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Review of variations in $M_w < 7$ earthquake motions on position and tec ($M_w = 6.5$ aegean sea earthquake sample)

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Abstract

Turkey is a country located in Middle Latitude zone and in which tectonic activity is intensive. Lastly, an earthquake of magnitude 6.5M_w occurred at Aegean Sea offshore on date 24 May 2014 at 12:25 UTC and it lasted approximately 40 s. The said earthquake was felt also in Greece, Romania and Bulgaria in addition to Turkey.

In recent years seismic origin ionospheric anomaly detection studies have been done with TEC (Total Electron Contents) generated from GNSS (Global Navigation Satellite System) signals and the findings obtained have been revealed. In this study, TEC and positional variations have been examined seperately regarding the earthquake which occurred in the Aegean Sea. Then The correlation of the said ionospheric variation with the positional variation has been investigated. For this purpose, total fifteen stations have been used among which the data of four numbers of CORS-TR stations in the seismic zone (AYVL, CANA, IPSA, YENC) and IGS and EUREF stations are used. The ionospheric and positional variations of AYVL, CANA, IPSA and YENC stations have been examined by Bernese 5.0v software. When the (PPP-TEC) values produced as result of the analysis are examined, it has been understood that in the four stations located in Turkey, three days before the earthquake at 08:00 and 10:00 UTC, the TEC values were approximately 4 TECU above the upper limit TEC value. Still in the same stations, one day before the earthquake at 06:00, 08:00 and 10:00 UTC, it is being shown that the TEC values were approximately 5 TECU below the lower limit TEC value. On the other hand, the GIM-TEC values published by the CODE center have been examined. Still in all stations, it has been observed that three days before the earthquake the TEC values in the time portions of 08:00 and 10:00 UTC were approximately 2 TECU above, one day before the earthquake at 06:00, 08:00 and 10:00 UTC, the TEC values were approximately 4 TECU below the lower limit TEC value.

Again, by using the same fifteen numbers of stations, positional variation investigation before and after the earthquake has been made for AYVL, CANA, IPSA and YENC stations. As result of the analysis made, positional displacements has been seen be-

fore and after earthquake at CANA station which is the nearest station to earthquake center. It is about 10 and 3 cm before three days and one day earthquake.

1 Introduction

Turkey takes place on the Alpine-Himalayan seismic belt. Many numbers of earthquakes occurred from the past until today in Turkey, 42 % of its surface area of which is situated on first degree seismic belt. Destructive earthquakes which are short time lasting in terms of occurrence, cause many numbers of people to lose their lives and material damage at significant level. Because, it is not experienced only in some specific regions in the world, earthquake can be named as a global issue. Several countries in the world, are trying to find a way of solution on measures and decisions which could be taken in shortest time against this global issue. For such reason, in our day, various studies are being conducted to reduce the damage to a minimum level against an earthquake possibility which could occur in various countries, among which Turkey is present, too (https://www.afad.gov.tr/Dokuman/TR/72-2014052616857-ege-denizi-depremi-on-raporu-r.pdf).

Even though GNSS systems are a significant part of our daily life, in recent years it has made great contribution in terms of determining the external parameters which influence the globe where we live together in. Particularly, the need to generate increasingly high precision positional data has created the need to develop such systems. However, GNSS has found to itself in time many more fields of application. Particularly, monitoring the ionosphere which is one of the parameters that affects the world in recent years, was started by means of GNSS systems. For such reason, GNSS can be seen as an instrument which generates not only positional data but also an instrument serving to monitor the ionosphere, too (Jin et al., 2015).

The ionosphere can be defined as a dynamic structure, height from the ground of which changes between 60–100 km and accommodates in itself many numbers of free electrons. This being a dynamic structure originates from this giving response against natural events such as, geographical position, night-daytime, magnetic storm, earthquake, sun spot activity etc. Ionosphere which is the upmost stratum of the atmosphere, causes the signal be exposed to some impacts during the travel of the signal until it comes to the receiver from approximately 20 200 km. This impact exhibits itself as a retarder impact for code measurements, accelerator impact for phase measurements. The impact strength occurring in the code and phase measurements is equal but in opposite directions. Refractice index for code measurements is represented as;

$$n_k = 1 + \frac{40.3}{f^2} N_e \quad (1)$$

and, refractive index for phase measurements as

$$n_f = 1 - \frac{40.3}{f^2} N_e. \quad (2)$$

The electrons present as free electrons in the ionosphere reacts to many factors such as geomagnetic effect, solar activity, daytime–nighttime, seasonal, 11 year solar-cycle, earthquake. Thus precise estimates of total electron content are important for space weather research and predictions of the ionospheric variability.

Earthquake forecasting studies have been started to be examined by making use of this change exhibited by the electron content. As result of some works done it has been observed that there are some changes occurring in the TEC data which are function of the ionosphere stratum before, during and after earthquake (Zolotov et al., 2012; Namgaladze et al., 2012; Masci, 2013; Yao et al., 2012; Saroso et al., 2008). TEC is being defined as the total content of electrons along a cylinder 1 m^2 cross-section from the satellite to the receiver.

TEC can be obtained easily by making use of code and phase measurements in L1 and L2 frequencies (Cahyadi and Heki, 2013). TEC is achieved in three ways in general.

The first one of these is to use the code measurements. The TEC value obtained by making use of these measurements is approximately in accuracy of 1–5 TECU

(Liu et al., 2005). Code measurements containing much more noise with respect to phase measurements, causes the accuracy of TEC value to be obtained from code measurements to decrease. On the other hand, TEC value is obtained also by using only phase measurements. The accuracy of the TEC value to be obtained by this way is higher than the TEC accuracy obtained from code measurements. However, the obligation to eliminate the integer phase initial ambiguities in the TEC value obtained by using only phase measurements, comes out to be the biggest obstacle in obtaining a high precision TEC value. For this reason, use of TEC value obtained from phase measurements is not being recommended.

