SEPARATION OF BLENDED DATA BY SPARSE INVERSION BASED ON THE RECIPROCITY THEOREM

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ABSTRACT

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Recently a great change of mindset in seismic acquisition has occurred and much attention has been drawn to blended acquisition. Different sources at several locations are shot in an overlapping fashion and blended records are acquired, so that acquisition efficiency and potentially image quality can be significantly improved. The key factor of blended acquisition is source separation, which is the procedure of recovering data as if they were acquired in the conventional survey. From the mathematics point of view, it can be formulated as solving an underdetermined equation such as $Ax = b$, yet a simple least-square inversion is only able to get pseudodeblend data where the blending noises are not able to be removed. In this paper we find that in the 2D regularization acquisition system, the blended data in common receiver domain can be simply connected with that in common source domain according to the reciprocity theorem, so that the above equation would be more determined to be solved. While in the implementation procedure, spgL1 norm basic pursuit sparse inversion algorithm is utilized calculating the reflection coefficients of the single source data, and then the deblended data are acquired via convolution. Ideal results could be produced in field data tests.

KEY WORDS: blended data, source separation, underdetermined equation, reciprocity theorem, L1 norm basic pursuit.

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INTRODUCTION

Seismic acquisition is a trade-off between economy and quality. Conventional acquisition surveys are designed such that the time intervals between successive shots are sufficiently large to avoid the interference between different source responses. However, in this situation both the image quality and measure parameters, such as azimuths and sampling density may not achieve the best. Recently a great change of mindset in seismic acquisition has occurred which is known as blended acquisition or simultaneous acquisition, where sources at different locations are shot in an overlapping fashion which significantly improved the acquisition efficiency and potentially image quality.

The concept of simultaneous shooting for vibroseis-type sources has been proposed by Silverman (1979). Sallas et al. (1998) and Krohn et al. (2003) developed the High Fidelity Vibratory Seismic (HFVS) method for the purpose of increase the productivity and acquisition efficiency. Bagaini (2006) compared different kinds of simultaneous vibroseis acquisition methods such as simultaneous sweeps, cascaded sweeps, and slip sweeps. Beasley et al. (1998) and Beasley (2008a,b) proposed simultaneous impulsive sources seismic acquisition with large spacing between illuminating shots. Vibroseis acquisition by means of Simultaneous Pseudorandom Sweep Technology (SPST) has been suggested by Sallas et al. (2008). Berkhout (2008) introduced blended seismic acquisition where different sources are shot with certain time delays, and extended it to the double blending (Berkhout et al., 2009), where incoherent shooting and incoherent receiving are combined together. Ikelle (2009) and Ikelle and Sturzu (2009) proposed a conic coding compression method to generate multishot data from the single source data. Ikelle (2010) fully introduced and discussed the collection, simulation and processing of multisource blended data.

Deblending is the procedure of recovering data as if they were acquired in the conventional way. Several approaches have been developed to attenuate the blending noise: Ikelle (2007) addressed deblending as a blind signal separation with phase-encoding and independent component analysis. Lin and Herrmann (2009) introduced an inversion approach constraining the separated data to be sparse in the curvelet domain. Moore (2010) regularizes this inversion in the Radon domain with a sparsity constraint, which is also utilized by Abma and Yan (2009) and Abma et al. (2010) to minimize the incoherent signals in the blended data. Mahdad et al. (2011) and Doulgeris et al. (2011) predicted and subtracted the blending noise iteratively with coherency constraint, which was developed by us (Tan et al., 2012) to improve the separation quality and efficiency. Wapenaar et al. (2012) introduced a direct inversion method without any above constraints.

From the mathematics point of view, deblending can be regarded as solving an underdetermined equation such as Ax = b, yet a simple least-squares procedure cannot remove the blending noise. In this paper we focus on the blended acquisition system instead of the inversion algorithm for the purpose of solving this ill posed inversion problem. According to our derivation in the regularized 2D acquisition system, the blended data in common receiver domain can be connected with that in common source domain, which making the above mentioned equation more determined. When applied to a numerically blended dataset, reflection coefficients of single source gather is calculated using spgL1 norm basic pursuit sparse inversion algorithm at first, and then separation results are acquired via convolution. Field data test shows that our method can get high quality separation results, which verified our theory and derivation.

