Method Article

Earthquake precursory detection using diurnal GPS-TEC and kriging interpolation maps: 12 May 2008, Mw7.9 Wenchuan case study

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ABSTRACT

This study presents an alternative vertical total electron content (VTEC) anomaly detection technique based on diurnal VTEC values. In order to assess the consistency of the results, Mw7.9 Wenchuan earthquake occurred on May 12, 2008 was chosen as case study because several researches were performed on this earthquake event. In this detection technique, the daily mean of VTEC (AVTEC) and standard deviation of diurnal VTEC (SVTEC) were adopted in the analytical process instead of quartile-based technique. The spatial distribution of VTEC was illustrated by AVTEC and SVTEC maps which created from ordinary Kriging interpolation technique. The anomalous day derived from AVTEC and SVTEC was observed on May 9, 2008. The anomalous zone significantly appeared within the earthquake preparation zone in the southeast of the epicenter. The results were corresponding to the previous studies in terms of time and space. Thus, AVTEC, SVTEC and instantaneous ionospheric maps created from ordinary Kriging interpolation technique should be an alternative approach for detecting ionospheric anomaly prior to earthquake occurrence.

- Simplified seismo-ionospheric anomaly detection technique
- Ionospheric distribution is modelled by ordinary Kriging interpolation maps
- The results are consistent with the previous studies in terms of time and space

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| Method name: | ASK-VTEC |
| Name and reference of original method: | J. Li, G. Meng, X. You, R. Zhang, H. Shi, Y. Han, Ionospheric total electron content disturbance associated with May 12, 2008, Wenchuan earthquake, Geod. Geodyn. 6 (2015) 126–134. https://doi.org/10.1016/j.geog.2015.01.003 |
| Name and reference of original method: | Y.J. Zhou Yi-Yan, Wu Yun, Qiao Xue-Jun, Fu Ying, Anomalous variations of ionospheric VTEC before M8.0 Wenchuan Earthquake, Chinese J. Geophys. 53 (2010) 556–566. https://doi.org/10.3969/j.issn.0001–5733.2010.03.009 |
| Name and reference of original method: | S.A. Pulinets, V.G. Bondur, M.N. Tsidilina, M. V. Gaponova, Verification of the concept of seismoionospheric coupling under quiet heliogeomagnetic conditions, using the Wenchuan (China) earthquake of May 12, 2008, as an example, Geomagn. Aeron. 50 (2010) 231–242. |
| Resource availability: | https://cddis.nasa.gov/ but it has moved to https://urs.earthdata.nasa.gov/ |
| Resource availability: | http://wdc.kugi.kyoto-u.ac.jp/ |
| Resource availability: | https://omniweb.gsfc.nasa.gov/ |

Method details

Introduction

Seismo-ionospheric coupling is one of the candidates for the earthquake precursory signal investigation. More and more studies on this topic have been intensively carried out by using ground-based stations as well as satellite data to confirming such mechanism. The most widely used technique for detecting seismo-ionospheric anomaly prior to earthquake is statistical-based analytical technique as sliding median together with inter quartile range (IQR) for constructing upper and lower boundaries for detecting ionospheric anomaly [1–5]. The other technique as artificial neural network (ANN) and Particle Swarm Optimization (PSO) [6], radon anomaly [7], very low frequency (VLF) radio wave [8] are also utilized. The most commonly used detection technique is the statistical-based which the threshold was set up to median±2IQR, however, in case of the observed VTEC lies very close to the threshold, it is questionable whether or not the value can be considered as the anomaly.

The main objective of this study is to presents an alternative vertical total electron content (VTEC) anomaly detection technique based on the daily mean of VTEC (AVTEC) and standard deviation of diurnal VTEC (SVTEC) instead of median and IQR values as the quartile-based technique.

The spatial distribution of total electron content (TEC) in global scale is generally illustrated by Global ionospheric maps (GIMs) which is modeled by mathematical function-based as spherical harmonic (SH) expansion, the spatial resolution of GIMs is 2.5° × 5° in latitude and longitude, respectively with the temporal resolution of 2 h [9]. Since 1° at the equator corresponds to approximately 110 km and 95 km in latitude and longitude, respectively [10], thus the spatial resolution of GIMs at the equator is about 275 km in latitude and 475 km in longitude. By this reason, local ionospheric distribution cannot be reproduced by GIMs [11], especially within earthquake preparation zone. The distribution of vertical electron content (VTEC) can be also estimated from VTEC values at a set of reference GNSS stations by “grid-based” technique as spatial interpolation. Many studies indicate that the VTEC instantaneous maps generated by grid-based technique are roughly equivalent or even better than the mathematical function-based technique [12,13] and also contain high accuracy close to final products provided by CODE analysis center [14]. Thus, in this study, the spatial distribution of VTEC maps were created by applying “Ordinary Kriging” interpolation technique for illustrating the variations of AVTEC and SVTEC over the study area. Min Li et al. [12], collected the data from the Crustal Movement Observation Network of China (CMONOC) and the International GNSS Service (IGS) from DOY60 to DOY90 of 2015 for investigating the performance of Ordinary Kriging (OrK), Universal Kriging (UrK), inverse distance weighting (IDW) and planar fit interpolation technique in modeling regional VTEC maps in China, the results showed that performance of both UrK and OrK are similar and both of the interpolation techniques achieve better results than IGS GIMs.
when applying for the ionospheric correction in GPS positioning. Moreover, the OrK is appropriate to be used for creating a surface map in local scale [15].