Another method is to obtain TEC value by smoothing the code measurements by phase measurements. While this method eliminates the obligation of removing the integer phase ambiguity, it also ensures in the same time the means to obtain TEC value in a practical way. When these three methods are compared with each other, no doubt the TEC value obtained by using phase measurements would be much more precise in case, the integer phase initial ambiguity is solved in the right way (Inyurt, 2015). However, the presence of many numbers of obstacles which would affect the solution of the integer phase ambiguity makes it difficult to obtain high precision TEC value from phase measurements. Because of the aforementioned reasons, the TEC values obtained in this study have been obtained from code measurements smoothed easily and with high accuracy (Inyurt, 2015).

TEC parameter is divided into two as STEC (Slant Total Electron Content) and VTEC (Vertical Total Electron Content). While STEC value represents the slant total electron content between satellite and receiver VTEC, represents the vertical electron content between satellite and receiver. STEC value is obtained from Eq. (3).

$$P_{4,a}^{h} = 40.3\left(\frac{f_2^2 - f_1^2}{f_1^2 - f_2^2}\mathrm{STEC}_a^h\right) + \mathrm{DCB}^h + \mathrm{DCB}_a \quad (3)$$

NHESSD
3, 5923–5956, 2015

The symbols here represent as follows; $P_{4,a}^{h}$: smoothed code observation, STEC_a^h: slant total electron content between satellite–receiver, DCB^h, DCB_a: receiver and satellite code bias value.

The TEC value obtained as slant has to be converted into vertical at an average ionospheric altitude. The STEC variations obtained by making use of GPS receivers in the study which single layer model has been used in, have been converted into VTEC by means of Single Layer Model (SLM). The Model assumes that all electrons present in the ionosphere are all accumulated in a layer of infinite thickness between 300 and 450 km from the earth. This model is a powerful method developed to draw the two dimensional map of the total electron content obtained by making use of GPS receivers.

2 The Aegean Sea (Gökçeada) earthquakes

An earthquake of magnitude $6.5M_\mathrm{w}$ occurred at Gökçeada offshore on date 24 May 2014 at 12:25 LT (Turkey time). The duration of the earthquake, central coordinates of which were determined as 40.2108° N, 25.3073° E, was recorded as 42 s. Within 48 h after the earthquake, 405 numbers of aftershocks occurred in various magnitudes. The aftershocks occurred are given in Fig. 1.

192, 186, and 27 numbers of aftershocks occurred on dates 24, 25, and 26 May 2014, respectively. The ionospheric and positional variations regarding the Gökçeada earthquake have been obtained by making use of CORS-TR (Continuously Operating Reference Station Network) stations. The distribution of the CORS-TR stations is given in Fig. 2.

NHESSD
3, 5923–5956, 2015

3 Determining the seismic origin tec variation

In this study, four numbers of CORS-TR stations (AYVL, CANA, IPSA, YENC) and 11 numbers of IGS and EUREF stations have been used. The distribution of the CORS-TR stations used is given in Fig. 3.

For four days before the earthquake, on the earthquake day and seven after the earthquake, the 30 s RINEX data from four stations (AYVL, CANA, IPSA, YENC) nearest to the central coordinates of the earthquake (40.2108° N, 25.3073° E) have been evaluated regarding ionospheric point of view. The RINEX data of IGS and EUREF stations have been obtained from ftp://igs.bkg.bund.de/IGS/obs/ address and the RINEX data of CORS-TR station from http://212.156.70.42/ address. Bernese 5.0v software offers two options to the user in obtaining the TEC values. While the first one of these is the Local Ionosphere Model in which Tylor expansion is used, the other one is the Regional/Global Ionosphere Model in which spherical harmonic expansion is used. In this study, the Tylor expansion falls short in obtaining TEC value. The Regional/Global ionosphere model uses spherical harmonic expansion in generating the TEC values. Because, it generates high precision TEC value, Regional/Global ionosphere model has been used in this study. During the evaluation phase, by means of the PPP.PCF module available in the Bernese software, the smoothed TEC values of AYVL, CANA, IPSA and YENC stations have been obtained in time intervals of two hours each. The SLM height used in converting the STEC value into VTEC has been determined as 450 km for Turkey, the maximum degree and rank of the spherical harmonic expansion (m, n) as (6, 6) (Inyurt, 2015). In order to investigate the accuracy of the TEC values obtained, the TEC values of the global ionosphere model (GIM) published by the Center For Orbit Determination in Europe (CODE) center have been downloaded from ftp://ftp.unibe.ch/aiub/CODE/2014/ address and comparison has been shown in Fig. 4. The TEC values of GIM are being published in IONEX (Ionosphere Map Exchange) format and its positional resolution is $2.5° \times 5°$, timewise resolution is two hours. In the first stage of the study the ionospheric variation in the seismic zone has been monitored by

NHESSD
3, 5923–5956, 2015

making use of AYVL, CANA, IPSA and YENC stations located at nearest position to the seismic zone present in Turkey. The TEC variations regarding the said stations are given in Figs. 4–7.

Figures 4–7 show the (PPP-TEC) generated as result of analysis and the (GIM-TEC) values published by the CODE center for CANA, AYVL, IPSA and YENC stations, respectively. The blue color in the figures shows the TEC values generated as result of analysis and the red color states the TEC values published by the CODE center. In order to be able to understand whether any anomaly is present before or after the earthquake, both, the TEC values generated as result of the analysis and the TEC values published by the CODE center have been examined separately. The minimum and maximum values of the TEC values obtained through both ways are shown in Table 1.

Table 1 shows the minimum and maximum values of the (PPP-TEC) generated as result of analysis and the (GIM-TEC) values published by the CODE center for four stations located in Turkey. According to the TEC values obtained as result of analysis, it has been seen that the maximum TEC value belongs to YENC station, whereas, the minimum TEC value belongs to AYVL station. In the evaluation made according to GIM-TEC values, it is being understood that the maximum TEC value is in AYVL station, whereas, the minimum TEC value belongs to CANA station.

