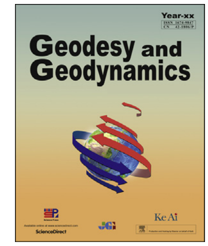
Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/en/journals/geog; http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml



Performance of GPS slant total electron content and IRI-Plas-STEC for days with ionospheric disturbance

Feza Arikan[a,*], *Seymur Shukurov*[a], *Hakan Tuna*[b], *Orhan Arikan*[b], *T.L. Gulyaeva*[c]

[a] *Department of Electrical and Electronics Engineering, Hacettepe University, Beytepe, Ankara 06800, Turkey*
[b] *Department of Electrical and Electronics Engineering, Bilkent University, Bilkent, Ankara 06800, Turkey*
[c] *IZMIRAN, Moscow, 142190 Troitsk, Russian Federation*

ARTICLE INFO

Article history:
Received 18 December 2015
Accepted 28 December 2015
Available online 3 March 2016

Keywords:
Ionosphere
Total Electron Content (TEC)
GPS
IRI-Plas

ABSTRACT

Total Electron Content (TEC) is an important observable parameter of the ionosphere which forms the main source of error for space based navigation and positioning systems. Since the deployment of Global Navigation Satellite Systems (GNSS), cost-effective estimation of TEC between the earth based receiver and Global Positioning System (GPS) satellites became the major means of investigation of local and regional disturbance for earthquake precursor and augmentation system studies. International Reference Ionosphere (IRI) extended to plasmasphere (IRI-Plas) is the most developed ionospheric and plasmaspheric climatic model that provides hourly, monthly median of electron density distribution globally. Recently, IONOLAB group (www.ionolab.org) has presented a new online space weather service that can compute slant TEC (STEC) on a desired ray path for a given date and time using IRI-Plas model (IRI-Plas-STEC). In this study, the performance of the model based STEC is compared with GPS-STEC computed according to the estimation method developed by the IONOLAB group and includes the receiver bias as IONOLAB-BIAS (IONOLAB-STEC). Using Symmetric Kullback–Leibler Distance (SKLD), Cross Correlation (CC) coefficient and the metric norm (L2N) to compare IRI-Plas-STEC and IONOLAB-STEC for the month of October 2011 over the Turkish National Permanent GPS Network (TNPGN-Active), it has been observed that SKLD provides a good indicator of disturbance for both earthquakes and geomagnetic storms.

* *Corresponding author*. Tel.: +90 312 297 7095; fax: +90 312 299 2125.
E-mail address: arikan@hacettepe.edu.tr (Arikan F.).
Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.geog.2015.12.009

1. Introduction

The ionosphere is an atmospheric layer which roughly lies between 100 km and 1000 km altitude and contains gases ionized primarily by solar radiation [1]. Ionosphere is the main source of error for satellite based communication, positioning and navigation systems and detrimental effects on the amplitude and phases of received signals need to be corrected as much as possible [2]. The disturbances in the ionosphere can result from solar, geomagnetic, gravitational, and seismic activities [3–5]. Thus, the inhomogeneous, anisotropic, temporally and spatially varying structural nature of ionosphere requires new techniques for observation and prediction of ionospheric disturbances [6].

The electron density is the main parameter of ionosphere and its distribution in space and time provides necessary information to investigate the ionospheric variability [1,6]. Unfortunately, ionospheric electron density cannot be measured directly. Ionosondes, incoherent scatter radars and beacon satellites are generally used for electron density reconstruction but the measurements are both spatially and temporally sparse and expensive [6].

Total Electron Content (TEC), which is defined as the line integral of electron density on a given ray path, is an observable parameter that can be estimated from earth based Global Navigation Satellite System (GNSS) receivers in a cost-effective manner [7,8]. The unit of TEC is TECU where 1 TECU $= 10^{16}$ el/m^2. Global Positioning System (GPS) is the foremost system that is used in estimation of Slant Total Electron Content (STEC) which provides the estimate for the total number of electrons on the receiver-satellite link [7–9].

International Reference Ionosphere (IRI) is the most acknowledged climatic model of ionosphere that provides electron density profile and hourly, monthly median values of critical layer parameters of the ionosphere for a desired location, date and time between 60 and 2000 km altitude [10,11]. IRI is accepted as the International Standard Ionosphere model as given in reference [12]. Recently, the IRI model is extended to the GPS satellite orbital range of 20,000 km and GPS-TEC can be input to the model to update the state of ionosphere [13–15]. The new version is called IRI-Plas and it can be obtained from http://ftp.izmiran.ru/pub/izmiran/SPIM/. A user-friendly online version is also provided at www.ionolab.org as a space weather service.

IONOLAB (www.ionolab.org) is a leading research group that develops state-of-the-art techniques for imaging of ionosphere and space weather. The TEC estimation method of IONOLAB group, IONOLAB-TEC, is the one of the most important contributions for ionospheric mapping and electron density reconstruction [6,16,17]. IONOLAB-TEC is based on IONOLAB-STEC that is computed from phase leveled observables and it includes receiver bias as IONOLAB-BIAS [18]. IONOLAB-TEC is offered as an online space weather service from IONOLAB webpage,www.ionolab.org [17].

Another important space weather service by IONOLAB group is the computation of STEC using IRI-Plas model (IRI-Plas-STEC) for any given location, date and time as provided at www.ionolab.org [19]. In the computation of model based STEC, the ionosphere and plasmasphere which extend from 100 km to 20000 km, are divided into horizontal layers by using pre-set altitude step sizes. For a given slant path, the spherical coordinates of the points where the slant path reaches the mean altitude of these layers and the length of the slant path within the corresponding layers are calculated and the electron density values are extracted using IRI-Plas. IRI-Plas-STEC values on the chosen ray path are calculated as the summation of the electron density contribution at each layer multiplied by the length of the corresponding layer. The user-friendly interface at www.ionolab.org allows the choice of location and date and the variability with respect to the hour of the day, elevation and/or azimuth angles can be obtained. The desired location can be chosen as a GPS receiver in IGS or EUREF networks automatically. Also, a GPS satellite can be tracked and STEC can be computed for a desired date and/or hour. The computed IRI-Plas-STEC values are presented directly on the screen or the output can be sent to the user via email.

