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Ultra-Low Frequency Electromagnetic Emissions Registered during the 21 May 2021 Yangbi M_S 6.4 Earthquake in China

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ABSTRACT

Four ULF (0.01 Hz - 20 Hz) electromagnetic stations had been gradually established and put into service from 2010 to 2011 in Zhaotong area, Yunnan province. Two stations of Qiaojia and Yongshan have been running with continuous and high quality recordings and free of influence of solar activities, like magnetic storms. In this investigation, daily recordings from 1 January 2020 to 22 May 2021 have been examined of these both stations. The results show that weak anomalous signals appeared at the beginning of March 2021 with relative low magnitudes of 0.6 nT at Qiaojia station and 0.3 nT at Yongshan station. At the end of this month, the emissions gained an abrupt increase and the amplitudes reached up to 3.8 nT at Qiaojia station and 1.2 nT at Yongsha station. Then, the amplitude decreased to be 0.5 - 1.5 nT and 0.6 - 1.3 nT respectively at both stations but with a high variation frequency in all components. This situation lasted till the Yangbi M_S 6.4 earthquake happened on May 21, 2021, more than 300 km away from these two ULF observing stations. Totally, the ULF magnetic emissions had been characterized by a synchronous variation in all components at two observing stations.

1. INTRODUCTION

Electromagnetic phenomena associated with seismic activities have been extensively investigated worldwide and examples with electromagnetic emissions have also been reported in an increasing number of literatures. These reports are mainly focused on events related to ULF (ultra low frequency) anomaly although electromagnetic emissions in wide frequency range from ULF to HF (high frequency) band prior to or during seismic activities have been effectively testified during the last few decades. The reason for these events maybe originates from the fact that signals in ULF band can easily propagate from the lithosphere without a significant attenuation. There are also different art of layout styles for sensors or electrodes for different installments and sensors are buried at a several meters' depth beneath the Earth for most ground-based observing. Unusual ULF magnetic signals were observed two weeks prior to the Loma Prieta M_S 7.1 earthquake (EQ), on October 17, 1989 (f = 0.01 - 10 Hz, d = 7 km, A = 1.5 nT) [1, 2]. Anomalous electromagnetic emissions prior to the great crustal M_S 6.9 EQ at Spitak, Armenia, on December 7, 1988 had been reported during the several following years [3, 4]. Hayakawa *et al.* [5, 6] reported obvious electromagnetic variations about one month and a few days before the 8 August 1993 M_S 8.0 Guam EQ and before the great M_S 8.2 Biak EQ in Indonesia on February 17 1996 respectively. Possible seismic related ULF anomalies occurred about two weeks before L'Aquila M_S 6.3 EQ with the distance up to 630 km [7]. Li *et al.* [8] had reported an obvious ULF electromagnetic abnormity lasted several months but with a climax 3 days prior to the large Wenchuan M_S 8.0 EQ on May 12, 2008, at Gaobeidian station 1400 km away from the epicenter. A sub-surface measurement of electromagnetic emissions due to its freedom from outer disturbances has also shown its effective results during some events. VLF (very low frequency) electric field perturbations had been observed by borehole antennas instead of terrestrial antennas, 16 days prior to the Chamoli M_S 6.6 EQ on 29 March 1999 in India [9]. VLF pulse-like electromagnetic signals also have been recorded by sub-surface antennas before the M_S 5.8 east Yamanashi Prefecture EQ [10]. Obvious pre-earthquake electromagnetic emissions and co-seismic variations had been recorded by an 800 m borehole antenna during four huge $M_S \geq 8.0$ EQs occurred in Asia and the Mojiang M_S 5.9 event on September 8, 2018 in China in ULF - VLF (CH1: 0.01 - 0.1 Hz), CH2: 0.1 - 1 Hz and CH3: 1 - 9 kHz) channels [11, 12]. However, Fraser-Smith *et al.* [13] have confirmed that no ULF emissions associated with either the 1992, M 7.4 Landers earthquake or the same Northridge earthquake were not recorded.

Many simulating rock-pressure experiments were carried out in order to understand the producing mechanism of the electromagnetic information associated with seismic activities and positive results have been gained [14-22]. However, up to now, no clear explanation has been given although several physical mechanisms have been proposed to interpret the generation of EM emissions and electrical currents observed either during seismic activity or in the laboratory experiments. These include the electrokinetic and magnetohydrodynamic, piezomagnetism, stress-induced variations in crustal conductivity, microfracturing, etc. [23-27].

In this paper, obvious ULF electromagnetic abnormity associated with a strong EQ will be investigated. An ULF electromagnetic monitoring system installed in Zhaotong area, Yunan Province, is firstly introduced in Section 2. Then, obvious ULF electromagnetic emissions probably associated with the last Yangbi M_S 6.4 EQ on May 21 2021 are described in detail in Section 3. Discussion including one possible producing mechanism of the electromagnetic signals associated with this Yangbi event is in Section 4. Conclusions are in Section 5.

