IOP Conf. Series: Earth and Environmental Science **132** (2018) 012014 doi:10.1088/1755-1315/132/1/012014

# Ionospheric earthquake effects detection based on Total Electron Content (TEC) GPS Correlation

**Bambang Sunardi[1], Buldan Muslim[2], Andi Eka Sakya[1], Supriyanto Rohadi[1], Sulastri[1], Jaya Murjaya[1]**

[1] Indonesian Meteorological Climatological and Geophysical Agency, Kemayoran, Jakarta, Indonesia
[2] Space Science Center, Indonesian National Institute of Aeronautics and Space, Bandung, Indonesia 40173

Email : bambang.sunardi@bmkg.go.id

**Abstract**. Advances in science and technology showed that ground-based GPS receiver was able to detect ionospheric Total Electron Content (TEC) disturbances caused by various natural phenomena such as earthquakes. One study of Tohoku (Japan) earthquake, March 11, 2011, magnitude M 9.0 showed TEC fluctuations observed from GPS observation network spread around the disaster area. This paper discussed the ionospheric earthquake effects detection using TEC GPS data. The case studies taken were Kebumen earthquake, January 25, 2014, magnitude M 6.2, Sumba earthquake, February 12, 2016, M 6.2 and Halmahera earthquake, February 17, 2016, M 6.1. TEC-GIM (Global Ionosphere Map) correlation methods for 31 days were used to monitor TEC anomaly in ionosphere. To ensure the geomagnetic disturbances due to solar activity, we also compare with Dst index in the same time window. The results showed anomalous ratio of correlation coefficient deviation to its standard deviation upon occurrences of Kebumen and Sumba earthquake, but not detected a similar anomaly for the Halmahera earthquake. It was needed a continous monitoring of TEC GPS data to detect the earthquake effects in ionosphere. This study giving hope in strengthening the earthquake effect early warning system using TEC GPS data. The method development of continuous TEC GPS observation derived from GPS observation network that already exists in Indonesia is needed to support earthquake effects early warning systems.

## 1. Introduction

Advances in sciences and technology made the GPS technology as a study facility in Total Electron Content (TEC) anomaly detection related with earthquake [1, 2, 3]. Recent studies have shown that earthquake and tsunami effects in ionosphere through the atmospheric gravity and acoustic waves have been found in the case of major earthquakes such as Aceh Earthquake, December 26, 2004 and Tohoku Earthquake, March 11, 2011. A possible cause of TEC anomaly related with earthquake and tsunami is the atmospheric gravity wave and infrasonic wave which spread to ionosphere. So, the ionosphere fluctuates in order of atmospheric gravity and infrasound wave periods [4].

Earthquakes influence on ionosphere occurs through Lithosphere-Atmosphere-Ionosphere (LAI) coupling. Lognonne et al. [5] explained that the greatest amplitude of seismic waves in the earth surface were surface waves, one of which is the Rayleigh wave. The seismic waves propagate along the earth surface through the crust and upper mantle with a speed between 3 - 4 km/sec. These waves can produce atmospheric wave that propagates upward with a period greater than 10 seconds. The

infrasonic waves spread in atmosphere, and when they reached ionosphere, their wave energy is transferred to ionosphere through collisions between ions and electrons so as to bring infrasonic waves in ionosphere. The infrasonic waves can be detected using some ionospheric observation equipment's including GPS.

In their study, Hao et al. [6] confirmed that ionospheric waves with a period of about 3 - 5 minutes caused by infrasonic waves due to Rayleigh waves, sourced from Tohoku earthquake, March 11, 2011, about 10 minutes earlier. The ionospheric disturbances phase velocity was about 3,6 km/sec which is equal to the speed of Rayleigh wave. Likewise, the results of Heki study [7] showed earthquake precursor as positive anomaly of ionospheric Total Electron Content (TEC) around the focal region detected by Japanese network of Global Positioning System (GPS). Huijun Le, et al. [8] investigated the ionospheric abnormal behaviors prior to the 2011 Tohoku-Oki earthquake by using TEC GPS data. The observation data revealed that on March 8, 2011, there was significant enhancement in TEC also in solar activity. They made conclusion that the significant enhancement in TEC on March 8, probably generated by the pre earthquake ionospheric disturbance. Woei Lin [9] used two dimensional principal component analysis (2DPCA) to detect Aegean-Sea TEC anomaly after magnitude M 6.4 earthquake on May 24, 2014. The results showed after earthquake, TEC anomaly became more intense, in at least 5 minutes time duration.

