Simultaneous source separation as a sequence of coherency pass operations

Daniel Blatter and Chris Leader

ABSTRACT

In conventional seismic data acquisition, sufficient time must elapse between seismic sources to prevent inteference. As a result, conventional surveys suffer from a balance between higher cost or insufficient spatial sampling. Seismic surveys acquired with multiple sources activated concurrently offer the potential advantages of a combination of denser sampling and reduced cost. In order for conventional algorithms to clearly image the data, however, they must first be deblended. Some deblending algorithms rely on a sequence of operations, including filters, transforms, mutes, and even data domain sorts, which use some criterion to remove interfering energy with minimal harm to the desired signal. The effectiveness of data deblending using these operations depends on the amount of intefering energy, the spatial proximity of the interference, the timing of the interfering sources, and other factors. This paper will demonstrate that an effective deblending algorithm makes clever use of a number of filters, mutes, transforms, and data sorts to almost completely remove interfering energy.

INTRODUCTION

Acquiring seismic field data using controlled sources is conventionally done with only one seismic source active at a time. Sufficient time must elapse between shots to avoid temporal interference (Lynn et al., 1987). In practice, this means that large seismic surveys require a significant amount of time to acquire, with corresponding implications for cost. Even so, conventional seismic surveys are often insufficiently sampled in (at least) one direction, leading to aliasing.

These difficulties – that seismic data are either insufficiently dense, time consuming, or some combination of the two - are potentially mitigated in part by using multiple sources simultaneously. For the same amount of time, a denser seismic survey can be conducted; or else for comparable density of data, the survery could be acquired in significantly less time (Beasley, 2008).

When multiple seismic sources are active simultaneously, interfering energy will be present after the raw data are windowed into gathers. This presents a challenge to imaging, as conventional imaging techniques are designed to work on conventionally acquired data. The “blended” (simultaneously acquired) data must be “deblended” before imaging, or else imaging techniques must be designed that can process the blended data simultaneously (Dai et al., 2010).

Early deblending methods include conventional imaging steps and algorithms. Lynn et al. (1987) and Beasley (2008) proposed viewing imaging algorithms including NMO and stack, Kirchoff migration and Reverse Time Migration (RTM) as coherency pass filters because the interfering energy is in the "wrong place" to be imaged coherently.

More recent methods instead select several operations (filters, transforms, mutes, etc) and combine them into one finely tuned deblending algorithm. If the interfering data can be rendered incoherent (i.e., random) in some domain or along some axis, then the deblending process can be treated as a denoising problem. When timing between interfering shots is random (the interfering shots are not synchronized) then sorting the data into common receiver, common offset, or common midpoint gathers can be considered a type of coherency pass operation that achieves this objective. Doulgeris et al. (2011), Moore et al. (2008), Mahdad et al. (2011), and Akerberg et al. (2008) make use of this property in their deblending algorithms.