The differences in model based STEC and measurement based STEC can be an indicator of disturbance both geomagnetic storms and earthquake precursors as discussed in reference [20]. In this study, the IRI-Plas-STEC and IONOLAB-STEC are compared using Symmetric Kullback–Leibler Distance (SKLD), Cross correlation (CC) coefficient and the metric norm (L2N). SKLD is a measure of entropy and it compares the likeness of two probability density functions. CC compares the similarity of two functions and L2N is the metric distance between two vectors [21–23]. The computation of these three methods is provided in Section 2. Section 3 contains the comparison results over the Turkish National Permanent GPS Network (TNPGN-Active) in mid-latitude ionosphere. The comparison is based on a quiet day period in April 2011 and a disturbed day period in October 2011. In October 2011, there have been both a large magnitude earthquake in Van, Turkey and a severe geomagnetic storm. It has been observed that IRI-Plas-STEC is in very much accordance with IONOLAB-STEC for quiet days and SKLD provides a good indicator of disturbance for both earthquakes and geomagnetic storms. The paper ends with conclusion section.

2. Model and methods

In order to compare IONOLAB-STEC with IRI-Plas-STEC, three different methods are used. The first method is known as Symmetric Kullback–Leibler Distance (SKLD), and it is a measure of difference between two probability density functions. The Cross correlation (CC) coefficient is a measure of similarity between two functions or vectors and the metric norm (L2N) gives the metric distance between two vectors [21–24]. In our study, the two vectors (or functions) are formed using the samples of IONOLAB-STEC and IRI-Plas-STEC as

$$\mathbf{X}_{u;d}^{m} = \left[X_{u;d}^{m}(1)X_{u;d}^{m}(2)\cdots X_{u;d}^{m}\left(N_{u;d}^{m}\right)\right]^{T} \quad (1)$$

$$\mathbf{Y}_{u;d}^{m} = \left[Y_{u;d}^{m}(1)Y_{u;d}^{m}(2)\cdots Y_{u;d}^{m}\left(N_{u;d}^{m}\right)\right]^{T} \quad (2)$$

where the superscript m denotes the GPS satellite number, the subscript u is the GPS receiver and d is day of the chosen month of interest. $N^m_{u;d}$ is the total number of samples for the given satellite and receiver pair for the chosen day d. The IONOLAB-STEC and IRI-Plas-STEC values are computed for satellites over 30° local elevation angle and the sampling period is chosen to be 15 min. The superscript T denotes the transpose operator.

In order to compute SKLD, the experimental probability density functions (pdf) are obtained by using an energy normalization for the vectors given in equations (1) and (2). The new vectors $\mathbf{Xn}^m_{u;d}$ and $\mathbf{Yn}^m_{u;d}$ can be given as

$$\mathbf{Xn}^m_{u;d} = \mathbf{X}^m_{u;d}\left[\sum_{n=1}^{N^m_{u;d}} X^m_{u;d}(n)\right]^{-1} \tag{3}$$

$$\mathbf{Yn}^m_{u;d} = \mathbf{Y}^m_{u;d}\left[\sum_{n=1}^{N^m_{u;d}} Y^m_{u;d}(n)\right]^{-1} \tag{4}$$

The SKLD is computed from equations (3) and (4) as

$$SKLD^m_{u;d} = \sum_{n=1}^{N^m_{u;d}} Xn^m_{u;d}(n)\ln\left[\frac{Xn^m_{u;d}(n)}{Yn^m_{u;d}(n)}\right] + \sum_{n=1}^{N^m_{u;d}} Yn^m_{u;d}(n)\ln\left[\frac{Yn^m_{u;d}(n)}{Xn^m_{u;d}(n)}\right] \tag{5}$$

The CC values are computed using

$$CC^m_{u;d} = \frac{1}{N^m_{u;d}\sigma_{X^m_{u;d}}\sigma_{Y^m_{u;d}}}\sum_{n=1}^{N^m_{u;d}}\left[X^m_{u;d}(n) - mX\right]\left[Y^m_{u;d}(n) - mY\right] \tag{6}$$

where σ denotes the standard deviation and mX and mY are the mean values of the vectors provided in equations (1) and (2), respectively.

The L2N, the metric norm between two vectors is computed using the following equation

$$L2N^m_{u;d} = \sqrt{\sum_{n=1}^{N^m_{u;d}}\left[Xn^m_{u;d}(n) - Yn^m_{u;d}(n)\right]^2} \tag{7}$$

Equations (5)–(7) will be used for computation of SKLD, CC and L2N between IRI-Plas-STEC and IONOLAB-STEC as discussed in the next section.

3. Results

In this study, the SKLD, CC and L2N between IONOLAB-STEC and IRI-Plas-STEC are computed for the chosen GPS stations of Turkish National Permanent GPS Network (TNPGN-Active) as given in Fig. 1 for the quiet day period in April 2011 and a disturbed day period in the month of October 2011 that contains one major earthquake and a geomagnetic storm [22,24].

The investigation is carried out for a quiet reference period in April 14–16, 2011 (which is indicated with a Quiet Day period, QD) and the Dst and Kp which indicate the disturbance level of ionosphere for April 2011 are provided in Fig. 2(a) and (b), respectively. QD period is also seismically quiet and there are no significant earthquakes over greater Turkey region.

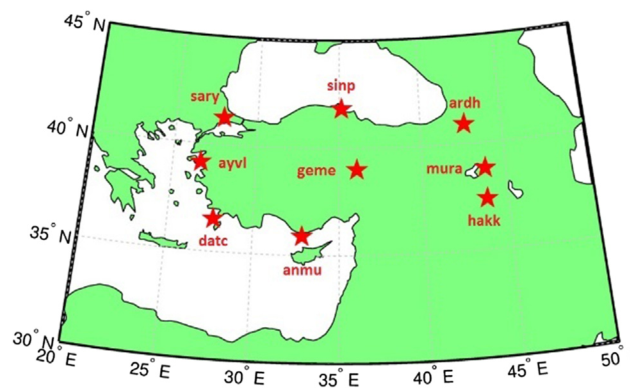


Fig. 1 – Locations of the chosen TNPGN-Active stations (red star).

