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Resolution enhancement of seismic data using stationary wavelet transform

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1. Summary

We present a way of extending the bandwidth of band-limited seismic datasets, thereby enhancing their resolution. We make use of the stationary wavelet transform (SWT) for implementing this resolution enhancement. We show that by using the known wavelet coefficients of the input dataset at higher scales (lower frequencies), it is possible to predict the lower scale (higher frequency) coefficients in an in-phase/coherent manner, thereby improving the resolution of the input seismic data. Improvements of ~ 1 octave in bandwidth are typical. We argue that the non-stationary, time varying nature of the seismic signal makes the wavelet transform domain the natural/ideal domain to work in, as opposed to the Fourier domain.

2. Introduction

The bandwidth of seismic data recorded on reflection seismograms is severely attenuated upon passage through earth. The earth acts as a filter chopping off high frequency part of the signal with a severity increasing with depth. This not only leads to a loss of resolution in the final stacked image, but also means that this loss of resolution is variable with depth.

This variable loss of resolution leads to loss of clarity and ambiguity in interpretation of the final stacked frame. Restoring the high frequency content of bandlimited seismic signals is an outstanding problem in exploration geophysics. The obvious lure/promise of being able to produce higher resolution images which allows us to resolve thin beds and pinchouts from existing datasets, without having to invest in expensive high resolution re-imaging surveys has captured the imagination of the geophysicists the world over. Here we present our results of using the stationary wavelet transform for achieving this goal.

3. Theory

Wavelet transform constitute a family of algorithms that form a part of the more general technique of multiresolution analysis. The basic driving force behind the development of multiresolution analysis was the realisation that given it's global nature, the application of the usual Fourier techniques is inappropriate for time-varying, non-stationary datasets. This requirement of having both time as well as frequency localisation led to the development of the rich field of multiresolution analysis (Mallat [1989]). The theory of wavelet transforms can be found elsewhere (Mallat [1989], Nason and Silverman [1995], Kumar et al. [1997]). The extension of seismic bandwidth in the wavelet transform domain has been reported earlier in literature (Zhou et al. [2004], Smith et al. [2008]).

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3.1 The resolution enhancement methodology

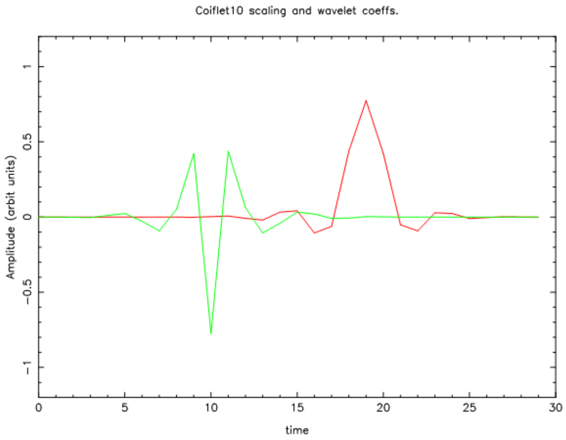


Figure 1: The coiflet scaling (red) and wavelet (green) functions.

We made use of the coiflet (Daubechies [1992]) scaling and wavelet coefficients each having 30 coefficients for implementing the SWT iterative scheme. These are shown in Fig. 1. The scaling function acts as a Low Pass (LP) filter while the wavelet function acts as a complementary quadrature-mirror High Pass (HP) filter. In the first iteration, the seismic trace is passed through the HP filter to produce the detailed output. The same trace is also passed through the LP filter to produce the smooth output. The detailed output captures the top half frequency content of the data while the smoothed output contains the bottom half. The detailed output is designated as the scale=1 wavelet coeffs. The smoothed output is then passed through the upsampled scaling and wavelet coeffs. to yield the next set of (scale=2) wavelet coeffs. This process is repeated iteratively till the desired frequency range has been covered. The lowest scale captures the 1/2 *fnyquist* to *fnyquist* frequency content of the original seismic dataset, while the subsequent scales cover progressively lower frequencies (down by a factor 2 for each subsequent scale). In case ideal half-band filters have been used for calculating the SWT, the wavelet coeffs. can be inverse transformed to exactly reproduce the original dataset. This property of perfect reconstruction is also satisfied in case of special wavelets such as Daubechies and Coiflet wavelets. This motivated us to use Coiflet wavelets for our work as perfect reconstruction is a prerequisite for a successful bandwidth extension algorithm.

Once the SWT coefficients have been obtained, we apply our technique of manipulating the wavelet coefficients so as to boost the power in lower scales (i.e. higher frequencies) in a coherent manner. This technique is based on the observation that an event in time domain has a finite spread in the wavelet domain across a number of scales. This fact that the events have finite spread across several scales give us the hope that perhaps we could be able to use this information for extending the signal bandwidth to lower scales where we had no flux to begin with. Hence we can utilise the wavelet coefficients of an event at higher scales to predict it's wavelet coeffs at lower scales. The inverse transform of these modified wavelet coefficients (with power leaked into the lower scales) yield a higher resolution stack in the time-domain.

