Determination of Regional TEC Values by GNSS Measurements, A Case Study: Central Anatolia Sample, Turkey

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Key words: GNSS, Ionosphere, Total Electron Content (TEC), Global Ionosphere Map (GIM)

SUMMARY

The atmosphere surrounding the earth as a cover is divided into different layers depending on its characteristics such as density, heat and height. Ionosphere layer can be defined as a layer which covers the area between 60 km and 1.000 km above ground and contains many free electrons and positive charged ions. Ionosphere is a natural plasma area shaped by solar radiations. The radiation from the sun forms positively charged ions and free electrons by ionizing the atoms and molecules in the ionosphere. The ionosphere is an important layer affecting GNSS (Global Navigation Satellite System) measurements. The quality of the GNSS measures is directly related to the changes in the ionosphere. Total Electron Content (TEC) is one of the important parameters expressed to character of the ionosphere which has great importance for satellite based positioning, shortwave and satellite communication systems. Determination of the TEC change is important for modeling the ionosphere.

CORS-TR (Continuously Operating Reference Stations – Turkey) network which consists of 146 stations covering Turkey and Turkish Republic of Northern Cyprus, is generated at 2009. In this study, data obtained from 12 IGS stations and 8 CORS-TR stations were evaluated in order to form regional ionosphere model. Bernese v5.2 GNSS software which was developed at the Astronomical Institute of the University of Bern (AIUB) have been used in evaluation. The TEC values for 2015 have been calculated at intervals of two hours. TEC values which were obtained from GNSS measurements compared with global ionosphere maps produced by CODE, ESA, JPL and IRI-2012 TEC produced by international reference model. In addition, correlation coefficients were calculated to determine the relationship between the regional TEC values obtained from result of study and the global TEC values. The best approach to the regional ionosphere model as a result of comparison is obtained respectively CODE, ESA and JPL global models. In the study, a TEC map was produced for the determined region by using regional and global TEC values.

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1. INTRODUCTION

Monitoring the ionosphere is important for mainly GNSS (Global Navigation Satellite System) and for study areas like communication, security, navigation as well. Changes in ionosphere effect satellite based studies directly. GNSS receivers are widely used in studies related ionosphere because they spread most of the world and the information (Total Electron Content, TEC) about ionosphere can be obtained from satellites monitored by these receivers. (Alçay et al., 2014).

Ionosphere is an atmosphere layer surrounds the world and consisted of sun rays and ionized gases and located at heights between 60 and 1000 km above ground. Most of the ionosphere consists of neutral gases. Ionized gases are mostly formed because of ionization with solar shortwave rays (ultraviolet and X-rays). Free electron content in ionosphere depends on many factors like time, location, geomagnetic movements (Aysezen, 2008). Electron density in ionosphere changes by getting affected all of the effects like daytime/nighttime, seasons, geographical location and magnetic storms at sun. Separating from electrons with solar radiation, free electrons reach the densest value in a day between 12:00 – 14:00 in local time. Ionization decreases at nights because of integration of electrons with ions. Seasonal electron density changes in ionosphere are caused by angle and distance changes between sun and world. Moreover 11 years solar cycle has effects over electron density in ionosphere (Komjathy, 1997). One of the parameters used to define the condition of ionosphere is Total Electron Content (TEC). TEC (Total Electron Content) is the total number of electrons integrated between satellite and its receiver, along a tube of one meter squared cross section and it is often reported in multiples of the so-called TEC unit (TECU), defined as TECU=10^{16} electron/ m^2 (Schaer, 1999; Dach et. al., 2015).

2. STRUCTURE OF IONOSPHERE

2.1. Ionosphere Regions

Ionosphere is divided three main region for geographical latitude; these are high latitude region, middle latitude region and polar region (Figure 1). Scientific studies grounds on these regions.

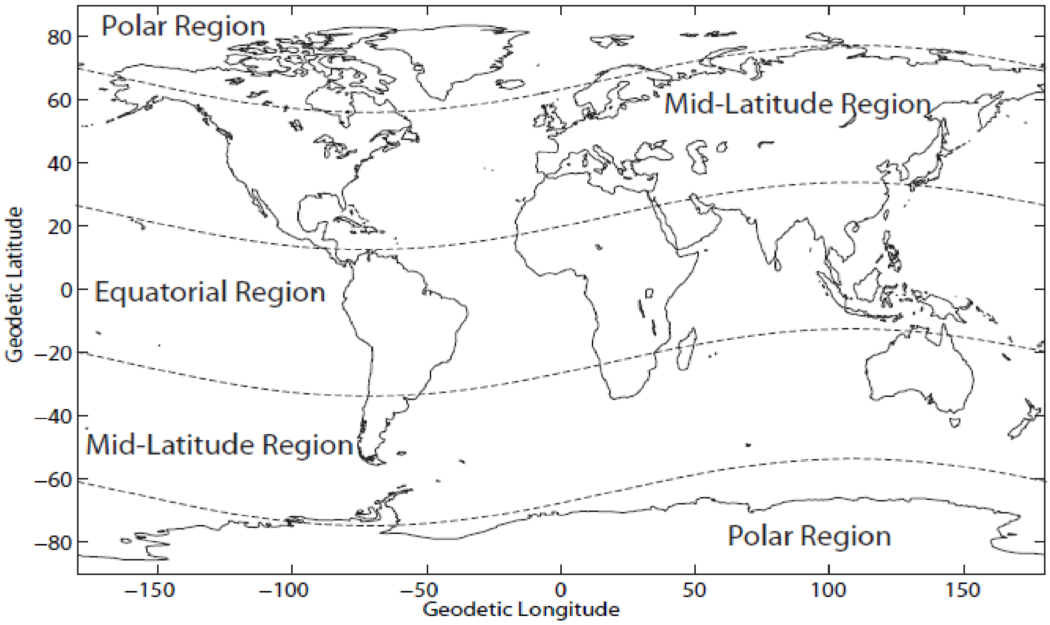

Figure 1. Ionosphere Regions (Memarzadeh, 2009)

