Highlighting discontinuities with variational mode decomposition based coherence

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SUMMARY

The coherence attribute is a powerful tool to delineate structural boundaries and discontinuity features, such as faults, channels, and karst collapse. Multispectral coherence is calculated from different band-pass filtered data volumes, providing improved images of the edges and boundaries over conventional broadband coherence. However, the lower signal-to-noise ratio high-frequency components of the band-pass filtered results often give rise to artifacts that can contaminate the result. The solution to this problem is to only use those spectral components that contain useful information. An alternative solution is to somehow separate signal from noise data components. To address this issue, we evaluate a coherence calculation workflow using variational mode decomposition (VMD) components as input. VMD is a data-driven signal decomposition method, which adaptively decomposes a signal into a series of band-limited intrinsic mode functions exhibiting greater lateral continuity than spectral components. In general, noise is contained in the residual of the data, that part not represented by the leading components. We first decompose the broadband seismic data into several intrinsic mode functions, each with its own central frequency. We then compute energy ratio coherence from each VMD component. We finally combine these results together, providing the VMD based coherence. We evaluate this VMD-based coherence method with a 3D seismic survey acquired over the Red Fork Formation of the Anadarko Basin, Oklahoma.

INTRODUCTION

Seismic coherence is commonly used to highlight seismic edges such as faults and channels. The quality of these images is dependent on the quality of the input seismic data. Structural-oriented filtering (SOF), spectral balancing, and other post-migration data conditioning algorithms are commonly used to improve the signal-to-noise (S/N) ratio of the data prior to attribute computation (Chopra and Marfurt, 2007). Whether because of the seismic data quality or the underlying geology, certain spectral components exhibit higher S/N ratio over other components. For example, thin-bed discontinuities are better illuminated at their higher amplitude (and thus usually higher S/N ratio) tuning frequency over the other frequencies.

Li and Lu (2014), Alaei (2012), Marfurt (2017), and Li et al. (2018) use multispectral coherence method to improve the imaging quality of the geologic discontinuities, combining the coherence results computed from different spectral components. Multispectral coherence better delineates the seismic edges and boundaries over the result computed from the broadband seismic data. Band-pass filtering (e.g. voice components of continuous wavelet transforms) is commonly used to extract the spectral components, followed by multispectral coherence calculation. Ideally, the interpreter examines the coherence from each component before combining them. In practice, such analysis requires the manual inspection of multiple intermediate volumes, and often reveals that high frequencies contribute valuable information in the shallow section but only noise in the deeper section. We therefore search for components that are more data adaptive.

Dragomiretskiy and Zosso (2014) proposed a variational mode decomposition (VMD) method to decompose a signal into a series of intrinsic mode functions (IMFs). VMD is a data-driven method, which contrasts with the interpreter-driven band-pass filter method. Each IMF after VMD contains an ensemble of spectral information, not limited to a specific bandwidth. Such analysis avoids the creation of apparent lateral discontinuities observed in the band-pass filtered components. VMD method has previously been applied to seismic data for time-frequency analysis (Liu et al., 2016), sequence stratigraphy interpretation (Li et al., 2017), seismic denoising (Li et al., 2017), and to constrain self-organizing map facies analysis (Zhao et al., 2017).

In this paper, we present a VMD based coherence method. We first introduce the theory of VMD. Next, we illustrate the VMD based coherence workflow. We then apply the proposed workflow on a 3D seismic survey located in the Anadarko Basin, Oklahoma. The results indicate that we can better delineate the additional edges and boundaries with the VMD based coherence.

METHOD

Review of VMD theory

To avoid the frequency mixture issue of the popular data-driven empirical-mode decomposition (EMD) method (Huang et al., 1998), Dragomiretskiy and Zosso (2014) develop the VMD method to decompose an input signal into a series of IMFs in the frequency-domain. An IMF is considered to be an elementary amplitude-frequency modulated harmonics of the non-stationary signal, which is compact around its own central frequency. In VMD, the adaptive decomposition of the input signal is performed by searching the optimal solution of the constrained variational mode. The central frequency and bandwidth of each IMF are updated in the iterative solution of the variational mode. In our study, the input signal is the seismic data, which is decomposed into IMFs by solving the following optimization problem:

$$\min_{\{u_k\},\{\omega_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\} \quad s.t. \quad \sum_k u_k = d(t) \tag{1}$$

