doi:10.1007/s11589-011-0820-4

Discussion on several important problems in earthquake-related electromagnetic disturbance monitoring in China*

Lanwei Wang♣ Shizhong Zhang Yu Zhang and Dapeng Liu

Institute of Crustal Dynamics, *China Earthquake Administration*, *Beijing* 100085, *China*

Abstract Earthquake-related electromagnetic observation aims at finding abnormal electromagnetic variation associated with earthquake possibly. The existing studies have proved that this method is, to a large extent, effective in short-term and impending earthquake predication. This paper summarizes progress and discusses some related problems in this field. Some requirements for observation system have been proposed to improve monitoring level. As a case observation using the reformed observation system in Jinghai seismologic station, Tianjin, some results are given.

Key words: **earthquake-related electromagnetic disturbance; geo-electric field; magnetic field; electromagnetic disturbance event**

CLC number: P315.72^{+}1, P315.72^{+}2 **Document code**: A

1 Introduction

With more and more earthquake-related electromagnetic phenomena observed in recent years, seismo-electromagnetic method has been becoming an important short-term earthquake predication method. The earthquake-related electromagnetic disturbance observation aims at finding abnormal electromagnetic signal from variations of geo-electric field and magnetic field with time in a fixed monitoring points or sites and then searching for their relation to earthquake.

Formal Soviet Union, Japan, USA and Greece were several countries to observe and study earlierly earthquake-related electromagnetic phenomena in the world. In the earlier stage, only HF signal (from several kHz to tens of kHz) was observed. For this frequency band, however, many interference coming from commercial sources might be accompanied during the observations, and it would not be so easy for the signal in this band to be transmitted from the deep Earth to the Earth's surface if hypocenter region being taken as a source of the signal, according to the principle of electromagnetic theory. Therefore on the latest stage seismologists have turned their attention to another bands such as SLF (from tens of Hz to a few hundred Hz) and ULF (from DC to tens of Hz) band, for example, the instruments used for measuring geo-electric field in VAN team in Greece and the group of Tokai University, were operated in the band of 0.1 Hz to 10 Hz, while instruments used for measuring geo-electric field and magnetic field in Stanford University were in the band of 0.01 Hz to 10 Hz, and that used for measuring magnetic field and geo-electrical potential in Chiba University was in the band from 0.01 Hz to 30 Hz respectively.

Electromagnetic disturbance observation in China, has been started after $M_{\rm S}7.8$ Tangshan earthquake in 1976 and developed rapidly since then. Up to now, more than 150 monitoring stations with electromagnetic observation have been set up in the seismic zones all over the country, in which, the main physical quantities in the observation are the magnetic field and/or electric field, and, like that developed in the countries mentioned above, ULF, SLF and LF have become, in general, the interested frequency bands for most stations (Zhao et al., 2003, 2009), and large amounts of data involved in many case studies which might be associated with strong earthquakes and some experiences in anomaly identification and interference elimination have

---

* **Received** 30 August 2011; **accepted in revised form** 16 November 2011; **published** 10 December 2011.

♣ **Corresponding author. e-mail**: wanglw829@126.com

been accumulated (Ma et al., 2003; Li et al., 1991, 2003; Zhao and Lu, 2003; Qian et al., 1996, 2009; Yuan et al., 1996; Hao et al., 1995; Guo 1994; Zhang and Zhang, 1992; Guan et al., 1996, 2000; Wang et al., 2007).

This paper discusses on the problems which need to be concerned seriously and the countermeasures of solving them in the studies on earthquake-related electromagnetic observation in China. The problems are discussed in detail in section 2, and the countermeasures are described in section 3. And finally, the tests for the scientificalness and rationality of the countermeasures in section 3, have been done and the results of tests are described in section 4.

2 Several important problems in the observations of monitoring earthquake-related electromagnetic disturbances in China

The problems in the research and practice on earthquake-related electromagnetic disturbance, which need to be seriously dealt with based on the long term earthquake monitoring in China, are as follows: (1) No synchronicity of anomalous phenomena recorded in different observational points; (2) no consistent and well-defined technical requirements for various instrumentation; (3) lack of clear physical expressions of output data for some observations and (4) in general, lack of strict inspection and calibration procedures for observation systems (Guan et al., 2007; Qian, 2010). The detailed description about these problems are shown in the following parts of this section.

