Denoising of Ship Gravity Data Using Wavelet Transform Approach

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Summary

A technique is suggested for denoising the ship gravity data using wavelet transform. The wavelet transform is a useful tool for analyzing the nonstationary signals. The denoising of a signal using wavelet transform is generally carried out using different types of thresholding. Three thresholding techniques of soft, hard and customized are tested on the synthetic gravity signals with white noise. The root mean square error and coefficient of determination between synthetic and denoised gravity signals indicate the superiority of customized thresholding. Further all the thresolding approaches are applied to the ship and satellite gravity data. The satellite gravity data was extracted along the ship tracks. Both (ship and satellite) gravity data is compared before and after denoising. Again the customized thresholding is found to provide better results.

Introduction

The real data acquired in the field do not exist without noise (unwanted component in the signal). The noise in the data affects the processing and interpretation of the data. The process of separating the unwanted component from the signal is called denoising. Sometimes denoising is also called as smoothing but basically both are conceptually and fundamentally different. Denoising removes the noise without harming the signal whereas smoothing tends to cut that portion of the signal that contains noise resulting in loss of signal along with noise. There are many methods to suppress noise from the signal. The Fourier transform method is mostly used for suppressing the noises. In Fourier transform based analysis the signal is transformed in frequency domain. In frequency domain various operations and filters are applied on to the signal to suppress the noise. After applying all the desired operations the signal is transformed back to the time domain. The applications of Fourier transform methods are good for the stationary signals but these are not suitable for nonstationary signals. Since many times geophysical signals are non-stationary in nature, therefore analyzing either in time or frequency domain is not appropriate. The main draw back of Fourier domain processing is edge effect and global denoising. On the other hand, the localized natures of the wavelet transform results in denoising with edge preservation (Rao & Bopardikar, 1998) and allows local as well as global denoising. The wavelet based techniques does not require any assumptions about the nature of the signal and permits discontinuities as well as spatial variations in the signal. The objective of this work is to find a suitable thresholding scheme for denoising the ship gravity data using wavelet transform. Wavelets transform have found various applications in geophysics (Kumar and Georgiou, 1994; Deighan and Watts, 1997; Leblanc et al., 1998; Ridsill-Smith and Denitith, 1999; Fedi et al., 2000; Lyrio et al. 2004)

Method

The Wavelet transform provides the opportunity to represent the signal in time and frequency domain. The wavelet transform provides a powerful tool for denoising the data. The discrete wavelet transform allows separating the signal into various scales, which broadly relate to the different frequencies. It also contains the information about spatial location of features in each level of the transform. The discrete wavelet transform (DWT) decompose a signal into discrete wavelet coefficients (w), from which original signal can be reconstruct. The discrete wavelet coefficients of a noised signal can be modified by using a thresholding function to represent coefficients of a signal. For constructing the thresholding function the DWT coefficients less than the threshold are set to zero. The Technique of denoising of a signal using thresholding scheme is described as below.

Assume that the observed data X (t) = S (t) + N (t) contains the true signal S (t) with additive noise N (t). Let (.) W and (.) 1 W - denote the forward and inverse wavelet transform operators. Let ( ) l ., D denote the denoising operator with the threshold l . Then the Process of Denoising can be applied in three steps as described below:

1. Linear forward wavelet transform-The wavelet transform is applied to the noisy signal to obtain the noisy wavelet coefficients.

   $Y=W(X)$

2. A nonlinear denoising-Selection of appropriate threshold technique and apply to the wavelet transformed coefficients.

   $Z=D(Y, l)$

3. Linear inverse transform-Inverse wavelet transform of the thresholded signals to obtain the denoised signal.

   $S = W^{-1}(Z)$

The whole process of wavelet denoising depends upon the type of thresholding.

Wavelet Thresholding

Soft thresholding

The soft thresholding functions shrink the wavelet coefficients towards zero and also called wavelet shrinkage function. Mathematically it may be defined as:

$fs(x) = x - \lambda$ if $x \geq \lambda$

$= 0$ if $|x| < \lambda$ otherwise

$= x + \lambda$ if $x \leq -\lambda$

The threshold λ is obtained by using the following expression;

$l = \sigma\sqrt{2 \log N}$

Where σ^2 is the noise variance and N is the length of the signal. The σ is assumed to be one for white Gaussian noise.

