Determination of Ionospheric Total Electron Content (TEC): Phase Measurement Based on Levelling Technique

Mohd AmirShaifulRazain Abu Zaini

Faculty of Electrical Engineering,
Universiti Teknologi Mara,
40450 Shah Alam, Selangor Malaysia

Abstract— **GPS has become a great tool for ionospheric studies and research. The accuracy or quality of coordination data of GPS receiver can be increased by determining the source and factor of the disturbances that produce at ionosphere layer. Basically, dual frequency carrier-phase and code-delay Global Positioning System (GPS) observations are combined to obtain ionospheric observables related to the slant TEC (TECs) along the satellite-Receiver line of sight (LoS). The Total Electron Content (TEC) data was taken from receiver station located at Universiti Teknologi Malaysia, Johor, UTMJ station and Wisma Tanah, Kuala Lumpur, KTPK station. A code-delay data produce high noise level compared to carrier-phase data. This research assessing the conversion of code-delay to carrier-phase data ionospheric observable and so-called "Levelling process" which applied to reduce code-delay ambiguities. It was found that the levelled carrier-phase has a low noise level and the remaining noise was discarded.**

Keywords—**Slant TEC (TECs), line of sight (LoS), Global Positioning System (GPS), Total Electron Content (TEC)**

I. Introduction

The Global Positioning System (GPS) technology is widely used in monitoring the ionosphere activities because of a low cost solution. In GPS positioning, ionospheric induced errors could be measured, estimated or eliminated depending upon requirement and the availability of the observables. There are several general methods for correcting the errors in the measurements. GPS positioning can be divided into short or medium baseline and long baseline. The most precise GPS positioning uses carrier phase as a final observable for real time and post-processed positioning and may also utilise code measurements in the algorithm. For example, single frequency receiver L_1 phase measurements alone can be used when the sunspot activity is low and a long period of data can be observed because GPS receivers can allow carrier phase ambiguity resolution for baseline distances up to 60 km. During higher sunspot activity, there can be problems even for short baselines (distances of 10 km) so that single frequency measurements plus an ionospheric model are required to improve results. [11].

The ambiguity (noisy) can be resolved by using levelling technique. However, this depends on the availability of data recorded by the single or dual frequency receivers at suitably spaced stations. For accurate, percise and less noisy results, the carrier phase was primarily used instead of code pseudorange measurements. It contributes valuable information to satellite and space probe navigation, space geodesy, radio astronomy and others [8].

II. Receiver Independent Exchange Format (RINEX)

The "Receiver Independent Exchange Format" RINEX format was first developed by the Astronomical Institute of the University of Berne and has been presented and accepted by the 5th International Geodetic Symposium on Satellite Positioning in Las Cruces, 1989. The RINEX was designed to facilitate the exchange of GPS data produced by receivers of different manufacturers. Most GPS manufacturers offer software to transform their native output format to the RINEX standard. The format consists of six ASCII file types, observation, navigation, meteorological, GLONASS navigation, GEO navigation, and satellite and receiver clock files. Each file type consists of a header section and a data section. The maximum record length for all types is 80 bytes per record [12].

III. Total Electron Content (TEC)

TEC is defined as the total number of electrons present along a path between two points, with units of electrons per square meter, where 10^{16} electrons/m² = 1 TEC unit (TECU). TEC is important in determining the 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 Global Positioning System satellites. TEC is strongly affected by solar activity.

The electron density in the ionosphere varies with geographic latitude, season, solar cycle and time of day. During quiet solar activity, the daytime maximum TEC occurs around noon and past noon local time while the minimum TEC occurrence is post midnight. The differential time delay measurements are used to remove the ambiguity term [11].

GPS satellites transmit electromagnetic waves for positioning on two frequencies: L_1 (1.57542 GHz) and L_2 (1.2276 GHz). The velocity of an electromagnetic wave at the GHz band is frequency dependent in the ionosphere. This enables us to extract the ionospheric TEC along the line of sight, satellite-receiver [11].

A GPS receiver satellite operates on two frequencies f_1 and f_2, where:

$f_1 = 1575.42MHz$
$f_2 = 1227.6MHz$

A. Ionospheric Delay and TEC

The ionosphere has a refractive index at radio frequencies which is different from unity and can affect GPS signals in a number of ways as they pass from satellite to ground [2].

The addition of ionospheric delay to GPS signals is one such effect that producing an external bias source to pseudorange and carrier phase observations which is difficult to correct in single frequency receivers. However, dual frequencies 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, at least to a first order.