2.1 No synchronicity of anomalous phenomena recorded in different observational stations

Results from many case studies show that electromagnetic phenomena are very complicated before earthquake, specially showing that for all the cases published up to now, the identified anomalies at different observation stations never appeared simultaneously, with the time differences being a few days, even several days in those stations, for each case (Guan, et al., 2007; Qian, 2010). This phenomenon, so called no synchronicity, would strongly imply that the identified anomalies at different observation stations would not originate from a single or the same electromagnetic source because the velocity of propagation of electromagnetic wave being 300 000 km/s, would show just tiny time differences related to the distance between the source and each stations in a region based on the electromagnetic theory. It would also suggest that the identified anomalies at different observation stations, if they are recognized to be associated with the coming earthquakes somewhere nearby, would be multiple-sources phenomena with different amplitudes, phases and even in different frequency bands, which could be called as earthquake-related electromagnetic disturbances and not be in the electromagnetic wave propagation mode, even the real physical mechanism of the disturbances has been unknown for the moment.

2.2 No consistent and well-defined technical requirements for various kinds of instrumentation

Up to now various kinds of electromagnetic observation systems have been developed and operated in monitoring stations with an outstanding feature of diversity of the instrumentation and observation configuration without consistent and well-defined technical requirements for the observation system. For example, the frequency range could be different in different stations without coincident or common band, and also single observation physical quantities, either geo-electric field or magnetic field being selected for most stations, with the exceptions of simultaneously measuring both geo-electric and magnetic fields only in small part of stations. This feature has caused a lot of troubles for the comprehensive studies by analyzing the earthquake-related electromagnetic data.

2.3 Lack of unified and clear physical expressions for output data for some observations

Unified and clear physical expressions of output time series should be one of the very important issues in the jointed analysis of the monitoring data from different stations. The situation is that in China , scientists have made efforts to construct the output time series from the original electromagnetic observation data (electric field and/or magnetic field) in terms of various kinds of expressions in order to easily identify the anomalies associated possibly with earthquakes. The following are some examples (Qian, 2010). Figure 1 shows a station taking the numbers of pulse per day of electric and magnetic field as the expressions of data output time series; Figure 2 shows another station taking the summation of the products of amplitude of variations of observed electric field exceeding over a given threshold, multiplying its corresponding time duration, during each day as the expression of the output time series, with the unit of s·mV/m, which is so called “the information quantity”; Figure 3 shows a station taking the summation of the time durations of the identified anomalies in each day as the expression of time series. In terms of the ways shown in the examples of Figures 1–3, people could find some fluctuations in the time series newly constructed, for which one would have better opportunities to find anomalies possibly related to earthquakes, although the physical meaning for those expressions might not be clear.

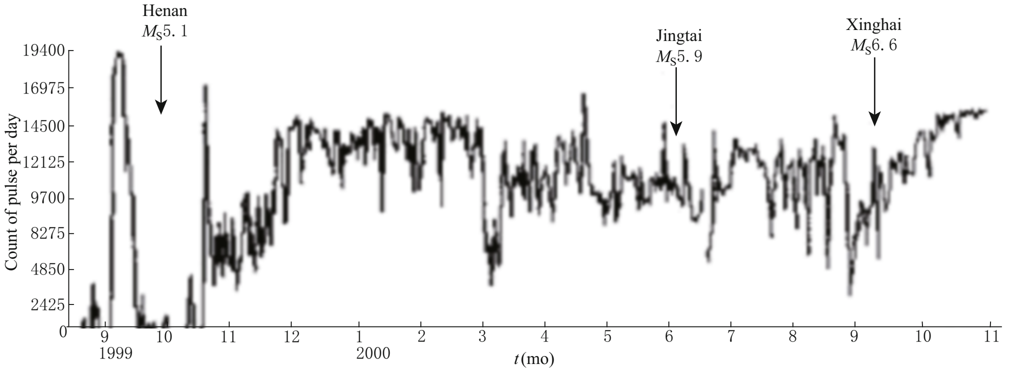

Figure 1 The temporal changes of the numbers of pulse per day of Pingan station in Shanxi province.

