GeoConvention 2015
GEOSCIENCE
new horizons
Telus Convention Centre • 4-8 May 2015 • Calgary, AB Canada

Seismic Signal Enhancement Using 2D Fast Discrete Curvelet Transform --- An Application to VSP and Common-Shot Gathers From a Hardrock Environment

Dong Shi, Bernd Milkereit

Department of Earth Sciences, University of Toronto

Summary

Obtaining seismic images with good quality in hardrock environments has been challenging. This condition applies to many mineral explorations using seismic methods including our study area where the data quality is strongly affected by soft, near-surface materials and a reflector with low contrast in rock physical properties. Until recently, no effective processing has been applied to the seismic data for improving signal-to-noise ratio (SNR) other than f-x deconvolution. Multiresolution analyses, requiring little in-situ rock physical information, are widely used as SNR improvement methods for pre- and post-stacked seismic traces. The directionally-representative nature of the curvelet transform makes itself an effective multiresolution method for seismic processing. We applied a denoising sequence using the fast discrete curvelet transform (FDCT) on two seismic data sets: a vertical seismic profiling (VSP) survey and a 3D shot record. The results show significant improvement on the SNR of the data.

Introduction

The wavelet transform is the basis of and most widely used multiresolution method. One of the primary problems of the wavelet transform is that it performs less effectively on the representation of the directional features of an image. Candes and Donoho (1999) proposed the concept of the ridgelet transform, which is an anisotropic wavelet transform in a higher dimension, optimally representing global straight-line singularities. For analysis of the local straight-line singularities, the same authors (2000) suggested performing the ridgelet transform on block partitions instead of the full image. This method is afterwards known as the first-generation curvelet transform, but has not been widely used because of the uncertainty in the shape of the ridgelets. These authors (2005, 2006) proposed the second-generation curvelet transform in both continuous and discrete forms that considers frequency partitioning of the image to be processed. The latter form, known as the FDCT method, has become a useful tool in image processing and signal analysis. For the application of the curvelet transform in seismic denoising, Hennenfent and Hermann (2006) suggested an extended form of FDCT based on non-uniformly sampled data. Curvelet transform application to seismic data is currently a practical method for signal processing. Other examples of this method are the primary-multiple separation in the curvelet domain (Herrmann et al ,2008) and the test of migration and demigration process (Chauris and Nguyen ,2008).

The primary objective of the seismic surveys in this study was to detect of the depth of the unconformity of a sedimentary sequence overlying basement metamorphosed rocks. Raw records showed low data quality. SNR of the seismic data was firstly affected by the strong attenuation caused by the unconsolidated overburden layer with variable thickness. Secondly, the reflection coefficient of the unconformity was significantly variable being controlled by the changing of the lithology of basement rocks and the clay content of the sandstone sequence. Conventional processing steps (for example, Juhojuntti et al., 2012) had been applied to the data showing unclear unconformity images in the vicinity of an ore body. This is believed to be caused by the hydrothermal alteration taken place associated with the formation of the ore mineralizaiton. We applied an FDCT denoising sequence on two sets of data: 1) a VSP survey and

2) a 3D common-shot gather. The software package used (www.curvelet.org) is based on the discussion of Candes et al. (2006).

Theory and Method

Using a window U_j with polar coordinates variables r and θ defined in the frequency domain:

$$\mathrm{U}_j(r,\theta) = 2^{[-\frac{3j}{4}]}\mathrm{W}(2^{-j}r)\mathrm{V}(\frac{2^{[\frac{j}{2}]}\theta}{2\pi})$$

where W and V are windows defined as:

$$\sum_{j=-\infty}^{\infty} \mathrm{W}^2\left(2^j r\right) = 1, \qquad r \in (\frac{3}{4},\frac{3}{2})$$

$$\sum_{l=-\infty}^{\infty} \mathrm{V}^2\left(t-l\right) = 1, \qquad t \in (-\frac{1}{2},\frac{1}{2})$$

