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Modelling the Spatial-Temporal Variability of the Ionosphere over Turkey using a GPS Network

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Abstract

Ionosphere is an atmospheric layer that has a high electron concentration and anisotropic, dispersive, inhomogeneous nature. Total Electron Content (TEC) is one of the most important parameters that provides necessary information to observe the ionospheric variability. In this study, spatial-temporal variability of the ionosphere is investigated using Symmetric Kullback Leibler Distance (SKLD), Metric Distance (L2N) and Cross Correlation Coefficient (CC) on Slant Total Electron Content (STEC) data provided by a midlatitude Global Positioning System (GPS) network. STEC data that are used are obtained by using IONOLAB-STEC method on Turkish National Permanent GPS Network Active (TNPGN-Active) stations during 2011 for quiet and disturbed days of ionosphere.

1. Introduction

Ionosphere is an atmospheric layer which contains gases ionized by solar radiation. The electron density is the main parameter of the ionosphere and the inner variability of the ionosphere is the main source of error for the High Frequency (HF) communication, satellite communication and navigation systems. The structure and the electron density of the ionosphere depends on many factors, such as time, geographical location, solar radiation and geomagnetic activities. Due to the importance of this layer, temporally and spatially varying structural nature of the ionosphere must be observed and characterized. Total Electron Content (TEC) is one of the most important parameters in observing the structural variability of the ionosphere. TEC is defined as the line integral of electron density on a given ray path and the unit of TEC is TECU where 1 TECU $=10^{16}$ el/m^2.

Global Positioning System (GPS) is the foremost system used in computation of Slant Total Electron Content (STEC) which provides an estimate for the total number of electrons on the receiver-satellite link [1]. Single Layer Ionosphere Model (SLIM) assumes that the electron density profile with respect to height is concentrated in a thin, spherical shell layer of constant height. The point where a given path intersects this thin layer is called as Ionospheric Piercing Point (IPP) [2]. Ionospheric piercing points of a satellite can take a number of different forms, depending on the satellite track.

In this study, a midlatitude GPS network is partitioned into regions of 2°x3° latitude and longitude, respectively. For every region, the station that is of equal distance to other receivers is chosen as reference. The other receivers are called as neighbors. The minimum distance to the neighbor is larger than or equal to 45 km and maximum distance to the neighbor is less than or equal to 100 km. For every reference station and neighbor, the similarity of STEC values and the relation between ionospheric piercing points are investigated using Symmetric Kullback Leibler Distance (SKLD), Metric Distance (L2N) and Cross Correlation (CC) Coefficient. STEC values are obtained for all the receiver-satellite pairs which falls above the local horizon limit of 40° by using IONOLAB-STEC. To observe the spatial and temporal variation of the ionosphere, this comparison is implemented throughout 2011 for quiet and disturbed days. In Section 2, IONOLAB-STEC data set is defined. In Section 3, SKLD, L2N and CC comparison methods are given, and in Section 4, investigation results are summarized.

2. IONOLAB-STEC

IONOLAB-TEC is a reliable and robust estimation method, independent of the choice of the maximum ionization height for all latitudes, both quiet and disturbed days by using RINEX, IONEX and satellite ephemeris data provided from the IGS centers [3]. IONOLAB-TEC combines data from all the GPS satellites that are above the local horizon limit of 10° for a desired time duration within the 24 hour period [4]. In order to reduce the distortion due to multipath signals, the optimum weighting function is implemented on IONOLAB-TEC [5]. The receiver code bias (DCB) is estimated using IONOLAB-BIAS algorithm [6]. IONOLAB-TEC is based on IONOLAB-STEC that is computed from phase leveled observables [7]. IONOLAB-TEC is provided as an online space weather service at www.ionolab.org [8].

