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# A NEW METHOD OF IDENTIFYING GROUND-BASED ELECTROMAGNETIC ANOMALIES – CASE STUDY OF THE SICHAN LUSHAN 7.0 EARTHQUAKE

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## ABSTRACT

Stereo-observation, being comprised of both ground-and space-based observations, is an important approach for likely making earthquake prediction to break through. The electromagnetic observation is considered as one of the most important measures in the stereo-observation, and should be one of the fields in which breakthrough is firstly and likely made and would be an effective device to obtain information for earthquake pre-warning. New techniques of alternating electromagnetic field observation, e.g., Controlled-Source Extremely Low Frequency (CSELF) and satellite observation, are gradually applied to the earthquake monitoring, which contain the more abundant information than those mainly observed in constant electric or magnetic field. This will increase the amount of recorded data greatly and inevitably require the robust techniques of data processing and analyzing. Previous analysis techniques mainly utilize the Fourier transform method for alternating electromagnetic field data, which cannot consider the information in time and frequency domains simultaneously. In this study we try to use the wavelet transform method to process alternating electromagnetic field data and carry out a case study, which aims to obtain the electromagnetic anomaly information in both frequency- and time-domains. The study is conducted on the data observed for 35 days during the strong aftershock period after the Lushan earthquake with Ms=7.0 in the Sichuan province in China. The preliminary results show that the wavelet transform method has an advantage and potential for identifying the electromagnetic anomalies relative to the earthquake events.

**Key words:** ground-based electromagnetic observation, electromagnetic anomaly, wavelet maxima, strong aftershock

## 1. INTRODUCTION

Earthquake is one of the natural disasters which cause severe tragedies of human life and damages of economics. Such a type of disasters is particularly serious in China. In the world, more than 50% of deaths have been caused by earthquakes among natural disasters since 1949, while in China more than 50% of loss of lives is caused by earthquakes in all natural disasters. For instance, more than 240000 people died due to the Tangshan earthquake occurred in 1976 and more than 80000 people lost their lives in the Wenchuan earthquake occurred in 2008 [1]. The earthquake prediction is one of the scientific propositions that is drawing the greatest attention of government and humans, and is also the most difficult research problem. Thus many countries have been paying the great attention on this problem.

The study of last half century on earthquake provides researchers with a more clear understanding of earthquake prediction and promotes the development of observation techniques for earthquake monitoring. At present the amount of observed data is significantly increased, the people particularly pay great attention on the electromagnetic monitoring on earthquake prediction [2, 3]. As indicated by IUGG that a lot electromagnetic anomalous phenomena prior to earthquakes were observed in the past decades and EM effects existed before earthquakes as evidenced by observations. Provided that earthquakes can be predicted based on the

understanding of the relationship between EM anomalies and physical processes under crust [4], statistics based on the satellite observations show that the extent of the relation between the EM anomalies and the earthquakes could reach about 80%, 90% or even more [5, 6].

After the Xingtai earthquake occurred in 1966, more than thousand seismic stations were established to monitor the earthquake-related anomalies in China, of which are hundreds of electromagnetic stations [7]. The DEMETER satellite designed for capturing earthquake-related EM radiation anomalies was launched by France in June 2004 [5], marking an outstanding achievement. It observed numerous earthquake-related phenomena, the relevant research indicated that the impending anomalies prior to earthquakes could be found but they come from the EM signal instead of stress signal, and suggested that the pre-warning systems based on the EM method should be developed [8, 9]. The present assertion on making the breakthrough of earthquake prediction is that researchers should carry out stereo electromagnetic monitoring by using ground- and space- based observations to enhance the ability to identify and catch the EM anomalies and study the relation between the anomalous phenomena with physical process evolving in the crust.

Ground-based and space-based observations have the similar effects in addition to their respective advantages. The observation on the surface is more sensitive than on space. But the observation with satellites can cover large regions and the gaps distributing among ground-based networks because of adverse terrain or climate conditions especially in oceans [10,11].

