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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 the middle latitude zone, where tectonic activity is intensive. Recently, an earthquake of magnitude 6.5 $M_{\rm W}$ occurred offshore in the Aegean Sea on 24 May 2014 at 09: 25 UTC, which lasted about 40 s. The earthquake was also felt in Greece, Romania, and Bulgaria in addition to Turkey.

In recent years, ionospheric anomaly detection studies have been carried out because of seismicity with total electron content (TEC) computed from the global navigation satellite system's (GNSS) signal delays and several interesting findings have been published. In this study, both TEC and positional variations have been examined separately following a moderate size earthquake in the Aegean Sea. The correlation of the aforementioned ionospheric variation with the positional variation has also been investigated. For this purpose, a total of 15 stations was used, including four continuously operating reference stations in Turkey (CORS-TR) and stations in the seismic zone (AYVL, CANA, IPSA, and YENC), as well as international GNSS service (IGS) and European reference frame permanent network (EPN) stations. The ionospheric and positional variations of the AYVL, CANA, IPSA, and YENC stations were examined using Bernese v5.0 software. When the precise point positioning TEC (PPP-TEC) values were examined, it was observed that the TEC values were approximately 4 TECU (total electron content unit) above the upper-limit TEC value at four stations located in Turkey, 3 days before the earthquake at 08:00 and 10:00 UTC. At the same stations, on the day before the earthquake at 06:00, 08:00, and 10:00 UTC, the TEC values were approximately 5 TECU below the lower-limit TEC value. The global ionosphere model TEC (GIM-TEC) values published by the Centre for Orbit Determination in Europe (CODE) were also examined. Three days before the earthquake, at all stations, it was observed that the TEC values in the time period between 08:00 and 10:00 UTC were approximately 2 TECU above the upper-limit TEC value; 1 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 15 stations, positional variation investigation for before and after the earthquake was undertaken for the AYVL, CANA, IPSA, and YENC stations. As a result of the conducted analysis, positional displacements were seen before and after the earthquake at the CANA station, which is the nearest station to the earthquake centre. Before and after the earthquake, positional displacements were observed as 10 and 3 cm respectively.

1 Introduction

Turkey is situated on the Alpine–Himalayan seismic belt. Many earthquakes have occurred in the past in Turkey, of which 42% of the surface area is situated on a first-degree seismic belt. Destructive earthquakes that are brief in terms of occurrence cause large numbers of people to lose their lives and inflict material damage at a significant level. Because they are not an isolated experience, earthquakes can be deemed a global issue. Several countries in the world are trying to find a solution for measures and decisions that could be developed in the shortest possible time against this global issue. For this reason, nowadays various studies are being conducted to discover how to reduce the damage to a minimum



Figure 1. Graphical distribution of aftershocks (URL-1)



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

level during an earthquake possibility, which could occur in various countries, including Turkey (URL-1).

Even though GNSS systems are a significant part of our daily life, in recent years they have made an even greater contribution in terms of determining external parameters, which influence the world in which we all live. In particular, the need to generate increasingly high precision positional data has created the need to develop such systems. However, GNSS has been used in many more fields of application. Monitoring the ionosphere, which is one of the parameters that has affected the world in recent years, was started by means of GNSS systems. For this reason, GNSS can be seen as an instrument that generates not only positional data; it is also an instrument that monitors the ionosphere (Jin et al., 2015).

The ionosphere can be defined as a dynamic structure. Its height above ground changes between 60 and 1000 km and accommodates in itself many numbers of free electrons. The structure's dynamism originates from this, giving response to natural events such as geographical position, night– daytime, magnetic storms, earthquakes, and sun spot activity. The ionosphere, which is the upmost stratum of the atmosphere, causes the signal to be exposed to certain impacts during the travel of the signal until it comes to the receiver



Figure 3. The CORS-TR stations used.