4. Example

We present our results with the help of a real dataset. We make use of a 2D migrated stack consisting of 327 individual CDPs sampled at 1 msec having a sample length of 2000 msec. This stacked dataset shows several linear structures at various depths. Some prominent features are located at ~ 640msec, 830msec, 860msec and 1170msec.

In Fig. 2(a) we show the SWT wavelet coefficients of CDP number 435 of our input migrated stack. Notice the lack of power at lower scales in general and the fact that the deeper (higher time) signal is more severely attenuated as compared to shallower signal which has some flux at smaller scales (higher frequencies) as well. Also note that the events are seen to be coherent across different scales as mentioned earlier. Fig. 2(b) shows the wavelet coefficients after power has been leaked into the lower scales using our technique explained in the last section. Notice that this leakage of power is coherent across scales and builds up on the pre-existing finite extent of the wavelet coefficients across different scales. These modified wavelet coefficients are then inverse transformed to obtain the resolution enhanced stack.

Figs. 3(a), 4(a) show two portions of the original migrated stack and figs. 3(b), 4(b) show the corresponding portions after the application of our resolution enhancement technique outlined above. Fig. 5 shows the amplitude spectrum of the migrated stack before and after the resolution enhancement. The improvement in resolution is self evident and is characterised by the following

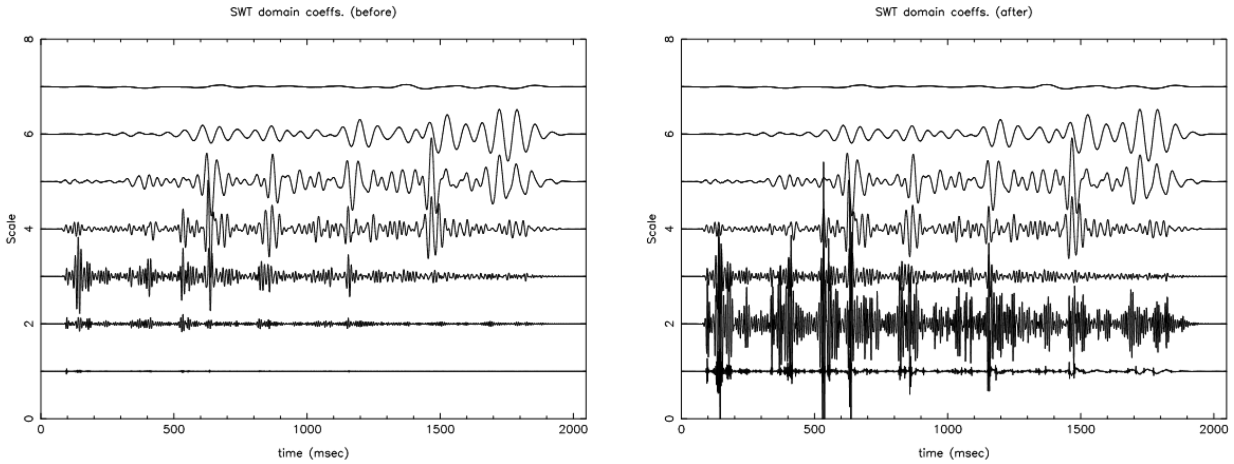


Figure 2: (a) SWT coefficients for CDP number 435 from the original input stack. Notice the more severe attenuation at larger times. Also, note that individual events have finite extent across different scales. (b) SWT coefficients after application of our bandwidth expansion algorithm yielding higher power at lower scales. Note that the leakage of power to lower scales is coherent across various scales.

1. The resolution enhancement technique sharpens the wavelet.
2. It extends the amplitude spectrum by ~1 octave.
3. It splits up previously barely resolved layers into doublets as expected.
4. It enhances continuity of layers compared to the input stack.

The resulting resolution enhanced stack is also robust against the application of phase rotations and allows any residual phase to be taken out of the stacked data if required.

The stationary wavelet transform is a very powerful technique for extending the bandwidth of seismic datasets. The non-stationary nature of the seismic signals makes it essential to use the wavelet transform (as opposed to Fourier transform) as it preserves the temporal information in addition to the frequency content of the signal. The wavelet transform not only tells us which frequencies are present in the signal, it also tells us where (at what time) those frequencies are present. This allows us to coherently leak power from higher scales to lower scales as shown in fig. 2. This time-frequency localization allows us to selectively boost higher frequencies at the location of the events (i.e. in-phase) rather than globally, as would have been done by the usage of Fourier transforms. This in-phase/coherent boosting of power at smaller scales ensures that we do not end up simply boosting high frequency noise as would have been the case if we were to use Fourier transforms instead of wavelet transforms. This also allows us to treat the case of varying attenuation as witnessed in case of seismic signals where signals recorded from deeper layers are more severely attenuated.

