Determination of GPS Total Electron Content using Single Layer Model (SLM) Ionospheric Mapping Function

Norsuzila Ya'acob[†], **Mardina Abdullah**[†,††] **and Mahamod Ismail**[†,††]

[†] Department of Electrical, Electronics and Systems Engineering,
Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor. MALAYSIA
[††] Affiliate fellow, Institute of Space Science,
Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor. MALAYSIA

Summary
The ionosphere layer is very important to the communication system. The ions produced from the striking process of the ultra violet light have an active role in reflecting and observing the earth radio waves. This layer also is an unstable medium because it is vulnerable to several distortions which affect its physical condition. Studies of Total Electron Content (TEC) have given important relationship to the ionospheric layers due to high density of electron concentration at F region. Total Electron Content (TEC) measurements from ground stations to Global Positioning System (GPS) satellite provide a rich source of information about the Earth's ionosphere. This research involves the determination of TEC content in ionosphere based on single layer model in order to determine the appropriate TEC value for Malaysia. This research assessing the errors translated from the code-delay to the carrier-phase ionospheric observable by the so-called "Levelling Process" which is applied to reduce carrier phase ambiguities from the data.

Key words:
GPS, TEC, ionosphere, levelling process

1. Introduction

The ionosphere causes GPS signal delays to be proportional to the total electron content (TEC) along the path from the GPS satellite to a receiver. Total electron content is a key parameter in the mitigation of ionospheric effects on radio system. Total electron observations using Global Positioning System (GPS) satellites are becoming a very powerful and valuable tool for investigating global and local ionospheric structures [1, 2, 3] because the world-wide coverage provided by the 27 satellites constellation and the increasing number of networks available such as the International Standard for the specifications of ionospheric densities and temperatures.

The highest TEC in the world occurs in the equatorial region. Comparatively, little corresponding research has been done on the low latitude (equatorial) ionosphere [4]. The major factors that determine the TEC are the solar cycle, season, local time, and geographic and geomagnetic coordinates. The main parameters of the ionospheric information (ionospheric electron content or electron density) are the altitude, local time, intensity of solar activity, season, position of station, and so on. 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, etc [5].

Modelling the altitude dependency of the electron density by a Chapman profile allows in turn to estimate the fractional TEC above the receiver altitude. The ionospheric path delay for positive elevations is then obtained from a thin layer approximation with a suitably chosen effective height of the residual ionosphere above the receiver.

The primary focus is on mitigation of inherent fluctuations in pseudorange due to bandwidth limited precision, receiver noise, and multipath, typical GPS receivers generally employ so-called phase smoothing or levelling of code. In the present study a single thin shell of infinitesimal thickness situated at a median ionospheric height of 400 km above the earth surface was assumed.

2. Measurement of Total Electron Content (TEC) Using Dual Frequency Technique

The TEC is defined as the total number of electrons integrated along the path from the receiver to each GPS. TEC is an indicator of ionospheric variability derived from the modified GPS signal through free electrons. It is also the parameter of the ionosphere that produces most of the effects on GPS signals. TEC is measured in unit (TECU) of 10^{16} electrons per m^2 [6].

GPS observations provide both carrier phase delays L and pseudoranges 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:

Manuscript received September 5, 2008.
Manuscript revised September 20, 2008.

$$f_1 = 154.fo = 1575.42 \text{ MHz} \quad \text{and}$$
$$f_2 = 120.fo = 1227.60 \text{ MHz} \qquad (1)$$

A dual-frequency GPS receiver can measure the difference in ionospheric delays between the L1 (1575.42 MHz) and L2 (1227.60 MHz) of the GPS frequencies, which are generally assumed to travel along the same path through the ionosphere. Thus, the group delay can be obtained as:

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

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 =1227.6 MHz), respectively.

