# GPS Total Electron Content (TEC) Prediction at Ionosphere Layer over the Equatorial Region

Norsuzila Ya'acob[1], Mardina Abdullah[1,2] and Mahamod Ismail[1,2]
[1]*Department of Electrical, Electronic and Systems Eng, Universiti Kebangsaan Malaysia*
[2]*Institute of Space Science, Universiti Kebangsaan Malaysia*
*Malaysia*

## 1. Introduction

Space weather is a fairly new field in science today and has very interesting effects on humans, environment and technology in general. Scientists are now studying space weather with a wide range of tools to try to learn more about the physical and chemical processes taking place in the upper atmosphere and beyond. One of these tools is Global Positioning System (GPS). GPS is currently one of the most popular global satellite positioning systems due to global availability of signal as well as performance. GPS is a satellite-based navigation radio system which is used to verify the position and time in space and on the Earth. GPS nowadays allows to measure positions in real time with an accuracy of few centimetres (Warnant et al., 2007). The advent of GPS has led to technical revolutions in navigation as well as in fields related to surveying. The GPS system - an all-weather satellite-based radio navigation system - can provide users on a world-wide basis with navigation, positioning, and time information which is not possible with conventional navigation and surveying methods.

Apart from geodesy and geophysical interest, GPS has great importance in scientific applications. The GPS satellites that are orbiting the Earth, at altitudes of about 20,200 km, transmit signals that propagate through the ionosphere that exists at about 60 –1500 km above the Earth's surface. The signals from the GPS satellites travel through the ionosphere on their way to receivers on the Earth's surface. The free electrons populating this region of the atmosphere affect the propagation of the signals, changing their velocity and direction of travel as shown at figure 1. Due to the inhomogeneity of the propagation medium in the ionosphere, the GPS signal does not travel along a perfectly straight line (Ioannides & Strangeways, 2000). The effects of the ionosphere can cause range-rate errors for users of the GPS satellites who require high accuracy measurements (Bradford & Spilker, 1996).

Ionosphere is highly variable in space and time (sunspot cycle, seasonal, and diurnal), with geographical location (polar, aurora zones, mid-latitudes and equatorial regions), and with certain solar-related ionospheric disturbances. Ionosphere research attracts significant attention from the GPS community because ionosphere range delay on GPS signals is a major error source in GPS positioning and navigation. The ionosphere has practical importance in GPS applications because it influences the transionospheric radio wave propagation. Observed ionospheric behaviour varies over the Earth and can be generalized into aurora, mid-latitude and equatorial regions. Ionospheric delays of 38 ~ 52 m were observed at low-latitude region during high solar activity period at an elevation cut off angle of 10˚ (Komjathy et al., 2002). The equatorial ionosphere differs significantly from what is typically observed at mid-latitudes. The geographic bands 10˚-15˚ north and south of the magnetic equator are referred to as the equatorial anomaly region, due to the occurrence of Appleton anomaly (Doherty et al., 2002).

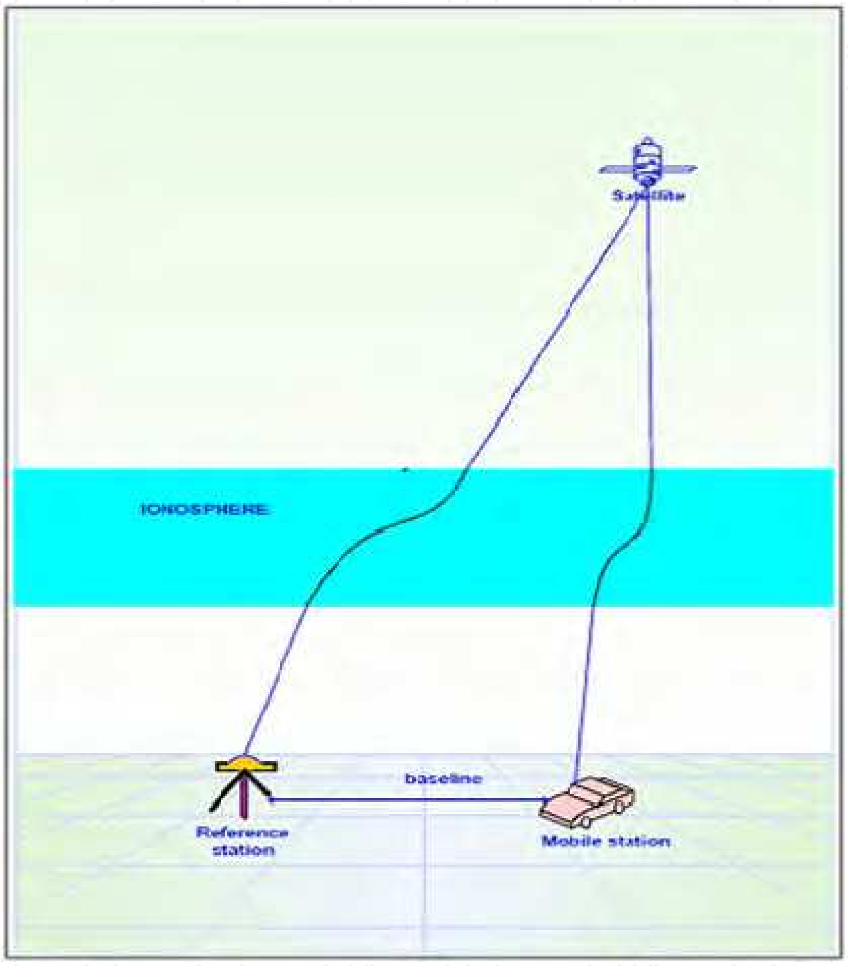



Fig. 1. Exaggerated view of GPS signal geometric paths

The parameter of ionosphere that produces most of the effects on radio signals is total electron content (TEC). By modelling TEC parameter, the evaluation of the ionospheric error and the correction of these ionospheric errors for differential GPS can be done. The ionosphere causes GPS signal delays to be proportional to TEC along the path from the GPS satellite to a receiver. TEC is defined by the integral of electron density in a 1 $m^2$ column along the signal transmission path. TEC is a key parameter in the mitigation of ionospheric effects on radio system. The TEC measurements obtained from dual frequency GPS receivers are one of the most important methods of investigating the Earth's ionosphere. 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 highest TEC in the world occurs in the equatorial region. In Malaysia there are few corresponding research done on the low latitude (equatorial) ionosphere.

Ionospheric research in the equator and tropical areas has sparked interests in several research groups. Ong and Kamarudin (2006) have conducted a research on the TEC distribution estimation with the Bent, IRI and Klobuchar modelling by using the GPS MASS station network. While Ho et al. (2002) reported on the typical hourly variations for quiet ionosphere over Malaysia for 24 hours on July 14, 2000. At Universiti Kebangsaan Malaysia (UKM) researchers have been analysing TEC since 1999. Abdullah et al. (2008) did an analysis of TEC determination over single GPS receiver station using Precise Point Positioning (PPP) technique. The ionosphere over Malaysia is unique because of its location near the equator line.

In this chapter, the focus is placed on the implementation of the method to the local area GPS reference network and the data analysis of its performance in ionospheric TEC predictions in support of GPS positioning and navigation. It investigated ionospheric TEC predictions using Dual frequency technique and TEC map using Bernese software (BGS) with PPP technique. For TEC dual frequency, it assessed the errors translated from the code-delay to the carrier-phase ionospheric observable by the so-called "Levelling Process", which was applied to reduce carrier-phase ambiguities from the data. The TEC data derived from GPS pseudorange measurements have a large uncertainty because the pseudorange has high noise level. In contrast, the noise level of carrier phase measurements is significantly lower than the pseudorange ones. To reduce the effect of pseudorange noise on TEC data, GPS pseudorange data can be smoothed by carrier phase measurements, for example, by using carrier phase smoothing technique, which is also often referred to as carrier phase levelling. Whereas, for TEC Map technique, GPS measurements from stations at the Equatorial region were used for producing maps. The Matlab and Bernese GPS software was used to derive TEC from GPS data.

This chapter describes the parameter of the ionosphere that produces most of the effects on GPS signal which is the TEC. TEC is measured to estimate the impact of ionosphere to the signal transmitted by GPS satellite to the receiver on Earth. It is a measure of the total amount of electrons along a particular Line of sight (LOS). Ionospheric delay correction is carried out through modelling the TEC along each satellite signal path due to high spatial variability of the ionosphere. Prediction of communication failures and radio interference additionally requires accurate information on TEC variations. Another technique to calculate TEC is by using Code's IGS TEC Map. It is based on spherical harmonic expansion parameterizations and computed based on the BGS Software and the output is in standard IONEX.

## 2. Total Electron Content (TEC) in Ionosphere

The TEC is defined as the total number of electrons integrated along the path from the receiver to each GPS. The TEC as an indicator of ionospheric variability that derived by the modified GPS signal through free electrons. TEC is measured in units of $10^{16}$ electrons meter per square area, where $10^{16}$ electrons/$m^2$ = 1 TEC unit (TECU) (Abdullah, 2009).

The nominal range is $10^{16}$ to $10^{19}$ with minima and maxima occurring at midnight and mid afternoon approximately. At night the TEC decays rather slowly due to recombination of electrons and ions. Maximum TEC usually occurs in the early afternoon and minimum TEC usually occurs just before sunrise. Also daily TEC variations increase as one travels from north to south, as sunlight is more direct.

There are several methods to obtain the TEC over the reference station. In this work TEC was obtained from dual frequency method and the IGS (International GPS Service) TEC map.

### 2.1 Dual Frequency Model TEC

TEC is significant in determining scintillation and group delay of a radio wave through a medium. Ionospheric TEC is characterized by observing carrier phase delays of received radio signals transmitted from satellites located above the ionosphere, often using GPS satellites. GPS satellites transmit electromagnetic waves for positioning on two frequencies which is L1 (1575.42 MHz) and L2 (1227.60 MHz) allowing receivers equipped with dual frequency operation to be used. This enables us to extract the ionosphere TEC along the line of sight, from satellite to receiver.

In this work, the TEC is observed at the F layer because this region has the highest variability of free electrons, causing the greatest effect on GPS received signal compared to other layers. More than two-third of electron concentration are located at F2 layer. This method is conducted by going through several processes. Figure 2 shows the flow chart of work progress to achieve the objective of the project.