Study on ionospheric anomalies before and after earthquake in Indonesia was conducted by Muslim [10]. He conducted correlation techniques test to detect ionospheric earthquake effect. The results showed that most earthquakes can be known their precursors, and many earthquake effects cannot be detected. Sunardi, et al. [11] monitored Total Electron Content (TEC) anomalies related to 2015 around Java earthquake events. The monitoring results indicated the emergence of TEC anomalies in most of earthquake cases. By considering only the TEC parameter observation and Dst index, anomalies can be classified as detected earthquake precursors and detected earthquake precursors / geomagnetic storm effects. Sunardi, et al. [12] also conducted study on Total Electron Content (TEC) anomalies observed before strong earthquakes (Mw > 6) that occurred in Indonesia during 2014. The results showed that most of TEC anomalies appear before the earthquakes. In general, TEC anomaly occurs less than 10 days before the earthquake occurrence.

This paper discussed the ionospheric earthquake effects detection using TEC GPS data. Case studies used were Kebumen earthquake January 25, 2014, magnitude Mw 6.2, Sumba earthquake, February 12, 2016 with magnitude Mw 6.2, and Halmahera earthquake, February 17, 2016 with magnitude Mw 6.1. This initial research will be useful in efforts to strengthen earthquake effect early warning systems in Indonesia. Study and development of continuous TEC GPS observation data derived from GPS observation network that already exists in Indonesia is required to support these efforts.

## 2. Data and method

Total Electron Content (TEC) data were obtained from Center for Orbit Determination in Europe (CODE) in the Global Ionosphere Map (GIM) form. The TEC data generated every day using GPS data from more than 200 GPS stations around the world [13]. TEC modeled in the reference frame of geomagnetic sun using spherical harmonic expansion to degree and order of 15 [14]. GIM is based on a single layer model as shown in Figure 1 [15].

Assumption of GIM model is all free electrons were concentrated in a spherical shell of infinitesimal thickness. Conversion of vertical TEC *Ev* to slant TEC (*E*) can be written as [15] :

$$E = F(z)E_v = \frac{1}{cos\ z'}E_v$$

with $$\sin z' = \frac{R}{R_0+H}\sin z \qquad (1)$$

Where *F(z) = 1/cos z'* showed a single layer mapping function. The $z$ and $z'$ variables are zenith distance at the height of station and at single layer respectively (Figure 1). $R$ is the radius of considered station. $R_0$ is the average radius of the Earth (~ 6,371 km) while $H$ is the height of a single layer on the average surface of the Earth. Ideal altitude of this $H$ layer is usually set with a high maximum electron density expected, for example, $H$ = 400 km [15].

Electron density model $E$, surface layer density which represents TEC distribution on a global scale is expressed as follows:

$$E = (\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \widetilde{P_{nm}} \ (\sin \beta)(a_{nm} \cos ms) + \ b_{nm} \sin ms \tag{2}$$

With $E$ is vertical Total Electron Content (TEC), $\beta$ is the latitude of geocentric from intersection point of satellite's receiver line and ionosphere, $s = \lambda - \lambda_0$ is sun fixed longitude from ionospheric penetrating point or sub ionospheric point, $n_{mak}$ is maximum expansion level of the spherical harmonic expansion, $\widetilde{P_{nm}} = \Lambda_{nm} P_{nm}$ are normalized legendre function of degree $n$ and order $m$ by a normalization factor $\Lambda_{nm}$ and classical Legendre function $P_{nm}$, and both $a_{nm}$ and $b_{nm}$ are TEC coefficients of spherical function [15].

