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An Assessment of Mapping Functions for VTEC Estimation using Measurements of Low Latitude Dual Frequency GPS Receiver

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Abstract

Monitoring of ionosphere is very crucial, which can be done by a dual frequency Global Positioning System receiver data. In the present work, slant total electron content is computed using recorded GPS data and then converted to vertical total electron content using single layer model (SLM), modified single layer model (MSLM) and Lear mapping functions to know the ionosphere variations. The collected data is from a dual frequency GPS receiver for an IGS station located at Hyderabad of Latitude:17°24'39"N, Longitude :78°33'4"E, Telangana, India , for a typical day ie on 11/09/2014. The data is then sampled at a sampling rate of 30 seconds over the entire day to estimate the ionospheric parameters like Slant Total Electron Content (STEC) and VTEC. Using the linear free combination algorithm for dual frequency GPS receiver data, STEC is computed. Three Mapping functions are Single Layer Mapping (SLM), Modified Single Layer Model (MSLM) and Lear are used for VTEC computation. SLM and MSLM are both height and elevation angle dependent whereas Lear mapping function is elevation angle dependent only. Computed VTEC is validated using IRI-2012 model. Investigating the effect of elevation angle on VTEC, the statistics and results shows that SLM & MSLM are having nearby results than Lear mapping function with reference to IRI-2012.

Keyword: Mapping function, Ionosphere, Total Electron Content, Slant Total Electron Content
Vertical Total Electron Content, Dual Frequency GPS Receiver.

INTRODUCTION

GPS is a satellite based service initially developed for Defense purposes by the United States of America [1]. GPS has three functional segments namely Space segment, Control segment and User segment. The GPS has become an important tool for monitoring and estimating total electron content of ionosphere. Ionosphere is the layer of the Earth's atmosphere, extending from fifty KM to more than thousand KM in altitude. Ionosphere is a dispersive medium comprising of free electrons and ions which affect the propagation of radio waves. When the GPS signal passes through the ionosphere, it causes the delay in the signal arrival at the GPS receiver, due to the refraction of the signal due to ultra-violet rays and X-Rays .

The arrived GPS signal's ranging equation is:

$$pr = \rho g + c(dosc - dorc) + d_{ion} + d_{tro} + N \qquad \text{.....(1)}$$

Where

'pr': measured pseudo range

'ρ_g' : geometric or true range

'c' : speed of light

'd_{osc} and d_{orc}' : offsets of satellite and receiver clocks

'd_{ion}','d_{tro}' : ionospheric delay and tropospheric delay

'N': effects of multipath and receiver measurement noise

In precise positioning applications, estimation of the ionospheric delay 'd_{ion}' is vital because it causes major error in navigation solution of ≈10 m. The error due to ionospheric delay accounts for more than 99.9% of the total ionospheric delay to the first order approximation, ignoring the second and higher order terms [2].

The first order approximation of ionospheric path delay can be given as

$$d_{ion} = \frac{40.3}{f^2} TEC \qquad \text{.......(2)}$$

The Total electron content (TEC) is defined as the total number of electrons present in a unit cross section area of one square metre along the propagation path of the satellite signal to receiver [3].

TOTAL ELECTRON CONTENT (TEC)

TEC is defined as the numbers of free electrons in a column of unit cross section area or it can be mathematically represented as integral of the electron density along the propagation path of the signal.

$$TEC = \int_P Ne(s)\, ds \qquad \text{........ (3)}$$

Where, Ne(s) is the electron content per unit volume and p is the propagation path between the source and the receiver. TEC is measured in TEC unit's i.e. TECU, which indicates 10^{16}

electrons in an area of one square metre. TEC of 1TECU causes a ranging error of 0.16 m.

In order to compute the STEC, Linear Free Combination Algorithm (LFCA) is used by considering the ranging measurements of a typical dual frequency GNSS receiver. The ranging measurements on L –band frequencies namely L1 and L2 carrier frequencies of GPS receiver can be represented by the given ranging equation Equation.1 By considering the ranging measurements on both frequencies, TEC can be estimated as given in Equation.4

STEC is estimated by:

$$STEC = \frac{1}{40.3}\left[\frac{1}{f_1^{\,2}} - \frac{1}{f_2^{\,2}}\right]^{-1} \left|(PR1 - PR2)\right| \quad \text{........ (4)}$$

PR1 and PR2 are pseudo range measurements on L1 and L2 frequencies.

Where f1=1575.4 MHz and f2=1227.6 MHz

Vertical TEC (VTEC) is useful to image the electron density at a height of ≈350 KM that is required for measuring ionospheric variability [4].