Let, $\mathbf{X}_{u;d}^{m}$ denote the STEC values for the reference station where m is the satellite, u is the station and d is the day as

$$\mathbf{X}_{u;d}^{m} = \left[\, \mathrm{X}_{u;d}^{m}(1) \quad \cdots \quad \mathrm{X}_{u;d}^{m}(n_s) \quad \ldots \quad \mathrm{X}_{u;d}^{m}(N_s) \right]^{\mathrm{T}} \qquad (1).$$

n_s is the moment when local horizon angle between satellite-receiver station pairs is larger than 40° and $1 \le n_s \le N_s$, the total number of STEC values T represents the transpose operator.

$\mathbf{Y}^m_{n_v;d}$ denotes the STEC values of the neighboring station where m is the satellite, n_v is the station and d is the day.

$$\mathbf{Y}^m_{n_v;d} = \left[\, \mathrm{Y}^m_{n_v;d}(1) \quad \cdots \quad \mathrm{Y}^m_{n_v;d}(n_s) \quad \ldots \quad \mathrm{Y}^m_{n_v;d}(N_s) \right]^{\mathrm{T}} \qquad (2).$$

n_s is the moment when local horizon angle between satellite-receiver station pairs is greater than 40° and it is limited between $1 \leq n_s \leq N_s$. Number of neighbor station can be different for each region, and for a region which has N_v neighbor stations, n_v is limited as $1 \leq n_v \leq N_v$.

3. Comparison Methods

In order to compare the similarity of STEC values for reference and neighbor stations, Symmetric Kullback Leibler Distance (SKLD), Metric Distance (L2N) and Cross Correlation (CC) Coefficient methods are used. These methods have been utilized in application for the investigation of the coupling of seismic and geomagnetic activity to the ionosphere through the variability of TEC data [9].

SKLD is a measure of entropy and it compares the likeness of two probability functions. Functions or distributions are first normalized using Eq. (3, 4) and SKLD is calculated using Eq. (5) as follows.

$$(\mathbf{X}_n)^m_{u;d} = \mathbf{X}^m_{u;d} \left(\sum_{n_s=1}^{N_s} \mathrm{X}^m_{u;d} \right)^{-1} \qquad (3).$$

$$(\mathbf{Y}_n)^m_{n_v;d} = \mathbf{Y}^m_{n_v;d} \left(\sum_{n_s=1}^{N_s} \mathrm{Y}^m_{n_v;d} \right)^{-1} \qquad (4).$$

$$\mathrm{SKLD}^m_{n_v;d} = \sum_{n_s=1}^{N_s} (\mathrm{X}_n)^m_{u;d}(n_s) \ln\left(\frac{(\mathrm{X}_n)^m_{u;d}(n_s)}{(\mathrm{Y}_n)^m_{n_v;d}(n_s)} \right) + \sum_{n_s=1}^{N_s} (\mathrm{Y}_n)^m_{n_v;d}(n_s) \ln\left(\frac{(\mathrm{Y}_n)^m_{n_v;d}(n_s)}{(\mathrm{X}_n)^m_{u;d}(n_s)} \right) \qquad (5).$$

L2N computes the metric distance between two vectors and can be calculated using Eq. (6) as

$$\mathrm{L2N}^m_{n_v;d} = \sqrt{\sum_{n_s=1}^{N_s} \left(\mathrm{X}^m_{u;d}(n_s) - \mathrm{Y}^m_{n_v;d}(n_s) \right)^2} \qquad (6).$$

CC compares the similarity of two functions and can be calculated using Eq. (7) as

$$\mathrm{CC}^m_{n_v;d} = \frac{1}{N_s \sigma_X \sigma_Y} \sum_{n_s=1}^{N_s} \left(\mathrm{X}^m_{u;d}(n_s) - \mu_X \right) \left(\mathrm{Y}^m_{n_v;d}(n_s) - \mu_Y \right) \qquad (7).$$

where μ_X, μ_Y are mean values of $\mathbf{X}^m_{u;d}$ and $\mathbf{Y}^m_{v_n;d}$ and σ_X, σ_Y are standard deviations.