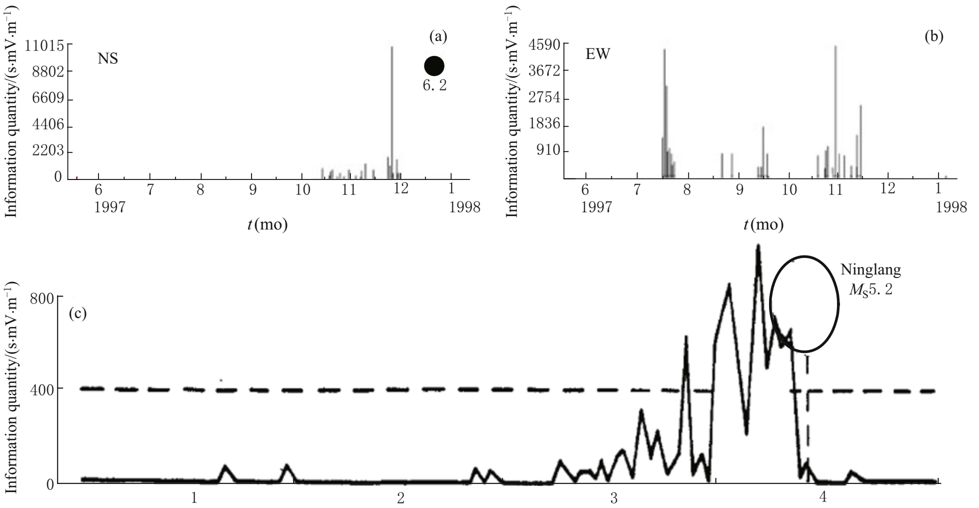

Figure 2 The temporary changes of “information quantity” from electric field observation. Data from Sanhe station in Hebei province with south-north (up) (a) and east-west (down) (b) components; data from in the western Yunnan Panegon earthquake predication test field in 1991 (c).

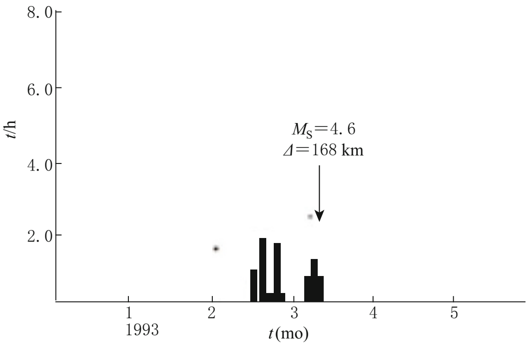

Figure 3 The temporal changes of abnormal time duration from magnetic field observation in Shimian station in Sichuan province in 1993.

The one of the fundamental requirements in the researches of earthquake prediction, is to construct a time series of data output, with clear physical meaning to express its temporal-spatial evolution, in terms of certain data processing of the observed quantity, so that it would be helpful to realize the nature of the evolutions and the possible relation to the earthquake preparation process. Apparently, the situation that expressions of individuation mentioned above, different from each other, with the feature of diversity, most of them being even lack of clear physical meaning, fully following the intentions or interest of individual scientists or technicians so that people could not easily compare the information from those deduced time series with different expressions in the researches and analysis of earthquake-related signals, is not possible to meet the requirement.

2.4 Lack of the strict inspection and calibration procedure for the observation system

The problem that lack of the strict inspection and calibration procedure for the observation system, has existed for many stations in China due to the fact either of no matched instruments or of no strict regulation (code) for the procedure having been made. To determine the instrument and the configuration system being operating in the normal state is first and indispensable one of important tasks of all the observation system, only those data outputted from the system being verified to operate in normal mode could be used to recognize the anomalous signals in monitoring electromagnetic disturbances and the background noises.

In summary, the above-mentioned problems not only make it difficult in data sharing, data analysis, but also in research on observation method and theory, which therefore obstructs the application of electromagnetic method to earthquake monitoring and predication. In order to solve the problems mentioned above, a set of unified requirements for earthquake-related electromagnetic disturbance observation as the countermeasures for the problems is proposed in the next section in this paper.

3 Requirements for earthquake-related electromagnetic disturbance observation

3.1 Selection of observation frequency band

The selection of appropriate frequency bands for monitoring the earthquake-related electromagnetic disturbances had been one of the important and also disputable issues. The important requirement is first to have lowest background level originated from natural noise and artificial or commercial noises due to mankind living demands, and second to have clear signals associated with earthquakes on the bases of the monitoring practice in the world. Based on the investigations in the field and the research papers, the band of 0.1 Hz to 10 Hz would be found as the optimal one. The reasons are as follows.

(1) Natural electromagnetic field has the minimum energy and thus has the weakest effect on electromagnetic disturbance observation within the band of 0.1 to 10 Hz (Figure 4, Zhao et al., 2009).

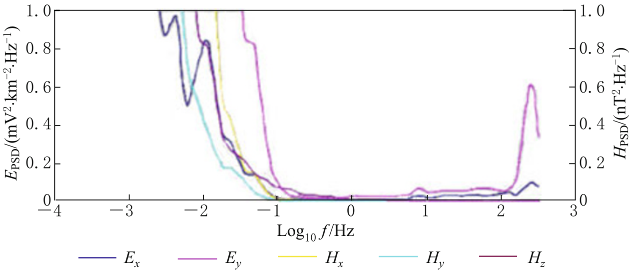

Figure 4 A spectra of natural electromagnetic field.