The TEC can also be obtained by writing (2) as

$$TEC = \frac{1}{40.3} \left(\frac{f_1 f_2}{f_1 - f_2} \right) (P_2 - P_1) \qquad (3)$$

if dual frequency receiver measurements are available;

where (P2 and P1) are the pseudoranges measured in L1 and L2, respectively. As the TEC between the satellite and the user depends on the satellite elevation angle, this measurement is called Slant TEC (TECs). Slant TEC is a measure of the total electron content of the ionosphere along the ray path from the satellite to the receiver, represented in Figure 1. It can be calculated by using pseudorange and carrier phase measurements as (3). 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 1 depicts the relationship between slant and vertical TEC. To compare the electron contents for paths with different elevation angles, the TECs must be transformed into equivalent vertical content or vertical TEC (TECv) by dividing it by the secant of the elevation angle at a mean ionospheric height. The TEC varies with times and over the space, and it depends on the solar activity, user location and the sv elevation angle.

GPS carrier phase derived TEC provides a smooth but relative measurement of ionospheric TEC, while code derived TEC provides a noisy but absolute measurement. To reduce the effect of pseudorange noise on TEC data, GPS pseudorange data can be smoothed by carrier phase measurements. Such carrier phase smoothing technique is also often referred as *"Carrier Phase Levelling"*. Carrier phase Levelling or phase smoothing is essentially some combination of the noisy code pseudorange with the comparatively smoothly varying carrier phase. The carrier phase contains much smaller measurement error than pseudoranges, so that ionospheric total electron content (TECs) can be obtained by carrier phase smoothing the pseudoranges [7, 8].

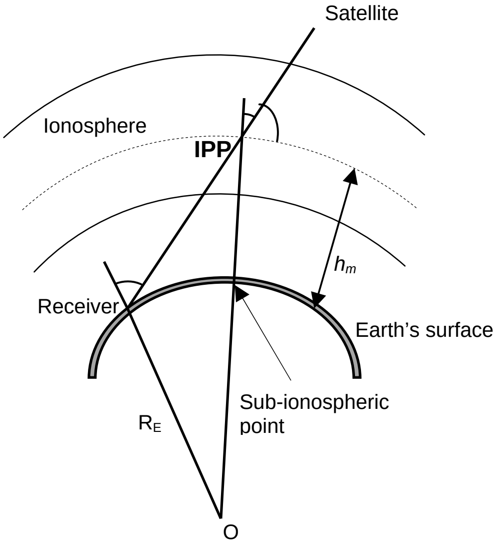


Fig. 1 Ionospheric single layer model, SLM

3. Mapping Function

Precision monitoring of ionosphere will have profound implications in almost all areas of GPS user communities. The ionospheric mapping function is one of the first assumptions to consider typically when ionospheric corrections are estimated or applied from Global Navigation Satellite System (GNSS) data. The typical assumption in many GNSS imaging and navigation systems is to consider a fixed mapping function constant, and associate it to a 2D distribution of electron content at a given effective height (typically some value between 300 and 500 km).

The line-of-sight TEC values were converted to vertical TEC values using a simple mapping function and were associated to an ionospheric pierce point latitude and longitude, assuming the ionosphere to be compressed into a thin shell at the peak ionospheric height of 350 km as illustrated in Fig. 1. Generally, by referring to Fig. 1, the slant TEC, TECs through a given sub-ionospheric point is obtained from

$$TEC = TECs \cos \chi' \qquad (4)$$

In some literature this is called the elevation-dependent single layer (or thin shell) model mapping function, SLM which can be written as

$$\begin{aligned} F(\chi) &= \frac{TEC(\chi)}{TEC(0)} \\ &= \frac{1}{\cos\chi' (\text{or} \sin\beta')} \qquad (5) \\ &= \frac{1}{\sqrt{1-\sin^2\chi'}} \end{aligned}$$

