Ionospheric earthquake signatures on GPS TEC

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Abstract. The ionospheric total electron content (TEC) can be derived from a ground based receiver of the global Positioning System (GPS). The GPS consist of 24 satellites, evenly distributed in 6 orbital planes around the globe at an altitude ~20200 km. Each satellite transmits signals on two frequencies (f1 = 1575.42 MHz and f2 = 1227.60 MHz) with two different codes, P1 (or C/A) and P2 and two different carrier phases, L1 and L2. Since the ionosphere is a dispersive medium, the speeds of propagation of the electro-magnetic waves transmitted by the GPS satellites depend on the frequency of radio waves. The carrier phase advance and group delay of GPS transmitted radio waves in the ionosphere is proportional to electron content integrated along the propagation path. From carrier phase and pseudo-range code data observed by GPS receivers located in the vicinity of Indonesia, we derived the ionospheric GPS TEC using phase levelling method. For the aim of finding the diurnal variation anomalies associated with the large earthquakes in Indonesia and surrounding areas, we used the harmonic analysis of TEC observed at several GPS stations. The results of harmonic analysis have revealed that the amplitude of diurnal variations of TEC decreases (negative anomaly) or increases (positive anomaly) several days before major earthquakes, and by using spatial analysis of the amplitude anomaly, the magnitudes of some major earthquakes can be estimated.

1. Introduction
The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. This ionization depends primarily on the sun and its activity. Electron density in the ionosphere varies greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar, auroral zones, mid-latitudes, low latitudes and equatorial regions), and with certain solar-related ionospheric disturbances. The major part of the ionization is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun. The most noticeable effect is seen as the Earth rotates with respect to the Sun; ionization increases in the sunlit atmosphere and decreases on the shadowed side. Although the sun is the largest contributor toward the ionization, cosmic rays have a small contribution. Any atmospheric disturbance also affects the distribution of the ionization. Because of its sensitivity to atmospheric changes, the ionosphere is a sensitive monitor of atmospheric events and earthquake precursors through lithosphere-atmosphere-ionosphere coupling.

The first publications dealing with ionospheric parameter variations as seismic precursors were study of the variations of foE parameter before the Tashkent earthquake 1966, and study of ionosphere electron variations before the same Tashkent quake [1-2]. Consequently, case study papers started to appear regularly. These were based mainly on ground-based ionosonde data; however, the first papers using satellite data began to appear as well [3].

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The ionospheric anomaly is one of several possible precursors of Taiwan’s earthquakes under investigation by [4]. According to the simulation-based tests together with reasonable criteria under study [5] show that 1 - 5 day alarms before the occurrence of earthquakes which are greater or equal to 5 in the Taiwan area during 1994 - 1999 on the basis of the foF2 anomalies reported in [6] is not due to random chance.

Vertical TEC is very sensitive to changes of foF2. As the electron concentration in the maximum of F2 ionosphere layer is one of the most sensitive parameter connected to seismic activity, we can use TEC data to estimate spatial sizes and temporal dynamics of pre-earthquake ionospheric effects in a seismo-active region.

In recent years there are vast possibilities to investigate the ionosphere modifications and in particular the ionospheric effects associated with seismic activities by use of the satellite-based Global Positioning System (GPS) signals measurements [7-12].

The dense network of GPS receivers (a few thousands all over the world) fulfills simultaneous coverage in global scale with high temporal resolution. GPS technique provides measurements of the group and phase delays of the signals L1=1575 MHz and L2=1228 MHz with a 30-sec interval. The ionospheric delay can be transformed into the content of electrons along the signal path between a GPS satellite and GPS receiver, and then recalculated into its vertical projection. The vertical total electron content (TEC) is very sensitive to changes of the maximum electron concentration (NmF2) in the F2 layer of the ionosphere. The extensive studies of the ionospheric earthquake precursors in GPS TEC measurements carried out in recent years have revealed that for strong mid-latitude earthquakes the seismo-ionospheric anomalies often look as local TEC increases and they are situated in the immediate vicinity of the earthquake epicenter area.

The zone of the maximum anomaly manifestation (TEC enhancement more than 35 %) has a spatial scale of some thousands km in longitude and about 1000 km in latitude [12-14]. These sizes are in a good agreement with results obtained from the combined analysis of ground based and satellite measurements. It was found that the spatial scale of the seismo-modified area of the ionosphere at F-layer heights maximum during the strong earthquake preparation time has the diameter of 20⁰-40⁰ in geographical coordinates [15]. The size of the area changes with the earthquake magnitude. The analyzed the GPS TEC measurements for the strong Mexico earthquake and found out an anomalous ionospheric modification in the spatial (latitude and longitude) distribution of TEC deviation [16]. The anomalous enhancement of the TEC was registered 3 days prior to the event and it reached the value of 55 % relative to the background conditions. Negative TEC disturbances (TEC decreases) were also observed, for example for the strong Turkey earthquakes of 1999 [17] and for several Taiwan and Sumatra earthquakes [18-19]. The spatial TEC showed the anomalies from UT = 08 to UT = 12 on September 21, 2013. On the other hand, the main shock of the Mw = 7.7 earthquake occurred on September 24, 2013 at 11:29:47 (UTC). It showed a complete alignment of the earthquake and TEC anomalies [20].

