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An attempt to detect earthquake-related Ionospheric disturbances with the use of GPS data

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Abstract
Ionospheric disturbances preceding large earthquakes have been reported, recently. Those are devided into two types; one is transmission anomaly of radio station signals such as VLF navigation system (Omega system) and VHF broadcasting signals and the other is anomalous density distribution of ionosphere. As for latter one, convincing results were reported by Liu et al(2000, 2001). It was pre-seismic ionospheric phenomena associated with Chi-Chi earthquake, Taiwan (21/09/1999, Mw 7.8) by using Ionosonde. The aim of this study is to verify the ionospheric disturbances of electron density associated with large earthquakes. In this paper, we analyzed total electron content (TEC) variation with the use of GPS (Global positioning System) data around the day of Tottori earthquake (06/10/2000 M7.3) and Geiyo earthquake(24/03/2001 M6.4).

1. Introduction
Electromagnetic phenomena are recently considered as a promising candidate for the short-term prediction of large earthquakes. There have been accumulated observational reports in a very wide frequency range (e.g. Hayakawa and Fujinawa (eds.),1994; Hayakawa (eds.),1999; Hayakawa and Molchanov (eds.), 2002). Measurements of electromagnetic phenomena can be classified into three types, which are the passive ground-based observation, the ground-based observation with use of transmitter signals, and the satellite observation. Ionospheric disturbances preceding large earthquakes are discovered by active transmission signals such as VLF and VHF broadcasting signals. They are one of the most promising approach to establish the short-term earthquake prediction. This approach is divided into two types; one is transmission anomaly of radio station signals such as VLF navigation system (Omega system) and VHF broadcasting signals and the other is anomalous density distribution of ionosphere. As for latter one, convincing results were reported by Liu's group (Liu et al., 2000, 2001, Chuo et al., 2002). They were pre-seismic ionospheric phenomena associated with Chi-Chi earthquake, Taiwan (21/09/1999, Mw 7.8) by using Ionosonde. The aim of this study is to verify the pre-seismic ionospheric disturbances of electron density for large earthquakes (Tottori earthquake 2000 and Geiyo earthquake 2001) in Japan.

2.Total Electron Content (TEC) and differential TEC
A GPS satellite broadcasts radio signals at 1.57542GHz and a1.2276GHz. The dispersive property of ionospheric medium causes the delay with respect to f^2. Using this delay, TEC (total electron content) can be estimated. Total Electon Content TEC is defined as follows,

$$\mathrm{E} = \int_R^S n_e(s)ds \tag{1}$$

where n_e is dencity (/m^3). Unit of TEC is TECU (1 TECU = 10^{16}/m^3). Refractive index depends on the frequency of radio wave due to dispersion.

$$n_I = 1 - \frac{\alpha\, n_e}{f^2} \tag{2}$$

where α is constant ($=4.03\times10^{17}\mathrm{ms}^{-2}\mathrm{TECU}^{-1}$)、 f corresponds to the career frequency of GPS system. Using (1) and (2), delay of ionosphere $\Delta\rho_I$ is calculated

$$\Delta\rho_I = \int_s (n_I - 1)ds = -\frac{\alpha \mathrm{E}}{f^2} \quad (3)$$

Then, we assume the length of free space is ρ, delays of ρ_1 for L1 and ρ_2 for L2 observed at a receiver are described as follows.

$$\rho_1 = \rho - \frac{\alpha \mathrm{E}}{f_1^2} + \lambda_1 N_1 \quad (4)$$

$$\rho_2 = \rho - \frac{\alpha \mathrm{E}}{f_2^2} + \lambda_2 N_2 \quad (5)$$

In the right hand, the third term is bias. The corresponding wavelength is multiplied. Then, ionospheric delay effect is obtained as follows,

$$LG = \rho_1 - \rho_2 = -\alpha\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)\mathrm{E} + \mathrm{B} \quad (6)$$

where $\mathrm{B} = \lambda_1 N_1 - \lambda_2 N_2$. From this,

$$\mathrm{E} = \frac{1}{\alpha} \times \frac{f_1^2 f_2^2}{f_1^2 - f_2^2}(LG - B) \quad (7)$$

This E gives TEC along the path between satellite and receiver. Therefore, a mapping function F (z') is adopted to estimate the vertical TEC E_V at the sub-ionospheric point under the assumption of single layer model which means that ionosphere is considered as single and thin layer at a certain height and all electrons exist in the layer.

$$\mathrm{E}_v = \mathrm{E} \times F(z') \quad (8)$$

R is earth's radius and H is altitude of ionosphere from the surface. Corresponding zenithal angles are z and z', then

$$F(z') = \cos z'$$

$$\sin z' = \frac{R}{R+H}\sin z$$

Note the obtained E_V is the value at the sub-ionospheric point and not at the site. Therefore, we have to get the coordinate of the sub-ionospheric point from the site and satellite location. Then, TEC is estimated with the use of Taylor expansion in Bernese.method

$$\mathrm{E}(\beta, s) = \sum_{n=0}^{n\max} \sum_{m=0}^{m\max} \mathrm{E}_{n,m} (\beta - \beta_0)^n (s - s_0)^m \quad (9)$$

Here, n max and m max is maximum order of latitude β and longitude s, respectively. $\mathrm{E}_{n,m}$ is TEC coefficient, (β_0, s_0) is the coordinate of the site, (β, s) is the coordinate of the sub-ionospheric point, where s is the sun-fixed longitude. The estimated TEC coefficient E_{00} indicate the TEC at the site.