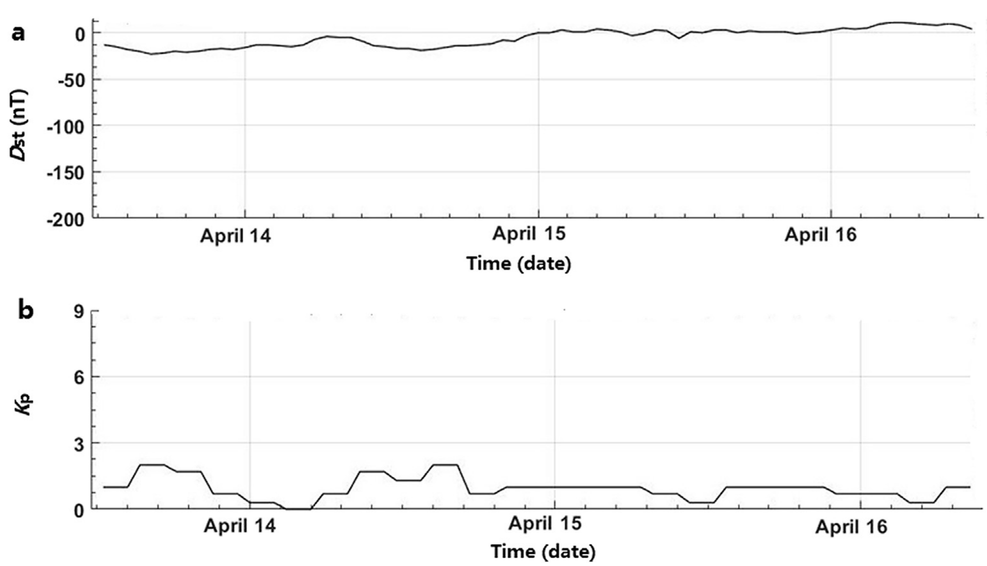


Fig. 2 – (a) Dst and (b) Kp in the April 14–16, 2011, quiet day period.

An example of IRI-Plas-STEC and IONOLAB-STEC is provided in Fig. 3 for anmu station for satellite number (PRN) 9 on April 14, 2011. It can be observed that IRI-Plas-STEC values are very close to IONOLAB-STEC values.

In order to observe SKLD, CC and L2N values for QD of April 14, 15 and 16, for PRN 9, 18 and 28, Figs. 4–6 are presented for all the GPS stations in Fig. 1. CC values for all satellites and dates are over 0.85, L2N is below 0.18 and SKLD is under 0.03. These results indicate that IRI-Plas-STEC and IONOLAB-STEC have very similar values and the function shapes are very similar as well. These results indicate that IRI-Plas-STEC can be used as a reference level and any deviation from this value may indicate a disturbance in the ionosphere.

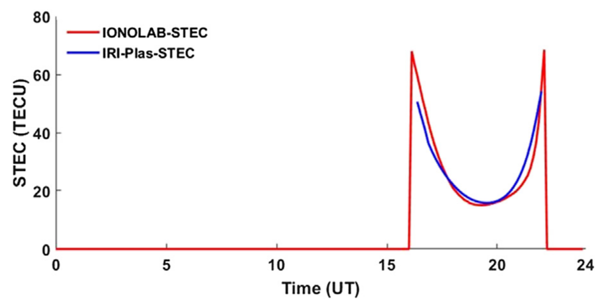


Fig. 3 – anmu station IONOLAB-STEC (red) and IRI-Plas-STEC (blue) data for PRN 9 on April 14, 2011, quiet day.

During the month of October 2011, there have been two minor and one major geomagnetic storm between October 14 and October 28, 2011 [24] (which is indicated with Disturbed Day period, DD) as given in variation of Dst and Kp in Fig. 7. The earthquakes that took place in Anatolia are provided in Table 1. The largest earthquake has a magnitude 7 that occurred in Tabanli, Van and it is followed by some significant aftershocks [22,24].

CC, L2N and SKLD values and proceeding day differences for mura station which is 43 km to the epicenter of Tabanli earthquake are provided in Fig. 8 for PRN 9, 18 and 28. The earthquake day is indicated by a red arrow. The most deviation in metric values is observed on PRN 28 and significant variations in SKLD values can be observed even 6 or 7 days before the earthquake. SKLD values for PRN 28 6 days before the earthquake are twice as much as those of the quiet day period for the same satellite and station pair. Also as seen from the Fig. 8 there is significant rise in SKLD values on 16 and 17 October for mura station which may be

