



# Comparison between IRI-2012 and GPS-TEC observations over the western Black Sea

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**Abstract.** The ionosphere is a dynamic layer which generally changes according to radiation emitted by the sun, the movement of the earth around the sun, and sunspot activity. Variations can generally be categorized as regular or irregular variations. Both types of variation have a huge effect on radio wave propagation. In this study, we have focused on the seasonal variation effect, which is one of the regular forms of variation in terms of the ionosphere.

We examined the seasonal variation over the ZONG station in Turkey for the year 2014. Our analysis results and IRI-2012 present different ideas about ionospheric activity. According to our analysed results, the standard deviation reached a maximum value in April 2014. However, the maximum standard deviation obtained from IRI-2012 was seen in February 2014. Furthermore, it is clear that IRI-2012 underestimated the VTEC values when compared to our results for all the months analysed. The main source of difference between the two models is the IRI-2012 topside ionospheric representation. IRI-2012 VTEC has been produced as a result of the integration of an electron density profile within altitudinal limits of 60–2000 km. In other words, the main problem with regard to the IRI-2012 VTEC representation is not being situated in the plasmaspheric part of the ionosphere. Therefore we propose that the plasmaspheric part should be taken into account to calculate the correct TEC values in mid-latitude regions, and we note that IRI-2012 does not supply precise TEC values for use in ionospheric studies.

**Keywords.** Ionosphere (mid-latitude ionosphere; modelling and forecasting)

## 1 Introduction

GPS systems have been used in many scientific studies in recent years. GPS satellites send signals to receivers on L1 and L2 carrier frequencies. The carrier frequencies connecting satellites to receivers are exposed to various factors that can change the GPS signal, which can result in positioning errors. One of the positioning error sources is the ionospheric layer. Since the ionosphere plays an important role in radio communication, ionospheric conditions should be monitored correctly. The total electron content (TEC) is an important parameter that provides information about ionospheric activity. TEC is calculated along the path from the receiver to the satellite in a column with a cross-sectional area of a square metre and is expressed as TECU  $10^{16} e/m^2$  (Chakraborty et al., 2014; Coley et al., 2014; Otsuka et al., 2002; Rama Rao et al., 2006; Schmidt et al., 2008; Spogli et al., 2013; Yildirim et al., 2016).

The ionosphere consists of different layers, such as  $D$ ,  $E$ ,  $F_1$ , and  $F_2$ , according to the electron density. These layers affect the propagation of radio signals differently. Consequently, understanding the behaviour of each ionospheric layer is of huge importance when it comes to modelling ionospheric errors.

The  $D$  layer is the lowermost layer of the ionosphere. It extends from 50 to 90 km. Ionization is less in this layer and disappears at night because of the high recombination of ions. Therefore it is thought that the  $D$  layer has little effect on GPS signals (Petrie et al., 2011). The  $E$  layer is called the middle layer of the ionosphere and stretches to 150 km. This layer is composed of  $E$  and sporadic  $E$  layers ( $E_s$ ), but ionization occurring in ( $E_s$ ) is not related to the  $E$  layer. Thus sporadic  $E$  can be thought of as separate from the  $E$  layer. Ionization results from soft X-ray and ultraviolet solar radi-

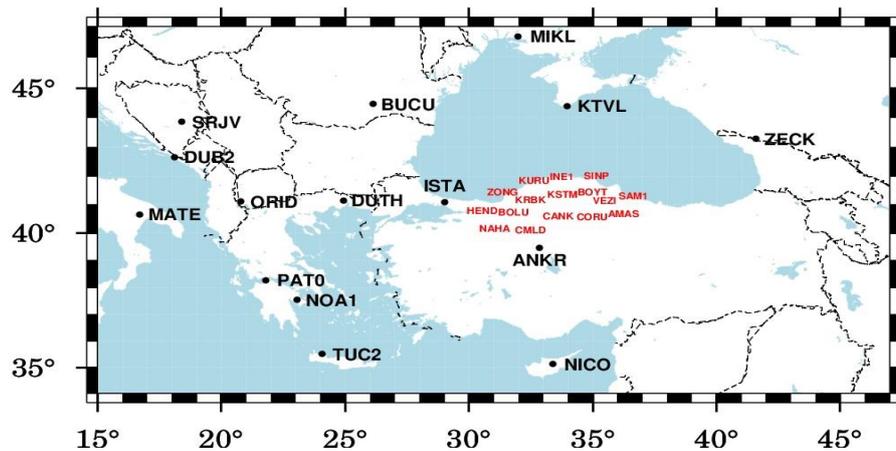


Figure 1. Distribution of stations.

