Vol 8. No. 2 Issue 2 – August, 2015

African Journal of Computing & ICT

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Ionodelay models for Satellite Based Navigation System

Mehul V. Desai[1] & Dr. Shweta N. Shah[2]
Ph. D Scholar[1], Assistant Professor[2]
Electronics Enginnering Department
S.V.National Institute of Technology
Gujarat-395007, India.
mvd.svnit@gmail.com[1], snshah@eced.svnit.ac.in[2]

ABSTRACT

The Indian government developed, regional navigation satellite system will provide accurate positioning information towards the low latitude equatorial Indian subcontinent. Always a large irregularity in ionospheric gradient presents in this region. Both L5 and S band signals of IRNSS are more affected by the Ionodelay. Due to this phenomena, position accuracy of the system will be degraded. To alleviate the effect of ionosphere is one of the effortful problem in satellite based navigation system. In this paper detail study about ionosphere and its effects on various parameters of navigation signal are covered with their mathematical expressions. The delay contribution due to ionosphere is measured using different models in term of Total Electron Content (TEC). Here, various single frequency ionodelay measurement and correction models like, Klobuchare, WARTEK, GRAPHIC, GIM, GIVE and Dual frequency technique have been encapsulated.

Keywords — Klobuchar model; Global Ionospheric Maps (GIMs); Wide Area Real Time Kinematic (WARTK); Group and Phase Ionospheric Combination (GRAPHIC); Grid Ionospheric Vertical Error (GIVE)

African Journal of Computing & ICT Reference Format:
Mehul V. Desai[1] & Shweta N. Shah[2] (2015): Ionodelay models for Satellite Based Navigation System
Afr J. of Comp & ICTs. Vol 8, No. 2, Issue 2. Pp 25-32.

1. INTRODUCTION

The United States Department of Defense controlled Global Positioning System (GPS) is a mature satellite based navigation system. Globally, it provides accurate services to military as well as civilian users [1]. Many countries do not want to depend on the GPS for their Precision Approach (PA) based military application. Therefore, they develop their own regional satellite based navigation system like, Indian Regional Navigation Satellite System (IRNSS), European Geostationary Navigation Overlay System (EGNOS) and the Chinese BeiDou Navigation Satellite System etc.

The accurate range measurement is very crucial for defense application. But this measurement is always affected by different unintentional natural error sources [2]. In space, ionosphere is located from the altitude about 60 km to 700 km, it has a highest error contribution in position measurement [3]. In India the performance of navigation application is always degraded for the reason that of large ionosphere irregularities. To improve the delay contribution, due to ionosphere different methods are available like, Differential GPS (DGPS), dual frequency technique, Satellite Based Augmentation System (SBAS) and single frequency ionodelay models. Among them, DGPS and SBAS are very much complex and cost effective due to its complex and expensive architecture, while single frequency ionomodels are cheaper and very easy to broadcast [2-5]. Hence, major research work is done on single frequency models.

The comparison of various models like, GRAPHIC[5], Klobuchare [6], WARTEK [7], GIM[8], GIVE [9] with their mathematical expression have been done. From this survey, it has been found that eight coefficient klobuchar model is very simple, but its performance has been worst compared to all others studied models. The GIVE model is one of the promising methods for effective ionodelay correction in low latitude, equatorial anomaly, India. Section 2 gives a description of the Ionosphere and its effects on different parameters. Brief explanation and comparison of all Single frequency models have been included in section 3. Finally, Conclusions related to the best model for ionodelay correction have been covered in section 4.

