SINGLE-FREQUENCY IONOSPHERIC-DELAY CORRECTION FROM BEIDOU & GPS SYSTEMS FOR NORTHERN HEMISPHERE

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ABSTRACT. The range delay caused by the ionosphere layer is the major current source of error for GNSS users with single-frequency receivers. GNSS advice users to correct this type of error using ionospheric models whose coefficients are sent in their navigation messages. GPS-users use the Klobuchar model to correct this type of error. GPS navigation message contains the model's eight coefficients which vary on the basis of seasonal ionospheric variations and average solar flux. The correction accuracy of Klobuchar model is about 50% (rms) of the ionospheric range delay. Beidou system calculates and broadcast 8 parameters of Klobuchar model based on continuous monitoring stations. BeiDou system updates the ionospheric coefficients every two hours. GPS-Klobuchar model uses completely different coefficients than BeiDou-Klobuchar model. This research demonstrates a comparison study between the Klobuchar model using the GPS broadcast coefficients and the same model using BeiDou-coefficients. The correction accuracy offered by the two models has been judged using the most accurate International GNSS Service-Global Ionospheric Maps (IGS-GIMs) for three different-latitude stations along northern hemisphere, one station in low-latitude region, the second station is in mid-latitude region and the third station is in high-latitude region to reflect models' behaviour in different geographic regions. The study was applied over three different months of the year 2017 that each of them reflects a different activity state for the ionosphere layer. The study proves that BeiDou model is able to show the ionosphere's day-to-day fluctuations while GPS model can't. It can be concluded that GPS model offers better behaviour than BeiDou model in correcting range delay in low-latitude and high-latitude geographic regions under any activity state for the ionosphere. BeiDou model offers better correction accuracy than GPS model in mid-latitude under any activity state for the ionosphere.

Keywords: Ionospheric-delay, Single-frequency, BeiDou, GPS

1. INTRODUCTION

The quality of GNSS operations are affected by different errors depending on three major error sources; satellite dependent errors, such as (satellite clock error and satellite orbital error), receiver dependent errors such as (antenna phase centre variations and receiver clock error), and signal path dependent errors such as (cycle slip, multipath, tropospheric error and ionospheric error). The ionospheric delay is the current major source of range delay faced by single-frequency GNSS observations (Kunches and Klobuchar, 2001). The applied ionospheric delay mitigation technique depends on the type of collected observations. Since the ionospheric delay is depending on the signal's frequency, so users of dual-frequency receivers can eliminate the first-order term of the ionosphere delay by a combination of dual-

frequency observations. Users of single frequency receivers must use differential or ionospheric correction model. The ionospheric delay is also dependent on the activity of the sun which is varying during the day time and follows a cycle of about eleven years. For mid-latitudes regions, GPS L1 pseudo-range is faced by an ionospheric zenith ranging delay of about 5–15 m on daytime, and 3 m in the evening. As the ionospheric activity is highly variable, so at the peak of solar activity the ionospheric delay can be up to hundreds of meters. Different models are used to eliminate the ionospheric error for single-frequency GNSS users. GPS system users use the Klobuchar model (Klobuchar, 1982) to mitigate the ionospheric delay. GPS control segment broadcasts eight parameters for Klobuchar model based on seasonal ionospheric variations and average solar flux, so the correction accuracy is about 50–60 % (Kunches and Klobuchar, 2001).

BeiDou system broadcasts also eight parameters for Klobuchar model based on continuous monitoring stations under the geographic coordinate system. The ionospheric delay of satellite-station direction can be identified using of dual-frequency pseudoranges. Satellite and receiver hardware delay can be deducted in combination observations. Through projection function, the Vertical Total Electron Content (VTEC) of corresponding puncture point can be evaluated. The eight parameters can be evaluated with the VTEC as model observables, and broadcast to BeiDou users.

This research presents the behaviour of the Klobuchar model using the GPS broadcast coefficients and the same model using BeiDou-coefficients. The ionospheric coefficients for both models used in this research were derived from IGS organization (IGS, 2018a). The ionospheric range delay correction offered by both models has been examined by the IGS-GIMs (IGS, 2018b) for three stations with different-latitudes along northern hemisphere (Table 1) to reflect models' behaviour in different geographic regions. The study covers three different (ionospheric-activity) months of the year 2017 that each of them reflects a different state of the ionosphere layer activity based on the solar activity (SIDC, 2018) (Table 2).