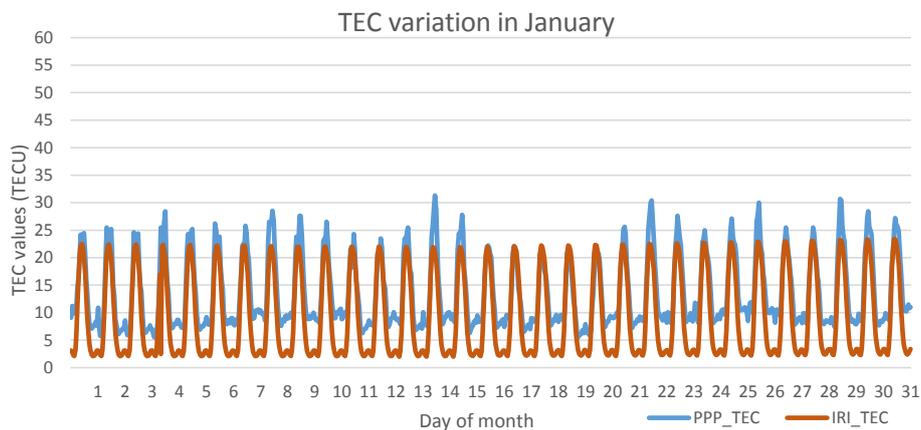


Figure 2. TEC variations in January 2014.

tion in this layer. The  $E$  layer becomes extinct at night owing to the recombination of ions, as is the case for the  $D$  layer.

The  $F$  layer is a major component of the ionosphere in terms of affecting the propagation of radio waves. The  $F$  layer includes more free electrons and ions than the other ionospheric layers and consists of two layers ( $F_1$  and  $F_2$ ). The  $F_1$  layer extends from 140 to 210 km and has a 10 % effect on GPS signals. The  $F_2$  layer, which extends from 210 to 1000 km, contains most of the free electrons, especially between 250 km and 450 km.  $F_2$  has more ionospheric variability than  $F_1$ . Thus we have focused on the  $F_2$  layer in order to determine the TEC values in this study.

GPS is essential for increasing satellite-based applications and studies, especially geodetic studies that call for high accuracy. A signal travelling from a satellite to a receiver is affected by many factors that lead to positioning errors. The ionosphere, which is an uppermost layer that extends from 60 to 1000 km, is the most important factor. The ionosphere includes a sufficient number of free electrons and ions and these cause changes in the direction of GPS signals. There-

fore TEC, which is needed to calculate ionospheric delay, should be computed for GPS users. TEC is of vital importance for understanding the behaviour of the ionosphere and can be readily determined using GPS dual frequency. However, it is more difficult to filter out ionospheric refraction with a single-frequency receiver.

## 2 Methods

The GPS technique presents an opportunity for use in real time or nearly real time as part of ionosphere services for space weather monitoring. Due to the high popularity of GPS-TEC observations for ionosphere research, including the generation of global and regional ionospheric maps with high temporal and spatial resolution, there is a great demand for a proper model for GPS-TEC specification. As mentioned above, the ionosphere changes in relation to seasonal variations. Therefore, the ionosphere should be described mathematically to allow it to be modelled correctly for GPS single-frequency users. Pseudorange equations are explained for