Hard thresholding

The most common choices for l are hard (universal) and the soft (wavelet shrinkage) thresholding function. The third type of thresholding used in this study is customized thresholding.

The hard thresholding function chooses all wavelet coefficients that are greater than the given threshold and sets all others to zero.

$f_h(x) = \{x$ if $|x| \geq \lambda$ otherwise 0

If a coefficient is greater than λ, then it is considered as significant otherwise we consider it due to the additive noise and discard the value. The hard thresholding function is also known as universal threshold because it is applied crudely. Hard threshold has the advantage of preservation of edges. The hard thresholding function is discontinuous at $|x| = \lambda$. Due to this discontinuity at the threshold, the hard thresholding function is known to yield abrupt artifacts in the denoised signal, especially when the noise level is significant (Chang et al., 2000).

Customized thresholding

A third type of thresholding known as customized thresholding based on non-garrote and firm shrinkage has been introduced by Gao (1998). The customized thresholding is like hard thresholding with smooth transition around the threshold λ and can be defined as:

$fc(x) = x - sgn(x)(1-\alpha)\lambda$ if $|x| \geq \lambda$

$= 0$ if $|x| \leq \gamma$ otherwise

$= \alpha \left(\frac{|x| - \gamma}{\lambda - \gamma}\right)^2 \left\{ (\alpha-3)\left(\frac{|x| - \gamma}{\lambda - \gamma}\right) \left| 4 - \beta \right| \right\}$

where $0 < \gamma < \lambda$ and $0 \leq \alpha \leq 1$.

Here γ is the cutoff frequency below which all the coefficients are putted below zero and α is the parameter that determines the shape of thresholding function. For various values of α, when $\lambda = 1$ and $\gamma = \lambda/2$ the customized thresholding function can be viewed as the linear combination of the hard thresholding function and the soft thresholding function $\alpha f_h(x + (1-\alpha) . f_s(x)$ that is made continuous around the threshold λ.

In case of: $\lim_{a=0} fc(x) = fs(x)$ and $\lim_{a \to 1, \lambda \to 1} fc(x) = fh(x)$ the customized thresholding function can be adapted to both the soft and hard thresholding (Yoon and Vaidyanathan, 2004).

Denoising of synthetic signals

The synthetic data is generated over two buried spheres of 20 km radius at a depth of 20 km separated by a distance of 20 km with a density contrast of 0.3 g/cm 3 (Figure 1a). Then white Guassian noise is added to the signal (Figure 1b). To remove the added noise from synthetic signal, the wavelet transform of the noised signal is taken. The thresholding parameter is decided by using $\lambda=\sqrt{2\log N \sigma^2}$

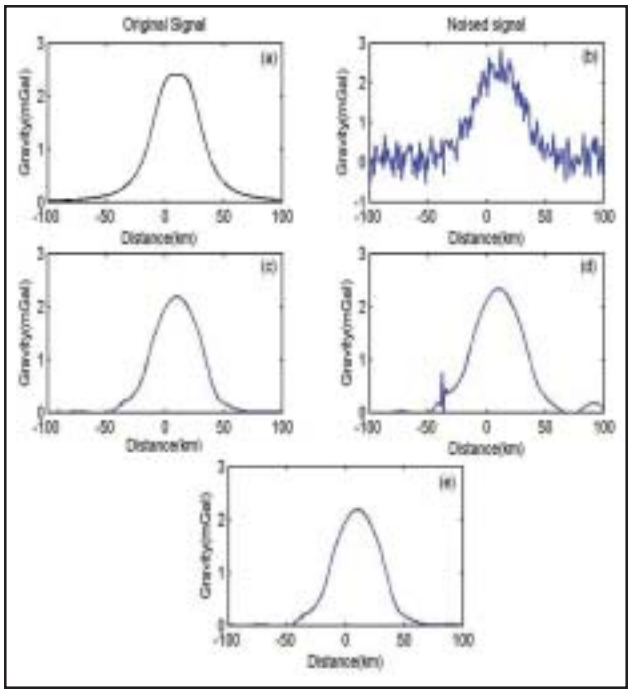

Fig. 1: (a) synthetic signal generated over two buried sphere at a depth of 20 km and having a radius of 20km each separated by a distance of 20 km; (b) signal plus white noise; denoised signal by using (c) soft; (d) hard and (e) customized thresholding.