The ionospheric time delay at the L1 carrier frequency f1 is given by [1]

$$t_1 = \frac{40.3}{cf_1^{\,2}}(TEC) \qquad (1)$$

where c is the speed of light in free space. A dual frequency receiver measures the difference in delay between the two frequencies, $\Delta t = t_2 - t_1$, given by

$$\Delta t = \frac{40.3}{c}(TEC)\left[\frac{1}{f_2^{\,2}} - \frac{1}{f_1^{\,2}}\right] \qquad (2)$$

where f_1 (1575.42 MHz) is the frequency of the L_1 wave and f_2 (1227.6 MHz) is the second frequency of the L_2 wave. Delay t_1 can be rewritten in the form

$$t_1 = \Delta t\left(\frac{f_2^{\,2}}{f_1^{\,2} - f_2^{\,2}}\right) \qquad (3)$$

where the delay t_1 can be regarded as the measured pseudorange at the L1 frequency.

B. Calculation of Slant and Vertical TEC

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) as the quantity *Ts*. Vertical TEC, Tv enables TEC to be mapped across the surface of the earth [3].

The receiver (known as a 'codeless' receiver because it does not require knowledge of the C/A or P pseudorandom noise codes), by cross correlating the L1 and L2 modulated carrier signals, obtains the time delay of the P code and the carrier phase difference. These are used to calculate the pseudorange and differential carrier phase respectively, and hence the slant code TEC and slant phase TEC respectively [3].

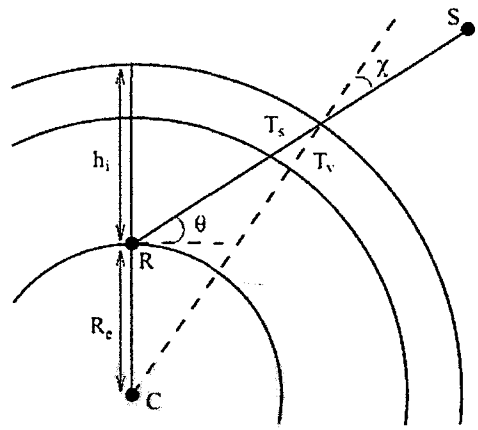

Fig.1. Geometry of Satellite-Receiver Link [3]

The absolute TEC, from equation (4) can be calculated using GPS signal [3].

$$TECs = \frac{1}{40.3} \times \left(\frac{f_1^{\,2} f_2^{\,2}}{f_1^{\,2} - f_2^{\,2}}\right)\left(\Delta p.c\right) \qquad (4)$$

where $\Delta\rho$ is the difference between time delays measured by the L_1 and L_2, C is the light velocity (m/s), f_1 (1575.42 MHz) is the frequency of the L_1 wave and f_2 (1227.6 MHz) is the second frequency of the L_2 wave.

The slant total electron content, Ts or TECs, along ray path ,*l* between a GPS satellite, Tx, and a ground-based receiver, Rx, can be written as in equation (5) and (6) [10]:

$$TECs = \int_{R_x}^{T_x} N dl = \frac{f^2}{40.3}\int_{R_x}^{T_x} (n^{-1} - 1) dl \qquad (5)$$

$$= \frac{f^2}{40.3}\int_{R_x}^{T_x}\left[\left(\sqrt{\left(1 - \frac{f_N^2}{f^2}\right)}\right)^{-1} - 1\right] dl \qquad (6)$$

where N is the electron density in el/m^3, n denotes the refractive index, and f and f_N represent radio wave and plasma frequency in Hz, respectively. The l-axis stands for the receiver-to-satellite direction.

The Code Different Slant TEC (*TECs*) can also be obtained by writing as in equation (7)

$$TECs = \frac{1}{40.3} \times \left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)(P_2 - P_1) \qquad (7)$$

where (P_2 and P_1) are the pseudoranges different or code delay. The Carrier Phase Different Slant TEC (*TECsPH*) can also be obtained by writing as in equation (8)

$$TECsPH = \frac{1}{40.3} \times \left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)(L_1 - L_2) \qquad (8)$$

where (L_1 and L_2) are the carrier phase different. As the TEC between the satellite and the receiver depends on the satellite elevation angle, this measurement is called Slant TEC (TECs).

The slant TEC (TECs) is then converted to vertical TEC using the obliquity correction factor as define in equation (9) [8][4]

$$TECv = TECs(cos\chi') \qquad (9)$$

where TECs is the value of slant TEC, χ' is the difference between 90° and zenith angle (90°-χ).