The mother curvelet φ_j is defined by its Fourier Transform:

$$\hat{\varphi}_j(\omega) = \mathrm{U}_j(\omega)$$

Thus, curvelets (examples of these curvelets are shown in Figure 1) are defined by scaling (j), rotating (l) and translating ($k_{(a,b)}$) of the mother curvelet:

$$\varphi_{j,l,k}(x) = \varphi_j(\mathrm{R}_{\theta_l}(x - x_k^{(j,l)}))$$

where

$$\mathrm{R}_\theta = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad \mathrm{R}_\theta^{-1} = \mathrm{R}_\theta^T = \mathrm{R}_{-\theta}$$

The coefficients of a curvelet transform (curvelet coefficients) are then expressed as:

$$\mathrm{c}(j,l,k) = \frac{1}{(2\pi)^2}\int \hat{f}\,(\omega)\mathrm{U}_j(\mathrm{R}_{\theta_l}\omega)e^{i(x_k^{(j,l)},\omega)}\mathrm{d}\omega$$

This is the second-generation basic continuous curvelet transform proposed by Candes and Donoho (2005). However, as described by Candes et al.(2006), the discrete form of the above curvelet transform is highly redundant. These authors designed the Curvelab software package focusing on reducing this redundancy via multiple strategies. We applied one, known as the Frequency Wrapping method, to denoise the seismic record.

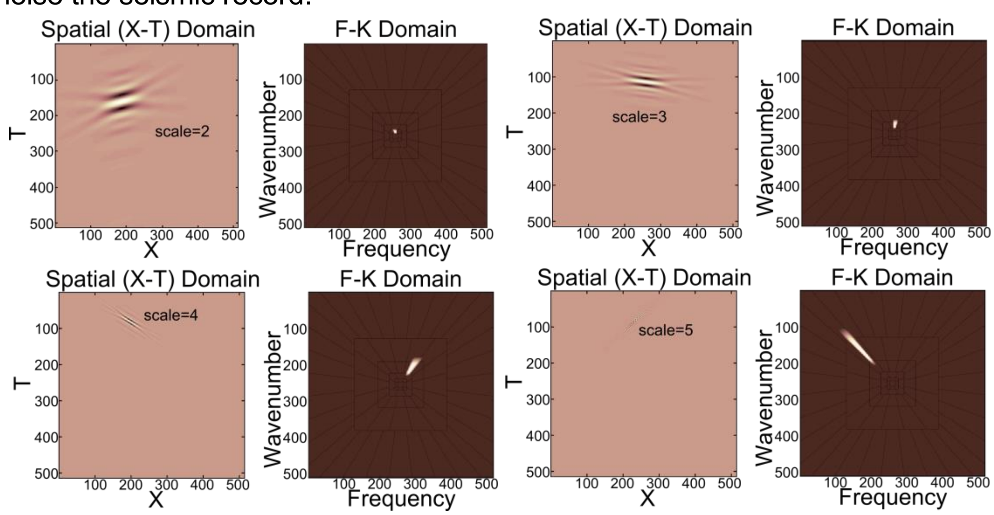

Figure 1. Displaying of curvelets both in spatial domain and frequency-wavenumber domain. Each display shows one example of curvelet at one scale with different rotation and translation coefficients.

The denoising sequence is as straight forward as other multiresolution signal analysis methods, which involves: 1) forward curvelet transform 2) applying a threshold and 3) inverse curvelet transform. There are currently mutiple thresholding methods being suggested, and we utilized the method associated with the Curvelab package, the simple hard threshold described by Starck et al. (2002).

Examples

Figure 2a shows an example of the vertical component of the original near-offset VSP, and Figure 2b shows the curvelet coefficients of the data displayed within different panels at different scales.

