Evaluation of Nominal Klobuchar Model Performance

Kaijing Zheng, Danielle Racelis

Abstract

Ionospheric delay is a major source of error for GNSS positioning, which is a vital tool in various industries. In particular, for single-frequency users, ionospheric delay presents a major issue.

This paper analyzes the nominal accuracy of the Klobuchar model, an ionospheric correction model for single-frequency GPS users based on a half-cosine function with varying amplitude and period with a fixed nighttime delay, at various latitudes. The delay derived from the IGS GIM (International GNSS Service Global Ionosphere Maps), which is assumed to be accurate in this paper, is compared to the ionospheric delay calculated using the Klobuchar model at 0°N, 30°N, and 60°N. From the experiments, it is seen that at low-latitudes, the Klobuchar model estimates ionospheric delay well and GPS L1 users can expect an average percent error of approximately 20%. At mid-latitudes, the Klobuchar model performs reasonably well, but tends to overestimate the delay by as much as 0.8 meters. Meanwhile, at high-latitudes, the model drastically overestimates ionospheric delay and is highly inaccurate compared to other regions. Our findings show that GPS L1 users can generally expect accurate positioning data at low-latitudes, however at higher-latitudes, the Klobuchar model is not reliable and requires improvement.

1. Introduction

Global Navigation Satellite Systems (GNSS) is an integral part of our modern world, using satellites orbiting the Earth to provide precise location and time information to users on the ground. GPS is the most well-known operated by the United States, but other systems such as GLONASS (Russia), Galileo (Europe), and BeiDou (China) also exist.

Errors in GNSS positioning arise from a variety of factors, such as slight inaccuracies in satellite clocks, variations in the orbit of satellites, receiver noise and tropospheric delay and ionospheric delay. The ionosphere, a layer of the earth's atmosphere that contains a high concentration of ions and free electrons and is able to reflect radio waves, is one of the biggest sources of error in GNSS positioning for single frequency users. Therefore, it is essential to have correction models to calculate and reduce this effect. The most well-known and widely used correction model is the Klobuchar model, which is popular due to its relatively straightforward methodology, based on a half-cosine function.

Much of previous study has compared the Klobuchar model with other single-frequency ionospheric correction models. The NeQuick G model, developed for Galileo, is a three-dimensional and time-dependent ionospheric electron density model based on an empirical climatological representation of the ionosphere and is found to be more accurate than Klobuchar, especially at high latitudes and during intense solar activity [1]. The Neustrelitz TEC models, named NTCM, which takes into account factors such as time variations, geomagnetic coordinates, ionization crest, and solar activity, has been found to possibly improve positioning accuracy by 30% compared with the Klobuchar model [2]. However, since the Klobuchar model is the official broadcast model for Global Positioning System (GPS) users to predict ionospheric delay corrections, it is important to analyze the Klobuchar model to provide GPS L1 users a better understanding of its accuracy.

In this study, the accuracy of the Klobuchar model at various latitudes, ranging from low to high latitude is analyzed. Delay is calculated using the Klobuchar coefficients and compared to the delay derived from the IGS GIM (International GNSS Service Global Ionosphere Maps). The delay derived from the IGS GIM is assumed to be accurate for this paper as it is one of the best ionospheric products with higher accuracy and reliability relative to individual GIMs used in the combination, which indicates that it is an excellent product to assess the consistency of different ionospheric models [3].

2. Ionosphere and Klobuchar Model Overview

Atmospheric delay, which consists of tropospheric and ionospheric delay, is a significant contribution to error in GPS. In comparison to the troposphere, the ionosphere is a dispersive medium, which means that the delay a radio signal faces by the ionosphere is dependent on its frequency. Ionospheric range delays for single-frequency measurements range between 10 centimeters and up to 500 meters while typical total tropospheric range delays are between 2.3 meters and up to almost 30 meters [4].

The ionosphere is a region of Earth’s upper atmosphere that contains a high concentration of ions, ionized by solar radiation. Although the ionosphere does not have sharp boundaries, there are 3 general regions of the ionosphere, which include the D, E, and F layer. The D region is the lowest, extending from 60 to 90 kilometers above the ground. Next is the E layer, ending at around 150 kilometers above ground. The F layer, which has the highest electron density, consists of one layer at night, but during the day, when the ionosphere becomes more heavily ionized, it forms into 2 layers. The ionosphere is always in flux, with constant variations in height and density. Changes are primarily driven by the sun’s activity, so in addition to daily fluctuations in the ionosphere, there are also seasonal changes as the intensity of solar activity varies. Furthermore, space weather phenomena, such as solar flares and geomagnetic storms, have large effects on the ionosphere.

As radio waves enter Earth's atmosphere from space some of the waves are absorbed by the electrons in the ionosphere while others pass through and are detectable to ground based observers. The frequency of the waves determines whether or not they will be absorbed or pass through the atmosphere. Lower frequency radio waves do not travel very far and are absorbed quickly or reflected back. Higher frequency waves are able to go further before being reflected. The free electrons in the ionosphere cause radio signals to refract as they pass through, leading to a delay.

