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A de-noising algorithm based on wavelet threshold-exponential adaptive window width-fitting for ground electrical source airborne transient electromagnetic signal

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ABSTRACT

The ground electrical source airborne transient electromagnetic system (GREATEM) on an unmanned aircraft enjoys considerable prospecting depth, lateral resolution and detection efficiency, etc. In recent years it has become an important technical means of rapid resources exploration. However, GREATEM data are extremely vulnerable to stationary white noise and non-stationary electromagnetic noise (sferics noise, aircraft engine noise and other human electromagnetic noises). These noises will cause degradation of the imaging quality for data interpretation. Based on the characteristics of the GREATEM data and major noises, we propose a de-noising algorithm utilizing wavelet threshold method and exponential adaptive window width-fitting. Firstly, the white noise is filtered in the measured data using the wavelet threshold method. Then, the data are segmented using data window whose step length is even logarithmic intervals. The data polluted by electromagnetic noise are identified within each window based on the discriminating principle of energy detection, and the attenuation characteristics of the data slope are extracted. Eventually, an exponential fitting algorithm is adopted to fit the attenuation curve of each window, and the data polluted by non-stationary electromagnetic noise are replaced with their fitting results. Thus the non-stationary electromagnetic noise can be effectively removed. The proposed algorithm is verified by the synthetic and real GREATEM signals. The results show that in GREATEM signal, stationary white noise and non-stationary electromagnetic noise can be effectively filtered using the wavelet threshold-exponential adaptive window width-fitting algorithm, which enhances the imaging quality.

1. Introduction

The GREATEM system combines the advantages of both ground and airborne electromagnetic system such as: considerable prospecting depth, lateral resolution and detection efficiency. Therefore, it is suitable for rapid exploration of deep mineral and groundwater resource under complex geological conditions (Mogi et al. 1998, 2009; Ito et al. 2011; Allah et al. 2013, 2014).

The measured GREATEM data are broadband which result in being vulnerably affected by stationary white noise and non-stationary electromagnetic noise (sferics noise, aircraft engine noise and other human electromagnetic noise). These noises will reduce the precision of imaging and influence the interpretation of underground electrical structure. To obtain high quality data, it is necessary to remove the noise from the measured GREATEM signal. Recently some achievements have been gained in the field of time-domain electromagnetic signal de-noising. Kass and Li (2008) proposed a kernel principal component analysis method to address the coherent and incoherent noise in transient electromagnetic data. Bouchedda et al. (2010) designed a filter using stationary wavelet transform to remove the sferics noise from airborne transient electromagnetic data. Reninger et al. (2011) adopted a singular value analysis method to remove white noise and sferics noise from airborne transient electromagnetic data. Li et al. (2013) focused on a combined wavelet transform algorithm for ground-airborne electromagnetic data. This method can reduce the white noise while solving the problem of baseline drift, but its suppression of other electromagnetic noise is limited. Wang et al. (2013) effectively filtered baseline drift using a wavelet-based correction method from ground-airborne electromagnetic data. Although the de-noising effect is great, the method can only address one target.

On the basis of developments in de-noising methods of different transient electromagnetic data (ground, airborne and ground-airborne transient electromagnetic data) and the characteristics of GREATEM data and major noises, a noise reduction algorithm is proposed for removal of stationary white noise and non-stationary electromagnetic noise from GREATEM data. In our study, the de-noising process is divided into two steps: first, the white noise is reduced using the wavelet threshold method, and then an exponential adaptive window width-fitting algorithm is designed to remove the electromagnetic noise

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effectively. Lastly, we verify the proposed de-noising algorithm via the synthetic and real GREATEM signals.

2. Characteristics of GREATEM responses and the noise

The characteristics of the electromagnetic response (from a calculation of the long wire source based on layered ground) and measured noise are analyzed, which provide a theoretical basis for the de-noising algorithm.

2.1. Analysis of theoretical GREATEM responses

The GREATEM system adopts a long grounding wire as its transmitter and a receiving coil carried by an unmanned aircraft or airship as continuous observer. According to the formulas of induction electromotive force produced by the long grounding wire based on layered ground deduced by Nabighian (1988), the vertical component V_z is defined as:

$$V_z = -i\omega \frac{I\mu_0 S}{4\pi} \int_{-L}^{L} \frac{y}{R} \int_{0}^{\infty} (1 + r_{\mathrm{TE}}) \exp(\mu_0 z) \frac{\lambda^2}{u_0} J_1(\lambda \mathrm{R}) d\lambda dx. \quad (1)$$

In formula (1), where I is the transmitting current, S is the active area of the receiving coil, y is the coordinates perpendicular to the direction of grounding wire, J_1 is the one-order Bessel function, λ is the integration variable, r_{TE} is the reflection coefficient, and μ_0 is the air permeability.

