Possible seismo-ionospheric precursor of the 12 February 2014 Yutian earthquake in China

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On 12 February 2014, a major earthquake occurred near the Yutian County, China. In this paper, the ionospheric variations around the time of this earthquake were analysed on the basis of the global positioning system vertical total electron contents (VTEC) and computerised ionospheric tomography (CIT) electron density distributions. Three ionospheric anomalies on 2, 17 and 19 February were detected with the global VTEC data from Center for Orbit Determination in Europe before and after the earthquake. Based on the analysis of the geomagnetic indices, we think the anomalies on 17 and 19 February could be related to the geomagnetic disturbances. Through further investigations on the temporal and spatial characteristics of the anomaly on 2 February, we draw the conclusion that the pre-earthquake ionospheric anomaly is probably the seismo-ionospheric precursor of the Yutian earthquake. In addition, the CIT results of the anomaly on 2 February were used to study the vertical distribution of this anomaly. The results showed that the ionospheric anomaly was mainly concentrated at the heights between 200 and 400 km.

Keywords. Ionospheric anomaly; earthquake; total electron content; computerised ionospheric tomography .

1. Introduction

Research on seismo-ionospheric effects can be traced back to the 1960s when Davies and Baker (1965) observed certain ionospheric disturbances near Boulder, Colorado, around the time of the 28 March 1964 Alaska earthquake. Since then, this research direction has gained the attention of more and more scientists around the world. Many seismo-ionospheric anomalies, including the pre-seismic and co-seismic ionospheric effects, have been found by a large number of case studies (Liu

et al. 2000; Pulinets and Legen'ka 2003; Pulinets *et al.* 2003, 2007; Singh *et al.* 2009; Harrison *et al.* 2010; Jhuang *et al.* 2010; Xu *et al.* 2010; Choi *et al.* 2012; Carter *et al.* 2013; Heki and Enomoto 2013; Le *et al.* 2013; Li and Parrot 2013; Zhu *et al.* 2014). Moreover, some possible interpretations for seismo-ionospheric anomalies, such as surface electric field and acoustic gravity waves, have been proposed (Freund 2000; Takeuchi *et al.* 2004; Yoshida and Ogawa 2004). Despite the previous achievements, the explorations of seismo-ionospheric anomalies are still ongoing.

To detect the pre-seismic ionospheric anomaly, some reliable ionospheric information, such as total electron contents (TEC) and electron density, are necessary. In the past, scientists observed these quantities directly by some instruments such as ionosondes and incoherent scattering radars. But these instruments were not economical to sustain large-scale observations. With the development of global positioning system (GPS), a global GPS observation network consisting of about 300 continuous-operating stations has been established. The network is being maintained by International GNSS Service (IGS) at present. In addition, some local networks with different levels, which are currently in charge of different nations or scientific organisations, also provide large amounts of data. High-precision ionospheric parameters can be obtained from GPS measurements with different processing techniques. The ionospheric parameters derived from GPS measurements will be applied in this research.

In this paper, we discuss the ionospheric effects triggered by the 2014 Yutian M 7.3 earthquake. According to the report of China Earthquake Networks Center (CENC), this earthquake occurred at 09:19 UT (17:19 LST) on 12 February 2014 and was located on the Altyn-Tagh fault zone in the south of Hotan, China (epicentre: 36.1°N; 82.5°E). Some research studies on the Yutian earthquake have been done to reveal its precursor deformation, kinetic process and post-earthquake tendency (Qin *et al.* 2014; Zhang *et al.* 2014). Unlike the previous research work, we focus on the changes of the ionosphere near the epicentre around the time of the Yutian earthquake. In this paper, we use different ionospheric parameters in a suitably long enough period of time before and after the earthquake, including vertical TEC (VTEC) derived from GPS measurements and the electron density distributions reconstructed by computerised ionospheric tomography (CIT), to detect ionospheric anomalies. Then we analyse the temporal and spatial characteristics of the anomalies, as well as the possible perturbation sources. At the end, we draw some conclusions.

2. Data and methods

In this section, the related data and the methods will be outlined, including GPS VTEC, CIT and a statistical method for detecting ionospheric anomalies.

