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Comparison of Ionospheric VTEC Predictions using the Holt-Winter and IRI-2016 Model over Malaysia

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Abstract

Total Electron Content (TEC) is an important parameter that considerably affects radio waves propagating through the ionosphere, causing delay errors in GPS satellite signals. Hence, identifying an effective TEC model is important. This research presents an analysis of ionospheric vertical TEC (VTEC) modeling during geomagnetic quiet and disturbed periods. The data were recorded using the Department of Survey and Mapping Malaysia's (DSMM) dual-frequency GPS located in Kedah (geographic coordinates 4.62°N-103.21°E, geomagnetic coordinates 5.64°N-174.98°E), Terengganu (geographic coordinates 6.46°N-100.50°E, geomagnetic coordinates 3.32°S-172.99°E), and Johor (geographic coordinates 1.36°N-104.10°E, geomagnetic coordinates 8.43°S-176.53°E). The VTEC was modeled using the statistical Holt-Winter method and the most recent version of the International Reference Ionospheric model (IRI-2016), using IRI01-corr, IRI-2001, and NeQuick topside electron density options. The daily variation of the measured and modeled VTEC during quiet and disturbed periods was compared. The minimum value of the VTEC was recorded in the early morning time and the maximum was recorded during the post-noon time. The diurnal hourly variation during the quiet periods indicated that IRI01-corr, IRI-2001, and NeQuick overestimated most of the time, while the Holt-Winter method showed better agreement with the GPS-TEC. During the disturbed period, IRI-2016 (IRI01-corr, IRI-2001 and NeQuick) did not show any response to the geomagnetic storm, while the Holt-Winter method underestimated the VTEC trend. However, the Holt-Winter displayed better performance and results compared to the IRI01-corr, IRI-2001, and NeQuick during the quiet and disturbed periods in the equatorial region over Malaysia.

1 Introduction

The ionosphere is the higher region of the earth's atmosphere that significantly influences the reliability and accuracy of satellite communication and navigation systems by changing the speed and direction of the signal propagation. Total Electron Content (TEC) is the main ionospheric parameter that mostly affects the satellite signals transmitted through the ionosphere, causing delay to the signals. TEC varies and its effect on GPS satellite signals depends on the variability of the time of day, season, solar cycle, geographical location, and geomagnetic activity. During the geomagnetic disturbed period, the concentration of charged particles differs, causing fluctuations in TEC values inducing a vertical range of error, which greatly affects the GPS navigation performance [1]. These effects are most obvious in the lower latitudes and the equatorial regions. Therefore, it is crucial to identify a precise prediction model for a particular region, such as the equatorial region, to eliminate such effects. A number of researches have been carried out using different models in different regions worldwide such as the Bent model, the Klobuchar model, and the Global Ionospheric Maps (GIMs). In addition, there are many alternative techniques developed for ionospheric prediction purposes, such as the Neural Network (NN) models, Autoregressive Moving Average (ARMA), and autoregressive and self-consistent models. The International Reference Ionosphere (IRI) model is the model most often used. IRI's capacity for predicting ionospheric behaviors is reviewed continually by the scientific community, showing successful results over the mid-latitude region [2]. Suwantragul used basic equations of the Holt-Winter method to predict the ionospheric delay over Thailand and improved the precision of GPS positioning by up to 50% [3].

This research presents a comparison of the statistical Holt-Winter and IRI-2016 (IRI01-corr, IRI-2001, and NeQuick) models during geomagnetic quiet and disturbed periods over Kedah (geographic coordinates 4.62°N-103.21°E, geomagnetic coordinates 5.64°N-174.98°E), Terengganu (geographic coordinates 6.46°N-100.50°E, geomagnetic coordinates 3.32°S-172.99°E), and Johor (geographic coordinates 1.36°N-104.10°E, geomagnetic coordinates 8.43°S-176.53°E). The data were collected from the Department of Survey and Mapping Malaysia (DSMM) in March 2013 using a dual-frequency GPS receiver. The measured and modeled VTEC was analyzed and the efficiency of the models was compared and tested to identify the most effective model with regards to precision level.