Stereo earthquake EM monitoring will greatly increase the amount of observed data. For instance, presently the CSELF observation network is only deployed in a small part of the mainland of China, covering the Beijing capital area and seismic active areas of the Sichuan and Yunnan province [12-15], but the amount of daily observed data is nearly 6 gigabyte (G). Every day the SWARM satellite constellation collects the amount of 5G data. Although some observation techniques have been already used in the earthquake monitoring, they have some deficits to some extent. In such a situation, development of new techniques for processing the flood of data and discovering more useful information is essential to the successful application of the alternating EM method in earthquake monitoring [16, 17].

This paper presents the latest advances of this aspect in recent years and the wavelet maxima method that is to be a potentially promising approach, We also carried out a case study based on the Lushan Ms=7.0 earthquake to illustrates the application of the wavelet method.

## 2. WAVELET METHOD USED IN THE GROUND-BASED EM DATA

The electromagnetic method is one of the most important techniques applied to the earthquake precursor monitoring. Since the 1966 Xingtai earthquake, electric and magnetic methods focused on the constant fields have been utilized and a great number of stations have been built for these methods [18-20]. The alternating electromagnetic field observations are drawing more attention in studies on the earthquake monitoring along with more EM anomaly phenomena relative to earthquake are recorded using EM methods of wider frequency bands [21-24]. Some stations are equipped with alternating EM methods instruments [12-15].

In order to enhance the quality of measured EM data in relation to earthquakes and the determinacy of the time and location of generated anomalies, the CSELF method was found and developed at the end of the 20th century to the beginning of 21th century [15]. With the CSELF method, a powered transmitter was built in a position which emitted strong alternating EM field signals and a observatory network was layout in the regions of thousands kilometers to transmitter for receiving the above powered alternation EM signals synchronously, which are serving for the recognition and capture of the anomaly phenomena. Each station of the network continuously records data every day capturing not only artificial signals but also the natural EM anomaly phenomena [15].

The amount of the observed data in alternating EM methods have increased by leaps and exponentially relative to those in constant EM methods, which urgently needs the advanced data processing methods for the flood of data. In the previous geophysical measurement, the alternating EM data are mainly analyzed by the fast Fourier transform to obtain the data spectra, surface impedance and apparent resistivity and so forth. These methods can reveal the frequency information of the observed data, but cannot get the information of the data relative to the time and space. The wavelet method can simultaneously analyzed the observed data in respect of frequency, time and space [25-27]and have been applied in some data analysis[17, 28-33]. However this method is rarely used in the alternating EM observation for earthquake prediction,

### 2.1. The technique of wavelet transform

As an example, the simulation models are presented in Fig.1 to show the difference between the FFT and wavelet methods. Two functions  $f_1(t)$  (Fig.1a) and  $f_2(t)$  (Fig.1b) are consisted of three pieces of time series with same time length of each section respectively but

with different signal frequencies for three sections. For function  $f_1(t)$  the frequencies are low, middle and high from the beginning to the end in time, but they are middle, high and low for function  $f_2(t)$ . When the FFT transform method is used in these two functions, the same results are obtained, but cannot give any information relative to the time even though the signals for different frequencies are at the different time (Fig.1c). When the wavelet transform method is used for the data, the information for both time and frequency can be simultaneously obtained, showing its advantages over the FFT [34, 35].

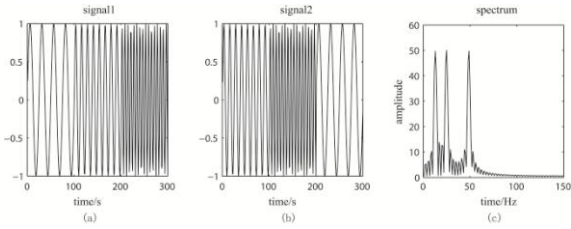


Figure. 1 Two different time series  $f_1(t)$  (a) and  $f_2(t)$  (b) their spectrum (c). [35]

The wavelet function  $\psi(t)$  used in this paper is *guas3*. The experiment shows when 16 scales in wavelet coefficient is used it is more suitable to anomaly analysis [17, 30]. The parameter scale, denoted by  $s$  represents the action of the protraction, contraction, and shift of the window for multi-scale analysis. Thus the wavelet transform  $W_s f(t)$  for observed signal  $f(t)$  with scale  $s$  is as follows

$$W_s f(t) = f(t) * \psi_s(t) = \int_{-\infty}^{\infty} f(\tau) \overline{\psi_s(t-\tau)} d\tau \quad (1)$$

Where symbol  $*$  stands for a convolution operation,  $\overline{\psi_s(t-\tau)}$  is the complex conjugation of  $\psi_s(t-\tau)$ ,  $\tau$  is a time shift parameter.

