Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 58 (2016) 598–608

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

The study of variability of TEC over mid-latitude American regions during the ascending phase of solar cycle 24 (2009–2011)

Yekoye Asmare Tariku *

University of Ambo, Department of Physics, Ambo, Ethiopia

Received 12 February 2016; received in revised form 6 May 2016; accepted 8 May 2016
Available online 14 May 2016

Abstract

This paper deals with the pattern of the variability of the Global Positioning System vertical total electron content (GPS VTEC) and the modeled vertical total electron content (IRI 2012 TEC) over American mid-latitude regions during the rising phase of solar cycle 24 (2009–2011). This has been conducted employing ground-based dual frequency GPS receiver installed at Mississippi County Airport (geographic lat. 36.85°N and long. 270.64°E). In this work, the monthly and seasonal variations in the measured VTEC have been analyzed and compared with the VTEC inferred from IRI-2012 model. It has been shown that the monthly and seasonal mean VTEC values get decreased mostly between 05:00 and 10:00 UT and reach their minimal nearly at around 10:00 UT for both the experimental and the model. The VTEC values then get increased and reach the peak values at around 20:00 UT and decrease again. Moreover, it is depicted that the model better estimates both the monthly and seasonal mean hourly VTEC values mostly between 15:00 and 20:00 UT. The modeled monthly and seasonal VTEC values are smaller than the corresponding measured values as the solar activity decreases when all options for the topside electron density are used. However, as the Sun goes from a very low to a high solar activity, the overestimation performance of the VTEC values derived from the model increases. The overall results show that it is generally better to use the model with IRI-2000 option for the topside electron density in estimating the monthly and seasonal VTEC variations, especially when the activity of the Sun decreases.

Keywords: GPS-VTEC; IRI-2012 VTEC; Solar cycle; Mid latitude ionosphere

1. Introduction

Due to sufficient number of GPS receivers installed at the middle latitude regions, such as the American regions, the ionosphere of middle latitude is the most explored and the best understood. There, the ionization is produced almost entirely by energetic ultraviolet and X-ray emissions from the Sun, and is removed again by chemical recombination processes that may involve the neutral atmosphere as well as the ionized species. The movement of ions, and the balance between production and loss, are affected by winds in the neutral air (Hunsucker and Hargreaves, 2003). The ionosphere is a three-dimensional field of ions and free electrons in the upper atmosphere of the Earth which changes with time. Hence, the ionosphere is a highly variable and complex physical system where ions and electrons are present in quantities sufficient to affect the propagation of radio waves (Matsushita and Campbell, 1967). The free electrons populating this region of the atmosphere affect the propagation of the signals (such as GPS signals), changing their speed and direction of travel. As a result, the accumulation of electrons affects the signal that passes through the ionosphere by inducing additional transmission time delay (Klobuchar et al., 1996). This

---

* Tel.: +251 912799754.
E-mail address: yekoye2002@gmail.com.

http://dx.doi.org/10.1016/j.asr.2016.05.012
0273-1177/

delay is directly proportional to the number of electrons through which the signal passes and inversely proportional to the square of the frequency of the signal (Hofmann-Wellenhof et al., 1992). The signals from the GPS satellites, rotating at about 20,200 km altitude from the earth's surface, travel through the ionosphere on their way to receivers on the ground; however, the free electrons accumulated in this region of the atmosphere affect the propagation of the signals by changing their velocity and direction of motion. As a result, according to Ioannides and Strangeways (2000), the GPS signals cannot travel along a perfect straight line and reach the desired position in the planed time. As it was mentioned previously, this delay in GPS signals is directly proportional to the TEC (Reddy, 2002). Hence, TEC is required for making appropriate range corrections. It is also believed to account for errors introduced in the range delays owing to the effects of space weather related events, such as geomagnetic storms and scintillations. It can be expressed in Total Electron Content Units (TECU) as follows

$$N_T = \int_R^S N_e ds, \tag{1}$$

where 1 TECU $= 1 \times 10^{16}$ electrons/m^2.

The GPS-TEC data used for this study are obtained employing pseudo-range and carrier phase measurements given as follows.