4. Results

Turkish National Permanent GPS Network Active (TNPGN-Active) is a GPS station network of 146 continuously operating receiver stations spread uniformly all over Turkey and North Cyprus. These stations form a dense network with the maximum distance between two neighboring stations closer than 100 km. In this study, SKLD, L2N and CC between reference and neighbor receiver stations are computed for the chosen GPS regions of TNPGN-Active for all satellites in view. An example is provided in Fig. 1, Region 1 and Region 9 of TNPGN-Active with ionospheric piercing points of satellite number (PRN) 11 and 20. First region reference station is tekr and second region reference station is kluu. In order to observe the SKLD, CC and L2N values for these regions, comparison methods are applied to STEC values for all days between 2009-2012. In this study, an example is provided for a quiet day of 17 April 2011 and a geomagnetically disturbed day of 25 October 2011. On 17 April 2011, Kp index is less than 2, Dst index is larger than -4 nT and AE index is less than 210 nT. On 25 October 2011, Kp index gets as large as 8, Dst index gets as low as -140 nT and AE index gets as large as 1000 nT.

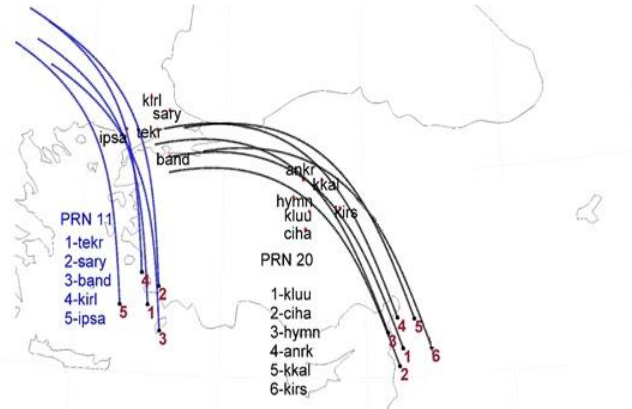

Figure 1 Location of the chosen TNPGN-Active receiver stations and ionospheric piercing points of PRN 11 and PRN 20, for Regions 1 and 9.

In Fig. 2 (a) STEC values of reference and neighbor stations of Region 9 is given for quiet day. In Fig. 2 (b) STEC values of reference and neighbor stations of Region 9 is given for disturbed day.

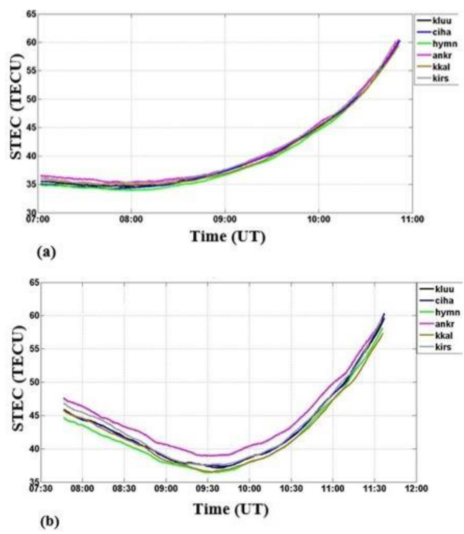

Figure 2 (a) STEC values of reference and neighbor stations of Region 9 for quiet day of 17 April 2011, (b) STEC values of reference and neighbor stations of Region 9 for disturbed day of 25 October 2011.

From Fig. 2, it can be seen that for a quiet day, STEC values of reference and neighbor stations are in very good agreement, while on disturbed days, STEC values differ from one other both in magnitude and shape. In Table 1 and Table 2, comparison results of STEC values obtained from Region 9 stations and PRN 20 are provided for quiet day of 17 April 2011 and disturbed day of 25 October 2011.