METHOD AND MODEL TEST

Data matrix and conventional survey

Fig. 1 depicts a regularized acquisition system where the detectors are fixed stationary while the source firing from the position of one detector to another. In the conventional survey, the time intervals between the firing of successive sources are set large enough.

Berkhout (1982) introduced the so-called data matrix P that can express the seismic records conveniently. Seismic records are Fourier transformed and rearranged by every frequency component ω, and get the data matrix P in the frequency domain. As illustrated in Fig. 2, every element of P corresponds to a complex valued frequency component of a recorded trace, each column represents a common source gather, whereas each row represents a common receiver gather. Obviously in this system, seismic records in common source domain are exactly the same as that in common receiver domain due to the reciprocity theorem. This is usually used in the marine seismic acquisition, when the negative offset data are not recorded actually, are able to be retrieved by reciprocity. The regularized survey system is very useful and convenient for seismic data processing such as SRME. However the actual field acquisition system is not always regularized, yet various preprocess such as interpolation could be used for the regularization.

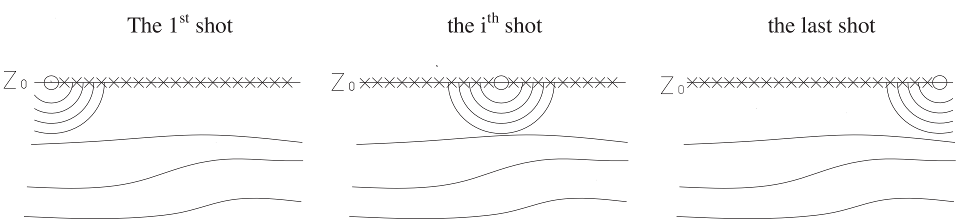

Fig. 1. The 2D regularized survey system.

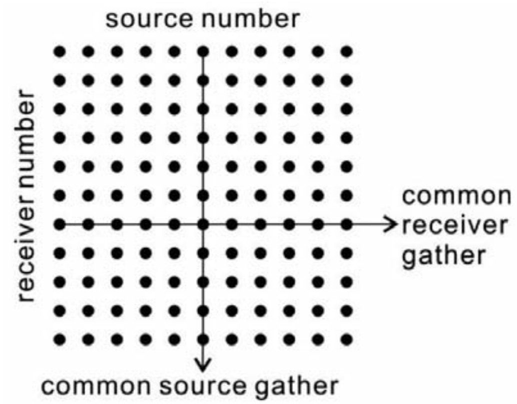

Fig. 2. Schematic representation of the data matrix. In the frequency domain every element represents a frequency component, while in the time domain represents a signal response.

In our model test, a regularization acquisition system with 256 receivers and 256 sources is designed. The source interval and receiver interval are both 10 meters. There are totally 256 source records been acquired and each one contains 256 traces and 500 time samples. The 60th and the 188th source gather are shown in Fig. 3.