2. POSITION DETERMINATION

The distance between satellites to the user is calculated if the signal travel time is known. The travel time is determined by finding the correlation between PRN code received from satellites and generated by the receiver itself. However, it is not accurate because always clock offset between satellites and a receiver is present and received signal is also affected by different intentional and unintentional error sources. Therefore, the measured range is not true, but it is pseudorange and it is givenby P[10];

$$\begin{aligned} P &= c[(T^u + t^u) - (T^s - \delta_t)] + d + mp_p + n_p \\ &= c(T^u - T^s) + c(t^u - \delta_t)] + d + mp_p + n_p \\ P_i &= R_i^t + c(\Delta_t) + d_i + mp_p + n_p \qquad (1) \end{aligned}$$

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Where, T^u and T^s are the time instants when signal left from the satellites and signal reached at the satellites, respectively. R_i^t is a true distance between the satellite and user. It can be calculated using [5],

$$R_i^t = \sqrt{(x_i{}^s - x^u)^2 + (y_i{}^s - y^u)^2 + (z_i{}^s - z^u)^2}$$

When four pseudoranges are observed, then i ranges from 1 to 4. (X^s, Y^s, Z^s) denotes 3D known geocentric coordinates of satellites and (X^u, Y^u, Z^u) are unknown geocentric coordinates of the user which are to be computed. The speed of propagation is denoted by c. Δ_t is the total time offset between satellites and receiver. Also, t^u and δ^t are the clock offset from system time for receiver and satellite respectively. d is the total atmospheric delay given by,

$$d = I_{pr} + T_r$$

Where, I_{pr} code delay due to the Ionosphere, which will be always positive in magnitude and T_r is the code delay because of troposphere which is independent of frequency. mp_p and n_p shows the effect due to psuedorange multipath delay and other pseudorange measurement noise [4]. From the literature, the GPS statistical ranging error budget is found and it is given in Table 1 [2] [5].

TABLE 1. Statistical ranging error budget (1sigma)[2][5].

Error Source	1 σ error (± meters)
Ephemeral Data	2.1
Satellite Clock	2.1
Ionosphere	4.0
Troposphere	1.4
Multipath	1.4
Receiver Measurement	0.5
User Equivalent Range Error	5.3

The Table 1. shows the contribution of above mentioned error sources, it can be seen that the major effect due to ionosphere [2]. Therefore, this effect has to be corrected, which is explained in section 3.

3. IONOSPHERE AND IT'S EFFECTS ON PARAMETER

The Ionosphere is located above the earth's surface from 60 km to 700 km. It is made of the neutral atoms which are photonised by Extreme Ultra Violet (EUV) from the Sun [3][5]. The amount of ionization depends on the EUV strength and atom density in the atmosphere, these parameters vary with sun activity. Therefore, the behavior of the ionosphere is changing from day to night and from season to season [4][7].

The ionosphere contains D (60km to 90km), E (90km to 130km) and F (130km to 400km) layer [4][6], which has different amount of plasma ions that can affect propagation of radio waves. During late afternoon and early evening hours, the rate of recombination exceeds the rate of ionization. Here, The Recombination is the opposite process, then photoionization in which neutral atoms produce by a combination of negatively and positively charged ions. At this duration the density of electron reduces in D, E and F1 (130km to 210km) layers. However, the F2 layer behaves differently is called mid-latitude seasonal anomaly. The electron density in the F2 (210 km to 400 km) layer has reached its minimum value just before that duration [5] [11]. Then, as the sun rises, photoionization take place and as a results electron density increase again. The larger density variation of the F2 and F1 layer are the major sources of ionospheric induced error for positioning and range measurement application [2][4][7].

The main types of ionospheric variations are regular and irregular. The regular type variations have a periodic form like diurnal, seasonal, latitudinal and solar cycle [5] [12]. Thus, these variations can be predicted at least approximately in advance and necessary precautions will be taken. Irregular variations are those such as a sporadic E and irregularities in the F region, called Traveling Ionospheric Disturbance (TID) [2][12]. These variations cannot easily be predicted in advance and hence the effects due to these variations generally have to be accepted by the users. The degree of magnetic disturbance or the characteristics of the ionosphere during each day is indicated by a variety of indices, such as K, K_p, A_p and D_{st} [12]. Most of the time, these indices correlate very well with the behavior of the ionosphere.