In order to validate the performance of seismo-ionospheric anomaly detected from AVTECSVTEC values, and ordinary Kriging interpolation maps, M7.9 Wenchuan earthquake was selected as a case study because the studies of seismo-ionospheric anomaly detection on this earthquake event have been widely reported [4,10,16,17,18]. The inland earthquake struck eastern Sichuan province of China on May 12, 2008 at 06:28 UTC and followed by many aftershocks. The earthquake is also known as “Sichuan earthquake”. The epicenter was located at 31.002°N and 103.322°E in latitude and longitude, respectively. The hypocenter depth of the earthquake was 19 km which considered as shallow earthquake. The previous studies show that the anomalies of this earthquake event were observed on May 3, 2008 and May 9, 2008, which is 9 days and 3 days prior to the earthquake occurrence [4]. Thus, the consistency of the anomalous days detected by the alternative technique proposed in this study can be validated whether the results are corresponding to the previous studies.

**Methodology**

The methodology of seismo-ionospheric anomaly prior to the earthquake occurrence using the proposed technique is as follows:

**Earthquake preparation zone determination**

The earthquake preparation zone (EPZ) was determined based on the equation proposed by Dobrovosky et al. [19] as express in Eq. (1):

\[ R = 10^{0.43M} \]  

(1)

where \( R \) is the radius of earthquake preparation area [km] measured from the epicenter and \( M \) is the moment magnitude of earthquake.

The earthquake information e.g. earthquake magnitude, location of the epicenter, date and time of the occurrence can be found online from Shakemap provided by United States Geological Survey (USGS) at https://earthquake.usgs.gov/

Since the moment magnitude of the earthquake is Mw7.9, according to Eq. (1) the radius of EPZ is equivalent to 2495 km. The boundary of EPZ was created by applying buffer operation as illustrates in Fig. 1.

In order to investigate the distribution of VTEC over the study area, the data were collected from the reference stations that both located inside, and outside EPZ with the distance of 2 × EPZ approximately to investigate whether or not the ionospheric anomalous zone emerges within the EPZ. Fig. 1 shows the International GNSS service (IGS) reference stations that located surrounding the earthquake epicenter.

**Data collection**

In this study, the data from 31 IGS reference stations were collected as shown in Table 1.

In Table 1, the first 12 stations are located within EPZ, while the rest are located away from the EPZ boundary. The receiver independent exchange observation (RINEX.o) files of 10 days and 5 days before and after the event were collected from every IGS reference stations states in Table 1, because

| Earthquake Event | IGS reference stations |
|------------------|------------------------|
| M7.9 Wenchuan EQ on 12 May 2008 | BJFS CHAN GUAO IRKM KUNM LHAZ SHAO SUJWN TNML URUM WUHN XIAN AIRA ARTU BAKO CHUM COCO DGAR GMSD HYDE KARR KIT3 NOVM NTUS NVSK PIMO POL2 TASH TOW2 XMIS YSSK |
the seismo-ionospheric anomalies usually emerge 0 up to 10 days prior to earthquake occurrences, moreover, the previous studies on M7.9 Wenchuan earthquake showed that the anomaly was observed on March 9, 2008, which is 3 days prior to the event [4]. The data can be achieved at ftp://cddis.gsfc.nasa.gov/gnss/data/daily. The daily data were recorded from 00:00:00 to 23:59:30 UTC with the sampling rate of 30 s.

**Data processing**

The downloaded data were processed by using an open source software so called “GPS-TEC” version 3.0 developed by Gopi Seemala, hence, only the GPS-TEC values were analyzed. The outputs obtained from the software contain both slant total electron content (STEC) and vertical total electron content (VTEC), only the latter values were taken into account in the analysis.

The daily mean of VTEC (AVTEC) as well as standard deviation of VTEC (SVTEC) at each IGS reference station were determined as following equations:

\[
AVTEC = \frac{\sum_{00:00:00}^{23:59:30} VTEC}{N} \quad (2)
\]

\[
SVTEC = \sqrt{\frac{\sum_{i=1}^{N} (VTEC_i - AVTEC)^2}{N - 1}} \quad (3)
\]

where AVTEC is the average of VTEC on day-to-day basis, SVTEC is the standard deviation of AVTEC, N is the total number of measured VTEC from 00:00:00 to 23:59:30. Since AVTEC and SVTEC were calculated based on daily basis, so that they will not be polluted by the VTEC values of the previous days.

In order to investigate the ionospheric anomaly, the time series of AVTEC and SVTEC were then plotted, the abrupt changes of AVTEC and SVTEC compared to the previous days are considered as the ionospheric anomaly.