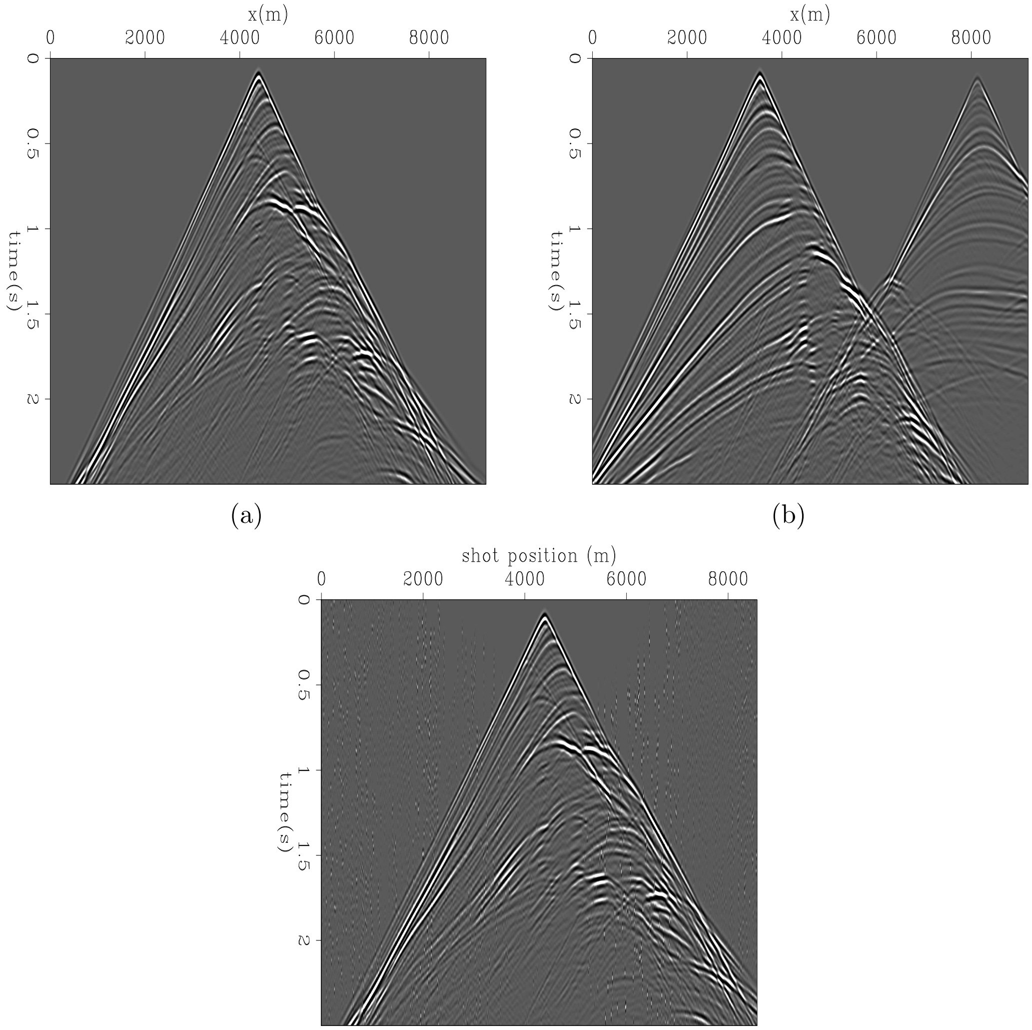
Instead of treating the interfering energy as noise, deblending can be set up as an inverse problem whose goal is to estimate the unblended data. Abma et al. (2010) use a sparsity constraint to minimize incoherent energy in the inversion, while Moore (2010) uses a sparsity constraint in the linear Radon domain. Another approach proposed by Yang and Ying (2013) uses a curvelet transform to deblend simultaneously acquired data.

What nearly all deblending methods have in common is the use of multiple operatons that apply coherency criteria in such a way as to remove nearly all interfering energy with minimal damage to the desired signal. The success of data separations using these operations, including filters, mutes, transforms, and data sorts, is sensitive to factors such as the amount of interfering energy in a gather, the randomness of the timing of interfering shots, and the spatial overlap of the desired signal with the interference.

This paper will examine several basic coherency operations that are used in many separation algorithms, as well as their sensitivity to the factors mentioned previously. A mute, a threshold and the common receiver sort will be analyzed in some detail. Then, one specific deblending algorithm proposed by Mahdad et al. (2011) will be presented to illustrate how many effective deblending algorithms may be decomposed as clever combinations of multiple coherency based operations.

COMMON RECEIVER DOMAIN SORT

While not always thought of as such, sorting data can be considered a coherency based operation in the context of simultaneous seismic source deblending. Figure 1 shows two synthetic shot gathers - one conventionally acquired and the other simultaneously acquired - and a simultaneously acquired (or "blended") receiver gather.