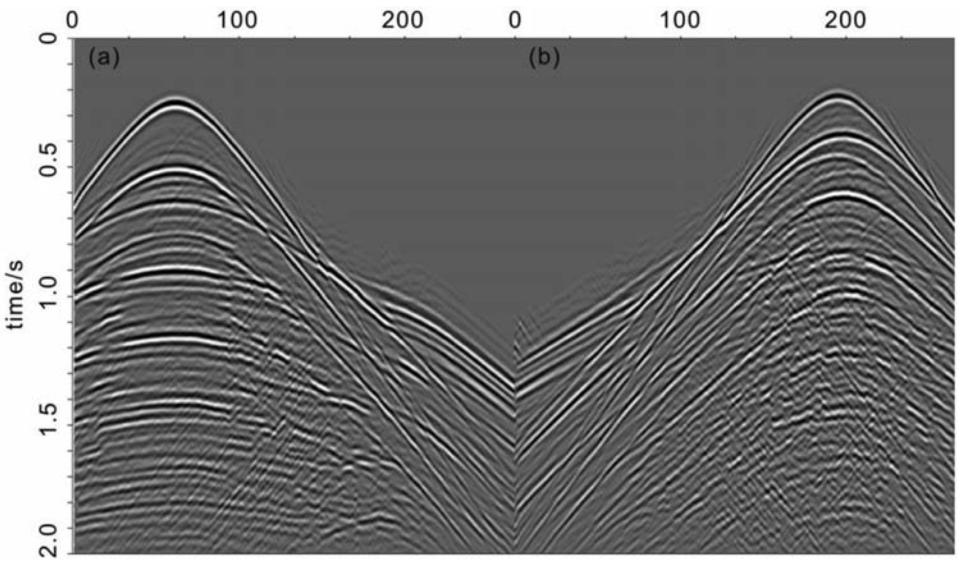

Fig. 3. Unblended data: (a) the 60th and (b) the 188th source gather.

Blended survey

Ikelle (2009) proposed that seismic waves can be generated from several locations simultaneously instead of one single-source location at a time. Berkhout (2008) introduced that blending can be easily written as a multiplication of the data matrix with a blending matrix:

$$P_{bl} = P\Gamma \quad , \tag{1}$$

where P_{bl} is the blended data matrix, blending matrix Γ contains the blending parameters. Each column of Γ_n is related to a blended shot record and its elements Γ_{mn} are the source codes that can be phase and/or amplitude terms. In the simple case of a marine survey with random firing times, $\Gamma_{mn} = e^{-j\omega\tau_{mn}}$ is a linear phase term that expresses the time delay τ_{mn} given to source m in blended source array n. In this paper we focus on the simplest situation where the blended sources are shot without any phase encoding, which means $\Gamma_{mn} = 1$. In this case the time slices of P are available for expression and eq. (1) could be expressed in the time domain.

In our model test, every two sources 1270 m apart from each other are blended together and totally 128 blended source records are acquired. The blended survey can be formulated as follow: where $P_{(i)}$ is the i-th single source gather and $P_{bl(i)}$ is the i-th blended source gather:

$$\left(P_{(1)} \cdots P_{(256)}\right) \begin{bmatrix} 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & 1 \end{bmatrix} = \left(P_{bl(1)} \cdots P_{bl(128)}\right) \quad . \tag{2}$$

For simplifying both the $P_{(i)}$ and $P_{bl(i)}$ are divided into two parts: the former 128 traces $P_{(i,a)}$, $P_{bl(i,a)}$ and the latter 128 traces $P_{(i,b)}$, $P_{bl(i,b)}$:

$$\begin{pmatrix} P_{(1,a)} & \cdots & P_{(256,a)} \\ P_{(1,b)} & \cdots & P_{(256,b)} \end{pmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{pmatrix} P_{bl(1,a)} & \cdots & P_{bl(128,a)} \\ P_{bl(1,b)} & \cdots & P_{bl(128,b)} \end{pmatrix} \quad . \tag{3}$$

Fig. 4 shows the 60th blended source gather which is taken as an example of our model test:

$$\begin{pmatrix} P_{(60,a)} & P_{(188,a)} \\ P_{(60,b)} & P_{(188,b)} \end{pmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{pmatrix} P_{bl(60,a)} \\ P_{bl(60,b)} \end{pmatrix} \quad . \tag{4}$$

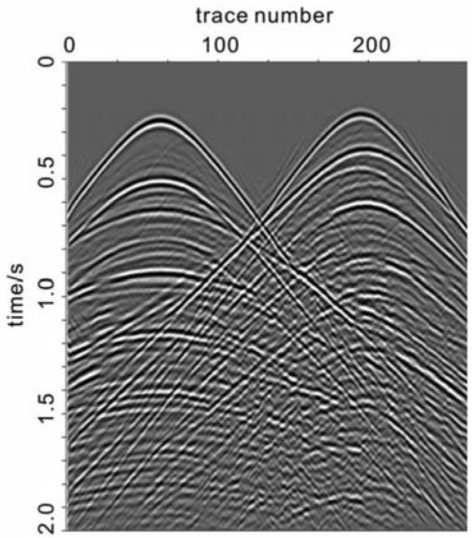

Fig. 4. The 60th blended source record.

