Stratigraphic discontinuities mapped through joint time-frequency seismic phase unwrapping

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Summary

Spectral decomposition has proven to be a powerful means of identifying strong amplitude anomalies at specific frequencies that are otherwise buried in the broad-band response. To date, most publications have focused on using the spectral magnitude components to identify lateral changes in stratigraphy, wavefield attenuation due to Q, and unconformities between geologic formations. Although seismic acquisition and processing does a much better job in preserving phase than it does in preserving amplitude, little has been published about interpreting the phase components resulting from spectral decomposition. This paper shows how to improve seismic spectral decomposition interpretation by unwrapping the joint time-frequency spectrum phase.

Introduction

Partyka et al. (1999) first showed how the seismic spectral response from a short time window can be used to map lateral changes in acoustic properties and thickness of stratigraphic layers. Since then, spectral decomposition has become a widely-accepted interpretation tool and has been applied to reservoir characterization (Matos et al., 2005, Liu and Marfurt, 2007), hydrocarbon detection (Castagna et al., 2003) and stratigraphic analysis (Hall and Trouillot, 2004). Most of the applications are based on the magnitude component of the joint time-frequency spectrum. Although, some of these techniques are quadratic-energy based, such as the Wigner-Ville distribution, and do not generate phase information, the short-window discrete Fourier transform, wavelet transform, and matching pursuit algorithms all produce complex spectra that can be represented by magnitude and phase components. Although we know that phase spectra respond to lateral discontinuities via local phase instability and have been successfully used to delineate faults, few applications of the spectral phase components have been shown. To our knowledge, very little has been published on the spectral phase response due to stratigraphy, and nothing has been published on mapping spectral phase discontinuities. This latter task requires first unwrapping each phase component.

Phase unwrapping review

Kaplan and Ulrych, (2007) report that phase unwrapping remains an important and challenging seismic data processing research topic while Ghiglia and Pritt (1998) report that it is also important to processing of SAR radar images and optical fringe-pattern analysis.

Phase is an important property of waves and is related to the delay from a reference instant of time or space. Instantaneous phase is usually calculated using the arc tangent function of a complex phasor (Taner et al., 1979) generating values that lie between **±π**. However, the true phase property is not wrapped and does not suffer from mathematical discontinuities between **±π**.

Shatilo (1992) identifies several different ways to unwrap one-dimensional seismic data. The simplest way is by making use of the expected continuity of the phase allowing us to unwrap using

$$\varphi_n = \psi_n + 2\pi c_n; \quad n = 0,1,2,...,N-1$$

$$where \quad c_n = \text{nint}\left(\frac{\psi_n - \psi_{n+1}}{2\pi}\right); \quad c_n \in Z \qquad (1)$$

and where the vector $\boldsymbol{\varphi}$ is the unwrapped phase, $\boldsymbol{\psi}$ is the wrapped phase, $\boldsymbol{c}$ indicates the number of integer cycles used in unwrapping, 'nint' is a function that provides the nearest integer, and n indicates the sample where the phase is unwrapped. Kaplan and Ulrych (2007) proposed a similar phase unwrapping computed in the Z-plane.

Using the concept that the instantaneous frequency is the phase first derivative, Itoh (1982) showed that the phase can be unwrapped by integrating wrapped phase differences. His process is commonly applied in two-dimensional phase unwrapping algorithms and consists of:

1. Computing the phase differences,
2. Computing the wrapped phase differences,
3. Initializing the first unwrapped value, and
4. Unwrapping by summing the wrapped phase differences.

Figure 1 shows a real seismic trace, its instantaneous phase (Taner et al., 1979) and the unwrapped phase calculated using the three methods above. The results are very close to each other, confirming the effectiveness of the three methods.

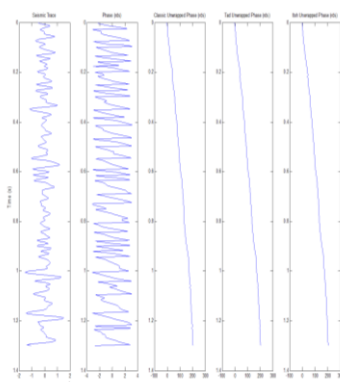

Figure 1. Real seismic trace, instantaneous phase, unwrapped phase by using the simplest , Z-plane, and Itoh (1982) methods.

Joint time-frequency phase unwrapping

The spectral decomposition of a seismic trace generates complex data that can be decomposed into magnitude and phase as a function of time and frequency. Figure 2 shows a real seismic trace and its magnitude and phase spectra.