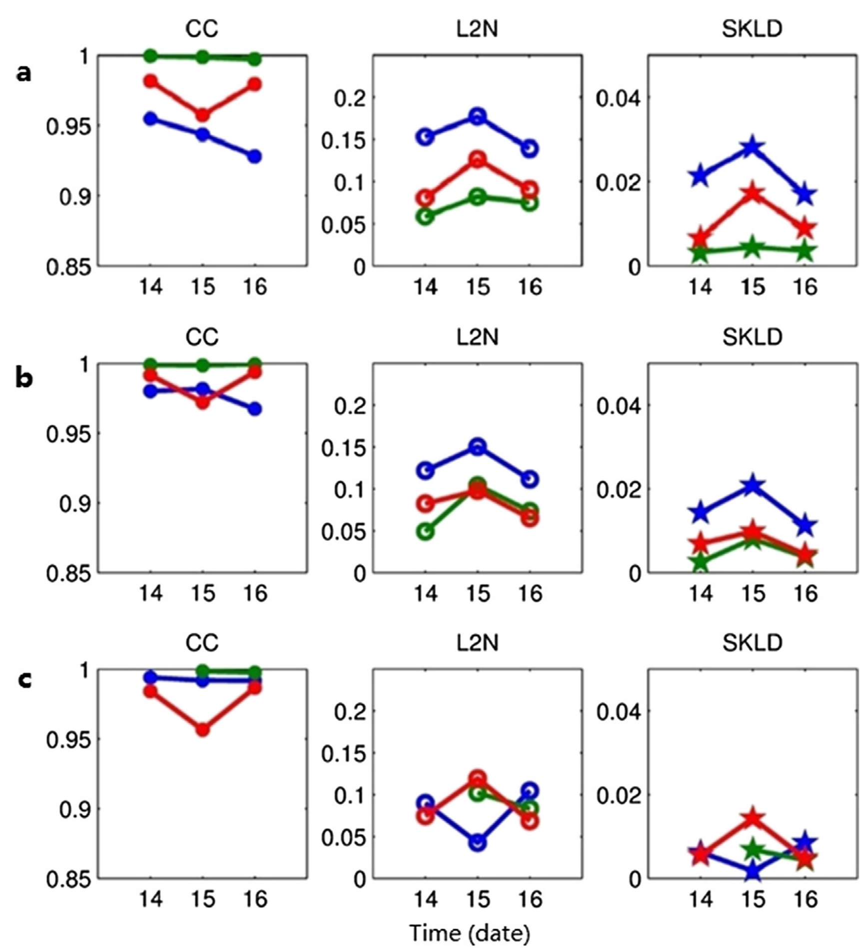


Fig. 4 – CC (dot), L2N (circle), SKLD (star) metrics of (a) sary, (b) datc, (c) ayvl stations for PRN 9 (blue), PRN 18 (red), PRN 28 (green) for 14–16 April, 2011, quiet day period.

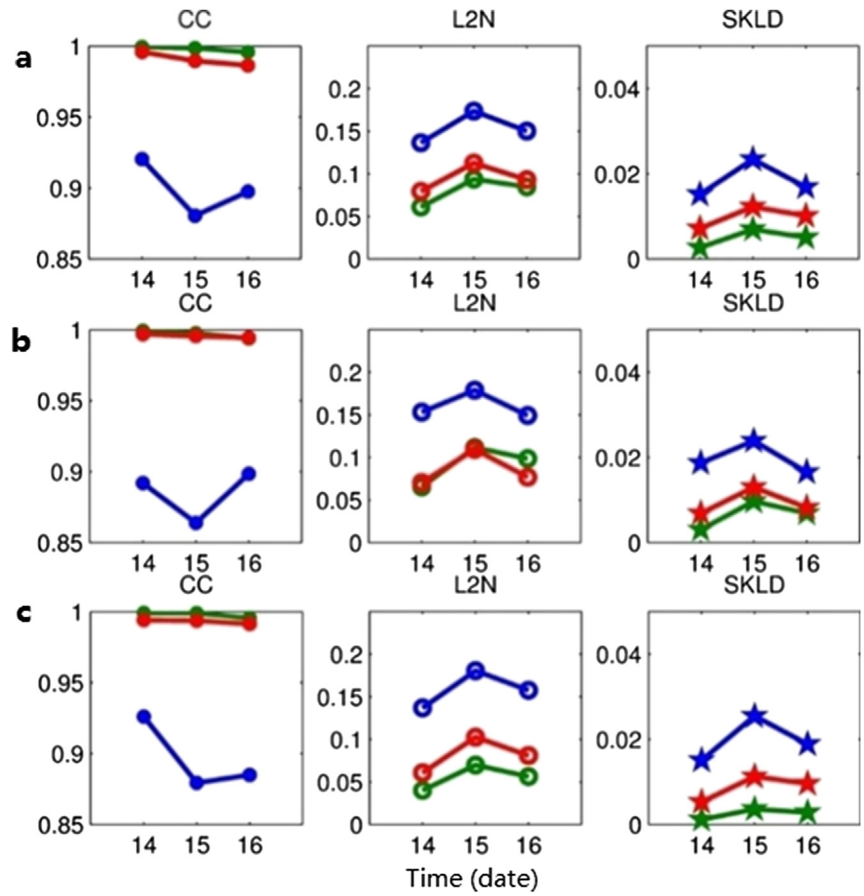


Fig. 5 – CC (dot), L2N (circle), SKLD (star) metrics of (a) mura, (b) hakk, (c) ardh stations for PRN 18 (red), PRN 28 (green) for April 14–16, 2011, quiet day period.

the earthquake precursor. There is notable change in SKLD magnitude after the October 23, which is caused by the earthquake and strong geomagnetic storm.

The variability is observed as the increase in the ionization level and IONOLAB-STEC values are significantly higher than IRI-Plas-STEC values for both 16th and 24th of October as given in Fig. 9. October 24 is also the beginning of a geomagnetic superstorm and it is noted as a positive disturbance. Also, the proceeding day difference of CC can be used to be an indicator for strong geomagnetic storms.

One of the most interesting results is obtained for the SKLD, L2N and CC values for the same period for sary station which is 1400 km from the Tabanli earthquake epicenter as provided in Fig. 10. The same level of disturbance can be observed in sary station for PRN 28 6 days before the earthquake day and SKLD is the best measure to indicate the precursory disturbance. Change in metric values for sary station are less than observed changes in mura station. Same possible earthquake precursor are also observed on October 17 and post storm effects are observable after October 24 from sary station.

In comparison of Figs. 8 and 10, it can be observed that the variability of all metrics are more intense in mura station compared to those in sary station. The effect of geomagnetic storm is also more pronounced for stations in the eastern part of Turkey compared to those in the west. This may be due to the onset of storm time and progress. One other important observation can be given as that it is very difficult to distinguish the cause of disturbance just by tracking the metric values. The information from the disturbance indices has be employed in discriminating the earthquake precursor from the geomagnetic storm effects. One of the reasons that the disturbance is to be observed for PRN 28 compared to other satellites may be that PRN 28 passes over Turkey during the night hours. For the other two satellites, the diurnal variability and solar effects are more dominant compared to the disturbance created by the earthquake precursor in the ionosphere. The STEC comparison is provided in Fig. 11 for sary station for October 17 and 26, 2011 and similar increase in ionization can be observed both before the earthquake and during the positive geomagnetic storm.

Similar results are observed for other stations given in Fig. 1. In Table 2, the minimum and maximum SKLD, CC and L2N values for all stations and satellites under investigation are provided for the QD and DD periods.