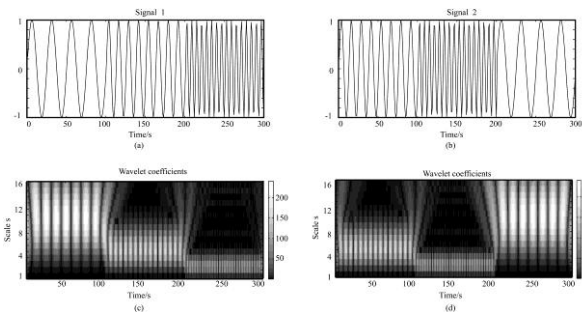


Figure 2 Two different time series  $f_1(t)$  (a) and  $f_2(t)$  (b) and their wavelet coefficients spectrum (c) [ref.35]

Fig.2 shows the results for  $f_1(t)$  and  $f_2(t)$  by using the wavelet transform method and indicates that ① the scale is relative to signal frequency, i.e., the lower frequency to the larger scale. ② The wavelet coefficients can give the time information about the signals, i.e., it can give different wavelet signal along with their occurrence time. ③ The wavelet coefficient maxima appeared at the time where the maximum change rate of the sinusoidal waves curve occurs, i.e., the position of maximum change gradient of signal curves in time domain. ④ The singular point of the signals can be clearly identified by wavelet coefficient, e.g., singular time position ( $t=100,200$ ). This indicates that the wavelet transform has the stronger ability to obtain the information of both the frequency and time than the FFT method.

The following example shows that wavelet analysis has the ability to capture anomalous information. Figure 3a shows a smooth sinusoidal function  $f(t) = \sin(0.1 * t + 1)$ ,  $t \in [1,300]$  with superposition of two different pulse signals. One pulse is at  $t=100$  and another is at  $t=200$  with  $f(100) = f(200) = 3$

The wavelet coefficients are displayed in Fig.3b, which indicate that the maxima of the wavelet coefficient appears at the ascending or descending inflection points in sinusoidal function curves. They also have the larger scale factors and are homogeneous for whole time section (0-300). The singular points appear at the  $t=100,200$  respectively with the smaller scale factors. Furthermore the maxima value is bigger at  $t=100$  than that at  $t=200$ , because the bigger pulse magnitude (the bigger change rate) appears at  $t=100$  than that at  $t=200$ . Therefore the wavelet can not only characterize spectra but also the time of anomaly.

## 2.2. Analysis of wavelet maxima

In order to determine the position of anomalies on time axis, the analysis method of the wavelet maxima is used.

Let a smooth function  $\theta(t)$  satisfying  $\int_{-\infty}^{\infty} \theta(t) dt = 1$ .

Suppose base function is differentiate, that

is  $\psi(t) = \frac{d\theta(t)}{dt}$  exist sin equation (1), which can be

written as ,

$$W_s f(t) = f(t) * \psi_s(t) = f(t) * \left( s \frac{d\theta_s(t)}{dt} \right) = s \frac{d(f(t) * \theta_s(t))}{dt} \quad (2)$$

It can be proved that at the time when the signal is disconnect,  $|W_{s_0} f(t_0)|$  is still differentiate with satisfying

$$\frac{\partial |W_{s_0} f(t)|}{\partial t} = 0 \text{ at } t_0 \text{ and the vicinity. In other words, } |W_s f(t)| \text{ will reach the maximum at } s_0, \text{ that means that the mutation point (singular point) is corresponding to the maximum value of the wavelet transform } W_s f(t).$$

Fig.3c shows the maximum value distribution of wavelet coefficients, which is derived from signal function  $f(t)$  shown in Fig.3a. There are seven continuous lines consisting of circles with different colors for the maximum values of wavelet coefficients. It can be noted that the lines 1(at  $t=1$ ) might be influenced by the boundary affection during the wavelet transform is used and thus they are ignored in analysis. Two lines at  $t=100$  and other four lines at  $t=148, 200, 242, 272$  contain the anomalous points in the signal  $f(t)$ . The following Lipschitz index  $\alpha$  can be used for measure whether they are singular points and when they occur.

