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Separability of simultaneous source data based on distribution of firing times

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Summary

Simultaneous source acquisition has been recognized as an important way of improving the efficiency and quality of seismic acquisition. Recently, many methods have been developed for separating the blended sources such that data acquired can be used into the conventional processing procedures. The common goal is to take the interferences from closely fired shots under control. In this paper, we study the separability of simultaneous source data based on different distributions of firing time. An inversion method named iterative rank reduction has been applied to estimate the unblended data from the blended acquisition. We also adopt the Monte Carlo test to analyze the relation between the firing time patterns and the signal to noise ratio (SNR) after deblending. Insights can be gained towards an optimal firing scheme for separating the blended sources.

Introduction

Simultaneous source acquisition, or blended acquisition, illustrates firing more than one seismic source at close time. The responses are then recorded by a set of receivers. The key is to make interferences appear incoherent in common receiver, common offset and common midpoint gathers by randomization of time delays (Hampson et al., 2008). Direct processing steps like pre-stack time migration and stacking are considered sufficient to suppress overlaps in 3D acquisition (Lynn et al., 1987; Krey, 1987). However, problems may rise when performing detailed analysis, such as AVO inversion and time-lapse seismic monitoring (Ayeni et al., 2011). Coherent pass filters have been applied in $f-k$ (Spitz et al., 2011; Huo et al., 2009) and $f-x$ (Maraschini et al., 2012) domains for suppressing the incoherent interferences. Better separation was achieved by transforming data to other domains, such as Radon (Akerberg et al., 2008; Moore et al., 2008), Fourier (Abma et al., 2010; Mahdad et al., 2011) and Curvelet (Lin and Herrmann, 2009; Mansour et al., 2012) domain, where the coherent constraints can be effectively implemented in terms of sparsity.

Although a variety of methods can be applied to separate and process simultaneous source data, criterion for the firing scheme has not been well studied. Different parameters, such as firing time delay and distances between the blended sources, would have significant impacts on the separation results. An inevitable question is how we can come up with an ideal firing mode that ensures the quality of separation and following processing steps. In this paper, we go through the Iterative rank reduction (IRR) method that is capable of separating seismic data from simultaneous source acquisition (Cheng and Sacchi, 2013). Monte-Carlo based tests with three different types of firing time distributions are adopted to test the validity of source separation. We consider this work as a starting point of optimizing the firing times in seismic acquisition design.

Source separation method

We use the matrix representation of seismic data proposed by Berkhout (2008). Data acquired from conventional seismic acquisition can be arranged into the so-called data matrix D. Each row of D represents a shot record and each column corresponds to a receiver gather. If we blend the sources with some small, random time delays, data acquired from simultaneous source acquisition D^{obs} can be expressed by

$$D^{obs} = \Gamma D, \tag{1}$$

where Γ is the blending operator that introduces small random phase shift to each source in frequency domain. Let's consider Equation (1) as a linear projection. The blending system is under-constrained as the signal received in each detector contains information from multiple sources. If we assume a seismic data set is composed of a superposition of linear events, the data can be expressed via a low rank matrix. The randomized interferences from simultaneously fired sources would increase the rank of spectral matrices in each common receiver gather. Low rank constraints can be imposed while honoring the blending system of observation. We can set up the following optimization problem:

$$min \quad \|D^{obs} - \Gamma D\|_2^2 \quad s.t. \quad rank(D) = k \;, \tag{2}$$

where k is the number of dips in a seismic section. Cheng and Sacchi (2013) show that Equation (2) can be solved via the projected gradient method. In each iteration, we minimize the cost function by updating model in the gradient descent direction. The solutions are then projected to a set of low (known) rank matrices

$$\begin{aligned} x_i &= D_i - \lambda \Gamma^* (\Gamma D_i - D^{obs}) \\ D_{i+1} &= P(x_i) \;. \end{aligned} \tag{3}$$

Γ^* is the adjoint operator also called pseudo-deblending, which implies the process of shifting time delays back and decomposing the blended shot into conventional unblended shot gathers. The projection operator P is given by

$$P[x] = S^* \sum_i R_k W_i S[x] \tag{4}$$

where S denotes sorting to common receiver gathers, W_i is the localized i-th patching window in common receiver domain $(t-x)$, R_k is the rank reduction projection operator implemented by Singular Spectrum Analysis (SSA) and S^* means sorting back to common source gathers after window patching. The window functions W_i are designed with overlaps that honor a partition of unity $\sum_i W_i = 1$.