Due to the ionospheric gradient, the radio wave will be refracted as they are propagated through the ionosphere and it will be continuously refracted in the ionosphere as it's a refractive index change from layer to layers. So, to finding the effect of ionosphere the refractive index of the layer must be known in advance. Appleton - Lassens determined equation that gives the ionospheric index of refraction in the presence of a static magnetic field [7].

$$\eta^2 = -\frac{X}{1 - jZ - \frac{Y_T^2}{2(1-X-jZ)} \pm \sqrt{\left[\frac{Y_T^2}{2(1-X-jZ)^2} + Y_L^2\right]}} \quad (2)$$

Where, $X = \frac{f_N^2}{f^2}$, $Y = \frac{f_H}{f}$, $Y_L = \frac{f_{H_L}}{f}$, $Y_T = \frac{f_{H_T}}{f}$, $Z = \frac{v}{w}$, w is the angular frequency, Y_L is the longitude component, Y_T is the transverse component, f_N is the frequency of plasma, $f_N^2 = 80.62N_e$, f is the electromagnetic wave frequency in MHz and v is the frequency of collision in Hz.

A. Major Effects due to Ionosphere

The major effects due to ionosphere is easily determined as the refractive index, which is differ from the unity due to the gradient of the ionosphere derived. The major effects are as follows

Group Delay: The signal delayed by the ionosphere gives error in range measurement, it can be measured in term of time or distance given by [5]

$$\Delta_t = \frac{1}{c}\int (1-\eta)dl \; or \; \Delta_r = \int (1-\eta)dl \qquad (3)$$

If only first order term of the refractive index considered then it will become $\eta = 1 - X/2$, where the value of X is $\frac{40.3}{f^2}\int N\,dl$. The quantity $\int N\,dl$ is the TEC in el/m. Finally, in general group delay can be represented by

$$\Delta_t = \frac{40.3}{c * f^2}\int N\,dl \qquad (4)$$

The amount of time delay difference $\delta(\Delta_t)$ due to ionosphere is measured by the dual frequency receiver [4-5]. So, from the equation (3), it can be written as

$$\delta(\Delta_t) = \frac{40.3}{c} * TEC\left[\frac{1}{f_2^2} - \frac{1}{f_1^2}\right] = \Delta_{t1}\left[\frac{f_1^2 - f_2^2}{f_2^2}\right] \qquad (5)$$

The term, $\left[\frac{f_1^2 - f_2^2}{f_2^2}\right]$ is called the scaling factor of the ionodelay calculation. For the GPS pair of frequencies, this factor is 1.546 and 1.894 for the IRNSS pair of frequencies [13].

Phase Advance: As a radio Signal propagate through the ionosphere, the some amount of phase of the signal is advanced compared to signal travel in free space[2].

$$\Delta_\phi = \frac{f}{2c}\int X\,dl = \frac{40.3}{cf} * TEC = \frac{1.34 * 10^{-7}}{f} * TEC \qquad (6)$$

In general, this additional phase due to ionosphere cannot be measured easily using a single frequency except both the receiver and the transmitter have excellent oscillator stability and the satellites ephemeris are known in advance [2]. Hence, for this measurement always analytically derived two frequencies are required. Hence, measured phase difference is related by [2-3].

$$\Delta_{\delta_\phi} = \left[\frac{1.34 * 10^{-7}}{f1 * \frac{m^2 - 1}{m^2}}\right] * \frac{1}{TEC}$$

Where, $m = f_1/f_2$.

Higher Order Ionospheric Effects: The term **X**, **Y**, $\mathbf{Y_L}$, $\mathbf{Y_T}$ and **Z** in equation (1) are very small compared to unity. Hence, by neglecting those terms whose magnitude are less than $\mathbf{10^{-9}}$. Brunner and GU have derived the new form of refractive index written as [2][14]

$$\eta = \left[-\frac{X}{2} \pm \left(\frac{XY}{2}Cos\theta\right) - \frac{X^2}{8}\right] \qquad (7)$$

