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Non-stationary 1D Thin Bed Model for Non-stationary Frequency Bandwidth Expansion Algorithms

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Abstract: Seismic resolution has always been a quest of a geophysicist to obtain detailed structural and stratigraphic information from the seismic data. New algorithm developed for frequency bandwidth expansion are usually tested on stationary thin bed models before their implementation on real seismic data. These models are created by using the Ricker or Rayleigh criterion. But seismic wavelet is non-stationary, which changes its shape, amplitude and frequency contents as the wave propagates subsurface. A new technique is presented in this paper to create non-stationary thin bed model where the frequency bandwidth of the seismic wavelet decreases smoothly. The study describes the comprehensive mathematical formulation of new technique and testing of new bandwidth expansion algorithms like Differential Resolution and Short Time Fourier Transform Half Cepstrum for their effectiveness for non-stationary and stationary thin bed models.

Key words: Seismic, algorithm, non-stationary, thin bed model

INTRODUCTION

Seismic resolution has always been a quest of a geophysicist to obtain maximum structural and stratigraphic information of the subsurface. This resolution leads to better geological interpretation, reserve estimation and precise decisions. Up to this end number of seismic resolution algorithms are presented in literature and these algorithms are tested on synthetic seismic data before to implement on real seismic data set. This synthetic seismic data provide the controlled environment which simulates the real data problems.

Synthetic 1 D thin bed model contains the Ricker (1953) and Rayleigh criteria (Kallweit and Wood, 1982) to define the resolution limit of the seismic wavelet. Figure 1 show the analysis of zero phase Ricker wavelet with the predominant frequency of 35 Hz. Rayleigh criteria (Tuning thickness) define the resolution limit as the half the distance between the two minima of the side lobe of the seismic wavelet, i.e., b/2. Whereas Ricker criteria (Flat spot thickness) define the resolution limit as half the distance between two inflection points of the wavelet.

Tuning thickness (Rayleigh Criterion) of this wavelet is 12 msec whereas resolution limit (Ricker Criterion) lies at 10 msec. Below the resolution limit, the two consecutive seismic events are merged with each other and it becomes difficult to separate them as two separate interfaces. Ricker developed this property and applied on model of two spikes with the same polarity, whereas videos (Widess, 1973) devoted his studies to two equal but opposite polarity spikes. Kallweit and Wood (1982) did a very nice comparative study of Rayleigh, Ricker (1953) and Widess (1973) definitions of seismic wavelet resolution and give nice equations for estimation of temporal resolution of the seismic wavelet. Ricker criterion can be obtained by using Eq. (1) where as the Rayleigh criteria can be obtained by using the Eq. 2 here f_{dom} is the predominant frequency which can be obtained from reciprocating the wavelet width b:

$$T_R = \frac{1}{3\times f_{dom}} \tag{1}$$

$$\frac{b}{2} = \frac{1}{2.6\times f_{dom}} \tag{2}$$

f_{dom} is predominant frequency

Another equation proposed by Chung and Lawton (1995) for tuning thickness estimation is shown in Eq. (3). Through this equation, Ricker wavelet with the dominant frequency of 35 Hz, will have tuning thickness of 11 msec. This 11 msec tuning thickness means that this is the minimum time separation between two connective events in time domain, below this, the event response interference starts to dominate and events become visually inseparable. In other words, if layer velocity is 2700 m sec^{-1} than its top and bottom interface is non-separable if the bed thickness is less than 15 m.

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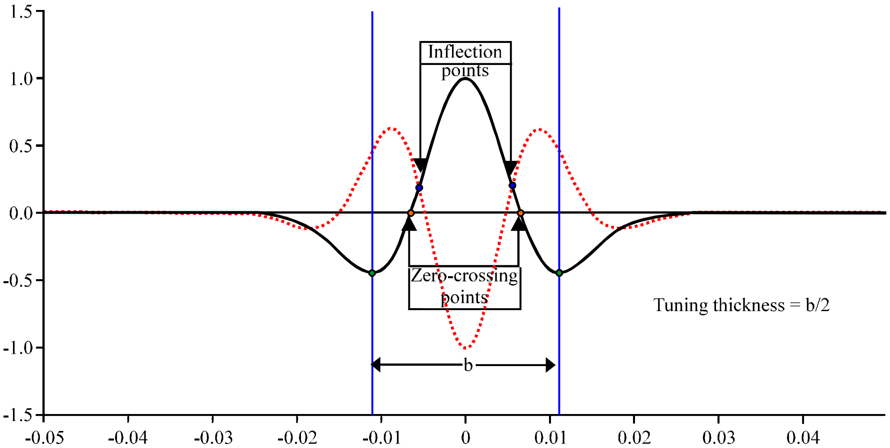