In this TEC research, to get more precise mapping, the Modified-Single Layer Model, M-SLM is use as define in equation (10) [4]

$$sin\chi' = \left(\frac{Re}{Re + hm}\right)\sin(a\chi) \qquad (10)$$

where *Re* = Mean earth radius, 6371 km, *hm* = maximum height of electron density, 450 km, a = correction factor, 0.9782, χ = zenith angle and χ' = (90°- χ). Typical value *Re and hm* are set to 6371 and 450km, respectively.

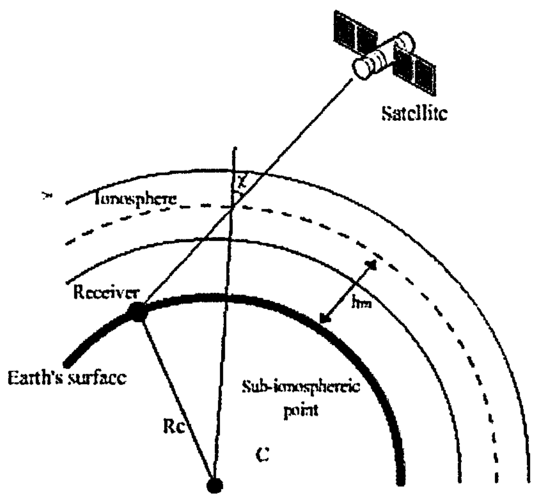

Fig.2. Ionospheric Single Layer Model

IV. Phase Levelling Measurement

A. Shifted Phase Levelling (sLev) & TECs

The shifted value of levelled carrier-phase different (L_1 - L_2) is calculated by adding up the value of carrier phase different with the different value of carrier phase different (L_1-L_2) and code delay different (P_2-P_1 or P_2-C_1). The shifted value can be written as in equation (11):

$$\begin{aligned} Dif &= codedif - phasedif \\ &= (P_2 - P_1) - (L_1 - L_2) \end{aligned} \qquad (11)$$

where *Dif* = different shifted value, *codedif* = code different, *phasedif* = carrier phase different. The shifted phase levelling (s*Lev*) can be obtained in equation (12)

$$\begin{aligned} sLev &= phasedif + Dif \\ &= (L_1 - L_2) + [(P_2 - P_1) - (L_1 - L_2)] \end{aligned} \qquad (12)$$

where s*Lev* = shifted phase levelling, *Dif* = different shifted value, *codedif* = code different, *phasedif* = carrier phase different.

A dual-frequency GPS receiver can measure the difference in ionospheric delays between the f_1 and f_2 of the GPS receiver satellite frequencies, which are generally assumed to travel along the same path through the ionosphere. Thus, the group delay can be define in equation (13)

$$(P_2 - P_1) = 40.3TEC\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) \qquad (13)$$

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.

V. Methodology

The observation and navigation are extracted from RINEX file by using MATLAB programming language. The purpose of this process is to check existing of code different parameter P_1 or C_1. This simulation shows 5 types of graph which are elevation angle, different phase (L_1-L_2) before scaled to different code (P_2-P_1), relative range error computed from the differential carrier phase advance, TECs scaled to (P_2-P_1) and comparison of TECs, SLM TECv and M-SLM TECv.