Evaluation of separability on firing schemes

In this paper, we study one special case of simultaneous source acquisition. We assume one vessel covering the whole survey area firing continuously without waiting for air gun responses. The receivers are ocean bottom nodes. The sources and receivers are deployed on a regular spatial grid. The firing time of the nth source is defined by

$$t_n = t_{n-1} + \delta t_n = \sum_{i=1}^{n} \delta t_i, \tag{5}$$

where δt_n is the time delay for the nth shot. If we use δt_0 to denotes the regular firing time interval for conventional seismic acquisition, we can define a compression rate α to denotes the acquisition time used for simultaneous source acquisition

$$\alpha = \frac{\bar{\delta t}}{\delta t_0}, \tag{6}$$

where $\bar{\delta t}$ is the expectation of time delays in blended acquisition. For example, if α equals to 0.5, the acquisition time using simultaneous sources is 50 % of the conventional acquisition. Figure (1) shows an example of the aforementioned acquisition design. The compression rate is 0.5 in this example.

In the cases where we know the true unblended data d_{true}, we can measure the quality of source separation by

$$snr = 10 \times log \frac{\|d_{true}\|_2^2}{\|d - d_{true}\|_2^2} \, (dB) \,, \tag{7}$$

where d denotes the unblended data after applying iterative rank reduction.

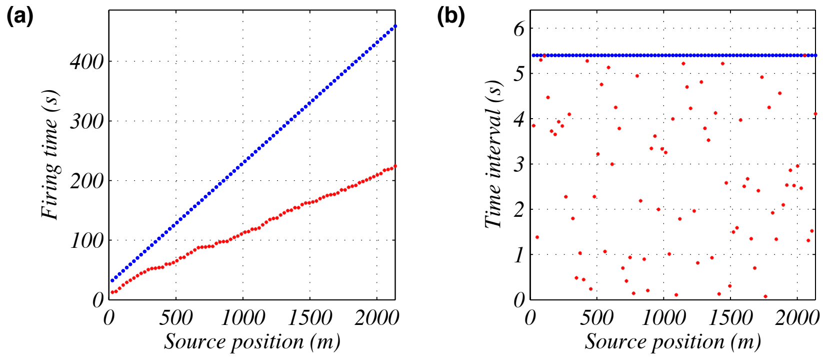

Figure 1 *Spatial and temporal distribution of firing time for conventional seismic acquisition (Blue) and 2D simultaneous source acquisition: one vessel scenario (red): a) Exact source Firing time of the whole acquisition b) Firing time intervals between adjacent sources*

Monte Carlo test based on distribution of firing times

Three different distributions of time delays were studied in this paper: uniform, binomial and exponential distribution. Figure (2) (a) shows the model generation function with uniform distribution, where the firing time intervals shows random pattern. The expectation of time delays for uniform distribution is given by $\alpha \times \delta t_0$. Figure (3) (a) shows the time delays of exponential distribution. There are more chances to generate a small time delay for each source. The few chances of large time delays would form gaps among different groups of closely fired sources. Figure (4) (a) shows the firing time delay that follows the binomial distribution. Binomial distribution measures the possibility of the number of successes over a given number of Bernoulli experiments. It can be shown that the time delays of all the sources are very close to the expectation, which is defined by $\alpha \times \delta t_0$. This firing scheme resembles the time jittered sampling proposed by (Mansour et al., 2012).

For each type of time delay distribution and for each compression rate from 0.1 to 1, we generate random time delays for 100 trials, apply blending and then separate the sources with the same parameter. Means and standard deviations of SNR for each scenario have been used to characterize the validity and stability of the separation algorithm. The convergence point is not identical for each trial. Figure (2) (b), Figure (3) (b) and Figure (4) (b) show the performance of the deblending algorithm under different firing mode and compression rate. The algorithm shows similar results for the three tested firing modes. The SNR becomes higher as we reduce the compression rate to avoid severe interferences. However, the separation algorithm turns out to be unstable when the firing time intervals follows the exponential distribution. On the other hand, binomial distribution of time delays seems to ensure an acceptable separation results when the compression rate is larger than 0.3.

