GEODESY AND GEODYNAMICS 2016, VOL 7 NO 1, 1–10

Available online at www.sciencedirect.com

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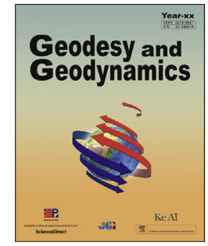
journal homepage: www.keaipublishing.com/en/journals/geog;
http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml



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

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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.

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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

$$\mathbf{X}^m_{u;d} = \left[X^m_{u;d}(1) X^m_{u;d}(2) \cdots X^m_{u;d}\left(N^m_{u;d}\right)\right]^T \quad (1)$$

$$\mathbf{Y}^m_{u;d} = \left[Y^m_{u;d}(1) Y^m_{u;d}(2) \cdots Y^m_{u;d}\left(N^m_{u;d}\right)\right]^T \quad (2)$$

where the superscript m denotes the GPS satellite number, the