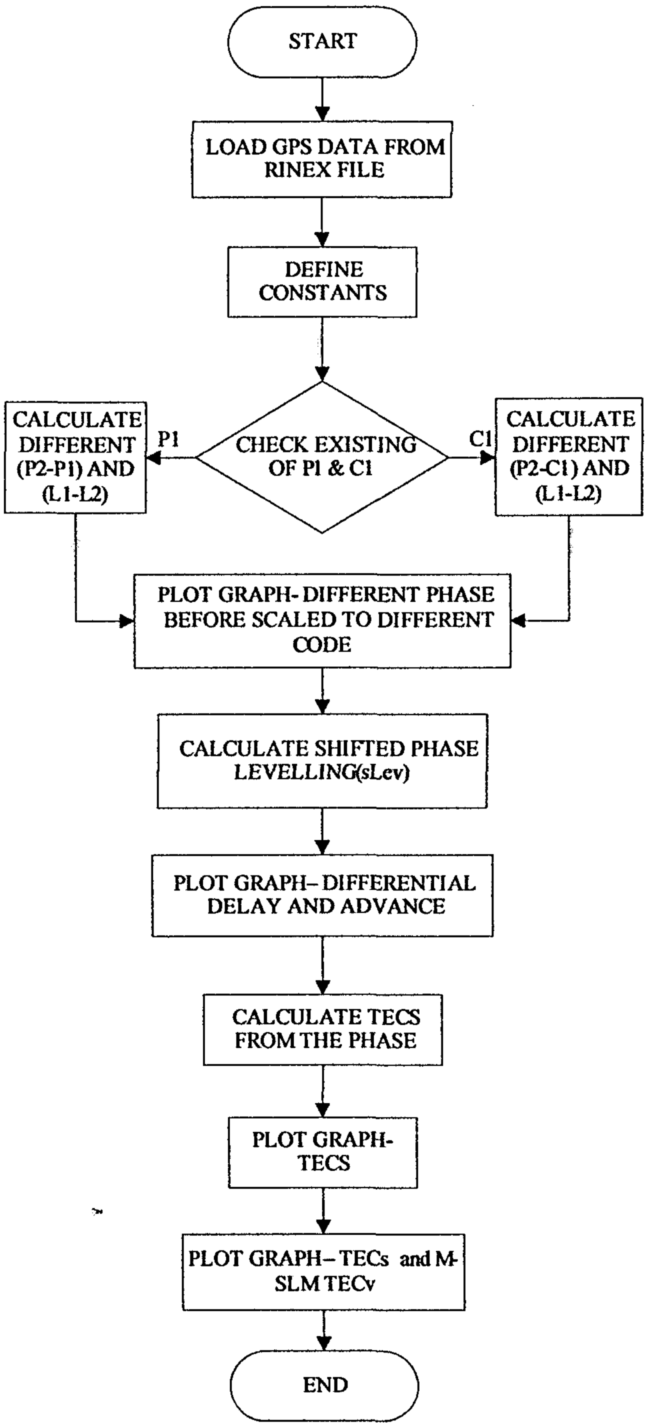

Fig.3. Flowchart process in Matlab simulation.

VI. RESULTS

The scope of this project is to analyze GPS data taken from JUPEM (Department Of Survey and Mapping Malaysia) for TEC measurement. The data taken from receiver station located at Universiti Teknologi Malaysia, Johor, UTMJ station and Wisma Tanah , Kuala Lumpur, KTPK station. The data was analysed for two hours period which is from 01:00 to 03:00 Local Time (LT).

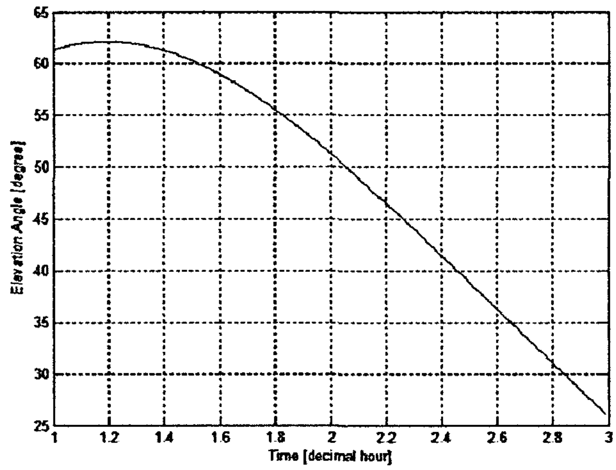

Fig.4(a). Elevation angle of PRN20 for UTMJ station.

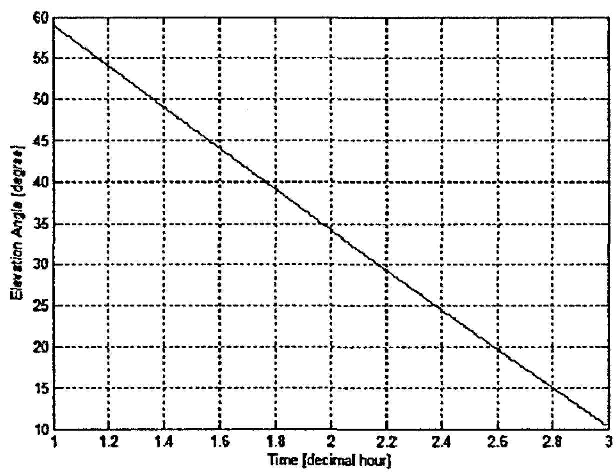

Fig.4(b). Elevation angle of PRN3 for KTPK station.