Conclusions

In this paper, we report an iterative algorithm named iterative rank reduction that is capable of simultaneous source separation. This algorithm can be classified among the family of deblending via inversion schemes. By implementing rank reduction as a projection, the solutions are constrained to have low rank structures and converge toward the unblended shots. To study the impact of the firing time on the separation results, we applied Monte-Carlo based test on different distributions of firing time. Generally, we can conclude that the longer the acquisition period is, the better chances we have for high quality separation. The proposed algorithm is not stable when the firing time delays are generated from exponential distribution. However, for other distributions like binomial and uniform distribution, the performance is promising. This work can be regarded as a starting point towards optimizing the spatial and temporal properties of seismic data acquisition. For future work, we can solve for an empirical firing mode utilizing nonlinear inversion assuming we have realistic synthetics.

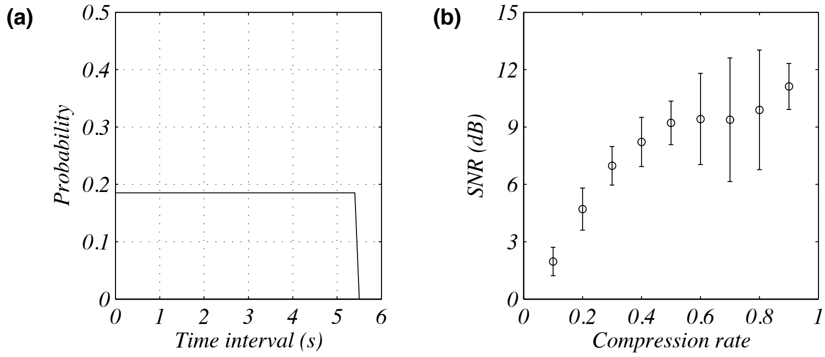

Figure 2 *Monte Carlo test with Uniform distribution: (a) Probability mass function of the random firing time interval for* $\alpha = 0.5$*. (b) The SNR after deblending versus compression rate* α*. The separation algorithm becomes unstable when the compression rate is around 0.7.*

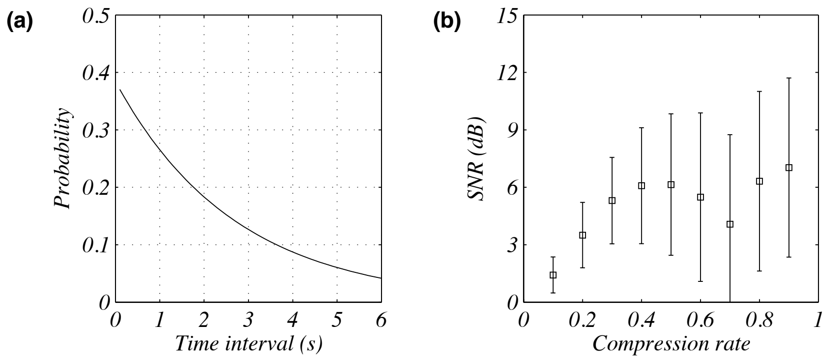

Figure 3 *Monte Carlo test with Exponential distribution: (a) Probability mass function of the firing time interval for* $\alpha = 0.5$*. (b) The SNR after deblending versus compression rate* α*.*

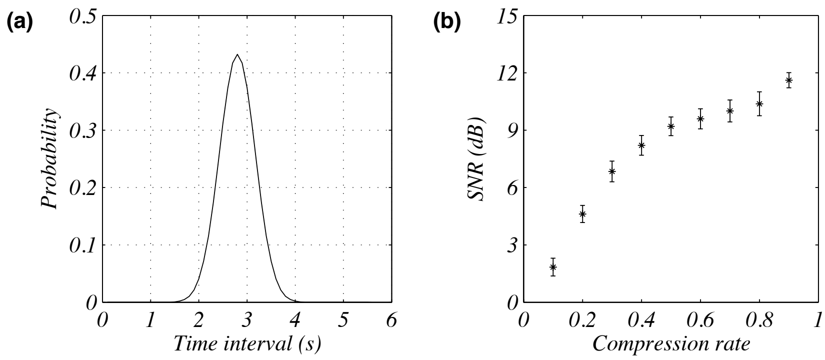

Figure 4 *Monte Carlo test with Binomial distribution: (a) Probability mass function of the firing time interval for* $\alpha = 0.5$*. (b) The SNR after deblending versus compression rate* α*.*

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