The TEC $E(\beta,s)$ is usually expressed in TECU (TEC Unit) where 1 TECU = 1 x $10^{16}$ free elektron/m$^2$. An equivalent set in the solar geomagnetic frame can be used for the coordinates $(\beta,s)$. Making the mean sun as sun fixed reference frame and sun geographic latitude $\beta_0$ is set to 0, the geographic longitude of the sun may be written as [15] :

$$\lambda_0 = \pi - UT \tag{3}$$

With $UT$ is the universal time. We can find the normalization factor $\Lambda_{nm}$ which is defined as :

$$\Lambda_{nm} = \sqrt{\frac{(n-m)!\ (2n=1)\ (2-\delta_{0m})}{(n+m)!}} \tag{4}$$

where $\delta$ denoted the Kronecker delta.

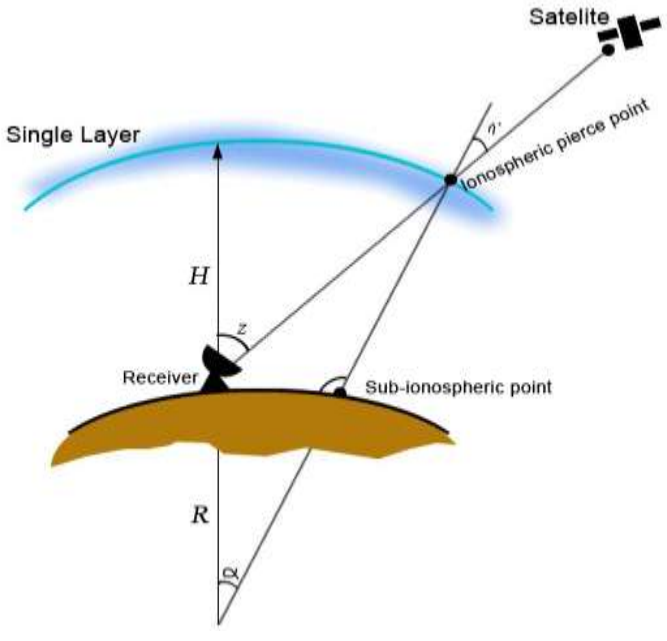


**Figure 1.** Single layer model of Global Ionosphere Map (GIM), modified from Schaer [15].

Ionospheric earthquake effect detection was done by using the closest to earthquake epicenter TEC data. TEC data from GIM are selected 31 days backward to represent normal conditions, so that there will always be 31 TEC data. At any observation time, it been calculated the average TEC at certain hours for 31 days in order to obtain the TEC monthly average diurnal variation. Correlation analyzes were conducted between TEC diurnal variation on a particular day of 31 days and TEC monthly average diurnal variation, which produces 31 correlation coefficients. Comparison between daily correlation coefficient deviation for 31 days and correlation coefficient average value (skk) divided by its correlation coefficient standard deviation (dskk) was used as an indicator of TEC anomalies in ionosphere. The anomaly threshold is when skk/dskk value was -1. TEC anomalies caused by earthquakes and or magnetic storms based on the value of skk/dskk less than -1. If TEC value met the requirement, then the day with skk/dskk less than -1 is set as ionospheric TEC anomalous condition. To determine the TEC anomalies occurred locally or globally, the TEC data closest to earthquake epicenter cross correlated with the vicinity TEC data. Geomagnetic disturbances like the magnetic storm will lead to global anomalies, otherwise the earthquake effect anomaly was more regionally.

Correlation method based on the assumption that major earthquake will affect the ionospheric layer which can make disturbances before and after the earthquake. However, ionospheric disturbances can also be caused by geomagnetic storms. Therefore, to determine whether ionospheric anomaly was caused by earthquake or magnetic storm, in addition to TEC data also required equatorial and low latitudes ionospheric disturbances index data. To clarify the TEC anomaly sources in low latitudes and the equator, it was needed Disturbance storm time (Dst) index data. Dst index can be used for characterize magnetic storms. Magnetic storm usually expressed by negative value indicates a decrease in earth magnetic field [16]. The magnetic storm intensity was classified into three classes as shown in Table 1 [17]. Dst index data can be real time obtained from the World Data Center for Geomagnetism, Kyoto [18].