with

$$\sin\chi' = \frac{R_E}{R_E + h_m} \times \sin\chi \qquad (6)$$

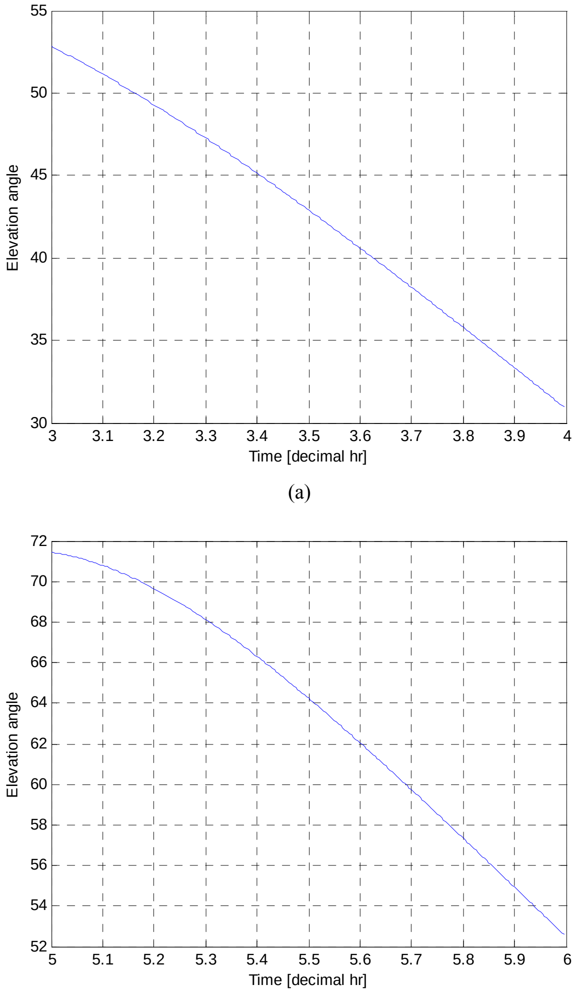
where R_E is the mean earth radius, hm is the height of maximum electron density, and χ and χ' are the zenith angles at the receiver sites and at the ionospheric pierce point IPP, respectively. χ can be calculated from a known satellite position and the approximate coordinates of the receiver location. 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 to 350 km at mid latitudes and from 350 to 500 km at equatorial latitudes. Typical value for R_E and h_m are set to 6371 and 450 km, respectively. If both the differential carrier phase and the differential group delay are measured with a dual-frequency GPS receiver, the user can easily obtain both the absolute TEC and its rate of change.

Generally, the ionosphere can be divided into several layers in altitude according to electron density, which reaches its peak value at about 350km in altitude. For 2D ionospheric modelling, the ionosphere is assumed to be concentrated on a spherical shell of infinitesimal thickness located at the altitude of about 350 km above the Earth's surface [9]. The thin layer model currently used in GPS has deficiencies resulting from conversion of slant TEC to effective vertical TEC. The deficiencies come from in appropriate attribution of the thin shell height. This conversion introduces a few errors in the middle latitude where electron density is small. But, it may result in obvious error at low latitude with large electron density and great gradient [10, 11].

Three dimensional models of electron density have been developed and demonstrated for improved accuracy. The approach using 3-D electron density model can improve the interpolation process.

