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High-Resolution Seismic Data Processing Based on SET Spectrum Whitening

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Abstract: Conventional spectral whitening methods often fail to enhance both time-domain and frequency-domain details simultaneously. To overcome this limitation, this paper proposes a high-resolution enhancement method that performs spectral whitening on the Synchroextracting Transform (SET) spectrum of seismic signals. The method first decomposes the signal using SET and then applies a whitening filter to the SET spectrum. Comparative experiments on synthetic and field seismic data demonstrate that the proposed method effectively improves resolution in both time and frequency domains, resulting in clearer and more continuous seismic events while maintaining a high signal-to-noise ratio.

Keywords: spectral whitening; time-frequency analysis; seismic resolution; synchroextracting transform

1. INTRODUCTION

Spectral whitening is a widely used technique for enhancing seismic resolution by flattening the amplitude spectrum within the effective frequency band [1]. This fundamental approach has been extensively applied in seismic data processing due to its effectiveness in broadening the spectral bandwidth and improving temporal resolution. However, traditional spectral whitening methods based on Fourier transform face significant limitations in balancing time and frequency localization, primarily due to the inherent constraints of the Heisenberg uncertainty principle [2]. These limitations substantially restrict their capability to resolve local signal details and characterize fine-scale geological features.

The challenges associated with conventional Fourier-based methods have prompted the development of various advanced techniques. Wavelet transform-based spectral balancing methods have demonstrated improved performance by providing multi-resolution analysis capabilities [3]. Similarly, signal subspace decomposition techniques have shown promising results in enhancing seismic resolution through sophisticated signal separation approaches [4]. These methods represent important steps forward in addressing the resolution limitations of traditional spectral whitening.

Recent advances in time-frequency analysis have further expanded the toolbox for seismic signal processing. The Empirical Mode Decomposition (EMD) and Hilbert-Huang Transform (HHT) have emerged as powerful tools for analyzing non-stationary signals [5,10], with successful applications in seismic data analysis [14,15]. The filter bank characteristics of EMD [11] and its effectiveness in noise attenuation [13] have been particularly valuable in seismic processing. Meanwhile, inverse Q-filtering methods [7] and Gabor deconvolution techniques [9] have provided alternative approaches for resolution enhancement through different physical mechanisms.

The introduction of Synchroextracting Transform (SET) represents a significant breakthrough in time-frequency analysis [6]. SET achieves superior time-frequency concentration by extracting only the most energy-significant components along instantaneous frequency trajectories, effectively overcoming the resolution limitations of conventional methods. This transformative capability makes SET particularly suitable for high-resolution seismic processing, where precise time-frequency localization is crucial for characterizing thin layers and complex geological structures.

Building upon these advancements, this paper introduces a novel approach that combines SET with spectral whitening, enabling simultaneous enhancement of temporal and spectral resolution through high-precision time-frequency decomposition. The proposed method leverages SET's exceptional time-frequency concentration to achieve more effective spectral whitening while preserving critical geological information. By integrating the strengths of SET with spectral whitening principles, this approach addresses the fundamental limitations of traditional methods and provides a robust framework for high-resolution seismic data processing.

2. THEORY

2.1 SET Time-Frequency Decomposition

The Synchroextracting Transform (SET) is employed to obtain a high-resolution time-frequency representation of seismic signals. Unlike conventional time-frequency analysis methods, SET effectively overcomes the limitations of the Heisenberg uncertainty principle by extracting only the most energy-concentrated components along instantaneous frequency trajectories.

For a seismic signal x(t), the SET procedure begins with the Short-Time Fourier Transform (STFT):

$$F(t,\omega)=\int_{-\infty}^{\infty}x(\tau)g(\tau-t)e^{-j\omega\tau}d\tau \tag{1}$$

where g(t) represents the window function. The instantaneous frequency ω0(t,ω) is then estimated from the STFT phase spectrum:

$$\omega_0(t,\omega)=-j\frac{\partial_t F(t,\omega)}{F(t,\omega)} \tag{2}$$

The synchroextracting operator $\Gamma(t,\omega)$ is defined as:

$$\Gamma(t,\omega)=\delta(\omega-\omega_0(t,\omega)) \quad (3)$$

The final SET time-frequency representation is obtained by:

$$S(t,\omega)=|F(t,\omega)|\cdot\Gamma(t,\omega) \quad (4)$$

This process results in a sparse and highly concentrated time-frequency distribution that accurately captures the signal's time-varying characteristics.

