Model Validation for GPS Total Electron Content (TEC) using 10th Polynomial Function Technique at an Equatorial Region

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Abstract: - GPS receivers have been profitably employed by researchers for investigations into ionospheric and atmospheric science. However, a number of improvements in measurement accuracy are necessary for today's applications. The ionosphere has practical importance in GPS applications because it influences transionospheric radio wave propagation. Total Electron Content (TEC) is one of the parameters of the ionosphere that produces the most effects in many radio applications such as radio communications, navigation and space weather. Delays in GPS signals affect the accuracy of GPS positioning. The determination of the TEC will aid in reliable space-based navigation system. By modelling this TEC parameter, the evaluation of the ionospheric error and the correction of these ionospheric errors for differential GPS can be done. Determination of the differential ionospheric error to sub-centimetre accuracy is described in this paper utilizing a developed model. An ionospheric delay model was developed to accurately determine the difference in ionospheric delay expected over a short baseline so that a more accurate differential GPS correction could be made. An ionospheric error correction model should be made applicable to any location including the equatorial region. The results showed that the developed algorithm is a function of elevation angle and TEC from the reference station path to the satellite and could give differential ionospheric delay in sub-centimetre accuracy.

Key-Words: - GPS, TEC, ionosphere, baseline, differential GPS, transionospheric

1 Introduction

Small low cost satellites are becoming more and more important in the last few years when the possibility of piggyback launch opportunities [1]. An impressive array of radio access technologies are already in play — from cellular in its various forms, to 3G and HSPA data networks, to short-range connectivity technologies, such as Bluetooth, Zigbee, UWB etc. along with location-position technology GPS, and Wi-Fi [2]. Global Positioning System (GPS) has become increasingly sophisticated and popular, and began to be integrated into the user's mobile terminal units [3]. GPS is space-based radio navigation system operated by the US Air Force for the United States Government [4]. GPS nowadays allows us to measure positions in real time with an accuracy of a few centimetres [5]. In North America and Europe, reference services provide positional accuracy of 1–5 m on the-go [6]. Such a level of accuracy can be reached after the removal or mitigation of different error sources.

As a result, GPS has become one of the important tools to study ionosphere. It provides continuous positioning and timing information, anywhere in the world under any weather conditions. The total signal for each satellite in GPS comprises of two transmission signals: the L1 signal having carrier frequency of 1575.42 MHz and the L2 signal of 1227.60 MHz [7]. The GPS transmit precise microwave signal that can be used to provide information on the location of a signal receiver on the Earth's surface. After travelling through the ionosphere, GPS signal should have arrived precisely at the receiver, and vice versa, so that a more precise time and position result could be measured [8]. The system has the potential to revolutionize the practice of surveying and navigation.

The ionosphere is the portion of the atmosphere in which free electrons exist. It extends from approximately 60 km to 1000 km above the Earth's surface. The most significant factors affecting the ionosphere are the time of day, time of year, solar cycle, and geomagnetic latitude. The ionosphere also has a big impact on GPS reception. Before a GPS satellite signal reaches the ground, it must first pass through ionospheric layer that bend, reflect and attenuate radio waves. The solar cycle may have a significant impact on GPS. The group delay, which is equal in magnitude to the phase advance, is directly proportional to the total electron content and inversely proportional to the frequency squared.

Understanding the ionosphere is important. The free electrons populating this region of the atmosphere affect the propagation of the signals, changing their speed and direction of travel. The ionosphere is the region of the Earth's atmosphere in which ionizing radiation causes electrons to exist in sufficient quantities to affect the propagation of radio waves. Due to the inhomogeneity of the propagation medium in the ionosphere, the GPS signal does not travel along a perfectly straight line.

In order to provide ionospheric corrections for positioning and navigation for single-frequency GPS receivers, the ionosphere needs to be mathematically described by a given ionospheric model. Moreover, precise ionospheric modelling is also important for other space-based observation and space weather studies as well as communication systems. .

Ray tracing is useful in applications where an accurate knowledge of radio wave propagation through the ionosphere is required. The ray-tracing utilizes the Nelder-Mead optimization algorithm to alter the values of the elevation and azimuth that have been passed to the function to minimize these values. The procedure is to determine the exact direction at the transmitter which will result in the ray arriving precisely at the receiver (or vice versa) after refraction due to the ionosphere [9].

