A novel and adaptive method of seismic resolution enhancement based on extrapolated multi-resolution singular value decomposition

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Summary

Inspired by the multi-resolution singular value decomposition (MRSVD), we propose a novel and adaptive method—Extrapolated Multi-resolution Singular Value Decomposition (EMRSVD)—to improve the resolution of seismic data. The proposed method first decomposes a signal into a series of approximate sub-signals and detailed sub-signals with the different resolution by using MRSVD. Next, the singular values corresponding to the detailed sub-signals are used to extrapolate a new singular value via polynomial fitting extrapolation to get a newly detailed sub-signal. Then, we construct some newly detailed sub-signals by repeating the above step. In order to optimize the signal-to-noise ratio and determine the number of frequency extrapolation sub-signals we introduce a modified variance model with exponential transformation. These extrapolated sub-signals are then added to the original signal providing a high-resolution. Using two synthetic models and a field seismic data shows that the proposed method significantly improves the resolution of the seismic data without greatly increasing seismic noise. Comparisons with conventional algorithms such as spectral whitening and zero phase deconvolution indicate that the proposed method performs better without any prior information and effectively resolves thin layers.

Introduction

Seismic resolution is the key to extracting stratigraphic detail from seismic data, such as the precise delineation of reservoir boundaries (Chopra, 2006; Chen, 2015). However, due to attenuation, the resolution of the original seismic data is often insufficient to delineate thin layers (Li, 2016). Our goal therefore is to increase the bandwidth and thereby improve the vertical resolution (Zhou, 2015). There are four main strategies to improve resolution: deconvolution (Doll, 1995; Wang, 2012), spectral whitening (Chopra, 2004; Liu, 2010), inverse Q filtering (Hargreaves, 1991; Wang, 2006; Li, 2015), and multi-scale joint analysis (Robinson, 1967; Wang, 2015). Although these methods perform well in enhancing seismic resolution, they all require some prior information, such as an accurate Q-model, access to well logs, or assumptions about the statistics of the unknown seismic reflectivity. In the absence of such prior information, inaccurate assumptions may improve the resolution but damage the amplitudes. In this paper, we propose a new method that adaptively defines parameters to improve seismic resolution.

Multi-resolution singular value decomposition (MRSVD) is a recently developed decomposition method that can be applied to both nonlinear and nonstationary signals. Zhao (2010, 2012) begins with a Hankel matrix representation of the seismic data and then recursively applies to locally decompose the data. Zhou (2016) finds that MRSVD provides improved vertical resolution than either variational mode decomposition (VMD) or empirical mode decomposition (EMD) methods. Like the commonly used continuous wavelet transform, MRSVD decomposes a seismic trace into a series of "approximate" and "detailed" sub-signals with different resolution. The "detailed" sub-signals provide the subtle, higher resolution information hidden in the original signal.

Principles

MRSVD

To better understand MRSVD applied to a discrete signal $\boldsymbol{X}$, let's first examine SVD decomposition. We begin by constructing the Hankel matrix $\boldsymbol{H}$ with two rows and decompose the matrix using SVD, resulting in

$$\boldsymbol{H} = \boldsymbol{USV}^T = \sigma_a \boldsymbol{u}_1 \boldsymbol{v}_1^T + \sigma_d \boldsymbol{u}_2 \boldsymbol{v}_2^T \tag{1}$$

Where, σ_a is the approximate singular value and σ_d is the detailed singular value. $\boldsymbol{H}_a = \sigma_a \boldsymbol{u}_1 \boldsymbol{v}_1^T$ is called an approximate matrix, and represents the larger singular value and therefore the main component of the signal. $\boldsymbol{H}_d = \sigma_d \boldsymbol{u}_2 \boldsymbol{v}_2^T$ is called a detailed matrix, and represents the smaller singular value and the smaller, more detailed component of the signal.

The approximate $\boldsymbol{A}$ and detailed sub-signals $\boldsymbol{D}$ can be computed from $\boldsymbol{H}_a$ and $\boldsymbol{H}_d$. The detailed matrix $\boldsymbol{H}_d$ has two-row vectors:

$$\boldsymbol{H}_d = \begin{pmatrix} \overbrace{d_1, \underbrace{d_2, d_3, \cdots, d_{N-1}}_{L_{d1}}}^{\sigma_d u_{2,1} v_2^T} \\ \underbrace{\overbrace{d_2, d_3, \cdots, d_{N-1}}^{L_{d2}}, d_N}_{\sigma_d u_{2,2} v_2^T} \end{pmatrix} \tag{2}$$