where σ^2 is the noise variance, which is 1 in case of white Gaussian noise. The soft, hard and customized thresholding are applied to transformed coefficients as described above. After applying the thresholding the inverse wavelet transform of coefficients is taken which gives the denoised signal. The denoised signal using soft, hard and customized thresholding are shown in figures 1(c, d, e). To study the linear relation between the synthetic and denoised gravity signal using soft, hard and customized thresholding, root mean square (RMS) error and coefficient of determination (R^2) are calculated and presented in Table 1. The R 2 is also called the goodness of fit and it describes how much the complexity in the original data is maintained after denoising. Since the wavelet transform is also suitable for localized denoising (Fedi et al., 2000). To test its suitability for localized denoising, the white noise is added in part of the signal and same technique of denoising is applied to this contaminated signal. The synthetic and noised synthetic are shown in figure 2 (a, b) The denoised signal using soft, hard and customized thresholding are shown in figure 2 (c, d, e). The RMS error and R 2 between the denoised and synthetic signal for the soft, the hard and customized thresholding are shown in Table 1. From the Table 1 and figures 1 and 2, it is clear that all the three- thresholding techniques remove noise by fair amount but in case of hard thresholding a noise peak is still remaining.

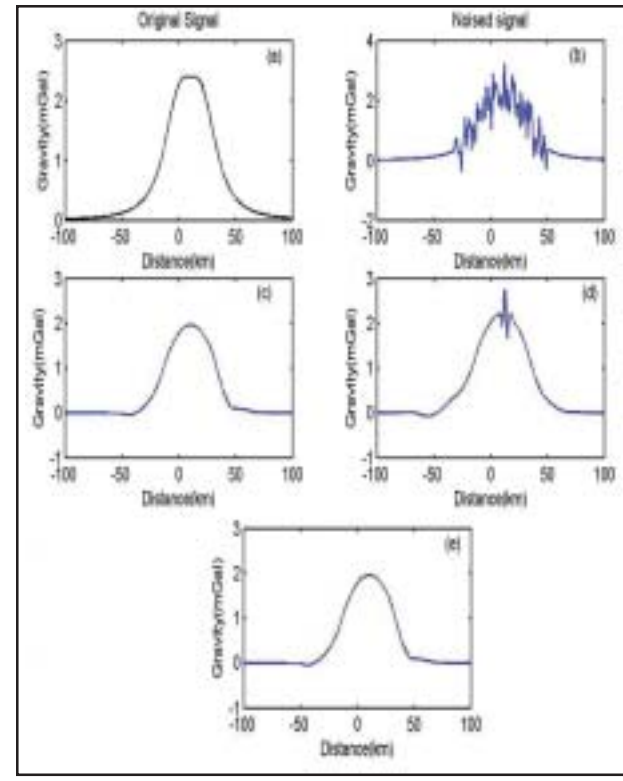

Fig. 2: (a) synthetic signal generated over two buried sphere at a depth of 20 km and having a radius of 20km each separated by a distance of 20 km; (b) signal plus white noise in the parts of signal; denoised signal by using (c) soft; (d) hard and (e) customized thresholding.

Table 1: The root mean square (RMS) error and coefficient of determination (R2) between the denoised and original synthetic signal using soft, hard and customized thresholding.

White noise added	Thresholding	RMS error	R^2
In whole signal	Soft	0.1491	99.5612
	Hard	0.1037	98.6909
In parts of the signal	Customized	0.1493	99.5640
	Soft	0.2389	99.0496
	Hard	0.1304	98.3048
	Custom	0.2386	99.0519

Table 2: Percentage of improvement in matching the ship and satellite gravity data after denoising the signals.

