A model of the deviation between IRI-2016 and ionospheric TEC observation based on GISTM at low latitude Indonesia region

A. Husin¹, Suraina², AY. Putra² and H. Rasidi²

¹Space Research Centre, Indonesia National Agency of Research and Innovation, Bandung, Indonesia
²Pontianak observatory, Indonesia National Agency of Research and Innovation, Pontianak, Indonesia

Email: asna001@brin.go.id

Abstract. The diurnal variation pattern of total electron content (TEC) from the International Recurrence Ionosphere (IRI-2016) model is generally good agreement with observational data at all latitudes. However, at low latitudes the IRI TEC is not as accurate as in midlatitudes. Some reports showed that the IRI-2016 TEC model at the maximum and minimum solar activities at low latitudes tends to be underestimate. In this paper, TEC from GISTM (GPS Ionospheric Scintillation and TEC Monitoring) that is installed at Pontianak station (0.03° S; 109.33° E geomagnetic latitude 9.7° S) used for validation and evaluation of IRI-2016 TEC model over the low latitude Indonesian sector. Data from the 2012 - 2014 period representing solar maximum and data from 2018 representing solar minimum, were used in this study. We also developed VTEC deviation (ΔTEC) model by using multiple linear regression and tested the model by using data 2019. Results show that IRI-2016 generally reproduces the diurnal variations pattern but underestimate the observation data for many hours each day especially during maximum solar activity 2012-20114. The highest deviation in the equinocial months and lowest during the June and December solstice. The deviation (ΔTEC) model showed good agreement with observation data on January and December but not for other months especially on equinox months. Testing of the VTEC deviation model using 2019 data did not show significant improvement compared to the IRI-2016 itself, which generally produces good TEC prediction in most of the months except for equinox months.

1. Introduction
The upper atmosphere contains electrons and ions at altitudes above 50 km up to 1000 km known as the ionosphere layer. The density of electron and ions reaches maximum level at an altitude of about 300 to 400 Km. These electrons and ions are generated by photo-ionization process of constituent molecules and atoms such as nitrogen and oxygen. Changes in electron and ion density are influenced by solar activity and have been reported to have an impact the propagation of electromagnetic waves especially radio waves. Signals from communication and navigation satellites are affected by the induced ionospheric delays [1]. The time delay of trans ionospheric satellite signal is proportional to the total electron content (TEC) [2][3]. Therefore, TEC is an important parameter that determines the success rate of radio wave propagation in satellite communication and accurate position solutions in satellite navigation applications. The time delay of trans ionospheric satellites is a function of TEC.
unit (TECU) and operating frequency. In the L band GPS/ GNSS frequency satellite, 1 TECU will introduce a pseudorange delay of 0.163 meters and 0.267 meters in L1 and L2 frequencies respectively.

The IRI-2016, is an empirical global model for ionospheric parameters which is a refinement of previous years' models. The output of the model includes the electron density in the ionosphere layer, the ionospheric plasma frequency starting from D layers, E, F and F2 (foF2), the height of the ionospheric layer, the total electron content (TEC) and other parameters. The IRI-2016 can be run via the page https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php. With regard to the output parameter of interest in this study, namely the TEC parameter, several studies have been reported such as IRI-78 [4][5][6][7] [8][9]. From those reports, the comparison or validation of the IRI model against TEC observation data from middle to low latitudes shows that the pattern of TEC variation agrees with the observational data at all latitudes. The level of TEC values is quite good in middle latitudes but not for low latitudes. However, the latest report by [10] and [11] regarding the response of the IRI-2016 TEC model at the maximum and minimum solar activities showed the TEC level at low latitudes tends to be lower than the observation data. In this paper, the TEC from GISTM (GPS Ionospheric Scintillation and TEC Monitoring) installed at Pontianak (0.03° S;109.33°E) was used for validation and evaluation IRI-2016 TEC model. The operation of GISTM at Pontianak often suffers from interruption so there are a lot of missing data. Later, a model will be developed to describe a relationship between IRI-2016 TEC model and observation.