### 2.3.Lipschitz index $\alpha$

If there are constant C and polynomials  $P(t)$  with  $m = [\alpha]$ , which satisfies

$$\forall t \in R, |f(t) - P(t)| \leq C|t - t_0|^\alpha \quad (3)$$

Where  $\alpha$  is called singularity index, and defined as follows:

$$\alpha = \frac{\log(|W_s f(t)|)}{\log(s)}$$

and  $P(t) = \sum_{k=0}^{m-1} \frac{f^k(t_0)}{k!} (t-t_0)^k$  is the Taylor polynomials at  $t_0$  and the vicinity[27, 36]. If function  $f(t)$  is

continuous or irregular the Lipschitz index  $\alpha$  will equal one. If  $f(t)$  is regular point at  $t_0$  with limited steps the Lipschitz index  $\alpha$  will equal zero. Thus  $\alpha$  can be used as an index to indicate the regularity of the function  $f(t)$ . The smaller  $\alpha$ , the bigger regularity is, which indicates the possible time position when an anomaly exists.

Fig.3d shows the Lipschitz index  $\alpha$  calculated from function  $f(t)$  shown in Fig.3a. The  $\alpha < 0$  is at  $t=100$  and  $\alpha < 0$  at  $t=200$  indicating there are the regular values. The regular value at  $t=100$  is bigger than that at  $t=200$ . But the Lipschitz index  $\alpha$  does not show any minimum values at  $t=148, 242, 272$ , indicating that there are no regular anomaly.

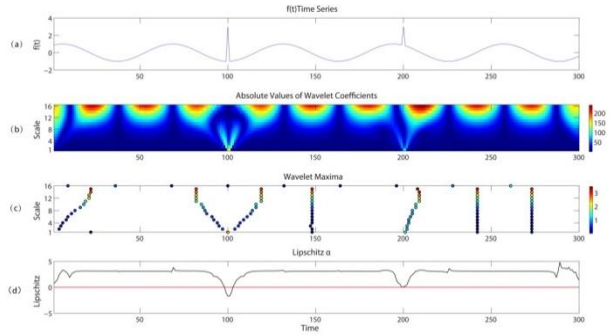


Figure. 3 The simulation of sinusoidal signals (a) and the wavelet transform coefficient (b), distribution of the maxima value (c), Lipschitz index (d).

### 3. ANALYSIS ON THE DATA FOR LUSHAN EARTHQUAKE

The Lushan earthquake ( $M_s=7.0$ ) occurred on the April 20 of 2013 in the Sichuan province. The magnetotelluric measurement (MT) was carried out at a site about 5km distance to the epicenter after the main shock. The measurements were continuously recorded from the May 4 to June 11 of 2013. The MT data were obtained using the mature methods and quality apparent resistivity and other data were also obtained. From the observed data the anomalous changes were found in the frequency band of 0.1 to 1Hz. The three magnetic components (NS, EW and vertical components denoted as  $H_x, H_y$  and  $H_z$ ) with frequencies 0.207Hz, 0.278 Hz, 0.373 Hz, 0.5 Hz, 0.671Hz, 0.9 Hz in a range of 0.1 and 1 Hz are chosen to analyze by using the wavelet method and the Lipschitz index.

Figure 4a shows the maxima distribution of wavelet

coefficients for the obtained NS magnetic component. The six blocks along the vertical axis are for six frequency bands. Fig 4b shows the energy distribution of the aftershocks during the measuring period. There are three days (May 15, 25 and June 6) when the wavelet coefficient maxima are bigger than those on the other days, which are possible to be related to the electromagnetic anomalies caused by the aftershocks.

