Accuracy Analysis of The Ionospheric Mitigation Effect Using Klobuchar Model And Ionosphere Free LC Method

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Abstract. Precise Point Positioning (PPP) of a Global Navigation Satellite System (GNSS) can be considered as an alternative solution from the differential GNSS positioning technique. Recently, PPP technique takes the spotlight due to its low cost and large number of users. Initially dual frequency PPP technique was implemented using GPS only observations. Nowadays, it has started to combine GPS+GLONASS observations in order to improve the position accuracy and reduce the convergence time. The main objective of this research is to examine the performance ionospheric correction methods of the real time PPP using RTKLIB. RTKLIB is an open source program package for GNSS positioning. The overall results show that the ionosphere free LC method of real time RTKLIB PPP present better accuracy rather than Klobuchar model for all positioning modes.

1. Introduction
In the last decade, it has been demonstrated that Precise Point Positioning (PPP) is capable of providing accurate position solutions at centimeter level for static applications, and at decimeter level for kinematic applications, using a dual frequency receiver. Based on the carrier phase observables along with the pseudorange, centimetrelevel positioning performance has been made available with very short observation time at the user end. This technique is called real-time kinematic (RTK)5; 9. The method RTK uses to deal with errors is observation space representation (OSR), by which the sum of error components is represented in observation space. In 2009, Takasu and Yasuda published RTKLIB program packages. This program can be used to conduct measurements GPS modules using various precise positioning methos such as static post processing, kinematic post processing as well as realtime kinematic GPS7.

The simplest and the most popular method to mitigate the ionospheric error is the use of the ionospheric coefficients broadcast from GNSS satellites in combination with the Klobuchar model because of its flexibility, single frequency, simplicity and cost-effectiveness. Although this method has the advantage that it can be also implemented in real-time, the Klobuchar model with broadcast ionospheric coefficients can only mitigate 50-60% of the total ionospheric effect3; 4.

The objective of this paper is to analysis the accuracy of of the ionospheric mitigation effect using Klobuchar model and Ionosphere Free Linear Combination (LC) method. Ionosphere Free Linear Combination (LC) method is ionospheric effect mitigation method for PPP using linear combination of GNSS observation on L1 and L2 frequencies to minimize the ionospheric bias on GNSS.
observation. For case study, GNSS data from BAKO station located at low latitude region during quiet and storm condition have been used to analyze the performance of Klobhuchar model and iono free LC method.

2. Theory

2.1 Klobuchar Model

Modern knowledge of the ionosphere has provided an adequate comprehension of its morphology as well as the basic mechanisms caused by solar radiation. The Klobuchar ionospheric model has been widely used due to its well-known properties such as computational simplicity. It is assumed that all free electrons of the ionosphere are densely distributed in a shell located at a fixed altitude of 350 km above Earth’s surface. For the pseudorange delay on the L1 frequency, the model is built on a constant offset term at night and a simple half-cosine function centered about 2:00 pm local time during the day\(^\text{10}\). With the series expansion of the cosine function, the Klobuchar ionospheric model can be expressed in the following equations.

\[
T_{\text{iono}} = \begin{cases} 
F \times DC + AMP \times \left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right), & |x| < 1.57 \\
F \times DC, & |x| \geq 1.57
\end{cases} 
\tag{1}
\]

\[
AMP = \begin{cases} 
\sum_{n=0}^{3} \alpha_n \phi_m^n, & AMP \geq 0 \\
AMP = 0, & AMP < 0
\end{cases} 
\tag{2}
\]

\[
PER = \begin{cases} 
\sum_{n=0}^{3} \beta_n \phi_m^n, & PER \geq 72000 \\
PER = 72000, & PER < 72000
\end{cases} 
\tag{3}
\]

\[F = 1.0 + 16.0 (0.53 - E)^3\]  
\[\phi_m = \phi_i = 0.064 \cos (\lambda_i - 1.617)\]  
\[\lambda_i = \lambda_o + \frac{\Psi \sin A}{\cos \phi_i}\]  
\[\phi_i = \begin{cases} 
\phi_i + \Psi \cos A, & |\phi_i| \leq 0.416 \\
\phi_i = 0.416, & \phi_i > 0.416 \\
\phi_i = -0.416, & \phi_i < -0.416
\end{cases}\]  
\[
\Psi = \frac{0.0137}{E + 0.11} - 0.022\]  
\[t = 4.32 \times 10^4 \lambda_i + \text{GPS time}\]
where