Evaluation based modelling techniques can be considered as an alternative to solve such complex problems [10]. Ionospheric models are usually computed by determining the TEC in the direction of all GPS satellites in view from a ground GPS network. Taking advantage of the dispersive property of the ionosphere, the GPS signals operating at two different frequencies can be used to measure the integral ionosphere density, namely TEC. The simple but less accurate method is the Klobuchar model for single frequency where the required parameters are available from the ephemerides data [11].

In Malaysia there are a few corresponding research that have been done on the equatorial ionosphere. Ionospheric research in the equator and tropical areas has sparked interests in several research groups. Ong and Kamarudin (2006) [12] have conducted a research on the TEC distribution estimation with Bent, IRI and Klobuchar modelling by using GPS MASS station network. Zain (2005) [13] has conducted an ionospheric research by using *ionosonde,* which is used to determine the parameter used to detect ionospheric layer in Malaysia. The observation and the analysis conducted by the group give critical frequency normal wave information at the F layer, f_oF2 and also the virtual height whereby the ionospheric reaction also occurs frequently at the layer.

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. An ionospheric error correction model should be made applicable at any location including the equatorial region. To date various ionosphere model based on GPS observations have been proposed [14,15]. A common characteristic of this model is based on Single Layer Mapping (SLM) function. In recent years, a number of techniques and models have been developed to generate 3D representations of the ionosphere by ingesting or assimilating available data [16,17]. Some proposed tomographic models have overcome the limitations of two-dimensional models [18,19]. Abdullah et al. (2008) [20] has also done an analysis of TEC Determination over Single GPS Receiver Station Using PPP Technique. From this analysis, it can be concluded that due to differential delay, determining TEC using dual frequency is better than using PPP.

In this paper, a strategy to determine the total electron content (TEC) and development of ionospheric modelling over the equatorial region using the Malaysian GPS reference data are described. The purpose of this work is to develop an accurate ionospheric model that best suits the equatorial region and that could get differential ionospheric delay in sub-centimetre accuracy.

2 Methodology

In order to get TEC value, GPS data is required. The data is in Receiver Independent Exchange Format (RINEX), which is the standard format used worldwide by most of GPS receiver stations. Therefore, the next progress is continued by requesting data from Malaysia Department of Survey and Mapping (JUPEM). This data was chosen from observation stations as shown in Fig. 1. They are well sited and the noise is small. Some of the receivers use an atomic clock that helps to reduce synchronizing errors with the satellite clock. In addition, this data is archived and has open access. All stations are equipped with dual frequency GPS receivers, which potentially track more than eight satellites continuously.

GPS data on 8 November 2005 from Wisma Tanah, Kuala Lumpur, (3˚ 10' 15.39" N, 101˚ 43' 3.38"E) KTPK as a reference station, and UPM Serdang, (2˚ 59' 36.22 N, 101˚ 43' 24.63" E) UPMS as a mobile station, was collected, processed and analysed as indicated in Table 1. Figure 1 shows the locations of GPS stations analyzed. The baseline length is 20 km. The GPS data was recorded in universal time system, whereby the sampling interval was 15 seconds and the cut-off elevation mask was 10˚. The satellite is identified by its pseudo random noise (PRN) number.

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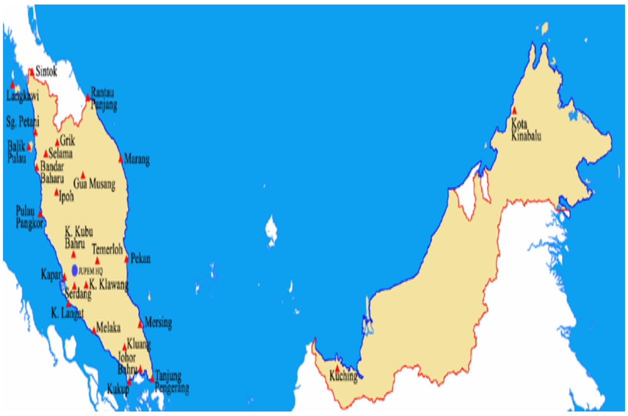