Fig. 1: Analysis of zero phase wavelet for its resolution, tuning thickness is half the distance between two consecutive minimum points of wavelet side lob (b/2) whereas flat spot thickness is the half the distance between the wavelet inflection points

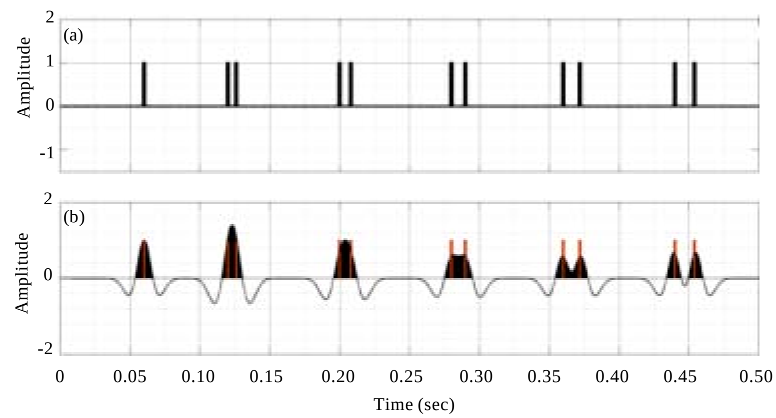

Fig. 2(a-b): (a) Reflectivity series where the distance between two consecutive events increases from left to right and (b) 1D synthetic seismic created from reflectivity series shows the resolution limit of the Ricker wavelet

$$T_R = \frac{\sqrt{6}}{2\pi f_{dom}} \quad (3)$$

Figure 2 shows the thin bed reflectivity model and its corresponding synthetic seismic trace, which is obtained by its convolution with Ricker wavelet. It presents the 1D thin bed model that contains six scenarios of events interference of same polarity when the distance between two events is:

- Single event wavelet (f_{dom}=35 Hz and tuning thickness = 12 msec)
- Two events are in between 0 to flat spot thickness (3 samples or 6 msec thickness)
- Two events are below flat spot thickness (4 samples or 8 msec thickness)
- Flat spot thickness (5 samples or 10 msec thickness) (Ricker criterion (Ricker, 1953))
- Tuning thickness (6 samples or 12 msec thickness) (Rayleigh Criterion (Kallweit and Wood, 1982))
- Greater than Tuning thickness (7 samples or 14 msec thickness)

This thin bed model is good enough to test the capability of the algorithms for events resolution but to verify the robustness of the algorithm for its handling of frequency bandwidth change with time, a non-stationary thin bed model is required. Normally non-stationary seismic resolution algorithms are tested on seismic trace by slicing the signal into small units where the seismic wavelet is considered to be slice wise stationary (Welch, 1967; Van der Baan, 2008; Van der Baan *et al*., 2010; Herrera and Van der Baan, 2012).

A new algorithm is presented in this paper to create a non-stationary thin bed model where the frequency bandwidth of the wavelet is reduced progressively without slicing or discontinuity of the synthetic trace. The algorithm uses Spectrogram created through Short Time Fourier Transform (STFT) with the spectral decomposition window length greater than the expected wavelet length so that it can cover the most of the frequency bandwidth of the seismic wavelet. Non-stationary Gaussian window filtering in spectrogram domain, smoothly band limit the frequency spectrum at each translation. Reconstruction from this non-stationary Gaussian window filtered spectrogram, leads to non-stationary thin bed synthetic model.

METHODOLOGY

Both vertical and horizontal resolution of the seismic data is limited. This imposes limits on the geological features that can be reorganized on seismic data. Vertical resolution is recognized by the input seismic wavelet and the filtering effect of the Earth as the wave propagates in the sub-surface. Resolution of seismic data depends on a number of factors as shown in Fig. 3, among them frequency bandwidth plays important role. Impulsive source like dynamite, air gun etc. produces large frequency bandwidth as shown in Fig. 4, whereas this frequency bandwidth decrease as the wave propagate in subsurface.