Pseudodeblend data

Obviously eq. (4) is underdetermined (i.e., P_{bl} has fewer columns than P), means that it is ill-posed. However, the pseudodeblend results could be calculated according to least-squares inversion which corresponds to the transpose of the blending data matrix:

$$\Gamma^{-1} = [\Gamma^T\Gamma]^{-1}\Gamma^T \quad , \tag{5}$$

$$P' = P_{bl}\Gamma^T \quad , \tag{6}$$

$$P' = \begin{pmatrix} P_{bl(60,a)} \\ P_{bl(60,b)} \end{pmatrix} [1 \quad 1] = \begin{pmatrix} P_{bl(60,a)} & P_{bl(60,a)} \\ P_{bl(60,b)} & P_{bl(60,b)} \end{pmatrix} \quad . \tag{7}$$

where P′ represents the pseudodeblend data which are shown in Fig. 5. Physically they are just two copies of the blended data so the blending noises are not able to be removed at all.

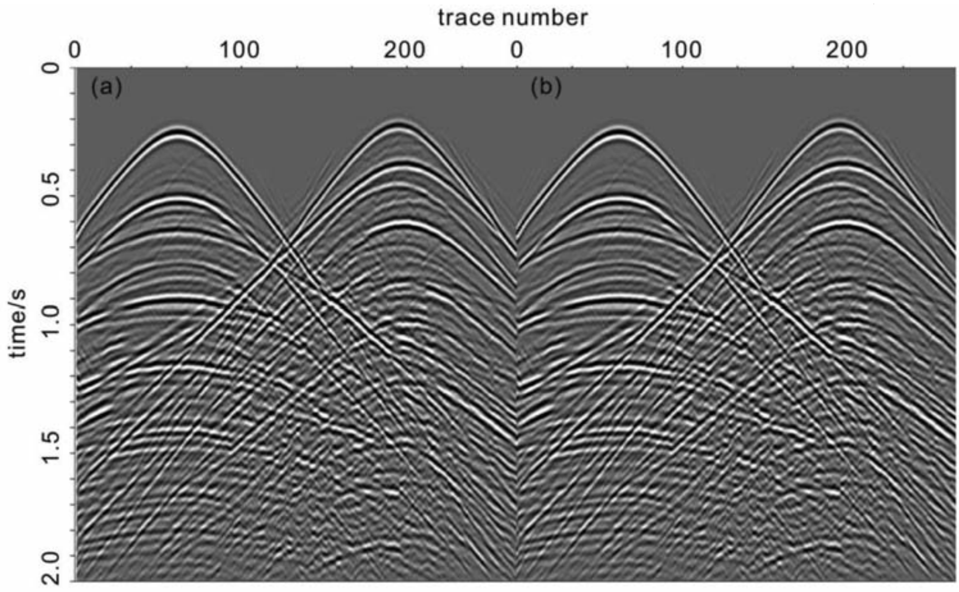

Fig. 5. Pseudodeblend data.

Combination of the blended data in different domain

Mathematically this equation is too underdetermined to be solved well just with the mathematic tools. Fortunately, seismic records have their unique characteristics which are different from the ordinary signals. For the purpose of making this ill posed problem less underdetermined, we take the transpose for both sides of (2).

$$\left(\left(P_{(1)} \cdots P_{(256)}\right) \begin{bmatrix} 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & 1 \end{bmatrix} \right)^T = \left(P_{bl(1)} \cdots P_{bl(128)}\right)^T \quad . \tag{8}$$

In the data matrix P and P_{bl}, each column represents a common source record, whereas each row represents a common receiver record. So when the transpose is taken for it, each column will represent a common receiver record, whereas each row will represent a common source record instead. So (8) is transformed into (9):

$$\begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & \ddots & 0 & 0 & \ddots & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \left(P_{cdg(1)} \cdots P_{cdg(256)} \right) = \left(P_{blcdg(1)} \cdots P_{blcdg(256)} \right) \quad . \tag{9}$$