2. EXPERIMENTAL SYSTEM

Zhaotong area locates in northeast Yunnan province, the conjunction between the Yun-Gui Plateau and the Sichuan Basin in southwest China. In this area, moderate and strong EQs took place frequently. A relative improved EQ monitoring network had been established between the 9th Five-Year Plan and the 12th Five-Year Plan. This network includes 10 digital seismometers, 20 strong motion observation instruments, 30 underground fluid observation instruments, 10 strain instruments, 7 inclinometers and 4 ULF electromagnetic observing instruments. The data in this network can be publicly used (http://www.eqzt.com/). In addition, some other observing instruments have also been gradually deployed by different teams from research institutes and universities in recent years.

These four ULF electromagnetic stations in this network had been established from 2010 to 2011 in Zhaotong area. They are named Qiaojia, Yongshan, Yudong and Suijiang, and their relative locations are shown in **Figure 1**.

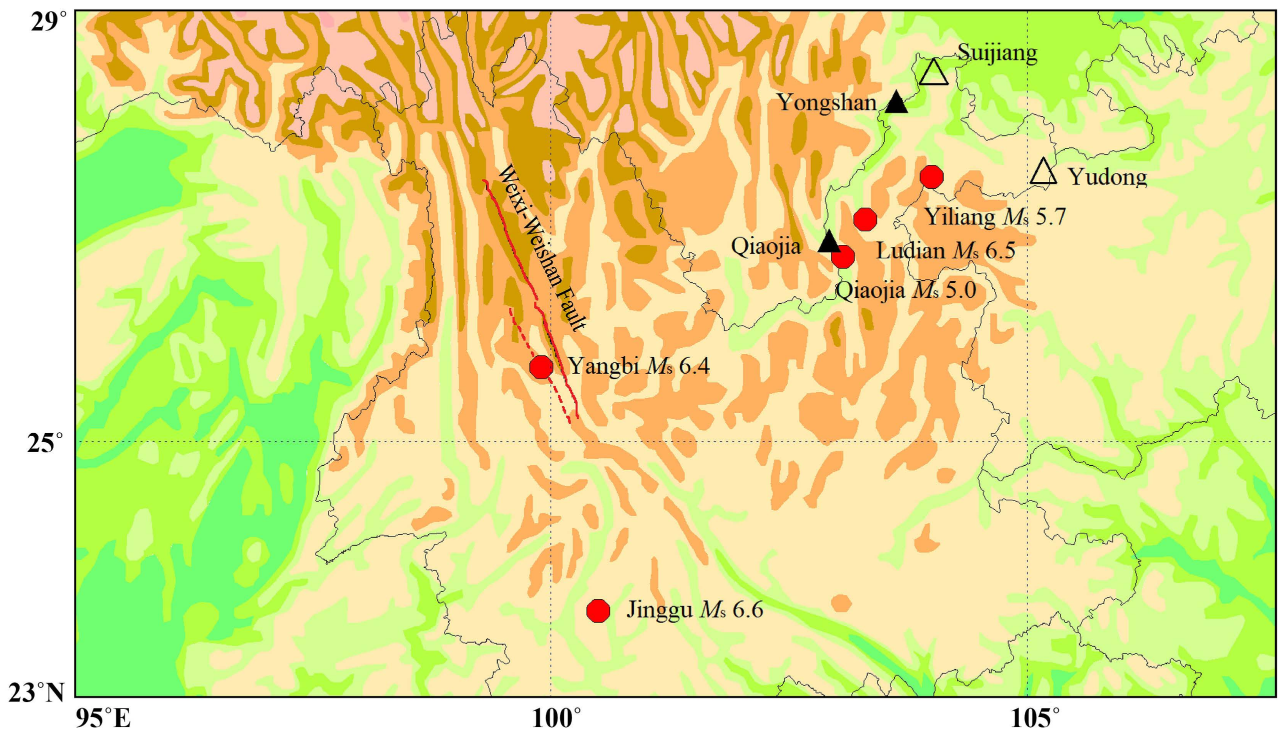


Figure 1. Locations of four ULF electromagnetic observing stations in the Zhaotong network and strong earthquakes recorded. Qiaojia station and Yongshan station are labeled by solid black triangles. Suijiang and Yudong stations marked by empty black triangles were out of order or with poor recordings. All related earthquakes are labeled by solid red circles. The red solid line stands for the main fault near the Yangbi event. The anonymous concealed fault inferred by Yang *et al.* [28] and Li *et al.* [29] has been labeled by a red dot line, which is thought to be seismogenic fault of this Yangbi EQ.

The ULF electromagnetic system includes two TDW-26 sensors (Figure 2(a)) and a TDP-0844i data collector (Figure 2(b)). This system was set up and put into service on 27 February 2010 at Qiaojia and Yongshan stations, on 5 March 2011 at Suijiang and Yudong stations. The TDW-26 sensors measure electromagnetic fields and give an output of magnetic signals in the response frequency 0.01 - 20 Hz. It has a time resolution of 0.1 nT and a survey range of ±1000 nT. At Qiaojia station, two sensors are buried 1 meter depth underground with 1 meter space and they are called NS (north-south) and EW (east-west) components. Sensors at Yongshan station are laid on the ground of an observing cave, which leads to relative obvious outer interferes, especially in summer, comparing with Qiaojia station (also see Figure 4). While the information at Yudong shows an annual variation too strong to distinguish useful signals. Suijiang station was out of order not long after its installment and these two stations are presented with empty black triangles in Figure 1. Thus, all data utilized in this paper are from Qiaojia and Yongshan stations, which are labeled by solid black triangles in Figure 1.

