Characterization of Ionospheric Mapping Function at Equatorial Region

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Abstract— **The parameter of ionosphere that contributes severe effects on radio signals is the total number of electron content or total electron content (TEC). TEC can be estimated from the code and phase measurements based on the extracted Global Positioning System (GPS) data. Information of TEC reflects the relationship to the ionospheric layers due to high density of electron concentration at F region. At equatorial region (geographical latitude: 25° S to 25° N), the peak electron density height region varies from 275 km to 575 km and varies marginally from 300 km to 350 km at and beyond the anomaly crest region. It is vital to use suitable mapping function at equatorial region so that TEC value can be obtained precisely. The equatorial's ionosphere is unique due to the exposure of ultraviolet (UV) radiation from the sun at this region is much higher. This paper clarify the characterization of TEC mapping based on Single Layer Model (SLM) and Modified Single Layer Model (M-SLM) in order to determine the appropriate TEC value in equatorial region. TEC is extracted using RINEX format GPS dual frequency data that supplied by JUPEM (Department Of Survey and Mapping Malaysia). This paper investigates the TEC parameter covered the period of 4 hours duration (day and night) on 8 November 2005 from two different GPS receiver stations, located at Wisma Tanah Kuala Lumpur, KTPK and at Universiti Sains Malaysia, USMP.**

Keywords— **Global Positioning System (GPS), Ionosphere, Total Electron Content (TEC), Modified Single Layer Model (M-SLM).**

1.0 Introduction

The ionosphere is related to solar activity that has an eleven years cycle. It is formed by ultraviolet (UV) ionizing radiation from the sun. Ionosphere exists at 60 km to 1500 km height above Earth's surface. Ionosphere composed of the C Layer (40 – 50 km), D Layer (50 – 85 km), E Layer (85 – 140 km) and F Layer (140 – 1000 km), named in order of increasing height [5].

The D, E and F1 regions are closely tied to the UV ionizing daytime radiation from the sun. At night time, the D and E regions are much reduced due to the recombination process while F1 region disappears after sunset when its combine with F2 region to become F region. The F2 region layer (210 km to 1000 km) has the highest electron density and has the most effect on radio signal. In this region, the total electron content will occurred in the highest density with the nominal value 10^{16} to 10^{19} with minimum and maximum occurring at midnight and mid afternoon approximately as illustrates in Figure 1.

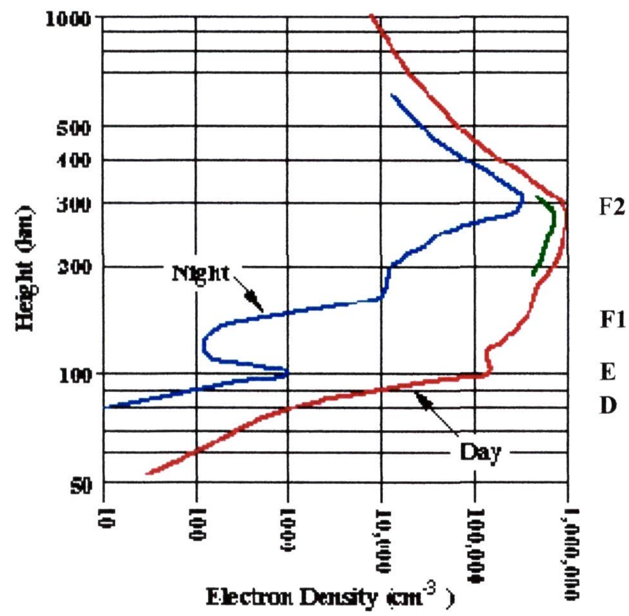

Figure 1: Total Electron Content in ionosphere at day and night time

The ionosphere causes GPS signal delays to be proportional to the TEC along the path from GPS satellite to a receiver. Process of conversion from slant TEC (TECs) to vertical TEC (TECv) was made based on few assumptions, where it assumed when the ionosphere is horizontally stratified and are spatially uniform. Moreover, the thin shell model was used and its height is the effective height which is taken as the Ionospheric Pierce Point (IPP) altitude.

1.1 Navigation System

All modern TEC measuring techniques rely on the observation of signal phase differences or on pulse travel time measurements based on geostationary and orbiting satellite signals. A standard way of measuring TEC is to use a ground-based receiver capable of processing signals from satellites in geostationary orbits. Types of navigation system used are like Global Navigation Satellite System (GLONASS) and Global Positioning System (GPS).