Table 1. The geographical positions of the tested stations.

Station ID	Latitude degree	Longitude degree	Height meters
Aswan (Egypt)	24.088 N	32.899 E	79.000
Sofia (Bulgaria)	42.700 N	23.333 E	549.000
Helsinki (Finland)	60.192 N	24.946 E	17.000

Table 2. The dates, activity states, average Sun Spot number of the tested periods (SIDC, 2018).

Ionospheric Activity state	Quiet	Medium	Active
Tested Month	January ,2017	April, 2017	September, 2017
Monthly Average Sun Spot no.	26.1	32.3	43.7

2. GPS-KLOBUCHAR MODEL

The Klobuchar model (Klobuchar, 1982) is a simple broadcast ionospheric model built on a simple cosine representation of the ionospheric delay. The model was designed based on Bent model (Llewellyn and Bent, 1973). The model has a fixed phase-zero at 14.00 hours local time and a constant night time offset of 5 nanoseconds. Due to the simplicity of model structure, it has been widely used in many single frequency GNSS positioning and navigation applications. The period and amplitude of the ionospheric delay are represented as third degree polynomials in local time and geomagnetic latitude. The eight time-varying

coefficients of the model are broadcast in the GPS navigation message. GPS master control station select those coefficients from 370 possible sets of constants based on two parameters, day of the year and average solar 10.7-cm flux value (Farah, 2008).

The Klobuchar model is generally formulated with monthly median parameters and can only predict the long-time average conditions of the ionosphere (Wang et al., 2016). (Dodson, 1988) concluded that the correction accuracy of the model is about 50-60% of the total delay. The model is unable to show any significant fluctuations from day to day as it assumes an ideal smooth behaviour of the ionosphere (Farah, 2008). (Newby et al., 1990) concluded also that the range error by the model can be of order of 50 m under severe ionosphere activity at low elevations.

Given the user approximate geodetic latitude (ϕ_u), longitude (λ_u), elevation angle in semicircles (E), azimuth (A) of the observed satellite and the coefficients (α_n) and (β_n) broadcasted in the GPS satellite navigation message (Klobuchar, 1987). The earth-centred angle (ψ), the latitude of the Ionospheric Pierce Point (IPP) (ϕ_I) and longitude of the IPP (λ_I) can be calculated using equations (1), (2) and (3) respectively;

$$\psi = \frac{0.0137}{E + 0.11} - 0.022 \quad (\text{semicircles}) \quad (1)$$

$$\phi_I = \phi_u + \psi \cos A \quad (\text{semicircles}) \quad (2)$$

If $\phi_I > +0.416$ the $\phi_I = +0.416$.

If $\phi_I < -0.416$ the $\phi_I = -0.416$.

$$\lambda_I = \lambda_u + \frac{\psi \sin A}{\cos \phi_I} \quad (\text{semicircles}) \quad (3)$$

The geomagnetic latitude of the IPP (ϕ_m) and the local time at the IPP (t) can be estimated using equations (4) and (5) respectively;

$$\phi_m = \phi_I + 0.064 \cos(\lambda_I - 1.617) \quad (\text{semicircles}) \quad (4)$$

$$t = 43200 \lambda_I + t_{GPS} (\text{seconds}) \quad (5)$$

where $\leq t < 86400$,

therefore: If $t \geq 86400$, subtract 86400. If $t < 0$, add 86400.

The amplitude of the ionospheric delay (A_I), the period of ionospheric delay (P_I) and the phase of the ionospheric delay (X_I) could be estimated from equations (6), (7) and (8) respectively;

$$A_I = \sum_{n=0}^3 \alpha_n \phi_m^n \quad (\text{seconds}) \quad (6)$$

if $A_I < 0$, then $A_I = 0$

$$P_I = \sum_{n=0}^3 \beta_n \phi_m^n \quad (\text{seconds}) \quad (7)$$

if $P_I < 72\,000$, then $P_I = 72\,000$.