**Illustration of VTEC spatial distribution**

The anomalous days can be observed from AVTEC and SVTEC plots in the previous step, then the ionospheric anomalous zones can be identified from the spatial distribution of AVTEC and
SVTEC. In this method, ordinary Kriging interpolation technique was adopted to generate AVTEC and SVTEC distribution maps in local scale. The technique is not only based on the values within the search radius as deterministic interpolation technique but the statistical relationship as spatial autocorrelation is also taken into account in the surface generation. So that in this study, the variation of VTEC over the study area that commonly presented by GIMs were replaced by AVTEC and SVTEC maps.

In order to investigate the day-to-day variations of VTEC prior to the occurrence of Wenchuan earthquake, the interpolated maps were created 10 days and 5 days before and after the event, although the running window of 27 days is required to be set to restrain periodic change due to the short-period oscillation of the ionosphere, but the previous studies of the earthquake case show that the anomaly was observed 3 days prior to the event, since the main objective of this study is to presents an alternative VTEC anomaly detection approach based on diurnal VTEC, the period of 10 days and 5 days before and after the event were sufficient for the validation of the results.

Although the temporal resolution of GIMs is 2 h, but the temporal resolution of AVTEC and SVTEC maps were analyzed on daily basis. The duration of TEC anomaly on anomalous day is about 4–6 h [5,18], based on statistical principle, the distribution characteristic of VTEC values on anomalous day would be affected by the influence of seismo-ionspheric mechanism, so that the diurnal VTEC (AVTEC) as well as its standard deviation (SVTEC) on anomalous day will be significantly different from the ordinary days.

Finally, on the anomalous day, the AVTEC/SVTEC variation maps with the temporal resolution of 2 h as GIMs will be created base on ordinary Kriging interpolation technique for investigating and analyzing whether the results correspond to the previous studies in terms of time and space.

**Influence of geomagnetic storms and solar activity investigation**

Ionospheric TEC disturbance is mostly associated with space weathers, so the influence of the space weathers on detected anomalous day must be monitored in order to investigate whether the detected anomaly is attributed to space weathers or earthquake preparation process. The magnitude of geomagnetic activity is measured by two indicators as disturbance storm time index (Dst) and geomagnetic index (Kp). Solar activity magnitude is presented by solar radio flux at 10.7 cm index (F10.7). These three indices can be achieved from the links given in Table 2.

| Index | Sources |
|-------|---------|
| Dst   | [http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html](http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html) |
| Kp    | [http://wdc.kugi.kyoto-u.ac.jp/kp/index.html#LIST](http://wdc.kugi.kyoto-u.ac.jp/kp/index.html#LIST) |
| F10.7 | [http://lasp.colorado.edu/lisird/data/noaa_flux/index.html](http://lasp.colorado.edu/lisird/data/noaa_flux/index.html) |

These three indices were used for distinguish whether the anomaly caused by seismo-ionspheric event or space activities and geomagnetic storm. If the solar-geomagnetic index exceeds the following limits, $|\text{Dst}| > 30$ nT, $\text{Kp}$ index $> 3$ and $\text{F}10.7 > 150$ sfu, it is difficult to judge whether the anomaly is induced by the influence of earthquake preparation process or space weathers [20,21].

**Results**

The AVTEC and SVTEC on daily basis were plotted with respect to the day of year (DOY), the results are shown in the following sections:

**Average diurnal vertical total electron content (AVTEC)**

AVTEC of 10 days before and 5 days after the earthquake events were plotted for investigating the variation of diurnal VTEC. The variation of AVTEC of 31 IGS stations illustrates in Fig. 2.
Fig. 2. TEC anomaly detection derived from diurnal AVTEC. Red star represents the day of earthquake event.

Fig. 2 shows the time series plot of AVTEC of each IGS reference station, the result shows that the variation of AVTEC at KUNM, the closest station to the epicenter, contained the lowest value of 9.01 TECU on DOY127 and started increasing on the next day and reached the maximum value of 15.34 TECU on DOY 131 (10 May 2008), 2 days prior to the earthquake occurrence, then the value decreased to 12.77 TECU on DOY 133, the earthquake event day. The reduction of AVTEC on DOY127 is corresponding to the previous studies that the anomalous reduction of VTEC was observed 6 days prior to the earthquake occurrence and the reduction zone was not appeared in great distance from earthquake epicenter [4,10,22,23]. Moreover, The variation of VTEC at KUNM station from April 26, 2008 (DOY117) to May 26, 2008 (DOY147) was analyzed by applying a statistical technique as running median and quartile range. The results also showed that the reductions of VTEC were observed several days prior to the earthquake occurrence [24]. According to such characteristic, it can be inferred that the VTEC on daily basis can be represented by AVTEC and the pre-earthquake signature can be investigated from the variation of AVTEC. The data at KUNM station on DOY 125 and DOY 126 were missing because of the unavailability of the data, so the AVTEC on such days were not possible to be plotted and investigated. The figure also shows that high AVTEC variations were significantly observed at KUNM station 2 days prior to the earthquake occurrence, while AVTEC at the other stations both within and outside the EPZ were lower than that of KUNM.