GLONASS was developed by the former Soviet Union and now operated for the Russian government by the Russian Space Forces. It is an alternative and complementary to the United States' Global Positioning System (GPS) and the planned Galileo positioning system of the European Union (EU). For this project, it uses the GPS to extract the raw data in RINEX format.

RINEX is a data interchange format for raw satellite navigation system data. The received data will be used (usually with other data unknown to the original receiver, such as better models of the atmospheric conditions at time of measurement) to produce a more accurate solution [7].

1.2 TOTAL ELECTRON CONTENT

TEC is the parameter of the ionosphere that produces most of the effects on GPS signals. One such effect is the addition of ionospheric delay to GPS signals, thereby introducing an external bias source to pseudorange and carrier phase observations which is difficult to correct in single frequency receivers [1]. However, dual frequency receivers are able to exploit the physics of the ionosphere as a dispersive medium in which the refractive index is a function of frequency, and introduce corrections which remove these effects.

The ionospheric time delay at the L_1 carrier frequency f_1 is given by [5].

$$t_1 = 40.3 \times \frac{TEC}{cf^2} \qquad (1)$$

$c = speed\ of\ light\ in\ free\ space$

Ionospheric TEC is characterized by observing carrier phase delays of received radio signals transmitted from satellites located above the ionosphere, often using GPS satellites [2]. GPS observations provide carrier phase delays, L and pseudorange, P of the dual frequencies. GPS operates on two different frequencies f_1 and f_2, which are derived from the fundamental frequency of 10.23 MHz [3]:

$$f_1 = 154f_o = 1575.42\ MHz \qquad (2)$$
$$f_2 = 120f_o 1227.60\ MHz \qquad (3)$$

By using a dual frequency GPS receiver, it can be used to measure the difference in ionospheric delays between L_1 and L_2 of the GPS frequencies, which are generally assumed to travel along the same path to the receiver, through the ionosphere. So, the TEC is taken to be equal for both frequencies along the line of sight, satellite-receiver. Thus, the group delay can be obtained as:

$$P_1 - P_2 = 40.3 \times TEC\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) \qquad (4)$$

Where P_1 and P_2 are the group path lengths corresponding to the high GPS frequency (f_1=1575.42MHz) and the low GPS frequency (f_2 =1227.60 MHz), respectively.

Slant TEC is a measure of the total electron content of the ionosphere along the ray path from the satellite to the receiver, while vertical TEC enables TEC to be mapped across the surface of the earth [4]. The slant TEC, TECs can be obtained by this equation:

$$TECs = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)(P_2 - P_1) \qquad (5)$$

Where P_2 and P_1 are the pseudorange measured in L1 and L2, respectively. Slant TEC (TECs) is the TEC between the satellite and the user where it depends on the satellite elevation angle. The TEC depends on the solar activity, user location and the satellite vehicle, SV elevation angle and it varies with times and over the space.

In practice, the calculation of TEC by using pseudorange data only, can produce a noisy result, thus the relative phase delay between the two carrier frequencies is vital in order to acquire a more precise result. Pseudorange gives the absolute scale for TEC while differential phase increases measurement precision [1].

1.3 MAPPING FUNCTION

As slant TEC is a quantity which is dependent on the ray path geometry through the ionosphere, it is desirable to calculate an equivalent vertical value of TEC which is independent of the elevation of the ray path. Figure 2 illustrates the relationship between TECs and TECv. The line of sight TEC values were converted to vertical TEC values using a mapping function and were associated to an ionospheric pierce point latitude and longitude. The ionosphere was assumed to be compressed into a thin shell at the peak ionospheric height of 350 km. In equatorial region, the peak electron density height varies from 275 km to 575 km. However the TECv computed from the measured GPS TECs for different altitudes ranging from 275 km to 575 km in the Equatorial region has revealed that the TEC does not change significantly with the IPP altitude, as long as the elevation angle of the satellite is greater than 50° [6].