So, the detailed sub-signal $\boldsymbol{D}$ can be expressed as:

$$\boldsymbol{D} = (d_1, (L_{d1} + L_{d2})/2, d_N) \tag{3}$$

In the same way, we can obtain the approximate sub-signal $\boldsymbol{A}$. This provides the first step in an iterative method. Thus, the second layer decomposition can be obtained by using $\boldsymbol{A}$ as $\boldsymbol{X}$ and then repeat the above SVD decomposition. To determine the decomposition level we define an error:

$$E_j = \sum \left| \boldsymbol{A}_{j-1} - \boldsymbol{A}_j \right|^2 \Big/ \sum \left| \boldsymbol{A}_{j-1} \right|^2, \ (j = 1, \cdots, M) \tag{4}$$

When E_j<=10^{-6}, the MRSVD decomposition process ends and the $\boldsymbol{M}$ decomposition layers are determined.

EMRSVD

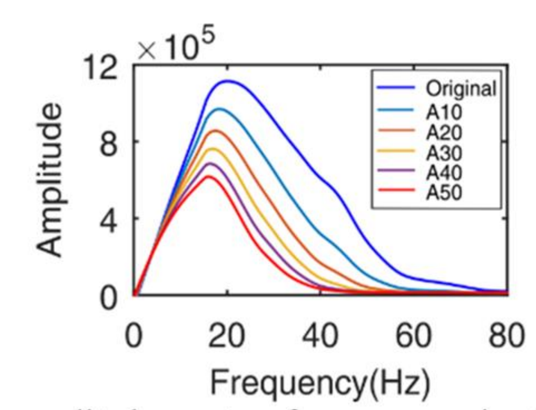

Fig. 1 The amplitude spectra of some approximate sub-signals

We decompose a seismic trace via MRSVD to obtain a series of sub-signals and compare their amplitude spectra (Fig. 1). $A_{10}, A_{20}, A_{30}, A_{40}, A_{50}$ denote the approximate sub-signals of the 10th, 20th, 30th, 40th and 50th levels respectively. It can be seen that the high frequencies of the signal are separated in the form of the detailed sub-signals with the increase of decomposition levels. However, the bandwidth determines the resolution of the seismic data. Inspired by the MRSVD and spectral whitening method, we propose an extrapolation MRSVD method (EMRSVD) to enhance the subtle high-frequency information of seismic data to enhance resolution. EMRSVD uses the following steps:

Step1: The given signal $\boldsymbol{X}$ is decomposed into the detailed and approximate sub-signals via MRSVD, and decomposition level $\boldsymbol{M}$ is determined by using Equation 4.

Step2: For each iteration j, a new singular value $F(j)$ is obtained from the previously computed detailed singular values:

$$F(j) = (j)^k \exp\left(\sum_{n=0}^{N} a_n j^n\right), \ k \geq 0 \tag{5}$$

After obtaining the new singular value, the extrapolated detailed sub-signal can be calculated by Equation 3.

Step3: The modified variance model $\boldsymbol{V}$ with exponential transformation is calculated to determine the i^{th} extrapolation number.

$$V_i = \sum_{t=1}^{N} \left[1 - \exp\left(-\frac{A_i^2(t)}{a^2} \right) \right]^2 \Bigg/ \left\{ \sum_{t=1}^{N} \left[1 - \exp\left(-\frac{A_i^2(t)}{a^2} \right) \right] \right\}^2 \tag{6}$$

If V_i falls below a user-defined threshold, we end the loop. Otherwise, we return to step 2.

Step4: Add all the extrapolated detailed sub-signals to the original signal, and compute the resolution enhanced result.

