

# DOLOČEVANJE REGIONALNEGA MODELA IONOSFERE TER PRIMERJAVA Z GLOBALNIM MODELOM

# DETERMINING REGIONAL IONOSPHERIC MODEL AND COMPARING WITH GLOBAL MODELS

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## IZVLEČEK

Signal GNSS (globalni navigacijski satelitski sistem) potuje do sprejemnika na Zemlji skozi različne sloje atmosfere. Eden izmed teh je ionosfera in se nahaja med približno 70 in 1000 kilometri nad površjem Zemlje. Razmere v ionosferi so odvisne od dnevnega in letnega časa, geografske lokacije in Sončeve aktivnosti. Vpliv ionosfere na signal GNSS je sorazmeren s količino prostih elektronov (TEC, angl. Total Electron Content). Za modeliranje ionosfere je ključno določevanje spremenljive vrednosti TEC. V našo raziskavo vrednosti TEC smo vključili opazovanja 26 postaj GNSS, 14 postaj omrežja TUSAGA-ACTIVE (CORS-TR) in 12 postaj omrežja IGS, ki smo jih obdelali s programskim paketom Bernese v5.2. Vrednosti TEC smo izračunali za dvournne intervale, za en dan v mesecu v obdobju med letoma 2009 in 2015. Vrednosti TEC, ki smo jih določili na podlagi opazovanj GNSS z uporabo modela enega sloja ionosfere (angl. Single Layer Model), smo primerjali z globalnimi kartami ionosfere (GIM-TEC), ki jih izdelujejo center CODE (Center for Orbit Determination in Europe), Evropska vesoljska agencija ESA, laboratorij JPL (Jet Propulsion Laboratory), ter z vrednostmi TEC (IRI-2012 TEC), pridobljenimi v okviru mednarodnega ionosferskega referenčnega programa. Za najboljša regionalna modela ionosfere sta se izkazala tista, ki ju zagotavljata CODE in ESA. Izdelali smo tudi karto regionalnih in globalnih vrednosti TEC za obravnavano območje.

## KLJUČNE BESEDE

GNSS, ionosfera, skupna vsebnost elektronov (TEC), globalna karta ionosfere (GIM)

## ABSTRACT

GNSS (Global Navigation Satellite System) signals pass through various layers of the atmosphere until reaching the receiver on the Earth. The ionosphere, one of these layers, is about 70 km to 1000 km above the Earth surface and constantly changes with the time of day, seasons, geographical location and solar explosions. The GNSS signals affected by the variable structure of the ionosphere are proportional to the total electron content (TEC). Determination of the TEC change is important for modelling of the ionosphere. In this study, totally 26 stations, including 14 TUSAGA-ACTIVE (CORS-TR) stations in Turkey and 12 IGS stations, were selected and evaluated. Bernese v5.2 GNSS software was used for evaluation. TEC values were calculated at intervals of two hours, one day per each month, from 2009 to 2015. TEC values, obtained from GNSS measurements using Single Layer Model, were compared with global ionosphere maps (GIM-TEC) issued by the Center for Orbit Determination in Europe (CODE), the European Space Agency (ESA), the Jet Propulsion Laboratory (JPL), and TEC (IRI-2012 TEC) values obtained from international ionosphere reference program. The best approach to regional ionosphere model obtained as result of comparison was shown by CODE and ESA. Additionally TEC map was produced for the selected area as utilizing regional and global TEC values.

## KEY WORDS

GNSS, ionosphere, total electron content (TEC), global ionosphere maps (GIM)

## 1 INTRODUCTION

The atmosphere can be divided into different layers according to ionization and distribution. Due to the vertical change of temperature, the atmosphere is generally defined by four layers consisting of the troposphere (up to 10 km), stratosphere (10 km to about 50 km), mesosphere (50 km to about 70 km), and thermosphere (70 km to about 400 km) (Memarzadeh, 2009) (Figure 1). The exosphere is the outermost layer of the atmosphere. According to the signal propagation, the atmosphere is divided into two regions, the troposphere and the ionosphere. The troposphere usually covers a region being up to 40 km from the sea surface, and the ionosphere covers about 70 km to 1000 km and even more (Başpınar, 2012).

With respect to the signal propagation, the atmosphere is subdivided into two main layers of the troposphere (also referred to as neutral atmosphere) and ionosphere (Memarzadeh, 2009). The troposphere has refraction effect and causes similar effects on both code and phase modulation and results in a delay of up to 30 meters for a horizontal path. Therefore, the effect of the troposphere is considered one of the major sources of errors imposed on the satellite signals. On the other hand, the ionosphere having a dispersing effect among ionized atmosphere layer(s) affects the signal code and phase modulation in an opposing way (Başpınar, 2012).