A data acquisition unit called TDP-0844i services to output second recordings, hourly recordings and daily recordings. The system can stably run with a relative high resolution and partly free of an influence from rain, lightings and other outer disturbances, especially for sensors buried beneath the earth, such as Qiaojia station. However, when electromagnetic observation is mentioned, solar activities have to be considered, like magnetic storms. Kp index is one of the parameters that can describe the degree of solar activity. The key point is that solar activity occurs globally and its influence keeps the same on all observing stations. Thus, it is advantageous to examine solar effect for searching for useful information.

(a) (b)

Figure 2. **ULF electromagnetic monitoring system in Zhaotong network. (a) TDW-26 sensors; (b) TDP-0844i data collector.**

To check effect from solar activities like magnetic storms, hourly output recordings have been examined. **Figure 3(a)** shows hour fluctuations (B_h) during 1-7 January 2011 in EW component at Qiaojia station (running more stably comparing with Yongshan station). From **Figure 3(a)**, we can see that there is a clear daily variation in the running line with a lowest point each day but this lowest point day by day occurred in different time from 13:00PM to 16:00PM instead of the similar time, just as geomagnetic vertical component Z with a daily lowest point occurring almost at the fixed time every day [30]. In order to further check the influence from solar activity on this variation, we have examined everyday lowest value during total January 2011 of the same parameter and recorded it as B_{min}. **Figure 3(b)** displays changes of the absolute value of B_{min} as the date goes during the period of January 2011. At the same time, Kp values (http://isgi.unistra.fr/) have also been checked in this time and **Figure 3(c)** presents their variations, clearly varying from that of B_{min}. Their calculated correlation coefficient is 0.2, which indicates there is little probability that this ULF electromagnetic information originates from outer space.

There are more disturbances during the first two years (from 2010 to 2011) after service of this instrument due to unstable observing system. **Figure 4** shows daily recordings from 2012 to 2013 for both observing stations of Qiaojia and Yongshan. They are NS and EW components at Qiaojia station, and NS and EW components at Yongshan station respectively from the top panel to the bottom one in **Figure 4**. From **Figure 4**, the fluctuations of daily recordings show no obvious annual or seasonal variations. Comparatively, Yongshan station tends to record occasional pules with a maximum magnitude less than 1 nT due to its exposed sensors mentioned above (see **Figure 4(b)**). The averaged values of absolute daily recordings during 2012 are 0.023 nT and 0.058 nT for SN Qiaojia and EW Yongshan, respectively, which indicates a lower background noise at these two stations that can be ignored when a precursor is distinguished during seismic activities. As for the occasional pules, they unavoidably bring us some difficult to distinguish precursor information although they contribute not much to the averaged values. Generally, these disturbances originate from two aspects, one is local outer interferes, like motors, and another is due to weak EQs in a near area. In regional tectonic structure, Zhaotong area lies in the mid-stage of the North-South seismic belt in China. The main faults in this region stay locked and with little displacements, which makes an EQ occurrence easily in recent decades [31].

With these being considered, it is advantageous to determine precursory signals associated with strong EQs in light of synchronous variations at two stations. In the following years after their installments, several strong EQs have happened in this area. The first one is the Yiliang M_S 5.7 EQ on 7 September 2012. In this case, anomalous emissions with a little magnitude (~1.2 nT at Yongshan and 0.2 nT at Qiaojia, which can be referred to **Figure 4**) appeared almost at the same time in two components at these two stations about two weeks before the event, 80 km and 120 km away from Yongshan and Qiaojia, respectively (see **Figure 1**). This shock induced various changes in each line in **Figure 4** but we still can distinguish a synchronous change at both observing stations.

