Implementation of time domain filtering in the complex wavelet framework for GPR noise attenuation

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ABSTRACT

GPR is one of the geophysical methods that uses high frequency non-stationary electromagnetic waves to image underground structures. The transported GPR data is generally polluted by various types of noise caused by other equipment emitting radio waves or man-made structures near the GPR system. Thus, improving the capability of causal temporal filtering as simple and efficient algorithms for removing noise from GPR signals is proposed in this paper. In this study, time-frequency analysis methods including Savitzky-Golay (SG) time domain filter and Dual-Tree Complex Wavelet Transform (DTCWT) to attenuate noise from GPR data has been investigated. Non-Gaussian noises were targeted for attenuation and ultimately led to the presentation of a new method of noise attenuation and signal preservation in sections obtained from the GPR method by designing a filter in a complex two-dimensional wavelet frame.

Keywords: GPR method, DTCWT domain, Savitzky-Golay filter, Noise reduction.

INTRODUCTION

Ground Penetration Radar (GPR) is one of the non-destructive geophysical inspection tools that is used for several applications (Ata et al., 2017). Three factors including: the target buried near the surface, the small geometric dimension of a target, and the small variation in permittivity of the target with the surrounding area cause difficulties in detecting the target with the GPR method (Daniels, 1996); these situations become more complicated when combined with unwanted signals and noise. Therefore, to achieve the high resolution of the GPR image with minimum signal loss, this research explores the DTCWT, SG time-domain filter and the combination of two domains to prepare a better result in the suppression of the noise of the GPR signal in the presence of non-Gaussian noise. DTCWT is an effective image processing technique to preserve details and visual effects. According to (Oskooi et al., 2015), the DTCWT method using non-negative garrote thresholding is a powerful tool for noise suppression from the GPR signal. The SG smoothing and differentiation filter as a powerful and efficient algorithm was introduced by Savitzky and Golay in 1964. The SG filter which depends on the two parameters of the window length and the polynomial degree can be administered in a series of data points as a low pass filter to amplify the SNR while preserving the shape of the original signal. Then, the smoothed points are calculated by shifting each data point by the value of its fitted polynomial.

Methodology

The SG filter is a temporal smoothing filter in which a piecewise adjustment of a polynomial function by least-squares approaches is performed on the signal. In the de-noising process with this method, we consider that the noisy data X(t) is (Sadeghi and Fereidoon, 2018):

$$X(l) = s(l)+n(l) \qquad l = 1, \dots, L \qquad (1)$$

Which $s(l)$ denotes the l-th sample of $s(t)$. The purpose of the SG filter is to reconstruct $s(t)$ from these samples, so a polynomial $P(i)$ with filter order n ($P(i) = \sum_{k=0}^{n} a_k i^k$, where a_k is the k-th coefficient of the polynomial and $k = 0, \dots, n$), is fitted to smoothing window with the number of data points N=2M+1 to minimize the following MSE:

$$\varepsilon_n = \sum_{i=-M}^{M}(P(i) - x(i))^2 = \sum_{i=-M}^{M}(\sum_{k=0}^{n} a_k i^k - x(i))^2 \qquad (2)$$

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The filtered signal in the first stage is the value of the polynomial in the central point ($Y(0)$) as follows:

$$Y(0) = P(0) = a_0 \qquad (3)$$

The next filtered point is calculated by shifting the window by one and repeating the operation. The ability of this filter to maintain the shape of the signal rather than the other conventional filters is one of the reasons for selecting this method. Moreover, the method is user-friendly and has the high processing speed.