As it can be observed from the comparison results between IONOLAB-STEC and IRI-Plas-STEC using SKLD, CC

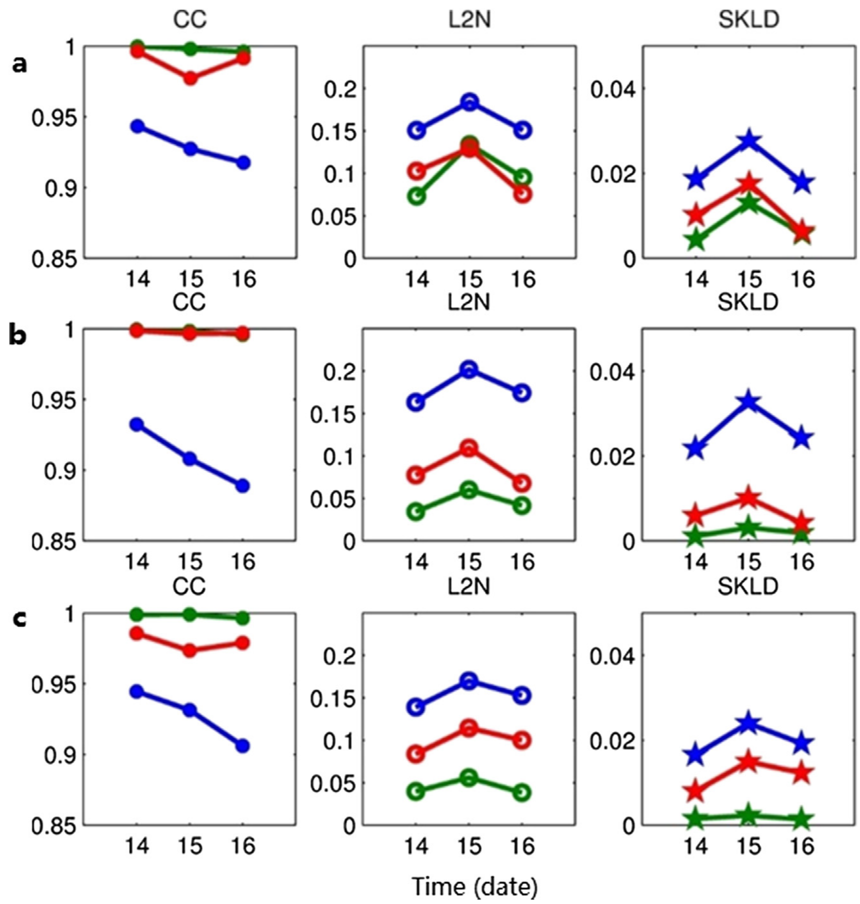


Fig. 6 – CC (dot), L2N (circle), SKLD (star) metrics of (a) anmu, (b) geme, (c) ardh stations for PRN 18 (red), PRN 28 (green) for April 14–16, 2011, quiet day period.

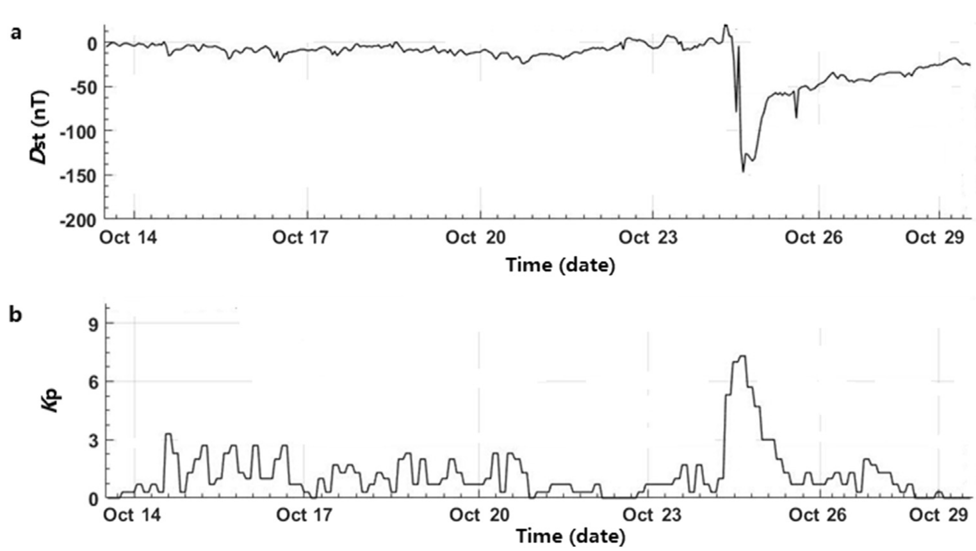


Fig. 7 – (a) Dst, (b) Kp in the October 14–29, 2011 period.

Table 1 – Earthquakes with magnitudes that are larger than $M > 5$ that took place over greater Turkish region between October 16–28, 2011 period. The data are obtained from Kandilli Observatory, Turkey.

Date	Epicenter	Coordinates	Time (LT)	Magnitude
October 23, 2011	Tabanli	38.76° N, 43.36° E	18:30	7.2
October 23, 2011	Gedikbulak	38.81° N, 43.45° E	20:26	5.5
October 25, 2011	Degirmenozu	38.77° N, 43.55° E	19:24	5.4
October 27, 2011	Hakkari	37.33° N, 43.93°E	08:04	5.4