where $\{u_k\} \equiv \{u_1, u_2, ..., u_K\}$ denotes the decomposed modes, and $\{\omega_k\} \equiv \{\omega_1, \omega_2, ..., \omega_K\}$ represents their corresponding central frequencies. $\delta(\cdot)$ is the Dirac impulse, and $d(t)$ denotes the broadband seismic data to be decomposed. The term $\left(\delta(t)+\frac{j}{\pi t}\right)*u_k(t)$ represent u_k and its Hilbert transform, and represents an analytic signal that can be represented positive frequencies. We use equation 1 to decompose the broadband seismic data into a series of IMFs.

VMD-based coherence

Gersztenkorn and Marfurt (1999) calculate the coherence by using the eigenvectors of the covariance matrix, which provides robust and high-quality coherence volume. It is also used in fault skeletonization (Qi et al., 2016). Each element of the covariance matrix is computed using the analytic trace thereby avoiding artifacts associated with small windows over zero-crossings:

$$C_{mn} = \sum_{k=-K}^{K} \left[d(t_k, x_m, y_m) d(t_k, x_n, y_m) + d^H(t_k, x_m, y_m) d^H(t_k, x_n, y_m) \right] \tag{2}$$

where c_{mn} denotes element of the covariance matrix, d is the original seismic data, d^H is its Hilbert transform, and t_k represents the structurally interpolated time sample at a distance (x_m, y_m) from the coordinate origin point. The energy ratio coherence is expressed as the ratio of the coherent energy and the total energy within an analysis window:

$$c_{ER} = \frac{E_c}{E_t + \varepsilon^2} \tag{3}$$

where ε is a small positive value to avoid division by zero, and the Karhunen-Loève, or KL-filtered coherent energy and the total energy are defined as

$$E_c = \sum_{m=1}^{M} \sum_{k=-K}^{K} \left\{ \left[d_{KL}(t_k, x_m, y_m) \right]^2 + \left[d_{KL}^H(t_k, x_m, y_m) \right]^2 \right\} \tag{4}$$

$$E_t = \sum_{m=1}^{M} \sum_{k=-K}^{K} \left\{ \left[d(t_k, x_m, y_m) \right]^2 + \left[d^H(t_k, x_m, y_m) \right]^2 \right\}. \tag{5}$$

In our study, we first decompose the broadband seismic data into IMFs. Then we compute the energy ratio coherence with equation 3 for each IMF data. Finally, we combine the coherence volumes from different IMFs together to produce the VMD-based coherence result.

FIELD APPLICATION

We apply the VMD-based coherence method on a 3D seismic survey, located in the Anadarko Basin, Oklahoma. A broadband seismic line is shown in Figure 1. The multiple stages of incision and fill result in an incised valley system with complex internal architecture. We calculate the energy ratio coherence with this broadband seismic volume, and display a representative time slice at 1.85s in Figure 2. The result indicates that it is difficult to clearly identify the boundaries of the incised valleys with the broadband coherence.

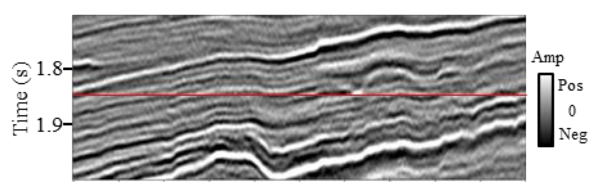


Figure 1: A broadband seismic line of our study survey located in the Anadarko Basin, Oklahoma. The red line indicates the time slice at 1.85s.

Highlighting discontinuities with variational mode decomposition based coherence

We then decompose the broadband seismic data into three IMFs using the VMD method. IMF-1 (Figure 3a) shows the lowest carrier frequency, while IMF-3 (Figure 3c) indicates the highest of the three carrier frequencies. Each component contains an ensemble of spectral information, which makes it continuous laterally. We then calculate the energy ratio coherence for each decomposed IMF and display corresponding representative time slices in in Figure 4. Note that each coherence result calculated from the different IMFs highlights different geologic features, indicated by the yellow arrows in Figure 4. We then combine these coherence results from different IMFs together, to produce the multi-IMF VMD-based coherence, shown in Figure 5b. We also show the broadband coherence of the same slice in Figure 5a for comparison. The VMD-based coherence reveals more geological information, which makes it easier to delineate the incised valley boundaries over conventional broadband coherence. In Figure 6, we also show the RGB corendering of the coherence volumes from the 3 IMFs (Figure 4). It provides additional information that which VMD component is predominant for specific structural or stratigraphic features.