By making use of the TEC values regarding the four stations, the average TEC values in time intervals of two hours each, have been produced from both, the TEC values generated as result of analysis and the TEC values published by the CODE center and by taking as reference these average TEC values, the standard deviation values regarding the days analyzed have been found. The numerical values obtained for AYVL, CANA, IPSA and YENC stations are shown in Tables 2–5.

In the evaluation made by taking into account the lower and upper limit TEC values of (PPP-TEC) values, it has been understood that in all four stations the TEC values three days before the earthquake at times 08:00 and 10:00 UTC were approximately 4 TECU above the upper limit TEC value. And, on the other hand, the TEC values at

NHESSD
3, 5923–5956, 2015

times 06:00, 08:00 and 10:00 UTC one day before the earthquake are approximately 5 TECU below the lower limit TEC value.

When the GIM-TEC values published by the CODE center are examined, still in all stations, these are approximately 2 TECU above the TEC values at times 08:00 and 10:00 UTC three days before the earthquake. One day before the earthquake at times 06:00, 08:00 and 10:00 UTC, TEC values are approximately 4 TECU below the lower limit TEC value. In order to understand whether the said variations originate from the earthquake or not, the K_p, D_{st} indices giving information about ionospheric activity have been examined for these days analyzed and it has been observed that the ionosphere was quite silent on those days.

4 Seismic origin positional variation

In the second part of the application, the positional variations have been examined in CORS-TR stations (AYVL, CANA, IPSA, YENC) arising from Gökçeada earthquake. The distribution of IGS and CORS-TR stations used in the application is shown in Fig. 8.

In the application for which Bernese 5.0v academic software has been used, first of all approximate coordinates have been calculated with PPP (Precise Point Positioning) (Yildirim et al., 2013). The approximate coordinates have been calculated by using the satellite-receiver time errors generated in 5 min intervals by IGS in addition to the code and phase measurements of CORS-TR stations. The coordinates of all stations used in the study have been calculated as independent from each other by not considering any network structure. The coordinates calculated have been used as before balance preliminary values of double difference solutions to be made later on. After the preliminary values are determined, the double difference solution has been started. In this stage the coordinate values of IGS points used in network structure established have been used. The parameters used in the evaluation stage are given Table 6a and b.

Coordinate variations before earthquake, during and after earthquake have been analyzed for AYVL, CANA, IPSA and YENC stations and coordinate variations for each station have been shown in Figs. 9–12.

Figures 9–12 show, respectively, the positional variations before and after earthquake at AYVL, CANA, IPSA and YENC stations. While the blue color taking place in the legend shows the change that occurred in x axis direction, the Orange and grey colors represent, respectively, the displacement in y and z axes direction. When looked at the figures, except CANA station, no meaningful change occurred in the other stations. And, in the CANA station which is the nearest one to the earthquake center, variations of approximately 10 cm have been experienced on all three axes particularly three days before the earthquake and a variations of approximately 3 cm particularly on X axis have been experienced one day before the earthquake. The said variations have lost their impact one week after the earthquake and reached at their original position.

5 Conclusions and recommendations

In recent years they are becoming increasingly accelerated the studies to determine the TEC value which is a function of the ionosphere that is the upmost stratum of the atmosphere. In this study it has been examined the correlation between the ionospheric and positional variation caused by the earthquake of magnitude $6.5 M_w$ occurred at Aegean Sea offshore on date 24 May 2014, by the data of total fifteen stations, four being TUSAGA-Active (CORS), for five days before earthquake and seven days after earthquake.

In the statistical analysis made for the TEC value (PPP-TEC) generated as result of analysis and the GIM-TEC values taken from the CODE center, it has been seen that in specific times before and after the earthquake, these have were deviated and gone out of the lower and upper limit TEC values. On the other hand, the positional variations of the said stations have been examined before and after earthquake. In the findings obtained, variation of approximately 10 cm has been detected in x, y and z directions three days before the earthquake, a variation of approximately 3 cm in x direction one day before the earthquake. These variations which occurred in CANA station located at a nearest position to the center of the earthquake have returned to their original position approximately one week after the earthquake. In this study, occurrence of variation in terms of both, ionospheric and positional sense particularly three days and one day before the earthquake, is strengthening the possibility of seismic origin anomaly occurence condition. However, in order it can be said definitely that it is a seismic origin anomaly, it is being thought that upper air, geophysical and geological data are required.

Acknowledgements. All Data were processed using the Bernese 5.0 software of Dach et al. (2011).

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Table 1. PPP-TEC and GIM-TEC maximum and minimum values representation.

Stations	Minimum (PPP-TEC) TECU	Maximum (PPP-TEC) TECU	Minimum (GIM-TEC) TECU	Maximum (GIM-TEC) TECU
AYVL	10.6	41.5	13.1	44.3
CANA	12.1	44.1	10.2	39.7
IPSA	13.0	43.1	10.6	39.8
YENC	13.1	44.4	10.4	41.0

NHESSD
3, 5923–5956, 2015

Table 2. AYVL station two-hour resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
00:00	14.79	2.19	18.09	2.11
02:00	12.22	1.07	15.35	1.41
04:00	19.47	1.99	22.71	2.20
06:00	25.99	3.52	28.57	3.81
08:00	29.03	4.85	31.28	5.28
10:00	31.34	6.21	33.45	6.68
12:00	30.18	5.12	32.43	5.49
14:00	28.27	4.06	31.78	4.32
16:00	27.32	3.15	30.79	3.58
18:00	26.69	3.39	30.03	3.89
20:00	20.89	2.99	23.40	3.14
22:00	16.24	2.16	18.50	2.28