High latitude region is divided into two as auroral and polar zones. Electron density values are lower than equatorial region has. Yet short-time ionospheric alterations in high latitude region are more than in equatorial region (Skone and Cannon, 1999; Danilov and Lastovicka, 2001).

Since most of the mid-latitude region is examined, it is the most known region where also Turkey is located. Ionosphere is calm and alteration is the lowest in mid-latitude region. Since the ionosphere research stations are mostly located in the countries in this region, the most of the ionosphere studies are carried on mid-latitude region. (Schaer, 1999). Ionization in this region is mostly occurs because of solar X-ray emission and charged ultraviolet radiation. Ionization ends with chemical process which includes ionized parts alongside of neutral atmosphere (Arslan, 2004).

Equatorial region is a region where electron density is the highest, signal's amplitude and phase are changing frequently. The reason for this is solar radiation and dense ionization. Ionospheric activity taking place at the equatorial region is named equatorial anomaly. Equatorial anomaly can be defined as decrease in electron density at geomagnetic equator because of reasons like magnetic storms. This anomaly changes with E layer's dynamo which causes regional electrical zone at equator and is controlled by global tidal winds. Daily equatorial anomaly starts in local time at between 9:00-10:00 and reaches its maximum value at between 14:00-15:00 (Gizawy, 2003).

2.2. Ionosphere Layers

Emission of different waved solar radiations and difference of ionization at different heights are determining the structure of ionosphere layer. The amount of the ionization increases as altitude rises. Ionization quantity changes in time since the position of ionosphere to the sun changes. Ionosphere layers are classified generally as D, E, F_1, F_2 (Figure 2).

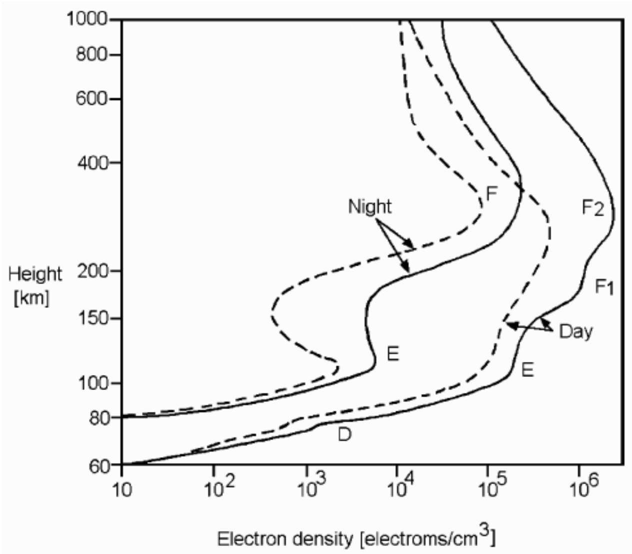

Figure 2. Ionosphere Layers (Hargreaves, 1992)

D layer where the least ionization takes place is located at height between 60 and 90 km above ground (Wild, 1994). It is considered that this layer has no significant effects over GNSS measurements (Petrie et al., 2011).

E layer is located between 90 and 150 km above ground. Irregular E_s where partly ionizing takes place has low effects over GNSS measurements. Having diffraction effect over signals E layer's weakening effect is quite less than D layer's. Ionization in E layer happens mostly via low energized X-rays. It is thought that ionization is not related with daytime E layer. In this layer an anomaly, occurred because of sun particles, causes polar lights (Schaer, 1999).

Located at 150 km above ground F layer is examined as two parts as F_1 and F_2 and it consists with solar ultraviolet rays. 10% of GNSS signal's delay at ionosphere layer is caused by F_1 layer (Parkinson and Spilker, 1996). This layer's structure is regular and controlled via solar changes and located at heights between 140 and 200 km above ground. F_2 layer has irregular structure and located at between 200 and 1000 km above ground. This layer is most effective against GNSS measurements (Parkinson and Spilker, 1996). Electron density of F_2 layer, which shows different alterations at polar region, decreases irregularly at nights. F_2 layer is very unstable at equatorial region; night time electron density can be more than noon time has (Wild, 1994; Poole, 1999). Features belong to ionosphere layers are shown in Table 1.

Table 1. Features of ionosphere layers (Wild, 1994; Arslan, 2004)

Layers	Altitude (km)	Electron Density (1/cm^3)		Neutral Gas Density (1/ cm^3)
		Night	Day	
D	60-90	10^2-10^4	---	10^{15}
E	90-140	10^5	2.10^3	2.10^{12}
F_1	140-200	3.10^5	10^3	10^{10}
F_2	200-1000	5.10^5	3.10^3	10^6-10^{10}

3. OBTAINING TEC VALUES WITH GNSS MEASUREMENTS

Identifying TEC values via GNSS signals is a fast and cheap method to be used to understand the structure of ionosphere (Ya'acob et.al., 2010). Data obtained via GNSS receivers includes code and phase observations. Ionospheric delay is positive for code measurements, negative for phase measurements. The graphic display of total electron content in ionosphere is given at figure 3. TEC should be a positive value, and if it is negative the reasons of this are receiver and satellite errors.