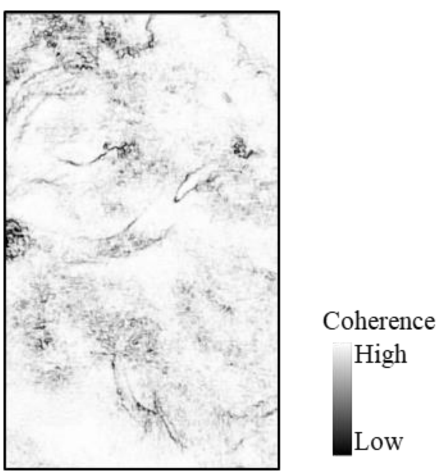
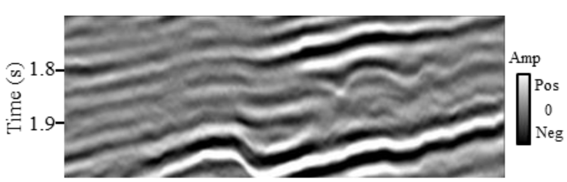
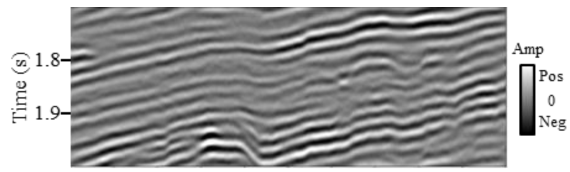


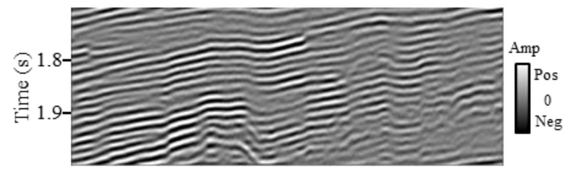
Figure 2: An energy ratio coherence slice at t=1.85s with broadband seismic volume.



(a) IMF-1



(b) IMF-2



(c) IMF-3

Figure 3: The broadband seismic data is decomposed using VMD method into three IMFs with an ensemble of spectral information: (a) IMF-1 with the lowest dominant frequency, (b) IMF-2 with higher dominant frequency, and (c) IMF-3 with the highest dominant frequency.

CONCLUSIONS

We have developed a VMD-based coherence method, which inherits the benefits of the multispectral coherence method. Additionally, the VMD components (IMFs) avoid the lateral discontinuities existing in conventional band-pass filtered data. The case study of the 3D seismic survey with complex incised valleys indicate that the VMD-based coherence result provides more abundant information over broadband coherence, which is helpful to better delineate the incised valley boundaries. Our future research will focus on the applications of the presented method on other structural features, such as faults and karst collapse.

