VLF Radio Signal Anomalies Associated with Strong Earthquakes

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Abstract

The VLF (Very Low Frequency) radio signal receiving network of Russian Alpha radio navigation system has been established in China since 2010. We applied a quartile-based method to study the variations of VLF signal propagation before the M⩾6.0 shallow earthquakes in the network. Results found that possible anomalies occurred around the two strong earthquakes, 2010 M7.1 Yushu and 2013 M7.0 Lushan earthquake, respectively. For earthquakes with magnitude 5.0⩽M⩽7.0, such anomalies are not detected. Preliminary statistical analysis with Dst and Kp indices show that there exists a good correlation between geomagnetic storms and VLF propagation anomaly.

1. Introduction

A number of papers have been published on the sub-ionospheric VLF/LF/VHF radio signal perturbations associated with earthquakes [1-6]. During the disastrous M7.3 Kobe earthquake in 1995 in Japan, a clear anomaly of TT (Terminator Time) of VLF signals occurred [7]. The statistical studies found that VLF radio signal propagation anomaly exceeding the 2 times standard deviation criterion is significantly correlated with earthquakes with shallow depth, however, there is no clear precursory of VLF signals before deep earthquakes [8]. Sub-ionospheric radio waves has been extensively used to investigate seismo-ionospheric perturbation. In 2010, we established three instruments in China to receive VLF radio signals from Russian Alpha radio navigation system. Here we present some preliminary results of the observations collected till now.

2. VLF radio signal network

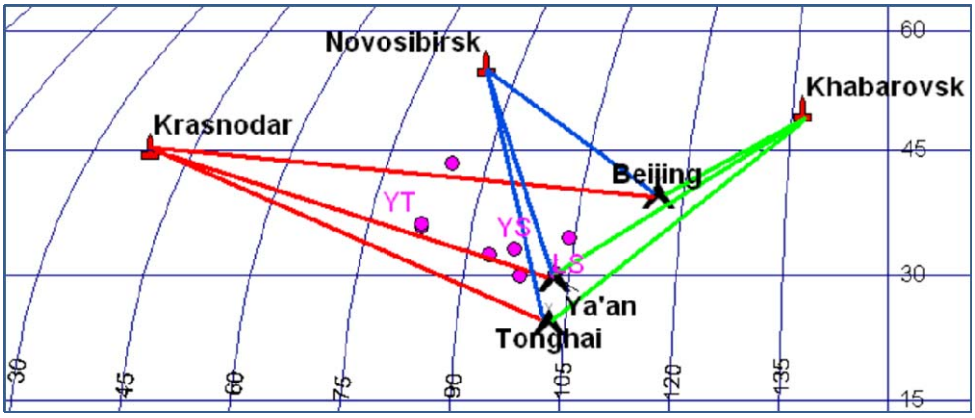

Figure 1. Map showing the location of the receivers and the Russian Alpha transmitters. The transmitters are Krasnodar, Nobosibirsk, and Khabarovsk; the receivers are located in Beijing, Ya'an, Tonghai city in China, respectively. The nine VLF radio paths are indicated by red, blue and green lines, respectively. The pink circles display the M⩾6.0 earthquakes. The horizontal and vertical axis represents geographic longitude and latitude.

978-1-4673-5225-3/14/$31.00 ©2014 IEEE

Figure 1 shows the location of the VLF transmitters and receivers, as well the earthquakes with M⩾6.0 (depth below 30 km) which occurred in the network since 2010 to Now. The pink circles indicate the epicenters. Table 1 shows the detailed information about the M⩾6.0 shallow earthquakes.

Russian Alpha (also called RSDN-20) is a system for long range radio navigation. The Alpha system consists of three transmitters, which stand in the proximity of Novosibirsk (55.8° N, 84.5° E), Krasnodar (45.4° N，38.2° E) and Khabarovsk (50.0° N, 136.6° E). These transmitters radiate signals of 0.4 second duration in a 3.6 second cycle on the three VLF frequencies: 11.9 kHz/12.6 kHz/14.9 kHz, respectively. Three VLF signal receivers were established in Beijing (39.9° N, 116.3° E), Ya'an city (30.0° N，103.0° E) in Sichuan province, and Tonghai city (24.1° N，102.75° E) in Yunnan province. This network has been in continuous operation from January 2010 to now.

Table 1. The detailed information of the earthquakes with M⩾6.0 and depth below 30 km occurred in the network since January 2010 to February 2014.