Where, $\frac{X}{2}$ or $1/f^2$ is the first order, $\left(\frac{XY}{2}Cos\theta\right)$ or $1/f^3$ is the second order and $\frac{X^2}{8}$ or $1/f^4$ is the third order frequency term. The contribution of higher order term is very less compared to the first order term. If only first ordered term is considered with assumption of that 1% worst accuracy is acceptable than refractive index is given by

$$\eta = 1 - \frac{X}{2}.$$

Ionospheric Doppler Shift: As the TEC varies the small amount, frequency is also changed, because frequency is related to phase. AS a result the small amount Doppler shift occurs, which is very less compared to normal geometric Doppler shift. Doppler shift due to this phenomena can be computed as [2]

$$\Delta_f = \frac{d_n}{d_t} = \left(\frac{1.34 * 10^{-7}}{f}\right)\frac{d_{TEC}}{d_t} \qquad (8)$$

Amount Of Faraday Rotation: The signal (GHz) from the satellite passes from the ionosphere then its plan of polarization is changed [15]. This additional rotation of polarization can be represented by [2][16]

$$\Omega = \frac{k}{f^2}\int B\cos\,\theta\,Ndl \qquad (9)$$

Where the quantity $B\cos\,\theta\,Ndl$ is the product of TEC times the Earth magnetic field measured longitudinally. This term is integrated toward the path of propagation.

Angular Refraction: The amount of angular refraction was derived by Millman and Reinsmith [17]. The signal is bending due to this refraction and as a result measured range has a error and it is given by [18]

$$\Delta_E = \left[\frac{(R + r_0\sin E_0)(r_0\cos\,E_0)}{[h_i(2r_0 + hi) + {r_0}^2 - sin\,{E_0}^2]} * \frac{\Delta_R}{R}\right] \qquad (10)$$

Where R is the apparent range, E_0 is the elevation angle, Δ_R is the range difference given by $\Delta_R = (40.3/f^2) * TEC$ [16], r_0 is the radius of earth's and h_i is the height from the center of the earth to above space up to 300km and 400 km, where TEC distributions are available.

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Distortion of Pulse Waveform: The spread spectrum signals of the satellites can be dispersed due to unexpected behavior of the ionosphere. The amount of this dispersion is very less, therefore it can be neglected. The time delays caused by this ionospheric dispersion are determined by [19]

$$\Delta_t = \left[\frac{80.6 * \Delta_f}{c * f^3}\right] * TEC \qquad (11)$$

Ionospheric Scintillation: As the signal propagation through the ionospheric irregularities, fluctuation in phase and amplitude of the signal done, called ionospheric scintillation [17]. The satellite-based communication and navigation systems are very much influenced by this ionospheric scintillation. All the radio signals whose frequency up to few GHz are very much affected by it. Due to amplitude scintillation received signal intensity drops below the threshold value, which is set for healthy satellite tracking. As the amplitude scintillation strong the signal is totally loss and hence the signal should be reacquire again [20]. Similarly, if the phase scintillation is sufficiently strong, then loss of phase lock will be occurred. Phase scintillation has a major effect on on phase sensitive application [21].

4. IONODELAY MODELS

Alleviates the effects due to ionosphere explained in section 3, different models are available. Models are classified in two parts 1) **Empirical models** depend on post processing logged Data and 2) **Physical models** depend on universal principles. In this section, Detail study of single frequency ionodelay correction empirical models and dual frequency method has been explained.

A. Single Frequency Ionodelay Correction Algorithm

The graphical representation of Total Electron Content (TEC) is shown in Figure. 1. The first order, 99% of total ionospheric delay is because of Slant TEC (STEC) and signal frequency f which is defined as

$$STEC = \int_R^S N_e \, dl \qquad (12)$$

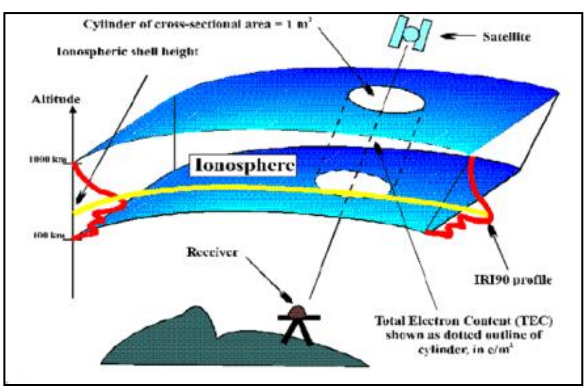

Figure1. Total Electron Content [5].

