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Denoising of Seismic Data in Wavelet Transform Domain

Satish Kumar Sinha[1] and Kalachand Sain[2]

[1]Rajiv Gandhi Institute of Petroleum Technology, Rae Bareli, India

[2] CSIR-National Geophysical Research Institute, Hyderabad, India

Presenting author, E-mail: Satish.Sinha@gmail.com

Abstract

For non-stationary signals like seismic, a processing which requires time-frequency representation, wavelet transform is best suited since it does not require a window function. In continuous wavelet transform (CWT), a signal is analyzed with respect to a wavelet function shifted and compressed or stretched. There is redundancy of scales in CWT and the coefficients depend on the wavelet. On one hand, this redundancy helps in identifying the scale of the noise; while on the other hand, it requires a significant amount of computation. Denoising or removal of undesired frequency is usually introduced at this stage. A scale or several of them representing noise in the signal are removed from the scalogram while reconstructing the signal.

The denoising algorithm allows us to pick certain scales and remove them. Its application on a real dataset is chosen from reflection seismic acquisition where very low frequency noise as well as random noise in high frequency is seen in the data. Results from the denoising algorithm in wavelet transform are encouraging and has helped in further processing of the seismic data. This methodology can be applied in poststack data as well as prestack data.

Introduction

In seismic data processing, wavelet transform has been widely used for various purposes, including suppression of coherent and random noise. It has also been shown that wavelet transform based time-frequency domain processing has advantages over other methods since it does not require user specified time windowing function (Sinha, 2002). Low frequency, high amplitude ground roll suppression in land seismic data using wavelet transform was suggested by Deighan and Watts (1997). Both continuous and discrete wavelet transforms, 1D and 2D wavelet transform, and several other variants of wavelet transform have been utilized as noise reducing techniques (Kim et al. 2008, Berkhout and Verschuur, 2006).

Before implementing any frequency filtering technique it is essential to recognize the bandwidth which needs to be removed. Once again, continuous wavelet transform based time-frequency analysis, namely TFCWT, has been shown to provide optimal time-frequency resolution for seismic data (Sinha et. al. 2005).

In this work, we have utilized TFCWT method to identify the very low frequency noise in the marine seismic data. Scales corresponding to those frequencies are identified and removed from the time-scale spectra. Inverse wavelet transform is applied to combine rest of the scales to get denoised signal.

Methodology

A signal $f(t)$ when convolved with a family of wavelets $\psi_{\sigma,t}\,(t)$ produces time-scale spectrum of the signal which essentially is the continuous wavelet transform of the given signal. It can be written as the inner product of the two as given below:

$$F_W(\sigma,\tau) = \langle f(t), \psi_{\sigma,t}(t) \rangle$$

$$= \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{\sigma}} \overline{\psi\left(\frac{t-\tau}{\sigma}\right)} dt \qquad \text{----- (1)}$$

where σ is the scale and $F_W(\sigma,\tau)$ is the time-scale map or scalogram. These scaled or dilated wavelet functions have different center frequency and bandwidth.

In the above equation the choice for the scale and the translation parameter can be arbitrary and we can chose to represent it anyway we like. To reconstruct the function $f(t)$ from the wavelet transform, we use the "resolution to identity", also known as Calderon's identity, given by,

$$f(t) = \frac{1}{C_\psi} \iint_{-\infty}^{\infty} F_W(\sigma,\tau) \psi\left(\frac{t-\tau}{\sigma}\right) \frac{d\sigma\, d\tau}{\sqrt{\sigma}\sigma^2} \qquad \text{----- (2)}$$

For the inverse transform to exist it is required that the analyzing wavelet satisfy the "admissibility condition" given by,

$$C_\psi = 2\pi \int_{-\infty}^{\infty} \frac{\left|\hat{\psi}(\omega)\right|^2}{\omega} d\omega < \infty$$

Further details of this method can be found in Sinha (2002).

Unlike the discrete wavelet transform where the scales are dyadic, the CWT can be performed at every scales. When the wavelet function satisfies the admissibility condition, the signal can be reconstructed from the scalogram. Scales with noise information are removed from the scalogram at this stage before applying equation (2).

Results

Several 2D seismic lines were acquired in Krishna-Godavari basin to evaluate the resource potential of gas hydrates. The data has unusually low frequency noise even though the system was not designed to sense such low frequencies; the source of this noise trail is not very clear. A trace from the raw seismic data is shown in Figure 1a and a time-gated shot gather is shown in Figure 4a. Time-frequency map the trace in Figure 1a is shown in Figure 1c. The data was acquired at 1ms sampling rate leading to Nyquist frequency of 500Hz. The low frequency component is not visible because of dominant energies from high frequency components. By displaying only low frequency energies as shown in Figure 2a, we can clearly see a quarter hertz signal through the entire data length.