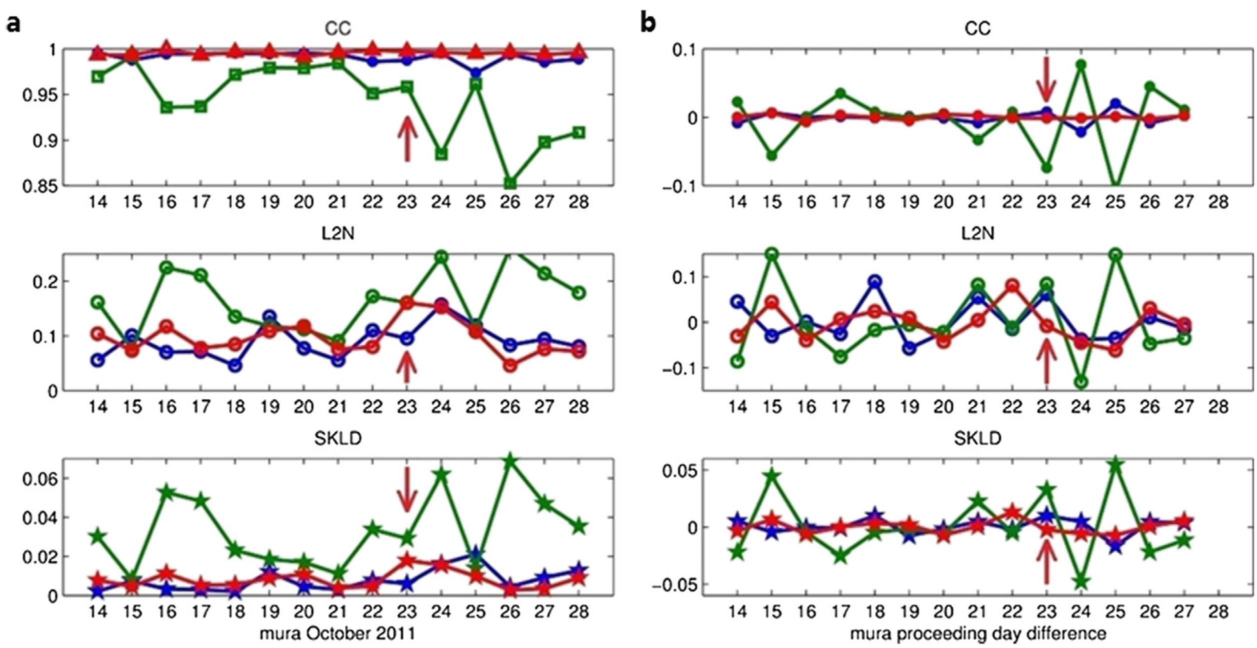


Fig. 8 – mura station, CC (top), L2N (middle), SKLD (bottom) (a) metric and (b) proceeding day difference values for DD period.

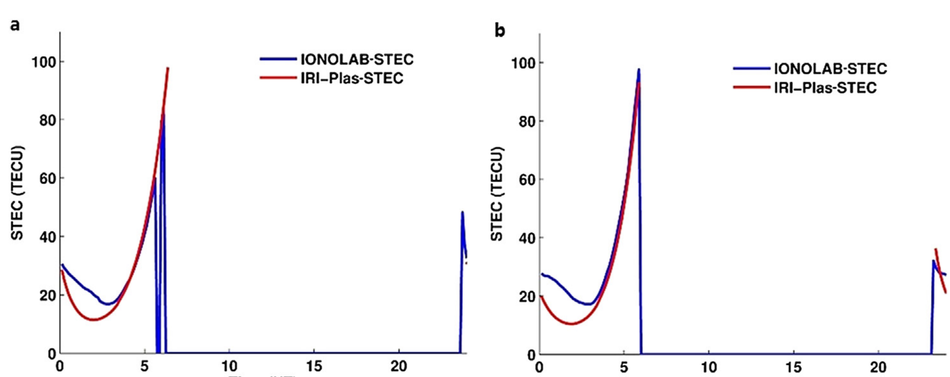


Fig. 9 – IONOLAB-STEC and IRI-Plas-STEC for mura station for October (a)16th and (b) 24th, 2011 for PRN 28.

and L2N norms for quiet and disturbed day periods over TNPGN-Active network in mid-latitude region, there are significant disturbances in the ionosphere that affect STEC values in terms of magnitude and shape compared to the quiet reference. IRI-Plas proved itself to be a reference basis for non-disturbed ionosphere. IRI-Plas-STEC and IONOLAB-STEC behave similarly both in shape and amplitude for quiet days. For the disturbed days, IONOLAB-STEC deviates from the model due to variations in the ionosphere. The best indicator of these deviations is determined to be SKLD, since it is a measure of entropy in the signal.

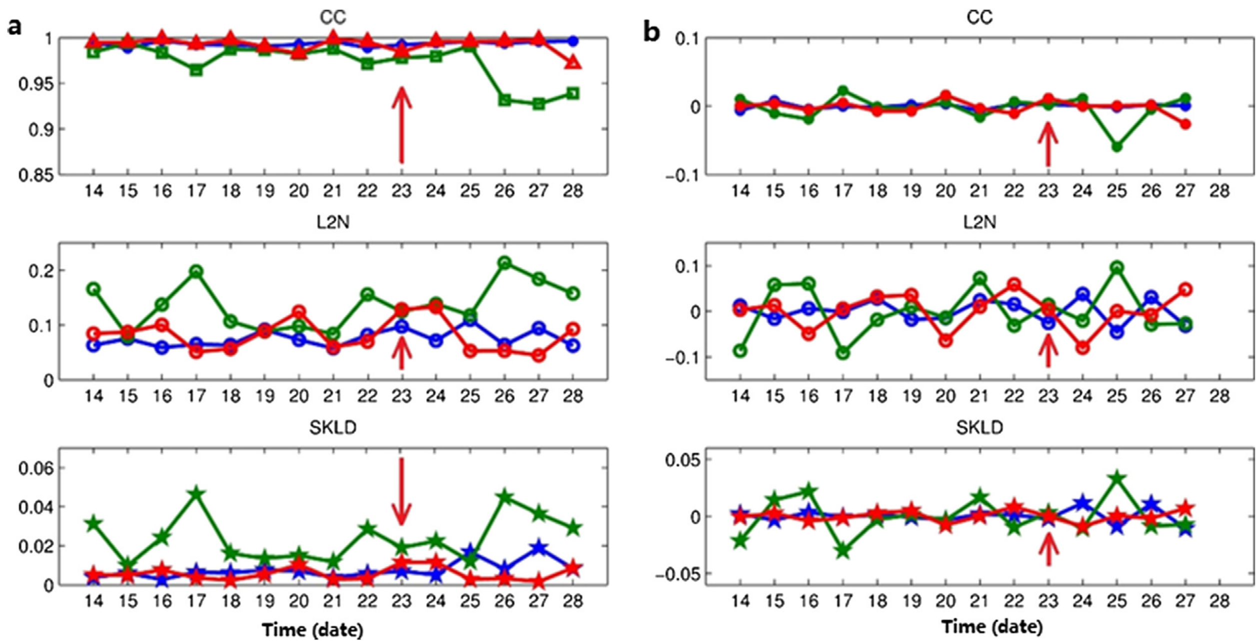


Fig. 10 – **sary station CC (top), L2N (middle), SKLD (bottom) (a) metric and (b) proceeding day difference values for DD period.**