(2) The results from earthquake case studies show that there are more than 80% anomalies appeared in the frequency range of 0.1 to 10 Hz (Zhao et al., 2009).

(3) Mathematic modeling results show that it is difficult to observe the signals with frequency higher than 1 Hz if the source locates in the deep Earth.

The numerical modeling in a model of the horizontally stratified medium with dipole source somewhere beneath the Earth surface shows that the observed anomaly amplitude of electric field on the Earth's surface would be closely related to the intensity, frequency, depth of dipole source and the crust's electric property. In the condition of typical layered crust's model and the source in the depth of 6 km, the electrical signal in the frequency range higher than 1 Hz would be much smaller than that in the frequency lower than 1 Hz, if dipole source being taken to simulate the influences of earthquake preparation (Qian, 2010).

(4) With the increase of frequency, the manmade electromagnetic interference, especially the industrial or commercial interference would increase sharply. And also, in order to record the real time waveform with high frequency components, relative high sampling rate and big storage capability are required, which would result in not only the increase of the observation system cost, but also the difficulties in data processing and application.

The term of "optimal" would mean the compatibility instead of the exclusiveness in the frequency selection in the practice of the researches of earthquake-related electromagnetic disturbances, i.e., it would be better to have the band of 0.1 to 10 Hz when people design their observation system.

3.2 The expressions of output time series with clear physical meaning

As mentioned in section 2, it is very important to propose an expression method of observation data, which is not only clearly defined in physical meanings, but also can be used conveniently in the daily monitoring and predication of earthquake as well as scientific research.

In the earthquake-related electromagnetic monitoring, the objects of all observation system are simply electric field and/or magnetic field, the energy should be the fundamental properties of electromagnetic field with very clear physical meaning. Therefore the average energy in a certain time period could be used as the one of the best expressions of output time series to describe the dynamic variation of the energy in electromagnetic disturbances or events.

3.2.1 Construction of RMS time series for the dynamic variation of electromagnetic disturbance in terms of energy density

The dynamic variation of electromagnetic field can be described by its energy density, which could be calculated in the following formula:

$$W = W_{\mathrm{E}} + W_{\mathrm{H}} = \frac{1}{2} \times \left(\varepsilon E^2 + \mu H^2\right), \tag{1}$$

$$W_{\mathrm{E}} = \frac{1}{2} \times \left(\varepsilon E^2\right), \tag{2}$$

$$W_{\mathrm{H}} = \frac{1}{2} \times \left(\mu H^2\right), \tag{3}$$

where W, W_{E} and W_{H} denote the total energy density of electromagnetic field, electric field energy density and magnetic field energy density respectively, and E and H are the instantaneous values of the electric and magnetic field intensities, ε and μ are the dielectric constant and magnetic susceptibility of the Earth media, respectively. In electromagnetic disturbance observation, because the electric field and magnetic field, the frequency components and the amplitude are in general, changed with time, it is reasonable to describe the temporal variations of the electric field and/or magnetic field in term of effective value i.e., the root mean square (RMS) value which are calculated through the average power of electric field and magnetic field in a certain time period (for example: one minute), which are widely used in electrical engineering with the following formula:

$$E = \sqrt{\frac{\sum\limits_{i=1}^{n} {E_i}^2}{n}}, \tag{4}$$

$$H = \sqrt{\frac{\sum\limits_{i=1}^{n} {H_i}^2}{n}}, \tag{5}$$

in which, E and H denote RMS value of the intensity of electric field and of magnetic field in one minute respectively, and n is the sampling rate in one minute, and E_i, H_i are the value of each sample.

The variation of electromagnetic field background value can be described by time series of the RMS value in each minute. On the bases of the time series, the RMS value in one hour, one day, five days, ten days, one month and even one year can be calculated, which is very useful for further data processing.

3.2.2 Construction of the time series for electromagnetic disturbance events

As described in section 2, no synchronicity of anomalous phenomena recorded in different observational points in earthquake-related electromagnetic monitoring, has shown the feature of multi-sources effects, so that each anomalous signal has been taken as one disturbance event. It would also be very useful to identify each event in the analysis of anomalous information. It refers to the real time waveform of electromagnetic field which is sampled at the highest sampling rate of the observation system in a certain time period and all information of electromagnetic disturbance can be obtained from it. The characteristics of an event can be expressed by some basic parameters such as the starting and ending time, duration, the maximum amplitude and the dominant frequency. The starting and ending time could be gotten from the RMS time series mentioned above. The maximum amplitude is the largest absolute value in the time series. The dominant frequency is the frequency at which there is the largest spectrum amplitude.