2. Material and Method

The observation data from GISTM installed at Pontianak station (0.03° S; 109.33° E geomagnetic latitude 9.7° S) and IRI-2016 TEC data from 2012 to 2014 periods were used to represent maximum solar activity and 2018 for minimum solar activity. Observation data from 2019 period were used for validation. The GISTM GSV4004B hardware was used in 2012-2014 and then due to technical problem observation failed during 2015-2017. During 2018, ionospheric TEC observation is continued by using the GPStation-6. The TEC measurement by combinations L1 as the primary frequency and secondary frequency Lx as follows:

\[
TEC_{L1Lx} = \frac{1}{40.3} \left[ \frac{f_{Lx}f_{L1}}{f_{L1}-f_{Lx}} \right] (PR_{Lx} - PR_{L1})
\]  

(1)

TEC derived from code (pseudorange) measurements in equation (1) are noisier. This noise must be removed. The absolute TEC value can be expressed as,

\[
TEC_{L1Lx} = TEC_{abs} + \delta_{SV}^{diff} + \delta_{rec}^{diff} + \epsilon_{MP} + \epsilon_{noise}
\]

(2)

where \( TEC_{abs} \) is the absolute TEC value, \( \delta_{SV}^{diff} \) and \( \delta_{rec}^{diff} \) are the differential (inter-frequency) biases within the satellite and the receiver. These biases typically vary by satellite and can change over time. The calculated satellites biases can be downloaded from http://iauws.unibe.ch/ ionosphere/p1c1.dbc.). \( \epsilon_{MP} \) and \( \epsilon_{noise} \) are errors caused by the presence of multipath and background noise. The GPStation-6 hardware provides (ISMRAWTEC log) and carrier phase (ISMRTECHE log) TEC measurements. The use of ultra-stable oven-controlled crystal oscillator (OCXO) and the narrow delay-locked loop (DLL) bandwidths (BW) by the hardware greatly reduces the noise contribution in raw TEC measurements. TEC calibration procedure of GSV4004B is done in post-processing mode by taking the minimum TEC value during pre-dawn. This allows us to determine the receiver bias offset to be subtracted corrected minus about 7 TECU. In this study, we used TEC measurement at 60 seconds resolution (TOW) convert to vertical TEC (VTEC) at the Ionospheric Pierce Point (IPP). The slant to vertical conversion factor in terms of the zenith angle at the IPP, \( \chi \), and the zenith angle at the receiver position, \( \chi' \), as follows:
\[ \text{VTEC} = \text{STEC} \times \cos(\chi') \quad (3) \]

\[ \chi' = \arcsin \left( \frac{R_e}{R_e + h_m} \sin \chi \right) \quad (4) \]

where \( R_e \) is the radius of the Earth, and \( h_m \) is the height of the ionospheric layer, assumed here to be 350 km. In this work, we used the GISTM TEC an hourly and daily basis. To obtain the daily profile, an hourly average was applied to TEC data with elevation mask 30°. A median TEC from 8 to 10 satellites channel every 60 seconds was used as the representative 1-minute TEC value, then the hourly mean was obtained by averaging the 1-minute data every 60 minutes. Simultaneous temporal, geographical latitude longitude of TEC data from the IRI-2016 model with the TEC GISTM of Pontianak station was analyzed. A deviation (\( \Delta \text{TEC} \)) model based on the linear relationship between TEC GISTM and TEC IRI-2016 was developed as a multi-linear regression model on the monthly basis. A multiple linear regression model with three predictor variables \( X_1, X_2, X_3 \) and a response \( \Delta \text{TEC} \) can be written as:

\[ \Delta \text{TEC}_{\text{Pontianak}}(t) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \quad (5) \]

Where

- \( X_1 = \) TEC from IRI2016,
- \( X_2 = \) SSN
- \( X_3 = \) F10.7 solar flux.