This difference in frequency bandwidth leads to deficiency of information in seismic wavelet. A typical seismic source wavelet in marine acquisition (air gun) contains the frequency bandwidth in the range 10 to 150 Hz. The upper limit of this frequency bandwidth decrease as wave propagate in earth and perhaps reaches to 50 Hz in TWT of 2 sec.

Fourier analysis is well known tool to decompose a signal into its orthogonal components of sine and cosine waves, Eq. 4. It transforms the signal from the time domain to the frequency domain. Amplitude and phase spectrum obtained through Fourier analysis is the solution of a stationary signal where the bandwidth of the signal doesn't change. The seismic wavelet is non-stationary which changes its shape and frequency contents as it propagates in the subsurface. Short Time Fourier Transform (STFT) which is the windowed version of fourier trans form Eq. 5 (Donoho, 1995; Jacobsen and Lyons, 2003, 2004), tries to accommodate the deficiency of Fourier transform:

$$F(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \tag{4}$$

$$F(\tau, f : h) = \int_{-\infty}^{\infty} x(t) h^*(t-\tau) e^{-j2\pi ft} dt \tag{5}$$

$x(t)$ = Time domain signal
τ = Translation of window along time axis
f = Frequency
t = Time
$h^*(t)$ = Decompostion window

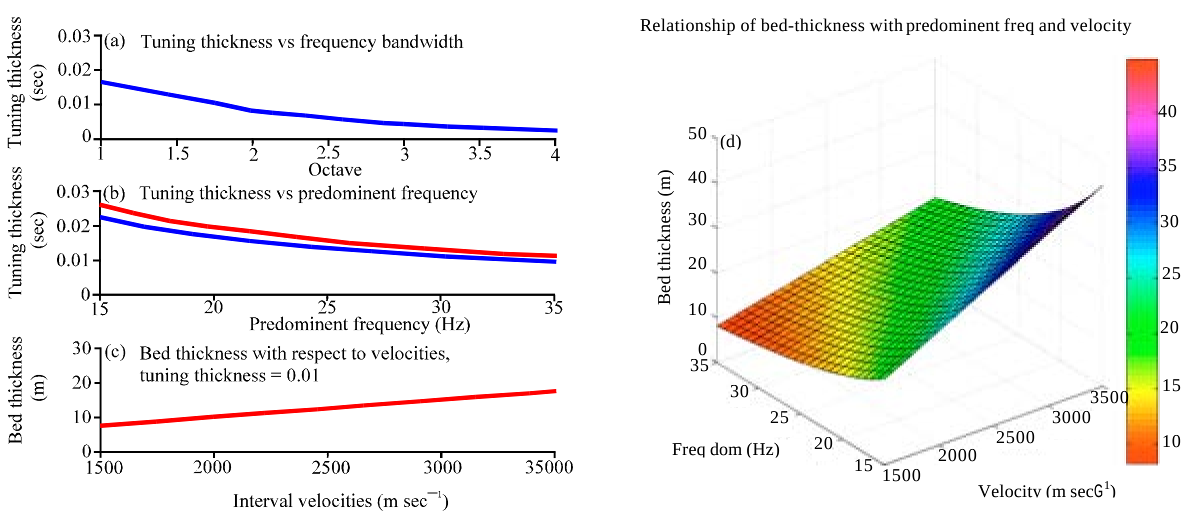

Fig. 3(a-d): Resolution of sea number wavelet depends on number of factors, (a-b) It increase with the increase in frequency bandwidth and predominant frequency, (c) Increase in layer velocity leads to increase is resolvable layer thickness and (d) Dependence of resolvable bed thickness on predominant frequency and layer velocity