(a)

(b)

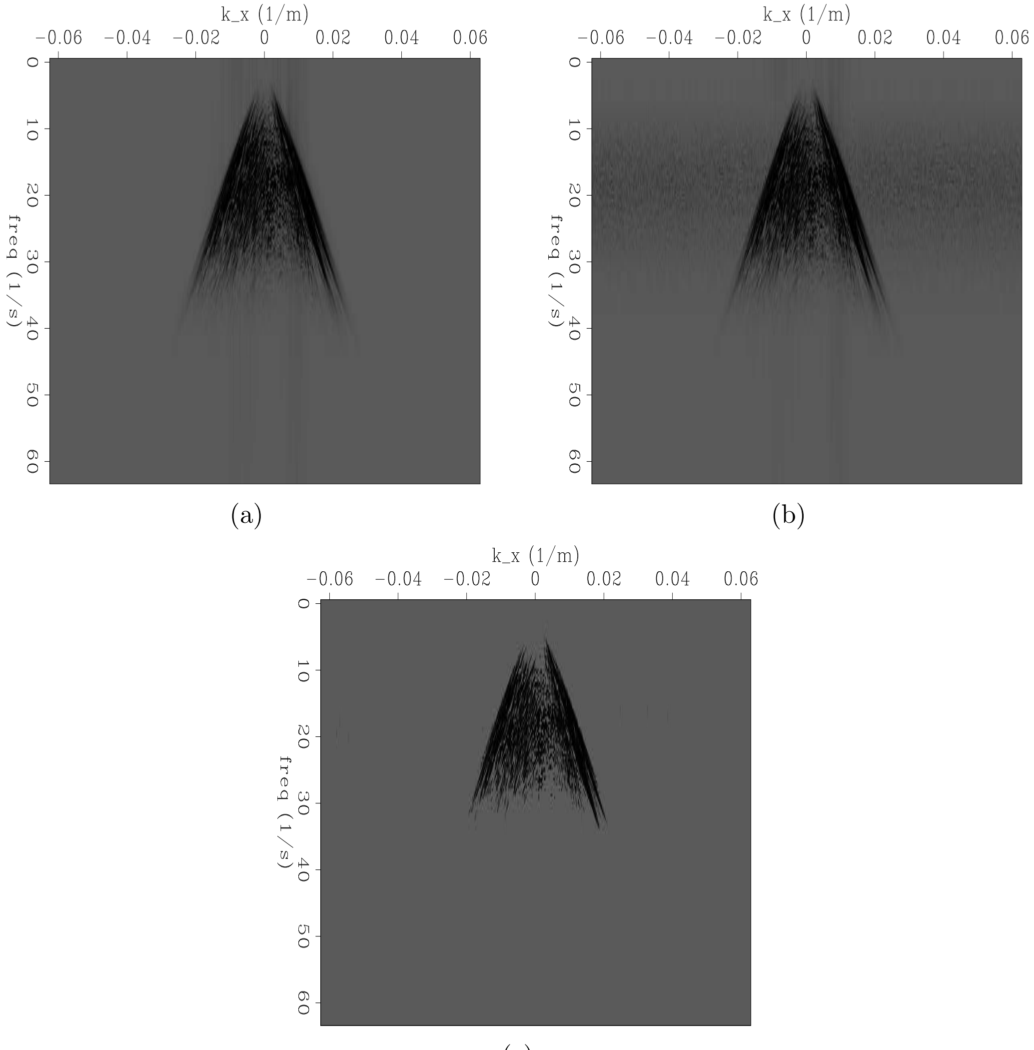
(c)

Figure 1: Synthetic common shot gather (left), with no blended data. Synthetic blended shot gather (right) with inteference. Synthetic blended receiver gather (below). Note how the energy from the interfering shots is incoherent in the spatial direction. [**CR**]

Because the timing between interfering shots was random, the common receiver sort has scrambled the interfering energy randomly, resulting in energy "spikes" in the spatial direction (the energy remains continuous in the temporal direction). An interesting point is that, because every shot is present in each common receiver gather, the interfering energy in Figure 1(c) is actually present in the same receiver gather as signal.

F-K THRESHOLD FILTER

The spectrum of conventionally acquired data lies in a narrow cone-shaped region centered around zero wavenumber. The bounds of the cone are defined by the slowest velocity events in the data domain, because these have the steepest time dip and hence the highest frequency in the spatial direction. In the case of simultaneously acquired data, the Fourier transform can take advantage of the incoherency of the interfering energy in the common receiver domain because the latter is composed essentially of random spikes which have a white spectrum in the Fourier domain.