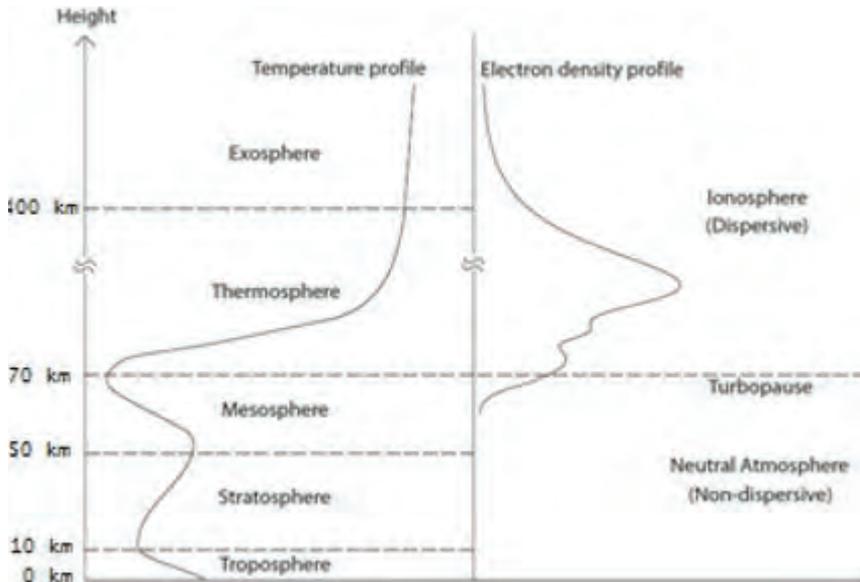


Figure 1: Atmosphere layers (Memarzadeh, 2009).

The ionosphere is an atmosphere layer, that is a region being from about 70 km to 1000 km from the Earth, and consists of gases surrounding the Earth and ionized by solar radiation. The most part of the ionosphere composes of neutral gases. Ionized gases are mostly formed by the short wave radiation (ultraviolet and X radiation). The amount of free electrons in the ionosphere depends on many factors such as time, location, geomagnetic mobility (Aysezen, 2008). The electron density in the ionosphere is changed by all effects like day/night, seasonal, geographic location, and magnetic

storms occurred at Sun. The electrons that gets free as getting independent from their electrons by solar radiation reach at their high density at between 12:00–14:00 during the local day time. At night, the ionization gets less since electrons unites with ions. Seasonal electron density changes in the ionosphere are caused by the angle and distance changes between the Earth and the Sun. However, the 11-year solar cycle has also an effect on the electron density in the ionosphere (Kojathy, 1997). One of the parameters used to define the status of the ionosphere is Total Electron Content (TEC). The TEC represents the total number of free electrons contained in a column with cross-sectional area of 1-square meter and its unit is TECU, where 1 TECU is  $10^{16}$  el/m<sup>2</sup> (Schaefer, 1999; Dach et. al., 2015).

Changes of the TEC in the ionosphere may be determined by GNSS observations before, during and after earthquakes (Ulukavak and Yařınkaya, 2014). Electrical and magnetic field changes may be occurred in the earthquake area and its vicinity due to earthquakes. As these changes proceed to the atmosphere, the electron density of ionosphere changes due to the uniting of neutral atmosphere and ionized plasma (coupling) (Calais et al., 1998). Before big volcanic eruptions, the rate of occurrence of TEC anomalies are related to volcanic type and geographical location (Li et al., 2016). Thus, the effects of earthquakes and volcanic eruptions may be monitored.

## 2 THE STRUCTURE OF THE INOSPHERE

### 2.1 The regions of the ionosphere

The ionosphere is divided into three major regions, geographically, the high latitude region, the middle latitude region and the equatorial region, and scientific studies are based on these regions (Figure 2).

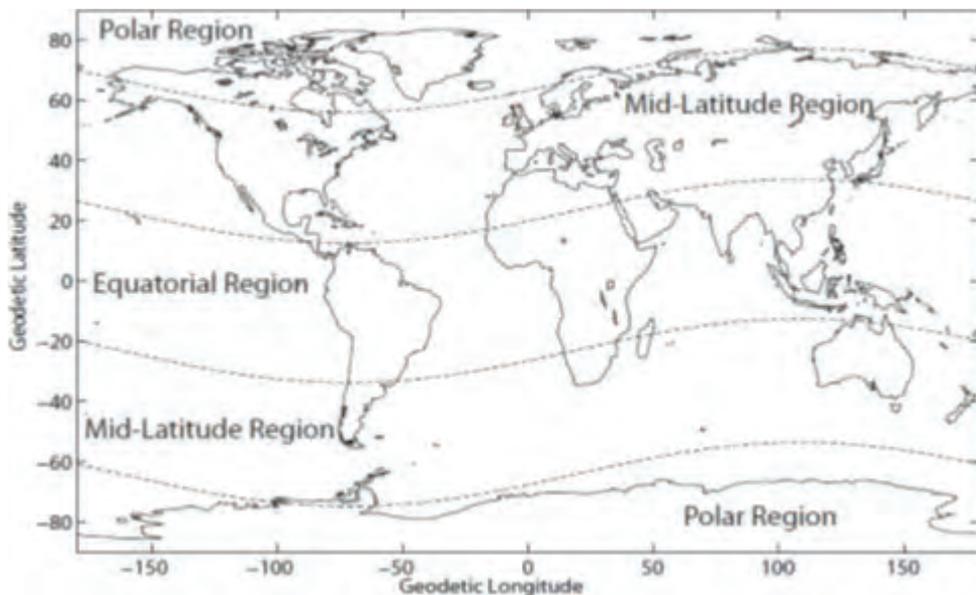


Figure 2: The regions of Ionosphere (Memarzadeh, 2009).