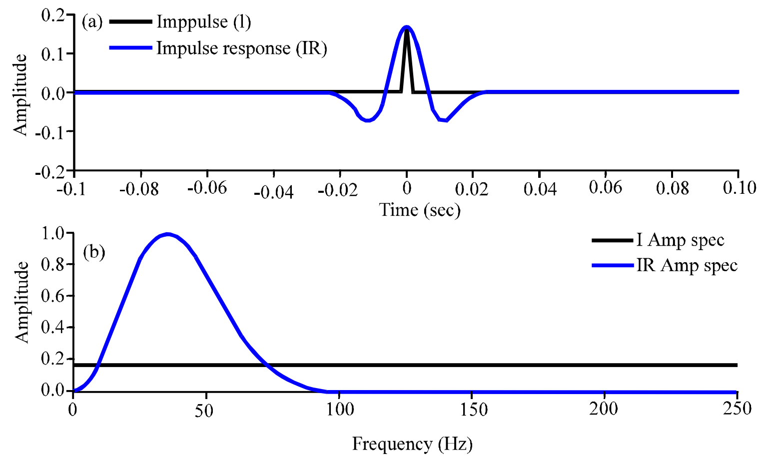

Fig. 4(a-b): (a) Overlaid comparison of impulse (black) and the earth system response (seismic wavelet), (b) Impuse contain almost all frequencies (i.e., 0 to nyquest frequency) whereas seismic wavelet is bandlimited which leads to limit in seismic resolution

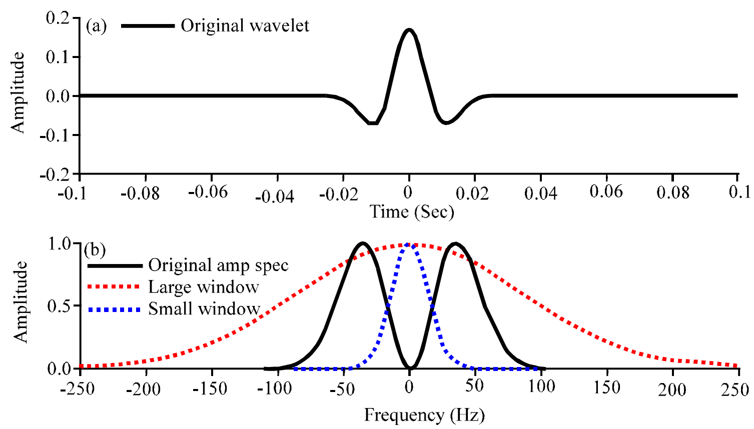

Fig. 5(a-b): (a) Ricker wavelet with the f_{dom} = 35 Hz and (b) Amplitude spectrum of the wavelet (black line), large and small Gaussian window with extension both negative and positive domain

Non-stationary thin bed model creation process is the extension of the bandpass filtering process used in signal processing. Figure 5 shows the graphical illustration of band pass filtering in fourier domain.

Figure 5a shows the input Ricker wavelet with the predominant frequency of 35 Hz. Figure 5b shows the amplitude spectrum of the input wavelet in black line. This amplitude spectrum is presented both in negative and positive domain so that the Gaussian windowing process can be better visualized whereas red and blue lines represents the large and small Gaussian window respectively. The point wise multiplication of these windows with the amplitude spectrum of the input wavelet, produce low and high predominant frequency spectrum respectively as shown in Fig. 6a and b.

Figure 6a show the original amplitude spectrum (black) and the spectrum after the application of large Gaussian window (red) which shows that almost all the frequencies are preserved through wide window size whereas Fig. 6b shows the comparison of original amplitude spectrum with small windowed amplitude spectrum which shows the that frequency bandwidth is reduced and the predominant frequency is shifted towards the low frequency side. In these amplitude spectrum's, the total energy of amplitude spectrum after the application of Gaussian filtering is normalized with respect to the original. Figure 7a and b show the comparison of the original wavelet with the wavelet reconstructed from wide and short window amplitude spectrum. Wide Gaussian window size preserved almost all the frequencies which leads to almost the original input seismic wavelet whereas shorter Gaussian window size leads to smaller frequency bandwidth and large wavelet duration. This decrease in frequency bandwidth leads to

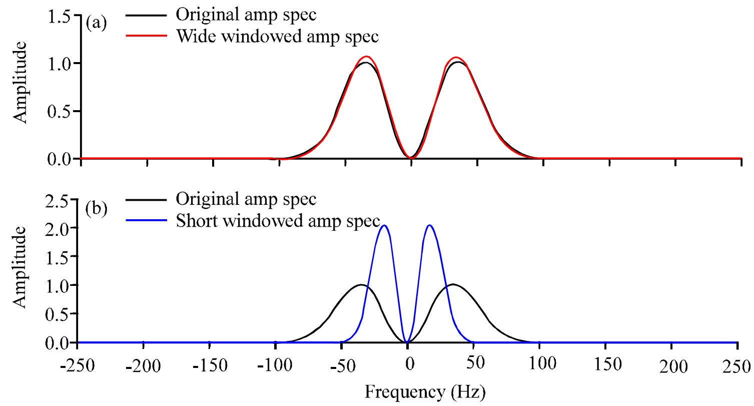

Fig. 6(a-b): Energy balanced, bandlimited amplitude spectrum obtained through Gaussian window in furier domain

