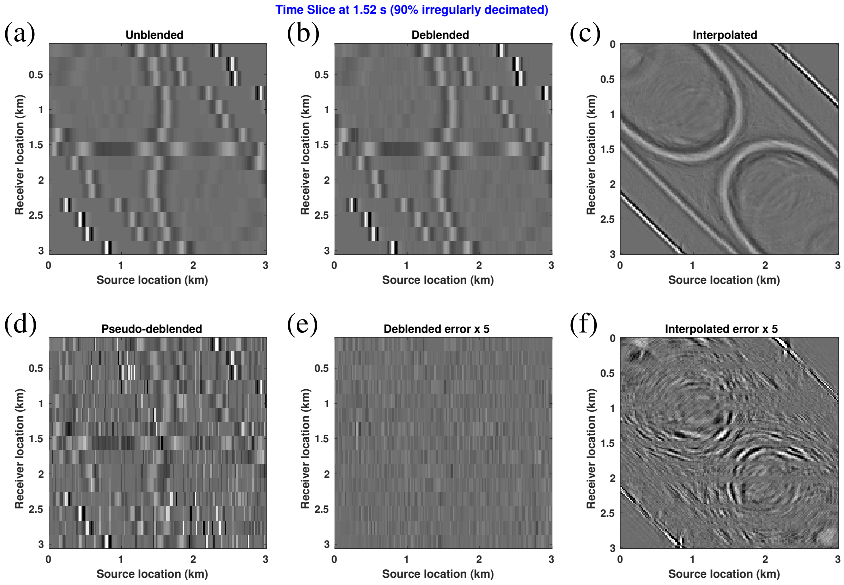


***Figure 4*** *Deblended and interpolated results in the time slice at 1.52 s: (a) the coarsely sampled data, (b) the deblended shot data, (c) the interpolated, deblended data, (d) the pseudo-deblended data, (e) the difference between Figure 4(a) and 4(b), amplified by a factor 5, (f) the difference between the time slice (1.52 s) of the dense sampled shot gather and Figure 4(c), amplified by a factor 5.*

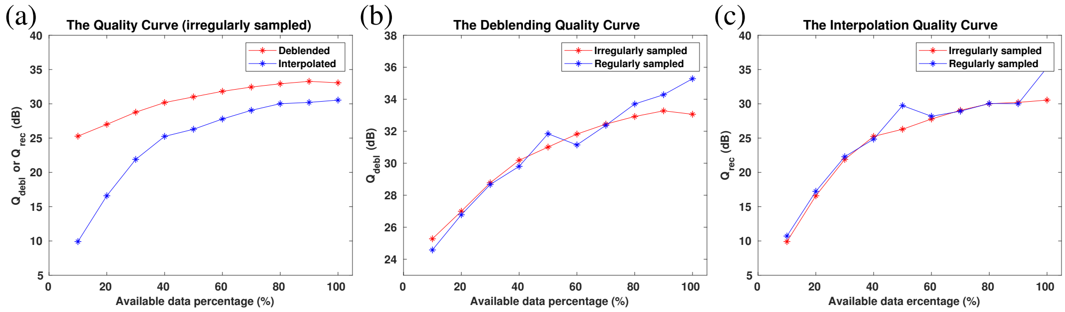


***Figure 5*** *(a) The deblending quality ($Q_{debl}$) curve and the interpolation quality ($Q_{rec}$) curve of the irregularly sampled blended data versus available percentage of the full data. The deblending quality curve (b) and the interpolation quality curve (c) versus available percentage of the full data when comparing that of the regularly sampled with the irregularly sampled blended data.*

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