In this analysis, we have used Morlet wavelet to generate time-frequency map as it gives high frequency resolution at low frequencies. The quarter hertz component has very low energy or amplitude and therefore, it is not detectable on Fourier transform. Passing the signal through a low frequency filter would remove more signal than desired. In continuous wavelet transform, the signal is decomposed into several scales, and each scale represents a frequency bandwidth. After removing the undesired scales, residual scales are recombined to form the signal. Figure 2b shows the time-frequency map of the denoised signal. Clearly quarter hertz component from the signal has been successfully eliminated. The process has been performed trace-by-trace and the result of a denoised shot gather is shown in Figure 3b.

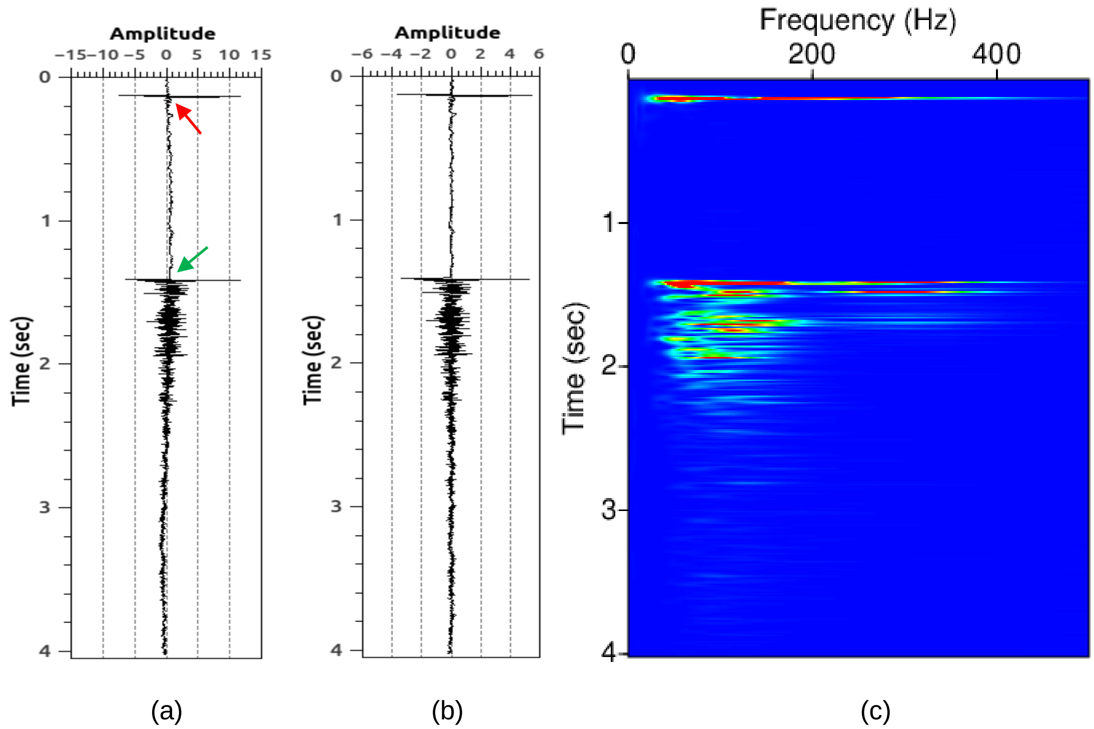

Figure 1. a) Single trace from a raw shot gather. The direct arrival is shown with red arrow and reflection from the sea floor is shown with green arrow. Also one can observe that there is very low frequency along the zero vertical gridline. b) The trace is shown after removal of very low frequency noise. c) Time-frequency spectrum of the raw trace. Low frequency noise in the data is not obvious.

Conclusions

Continuous wavelet transform based denoising technique has been very useful in cleaning up the seismic signal. This is especially so as the seismic signal is non-stationary in nature. CWT based spectral decomposition was helpful in identifying the low frequency noise component. Scales representing the noise was successfully removed from the data. Cleaned up seismic data helped us in further processing.