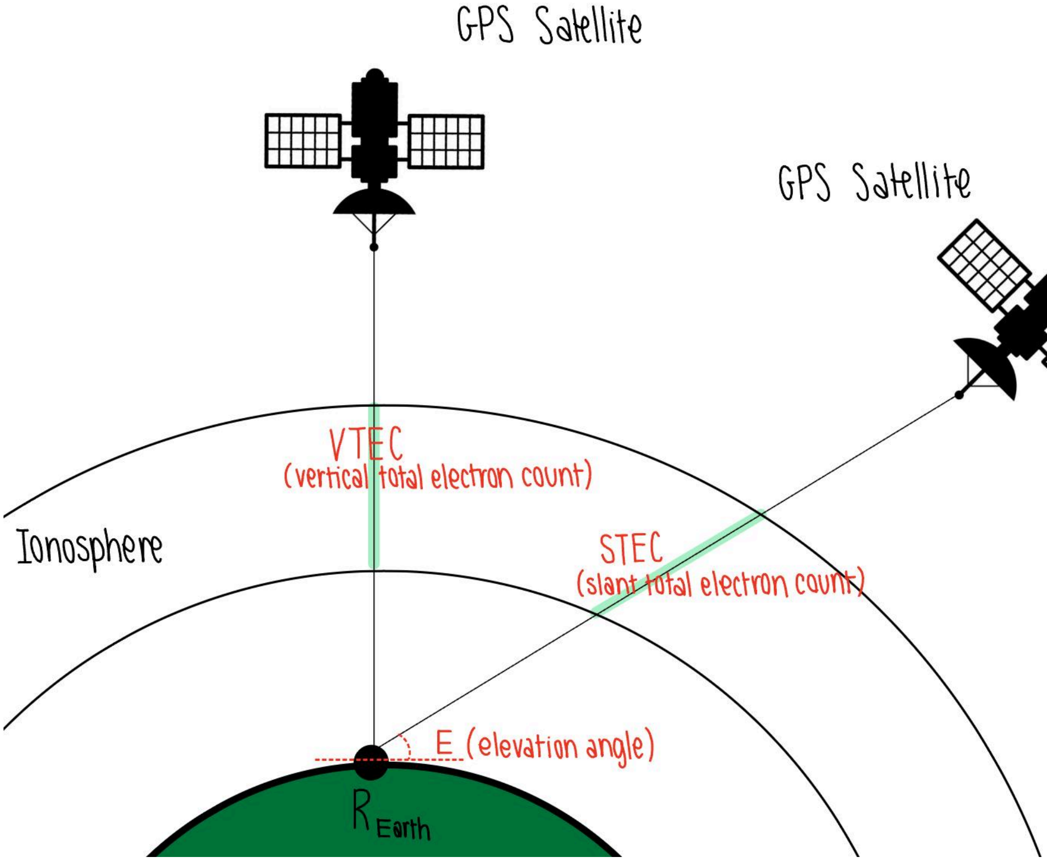

Figure 1: Depiction of how the ionosphere causes disturbances to radio waves passing through (Not to scale)

The frequency dependence of the ionospheric effect is described by the following expression [5]:

$$Delay = \frac{40.3}{c \cdot f^2} \cdot TEC$$

$$c = speed\ of\ light\ in\ meters\ per\ second$$

$$f = frequency\ of\ signal\ in\ Hertz$$

As ionospheric delay is a serious issue regarding the accuracy of GPS, various correction models have been utilized to mitigate the effects of ionospheric delay. One such model is the Klobuchar ionosphere model, designed to minimize user computational complexity and user computer storage. It is currently the most widely used model for single-frequency GPS users. The broadcast model is based on an empirical approach and is estimated to reduce about 50\% RMS (Root Mean Square) ionospheric range error worldwide. However, its performance is less than perfect during severe space weather, geomagnetic and ionospheric disturbances. The Klobuchar model assumes the ionosphere is a single layer at the height of 350 kilometers and gives a representation of the mean vertical delay at the GPS L1 frequency as a half-cosine function with varying amplitude and period with a fixed nighttime delay. The Klobuchar model based ionospheric delay is calculated from eight parameters broadcasted in the navigation message by GPS satellites [6].

3. Data Preparation

In order to determine the accuracy of the nominal Klobuchar ionospheric model, the ionospheric delays must be calculated using both the Klobuchar ionospheric model and from the IGS GIM (International GNSS Service Global Ionosphere Maps). The Klobuchar-derived ionospheric delays are compared to the IGS GIM-derived ionospheric delays, which have centimeter-level errors.

