Some applications of wavelet transform in seismic data processing

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Summary

Many different techniques based on Fourier transforms are being used to suppress noise in exploration seismology. Ground-roll, swell noise, guided waves and random noise are just some of the most persistent types of noise in land and marine data that can be hard to remove with these traditional methods. Wavelet transforms present a relatively new tool to aid seismic processing that has been successfully applied for compressing and de-noising purposes.

In this paper we reproduce several algorithms currently used in the research community in order to evaluate their effectiveness in suppressing difficult-to-remove noise. We use both 1D and 2D Stationary Wavelet Transform (SWT) -based filters to suppress ground-roll, acquisition footprints, and random noise. We also address resolution enhancement in the wavelet transform domain, and provide some observations and preliminary results.

SWT-based filters and techniques produce results of high quality that are equal or exceed those produced by classical Fourier-based techniques. In addition, since SWT-based filters can be applied to postmigrated data, they present the interpreter with relatively intuitive and computationally efficient solutions.

Introduction

There are several types of noise in pre and poststack seismic data that have proven to be very hard to suppress with conventional techniques. This is particularly important for land data where aliased ground-roll noise and limited acquisition design lower the quality of seismic data and make interpretation challenging at best. Ground-roll, swell noise and tube waves are the types of noise that are the most difficult to remove. Traditional Fourier-based filtering approaches can filter out these events but they also damage useful parts of the signal.

The wavelet transform is a relatively new technique that has been shown to be a useful application for several seismic processing tasks. For prestack filtering, 1D and 2D wavelet transform-based filters have been proposed by Deigahn and Watts (1998), Yu et al. (2002), Yu and Garossino (2005) and Abdul-Jauward and Khene (2000). In our study we acquired or reproduced what appeared to be the more promising 1D and 2D wavelet transforms described in the literature and calibrated them against real data. We emphasize application to real data sets because we believe this is the way to properly test all aspects of new technologies.

1D and 2D SWT filtering methodology

Details about the 1D SWT can be found in Yu et al. (2004), while Abdul-Jauwad at al. (2000) provides an overview of 2D SWT. For seismic data processing purposes we use 1D and 2D SWT filtering methodologies that apply threshold filters to noise-contaminated wavelet coefficients.

Filtering in the wavelet domain is similar to filtering in any other domain, and contains three main steps:

- compute forward wavelet transform,
- mute or taper unwanted components in the wavelet domain, and
- compute the inverse wavelet transform.

Figure 1 shows a generalized 1D SWT filtering scheme. Computing the forward transform decomposes the input seismic gather or section into one or more scales of wavelet coefficients. Lower scales correspond to the higher frequency content of the data, while higher scales contain lower frequencies. Note that the spectra of neighboring scales overlap. If the amplitude of seismic noise is concentrated in one or more decomposition scales we apply a mute or taper to diminish their effect.

In our work, we find that a reasonable number of decompositions for 1D SWT is 5 to 6 scales. More decomposition levels increase computational time significantly without providing significant advantages to seismic analysis. While we used Coiflet wavelet with 5 vanishing moments (zero crossings), we found wavelets from other families provide comparable results. Data storage resulting from multiple output volumes are the main disadvantages of multidimensional and multidirectional filters such as 2D SWT- and Curvelet-transform- based filters.

Figure 2 shows a simplified 2D SWT flow. The 2D wavelet transform decomposes the seismic image into several scales where each of them has horizontal, diagonal, and vertical

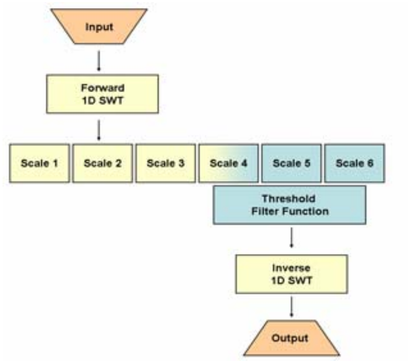

Figure 1: Proposed 1D SWT filtering scheme. The high scales correspond to the low frequencies and low scales to high frequencies. This cartoon shows scales 1-3 with a hard mute, scale 4 with a taper or soft mute, and scales 5-6 with no mute, thereby providing a high-pass filter. Each overlapping time window is muted independently, resulting in a nonlinear (because of the thresholding), time-variant band-pass filter.