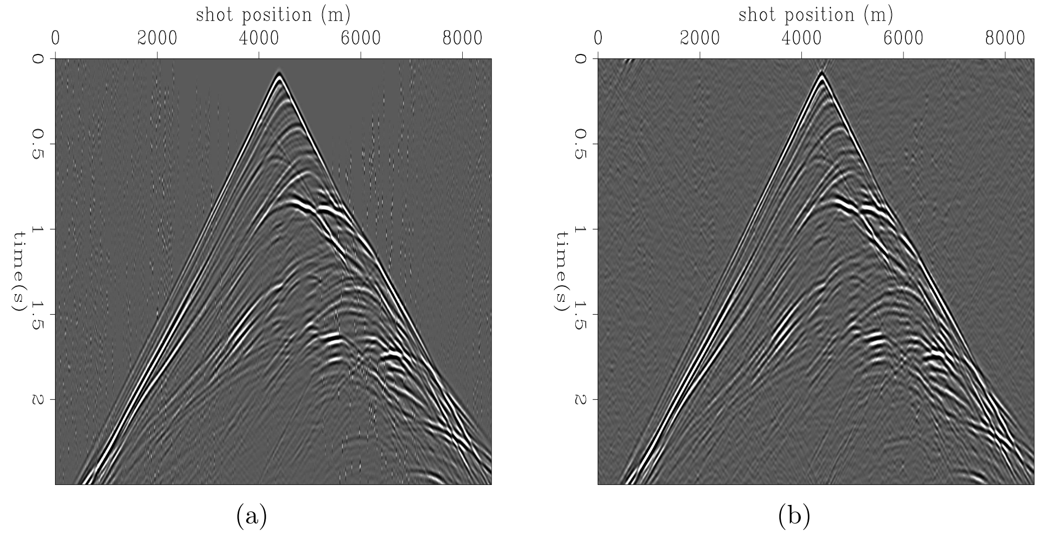
(a)

(b)

(c)

Figure 2: f-k spectrum of common shot gather (left) with no blended data, and blended receiver gather (right). Note the white sprectrum of the interfering energy in the blended receiver gather. The spectrum of the blended receiver gather after applying a 7.0 per cent threshold filter is plotted below. [**CR**]

Because the interfering energy is spread out over a much larger portion of f-k space than the signal, the amplitude of its Fourier coefficients should be lower. As a result, an f-k threshold filter that deletes any coefficient below a certain amplitude should be able to erase the interfering energy while passing some (hopefully most) of the signal. Figure 2 shows the spectrum of a synthetic, conventionally acquired shot gather in the Fourier domain alongside the equivalent for a *blended* receiver gather. The result of applying a 7.0 per cent threshold filter in the Fourier domain is shown as well. Figure 3 shows the result of thresholding in the data domain. Note how the removal of a majority of the Fourier coefficients associated with the interfering energy has replaced the spikes in the data domain with a background low amplitude wave pattern. The signal has, for the most part, remained unaffected.



(a) (b)