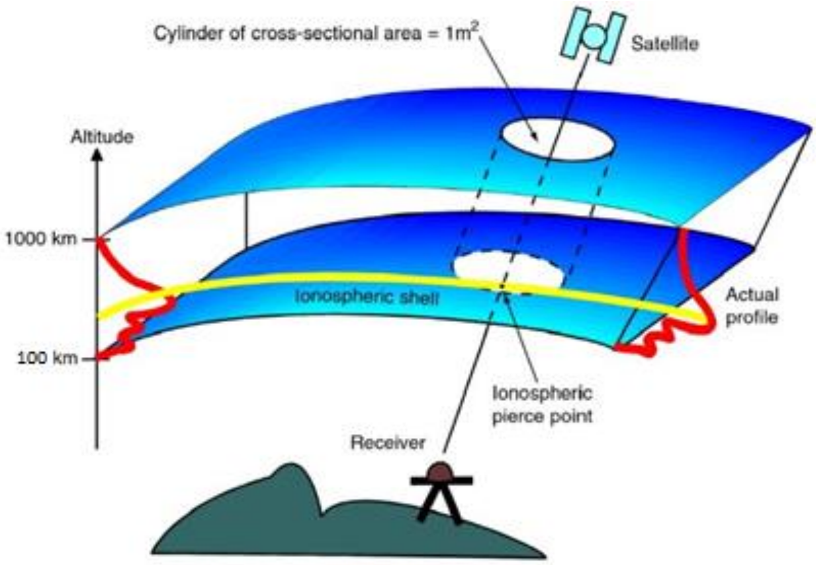

Figure 3. Graphical display of Total Electron Content (Langley, 2002)

Ionosphere layer's height is generally taken as 450 km in software and TEC value at this height is considered as the highest value (Komjathy and Langley, 1996).

GNSS measurements and TEC values can be obtained both from directly data belongs to the station and from generated GNSS based models. GIM (Global Ionosphere Map) can be an example for this. Moreover today International Reference Ionosphere (IRI) model can offer some parameters belonging to ionosphere like electron density, ion and electron heat alongside of TEC information.

4. GLOBAL IONOSPHERE MAPS (GIMs)

In June 1998, International GNSS Service (IGS), initiated an international project to calculate different global ionosphere maps (GIMs) daily by using GPS data. Institutions that generate global ionosphere TEC maps are named Ionosphere Associate Analysis Center (IAAC) and listed below (Feltens and Schaer, 1998; Orús Pérez, 2005; Orús Pérez et. al., 2005).

CODE	: Centre for Orbit Determination in Europe, Bern, Switzerland,
DLR	: Fernerkundungsstation Neustrelitz, Germany,
ESA/ESOC	: European Space Operations Center, Darmstadt, Germany,
JPL	: Jet Propulsion Laboratory, Pasadena, CA, U.S.A.,
NOAA	: National Oceanic and Atmospheric Administration, Silver Spring, U.S.A.,
NRCan	: Natural Resources, Ottawa, Ontario, Canada,
ROB	: Royal Observatory of Belgium, Brussels, Belgium,
UNB	: University of New Brunswick, Fredericton, N.B., Canada,
UPC	: Politechnical University of Catalonia, Barcelona, Spain,
WUT	: Warsaw University of Technology, Warsaw, Poland.

Global ionosphere map (GIM) is generated in IONEX (IONosphere map EXchange) format. IONEX formatted global ionosphere maps are manufactured in two hours intervals. For TEC values, raise in longitude is 5^o and latitude is 2.5^o (Arslan, 2004; Orús Pérez, 2005). TEC values in IONEX format are alined to cover all the world. To define TEC in TECU format, calculated value should be multiplied with 0.1. The validation of TEC values generated from IONEX format can change 2 to 8 TECU.

5. INTERNATIONAL REFERENCE IONOSPHERE MODEL (IRI)

IRI is a model developed by International Union of Radio Science (URSI) and Committee on Space Research (COSPAR) and it is maintained and developed regularly. The last version of the model whom we can gather online data is IRI-2012 (Bilitza et.al., 2014). IRI can present so many parameters belonging to ionosphere including TEC values for given location, date and time between 60 and 2000 km altitudes. The main data sources of IRI are ionosonde, radar, international satellites for ionosphere studies and Aloutte receivers (Leong et. al., 2015). In this study web interface in IRI main website is used to gather TEC values from IRI-2012. (Figure 4).