P_{cdg} means the common receiver gathers of P, P_{blcdg} means the common receiver gathers of P_{bl}. When we take the transpose for P, its columns $P_{(i)}$ is replaced by the rows $P_{cdg(i)}$. In our regularization system, the common source gathers $P_{(i)}$ are exactly the same as the detector gathers $P_{cdg(i)}$ due to the reciprocity theorem: the seismic data fired from the i-th source and received by the j-th trace $P_{(i,j)}$ is exactly the same as that fired from the j-th source and received by the i-th trace $P_{(j,i)}$. So the transpose of data matrix P is still itself:

$$P^T = \begin{pmatrix} P_{(1,1)} & \cdots & P_{(256,1)} \\ \cdots & \cdots & \cdots \\ P_{(1,256)} & \cdots & P_{(256,256)} \end{pmatrix}^T = \begin{pmatrix} P_{(1,1)} & \cdots & P_{(1,256)} \\ \cdots & \cdots & \cdots \\ P_{(256,1)} & \cdots & P_{(256,256)} \end{pmatrix} = \begin{pmatrix} P_{(1,1)} & \cdots & P_{(256,1)} \\ \cdots & \cdots & \cdots \\ P_{(1,256)} & \cdots & P_{(256,256)} \end{pmatrix} = \mathrm{P} \, . \tag{10}$$

So eq. (9) can be derived into:

$$\begin{bmatrix} 1 & 1 \end{bmatrix} \begin{pmatrix} P_{(1,a)} & \cdots & P_{(256,a)} \\ P_{(1,b)} & \cdots & P_{(256,b)} \end{pmatrix} = \left(P_{blcdg(1)} \cdots P_{blcdg(256)} \right) \quad . \tag{11}$$

In our example:

$$\begin{bmatrix} 1 & 1 \end{bmatrix} \begin{pmatrix} P_{(60,a)} & P_{(188,a)} \\ P_{(60,b)} & P_{(188,b)} \end{pmatrix} = \left(P_{blcdg(60)} \quad P_{blcdg(188)} \right) \quad . \tag{12}$$

The blended common receiver gathers are shown in Fig. 6.

Finally we combine (4) with (12), and get the following equation, which is obviously less underdetermined than the above two:

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{pmatrix} P_{(60,a)} \\ P_{(60,b)} \\ P_{(188,a)} \\ P_{(188,b)} \end{pmatrix} = \begin{pmatrix} P_{bl(60,a)} \\ P_{bl(60,b)} \\ P_{blcdg(60)} \\ P_{blcdg(188)} \end{pmatrix} \quad . \tag{13}$$

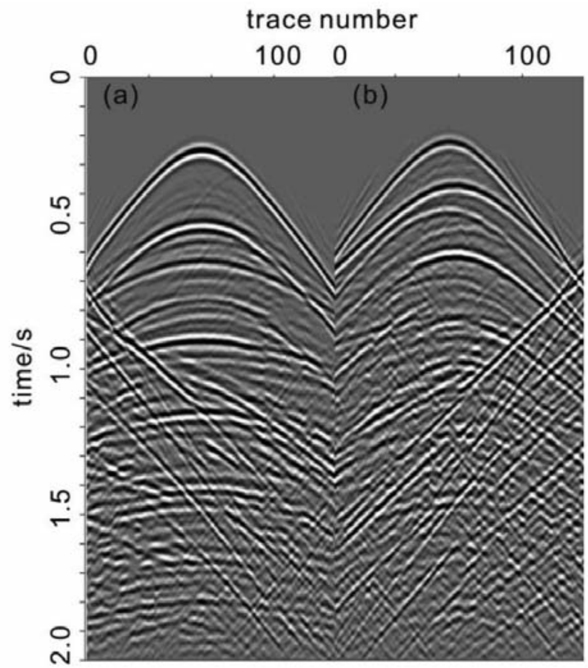

Fig. 6. Blended common receiver records: (a) the 60-th and (b) the 188-th.

Fig. 7 shows the least square inversion results, where the blending noise is attenuated to some extent, but also there are some other noises being introduced into the separation results. SpgL1 norm basic puisuit (van den Berg and Friedlander, 2008) is an ideal method for solving the sparse solution of underdetermined equations, which is suitable for our inversion problem. For the seismic records that are not sparse in the time domain, sparse deconvolution is adopted at first and blended reflection coefficients r_{bl} are acquired. So eq. (13) is transformed into eq. (14).