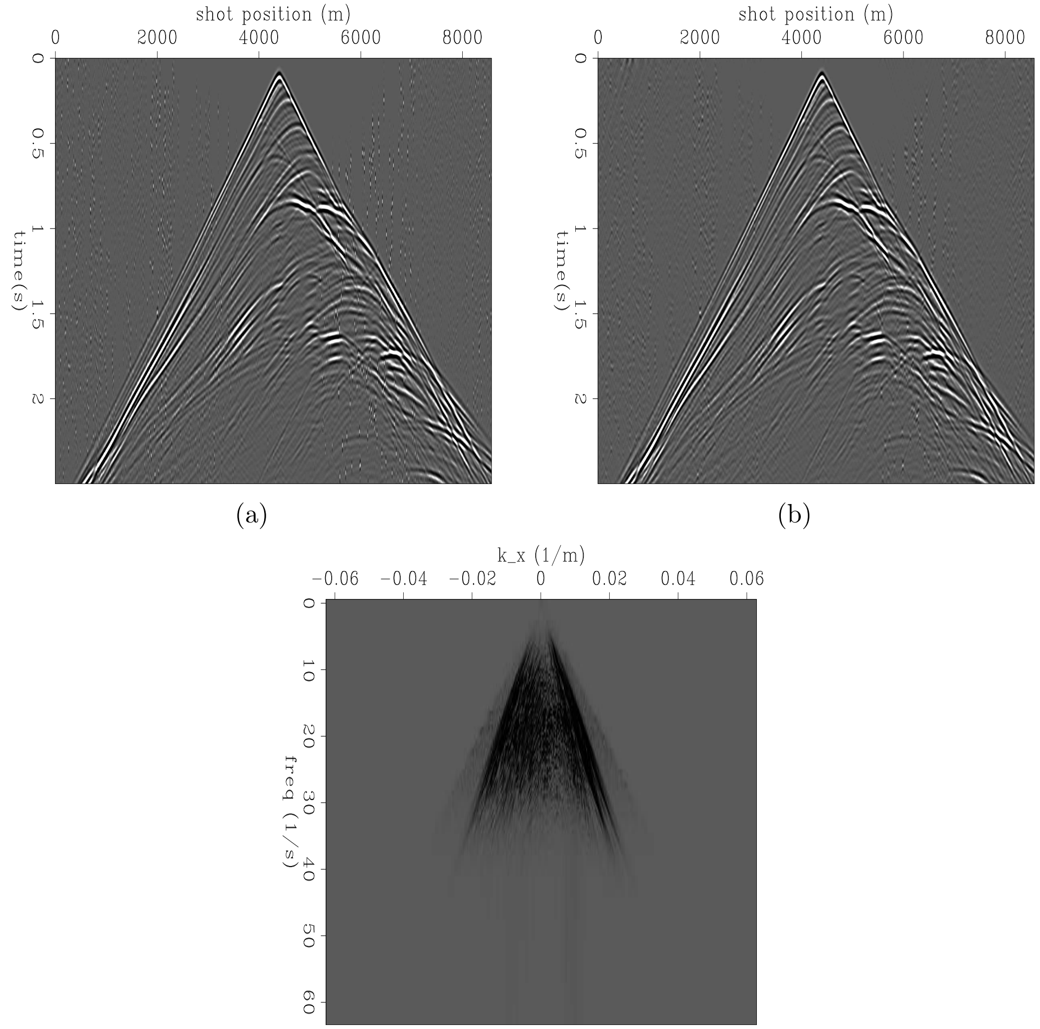
Figure 3: Partially deblended common receiver gather after a 7 per cent threshold filter was applied in f-k domain (right). The original receiver gather is plotted on the left for reference. [**CR**]

This method is fairly effective by itself so long as the interfering energy amplitudes are low in the f-k domain. If this is not the case (if the ratio of interfering energy to signal energy is high), then one is faced with a choice between raising the threshold and sacrificing more signal, or else passing (more) interfering energy. Also, the higher the interference-to-signal ratio the more pronounced the background wave pattern in the data domain will be, which risks masking low amplitude events in the signal.

F-K MUTE

In contrast to the threshold filter, a simple spatial mute in the f-k domain allows the removal of much of the interfering energy without any risk of harming the signal. In the absence of interference no energy is expected in the Fourier domain outside of the signal cone, so such energy can safely be deleted (with appropriate tapering to avoid artifacts). Figure 4 shows the results of applying the f-k mute to the same blended common receiver gather as before. The results in the data domain are shown, as well as the spectrum after muting.

The mute is effective at reducing the amplitude of the interfering energy, although the inteference itself is still quite visible. The f-k mute has the advantage of leaving the signal untouched and largely avoiding the background noise introduced by the threshold filter. The f-k mute, like its cousin, is also sensitive to the amplitude of the interfering energy. Since the mute cannot remove the interference where it coincides with the signal cone, as the former increases in amplitude more interference will remain in the data domain after muting.