To identify the event, usually there are two electromagnetic event-triggered algorithms being used, one is so called threshold algorithm, and the other is the algorithm taking the ratio of long- and short- term average. For threshold algorithm, a preset threshold would be set in advance. If the observation data value is larger than the threshold value, the event triggers, which means the starting time being found. The advantage of this algorithm is that the algorithm is simple while the disadvantage is easy to be interfered by noise. If a high level of threshold value is preset in this algorithm, some events would be lost, and if a low level of threshold value preset, there would have many mis-triggered events which are caused by interferences.

The algorithm of the ratio of long- and short-term average would avoid mis-triggered effects. This algorithm requires firstly to split a data segment with the first data point as the beginning, into successive two parts: long piece window and short window, with the length of long window several times that of the short one, take the averages of the RMS values for each window, and then calculate the ratio of the average of the

RMS value of short window over that of long one. This procedure could be smoothly moved to the data segment with the next data point as the beginning, and make two marks between the time when the ratio becomes larger than the preset value as the starting point of a event, and the time when the ratio being recovered to the value lower than the preset one as the ending point of the event. The advantage of this algorithm is less affected by interferences while the disadvantage is that the algorithm is complicated.

The ratio of average of short term window to long term window could be calculated by

$$\overline{V}_{\mathrm{L}} = \frac{\sum\limits_{i}^{N} x(i)}{N}, \tag{6}$$

$$\overline{V}_{\mathrm{S}} = \frac{\sum\limits_{i}^{M} x(i)}{M}, \tag{7}$$

where N and M is the length of long- and short- time window respectively. $x(i)$ is the observation data, Z_0 is the pre-set threshold. If $(\overline{V}_{\mathrm{S}})/(\overline{V}_{\mathrm{L}})>Z_0$, the event record mode would be triggered.

Usually, the length of long time window is about 10 minutes while the short time window is 2 to 3 minutes which can be used to avoid random interferences in very short time (for example one minute). Because the maximum period of observation signal is 10 s, for 2 minutes (120 s) it would include 12 signal cycles which is very helpful for reflecting the whole signal information.

3.3 The design and requirements of inspection system

The inspection system is a kind of guarantee facility for checking whether the operating state of the observation system being normal in the long term of monitoring process. It can generate a known electric field and magnetic field in a certain area by applied an AC current to the ground, so we can judge the work state of the observation system by measuring this known signal.

In Figure 5, the capital letter M_1 and M_2 denote two magnetic sensors arranged at the EW and NS direction, respectively. A, B, A_1, A_2, B_1 and B_2 denote the positions of six electrodes, among which A, B are called current electrodes and connected to low frequency signal source, A_1, A_2, B_1, B_2 are called potential electrodes and connected to the measurement system by screen cable. L denotes power line which passes through the intersection of the two magnetic sensors and with an angle of 45° with the north.

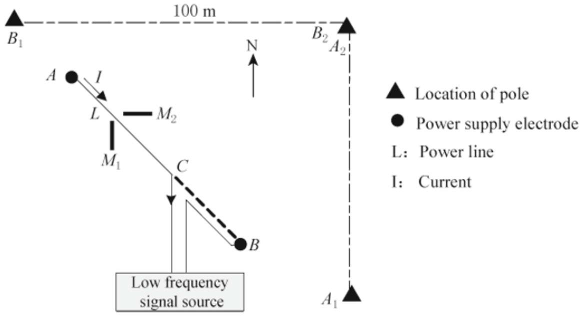

Figure 5 The deployment map of observation system and inspection system in the station.

When the low frequency signal source is switched on, an AC current (I) is applied to the ground through electrodes A and B. which generate a given alternating magnetic field around the line L and an artificial electric field in a certain area.

Theoretical results show that if L=40 m, I=0.2 A and the resistivity of the field is about 10 Ω·m, the electric field generated between two measuring electrodes in Figure 5 is about 2.8 mV. In observation practice, because the distance between the measuring electrode and current electrode is shorter than that of the two measuring electrodes in Figure 5 and the resistivity of the field is, in general, larger than 10 Ω·m, the potential difference of several mV can be generated.

Seen from Table 1, if r=5 m, h=1 m and I=0.1 A, then the intensity of the generated magnetic field would be 0.5 nT (H=0.5 nT).

4 Experimental observation

4.1 Construction of observation system

In order to verify the method mentioned above, a new electromagnetic disturbance observation experiment arranged strictly according to the above requirements was carried out in Jinhai station, Tianjin Municipality from March to October in 2006. An instrument specially designed is used in the experiment.

The experimental observation system was designed for measuring the 0.1–10 Hz electric field (E) and magnetic field (H) on the Earth's surface. This system consists of five parts: measurement unit, four potential electrodes, two magnetic sensors, measurement lines and inspection system as shown in Figure 5.