The forward/ inverse DTCWT structure of the signal x(n) which has been proposed by Kingsbury (1998), is calculated with two samples of DWT included of two trees of FBs defined by h(n) and g(n). These FBs produce real and imaginary parts of the complex coefficients. Each FB employs two real filters; the upper real filter on each tree is a low pass filter and the lower one is a high pass filter marked by h0(n) and h1(n), respectively. The real filters of the lower FB are labeled similarly. The synthetic structure is similar to the analysis structure while its filter banks are a time recursive version of analysis FBs. To get the optimum reconstruction condition, the filters of lower and upper trees should satisfy the properties of approximate half sample property, Perfect Reconstruction (Orthogonal or Biorthogonal), Finite support (FIR filters), and Vanishing moments/good stopband, Linear phase. The algorithm of de-noising with the DTCWT method is included in the following steps of (1) decomposing the signal using analysis filter banks of the proposed method to prepare the wavelet coefficients, (2) Estimating a thresholding value to threshold the wavelet coefficients by one of the thresholding functions and (3) combining the new coefficients by synthesis filter banks of the DTCWT to reconstruct the de-noised signal. After the decomposition of a signal into wavelet coefficients, processing should be done on them. In this research, we have applied the soft and non-negative garrote thresholding functions which have a good performance in GPR signal de-noising (Oskooi et al., 2015). The proposed approach is highlighted in the following steps: (1) DTCWT is applied to the noisy GPR signal to obtain the detailed subbands. (2) The SG filter is applied to each subband separately and (3) the reverse of DTCWT using non-negative Garrote thresholding is applied to the sub-bands.

The Gaussian distribution of geophysical data is far from the reality in the field. For this reason, to assess the capability of the proposed methods, non-Gaussian noise (cheynet, 2020) was applied to the synthetic GPR data with SNR = 5 dB. As shown in Fig. 1 .c noise covers borders. Figures 1.d, e, f, and g show the application of the DTCWT method with soft and non-negative thresholds and SG-DTCWT with non-negative threshold and SG time domain filter, respectively. As can be seen in these figures, the improvement of the synthetic model is visible with the SG-DTCWT method, and the layers are also well separated. From the point of view of the power spectrum shown in Figure 1.h, the noisy data does not follow the Gaussian probability distribution. The weakest result is related to the application of the time domain SG filter in the presence of non-Gaussian noise. But for the other mentioned methods, the designed SG in the CWT domain has yielded acceptable results which in addition to the signal retention power associated with this particular type of noise, the results of noise attenuation is quite comparable to thresholding methods. It should be noted that in this type of data, the frequency response of thresholding methods for non-Gaussian noises indicates the elimination of some frequencies. To test the capability of the proposed de-noising methods in the case of real data, the eighty traces of real GPR data after applying the gain as an amplitude recovery function was selected according to Fig.2. As presented in Fig.2.a, the amount of noise in the data is high and the events of the section are completely covered. As expected, the SG filter in the DTCWT frame (Figure 2.d) has the highest noise attenuation in terms of visual results and power spectrum. All three methods can reduce the noise of GPR data; but the important point is that signal maintenance should be done in parallel with noise reduction.