MAPPING FUNCTION :

When monitoring of ionosphere is done using Global Navigation Satellite System (GNSS) data, then mapping function is first considered and next consideration is that electrons concentrate in a layer form in the ionosphere [5]. With the help of mapping function, the STEC which is the total electron content in the line-of-sight of the satellite and receiver, is converted into VTEC. The height of this layer is called shell height or ionospheric effective height.

The mapping function is for satellite-based TEC conversion that transforms the slant delay to vertical direction. In this work , two geometric mapping functions namely : SLM (Single Layer Model) and MSLM (Modified Single Layer Model) , are used to compute the VTEC along with an space based empirical mapping function called as LEAR mapping function to investigate the suitability of the space based mapping function for ground based receivers [6].

Using the STEC, equivalent vertical TEC (VTEC) can be obtained by multiplying the STEC with inverse of the mapping function ‘mf ‘, which, in general, is defined as:

$$VTEC = STEC / mf \quad \text{…….. (5)}$$

GEOMETRIC MAPPING FUNCTIONS :

In this section, the two geometric mapping functions designed for ground based receivers : SLM Single Layer Model SLM & MSLM (Modified Single Layer Model) mapping functions are mentioned.

SINGLE LAYER MODEL (SLM) OR THIN LAYER MAPPING FUNCTION :

A commonly used mapping function called single-layer model (SLM) is mentioned, using a fixed height of the ionosphere at 350 KM is shown in Figure 1.

The thin mapping function f_{TM} is defined as:

$$f_{TM} = 1 /(1 - ((ra \cos(ele) / (ra+ ht))^{2})^{1/2} \quad \text{.....(6)}$$

Where ‘ele‘ is the elevation angle, ’ ht’ is the height about 350 to 450 KM and ‘ra’ is the radius of Earth’s 6371KM.

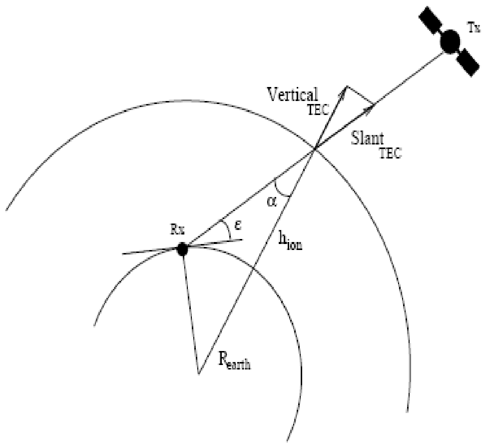

Figure.1 SLM or thin layer model where TX is transmitter and RX is receiver.

MODIFIED SINGLE LAYER MAPPING FUNCTION:

The MSLM mapping function f_{MM} is defined as:

$$f_{MM} = 1/(1 - ((ra \cos(\alpha{*}ele) /(ra + ht))^{2})^{1/2} \quad \text{---------(7)}$$

f_{MM} is the modified form of SLM mapping function where ‘ele’ is the elevation angle,’ ht ‘is the height of the ionosphere layer, this height is about 350 to 450 KM and ‘ra’ is the radius of Earth’s ie. 6371KM. Best mapping function MSLM is achieved at height of 506.7 KM and scaling factor α of 0.9782 with radius of Earth as 6371 KM.

EMPIRICAL MAPPING FUNCTION :

In order to convert the STEC into VTEC, an empirical mapping function is proposed by ‘Lear W’ and is named after him as Lear mapping function which was recommended for LEO satellite observations [7]. The LEAR mapping function has complete dependency on zenith angle ‘Ze’ of the satellite and is given in Eq.(8)

$$m(E) = \left\lfloor \frac{2.037}{\sqrt{(1.076 - (\sin Ze)^{2})} + \sin Ze} \right\rfloor \quad \text{……..(8)}$$

Where ‘Ze’ is the zenith angle of the satellite w.r.t. receiver.

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In this work, the suitability of the Lear mapping function for TEC conversion using the ground based GNSS receiver data is investigated.

RESULTS AND DISCUSSION

The data is collected from the GPS Receiver (dual frequency) for the IGS station located at Hyderabad situated at Latitude: 17°24'39"N /Longitude: 78°33'4"E, Telangana, India, for a day ie. 11/09/2014.

Figure.2 shows the visibility plot of the satellites over the entire day of 11/09/2014, where twenty nine satellites are visible. From the plot it is clear that each satellite is visible to the receiver for a minimum period of four hours and at any instant of time more than six satellites are visible.