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from approximately 20 200 km. This impact exhibits itself as a retarder impact for code measurements and as an accelerator impact for phase measurements. The impact strength, occurring in the code and phase measurements, is equal but in opposite directions. The refractive index for code measurements is represented as

$$n_{\rm k} = 1 + \frac{40.3}{f^2} N_{\rm e} \tag{1}$$

and the refractive index for phase measurements is represented as

$$n_{\rm f} = 1 - \frac{40.3}{f^2} N_{\rm e}.$$
 (2)

Equations (1) and (2) show the refractive index for code and phase measurements. While N_e states electron density, f indicates frequency in Eqs. (1) and (2). It can be seen from the refractive index formula that the propagation of microwave signals through the ionosphere depends on the frequency of the signals. In order to quantify these effects, the refractive index of the ionosphere should be specified. The electrons presented as free electrons in the ionosphere react to many factors, such as geomagnetic effects, solar activity, daytime and nighttime, seasons, 11-year solar cycles, and earthquakes. Thus, precise estimates of TEC are important for space weather research and predictions of ionospheric variability.

Earthquake forecasting studies have started to be examined by making use of the change exhibited by the electron content. As a result of some research, it has been observed that there are changes occurring in the TEC data, which are functions of the ionosphere stratum before, during, and after earthquakes (Zolotov et al., 2012; Namgaladze et al., 2012; Masci, 2013; Yao et al., 2012; Saroso et al., 2008). TEC is defined as the total content of electrons along a cylinder with a 1 m² 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). In general, TEC is achieved in three ways.





21 May 2014 TEC variation for CANA

Figure 4.

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

The first of these methods is the use of code measurements. The TEC value obtained by making use of these measurements has an accuracy of approximately 1–5 TECU (Liu et al., 2005). Code measurements, containing much more noise with respect to phase measurements, cause decreases in the accuracy of the TEC value obtained. On the other hand, the TEC value is also obtained by using only phase measurements. The accuracy of the TEC value obtained in 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, is the biggest obstacle in obtaining a high-precision TEC value. For this reason, use of the TEC value obtained from phase measurements alone is not recommended.

Another method for obtaining the TEC value is by smoothing the code measurements with phase measurements. While this method eliminates the obligation of removing the integer phase ambiguity, it also simultaneously ensures the means to obtain TEC value in a practical way. When these three methods are compared, there is no doubt that the TEC value obtained by using phase measurements would be much more precise if the integer phase initial ambiguity is solved correctly (Inyurt, 2015). However, the presence of many obstacles, which would affect the solution of the integer phase ambiguity, makes it difficult to obtain high-precision TEC values 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).

The TEC parameter is divided into two: the slant total electron content (STEC) and the vertical total electron content (VTEC). While the STEC value represents the slant total electron content between satellite and receiver, VTEC represents the vertical electron content between satellite and receiver. The STEC value is obtained from

$$P_{\rm a}^{\rm h} = 40.3 \left(\frac{f_2^2 - f_1^2}{f_1^2 f_2^2} \right) {\rm STEC}_{\rm a}^{\rm h} + {\rm DCB}^{\rm h} + {\rm DCB}_{\rm a}, \tag{3}$$

where P_a^h is smoothed code observation, STEC_a^h is slant total electron content between satellite and receiver, DCB^h, DCB_a are receiver and satellite code bias values, and f_1 , f_2 are signal frequencies (1575.42 and 1227.60 MHz).

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 GNSS receivers in the study, in which a single-layer model (SLM) was used, was converted into VTEC by means of the SLM. The model assumes that all electrons present in the ionosphere are accumulated in a layer of infinite thickness between 300 km and 450 km from the Earth. This model is a powerful method, developed to draw a two-dimensional map of the TEC obtained by making use of GNSS receivers.







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

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

2 The Aegean Sea (Gokceada) earthquakes

An earthquake of magnitude $6.5 M_w$ occurred offshore at Gokceada on 24 May 2014 at 12.25 local time (LT). The duration of the earthquake, the central coordinates of which were determined as $40^{\circ}2108'$ N, $25^{\circ}3073'$ E, was recorded as 40 s. Within 48 hours of the earthquake, 405 aftershocks occurred at various magnitudes. The aftershocks that occurred are given in Fig. 1.