(a) (b)

(c)

Figure 4: Blended receiver gather after applying f-k mute to remove interfering energy (right). Original receiver gather plotted on the left for reference. The spectrum after muting is shown below. [**CR**]

Each of the coherency pass filters discussed so far rely on the randomness of the shot timing between interfering shots. If this is not the case (i.e. if the shots are synchronized such that the time delays between interfering shots are constant throughout the survey), then the common receiver gather sort no longer acts as a coherency pass filter. In this case the interfering energy will be passed coherently like the signal. Such a situation might arise in a marine setting, where multiple sources on the same boat might be synchronized for various reasons. Obviously, a different set of coherency pass filters would be needed in this case. Such filters might include Radon transforms (linear or hyperbolic) that can distinguish energy with different time dips in the data space, enabling filtering of interfering energy in the common shot domain (provided there is sufficient spatial separation between interfering shots).

DEBLENDING ALGORITHM EXAMPLE

Deblending algorithms (as opposed to simple coherency pass filters) can be thought of as a sequence of carefully chosen coherency pass filters, designed to combine their strengths in such a way as to leave minimal interfering signal behind, producing data as if it had been acquired conventionally. Mahdad et al. (2011) propose one such algorithm, which is briefly presented here to illustrate this argument. A schematic of their algorithm is given in Figure 5.

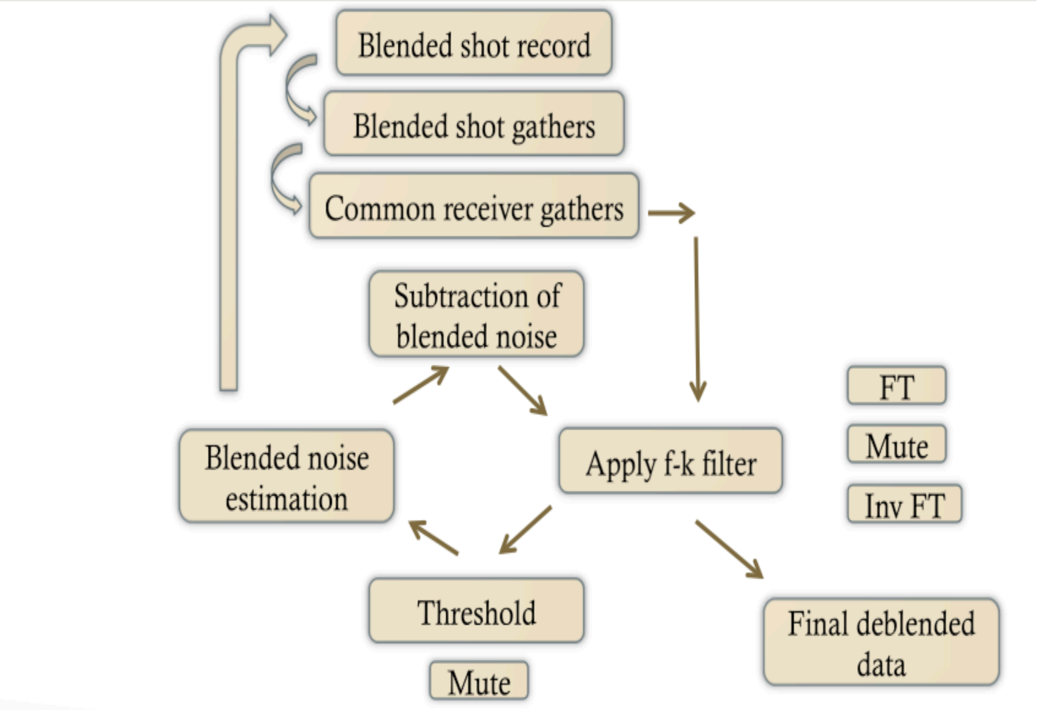


Figure 5: Schematic of the algorithm of Mahdad et al. (2011). [**NR**]

The algorithm begins with a blended shot record, containing all shots for the entire survey. This is sorted first into individual common shot gathers, then common receiver gathers. These two steps, though seemingly trivial, are actually of critical importance to the algorithm. A common receiver gather is then Fourier transformed, where a mute is applied outside the signal cone. After application of an inverse Fourier transform, a threshold filter is applied in the data domain. The objective of this is to obtain part of the signal without any contaminating interference. While the interfering energy in the data domain is initially of comparable amplitude to that of the signal (the interference is in fact copies of the signal), the f-k mute ensures that the former has been sufficiently reduced to allow a threshold filter to pass only signal. An example of the output of this step is shown in Figure 6.