In this paper we exploit GPS data for deriving ionospheric TEC and subsequently study possible earthquake ionospheric precursors. Diurnal variation anomalies of ionospheric TEC were obtained by using harmonic analysis of TEC few days before large earthquakes.

2. Materials and Methods
2.1 Materials
GPS data used for analysis of ionospheric anomaly before earthquake are obtained from IGS stations in the vicinity of Indonesia: NTUS, SAMP, BAKO, DARW, IISC, DGAR, GUAM, WUHN, KUNM, etc., as shown in Figure 1.
Figure 1. GPS stations used for ionospheric TEC derivation. The GPS data can be downloaded from ftp://ngdc.gsfc.nasa.gov/gps/data/daily

2.2 Methods

2.2.1 Ionospheric GPS TEC derivation

Ionospheric GPS TEC is derived from GPS dual frequency observations by using phase leveling method that can be expressed as [21]

$$\text{STEC}_{\text{SM},n} = \frac{f_i^2(\lambda_i \Phi_i - \lambda_2 \Phi_2)}{40.3(1-\gamma)} + \frac{1}{N} \sum_{m=1}^{N} \left( \frac{f_i^2(P_i - P_2) + (\lambda_i \Phi_i - \lambda_2 \Phi_2)}{40.3(1-\gamma)} \right) + \frac{f_i^2(b_p - B_p)}{40.3(1-\gamma)}$$

(1)

where $\lambda_i$ is the wavelength of GPS signal on $L_i$, $\Phi_i$ is the carrier phase observation on $L_i$, $\gamma$ is the squared L1 and L2 frequency ratio ($\frac{f_1^2}{f_2^2}$), $f_i$ is the carrier wave frequency on $L_i$, $N$ is the epoch of $N^{th}$, $b_p$ is the receiver differential code bias (DCB) between $L_1$ and $L_2$, $B_p$ is the DCB of satellite between frequency of $L_1$ and $L_2$.

After TEC calibration from DCB of receiver and satellite between $L_1$ and $L_2$, the hourly average of ionospheric GPS TEC with cut off elevation angle of 40° can be used for ionospheric GPS TEC anomaly detection related to the earthquake by using harmonic analysis

$$\text{TEC} = a_0 + \sum_{m=1}^{N} a_m \cos(m\omega t) + \sum_{m=1}^{N} b_m \sin(m\omega t)$$

(2)

where $a_0$ is the daily mean of TEC, $A_m = \sqrt{a_m^2 + b_m^2}$ is the amplitude of $m^{th}$ order of daily diurnal variation of TEC, $m$ is the order of harmonic analysis with $m = 1$ for diurnal variation, $m = 2$ for semidiurnal variation, $m = 3$ for terdiurnal variation and so on, $N$ is maximum order of harmonic analysis of TEC.

To distinguish the daily variations anomaly of ionospheric TEC globally caused by solar activity and locally caused by seismic activity, the spatial variation of diurnal variation of TEC over earthquake preparation zone from IGS stations are analysed. If the amplitude of daily ionospheric TEC diurnal variation decreases as the radius of IGS station increases from the epicenter, the anomaly on the diurnal variation of ionospheric TEC can be attributed to a local earthquake source.
3. Results and Discussion

3.1 Case of December 26, 2004 Sumatran Earthquake

A great earthquake occurred off the west coast of Northern Sumatra, Indonesia, at 7:58 local time, on December 26, 2004 in Indonesia. The magnitude of this earthquake has been revised to 9.0 based on additional data. This is now the fourth largest earthquake in the world since 1900 and is the largest since the 1964 Prince William Sound, Alaska earthquake. The magnitude was determined by the Dept. of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts.

The diurnal variation of GPS TEC derived from SAMP station during December 2004 is shown in Figure 2 (upper panel). On December 21, 2004, five days before Aceh earthquake, the diurnal variation of ionospheric GPS TEC has minimum amplitude of about 11 TECU. The deviation of the minimum amplitude from average amplitude is about -4.7 TECU. The diurnal variation amplitude of TEC derived from BAKO station on December 21, 2004 is about 15 TECU and its deviation from the monthly average of ionospheric TEC diurnal variation amplitude is about -4.5 TECU. Meanwhile from IISC station, the deviation amplitude of TEC diurnal variation is about -3.9 TECU. The absolute value of diurnal amplitude variation deviations on December 21, 2009 as a function of distance of GPS stations from earthquake epicenter is plotted in Figure 3. As shown in the figure the deviations of daily diurnal variations amplitude of ionospheric TEC are decreasing as distances from epicenter increasing. This is as indication that the ionospheric anomalies have local source and can be related to the December 26, 2009 Aceh earthquake. Using the exponential function, the radius of the earthquake preparation zone can be estimated. This is the point of intersection between an exponential line of ionospheric TEC diurnal variations anomalies and a straight line as the anomaly boundary that is the monthly average of daily diurnal TEC variation amplitude on a month when earthquake is occurred. Horizontal straight line is the limit value of ionospheric TEC diurnal variation amplitude anomaly. Above this limit value the diurnal amplitude of TEC is considered as abnormal (disturbed). If the value of the amplitude deviation of TEC diurnal variation is smaller than the limit value, the ionosphere is considered under normal conditions.