2 Method and Data Analysis

2.1 Holt-Winter Method

The Holt-Winter is a statistical method that utilizes mathematical recursive functions to predict the ionospheric VTEC's behavior trend. It uses a time-series with a repeated trend and a seasonal pattern to make the predictions on the assumption that future data will follow a similar pattern. The exponential smoothing function method is used to minimize data fluctuations in the time-series. There are three smoothing coefficients including the level (α), the trend (β), and the seasonal (γ). These smooth constant values vary between 0 and 1. Holt-Winter has Multiplicative and Additive models. According to the results of Elmunim's study, the Multiplicative Model had predicted the results more accurately compared to the Additive model [4]. Therefore, the Multiplicative model was used in this research. The best smoothing coefficient values were identified and used to provide more accurate results. The Holt-Winter Multiplicative seasonal model equations are given as:

$$L_t = \alpha \frac{Y_t}{S_{t-1}}(Y_t - S_{t-1}) + (1-\alpha)(L_{t-1} + b_{t-1}) \quad (1)$$

$$b_t = \beta(L_t - L_{t-1}) + (1+\beta)b_{t-1} \quad (2)$$

$$S_t = \gamma \frac{Y_t}{L_t} + (1-\gamma)S_{t-s} \quad (3)$$

$$F_t = (L_{t-1} + b_{t-1})S_{t-1} \quad (4)$$

$$F_{t+m} = (L_t + b_t m)S_{t-s+m} \quad (5)$$

given that Lt, bt, and St are the level, trend, and the seasonal, respectively; Yt is the VTEC; t is the period; Ft the predicted value; Ft+m is the monthly prediction for the period t; α, β and γ are exponential smoothing coefficients; s is the seasonal duration, and m is the predicted period, S1 is the seasonal component initial value and Ls is the seasonal duration level that is estimated by using the following equations:

$$S_1 = \frac{Y_1}{L_1}, S_2 = \frac{Y_2}{L_2}, \ldots, S_s = \frac{Y_s}{L_s} \quad (6)$$

$$L_s = \frac{1}{s}(Y_1 + Y_2 + \ldots + Y_s) \quad (7)$$

The data were recorded in March 2013 from the dual-frequency GPS receiver at DSMM over Terengganu, Kedah, and Johor stations. The pseudo-ranges and carrier phases were measured at frequency bands L1 =1575.42 MHz and L2 =1227.60 MHz, which were derived from the fundamental frequency 10.23 MHz. The slant TEC (STEC) was determined from the GPS RINEX observation files that were obtained from DSMM. The GPS RINEX file was processed using the analysis software for GPS-TEC developed by Gopi at Boston College's Institute for Scientific Research. The software is available online at http://seemala.blogspot.com. The elevation cut-off point of 20° was used to reduce the multipath effects on the GPS data. Using the obliquity factor, the STEC was converted to the VTEC [5]. By using the Holt-Winter method, three days of data were used to predict the following day.

2.2 IRI-2016 Model

The International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR) launched the IRI project in 1960. The IRI model has continuously been improved since version IRI-78 to the latest which is the IRI-2016. In this research, the bottom side ABT-2009 option was used in URSI, F peak model. The upper boundary height of 1500 km was used to measure the ionospheric VTEC using IRI01-corr, IRI-2001, and NeQuick topside options, respectively. Additionally, the measured VTEC (GPS-TEC) was compared to the model from the Holt-Winter and IRI-2016 (IRI01-corr, IRI-2001, and NeQuick). The ionospheric VTEC's diurnal hourly median was calculated during the geomagnetic quiet and disturbed periods. This period was selected based on the geomagnetic indexes (Kp, Dst). The Percentage Deviation (%PD) was derived from the variations in the ionospheric VTEC during both geomagnetic periods using the equation where VTECx and VTECy represented the measured and modeled VTEC, respectively.