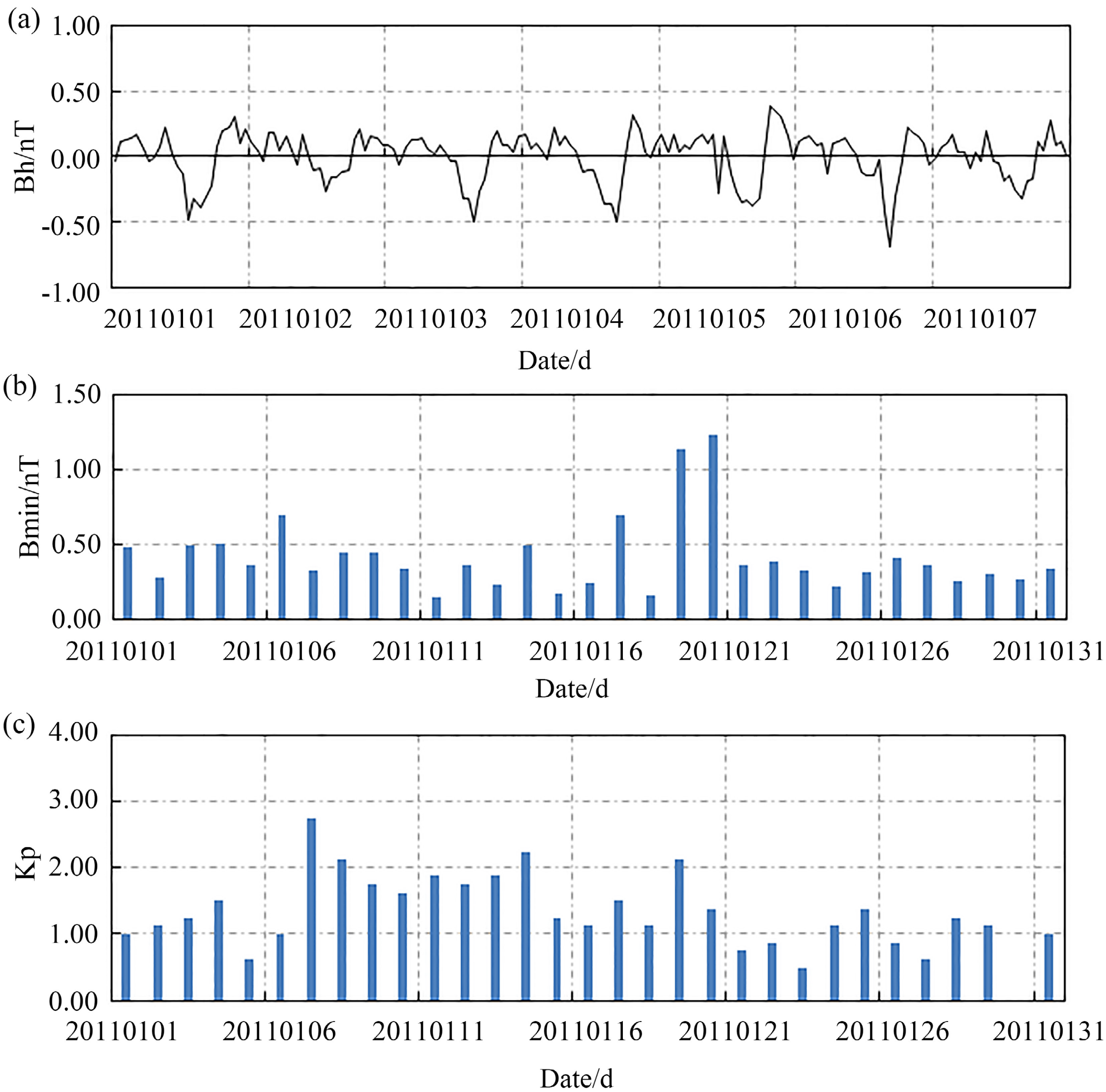


Figure 3. (a) Hourly fluctuations during 1-7 January 2011 in EW component at Qiaojia station; (b) Fluctuations of the absolute value of the lowest point each day from 1st January to 31st January 2011 in EW component of Qiaojia station; (c) Daily Kp values during January 2011.

Events with a magnitude equal to or more than 6 did not happen in this area until the Ludian M_S 6.5 EQ on 3 August, 2014. And then, two months later, another strong EQ with a magnitude $M_S = 6.6$ took place on 7 October in south Yunnan. These two events are also displayed in Figure 1. More details on these two strong EQs and associated unusual electromagnetic disturbances will be illustrated in other literatures.

While, the background value changes a lot after a new CPU (central processing unit) was installed into the data acquisition unit TDP-0844i on March 12 2019. The background magnitudes are ~6100 nT and ~5400 nT in NS and EW components instead of previous near zero nT but still with a similar daily variation. These high background values are eliminated during data processing in the following parts.