Table 1 Region 9 reference-neighbor station STEC values comparison method results for quiet day of 17 April 2011.

Station Pairs	SKLD	L2N	CC	Dist. (km)
kluu-ciha	2,48 $x10^{-5}$	4,94	0,9997	49,30
kluu-hymn	2,80 $x10^{-5}$	12,83	0,9998	63,07
kluu-anrk	5,07 $x10^{-5}$	12,97	0,9993	88,50
kluu-kkal	7,14 $x10^{-5}$	7,80	0,9991	93,53
kluu-kirs	6,72 $x10^{-5}$	7,36	0,9996	94,62

Table 2 Region 9 reference-neighbor station STEC values comparison method results for disturbed day of 25 October 2011.

Station Pairs	SKLD	L2N	CC	Dist. (km)
kluu-ciha	1,15 $x10^{-5}$	3,82	0,9997	49,30
kluu-hymn	4,13 $x10^{-5}$	18,20	0,9998	63,07
kluu-anrk	8,00 $x10^{-5}$	25,21	0,9993	88,50
kluu-kkal	6,73 $x10^{-5}$	15,84	0,9991	93,53
kluu-kirs	15,2 $x10^{-5}$	12,38	0,9996	94,62

In Table 1, it can be observed from CC results that STEC values of reference and neighbor stations are highly correlated, but CC results cannot be used to distinguish stations. L2N results of stations form a group according to distance to the reference station, but results are not sorted based on the distance. In SKLD results stations form a group according to the distance and as the neighbor station gets further, SKLD result gets larger. SKLD is chosen to be the best indicator of deviations in STEC data, since it is a measure of entropy. In this study to observe the similarity between STEC data, priority will be given to SKLD, L2N and CC respectively. In Table 1 and Table 2, it can be seen that as distance to the reference station increases, SKLD and L2N results gets larger. For the quiet day, the most similar STEC values to the reference station STEC values belong to ciha→ hymn→ anrk→ kirs→ kkal, respectively. For the disturbed day the most similar STEC values to the reference station STEC values belong to ciha→ hymn→ kkal→ anrk→ kirs, respectively.

In Fig. (3) (a) STEC values of reference and neighbor stations of Region 1 is given for quiet day, (b) STEC values of reference and neighbor stations of Region 1 is given for disturbed day.

In Table (3) and Table (4), comparison results of STEC values obtained from Region 1 stations and PRN 11 are provided for quiet day and disturbed day.

For the quiet day the most similar STEC values to the reference station STEC values belong to sary→ ipsa→ kirl→ band, respectively. For the disturbed day the most similar STEC values to the reference station STEC values belong to sary→ ipsa→ kirl→ band, respectively.

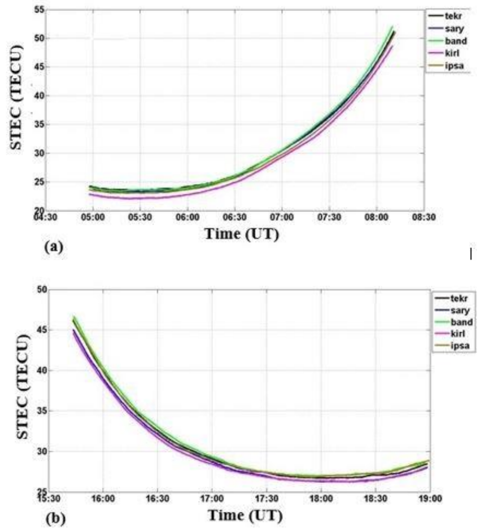

Figure 3 (a) STEC values of reference and neighbor stations of Region 1 for quiet day of 17 April 2011, (b) STEC values of reference and neighbor stations of Region 1 for disturbed day of 25 October 2011.

Table 3 Region 1 reference-neighbor station STEC values comparison method results for quiet day of 17 April 2011.