$$\%PD = \left(\frac{\mathrm{VTEC_y} - \mathrm{VTEC_x}}{\mathrm{VTEC_x}}\right) \times 100 \quad (8)$$

3 Result and Discussions

The diurnal variation of the VTEC in Kedah, Terengganu, and Johor stations during a typical quiet day ($Kp \leq 1$) on 7 March 2013 is shown in Figure 1. The VTEC in TECU unit is plotted on the vertical axis and the local time (LT) on the horizontal axis (Malaysia local time is eight hours added to the universal time).

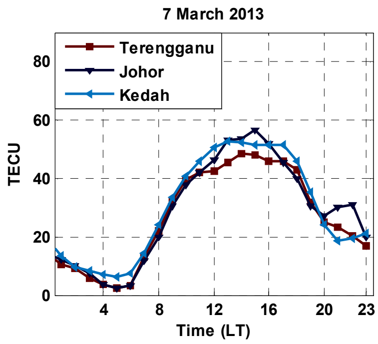

Figure 1. The diurnal variations of the VTEC over Kedah, Terengganu, and Johor.

During the sunrise period between 4:00-6:00 LT, the VTEC trend was at a minimum, and it then gradually increased to attain its maximum during the post-noon time between 12:00-17:00 LT. The VTEC in most of the daily hours was slightly higher at the Kedah station compared to that of the Terengganu and Johor stations. However, during the time of 14:00-15:00 LT, a sudden increase in the VTEC in Johor station. The difference in the VTEC trend at those stations was observed clearly during peak hours at the post-noon time because of the high proportion of electron density near the magnetic equator [6]. During 7:00-10:00

LT, the VTEC trend had a similar value to the Kedah, Terengganu, and Johor stations.

The daily variation of the measured VTEC from the GPS-TEC with the modeled VTEC using Holt-Winter and IRI-2016 (IRI01-corr, IRI-2001, and NeQuick) during the quiet period from between 7 to 11 March 2013 is shown in Figure 2. The IRI-2001 had an overestimation agreement with the GPS-TEC most of the time except the peak hours at the post-noon time for all the stations. The IRI01-corr and NeQuick model followed a similar trend, overestimating during the early morning hours following an underestimation at post-noon. The Holt-Winter showed slight underestimation agreement with the GPS-TEC during the peak hours at the post-noon time.

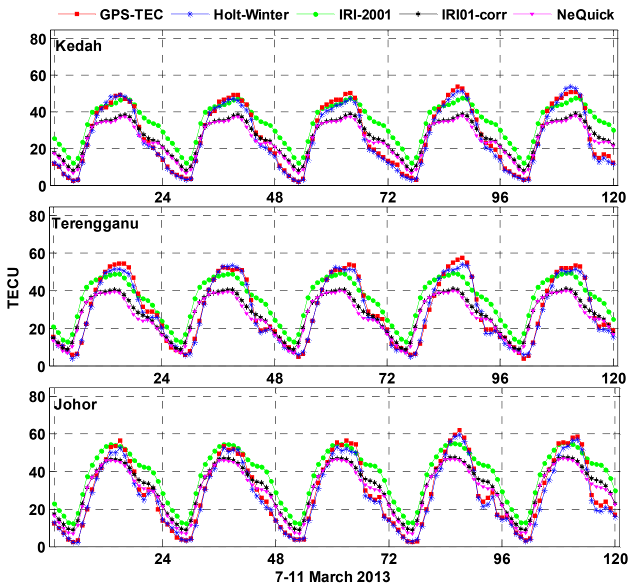

Figure 2. The daily variations of the VTEC during the quiet period.