DC is the nighttime constant offset term of the vertical time-delay (5 £ 10⁻⁹ s), AMP is the amplitude term of the cosine function, namely the maximum time-delay in daytime, PER is the period of the cosine function, and implicates the interval of the ionospheric activity in daytime, 50400 means the local time of the maximum vertical ionospheric delay (seconds), namely 14:00 hours of the day, \( \phi_m \) is the geomagnetic latitude of the earth projection of the ionospheric intersection point (mean ionospheric height 350 km) (semi-circles), \( \lambda_i \) is the geodetic longitude of the earth projection of the ionospheric intersection point (semi-circles), \( \phi_i \) is the geodetic latitude of the earth projection of the ionospheric intersection point (semi-circles), \( \phi_u \) is the user geodetic latitude (semi-circles) in WGS-84, \( \lambda_u \) is the user geodetic longitude (semi-circles) in WGS-84, \( \Psi \) is Earth’s central angle between the user position and the earth projection of the ionospheric intersection point (semi-circles), E is the elevation angle between the user and satellite (semi-circles), A is the azimuth angle between the user and satellite, measured clockwise positive from the true North (semi-circles), \( t \) is the local time (s), F is the obliquity factor projecting vertical ionospheric delay into the line-of-sight, \( \alpha_n, \beta_n \) (n = 0, 1, 2, 3) are the GPS broadcast message and are selected from 370 sets of constants that are based on 37 sets of seasonal values for a ten-day interval and the five-day running average of the observed solar flux numbers, which are separated into 10 different solar activity levels.

2.2 Ionosphere Free Linear Combination (LC) Method

To eliminate the ionosphere effects in the GNSS signal measurements, a LC (linear combination) of dual-frequency measurements is often utilized in GNSS data processing. The ionosphere-free LC of \( L_i \) and \( L_j \) pseudorange and phase-range are expressed as:

\[
P_{Y,LC} = C_i P_{Y,i} + C_j P_{Y,j} \tag{10}
\]

\[
\phi_{Y,LC} = C_i \phi_{Y,i} + C_j \phi_{Y,j} \tag{11}
\]

where \( C_i \) and \( C_j \) are the coefficients of the ionosphere free LC. The \( C_i \) and \( C_j \) are derived from:

\[
C_i = \frac{f_i^2}{f_i^2 - f_j^2} \quad \text{and} \quad C_j = \frac{-f_j^2}{f_i^2 - f_j^2} \tag{12}
\]

where \( f_i \) and \( f_j \) are the frequencies (Hz) of \( L_i \) and \( L_j \) measurements. Current version RTKLIB always uses \( L_1 \) and \( L_2 \) for GPS, GLONASS and QZSS, \( L_1 \) and \( L_5 \) for Galileo for the ionosphere-free LC. If setting the processing option "Ionosphere Correction" to "Iono-Free LC" in the Single or PPP modes, the ionosphere-free LC is used for basic measurements to eliminate the ionosphere term. Note that the ionosphere-free LC model is not applied for the Kinematic, Static or Moving-base modes.

3. Data and Method

In order to conduct the accuracy analysis, 24-hour daily observation datasets collected from SUGAR station. For case study, we used TEC Data on August 14, 2018; October 29-31, 2003 and

After that, the data processing is done for Klobuchar model, by using equation (1) until to (9). And then, for Ionosphere Free LC method is done by using equation (10) until to (12).
Figure 1. (Left) Positioning error of hourly GPS TEC data on March 17, 2013 from Klobuchar model and (right) from ionosphere free LC method.

The output in Figure 1 then convert to be position (centimeter).

Figure 2. (Left) Positioning error (in centimeter) of hourly GPS TEC data on March 17, 2013 from Klobuchar model and (right) from ionosphere free LC method.

The output from Klobuchar model and Ionosphere Free LC method are compared and analysis.

The last, is conclusion.
4. Result and Analysis

**Figure 3.** (Top) Dst Index on August, 2018 ([http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/201808/index.html](http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/201808/index.html)); (bottom) Improvement of positioning error between Klobuchar model and Ionosphere Free LC method on August 14, 2018.

**Figure 4.** (Top) Dst Index on October, 2003 ([http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/200310/index.html](http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/200310/index.html)); (Bottom) Improvement of positioning error between Klobuchar model and Ionosphere Free LC method on October 29-31, 2003 (Halloween day).
Figure 5. (Top) Dst Index on March, 2013 (http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/201303/index.html); (Bottom) Improvement of positioning error between Klobuchar model and Ionosphere Free LC method on March 17-18, 2013.

From Figure 3, shown geomagnetic activity and Improvement of positioning error between Klobuchar model and Ionosphere Free LC method during quiet time condition (no storm). It is clear that the differences between Klobuchar model and Ionosphere Free LC method in quiet time condition are not more than 5 centimeter (±3%).

From Figure 4, it is clear that the differences between Klobuchar model and Ionosphere Free LC method in storm time condition are 50 centimeter or more (±70%).

From Figure 5, it is clear that the differences between Klobuchar model and Ionosphere Free LC method in storm time condition are 30 centimeter or more (±85%).

From data processing result, we can see that Ionosphere Free LC method better that Klobuchar method in all condition.

So, in the storm day condition, Klobuchar model is not good to use in the positioning correction of GPS.

5. Conclusion
The ionosphere free LC method has better performance for PPP especially during ionospheric storm conditions. Meanwhile during quiet condition, the ionosphere free LC method and Klobuchar model have almost the same performance in mitigating the effects of ionosphere on PPP.

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