$$X_I = \frac{2\pi(t - 50\,400)}{P_I} \quad (\text{radians}) \quad (8)$$

Finally the slant factor (F) and the ionospheric time delay (I_{L1GPS}) could be calculated using equations (9) and (10) respectively;

$$F = 1.0 + 16.0 (0.53 - E)^3 \quad (9)$$

$$I_{L1GPS} = \begin{cases} \left[5 \cdot 10^{-9} + \sum_{n=0}^3 \alpha_n \phi_m^n \cdot \left(1 - \frac{X_I^2}{2} + \frac{X_I^4}{24} \right) \right] \cdot F & ; |X_I| \leq 1.57 \\ 5 \cdot 10^{-9} \cdot F & ; |X_I| \geq 1.57 \end{cases} \quad (10)$$

The delay for any GNSS signal (I_f) transmitted on frequency (f) is given by:

$$I_f = \left(\frac{f_{L1GPS}}{f} \right)^2 I_{L1GPS} \quad (11)$$

3. BEIDOU-KLOBUCHAR MODEL

Beidou system uses eight parameters-Klobuchar model for correcting the ionospheric delay for single frequency users. According to; (Zhao et al., 2014) & (Prasad and Sarma, 2004) and (Sharma and Galav, 2011), the zenith ionospheric delay can be calculated as follows;

$$I_z(t) = \begin{cases} 5 \times 10^{-9} + A_2 \cos \left[\frac{2\pi(t - 50,400)}{A_4} \right] & |t - 50,400| < A_4/4 \\ 5 \times 10^{-9} & |t - 50,400| \geq A_4/4 \end{cases} \quad (12)$$

Where;

I_z is the zenith ionospheric delay for signal frequency B1 (seconds).

t is time of intersection between the line of receiver to satellite and the ionosphere (in the range of 0–86400) in seconds.

A_2 is the amplitude of the cosine curve on the day calculated by α_n coefficients.

$$A_2 = \begin{cases} \sum_{n=0}^3 \alpha_n |\phi_M|^n A_2 > 0 \\ 0 & A_2 < 0 \end{cases} \quad (13)$$

A_4 is the period of a cosine curve calculated using the coefficients β_n (seconds).

$$A_4 = \begin{cases} 1,72,800 & A_4 \geq 1,72,800 \\ \sum_{n=0}^3 \beta_n |\phi_M|^n & 1,72,800 > A_4 \geq 72,000 \\ 7,200 & A_4 < 72,000 \end{cases} \quad (14)$$

where, ϕ_M is the latitude of puncture point (radians). ϕ_M and λ_M can be calculated as follows:

$$\phi_M = \arcsin(\sin \phi_u \cos \psi + \cos \phi_u \sin \psi \cos A) \quad (15)$$

$$\lambda_M = \lambda_u + \arcsin\left(\frac{\sin \psi \sin A}{\cos \phi_M}\right) \quad (16)$$

where,

ϕ_u is the user geographic latitude (radians).

λ_u is the user geographic longitude (radians).

A is satellite azimuth (radians).

ψ is geocentric opening angle between user and puncture (radians) which is calculated as follow:

$$\psi = \frac{\pi}{2} - E - \arcsin\left(\frac{R}{R+h} \cos E\right) \quad (17)$$

where,

R is the radius of the Earth (6,378 km).

E is satellite elevation angle (radians).

h is the height of the ionosphere monolayer (375) km.

$$I_z(t) \text{ can be converted to } I_{B1I}(t) \text{ through } I_{B1I}(t) = \frac{1}{\sqrt{1 - \left(\frac{R}{R+h} \cos E\right)}} \cdot I_z(t). \quad (18)$$

4. BEHAVIOUR TEST STUDY

This research presents the behaviour of GPS model and BeiDou model for zenith ionospheric delay correction comparing to the IGS-GIMs under different activity states of the ionosphere. The study is implemented for three (different-latitude) stations on northern hemisphere (Table 1) to reflect different geographical regions (low, mid and high). The zenith range delay corrections offered by the two models were judged by the IGS-GIMs for (GPS-L1 signal) (1575.42 MHz). The tested three months reflect three different states of ionosphere layer's activity (quiet, medium and active) (Table 2) based upon Sun Spot Number (SSN) values which reflects the intensity of solar activity.

4.1 LOW-LATITUDE GEOGRAPHIC REGION

The zenith ionospheric delay corrections presented by GPS model, BeiDou model and the IGS-GIMs for low-latitude station (Aswan) is presented by figures 1, 2 and 3. The zenith ionospheric delay differences for both models w.r.t. the IGS-GIMs are presented by figures 4, 5 and 6.