However, eq. (6) includes bias B, so absolute TEC cannot be estimated. Therefore, P code is used for calculation of absolute TEC as follows.

$$PG = -(P_1 - P_2) = \alpha\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)\mathrm{E} \quad (10)$$

P_1 and P_2 correspond to the P code of L1 and L2 bands, respectively. Then, TEC is

$$\mathrm{E} = \frac{1}{\alpha} \times \frac{f_1^2 f_2^2}{f_1^2 - f_2^2}(PG) \quad (11)$$

Using the mapping function, the vertical TEC is obtained.

$$\mathrm{E}_v = \mathrm{E} \times F(z') \quad (12)$$

$$F(z') = \cos z'$$

$$\sin z' = \frac{R}{R+H} \sin z$$

In this study, we take earth's radius $R = 6371$ km, height of ionosphere H=350 km. In the Bernese method, Taylor expansion of Ev is used but we use Ev without expansion. When the zenith angle is law, the effects of cycle slip and multiple paths from contamination of reflected waves. To avoid this, satellites with zenith angle > 60 degree have been used for this analysis.

In this analysis P code have been used to avoid the influences of the bias. The sampling rate was 30 seconds. We also took account of background variation of TEC. 15 days backward median values at each sampling time were considered as the standard background values of TEC. It is mainly diurnal variation of TEC. The variation of the differential between the estimated and the standard TEC have been investigated in this paper. This is called dTEC.

3. Application to Tottori earthquake (M7.3) and Geiyo earthquake (M6.4)

For Tottori EQ, the data using this paper were observed in Chugoku-Shikoku area by GEONET operated by Geophysical Survey Institute, Japan. The number of ground-based station was 76. TEC have been calculated with the use of GAMIT GPS software over one year data from August 2000 to July 2001.

The temporal and spatial distribution of dTEC has been investigated. The result shows the dTEC variation around the origin time of the earthquake there is no apparent anomalous behavior on the day. 4 days before the EQ, dTEC apparently increased by 30TECU and the disturbance of dTEC lasted 3 days. And one day before the EQ, dTEC recovered the standard level and the day of the earthquake, dTEC showed the lower values against the standard level. This is the opposite result to the Liu's ionosonde result.

The relationship between dTEC and geomagnetic variations (ΣKp and Dst indexes) has been also examined. Periods of larger values of ΣKp index and disturbed Dst index correspond to the geomagnetic storm day. The beginning of Dst disturbance shows the onset of the storm. Generally, the probability for the appearance of dTEC disturbance after the magnetic storm is higher over the analyzed period. On the day of the earthquake, however, there is a fluctuation of dTEC and then a magnetic storm occurred.

As for Geiyo EQ, TEC over the site has been investigated but dTEC have been not investigated so far. But this preliminary result shows a good agreement with Liu's result. It means that there was a decrease of density 3 days before the earthquake. However, the very limited data have been used and no spatial and temporal variations have been investigated deeply yet. So further analysis is highly required.

4. Conclusion and future problems

The results showthat 4 days before the EQ, dTEC increased by 30TECU and it lasted 3 days. And one day before the EQ, dTEC deceased. The probability for the appearance of dTEC disturbance after the magnetic storm is higher. This is the opposite result against the Liu's ionosonde result.

As for Geiyo EQ, similar analysis had been done. The result seems consistent with Liu's result. It means that there was a decrease of density 3 days before the eqrthquake. However, the very limited data have been used and no spatial and temporal variations have been investigated yet. So further analysis is highly required.

Investigation on ionospheric disturbances associated with 2000 Tottori EQ with the use of dTEC analysis based on GPS satellite data provides us the following results

(1) 4 days before the EQ, dTEC increased by 30TECU and it lasted 3 days.
(2) One day before the EQ, dTEC deceased.
(3) The probability for the appearance of dTEC disturbance after the magnetic storm is higher.
(4) I is important to find out the clear criteria between normal TID (travel ionospheric disturbances) and earthquake related ionospheric disturbances.
(5) Further investigation will be required for verification of existence of pre-seismic ionospheric disturbances at mid-latitude; accumulation of events, statistical analysis, and so on.

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