The high latitude region consists of auroral and polar regions. The electron density values are lower in this region than equatorial region. However, the short cyclic ionospheric variations are greater than in the equatorial region (Skone and Cannon, 1999; Danilov and Lastovicka, 2001).

The middle latitude region, in which Turkey is also located, is the best-known region, since a large part of research refers to this region. The region in which the ionosphere is calm and has little change is the middle latitude region. For this reason, the majority of the ionosphere survey stations and ionospheric studies are conducted in the countries in the middle latitude region (Schaer, 1999). The ionization that occurs in this region is usually produced by solar X-ray emission and energy-loaded ultraviolet radiation. Ionization ends up with chemical processes involving ionized moieties as well as neutral atmosphere (Arslan, 2004).

The equatorial region is the region that has the highest electron density, and the amplitude and phase of the signal are frequently changed. The reason of that is strong solar radiation and intense ionization. The ionospheric activity occurred in the equatorial region is called as equatorial anomaly. The equatorial anomaly is defined as the decrease in electron density due to magnetic storms. This anomaly changes with the dynamo of the E layer, which causes the regional electric field in equator and is controlled by global tide winds. The daily equatorial anomaly starts at 9:00–10:00 local time and reaches its highest value at 14:00–15:00 (Gizawy, 2003).

## 2.2 Ionosphere Layers

The ionosphere consists of different layers. Each of these layers which are caused by the severity of ionization level behaves differently during the day and these layers are generally classified as D, E, F1, F2 (Figure 3).

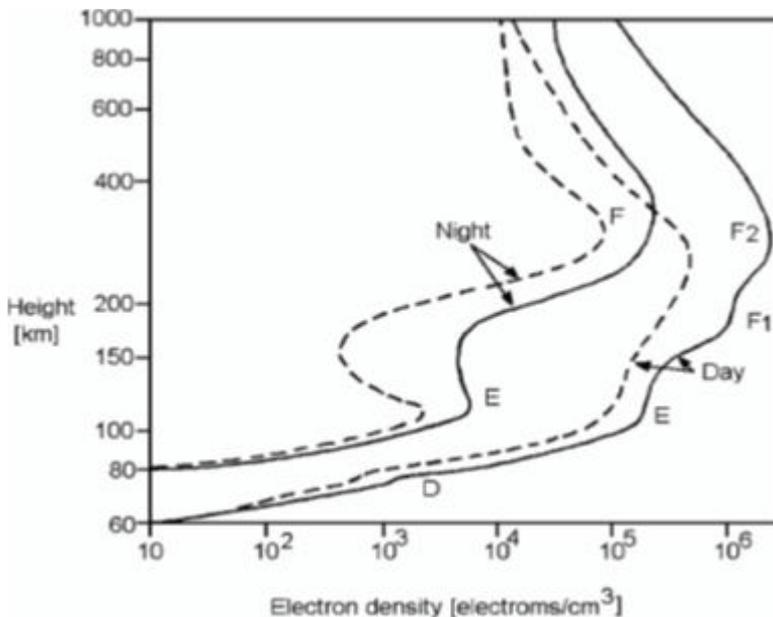


Figure 3: Ionosphere Layers (Hargreaves, 1992).

The D layer is the least ionized layer and is 60–90 km high from the Earth's crust (Wild, 1994). It is not thought that this layer has strong effects on GNSS measurements (Petrie et al., 2011). The E layer, which is formed by the influence of weak X-ray, is 90–140 km above the Earth's crust. This layer where the partial ionization, called as irregular Es, occurs has a little effect on GNSS measurements. The ionization is not thought to be related to the E layer during daylight hours, the anomaly formed by solar particles cause sparkles in polar region (Arslan, 2004).

The F layer, which is investigated in two parts, F1 and F2, is located 150 km over the Earth's crust and is formed by ultraviolet rays of the sun. Approximately 10% of the delay of the GNSS signal in the ionosphere is due to the F1 layer (Parkinson and Spilker, 1999). The structure of this layer is regular and controlled by changes in the Sun, 140–200 km above sea level. The F2 layer, which has the most impact on GNSS measurements, has an irregular structure and is 200–1000 km above the Earth's surface (Parkinson and Spilker, 1999). The electron density of the F2 layer, which shows different changes in polar regions, irregularly decreases at night. This layer is very irregular in the equatorial region, and the electron density at night time may be higher than at noon (Wild, 1994, Poole, 1999). The ionosphere layers and their specifications are presented in Table 1.

Table 1: Ionosphere layers and features (Wild, 1994; Arslan, 2004).

| Layers         | Height (km) | Electron Content (1/cm <sup>3</sup> ) |                   | Neutral gas content (1/cm <sup>3</sup> ) |
|----------------|-------------|---------------------------------------|-------------------|--|
|                |             | Night                                 | Day               |  |
| D              | 60–90       | 10 <sup>2</sup> –10 <sup>4</sup>      | ---               | 10 <sup>15</sup>                         |
| E              | 90–140      | 10 <sup>5</sup>                       | 2·10 <sup>3</sup> | 2·10 <sup>12</sup>                       |
| F <sub>1</sub> | 140–200     | 3·10 <sup>5</sup>                     | 10 <sup>3</sup>   | 10 <sup>10</sup>                         |
| F <sub>2</sub> | 200–1000    | 5·10 <sup>5</sup>                     | 3·10 <sup>3</sup> | 10 <sup>6</sup> –10 <sup>10</sup>        |