Following the earthquake, 192, 186, and 27 aftershocks occurred on 24, 25, and 26 May 2014, respectively. The ionospheric and positional variations regarding the Gokceada earthquake were obtained by making use of the CORS-TR stations. The distribution of the CORS-TR stations is given in Fig. 2.

3 Determining the seismic origin TEC variation

In this study, four CORS-TR stations (AYVL, CANA, IPSA, and YENC) and 11 IGS and EPN stations (ANKR, BUCU, GRAS, GRAZ, MATE, NICO, POTS, RAMO, SOFI, VILL, and ZIMM) were used. The distribution of the CORS-TR stations used is given in Fig. 3.

For data from 4 days before the earthquake, on the earthquake day, and 7 days after the earthquake, the 30 s receiverindependent exchange format (RINEX) data from four stations (AYVL, CANA, IPSA, and YENC) nearest to the central coordinates of the earthquake ($40^{\circ}2108'$ N, $25^{\circ}3073'$ E) were evaluated regarding the ionospheric point of view. A pre-earthquake data span of 4 days is considered sufficient since the detected ionospheric anomalies for large earthquakes (such as M_w 9.0 Great Tohoku (Japan, Sendai) on 11 March 2011 and M 7.1 Turkey Van on 23 October 2011) are within 3 days before the earthquake in the literature (Zolotov



Figure 6.

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

Table 2. AYVL station 2 h resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
0	14.79	2.19	18.09	2.11
2	12.22	1.07	15.35	1.41
4	19.47	1.99	22.71	2.20
6	25.99	3.52	28.57	3.81
8	29.03	4.85	31.28	5.28
10	31.34	6.21	33.45	6.68
12	30.18	5.12	32.43	5.49
14	28.27	4.06	31.78	4.32
16	27.32	3.15	30.79	3.58
18	26.69	3.39	30.03	3.89
20	20.89	2.99	23.40	3.14
22	16.24	2.16	18.50	2.28

et al., 2012). The RINEX data of the IGS and EPN stations were obtained from the URL-2 address, and the RINEX data of the CORS-TR station from the URL-3 address. Bernese v5.0 software offers two options to the user in obtaining the TEC values. While the first option is the local ionosphere model, in which Taylor expansion is used, the other is the regional/global ionosphere model, in which spherical harmonic expansion is used. In this study, the Taylor expansion falls short in obtaining the TEC value. The regional/global ionosphere model uses spherical harmonic expansion in generating the TEC values. Because it generates a high-precision TEC value, the 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 the AYVL, CANA, IPSA- and YENC stations were obtained in time intervals of 2 h each. The SLM height used in converting the STEC value into VTEC was determined as 450 km for Turkey, and the max-



Figure 7.

PPP GIM

20 22

- PPP GIM

20 22

PPP GIM

20

PPP GIM

22



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

Table 3. CANA station 2 h resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC)U) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
0	17.55	1.39	14.08	1.91
2	14.79	1.52	11.68	0.93
4	22.00	2.42	19.12	2.01
6	28.15	4.12	25.40	3.70
8	31.09	5.44	28.16	4.93
10	33.56	6.57	29.99	6.13
12	34.09	5.65	28.56	4.97
14	32.22	4.31	27.17	3.97
16	31.34	3.50	26.35	3.08
18	30.02	3.81	26.20	3.33
20	23.91	2.72	20.32	2.94
22	19.34	1.97	15.48	2.06

imum 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 CODE, were downloaded from the URL-4 address and a comparison is made in Fig. 4. The TEC values of GIM were published in the ionosphere map exchange (IONEX) format and TEC maps, which are produced by CODE; these have a spatial resolution of $2.5^{\circ} \times 5^{\circ}$ in

the geographic latitude and longitude. CODE GIMs continually produce bi-hourly snapshots of the global ionosphere. In the first stage of the study, the ionospheric variation in the seismic zone was monitored by making use of the AYVL, CANA, IPSA, and YENC stations, located at the nearest positions to the seismic zone present in Turkey. The TEC variations regarding these stations are given in Figs. 4–7.