In the conventional technique, the running median and quartile range were adopted for constructing the upper and lower boundaries for detecting the anomalies, the variation of VTEC at each IGS observed station was individually plotted station by station, so that the variations of VTEC at each station cannot be compared and the anomalous change will not be easily identified, According to Fig. 2, the abnormal AVTEC variation was significantly observed at KUNM station, especially, the drastically reduction of AVTEC on DOY127. This result proves that the variation of VTEC on daily basis can be investigated from AVTEC while the upper and lower quartiles were not necessary to be constructed for detecting the VTEC anomalies as in conventional technique. Moreover, the anomaly derived from AVTEC yielded the same results as the previous studies and the analytical process is less complex compared to the quartile-based technique.

In order to investigate the spatial distribution of AVTEC over the study area, the time series of AVTEC maps from DOY 123 to DOY 138 (2–17 May 2008) were created by applying ordinary Kriging interpolation technique. The time series maps of AVTEC illustrate in Fig. 3.

Fig. 3 shows that high concentration areas of AVTEC were observed on DOY123, DOY129 to DOY138. However, the anomalous AVTEC in EPZ was first observed on DOY129 (May 7, 2008) in the Southeast of the epicenter at KUNM, and reached its peak on DOY 131 (May 10, 2008), it obviously seen that the high AVTEC concentration area on such day emerged within EPZ. The AVTEC concentration was proportional decreased with respect to the distance from the anomalous area. High AVTEC concentration zone remained within the EPZ from DOY129 until DOY138, and the anomalous zone
Fig. 3. Time-series maps of AVTEC from May 2, 2008 to May 17, 2008 (DOY123 to DOY138). Red solid star represents the earthquake epicenter and red circle represents EPZ.

was in the southwest of the epicenter as on DOY130. The AVTEC variation characteristic at KUNM after the earthquake was caused by several aftershocks with the magnitude of M5.0 to M5.8 that occurred around the epicenter of the mainshock until the end of May 2008, the result coincide with the previous study that the VTEC at KUNM remained high for several days after the mainshock [24].

Although the results derived from AVTEC spatial distribution maps illustrate that the AVTEC anomalies were emerged within the EPZ and the anomalous zone was located at the same area as in the previous studies, but it is questionable whether the AVTEC anomaly emerged on DOY123 was associated with the Wenchuan earthquake because such anomaly also appeared at the great distance from the epicenter, moreover, the anomaly on DOY123 was not reported in the previous studies, thus, the AVTEC anomaly on DOY123 was likely to be influenced by other natural phenomena as solar activity or geomagnetic storms. The AVTEC anomalies were also observed on DOY125 to DOY127 but the anomalous zones were emerged outside the EPZ, so that such anomalies were likely to be caused by other phenomena rather than Wenchuan earthquake preparation process. The influence of geomagnetic activity and solar activity will be investigated in the other section.

Standard deviation of diurnal vertical total electron content (SVTEC)

In general, on the anomalous day, the VTEC anomaly last for 4–6 h, so that the electron content in the ionosphere is disturbed by the exceeding particle charges generated by earthquake preparation process and it causes the variation in data distribution. The assumption of the VTEC anomaly detection derives from the daily standard deviation of VTEC (SVTEC) is that an abnormal peak of SVTEC will be
observed on the anomalous day because the standard deviation of VTEC on the anomalous day should be significantly different from the ordinary days. The time series distribution plot of SVTEC 10 days before and 5 days after the earthquake illustrates in Fig. 4.

Fig. 4 shows that the peak of SVTEC was significantly observed at some IGS reference stations on DOY 130 (May 9, 2008), 3 days prior to the event, while the SVTEC at some stations were slightly constant, especially the stations that located at great distance from the EPZ boundary.

The figure clearly shows the abnormalities of SVTEC on DOY130 were observed at KUNM, TNML, WUHN, XIAN and BJFS station which mostly located in the southern part in the EPZ, while the variation of SVTEC in the other stations were not significantly observed. The SVTEC at KUNM shows the same characteristic as AVTEC, which extreme reduction of SVTEC was observed on DOY127, 6 days prior to the earthquake occurrence, then it gradually increased from 7.010 TECU on DOY127 to the maximum value of 12.34 TECU on DOY130, which was 3 days prior to the earthquake., after that the SVTEC at KUNM decreased from 12.34 TECU to 8.76 TECU on DOY133, the event date. The variation of SVTEC during DOY127 to DOY133 contained the same characteristic as the previous studies that the running median technique was adopted. The SVTEC variation plot also shows that the abnormal SVTEC variation was significantly observed at KUNM, the closest station to the epicenter. Thus, SVTEC could be considered as a candidate to be used to identify ionospheric anomaly.

The spatial distributions of SVTEC over the study area were illustrated as SVTEC spatial distribution maps. The maps were created by applying statistical interpolation technique so called “Ordinary Kriging”. The time series of SVTEC spatial distribution from DOY 123 to DOY 138 (May 2, 2008 to May 17, 2008) illustrates in Fig. 5.