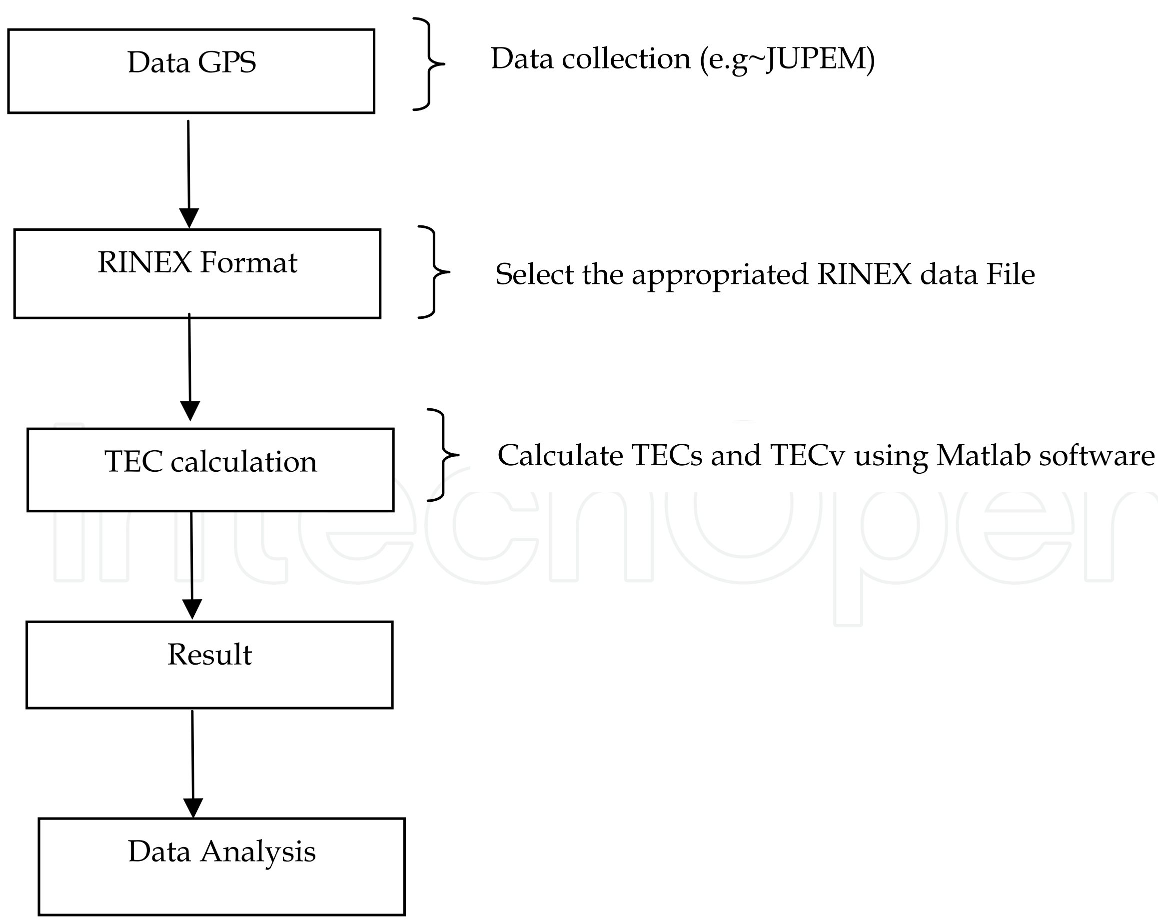



Fig. 2. Flow chart of TEC processing

The process of extracting data from RINEX (Receiver Independent Exchange) file was done by using Matlab programming language whereby the RINEX file was obtained from the GPS receiver as shown in figure 3. 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, different phase, different delay, slant TEC (TECs) and vertical TEC (TECv) versus time. This data of TECv were used since its value is not depending on the location of satellite receiver compared to TECs.

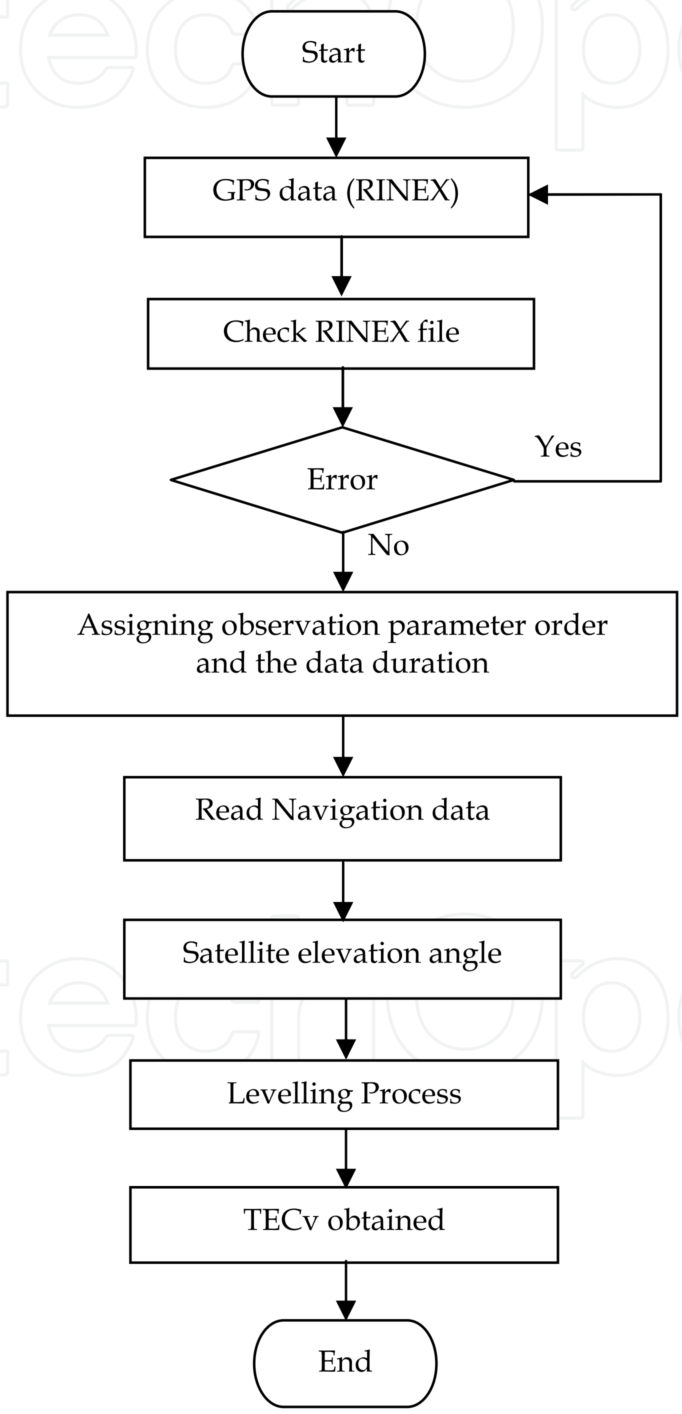



Fig. 3. Flowchart of TEC processing

### 2.1.1 Determination of TEC

Dual-frequency carrier phase and code-delay GPS observations are combined to obtain ionospheric observables related to the (TECs) along the satellite-receiver line of sight (LOS). Pseudorange is applicable to P(Y)-codes and C/A-codes. The pseudorange equation in units of length can be expressed as:

$$P_r^S = c\left(t_r - t^S\right) = c\tau_r^S = \rho_r^S + c(\delta t_r - \delta t^S) + I + T + mpp + \varepsilon \quad (1)$$

Where $P_r^S$ is pseudorange measured at receiver; $c$ is speed of light in vacuum, $t^S$ is transmission time of signal measured by time frame of satellite, s; $t_r$ is reception time of signal measured by the clock of receivers r; $\tau_r^S$ is signal travelling time, $P_r^S$ is LOS range from satellite antenna and receiver antenna, $\delta t^S$, $\delta t_r$ is satellite and receiver clock error due to the difference in system time; $I$ is ionospheric induced error; $T$ is tropospheric induced error, $mpp$ is multipath error and $\varepsilon$ is noise or random error.

Carrier phase is the measurement of the phase difference between the carrier signal generated by the receiver's internal oscillator and the carrier signal transmitted from a satellite. The basic equation for the carrier phase measurement is:

$$L_r^S = \rho_r^S + c\left(\delta t_r - \delta t^S\right) - I + T + \lambda N_r^S + mpL + \varepsilon \quad (2)$$

Where $L_r^S$ is phase measurement in units of length, $N_{\mathrm{r}}^{\mathrm{S}}$ is integer ambiguity between the satellite and receiver, $mpL$ is multipath error.

The true range or geometric range can be represented by:

$$\rho_r^S = \sqrt{\left(X^S - x_r\right)^2 + \left(Y^S - y_r\right)^2 + \left(Z^S - z_r\right)^2} \quad (3)$$

Where $X$, $Y$ and $Z$ are the satellite coordinates, $x$, $y$ and $z$ are the receiver coordinates

Dual band GPS receivers were considered in the measurable linear combination (LC). Dual frequency observations can be used to measure the ionosphere delay. This delay can then be removed from the measurements by combining the frequencies, $L_1$ and $L_2$. Ionosphere delay can then be removed from the measurements by combining the frequencies and providing the Linear Combination (LC) solution. All observables have the dimension of length, terms due to noise and multipath are not explicitly shown, and higher-order ionospheric terms are ignored:

$$L_1 = \rho - I_1 + \lambda_1 N_1$$

$$L_2 = \rho - \left(f_1^2 / f_2^2\right) I_1 + \lambda_2 N_2$$

$$P_1 = \rho + I_1$$

$$P_2 = \rho + \left(f_1^2 / f_2^2\right) I_1 \tag{4}$$

Where $\rho$ is non dispersive delay, contains LOS, clocks and troposphere bias, $I_1$ is dispersive delay of first frequency and $N_1, N_2$ is integer ambiguities on L1 and L2.
The integrated TEC from the receiver to the satellite is proportional to the accumulated effect by the time the signal arrives at the receiver. This affects the GPS range observables: a delay is added to the code measurements and advance to the phase measurements. To achieve very precise positions from GPS, this ionospheric delay or advance must be taken into account. A GPS operates on two different frequencies $f_1$ and $f_2$, which are derived from the fundamental frequency of = 10.23 MHz:

$$f_1 = 154.fo = 1575.42\ MHz \text{ and}$$
$$f_2 = 120.fo = 1227.60\ MHz \tag{5}$$

A dual-frequency GPS receiver can measure the difference in ionospheric delays between the L1 and L2 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:

$$P_1 - P_2 = 40.3TEC\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) \tag{6}$$

Where $P_1$ and $P_2$ are the group path lengths corresponding to the high GPS frequency ($f_1$=1575.42 MHz) and the low GPS frequency ($f_2$ =1227.6 MHz), respectively.
The TEC can also be obtained by writing Eq. (6) as

$$TEC = \frac{1}{40.3}\left(\frac{f_1 f_2}{f_1 - f_2}\right)(P_2 - P_1) \tag{7}$$

if dual frequency receiver measurements are available;
where ($P_1$ and $P_2$) are the pseudoranges measured in L1 and L2, respectively.
TEC can be divided into two parts. There are:
(a) Slant TEC (TECs)
(b) Vertical TEC (TECv)
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 4. Although TECs is measured at differing elevation angles, usually the TECv is modelled. TECv enables TEC to be mapped across the surface of the Earth.
TEC measurements are taken from different GPS satellite observed at arbitrary elevation angles. This causes the GPS signals to cross largely different portion of the ionosphere. To compare the electron contents for paths with different elevation angles, the TECs must be transformed into equivalent vertical content or TECv by dividing it by the secant of the

elevation angle at a mean ionospheric height, which usually taken to be between 350 and 450 km. Generally by referring to figure 4, the slant TEC, TECs through a given sub-ionospheric point is obtained from Eq. (8).