Figures 4–7 show the PPP-TEC, generated as a result of analysis, and the GIM-TEC values published by CODE for

Table 4. IPSA station 2 h resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC)U) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
0	17.70	1.87	14.08	1.91
2	15.15	1.30	11.68	0.93
4	22.61	2.20	19.12	2.01
6	28.16	3.88	25.40	3.70
8	30.66	5.34	28.16	4.93
10	32.63	6.62	29.99	6.13
12	31.26	5.30	28.56	4.97
14	30.98	4.25	27.17	3.97
16	30.20	3.54	26.35	3.08
18	29.45	3.80	26.20	3.33
20	22.90	3.14	20.32	2.94
22	17.95	2.26	15.48	2.06

Table 5. YENC station 2 h resolution average TEC data.

Time (UTC)	Average (PPP-TEC) (TECU)	Standard deviation (PPP-TEC)U) (TECU)	Average (GIM-TEC) (TECU)	Standard deviation (GIM-TEC) (TECU)
0	18.08	2.13	14.50	2.08
2	15.37	1.41	12.02	0.97
4	22.90	2.21	19.55	2.07
6	28.69	3.76	25.91	3.59
8	31.41	5.31	28.90	4.92
10	33.53	6.70	31.01	6.20
12	32.43	5.47	29.62	5.07
14	31.85	4.32	27.88	4.00
16	30.80	3.60	27.05	3.12
18	30.02	3.89	26.50	3.38
20	23.35	3.12	20.65	2.97
22	18.47	2.30	15.95	2.14

the CANA, AYVL, IPSA, and YENC stations, respectively. The blue colour in the figures shows the TEC values generated as a result of analysis and the red colour shows the TEC values published by CODE. When PPP-TEC and GIM-TEC results are examined, it can clearly be seen that there is some difference between PPP-TEC and GIM-TEC. GIM-TEC are generated on a daily basis at CODE, which uses about 200 GNSS sites of the IGS and other institutions. There are only three GNSS sites of IGS in Turkey to compute VTEC values. This difference could be caused by a lack of IGS stations in Turkey. To be able to understand whether any anomaly is present before or after the earthquake, both the TEC values generated as a result of the analysis and the TEC values published by CODE were examined separately. The minimum and maximum values of the TEC values obtained through both are shown in Table 1.

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

By making use of the TEC values of the four stations, the average TEC values in time intervals of 2 h were produced from both the TEC values generated as a result of analysis and the TEC values published by CODE. By taking these average TEC values as reference, the standard deviation values regarding the days analysed were obtained. Standard deviation is considered based on the 95 % confidence interval,



Figure 8. *D*_{st} index value for analysed days.



Figure 9. CORS-TR and IGS station distribution.

namely

$$\mu = \sqrt{\frac{\sum (x_i - x)^2}{N - 1}}.$$
(4)

In Eq. (4), μ which was produced for generated and GIM-TEC values separately, demonstrates standard deviation, x_i states TEC values that were produced for every 2 h, x indicates mean TEC values and, N indicates analysed days, respectively. After determining standard deviation for every 2 h, we can easily describe upper and lower TEC values. Lower and upper TEC values are equal to the $x - \mu$ and $x + \mu$ for generated and GIM-TEC values, respectively. The outliers, which can be described as points outside of the range of $x - \mu$ and $x + \mu$, are considered anomalies.

The numerical values obtained for the AYVL, CANA, IPSA, and YENC stations are shown in Tables 2–5.

In the evaluation made by taking into account the lowerand upper-limit TEC values of PPP-TEC values, it can be understood that, in all four stations, the TEC values 3 days before the earthquake, at times 08:00 and 10:00 UTC, were approximately 4 TECU above the upper-limit TEC value. On the other hand, the TEC values at times 06:00, 08:00, and 10:00 UTC 1 day before the earthquake were approximately 5 TECU below the lower-limit TEC value.