**Table 1.** The intensity of geomagnetic storms based Dst index [17].

| No | Dst Index | Category |
|---|---|---|
| 1 | -50 nT < Dst < -30 nT | Weak storm |
| 2 | -100 nT < Dst < -50 nT | Intermediate storm |
| 3 | Dst ≤ -100 nT | Strong storm |

## 3. Result and analysis

In case of January 25, 2014 Kebumen earthquake event with magnitude Mw 6.2, the value of the correlation coefficient deviation comparison with standard deviation of the correlation coefficient (skk/dskk) and cross correlation are shown in Figure 2. The value of skk/dskk reached -4.2 occurred on Day of Year (DOY) 25 (January 25, 2014). This value is smaller than ionospheric TEC anomaly threshold that qualified as anomaly (skk/dskk =-1). Cross correlation results showed anomalies that occurred on January 25, 2014 around the earthquake epicenter, i.e. $8.23^0$ S and $109.2^0$ E. Dst index data on January 25, 2014 showed a value of about -9.6 nT, as shown in Figure 3. The value can be categorized as normal condition. Thus reinforces analysis that TEC anomaly on January 25, 2014 probably as Kebumen earthquake effect.

In case of February 12, 2016 Sumba earthquake with magnitude Mw 6.2, the value of the correlation coefficient deviation comparison with a standard deviation of the correlation coefficient (skk/dskk) and cross correlation were shown in Figure 4. The value of skk/dskk reached -4.5 occurred on DOY 43 (February 12, 2016). Cross correlation results showed anomalies that occurred in February 12, 2016 around the earthquake epicenter, i.e. $9.86^0$ S and $119.32^0$ E. Dst index data on February 12,

2016 indicated a value of about -11.3 nT, categorized as normal, as shown in Figure 5. This TEC anomaly could be the result of earthquake or the effect of Sumba earthquake which was detected in the ionosphere. TEC anomaly also appeared on DOY 34, but Dst index values showed the emergence of a geomagnetic storm that could be classified as intermediate storm. Thus the anomaly in the day could be geomagnetic storms effect.