Klobuchar Ionospheric Model: The empirical model based on 8 coefficient is called Klobuchar model. This model was designed to reduce the computational complexity as well as storage capacity by keeping only 8 coefficients to transmit from satellite to the user [22-24]. This simple empirical broadcast model is reduced about the 50 % RMS ionospheric range error. As shown in Figure. 2, first vertical delay at the Ionospheric Pierce Point (IPP) is calculated then it is converted into slant delay by multiplying the obliquity factor or the mapping function.

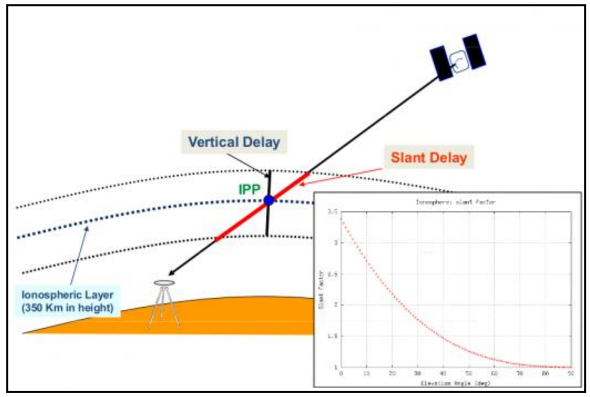

Figure 2. Ionospheric Pierce Point [6][7].

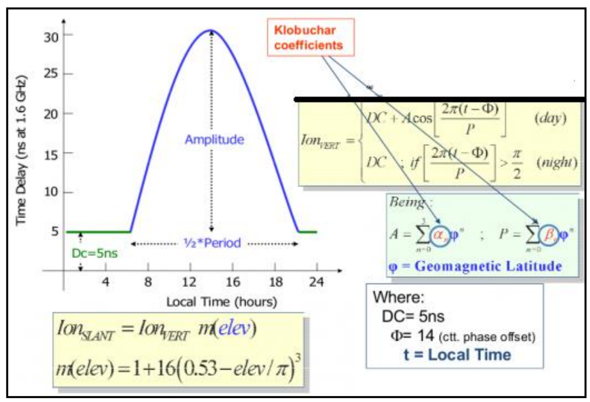

Figure. 3 Klobuchar Model Behavior [5][6][23].

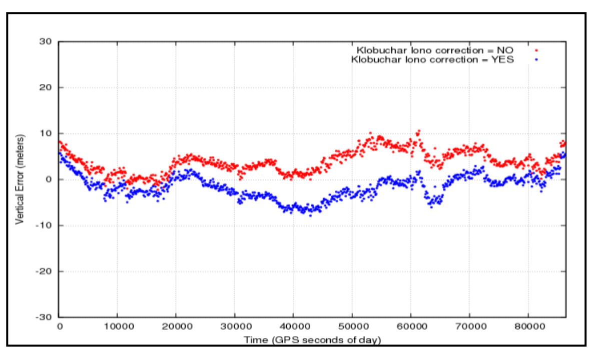

Figure. 4 Klobuchar Model Behavior [5][6][23].

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The Klobuchar algorithm works for the single frequency receiver. Based on the available parameter various quantities are to be calculated as [6][22].

$$\Delta_{T_{iono}} = A1 + A2\cos\left[(2\pi(\tau - A3))/A4\right] \qquad (13)$$

Where, A_1 is night time value ($5 * 10^{-9}$) seconds, A_3 is phase (1400 hrs LT), A_2 is the amplitude given by [6][22]

$$A_2 = \alpha_1 + \alpha_2\phi_m + \alpha_3{\phi_m}^2 + \alpha_4{\phi_m}^3$$

Similarly, A_4 is period given by [6][22]

$$A_4 = \beta_1 + \beta_2\phi_m + \beta_3{\phi_m}^2 + \beta_4{\phi_m}^3$$

Where ϕ_m is the geomagnetic latitude at IPP. The behavior of a Kobuchar model for 24 hours shown in Figure. 3. The amount of improvement is done after applying Klobuchar model is shown in Figure. 4.