The spatial distribution of SVTEC in Fig. 5 shows that the high concentration zone of SVTEC appeared at the southeastern part of the epicenter outside EPZ on DOY123, M6.8 that occurred on DOY 130 (March 9, 2008) at 12.516 N, 143.181E in Guam region was suspected as the source of the SVTEC anomaly in that area because its epicenter was located close to the high concentration zone, however, further study on the mentioned earthquake should be conducted. Moreover, the high concentration of SVTEC could be caused by geomagnetic activity or solar activity because the anomalous zone appeared within EIA region. The influence of such natural phenomena will be investigated in the next section.

The SVTEC anomaly within the EPZ was observed on DOY124 (March 3, 2008), 9 days before the earthquake. The previous study reported that the anomalous day prior to Wenchuan earthquake was first detected on DOY124 [18], however, the SVTEC anomaly on such day was also observed outside the EPZ in the south direction. Such southern anomalous zone appeared around BAKO station which located at 6.49’S and 106.85’E in geographic coordinate system which equivalent to 16.64’S and 178.76’E in magnetic coordinate system, so that the anomaly in the south was likely to be caused by geomagnetic activity. The anomalous SVTEC regions also appeared on DOY125 to DOY127 but the anomalous zone appeared outside the EPZ in the south direction, so that such anomalies
were not related to the Wenchuan earthquake. The SVTEC anomaly that appeared within the EPZ was significantly observed on DOY130 (March 9, 2008), 3 days prior to earthquake occurrence. The results correspond well with the previous studies [4,18], which quartile-based detection technique was utilized. The anomalous SVTEC still remained within the EPZ until DOY132 and gradually decreased until it disappeared on DOY138.

The SVTEC spatial distribution on DOY130 shows that the high concentration of SVTEC emerged in the southeast of epicenter within EPZ, and the concentration decreased with respect to the distance from KUNM station. According to the characteristic of the SVTEC spatial distribution on DOY130, it can be summarized that VTEC anomaly was detected on DOY130, 3 days prior to the earthquake occurrence. However, high SVTEC also observed at XMIS station on DOY130, but the station located 4593.79 km in the south direction of the epicenter, and it also located outside EPZ, so that high SVTEC at XMIS was not associated to Wenchuan earthquake preparation process.

Fig. 5 reveals that the high concentration of SVTEC was observed in EPZ on DOY 130, 3 days prior to the event, the location of the anomalous zone was in the southeastern part of the epicenter as in AVTEC map, after the anomalous day, the anomaly still remained in EPZ at KUNM station but the concentration of the SVTEC on those days were less compared to DOY130. As mention in previous section, numbers of the aftershocks occurred in the same area as the mainshock, so that the SVTEC anomalies were also observed within the EPZ after the mainshock.

In order to validate the performance of the interpolated SVTEC maps created from ordinary Kriging technique, the spatial distributions of SVTEC on the anomalous day were investigated, since the

Fig. 5. Time-series maps of SVTEC from May 2, 2008 to May 17, 2008 (DOY123 to DOY138). Red solid star represents the earthquake epicenter and red circle represents EPZ.
Fig. 6. Spatial distribution of regional VTEC at 02:00 UT to 24:00 UT on DOY 130 (March 9, 2008). Red solid star represents the earthquake epicenter and red circle represents EPZ.

The anomalous zone was significantly observed on DOY 130 compared to DOY 124, the spatial distributions of SVTEC on DOY 130 were created with the temporal resolution of 2 h as GIMs, the output maps illustrates in Fig. 6.

According to Fig. 6, it can be seen that the anomalous SVTEC was observed in the southeast of the epicenter from 08:00 UT to 12:00 UT on DOY 130. The result corresponds to the study conducted by Li et al. [4] in terms of time and space. The SVTEC distribution maps also reveal that in the local scale, the map generated by grid-based technique gives better results compared to mathematical-based which spherical harmonic expansion was applied. Thus, it can be concluded that in a local scale, GIMs can be replaced by OrK interpolated maps. The advantage of the interpolation technique is the lesser complexity compared to GIMs because the differential TEC (dTEC) maps are not necessary to be created from GIMs for investigating the anomalous zone, moreover, SVTEC distribution maps also provide equivalent or even better output maps compared to GIMs.

Influence of solar activity and geomagnetic storm

The electron density in the ionosphere is normally affected by solar activities and geomagnetic storm, thus, the level of both phenomena on the anomalous days must be monitored in order to investigate whether the VTEC anomaly is attributed by such phenomena or earthquake preparation process. The magnitude of geomagnetic activity is indicated by 2 indices as disturbance storm time index (Dst) and geomagnetic index (Kp), when the ionosphere is disturbed by geomagnetic storm, the values of $|\text{Dst}| > 30$ nT and Kp > 3. The magnitude of solar activity is indicted by solar radio flux at 10.7 cm index ($F_{10.7}$), in case the index greater than 150 SFU, it indicates that the ionosphere is disturbed by solar activities.