Fig. 1: GPS Reference Stations Map

2.1 Short Distance Ionospheric Model

The Modified Jones 3-D ray tracing is used to investigate the difference in delay between reference and mobile stations which is then used to investigate the ratio with variation of TEC at different elevation angles [21]. The 3-D Jones ray tracing program is a numerical complex that is used to investigate the ionospheric effect for both carrier phase and group delay in transionospheric propagation. The analytical ray tracing program (based on the MQP model) has the disadvantage of horizontal gradients in the electron density and the effect of the geomagnetic field cannot be included in the determination of the ray path characteristics [22].

For the most accurate results, it was found that the ray tracing technique requires an electron density model which is a continuous function, and also has first, second, third and higher order in spatial derivations that are also continuous. Therefore, new model has been proposed. A new model for the ionospheric profile that can be used with a ray tracing program is presented here based on exponential functions as given in Eq. (1) in order to fit the true profile [23].

$$N_e = N_m \exp\left[-\left(\frac{h-h_m}{\sigma}\right)^a\right] \qquad (1)$$

where

Nm : maximum electron density of the exponential layer
h : height above the Earth
h_m : height of Nm
σ : semi-thickness of the layer

2.1.1 Nequick Model

A particular ionospheric condition is inserted into the ray tracing program using a model or a measured electron density profile. The electron density profile model used for this analysis is the International NeQuick. For this research, *eldens*.exe that is an executive Fortran program of NeQuick is used to calculate total electron content (TEC) as shown in Fig.2.

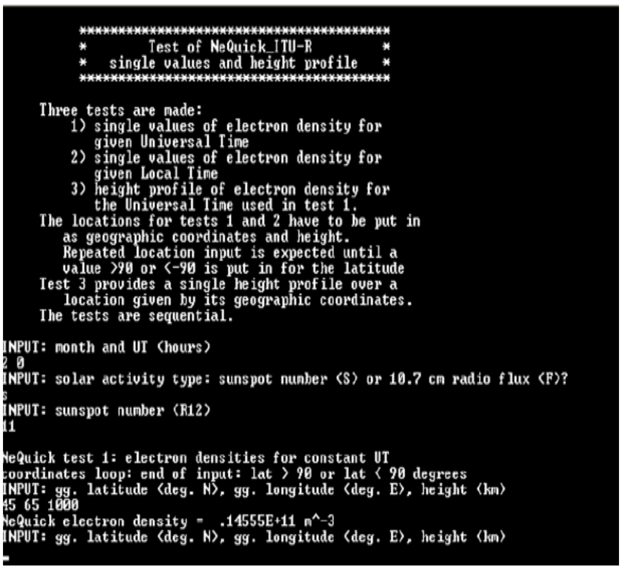

Fig. 2: Input used *Eldens.exe* programme

The ionospheric model used in the ray tracing is determined by fitting realistic ionospheric profiles with a number of exponential layers to arrive at minimum total electron content (TEC) residual as required. The main parameter to be considered in the modelling is the variations of ionospheric delay.

2.1.2 Total Electron Content (TEC)

TEC is defined as the total number of electrons integrated along the path from the receiver to each GPS [24]. It is an indicator of ionospheric variability that is derived from the modified GPS signal through free electrons. It is measured in units of 10^{16} electrons meter per square area, where 10^{16} electrons/m² is equal to 1 TEC unit (TECU).

The nominal range is 10^{16} to 10^{19} with its minimum and maximum occurring at midnight and mid afternoon approximately. At night the TEC decays rather slowly due to recombination of electrons and ions. Maximum TEC occurs in the post local noon and minimum TEC usually occurs just before sunrise.