Synthetic Examples

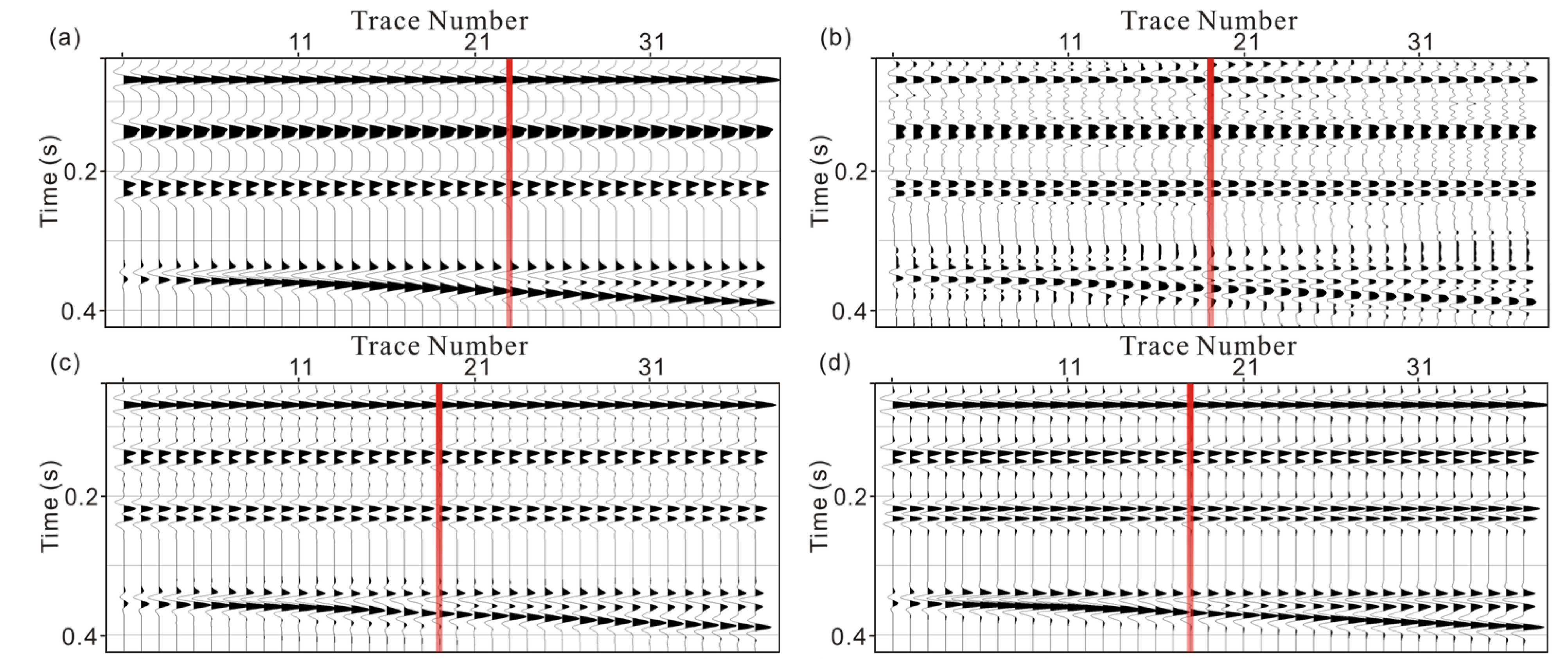

Fig. 2 A 2-D synthetic section example. (a) The original section. (b) The result obtained by zero phase deconvolution. (c) The result obtained by the spectral whitening algorithm. (d) The result obtained by EMRSVD.

Figure 2 is a model of three thin beds and a wedge containing two reflectors. Because of waveform distortion, the result in Figure 2b shows a lower SNR than the other two results. The results in Figure 2c and 2d are comparable showing the two horizontal thin layers are well resolved. For the wedge layer, the limits of resolution (the vertical red line) appears at trace 19 (9.1 ms) in Figure 2c and 18 (8.6 ms) in Figure 2d. Examining the third flat layer in Figure 2c with 2d note that the event is completely separated by EMRSVD, which is obviously superior to that by spectral whitening. Therefore, The EMRSVD is more effective and satisfactory in enhancing the resolution of seismic data.