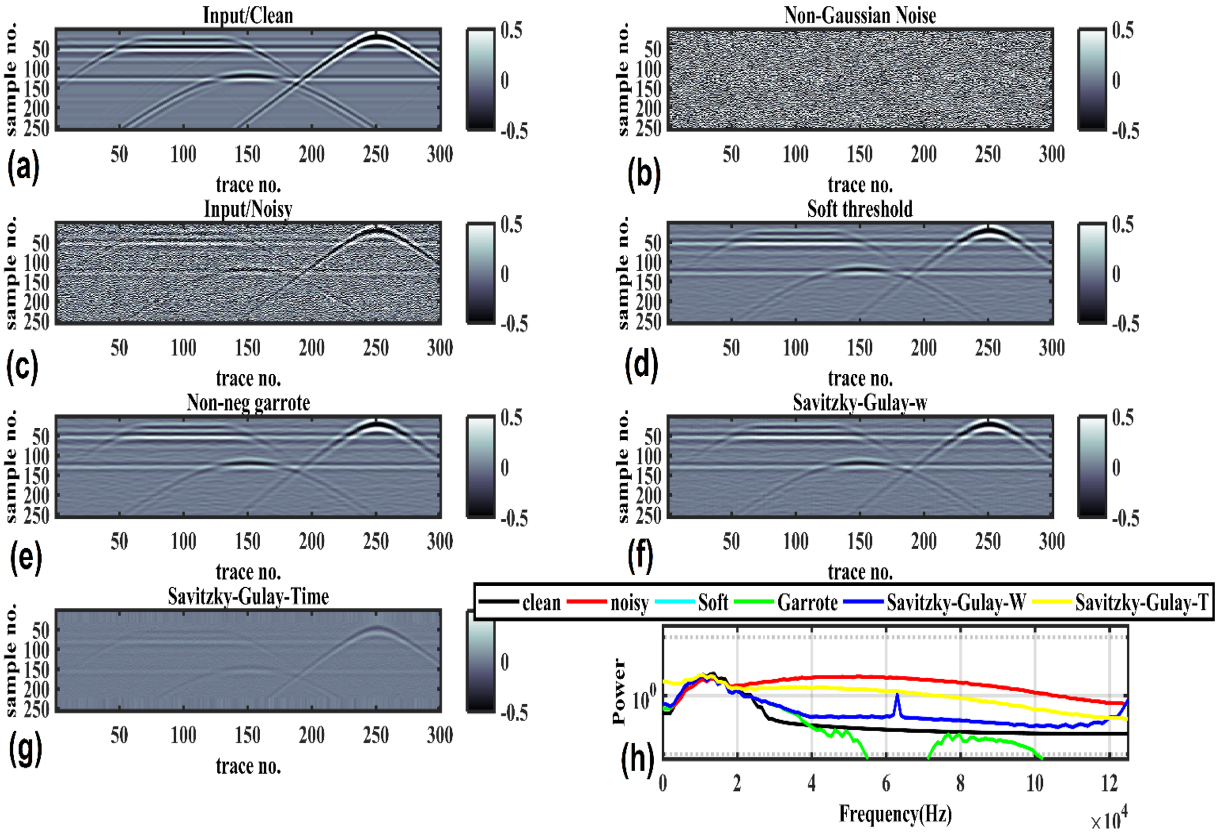

Figure 1. (a): The clean synthetic GPR model, (b). Non- Gaussian noise, (c). Non-Gaussian noisy input with SNR=5 dB, (d). De-noised by DTCWT with soft thresholding, (e). De-noised by DTCWT with non-neg garrote thresholding, (f). De-noised by SG-DTCWT with non-neg garrote thresholding, (g). De-noised by SG filter, and (h). the power spectrum of proposed methods.

The rectangular boxes in this figure show the superiority of the SG-DTCWT method over others in noise suppression and signal preservation. From Figure 2.f it can be seen that the application of the SG time-domain method leads to an increase in low-frequency noise due to noise distortion and as a whole, irrational and nonlinear behavior in attenuation of the noise of GPR signals. However, by examining the power spectrum of SG-DTCWT, event preservation by applying this method has better performance in the noise removal process. At low frequencies, part of the data has been affected. In the mid and high frequencies, the noise reduction was done well and the SG-DTCWT filter has a more logical noise reduction response than the DTCWT. The algorithm proposed in this research confirms the success of the new approach concerning the application of the SG filter of the time domain within the framework of the complex wavelet transform.

CONCLUSION

This paper focuses on the attenuation of non-Gaussian random noise from GPR data using time-frequency analysis methods. The synthetic results in the presence of non-Gaussian noise indicate the superiority of the soft and non-negative Garrote thresholding methods in the DTCWT domain compared to the SG method. However, matching the frequency spectrum of thresholding methods demonstrates that the signal is lost in the mid-frequency range. Therefore, from the point of view of signal preservation, the SG method is more efficient. For further investigation, the SG filter with the same wavelet field parameters in the presence of non-Gaussian noise was applied to synthetic and real data. The algorithm applied in the wavelet domain has provided more reliable results in terms of signal preservation and noise attenuation. Since the random noise in the GPR data does not follow the Gaussian distribution, the proposed algorithm can be a reliable method of noise attenuation.