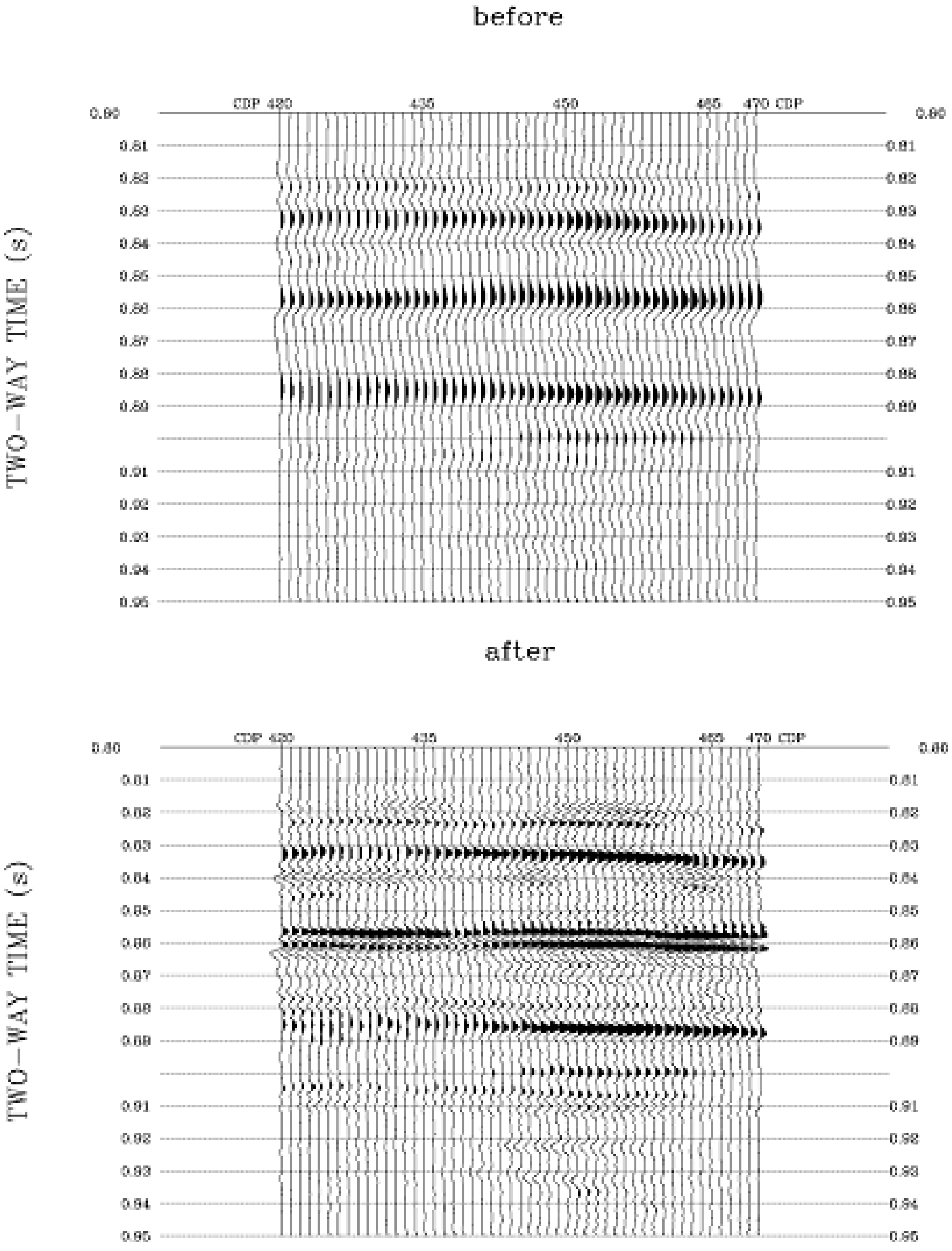
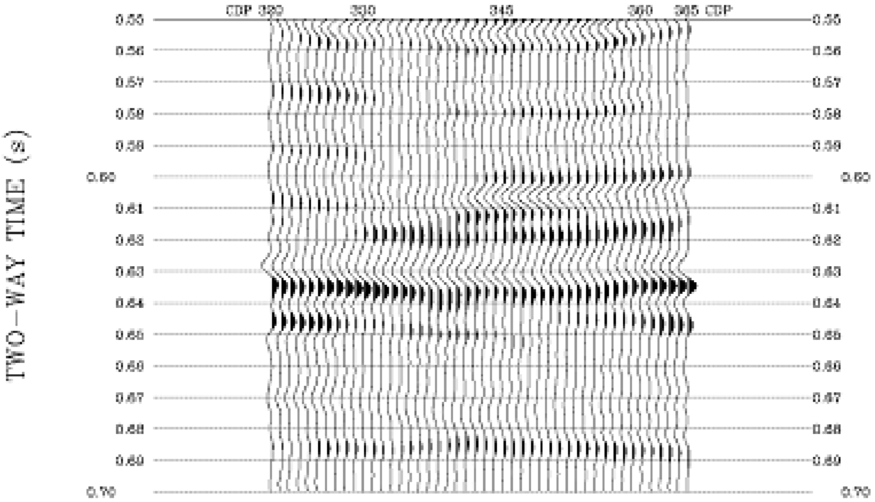


