Low Latitude Ionosphere Error Correction Algorithms for Global Navigation Satellite System

B. Shivani, Swapna Raghunath

Abstract*:The ionospheric errors occur due to loss of data in ionospheric region. Low latitudinal regions are the most affected regions due to ionospheric errors and also causes loss of signal or data for space based augmentation system(SBAS) such as aircraft. So to reduce these ionospheric errors in low latitude regions of Global Navigation Satellite System(GNSS) Klobuchar algorithm is used which mitigates the errors occurring in low latitude regions and is used as a standard algorithm in US Global Positioning System(GPS) till now; however, this model can reduce the ionospheric error by approximately 50-60% Root Mean Square(RMS) error in low-latitudes. So in order to increase the percentage deviation of errors in low-latitude regions, Enhanced Klobuchar algorithm is proposed which enhances the correction of low-latitude ionospheric errors approximately up to 80% RMS for a single frequency GPS user. In this paper error correction algorithms are performed over International GPS Service(IGS) data was collected using Hyderabad station receiver, Telangana (latitude- 17.41728°, longitude-78.55088°) in southern part of India during year 2016.

***Keywords*: Ionospheric errors, IGS, IRNSS, GAGAN, GPS, GNSS, SBAS, low latitude ionospheric error corrections.**

I. INTRODUCTION

Ionosphere is the region where large number of electrically charged atoms and molecules collectively form a region in earth's atmosphere. The earth's upper atmosphere from 60km to 1000km is known as ionosphere region[1]. There are many errors to be concerned in the ionosphere region which lead to data loss, delay etc. The radio signals are effected which ranges from few meters to tens of meters due to ionosphere depending on several factors like amplitude and phase scintillation. This is one of the main source of concern in satellite based augmentation system(SBAS). Most of these effects depend on The ionospheric total electron content (TEC) is the major factor by which most of these effects are occurred is the no. of electrons in a vertical column of 1 m^2 cross sectional area. The values for TEC ranges between 10^{16} e/m^2 and 10^{19} e/m^2 which depends on local time, position, season, solar, geomagnetic activities, etc.[2].

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Especially these errors occur in low-latitudinal regions. The regions of ionosphere in India of low latitudeswere categorized by variations like spatial and temporal which were invented fromlow latitude electrodynamicsand equatorialwhichexhibits a phenomena during daytime as equatorial ionization anomaly (EIA)and during night-time have large scale plasma depletions known as equatorial plasma bubbles (EPB). Electron density perturbations of equatorial and in low latitude ionospheric regionsin F-region were produced by EPBs[3].

Global Positioning System(GPS), Global Navigation Satellite System(GLONASS), and Galileo are the satellite navigation systems which are been currently used. The Global Navigation Satellite System (GNSS) conducts its development in various areas such as signal generation, precise positioning, high-precision geodesy and survey in relation to individual satellite navigation systems, has drawn more attention in recent years[4]. Ionospheric effects are complex and inhomogeneous nature of the medium on GNSS signals which are difficult to mitigate. GPS Aided Geo Augmented Navigation (GAGAN) is the navigation systemserving the aircraft navigation over Indian subcontinent used in India's regional SBAS which has been fully operative since 2014. It is mostly concerned for its low-latitude ionospheric errors such as Equatorial Electro Jet (EEJ), EPB, Scintillation effects etc.[5]. In order to mitigate these errors in low-latitude ionospheric regions, error detection and correction algorithms are used.

The low-latitude ionospheric errors are corrected over a particular station's data using error correction algorithms. Here Klobuchar algorithm is used for error correction of low-latitude ionospheric errors over single frequency receivers. The Klobuchar algorithm mitigates the errors in low-latitude ionosphere and is used as a standard algorithm in US GPS till now and it is the most widely used algorithm for ionospheric correction because it is simple in structure and easy to calculate[6][7]. The drawback of the Klobuchar algorithm is that it reduces the errors only 50-60% Root Mean Square(RMS) error in low-latitudinal regions.

So in order to enhance the ionospheric error correction proportion percentage enhanced version of Klobuchar algorithm is proposed known as EnhancedKlobuchar algorithm. The Enhanced Klobuchar algorithm improves about 80% on average of the ionospheric errors, which are useful to single frequency GPS users[8]. The Enhanced Klobuchar algorithm corrects the low-latitude ionospheric errors of 30% RMS more than Klobuchar algorithm by calculating the difference between TEC of both the algorithms[9].