The aftershock energies are estimated based on the earthquake catalogue of CEA[37]. The whole measurement time is divided into many time fragments with four hour intervals for each. Equation (4) is used in calculation.

$$E = \sum_{i=1}^n 10^{11.8+1.5M_i} \quad (4)$$

Where  $M_i$  represents the aftershock magnitude ( $M > 3.0$ ),  $n$  is the number of aftershocks. It is found that three anomalous phenomena also appeared on the same days (May 15, 25 and June 6). The first two energy anomalies occurred at 12 hours after the wavelet maxima anomalies and third anomaly occurred at 4 hours before a wavelet maxima anomaly (Fig. 4a and 4b).

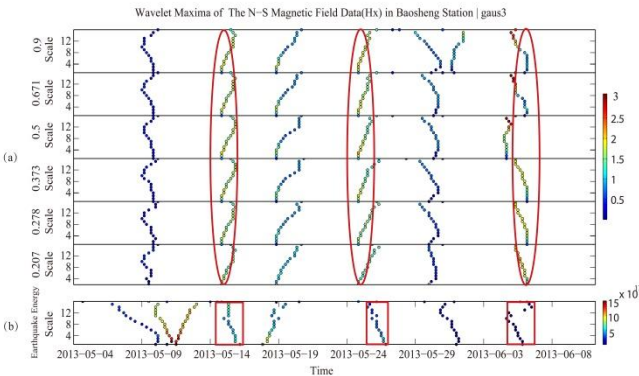


Figure.4 The wavelet maxima distribution of the NS magnetic component observed during the aftershock period (a) and seismic energy distribution (b).

In order to make sure that the above anomalies truly reflect the abnormal changes captured in the observed data, we use the Lipschitz index for a further analysis on the data (Fig.5). The obvious negative pulse anomalies appear on the three days that are same as the aforementioned dates, indicating the anomalies of NS magnetic component would be valid.

The consistence of time for six different frequencies exists for both the first and second anomalies (Fig.4) and the negative minimum pulse of  $\alpha$  also appear for these two anomalies (Fig.5). This indicates there are strong

magnetic anomalies and they may have wider frequency band for the first and second anomalies. In addition, the value of wavelet maximum is seemingly decreasing with increasing scales, indicating that the more clear anomalies appear in the smaller scale (higher frequency) for the first two anomalies, i.e., the anomalies are narrow pulse..

The less time agreement for six different frequencies appears for the third anomaly than that for the first two anomalies (Fig.4) e.g., the time of maximum curve for scale 0.5 deviates the time of other five maximum curves. The value of maxima is increasing with increasing scale indicating that the anomaly is a wider pulse. The above conjecture can be supported by the Lipschitz index  $\alpha$  values that are near zero (Fig.5).

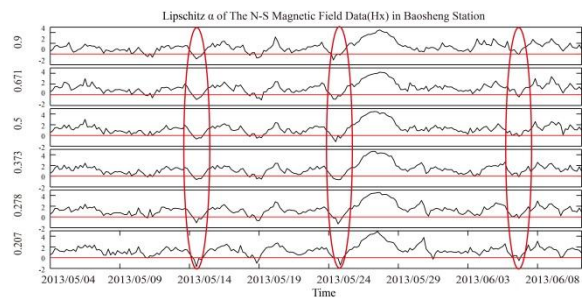


Figure. 5 Lipschitz index  $\alpha$  for NS magnetic component.

#### 4.DISCUSSION

The study of wavelet method analysis is just at the preliminary stage of application in the observed alternating EM field data for seismic research and this paper presents a case study result for exploration. The analysis on the observed alternating EM data during the aftershock of the Lushan earthquake does not pursue the exact relationship between the EM anomalies and the earthquake, instead it focuses on presenting the potential of wavelet transform methods and its superiority over FFT methods. It can not only identify anomalous information within the observed data but also determine the time of anomalous occurrence by using the wavelet which is great useful for comprehensive analysis on the anomaly phenomenon caused by earthquakes.

Ground-based electromagnetic field observation is one of the most important parts of stereoscopic observations for anomalous phenomena relative to earthquake events. Although the previous measurements have already obtained large amount of data, the future observation data will be certainly larger than before which will request advanced techniques for seismic study. It is expected that the study in this paper will help the development of the new advanced techniques which is suitable to investigate time-frequency-space characters of EM anomalies potentially caused by earthquakes.

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