### 2.1.2 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 associated 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 TECv values using a simple mapping function and were associated to an ionospheric pierce point (IPP) latitude and longitude, assuming the ionosphere to be compressed into a thin shell at the peak ionospheric height of 350 km as illustrated in figure 4. The thin shell model was used and its height is the effective height which is taken as the ionospheric pierce point altitude. Generally, the ionosphere can be divided into several layers in altitude according to electron density, which reaches its peak value at about 350 km in altitude.

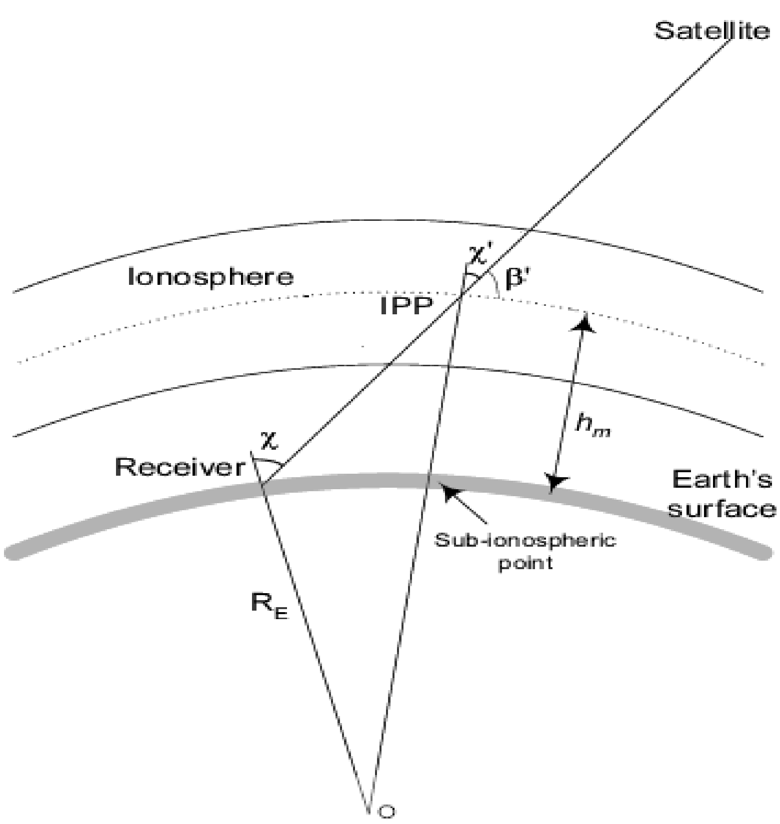



Fig. 4. Ionospheric Single Model (SLM)
Source: Schaer 1996

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 many result in obvious error at low latitude with large electron density and great gradient (Horvath, 2000). Usually, the ionospheric delay resulting from observation noises, less than 1 TECU, is omitted. It is assumed that, in the two-dimensional spherical shell model, the majority of electron density is concentrated in a thin layer with a height of 350-450 km above the surface of the Earth.
Generally by referring to figure 4, TECs through a given sub-ionospheric point is obtained from Eq. (8)

$$TEC_V = TEC_S \left(\cos \chi^{'}\right) \tag{8}$$

Where TECs is the value of slant TEC, $\chi'$ is the difference between 90° and zenith angle (90°-$\chi$). In some literature this is called the elevation-dependent single layer (or thin shell) model mapping function, SLM where can be written as

$$F\left(\chi\right) = \frac{TEC\left(\chi\right)}{TEC\left(0\right)} = \frac{1}{\cos \chi^{'}\left(or \sin \beta^{'}\right)} = \frac{1}{\sqrt{1-\sin^2 \chi^{'}}} \tag{9}$$

$$\sin \chi^{'} = \frac{R_e}{R_e + h_m} \sin \chi \tag{10}$$

Where $R_e$ is the mean earth radius, $h_m$ is the height of maximum electron density, and $\chi$ and $\chi'$ are the zenith angles at the receiver site and at the IPP (or $\beta'$ is the elevation angle at IPP), respectively. $\chi$ 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. The more precise mapping function according to Schaer et al. (1996) and currently applied in the IGS Global TEC map is the modified single layer model, M-SLM. This is defined as;

$$\sin \chi^{'} = \frac{R_e}{R_e + h_m} \sin\left(a\chi\right) \tag{11}$$

where α is correction factor which is close to unity. The value is chosen to be 0.9782 when using $R_e$ and $h_m$ as 6371 and 506.7 km, respectively and assuming a maximum zenith angle of 80°.

$F(\chi)$ is also known as the slant or obliquity factor in the Klobuchar model and varies from 1 to slightly above 3 at $h_m$ = 350 km. For low elevation angles slant TEC can reach until 3 times the value of TEC at zenith. However the oblique-to-zenithal thin shell conversion including the determination of $h_m$ is still being developed further. It has also been suggested that $h_m$ should be taken to be between 600 and 1200 km which is greater than the commonly adopted value. If this is correct, assuming a lower value could produce an error of 15 to 30% or more in TEC.

### 2.1.3 Carrier phase levelling process

GPS signals can be used to extract ionospheric parameters such as TEC. For single frequency GPS users, models of the ionosphere such as the Klobuchar model (Klobuchar, 1987), which is also known as the GPS broadcast model, have been constructed utilizing ionospheric parameters given in the GPS broadcast message. It is represented by a third degree polynomial where the coefficients of the polynomial are transmitted as part of the broadcast message header. The TEC can also be obtained as in Eq. (7), if dual frequency receiver measurements are available. As the TEC between the satellite and the user depends on the satellite elevation angle, this measurement is called TECs. The TEC varies with times and over the space, and it depends on the solar activity, user location and the PRN elevation angle.

In practice, calculation of TEC by the above means, using pseudorange data only, can produce a noisy result. It is desirable to also use the relative phase delay between the two carrier frequencies in order to obtain a more precise result. Differential carrier phase gives a precise measure of relative TEC variations but because the actual number of cycles of phase is not known, absolute TEC cannot be found unless pseudorange is also used. Pseudorange gives the absolute scale for TEC while differential phase increases measurement precision. The TEC data derived from GPS pseudorange measurements have a large uncertainty because the pseudorange has high noise level. In contrast, the noise level of carrier phase measurements is significantly lower than the pseudorange ones. To reduce the effect of pseudorange noise on TEC data, GPS pseudorange data can be smoothed by carrier phase measurements. For example is by using carrier phase smoothing technique, which is also often referred to as carrier phase levelling. Carrier phase levelling or phase smoothing is essentially some combination of the noisy code pseudorange with the comparatively smooth varying carrier phase. The carrier phase contains much smaller measurement error than pseudoranges, so that ionospheric TECs can be obtained by carrier phase smoothing the pseudoranges (Hansen et al., 2000). This was done as shown below:

Firstly, the phase observations, measured in cycles, are scaled to units of length by multiplying with the wavelength. Because the phase measurements are ambiguous, so the phase derived slant delay, obtained from geometry free linear combination, $L_4$ calculated from Eq. (12) was scaled to zero relative range error at the first epoch. This eliminates the integer ambiguity provided there are no cycle slips.

$$L_4 = L_1 - L_2 = \left(1 - f_1^2 / f_2^2\right) I_1 + \left(\lambda_1 N_1 - \lambda_2 N_2\right) \tag{12}$$

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.

This was done by defining a shift value and was added to the relative phase to fit the code differential delay. This results in the absolute differential delay and the remaining noise was discarded.

Figure 5 shows the differential delays determined using the above procedure. This smoothed differential delay (with less noise and multipath) was then translated to the absolute TECs by multiplying with a constant (see Eq. (7)). A mapping function, SLM is used together with Eq. (8) to convert TEC to the vertical from the slant value. For a good description on the determination of absolute TEC from dual frequency GPS measurements refer to Parkinson and Spilker (1996).¸

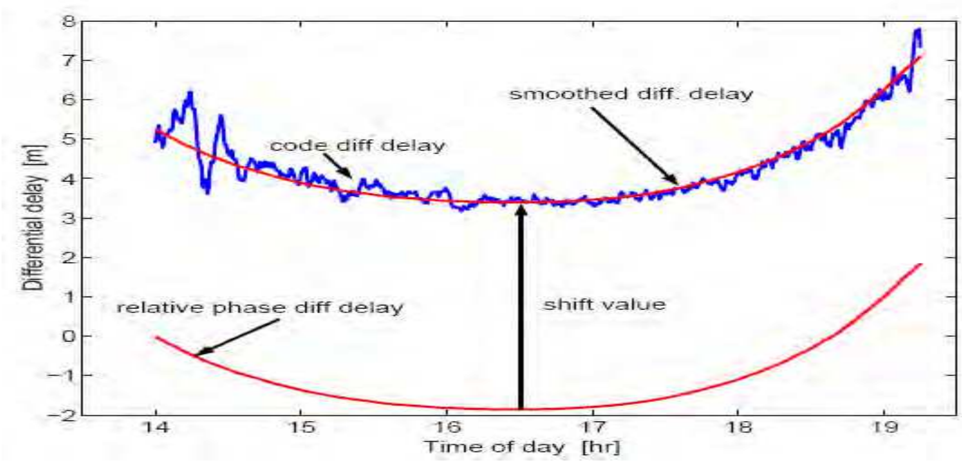



Fig. 5. Phase smoothed code differential delay

### 2.2 TEC Map

Bernese GPS Software (BGS) was used to map the ionosphere in this work. BGS is commonly used by scientists for research and education, survey agencies responsible for high-accuracy GNSS surveys, agencies responsible for maintaining arrays of permanent GPS receiver and also commercial users with complex applications demanding high accuracy, reliability and high productivity (Dach, 2007). TEC map has gained much attention in the recent years because of the ionospheric effects to the GPS-based navigation application. A range delay caused by the ionosphere during quiet and disturbed geomagnetic days can be approximated using the measurements of TEC map.