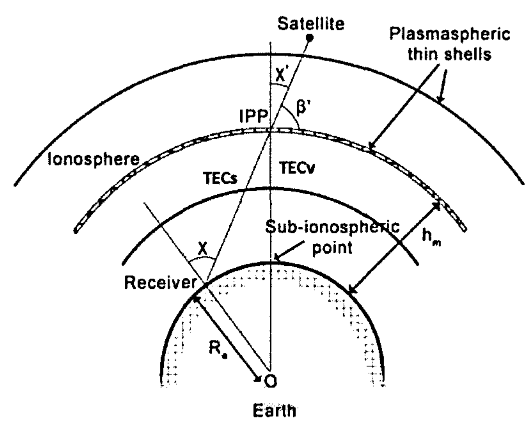

Figure 2: Geometry of Satellite-Receiver Link

Where $R_e = 6371\ km$, χ and χ' are the zenith angles at the receiver site and at the Ionospheric Pierce Point (IPP) (or β' is the elevation angle at IPP), respectively. The TECv through a given sub-ionospheric point can be obtained from the equation below:

$$TECv = TECs \cos\chi' \tag{6}$$

A. Klobuchar Model

The Klobuchar model is a global, polynomial-based model. It was developed for correcting the single frequency receivers' L_1signals for ionospheric delay. A global TEC product derived from Klobuchar coefficients was produced by Center for Orbit Determination Europe (CODE). The Klobuchar model approximates the ionospheric delay, T_g by a polynomial [9]. The relation between the GPS ionospheric time delay and the TEC is expressed as:

$$T_g = \frac{40.3}{cf^2} \times \int_{h1}^{h2} N(h) \cdot dh \tag{7}$$

$$TEC = \int_{h1}^{h2} N(h) \cdot dh \tag{8}$$

Where c is the velocity of light in free space, f is the frequency of the GPS radio signal and $N(h)$ is the ionosphere electron density at the height h above the Earth's surface. The ionospheric time delay, $T_{g\,(Klobuchar)}$ in seconds is calculated as:

$$T_{g\,(Klobuchar)} = \begin{cases} k\left[dc + A\left(1 - \frac{x^2}{2} + \frac{x^4}{4}\right)\right], & |x| \le \frac{\pi}{2} \\ k \times dc & |x| \ge \frac{\pi}{2} \end{cases} \tag{9}$$

$$x = \frac{2\pi(t - T_p)}{P} \quad (radians) \tag{10}$$

k is an elevation scaling factor:

$$k = 1 + 2\left[\frac{96^o - el}{90^o}\right]^3 \tag{11}$$

Where the night time component constant, dc and phasing, T_p, are respectively held constant at 5 ns and 14:00 (50400s) local time. The amplitude of daily cosine component, A and period of the daily cosine component, P are modeled as third-order polynomials constructed from broadcast coefficients α_n, β_n [9]. The Klobuchar Model, can only correct up to 70% of ionospheric delay. The success of the Klobuchar Model is much more pronounced during stable ionospheric condition while performs poorly during the severe ionospheric disturbances [10].

B. Single Layer Model (SLM)

For GPS dual frequency data, the mapping function used in this project is Single Layer Model, SLM and Modified Single Layer Model, M-SLM. SLM can be written as:

$$F(\chi) = \frac{TEC(\chi)}{TEC(0)} = \frac{1}{\cos\chi'(or \sin\beta')} = \frac{1}{\sqrt{1 - sin^2\chi'}} \tag{12}$$

and

$$\sin\chi' = \frac{R_E}{R_E + h_m} \sin\chi \tag{13}$$

$$\chi = 90° - Elevation\ Angle \tag{14}$$

Where R_E is the mean earth radius and h_m = 450 km is the height of maximum electron density. χ can be calculated from a known satellite position and the approximate coordinates of the receiver location. For h_m, in general the value is taken as the height corresponding to the maximum electron density at the F2 peak. The peak altitude ranges from 250 km to 350 km at mid-latitudes and from 275 km to 575 km at equatorial latitudes [7]. Typical value for R_E and h_m are set to 6371 km and 450 km, respectively.

C. Modified Single Layer Model (M-SLM)

The more precise mapping function according to Schaer [8] and currently applied in the IGS Global TEC map is the modified single layer model, M-SLM. Modified Single Layer Model, M-SLM mapping function is the improvement of the Single Layer Model, SLM by introducing the correction factor, α. M-SLM is defined as:

$$\sin\chi' = \frac{R_E}{R_E + h_m} \sin\alpha\chi \tag{15}$$

The value for correction factor, α is chosen to be 0.9782 while R_E and h_m as 6371 km and 506.7 km, respectively. The maximum zenith angle is assumed to be at 80° due to multipath effect if the angle is lower than 50°.