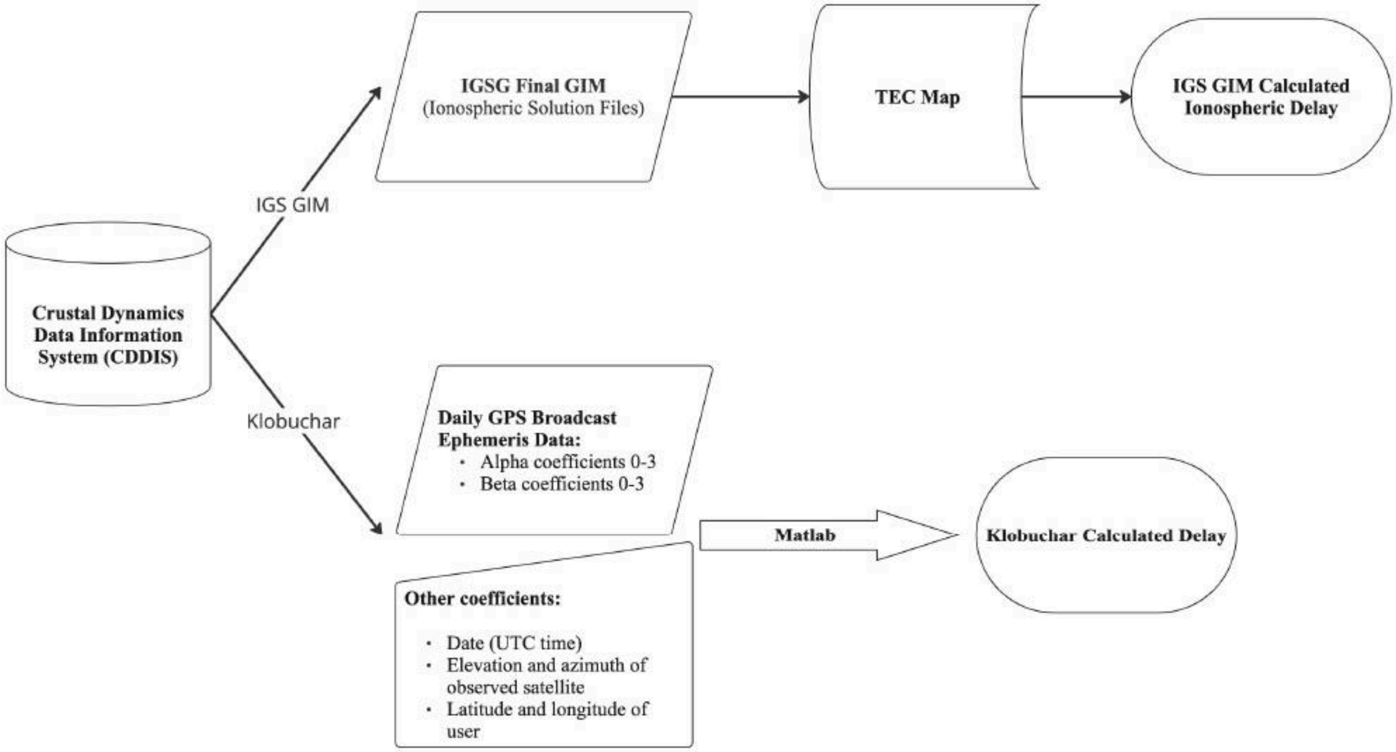

Figure 2: General methodology of calculating the delay using both the Klobuchar Model and IGS GIM

3.1 Site and Date Identification

Prior to calculating the delays,an appropriate site, date and time must be chosen. In order to ensure the accuracy of both calculations, the date, latitudes and longitudes imputed into the Klobuchar model must match the latitude and longitude of the site chosen from the IGS Network.

The longitude chosen is 0°E, in order to remain consistent across all calculations. For the purpose of analyzing the accuracy of the Klobuchar model at various latitudes, latitudes of 0°N, 30°N, and 60°N, were chosen to incorporate low-latitude, mid-latitude, and high-latitude regions to properly access the accuracy at various regions of the earth. Due to the general symmetry of the earth around the earth, there is no need to analyze the delay at 30°S and 60°S, since it can be assumed they should align with the results from 30°N and 60°N.

The date chosen for analyzing the accuracy of the model was December 1, 2019. The last solar cycle minimum, which is when the sun is least active, occurred in December 2019. Solar activity greatly leads to a greater amount of ionized particles in the ionosphere, elevating TEC and causing variations throughout a single day and different seasons. As such, this date in winter during a solar minimum was chosen to ensure a lower TEC count for an analysis of the nominal accuracy of the Klobuchar model.

3.2 Ionospheric Delay Using the Klobuchar Model

To calculate the delay using the Klobuchar model, the date in UTC time, which includes the year, month, day, hour, minute, and second, elevation and azimuth of the satellite, the latitude and longitude of the user, and the alpha and beta parameters from the broadcast ephemeris data must be found.

The alpha and beta parameters, which number eight in total, are accessed from the daily broadcast files from the CDDIS (Crustal Dynamics Data Information System) in the header. Each year's folders contain folders for each day of year and inside each day of year folder are navigation files, which contain files corresponding to different sites from the IGS Network, as well as one, non-redundant file that can be utilized by users instead of the many individual navigation files - the brdc file. After locating the alpha and beta partners, they are inputted into the Klobuchar equations through a Matlab model to calculate ionospheric delay in meters at the chosen latitude and longitude of the selected date at one hour increments.

For the purpose of this paper, the elevation and azimuth of the observed satellite 90°N and 0°E respectively. The Klobuchar model calculates the slant delay from the vertical delay at the Ionospheric Pierce Point multiplied by an obliquity factor [6]. Lower elevation angles increase the ionospheric delay since the signal must take a longer path to reach the Earth receiver as seen in figure 3. As the purpose of this paper is to analyze the nominal performance, it is important to make to calculate the least amount of delay in meters using the Klobuchar model at the selected regions.