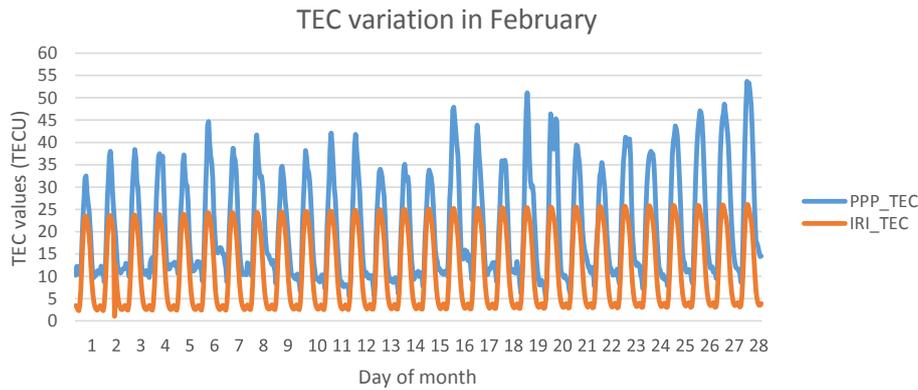


Figure 3. TEC variations in February 2014.

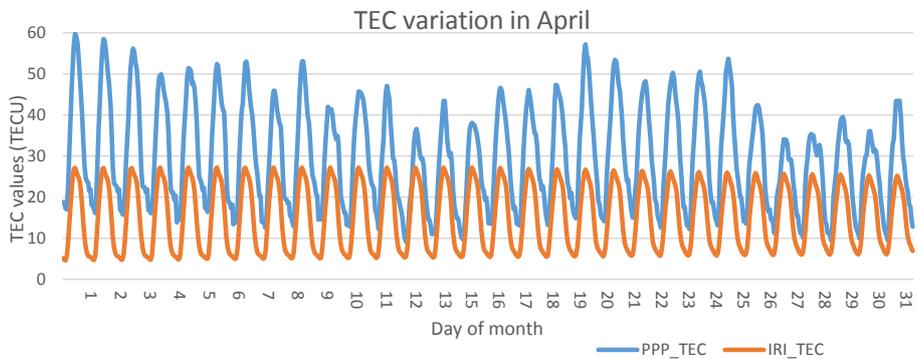


Figure 4. TEC variations in April 2014.

dual-frequency receivers as shown below:

$$P_{1,a}^h = P_a^h + c(\Delta t^h - \Delta t_a) + I_{1a}^h + T_a^h + d_1^h + d_{1,a} + \varepsilon_{p,1,a}^h, \quad (1)$$

$$P_{2,a}^h = P_a^h + c(\Delta t^h - \Delta t_a) + I_{2a}^h + T_a^h + d_2^h + d_{2,a} + \varepsilon_{p,2,a}^h, \quad (2)$$

where  $\Delta t^h$  is satellite clock error,  $\Delta t_a$  is receiver clock error,  $I_{1a}^h$  and  $I_{2a}^h$  are ionospheric effects,  $T_a^h$  is tropospheric effect,  $c$  is the velocity of light,  $d_1^h$  and  $d_2^h$  represent the code delay for satellite instrument bias,  $d_{1,a}$  and  $d_{2,a}$  represent the code delay for receiver instrument bias,  $\varepsilon_{p,1,a}^h$  and  $\varepsilon_{p,2,a}^h$  are random errors,  $P_{1,a}^h$  and  $P_{2,a}^h$  are pseudorange measurements, and  $P_a^h$  is the true distance between a receiver and a satellite.

The simple equation for carrier phase measurements can be stated as follows:

$$\begin{aligned} \varphi_{1,a}^h(t) = & \varphi_a^h + c(\Delta t^h - \Delta t_a) - I_{1a}^h + T_a^h \\ & - \lambda(b_{1,a}^h + N_{1,a}^h) + \varepsilon_{p,1,a}^h, \end{aligned} \quad (3)$$

$$\begin{aligned} \varphi_{2,a}^h(t) = & \varphi_a^h + c(\Delta t^h - \Delta t_a) - I_{2a}^h + T_a^h \\ & - \lambda(b_{2,a}^h + N_{2,a}^h) + \varepsilon_{p,2,a}^h, \end{aligned} \quad (4)$$

where  $\varphi_{1,a}^h$  and  $\varphi_{2,a}^h$  are phase measurements,  $\varphi_a^h$  is the true distance between satellite and receiver,  $I_{1a}^h$  and  $I_{2a}^h$  are ionospheric effects,  $T_{1a}^h$  and  $T_{2a}^h$  are tropospheric effects,  $b_{1,a}^h$  and  $b_{2,a}^h$  represent the phase advance of the satellite instrument bias,  $\varepsilon_{p,1,a}^h$  and  $\varepsilon_{p,2,a}^h$  are GPS residuals,  $N_{1,a}^h$  and  $N_{2,a}^h$  represent the integer phase ambiguity, and  $\lambda$  is the wavelength at frequency.