2.0 Methodology

In this paper, the data used to be analysed is on 8 November 2005. The data which in RINEX (Receiver Independent Exchange Format) format collected from JUPEM (Department Of Survey and Mapping Malaysia) at Kuala Lumpur. The details are as in Table 1 below:

TABLE I
SCOPE OF PROJECT

Station	Longitude (N)	Latitude (E)	Time, LT (Hour)	PRN Track
KTPK	3.2°	101.7°	11:00-15:00	10
			18:00-22:00	21
USMP	5.1°	99.8°	11:00-15:00	10
			18:00-22:00	21

The process of extracting data from RINEX file was done by using Matlab programming language whereby the RINEX file was obtained from the GPS receiver. The program will analyse and extract the information needed in calculating the TEC from the observation and navigation RINEX file. The result will show the graph of elevation angle, line of sight (LOS), different phase, different delay, TECs and TECv versus time. This data of TECv were used since its value is not depending on the location of satellite receiver compared to TECs.

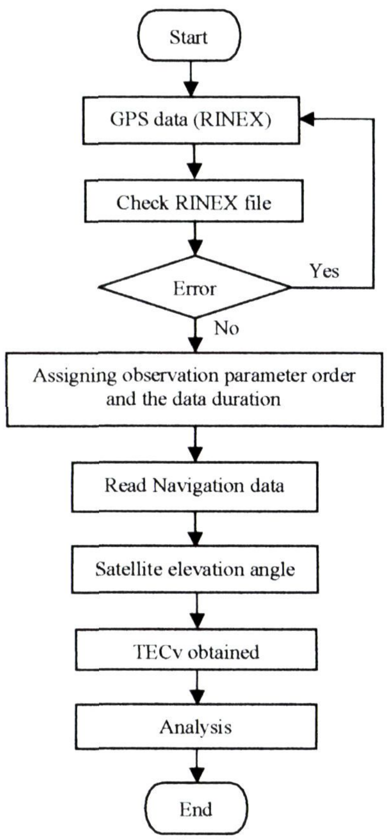

Figure 3: Flowchart process in TEC processing

3.0 RESULTS

The plotted graphs obtained based on the programming show the graphs for elevation angle, line of sight (LOS), different phase, different delay, TECs and TECv using SLM and M-SLM against time in hour. In this paper, the graphs that will be discussed are the elevation angle and TECv. The following graphs are between the time of 11:00 and 15:00 local time, from the Wisma Tanah Kuala Lumpur, KTPK GPS receiver station.

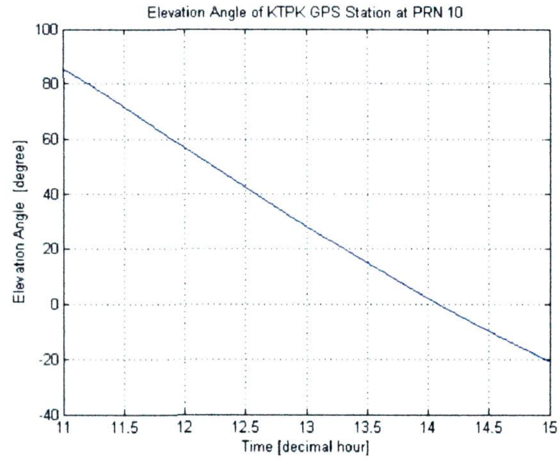

Figure 4: Graph of elevation angle against time

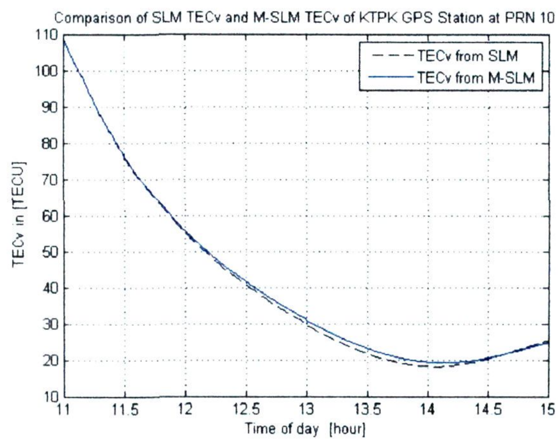

Figure 5: Graph of TECv against time

The second set of result is also from KTPK GPS receiver station, from 18:00 until 22:00 local time.