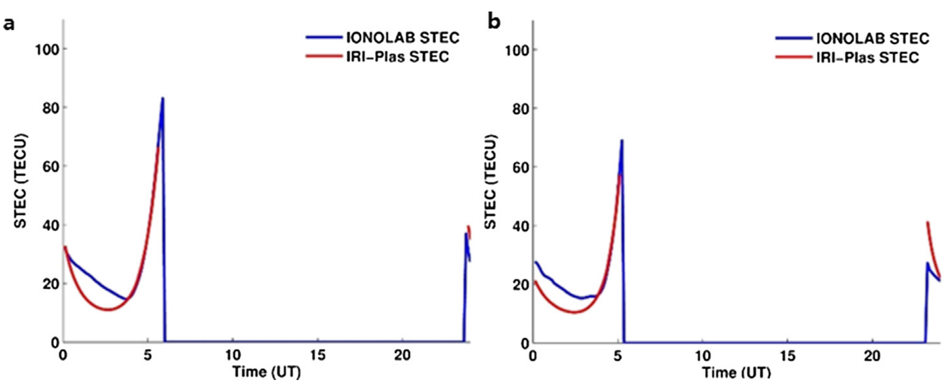


Fig. 11 – **IONOLAB-STEC and IRI-Plas-STEC for sary station for 16 (a) and 24 (b) October 2011 for PRN 28.**

Table 2 – **Minimum and maximum values for the CC, L2N and SKLD metrics for QD and DD periods.**

Metric type	QD (minimum value)	DD (minimum value)	QD (maximum value)	DD (maximum value)
CC	0.85	0.85	1	1
L2N	0.03	0.02	0.2	0.25
SKLD	0.005	0.002	0.03	0.06

4. Conclusion

In this study, model based IRI-Plas-STEC and GPS based IONOLAB-STEC values are compared with each other for both quiet and disturbed day period for a mid-latitude region using TNPGN-Active network. The methods of comparison are SKLD, L2N and CC. The IRI-Plas-STEC and IONOLAB-STEC are first compared for a quiet day period, where there is no significant disturbance in the local and global ionosphere. It is observed that for all metrics that are used in this study, IRI-

Plas-STEC and IONOLAB-STEC are in very good agreement with each other. It is determined that IRI-Plas-STEC forms a quiet reference value for any GPS receiver-satellite link in mid-latitude ionosphere.

For disturbed day period, differences between IONOLAB-STEC and IRI-Plas-STEC are observed due to the fact that ionosphere deviates from the quiet reference. These deviations are more significant during the period starting from 10 days before the earthquake, especially during the night hours where the effect of solar activities subside. The best indicator of both pre-seismic and geomagnetic disturbance is determined to be SKLD since it can indicate the disturbance both in amplitude and shape of the measured STEC values. For the geomagnetic storms, the proceeding day difference of CC can be used as an indicator of disturbance. For DD period, there are observable changes in magnitude of L2N but they are small compared to the L2N magnitude of the quiet days. For DD, SKLD values are much higher than those of quiet days. For example, on October 16, 2011, 6 days before the strong earthquake, there are 10 times rises in magnitude of SKLD from the satellite that pass over Turkey during the night time. While the maximum values for CC and L2N for the chosen stations during DD do not change compared to those for QD, the maximum value of SKLD is twice as much as the SKLD for the QD period.

It can be concluded that IRI-Plas-STEC forms a reasonable quiet reference for GPS-STEC and any deviation from it can be used as an indicator or precursor of ionospheric disturbance. The best indicator of disturbance compared to the model is decided to be SKLD since it can provide the deviations from the trend values of STEC that are represented with IRI-Plas model. In the future studies, IRI-Plas-STEC and IONOLAB-STEC will be investigated in further detail to differentiate the earthquake precursors from geomagnetic storm disturbances.

Acknowledgments

This study is supported by the joint grants of TUBITAK 112E568 and RFBR 13-02-91370-CT_a and TUBITAK 114E092 and Atmospheric Sciences Institute Czech Republic (AS CR) 14/001 projects. The GIM-TEC, Satellite DCB and ephemeris data that is used in computation of IONOLAB-STEC is obtained from IGS Iono Working Group Data Analysis Center of Jet Propulsion Laboratory at ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/. TNPGN-Active RINEX data set is made available to IONOLAB group for TUBITAK 109E055 project. This data set can be accessed by the permission from TUBITAK and General Command of Mapping of Turkish Army (http://www.hgk.msb.gov.tr/). The Kp and Dst data are obtained from Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto University, Japan (http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/index.html and http://wdc.kugi.kyoto-u.ac.jp/kp/index.html). The catalogue of ionospheric and plasmaspheric disturbances are provided at http://www.izmiran.ru/ionosphere/weather/cat/. The earthquake information is obtained from http://m.koeri.boun.edu.tr/dbs/.

REFERENCES

[1] Budden KG. The ionosphere and magnetosphere. In: The propagation of radio waves. 1st ed. Cambridge: Cambridge University Press; 1988. p. 1–20.

[2] Feynman J, Gabriel SB. On space weather consequences and predictions. J Geophys Res 2000;105(A5):10543–64. http://dx.doi.org/10.1029/1999JA000141.

[3] Jin S, Jin R, Li JH. Pattern and evolution of seismo-ionospheric disturbances following the 2011 Tohoku earthquakes from GPS observations. J Geophys Res 2014;119(9):7914–27. http://dx.doi.org/10.1002/2014JA019825.