3. Result

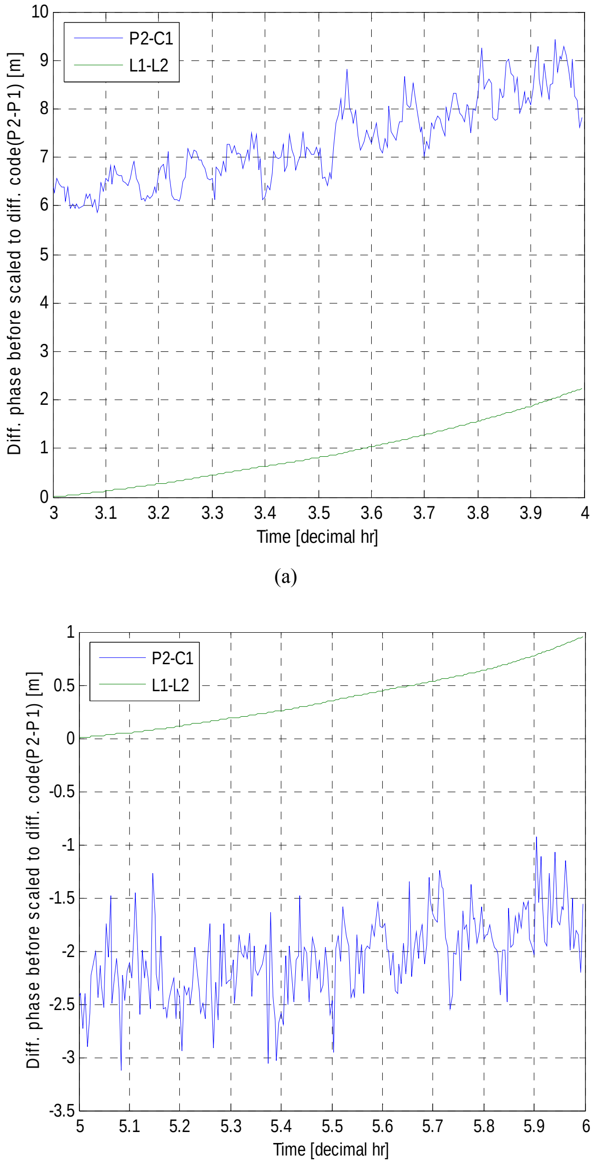
GPS data from Wisma Tanah Kuala Lumpur, KTPK station (3° 10' 15.44"N; 101° 43' 03.35"E) and Kukup, Johor (1°19'59.791"N, 103°27'12.354"E), KUKP station on 8 November 2005 was processed and analysed.. The GPS data was recorded in universal time system, whereby the sampling interval was 15 seconds and the cut-off elevation mask was 10°.



(b)

Fig. 2 (a) Elevation angle of PRN 1 for KTPK station
(b) Elevation angle of PRN 23 for KUKP station

Figure 3 (a) and (b) show that the elevation angle for KTPK station and KUKP station for PRN 1 and PRN 23. The elevation angle for KTPK is 54° to 30° and KUKP is 71.8° to 52.5°.