The two magnetic sensors were buried at about one meter depth under the ground and arranged at NS and EW directions respectively at a distance about

Table 1 The calculated H at different distances r and height differences h between the center of magnetic sensors and L

R/m	H/nT				
	h=0.5 m	h=1 m	h=1.5 m	h=2 m	h=2.5 m
0.5	14.140 0	11.312 0	8.484 0	6.654 1	5.438 5
1.0	5.656 0	7.070 0	6.526 2	5.656 0	4.875 9
2.0	1.663 5	2.828 0	3.393 6	3.535 0	3.448 8
3.0	0.764 3	1.414 0	1.885 3	2.175 4	2.318 0
4.0	0.435 1	0.831 8	1.162 2	1.414 0	1.588 8
5.0	0.280 0	0.543 8	0.778 3	0.975 2	1.131 2
6.0	0.195 0	0.382 2	0.554 5	0.707 0	0.836 7
7.0	0.143 6	0.282 8	0.413 9	0.533 6	0.639 8
8.0	0.110 0	0.217 5	0.320 2	0.415 9	0.503 2
9.0	0.087 0	0.172 4	0.254 8	0.332 7	0.405 2
10.0	0.070 5	0.140 0	0.207 4	0.271 9	0.332 7
11.0	0.058 3	0.115 9	0.172 1	0.226 2	0.277 8
12.0	0.049 0	0.097 5	0.145 0	0.191 1	0.235 3
13.0	0.041 8	0.083 2	0.123 9	0.163 5	0.201 7
14.0	0.036 0	0.071 8	0.107 0	0.141 4	0.174 8
15.0	0.031 4	0.062 6	0.093 3	0.123 5	0.152 9

five meters. A_1, A_2, B_1 and B_2 denote four potential electrodes which were arranged with L-type layout and buried about 1.5 m depth under the ground, their mutual distance is about 100 m for the two couple's electrodes (A_1A_2 and B_1B_2) in the NS and EW direction respectively. The potential electrodes are connected by screen cable to the measurement unit. A and B denote two current electrodes which are put into the ground 1 m depth and the distance between them is about 40 m.

The specifications of the measuring system used for the experimental observation are as follows.

1) The specifications of measuring unit

Frequency range: 0.1–10 Hz

Dynamic range: ≥80 dB

Resolution: electric field: better than 1 μV/m

Magnetic field: better than 0.01 nT

Sampling rate:

Normal mode: 1 sample/min; event record mode: 50 samples/s

Nonlinearity: better than 0.5%

2) The specifications of magnetic sensor

Frequency range: 0.1–100 Hz

Output sensitivity: ≥1 mV/nT (0.1–1 Hz); ≥10 mV/nT (1–10 Hz)

3) Main features of observation system

Recording the RMS value of electric field and magnetic field; auto-judging and recording electromagnetic disturbance event and outputting the parameters of electromagnetic event, including the start and the end time, dominant frequency and the most significant amplitude.

4.2 Experimental results

4.2.1 Dynamic variation

Figure 6 is the dynamic variation of daily average RMS value from March to September in 2006. The daily average RMS value was calculated by

$$\overline{X}=\sqrt{\frac{\sum\limits_{i=1}^{n}{X_i}^2}{n}}, \tag{8}$$

where $\overline{X}$ is daily average RMS value, X_i is RMS value in one minute (observation data), n is the total number of X_i in one day, normally, n=1 440.

We obtained the normal variation range of the electromagnetic filed in Jinghai station through analyzing the observation data. The variation ranges of RMS value of its magnetic field are about 0.021–0.228 nT and 0.039–0.172 nT at the NS and EW direction respectively, and those of its electric field are about 0.49–27.0 mV/km and 0.22–18.4 mV/km.

During electromagnetic disturbance event period, the statistic study results show that the maximum amplitude of its magnetic field at NS direction is 3.41 nT, while 14.1 nT at EW direction and that of its electric field at NS direction is 144 mV/km, while 365 mV/km at EW direction. Figure 6 shows the curve of daily average RMS value after eliminating interference data.