The equation(1) is used to evaluate the performance of the models by computing percentage of deviation (PD) from observed data [10].

$$PD = \frac{\text{Experimental} - \text{Model}}{\text{Experimental}} * 100 \qquad (1)$$

The TEC values of the algorithms are calculated using the below equation in terms of TEC units(TECU)[11].

$$TEC_{experimental} = \frac{iono_{error} * f^2}{40.3} \qquad (2)$$

II. METHODOLOGY

The observations recorded by the GAGAN receiver of Hyderabad station (latitude- 17.41728°, longitude-78.55088°)located in Telangana, India were preprocessed. The data of year 2016 of Hyderabad station is collected from Scripps Orbit and Permanent Array Center(SOPAC) website. SOPAC is a main contributor in the International GPS Service(IGS), which serves as a Global Data Center and a Global Analysis center. The obtained data is in Receiver Independent Exchange Format(RINEX). The RINEX format is aimed to change time from universal to local, familiarizing to new types of measurements and satellite navigation systems. The updated version at present is 2.11.The files required to be downloaded are RINEX file and NAV file. This data file is then given as input to GPS TEC Analysis software (An application developed by Dr. Gopi Krishna Seemala) which converts RINEX format files into .cmn files. These are in system management server update file format. These files are then converted to excel sheets. The lower elevation angles less than 30° are related with deeper fades and distortions due to longer propagation path and increased number of obstacles along the path. Hence only data corresponding to elevation angle greater than 30° were considered.

After preprocessing the data of year 2016 the error correction algorithms of low-latitude ionosphere were implemented.

A. KLOBUCHAR ALGORITHM

GPS satellites broadcast the parameters of the Klobuchar ionospheric model for single frequency users which was designed to lessen user computational complexity and user computer storage as far as to keep a least number of coefficients to convey on satellite-user link[6]. In this algorithm, ionospheric error of GPS is estimated by calculating no. of TEC between satellite and receiver of GPS, and 50-60% RMS of the total ionospheric error can be eliminated depending on the solar activity or the region.

The Klobuchar model pays geomagnetic latitude on ionosphere pierce point (IPP) as shown in fig. 1. IPP is defined as the point where the line of sight intersecting the GPS satellite signal reception point meeting on single layer. The change of TEC at IPP is affected by seasons and the geomagnetic field which are closely related with the sunspot activityand is varied following the solar activity in the period of 11 years.

The Klobuchar coefficients, α_n and β_n, are required to implement Klobuchar model and they are generated by two criteria. The observation dateis thefirst criterion. The shared one-year data of GPS Master Control Station is divided into 37 intervals and each interval is assigned with Klobuchar coefficients.

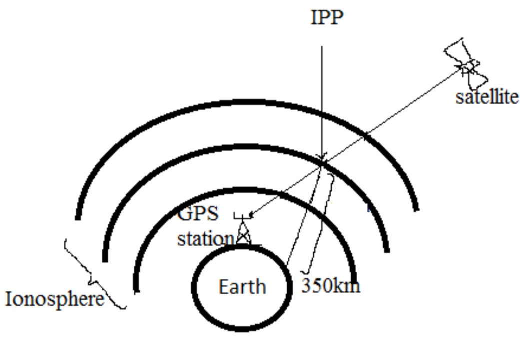

fig. 1 Ionospheric Pierce point(IPP)

The mean of solar flux is second criterion for the previous file days including the corresponding day where the Klobuchar coefficients groups are selected for the individual grades which is categorized into 10 grades. Theα_n and $\beta_n$values are considered by GPS Master Control Station which selects the observed data and the solar flux values provided through the satellite navigation message. The α_n and β_n values are calculated using first criteria and these values are given in the navigation file when run in Dr. Gopi Krishna Seemala software. The ionospheric delay of the Klobuchar model is calculated by following the procedure from Eq. (2) to Eq. (14). The detailed explanation on the equations can be found in[6]. In equations (3) and (4), ψ denotes the Earth-centered angle, E the GPS satellite elevation angle, ϕ the geodetic latitude, AZ the GPS satellite azimuth, and $\emptyset_{IPP}$ the sub-ionospheric latitude.

