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Modeling and analysis of GPS-TEC low latitude climatology during the 24th solar cycle using empirical orthogonal functions

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Abstract

The Total Electron Content (TEC) is an essential component describing the temporal and spatial characteristics of the ionosphere. In this paper, an empirical orthogonal function (EOF) model is constructed by using ground based Global Navigational Satellite System (GNSS) TEC observation data at the Bangalore International GNSS Service (IGS) station (geographic – 13.02° N, 77.57° E; geomagnetic latitude 4.4° N) during an extended period (2009–2016) in the 24th solar cycle. EOF model can be decomposed into base functions and its corresponding coefficients. These decomposed modes well represented the influence of solar and geomagnetic activity towards TEC. The first three EOFs modes constitute about 98% of the total variance of the observed data sets. The Fourier Series Analysis (FSA) is carried out to characterize the solar-cycle, annual and semi-annual dependences by modulating the first three EOF coefficients with solar (F10.7) and geomagnetic (Ap and Dst) indices. The TEC model is validated during daytime and nighttime conditions as well as under different solar activity and geomagnetic conditions. A positive correlation (0.85) of averaged daily GPS-TEC with averaged daily F10.7 strongly supports those time-varying characteristics of the ionosphere features depends on the solar activity. Further, the validity and reliability of EOF model is verified by comparing with the GPS-TEC data, and standard global ionospheric models (International Reference Ionosphere, IRI2016 and Standard Plasmasphere-Ionosphere Model, SPIM). The performances of the standard ionospheric models are marked to be relatively better during High Solar Activity (HSA) periods as compared to the Low Solar Activity (LSA) periods.

Keywords: EOF; FSA; GNSS; TEC

1. Introduction

The ionospheric electron density and its spatio-temporal variations play a crucial role in transionospheric navigation and communication system applications by introducing range delays in the transmitted signals (Langley, 1996). The variability in ionospheric electron density further relay on various forces from above and below the ionosphere, such as solar and magnetospheric effects, momentum and energy fluxes connected with neutral wind dynamics and lithospheric effects (Singh et al., 2011). Total electron content (TEC) is one of the essential measures of ionospheric electron density to determine the delays introduced in the traversing Global Positioning System (GPS) signal. Moreover, the TEC varies in space and time with latitudinal as well as the longitudinal gradients; the magnitude is more towards the equatorial and low latitude region (Dabas et al., 2006). In particular, the estimate of the TEC over the equatorial and low latitude region is a crucial task in view of the large spatio-temporal gradients associated with the local electrodynamic parameters, such as equatorial electrojet strength (EEJ) and Equatorial Ionization Anomaly (EIA).

In present days, the GPS measurements from IGS ground receiver across the global and regional network