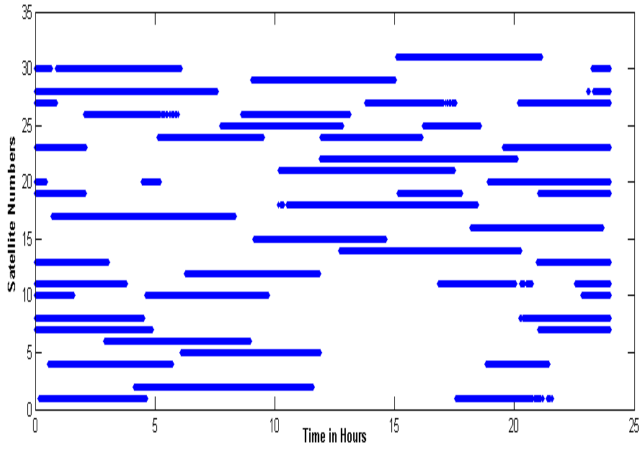

Figure 2. Visibility of the satellites on 11/09/2014 over the entire day with x-axis as time in hours and y – axis as satellite number.

The observation file of the receiver on the typical day is processed in order to retrieve the pseudo range measurements on both the carrier frequencies. With these pseudo range measurements, Slant TEC is estimated using Eq.4.

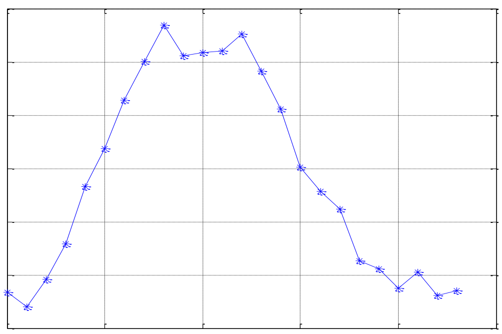

Figure 3. Variation of estimated Slant TEC (STEC) in TECU with time in hours over the entire day i.e. 11/09/2014.

From Figure.3, it is observed that STEC is maximum (113.8 TECU) at 8:08 hours and is minimum (8.081 TECU) at 1:08 hours.

In order to compute Verticle TEC(VTEC), different maping functions are used and their performance in comparison with IRI-2012 model is presented.

Variations of the Different Mapping Functions w.r.t time are shown in Figure.4; the SLM mapping function has a maximum value 2.0817 at 20:01 hours and a minimum of 1.5291 at 3:08 hours. In case of MSLM mapping function, maximum value of 2.2017 is observed at 20:01 Hrs and minimum value of 1.6474 is observed at 3:08Hrs.

In case of Lear mapping function, maximum mapping function value of 2.5538 is observed at 20.01 Hrs and minimum of 1.6769 is observed at 3:08 Hrs.

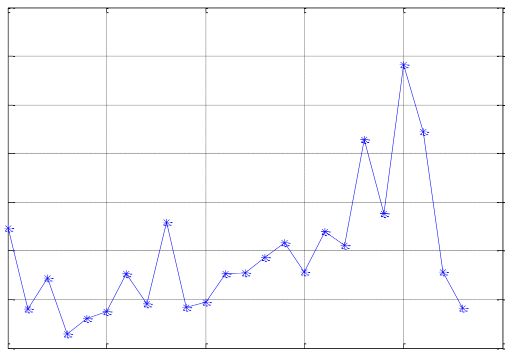

Figure.4 (a). Variations of the SLM Mapping Functions over the entire day i.e.11/09/2014

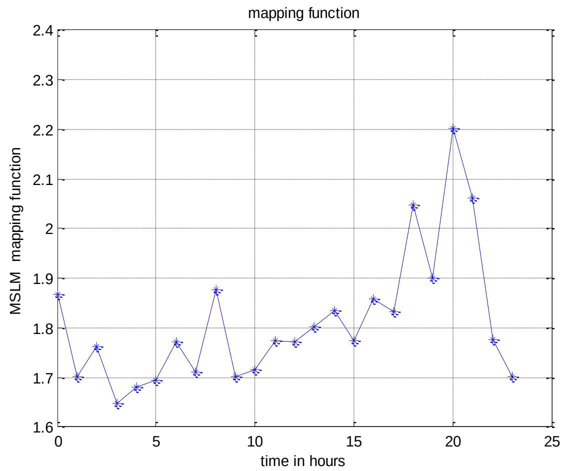

Figure.4 (b). Variations of the MSLM Mapping Functions over the entire day i.e.11/09/2014