After calculating the sub-ionospheric latitude, the sub-ionospheric latitude, λ_{IPP}, is calculated using Eq. (5) where λ denotes the geodetic longitude[2].The ionospheric time delay of single frequency GPS user of Klobuchar algorithm follows the below procedure[7][8][9].

Initially Earth centered angle (ψ) is calculated in terms of semicircles with an elevation angle E using equation (3)

$$\varphi = \frac{0.0137}{E + 0.11} - 0.022 \ \text{(semicircles)} \qquad (3)$$

By using earth centered angle equation (3) the latitude of IPP has been calculated in terms of semicircles using equation (4)

$$\emptyset_I = \emptyset_u + \varphi cosA \ \text{(semicircles)} \qquad (4)$$

$$\text{If } \emptyset_I = \begin{cases} > +0.416 \ then \ \emptyset_I = +0.416 \\ < -0.416 \ then \ \emptyset_I = -0.416 \end{cases}$$

Then by using the value of latitude of IPP the longitude of IPP has been calculated in terms of semicircles using equation (5)

$$\lambda_I = \lambda_u + \frac{\varphi \sin A}{\cos \phi_I} \text{(semicircles)} \qquad (5)$$

Then by using equation (5) the geomagnetic latitude of the IPP has been calculated in terms of semicircles using equation (6).

$$\phi_m = \phi_I + 0.064\cos(\lambda_I - 1.617)\ \text{(semicircles)} \quad (6)$$

Then the local time of IPP has been calculated in terms of seconds using equation (7)

$$t = 43200\lambda_I + t_{GPS}\text{(seconds)} \quad (7)$$

$$\text{If } t = \begin{cases} \geq 86400 & \text{subtract } 86400 \\ < 0 & \text{add } 86400 \end{cases}$$

Then the amplitude of the ionospheric delay has been calculated in terms of seconds using equation (8)

$$A_I = \sum_{n=0}^{3} \alpha_n \phi_m^n \text{ (seconds)} \quad (8)$$

$$\text{If } A_I < 0 \quad \text{then } A_I = 0$$

If the amplitude values are less than zero, then those values are equaled to zero. Then the period of the ionospheric delay has been calculated using equation (9) in which if the period of ionospheric delay is less than 72000 seconds then it is equaled to 72000 seconds.

$$P_I = \sum_{n=0}^{3} \beta_n \phi_m^n \text{ (seconds)} \quad (9)$$

$$\text{If } P_I < 72000 \quad then \quad P_I = 72000$$

Then the phase of ionospheric delay has been calculated in terms of radians using equation (7) and equation (9) in equation (10)

$$X_I = \frac{2\pi(t - 50400)}{P_I} \text{ (radians)} \quad (10)$$

Then the slant factor has been calculated with an elevation angle E in terms of semicircles using equation (9)

$$F = 1.0 + 16.0(0.53 - E)^3 \text{(E in semicircles)} \quad (11)$$

The ionospheric time delay has been calculated in terms of seconds using equations (8), (10), & (11) which is given as equation (12).

$$I_{L1_{GPS}} = \begin{cases} \left[5 * 10^{-9} + \sum_{n=0}^{3} \alpha_n \phi_m^n \left(1 - \frac{X_I^2}{2} + \frac{X_I^4}{24}\right)\right] F & if\ |X_I| \leq 1.57 \\ 5 * 10^{-9} * F; & if\ |X_I| \geq 1.57 \end{cases} \text{(secs.)} \ (12)$$

Then the ionospheric error in meters of delay has been calculated by multiplying speed of light (c) to convert the ionospheric time delay in seconds to meters of delay using equation (13).

$$iono_{error} = I_{L1_{GPS}} * c \ \text{(meters)} \quad (13)$$

Total electron content (TEC) of Klobuchar algorithm has been calculated using equation (14) in terms of TECU.

$$tec_{klobuchar} = \frac{iono_{error} * f^2}{40.3} \quad (14)$$

B. ENHANCED KLOBUCHAR ALGORITHM

For ground GPS,The Klobuchar model works well which can be verified by dual-frequency results but the Enhanced Klobuchar model corrects approximately about 80% on average of ionospheric delays, which were beneficial to single-frequency GPS[8].