Code and phase measurements have been affected by the ionosphere. These effects, grouped and referred to here as the delay for code measurement and phase advance for phase measurement, can be explained with geometry-free linear combinations. Dual-frequency GPS receivers save not only the code pseudo-range, but also the phase measurements on L1 and L2 frequencies.

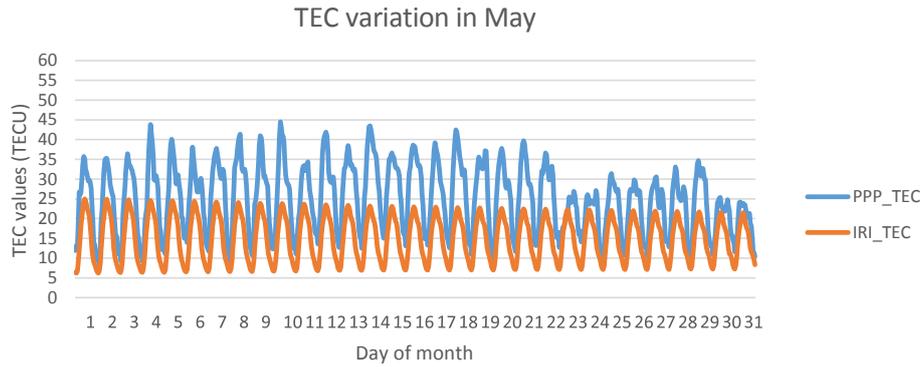


Figure 5. TEC variations in May 2014.

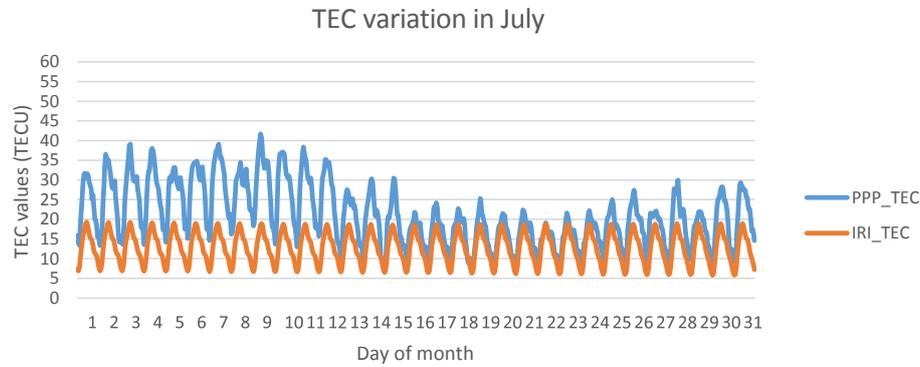


Figure 6. TEC variations in July 2014.

The calibration of the TEC (prediction of the different errors affecting the measurements, such as inter-frequency biases, multipath phase ambiguity, and cycle slips) derived from GNSS code and phase carrier delays should be applied correctly in ionospheric studies (Ciraolo et al., 2007). Calibrated TEC measurements are needed to obtain the spatial variations in TEC and create ionospheric grid maps (Cesaroni et al., 2015). Therefore we have used calibrated TEC values to study seasonal ionospheric variations over the ZONG station.

Generally, TEC values are obtained in various ways. Firstly, we obtain TEC values using only code pseudo-range measurements that provide us with TEC values with an accuracy of 1–5 TECU (Liu et al., 2005). The literature states that code measurements include an element of noise which leads to decreased accuracy in TEC values when compared to phase measurements. Using only code measurements to determine TEC values is therefore not suitable. Another possibility is that TEC values can be achieved by using phase measurements. The accuracy of these TEC values is higher than that obtained from code measurements. However, this method is not suggested to determine correct TEC values because we need to eliminate integer phase initial ambiguities for each GNSS measurement.