Time	*Latitude*	*Longitude*	*Magnitude*	*Depth*	*Location*
20100324	32.4°	93.1°	6.1	7 km	NieRong(NR), Tibetan
20100414	33.2°	96.6°	7.3	14 km	YuShu(YS), QingHai
20100414	33.2°	96.6°	6.4	17 km	Yushu(YS), Qinghai
20120630	43.4°	84.7°	6.6	7 km	Xinyuan(XY), Xingjiang
20120812	35.9°	82.6°	6.3	28 km	Yutian(YT),Xingjiang
20130420	30.3°	103°	7.0	17 km	Lushan(LS), Sichuan
20130722	34.5°	104.2°	6.7	15 km	Minxian(MX), Ganshu
20130812	30°	98°	6.1	15 km	Zuogong(ZG), Tibetan
20140212	36.2°	82.5°	7.3	10 km	Yutian(YT), Xingjiang

3. Method and Results

Take the Lushan earthquake as an example, we describe the method and results in this Section. The M7.0 Lushan earthquake occurred at 08:02 Beijing Time on April 20, 2013. The daily variation of amplitude significantly changes from hour to hour, so we applied a moving quartile-based method to obtain the trend variation and anomaly. Figure 2 gives variations for the amplitude of VLF 14.9 kHz at the radio path *Novosbirsk-Ya'an* from April 1th to May 6th .

At each time point of the Nth day, we compute the median value $\overline{m}$ of amplitude data within every successive (N-n)th to the Nth day, n is defined as step for moving average. For example, when Nth is April 4th and n=3 days, the data from 1th (4-3) to 4th is taken into computation. The lower quartiles (LQ) and the upper quartiles (UQ) of data at same time point from the (N-n)th to the Nth day are also calculated. The interquartile range (IQR) is defined as: IQR=UQ-LQ. To have a stringent criterion, we set the lower bound, LB = $\overline{m}$ -IQR, and upper bound UB= $\overline{m}$ +IQR. The median value $\overline{m}$ together with the associated LB and UB provide references for the variations of VLF propagation on the Nth day. Only the amplitude data are analyzed here, because the phase data are sometimes not good enough for further analysis.

The Alpha system usually maintains the navigation system about 2-3 days at the end of every month. For example, in April, 2014, from 24th to 26th during the maintenance, the Alpha system radiates very disturbed signals instead of regular information, so we directly discard data of those days (See Fig.2). For the $\overline{m}$, LQ, UQ and IQR of April 27th, we used the data of 23th and its previous days.

It can be seen in Figure 2 that there is a significant anomaly of amplitude of VLF 14.9 kHz on April 20th . The amplitude anomaly is characterized by a significant increase in trend and the observed data simultaneously exceeds the upper bound in April 20th to the early time of April 21th. The anomaly takes place about 2 hours (~06:15 Beijing Time) before the main shock (08:02 Beijing Time) which indicated by the arrow in Fig. 2. It sustained enhancement of amplitude intensity in the next 2 days. Unfortunately, the lack of data on 24th to 26th make it difficultly to track the trend in more days.

Figure 3 shows the variations of the Dst and Kp indices, which indicate the geomagnetic activity were relatively quiet around time of Lushan earthquake. It can be said that the observed perturbations were independent of geomagnetic field disturbances, and might be attributed to seismic activity.

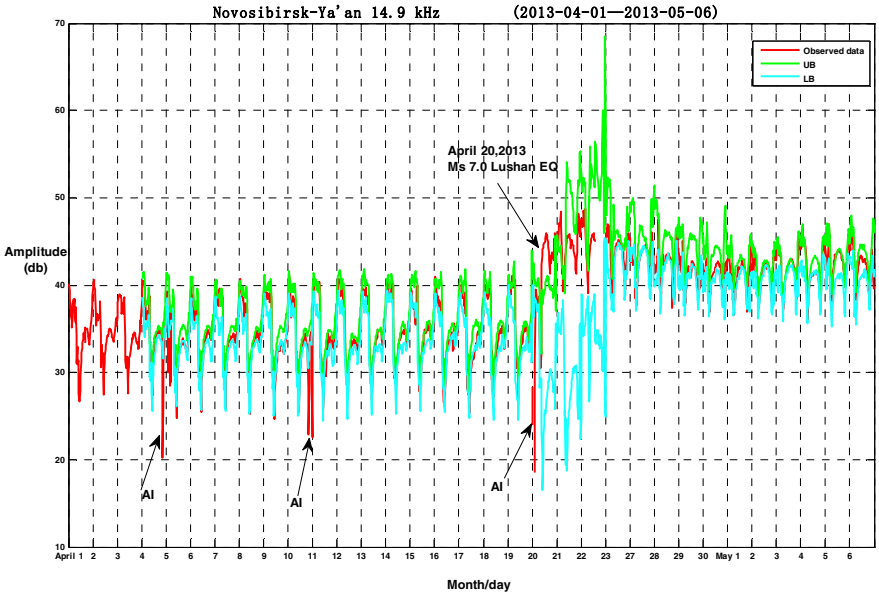

Figure 2. The variations of amplitude of 14.9 kHz VLF radio signal at the radio path *Novosbirsk-Ya'an*. Green and blue lines represent the upper bound (UB) and lower bound (LB) identified by the computer routine, respectively. The red line denotes the observed amplitude data. The sharp decreases are induced by the artificial interference (AI).