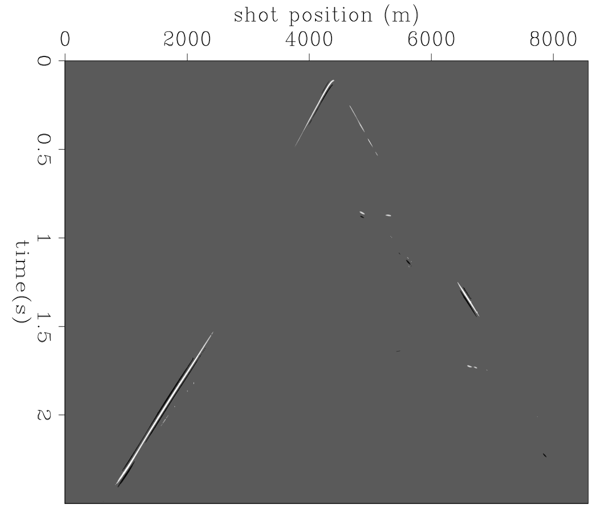


Figure 6: Output of data threshold step, containing part of the desired signal but with none of the interfering energy. [**CR**]

The importance of this is evident in the next step: the portion of signal output by the previous step is sent through the sorting process from blended shot record to common receiver gather, and in the process is copied and reappears as both signal and inteference in the (admittedly sparse) output receiver gather. Recall the comment made previously that the interfering energy in a common receiver gather comes from the signal in the same gather. In other words, the sorting steps reveal where the signal from Figure 6 shows up as interference in other traces. This can then be subtracted from those traces (before any filtering was performed), producing a gather that contains less interfering energy than before. This process is then repeated, lowering the threshold in the data domain each time as more and more interfering energy is removed, allowing more and more interference to be estimated by the subsequent re-sorting step.

CONCLUSION

Source separation (deblending) often involves the application of multiple coherency pass filters. By themselves, each filter is insufficient to produce full data separation, but combined in an intelligent manner they can form an effective deblending scheme. Future work will include application of coherency pass filters using various Radon transforms, in addition to those implemented here in the Fourier domain.

REFERENCES

Abma, R., T. Manning, M. Tanis, J. Yu, and M. Foster, 2010, High quality separation of simultaneous sources by sparse inversion: Presented at the 72nd EAGE Conference & Exhibition.

Akerberg, P., G. Hampson, J. Rickett, H. Martin, J. Cole, et al., 2008, Simultaneous source separation by sparse radon transform: Presented at the 2008 SEG Annual Meeting.

Beasley, C. J., 2008, A new look at marine simultaneous sources: The Leading Edge, **27**, 914–917.

Dai, W., C. Boonyasiriwat, G. T. Schuster, et al., 2010, 3d multi-source least-squares reverse time migration: Presented at the 2010 SEG Annual Meeting.

Doulgeris, P., A. Mahdad, G. Blacquiere, et al., 2011, Iterative separation of blended marine data: discussion on the coherence-pass filter: 81st Annual International Meeting, SEG, Expanded Abstracts, 26–31.

Lynn, W., M. Doyle, K. Larner, and R. Marschall, 1987, Experimental investigation of interference from other seismic crews: Geophysics, **52**, 1501–1524.

Mahdad, A., P. Doulgeris, and G. Blacquiere, 2011, Separation of blended data by iterative estimation and subtraction of blending interference noise: Geophysics, **76**, Q9–Q17.

Moore, I., 2010, Simultaneous sources–processing and applications: Presented at the 72nd EAGE Conference & Exhibition.

Moore, I., B. Dragoset, T. Ommundsen, D. Wilson, D. Eke, C. Ward, et al., 2008, Simultaneous source separation using dithered sources: Presented at the 2008 SEG Annual Meeting.

Yang, H. and L. Ying, 2013, Synchrosqueezed curvelet transform for 2d mode decomposition: arXiv preprint arXiv:1310.6079.