TEC ionopheric values and maps can be delivered by the International GPS Service (IGS). IGS has developed the global ionospheric gridded data representing the TEC over the whole globe. Analysis centres deliver their results of TECv and DCBs in the IONosphere Exchange (IONEX) format (Schaer et al., 1998).

In this new version of BGS, PPP was processed using BPE. BPE consists of data, user scripts and four process control file (PCF) where one of the PCF is PPP. PCF in PPP mode has been selected to run PPP. In this PPP.PCF, regional ionosphere model is generated and stored in Bernese ionosphere file and in IONEX file using GPS Estimation (GPSEST) program. GPSEST is the program that able to generate TEC maps in IONEX (Schaer et al., 1998). GPSEST program is used to model and estimate the ionosphere. In GPSEST program, geometry-free linear combination from the zero-difference code observations was used because it principally contains ionospheric information. Geometry-free linear combination of this un-differenced GPS observations is then applied in GPSEST to generate TEC map.

A MSLM was used for mapping the TEC, approximated by a spherical layer with infinitesimal thickness assuming that all free electrons are concentrated in altitude, *H*, above the spherical Earth. The altitude *H* of this idealized layer is set to 350 km. Based on this model, TEC values were calculated in geographic reference system which was able to produce the epoch-specific instantaneous regional maps of the ionosphere. Using MSLM noted above, a vertical TEC can be obtained at IPP. It can be shown that a single GPS receiver can probe the ionosphere in a radius of 960 km assuming 10° elevation cut-off angle and 450 km height.
This proved that PPP technique can be used to determine TEC over single station in Malaysia. With the new BGS version 5.0; PPP technique is now available to produce ionosphere maps. PPP is known as a valuable tool to provide an accurate position anywhere on Earth, also for investigating many geophysical processes at the millimetre level.

## 3. Analysis of TEC

The ionosphere GPS-TEC measurements were carried out using GPS receiver networks from Department of Survey and Mapping, JUPEM. GPS data on 8 November 2005 were analyzed for this initial analysis. The stations were at Wisma Tanah, Kuala Lumpur, (3˚ 10′ 15.44″N; 101˚ 43′ 03.35″E) KTPK station and Universiti Teknologi Malaysia, Johor (1˚33′ 56.934″N, 103˚38′22.429″E), UTMJ station as shown in figure 6. This analysis was based on one hour observations from 5:00 – 6:00 UT (13-14 PM (LT)) using GPS satellite PRN 23 for KTPK station and also using GPS satellite PRN 23 for UTMJ station. The GPS data was recorded in universal time (UT) system. The sampling time interval is 15 second and the cut-off elevation mask is 15°. GPS data used in this project were recorded on a quiet geomagnetic day where the geomagnetic index Kp is 1.

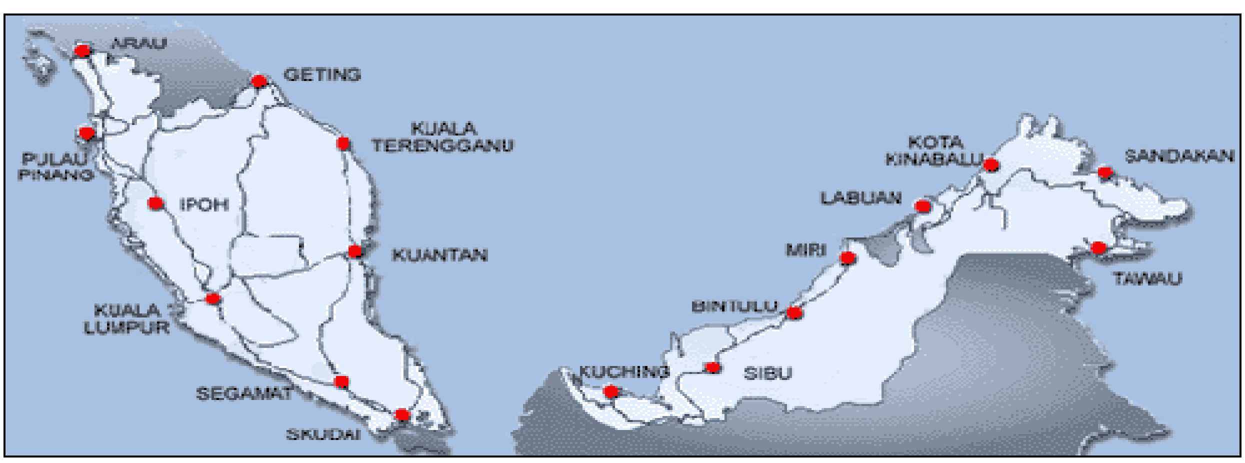
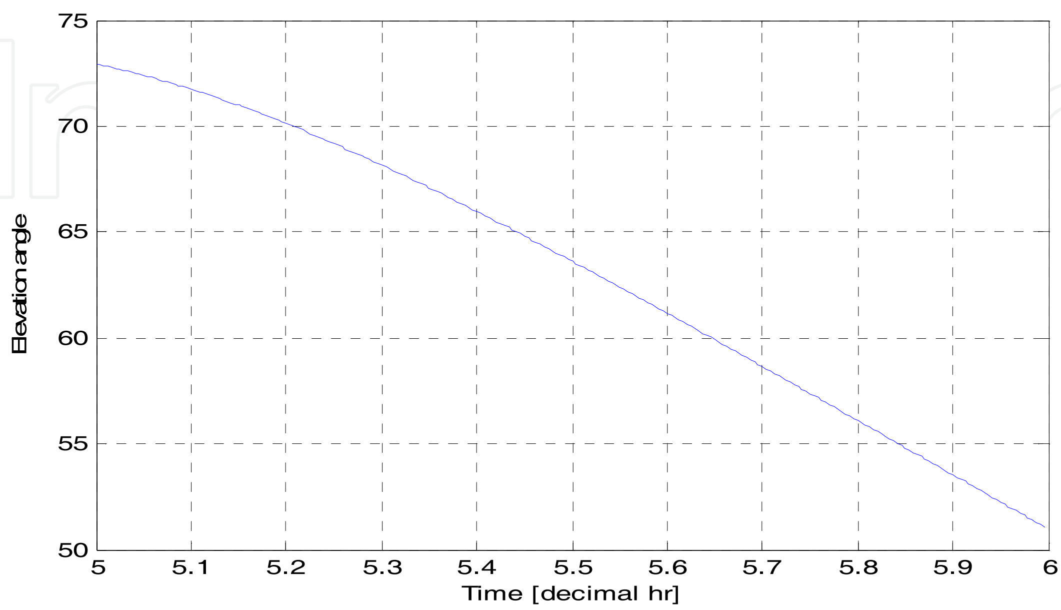


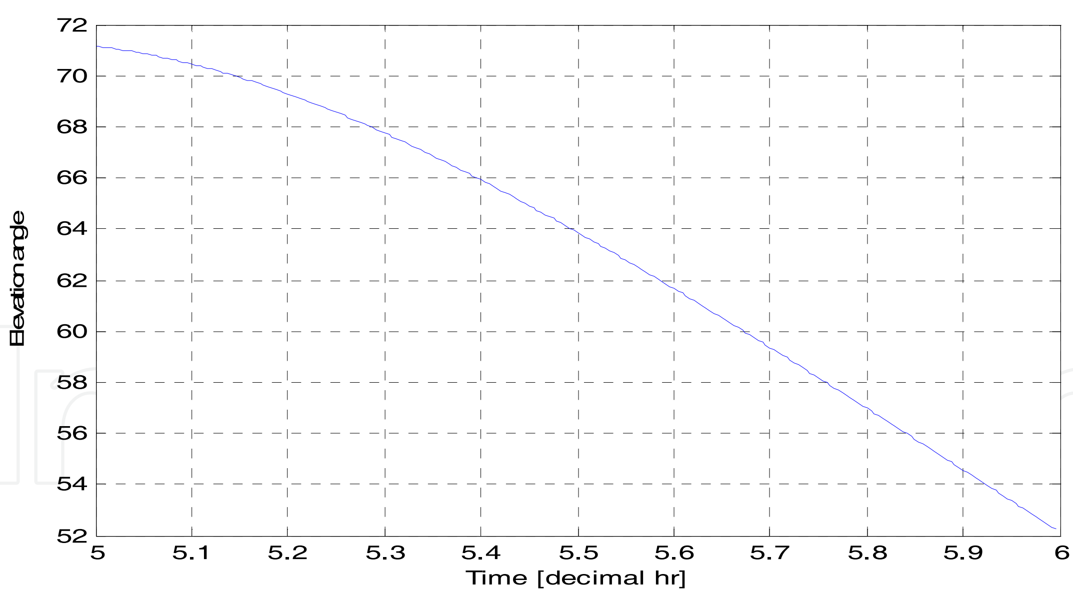
Fig. 6. MASS stations in Malaysia
Source: JUPEM 2009

### 3.1 TEC Dual- frequency using levelling process

Figure 7 to 11 show representative cases of the different situations found in the analysis. The absolute slant TEC from the KTPK station and UTMJ station can be measured directly from this dual frequency method. This can be calculated by using pseudorange and carrier phase measurements from the satellites (e.g. PRN 23) used in this study. Figure 7 (a and b) shows the elevation angle of GPS satellite PRN 23 at 5:00 – 6:00 (UT) for KTPK Station and 5:00 - 6:00 (UT) for UTMJ station. The elevation angle can be calculated from the GPS navigation data (or ephemeris). The elevation angle for KTPK and UTMJ station can be illustrated as below:



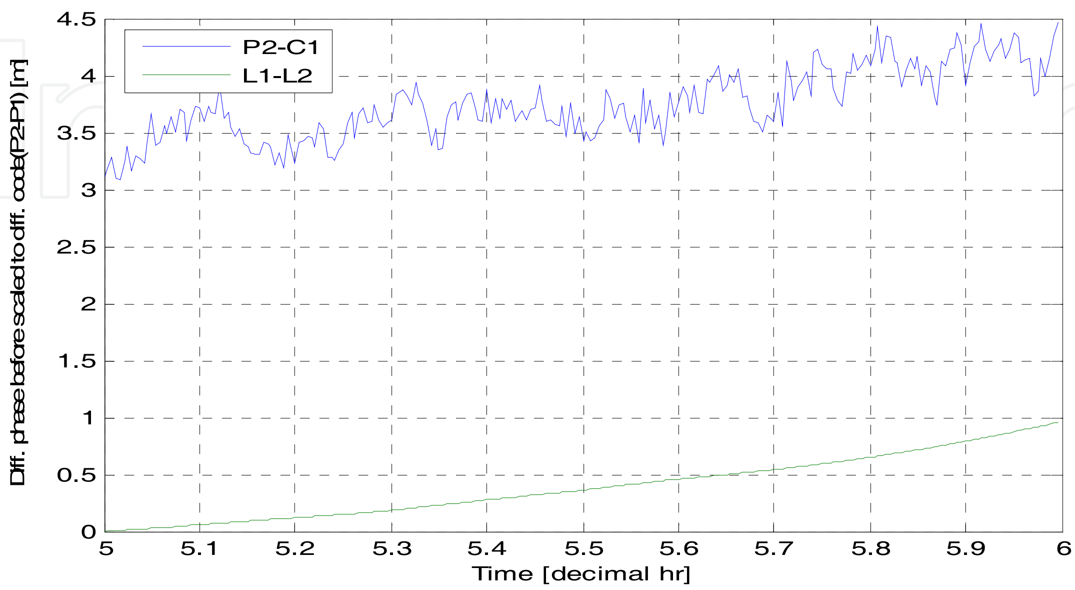

(a)



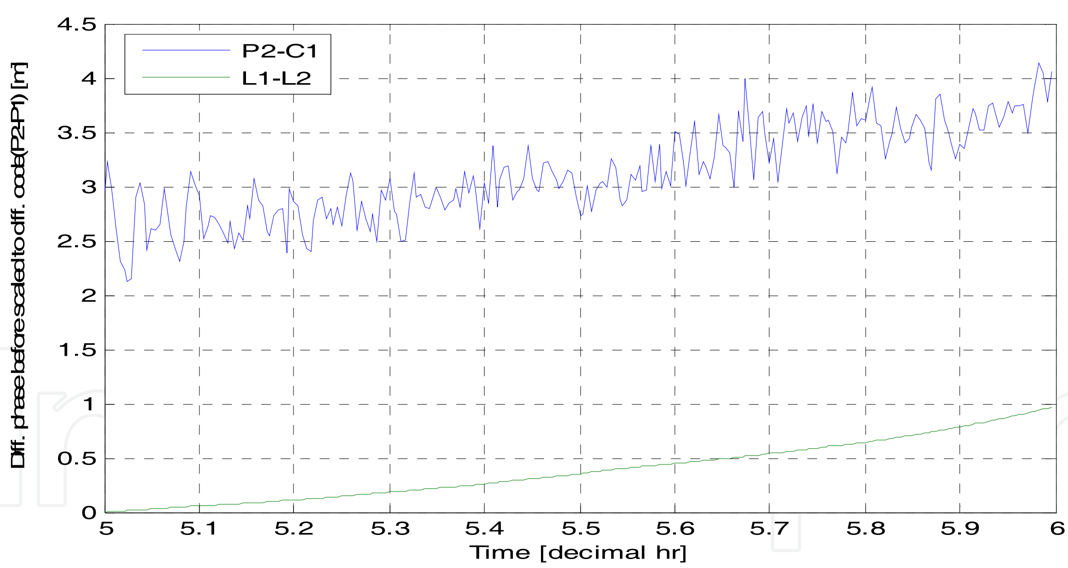

(b)

Fig. 7. (a) Elevation angle of GPS Satellite PRN 23, 5:00-6:00 (UT) (KTPK station)
(b) Elevation angle of GPS Satellite PRN 23, 5:00-6:00 (UT) (UTMJ station)

Figure 8 (a and b) clearly indicate the code TEC and phase TEC of PRN 23 for elevation from 74˚ to 51˚ and 71˚ to 52˚. The differential delay (=P2-C1) from code measurements is noisy and influenced by multipath while the phase measurements, are ambiguous and less effected by the multipath, were used to smooth the code differential delay. Then the vertical TEC can be obtained. This eliminates the integer ambiguity provided there are no cycle slips.

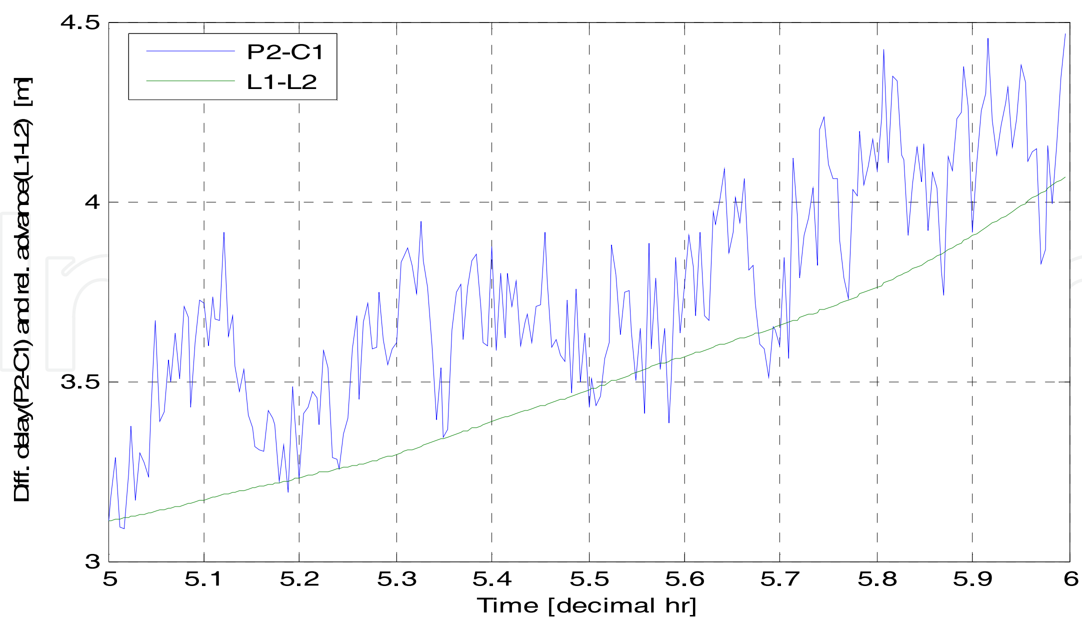



(a)

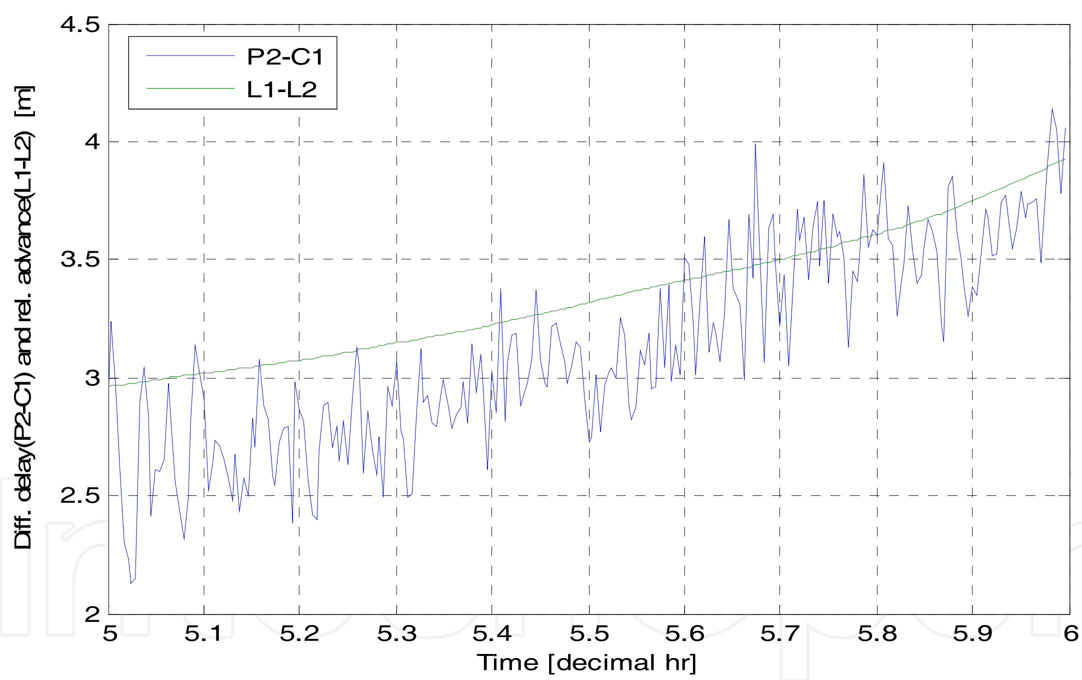



(b)

Fig. 8. (a) Different phase (L1-L2) before scale to different code (P2-C1) for GPS Satellite PRN 23, 5:00-6:00 (UT) (KTPK station)
(b) Different phase (L1-L2) before scale to different code (P2-C1) for GPS Satellite PRN 23, 5:00-6:00 (UT) (UTMJ station)



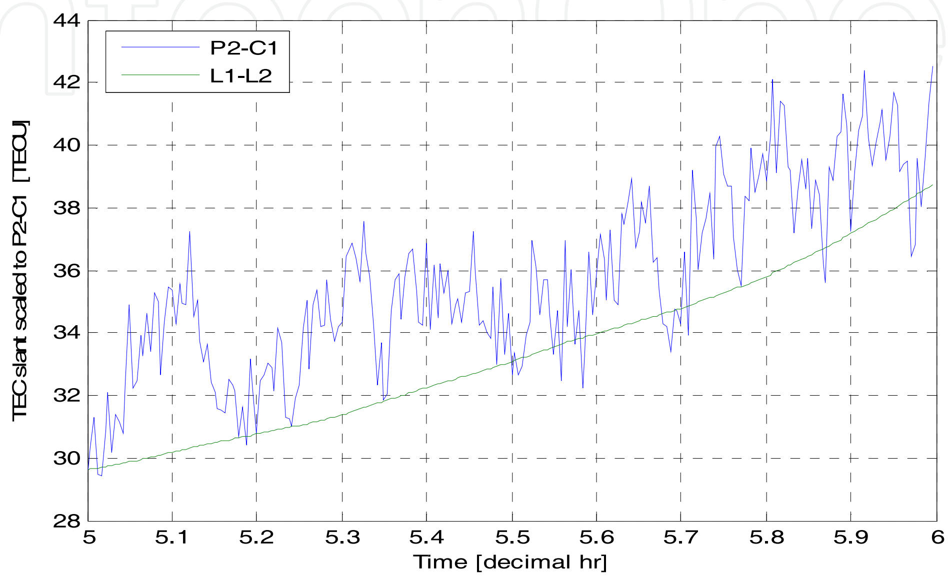

(a)