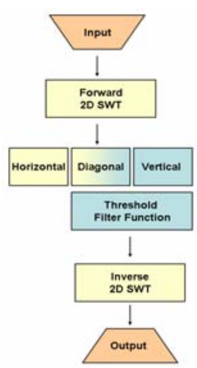

Figure 2: Proposed 2D SWT filtering scheme. This cartoon shows scales the horizontal scale with a hard mute, the diagonal scale with a taper or soft mute, and vertical scale with no mute, thereby providing a dip filter. Each overlapping space-time window is muted independently, resulting in a nonlinear (because of the thresholding), time-variant band-pass filter. In practice, each dip component is further subdivided into the scales shown in Figure 1.

Because of the amplitude-based muting (based on thresholds) wavelet-transform-based filters are in general nonlinear and can be readily applied to nonstationary signals. Wavelet filters are nearly as computationally efficient as the FFT and can be used for filtering several types of noise in seismic data at the same time.

Prestack filtering

Ground-roll suppression

Ground-roll filtering by wavelet-transform-based filters was one of the first applications of wavelet theory in seismic data processing. We tested several of the proposed algorithms on shot gather 25 from Yilmaz (1987). First, we test the 1D SWT filter (using 6 scales) proposed by Yu et al. (2002) and Yu and Garossino (2005). Usually, ground-roll noise is dominant in higher scales (lower frequency), specifically at the 4^{th}, 5^{th} and 6^{th} scale. High energy ground-roll noise in a given time window will be represented by high amplitude wavelet coefficients in those scales. By applying a threshold function to a subset of scales (4^{th}, 5^{th} and 6^{th} scale) these events can be filtered out with minimal damage being done to the high frequency components of the signal below the ground roll and no damage to any of the signal in the time windows where the ground roll falls below the threshold. Note that the band-pass filtering is data-driven and is triggered by the actual amplitude of the low-frequency noise components, and not by a predetermined filter as in time-variant Fourier-based band-pass filtering. Yu and Garossino (2005) showed that this type of filtering gives the best results for aliased noise in land data. Applying the 1D SWT filter to shot gather 25, Yilmaz (1987) we see that almost all ground-roll noise is removed (yellow arrows in Figure 3), with only a small portion of the noise cone still remaining. Note that some of the linear events deeper in the gather are still present. The residual section shows the low frequency component of several strong reflectors that has been removed (red arrows); this part of the signal is very hard to retain, since it overlaps with noise even in the wavelet domain.

The 2D SWT filters we apply for ground-roll removal are similar to those proposed by Castro de Matos and Ossorio (2002), and Abdul-Jauward and Khene (2000). We successfully reproduced most of the algorithms in the literature and although the process of automatic removal of dipping events in each desired scale is fast, it produces significant artifacts. Removal or thresholding of events in vertical panels corresponds to removal of noisy dipping events but o produces smearing artifacts. When reflections have a certain dip, it is hard to separate them from aliased dipping events so they will be partially removed. Artifacts can also be introduced to the de-noised section if noisy high-energy traces (which erroneously trigger the threshold) are not edited. Such high-energy 'spikes' will generate the wavelet equivalent of the well-known Gibb's phenomenon, generating chessboard-looking artifacts that will correspond to the size of the 2D wavelet basis functions. For clarity purposes, we do not show results of 2D SWT filters in this paper.

Potentially the best result can be obtained when combining 1D and 2D stationary wavelet-transform-based filters. Welford and Zhang (2005) first proposed filtering with physical wavelet-frame de-noising by combining properties of 1D and 2D wavelet transforms. We have tested several types of 1D and 2D wavelet decomposition schemes and present results of our preferred implementation in Figure 4.