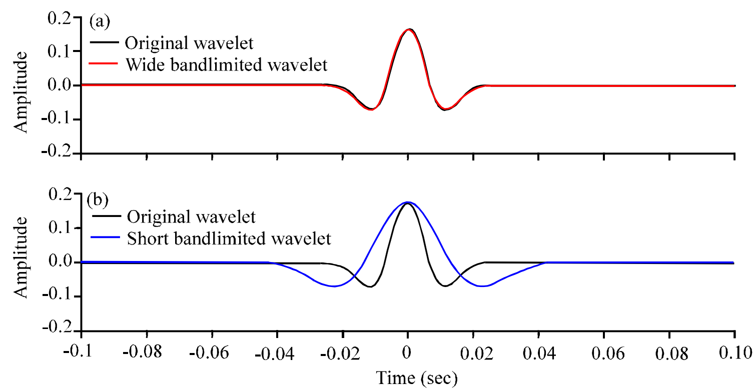

Fig. 7(a-b): Comparison of the (a) Original wavelet with the large Gaussian window filtered wavelet and (b) Original wavelet with the wavelet reconstructed from small windowed filtered amplitude spectrum

increase in tuning thickness of the seismic wavelet from 12 to 24 msec as shown in Fig. 8.

This predominant frequency shift process is implemented on the amplitude spectrum of each windowed version of the signal obtained through spectral decomposition. The Gaussian window filtering width is non-stationary which has a half-width of 80 Hz on the left side and progressively reduce to 10 Hz on the right side. This non-stationary Gaussian window limits the frequency bandwidth and shift the predominant frequency from high to low progressively which leads to non-stationary thin bed model.

Figure 9 shows the input stationary thin bed model, which contain 6 thin bed events where each event is at tuning thickness where as Fig. 9b shows its spectrogram created while using Gaussian window of half length of 20 samples. Figure 9c show the non-stationary Gaussian window which changes its width from 80 to 10 Hz progressively from left to right. This non-stationary Gaussian window when multiplied point wise with spectrogram of the stationary thin bed model, limits the bandwidth at each translation. Figure 9d shows the reconstructed non-stationary thin bed model. Where the events which were at tuning thickness become progressively unresolvable on the right side because of this lose of frequency bandwidth.

Figure 10a shows the thin bed reflectivity model with the event at equal spacing whereas Fig. 10b shows the non-stationary thin bed model where the frequency bandwidth is progressively decreased from left to right. Figure 11 shows the comparison between the stationary and non-stationary thin bed model which show the decrease in resolving power of non-stationary thin bed model without producing point discontinuities.

TESTING OF NEW SIGNAL PROCESSING TECHNIQUES

Recently developed algorithms like Differential Resolution (DR) (Sajid *et al*., 2012) and Short Time Fourier Transform Half Cepstrum (STFTHC) (Sajid *et al*., 2013) algorithm are compared for seismic resolution and handling of non-stationary thin bed model.