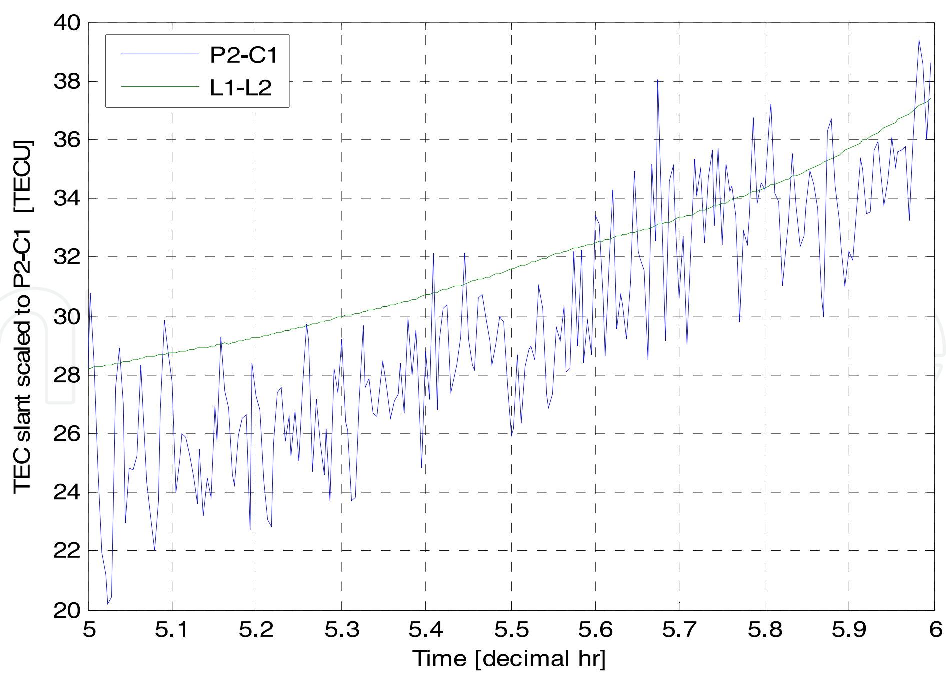

(b)

Fig. 9. (a) Relative range error computed from the differential carrier phase advance for GPS Satellite PRN 23, 5:00-6:00 UT (KTPK station)
(b) Relative range error computed from the differential carrier phase advance for GPS Satellite PRN 23, 5:00-6:00 UT (UTMJ station)

Shown in figure 9 (a and b) are the absolute ionospheric range error obtained from differential group delay. At this stage, levelling process was applied to eliminate the code multipath effect especially at low elevation angles. This was done by defining a shift value and adding it to the relative phase to fit the code differential delay. For the levelling process, it assumed the average at the elevation angle (± 60°-90°) as reference and it can be seen in figure 7. This value was chosen because there is no multipath at the high elevation angle and during low elevation angle multipath where it can still be seen. After the differential carrier phase was converted to an absolute scale by fitting it to the differential group delay curve over the desirable, low multipath portion of each pass, the differential group delay data were simply discarded.



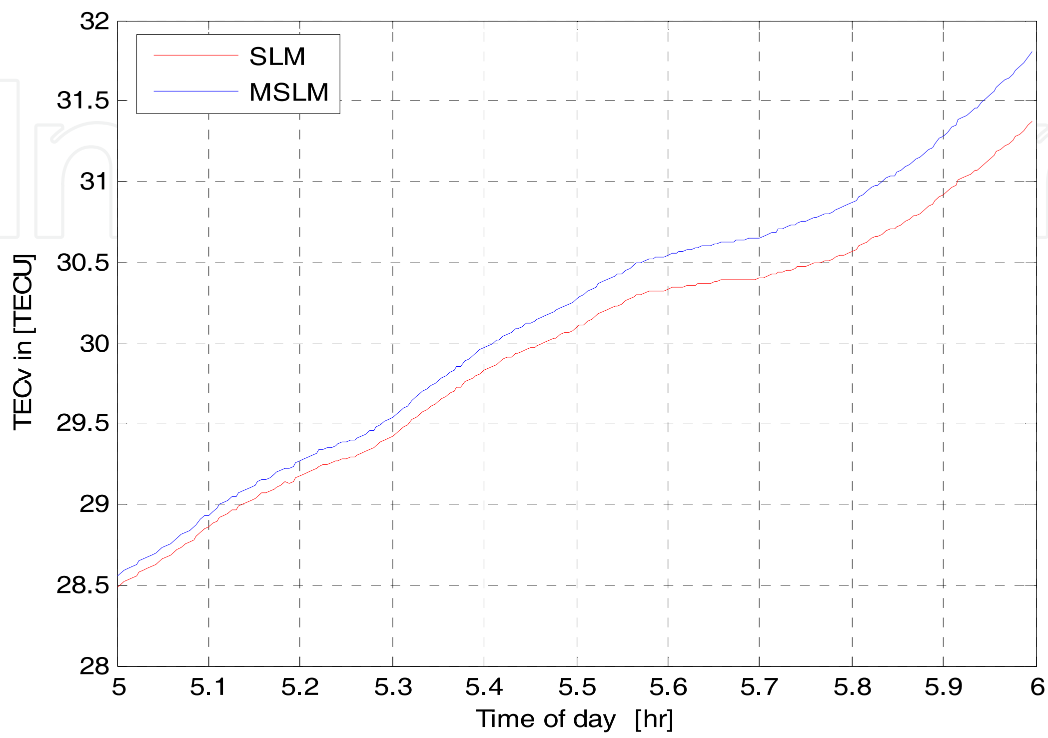

(a)



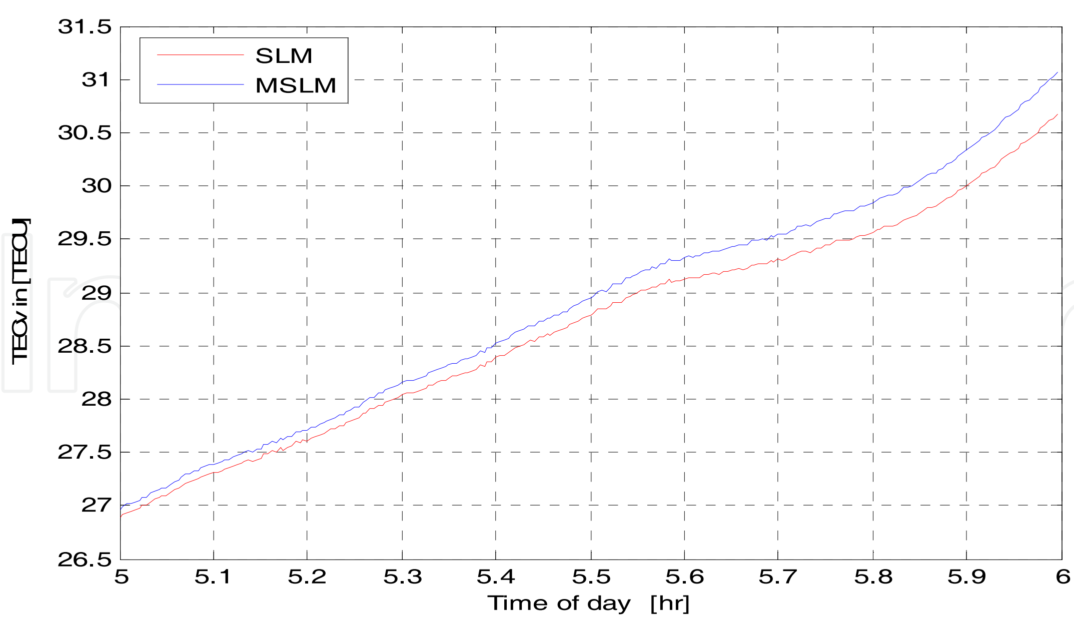

(b)

Fig. 10. (a) TEC slant scale to (P2- C1) TECU for PRN 23, 5:00-6:00 UT (KTPK station)
(b) TEC slant scale to (P2- C1) TECU for PRN 23, 5:00-6:00 UT (UTMJ station)

This smoothed differential delay (with less noise and multipath) was then translated to the absolute slant TEC by multiplying it by a constant Eq. (7) as shown in figure 10 while figure 11 shows TEC vertical for GPS satellite PRN 23 for KTPK and PRN 23 for UTMJ station.




(a)




(b)

Fig. 11. (a) TEC SLM, TEC M-SLM, GPS Satellite PRN 23, 5:00-6:00 UT (KTPK station)
(b) TEC SLM, TEC M-SLM, GPS Satellite PRN 23, 5:00-6:00 UT (UTMJ station)

Figure 11 shows that SLM was used to convert the slant TEC to vertical TEC. The analysis at an equatorial region used SLM mapping function. The peak altitude ranges from 350 to 500 km at equatorial latitudes. However, from the figure it also shows that the MSLM which is TEC for SLM is small compared to MSLM. The vertical 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.

### 3.2 TEC Map

TEC Map is computed with the BGS software using the PPP program and the output is in standard IONEX format. A MSLM was used for mapping the TEC, approximated by a spherical layer with infinitesimal thickness assuming that all free electrons are concentrated in altitude, *H*, above the spherical Earth. The altitude *H* of this idealized layer is set to 450 km. Based on this model, TEC values were calculated in geographic reference system which was able to produce the epoch-specific instantaneous regional maps of the ionosphere.

Using MSLM noted above, a vertical TEC can be obtained at IPP. It can be shown that a single GPS receiver can probe the ionosphere in a radius of 960 km assuming 10° elevation cut-off angle and 450 km height. In order to suit the geographic location to all observational epochs, region located between 0° to 7° north of geographic latitude and 90° to 110° longitude was selected. This map covers a 24 hour time period at intervals of 2 hours starting from 00.00.00 hour.

Figure 12 illustrates the longitudinal vertical TEC map for KTPK station on 8 November 2005 produced with PPP technique with two-hour intervals between each map, starting from 00:00 to 22:00 UT where local time (LT) is +8. Based on figure 12, TEC starts increasing at 00:00 UT at about 7 TECU and gradually increased reaching a maximum level of 28 TECU at 06:00 UT (14:00 LT) then decreased steadily until nearly 20:00 UT before sunrise and rate of ion production is low. It showed that the maximum value of TECU usually happens near midday while the minimum value of TECU occurs at night. The low TEC over equatorial region is mostly due to the Kp and Dst index.