According to Sections 3.1 and Section 3.2, the anomalous days were detected on May 3, 2008 and May 9, 2008, which is 9 days and 3 days prior to the earthquake occurrence, respectively. In order to exclude the influence of geomagnetic storm and solar activities from the ionospheric disturbance, the
Fig. 7. Variations of geomagnetic storm indices (Dst and Kp) and solar activity index (F10.7) from DOY123 to DOY 138 (May 2, 2008 to May 17, 2008), vertical red dashed line represents Wenchuan earthquake occurrence day, and vertical green dashed line represents the anomalous day.

levels of such phenomena were monitored. Fig. 7 shows the variations of geomagnetic storm and solar activities indices of 10 days before and 5 days after the earthquake (DOY123 to DOY138 of 2008).

Fig. 7 shows that the geomagnetic activity and solar activity during the observation period were both quiet because |Dst| were lower than 30nT. However, Kp on DOY123, DOY126 and DOY127 was greater than 3, which indicated that the ionospheric electron content was disturbed by geomagnetic storm. According to Figs. 2 and 4, it can be seen that high AVTEC and SVTEC values were both observed at KUNM, the station located at 25.0295°N and 102.7972°E in geographic coordinate system which equivalent to magnetic latitude of 14.39° and magnetic longitude of 175.16° in geomagnetic coordinate system (http://www.geomag.bgs.ac.uk/data_service/models_compass/coord_calc.html). Since the equatorial ionization anomaly (EIA) crests created by ExB plasma fountain generally appeared around ±15° of magnetic latitude [25], thus the ionospheric electron content over KUNM was severely disturbed by geomagnetic storm on DOY123 because the station located in the same region as northern EIA crest. Fig. 3 also shows that anomalous AVTEC on DOY123 appeared within EIA, thus, the AVTEC as well as SVTEC anomalies on DOY123 were not associated with Wenchuan earthquake but they were influenced by geomagnetic activity. Fig. 7 also shows that the ionosphere was disturbed by geomagnetic activity on DOY123 to DOY127 because the Kp index was relatively high compared to the other days during the observation period (DOY123 to DOY138). The geomagnetic conditions during DOY128 to DOY138 were quiet, thus the anomalies which appeared within EPZ during the period of time were likely to be caused by earthquake preparation process. Since DOY130 was a geomagnetic quiet day, thus, the anomaly within the EPZ was probably caused by Wenchuan earthquake preparation process. The magnitude of F10.7 index also indicated that the
ionosphere during the observation period was not disturbed by solar activities because \( F10.7 \) was lower than 150 sfu., thus, the anomalous days on DOY124 and DOY130 could be considered as solar activity quiet day, so it can be concluded that the VTEC anomaly on May3, 2008 and May 9, 2008 was not causes by geomagnetic storm or solar activities.

**Long terms of AVTEC and SVTEC variations**

This study aims at propose a simplified VTEC anomaly detection technique based on the daily mean of VTEC (AVTEC) and its standard deviation (SVTEC), in order to validate the results with the previous studies, the observation period of 10 days prior to the earthquake and 5 days after the earthquake were analyzed. Since the ionospheric electron content is influenced by many natural phenomena, so that the normal values of AVTEC and SVTEC cannot be expected. Thus, the long term variations of AVTEC and SVTEC were investigated in this section. The AVTEC and SVTEC of BAKO, NTUS, TNML, TOW2, WUHN, XMIS and KUNM from DOY100 (April 9,2008) to DOY152 (May 31, 2008) were determined because these IGS stations located both within and outside the EIA region, so that the influence of geomagnetic activity as well as solar activity to the AVTEC and SVTEC variations can be investigated.

Figs. 8(a) and (b) illustrate that the variations of AVTEC and SVTEC at KUNM were higher than that of the other stations, especially during DOY100 to DOY124, the variation plots of both AVTEC and SVTEC reveal that both values were influenced by geomagnetic condition, as it can be seen in Fig. 8(c) and (d) that on DOY108 and DOY114, when Kp index and \( |Dst| \) were greater than 3 and 30 nT, respectively, the AVTEC at KUNM suddenly increased. However, the abrupt change of AVTEC and SVTEC were not observed at TOW2 because this station located away from the southern EIA crest, unlike at KUNM that located at the same magnetic latitude of the northern EIA crest, so that the ionospheric electron content at KUNM was severely disturbed by geomagnetic storm, thus, the AVTEC and SVTEC at KUNM were always higher than that of the other stations. Fig. 8(c) shows that the geomagnetic storm occurred quite frequently during DOY100 to DOY123 and during DOY142 to DOY152, thus, abrupt changes of AVTEC and SVTEC during mentioned period of time cannot be considered as earthquake precursory signals, especially on DOY108 and DOY114. The expected normal values of AVTEC and SVTEC at KUNM could not be evaluated although long-term period of AVTEC and SVTEC were both analyzed, because most of the observation dates were not geomagnetic quiet days.

According to Fig. 8(c), the geomagnetic quiet days were observed during DOY128 to DOY141 because the Kp index was very much lower than 3. But abrupt change of AVTEC and SVTEC at KUNM were observed on DOY130, which was 3 days prior to earthquake occurrence, since the day was geomagnetic and solar quiet day, so that the abrupt changes of both values were likely to be caused by earthquake preparation process. Fig. 8(a) illustrates that AVTEC values after the mainshock remained high and suddenly increased on DOY142, then it suddenly decreased on DOY148, the cause of this variation was the geomagnetic activity,because Kp index of 4- and 1 were observed on DOY142, and DOY148, respectively. Thus, these results indicate that the variations of VTEC on daily basis can be represented by AVTEC and SVTEC.