Table 3. CANA station two-hour resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
00:00	17.55	1.39	14.08	1.91
02:00	14.79	1.52	11.68	0.93
04:00	22.00	2.42	19.12	2.01
06:00	28.15	4.12	25.40	3.70
08:00	31.09	5.44	28.16	4.93
10:00	33.56	6.57	29.99	6.13
12:00	34.09	5.65	28.56	4.97
14:00	32.22	4.31	27.17	3.97
16:00	31.34	3.50	26.35	3.08
18:00	30.02	3.81	26.20	3.33
20:00	23.91	2.72	20.32	2.94
22:00	19.34	1.97	15.48	2.06

Table 4. IPSA station two-hour resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
00:00	17.70	1.87	14.08	1.91
02:00	15.15	1.30	11.68	0.93
04:00	22.61	2.20	19.12	2.01
06:00	28.16	3.88	25.40	3.70
08:00	30.66	5.34	28.16	4.93
10:00	32.63	6.62	29.99	6.13
12:00	31.26	5.30	28.56	4.97
14:00	30.98	4.25	27.17	3.97
16:00	30.20	3.54	26.35	3.08
18:00	29.45	3.80	26.20	3.33
20:00	22.90	3.14	20.32	2.94
22:00	17.95	2.26	15.48	2.06

NHESSD
3, 5923–5956, 2015

Table 5. YENC station two-hour resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
00:00	18.08	2.13	14.50	2.08
02:00	15.37	1.41	12.02	0.97
04:00	22.90	2.21	19.55	2.07
06:00	28.69	3.76	25.91	3.59
08:00	31.41	5.31	28.90	4.92
10:00	33.53	6.70	31.01	6.20
12:00	32.43	5.47	29.62	5.07
14:00	31.85	4.32	27.88	4.00
16:00	30.80	3.60	27.05	3.12
18:00	30.02	3.89	26.50	3.38
20:00	23.35	3.12	20.65	2.97
22:00	18.47	2.30	15.95	2.14

NHESSD
3, 5923–5956, 2015

Table 6. (a) Evalution strategy of gps measurements with Bernese 5.0v software (model). **(b)** Evalution strategy of GPS measurements with Bernese 5.0v software (parameters).

(a)
Pre-assessment: on the base-base mode, it has been performed by using phase measurements and triple difference method. Different linear combinations of L1 and L2 carrier phases have synchronously been examined and the cycle slips have been fixed. In cases where cycle slips could not be determined exactly, incorrect measurements have been removed or ambiguity has been added. Basic measurements: carrier phase measurements have been used. Code measurements were used for synchronization of receiver clock and GPS time only. Cut-off Angle: 10° Data interval: 30 s Weighting: on zenith angle, for double difference measurements independent from ionosphere, 6 mm has been taken. Weighting function dependent from elevation angle has been taken as $1/\cos(z)^2$. Modelled Measurements: linear combinations of double difference measurements are considered independent from ionosphere. GPS antenna phase centre calibration: elevation angle-dependent phase centre corrections have been applied according to the IGS05.ATX model and during evaluation of measures absolute corrections were applied to the receiver antennas. The PHAS _COD.I05 file was used for receiver antennas. The SATELLIT.I05 file was used for GPS satellite antennas. Troposphere: A priori model: hydrostatic component has been modelled with dry-Niell correction function and the Saastamoinen model was applied. Meteorological data: not used The unknowns of zenith delay have been calculated by using the wet-Niell projection function for each station in intervals of 2 h. Constraints: 1 m has been defined as pre-condition for relative zenith delay values. Correction function: for both dry and wet components, the Niell correction function was used. Ionosphere: it has not been modelled (first-degree influences have been eliminated by the combination of L1 and L2 carrying phase measurements independent from ionosphere). In addition, for the solution of initial phase of uncertainty (ambiguity), the global ionosphere values obtained from Centre for Orbit Determination in Europe (CODE) by using GPS were used. Earth rotation parameters: IGS combined earth rotation parameters (final) Orbit Models: IGS precise orbit (final) Earth geo-potential model: JGM3 Planet ephemeris: JPL DE200 Tide touring of solid earth: IERS 1996 Ocean: FES2004 Atmospheric Loading: not applied. Crustal Movements: the velocities of IGS points have been taken in the ITRF2008 coordinate system.
(b)
Adjustment Point Coordinates: the least squares method was applied Point Coordinates: the ITRF 2008 coordinate system has been used with using point coordinates and velocities of the stations given during solution of IGS08.SNX. Satellite Clock Errors: satellite clock errors have been eliminated by double differences method Receiver Clock Errors: receiver clock errors have been calculated with using pseudo-range measures during pre-assesment phase have been removed from the evalution Base Selection: OBSMAX principle has been used. Ambiguity: the QIF has been applied.

NHESSD
3, 5923–5956, 2015

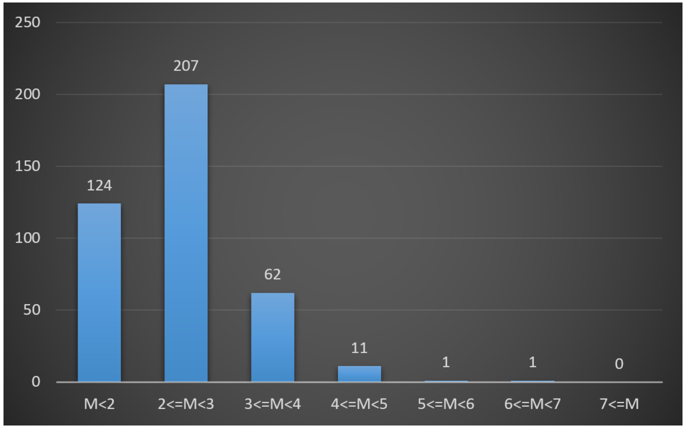

Figure 1. Graphical distribution of aftershocks (https://www.afad.gov.tr/Dokuman/TR/72-2014052616857-ege-denizi-depremi-on-raporu-r.pdf).