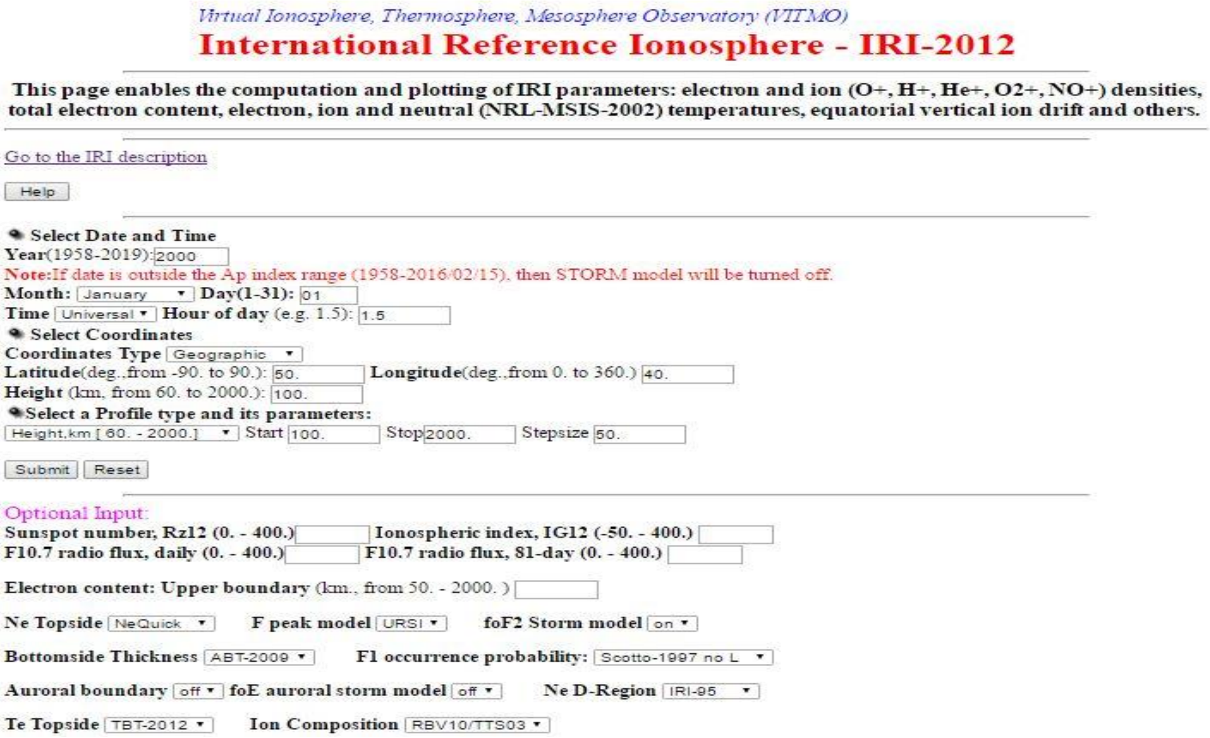

Figure 4. IRI-2012 program (URL 1)

6. APPLICATION

In this study, to generate a regional ionosphere model, data obtained from 12 IGS stations and 8 CORS-TR stations, which are located in Turkey between 37°-41° latitudes and 31°-37° longitudes were evaluated. RINEX data of aforementioned stations for 2015 were obtained. Regional TEC values for 2015 for the selected area was obtained via evaluation done with the help of Bernese v5.2 GNSS software. For comparison of generated TEC values, GIM values generated by CODE, ESA, JPL and IRI-2012 model (International Reference Ionosphere) developed by Committee on Space Research (COSPAR) and International Union of Radio Science (URSI) were used.

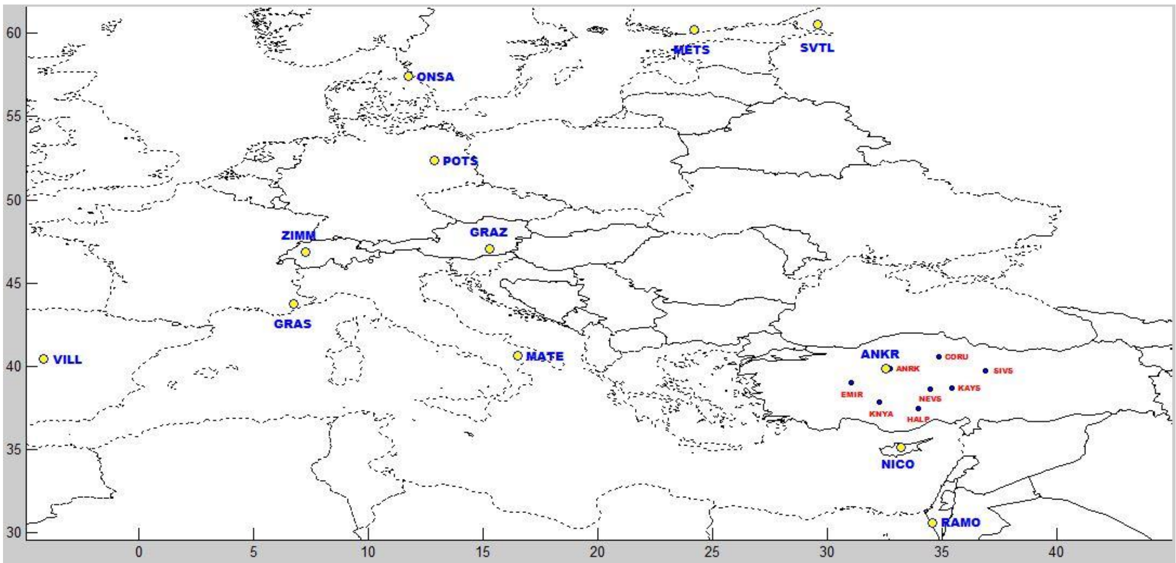

Figure 5. General Structure of Network

In figure 5 CORS-TR and IGS (International GNSS Service) stations used for analysis are given. GNSS data in RINEX format belongs to CORS-TR stations was obtained from website (URL 2), GNSS data in RINEX format belongs to IGS stations was obtained from website (URL 3).