4.2.2 Analysis of electromagnetic disturbance event data

There are about 382 events recorded during the whole experiment period. Among these events, some are the real events; others are interferences caused by

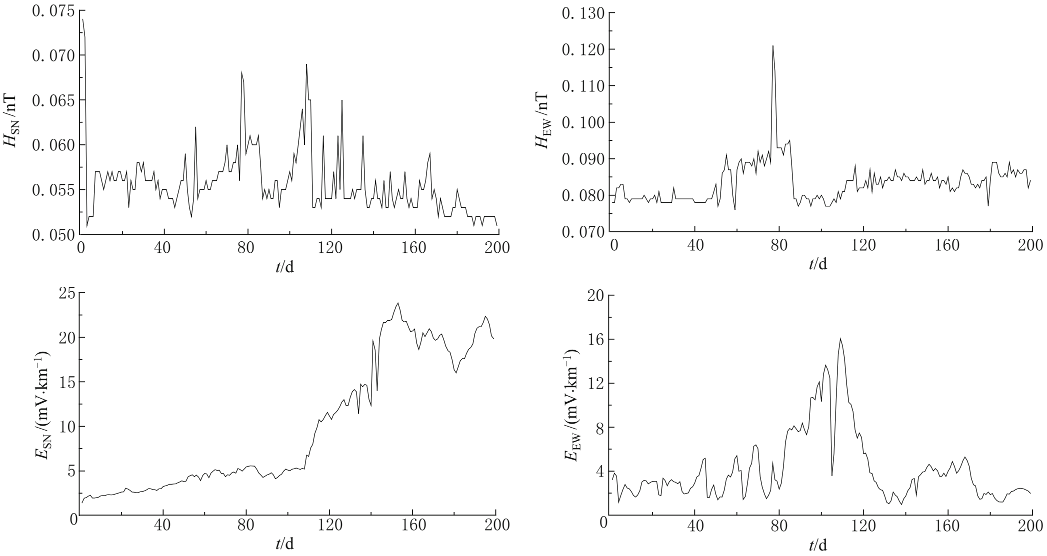

Figure 6 Dynamic variation of daily average RMS value from March to September in 2006.

human activities, so we need to distinguish the real events from the interferences based on the following principles. (1) The data change synchronously in multiple channels; (2) The duration of change is longer than a certain period.

Finally, 108 real events were selected out as shown in Figure 7. In June and July in 2006, the amount of real events increased, and then the M_S5.1 earthquake occurred at Wen'an county, Hebei province on 4th, July 2006, whose epicenter is 30 km from Jinghai station.

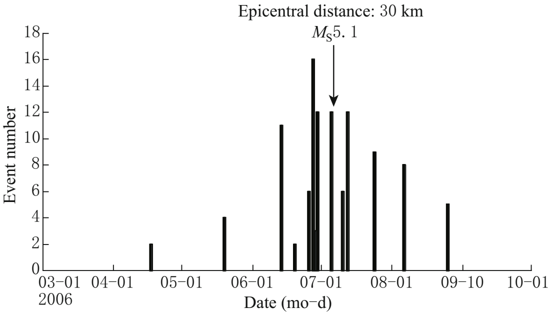

Figure 7 The selected real event number from March to September in 2006.

4.2.3 Summary of experimental observation

The results of the experimental observation show that it is rational to describe the earthquake-related electromagnetic disturbance using dynamic variation and event record. They not only have a clear physical meaning, but also are very convenient to be applied in earthquake predication. The observation system used for the experimental observation in Jinghai station can meet the needs of electromagnetic disturbance observation (Wang, et al., 2007; Zhao, et al., 2007).

5 Conclusions

The objective of earthquake-related electromagnetic disturbance observation is to obtain the abnormal EM signals that might be associated with earthquake preparation process and occurrence but not the regular changes of electromagnetic field on the Earth's surface. Although the observation and research results in the past years show that the abnormal electromagnetic disturbance changes associated with earthquake exist indeed, the applications of this method in earthquake predication are still in the exploratory stage and many problems have not been understood very well, such as the asynchronous abnormal information. Therefore it is expected to conduct a comprehensive observation in multiple frequency bands, especially to measure simultaneously the electric field and magnetic field in the same site. It is, however, a reasonable choice in present condition to do the observation of electric field and magnetic field in the same site in a proper frequency band. Based on the previous study results, the optimal band for the observation is from 0.1 to 10 Hz.

It is scientific and rational to describe the earthquake-related electromagnetic disturbance on the bases of the dynamic variation and event record. They not only have clear physical meaning and are very convenient to be used in earthquake predication, but also provide basic data for further analysis of abnormal electromagnetic information and mechanism. The experimental observation results show that it is beneficial to data sharing and processing using this expression method of output data.

The experimental observation results also demonstrated that the technical requirements for the observation system and inspection system is scientific and can satisfy the demands of earthquake-related electromagnetic disturbance observation. This is very important for unification and regulation of this observation. The observation system and inspection system used in the experimental observation provide a model for the future construction of electromagnetic disturbance observation station.