Field Data Examples

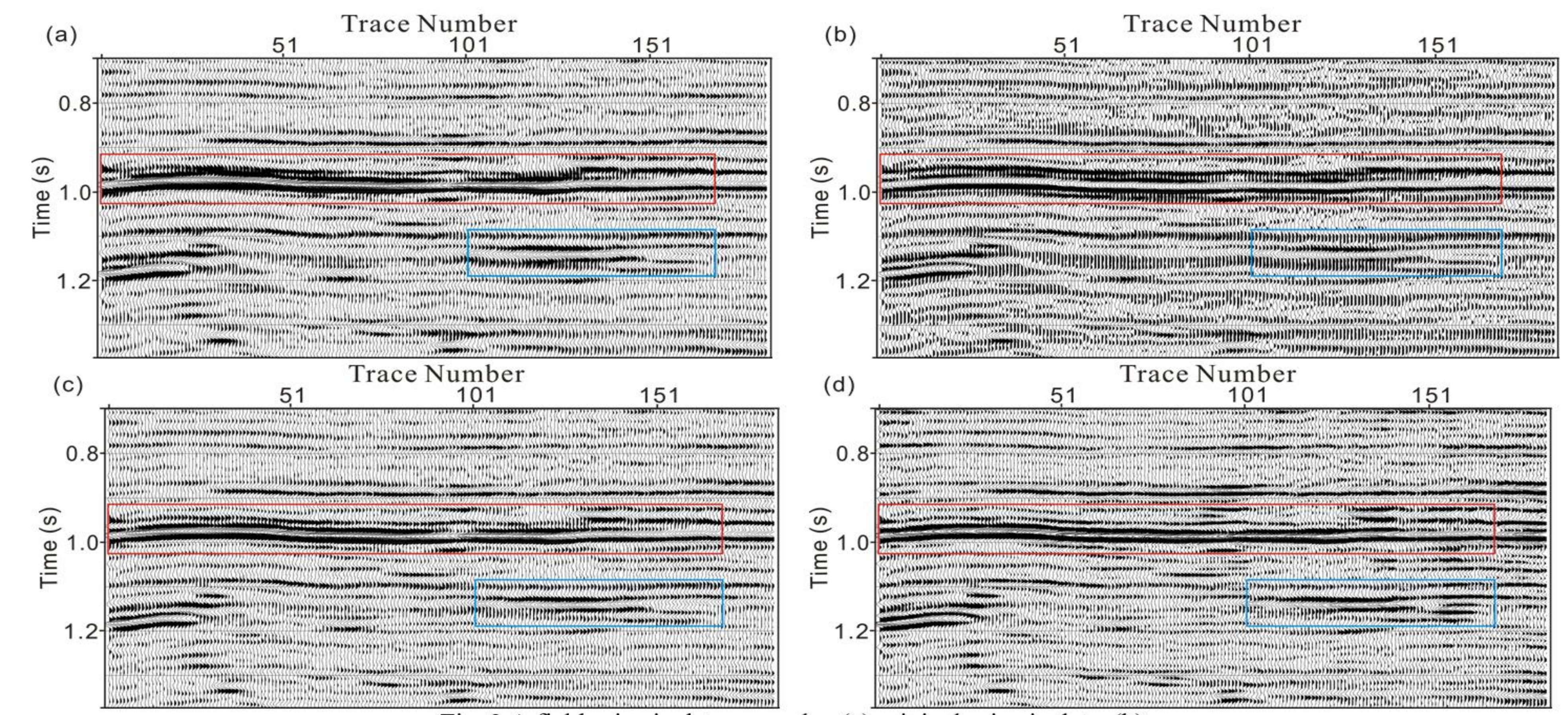

Fig. 3 A field seismic data example. (a) original seismic data. (b), (c) and (d) are the results obtained by zero phase deconvolution, spectral whitening algorithm, and EMRSVD method respectively.

Figure 3 compares the same algorithms for a real data example. All three methods improve the data resolution and reveal the hidden features. However, comparing these three results in detail, the effect of EMRSVD is superior as indicated by the red and blue rectangles. Here, the thin layers are poorly resolved in Figure 3b but are clearly seen in Figure 3c and 3d. Moreover, the resolution of thin layers within red rectangles in Figure 3d is much higher than that in Figure 3c, and the events marked by blue rectangles in Fig3d are much more continuous than those in Figure 3c.

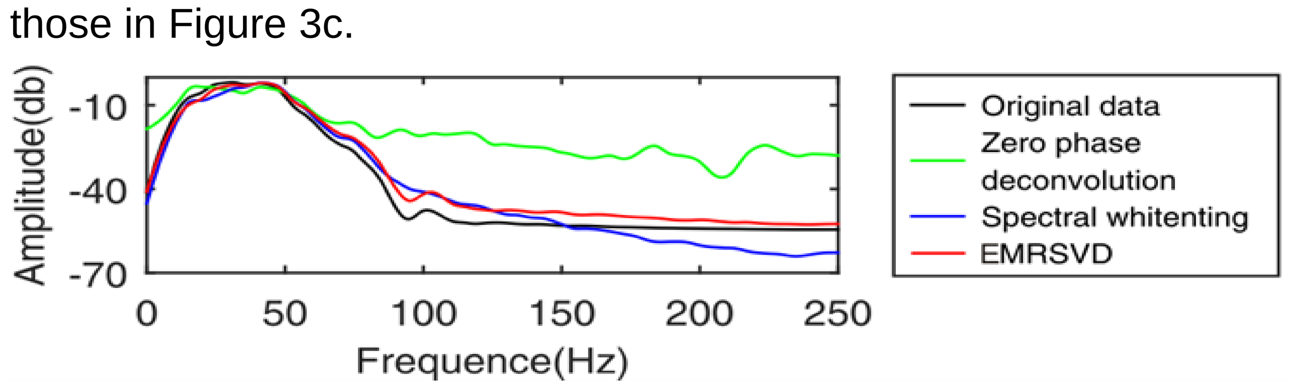

Fig. 4 Comparison of amplitude spectra.

In Figure 4, we evaluate these results by analyzing their amplitude spectra. It is obvious that the zero phase deconvolution method changes the low-frequency information that is important to seismic inversion and reservoir detection. The zero phase deconvolution method and the spectral whitening method both adjust the high frequencies, which may reduce the SNR of signals. However, EMRSVD preserves the low frequencies of the seismic data well, and the frequency spectrum is broadened without adding extra high frequency artificially.