### 3 THE EFFECT OF THE IONOSPHERE ON GNSS SIGNALS

The ionospheric data can be available in detail based on a large number of GNSS observation stations and GNSS satellites scattered all around the Earth. TEC values may be determined by the help of L1 and L2 carrier phases sent from GNSS satellites since the ionosphere is a scattering medium. TEC values contain data about the global or regional ionosphere structure (Davies and Hartmann, 1997; Fedrizzi et al., 2001). The local (regional) TEC map is obtained by applying the Taylor expansion to the L4 linear combination, which is equal to the difference of L1 and L2 phase measurements.

$$L_4 = L1 - L2 \tag{1}$$

For modelling of global ionosphere effects, spherical harmonic expansion is used since the Taylor expansion being regional is insufficient (Arslan, 2004).

#### 3.1 Obtaining TEC values with GNSS measurements

Determining TEC values with GNSS measurements is a fast and low-cost method used to understand the structure of the ionosphere. The graphical representation of the total electron content in the ionosphere is given in the Figure 4. TEC is a value with plus sign; if there is a negative value this is the cause of receiver and satellite errors.

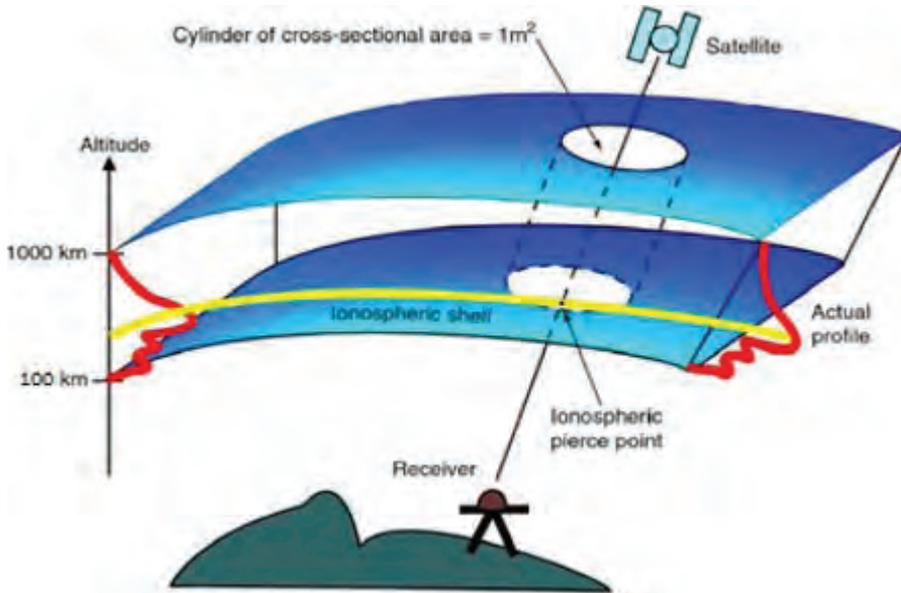


Figure 4: The graphical representation of the total electron content (Langley, 2002).

The height of the ionosphere is generally accepted as 450 km by softwares and it is assumed that TEC being at this height is at its highest value (Komjathy and Langley, 1996).

### 3.2 Single Layer Model

Ionosphere has a wide band. For defining this band, the single layer model, where free electrons with the maximum density are considered to be in an infinitely thin area is utilized (Hugentobler et al., 2001). The model assumes that all electrons in the ionosphere gather in an infinitely thin layer, which is between 300 and 450 km over the Earth surface (Inyurt, 2015). In the figure 5 the single layer model is shown.

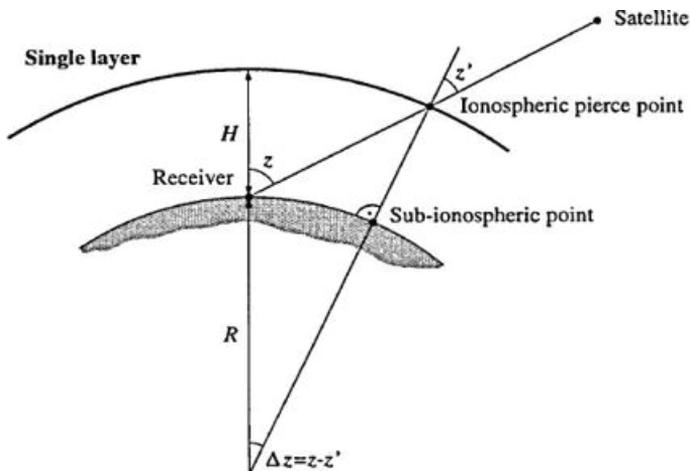


Figure 5: The Single Layer Model (Schaer, 1999).

The Single Layer Projection Function  $F_p$

$$F_I(z) = \frac{E}{E_v} = \frac{1}{\cos Z'} \tag{2}$$

$$\sin Z' = \frac{R}{R+H} \sin Z \tag{3}$$

is obtained by these equations. In the equations (2) and (3),  $E$  is electron content along the signal way,  $E_v$  is vertical electron content,  $z$  and  $z'$  are zenith angles,  $R$  is the mean Earth radius,  $\Delta z$  is difference between  $z$  and  $z'$  zenith angles,  $H$  is the height of the single layer.