To analyze data for regional TEC values in Bernese v5.2 software there are some steps that should be followed beforehand. The first and the most important of them is a campaign directory should be created for the day which is going to be analyzed for user to evaluate. After creating the campaign directory for related day to analyze, following data is downloaded from IGS server (URL 4) and from server of Astronomical Institute, University of Bern (AIUB) (URL 5).

- Precise satellite orbits and clocks files (.sp3, .clk),
- Earth rotation parameters (.erp),
- Instrumental biases (Differential P1-P2 code biases – DCB), is guessed as constant value for everyday from GNSS satellites. Monthly P1C1-P1P2 resolution (P1P2yymm.DCB – ionosphere determining and P1C1yymm.DCB – clock estimation) files are available at (URL 5) since October 1997,
- Ionosphere (.ION), ephemeris files (.EPH), clock correction (.CLK), earth rotation parameters (.ERP).

Regional TEC values for 2015 was obtained by running PPP_DEMO.PCF automatic analysis (Bernese Processing Engine-BPE) in Bernese v5.2 GNSS software with these GNSS data.

GIM-TEC values, published by CODE, ESA and JPL to compare regional TEC values obtained from GNSS measurements with Bernese v5.2 software, were downloaded from website (URL 3). TEC values obtained from IRI were calculated online on the website (URL 1) via latitudes and longitudes of related day’s location.

Graphics of the TEC values obtained via analysis were prepared with **MATLAB** program. After executing the graphic_draw.m Matlab code and selecting excel files where TEC values were saved, TEC values' graphics were done. As a result, the average TEC values of 2015 were calculated and compared with IRI and GIM (JPL, ESA, CODE) average TEC values (Figure 6, Figure 7).

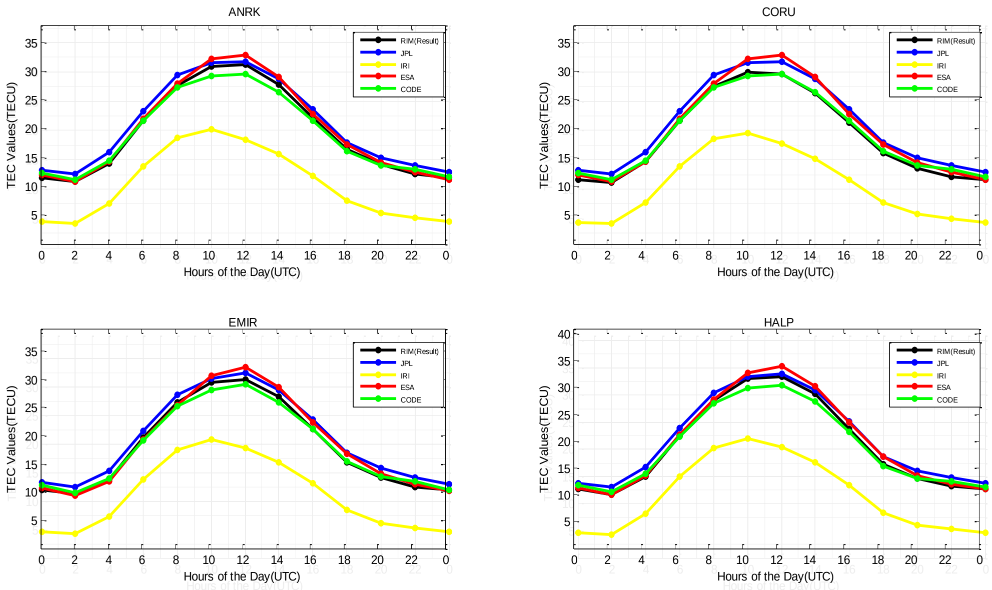

Figure 6. Comparing ANRK, CORU, EMIR, HALP stations' average TEC (RIM-Result) values obtained via analysis with CODE, ESA, JPL, IRI values for 2015

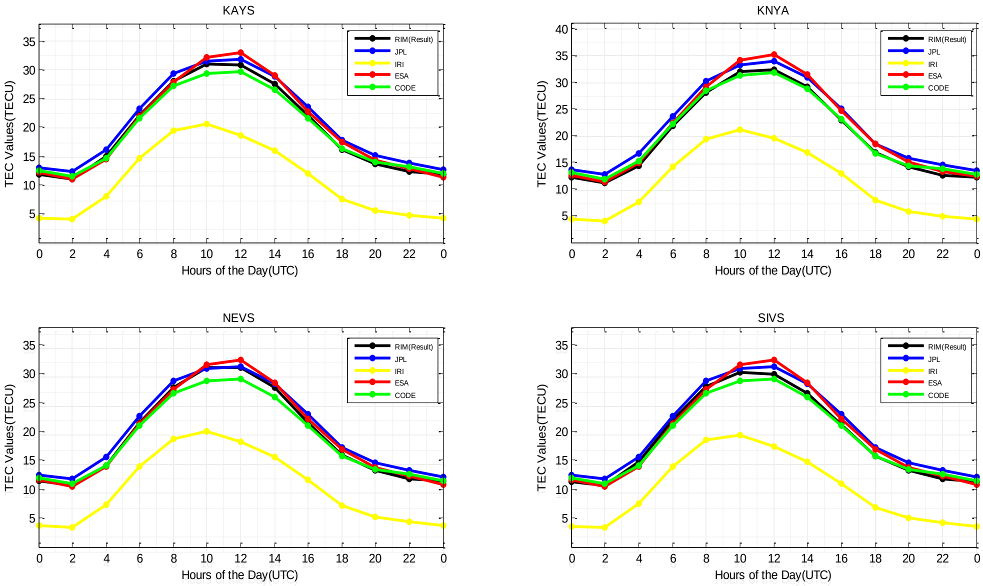

Figure 7. Comparing KAYS, KNYA, NEVS, SIVS stations' average TEC (RIM-Result) values obtained via analysis with CODE, ESA, JPL, IRI values for 2015