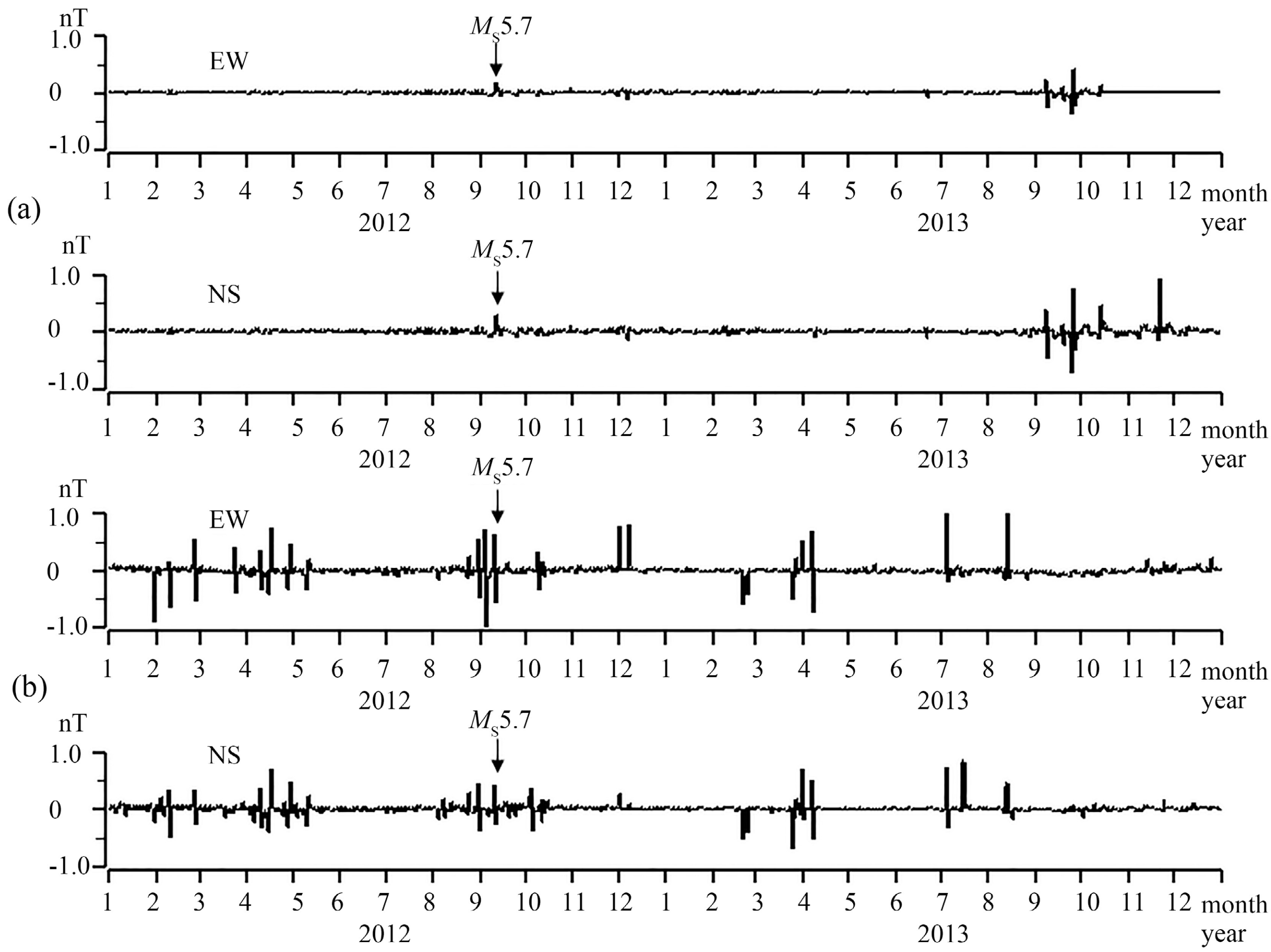


Figure 4. Daily electromagnetic variations from 2010 to 2013 in Zhaotong area: (a) Qiaojia station and (b) Yongshan station. The Yiliang M_S 5.7 EQ on 7 September 2012 is labeled with black arrows in each panel.

3. ULF ANOMALOUS EMISSIONS DURING THE YANGBI M_S 6.4 EARTHQUAKE

A strong EQ with a magnitude being M_S 6.4 hit Yangbi, Yunnan province, at 21:48:34, May 21, 2021 CST (China Standard Time) with the epicenter located at 99.9˚N and 25.7˚E and at a depth of 8 km (see Figure 1). Remarkable enhancements in ULF electromagnetic signals in the Zhaotong network have been registered at Qiaojia station, as well as at Yongshan station prior to this event.

Unfortunately, the point we have to mention in this time is that there was clear disturbance information in Qiaojia SN component and this interfere signal appeared firstly on 7 May and occurred discontinuously with the largest magnitude of ~25 nT till this EQ occurrence. Fortunately, it has been testified to be due to installment aging. This disturbance information has also been eliminated during data processing and we also do not show data variations after this Yangbi event.

Daily recordings from 1st January 2020 to 22 May 2021 have been considered at Qiaojia station, as well as at Yongshan station. We have mentioned above that background values are of ~6100 nT and ~5400 nT in NS and EW components respectively at Qiaojia station. Firstly, taking the daily recordings from January to March in 2012 (no obvious seismic activities occurred during this period) as references, the calculated averaged values are 6183.86 nT and 5418.17 nT for NS and EW components. Secondly, a difference has been attained by subtracting the averaged values for original records in each component from 1st January 2020 to 22 May 2021. All these differences have been kept although their averaged rang is 0.5

nT (this value can be eliminated when abnormal amplitude is calculated) in order to maintain a complete fluctuation of precursor information. We also checked daily recordings from January to March in 2012 and the calculated averaged values vary 0.07 nT around zero line, so we do no further data processing although its occasional pulses still occur.