From 15 to 20 March 2013, the VTEC data were affected by an intense geomagnetic storm which occurred on 18 March between 9:00-15:00 LT. It had a negative Dst value of around -132 nT. The daily variation of the measured GPS-TEC and that modeled from the Holt-Winter and IRI-2016 (IRI-2001, IRI01-corr, and NeQuick) during the geomagnetic disturbed period over Kedah, Terengganu, and Johor is shown in Figure 3. During the three days before the geomagnetic storm, the Holt-Winter method was in good agreement, while during the storm, it showed an underestimation agreement with the GPS-TEC. This underestimation occurred because of the sudden increase in the observed VTEC during the geomagnetic storm. This increase has shown clearly at the Kedah station. The IRI-2016 storm option did not respond during the disturbed period. Meanwhile, the IRI-2001, IRI01-corr, and NeQuick topside options predictions did not show a clear response to the increase of the VTEC trend during the considered geomagnetic storm period.

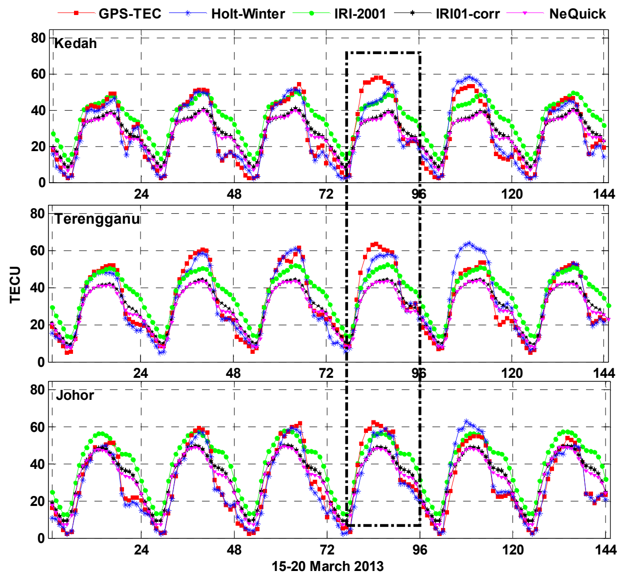

Figure 3. The daily variations of the VTEC during the disturbed period.

The percentage deviation of the Holt-Winter and IRI-2016 (IRI01-corr, IRI-2001, and NeQuick) topside options was calculated during the geomagnetic quiet day on 7 March and during the disturbances of the geomagnetic storm on 18 March, at the Kedah, Terengganu, and Johor stations as shown in Figure 4. The maximum value of the %PD was observed during sunrise and the minimum value was observed during the post-noon time for both geomagnetic periods. During the time between 20:00 to 08:00 LT, the IRI-2001 model had the highest value of the %PD as compared to the IRI01-corr and NeQuick models, while the Holt-Winter method had comparatively lower values of %PD. The %PD of the IRI-2016 (IRI01-corr, IRI-2001, and NeQuick) during the quiet period was high as compared to that of the disturbed period because the IRI-2016 model did not clearly respond to the geomagnetic storm activity. During the disturbed periods, the Holt-Winter method showed high %PD as compared to that of the quiet period. The maximum %PD during the quiet period were 9, 8, and 22 (Holt-Winter), 459, 423, and 268 (IRI01-corr), 298, 316, and 185 (IRI-2001), and 232, 252, and 168 (NeQuick) while the maximum %PD during the disturbed period was 56, 81, and 49 (Holt-Winter), 248, 242, and 261 (IRI01-corr), 141, 161, and 181 (IRI-2001), 98, 217, and 168 (NeQuick), for the Terengganu, Kedah, and Johor stations, respectively. Figure 5 shows a closer inspection of the %PD during quiet and disturbed periods at the time from 8:00-20:00 LT in Kedah station. During the post-noon time from 12:00-16:00 LT, all the models showed better predictions compared with the other hours during the considering day. During the quiet day, the Holt-winter method had better prediction with minimum %PD compared to the one during the disturbed day. Generally, IRI-2012 topside options showed good prediction results during 09:00-20:00 LT. The IRI01-corr and NeQuick topside options had almost similar trend during quiet and disturbed periods. The maximum %PD in Figure 5. was around 7 (Holt-Winter), 59 (IRI-2001), 27 (IRI01-corr) and 19 (NeQuick) during the quiet day and 42 (Holt-Winter), 53 (IRI-2001), 28 (IRI01-corr) and 32 (NeQuick) during the disturbed day. However, since the statistical Holt-Winter method predictions are depending on previous days data, it demonstrated better prediction results overall during the quiet and disturbed periods in comparison to the IRI-2016 topside options.