TEC values, obtained from regional ionosphere model (RIM), from global ionosphere model (CODE, ESA, JPL), started to increase at 02:00 am and reached maximum at 12:00 pm. It was seen that the values started to decrease at 12:00 pm and reached minimum at 02:00am. The density was seen at maximum between 10:00 am – 14:00 pm.

TEC values, obtained online from IRI model, started to increase at 02:00 am and reached maximum at 10:00 am. It was seen that the IRI_TEC values were at minimum at 02:00 am and at maximum between 08:00 am – 12:00 pm.

In regional Ionosphere Model (RIM) TEC values, obtained via analysis, started to increase at 02:00 am and reached maximum at 12:00 pm as in global ionosphere model. It was seen that the RIM_TEC values are at minimum at 02:00am and at maximum between 10:00 am – 14:00 pm similar to global TEC values.

When TEC values obtained from CORS-TR stations used for evaluation are examined (Figure 6, Figure 7), it is seen that RIM-TEC values obtained via analysis and GIM_TEC (CODE, ESA, JPL) values were in harmony and the difference between them reached max 2.3 TECU and min -3.3 TECU. TEC values obtained from IRI model are generally lower than the RIM-TEC values obtained via analysis and the difference between RIM_TEC and IRI_TEC reached max 13.1 TECU and min 6.5 TECU.

For detailed analysis of obtained results, maximum, minimum, average, standard deviation value and correlation coefficients of the difference between regional TEC (RIM_TEC) values obtained via analysis and global TEC (GIM_TEC) and IRI model are given at Table 2. It can be said that RIM_TEC and GIM_TEC values are all in harmony in all stations however, TEC values obtained from IRI model are lower than regional and global TEC values. When standard deviation values of differences among RIM_TEC, GIM_TEC and IRI_TEC are examined it can be seen that RIM_TEC-JPL results are better in all stations. When correlation coefficients among RIM_TEC, GIM_TEC and IRI_TEC values are examined, one can say that there is a positive and high-level relationship between RIM_TEC values and GIM_TEC, IRI_TEC values.

Table 2. Statistical values of TEC values obtained from stations used in evaluation (TECU)

Station Name	Difference Statistics	RIM-CODE	RIM-ESA	RIM-JPL	RIM-IRI
ANRK	Maximum	1.5	0.4	-0.6	12.7
	Minimum	-0.9	-1.8	-2.0	6.8
	Average	0.2	-0.6	-1.3	8.9
	Std. Deviation	0.85	0.50	0.42	1.93
	Correlation	0.998584	0.999210	0.998770	0.986824
CORU	Maximum	0.6	0.1	-1.2	11.9
	Minimum	-1.3	-3.3	-2.5	7.0
	Average	-0.3	-1.1	-1.8	8.7
	Std. Deviation	0.52	1.03	0.31	1.69
	Correlation	0.998917	0.995621	0.999367	0.989486
EMIR	Maximum	1.4	0.5	-0.6	12.1
	Minimum	-0.9	-2.0	-1.7	6.5
	Average	0.2	-0.6	-1.3	8.5
	Std. Deviation	0.71	0.88	0.33	1.83
	Correlation	0.999205	0.995634	0.999371	0.988279
HALP	Maximum	1.7	0.1	-0.3	13.1
	Minimum	-0.9	-1.9	-1.9	6.7
	Average	0.3	-0.6	-1.2	9.1
	Std. Deviation	0.88	0.63	0.45	2.08
	Correlation	0.999160	0.998478	0.999292	0.984730
KAYS	Maximum	1.7	0.5	-0.6	12.0
	Minimum	-1.0	-2.1	-1.6	6.8
	Average	0.3	-0.5	-1.2	8.7
	Std. Deviation	0.79	0.76	0.28	1.78
	Correlation	0.999347	0.996673	0.999566	0.986339
KNYA	Maximum	0.7	-0.1	-1.3	12.7
	Minimum	-1.2	-2.9	-2.3	6.7
	Average	-0.3	-1.2	-1.7	8.9
	Std. Deviation	0.61	0.86	0.30	1.96
	Correlation	0.999032	0.998485	0.999282	0.986150
NEVS	Maximum	2.3	0.6	0.1	12.9
	Minimum	-0.9	-1.2	-1.6	6.7
	Average	0.5	-0.3	-1.0	8.9
	Std. Deviation	1.03	0.47	0.54	2.01
	Correlation	0.999068	0.998462	0.998933	0.984971
SIVS	Maximum	1.6	0.8	-0.6	12.4

	Minimum	-0.8	-2.4	-1.7	7.2
	Average	0.3	-0.5	-1.2	9.0
	Std. Deviation	0.73	0.98	0.35	1.79
	Correlation	0.998634	0.994339	0.998960	0.986824

TEC maps were generated in MATLAB via help of Global TEC values and TEC values obtained via result of analysis for selected region for 2015. TEC maps were generated with TECmap_Interface.m command executed on MATLAB after selecting ionosphere map model and desired year range. Obtained TEC maps covers 24 hours starting from 00:00 with two hours intervals (Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12).