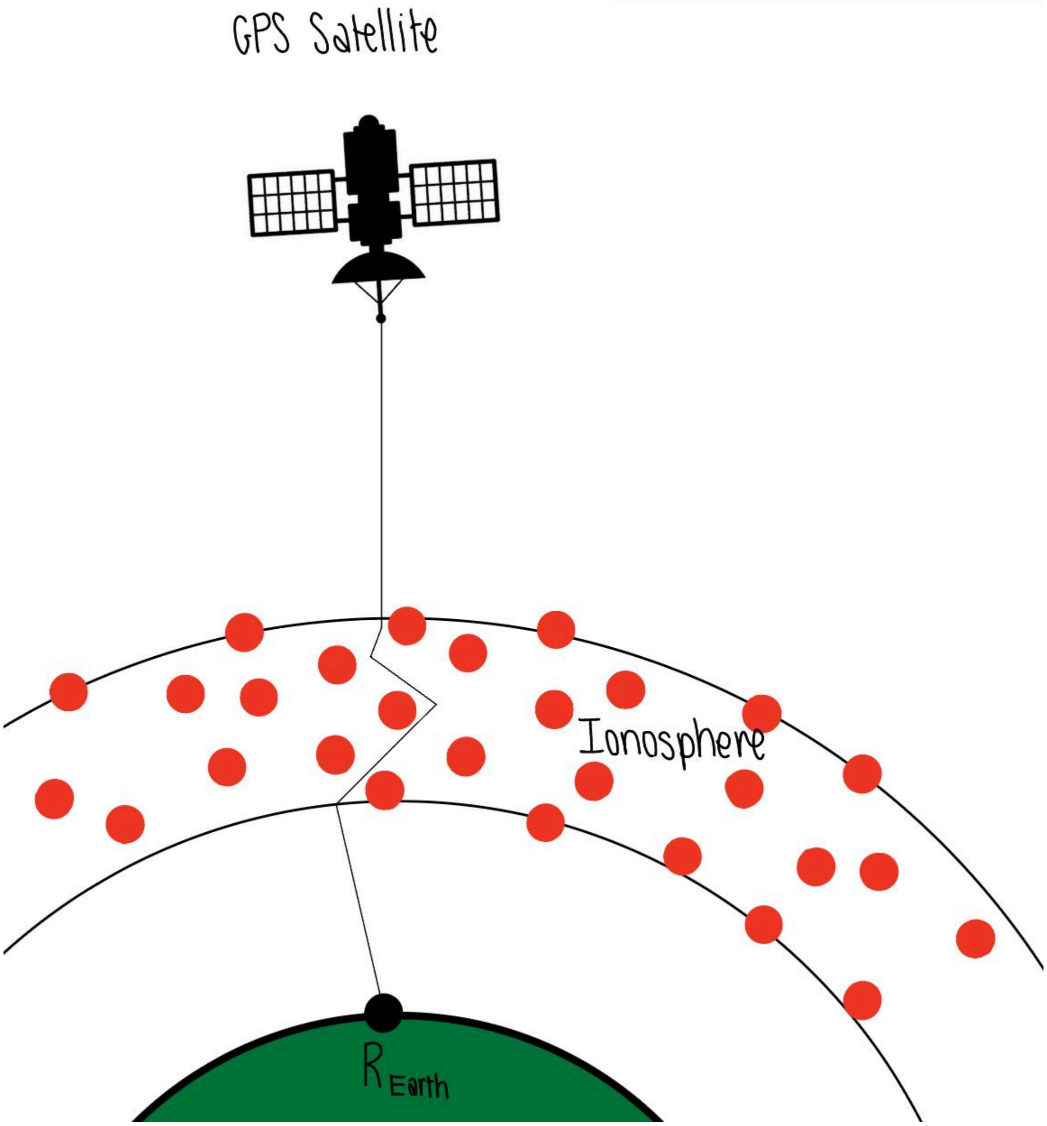

Figure 3: Depiction of the effect of a lower elevation angle on ionospheric delay due to the longer path the signal must traverse between the satellite and the receiver

The Klobuchar model equations are as follows [6]:

$$E = elevation\ angle$$

$$A = azimuth\ of\ observed\ satellite$$

$$\phi_u = user\ latitude$$

$$\lambda_u = user\ longitude$$

$$a_n = alpha\ coefficients\ broadcasted\ in\ satellite\ navigation\ message$$

$$b_n = beta\ coefficients\ broadcasted\ in\ satellite\ navigation\ message$$

1. Calculate the earth-centered angle (elevation in semicircles):

$$\psi = \frac{0.0137}{E + 0.11} - 0.022$$

2. Compute the latitude of the Ionospheric Pierce Point:

$$\phi_I = \phi_u + \psi cos(A)$$

3. Compute the longitude of the Ionospheric Pierce Point:

$$\lambda_I = \lambda_u + \frac{\psi sin(A)}{cos(\phi_I)}$$

4. Find the geomagnetic latitude of the Ionospheric Pierce Point (semicircles):

$$\phi_m = \phi_L + 0.064 cos(\lambda_I - 1.617)$$

5. Find the local time at the Ionospheric Pierce Point:

$$t = 43200\lambda_I + t_{GPS}$$

6. Compute the amplitude of the ionospheric delay:

$$A_I = \sum_{n=0}^{3} \alpha_n \phi_m^n$$

7. Compute the period of ionospheric delay:

$$P_I = \sum_{n=0}^{3} \beta_n \phi_m^n$$

8. Compute the phase of ionospheric delay:

$$X_I = \frac{2\pi(t-50400)}{P_I}$$

9. Compute the slant factor:

$$F = 1.0 + 16.0(0.53 - E)^3$$

10. Compute the ionospheric time delay:

$$I_{L1} = 5 \cdot 10^9 + \sum_{n=0}^{3} \alpha_n \phi_m^n \cdot \left(1 - \frac{X_I^2}{2} + \frac{X_I^4}{24}\right) \cdot F,\ if\ |X| \leq 1.57$$

$$I_{L1} = 5 \cdot 10^9 \cdot F,\ if\ |X| \geq 1.57$$

3.3 Ionospheric Delay Using GIM

To calculate the delay using GIM (Global Ionosphere Maps), the latitude and longitude of the user and the data regarding the TEC (Total Electron Count) is required. The files for the TEC are accessed from the CDDIS (Crustal Dynamics Data Information System), which holds the ionospheric solution files. These files contain folders from each year and inside each folder for a specific year, there are folders for each day of year.