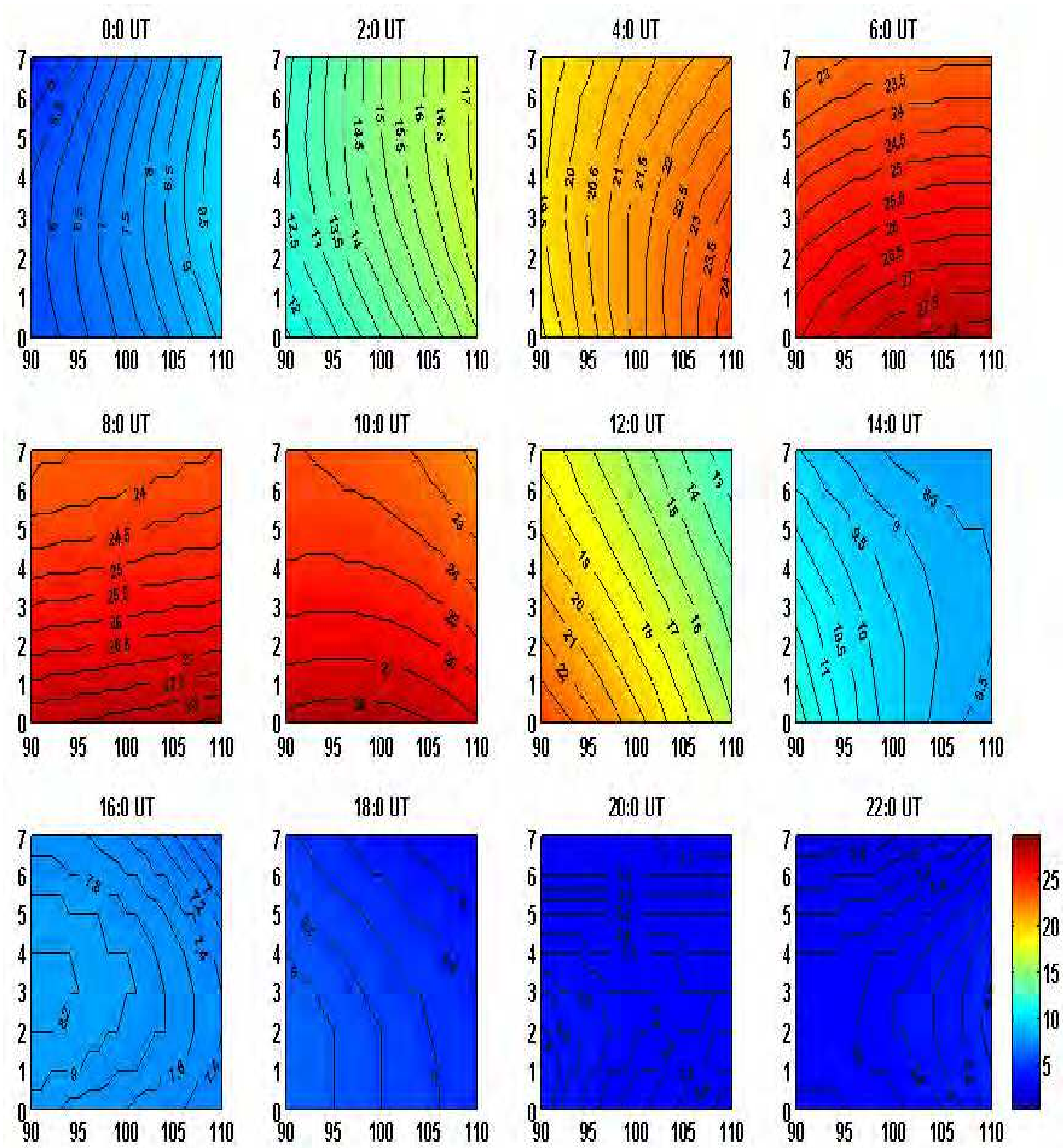



Fig. 12. TEC Map for KTPK station, 8 November 2005

A comparison was made with Global Ionosphere Maps (GIM) downloaded from Centre for Orbit Determination in Europe (CODE) as shown in figure 13. GIM from CODE was generated using data from about 150 GPS receivers around the globe. GIM used 5.0º and 2.5º in longitude and latitude of special resolution with two-hour intervals. For the comparison purpose, an area covering regional model was extracted from IGS maps. Both figures show the same pattern of longitudinal variation of TEC starting from 00:00 UT to 22:00 UT. It is noticeable however, that TEC from GIM is higher by about 0 to 5 TECU, as compared with the maps generated by PPP.

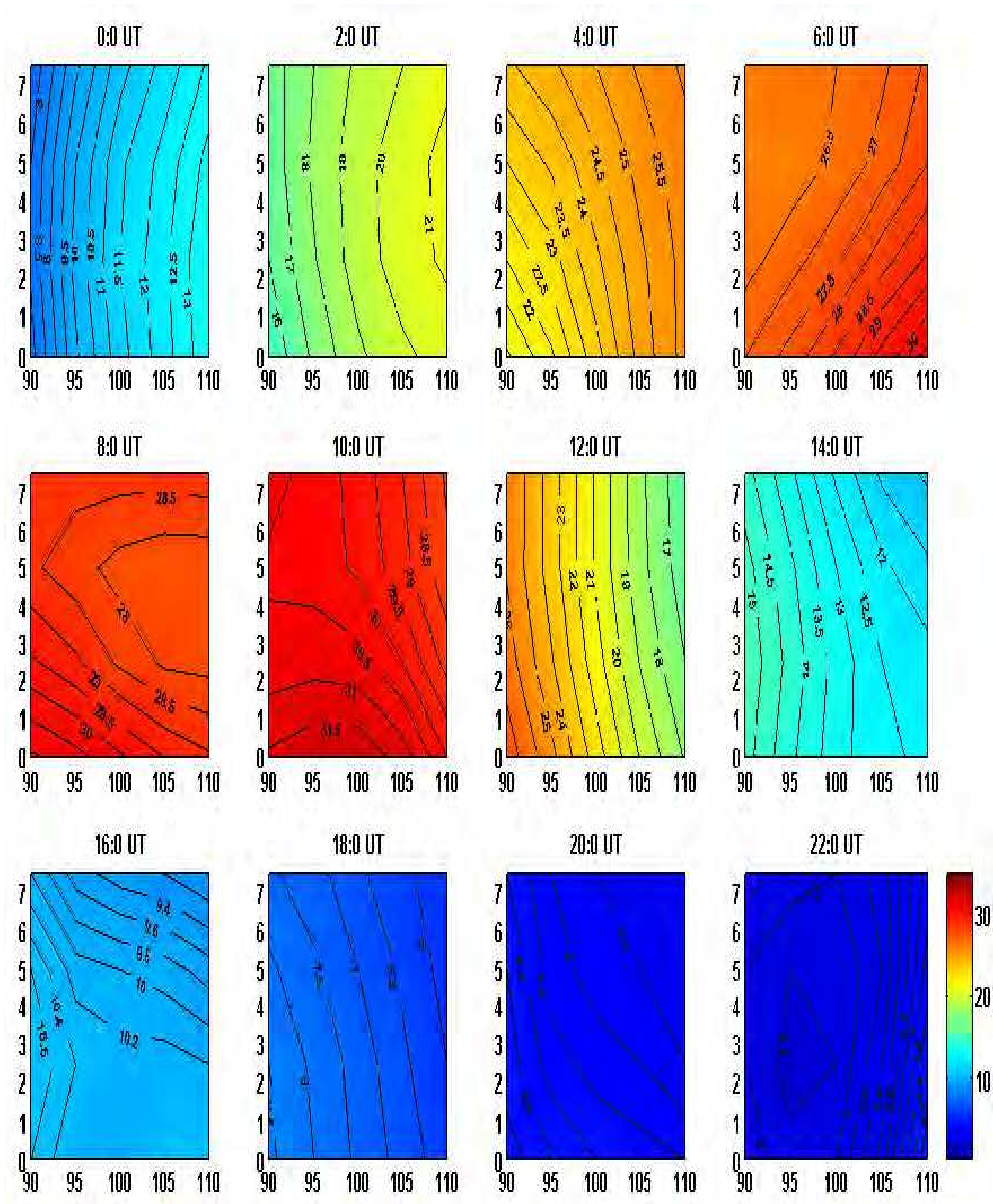



Fig. 13. TEC map from IGS, 8 November 2005

This data was 12 plotted as a 24 hour contour map as a function of longitude as illustrated in figure 12. The TEC above the reference station was extracted from interpolation of this data at every epoch (30s interval) as illustrated in figure 14.

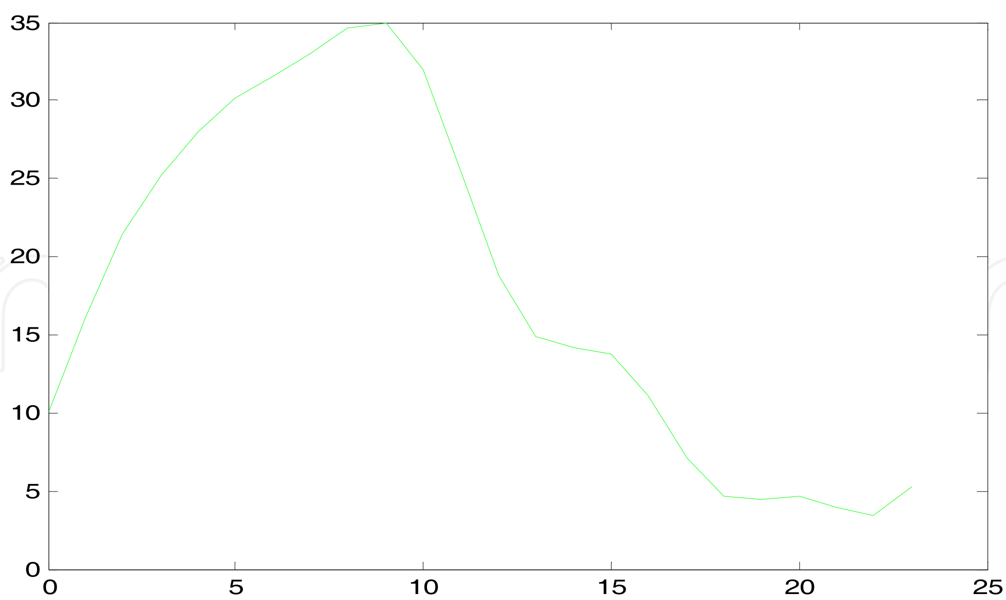



Fig. 14. TEC extracted from TEC map

The difference between the two maximum TEC is because there was no IGS station located in Malaysia. The diurnal profile of ionospheric variation from both figure showed a good agreement. This proved that PPP technique can be used to generate TEC map over single receiver station. Figure 15 clearly indicates the 3-D maps based on IONEX data. The IONEX data have been generated from the BGS software with PPP program. The effective height obtained for 450 km (MSLM) for KTPK station with TEC is 34 TECU.