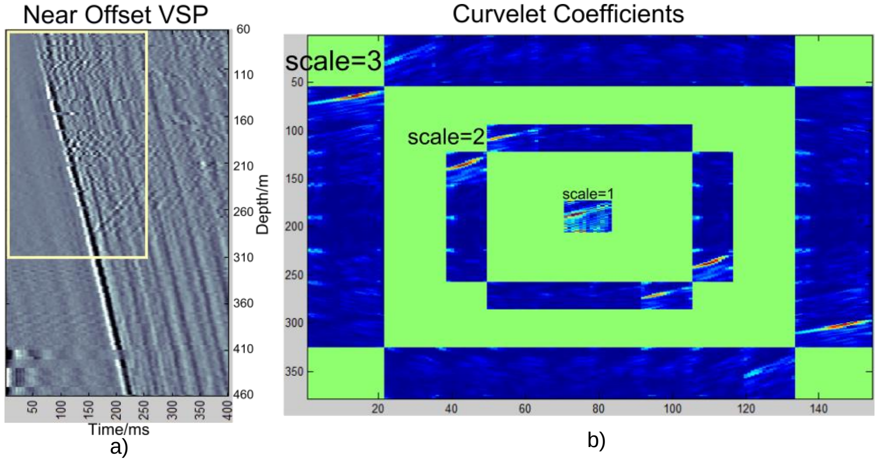

Figure 2. a) An example of the vertical component of the original near-offset VSP (band-pass filtering and AGC scaling have been applied). b) Curvelet coefficients display of the VSP data in a). Corse scale (scale=1) coefficients are displayed in the centre. Each panel represents one rotating angle of the curvelet transform.

By applying the hard threshold condition on the transformed curvelet coefficients, the image can be restored by inverse curvelet transform. The example of the curvelet denoised seismic image within the block from the VSP data shown in Figure 2a is displayed in Figure 3b. Figure 3c shows the difference between the original and denoised images. The obvious improvement of the seismic image can be noticed. By inspecting the difference of the denoising, the lack of coherent features denotes that the curvelet denoising process brought little harm to the useful signal.

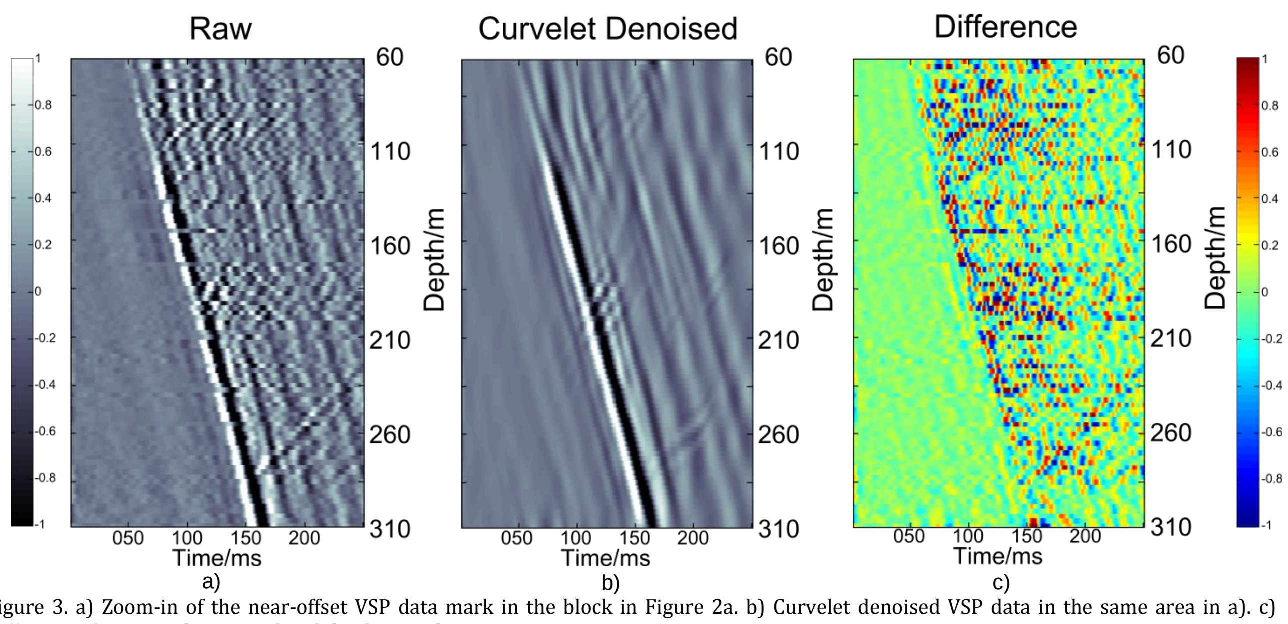

Figure 3. a) Zoom-in of the near-offset VSP data mark in the block in Figure 2a. b) Curvelet denoised VSP data in the same area in a). c) Differences between the original and the denoised images.