Inside the day of year folder contains data on the GIM (Global Ionosphere Maps) from various IAAC (Ionosphere Associated Analysis Centers) and data from a combination of IAAC. Currently, there are eight IAAC, which include CODE/Switzerland, ESOC/Germany, JPL/U.S.A, UPC/Spain, CAS/China, WHU/China, NRCan/Canada and OPTIMAP/Germany. Each IAAC computes their GIMs independently and with different methods. Products include predicted, rapid and final GIMs (Global Ionosphere Maps) which give the ionospheric TEC in various increments of latitude and longitude. Out of the three main types, the final GIM provides a more accurate ionosphere map [5]. In addition to the GIMs provided by individual analysis centers, GIMs that are a combination of multiple TEC maps are also provided.

Previous investigations show that the IGSG, which combines data from multiple IAACs, is one of the highest precision final GIM products and is often used to validate the performance of other GIM products [8]. Therefore, for the calculated delay using the Klobuchar model, the final GIM IGSG is chosen. After opening the file corresponding to the IGSG GIM at the chosen date of December 1, 2019, the TEC at various latitudes, longitudes and hours of the day is found. Using Matlab, the TEC for 0°N, 30°N, and 60°N and 0°N throughout the twenty-four hours of the day December 1, 2019 is found. The ionospheric delay is then calculated from the TEC [5].

$$Delay_{L1} = 40.3 \cdot f_{L1} \cdot TEC \cdot 10^{16}$$

4. Results

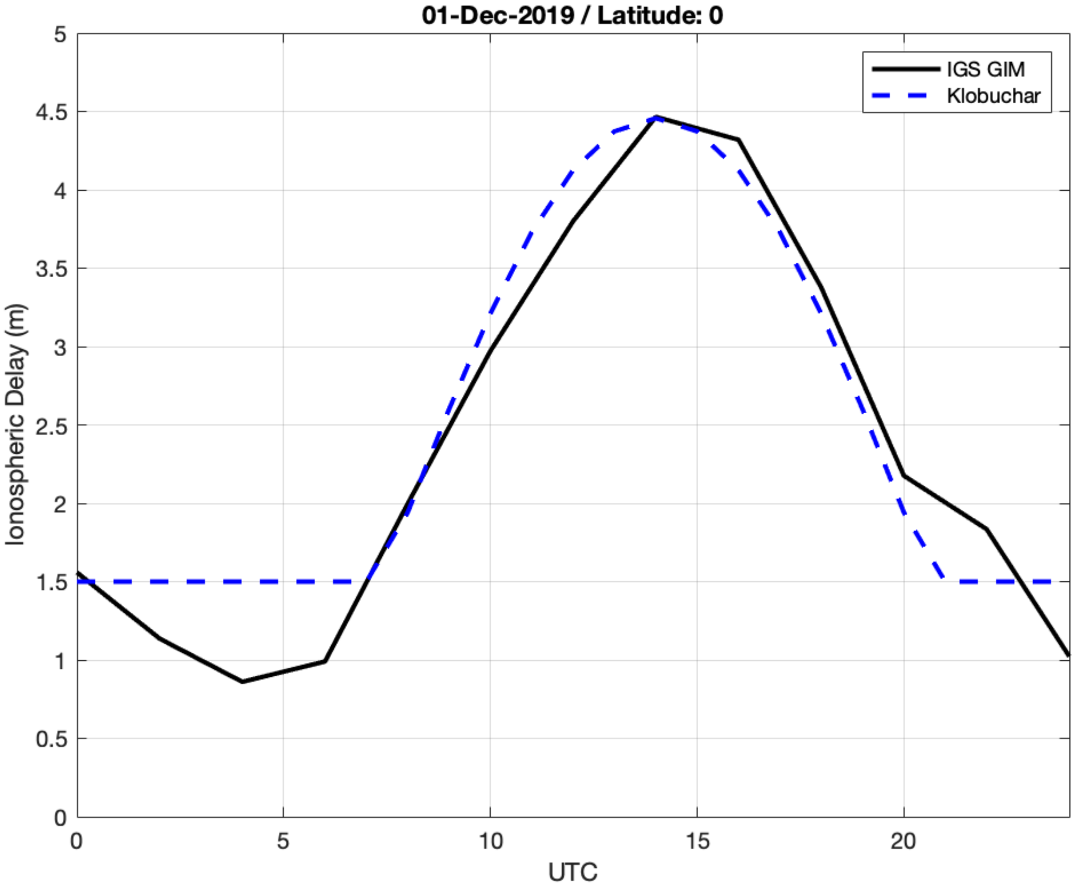

Figure 4: Ionospheric delay computed using Klobuchar Model and IGS GIM for December 1 2019 at 0°N and 0°E