Figure 4(a) shows processed ULF electromagnetic variations of Qiaojia station from 1st January 2020 to 22 May 2021 and Figure 5(b) shows ULF original daily variations of Yongshan station during this period. From Figure 5, ULF electromagnetic emissions totally are divided into two stages. Weak signals were first recorded at the beginning of March 2021 almost simultaneously both at Qiaojia station and at Yongshan station but with different peak magnitudes of ~0.1 nT in Qiaojia components (Figure 5(a)) and ~0.3 nT at Yongshan components (Figure 5(b)). And then these changes went through a decrease till an abrupt pulse occurred on 20 March with enhanced amplitudes of 3.8 nT at Qiaojia and 1.2 nT at Yongshan (see also Figure 5(a) and Figure 5(b)). Several peaks occurred occasionally by a relative big time gap from the beginning of March to the end of April. From now on, the magnetic fluctuation gained a high frequency variation with 0.5 - 1.5 nT in Qiaojia components and 0.5 - 1.3 nT in Yongshan components, but with a big difference from a normal annual variation shown in Figure 5. This situation went on about one month before the Yangbi M_S 6.4 EQ, which took place on 21 May 2021, 330 km and 460 km away from Qiaojia and Yongshan stations respectively.

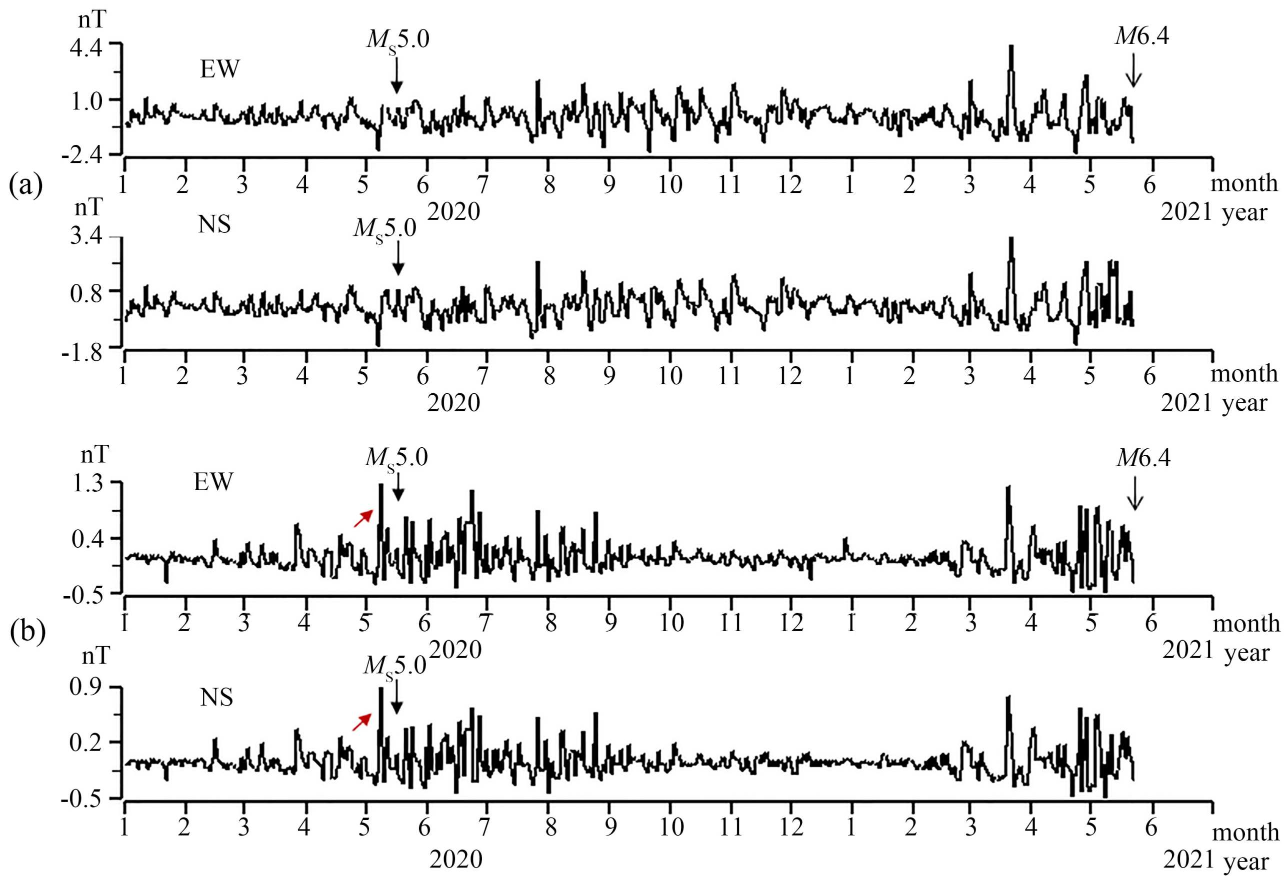


Figure 5. ULF electromagnetic fluctuations from 1st January 2020 to 22 May 2021 at (a) Qiaojia station, with subtracting their background values of 6183.86 nT and 5418.17 nT in NS and EW components, and (b) Yongshan station of their original daily recordings in NS and EW components. The pulses labeled by red arrows are disturbance signals. The Qiaojia M_S 5.0 EQ on 18 May, 2020, and this Yangbi M_S 6.4 EQ on 21 May 2021 have been labeled by black arrows with a number.