The receivers above 350 km altitude are usually referred as spaceborne GPS, and the height of single layer needs to be adjusted to 500 km for Gravity Recovery and climate Experiment (GRACE). Similar to the Klobuchar model of ground users, calculations are simplified and many cases are assumed for spaceborne users to reduce the calculation complexity, while preserving effectiveness of the Klobuchar model. As the height of the single layer changes from 350 to 500 km, parameters of altitude-related needed to be changed. Earth angle between the IPPand the receiver was computed using equation (15).

$$\psi = 90 - E_A - \arcsin\left(\frac{R}{R+H} \cos E_A\right) \quad (15)$$

where ψis Earth angle in terms of semicircles, $E_A$is elevation angle, Ris the mean radius of the Earth,His the height of the single layer above the Earth. The approximate equation given by (3) will not be suitable in this case. Instead, the parameters are adjusted in Klobuchar's equation to develop a new approximate form for spaceborne GPS users which reduces computational time using equation (16) in terms of semicircles.

$$\psi = \frac{700}{E_A + 25} - 6 \quad \text{(semicircles)} \quad (16)$$

where E_A is elevation angle

Slant factor is the another related parameter which can be defined as the secant of the zenith angle at the mean ionospheric height. The approximate form of enhanced slant factor was computed using equation (17) in terms of semicircles.

$$F_I(Z) = 1 + 1.7\left(\frac{95 - E_A}{90}\right)^{2.75} \text{(semicircles)} \quad (17)$$

The Enhanced Klobuchar algorithm to run in a single frequency receiver is provided as follows:

Initially the Earth centered angle ψ using equation (16).

Then the sub ionospheric latitude is calculated using equation (4). The sub ionospheric longitude is calculated using equation (5). The geomagnetic latitude is calculated using equation (6).

Local time of IPP is calculated using equation (7). The amplitude, period and phase of ionospheric delay were calculated using equations (8), (9), & (10) respectively. The slant factor is calculated using equation (17).

The ionospheric time delay has been calculated in terms of seconds using equations (8), (9), & (10) which is given as equation (18).

$$T_{IONO} = [5 * 10^{-9} + \sum_{n=0}^{3} \alpha_n \phi_m^n * (1 - \frac{x_I^2}{2} + \frac{x_I^4}{24})]*F_I \text{ (seconds)} \quad (18)$$

Then the ionospheric error in meters of delay has been calculated by multiplying speed of light (c) to convert the ionospheric time delay in seconds to meters of delay using equation (19).

$$iono_{error} = T_{IONO} * c \text{ (meters)} \quad (19)$$

Total electron content (TEC) of Klobuchar algorithm has been calculated using equation (20) in terms of TECU.

$$tec_{modklobuchar} = \frac{iono_{error} * f^2}{40.3} \quad (20)$$

III. RESULTS

The processing of algorithms was carried out in MATLAB software of version 2019a. The data was collected from IGS receiver located at Hyderabad, Telangana, India of year 2016. The time, PRN, STEC, elevation and azimuthal angle were extracted from the RINEX file. The time in seconds were converted to local hours. Error in low latitude ionospheric layer is calculated as ionospheric range delay in meters. The error correction in percent deviation of RMS of TEC is recorded for both the algorithms.

The below fig. 2 shows the ionospheric time delay for Klobuchar model and Enhanced Klobuchar model ionospheric delay in meters (y-axis) with respect to time in hours (x-axis).

The fig. 3 shows the expanded image of Ionospheric delay for Enhanced Klobuchar model with ionospheric delay in meters (y-axis) with respect to time in hours (x-axis).

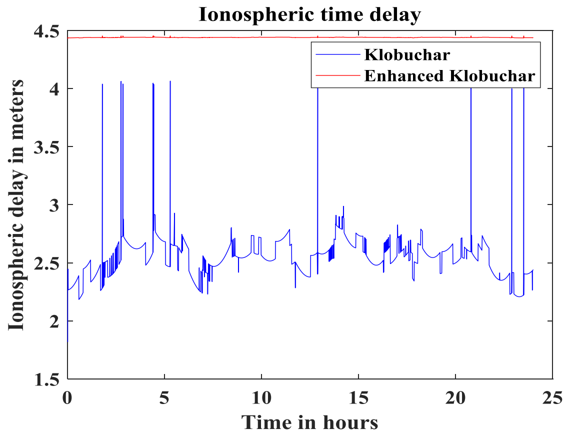

fig. 2 Ionospheric time delay

The ionospheric time delay of Klobuchar algorithm corrects 2-4 meters of delay approximately for day 4 of year 2016. The maximum ionospheric delay is mostly during night time of a day i.e., from 22:00hrs to 06:00hrs.