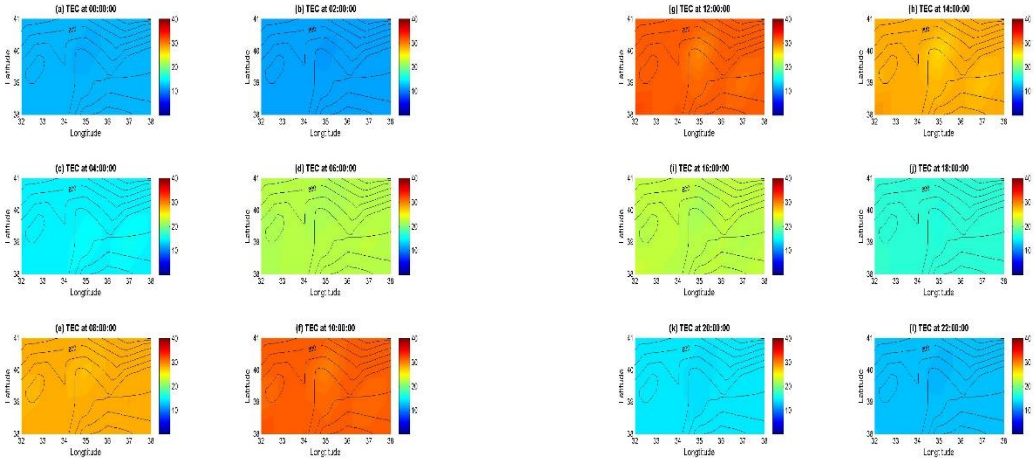

Figure 8. Regional RIM TEC maps generated in two hours intervals for 2015

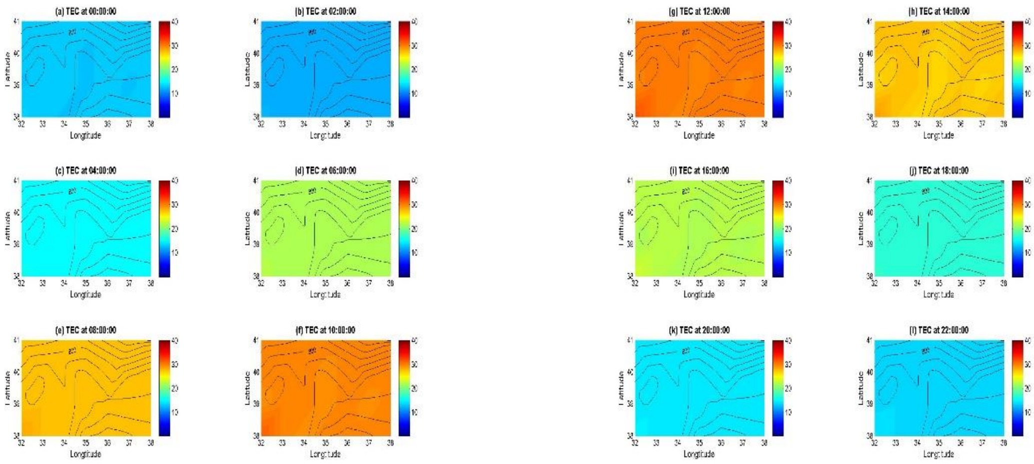

Figure 9. CODE TEC maps generated in two hours intervals for 2015

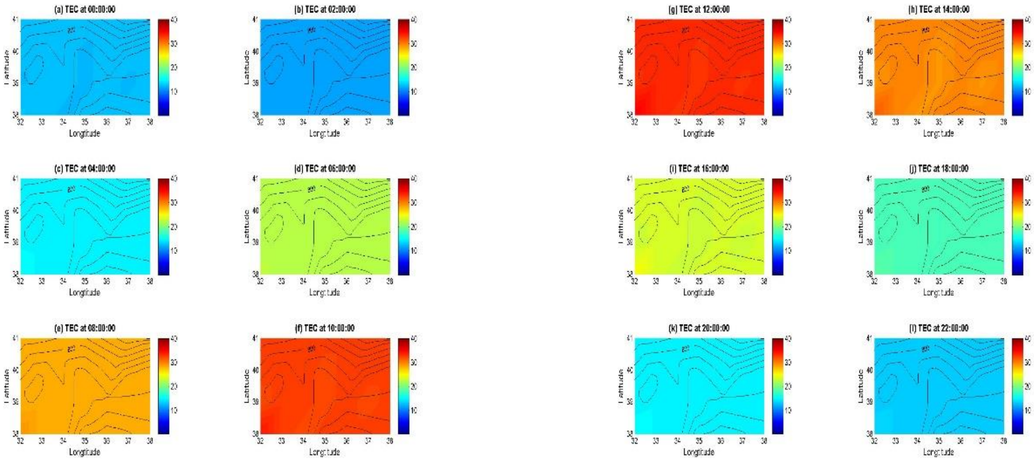

Figure 10. ESA-TEC maps generated in two hours intervals for 2015

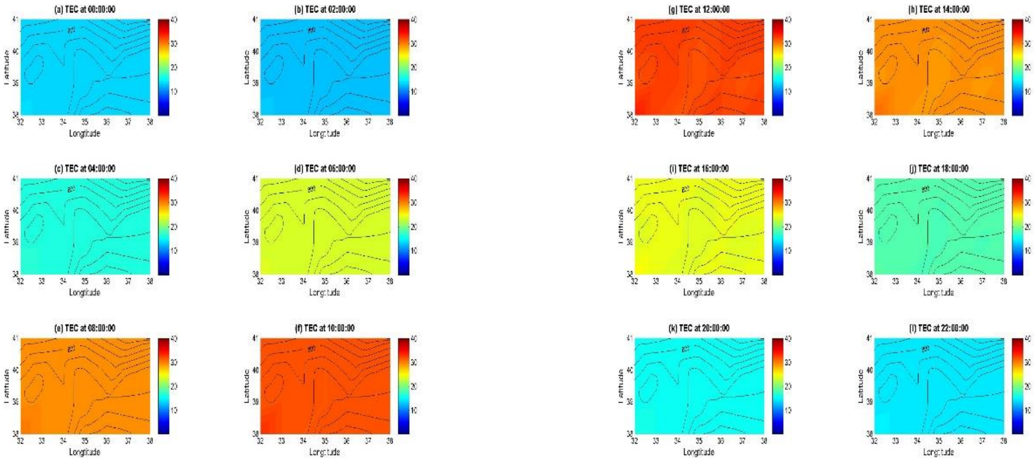

Figure 11. JPL-TEC maps generated in two hours intervals for 2015

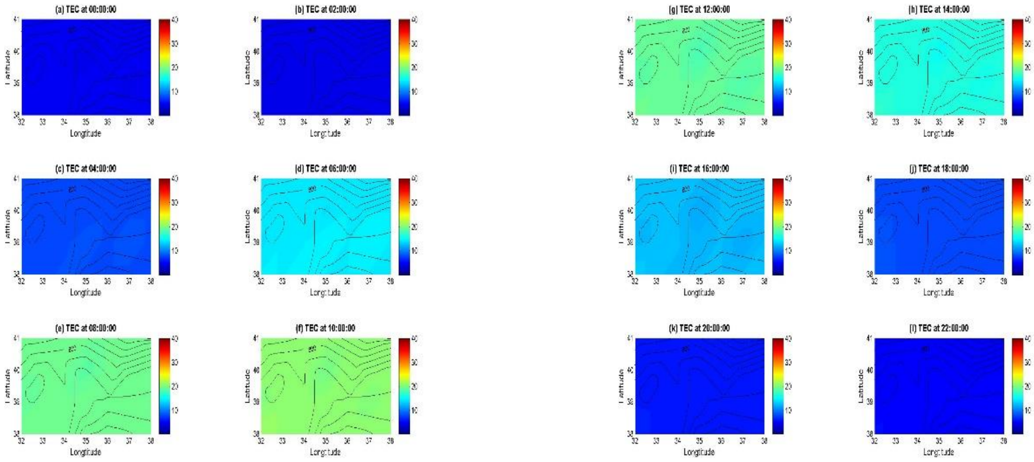

Figure 12. IRI-TEC maps generated in two hours intervals for 2015

7. CONCLUSION

Signals going through atmosphere and reaching GNSS receivers, are affected highly by ionosphere’s unstable structure. Sun has very important role upon this unstableness. Ionosphere which changes constantly depending day time and with the effect of solar eruptions, has constantly changing electron density depending whether it is day or night, seasons, latitude and longitude.

In this study, to generate a regional ionosphere model, data obtained from 12 IGS stations and 8 CORS-TR stations, which are located in Turkey between 37^o-41^o latitudes and 31^o-37^o longitudes were evaluated. Generated regional ionosphere model was compared with IRI model and global ionosphere models (CODE, ESA and JPL) published by IGS, ionosphere maps, covering selected area, were generated by defining correlation coefficients to determine the relationship between global TEC values and obtained regional TEC values. To determine regional TEC values Bernese v5.2 GNSS software was used.