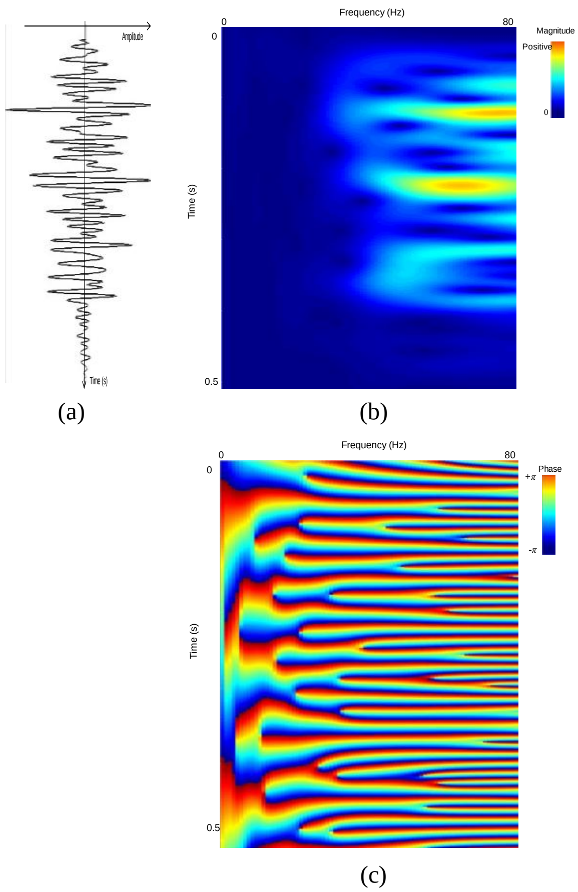

Figure2. (a) Seismic trace and its (b) magnitude and (c) phase time-frequency spectra.

One might anticipate that the time-frequency phase unwrapping can be simply solved by unwrapping each frequency phase using the one dimensional techniques presented before (Leonard, 2007). Figure 3a shows the unwrapping result using this “component independent” process where we note that unwrapped phases are not only discontinuous but also incorrect, since, for this seismic trace, the real phase should decrease along time and increase along frequencies. This shortcoming suggests taking into account the phase relationships along the frequency as well as the time axis to unwrap the data, thereby requiring a two-dimensional phase unwrapping methodology.

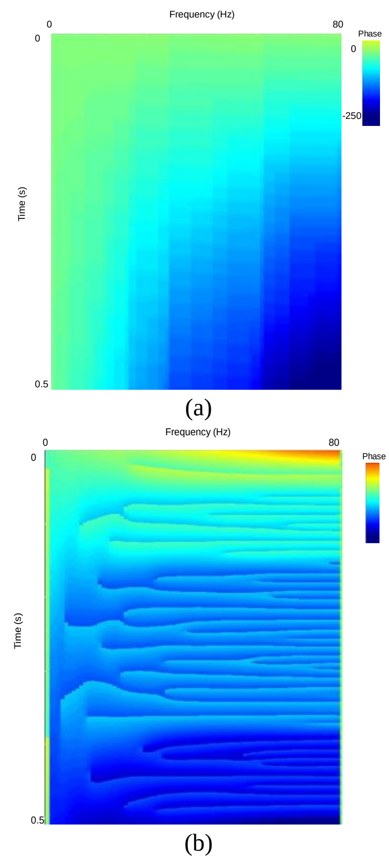

Figure 3. Unwrapped phase computed by (a) frequency-independent unwrapping each phase component using a 1D algorithm, and (b) using the proposed 2D algorithm.

Basically, two-dimensional phase unwrapping is embodied in the solution of the line integral:

$$\varphi(r) = \int_{c} \nabla \varphi dr + \varphi(r_0) \tag{2}$$

which is simply Itoh’s (1982) equation expressed for two or more dimensions. Aliasing, singularities, and noise can make equation 2 highly dependent on the integration path. Ghiglia and Pritt (1998) provide an excellent survey on 2D phase unwrapping technique and find path-dependent, quality path, and least-squares approaches to be three of the most promising solution techniques.

In this paper, we evaluate the quality-guide path approach. The first step is to compute derivative Laplacian operator, Q(f,t)

$$Q(t,f) = 1/\sqrt[2]{H(t,f)^2 + V(t,f)^2 + D_1(t,f)^2 + D_2(t,f)^2} \tag{3}$$

Where:

$$\begin{aligned} H(t,f) &= \big(\varphi(t-1,f) - \varphi(t,f)\big) - \big(\varphi(t,f) - \varphi(t+1,f)\big) \\ V(t,f) &= \big(\varphi(t,f-1) - \varphi(t,f)\big) - \big(\varphi(t,f) - \varphi(t,f+1)\big) \\ D_1(t,f) &= \big(\varphi(t-1,f-1) - \varphi(t,f)\big) - \big(\varphi(t,f) - \varphi(t+1,f+1)\big) \\ D_2(t,f) &= \big(\varphi(t-1,f+1) - \varphi(t,f)\big) - \big(\varphi(t,f) - \varphi(t+1,f-1)\big) \end{aligned} \tag{4}$$

In the second step, we use the Laplacian operator as a measure of quality and unwrap each time-frequency surface starting at a reference point where the time and frequency is set to zero. We find a good reference point to be the value of the dominant frequency at the first coherent reflector of interest.