Normally, in conventional technique, the running median with quartiles or sliding mean with standard deviation was adopted to construct boundaries for detecting VTEC anomalies, thus, the ranges of the lower and upper boundaries are mainly depending on the VTEC values of the previous days, in case of the previous days were disturbed by high level of geomagnetic activity or solar activity, the range between upper and lower boundaries would be increased and the VTEC anomalies caused by earthquake will not be able to be detected. Moreover, the conventional technique is not practical because, the observed GPS stations must be individually analyzed, but in reality, the earthquake epicenter will not possible to be forecasted, so that the selection of GPS stations for analyzing the anomalies prior to earthquake occurrence is quite difficult when the epicenter is unknown. The advantage of AVTEC and SVTEC over the conventional technique is that the AVTEC and SVTEC will be individually determined on daily basis and the values will not be polluted by the solar activity and geomagnetic activity coming from the previous days, and the AVTEC and SVTEC variation of each GPS station can be simultaneously plotted in the same graph, so that the abnormal variations
Fig. 8. (a) AVTEC variation during DOY100 to DOY152 (b) SVTEC variation during DOY100 to DOY152 (c) Kp index during DOY100 to DOY152 (d) Dst index during DOY100 to DOY152 (e) F10.7 index during DOY100 to DOY152. Red dashed box denotes the analytical period.
of AVTEC or SVTEC at some GPS station, especially the closest station to the suspected epicenter can be investigated and analyzed.

Fig. 8(e) reveals that during the long-term observation period, the ionospheric electron content was not disturbed by solar activity because the F10.7 index during the observation period was lower than 15 sfu.

Discussion

VTEC anomaly prior to M7.9 Wenchuan earthquake were observed on May 3, 2008 and May 9, 2008 by SVTEC, while only the anomaly on May 9, 2008 was detected by AVTEC, the results correspond to the previous studies that the anomalous day was detected 9 days and 3 days prior to the earthquake occurrence [4,18]. The anomalous zone was not appeared in vertical projection of the epicenter but it was observed in the southeastern part of the epicenter because of $E \times B$ drift [26] generated by vertical electric field on the earth surface during earthquake preparation process penetrated across earth magnetic field to the ionosphere, resulting in ionospheric anomaly, however, the anomaly did not appeared at great distance from the epicenter but it appeared within the earthquake preparation zone (EPZ). Thus, it is concluded that the spatial distribution of VTEC represented by SVTEC maps correspond to the dTEC maps derived from to global ionosphere maps (GIMs). The VTEC spatial distribution over the study area represented by AVTEC and SVTEC maps were created based on ordinary Kriging interpolation technique. The advantage of the interpolated AVTEC and SVTEC maps over GIMs is that they are more appropriate to represent the ionosphere variation in a local scale, moreover the analytical process is not too complicate to be implemented.

VTEC anomaly was observed from both AVTEC and SVTEC variation plots on May 9, 2008, 3 days prior to earthquake occurrence, but VTEC anomaly was significantly observed by SVTEC compared to AVTEC. The enhancement of VTEC with magnitude of 10–15 TECU was obviously observed in the southeast direction of the epicenter from 16:00 to 18:00 LT on the anomalous day [17], since the variation degree of daily VTEC in this study was represented by SVTEC, so that the sudden change of SVTEC was observed at the same location where the VTEC enhancement occurred. The SVTEC spatial distribution map also confirmed that the ionospheric anomaly was significantly observed in the southeast of the epicenter. Thus, although the ionospheric anomaly can be detected by both AVTEC and SVTEC, but in term of VTEC spatial distribution visualization, SVTEC gives clearer anomalous zone compared to AVTEC.

Although the day-to-day variation of VTEC is high, and it is difficult to determine the expected normal values of AVTEC and SVTEC at each observed station, but large variation cannot be generated if the sudden changes of VTEC do not occur in solar-terrestrial environment, so that when AVTEC and SVTEC dramatically increase compared to the days before, there should be a possibility that the ionosphere is disturbed by some phenomena as geomagnetic storm or solar activities. However, during the earthquake preparation process, the vertical electric field is generated and penetrates the atmosphere to the ionosphere, so that the ionosphere is also disturbed by this mechanism as well. Generally, the influence of geomagnetic storm and solar activity covers large area while seismo-ionospheric coupling perturb the ionosphere only within EPZ but not at great distance from epicenter, thus the VTEC anomaly can be distinguished whether the ionospheric anomaly is caused by geomagnetic storm and solar activities or earthquake preparation process. In this study, the geomagnetic and solar activity were both quiet on the anomalous day, so the ionospheric anomaly on May 9, 2008 was likely to be Wenchuan earthquake precursor.