Acknowledgement

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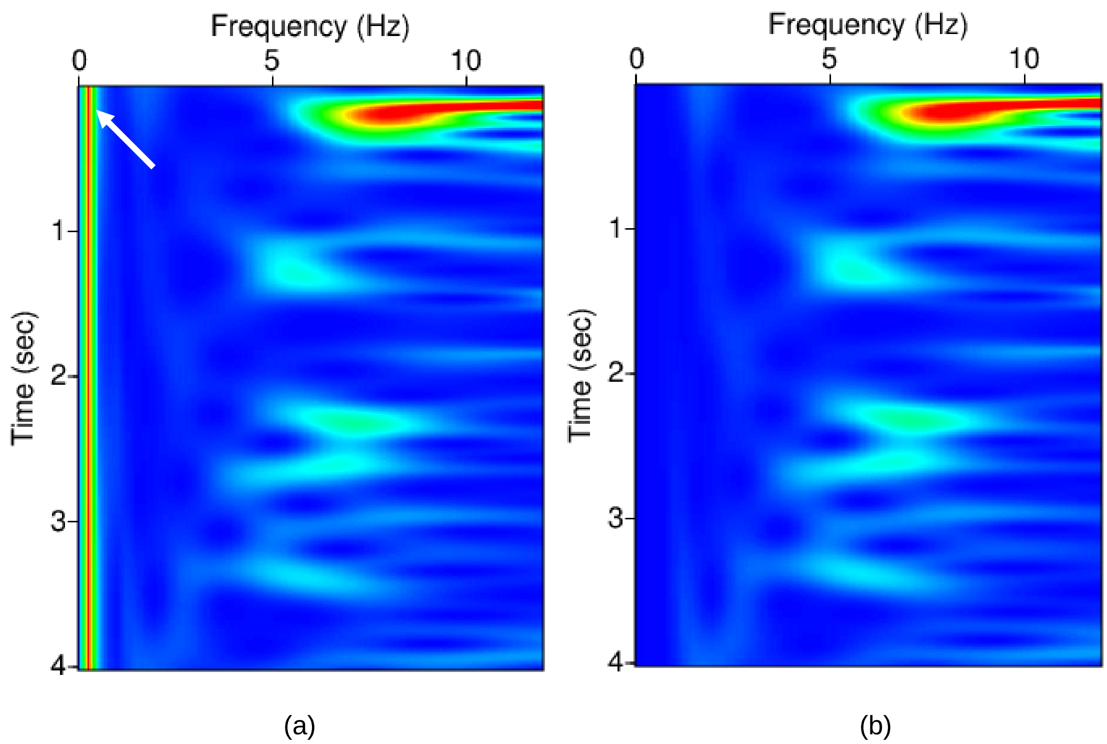

Figure 2. a) Time-frequency spectrum of the raw trace (figure 1a) between 0 to 12 Hz frequency range. The white arrow shows presence of very low frequency noise (~0.25 Hz) in the data. b) Time frequency spectrum of the denoised trace (figure 1b).

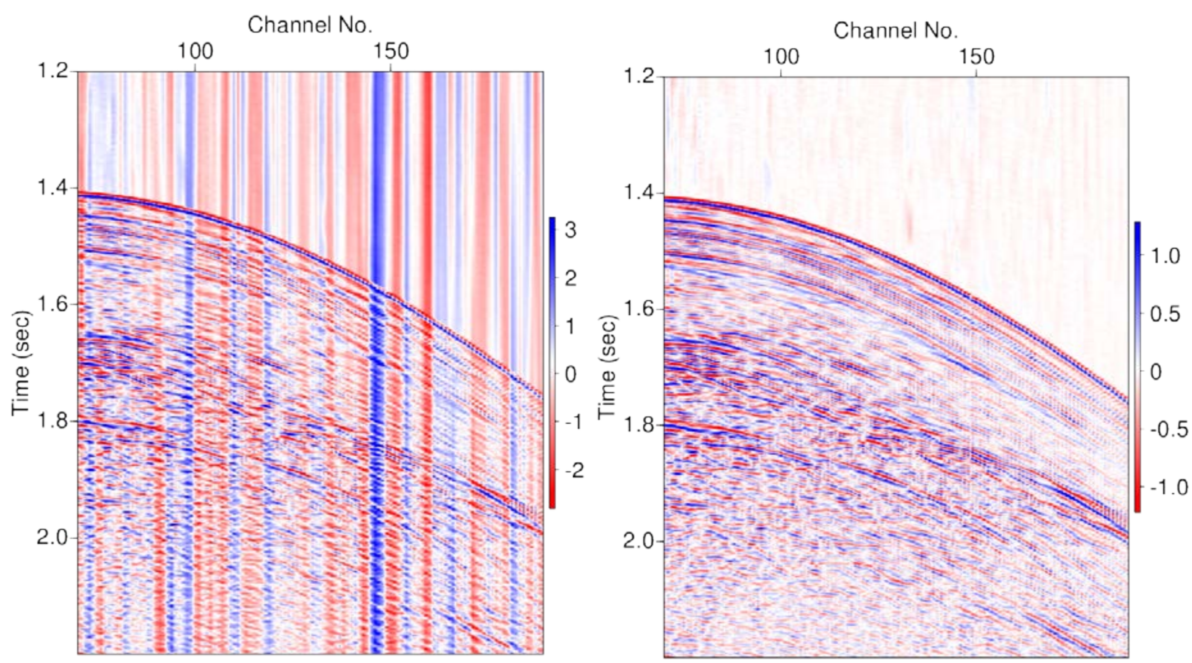

Figure 3. a) Raw shot gather showing the presence of very low frequency noise in the entire dataset. b) After removal of low frequency noise using CWT method.

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