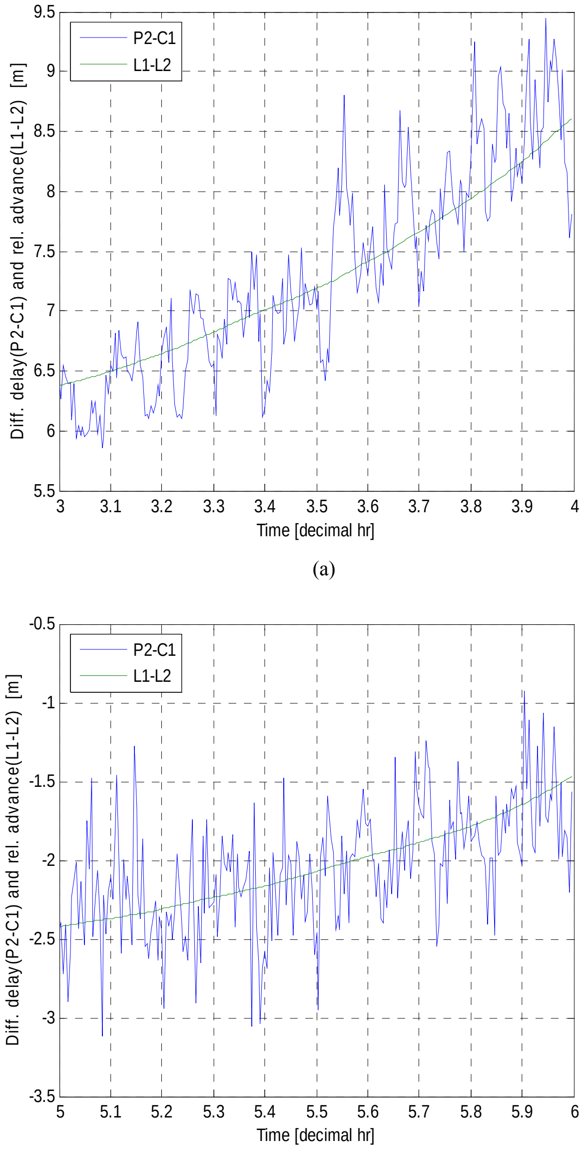


(a)

(b)

Fig. 3 (a) Different phase before scale to different code for KTPK station
(b)Different phase before scale to different code for KUKP station

Figure 3 (a) and (b) clearly indicate the code TEC and phase TEC for one hour observation of PRN 1 and PRN 23 for elevation from 54˚ to 30˚ and 71.8˚ to 52.5˚. The differential delay (=P2-C1) from code measurements is noisy and influenced by multipath while the phase measurements, are ambiguous, so the phase derived slant delay. This eliminate the integer ambiguity provided there are no cycle slips.

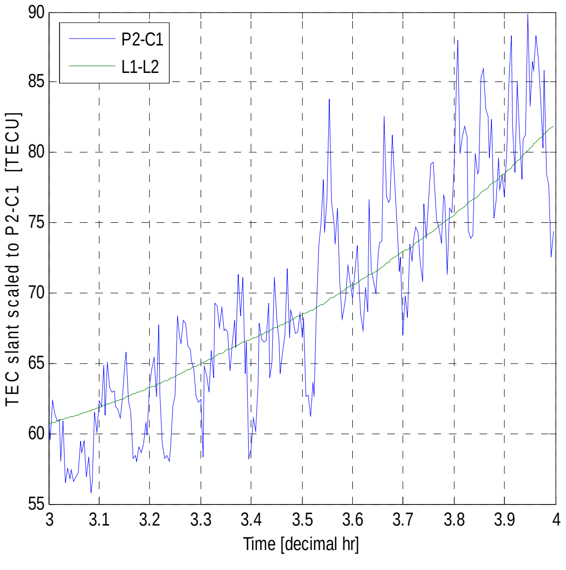


(a)

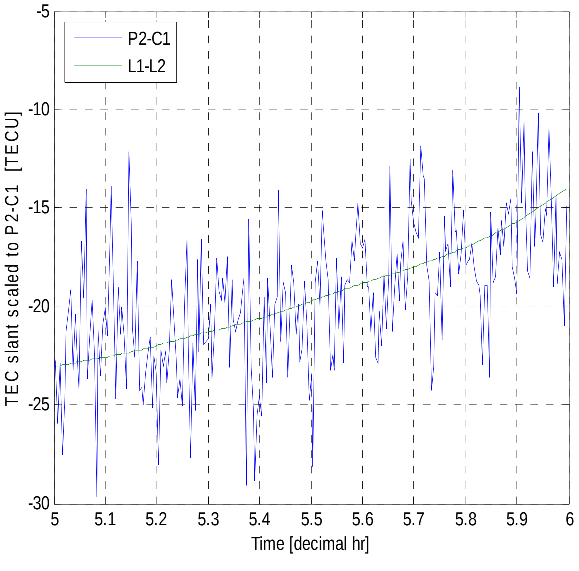
(b)

Fig. 4 (a) Relative range error computed from the differential carrier phase for KTPK station
(b) Relative range error computed from the differential carrier phase for KUKP station

According to figures 4 (a) and (b), the code TEC displayed here has been smoothed by phase TEC. The smoothed code TEC estimates are considerably smoother than the raw TEC estimate that shows noise and multipath fluctuations. To eliminate the code multipath effect that is normally seen at both ends of the path or at low elevation angles, the code differential delay was fitted at the higher elevation angles (± 60˚to 90˚) as reference. This is called “Levelling Process”, applied to reduce carrier-phase ambiguities from the data.