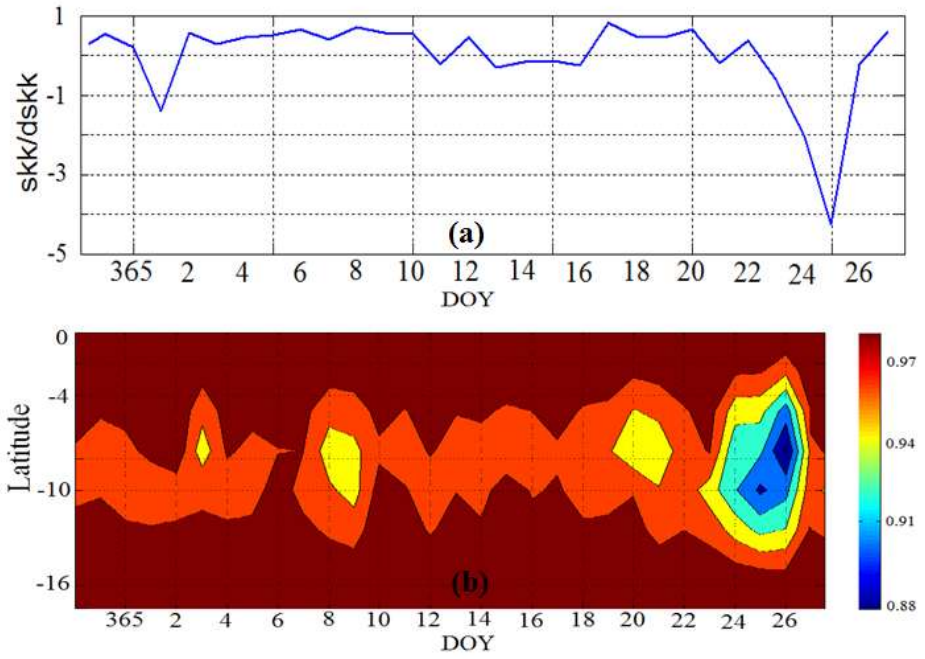


**Figure 2.** Skk/dskk value (a) and cross correlation of TEC data (b) from December 29, 2013 to January 28, 2014.

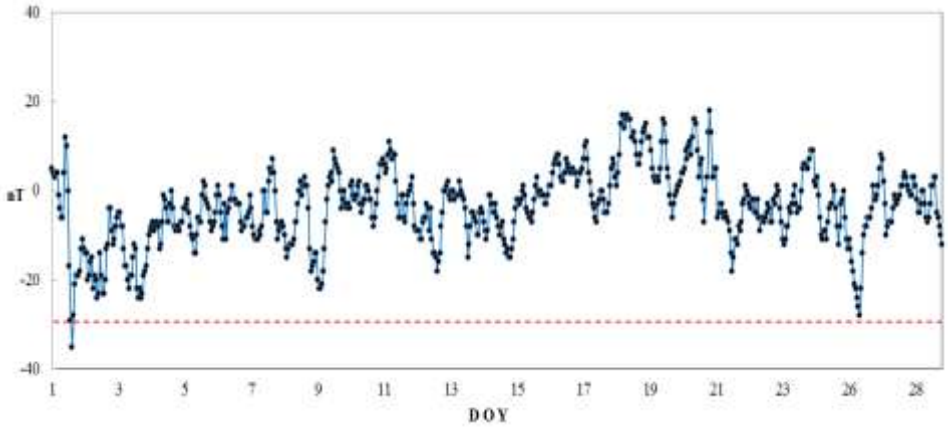


**Figure 3.** The Dst index values from January 1 to January 28, 2014.

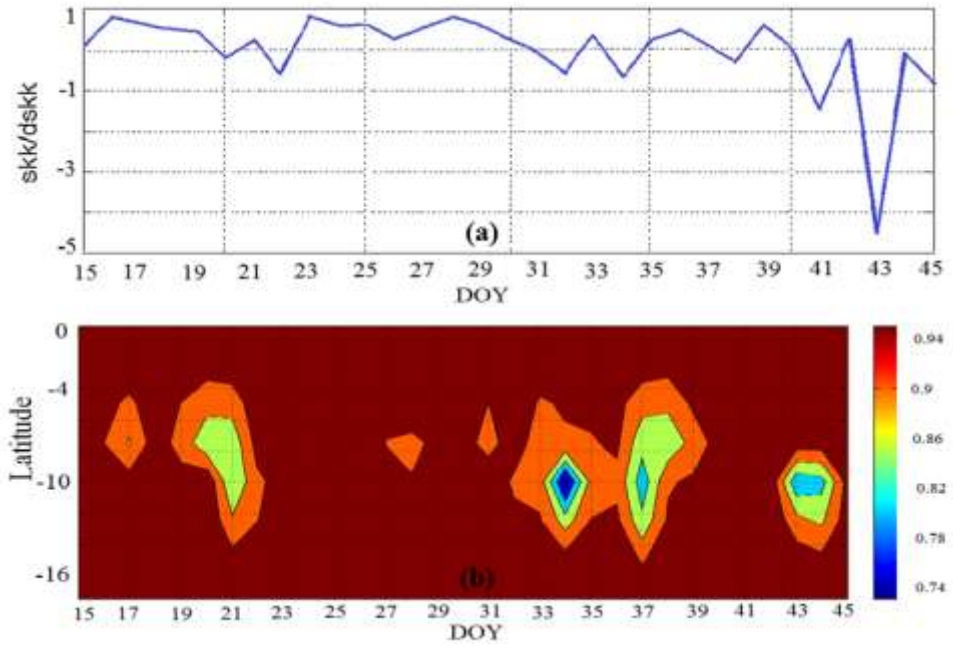


**Figure 4.** Skk/dskk values (a) and cross correlation of TEC data (b) from January 15 to February 14, 2016.

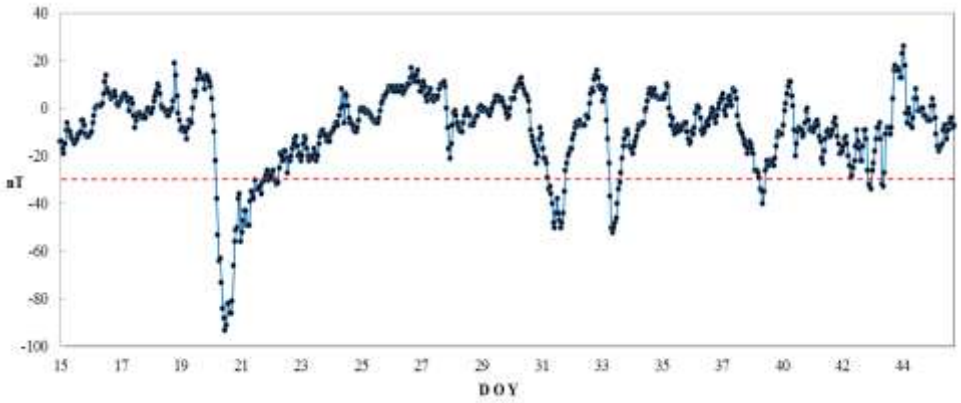


**Figure 5.** The Dst index values from January 15 to February 14, 2016**.**

Not all of earthquake effects can be detected using this method, for example in the case of February 17, 2016 Halmahera earthquake with magnitude Mw 6.1, as shown in Figure 6. In this case, it was not detected any TEC anomalies in the ionosphere as earthquake effect even though its magnitude almost similar to the previous earthquakes. TEC anomalies before an earthquake can be classified as earthquake precursor. The failure of correlation techniques to detect the earthquake effect was not caused by the incompatibility of this method for detecting the ionospheric effect, but due to the temporal resolution of the TEC data