Acknowledgements We would like to thank Professors Jiadong Qian and Jialiu Zhao for discussion on this manuscript and their constructive suggestions. This study is financially supported by Public Science and Technology Research Funds Project of Earthquake (No.20080830).

References

Guan H P and Chen Z Y (1996). Quantitative analysis of the relation between seismicity and electromagnetic radiation. *Earthquake* **l6**(2): 168–176 (in Chinese with English abstract).

Guan H P, Chen Z Y and Yu S R (2000). Study on seismic precursor feature of electromagnetic radiation in the capital circle and its surrounding area. *Earthquake* **20**(1): 65–70 (in Chinese with English abstract).

Guan H P, Xiao W J and Li M (2007). The observation research of electromagnetic disturbance in China. *Earthquake* **27**(Suppl.): 71–79 (in Chinese with English abstract).

Guo Z Q (1994). Investigation on low frequency seismo-electromagnetic emission. *Acta Geophysica Sinica* **37**(Suppl.1): 261–267 (in Chinese with English abstract).

Guo Z Q, Guo Z Q, Qian S Q, Li S Y, Liu X H and Luo X L (1999). Electro-acoustic effect in rock fracture. *Chinese J Geophys* **42**(1): 74–83 (in Chinese with English abstract).

Hao J G, Zhang Y F, Pan H W, Li D R, Tang T M and Liu X Q (1995). Ultra low frequency electromagnetic wave anomaly and its spectrum characteristics before earthquakes. *Acta Seismologica Sinica* **8**(1): 101–109.

Li W X, Jin M P and Ma J K (2003). Electromagnetic wave anomaly characteristics before strong earthquakes and its predication significance in Yunnan area. *Earthquake* **23**(2): 77–84 (in Chinese with English abstract).

Li Y T and Guo Y (1991). The observation of EM signal prior to the earthquake events. *Acta Seismologica Sinica* **13**(1): 121–124 (in Chinese with English abstract).

Ma Q Z, Yin J Y and Gu X Z (2003). The electromagnetic anomalies observed at Chongming station and the Taiwan strong earthquake (M=7.5, March 31, 2002). *Earthquake* **23**(4): 49–56 (in Chinese with English abstract).

Qian J D edit-in-chief (2010). the theoretic foundation and Observation Techniques of Earthquake-related Electromagnetics. seismoligical Press, Beijing, 240–265 (in Chinese).

Qian S Q (2009). Observation and experiment research on seismological electromagnetic radiation and earthquake predication. *Recent Developments in World Seismology* (7): 57–62.

Qian S Q, Chen Z Y, Li Y T, Lu Z, Ren K X, Xu D H, Guo Y and Ji Z Y (1996). Analysis of the seismo-electromagnetic anomaly before the 5.5 magnitude earthquake on 18th October, 1989 in Datong, Shanxi Province. *Seismological and Geomagnetic Observation and Research* **17**(1): 54–60 (in Chinese with English abstract).

Wang L F, Wang J J, Chen X B and Zhao G Z (2007). Experimental and theoretical investigations of electromagnetic radiation induced by rock fracture. *Progress in Geophysics* **22**(3): 715–719 (in Chinese with English abstract).

Wang L W, Zhao J L, Wang Z Y, Wang Y Q, Han R Q and Xu X G (2007). Experiments of electromagnetic disturbance observation and data analysis. *Earthquake* **27**(Suppl.): 96–102 (in Chinese with English abstract).

Yuan J Z, Takahashi K, Qian S Q, Fujinawa Y, Zhao H X and Ren K X (1996). Observation and research on ULF and VLF seismo-electromagnetic radiation. *Acta Seismologica Sinica* **9**(2): 351–355.

Zhang Q X and Zhang M C (1992). The observation study on electromagnetic radiation before medium and strong earthquakes in Yunnan area. *Acta Seismologica Sinica* **14**(3): 325–331(in Chinese with English abstract).

Zhao G Z and Lu J X (2003). Monitoring and analysis of earthquake phenomena by artificial SLF waves. *Engineering Science* **5**(10): 27–33 (in Chinese with English abstract).

Zhao J L, Cai J A, Guan H P, Wang L W, Qian J D, Xi J L, Huang W, Wang Y Q, Lu J, Li M, Du X B, Xu D H, Han R Q, Tang Y X, Tan D C, Wang Z Y and Zhang S Z (2009). The method of earthquake-related geoelectrical monitoring: LF electro-magnetic disturbance observation.

Zhao J L, Wang L W, Zhang S Z, Wang Z Y, Zhang S P, Wang Y Q and Xu X G (2007). Experimental study on electromagnetic disturbance observation. *Earthquake* **27**(Suppl.): 59–70 (in Chinese with English abstract).