Figure 3b shows the unwrapped phase using the 2D phase unwrapping algorithm for a trace decomposed using a Morlet continuous wavelet transform (CWT), and appear to be much more continuous than that using the 1D unwrapping algorithm shown in Figure 3a.

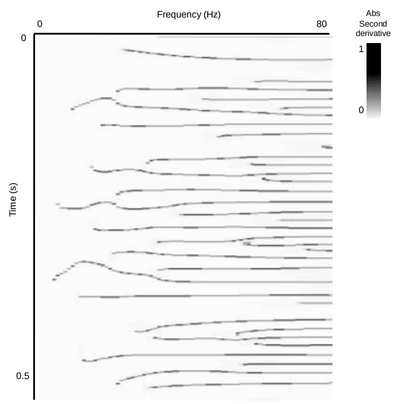

Figure 4. Absolute value of the Laplacian, $|Q(t,f)|$, of the time-frequency phase after unwrapping.

Application to seismic interpretation

Phase is sensitive to subtle variations in the seismic and therefore is ideal for detecting lateral acoustic discontinuities (Partyka, 1999). Stark (2003) also showed that high gradient values of the 2D unwrapped instantaneous phase obtained from complex trace analysis are indicative of faults and unconformities.

Cohen (1994) showed that complex trace provides the expected value or average phase for the wavelet at a given time, statistically representing the frequency spectrum with a single measure. For non-Gaussian spectra, such as occurs with thin bed interference, this approximation breaks down. Indeed, Taner (2000) and others use this phenomena as a "thin-bed indicator" attribute. To improve upon this observation, we propose first to compute the time-frequency phase spectrum, unwrap it, and then take the second vertical derivatives to estimate the transients in phase that can be associated with unconformities.

Figure 4 shows the second derivative of the time-frequency phase after unwrapping. We note that the high frequencies carry details that can be associated to the structure. We now apply this technique to a high-resolution 2D seismic line acquired from a turbidite outcrop in Wyoming, USA described by Slatt et al. (2009). This outcrop analogue to deep-water turbidite reservoirs has been mapped using not only 2D seismic, but also by well logs and cores. Figure 5 shows the interpreted relative acoustic impedance and seismic. The stratigraphy of this seismic section is discussed by Slatt et al. (2009). The seismic section is divided into two segments, an upper segment of discontinuous boundaries and a lower segment of continuous boundaries. The upper interval consists of 10 channel sandstones encased in thin-bedded mudstones. They are the fill of a 'master channel' shown by the solid black line. The lower interval is comprised of laterally continuous sheet sandstones.

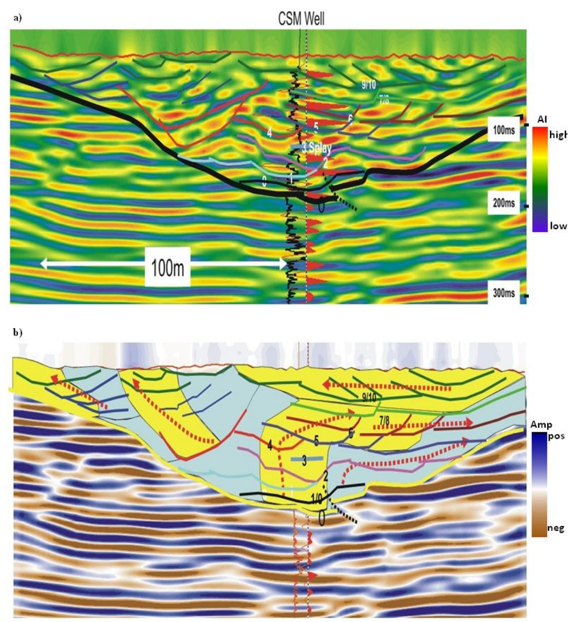

Figure 5. Interpreted relative acoustic impedance and seismic (from Slatt et al., 2009).

Figure 6 shows the instantaneous phase, unwrapped phase and second vertical derivative of the unwrapped phase. Figure 7 shows the iso-frequency second derivative of the time-frequency unwrapped phase at 60 Hz. Note that 6c and 7a provide clear delineation of sequence boundaries between channel fills, levee, and sheet sandstones. Comparing Figure 6c with Figure 7a we note that we have added considerable detail that is consistent with the adjacent outcrop control. This additional control (Figure 7) allows an enhanced interpretation of the channel and sheet sand intervals grouped in Figure 5. Individual channels migrate vertically and laterally and adjacent levee mudstones are more readily visible. The continuity of the sheet sandstones is also more clearly evident, and in fact, some compensation style deposition of individual sheets is apparent. Also, some indications of channelized facies also are apparent.