When the GIM-TEC values published by CODE were examined for all stations, research revealed that these were approximately 2 TECU above the TEC values at 08:00 and 10:00 UTC 3 days before the earthquake. One day before the earthquake at 06:00, 08:00, and 10:00 UTC, TEC values were



Figure 10. AYVL station coordinate variations.

approximately 4 TECU below the lower-limit TEC value. In order to understand whether the said variations originate or not from the earthquake, the Planetary *K*-Index (K_p) and Disturbance Storm Time Index (D_{st}), which give information about ionospheric activity, were examined for these specific days. While the K_p index is regularly published with 3 h increments, D_{st} index values are published with 1 h intervals by the World Data Center for Geomagnetism in Kyoto.

While D_{st} values change between $-20 > D_{st} > -50$ and $D_{st} > -20$, K_p values were nearly <5 during 20–31 May 2014. These values indicate that the ionosphere was quiet for these analysed days. K_p and D_{st} index values are shown in Table 6 and Fig. 8. K_p and D_{st} index values were downloaded from URL-5 and URL-6, respectively. They indicate an ionospheric activity caused by a magnetic storm if K_p and D_{st} values are in the range of the geomagnetic storm scale, which is shown in Table 7.

4 Determining the seismic origin positional variation

In the second part of the application, the positional variations arising from the Gokceada earthquake were examined in the CORS-TR stations (AYVL, CANA, IPSA, and YENC). The distribution of the IGS and CORS-TR stations used in the application is shown in Fig. 9.

In the application, for which Bernese v5.0 academic software was used, approximate coordinates were calculated with PPP (Yildirim et al., 2013). The approximate coordinates were calculated by using the satellite–receiver time er-

Analysed days	00:00 UTC	03:00 UTC	06:00 UTC	09:00 UTC	12:00 UTC	15:00 UTC	18:00 UTC	21:00 UTC
20 May 2014	0+	1	1	1+	1+	1	0+	0
21 May 2014	0+	0	0	0+	0+	0+	0+	0+
22 May 2014	1	1	1-	1-	2	3+	2+	3+
23 May 2014	3	2-	1 +	0+	1	4—	4	5+
24 May 2014	2-	1+	2-	0+	1+	1	1-	1
25 May 2014	1+	1+	1-	0+	0+	1 +	0+	0
26 May 2014	1	1-	1	1-	0+	0+	0+	0+
27 May 2014	0	0	0+	1-	1	1	2-	1
28 May 2014	1+	1+	0+	1-	1-	1	1-	1
29 May 2014	0+	1-	1-	3–	2	2	2	1
30 May 2014	0	1+	1+	2+	2+	3-	4+	1 +
31 May 2014	1	1	0+	0+	0+	0+	1-	0

Table 6. *K*_p index values for analysed days.

Table 7. Magnetic storm scale.

Geomagnetic storm	$K_{\rm p}$ index	D _{st} index
G5 Extreme	9	$D_{\rm st} < -300$
G4 Severe	8	$-100 > D_{\rm st} > -250$
G3 Strong	7	$-50 > D_{\rm st} > -100$
G2 Moderate	6	$-20 > D_{\rm st} > -50$
G1 Minor	5	$D_{\rm st}>-20$



Figure 11. CANA station coordinate variations.

rors generated in 5 min intervals by IGS, in addition to the code and phase measurements of the CORS-TR stations. The coordinates of all stations used in the study were calculated as independent from each other by not considering any network structure. The coordinates calculated have been used as before to balance preliminary values of double difference solutions to be made later on. After the preliminary values were determined, the double difference solution was started. In this stage, the coordinate values of IGS points used in the established network structure were used. The parameters used in the evaluation stage are given Table 8.

Coordinate variations for before, during, and after the earthquake were analysed for the AYVL, CANA, IPSA, and



Figure 12. IPSA station coordinate variations.

YENC stations and coordinate variations for each station are shown in Figs. 10–13.