For the second example, the denoising sequence has then been applied to a 3D raw common-shot gather from a seismic survey. An example from one line is shown in Figure 4.

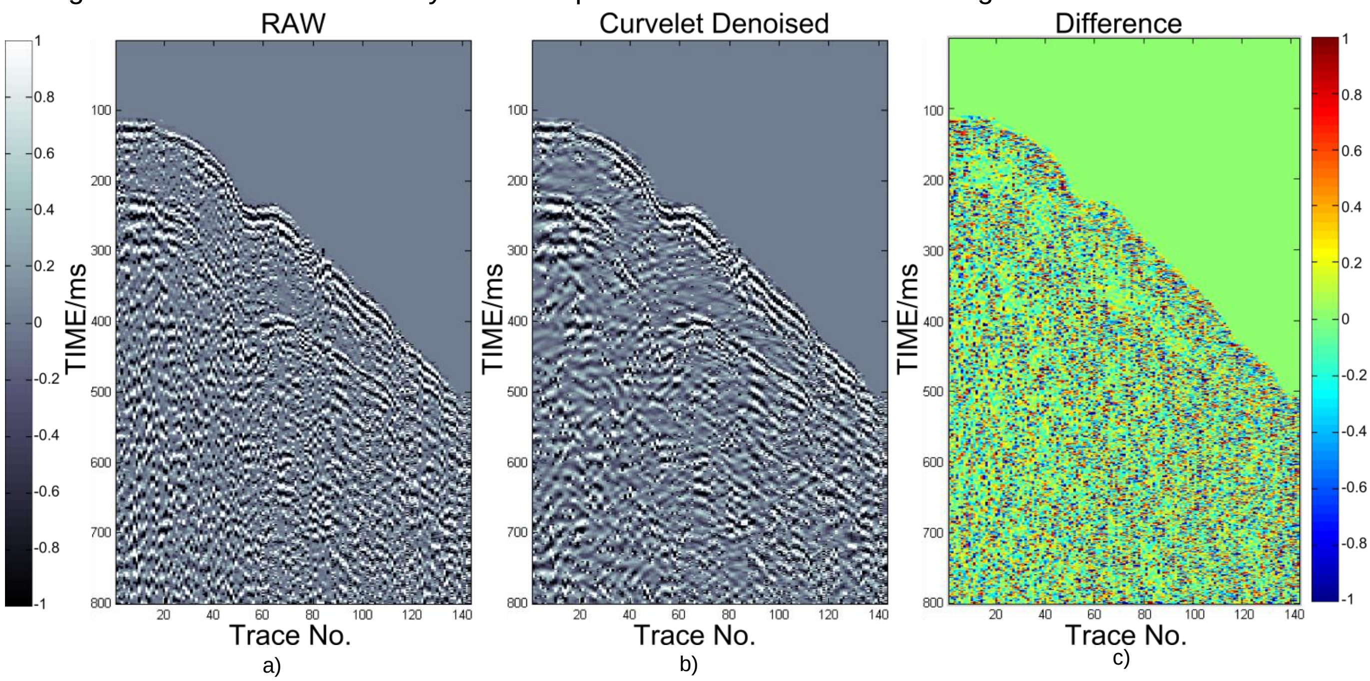

Figure 4. a) A comparison of one raw common-shot gather (AGC 200ms, band-pass filtered), and b)the curvelet denoised result. c) The difference between the two images.

Conclusions

The nature of optimally representing straight-line singularities makes the curvelet transform an acceptable tool on denoising process of seismic data. Our applications on the VSP and 3D shot-record examples shows promising improvement to the SNR. By inspecting Figure 3b, it is apparent that the denoising process is harmless to useful signals. Further study can focus on optimizing the thresholding methods for this specific problem. Moreover, the denoising sequence can be applied to the pre-migrated or pre-stacked data to avoid the effects of processing artifacts.

Acknowledgements

The research is supported by Natural Sciences and Engineering Research Council of Canada (NSERC). Thanks to Curvelet.org team for providing the Curvelab open source code.

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