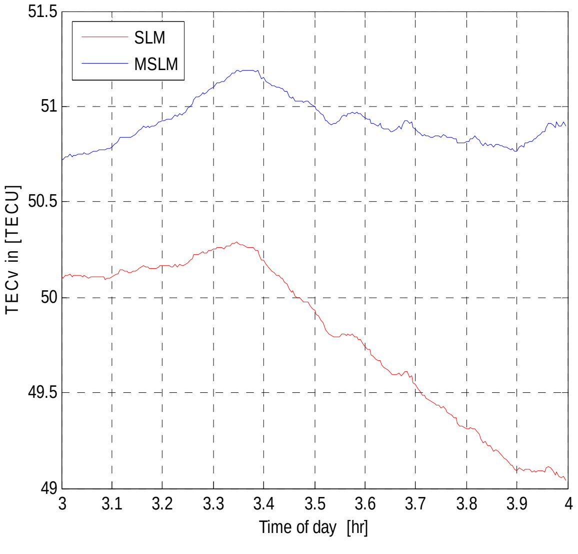
(a)



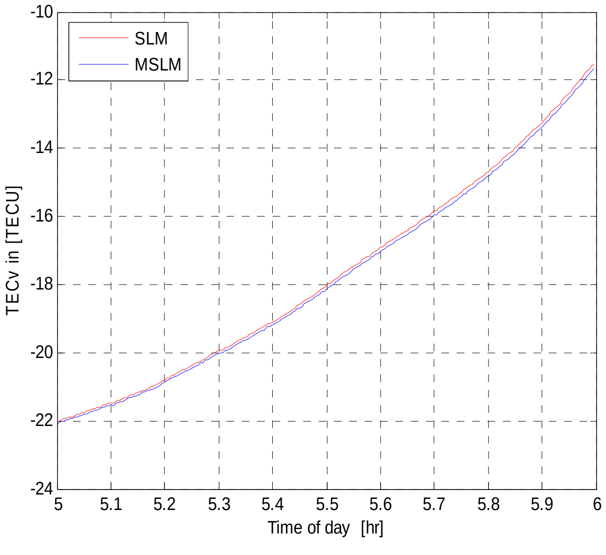
(b)

Fig. 5 (a) Tec slant scale to P2- C1 TECU for KTPK station
(b) Tec slant scale to P2- C1 TECU for KUKP station

Figures 5 (a) and (b) show that this smoothed differential delay (with less noise and multipath) was then translated to the absolute slant TEC by multiplying it by a constant (see equation (3)). The final TEC values are precise, accurate and without multipath, unless the multipath environment is really terrible, in which case a small, residual amount of multipath can even be seen in the differential carrier phase.



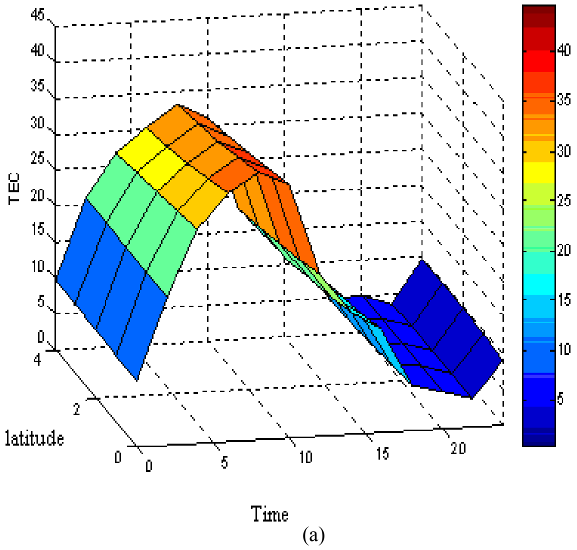
(a)