2.1 Global positioning system vertical total electron contents

VTEC is defined as the path integral of the electron densities in the vertical direction. It is used to record the ionospheric gross variations during a period of time over a fixed point. Based on the GPS dual-frequency ($f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz) pseudorange and carrier phase observations, the method to solve VTEC was established and described in some research studies (Mannucci *et al.* 1998; Li *et al.* 2012). The method was proved to be practical, just applying a spherical harmonics expansion up to order 15 and a modified single-layer model mapping function (Alizadeh *et al.* 2011). So the VTEC maps in a certain scale can be naturally produced with the method mentioned above. At present, the global VTEC products referred to as global ionospheric maps (GIMs) are offered to the public by the Center for Orbit Determination in Europe (CODE). We can directly use the products for this research.

2.2 Computerised ionospheric tomography

As stated by Austen *et al.* (1988), the mathematical expression of CIT can be written as a linear equation set after dividing a continuous ionospheric region into discrete voxels (shown in figure 1):

$$\begin{aligned} (\text{TEC}_i)_{i=1}^m &= \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \\ &= \mathbf{A}\mathbf{X}, \end{aligned} \quad (1)$$

where x_j ($j = 1, 2, \dots, n$) is the mean electron density in the voxel j . a_{ij} in the matrix A is the propagation distance of the ray i through the voxel j . We employ a numerical algorithm, namely multiplicative algebraic reconstruction technique (MART), which is suitable for CIT and able to accelerate the computation, to solve the equation set. As an iterative algorithm, MART requires a group of reasonable initial values to start running. The initial values can be obtained from some empirical models, for instance, international reference ionosphere or parameterised ionospheric model. The technical details of MART were described in the previous article (Raymund *et al.* 1990).

Figure 1. The schematic of CIT. We can see that, for the purpose of numerical computation, the ionosphere has been divided into several voxels. GPS stations are represented by solid diamonds.

2.3 Anomaly detection method

To find out ionospheric anomalies, we developed a statistical analysis method. The method has been applied successfully in many seismic cases (Zhou *et al.* 2009, Zhu *et al.* 2013). So we also used it in this research. The method is based on the hypothesis that the stochastic process of the normal ionospheric variations follows Gaussian distribution. Let $X^{n+1}(t)$ be the ionospheric parameter at the time t in the day $n + 1$. To determine whether $X^{n+1}(t)$ is the anomalous parameter or not, taking the ionospheric parameters at the same time in n days before (usually let n be 10), namely, $X^1(t)$, $X^2(t)$, $\dots$, and $X^n(t)$, computing their average $N(t)$ and standard deviation $\sigma(t)$, we build the following determination function:

way, the confidence factor α was set as 3, which makes the confidence of the above judgment reach about 99%.

3. Results and discussions

Investigating the 1–13 February GIMs using the anomaly detection method mentioned above, we found an obvious ionospheric anomaly occurring on 2 February, which is demonstrated in figure 2. The anomaly was local and mainly appeared near the epicentre in the area of 20–40°N and 60–110°E.

Investigating further the ionospheric variations in 31 days before and 10 days after the main shock of the Yutian earthquake, we found the anomalies

$$F(t) = \begin{cases} 0 & \text{if } |X^{n+1}(t) - N(t)| \leq \alpha\sigma(t), \\ X^{n+1}(t) - [N(t) + \alpha\sigma(t)] & \text{if } X^{n+1}(t) - N(t) > \alpha\sigma(t), \\ X^{n+1}(t) - [N(t) - \alpha\sigma(t)] & \text{if } X^{n+1}(t) - N(t) < -\alpha\sigma(t). \end{cases} \quad (2)$$

If $F(t) = 0$, i.e., $X^{n+1}(t) \in [N(t) - \alpha\sigma(t), N(t) + \alpha\sigma(t)]$, we determine that $X^{n+1}(t)$ is a normal quantity. Otherwise, it denotes an anomaly. By the

only occurring around the epicentre on 2, 17 and 19 February. In order to describe the anomalies in a convenient way, two ground fixed points (located

Figure 2. The global Δ VTEC maps at 04:00–10:00 UT on 2 February 2014. In the figure, an obvious abnormal enhancement of VTEC can be found in a local area near the epicentre that is marked by a black dot in each panel. In addition, the mapping of the anomaly appears in the magnetically conjugated area of the southern hemisphere.

on 36.0°N , 82.0°E and 31.0°N , 82.0°E , respectively) near the epicentre were chosen, and a VTEC *vs.* time graph over the two points is presented in figure 3. In figure 3, the upper group of panels corresponds to the result of the north point (36.0°N , 82.0°E), and the lower to the southern one (31.0°N , 82.0°E). The blue curve represents $N(t) - 3\sigma(t)$, and the red one represents $N(t) + 3\sigma(t)$ (refer to section 2.3). The black bold curve represents the actual VTEC observations. When the black curve goes beyond the red or blue one, we regard the ionospheric variation as abnormal behaviour. Thus the three notable anomalies nearly at 06:00–08:00 UT (14:00–16:00 LST) on 2, 17 and 19 February are marked by the arrows in figure 3.