\( \beta_0, \beta_1, \beta_2 \) and \( \beta_3 \) Regression coefficient, It can be written in matrix form:

\[ Y = XB \quad (6) \]

\[ Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{12} \end{bmatrix}, \quad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}, \quad B = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix} \quad (7) \]

3. Result and Discussion

Data used in the analysis are monthly mean diurnal VTEC. Figure 1(a) shows an example taken on April 5th, 2012, where the daily processing of the TEC derived from GISTM Pontianak for every minute are recorded for every channel of GPS satellite observation (indicated by collared line). The curves that are shown in figure 1(a) are then averaged for every hour which gives us the result shown in figure 1(b) (blue line). The TEC from IRI-2016 model that is shown in figure 1(c) as a comparison. This is an example where the IRI-2016 model underestimate the observed TEC. The daily TEC data are then smoothed by hourly average for each month of the year as shown in figure 1.

**Figure 1.** a) The daily VTEC taken on April 5, 2012 derived from GISTM Pontianak from every channel of GPS satellite observation (indicated by colored line), b) averaged every hour and c) TEC values from IRI-2016 model.
Figure 2 shows contour plot of monthly mean VTEC variations from GISTM (figure A) and IRI-2016 model (figure B) over Pontianak station from 2012-2014 and 2018 combined with the sunspot number SSN data (figure C) and solar flux F10.7 (figure D) which indicated the maximum and minimum solar activities during that time. In this plot, the two-peak maximum of VTEC during the equinox, month March-April and September-October, can be clearly seen. These two peaks are not symmetrical, as the March equinox peak is higher than the other.[13] [14] reported that these equinoctial asymmetries present at low latitude are influenced by the thermosphere and ionospheric dynamics processes and meridional wind control as well. Also, we can see that during maximum solar activity 2014, TEC GISTM and IRI-2016 reach maximum 80 TECU and 40 TECU respectively at the March equinox. In other words, maximum TEC from IRI-2016 model reached only half of TEC from GISTM. During minimum solar activities in 2018, TEC also reached their lowest levels in both GISTM and IRI-2016 which were about 40 TECU and 15 TECU, respectively.

Figure 2. Contour plot of monthly mean VTEC variations from GISTM and IRI-2016 model over Pontianak station from 2012-2014 and 2018 combined with the sunspot number SSN data (figure C) and solar flux F10.7 (figure D) which indicated the maximum and minimum solar activities

The diurnal variations VTEC both GISTM and IRI-2016 in different months during the four years from 2012-2014 and 2018 are shown in figure 3. We use selected month March - September as representative of equinoctial months and June - December representative of solstice month. Unfortunately, there are no observation data during September and December in 2012. As we can see the VTEC generally follows the diurnal variations but underestimates the observation data in absolute value for many hours of the day. The hourly VTEC are enhanced during the equinoctial months, with the March equinox higher than September equinox, and depleted in the solstice months, with the December solstice higher than the June solstice. Also, the VTEC attains its maximum values between 9:00–15:00 UT (12:00–18:00 LT), and minimum between 21:00–24:00 UT (00:00–3:00 LT). In the right panel in figure 3 we present the deviation between the GISTM and IRI-2016 predicted values in the monthly mean VTEC. The highest deviation occurred in the equinoctial months (Mar–Sept), about 50%, and lowest during the solstices, although the deviation is slightly higher in December solstice than June solstice. The highest deviation of about 55 TECU occurred in March 2014 during maximum solar activities and the lowest occurred (just under 20 TECU) during minimum solar activities in 2018. These variations of ΔTEC are modeled by using multiple regression by using equation 5 to obtain ΔTEC model. The model can be used to improve the VTEC prediction of IRI-2016 specifically for Pontianak station.

