Analysis Of Ionospheric GPS-TEC Variability Over Uganda IGS Station During Descending Phase Of 24th Solar Cycle, 2018 Year

Jean de Dieu Nibigira, DR Venkat, GSV Prasad

Abstract: Global Positioning System (GPS) with the constellation of satellites provides continuous Positioning, Navigation and Timing (PNT) services. Ionosphere as an atmospheric medium which have the free electrons in the path of satellite signals affects the services of GPS by degrading their measurements. Hence, this paper is intended to investigate the ionospheric electron content variability during the descending phase of the 24th solar cycle, 2018 year over Mbarara (MBAR) International GNSS Services (IGS) station, Uganda. Using the Dual-frequency GPS-derived Total Electron Content (TEC) observations, the diurnal, seasonal and annual variations of the TEC are studied over MBAR station. The Dual-frequency system was introduced in order to estimate the time delay error for GPS signals. The maximum vertical TEC (VTEC) peak values are obtained at around 13:00 UT. Seasonally, the March Equinox got the highest VTEC peak value of 38 TECU and the June solstice reached the lowest VTEC peak value of 22 TECU. The present study confirms that the GPS-derived TEC agree with the International Reference Ionosphere (IRI) (IRI-2016) model predictions with average deviation of 5 TECU in June Solstice. The accuracy of IRI-2016 model with the GPS-VTEC is also evaluated using the Root Mean Square Error (RMSE). It was observed that the correlation is high during the September Equinox and that the IRI-2016 model VTEC measurements are overestimated/underestimated in other remaining seasons. Therefore, the timing for huge mismatching (-100% to -300%) of IRI-2016 model is at 5:00 UT for all seasons.


1 INTRODUCTION
The United States (US) developed Global Positioning System (GPS) has been a research tool ever since its implantation for space weather and real-time positioning and navigation applications. GPS is among the most useful technologies for humanity through its positioning and navigation services for both commercial and civilian applications [1,2,3,4,5]. Ionosphere is one layer of the Earth Atmosphere layers. It is situated from an altitude of approximately 60km to 1000km. One of the variables to be taken in account for studying the ionospheric variability is the Total Electron Content (TEC). The TEC is the total electron density that a GPS satellite signal encounters while propagating until it reaches the earth GPS receiver. One TEC unit (TECU) is equal to 1016 electrons per square meter (1TECU=1016/m2). The ionospheric TEC varies diurnally, seasonally due to the sun radiation (solar activity), location relatively to the magnetic equator (latitudinally), etc. The particularity of this layer is that it is constituted of charged particles (electrons and ions). The GPS uses two L-band frequencies (L1=1575.42 MHz and L2=1227.60 MHz) in order to calculate the time-delay and then evaluate the TEC along the transmission signal. When GPS satellites, orbiting at a height of 20200 km above the Earth surface, emit one-way L-Band signals, these signals are dispersed by the ionosphere which causes the time delay in GPS receivers on ground.

For many decades, the study of ionospheric effects on GPS signals have been carrying on due to its significant effects on the GPS applications [2,3,4,5,6,7,8,9,10]. These effects are related to the ionospheric time delay [6,7,8,9] or the ionospheric scintillation effect [7,11,12,13,14,15] which is the change in signals’ amplitude and phase. The tools used for investigating the ionosphere are the International GNSS Services (IGS) stations, ground based GPS receivers, ionosondes, and COSMIC RO (Radio Occultation) [16]. Many global ionospheric TEC models such as the International Reference Ionosphere (IRI) model are consistently updated with new datasets from different ground and space-based sensors/equipment to model or predict the upper atmospheric TEC [17,18,19,20,21,22,23,24,25]. In the present work, we used the raw data from the equatorial IGS station at Mbarara (MBAR) in UGANDA. Its geographical coordinates are -0.60°S and 30.737°E with a magnetic latitude of 10.22°S. In this paper, the statistical parameters are used to validate the performance of IRI-2016 model over one GNSS station, MBAR, Uganda.