To analyse the ionospheric perturbation sources, we firstly consider the solar–terrestrial environment, because it has a main effect on the ionosphere. The solar–terrestrial environment can be reflected indirectly by the geomagnetic indices such as K_p and D_{st} . By scanning over the geomagnetic indices in 42 days between 12 January and 22 February shown in figure 4, we found that no

storm occurred around the time of 2 February ($K_p < 4$ and $D_{st} > 30$), but the geomagnetic disturbances existed in the days of 15–20 February. The ionospheric anomalies on the days of the geomagnetic disturbances, such as 19 February, presented large-scale distributions (shown in figure 5). So we think that the ionospheric anomalies on 17 and 19 February could be excited by the geomagnetic disturbances.

In contrast to the above situation, the pre-earthquake ionospheric anomaly on 2 February appeared in the quiet geomagnetic background and was distributed in a local area. It could be irrelative to the solar–terrestrial environment. Looking back to figure 2, we easily find that the main body of the anomaly is not located right above the epicentre but offsets slightly southward, and the anomaly also generates in the magnetically conjugated area of the southern hemisphere. It is known that equatorial ionisation anomaly (EIA), as a particular phenomenon of the Earth’s ionosphere produced by neutral atmospheric fluctuations, has similar spatial characteristics. However, for the reason that

Figure 3. Time series plots of the point VTEC data derived from GIMs. The upper group of panels corresponds to the result of the northern ground point (36.0°N, 82.0°E), and the lower to the southern one (31.0°N, 82.0°E). The blue and red curves are plotted according to $N(t) - \alpha\sigma(t)$ and $N(t) + \alpha\sigma(t)$, respectively. The black heavy line represents the measured VTEC values. The time of the main shock is marked by a purple dot in each of group of panels. Three ionospheric anomalies are pointed out by arrows.

EIA walks along the equator on a 1-day return cycle, its main impact on the ionospheric anomaly can be naturally canceled in formula (2). So we hold the opinion that the ionospheric anomaly on 2 February has no correlation with EIA. As for the other perturbation sources, such as lightning (Taratenko *et al.* 1993), volcano (Heki 2006) and typhoon (Xiao *et al.* 2007), we found that they did not happen around the day of 2 February according to the meteorological and geographical records of the Yutian area. These effects can also be ruled out.

In fact, the former analysis indicates that there is a good spatial-temporal correlation between the anomaly on 2 February and the Yutian earthquake. Moreover, according to Dobrovolsky's empirical formula (Dobrovolsky *et al.* 1979) $R = 10^{0.43M}$, where R and M represent, respectively, the size of the earthquake preparation zone and the earthquake magnitude. It is easily known that the Yutian M 7.3 earthquake corresponds to a preparation zone stretching over 2500 km, which is comparable to the distribution area of the pre-earthquake

Figure 4. The diagram of the solar–terrestrial space conditions in the days between 12 January and 22 February. The upper and lower portions of each panel correspond to the geomagnetic K_p and D_{st} indices, respectively.

ionospheric anomaly. In addition, there were some opinions (Pulinets 1998; Ruzhin *et al.* 1998; Pulinets *et al.* 2003) that some pre-earthquake ionospheric anomalies could be projected to the magnetically conjugated area of the opposite hemisphere. This phenomenon also appeared in figure 2. In conclusion, we infer that the ionospheric anomaly on 2 February is probably related to the Yutian earthquake.