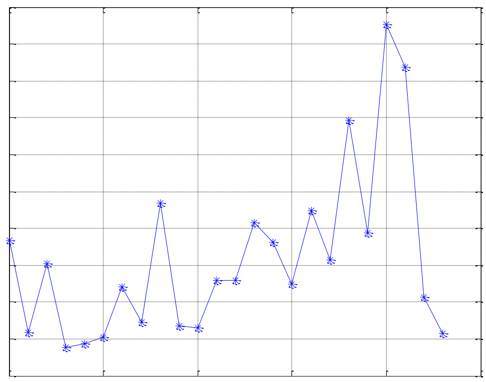

Figure.4 (c). Variations of the Lear Mapping Functions over the entire day i.e.11/09/2014

Table 1: Statistics of Mapping Function value on 11/09/2014 using SLM, MSLM and Lear mapping functions.

Mapping function	Mapping function values	Time (hours)
SLM	2.0817 (Max)	20.01
	1.5291 (Min)	3.08
MSLM	2.2017 (Max)	20.01
	1.6474 (Min)	3.08
Lear	2.5538 (Max)	20.01
	1.6769 (Min)	3.08

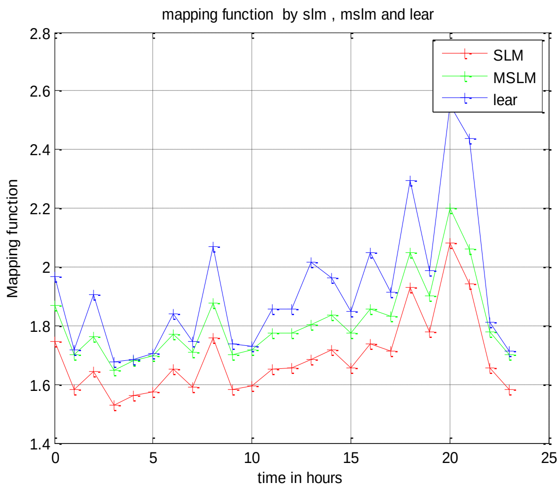

Figure 5. Comparison of mapping function value using SLM, MSLM and Lear on 11/09/2014 with x axis as time in hours and y-axis as mapping function

It can be observed from Figure .6 that values of the mapping functions are maximum at low elevation angle (6.306^0) and minimum at high elevation angle(30.28^0 and 33.77^0). Table 2 shows statistics of mapping function values with SLM, MSLM & Lear with respect to elevation angles on 11/09/2014.

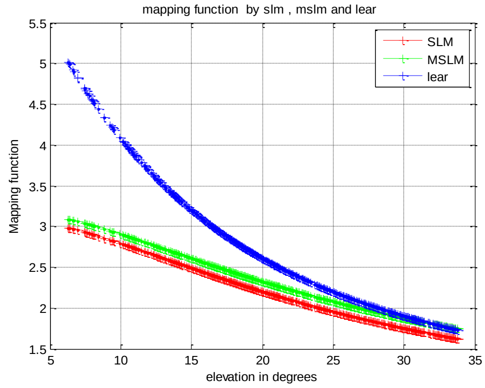

Figure 6. Variation of SLM, MSLM and Lear mapping function with Elevation angle over the entire day i.e. 11/09/2014.

Table 2 Statistics of mapping function value with SLM, MSLM & Lear with respect to elevation angle on 11/09/2014.

Mapping function	Mapping function values	Elevation angle (degrees)
SLM	2.984 (Max)	6.31^0
	1.624 (Min)	33.77^0
MSLM	3.091 (Max)	6.31^0
	1.741 (Min)	30.28^0
Lear	5.01 (Max)	6.31^0
	1.732 (Min)	33.77^0

Figure.7 shows VTEC computed using the SLM (Single Layer mapping function), MSLM (Modified Single Layer mapping function) and Lear mapping function. It shows with SLM mapping function, maximum value of VTEC is 67.36 TECU at 12:01Hrs and minimum of 5.249 TECU at 1:08 hours. With MSLM, maximum value of VTEC observed is 66.61 TECU at 12:01Hrs and minimum of 5.179 TECU at 1:08Hrs. With Lear mapping function, maximum VTEC of 62.12TECU is observed at 12.01Hrs and a minimum of 4.96TECU is observed at 1:08 hours which is tabulated in Table 3.