Global Ionospheric Maps: Data from more than 100 continuously monitoring station (Global network) are being collected to map ionosphere's TEC on global maps [24]. These Global Ionosphere Maps (GIM) give the real time TEC distribution globally. It has collected the data from 6 to 8 near station from the global network at every 30 second and interpolating it both time and space to map it globally. The maps can be updated with the rate of 5-15 minutes delayed by real time, which is shown in Figure.5 [25].

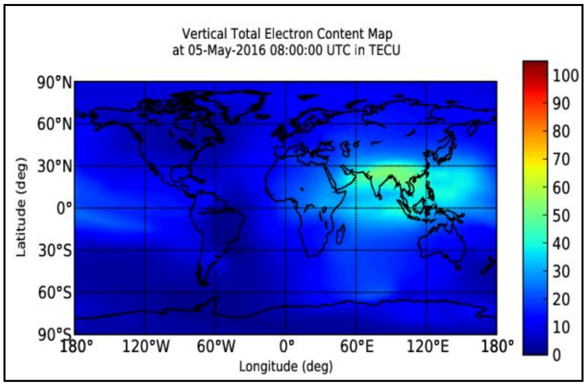

Figure.5 Global TEC Distribution[23].

Wide Area Real Time Kinematic: In the late 1990s the another empirical model was introduced called The Wide Area Real Time Kinematic (WARTK). This concept was developed by the Research Group of Astronomy and Geomatics (gAGE) from the Technical University of Catalonia (UPC) to reduce the deficiency of Real Time Kinematic (RTK) [26]. The WARTK method increases the service area of RTK up to 1000 kilometers and hence it reduced baselines required 1000 times than RTK to cover a wide region[26]. The WARTK is a differential technique, which uses a 3D voxel model for computing the very precise ionospheric corrections in real time. 3D voxel model is using a Kalman filter for estimation of information from the Global Navigation Satellite System (GNSS) data collected from monitoring stations separated by a few kilometers [27]. WARTK user receiver layout approach is shown in Figure.6 [27].

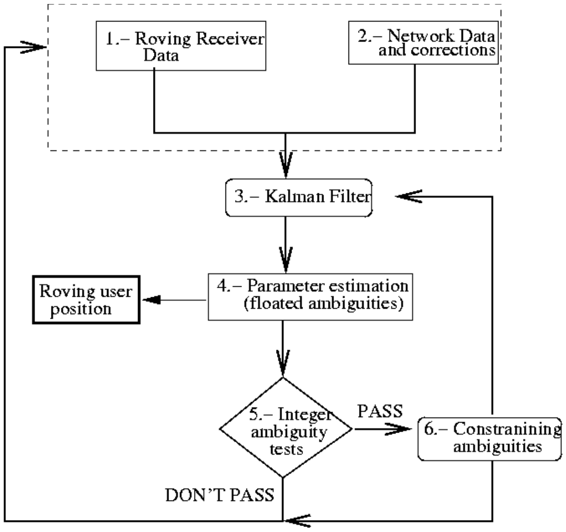

Figure. 6 WARTK Algorithm [27][28].

Group and Phase Ionospheric Combination: Group and Phase Ionospheric Combination (GRAPHIC) is the average of the code and phase measurement, which eliminated the error which are common to both measurement [29]. It is used in a single frequency satellite based applications because it is only able to alleviate the effect of ionosphere but at the same time phase ambiguity is present.