As GPS signals propagate through the ionosphere, the propagation of the GPS signals are changed in proportion to the varying electron density along the line of sight between the receiver and the satellite. The integrated total electron content (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:

$$f_1 = 154.fo = 1575.42 \text{ MHz} \quad \text{and}$$
$$f_2 = 120.fo = 1227.60 \text{ MHz} \qquad (2)$$

Both code and phase measurements are affected by the dispersive behaviour of the ionosphere, but with different leading signs, which the absolute value of the group delay can be written as:

$$I_{\phi,g} = \int \frac{X}{2} ds = \frac{80.6}{2f^2} \int N_e ds \qquad (3)$$

where

$X = \frac{f_p^2}{f^2}$,

f = the plasma-gyro-, and transmission frequencies in Hz respectively

N_e = number of electron in el. m^{-3}

This delay is characterized by the total electron content where $TEC = \int N_e ds$. Substituting TEC into (3) yields

$$I_{\phi,g} = \frac{40.3}{f^2} TEC[m] \quad \text{or} \quad \Delta t = \frac{40.3}{cf^2} TEC[s] \qquad (4)$$

where

c = velocity of light in vacuum, 2.998 x 10^8 ms^{-1}

These delays can be expressed in units of distance or time delay by dividing the right hand side of Eq. (4) measured in metres by the velocity of light [25].

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 from (4) as:

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

where

P1 and P2 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.

By processing the data from a dual-frequency GPS receiver, it is actually possible to estimate just how many electrons encountered by the signal along its path – the total electron content (TEC). A dual-frequency GPS receiver measures pseudo ranges and carrier phases at L1/L2 and its observables are used to compute TEC. The “phase levelling” technique is used to compute precise phase-derived slant TEC for each tracked satellite at each observation epoch [26]. The GPS observables are biased on the instrumental delays and therefore, it is necessary to remove the differential instrumental biases from receivers and satellites for accurate estimation of the TEC [27].

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. 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 [28].

2.1.3 Development of Ionospheric Delay Model

To obtain the LOS, the receiver and satellite positions should be known, and there are several methods to obtain them. The difference in the delays (Δtd) between the paths can be found from the difference in delays between the reference and mobile stations [29].

$$\Delta td = td_{ref} - td_{mob} \quad (6)$$

The difference in LOS (ΔLOS) can be found from the difference in LOS between the reference and mobile station as shown in Eq. (7). The real time satellite position is sufficient in this application and the precision of LOS is not so crucial compared to other parameters in the model.

$$\Delta LOS = LOS_{ref} - LOS_m \quad (7)$$

where

LOS_{ref} : line of sight at reference station

LOS_m : line of sight at mobile station

The ratio as a function of elevation angles was examined. The relation between Δt_d and the difference in true range (ΔLOS) for a given satellite position and their ratio as:

$$Ratio = \frac{\Delta LOS}{\Delta td} \quad (8)$$

The ratio has been determined for the baseline orientations as a function of elevation angle for a given ionospheric model. It is approximately constant at any elevation angles (at least for elevations less than 60˚) and also independent of the orientation of the baseline and the azimuth angle.

3 Result

GPS data on 8 November 2005 from Wisma Tanah, Kuala Lumpur, KTPK (3˚ 10’ 15.44”N; 101˚ 43’ 03.35”E) as a reference station, and UPM Serdang, UPMS (2˚ 59’ 36.22”N; 101˚ 43’ 24.63”E) as a mobile station, was collected, processed and analysed. The baseline length is 20 km. The GPS data was recorded in universal time system, with the sampling interval of 15 seconds and cut-off elevation mask of 10˚.

3.1 Ionospheric Model

The ionospheric model used in the ray tracing is determined by fitting a number of exponential layers to NeQuick. In this work, the electron density profile, N_e known as NeQuick model was fitted with exponential layers and used as the input to improve the ray tracing program. Figure 3 and 4 show the process of fitting the NeQuick ionospheric profile by 40 exponential layers with 31 TECU. The vertical total electron content for this profile, which is for equatorial, is 31 TECU.

The ratio for 20˚azimuth for the S-N direction was modelled for the range of β up to 60˚ determined from ray tracing by fitting the obtained relationships with 10^{th} polynomial functions, $f(\beta)$ as defined in Eq. (9). The ratio for S-N direction is almost constant with azimuth at lower elevations but slightly dependent on azimuth at high elevations. Differential delay is actually higher at 20˚ at elevations less than 60˚ but so ΔLOS .