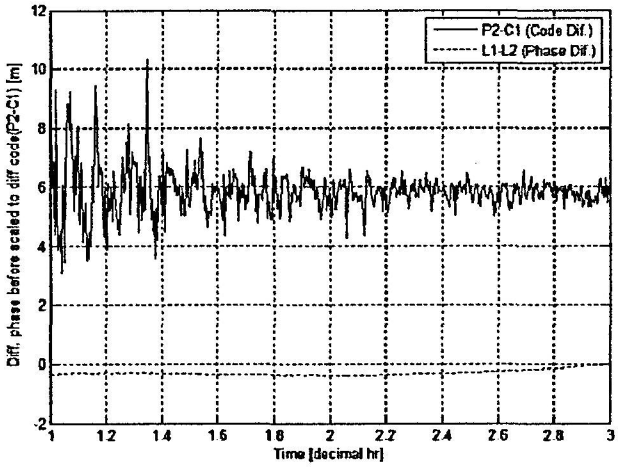

Fig.5(a) Different phase (L_1-L_2) before scaled to different code (P_2-C_1) at UTMJ station.

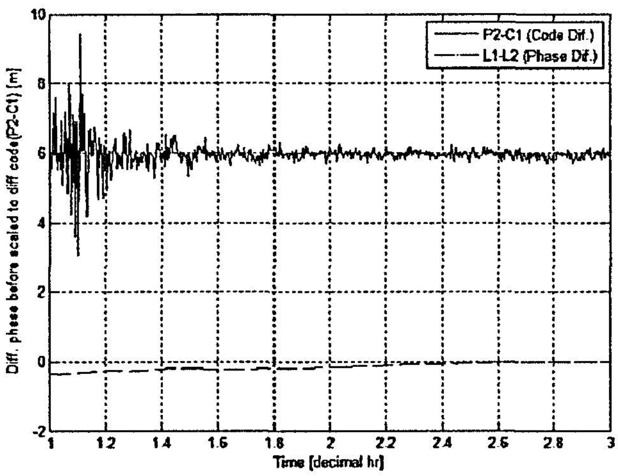

Fig.5(b) Different phase (L_1-L_2) before scaled to different code (P_2-C_1) at KTPK station.

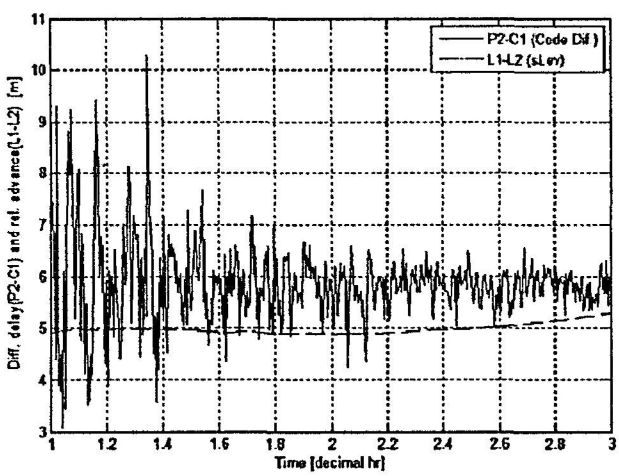

Fig.6(a) Relative range error computed from the differential carrier phase advance at UTMJ station.

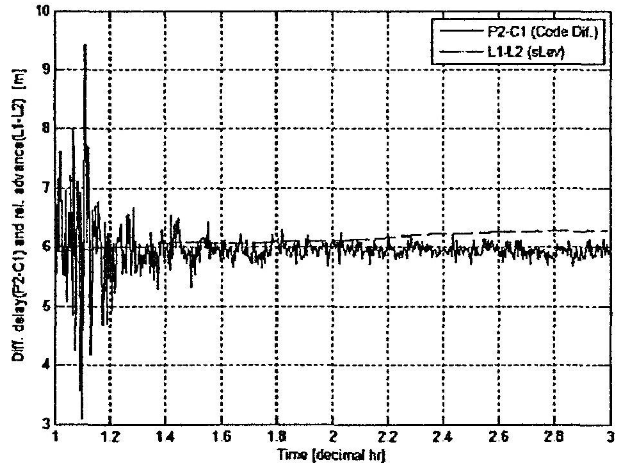

Fig.6(b) Relative range error computed from the differential carrier phase advance at KTPK station.