In total, these ULF electromagnetic emissions persisted more than two months before the Yangbi event and this variation is characterized by a good synchronization during the magnetic signals appearance in four components of two observational stations. As a contrast, this situation seemly did also occurred during the May 18 2020 Qiaojia M_S 5.0 EQ but showing a synchronous decreasing, 10 km and 150 km away from Qiaojia and Yongshan ULF observing stations (**Figure 5** and **Figure 1**). Weak signals appeared in the middle of April 2020 at both observing stations of Qiaojia and Yongshan. And there was an enhancement in ULF magnetic emissions at the beginning of May and reached its climax of ~1.5 nT for Qiaojia station and of ~0.2 nT at Yognshan site on May 7 (which is checked in the data sets rather than labeled by a red arrow in **Figure 5**). These obvious ULF magnetic emissions lasted more than one month and also were of synchronous fluctuations at all components (see **Figure 5**).

4. DISCUSSION

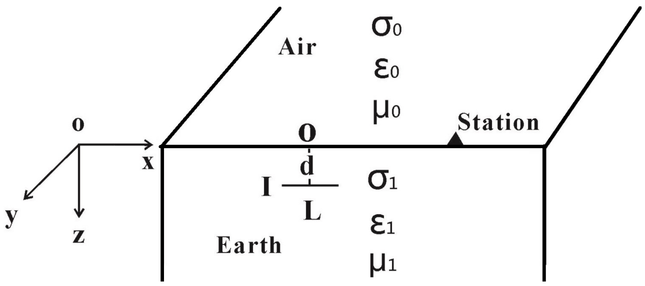
Up to now, two ULF electromagnetic stations named Qiaojia and Yongshan have run more than ten years since they were put into service in Zhaotong seismic observing network. This ULF recording is of regular daily variations in hourly recordings with relative low background noises. It indicates that the system can record some information from outer space but is free of influence from solar activities, like magnetic storms. The sensors at Yongshan station are laid on the ground of the observing cave and they are easily affected by outer interferes, such as motors, constructions and so on. Fortunately, this kind of pulses can be easily distinguished according to their figures or appearing time. However, the fact that the interference signals mixing together with useful information leads to a difficulty during discriminating precursors associated with seismic activities, such as the Qiaojia event illustrated above.

In general, there are three layout styles of sensors or probes for ground-based seismic electromagnetic observation: in the air, on the ground or in the borehole. It is clear that there are heavy influences on the installment from outer surroundings if a probe in a shallow depth. Thus, the long-term observing practice has promoted the development of a stereo monitoring system. The seismic monitor is of a trend to deeper and higher. On one hand, a monitoring system can be buried in a deeper location beneath the Earth. Li *et al.* [12] have reported a borehole TOA installment with a depth of 800 meters. This system could be sensitive to seismic activities but beyond of many outer effects. On the other hand, the probe can be pointed to a wide space. As the development of satellite-Earth observation, especially the lunch of DEMETER (Detection of Electro-Magnetic Emissions Transmitted from EQ Regions) satellite in France, the investigation of seismic influence on ionosphere has gained a new enhancement. The CSES (China Seismo-Electromagnetic Satellite) has lunched successfully, which will win much investigation on electromagnetic mechanism, ionosphric precursors and LAI (lithosphere-atmosphere-ionosphere) coupling.

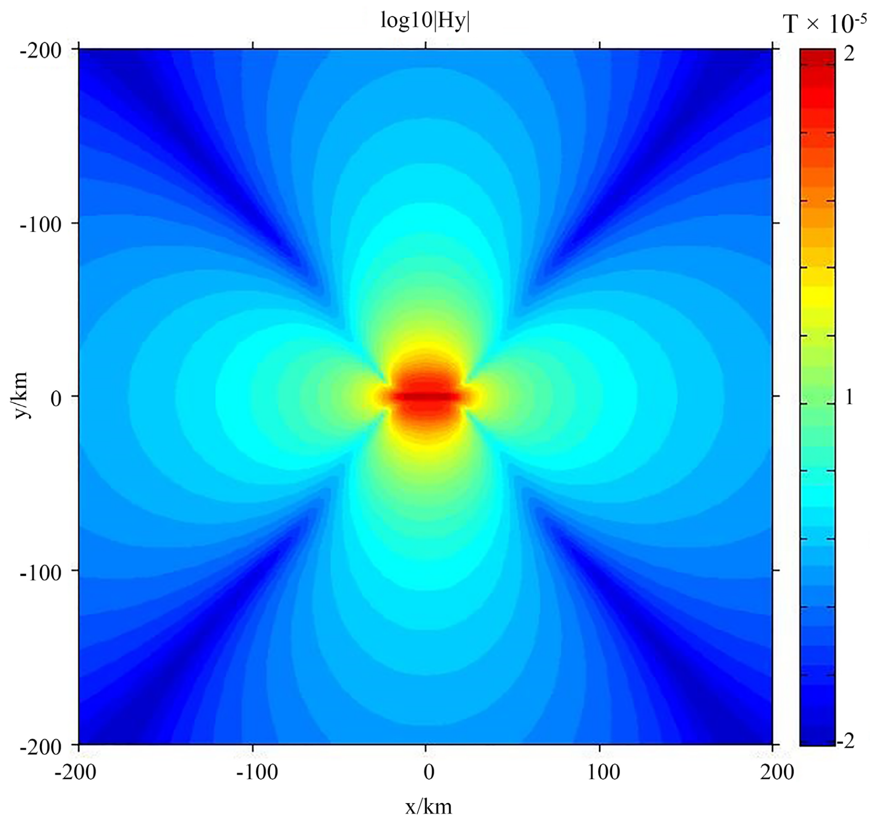
From the data variation process prior to the Yangbi M_S 6.4 EQ on May 21, 2021, the typical character is that magnetic information varies almost simultaneously in all four components at Qiaojia and Yongshan stations (also see **Figure 5**) and the most important is these two stations are about 150 km away. On one hand, these phenomena occurred probably because these two stations locate in the same direction to the Yangbi epicenter and they are sensitive to this information from this direction (**Figure 1**).