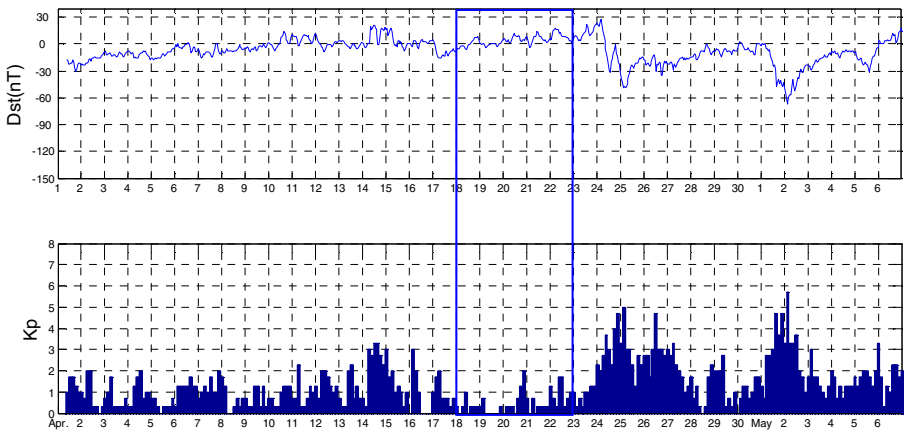

Figure 3. The variations of Dst and Kp indices from April 1th to May 6th 2013.

4. Dicussion and Conclusion

Using the same method, we examined the variations of all three frequency band (11.9/12.6/14.9 kHz) VLF signals at the nine radio paths for the shallow (depth below 30 km) earthquakes with M⩾6.0 which occurred in the network. Results found that there are possible subionospheric perturbations before 2010 M7.1 Yushu, 2013 Lushan M7.0 earthquake during the quiet geomagnetic condition. While for the earthquakes 6.0⩽ M⩽ 7.0, we did not found such perturbations of VLF signals. It seems indicates that the strong shallow earthquakes with magnitude over than 7 more likely generate the subionospheric perturbations.

The drawback of Alpha system is that it maintains its system 2-3 days every month, which affect the continuity of data set. In addition, the radio path from Russian to China is a long distance (about from 3200 km to 6000 km). Many of previous studies are based on data over relatively short distance [1-9]. The long distance radio path may be not sensitive to the earthquakes below M⩽7.0.

The VLF signal waves are trapped between the ground and the lower ionosphere. Any variations of the earth-ionosphere waveguide, especially the variations on the ionospheric D/E region, can lead to the changes in VLF

propagation conditions [3, 8, 9]. There are some specific sources which can affect the earth-ionosphere waveguide, such as solar activities, and corresponding geomagnetic activities [2, 7]. We also applied a preliminary statistical analysis on the correlation of VLF amplitude and Kp, and Dst indices based on the same quartile-based method with one year data (2010) on the radio path *Krasnodar to Ya'an*. Results found that 78% of geomagnetic storms (Dst⩽-30 nT & Kp⩾3+) influenced the VLF propagation.

There is a hypothesis that rocks under stress can emit waves with various frequencies, and that these waves can propagate from ground to atmosphere and ionosphere, and then modify the plasma parameters and the electromagnetic field. The changes of parameters of sub-ionosphere, thus lead the anomaly of VLF wave guide. For the 2010 M7.1 Yushu earthquake, we also found the anomaly at ELF/VLF frequency by the DEMETER satellite [10]. The mechanism of VLF transmitter signals anomaly associated with earthquake is complex, and has not yet been fully understand [1-10]. Previous studies[1-9] indicate that VLF signal monitoring could be valuable for the prediction of seismic activity. However, there are so many unknown factors, the careful analysis of more data and enhanced theoretical investigation are needed for further study.

5. Acknowledgments

This work was supported by the ISTCP 2014DFR21280, NSFC Grant 41204136, and the Fundamental Research Funds for earthquake research 02132429 and 02132406.

6. References

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