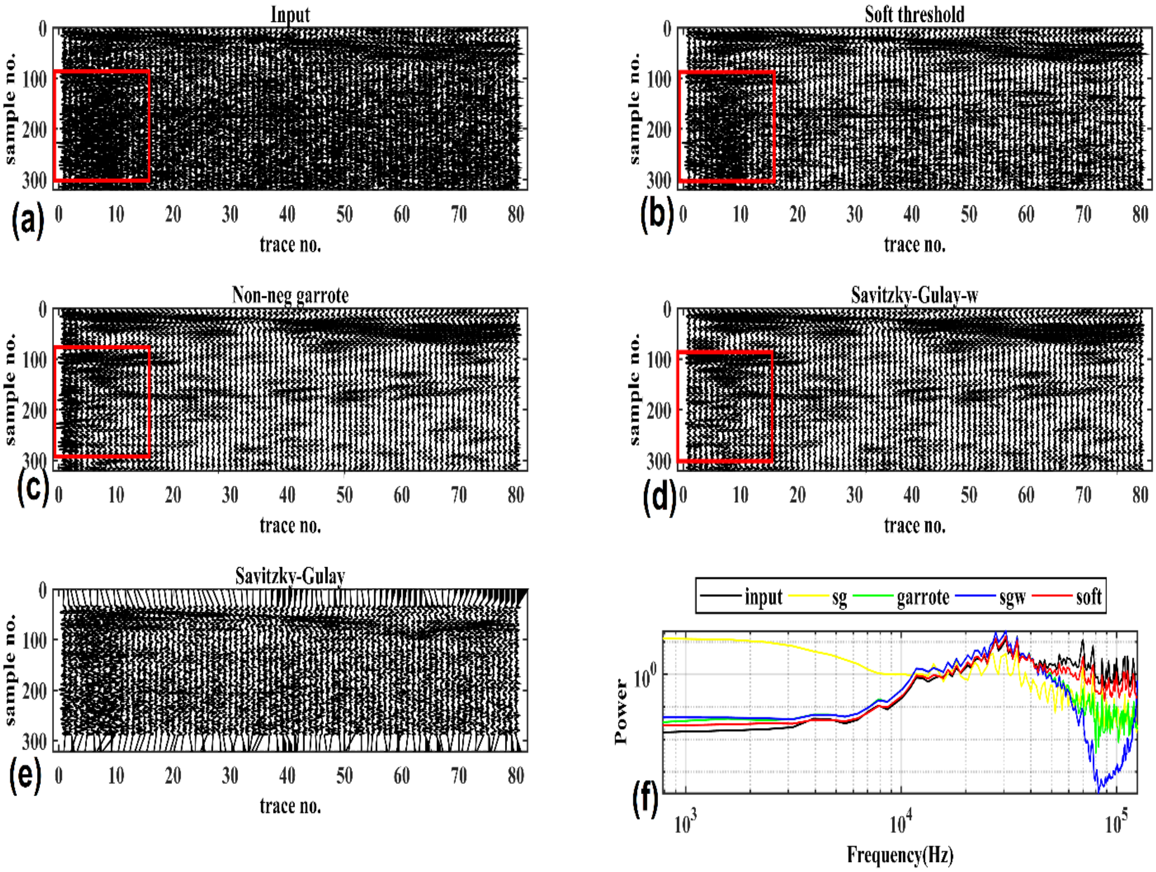

Fig. 2. (a). 80 traces of the real GPR data, (b). De-noised by the DTCWT with soft thresholding method, (c). De-noised by the DTCWT with non-neg thresholding method (d). De-noised by the SG-DTCWT with non-neg thresholding method, (e). De-noised by the SG time-domain method and (f). Power spectral densities of data by proposed methods**.**

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