Figures 10–13 show, respectively, the positional variations before and after the earthquake at the AYVL, CANA, IPSA, and YENC stations. While the blue colour shows the change that occurred in the x axis direction, the orange and grey colours represent, respectively, the displacement in the y and z axes directions. When we looked at the figures, except for at the CANA station, no meaningful change occurred. At the CANA station, which is the nearest station to the earthquake's centre, variations of approximately 10 cm were experienced on all three axes, particularly 3 days before the earthquake, and a variation of approximately 3 cm, particularly on the x axis, was experienced 1 day before the earthquake and returned to their original position.

5 Conclusions and recommendations

In recent years, research to determine the TEC value, which is a function of the ionosphere, has accelerated. In this study, we examined the correlation between the ionospheric and positional variation caused by an earthquake of magnitude Table 8. Evaluation strategy of GPS measurements with Bernese v5.0 software (a) (model), (b) (parameters).

(a) Pre-assessment: on the base-base mode, it was performed by using phase measurements and the triple difference method. Different linear combinations of L1 and L2 carrier phases were synchronously examined and the cycle slips were fixed. In cases where cycle slips could not be determined exactly, incorrect measurements were removed or ambiguity was added. Basic measurements: carrier phase measurements were used. Code measurements were used for the synchronisation of the receiver clock and GPS time only. Cut-off angle: 10°. Data interval: 30 s. Weighting: On zenith angle, for double difference measurements independent from the ionosphere, 6 mm was taken. Weighting function dependent from elevation angle was taken as $1/\cos^2(z)$. Modelled measurements: linear combinations of double difference measurements were considered independent from the ionosphere. GPS antenna phase centre calibration: Elevation angle-dependent phase centre corrections were applied according to the IGS05.ATX model. During the evaluation of measurements 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: The hydrostatic component was modelled with the dry-Niell correction function and the Saastamoinen model was applied. Meteorological data: Not used. The unknowns of zenith delay were calculated using the wet-Niell projection function for each station in intervals of two hours Constraints: 1 m was defined as the pre-condition for relative zenith delay values. Correction function: For both dry and wet components, the Niell correction function was used. Ionosphere: it was not modelled (first-degree influences were eliminated by the combination of L1 and L2 carrying phase measurements independent from ionosphere). In addition, for the solution of the initial phase of uncertainty (ambiguity), the global ionosphere values obtained from 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 were taken in the ITRF2008 coordinate system.

(b) Adjustment point coordinates: the least-squares method was applied.

Point coordinates: the ITRF 2008 coordinate system was used, using point coordinates and velocities of the stations given during solution of IGS08.SNX.

Satellite clock errors: satellite clock errors were eliminated using the double differences method.

Receiver clock errors: receiver clock errors that were calculated using pseudo-range measurements during the pre-assessment phase have been removed from the evaluation.

Base selection: the OBSMAX principle was used.

Ambiguity: the QIF was applied.





 $6.5 M_{\rm w}$, which occurred offshore in the Aegean Sea on 24 May 2014. We used the data of 15 stations, of which four were CORS-TR, taken 4 days before the earthquake and 7 days after the earthquake.

In the statistical analysis carried out for the TEC value, the PPP-TEC generated as a result of analysis, and the GIM-TEC values taken from CODE, it could be seen that at specific times before and after the earthquake, these values deviated and exceeded the lower- and upper-limit TEC values. The positional variations of the aforementioned stations were also examined before and after the earthquake. In the findings obtained, a variation of approximately 10 cm was detected in the x, y, and z directions 3 days before the earthquake, and a variation of approximately 3 cm in the x direction was seen 1 day before the earthquake. These variations, which occurred at the CANA station, which is located at the nearest position to the centre of the earthquake, returned to their original position approximately 1 week after the earthquake. In this study, the occurrence of variation in terms of both the ionospheric and positional sense, particularly 3 days and 1 day before the earthquake, strengthens the possibility of the seismic origin anomaly occurrence condition. However, it can definitely be said that it is a seismic origin anomaly but it is thought that upper air, geophysical, and geological data are required.

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