Station Pairs	SKLD	L2N	CC	Dist. (km)
tekr-sary	2,01$x10^{-5}$	4,15	0,9999	64,40
tekr-band	2,62 $x10^{-5}$	4,07	0,9998	81,59
tekr-kirl	11,7 $x10^{-5}$	18,96	0,9998	89,87
tekr-ipsa	2,67 $x10^{-5}$	11,34	0,9998	94,01

Table 4 Region 1 reference-neighbor station STEC values comparison method results for disturbed day of 25 October 2011.

Station Pairs	SKLD	L2N	CC	Dist. (km)
tekr-sary	8,07$x10^{-6}$	9,01	0,9997	64,40
tekr-band	5,10 $x10^{-5}$	9,83	0,9996	81,59
tekr-kirl	4,06 $x10^{-5}$	12,51	0,9996	89,87
tekr-ipsa	5,46 $x10^{-5}$	4,34	0,9986	94,01

To observe the seasonal variability of ionosphere, reference and neighbor stations STEC values are investigated using comparison methods during 2011. GPS satellites retraces the same orbit path twice a day and returns to the same position in the sky about 4 minutes earlier each day. The satellites complete the 24 hour cycle in one year.

In Fig (4) and Fig (5) for Region 1, PRN 11 and Region 9 PRN 20 comparison method results can be seen for 2011.

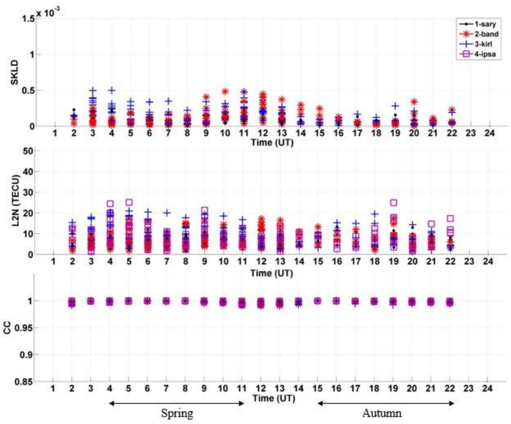

Figure 4 Comparison method results for Region 1, PRN 11 STEC data during 2011.

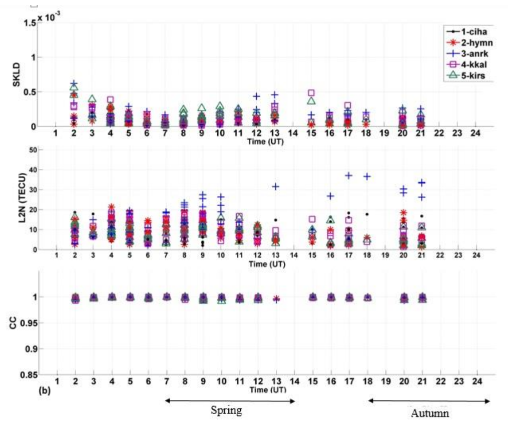

Figure 5 Comparison method results for Region 9, PRN 20 STEC data during 2011.

In SKLD and L2N, the most distant neighbor station, has the largest deviation from the mean values. From SKLD, seasonal variability can be observed.

5. Conclusion

In this study, the similarity of STEC values for reference and neighbor stations and the relation between ionospheric piercing points are investigated to observe the spatial-temporal variability of the ionosphere. Comparison methods are applied to STEC data of all receiver-satellite pairs in regions of TNPGN-Active network for 2009-2012, retrospectively. It is observed that for both quiet and disturbed days and all types of ionospheric piercing points, the closest neighbor station to the reference station has the most similar STEC values compared to reference station STEC values. The best method to observe the similarity between STEC values is determined to be SKLD since it can compare the STEC values both in shape and amplitude. In the future studies, these results will be used to form a database to monitor the variability of regional ionosphere in near-real time.

6. Acknowledgements

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7. References

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