Hence, the measurements are more noisy compared to pure carrier phase combination [5]. In GRAPHIC, this ambiguity and noise free position measurement can not be estimated using a single time observation, but it requires multiple observation. Based on this fact the cumulative measurements are done by Heroux et al in 2004. They found that the estimation process always needed multiple hours observation to converge the phase carrier ambiguity problem [30].

$$G_i = \frac{P_i + \phi_i}{2}$$
$$G_i = \sigma_i + cd_t + mwZ_{wd} + \frac{\lambda_i N_i^{-}}{2} + \frac{\epsilon_{pi} + \epsilon_{\phi_i}}{2} \qquad (14)$$

Where σ is the geographical range between the satellite to the receiver, d_t is the clock bias of the receiver, N_i is the ambiguity of carrier phase measurements, λ is the wavelength of the carrier phase, m_w is the mapping factor of wet, zwd is the tropospheric wet part and ϵ_{phi} & ϵ_{pi} are measurement noise in code and phase due to multipath [7]. In Fig.7 comparison of above three models has been shown, it has been found that Klobuchar method performs much worse compared to GRAPHIC and WARTK methods, only few amount meter accuracy was obtained.

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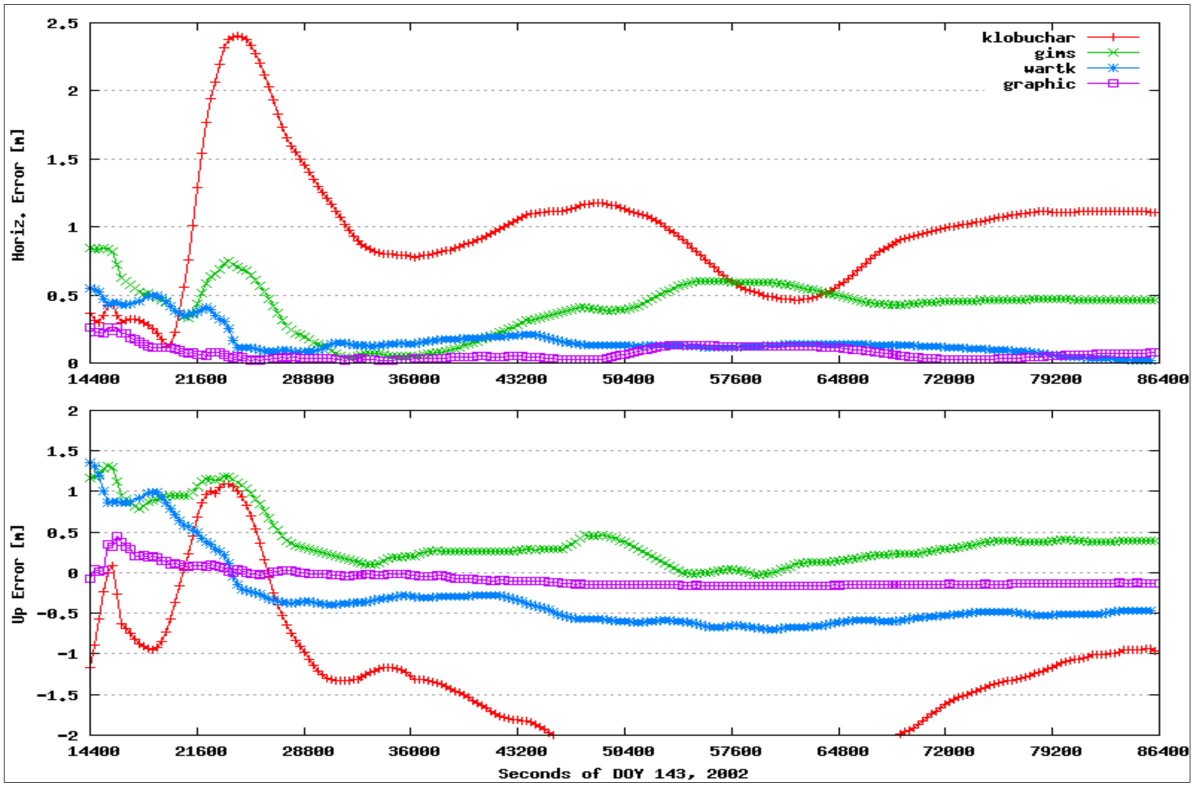

Fig 7. Klobuchar, GIM, WARTK and GRAPHIC Comparison[7].