### 3.3 Local TEC Model

If  $E_v(\beta, s)$  is expanded as to two-dimensional Taylor series to present total vertical electron content:

$$E_v(\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{m_{max}} E_{nm} (\beta - \beta_0)^n \cdot (s - s_0)^m \tag{4}$$

In this equation;  $n_{max}$  and  $m_{max}$  are the maximum orders of the two-dimensional Taylor series expansion in latitude and longitude,  $E_{nm}$  is the unknown coefficients of the Taylor series expansion,  $(\beta, s)$  are the solar-geographic coordinates of the ionospheric pierce point,  $(\beta_0, s_0)$  are the coordinates of the origin of Taylor series expansions. The unknown parameters for each satellite and receiver  $E_{nm}$ , are estimated by applying the least squares method. The angle of Taylor series depends on the behaviour of the ionosphere. If the angle is too high, the reliability of the estimated ionosphere parameters decreases (Wild, 1994). Zero angle defined as  $E_{00}$  informs about TEC on the reference station which TEC parameters are expanded by series. GNSS measurements and TEC values can be derived directly from the station-related data, as well as from GNSS-based models generated. GIM (Global Ionosphere Maps) can be an example for that. In addition, at our present time the International Reference Ionosphere (IRI) model provides ionospheric parameters such as electron density, ion and electron temperature as well as TEC information.

### 3.4 Global TEC Model

The Taylor expansion used for local models is insufficient for a global TEC model. The spherical harmonic expansion is accepted as an ideal approach to determine a global TEC (Schaer et al., 1995). The spherical harmonic expansion is as

$$E_v(\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{m_{max}} P_{nm}(\sin \beta) (C_{nm} \cos(ms) + S_{nm} \sin(ms)) \tag{5}$$

In this equation,  $E_v(\beta, s)$  is the vertical total electron content,  $P_{nm}(\sin \beta)$  is the normalized Legendre Function,  $C_{nm}$  and  $S_{nm}$  are the unknown spherical harmonic coefficients and global ionosphere map parameters, respectively,  $n_{max}$  and  $m_{max}$  are the maximum degree of the spherical harmonic expansion,  $\beta$  is the latitude,  $s$  is the sun-fixed longitude (Arslan, 2004).

There are a lot of institutions which produces Global Ionosphere TEC maps all over the world. These are the CODE (Center for Orbit Determination in Europe), DLR (Fernerkundungstation Neustrelitz)

tz, Germany), ESA/ESOC (the European Space Agency, Germany), JPL (Jet Propulsion Laboratory, USA), NOAA (National Oceanic and Atmospheric Administration, USA), NRCAN (Natural Resources, Canada), ROB (Royal Observatory of Belgium, Belgium), UNB (New Brunswick University, Canada), UPC (Polytechnic University of Catalonia, Spain), WUT (Warsaw University of Technology, Poland) (Schaer, 1999). The Global ionosphere map (GIM) is issued in the format of IONEX (IONosphere map EXchange). IONEX formatted TEC values are lined up as involving all over the world. The TEC value at required point may be obtained from this line. If the latitude and longitude of a point are known, the relevant TEC value is obtained with the help of the 4 nearest TEC values covering two variable interpolation points (Schaer et al., 1998). When the value calculated to determine the TEC in the TECU unit is multiplied by 0.1, the TEC value of the relevant point is determined in the TECU unit. IONEX formatted global ionosphere maps are produced at intervals of 2 hours. For TEC values, the increase in the longitude is  $5^\circ$  and the increase in the latitude is  $2.5^\circ$  (Arslan, 2004). The accuracy of TEC values published in IONEX format varies between 2–8 TECU.

The solutions to GIM maps can be downloaded from the IGS data center (URL 1). Up to the present, there have been no discrepancy between the solutions issued by different analytic centers. The IRI model was produced by the cooperation of the International Union of Radio Science (URSI) and COmmittee on SPAc Research (COSPAR) and is still regularly developed and improved. The last version of the model that you may get online is IRI-2012 (Bilitza et al., 2014). IRI can present a number of parameters related to the ionosphere, including the TEC value for ionospheric heights between 60 km and 2000 km, as to required location, date and time (Leong et al., 2015). TEC values can be calculated with international ionosphere reference model (IRI-2012) via internet address (URL 2).

#### 4 APPLICATION

In this study, 14 of TUSAGA-ACTIVE (CORS-TR) stations located between 36–40 latitudes and 27–35 longitudes in Turkey was used to set a regional ionosphere model. Totally 26 stations were used – the others were IGS stations. RINEX data related to designated stations from 2009 till the end of 2015 was obtained. Regional TEC values for the selected region from 2009 until 2015 were determined through the evaluation made by Bernese v5.2 GNSS software. The GIM values produced by CODE, ESA and JPL and the IRI-2012 (International Reference Ionosphere) model developed by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) were used to compare the produced TEC values.