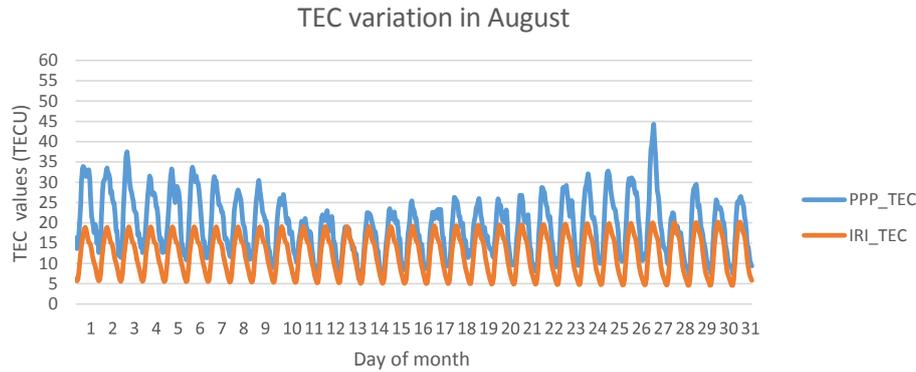
The third possible method is that TEC values can be acquired through smoothing code measurements using phase measurements. Thanks to this method, we can both eliminate the obligation of removing the integer phase ambiguity and obtain TEC values easily.

STEC indicates the slant total electron content from satellite to receiver, while VTEC is defined as the vertical total electron content along the ray path in the direction of the zenith:

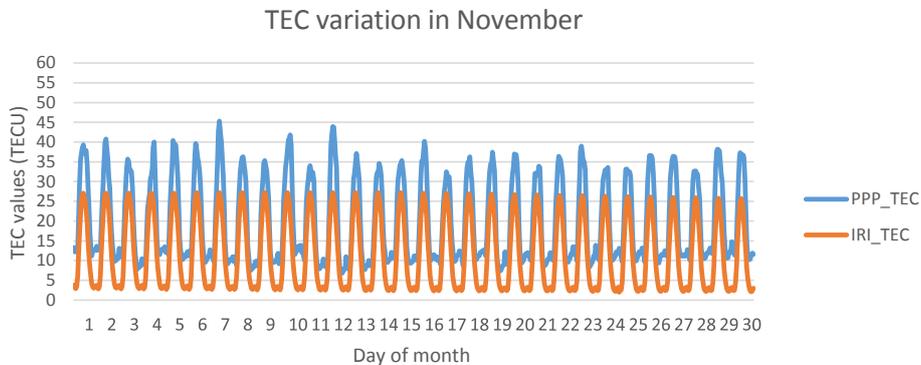
$$STEC_a^h = -\frac{f_1^2 f_2^2}{40.3 (f_1^2 - f_2^2)} (P_{4,a}^h - cDCB_a - cDCB^h). \quad (5)$$

In this formula,  $f_1$  and  $f_2$  indicate GPS frequencies,  $c$  indicates the velocity of light,  $P_{4,a}^h$  states the differences in  $P_{1\text{smt},a}^h - P_{2\text{smt},a}^h$  smoothed code measurements, and  $DCB_a$  and  $DCB^h$  express differential code biases for receiver and satellite respectively (Dach et al., 2011). After obtaining correct STEC values, they are converted to VTEC using a mapping function (MF), which indicates that all electrons are contained in an infinitesimal thickness for each period (Manucci et al., 1993). The altitude of this layer is set at 350 km for Turkey. Equation (6) describes how to obtain VTEC values using MF:

$$VTEC = STEC \times \cos(\arcsin\left(\frac{R \times \sin z}{R + H}\right)). \quad (6)$$



**Figure 7.** TEC variations in August 2014.



**Figure 8.** TEC variations in November 2014.

In this formula  $R$  expresses the earth's radius,  $H$  is the thin shell height of the ionosphere (350 km), and  $z$  is the satellite zenith angle.