To illustrate the model’s predictability, IRI-2016 VTEC is shown in figure 4. Entire data from against GISTM-TEC of the entire years from 2012–2018 at Pontianak, as presented in figure 4. We
also calculated the correlation coefficient (R) and the best fit line (red line). Results in figure 4 confirmed that the IRI-2016 model predicted VTEC values generally follow the diurnal variations of measured values. High positive correlation coefficients value in the range of R = 0.81–0.89 at Pontianak station indicate a generally good agreement between GISTM observed TEC and IRI-2016. However, VTEC IRI-2016 model tends to underestimate VTEC observations from GISTM Pontianak. Previous reports by [15] and [10] showed IRI-2016 model tends to underestimate VTEC at low latitude, due to the presence of equatorial ionospheric anomaly.

![Figure 3](image3.png)

**Figure 3.** Seasonal variations of VTEC from GISTM and IRI-2016 model over Pontianak Station station (left) and the deviation between GISTM and IRI-2016 (ΔTEC) from 2012-2014 and 2018

![Figure 4](image4.png)

**Figure 4** Scatter plots of GISTM TEC against IRI TEC over Pontianak stations during the year 2012–2018. The regression line is also shown with its correlation coefficient.

The deviation (ΔTEC) model by using multi-linear regression in equation 7, obtained a set of regression coefficient values for each month, from January to December as shown in table 1. These coefficients are used to predict the deviation of VTEC between IRI-2016 and GISTM data, then those values were added to IRI-2016 TEC as correction.

| Month | β₀   | β₁   | β₂   | β₃   |
|-------|------|------|------|------|
| Jan   | 7.66 | 1.24 | 0.07 | -0.09|
| Feb   | 8.61 | 1.22 | 0.17 | -0.15|
| Mar   | -40.98 | 1.05 | -0.30 | 0.57|
| Apr   | -40.15 | 1.01 | -0.38 | 0.60|
| May   | 44.86 | 0.79 | 0.32 | -0.67|

Table 1. Regression coefficient values for each month, from January to December.
Testing ΔTEC model using observation data from 2019 is shown in figure 5. As shown in figure 5, ΔTEC model good agreement with observation data from January and December but not for other months especially on equinox month. Generally, the ΔTEC model did not perform much better than the original IRI-2016 model output, as shown in figure 6. As we can see in figure 6, IRI-2016 good agreement in most of the month except for equinox month. From these results, the attempt to build a model TEC deviation using linear regression method has not been able to improve, since even the IRI-2016 model can provide better prediction as shown in figure 6.

![Figure 5 Test validation ΔTEC model using GISTM VTEC data period 2019](image)

![Figure 6 Comparison of IRI TEC against GISTM VTEC during the year 2019](image)

4. Concluding Remarks
In this article, we have validation VTEC IRI-2016 model using the GISTM data at a low latitude station in Pontianak, Indonesia (0.03° S;109.33°E geomagnetic latitude 9.7°S ) from 2012-2014 and 2018. The comparison was investigated in terms of monthly mean diurnal VTEC variations. Results show that predicted VTEC from the IRI-2016 model generally follow the diurnal variations but are underestimation in most of the hours in the observation data. The highest deviation (ΔTEC) in the equinoctial months (Mar–Sept) and lowest in June and December solstices. We also developed a VTEC deviation (ΔTEC) model by using multiple linear regression to improve the IRI-2016 output. The model good agreement with observation data in January and December but not for other months
especially equinox month. The $\Delta$TEC model did not perform much better compared to the IRI-2016 itself. IRI-2016 good agreement in most of months except for equinox months. However, user must be concern in this period, especially during extreme space weather because IRI predictions become most inaccurate. From these results, the current attempt to build a model TEC deviation with the linear regression method has not been able to offer improvement even the IRI-2016 model performed better in prediction. Other methods such as machine learning/ deep learning may be used to improve the $\Delta$TEC model.

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