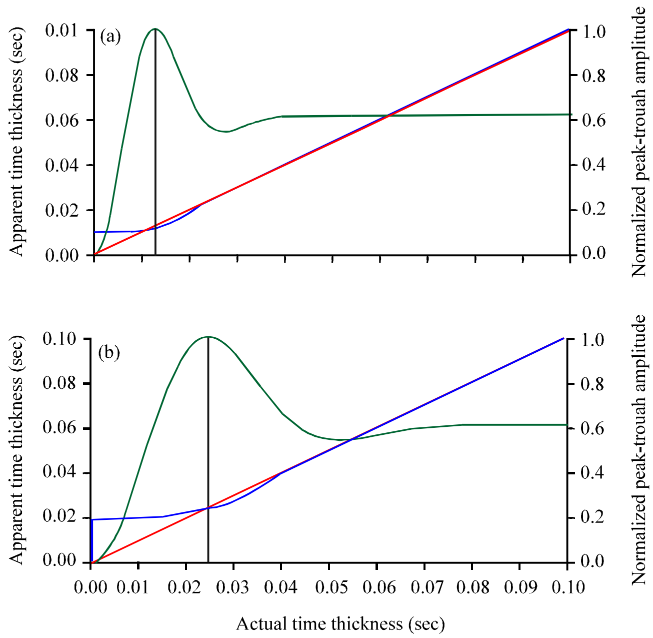

Fig. 8(a-b): Comparison of tuning analysis of the seismic wavelet after Gaussian window filtering. Tuning analysis of (a) The wide frequency bandwidth wavelet, (b) Short frequency band width wavelet

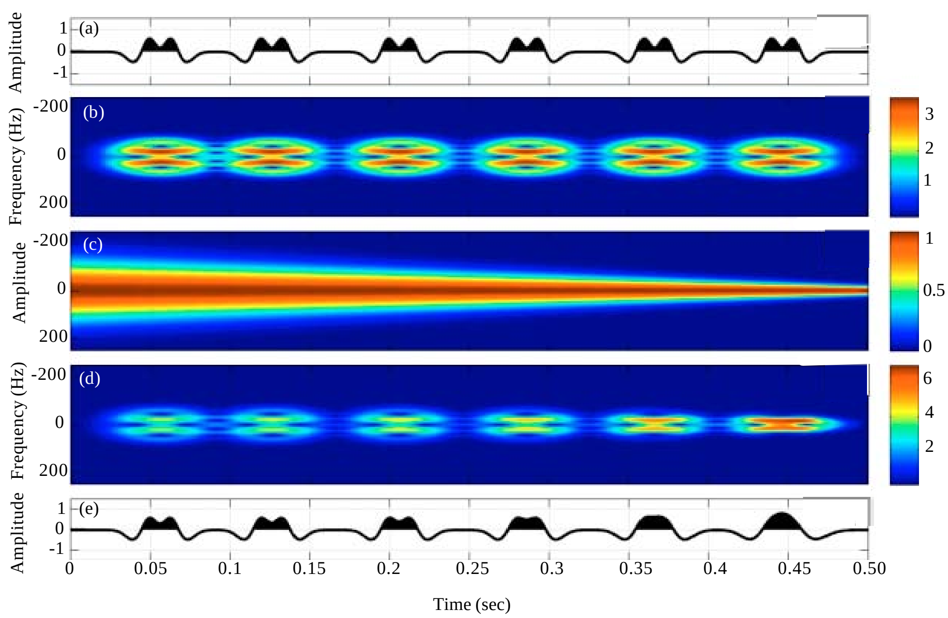

Fig. 9(a-e): Conversion of stationary thin bed to non-ststionary thin bed model through non-stationary Gaussian filtering

Figure 12a shows the application of Differential Resolution (DR) algorithm on stationary thin bed model where the event: Which were unresolvable because of the interference effect of the wavelet, become resolvable after the application on DR algorithm. Whereas Fig. 12b show the application of DR on non-stationary thin bed model. As the algorithm is based on the idea of variation of amplitude with respect to time and the input variable of the algorithm (i.e., -2nd, 4th, -6th differential, smooth version and original signal) are normalized respect to whole seismic traces, so algorithm is able to resolve the seismic event when the seismic wave

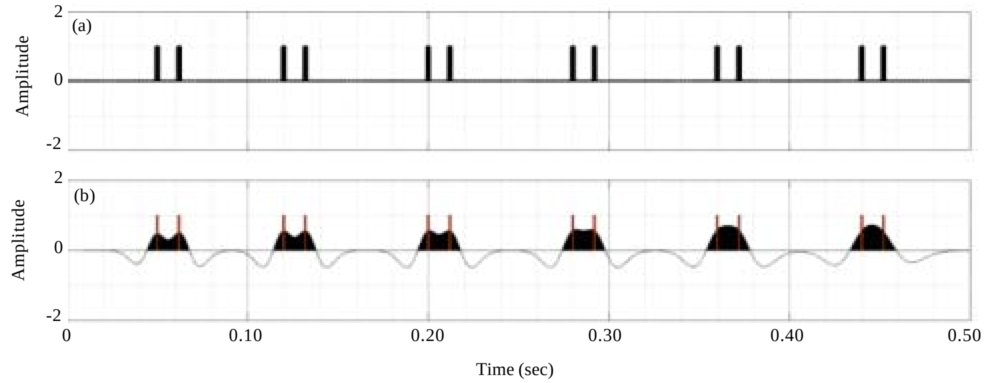

Fig. 10(a-b): (a) Original thin bed reflectivity model and (b) Events become unresolvable as bandwidth decreased from left to right in synthetic seismic