### 3 Study area and data

Several studies have been conducted on seasonal variations in the ionosphere over the last few years (Chowdhary et al., 2014; Zakherenkova et al., 2015; Kumar et al., 2014, 2015; Themens and Jayachandran, 2016; Tsai et al., 2001; Wang et al., 2016; Karia et al., 2015; Ssessanga et al., 2015). These studies have concluded that determining the correct VTEC value is important for understanding the behaviour of the ionosphere in terms of seasonal variations. The monitoring of ionospheric variations provides advantages for various disciplines, especially GPS users. In this study, seasonal ionospheric variations were tracked over the western Black Sea at the ZONG station, which is part of a network of continuously operating reference stations in Turkey (CORS-TR). In this respect, a GPS network which includes a total of 41 stations was built. This network includes the International GNSS Service (IGS), the European Reference Frame Permanent Network (EPN), and CORS-TR. All stations used are shown in Fig. 1.

Figure 1 shows the IGS and EPN stations with black labels. These are ANKR, BUCU, CMLD, DUB2, DUTH, GLSV, GRAS, GRAZ, ISTA JOZE, KHAR, KTVL, MATE, MIKL, NICO, NOA1, ORID, PAT0, PENC, POLV, RAMO, SRJV, TUC2, VILL, ZECK, and ZIMM. CORS-TR stations are represented by red labels: AMAS, BOLU, BOYT, CANK, CORU, HEND, INE1, KRBK, KSTM, KURU, NAHA, SAM1, SINP, VEZI, and ZONG. The RINEX data from the IGS and EPN stations were obtained from the URL-1, and the RINEX data from the CORS-TR stations were downloaded from the URL-2. IRI-2012 VTEC values are obtained from URL-3. The time interval was 30 s and the minimum elevation angle was defined as  $10^\circ$  for processing.

To investigate seasonal ionospheric variation over the ZONG station in Turkey, the International Reference Ionosphere (IRI-2012) model and Bernese 5.2 academic software were used. IRI-2012, which is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), is an on-line tool to obtain VTEC values in desired increments. We selected NeQuick and the  $F$  peak model to be defined as URSI input parameters when analysing with the IRI-2012 model. Bernese 5.2 is scientific high-precision data processing software developed at the Astronomical Institute at the University of Bern (AIUB).

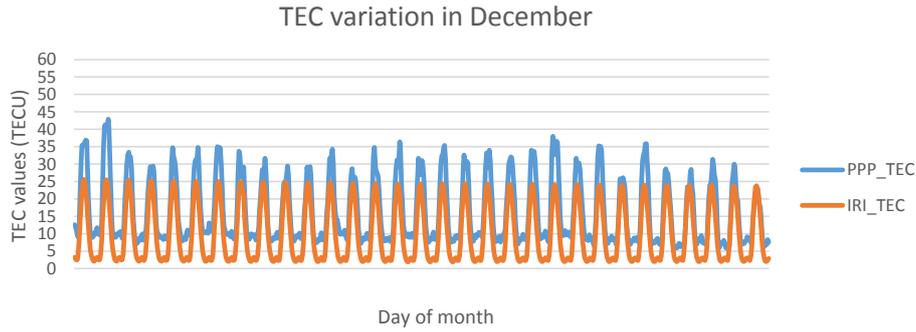


Figure 9. TEC variations in December 2014.

Table 1. Statistical results that produced PPP\_TEC.

Months	Min. TEC (TECU)	Max. TEC (TECU)	Mean TEC (TECU)	Standard deviation (TECU)
Jan	5.5	31.3	13.35	6.41
Feb	4.9	53.7	20.90	11.73
Apr	9.0	59.8	29.73	12.52
May	8.5	44.5	24.98	8.67
Jul	7.2	41.7	21.09	7.84
Aug	6.2	44.3	19.23	7.07
Nov	6.8	45.3	19.52	10.67
Dec	5.2	42.9	16.11	9.4

Table 2. Statistical results that produced IRI\_TEC.