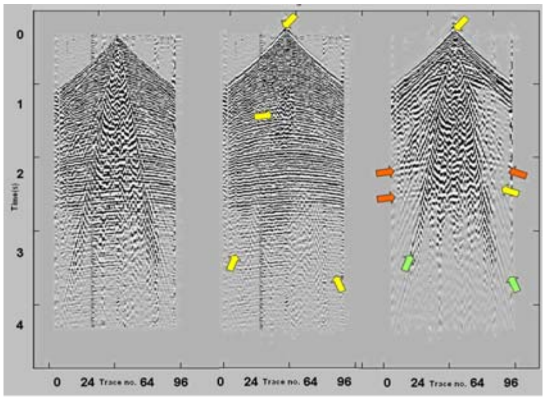

Figure 3: 1D SWT filter for ground-roll suppression of shot gather 25, Yilmaz (1987). (a) Shot gather 25, (b) 1D SWT filtering result and (c) the difference. Green arrows point where filtering is good, yellow where it is acceptable, and orange where signal is being filtered out.

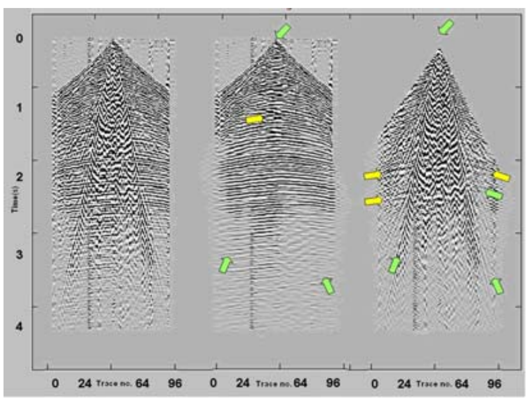

Figure 4: 1D+2D SWT filter for ground-roll suppression of shot gather 25, Yilmaz (1987). (a) Shot gather 25, (b) 1D+2D SWT filtering result and (c) the difference. Green arrows indicate where filtering is good and yellow where it is unacceptable.

Yellow arrows show that the useful part of the data is less affected with some of the remaining noise energy in the middle of the gather. Almost all linear events are removed with a missing trace being interpolated.

Our conclusion for this example is that the best practice is to filter the original shot gather using the 2D wavelet filter to partially or completely mute low scales or high frequency diagonal and vertical details. This removes random noise and enhances and smoothes horizontal details. Currently, we are designing a similar filtering workflow for marine and OBC data filtering, with to the goal of suppressing mud-roll and swell noise.

F-X Deconvolution

F-X deconvolution is commonly applied in later stages of preprocessing for suppression of residual and random noise. F-X deconvolution can be applied both to gathers and to stacked sections: however, even with careful parameterization the signal can be adversely affected. Figures 5a and 5b show results of F-X deconvolution applied to a stacked 2D marine line. The difference section shows that a significant part of the primary energy has been filtered out. These results can be improved in the 2D wavelet transform domain.

For flat-layer geology, reflectors will show up in horizontal decomposition panels. There are two ways to improve results of F-X deconvolution on stacked data. One is to decompose the input stacked section using the 2D SWT and applying F-X deconvolution to all but the horizontal panels, thereby avoiding altering that component that has most of the useful signal. Figures 5c and 5d show the results of such filtering. The stacked section exhibits less noise, while the difference section shows almost no signal being removed.

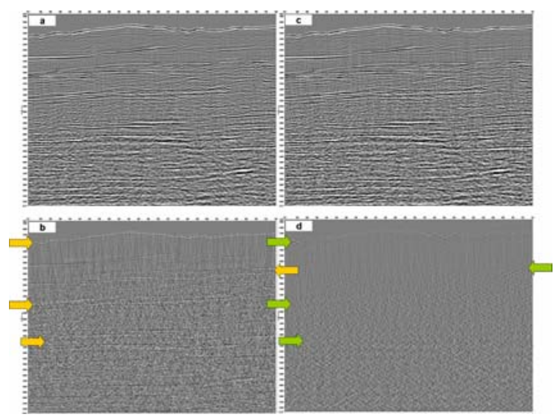

Figure 5: (a) Seismic section after F-X deconvolution, (c) combined 2D SWT and F-X deconvolution, and (b) and (d) corresponding differences or rejected data. Note that the difference from combined technique shown in (d) removes very little reflection energy (yellow and green arrows).

A alternative to this 2-filter flow is to take the SWT difference sections and use F-X deconvolution to remove signal from it. Since signal in the stacked section is sub-horizontal it will retain its orientation in the difference section as well. By removing some of the horizontal panels from the difference section, only the noisy more-steeply dipping events remain. In practice we find that it is harder to remove useful reflectors from difference sections because of their strong overlap with noise in wavelet domain.