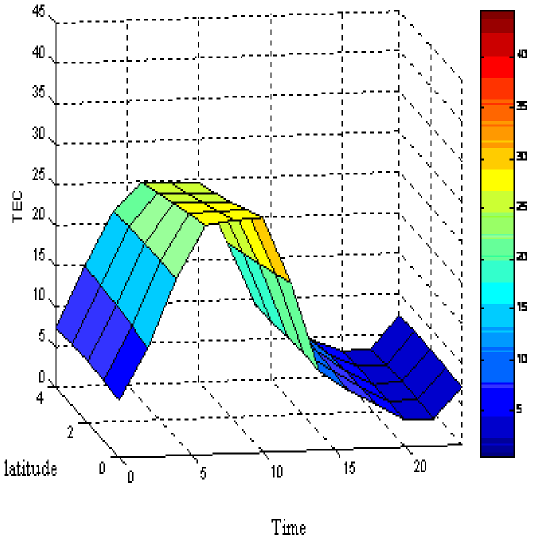
(b)

Fig. 6 (a) TEC vertical for KTPK station
(b) TEC vertical for KUKP station

A mapping function, Single Layer Model (SLM), was used to convert slant TEC to the vertical TEC using dual frequency as shown in Figs. 6 (a) and (b). The total electron using dual frequency for GETI station is 23.3 to 26 TECU and for RTPJ station is -14 to -28 TECU.



(a)



(b)

Fig. 7 (a) 3-D single layer model (SLM) for KTPK station
(b) 3-D single layer model (SLM) for KUKP station

Figure 7 (a) and (b) clearly indicate the 3-D maps based on IONEX data. The IONEX data have been generated from the Bernesse software. The effective height obtained for 350 km (SLM) for KTPK station with total electron content is 34 TECU and for KUKP station is 25 TECU.

3. Conclusion

In this paper, dual frequency carrier-phase and code-delay GPS observations are combined 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 single layer model (SLM) was used for mapping function.

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 etc. Knowing the history of the ionosphere and its correlation with Kp index more accurate predicted VTEC models can be found.

Acknowledgments

This research is funded by the Malaysian Government through University Kebangsaan Malaysia under the Science Fund 04-01-02-SF191. We are grateful to Jabatan Ukur dan Pemetaan Malaysia (JUPEM) for providing the GPS data. The author would like to express her grateful thanks to Universiti Teknologi Mara (UiTM) for giving the author study leave and scholarship enabling her to conduct the research.

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Biography

Norsuzila Ya'acob received her MSc. in Remote Sensing and GIS from UPM, Serdang. She has been a lecturer with UiTM since 2001 and now working towards her PhD in mobile communication at Universiti Kebangsaan Malaysia, Bangi. Malaysia. She also heads several IRDC-UiTM grant funded research projects and is a member of IEEE.

Mardina Abdullah received her B.Eng degree in Electronics and Information Engineering from University of Ryukyus, Japan in 1991. She obtained her M. Sc degree from Universiti Kebangsaan Malaysia (UKM) in Electrical, Electronic and System Engineering in 1995. In 2004, she was awarded a PhD in Electrical Engineering from The University of Leeds, UK for a work on ionospheric effects on GPS range finding and precise positioning.

Mahamod Ismail received his B.Sc. degree in Electrical and Electronics from University of Strathclyde, U.K. in 1985, the M.Sc. degree in Communication Engineering and Digital Electronics from UMIST, Manchester U.K. in 1987, and the Ph.D. from University of Bradford, U.K. in 1996. He is currently a Professor with the Department of Electrical, Electronics and System Engineering, Universiti Kebangsaan Malaysia. His research interests include mobile communication and wireless networking particularly on the radio resource management.