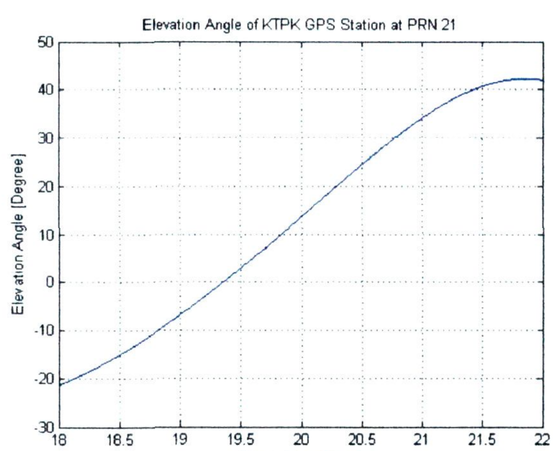

Figure 6: Graph of elevation angle against time

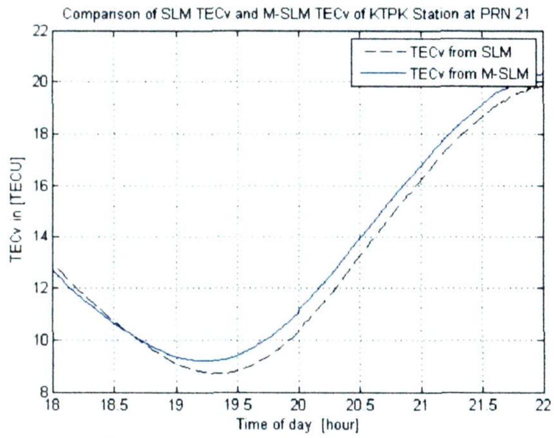

Figure 7: Graph of TECv against time

The data for the following graphs are on 8 November 2005, between 12:00 and 14:00 local time, from the Universiti Sains Malaysia, USMP GPS receiver station.