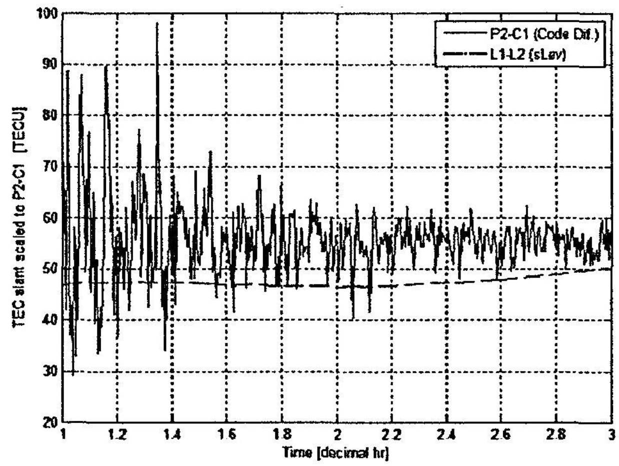

Fig.7(a) TECs scaled to P2-C1 at UTMJ station.

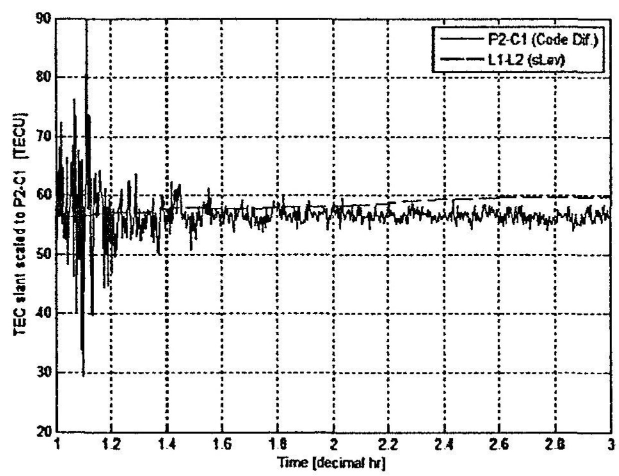

Fig.7(b) TECs scaled to P2-C1 at KTPK station

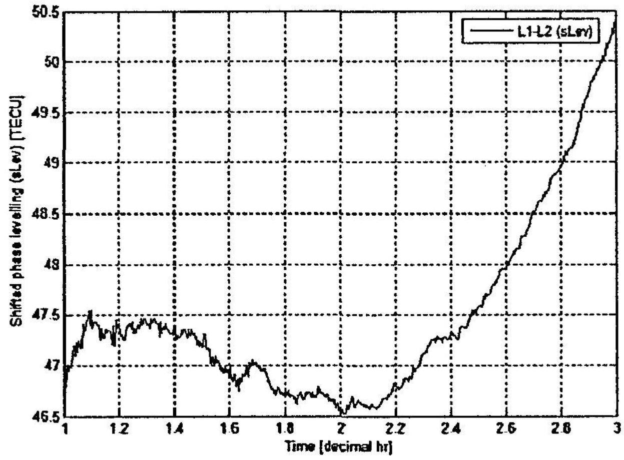

Fig.8(a) Shifted Phase Levelling (sLev) at UTMJ station

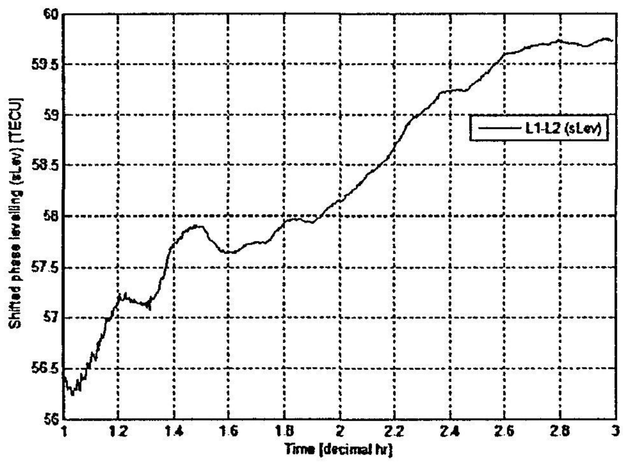

Fig.8(b) *Shifted Phase Levelling (sLev)* at KTPK station.