The radius of earthquake preparation zone, \( \rho \), and earthquake magnitude, \( M \), can be expressed by using formulation [22]

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

(3)

From Figure 3 the radius of earthquake preparation zone can be obtained from ionospheric TEC diurnal variations amplitude anomalies are about 3637 km.

By using equation (3) the radius of earthquake preparation zone is about 3637 km from the earthquake epicenter. It is related to earthquake that will occur with magnitude of about 8.3 RS. The value of this estimate is lower than the estimate of the earthquake that was issued by the USGS.

3.2. Case of May 12, 2008 Sichuan earthquake.

Different to the case of Aceh earthquake, the ionospheric precursors of the May 12, 2009 Sichuan earthquake gives a positive anomaly that can detected from diurnal variation of ionospheric TEC derived from KUNM, WUHN and HYDE IGS stations, on May 9, 2009, three days before earthquake as shown in Figure 4. Unlike the Aceh ionospheric precursors, the Sichuan ionospheric precursor manifested as a positive anomaly where the amplitude of ionospheric TEC diurnal variation has largest value on May 2008 when earthquake has occurred.

By using the same method as for the case of December 26, 2004 Aceh earthquake, the radius of earthquake preparation zone from ionospheric anomaly is about 2950 km as shown in Figure 5, related to earthquake magnitude of 8.1 SR. The Sichuan earthquake magnitude estimation issued by USGS is about 7.9 RS so the estimation of earthquake magnitude based on ionospheric precursors is slightly higher than its estimation from seismic data.

By using the same method, the earthquake magnitude for September 12, 2008, Bengkulu earthquake and November 17, 2008, Gorontalo earthquake is estimated at 8.01 and 7.89 SR respectively.
3.3. Earthquake preparation zone model based on ionospheric TEC anomaly

Taking the logarithm value for the radius of the earthquake preparation zone and plotting large earthquakes versus log (radius) is obtained as shown Figure 6. It can be seen that the Dobrovolsky model has a smaller gradient (1/0.43 = 2.33) compared with the gradient model of earthquake preparation zone derived from ionosphere TEC (1/0.0928 = 10.78).

Figure 2. Diurnal ionospheric variation of TEC derived from SAMP (upper panel), BAKO (middle panel) and IISC (lower panel) on December 2009
Distance from epicenter (km)

Figure 3. Estimation of radius of earthquake preparation zone from deviation of TEC diurnal variations of December 26, 2004 Aceh earthquake

Figure 4. Daily ionospheric TEC diurnal variation amplitude on May 2009 derived from WUHN IGS station

The opposite of the gradient value (0.0928) is the exponential constant of relationship between the radius of earthquake preparation zone ($\rho$) and magnitude of earthquake ($M$) (> 7 RS) would happen so that the model of radius of earthquake preparation zone and its relation to magnitude of earthquakes based on ionospheric diurnal variation anomalies can be written as

$$M = \frac{\log(\rho)}{0.0928} - 29.38 \quad (4)$$

or can be expressed as

$$\rho = 10^{0.0928(M+29.38)} \quad (5)$$

The model of the relationship between the radius of the earthquake preparation zone based on a diurnal ionospheric anomaly must be evaluated and validated through scientific earthquake studies based on GPS-based TEC data that have are available online globally. This could enable strong earthquakes prediction based on diurnal ionospheric anomaly a few days before the large earthquakes.
Figure 5. Amplitude deviation of ionospheric TEC diurnal variation derived from KUNM, WUHN and HYDE IGS stations on May 9, 2008

Figure 6. Magnitude of earthquake (RS) versus log of radius of earthquake preparation zone for large earthquake (> 7 RS)

4. Conclusion
This study investigates the hypothesis that precursors of large earthquakes (> 7) can be revealed from GPS TEC data by using harmonic analysis to estimate the amplitudes of TEC diurnal variations. The magnitudes of earthquake can also be estimated by using spatial analysis of amplitudes of diurnal variation ionospheric anomalies a few days before the earthquake. The earthquake preparation zone of Dobrovolsky model has a smaller gradient (1/0.43 = 2.33) compared with the gradient model of earthquake preparation zone derived from ionosphere TEC (1/0.0928 = 10.78).

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