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{pmatrix} r_{(60,a)} \\ r_{(60,b)} \\ r_{(188,a)} \\ r_{(188,b)} \end{pmatrix} = \begin{pmatrix} r_{bl(60,a)} \\ r_{bl(60,b)} \\ r_{blcdg(60)} \\ r_{blcdg(188)} \end{pmatrix} \quad . \tag{14}$$

After that the reflection coefficients of single source data r are calculated according to (15):

$$\min \| r \|_1 \ \text{ subject to } \ Ar = r_{bl} \quad . \tag{15}$$

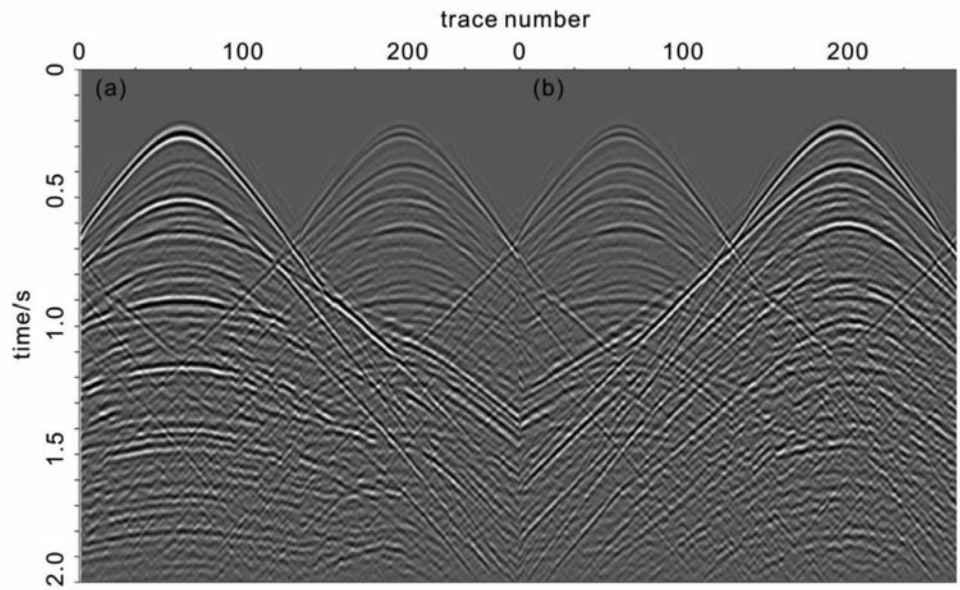

Fig. 7. Deblend results according to (13): (a) the 60th and (b) the 188th source gather.

Then we get the final separation results via convolution. As illustrated in Fig. 8, the two shot records have been separated well. The signal-to-blending noise ratio (S/N) is calculated as follows:

$$S/N = 20\log_{10}[P_{rms}/(P_i - P)_{rms} \quad , \tag{16}$$

where the subscript rms stands for root mean square; the mean being computed over all elements of P. The S/N of blended data is around 0db which means the signals are almost equal to the blending noises. While the separation results are close to the unblended records, with S/N around 15.16 db.

FIELD DATA TEST

We have simulated a 2D blended marine survey based on a subset of the unblended data set which is acquired in the East China Sea. The traditional acquisition design consists of one streamer with the source interval of 50 m and the detector interval of 25 m. There are totally 75 sources and each one contains 150 receivers and 600 time samples. The missing source records are calculated via interpolation, and the negative-offset traces are obtained according to reciprocity. In addition, the missing near-offsets were obtained by interpolation.