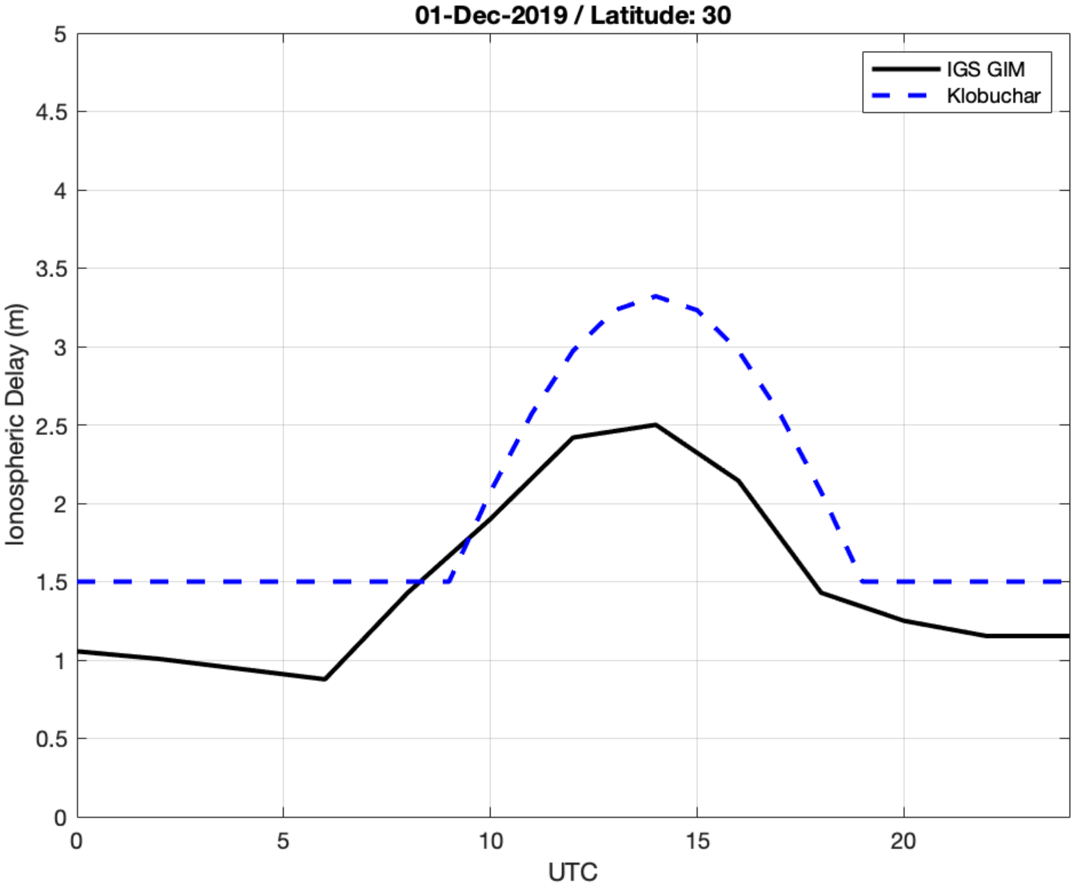

Figure 5: Ionospheric delay computed using Klobuchar Model and IGS GIM for December 1 2019 30°N and 0°E

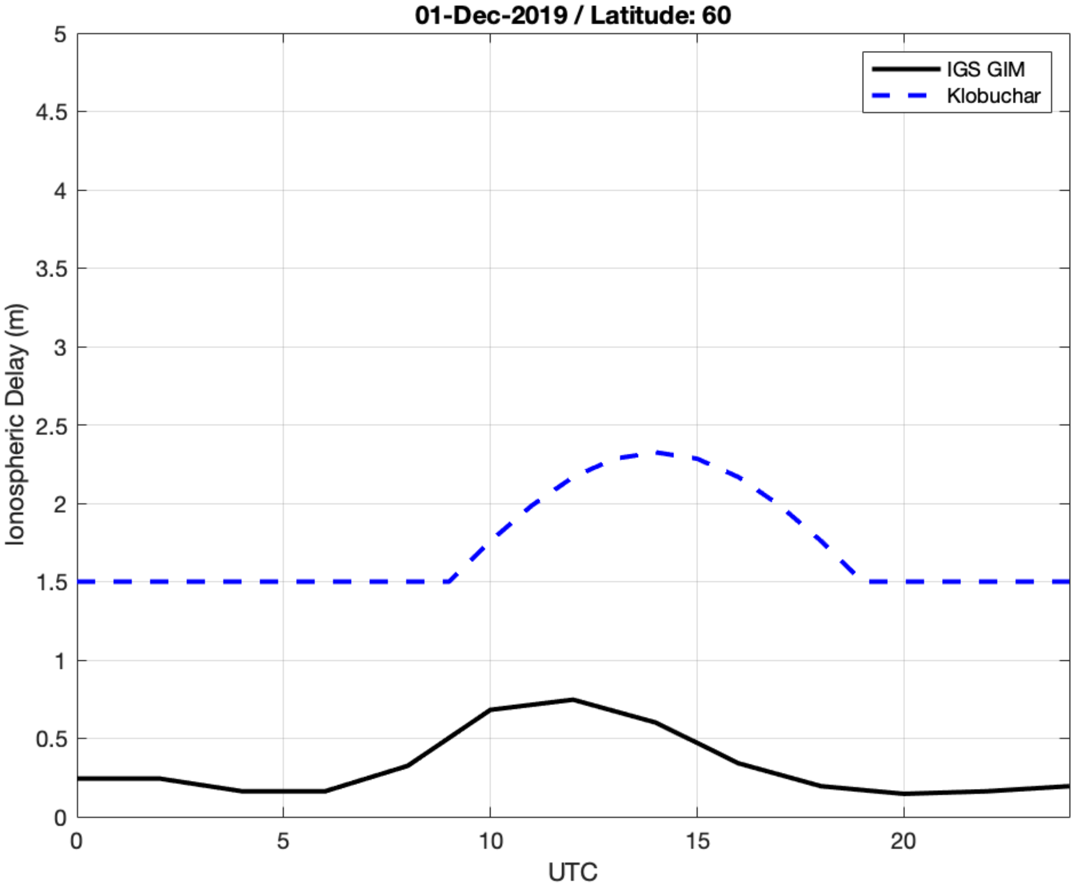

Figure 6: Ionospheric delay computed using Klobuchar Model and IGS GIM for December 1 2019 60°N and 0°E