2 METHODOLOGY AND PROCEDURES
In the present study, we used two methods: one is using the GPS dual frequency technique and another one is considering the TEC values given by the IRI-2016 model. The IRI-2016 data are downloaded from the IRI website (https://ccmc.gsfc.nasa.gov/cgi) and the IGS data are downloaded from the SOPAC website (http://sopac-old.ucsd.edu/). The data process is done using the GPS-TEC GOPI Seemla Software [27] and we get the Vertical Total Electron Content (VTEC) after elimination of the satellite and receiver biases included in the Differential Code Bias (DCB) of the IGS stations. The provided data are called Receiver INdependent EXchange (RINEX). The ionospheric single layer method, SLM, is used by assuming that ions and free electrons are accumulated in an infinitesimal layer located at a height of almost 350km [28] with an elevation angle less than 20 degrees. The Vertical Total Electron Content (VTEC) at the
Ionosphere Pierce Point (IPP) is evaluated by using the Slant TEC (STEC) and the mapping function (MP) [28] as follows:

\[
\text{VTEC} = \text{MF} \times \text{STEC} \\
\text{MF} = f(\alpha) = \left[ 1 - \left( \frac{R_E \sin \alpha}{R_E + h_m} \right)^2 \right]^{-0.5} \\
\text{STEC} = \frac{(P_1 - P_2)}{40.3} \left( \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \right)
\]

where \(P_1\) and \(P_2\) are the pseudo-ranges for the frequencies \(f_1\) and \(f_2\) through the fundamental frequency \(f_0=10.23\text{MHz}\), \(R_E\) is the mean earth radius, \(h_m\) is the height with a maximum electron density, 350 km, \(\alpha\) is the zenithal angle of the receiver and \(a\) is the correction factor close to unity. Comparison between GPS-TEC and IRI-2016 TEC is performed for getting an idea on the effectiveness of the IRI-2016 model at MBAR IGS station, Uganda. This can also be performed using the following formula (5):

\[
\text{DEV} = \frac{\text{GPS}_{\text{TEC}} - \text{IRI}_{\text{TEC}}}{\text{GPS}_{\text{TEC}}} \times 100
\]

where \(\text{IRI}_{\text{TEC}}\) is the derived TEC from IRI-2016 model and \(\text{GPS}_{\text{TEC}}\) is the GPS-TEC observations.

The Root Mean Square Error (RMSE) is calculated using the below expression:

\[
\text{RMSE} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( \text{GPS}_{\text{TEC}} - \text{IRI}_{\text{TEC}} \right)^2}
\]

where \(N\) is the number of observations.

### 3 SECTIONS

The present investigation is significant to understand the ionospheric impact for GPS signal delays. The ionospheric variability over MBAR station is investigated and the IRI-2016 model performance also evaluated during the descending phase of 24\textsuperscript{th} solar cycle. The experimental GPS VTEC data, which is collected from IGS station, at MBAR station, Uganda shown in Figure 1. The Figure 1 shows the annual and diurnal VTEC values with increasing values during the sunrise from 07:00-11:00 UTC followed by peak values during midday and decreasing values during sunset and reached the minimum values at nighttime. The diurnal variabilities are due to the generation/photoionization (ionization) and recombination of ions with electrons during and after the solar radiation process. This variability can also be caused by the high earth magnetic activity which may lead to the Equatorial Ionospheric Anomaly (EIA) [29].

In order to analyze the seasonal VTEC variations over MBAR station, the seasons are considered as March Equinox (MAR-Equ): February, March and April; June Solstice (JUN-Sol): May, June and July; September Equinox (Sep-Equ): August, September and October; December Solstice (Dec-Sol): November, December, January. Figure 2 shows the high VTEC values during March Equinox (peak VTEC value: 28 TECU), followed by September Equinox (peak VTEC value: 27 TECU), moderate VTEC values during December solstice (peak VTEC value: 25 TECU) and less VTEC values during June Solstice (peak VTEC value: 22 TECU). The Uganda local time is three hours ahead to the Greenwich Mean Time (GMT). The Figure 2 reveals that the maximum values of GPS-VTEC are nearly reached at the same time for all seasons, that is around 13:00 UTC. The decreasing GPS-VTEC values are observed from approximatively 16:00 UTC until 08:30 UTC and the increasing ones are seen early morning from around 4:00 UTC to 12:30 UTC as shown in Figure 2. The seasonal variations illustrate that the semi-annual variation of VTEC values over MBAR station during the descending phase of 24\textsuperscript{th} solar cycle, 2018 year. Figure 3 shows the VTEC values predicted using IRI-2016 model during 2018 year over MBAR station, Uganda. It is observed that the IRI-2016 model has good agreement with the diurnal, yearly and seasonal VTEC patterns of measured GPS-VTEC values. However, there are few TECU of overestimations/underestimations observed (an average of 5TECU).