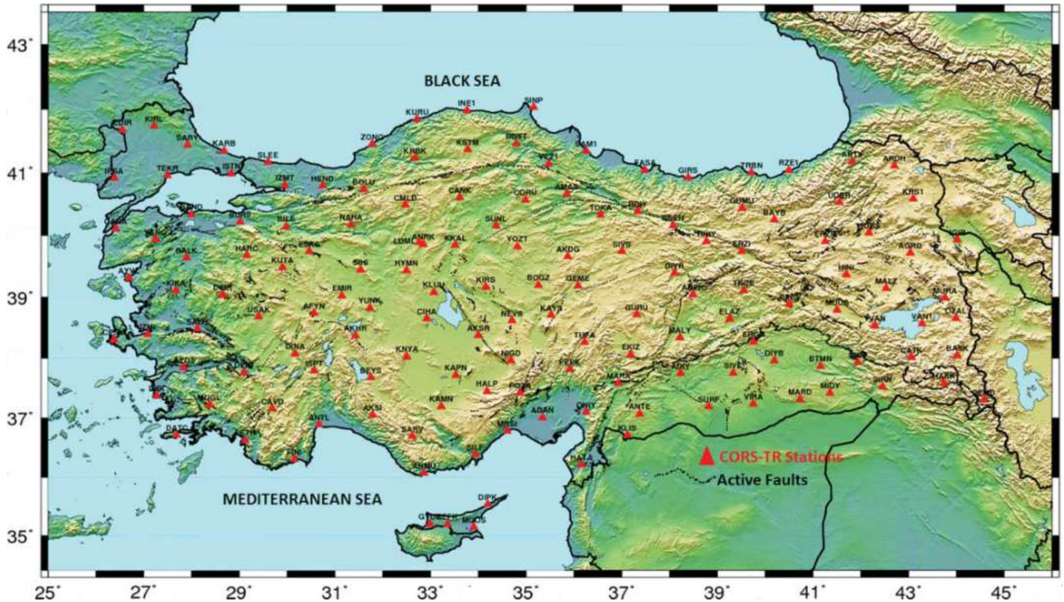

Figure 2. CORS-TR stations (Yildirim et al., 2013).

NHESSD
3, 5923–5956, 2015

Review of variations in $M_w < 7$ earthquake motions

O. Yildirim et al.

Figure 3. The CORS-TR stations used.

NHESSD
3, 5923–5956, 2015

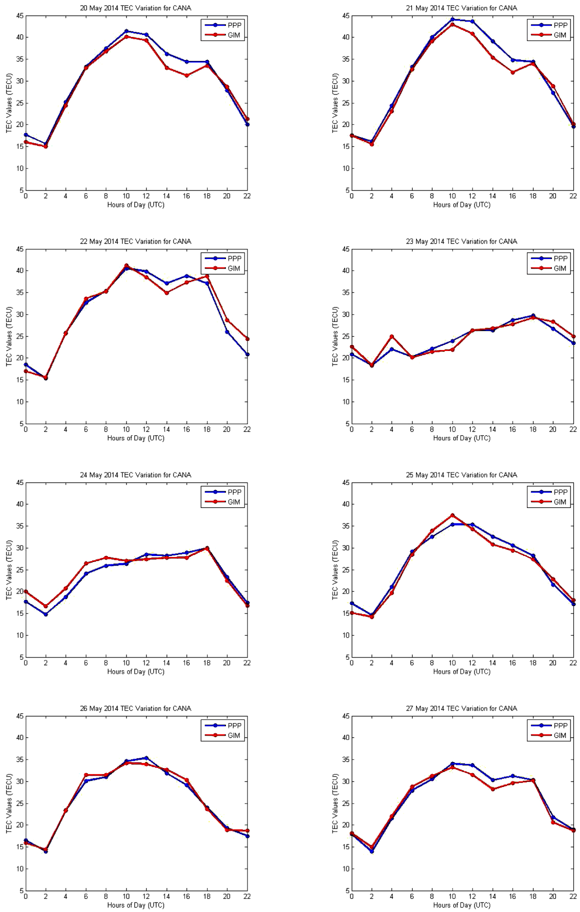

Figure 4.

NHESSD

3, 5923–5956, 2015

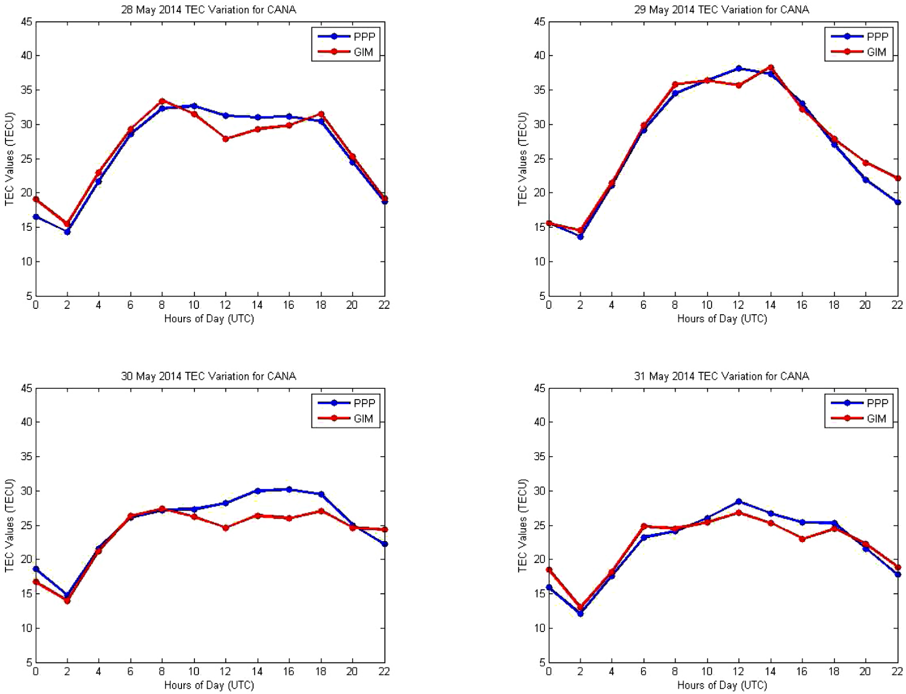

Figure 4. Representation of PPP and GIM TEC values for CANA station.