Conclusions

Zhou et al. [18] investigated VTEC anomaly of Wenchuan earthquake by collecting the data from Chinese GPS network (CMONOC), the data from 25 GPS stations that located in Sichuan province of China were collected. The results show that the VTEC anomaly was also observed on May 9, 2008 and the anomalous zone was in the southeast of the epicenter [18]. It proves that the proposed analytical technique yields the same result as the quartile-based technique.
The main objective of this study is to propose a new technique that based on the daily mean of VTEC (AVTEC) as well as its standard deviation (SVTEC) for detecting VTEC anomaly prior to earthquake occurrence, thus M7.9 Wenchuan earthquake was selected for the validation of the results. The long-term variations of AVTEC and SVTEC were analyzed for determining the expected values of AVTEC and SVTEC, but during the observation period (DOY100 to DOY127), in the most cases, the ionosphere was disturbed by geomagnetic storm, so that the normal values of AVTEC and SVTEC could not be evaluated. However, the observation period of 10 days prior to the earthquake occurrence, the variations of AVTEC contained the same characteristic as in the conventional technique. The extreme reduction of the value was observed on DOY127, 6 days prior to the earthquake occurrence and gradually increased to the maximum values on DOY130, 3 days prior to the earthquake occurrence, then the values decreased on the earthquake event date. After the earthquake, AVTEC remained high until the end of the observation period on DOY138, thus, it can be concluded that the variation of VTEC can be represented by AVTEC. The variation of SVTEC also contained the same characteristic as in the conventional technique but it provides better results because the SVTEC extremely decreased on DOY127 and abrupt change of SVTEC was significantly observed on DOY130, 3 days prior to the earthquake occurrence, the anomalous day observed on DOY130 is well agree with the previous studies, and the VTEC anomaly detection can also be investigated from SVTEC variation. The variation characteristics of AVTEC and SVTEC, especially prior to the earthquake occurrence (DOY127 to DOY133) confirm that long-term variation of AVTEC and SVTEC were not necessary to be investigated because the variations of both values contained the same characteristic as in the previous study.

The spatial distributions of AVTEC and SVTEC derived from OrK technique show that the anomalous zones were significantly appear within the EPZ compared to the results derived from GIMs. Although, in some cases the anomaly was observed within the EPZ as on DOY123, but the anomaly on such day was caused by geomagnetic storm instead of the earthquake preparation process. Thus, the investigation of geomagnetic activity as well as solar activity must be performed in order to exclude such phenomena from the earthquake precursory analysis.

The VTEC anomaly prior to the earthquake occurrence was investigated from the variation of daily mean VTEC (AVTEC) and its standard deviation (SVTEC). The abrupt change of AVTEC and SVTEC were considered as VTEC anomaly. In this study, the results are coincide with the previous studies in terms of time and space that the anomalous day was observed on DOY130, 3 days prior to the earthquake event, and the anomalous zone appeared in the southeast of the epicenter [4,18]. Thus, this approach should be utilized as an alternative approach for detecting seismo-ionospheric anomaly.

The advantage of this alternative technique is that the analytical process is easier and simpler to be implemented compared to the conventional technique as the quartile-based, but the equivalent results can be achieved. Since the VTEC is analyzed based on diurnal basis without sliding mean as in the conventional approach, only simple statistical values as average and standard deviation are utilized, so the AVTEC and SVTEC will not be polluted by anomalies or perturbations coming from the previous days. The variations of AVTEC and SVTEC of each IGS reference station can be simultaneously plotted in the same graph, so that the variation of each station can be investigated and the abnormal characteristic of the variation can be identified at the same time, while in the conventional technique, each IGS reference station must be individually analyzed. Moreover, the spatial distribution of VTEC in global scale as GIMs are not required in the analysis because it is replaced by local ionospheric maps created from SVTEC and AVTEC values. Thus, this technique is considered as a simplified version of seismo-ionospheric anomaly detection that can be implemented in earthquake precursory detection.

**Recommendation**

The accuracies of AVTEC and SVTEC rely on the distribution of reference stations within the study area. In ideal case, when the reference stations eventually distributed throughout the study area, the variation of VTEC map of the study area would be more reliable. The densification of reference station can be done by integrating the data acquired from other network agencies in the analysis. In this study, 31 stations were selected from IGS network, and only 12 stations located within EPZ, however the anomaly could be significantly observed, if the data from reginal GPS network as Crustal Movement Observation Network of China (CMONOC) and Continuously Operating Reference Stations
(CORS) were integrated in the analysis, the accuracy of the VTEC spatial distribution map could be enhanced.

The data were collected from IGS network in 2008, nowadays, the numbers of IGS stations have been increased, so that the accuracy of the interpolated maps can be enhanced compared to 2008. In order to investigate the performance and enhance the reliability of VTEC anomaly detection by utilizing ASK-VTEC method, more numbers of earthquake cases, especially M6.0+ earthquakes should be carried out.

Data availability statement

The data that support the results in this research are openly available in NASA’s Crustal Dynamics Data Information System (CDDIS), World Data Center for Geomagnetism of Kyoto University, NASA’s Goddard Space Flight Center (OMNIWeb Plus) at https://cddis.nasa.gov/, http://wdc.kugi.kyoto-u.ac.jp/ and https://omniweb.gsfc.nasa.gov/, respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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