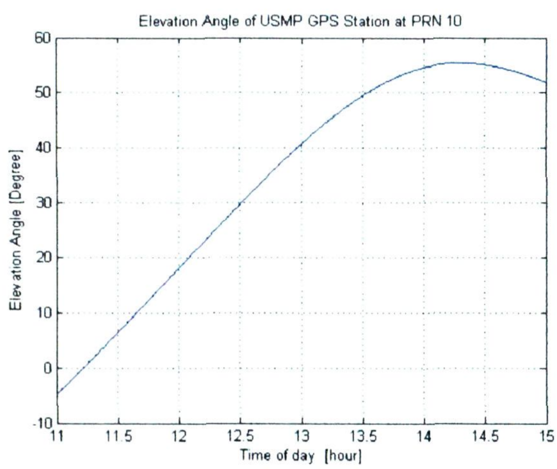

Figure 8: Graph of elevation angle against time

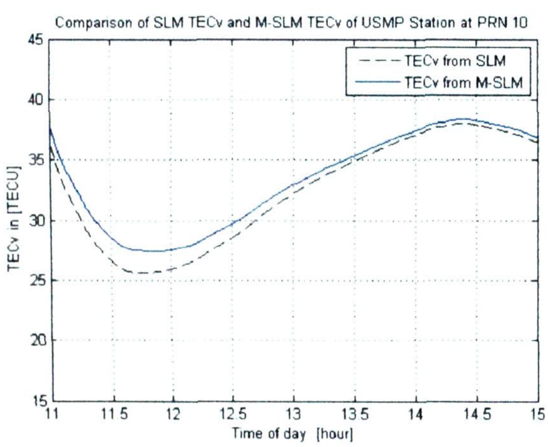

Figure 9: Graph of TECv against time

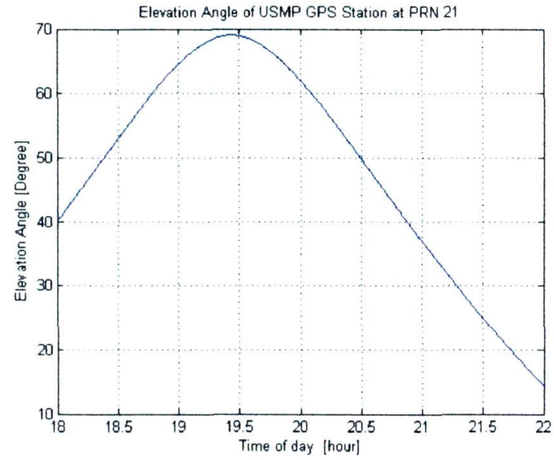

Figure 10: Graph of elevation angle against time

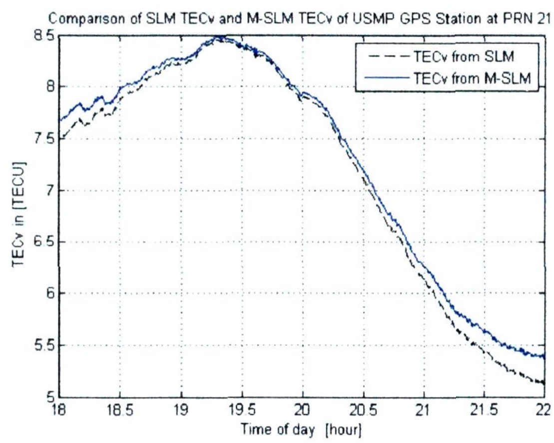

Figure 11: Graph of TECv against time

TABLE II
COMPARISON OF TECv VALUES BETWEEN STATIONS

Time (Hour)	KTPK		USMP	
	SLM (TECU)	M-SLM (TECU)	SLM (TECU)	M-SLM (TECU)
1100	108.55	108.57	36.36	37.82
1300	30.08	31.35	32.18	32.96
1500	22.29	24.73	36.50	36.92
1800	12.67	12.97	7.48	7.66
2000	10.25	11.01	7.86	7.91
2200	19.85	20.31	5.11	5.36

Figure 12 below shows the correlation between time, GPS receiver's latitude, and TECv in form of 3D graph. It gives clearer monitoring data of TEC between day and night.

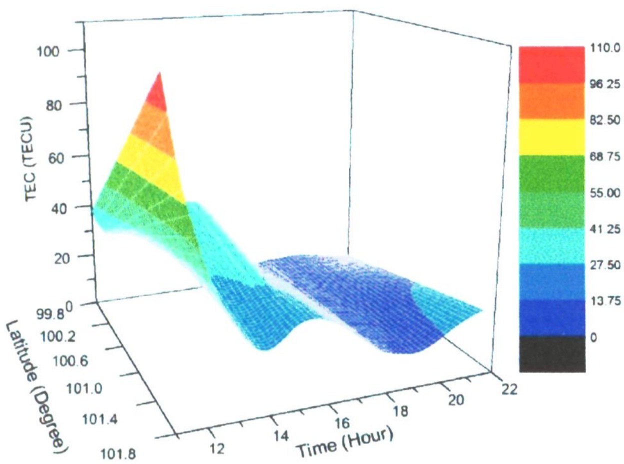

Figure 12: 3D graph of time, GPS receiver's latitude, and TECv

4.0 Discussion

The mapping functions analysed in this paper are SLM, M-SLM and Klobuchar Model. Due to availability of data, the simulation only focus on SLM and M-SLM mapping functions. For M-SLM, correction factor, α was introduced in order to calculate the zenith angle at IPP as in equation (15). The maximum height of electron density, h_m used in M-SLM is higher than SLM, thus it is much applicable to use M-SLM to estimate the TEC in Equatorial region. The maximum height of electron density at equatorial region can be up to 575 km [6]. Comparing the graph of TECv for KTPK station (Figure 5 and Figure 7) referring to M-SLM, the highest TEC reading occurred at day, at 108.57 TECU while the lowest TEC is 20.31 TECU, occurred at night. This occasion goes the same at USMP station where the highest TECv reading during the day is 37.82 TECU and the lowest is at night, 5.36 TECU. Theoretically, TECv is much higher during the day compare at night due to the exposure of UV radiation produced by the sun at Equatorial region [7].

The elevation angle graphs indicate that the distance between the satellite and GPS receiver is closer as the elevation angle increase. Therefore, the best TECv reading can be estimated more precisely at high elevation angle due to less multipath effect. However, the vertical TEC computed from the measured GPS TECs for different IPP altitudes in the Equatorial region has revealed that the TEC does not change significantly with the IPP altitude, as long as the elevation angle of the satellite is greater than 50° [6]. Thus the acceptable elevation angle for TEC analysis is between 50° and 85°.

5.0 Conclusion

GPS signals can be used to extract ionospheric parameters such as TEC. In this paper, the combinations of dual frequency carrier-phase and code-delay GPS observations are vital in order to obtain ionospheric observables related to the slant TEC (TECs) along the satellite-receiver line of sight (LOS). This results in the absolute differential delay. The remaining noise is discarded. The Modified Single Layer Model (M-SLM) was used for mapping function for KTPK station and USMP station which is at the Equatorial region.

The TEC itself is hard to accurately determine from the slant TEC because this depends on the sunspot activity, seasonal, diurnal and spatial variations and the line of sight which includes knowledge of the elevation and azimuth of the satellite. The acceptable choice of effective height of electron at Equatorial region is essential in determining the TEC. Knowing the history of the ionosphere and its correlation with MAGDAS Data, more accurate determination of TECv models can be constructed.

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