As for the spatial characteristics of the pre-earthquake ionospheric anomaly on 2 February, we still have no idea how it distributes in the vertical direction. Thus, an additional investigation on the vertical structure of the anomaly was made by CIT. According to the area and typical duration of the anomaly (figure 2), we set the reconstruction area as 30–42°N and 80–105°E, and only reconstructed the electron density distributions at

07:00 UT in the period between 28 January and 11 February. The observational data were collected by the GPS receivers of Crustal Movement Observation Network of China (CMONOC) in the reconstruction area. As is known, CIT involves ill-posed inversion because of the limitation of the observational elevation angles and the low coverage of the GPS signal rays leading to the rank defect of formula (1) (Choi *et al.* 2006; Wen *et al.* 2007). To decrease its ill-condition, some improvement strategies (e.g., providing enough and evenly distributed GPS tracking stations) should be incorporated before reconstruction by MART (Yeh and Raymund 1991; Wen and Liu 2010). In this study, we pick out 38 evenly distributed tracking stations of CMONOC in the reconstruction area to improve the reconstruction accuracy. The locations of these stations and the epicentre of the Yutian earthquake

Figure 5. The global $\Delta VTEC$ maps at 08:00–10:00 UT on 19 February 2014. Compared with figure 2, it presents a great ionospheric anomaly that distributes on a global scale. Due to the stormy activities in the days of 15–20 February, the anomaly is confirmed as the geomagnetic storm effect.

Figure 6. The schematic of the Yutian earthquake and the GPS stations in the reconstruction area. The epicentre is represented by a red dot and the stations, which were picked out from CMONOC on the principle of even distribution, are denoted by black dots.

are shown in figure 6. We can see that the tracking stations in the reconstruction area distribute ideally except in the southwest region where we do not have enough GPS stations.

Checking all of the reconstruction results, we also find an obvious anomaly on 2 February (shown in figure 7, where we only provide comparisons among the reconstruction results of 2 February, the previous day and the next day). Figure 7 contains different slice diagrams to show the three

dimensional distributions of the anomaly on 2 February. Due to inadequate observations in the southwest corner of the reconstruction area, the abnormal increase of the ionospheric electron density in that region is unapparent in comparison to the surroundings, looking like a hole. Despite the hole, the most notable characteristic in figure 7 is that the anomaly mainly appears at the heights between 200 and 400 km, that is, in the ionospheric F2 region.

Figure 7. The diagram of the electron density distributions reconstructed by CIT in the area of 30–42°N and 80–105°E at 07:00 UT on 1–3 February (DOY: 32–34). The reconstruction results are presented in the form of three-dimensional slices along orthogonal directions. The ionospheric anomaly on 2 February is apparent in the figure and it mainly appears at the heights between 200 and 400 km in the ionospheric F2 region.

4. Conclusions

This paper mainly focuses on the seismo-ionospheric effects of the Yutian M 7.3 earthquake which occurred on 12 February 2014. We firstly investigated the changes of the global ionospheric VTEC (Δ VTEC) during the period between 12 January and 22 February. The ionospheric anomalies on 2, 17 and 19 February were detected. Analysing the geomagnetic indices, we think that the post-earthquake ionospheric anomalies on 17 and 19 February could be related to the solar–terrestrial environment, whereas the pre-earthquake ionospheric anomaly could not be related.

A further investigation on the pre-earthquake ionospheric anomaly shows the following temporal and spatial characteristics:

- (1) The anomaly appeared near the epicentre on the 10th day before the earthquake. It stretches over a wide area that is comparable to the size of the earthquake preparation zone.
- (2) The main body of the anomaly is not located right above the epicentre of the Yutian earthquake, but offsets somewhat to the south. In addition, the anomaly can also be observed in the magnetically conjugated area of the southern hemisphere.

The above analysis indicates that the ionospheric anomaly on 2 February has a good spatial–temporal correlation to the subsequent Yutian earthquake. We think that the anomaly is not the effect of EIA. We also investigated some other ionospheric perturbation sources, such as lightning, volcano and typhoon that could make apparent disturbances to the earth's ionosphere, but ruled out their effects according to the historical records on meteorology and geography of the Yutian area. Based on the above analysis, we conclude that the ionospheric anomaly on 2 February is probably the seismo-ionospheric precursor of the Yutian M 7.3 earthquake.

Finally, an additional investigation on the vertical distribution of the ionospheric anomaly on 2 February was also made by CIT. We reconstructed the electron density distributions at 07:00 UT in the period between 28 January and 11 February, with the reconstruction area of 30–42°N and 80–105°E. We can find the prominent anomaly on 2 February and it almost concentrates at the heights between 200 and 400 km, which indicate that the anomaly is most obvious in the ionospheric F2 region.

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