used i.e. 1 (one) hours, so the earthquake effects in gravitational waves acoustic form with period less than half an hour will not be appear in the one hour resolution TEC data. The results of this study provide hope to strengthen the earthquake and tsunami early warning system using TEC GPS data. The method development of continuous TEC GPS observation derived from GPS observation network that already exists in Indonesia is needed to support earthquake effects (or tsunami) early warning systems.

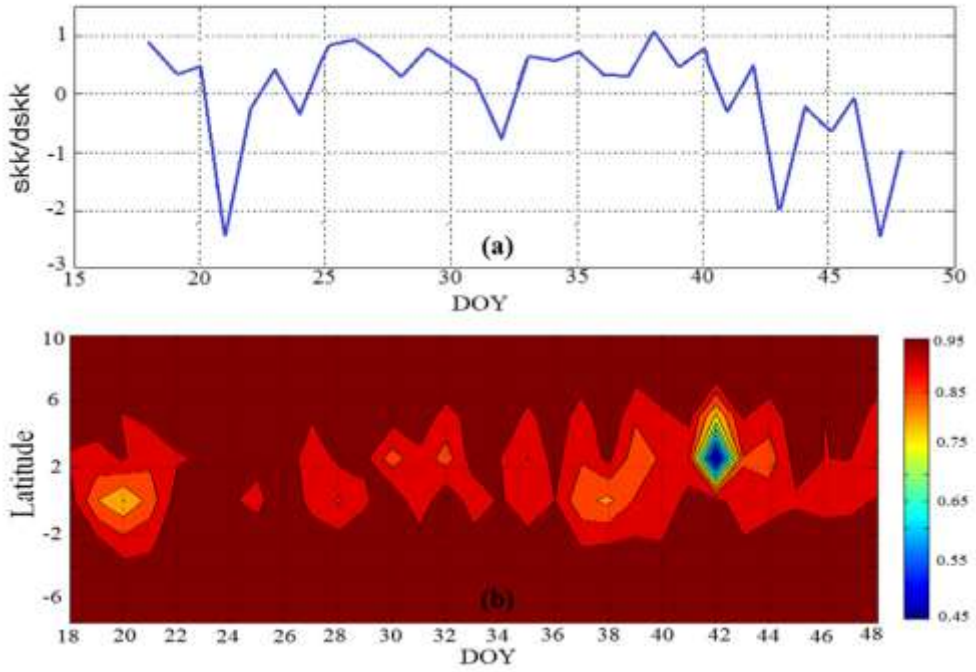


**Figure 6.** Skk/dskk values (a) and cross correlation of TEC data (b) from January 18 to February 17, 2016.

## 4. Conclusion

Based on Total Electron Content (TEC) data correlation, effects of The January 25, 2014 Kebumen earthquake and the February 12, 2016 Sumba earthquake could be detected in the ionosphere as TEC anomalous. However, not all earthquake effect could be detected in the ionosphere using this method. The failure of TEC data correlation method was due to poor temporal resolution of the TEC data. It was required the continuous monitoring of TEC GPS data to detect the earthquake effects in ionosphere.