The TUSAGA-ACTIVE (CORS-TR) and IGS (International GNSS Service) stations used are geographically presented in the Figure 6. The data belonged to TUSAGA-ACTIVE stations was obtained from (URL 3) website and the data from the IGS stations was obtained from (URL 4) website. Regional TEC values from 2009 to 2015 were obtained as a result of the conducted research. In order to compare the regional TEC values obtained from the GNSS measurements with the Bernese v5.2 GNSS software, the GIM-TEC values published by the CODE, ESA and JPL were downloaded from the web (URL 1) and TEC values obtained from IRI were calculated using the provided online solution (URL 2). The minimum (Table 2) and maximum (Table 3) results achieved in the study are presented in the Table 2 and Table 3.



Table 3: Maximum observed TEC values.

| Years | Maximum Observed Values |          |       |          |       |          |       |          |       |          |
|-------|-------------------------|----------|-------|----------|-------|----------|-------|----------|-------|----------|
|       | RIM                     |          | CODE  |          | ESA   |          | JPL   |          | IRI   |          |
|       | TEC                     | UTC Time | TEC   | UTC Time | TEC   | UTC Time | TEC   | UTC Time | TEC   | UTC Time |
| 2009  | 13.40                   | 10:00    | 14.23 | 10:00    | 12.94 | 10:00    | 16.62 | 10:00    | 10.33 | 10:00    |
| 2010  | 18.63                   | 10:00    | 19.54 | 10:00    | 17.21 | 10:00    | 21.37 | 10:00    | 12.96 | 10:00    |
| 2011  | 29.67                   | 12:00    | 29.49 | 12:00    | 29.27 | 12:00    | 31.59 | 12:00    | 18.43 | 10:00    |
| 2012  | 35.22                   | 10:00    | 34.83 | 10:00    | 33.28 | 10:00    | 37.12 | 10:00    | 22.09 | 10:00    |
| 2013  | 34.71                   | 12:00    | 34.28 | 10:00    | 35.09 | 12:00    | 36.84 | 12:00    | 23.92 | 10:00    |
| 2014  | 41.07                   | 10:00    | 40.96 | 10:00    | 44.71 | 12:00    | 43.27 | 10:00    | 25.98 | 10:00    |
| 2015  | 34.24                   | 12:00    | 34.46 | 12:00    | 37.76 | 12:00    | 36.33 | 12:00    | 22.72 | 10:00    |

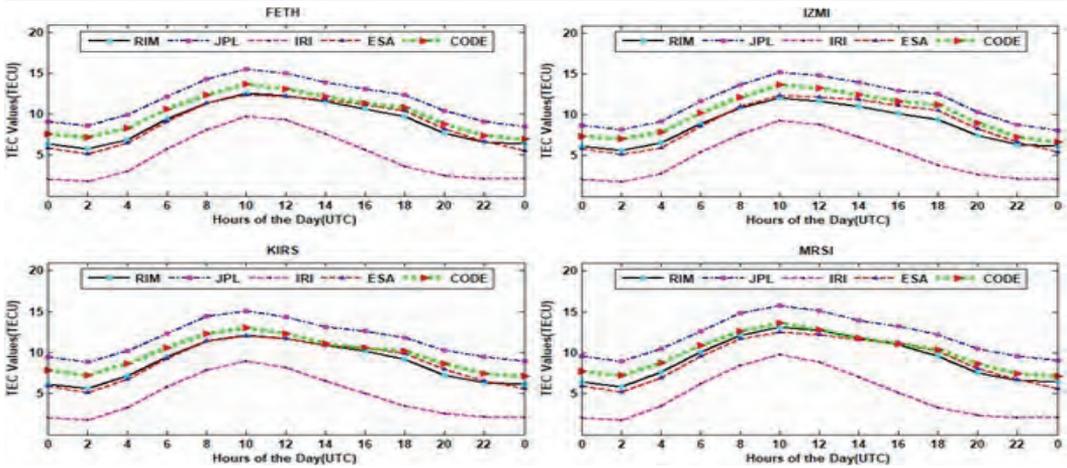


Figure 7: Comparison of mean TEC values (RIM-Result) obtained at FETH, IZMI, KIRS, MRSI points with CODE, ESA, JPL, IRI values for 2009.

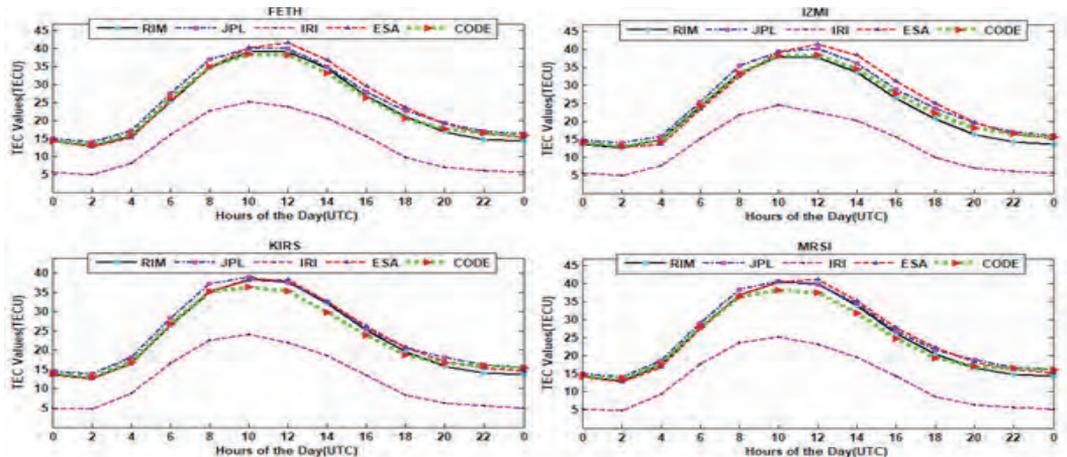


Figure 8: Comparison of mean TEC values (RIM-Result) obtained at FETH, IZMI, KIRS, MRSI points with CODE, ESA, JPL, IRI values for 2014.