Whatever the physical mechanism of electromagnetic generation is, it is well established that, during rock experiments conducted under laboratory conditions, a strong electrical current is produced when rocks are stressed, especially at the stage of the main rupture. Qian *et al.* [14, 15] and Hao *et al.* [16] have reported that the large magnetic pulses of shorter-period which appeared at the last stage of the experiment may be induced by instantaneous electric current of the accumulated charges during the main cracking acceleration. Freund *et al.* [17-19] has presented that there is a production of current and electromagnetic signals in p-hole theory. Using a simple physical model, Bortnik *et al.* [32] estimated that for an observed 30 nT pulse at 1 Hz (d = 2 km), the expected seismo-telluric current magnitudes fall in the range ~10 - 100 kA, and the simulation results show that deep nulls in the signal power develop in the non-cardinal directions relative to the orientation of the source current, indicating that a magnetometer station located in those regions may not observe a signal even though it is well within the detectable range. Using an ionospheric influence finite length dipole current source, Li *et al.* [33] have attained that the seismo-telluric current can be up to 5.0×10^7 A for 1.3 mV·m^{-1} electrical field at f = 1 Hz at 1440 km Gaobeidian observing station and their results also convince that it is advantageous for this far station to record obvious anomaly mainly due to its locating on the prolong-line of the Longmenshan fault.

Taking these results into consideration, a two–layer model (Earth-air model) including an Earth medium ($z > 0$), as well as an air medium ($z < 0$), is established during the study, with z direction being downward. An x–directed dipole of a length L and a current I is placed in the bottom medium (Earth: $z > 0$), which is homogeneous and has the electrical properties: magnetic permeability μ_1, permittivity ε_1, and conductivity σ_1. The upper medium (air $z < 0$) is described by its electrical properties μ_0, ε_0 and σ_0 (**Figure 6(a)**).



(a)



(b)

Figure 6. **(a) An *x*-directed dipole current source, with its central coordinate (0, 0, d), is placed in the bottom medium (Earth) of a two layer modeling (Earth-air model), where *z* is defined positive in the downward direction. (b) 2-D distributions of magnetic field power |Hy| after a logarithm calculation for the Yangbi source using Earth-air model.**

In order to illustrate the ULF anomaly phenomena prior to the Yangbi EQ, the parameters associated with this event have been specified: L = 30 km, the rupture length of the Yangbi event and its strike is 310˚ north-west, along x direction in **Figure 6(a)** (the same location with the Yangbi fault, the red dot line in **Figure 1**); d = 8 km (the focal depth) [28, 29]. In order to get our results easily, we set the current I = 100 A. **Figure 6(b)** shows the 2–D distributions of magnetic field power |Hy| after a logarithm calculation for the Yangbi source using Earth-air model on the Earth's surface. It can be seen from **Figure 6(b)** that the strong field radiates outward surrounding two main axes, x-direction and its perpendicular direction. From **Figure 1** we have known that Qiaojia ang Yongshan station locate approximately in the perpendicular direction of the Yangbi fault, which gains the probability for these two stations to record obvious ULF magnetic emissions.

5. CONCLUSIONS

The Zhaotong ULF electromagnetic observing network has been established more than ten years. It is sensitive to small seismic activities in near areas and strong EQs in relative large areas and has played an important role in seismic observation and investigation.

In this paper, daily recordings at Qiaojia and Yongshan stations from January 2020 to May 2021 prior to the last Yangbi M_S 6.4 on 21 May 2021 have been examined. The results show that initial weak information appeared at the beginning of March 2021 with the magnitudes of 0.6 nT at Qiaojia station and 0.3 nT at Yongshan station and an enhanced peak occurred at 20 March and its maximum value reached to 3.8 nT at Qiaojia and 1.2 nT at Yongshan. Then, the emissions gained a relative high frequency fluctuation with moderate amplitudes of 0.5 - 1.5 nT and 0.6 - 1.3 nT respectively at both stations. The total process persisted more than two months and it is characterized by an almost synchronous variation at two stations. As the information was of a decrease, a strong EQ with a magnitude equal to 6.4 took place on May 21, 2021 in Yangbi area, more than 300 km away from these two observing stations. So these ULF electromagnetic emissions are possibly related with this event.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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