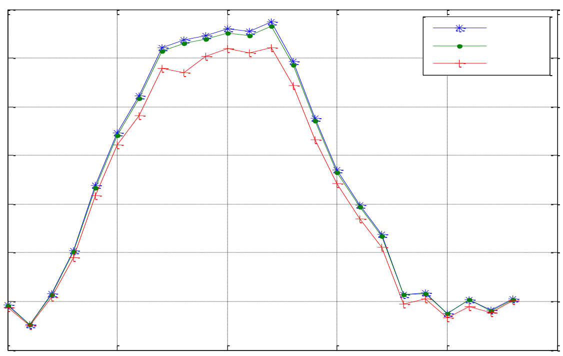

Figure 7. VTEC computed on 11/09/2014 using SLM, MSLM and Lear mapping functions

Table 3: Statistics of STEC and VTEC on 11/09/2014 using SLM, MSLM and Lear mapping functions.

Parameter	values	Time (hours)
STEC (TECU)	113.8(max)	8.08
	8.081(min)	1.08
VTEC(SLM) (TECU)	67.36(max)	12.01
	5.249 (min)	1.08
VTEC(MSLM) (TECU)	66.61(max)	12.01
	5.179 (min)	1.08
VTEC(Lear) (TECU)	62.12(max)	12.01
	4.96 (min)	1.08

In order to assess suitability of the three mapping functions presented in this paper, over low latitude regions like India, VTEC is computed using web based IRI-2012 (NEQUICK) model for the entire day i.e. 11/09/2014.

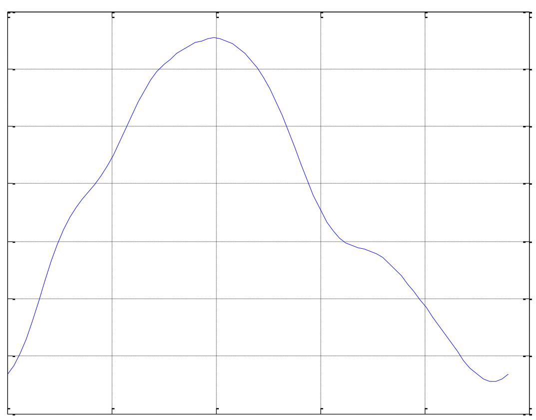

Figure. 8: VTEC plot using IRI-2012 over the entire day of 11/09/2014, x-axis is time (hours) & y –axis is TEC (TECU)

Figure.8 shows the VTEC in TECU graph versus time in hours where VTEC is estimated using IRI-2012.From the graph , the VTEC maximum of 65.3 TECU is observed at 10:00Hrs of the day and minimum of 5.6 TECU at 23.1 hours by IRI-2012 which is comparable with VTEC maximum (67.36 TECU, 66.61TECU) obtained due geometric mapping functions:Single layer Mapping function & Modified Single layer Mapping function at 350km . Summary of VTEC in TECU is shown in Table 4.

Table 4: Comparison of VTEC estimated using SLM, MSLM and Lear mapping functions with IRI-2012 Ne Quick model on 11/09/2014.

Altitude is 350 Km	
Model/Mapping function	Max values VTEC (TECU)
IRI-2012 NEQUICK	65.3
SLM	67.36
MSLM	66.61
Lear	62.12

CONCLUSION

The results obtained in this paper are based on the data collected from the dual frequency GPS Receiver located at Hyderabad, Telangana in India, for a typical day i.e. 11/09/2014.

The main purpose is to compute the STEC (slant total electron content) and VTEC (vertical total electron content). STEC is calculated using linear free combination algorithm (LFCA).VTEC is calculated using geometric mapping functions namely SLM, MSLM and empirical mapping function called Lear. Geometrical based model simplify the assumptions on the distribution of electron density within a spherical shell. In the thin shell model, the shell has infinitesimal thickness and this allows broadening model for including dependency of electron content on horizontal position. The Lear mapping function is suitable for space based GPS receiver.

From the statistics obtained by the above work it shows that maximum mapping function value is obtained at 20.01 hours and minimum at time 3.08 hours , which also shows that VTEC is maximum at 12.01 hours and minimum at 1.08 hours for all the three mapping functions i.e. SLM, MSLM and Lear mapping function.

The calculated VTEC by SLM, MSLM and Lear mapping function are validated with web based IRI-2012 model. The maximum valued of VTEC in TECU using SLM is 67.36, MSLM is 66.61 and Lear mapping functions is 62.12 at 350 KM and with IRI-2012 model is 65.3 TECU. The statistics and results shows that SLM & MSLM are having nearby results than Lear mapping function with reference to IRI-2012.

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