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have been widely used to access the TEC with high spatio-temporal resolution (Zhang and Xiao, 2003; Mendillo, 2006). The GPS technique has its advantages in monitoring ionospheric TEC variations at different locations on or above the earth, as well as producing real-time Global Ionosphere Maps (GIMs) and Regional Ionosphere Maps (RIMs) (Sayin et al., 2008). Further research in the intrinsic characteristics of ionospheric perturbations is important for understanding the short-term and long-term variations in ionospheric variability. Based on the GPS-TEC observations, earlier researchers have proposed the empirical models to fulfil the scientific and technological application needs. These include Empirical Storm-Time ionospheric correction Model (STORM) (Araujo-Pradere et al., 2005), Incoherent Scatter Radar (ISR) -based Ionospheric Model) and International Reference Ionosphere (IRI) model (Bilitza and Reinisch, 2008). These models estimate various ionospheric parameters, namely NmF2, hmF2, foF2 and ion temperatures at any location based on solar (F10.7) and geomagnetic (Ap) indices as a function of Local Time (LT), latitude and season (Zhang and Holt, 2008; Zhang et al., 2002). Extensive studies have been carried out for developing the global and regional ionospheric TEC models by several authors using various techniques such as, statistical Eigen Mode (EM), Principal Component Analysis (PCA), Spherical Cap Harmonic Analysis (SCHA), Singular Value Decomposition (SVD) and Empirical Orthogonal Function (EOF) involving Taylor series as well as Fourier series expansion techniques (Zhao et al., 2005; Opperman et al., 2007; Bouya et al., 2010; A et al., 2011, 2012; Mukhtarov et al., 2013; Dabbakuti et al., 2016). However, these models are very similar to typical empirical models, which are based on statistical analysis of wide data sets by using monthly median parameters, and represent the state of the ionosphere for different phases of solar cycle activities (Bilitza and Reinisch, 2008). The regional ionospheric TEC models rather than the global ionospheric models can achieve a relatively clear ionospheric prediction as the former includes the local driving phenomena (Gulyaeva, 1999). A number of regional TEC models have been proposed by researchers to describe the ionospheric morphology over different territories such as, China (Mao et al., 2008), Denmark (Jakobsen et al., 2010), Japan (A et al., 2011) and Southern Africa (Habarulema et al., 2011). Concerning equatorial and low latitude region over Indian sub-continent, a number of studies also have been conducted to analyse the ionospheric TEC variations with reference to the equatorial ionization anomaly (EIA) phenomena and the solar-terrestrial as well as the geomagnetic effects (Rama Rao et al., 2006; Bagiya et al., 2009; Kumar et al., 2012; Sharma et al., 2012; Dashora and Suresh, 2015). The consequences from the above studies contribute to the climatological improvements in the IRI model to some extent.

EOF model is one of the prominent techniques to model and analysis ionospheric variations such as, short-term, temporal and spatial variation (Zhao et al., 2005; Mao et al., 2008; Zhang et al., 2009; A et al., 2011, 2012; Chen et al., 2015; Uwamahoro and Habarulema, 2015; Dabbakuti and Venkata Ratnam, 2016). It has been noticed that modeling and analysis of ionospheric variations based on EOF model performs better over the region and yields better accuracy than IRI2007 and IRI-2012 models. Several observational studies with different versions of the IRI model have been demonstrated inconsistency in the estimation of electron density over the equatorial and low latitudes suggesting further improvements in the model (Olwendo et al., 2012; Venkatesh et al., 2014). Dabbakuti and Venkata Ratnam (2016) built the EOF model to characterize the ionospheric variability over the three low latitude regions during the ascending solar maximum phase (2013). In this study, it was demonstrated that EOF model effectively depict the temporal ionospheric characteristics and shows better accuracy than the IRI2012 model. However, it is required to validate the model in terms of assessing the inherent variations across the region during different solar activity phases for further improvement in the performance of standard ionospheric models in estimating the precise electron density over the equatorial and low latitudes. In this paper, an empirical TEC model is constructed by applying EOF decomposition of the diurnal and temporal variations and FSA analysis to fit the corresponding EOF coefficients, describing the solar-cycle, annual and semi-annual dependences. The reliability of the model is verified during daytime and nighttime as well as under different solar and geomagnetic conditions and representing the TEC variations over the region. Further, the EOF model has been validated by comparing with observational TEC data and with the current version of standard models of IRI (IRI2016) and SPIM. While IRI became the official international standardization organization (ISO) standard for the ionosphere during 2014, another model named standard plasmasphere-ionosphere model (SPIM) has been recently developed under ISO (Bilitza et al., 2014; Gulyaeva, 2011). The newest IRI version (IRI2016) is an improvement to its preceding version IRI2012 with the introduction of two new F2 peak electron density height (hmF2) models, perfections of the ion composition at low and high solar activity, improvements in the input parameters including solar and ionospheric indices, and lastly advances in the program code to expedite the computational time. The main intention of recent version of IRI2016 model is towards the development of the real-time scenario. The SPIM model is basically an extension of the IRI model towards the plasmapause (up to 36,000 km) by merging it with the Russian Standard Model of Ionosphere (SMI).

2. Modeling and data processing

Ionospheric characteristics during the year (2009–2016) are considered over the Bangalore (13.02° N, 77.57° E), in India. The observations were recorded every 30 s (ftp://cddis.gsfc.nasa.gov/). RINEX observation data are

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