Figure 3 shows the basic fitting for ratio using 10^{th} order polynomial function as a function of elevation angle and the fitted ratio can be seen in Fig. 4. This ratio is for the TEC of 31 TECU. The baseline was 10 km length and it used 16 elevation angles.

$$f(\beta) = 8.1 \times 10^2\beta^{10} - 3.7 \times 10^3\beta^9 + 4.5\times 10^3\beta^8 + 2.7\times 10^2 \beta^7 - 4.7\times 10^2\beta^6 - 8.1\times 10^3\beta^5 + 1.4 \times10^4\beta^4 - 3.2 \times 10^4\beta^3 + 5.2\times 10^4\beta^2 + 2\times 10^5\beta + 4.8 \times10^5 \quad (9)$$

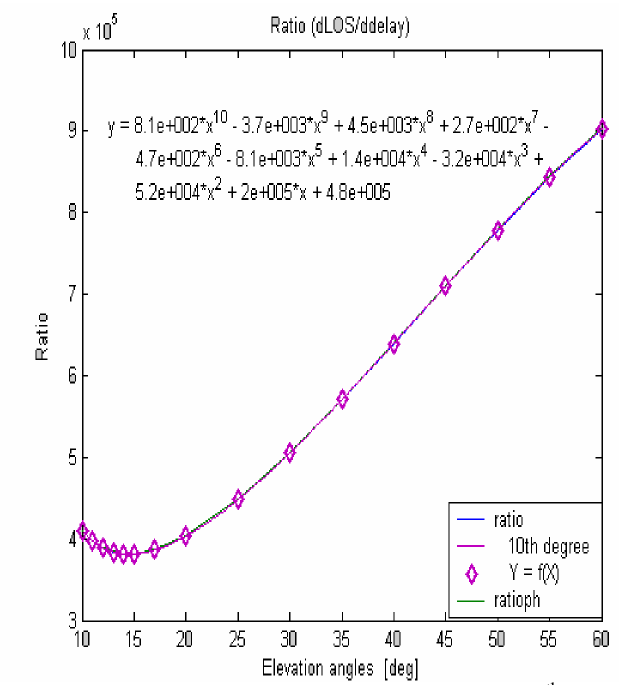

Fig. 3: The basic fitting for ratio using 10^{th} order polynomial function.

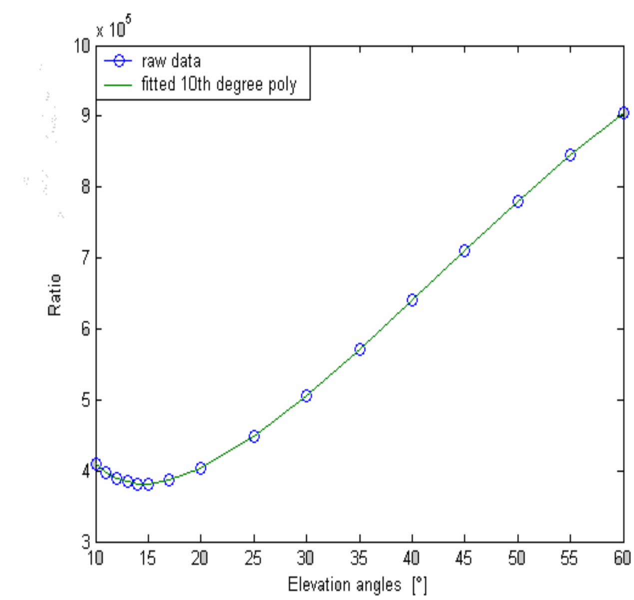

Fig. 4: Fitted ratio (TEC=31TECU)

Figure 3 shows the basic fitting using 10^{th} order polynomial function. From the fitting, the coefficients and norm of residuals can be obtained. For this case, the norm of residuals is 37.345. The ratio is for the TEC 31 TECU. From (8) and (9), the difference in ionospheric delay at the mobile station compared with reference station is given as:

$$\Delta td = \frac{\Delta LOS}{f(\beta)} \quad (10)$$

ΔLOS must be known to determine the difference in delay. The delay at mobile station can be obtained by substituting (6) with (10) provided that the ionospheric delay at reference station is known. This is given as:

$$td, mob = td, ref - \frac{\Delta LOS}{f(\beta)} \quad (11)$$

In addition to the variation in elevation angles, the variation in TEC also affects the difference in delay between the two stations as:

$$f(TEC) = \frac{TEC\ from\ satellite\ to\ receiver\ path}{TEC\ used\ in\ f(\beta)} \quad (12)$$