The mean TEC values, which were produced at intervals of two hours for the selected days by using the TEC values obtained from the evaluation, were compared with the mean TEC values of GIM and IRI. In the graphs, the horizontal axis represents the universal time in hours, and the vertical axis represents TEC in TECU units.

The TEC values obtained from the global ionosphere model (CODE, ESA, JPL) began to increase at 02:00 am and reached to its maximum value at 12:00. In general, the global TEC values are of the lowest value at 2:00 am and the highest value between 10:00 am and 12:00 pm. The TEC values obtained online in the IRI model are of the lowest value at 02:00 am and the highest value at 10:00 am. In the regional ionosphere model (RIM), the TEC values obtained from the result of the evaluation began to increase at 02:00 am and rise to 12:00 pm, as in the global ionospheric models. In general, it is seen that the RIM-TEC values are at the lowest value at 02:00 am, similar to the global TEC values, and at the highest value between 10:00 am and 12:00 pm (Figure 7–8, Table 2, 3).

As utilizing the regional TEC values obtained from the evaluation and the global TEC values, and writing a command called as *TECmap* via **MATLAB**, and TEC map was produced by using mean TEC (RIM-TEC) values obtained from analysis for selected region and GIM (CODE) mean TEC values. The obtained TEC maps involve 24-hour time period starting from 00:00 hours at 2 hours intervals (Figure 9–12).