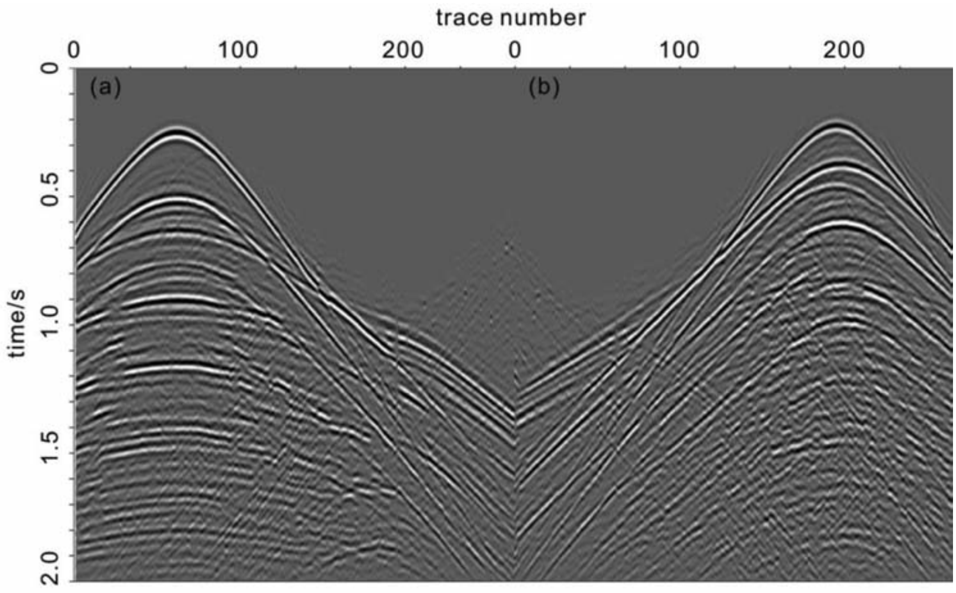

Fig. 8 Deblend results according to (14) and (15): (a) the 60th and (b) the 188th source gather.

Finally we get 150 shot records with 150 traces. The 40th and 115th source gathers are shown in Fig. 9. While in the blended acquisition, we assume that there are two boats 1850 m apart from each other firing simultaneously. So every two sources with constant distance of 1850 m are fired without any phase or amplitude terms and the 40th blended source records are shown in Fig. 10. Separation results are shown in Fig. 11 which are close to the ideal output, with S/N around 17.2 db.

CONCLUSION and DISCUSSION

Blended seismic acquisition is able to achieve better efficiency and potentially image quality than the conventional method. The key is whether we are able to get the high quality separated single source data, so that the conventional processing could be carried on. In the future, the processing of blended data would probably be the direct imaging without deblending. However, even though a deblending algorithm may still be applicable as a valuable preprocessing tool especially when the high quality pre-stack data are desired.

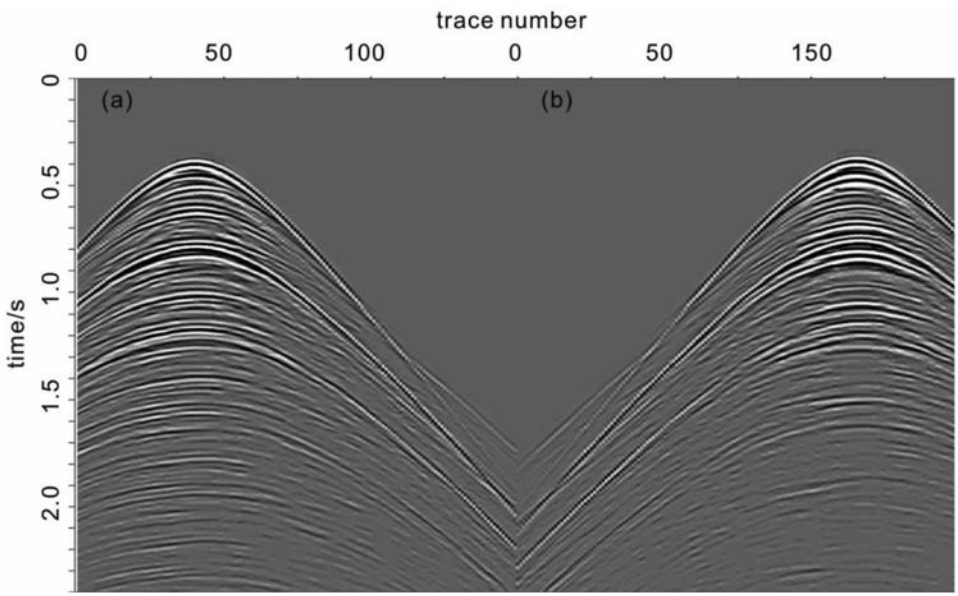

Fig. 9. Unblended data: (a) the 40th and (b) the 115th source gather.