Ionospheric models are usually computed by determining the TEC in the direction of all GPS satellites in view from a ground GPS network. From this model, there are two main parameters that need to be determined: the difference in LOS and TEC. Apart from these, the ratio as a function of elevation angles was examined. The difference in ionospheric induced error between two stations can be expanded as:

$$\frac{1}{Ratio} = \frac{\Delta t_d(TEC)}{\Delta LOS} = f(TEC)$$

$$\Delta td\left(\beta, TEC\right) = \frac{\Delta LOS}{f(\beta)} f(TEC) \qquad (13)$$

where

TEC : total electron content
ΔLOS : differential in line of sight
β : elevation angle at reference station
Δtd : differential delay, in metre

3.2 Model Validation using Real GPS Data

Real GPS data was used for model validation. Figures 5 to 8 show representative cases of the different situations found in the analysis. The elevation angles for reference station at PRN 23 are 31° to 58° as shown in Fig. 5 as used in this study. A model for computing the effects of the ionosphere was presented. The differential delay model can be seen for 1 hour, which is from 0300 to 0400 (UT) which is 11:00 to 12:00 AM (LT) for GPS satellite PRN 23.

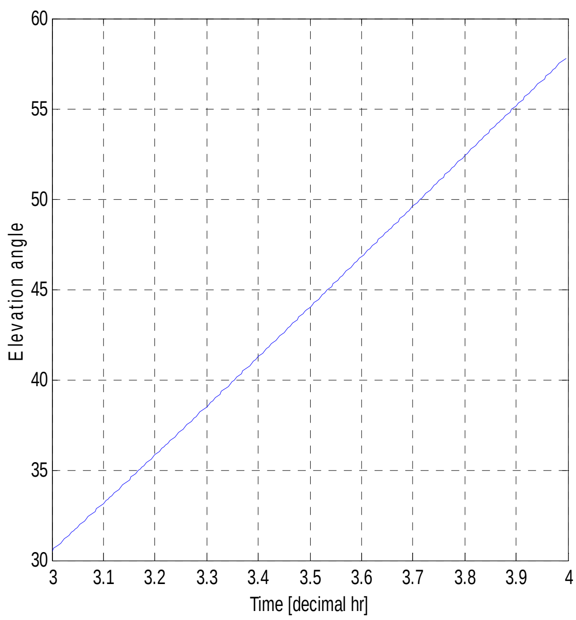

Fig. 5: Elevation angles for PRN23

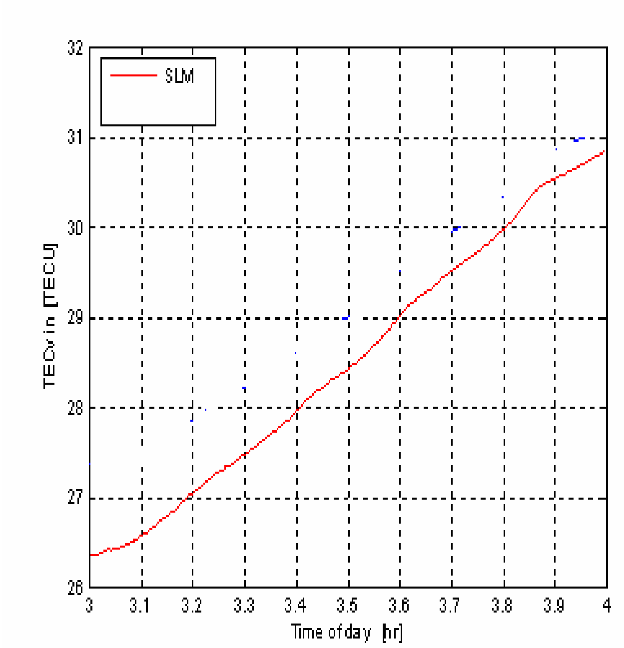

Fig. 6: TEC vertical for PRN 23

Figure 6 shows the TEC vertical for GPS satellite PRN 23. Single Layer Model (SLM) was used to convert the slant TEC to vertical. This analysis at an equatorial region used SLM mapping function. The peak altitude ranges from 350 to 500 km at equatorial latitudes. The final TEC values are precise, accurate and without multipath.