We used the standard parameters of the GREATEM system developed by Jilin University: the length of long grounding wire is 1000 m, the transmitting current is 13 A, and the effective area of receiving coil is 10,000 m^2. In the layered earth model, the resistivity of each layer is 100 Ω·m, 10 Ω·m and 100 Ω·m. The thicknesses of the 1st layer and the 2nd layer are 200 m and 20 m, respectively. The calculated theoretical GREATEM response and its spectrum are shown in Fig. 1.

1200 sampling points within 40 ms are achieved in the calculated theoretical GREATEM response. The effective bandwidth of the receiving system is 15 kHz. By analyzing the theoretical response and frequency components in Fig. 1, following characteristics of theoretical response could be concluded:

(1) The amplitude of GREATEM response has a large dynamic range, with a span of three to four orders of magnitude from the early time to the latter time. The latter time response is only approximately a few nanovolts, therefore, it is extremely easy to mix with noise and difficult to distinguish.
(2) The GREATEM response decays approximately as the E index. The latter time response decays much more slowly than the early time. The attenuation slope is the main characteristic parameter.
(3) In theory, the frequency of GREATEM response is infinite. However, the frequency of the measured data depends on the bandwidth of receiving system, and the general frequencies of different GREATEM data are within 100 kHz.

As the characteristics above indicated, the GREATEM data especially the latter time data is highly vulnerable to the noise and thereby produces difficulty in the data inversion and interpretation.

2.2. Analysis of stationary and non-stationary noise

The measured GREATEM data generally include sferics noise, human electromagnetic noise and engine noise of the aircraft. To sum up, there are two categories: the stationary white noise and the non-stationary electromagnetic noise. In order to analyze the characteristics of these noises, the spectrums of the measured noise are computed. Fig. 2 and Fig. 3 present the spectrums of the measured stationary and non-stationary noise, respectively.

As shown in Fig. 2, the white noise is distributed equably and stably throughout the time domain. It is distributed widely and its energy is spread equably within the effective frequency (0 to 15 kHz). Fig. 3 shows the measured non-stationary electromagnetic noise and its frequency components. The electromagnetic noise appears random as short duration transient signals or spikes in the time domain, and it changes rapidly. Its frequency range is primarily between 1 kHz and 10 kHz.

3. Wavelet threshold-exponential adaptive window width-fitting de-noising algorithm

The analysis of the theoretical GREATEM response and the measured noise indicates that GREATEM data primarily contains the stationary white noise and non-stationary electromagnetic noise. Thus, the combination of the wavelet threshold method and the exponential adaptive window width-fitting algorithm is adopted to filter these two kinds of noises simultaneously.

First, the GREATEM data are decomposed with a discrete orthogonal wavelet transform, and a wavelet threshold is used to shrink the wavelet coefficient on each scale. In this way, the white noise is removed from the data. Then, the data were segmented according to the even logarithmic interval. The data polluted by electromagnetic noise in each window are distinguished according to the energy detection principle, and the attenuation characteristics of the data are extracted.

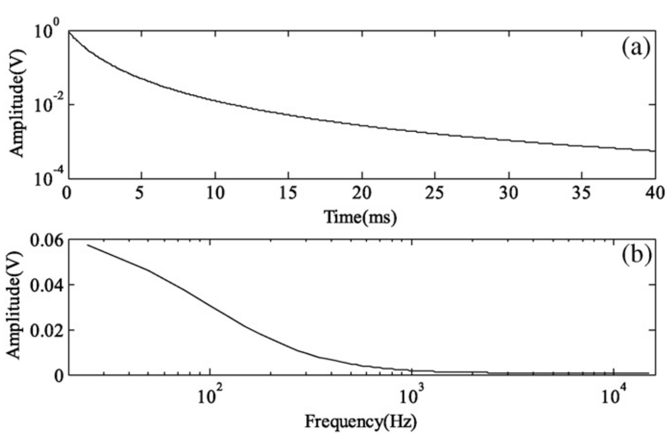

Fig. 1. (a) Theoretical GREATEM response and (b) spectrum components of theoretical GREATEM response.

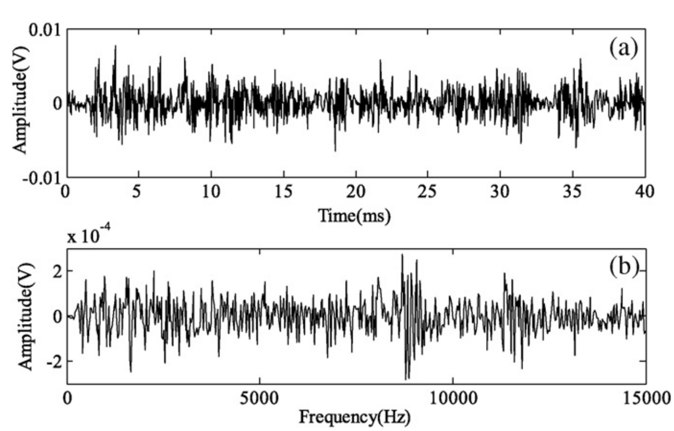

Fig. 2. (a) The measured stationary white noise and (b) spectrum of the stationary white noise.