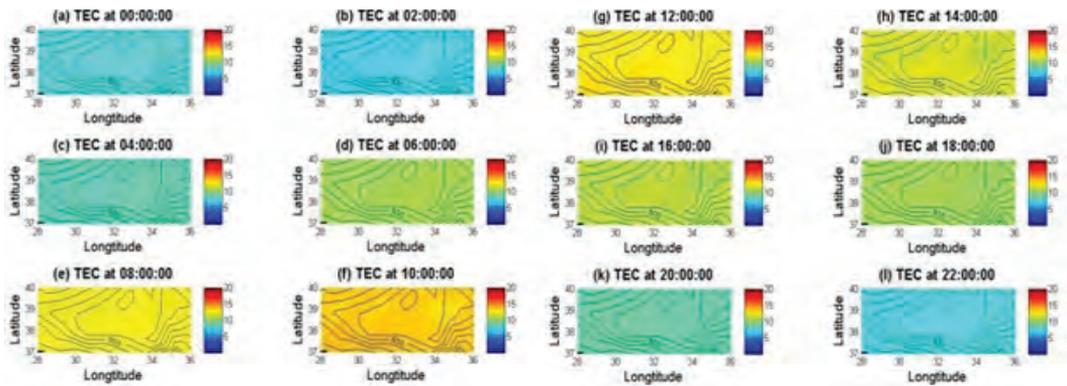


Figure 9: Global CODE TEC maps produced at 2 hour intervals for 2009

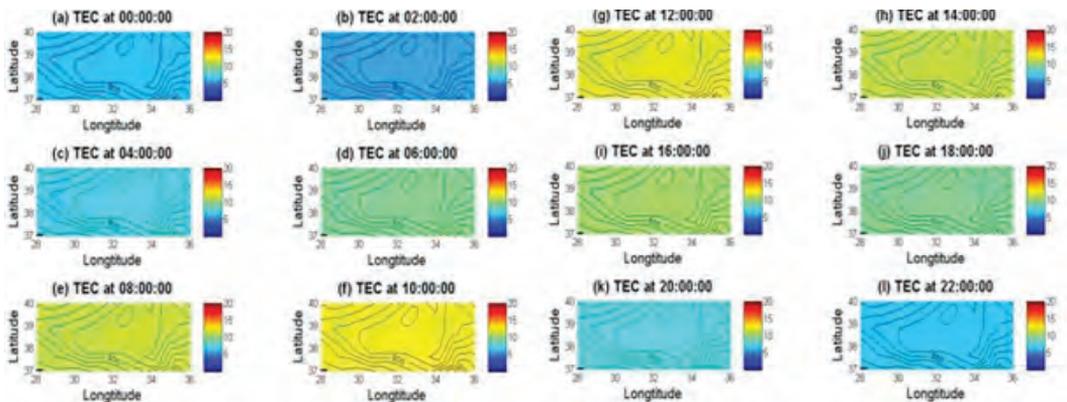


Figure 10: Regional RIM TEC maps produced at 2 hours intervals for 2009

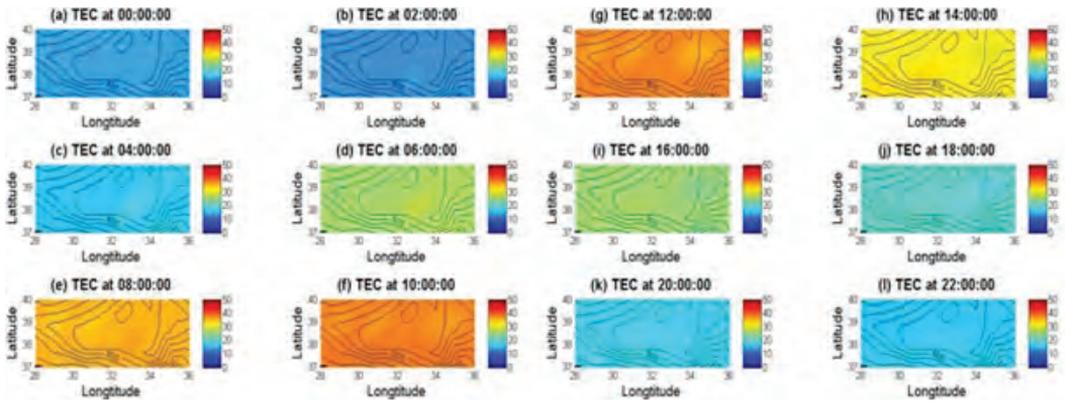


Figure 11: Global CODE TEC maps produced at 2 hour intervals for 2014

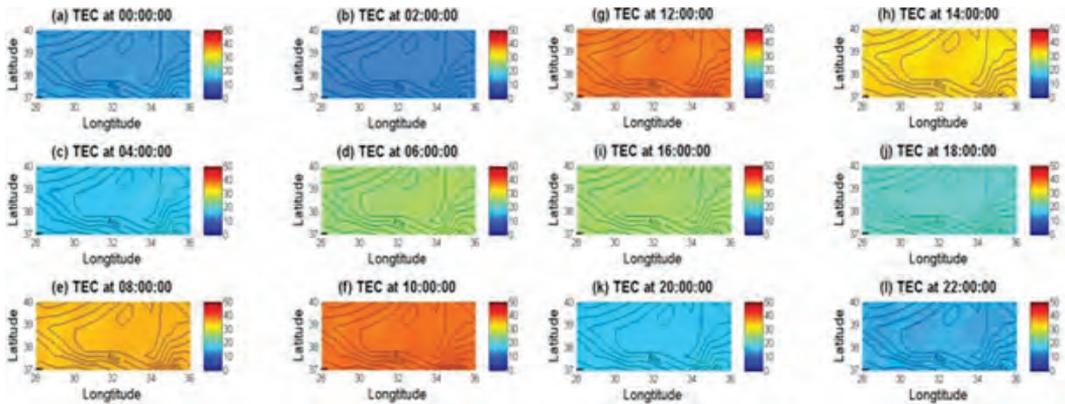


Figure 12: Regional RIM TEC maps produced at 2 hour intervals for 2014.

TEC maps were produced as calculating the mean of TEC values belonged to 14 TUSAGA-ACTIVE (CORS-TR) stations used for evaluation at various times of day. When examined all the maps produced from 2009 to 2015, it is seen that all TEC values increased until noon times and after that they decrease (Figure 9–12).

## 5 CONCLUSION

In this study, the regional ionosphere model was set by utilizing totally 26 GNSS stations as 14 of these were TUSAGA-ACTIVE (CORS-TR) stations located between 36–40 latitudes and 27–35 longitudes in Turkey. The regional ionosphere model that had been set was compared with global ionosphere model (CODE, ESA and JPL) issued by IGS and the IRI-2012 and the ionosphere maps covering the selected region were produced. Hence, Bernese v5.2 GNSS software was used to determine regional TEC values.

TEC values obtained from the regional ionosphere model (RIM), global ionosphere model (CODE, ESA, JPL) and IRI model generally began to increase at 02:00 am and reached at their maximum values at 12:00 pm. They began to decrease after 12:00 pm. Additionally, the density is at minimum values at 02:00 am and maximum values between 10:00–12:00.

When examining the Figure 7–8, it is seen that there is a substantial similarity between obtained regional (RIM) TEC values and global (CODE, ESA, JPL) TEC values, and TEC values obtained from IRI-2012 are lower in comparison to those four values. The most important reason why the IRI-2012 TEC estimate is low is that the TEC estimate obtained is kept low due to the absence of the ionosonde station in Turkey. On the other hand, it has been shown that five different TEC values obtained had similar behaviour during the day. It is generally seen that the five TEC values obtained increased until noon, and then the TEC values decreased due to the recombination of the ions in a free state. One of the most important reasons for that is thought to be the sun rays. At noon, when the sun rays are most forceful, the molecules in the air are separated by the effect of this radiation, and that causes increasing number of electrons in free state.

TEC maps that shows TEC changes as to latitude and time were produced for the selected region covering the 24-hour time period at 2 hours intervals by utilizing the regional TEC values obtained from the evaluation made from 2009 till the end of 2015 and the global TEC and IRI TEC values. When examined figure 9-12, it is seen that the produced TEC maps and TEC values belonged to points at Figure 7-8 shows similar results.

Establishing a system which will continuously monitor the change of TEC values as the most important function of the ionosphere, especially at the TUSAGA-ACTIVE (CORS-TR), will make a great contribution to studies about earthquake, volcanic eruptions, and determining the location of the missiles and for both improving accuracy of location and examining the relationship with ionosphere.

## Acknowledgments

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