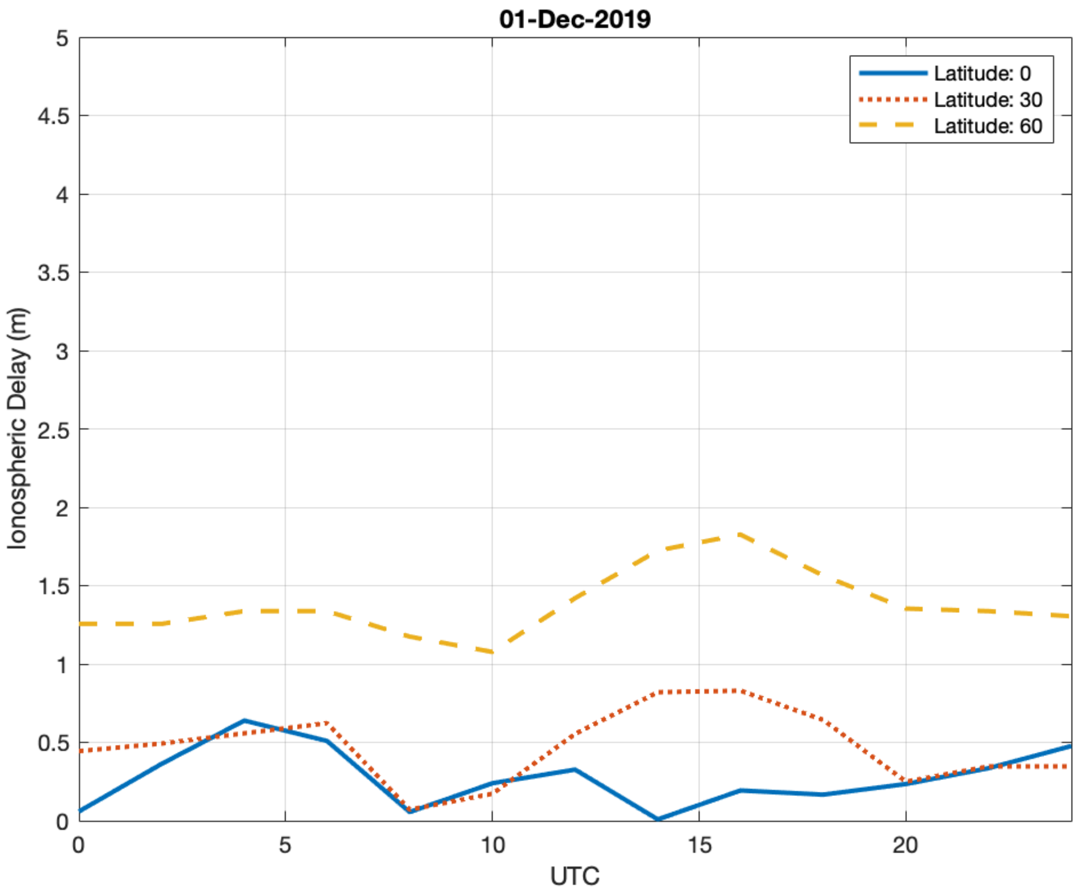

Figure 7: Difference in delay computed using Klobuchar Model and IGS GIM for December 1 2019 at 0°N, 30°N, and 60°N and 0°E

At all latitudes, the Klobuchar model tends to overestimate the nighttime ionospheric delay, in some cases, by over 2 meters. At 0°N, the Klobuchar model is the most accurate, having almost a negligible difference of less than 0.1 meters from the IGS GIM derived ionospheric delay at 0:00, 8:00 and 14:00 UTC. However as the latitude increases to 30°N and 60°N, the difference between the Klobuchar model derived ionospheric delay and the IGS GIM derived ionospheric delay becomes greater and greater, having a maximum difference of 1.8 meters at 60°N at 16:00 UTC.

5. Discussion

This paper explores the nominal accuracy of the Klobuchar model at 0°E longitude, and at three example latitudes: 0°N, 30°N, and 60°N. The accuracy of Klobuchar-based ionospheric delays is evaluated by comparing it with that derived from the reference IGS GIM ionospheric delay. The results show that the Klobuchar model is most accurate at equatorial regions, with an average error of 0.2 meters throughout the day. The Klobuchar-model-based errors increase at higher latitudes, with as much as 1.8 meters of error at high latitudes. From the data, it can be seen that at low and mid-latitudes, the Klobuchar model tends to overestimate the night-time ionospheric delay.