Fig. 1. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Aswan Station during January 2017 .

Fig. 2. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Aswan Station during April 2017 .

Fig. 3. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Aswan Station during September 2017 .

Fig. 4. L1 range delay difference (Aswan station) (January, 2017).

Fig. 5. L1 range delay difference (Aswan station) (April, 2017).

Fig. 6. L1 range delay difference (Aswan station) (September, 2017).

4.2 MID-LATITUDE GEOGRAPHIC REGION

The zenith ionospheric delay corrections presented by GPS model, BeiDou model and the IGS-GIMs for mid-latitude station (Sofia) is presented by figures 7, 8 and 9. The zenith ionospheric delay differences from both models w.r.t. the IGS-GIMs are presented by figures 10, 11 and 12.

Fig. 7. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Sofia Station during January 2017 .

Fig. 8. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Sofia Station during April 2017.

Fig. 9. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Sofia Station during September 2017.

Fig. 10. L1 range delay difference (Sofia station) (January, 2017).

Fig. 11. L1 range delay difference (Sofia station) (April, 2017).

Fig. 12. L1 range delay difference (Sofia station) (September, 2017).

4.3 HIGH-LATITUDE GEOGRAPHIC REGION

The zenith ionospheric delay corrections presented by GPS model, BeiDou model and the IGS-GIMs for high-latitude station (Helsinki) is presented by figures 13, 14 and 15. The zenith ionospheric delay differences from both models w.r.t. the IGS-GIMs are presented by figures 16, 17 and 18.

Fig. 13. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Helsinki Station during January 2017.

Fig. 14. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Helsinki Station during April 2017 .

Fig. 15. L1 Ionospheric Delay using BeiDou Model, GPS Model and IGS GIMs for Helsinki Station during September 2017 .

Fig. 16. L1 range delay difference (Helsinki station) (January, 2017).

Fig. 17. L1 range delay difference (Helsinki station) (April, 2017).

Fig. 18. L1 range delay difference (Helsinki station) (September, 2017).

Tables 3, 4 and 5 offer the statistical analysis of the L1 range delay differences from both models w.r.t. IGS-GIMs for the different geographical regions (stations) and the different tested months.

Table 3. Statistical analysis for L1 zenith ionospheric delay difference (meters) from both (GPS model & BeiDou model) w.r.t. IGS GIM's for Aswan station (low-latitude).

Tested Month	Less Ionospheric activity (January 2017)		Medium Ionospheric activity (April 2017)		High Ionospheric Activity (September 2017)	
Model	GPS Model	BeiDou Model	GPS Model	BeiDou Model	GPS Model	BeiDou Model
Average (m)	-0.425	-1.546	-0.919	-2.331	-0.231	-1.301
Maximum (m)	0.369	-0.737	0.475	-0.775	1.264	0.329
Minimum (m)	-1.074	-2.382	-3.391	-3.879	-1.919	-3.244
Root Mean Square (m)	0.349	0.448	0.863	0.848	0.764	0.955

Table 4. Statistical analysis for L1 zenith ionospheric delay difference (meters) from both (GPS model & BeiDou model) w.r.t. IGS GIM's for Sofia station (mid-latitude).

Tested Month	Less Ionospheric activity (January 2017)		Medium Ionospheric activity (April 2017)		High Ionospheric Activity (September 2017)	
Model	GPS Model	BeiDou Model	GPS Model	BeiDou Model	GPS Model	BeiDou Model
Average (m)	-0.524	-0.547	-1.953	0.110	-1.887	0.048
Maximum (m)	-0.075	0.757	-0.756	1.087	-0.215	1.336
Minimum (m)	-0.804	-1.361	-3.969	-0.835	-3.375	-1.085
Root Mean Square (m)	0.179	0.555	0.689	0.572	0.723	0.660

Table 5. Statistical analysis for L1 zenith ionospheric delay difference (meters) from both (GPS model & BeiDou model) w.r.t. IGS GIM's for Helsinki station (high-latitude).