Months	Min. TEC (TECU)	Max. TEC (TECU)	Mean TEC (TECU)	Standard deviation (TECU)
Jan	2.0	23.4	9.11	7.64
Feb	1.0	26.1	11.37	8.56
Apr	4.6	27.2	15.24	7.91
May	6.2	25.0	14.99	5.6
Jul	5.8	19.3	12.83	3.87
Aug	4.6	20.2	12.39	4.79
Nov	2.0	27.1	11.48	9.1
Dec	1.9	25.6	9.9	8.23

### 4 Results

In this study, attempts were made to monitor ionospheric conditions in terms of seasonal variations. Therefore 2-month RINEX data from the ZONG station for each season were processed to analyse ionospheric variations over the western Black Sea in Turkey. All the results are shown in Figs. 2 to 9. The blue labels indicate the PPP\_TEC results that were produced using Bernese 5.2, while the red labels explain the results for IRI\_TEC that were obtained using IRI-2012.

When all figures are examined, it can be clearly seen that the IRI-TEC values produced nearly the same response in terms of monthly ionospheric activity. For example, the maximum TEC value is nearly 25 TECU for each day in December 2014. However, GPS\_TEC gives different responses for these days. On the other hand, IRI-2012 underestimated the values for every month when compared to the GPS\_TEC values. The changes in the obtained TEC values from IRI-2012 and Bernese 5.2 were statistically analysed for each month to monitor seasonal variations over the ZONG station in Turkey. The results obtained are shown separately in Tables 1 and 2.

In the current research, while the maximum TEC value was seen in April 2014, the minimum TEC value was produced in February 2014 according to the PPP\_TEC results. When the IRI\_TEC values are examined, it is clearly understood that the maximum TEC value was obtained in

April 2014, while the minimum TEC value was achieved in February 2014. When the mean TEC values are examined, the highest mean TEC value was seen in April 2014 for both PPP\_TEC and IRI\_TEC, and the lowest mean TEC value was presented in January 2014 for both models. The standard deviation reached a peak value in April 2014 and the lowest value in January 2014 according to the PPP-TEC results. When the IRI\_TEC results are examined, it is understood that the maximum standard deviation was seen in April 2014, while the minimum standard deviation was observed in July 2014. It is well understood that the ionosphere has a dependence on seasonal variations. Therefore, seasonal ionospheric effects should be taken into account in all signal-based studies.

### 5 Conclusions

The ionosphere can be monitored using a variety of instruments, such as ionosondes, incoherent scatter radar, topside sounders, and onboard satellites. Since these instruments are expensive and extract limited information about the ionosphere, GPS has become an optimal way to examine ionospheric behaviour.

Many researchers have demonstrated that the ionosphere is affected by seasonal variations and that such effects have been shown in terms of GPS measurements. In this study, seasonal ionospheric variations over Turkey from the ZONG

station were implemented using GPS-based TEC and IRI-2012. When the results are examined for the two models, we obtained different TEC values for each season. Furthermore, the IRI-2012 results were compared with the GPS results, and it is clear that IRI-2012 underestimates the TEC values for each month analysed. On the other hand, we know that the IG12 ionospheric index and the Rz12 sunspot index generate only 1 value per month and that they are interpolated by the model. The model was not intended to track day-to-day variations accurately. Therefore the IRI-2012 results produce nearly the same TEC values at any time of day within the month. When the ionosphere is considered as a dynamic layer, the IRI-2012 results do not represent real ionospheric conditions. Therefore we conclude that IRI-2012 does not provide a sufficiently accurate daily ionospheric activity response. The main reason for TEC differences may stem from the absence of a correct representation of the plasmaspheric part of the ionosphere. While IRI-2012 produces VTEC as a result of the integration of the electron density profile within altitudinal limits of 60–2000 km, GPS is set to 20 200 km from the ground. We conclude from this study that the plasmaspheric part of the ionosphere should be correctly taken into account in monitoring the ionosphere.

*Data availability.* The RINEX data from the IGS and EPN stations were obtained from URL 1, and the RINEX data from the CORS-TR stations were downloaded from URL 2. IRI-2012 VTEC values are obtained from URL 3. The URLs are as follows: URL 1: <ftp://igs.bkg.bund.de/IGS/obs/>, 2014. URL 2: <http://212.156.70.42/>, 2014. URL 3: [https://omniweb.gsfc.nasa.gov/vitmo/iri2012\\_vitmo.html](https://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html).

*Competing interests.* The authors declare that they have no conflict of interest.

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