Profile	% of improvement		
	Soft	Hard	Customized
1	6.36	0.49	6.30
2	4.06	1.44	4.08
3	9.60	1.80	9.64

The soft and customized thresholding techniques seem to be more effective. The soft thresholding results in over smoothing the data, therefore it is suggested that the customized thresholding should be prefer. All the three techniques are applied to the ship and satellite gravity data.

Denoising of ship and gravity data

The three profiles of marine gravity data in the Bay of Bengal are selected from the dataset collected onboard ORV Sagar Kanya (Ramana et al., 1997) and satellite gravity data (Sandwell and Smith, 1997, version 9.2) interpolated onto the ship track at each observation point. The satellite gravity data seems to be highly filtered by low pass filter and noise level seems to be less, whereas ship data suffer from the noise problem. There may be different type of noises in the ship track but main type of noises observed in the ship data are as follows: (a) Heave motion noise: caused due to upward and downward motion of the vessel, (b) Roll and pitch noise: caused due to sideways, front and back motion of the ship; (c) Inherent noise: arises due to the circuit of the instrument and it is always present in the data. The noise level also depends on the type of vessel used. The ship and satellite gravity profiles are denoised by using soft, hard and customized thresholding as described above. Both datasets are denoised by assuming Gaussain random noise. An example of ship track profile and denoised signal by using soft, hard and customized thresholding is presented in figure 3. Ship and satellite gravity data represent the gravity anomaly over the same location and should match to each other. But due to different mode of recording and environment there is much discrepancy between these two datasets. The two datasets are compared before and after denoising and percentage of improvement in matching the two datasets after denoising is presented in Table 2. From Table 2 it can be seen that improvement using soft and customized thresholding is high. Therefore again it suggested that customized thresholding is best for the ship track data.

Conclusions

Three types of thresholding schemes are tried for denoising the ship and satellite gravity data using wavelet transform. In case of synthetic as well as marine data customized thresholding is found to perform better than other type of thresholding.

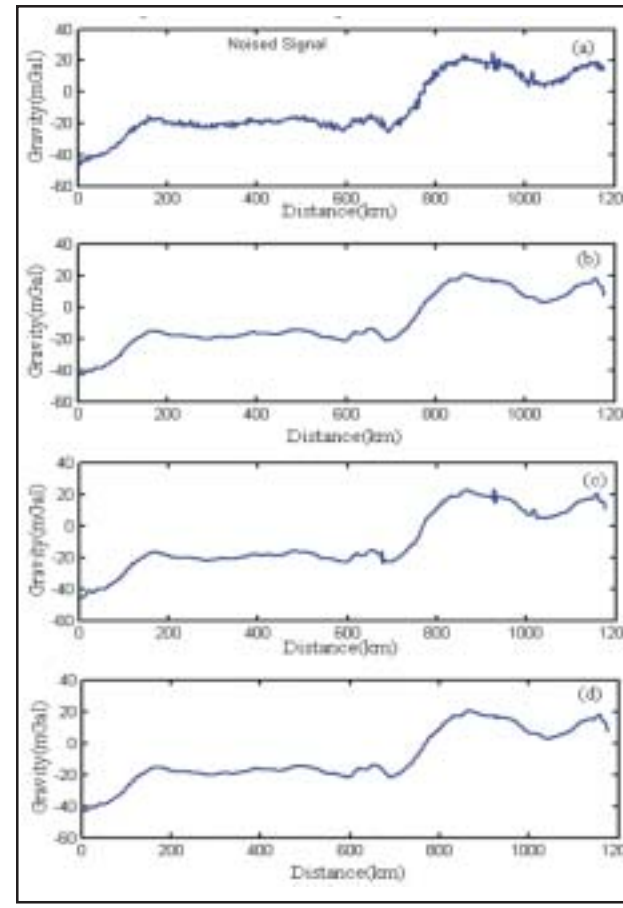

Fig. 3: (a) An example of ship track gravity anomaly; denoising of signal by using (b) soft; (c) hard and customized thresholding

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