Tested Month	Less Ionospheric activity (January 2017)		Medium Ionospheric activity (April 2017)		High Ionospheric Activity (September 2017)	
Model	GPS Model	BeiDou Model	GPS Model	BeiDou Model	GPS Model	BeiDou Model
Average (m)	-0.732	-5.232	-1.604	-2.746	-1.652	-4.004
Maximum (m)	-0.341	-3.093	-0.816	-0.945	0.034	-0.649
Minimum (m)	-1.056	-7.535	-3.185	-5.144	-3.158	-8.753
Root Mean Square (m)	0.148	1.317	0.521	0.906	0.655	1.802

5. DISCUSSION

This research presented the behavior of the two models adopted by GPS system and BeiDou system for zenith ionospheric delay correction. The research covers three different-latitude stations over three different-ionospheric activity states. Low-latitude geographic region has the maximum ionospheric delay faced by GNSS observations due to high solar activity comparing with other geographic regions. It can be concluded from this research that GPS model is offering better behaviour than the BeiDou model for low-latitude region (Aswan station). GPS model presents more accurate range corrections than BeiDou model w.r.t. to IGS-GIMs corrections. BeiDou model is able to model day-to-day significant fluctuations in the ionosphere layer behavior due to its dependence on two hours-updated ionospheric

coefficients. GPS model sometimes unable to model day-to-day fluctuations as the GPS-ionospheric coefficients are not always updated on daily bases. Table 3 presents the conclusion that for low-latitude geographic region, GPS model is modeling the ionospheric delay better than the BeiDou model by 73%, 60% and 82% on average for quiet, medium and active ionospheric activity states respectively.

For mid-latitude geographic region (Sofia station), the BeiDou model is modeling the ionospheric delay better than the GPS model w.r.t. the IGS-GIMs corrections. Table 4 concludes that for mid-latitude geographic region, the zenith ionospheric delay corrections by BeiDou model is better than GPS model by 5%, 94% and 97% on average for quiet, medium and active ionospheric activity states respectively.

For (Helsinki) station as an example of high-latitude geographic region, the GPS model is modeling the ionospheric delay better than the BeiDou model w.r.t. the IGS-GIMs corrections during all states of ionospheric activity. Table 5 imply that, the behaviour of GPS model is better than the BeiDou model for high-latitude geographic region by 86%, 41% and 59% on average for quiet, medium and active ionospheric activity states respectively

As a general conclusion, GPS model offers better behavior in correcting the ionospheric delay comparing with BeiDou model in low-latitude and high-latitude geographic regions under any activity state for the ionosphere. BeiDou model offers better accuracy in correcting range delay comparing with GPS model in mid-latitude region under any activity state for the ionosphere. BeiDou model offers more realistic behaviour for the range delay corrections caused by day-to-day significant fluctuations from the ionosphere layer. BeiDou model is presenting day-to-day range delay variations due to BeiDou-ionospheric coefficients' dependence on continuous monitoring stations. While the GPS model is not offering this behaviour due to the limitation in ionospheric coefficients updating. BeiDou model offers better behavior in correcting range delay in medium and active state of the ionosphere comparing with quiet-state of the ionosphere.

6. CONCLUSIONS

GPS model is modeling the ionosphere layer behaviour better than BeiDou model as it provides more-accurate range delay corrections in low-latitude and high-latitude geographic regions under any activity state for the ionosphere w.r.t. IGS-GIMs. BeiDou model is modeling the ionosphere layer behaviour better than GPS model as it provides more-accurate range delay corrections in mid-latitude region under any activity state for the ionosphere.

BeiDou model is able to model the ionosphere's day-to-day fluctuations due to its dependence on two hours-updated coefficients per day based on continuous monitoring stations while GPS model is unable to show those fluctuations due to inconsistency in ionospheric-coefficients updating.

GPS model is behaving better than BeiDou model for low-latitude and high-latitude regions by 72% and 62% respectively in different states of ionospheric activity. BeiDou model is behaving better than GPS model for mid-latitude geographic regions by 96% in different states of ionospheric activity.

The findings of this study are in agreement with the study conducted by (Zhao et al., 2014) where the behaviour of BeiDou model in mid-latitude region was better than its behaviour in low-latitude and high-latitude regions. BeiDou model provides correction residuals RMS of 0.6 m (Zhao et al., 2014). The correction residuals from BeiDou model from this research provide RMS of 0.596 m.

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