Conclusions

We show a new time-frequency phase unwrapping algorithm that can be directly applied to detect subtle discontinuities in seismic data. We believe this technique is sensitive to the same kinds of singularities detection based on the spectral magnitudes described by Matos et al. (2007) using wavelet transforms and Li and Liner (2008) using the CWT to classify singularities and map stratigraphic unconformities. Since the phase is often a more robust seismic measure than magnitude, we believe it holds significant promise in mapping stratigraphic unconformities.

Acknowledgments

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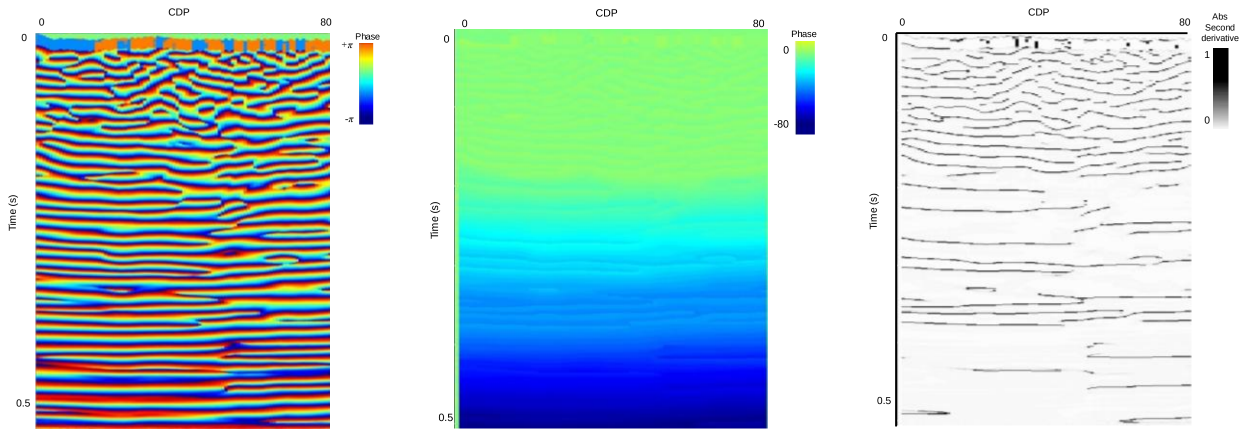
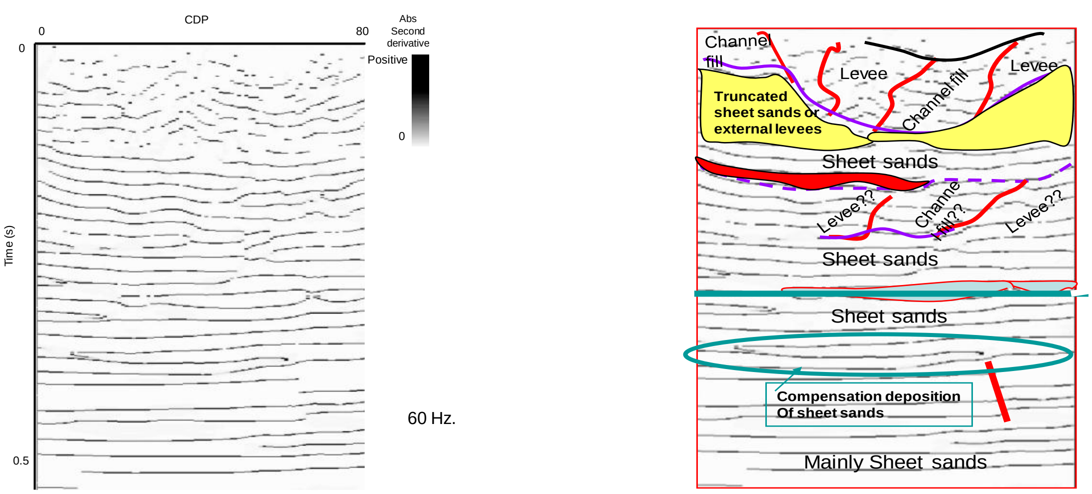


(a) (b) (c)

Figure 6. a) Instantaneous phase; b) unwrapped phase and c) second derivative of the unwrapped phase.



(a) (b)

Figure 7. a) Iso-frequency second derivative of the time-frequency unwrapped phase at 60 Hz; b) interpreted iso-frequency second derivative of the time-frequency unwrapped phase at 60 Hz.

EDITED REFERENCES

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