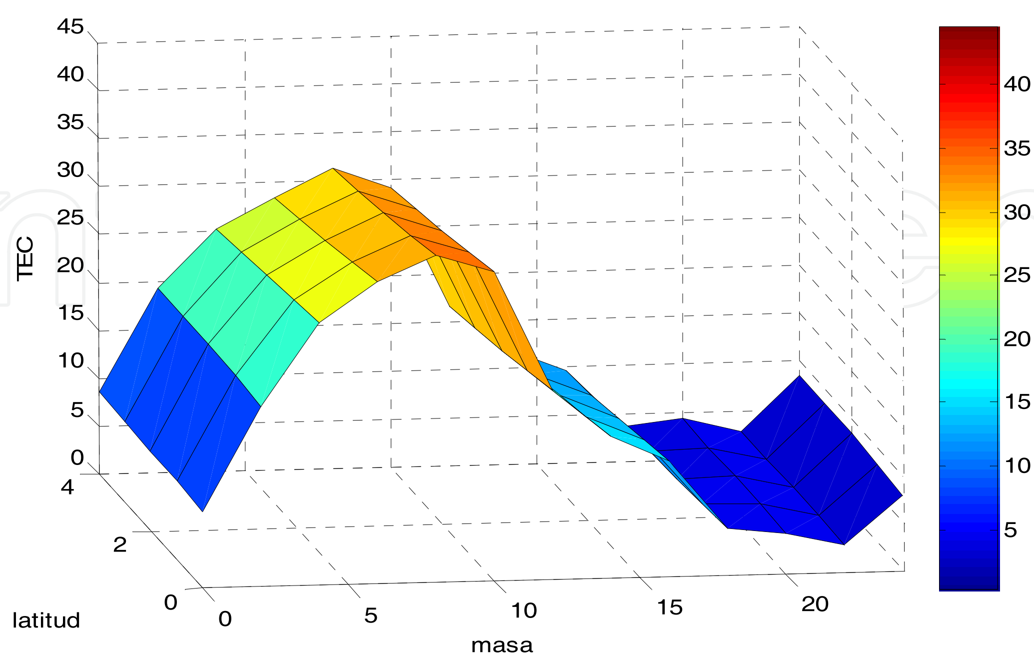



Fig. 15. 3-D MSLM for KTPK station

## 4. Future Work

The research has also identified several possibilities of GPS methodology including accuracy issues and further improvement on TEC that can be incorporated in future research. The following issues and directions have been noted:

i). In this work, only two signal involve which is L1 and L2 to investigate ionospheric TEC. Further, it would be necessary to include new improved signal, which is L5 for more precise and accurate.

ii). Utilize data taken from other satellite navigation systems such as GLONASS, Galileo, etc

iii). More detailed work for different ionospheric condition needs to be verified and compared for other region such as high latitude, Antartic and Artic.

Implementing this suggested further work would extend the TEC measurements at any location with any ionospheric conditions. The outcome gives a different approach that could be considered also for current or future GNSS augmentation systems to overcome the ionospheric error.

## 5. Conclusion

In this chapter we have presented methods for processing TEC which utilize different techniques. Two scenario of obtaining TEC were studied such as TEC dual frequency and TEC Map. First, for TEC Dual Frequency, 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 mitigate inherent fluctuations in pseudorange due to bandwidth limited precision, receiver noise, cycle slip, multipath etc, Levelling Process was applied to reduce carrier-phase ambiguities from the data. As a result, the remaining noise is discarded.

Mean while for TEC Map, analysis results showed that TEC have similar variations, where the TEC values start to increase gradually from morning and reach its maximum at noon and decrease around afternoon. Bernese software, the scientific GPS software packages has already proved its ability to determine an accurate regional TEC map. The PPP technique can be used to generate the TEC map. TEC map are needed in order to characterize the ionospheric behaviour. The result proved that PPP technique can be performed at cm- level. Besides, extraction of TEC information can also be done.

Considering the variability of the ionosphere in the equatorial region, it is recommended to analyze other mapping functions to project the line-of-sight ionosphere delay into the vertical used in the proposed approach.

## 6. References

Abdullah, M.; Strangeways, H.J. & Walsh, D.M.A. (2009). Improving ambiguity resolution rate with an accurate ionospheric differential correction. *Journal of Navigation, Vol.* 62, No. 1, pp. 151-166, ISSN: 0373-4633.

Abdullah, M.; Bahari S.A. & Yatim, B. (2008). TEC determination over single GPS receiver station using PPP technique, *International Symposium on GPS/GNSS 2008*, November 11-14, 2008 Tokyo

Bradford, W.P. & Spilker, J.J.J. (1996). Global Positioning System: Theory and applications, *American Institute of Aeronautics and Astronautics*, Vol. I and II Washington DC, USA.

Doherty, P.H.; Dehel, T.; Klobuchar, J.A.; Delay, S.H.; Datta-Barua, S.; de Paula E.R. & Rodrigues, F.S. (2002). Ionospheric effects on low-latitude space based augmentation systems, *Proceedings of ION GPS 2002*, September 24-27, 2002, Portland, pp. 1321-1329, Oregon.

Dach, R.; Hugentobler, U.; Fridez, P. & Meindl, M. (2007). *Manual of Bernese GPS Software Version 5.0*, Astronomical Institute, University of Bern.

Hansen, A.; Blanch, J. & Walter, T. et al. (2000). Ionospheric correction analysis for WAAS quiet and stormy. *ION GPS*, Salt Lake City, Utah, September 19-22, 2000, pp 634-642, America.

Horvath. I & Essex. E.A. (2000). Using observations from the GPS and TOPEX satellites to investigate night-time TEC enhancement at mid-latitudes in the southern hemisphere during a low sunspot number period, *Journal of Atmospheric and solar Terissterial-Physics*, Vol .62, No.5, pp. 371-391.

Ho, Y.H.; Zain, A.F.M. & Abdullah, M. (2002). Hourly variations total electron content, TEC, for quiet ionosphere over Malaysia. *Proceeding of the Annual Workshop National Science Fellowship (NSF) 2001*, Petaling Jaya, pp. 77-79, Kuala Lumpur.

Ioannides, R.T. & Strangeways, H.J. (2000). Ionosphere-induced errors in GPS range finding using MQP modelling, ray-tracing and nelder-mead optimization. *Millennium Conference on Antennas and Propagation*, AP2000, vol. II, Davos, pp. 404–408, Switzerland.

JUPEM. (2009). MASS station. Malaysia [10 January 2009]. http://www.jupem.gov./

Klobuchar, J.A. (1987). Ionospheric time-delay algorithm for single-frequency GPS users, *IEEE Transactions on aerospace and electronic systems*, Vol. 23, No. 3, pp. 325-331.

Komjathy, A. (1997). Global ionospheric total electron content mapping using the Global Positioning System. Ph.D. dissertation. Department of Geodesy and Geomatics Engineering Technical Report No. 188. University of New Brunswick, Fredericton, New Brunswick, Canada. p 248.

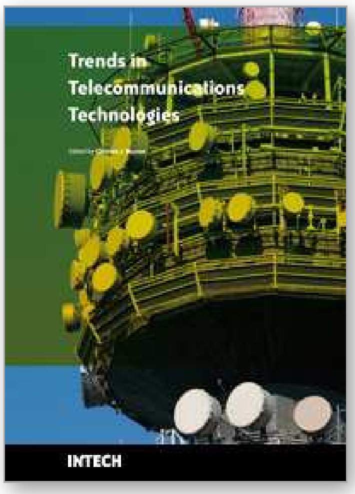
Ong, H. P. & Kamarudin, M.N. (2006). Calculation in Estimating Total Electron Content GPS. Universiti Teknologi Malaysia.

Parkinson, B.W. (1996). *GPS error análysis, in Global Positioning System: theory and application,* Vol. 1, Edited by Parkinson & Spilker, American Institute of Aeronautics and Astronautics, Inc., Washington D.C., pp. 469-483.

Schaer, S.; Markus, R.; Gerhard, B. & Timon, A.S. (1996). Daily Global Ionosphere Maps based on GPS Carrier Phase Data Routinely produced by the CODE Analysis Center, *Proceeding of the IGS Analysis Center Workshop,* Silver Spring, Maryland, pp. 181-192, USA.

Schaer, S.; Gurtner, W. & Feltens, J. (1998). IONEX: The IONosphere map exchange format version 1, *Proceeding of IGS Analysis Center Workshop*, pp. 233-247.

Warnant, R.; Ivan, K.; Marinov, P.; Bavier, M. & Lejeune, S. (2007). Ionospheric and geomagnetic conditions during periods of degraded GPS position accuracy: 2.RTK events during disturbed and quiet geomagnetic conditions, *Advances in Space Research,*Vol. 39, No. 5., pp. 881-888.




**Trends in Telecommunications Technologies**
Edited by Christos J Bouras

ISBN 978-953-307-072-8
Hard cover, 768 pages
**Publisher** InTech
**Published online** 01, March, 2010
**Published in print edition** March, 2010

The main focus of the book is the advances in telecommunications modeling, policy, and technology. In particular, several chapters of the book deal with low-level network layers and present issues in optical communication technology and optical networks, including the deployment of optical hardware devices and the design of optical network architecture. Wireless networking is also covered, with a focus on WiFi and WiMAX technologies. The book also contains chapters that deal with transport issues, and namely protocols and policies for efficient and guaranteed transmission characteristics while transferring demanding data applications such as video. Finally, the book includes chapters that focus on the delivery of applications through common telecommunication channels such as the earth atmosphere. This book is useful for researchers working in the telecommunications field, in order to read a compact gathering of some of the latest efforts in related areas. It is also useful for educators that wish to get an up-to-date glimpse of telecommunications research and present it in an easily understandable and concise way. It is finally suitable for the engineers and other interested people that would benefit from an overview of ideas, experiments, algorithms and techniques that are presented throughout the book.

IntechOpen