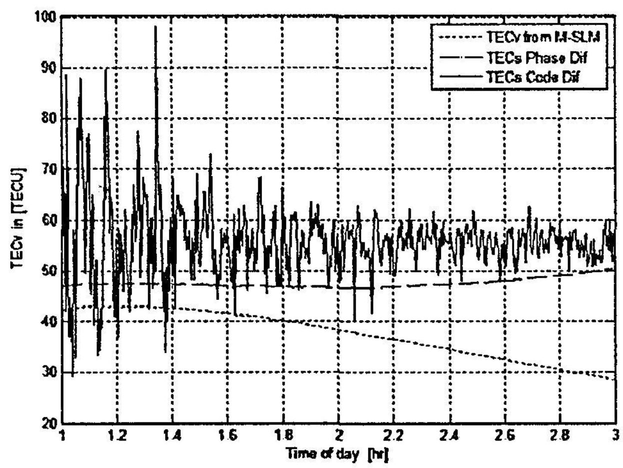

Fig.9(a) Comparison of TECs Code Different, TECs Phase Different and M-SLM TECv at UTMJ station

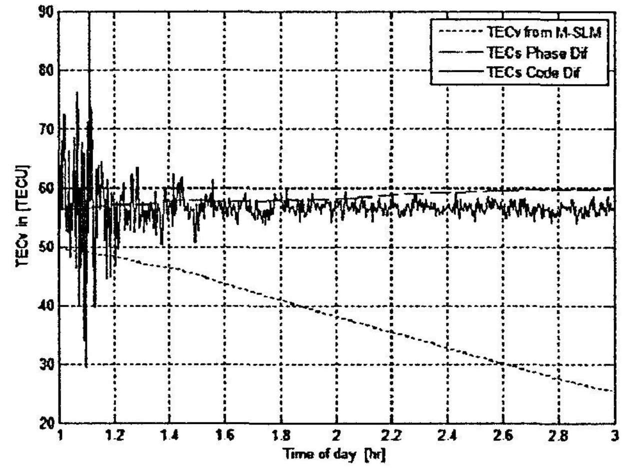

Fig.9(b) Comparison of TECs Code Different, TECs Phase Different and M-SLM TECv at KTPK station

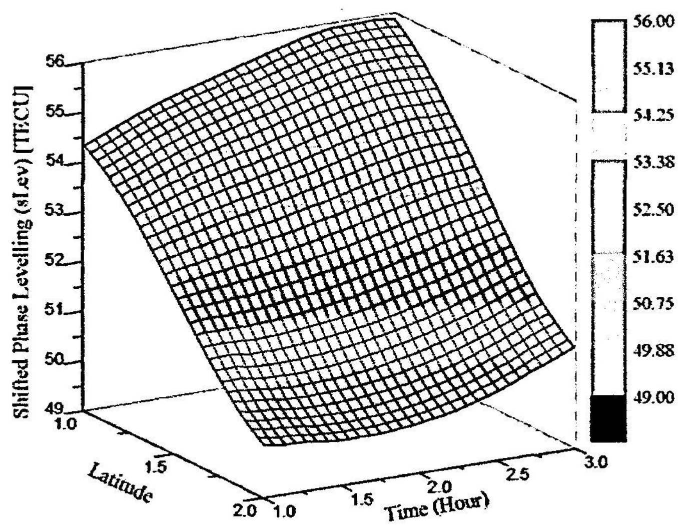

Fig.10 3-D Shifted Phase Levelling (sLev) at KTPK (Latitude=1) and UTMJ (Latitude=2) stations

VII. Discussion

Figure 4(a) and (b) shows the elevation angle of GPS satellite for UTMJ Station and KTPK station. The elevation angle can be calculated from the GPS navigation data from RINEX. The elevation angle for UTMJ station is 25° to 62° and KTPK is 10° to 60°.

The plots in Fig. 5(a) and (b) are different phase before they were scaled to different code (P_2-C_1) in meters. The code different and phase different for two hour observation. The differential delay (P_2-C_1) from code measurements was noisy and influenced by multipath. The phase measurements were ambiguous, so the phase derived slant delay was scaled to zero relative range error at the first epoch. This eliminates the integer ambiguity provided there are no cycle slips.

Shown in Fig. 6(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 [8][9]. This was done by determining the shifted phase levelling (*sLev*) from (Eq.12) to fit the code differential delay. There is no multipath at the high elevation angle.

This phase levelling differential delay (low noise level and multipath) was converted to the absolute slant TEC (TECs) by multiplying it by a constant (Eq. 7 and 8) as shown in Fig. 7(a) and (b). From the Fig. 8(a) and (b), the phase levelling curve can be seen clearly by eliminating the code different observation data (P_2-C_1) from graph. The final result 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[8].