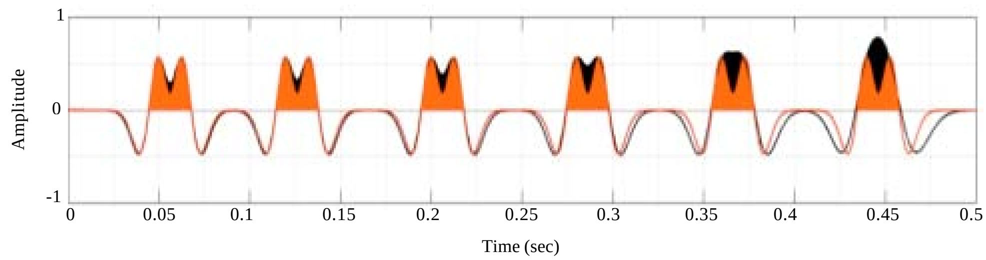

Fig. 11: Comparison of stationary (red color) and non-stationary (black color) thin bed model

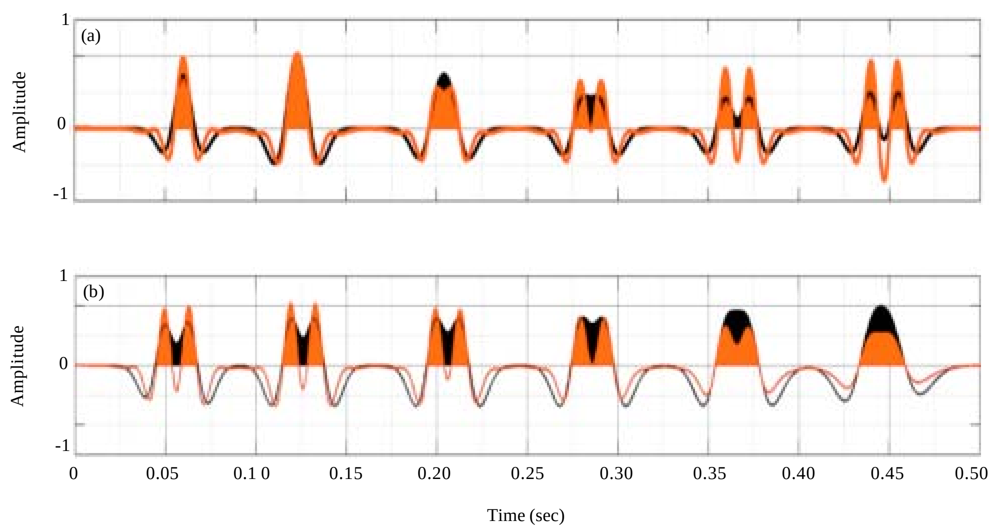

Fig. 12(a-b): Application of differential resolution on stationary and non-stationary thin bed model, (a) Application of differential resolution improved resolution of stationary thin bed model and (b) Resolution achieves through DR, depends upon the frequency contents of the seismic waveform