Regional (RIM) TEC values were generated for the year of 2015. Obtained results were compared with average values of GIM values published by CODE, ESA, JPL and TEC values obtained by IRI-2012 (Figure 6, Figure 7). When results are evaluated, it is seen that regional (RIM) TEC values obtained via analysis are in harmony with global (CODE, ESA, JPL) TEC values, however, TEC values obtained from IRI is lower than these four values. These obtained five different TEC values are observed to behave similarly in a day. It is seen that each of the five values are increased till noon than, the TEC values are decreased because of regrouping of free ions.

TEC values, obtained from regional ionosphere model (RIM), from global ionosphere models (CODE, ESA, JPL) and from IRI model, in general, started to increase at 02:00 am and reached maximum at 12:00 pm. It was seen that the values reached minimum at 02:00am and the density was seen at maximum between 10:00 am – 14:00 pm.

With the help of TEC values obtained via analysis for 2015, global TEC values and IRI TEC values, TEC maps, which shows TEC changes according to latitude and time, were generated for selected area in two hours intervals for 24 hours.

Via CORS-TR with instant data obtained from 142 stationary GNSS station, near real time model of ionosphere will be done more precisely. Since there are not enough old data about ionosphere which has an important role in shortwave communications and navigation, GNSS measurements done before will be crucial for new models.

8. ACKNOWLEDGMENTS

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In this study regional TEC values were obtained with Bernese v5.2 GNSS software.
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