All the comparison is done under ionospheric behavior with an Ap index 78[30]. The Klobuchar model performance is not well in all the region as it describes the ionospheric behavior by only the 8 coefficients. The GIMs, WARTK and GRAPHIC performances are always better compared to simple Klobuchar. From the multiple days observation, it is found that the accuracy of GIMs is two times better than the WARTK and GRAPHIC. The GIMs performance not only depends on tracking network, but also depends station location. Hence at the station where a high electron density present or mid latitude region the GIM performance is obtained weaker compared to those the equatorial or high-latitude regions.

NeQuick model: NeQuick is an another empirical model developed for Galileo to measure the spatial and temporal variation of electron density of the ionosphere. It is finding electron density in main E, F1, and F2 layers of the ionosphere [31]. It normally uses the solar flux index F10.7 for finding the monthly average. Therefore, in real time application to measure the daily variation and atmospheric condition this solar index F10.7 must be replaced [32]. $(\hat{A}_z)$ is a daily variation represented by

$$(\hat{A}_Z) = a_0 + a_1\mu_1 + a_2\mu_2{}^2$$

Where $\mu = a\tan\frac{I}{\sqrt{COS\phi}}$ is modified latitude and a_1, a_2 and a_3 are the coefficients of permanent stations computed through a global network and broadcasted in the Galileo navigation message [32].

Grid Ionospheric Vertical Error: In this model correction are provided at 5^0 X 5^0 grids at 350 km altitudes. The user first computes the point where its LOS cuts the 350 km altitude [33-34] This point is termed as the Ionosphere Pierce Point (IPP) of the user. After calculating the 3D position of users at IPP the Ionospheric Grid Points (IGPs) are selected based on following steps.

- Select the four IGPs (minimum 3 IGPs) around IPP with ***GIVEI ≤ 14***
- If of the selected IGP have ***GIVEI > 14***, then no ionospheric correction are available for that IPP

User Ionospheric Vertical Error (UIVE) will be calculating by interpolating the GIVEs value of the selected IGP [13].

$$\sigma_{UIVE} = \sum_{n=1}^{4(\min)} W_n * X_{PP} * Y_{PP} * \sigma_{GIVEn} \tag{15}$$

Finally, Ionodelay Correction(IC) at defined IPP is given by [13],

$$IC = -\tau_{SPP}(\phi_{PP}, \lambda_{PP}) = -F_{PP} * \tau_{VPP}(\phi_{PP}, \lambda_{PP}) \tag{16}$$

Where, $-T_{SPP}$ is the slant ionodelay, F_{PP} is obliquity factor. Preliminary analysis of GIVE for GAGAN has been introduced by A.D Sharma et. al in 2007, they observed that quit days the estimated GIVEs are less than the GIVEs for a magnetically moderate days [34].

Dual Frequency Method: The two frequencies of different band used, then user shall correct for the group delay due to 1st order ionospheric effects by applying the given relationship

$$\sigma = \frac{\sigma_{B1} - \gamma\sigma_{B2}}{1 - \sigma} \tag{17}$$

where, $\gamma = \frac{f_{B2}^{\,2}}{f_{B1}^{\,2}}$ denoting the correcting factor.

5. CONCLUSION

In this paper detailed study about ionosphere and its effect on satellite based navigation system has been done. Navigation system error budget is studied for understanding of the contribution of the various non intentional sources in parameters measurement. It is observed that Ionospheric effects have a maximum error contribution in it. Hence, it has been deduced that ionodelay correction is very important task for navigation applications, where large iono gradient irregularity present like low latitude Indian subcontinent.

Survey related to the different ionolayer, its TEC contributions and the different affected parameter of signal like, frequency, phase, velocity, refractive index and polarization due to ionosphere are included and detailed mathematical outcomes are studied. Various ionodelay correction models for developing IRNSS system are proposed. Different single frequency model performance likes, Klobuchar, GIM, WARTK, GRAPHIC, Nequick are discussed and it has been deduced that Klobuchar model is very simple, but at the same time it can correct only 50 % of ionospheric effects. Where, all others models performance are better than Klobuchar model. The newly promising grid based model is introduced for IRNSS, called GIVE and it has beenconcluded that the most of the ionodelay correction will be mitigated thorough it. Finally the dual frequency approach to correct the ionospheric effect has been covered.

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