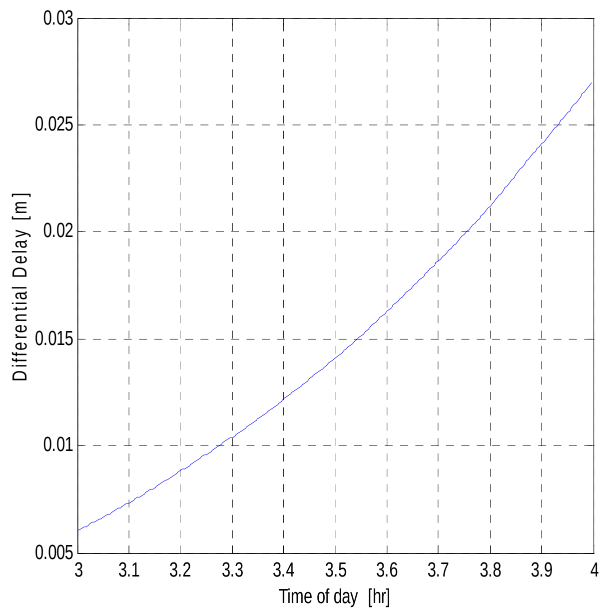

Fig. 7: Differential Delay Model for PRN 23

The differential ionospheric delay (Δt_d) calculated from the model is shown in Fig. 7. The correction model in (13) was used by substituting the above parameters at elevation angles roughly between 10° and up to 90°, that were visible to the satellites for one hour with 15 second intervals. The accuracy was achieved at sub-cm level.

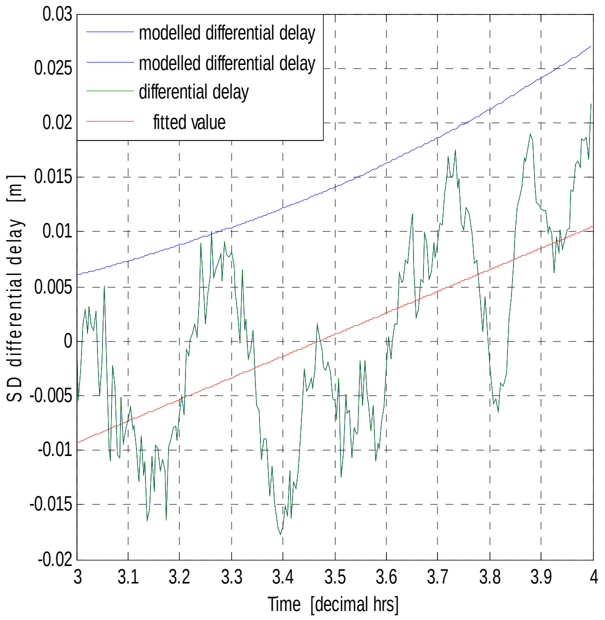

Fig. 8: Differential delay scaled to L_1 of PRN 23

Figure 8 shows the modelled differential delays. The computed values from L_4 residual (scaled to L_1) are shown in the same figure. From Fig. 8, the model and the geometry-free linear combination, L_4 (L_4=L_1-L_2) residual show approximately the same trend which is the differential delay at one hour processing.

4 Conclusion

The work presented here has shown encouraging results based on the utilisation of carrier phase observation for precise positioning. The empirical formulae as a function of elevation angle and TEC have been developed for differential GPS that can be used for any location over equatorial region. Since this model is independent of azimuth, baseline length and orientation, it has the potential to improve the single frequency method over the network solution.

The developed differential ionospheric correction model has been validated and evaluated using real GPS measurements over the equatorial region. From the validated model, it shows that the pattern is the same for both computed values from geometry-free linear combination, L_4 residual and differential delay output. The developed algorithm is a function of elevation angle and TEC from the reference station path to the satellite.

The model is mostly suitable for short baseline and could also be used by single frequency users. From the model we can get differential ionospheric delay in sub-centimetre accuracy.

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