The SET spectrum S(t,ω) provides a precise representation of the signal's energy distribution in the time-frequency plane. Compared to conventional Hilbert spectrum or other time-frequency representations, the SET spectrum exhibits superior energy concentration and resolution, making it particularly suitable for analyzing non-stationary seismic signals with complex frequency components.

2.2 Spectral Whitening

The spectral whitening process is performed directly on the SET spectrum to enhance seismic resolution while preserving the signal's phase information. An adaptive whitening filter

f(ω) is designed based on the spectral characteristics of the input signal:

$$f(\omega)=\frac{v}{e(\omega)+\epsilon v} \quad (5)$$

where v represents the maximum value of the spectral envelope e(ω), and ϵ is the noise suppression factor that controls the trade-off between resolution enhancement and noise amplification.

The whitening process is applied to the SET spectrum as follows:

$$\tilde{S}(t,\omega)=S(t,\omega)\cdot f(\omega) \quad (6)$$

The enhanced seismic signal is subsequently reconstructed from the whitened SET spectrum through inverse transformation:

$$\tilde{x}(t)=\mathrm{Re}\int_{-\infty}^{\infty}\tilde{S}(t,\omega)e^{j\theta(t)}d\omega \quad (7)$$

where $\theta(t)$ represents the phase information preserved during the whitening process.

This adaptive approach enables simultaneous enhancement of both temporal and spectral resolution while maintaining the signal's structural characteristics and controlling noise amplification. The method effectively addresses the limitations of conventional spectral whitening techniques by leveraging the high resolution of SET decomposition and adaptive filtering in the time-frequency domain.

3. NUMERICAL EXAMPLES

3.1 Synthetic Data

A synthetic seismic section was generated by convolving a 20 Hz Ricker wavelet with a reflectivity series. As shown in Fig. 1, the original synthetic data exhibits overlapping wavelets. After applying the SET spectrum whitening method, the wavelets are better separated, and the resolution is significantly improved due to SET's superior time-frequency concentration.

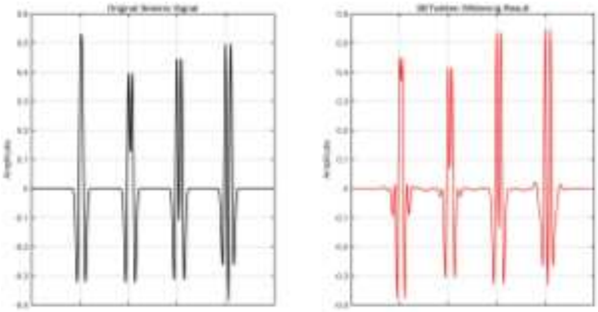

Figure 1. Synthetic data before and after whitening. (a) Original synthetic section; (b) Processed section using the proposed SET-based method.

3.2 Field Data

A real seismic trace from a coal mining area was processed using both the time-varying spectral whitening (TVSW) method and the proposed SET-based method. Fig. 2 compares the amplitude spectra of the original and processed signals. The SET spectrum whitening method achieves a more balanced amplitude spectrum across the effective frequency band with better energy concentration, indicating enhanced resolution without significant noise amplification.

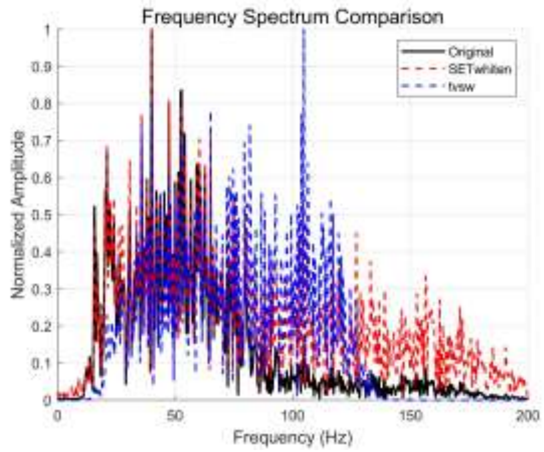

Figure 2. Comparison of amplitude spectra: original, tvsw, and SET spectrum whitening.

4. CONCLUSION

The SET spectrum whitening method effectively enhances seismic resolution by leveraging SET's high time-frequency concentration to adaptively balance energy in both time and frequency domains. Experimental results on synthetic and field data confirm that the method improves the clarity and continuity of seismic events, facilitating better interpretation of thin layers and small faults. This approach offers a valuable tool for high-resolution seismic processing in complex geological settings, overcoming the limitations of conventional whitening methods.

5. REFERENCES

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