Figure 3: (a) Portion of the original migrated stack (b) The same portion of the stack after application of our resolution enhancement algorithm. Note the sharper wavelet and the ability of the algorithm to resolve layers which were originally unresolved.

before



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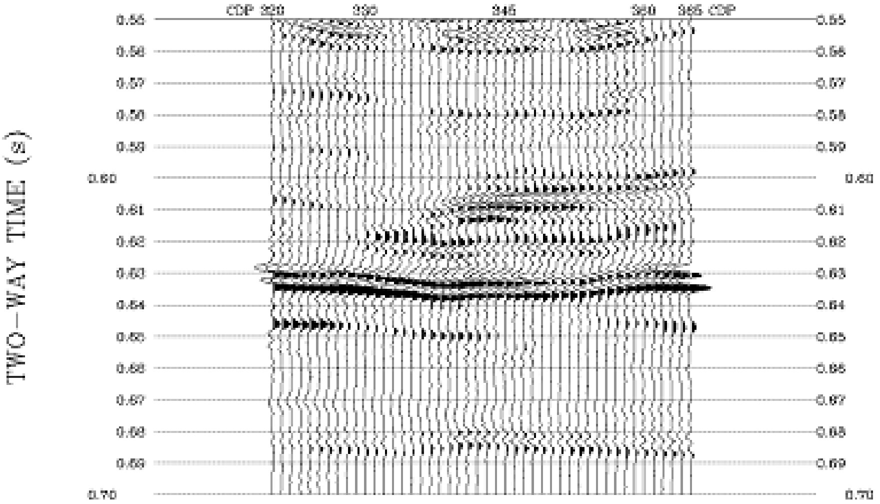

Figure 4: (a) Portion of the original migrated stack (b) The same portion of the stack after application of our resolution enhancement algorithm. Note the sharper wavelet and the ability of the algorithm to resolve layers which were originally unresolved.

While we have shown our results using a stack which already had quite high bandwidth to begin with (~ 160Hz), our algorithm has been tested on other more typical stacked datasets having bandwidth of ~80Hz as well and has proven to be equally successful in all such cases, yielding improvements of ~1 octave or more.

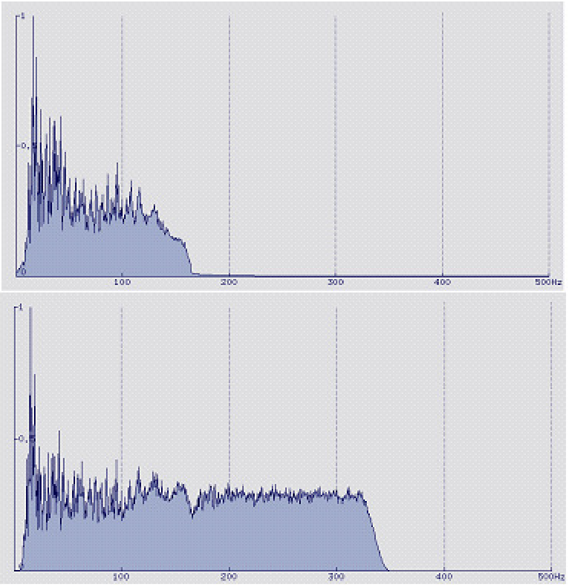

Figure 5: (a) Amplitude spectrum of the input migrated stack (b) Amplitude spectrum of the resolution enhanced stack showing an improvement of ~1 octave.

Conclusion

In this work we have presented a new technique for enhancing the resolution of band-limited seismic datasets using the Stationary Wavelet Transform (SWT). Improvements of ~ 1 octave in bandwidth are typical. We demonstrated using a real dataset how the resolution of the input seismic improved as a result of extending the wavelet coefficients from higher scales to lower scales in an in-phase/coherent manner. We argued that the time-frequency localization offered by SWT is essential for thispurpose, given the non-stationary nature of seismic datasets. We conclude that this technique shows very promising results for resolution enhancement of band-limited seismic datasets.

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