The TEC inferred from the pseudo-range measurement is given by:

$$\mathrm{TEC}_P = \frac{1}{40.3}\left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right](P_2 - P_1). \tag{2}$$

Similarly, the TEC from carrier phase measurement can be given as

$$\mathrm{TEC}_\Phi = \frac{1}{40.3}\left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right](\Phi_1 - \Phi_2), \tag{3}$$

where f_1 and f_2 can be related with the fundamental frequency, $f_o = 10.23$ MHz

$$\begin{aligned} f_1 &= 154 f_o = 1575.42 \text{ MHz}, \\ f_2 &= 120 f_o = 1227.60 \text{ MHz}. \end{aligned} \tag{4}$$

As it is described by Gao and Liu (2002), however relatively much noise it is, TEC from code pseudo-range measurements is free of ambiguity. On the other hand, though TEC from carrier phase measurements is ambiguous, it has relatively less noise. Hence, a linearly combination has been used between carrier phase and pseudo-range measurements to resolve this problem. This combination is used to reduce the pseudo range noise by smoothing GPS pseudo range data with carrier phase measurements (Hansen et al., 2000). The Sardon et al. (1994) approach was then followed to remove differential instrument biases for accurate TEC estimation. This has been carried out as satellites and receivers for the GPS observables are biased on the instrumental delays (Norsuzila et al., 2009). Hence, linearly combining both code pseudorange and carrier phase measurements for the same satellite pass is supposed to increase the degree of accuracy for TEC (Klobuchar et al., 1996). This resultant absolute TEC is the GPS-derived STEC along the signal path between the satellite and the receiver on the ground. In order to make the STEC free from dependence of the ray path geometry from the satellite to the receiver through the ionosphere, it is necessary to convert the STEC to the VTEC. Moreover, the VTEC is a more compact parameter to characterize the TEC over a given receiver position and used as a good indicator for the overall ionization of Earth's ionosphere (Komjathy and Langley, 1996). Hence, the STEC has to be converted to the VTEC (as shown in Eq. (5)) by assuming that the ionosphere is equivalent to a thin shell encircling the Earth with its center the same as that of the Earth (Mannucci et al., 1998). Hence, in terms of the zenith angle χ' at the Ionospheric Piercing Point (IPP) and the zenith angle χ at the receiver position on the ground, the relationship between STEC and VTEC can be given by:

$$\mathrm{VTEC} = \mathrm{STEC}(\cos\chi'), \tag{5}$$

where,

$$\chi' = \arcsin\left[\frac{R_e}{R_e + h_m}\sin\chi\right]. \tag{6}$$

Substituting Eq. (6) into Eq. (5) and rearranging, we get

$$\mathrm{VTEC} = \mathrm{STEC}\left\{\cos\left[\arcsin\left(\frac{R_e}{R_e + h_m}\sin\chi\right)\right]\right\}. \tag{7}$$

Here, R_e is Earth's radius in kilometers and h_m is the height of maximum electron density at the F2 peak, which ranges from 250 to 350 km at the mid latitude regions (Norsuzila et al., 2009). In addition to GPS there are also other empirical models that are vital for predicting ionospheric characteristics of the specific region with specific time, latitude and longitude in regions where measured values are not available. For such purposes ionospheric empirical models, such as the International Reference Ionosphere (IRI) model, apparently play a vital role in all parts of the Sun–Earth environment as they offer the scientists, engineers, and educators easy access to a condensed form of the available empirical evidences for a specific parameter based on all reliable data sources that exist for the parameter (Bilitza 1990; Rawer et al., 1978). The IRI model has been undergoing improvements when new data and new techniques are available and this process has resulted in the latest version called IRI 2012 model. The IRI 2012 model with some new input parameters has been released in 2013. For a given location, time and date, IRI-2012 model provides the monthly average electron density, the electron content, ion composition, electron and ion temperature in the altitude range from about 50 to 2000 km (Bilitza et al., 2014; http://IRImodel.org).

Using the IRI 2012 TEC and GPS TEC data, different studies have been conducted over mid-latitude regions to