NHESSD
3, 5923–5956, 2015

Review of variations in $M_w < 7$ earthquake motions

O. Yildirim et al.

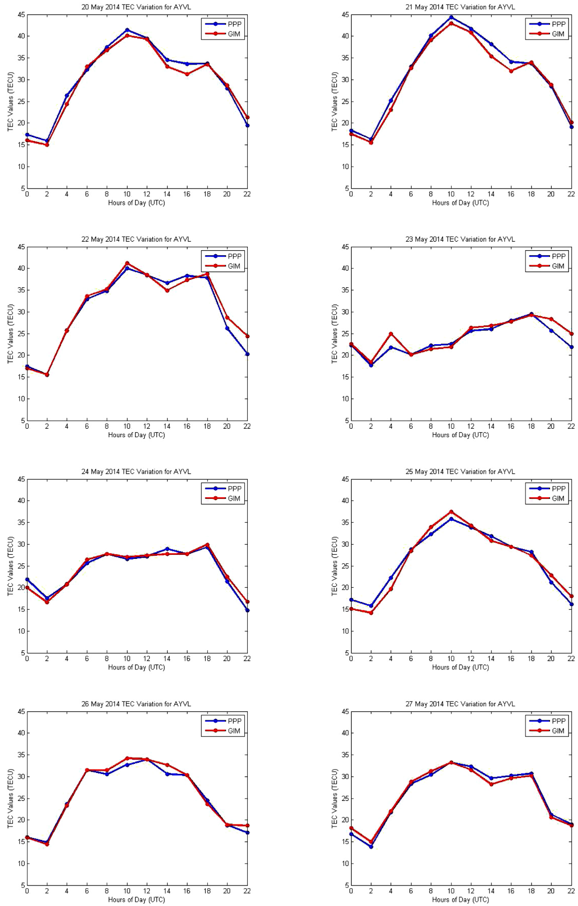

Figure 5.

NHESSD
3, 5923–5956, 2015

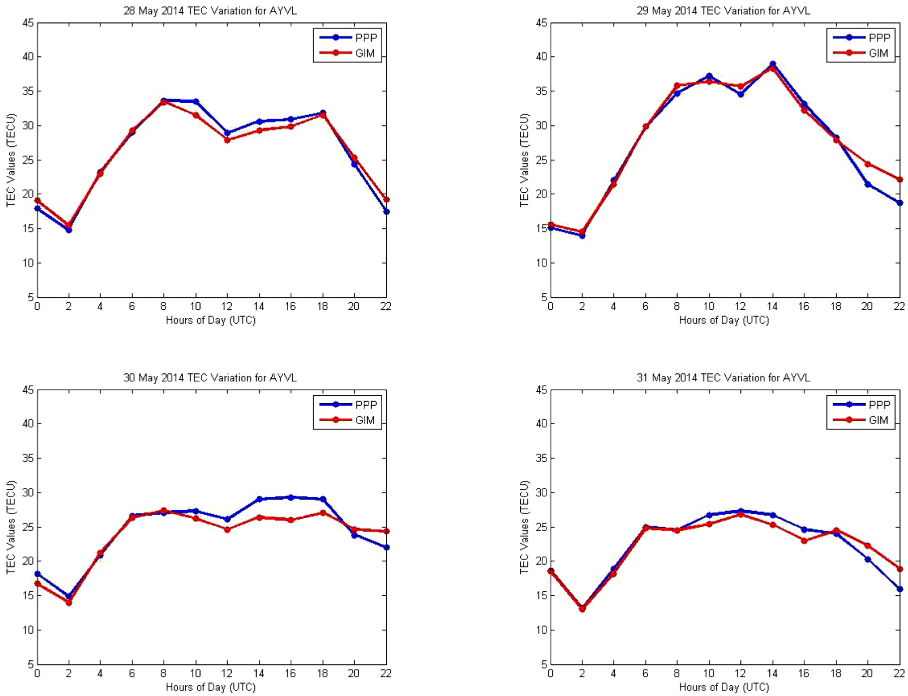

Figure 5. Representation of PPP and GIM TEC values for AYVL station.

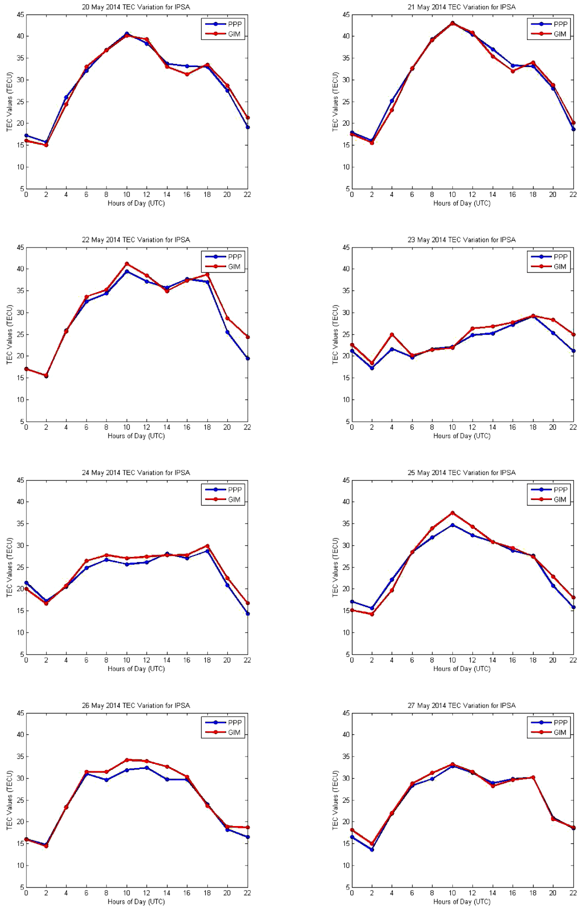
20 May 2014 TEC Variation for IPSA
21 May 2014 TEC Variation for IPSA
22 May 2014 TEC Variation for IPSA
23 May 2014 TEC Variation for IPSA
24 May 2014 TEC Variation for IPSA
25 May 2014 TEC Variation for IPSA
26 May 2014 TEC Variation for IPSA
27 May 2014 TEC Variation for IPSA
PPP
GIM
TEC Values (TECU)
Hours of Day (UTC)

Figure 6.