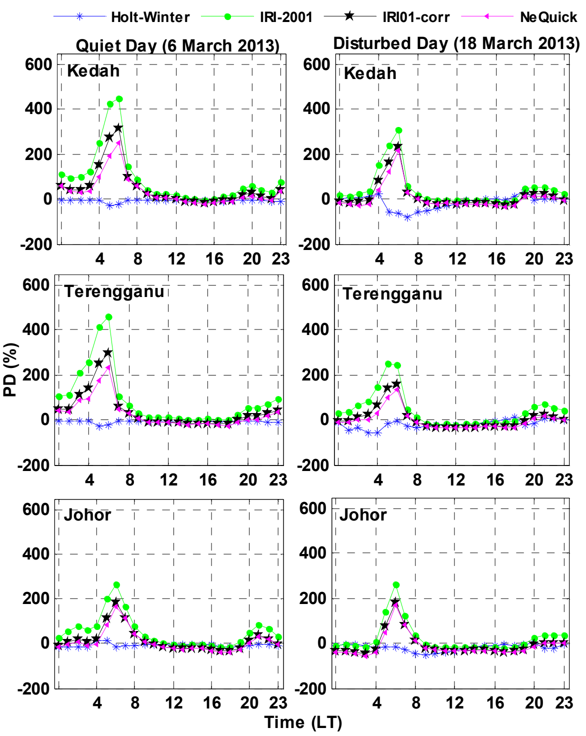

Figure 4. The percentage deviation of the Holt-Winter method and the IRI-2016 (IRI01-corr, IRI-2001, and NeQuick) during the quiet and disturbed periods.

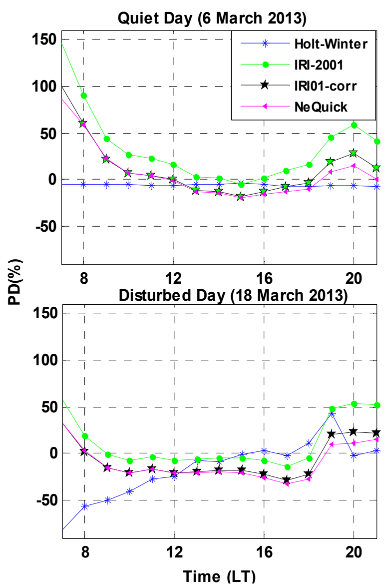

Figure 5. The percentage deviation of the Holt-Winter method and the IRI-2016 (IRI01-corr, IRI-2001, and NeQuick) in the post-noon time at Kedah station.

4 Conclusion

In this paper, the ionospheric VTEC was measured and modeled using the statistical Holt-Winter method and IRI-2016 (IRI01-corr, IRI-2001, and NeQuick) topside options, in which the trends were analyzed and compared during the geomagnetic quiet and disturbed periods in Kedah, Terengganu, and Johor stations over Malaysia. The efficiency of the models was also evaluated in both geomagnetic conditions. The IRI-2012 topside options showed good prediction results during the time from 09:00-20:00 LT. The IRI01-corr and NeQuick options had better predictions compared to the IRI-2001 option. As compared to the IRI01-corr, IRI-2001, and NeQuick models, the Holt-Winter method proved its effectiveness in predicting the VTEC during the quiet and disturbed periods. The result obtained can help represent the model error for data assimilation for improvements of ionospheric models. Additionally, this comparative study is essential in identifying appropriate models for improving the accuracy of GPS positioning in equatorial regions.

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