Our findings concerning the nominal accuracy of the Klobuchar model present what GPS L1 users can generally expect regarding the accuracy of their navigation and positioning services. Previous work has discussed the limitations of the Klobuchar model, particularly its use of a constant value for calculating the nighttime ionospheric delay. Some specialists have discussed improving the performance of the Klobuchar model from re-estimating the eight Klobuchar coefficients or reconstructing the Klobuchar model by adding more parameters. The NVTEC (Nighttime Vertical Total Electron Content) average is a significant parameter in Klobuchar model and based on a past study, the use of a fixed 9 TECU in the Klobuchar model for certain navigation and positioning applications is not adequate due to large deviations at different seasons and latitudes [9]. Our study extends upon analyzing the reliability of the nighttime constant in the Klobuchar model to analyzing the model's predicted delay as a whole at different latitudes in order to better assess its accuracy.

The Klobuchar model is the most widely used ionospheric correction model for GPS L1 users. Although there are other correction models that provide more accuracy, the Klobuchar model is popular due to its simplicity. Similarly, dual-frequency GPS is much more accurate and reliable than single-frequency, but is costly and therefore, not as widely used by civilians. GPS accuracy is vital in a variety of fields, such as precision agriculture, autonomous applications and marine applications. When it comes to precision farming, a few centimeters of error in machine positioning can severely impact operations by increasing input waste, reducing efficiency and decreasing production. Because of the mass production of vehicles, automotive positioning is often achieved through low-cost GNSS chipsets, however, GNSS positioning is not as accurate or as resilient to ionospheric scintillation when only one frequency is used. GNSS is vital for operations at sea, particularly when offshore, where there are no landmarks to navigate by. Also, nearshore applications like dredging, port operations and hydrographic survey rely on precise GNSS positioning for efficient operations and the safety of vessels and crew. When ionospheric interference occurs, operations must entirely stop to maintain safety standards, which can be costly. Therefore, it is of utmost importance to research and analyze the accuracy of the Klobuchar model to better understand its precision and limitations for future improvement.

Overall, our study shows that the Klobuchar model is most accurate at low-latitudes in comparison to mid and high-latitude regions, however, more study should be conducted during varying ionospheric conditions to further validate this claim. However, the Klobuchar model's relative inaccuracy holds many negative implications for industries requiring the use of single-frequency GPS in high-latitude regions. Beyond work already done, there is definitely more room for research to be done on the improvement of ionospheric correction models that can benefit all of mankind due to the almost universal use of GNSS.

6. Conclusion

Ionospheric delay caused by scintillation is considered as one of the biggest errors for single frequency use of space based Global Navigation and Satellite System (GNSS). Delay is a serious issue for GNSS so correction models are required for mitigating ionospheric propagation errors. The most well-known and widely used correction model is the Klobuchar model, which is popular due to its relatively straightforward methodology, based on a half-cosine function. In this study, the accuracy of the Klobuchar model at low, mid, and high-latitudes are analyzed. Delay is calculated using the Klobuchar coefficients and compared to the delay derived from the IGS GIM (International GNSS Service Global Ionosphere Maps), which is assumed to be accurate for this paper as it is one of the best ionospheric products with higher accuracy and reliability relative to individual GIMs used in the combination, which indicates that it is an excellent product to assess the consistency with different ionospheric models [3]. At low-latitudes, the Klobuchar model estimates ionospheric delay well and GPS L1 users can expect an average percent error of approximately 20%. At mid-latitudes, the Klobuchar model performs reasonably well, but tends to overestimate the delay by as much as 0.8 meters. At high-latitudes, the model drastically overestimates ionospheric delay and is highly inaccurate compared to other regions.

References

1. U. Ngayap, C. Paparini, M. Porretta, P. Buist, K. S. Jacobsen, M. Dähnn, N. Hanna, D. Halilovic, A. Świątek, and Paulina Gajdowska, “Comparison of NeQuick G and Klobuchar Model Performances at Single-Frequency User Level,” *Engineering Proceedings*, vol. 54, 2023.
2. X. Zhang, F. Ma, X. Ren, W. Xie, F. Zhu, and X. Li, “Evaluation of NTCM-BC and a proposed modification for single-frequency positioning,” *GPS Solutions,* p. 1535–1548, 2017.
3. J. Chen, X. Ren, X. Zhang, J. Zhang, and L. Huang, “Assessment and Validation of Three Ionospheric Models (IRI-2016, NeQuick2, and IGS-GIM) From 2002 to 2018,” *Space Weather*, vol. 18, 2020.
4. G. Seeber, *Satellite Geodesy Foundations, Methods, and Applications 2nd Edition*. De Gruyter, 2003.
5. P. Misra, *Global Positioning System: Signals, Measurements, and Performance (Revised Second Edition*). Ganga-Jamuna Press, 2012.
6. J. A. Klobuchar, “Ionospheric Time-Delay Algorithm for Single-Frequency GPS Users,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-23, 1987.
7. J. Chen and Y. Gao, “Real-Time Ionosphere Prediction Based on IGS Rapid Products Using Long Short-Term Memory Deep Learning,” *NAVIGATION: Journal of the Institute of Navigation*, vol. 70, no. 2, 2023.
8. H. Liu, X. Ren, and G. Xu, “Investigating the Performance of IGS Real-Time Global Ionospheric Maps under Different Solar Conditions,” *Remote Sens*., vol. 15, 2023.
9. W. Zhou, S. Song, Q. Chen, N. Cheng, and H. Xie, “Determination of nighttime VTEC average in the Klobuchar ionospheric delay model,” *Geodesy and Geodynamics,* vol. 9, 2018.