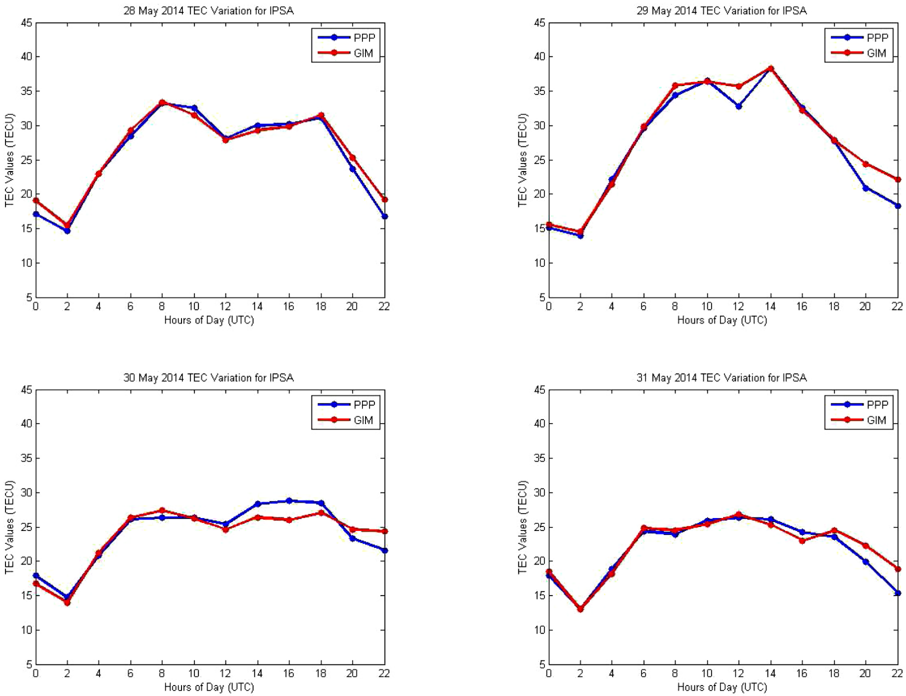

Figure 6. Representation of PPP and GIM TEC values for IPSA station.

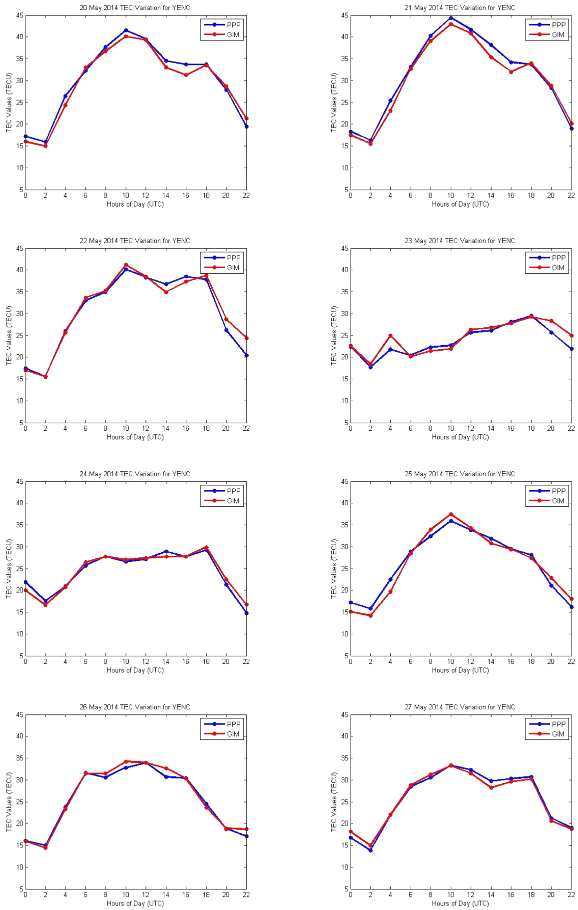

Figure 7.