[4] Jin S, Luo OF, Park P. GPS observations of the ionospheric F2-layer behavior during the 20th November 2033 geomagnetic storm over South Korea. J Geodesy 2008;82(12):883–92. http://dx.doi.org/10.1007/s00190-008-0217-x.

[5] Jin S, Occhipinti G, Jin R. GNSS ionospheric seismology: Recent observations evidences and characteristics. Earth-Sci Rev 2015;147:54–64. http://dx.doi.org/10.1016/j.earscirev.2015.05.003.

[6] Tuna H, Arikan O, Arikan F. Regional model-based computerized ionospheric tomography using GPS measurements: IONOLAB-CIT. Radio Sci 2015;50(10):1062–75. http://dx.doi.org/10.1002/2015RS005744.

[7] Davies K, Hartmann GK. Studying the ionosphere with the Global Positioning System. Radio Sci 1997;32(4):1695–703. http://dx.doi.org/10.1029/97RS00451.

[8] Schaer S. Mapping and predicting the Earth's ionosphere using the global positioning system. Bern Switzerland: Univ of Bern; 1999 [PhD thesis].

[9] Arikan F, Erol CB, Arikan O. Regularized estimation of vertical total electron content from Global Positioning System data. J Geophys Res 2003;108(A12). http://dx.doi.org/10.1029/2002JA009605.

[10] Bilitza D. International reference ionosphere 2000. Radio Sci 2001;36(2):261–75. http://dx.doi.org/10.1029/2000RS002432.

[11] Bilitza D, McKinnell LA, Reinisch B, Fuller-Rowell T. The International Reference Ionosphere (IRI) today and in the future. J Geod 2011;85(12):909–20. http://dx.doi.org/10.1007/s00190-010-0427-x.

[12] Gulyaeva TL, Bilitza D. Towards ISO Standard Earth Ionosphere and Plasmasphere Model. In: Larsen RJ, editor. New developments in the standard model; 2012. p. 1–39.

[13] Gulyaeva TL. Storm time behavior of topside scale height inferred from the ionosphere–plasmasphere model driven by the F2 layer peak and GPS-TEC observations. Adv Space Res 2011;47(6):913–20. http://dx.doi.org/10.1016/j.asr.2010.10.025.

[14] Gulyaeva TL, Arikan F, Stanislawska I. Inter-hemispheric imaging of the ionosphere with the upgraded IRI-Plas model during the space weather storms. Earth Planets Space 2011;63(8):929–39. http://dx.doi.org/10.5047/eps.2011.04.007.

[15] Gulyaeva TL. Empirical model of ionospheric storm effects on the F2 layer peak height associated with changes of peak electron density. J Geophys Res 2012;117(A2). http://dx.doi.org/10.1029/2011JA017158.

[16] Nayir H, Arikan F, Arikan O, Erol CB. Total Electron Content estimation with Reg-Est. J Geophys Res 2007;112(A11). http://dx.doi.org/10.1029/2007JA012459.

[17] Sezen U, Arikan F, Arikan O, Ugurlu O, Sadeghimorad A. Online automatic, near-real time estimation of GPS-TEC: IONOLAB-TEC. Space Weather 2013;11(5):297–305. http://dx.doi.org/10.1002/swe.20054.

[18] Arikan F, Nayir H, Sezen U, Arikan O. Estimation of single station interfrequency receiver bias using GPS-TEC. Radio Sci 2008;43(4). http://dx.doi.org/10.1029/2007RS003785.

[19] Tuna H, Arikan O, Arikan F, Gulyaeva TL, Sezen U. Online user-friendly slant total electron content computation from IRI-Plas: IRI-Plas-STEC. Space Weather 2014;12(1):64–75. http://dx.doi.org/10.1002/2013SW000998.
[20] McDonald SE, Basu S, Basu S, Groves KM, Valladares CE, Scherliess L, et al. Extreme longitudinal variability of plasma structuring in the equatorial ionosphere on a magnetically quiet equinoctial day. Radio Sci 2006;41(6). http://dx.doi.org/10.1029/2005RS003366.
[21] Karatay S, Arikan F, Arikan O. Investigation of total electron content variability due to seismic and geomagnetic disturbances in the ionosphere. Radio Sci 2014;45(5). http://dx.doi.org/10.1029/2009RS004313.
[22] Arikan F, Deviren MN, Lenk O, Sezen U, Arikan O. Observed Ionospheric Effects of 23 October 2011 Van, Turkey Earthquake. Geomatics Nat Hazards Risk 2012;3(1):1–8. http://dx.doi.org/10.1080/19475705.2011.638027.
[23] Karatay S. Investigation of the relationship between earthquakes and total electron content [PhD dissertation]. Elazig, Turkey: Firat University; 2010 [in Turkish with abstract in English].
[24] Shukurov S, Gulyaeva T, Arikan F, Deviren MN, Tuna H, Arikan O. Comparison of IRI-Plas and IONOLAB Slant Total Electron Content for Disturbed Days of Ionosphere. Presentation 40th COSPAR Scientific Assembly, Moscow, Russia 2-10 August, 2014. Abstract C4. 1-17-14.

Arikan Feza was born in Sivrihisar, Turkey, in 1965. She received the B.Sc. degree (with high honors) in Electrical and Electronics Engineering from Middle East Technical University, Ankara, Turkey, in 1986 and the M.S. and Ph.D. degrees in Electrical and Computer Engineering from Northeastern University, Boston, MA, USA in 1988 and 1992, respectively. Since 1993, she has been with the Department of Electrical and Electronics Engineering, Hacettepe University, Ankara, where she is currently a Full Professor. She is also the Director of the IONOLAB Group. Her current research interests include radar systems, HF propagation and communication, HF direction finding, Total Electron Content mapping and computerized ionospheric tomography. Prof. Arikan is a member of the IEEE, American Geophysical Union, chair of URSI-Turkey Commission G, and first Turkish member of IRI Workgroup.

Address: Hacettepe University, Department of Electrical and Computer Engineering
Beytepe, 06800 Ankara, Turkey
Tel.: +90 312 2977095
Fax: +90 312 2992125
E-mail: arikan@hacettepe.edu.tr
http://www.ee.hacettepe.edu.tr