The ionospheric time delay of Enhanced Klobuchar algorithm corrects 4.3-4.5 meters of delay approximately for day 4 of year 2016. The maximum ionospheric delay is mostly during night time of a day i.e., from 22:00hrs to 06:00hrs.

The percentage deviation of the Klobuchar algorithm is calculated by calculating the total electron content(TEC) of Klobuchar algorithm and STEC values of data in RMS values using equation (1) where the experimental values are the TEC of Klobuchar and Enhanced Klobuchar algorithms and the observed value are the STEC value driven from RINEX data.

To calculate the TEC values of Klobuchar and Enhanced Klobuchar algorithms, equation (14) and equation (20) are used respectively.

The Klobuchar algorithm mitigates the low-latitude ionosphere errors of IGS Receiver of Hyderabad station of year 2016 of 59.43% RMS percentage deviation whereas the Enhanced Klobuchar algorithm for IGS Receiver of Hyderabad station of year 2016 has the percentage deviation of ionospheric errors of 85.19% RMS which clearly says that Enhanced Klobuchar model has more error correction proportion in terms of RMS over Klobuchar model.

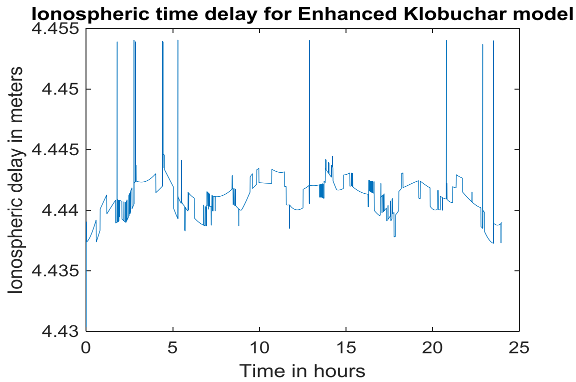

fig. 3 Ionospheric time delay forEnhanced Klobuchar model

The fig. 4 represents the percentage deviation of low-latitude ionospheric errors of IGS Receiver Hyderabad station of year 2016. The maximum difference between Klobuchar model and Enhanced Klobuchar model is occurred in months of April and October. And there is less percentage deviation of error correction in months of Jan, Feb, Nov, andDec.

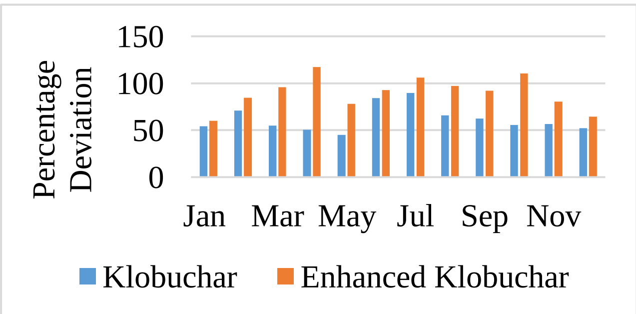

fig. 4 Month wise Percentage Deviation of year 2016 of Hyderabad station

IV. CONCLUSION

In this paper the IGS data has beenanalyzed for the year of 2016, over the low-latitude region of Hyderabad, Telangana, India. The Ionospheric disturbances which effect the GNSS signals were discussed. The algorithms which are used to mitigate the low latitude ionospheric errors have been discussed.The Klobuchar model corrects up to 2-4 meters of delay for day 3 data of year 2016 at Hyderabad station whereas theEnhanced Klobuchar model corrects up to 4.3-4.5 meters of delay for the same data.Time of occurrence of disturbances were mostly found between 01:00 to 05:00 hrs. LT and 20:00 to 24:00 hrs. LT. The methodology was accurate in correcting the ionospheric errors in low latitudes for Klobuchar algorithm.The Klobuchar model corrects up to 59.4% RMS of low-latitude ionospheric errors whereas the Enhanced Klobuchar model corrects up to 85.1% RMS of low-latitude ionospheric errors. This shows that Enhanced Klobuchar model can be effectively used to mitigate the low-latitude ionospheric errors efficiently. These error correction algorithms can also be used over GAGAN data to mitigate Ionosphere induced errors.

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