Other applications of 1D and 2D SWT

There are several other possible applications of 1D and 2D SWT from which we have encouraging preliminary results. One of them is resolution enhancement both with 1D and 2D SWT filters.

Devi (2006) uses a discrete wavelet transform (DWT) combined with well logs to improve seismic resolution and delineate faults and channels. The seismic resolution enhancement that we mimic is inspired and based on work by Yu and Garossino (2004). They exploit properties of the SWT along with an adaptive filtering approach to improve the high frequency component of synthetic seismic traces.

We apply this seismic resolution enhancement workflow to postmigration data using both 1D and 2D SWT filters. We decompose seismic sections into several scales and orientations and balance the amplitude of the lower (high frequency) scales to be closer to those of the amplitude of the higher (low frequency) scales. We apply this workflow to improve high temporal and spatial frequency of a 3D land dataset from Mexico. We note some improvement of vertical resolution, especially in the deeper parts of Figures 6 and 7. This can also be seen on deeper time slices where improved vertical resolution means more geological detail compared to the original volume. Most of these features, such as turbidites and mass transport deposits, were only clearly visible on coherence time slices. Another advantage of postmigration resolution enhancement is filtering in the wavelet domain, which can reduce different types of noise at the same time. De-noising in the wavelet domain can tackle several different dips at different scales, which may be completely guided by an interpreter who may feel confident in differentiating geologic dip from dipping seismic noise. There are some limitations and constraints to this approach. So far, we have no verification of improved resolution of details. No geological constrains were used and without log or VSP information we can not be certain that some of the high resolution features are real. Wavelet-based enhanced data seem to be significantly less sensitive to noise than spectral balancing or spectral whitening.

Another application of wavelet transforms is for de-multiple in combination with Radon domain filters. Radon transform filtering can successfully eliminate parabolic events from NMO-corrected CMP gathers. By applying the same process in just diagonal and vertical panels of 2D SWT decomposition panels, we can minimize removal of useful data. Although the quality of results of this type of filtering is very good, the filter itself is computationally expensive. Parameterization and computation of combined 2D SWT and Radon de-multiple filters can be significantly more expensive than the Radon filter itself.

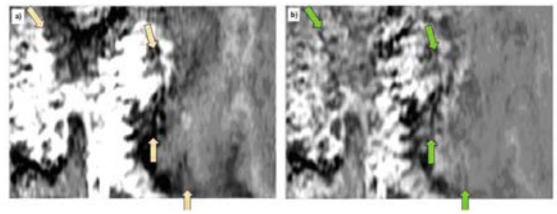

Figure 6: Time slice from Agua Fría-Coapechaca-Tajín, Mexico, (a) before and (b) after 1D SWT resolution enhancement, respectively left and right. Arrows indicate where some geological features are more visible and distinguished; probably being subtle channel belts (data courtesy of PEMEX).

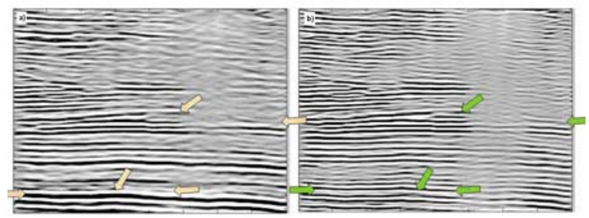

Figure 7: Time section from Agua Fría-Coapechaca-Tajín, Mexico, (a) before and (b) after 1D SWT resolution enhancement. Arrows point to the parts where resolution-enhanced results show better resolved or completely new features (data courtesy of PEMEX).

Conclusions

We have presented several applications of 1D and 2D SWT in seismic data processing, with preliminary ideas and other possible research topics. We find the 2D SWT and new multidimensional and multidirectional transforms provide good results in a wide area of seismic data processing, at the expense of increased computation and data storages. We are still testing and comparing computation times for different multidimensional wavelet-based algorithms. Also, partial rotation of seismic images might improve results of 2D SWT filters. We believe that 3D wavelet transform along with 3D Curvelet transform filters will be more suitable for de-noising of 3D seismic data volumes, especially for acquisition footprint and random noise suppression. Geometric attributes have proven to be practical tool for quality control for de-noising algorithms for 3D datasets.

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