NHESSD
3, 5923–5956, 2015

Review of variations in $M_w < 7$ earthquake motions

O. Yildirim et al.

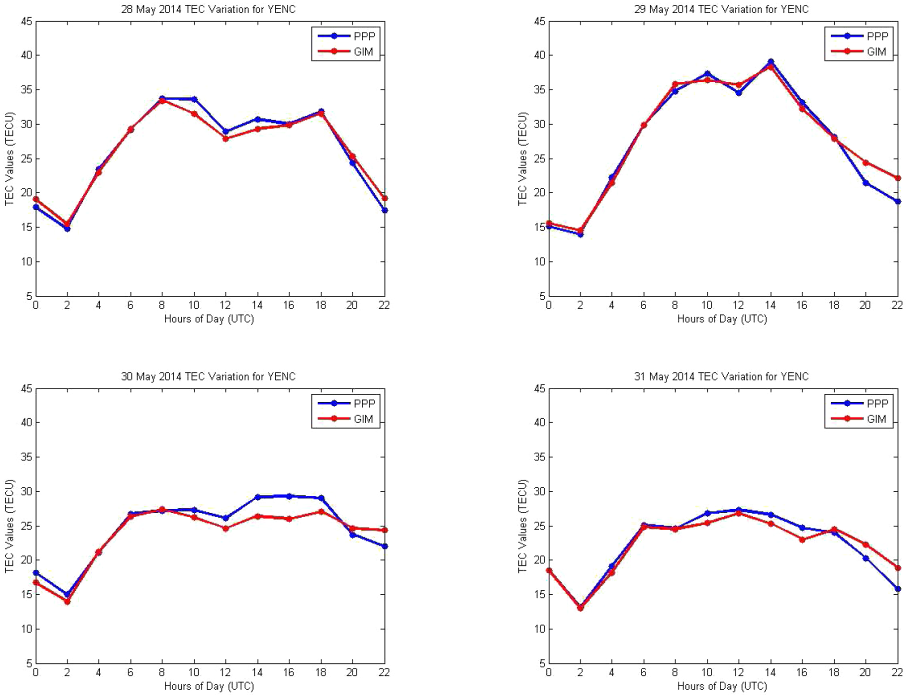

Figure 7. Representation of PPP and GIM TEC values for YENC station.

NHESSD
3, 5923–5956, 2015

Figure 8. CORS-TR and IGS stations distribution.

NHESSD
3, 5923–5956, 2015

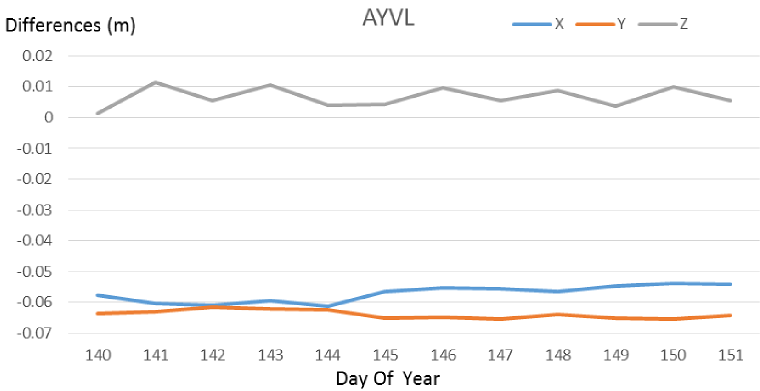

Figure 9. AYVL station coordinate variations.

NHESSD
3, 5923–5956, 2015

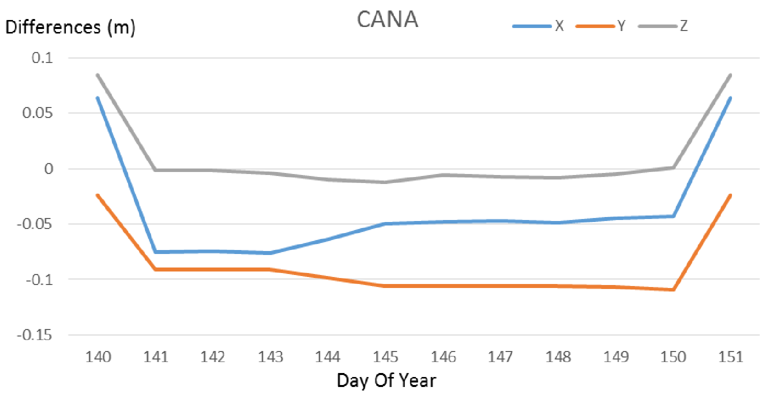

Figure 10. CANA station coordinate variations.

NHESSD
3, 5923–5956, 2015

Review of variations in $M_w < 7$ earthquake motions

O. Yildirim et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

NHESSD
3, 5923–5956, 2015

Review of variations in $M_w < 7$ earthquake motions

O. Yildirim et al.

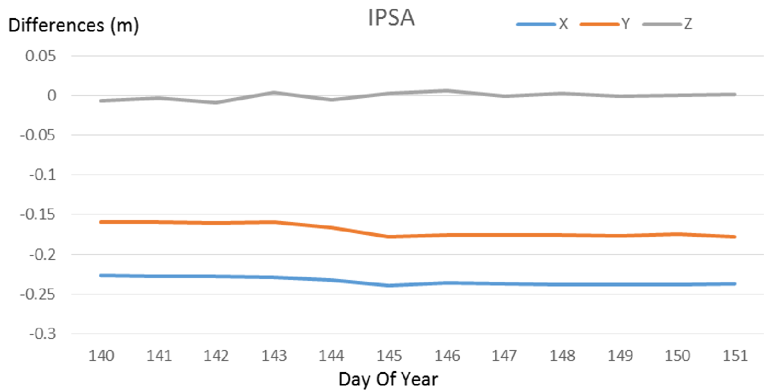

Figure 11. IPSA station coordinate variations.

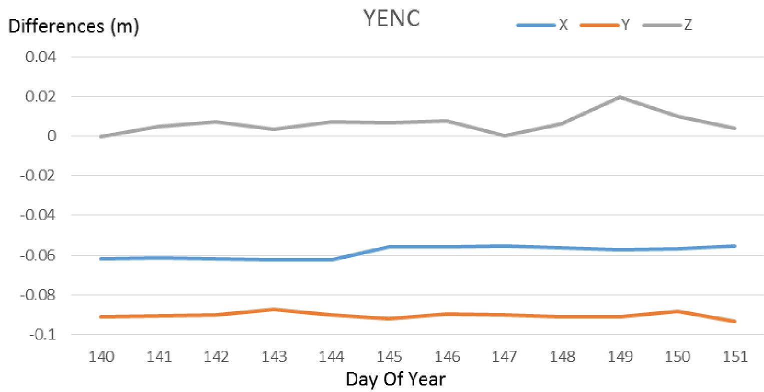

Figure 12. YENC station coordinate variations.

NHESSD
3, 5923–5956, 2015

Review of variations in $M_w < 7$ earthquake motions

O. Yildirim et al.