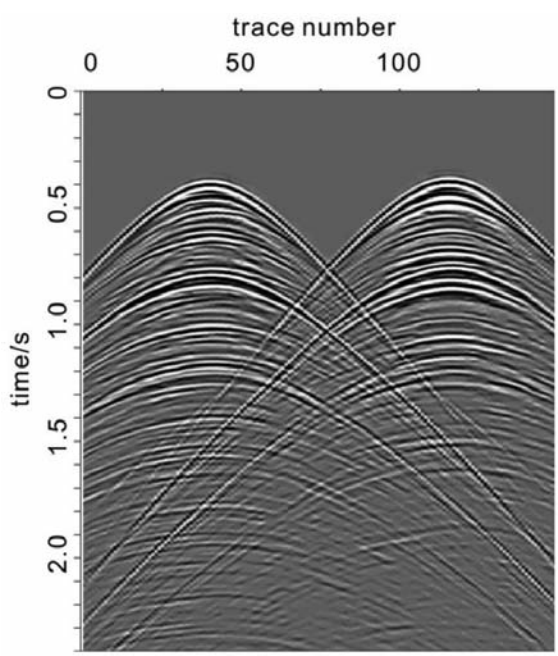

Fig. 10. The 40th blended source records.

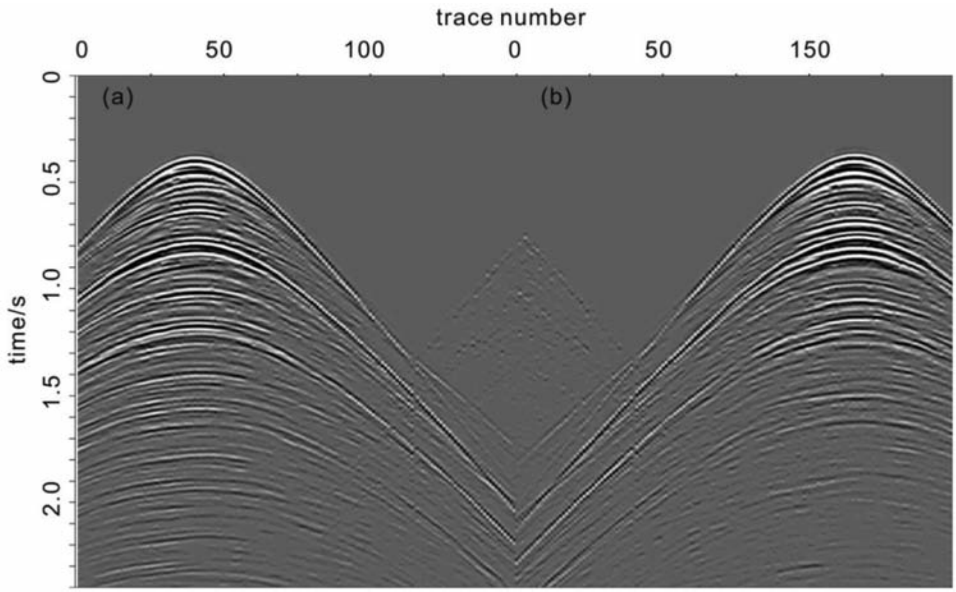

Fig. 11. Deblended data: (a) the 40th and (b) the 115th source gather.

In this paper, a sparse inversion deblending method based on reciprocity theorem is introduced. We have demonstrated that in a regularized 2D acquisition system, with the combination of blended data in different domain, blended records can be separated by a simple inversion algorithm. Although most of the marine seismic surveys could not fulfill this due to the missing shot records and negative offset records, we still can regularize the survey system via interpolation and reciprocity etc. While dealing with more complicated acquisition system such as OBC or 3D situation, interferometry would be available for the regularization, which will be shown in our later papers. We have applied a simple implementation of our scheme to a field data set that are blended numerically, ideal results could be produced.

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