A mapping function, Single Layer Model (SLM), was used to convert TEC to the vertical TEC (TECv) from the slant value. Figure 9(a) and 9(b) shows both of TECs computed from this method.

3-D maps based on the shifted phase levelling (*sLev*) for the both stations shows in the Fig. 10. Latitude=1 represent for KTPK station and latitude=2 stand for UTMJ station.

VIII. CONCLUSION

GPS signals can be used to extract ionospheric parameters such as TEC. From this research assessed the errors translated from the code-delay to the carrier-phase ionospheric observable by the so-called Levelling. This technique applied to reduce ambiguities from the GPS data. The Shifted Phase Levelling (*sLev*) was implemented to eliminate the code multipath effect especially at low elevation angles.

The levelled carried-phase ionospheric observable is affected by systematic errors, produced by code-delay multipath through the levelling procedure whose effects do not cancel after averaging all the data. A dual-frequency GPS receiver can eliminate (to the first order) the ionospheric delay through a linear combination of L1 and L2 observable.

Dual, frequency carrier-phase and code-delay GPS observations are combined to obtain ionospheric observable related to the slant TEC (TECs) along the satellite-receiver line of sight. This results in the absolute differential delay and the remaining noise is discarded.

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.

ACKNOWLEDGMENT

I would like to acknowledge the people who contribute this project : my supervisors, En. Mohamad Huzaimy Jusoh and research assistant, Cik Faizatul Noor Abu Bakar, for their valuable ideas and guidance through this project.

REFERENCES

[1] Kyriaky Eftaxiadis, Dr Manuel A. Cervera, Dr Richard M. Thomas, A Global Positioning System Receiver for MonitoringIonospheric Total Electron Content. Surveillance Systems Division Electronics and Surveillance Research Laboratory, 1999.

[2] Klobuchar, J A, "Ionospheric Effects on GPS", in "Global Positioning System: Theory and Applications, Vol 2", edited by Parkinson, B W and Spilker, J J, Progress in Astronautics and Aeronautics, Vol 164, page 485, 1996

[3] Norsuzila Ya'acob, Mahamod Ismail and Mardina Abdullah , "Investigation of the GPS Signals Ionospheric Correction: Ionospheric TEC Prediction over Equatorial", 2007 IEEE International Conference on Telecommunications and Malaysia International Conference on Communications, Penang, Malaysia

[4] Faizatul Faizatul Noor Abu Bakar, "Determination of Traveling Ionospheric Disturbances of Geomagnetic Storm by using Dual Frequency GPS Data", Faculty of Electrical Engineering, Universiti Teknologi Mara, Shah Alam, Selangor, Malaysia.

[5] Mardina Abdullah, "Modelling and Determination of Ionospheric Effects on Relative GPS Measurements" The University of Leeds, School of Electronic and Electrical Engineering, August 2004.

[6] Total Electron Content, (Mac 2009), available: *http://en.wikipedia.org/wiki/Total_electron_content*

[7] Ionospheric Layers, (Mac 2009), available: *http://en.wikipedia.org/wiki/Ionosphere*

[8] [1]Norsuzila Ya'acob, [1,2]Mahamod Ismail and [1,2]Mardina Abdullah "Leveling Process of Total Electron Content (TEC) Using Malaysian Global Positioning System (GPS) Data", [1]Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia, [2]Institute of Space Science, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

[9] [1]Norsuzila Ya'acob, [1,2]Mahamod Ismail and [1,2]Mardina Abdullah "Determination of GPS Total Electron Content using Single Layer Model (SLM) Ionospheric Mapping Function", [1]Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia, [2]Institute of Space Science, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

[10] Andrzej Krankowski[1], Irina E.Zakharenkova[2], Irk I. Shagimuratov[3], "Response of the ionosphere to the Baltic Sea earthquake of 21 September 2004", [1]Institute of Geodesy, University of Warmia and Mazury ul. Oczapowskiego1, 10-957 Olsztyn, Poland, [2]Immanuel Kant State University of Russia 14, 236041 Kaliningrad, Russia, [3]WD IZMIRAN Prospekt Pabedy 41, 236017 Kaliningrad, Russia

[11] [1]Mardina Abdullah, [2]Hal J. Strangeways, [2]David M. A. Walsh, "Improving Ambiguity Resolution Rate with an Accurate Ionospheric Differential Correction", [1]Universiti Kebangsaan Malaysia, [2]University of Leeds.

[12] Werner Gurtner, "The Receiver Independent Exchange Format Version 3.00, RINEX", Astronomical Institute University of Bern.