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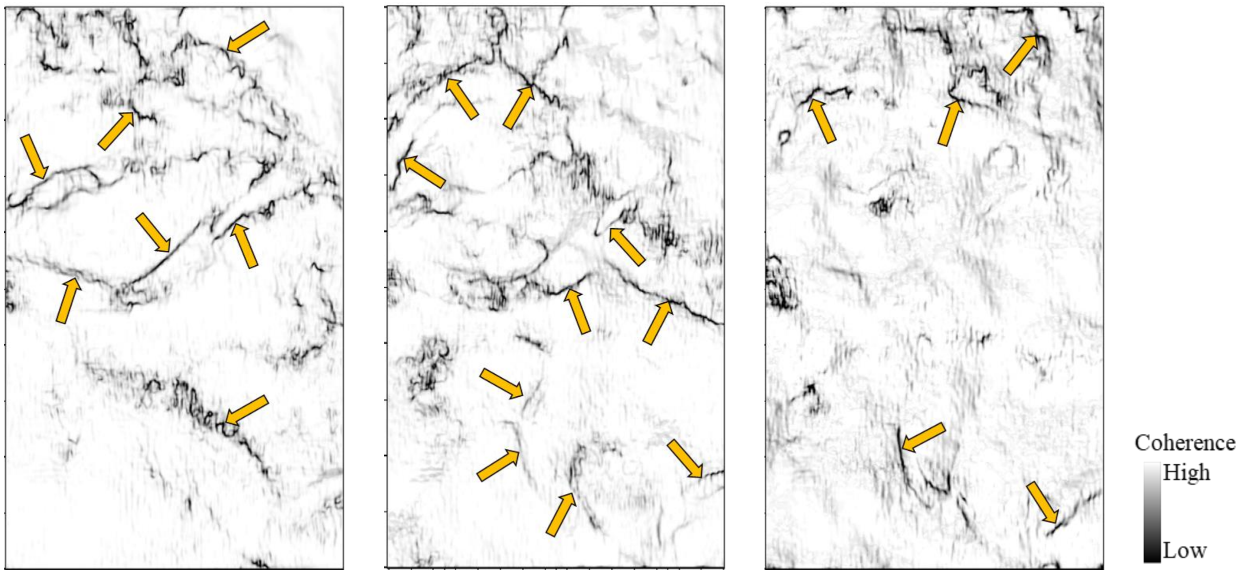
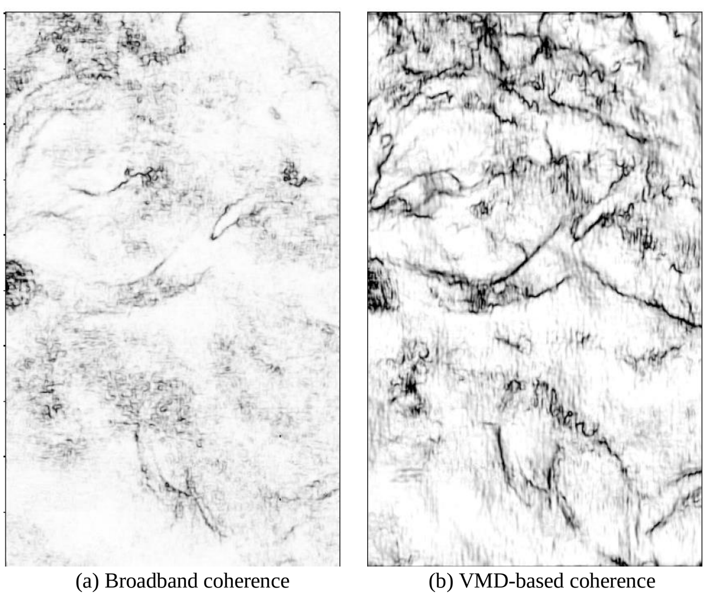


(a) Coherence with IMF-1 (b) Coherence with IMF-2 (c) Coherence with IMF-3

Figure 4: The energy ratio coherence slices at t=1.85s by using different IMFs: (a) coherence with IMF-1, (b) coherence with IMF-2, and (c) coherence with IMF-3. Note that each coherence result calculated from the different IMFs highlights different geologic features, indicated by the yellow arrows.



(a) Broadband coherence (b) VMD-based coherence

Figure 5: The comparison between (a) broadband coherence and (b) VMD-based coherence at time t=1.85s. indicates that the VMD-based coherence reveals more geological information, which helps delineate the valley boundaries.

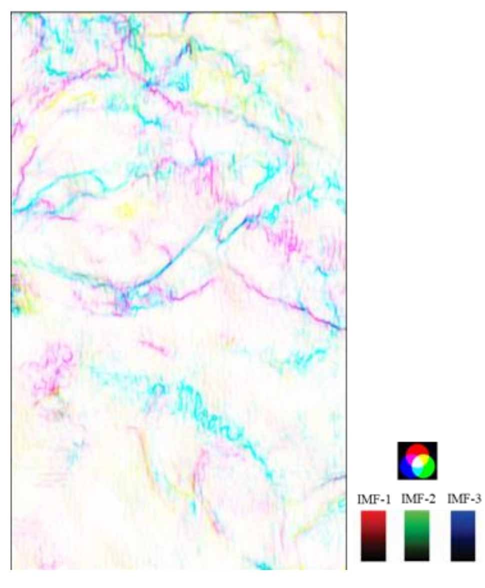


Figure 6: An RGB corendering of the coherence volumes from IMF 1 (in red) IMF 2 (in green) and IMF 3 (in blue).

Highlighting discontinuities with variational mode decomposition based coherence

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