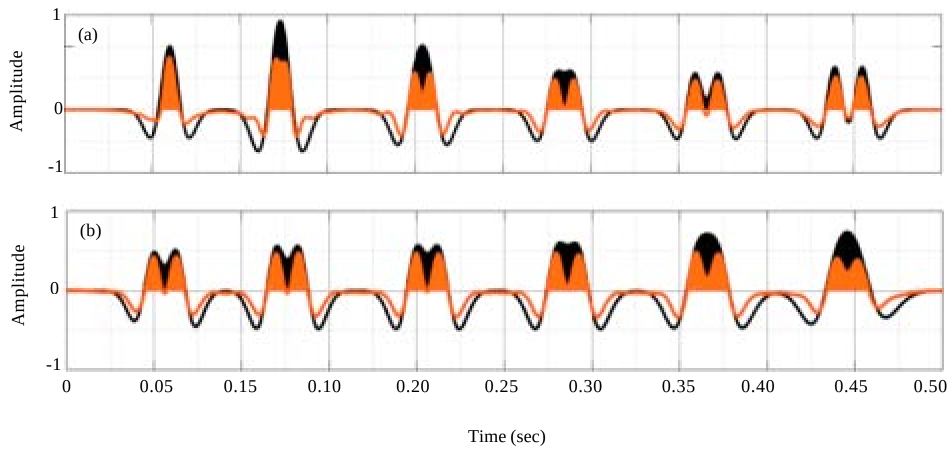

Fig. 13(a-b): Application of STFTHC algorithm on stationary and non-stationary thin bed model, (a) Algorithm is able to resolve thin bed featurs far below the tuning thickness, (b) Algorithm is effectively able to resolve thin bed features of non-ststionary thin bed model

form contains the high frequencies but the absence of high frequency effects the resolving power of the algorithm.

The Short Time Fourier Transform Half Cepstrum is the bandwidth expansion algorithm. It expands the frequency bandwidth at each translation of spectrogram by implementing the logarithm on windowed signal amplitude spectrum. This broader frequency spectrum can be observed both in stationary (Fig. 13a) and non-stationary (Fig. 13b) thin bed model through better seismic resolution and low value of side lobes. As this frequency broadening is implemented at each translation of the spectral decomposing window so the algorithm is capable to improve the resolution of non-stationary thin bed model. This broadening of frequency spectrum depends upon the frequency content at each window interval which keep the algorithm from high frequency boost and from false seismic features creation.

CONCLUSION

Testing of seismic resolution algorithm on synthetic thin bed model is the first step to check the effectiveness of the algorithm for seismic resolution. There are a number of factors which affect the seismic resolution; one of them is seismic frequency bandwidth. The frequency bandwidth of the seismic is non-stationary and it decreases with time as wave propagates subsurface. The new presented technique is capable to modify the frequency bandwidth of synthetic seismic without producing point discontinuities. The new non-stationary thin bed model provides the criteria to test the effectiveness of the algorithms for hidden feature extraction.

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REFERENCES

Chung, H.M. and D.C. Lawton, 1995. Amplitude responses of thin beds: Sinusoidal approximation versus Ricker approximation. Geophysics, 60: 223-230.

Donoho, D.L., 1995. De-noising by soft-thresholding. IEEE Trans. Inform. Theor., 41: 613-627.

Herrera, R.H. and M. Van der Baan, 2012. Short-time homomorphic wavelet estimation. J. Geophys. Eng., 9: 674-680.

Jacobsen, E. and R. Lyons, 2003. The sliding DFT. IEEE Signal Process. Mag., 20: 74-80.

Jacobsen, E. and R. Lyons, 2004. An update to the sliding DFT. IEEE Signal Process. Mag., 21: 110-111.

Kallweit, R. and L. Wood, 1982. The limits of resolution of zero-phase wavelets. Geophysics, 47: 1035-1046.

Ricker, N., 1953. Wavelet contraction, wavelet expansion and the control of seismic resolution. Geophysics, 18: 769-792.

Sajid, M., D.P. Ghosh and Z. Zahir, 2012. Seismic resolution and analysis of thin pay beds. Proceedings of the Petroleum Geoscience Conference and Exhibition, April 23-24, 2012, Kuala Lumpur, Malaysia.

Sajid, M., D.P. Ghosh and Z. Zahir, 2013. Novel method to improve seismic resolution through STFTHC algorithm. Proceedings of the Petroleum Geoscience Conference and Exhibition, March 18-19, 2013, Kuala Lumpur, Malaysia.

Van der Baan, M., 2008. Time-varying wavelet estimation and deconvolution by kurtosis maximization. Geophysics, 733: V11-V18.

Van der Baan, M., S. Fomel and M. Perz, 2010. Nonstationary phase estimation: A tool for seismic interpretation? Leading Edge, 29: 1020-1026.

Welch, P.D., 1967. The use of fast Fourier transform for the estimation of power spectra: A method based on time-averaging over short, modified periodograms. IEEE Trans. Audio Electroacoust., 15: 70-73.

Widess, M.B., 1973. How thin is a thin bed? Geophysics, 38: 1176-1180.