## References

[1] Lin J W 2015 Early warning of tsunami from seismo-ionospheric fluctuation after Japan's March 11, 2011, M=9.0 Tohoku earthquake using two-dimensional principal component analysis *Annals of Geophysics* **58**

[2] Khegai V V, Legen'ka A D and Kim V P 2013 Anomalous variations in the foF2 critical frequency Above Japan prior to the earthquake of March 9, 2011 *Geomagn. Aeronomy* **53** (4) 529-533.

[3] Jin S G, Jin R and Li J H 2014 Pattern and evolution of Seismo-ionospheric disturbances following the 2011 Tohoku earthquakes from GPS observations, *J. Geophys. Res. Space Physics* **119**, 7914-7927.

[4] Muslim B, Effendi J, Aldrian E, Fachrizal, Sunardi B, and Angga 2014 Pengembangan Sistem Monitoring Gelombang Ionosfer Terkait Gempa Bumi Menggunakan Data GPS (GPSIonoquake), *Prosiding Seminar Nasional Sains Atmosfer dan Antariksa* 12–29.

[5] Lognonné P, Artru J, Garcia R, Crespon F, Ducic V, Jeansou E, Occhipinti G, Helbert J, Moreaux G, Godet P E 2006 Groundbased GPS imaging of ionospheric postseismic signal *Planetary and Space Science* **54** 528–540.

[6] Hao, Y Q, Xiao Z, and Zhang D H 2012 Multi-Instrument Observation on Co-Seismic

Ionospheric Effects after Great Tohoku Earthquake *Journal of Geophysical Research* **117**.
[7] Heki K, Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake *Geophys. Res. Lett.* **38** L17312.
[8] Le H, Liu L, Liu J Y, Zhao B, Chen Y, Wan W 2013 The ionospheric anomalies prior to the M 9.0 Tohoku-Oki earthquake *Journal of Asian Earth Sciences* **62** 476–484.
[9] Lin J W 2015 Early warning from seismic ionospheric anomaly of the 24 May 2014, M = 6.4 Aegean-Sea earthquake: two-dimensional principal component analysis (2DPCA) *Geofísica internacional* **54**-2 191-198.
[10] Muslim B, Pengujian teknik korelasi untuk deteksi pengaruh aktivitas gempabumi pada ionosfer *Jurnal Sains Dirgantara* **12** 87-101.
[11] Sunardi B, and Sulastri 2016 Pemantauan anomali Total Electron Content (TEC) berkaitan dengan kejadian gempabumi di sekitar wilayah Jawa tahun 2015 *SPEKTRA: Jurnal Fisika dan Aplikasinya* **1** (2) 95-102.
[12] Sunardi B, Buldan M, Pakpahan S 2015 Anomali Total Electron Content (TEC) sebelum gempabumi kuat di Indonesia Tahun 2014, *Prosiding Seminar Nasional Jurusan Fisika FMIPA Unesa* Surabaya.
[13] Rothacher M, Beutler G, Brockmann E, Mervart L, Schaer S, Springer T A, Wild U, Wiget A, Boucher C, Seeger H 1996a Annual Report 1995 of the CODE Analysis Center of the IGS, Astronomical Institute, University of Berne.
[14] Schaer S 1999 Mapping and Prediction the Earth Ionosphere using the Global Positioning System Doctoral Thesis University of Bern.
[15] S. Schaer 1997 How to use CODE's Global Ionosphere Maps Astronomical Institute, University of Berne.
[16] Gonzalez W D 1994 What is a geomagnetic storm*? J. Geophys. Res.* **99** 5771.
[17] Gonzales W D, Tsurutani B T, Clua de Gonzales A L 1999 Interplanetary origin of magnetic storms *Space Sci. Rev.* **88**.
[18] Real-time (Quicklook) Dst index [cited 2016 July 30]; available from : http://wdc. kugi.kyoto-u.ac.jp/dst_real time/index.html.