![Figure 1: Day to Day GPS-TEC Variations over MBAR IGS station, year 2018](image1)

![Figure 2: The seasonal VTEC variations measured from GPS observations over MBAR station](image2)

![Figure 3: The annual and diurnal VTEC variations of IRI-2016 model](image3)
In order to evaluate the performance of the IRI-2016 model in predicting the East African ionospheric TEC values, the statistical parameter, Root Mean Square Error (RMSE) and percentage deviation of the model are considered. The seasonal VTEC values of the IRI-2016 model are compared with the GPS estimated VTEC values as shown in Figure 4. It is observed that IRI-2016 model has well predicted the GPS-VTEC values with less discrepancies during September equinox. However, the maximum overestimations for the remaining seasons (March and September equinoxes and December Solstice) are noticed during 05:00-17:00 UTC hours as seen from Figure 4. Furthermore, during 18:00-23:00 UTC hours, the discrepancies between the GPS-VTEC and IRI-2016 model are relatively very less. Figure 5 shows the percentage deviations of the IRI-2016 model with respect to the GPS-VTEC values. It is observed that the maximum percentage of deviations are reported during early morning 05:00 UTC hours due to shape of electron density profile could not be well predicted by the IRI model [30]. The maximum of deviations is noticed for March equinox up to -300% followed by -200% for December solstice, then -100% for June solstice, whereas very less percentage of deviations are recorded for September equinox i.e. only -23%. Moreover, the RMSE values are also calculated about the IRI-2016 model for each season and the values are tabulated as shown in the Table 1.

It is observed from the Table. 1 that 6.12 TECU of RMSE values for March equinox, 4.23 TECU of RMSE value for June solstice, 5.13 TECU for December solstice and very less RMSE value (1.57 TECU) for September equinox. The seasonal percentage deviations of the IRI-2016 model are apparently evidence with the RMSE values which shows the required improvements for the model with new datasets and modifications.

### Table 1: The seasonal RMSE values of IRI-2016 model during the year 2018

<table>
<thead>
<tr>
<th>Season/Model</th>
<th>Mar Eq</th>
<th>Jun Sol</th>
<th>Sep Eq</th>
<th>Dec Sol</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI-2016 RMSE (TECU)</td>
<td>6.12</td>
<td>4.23</td>
<td>1.57</td>
<td>5.13</td>
</tr>
</tbody>
</table>

### 4 CONCLUSION

This study shows the ionospheric GPS-TEC variability diurnally yearly and seasonally over MBAR IGS station. We compared the GPS-VTEC measurements with the IRI-2016 model VTEC predictions. This study also concluded that the 2018 year is in accordance with the descending phase of the 24th solar cycle. This work also mentioned through the Table 1 and Figure 5 that the deviation percentages and the RMSE overestimated/underestimated during March Equinox, June Solstice and December Solstice but they are approximatively matching for the September Equinox period. The diurnal and seasonal variations of the ionospheric TEC over MBAR and the deviation (in percentages) of IRI-2016 model with respect to GPS measured VTEC are calculated and discussed. It was observed that the deviation of IRI-2016 model is huge at nearly 5:00 UTC with extremes of (-300%, -200%) in March Equinox and December solstice respectively and the same matching with the RMSE calculations, 6.12 TECU for March Equinox and 5.13 TECU during September Equinox.

### 5 REFERENCES


[8] Dabbakuti J.R.K.K., Ratnam D.V., Sunda S.,


