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Abstract. Inter-frequency clock bias (IFCB) should be considered when performing triple-frequency GNSS precise point positioning (PPP). Traditional approach of IFCB estimation is by averaging IFCB of all stations. However, this method doesn't consider the variation of receiver IFCB, so the averaged receiver IFCB is lumped into satellite IFCB. If the receiver IFCB can't eliminate by averaging when station number is limited, this method is not theoretical compactness. In this paper, we propose a more compactness IFCB estimation method based on network solution. In this method, the satellite and receiver IFCB are estimated together under a constraint of satellite IFCB. To validate this method, we select a 60-days global MGEX data and estimate the BDS IFCB between B1B2 and B1B3. Results show that BDS IFCB is within 10 cm and the RMS for all satellites are within 3 cm, while for receiver IFCB, it has a similar periodic performance as satellite. After correcting IFCB in kinematic PPP using B1B3 combination, statistical results among 13 MGEX stations show about 0.5 cm improvement in horizontal and vertical comparing with uncorrected IFCB PPP solution.

Keywords: Inter-frequency clock bias · Epoch difference · Network solution · Precise point positioning

1 Introduction

With the development and modernization of GNSS systems, triple frequency signal is now available. The existing GPS Block IIF and the ongoing Block III satellites provide L5 signal besides of L1 and L2 frequency[1]. Galileo, BDS and QZSS all provide triple or even four frequency signals at the beginning of system design. With the redundant

[1] https://www.gps.gov/systems/gps/space/.

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information of triple frequency, precise point positioning (PPP) users could benefit in positioning accuracy and convergence performance (Geng and Bock 2013; Mohamed 2015; Cao et al. 2018).

Conventional IGS precise clock solution is based on L1/L2 ionosphere-free combination. When performing SPP (single point positioning) or PPP in other frequency or other frequency combinations, one should consider the signal delay difference on code, namely timing group delay (TGD) or differential code bias (DCB) (Ge et al. 2017; Montenbruck et al. 2018).

However, Montenbruck found that there also exists inter-frequency clock bias (IFCB) between L1/L2 and L1/L5 for GPS (Montenbruck et al. 2012; Li et al. 2013a). For BDS, researches also prove the existence of IFCB between B1/B2 and B1/B3 (Li et al. 2013b; Pan et al. 2016). For both GPS and BDS, IFCB exhibits periodic characteristic with a notable period of 24 h, which makes it possible to predict IFCB change according to pre-day estimation of IFCB (Li et al. 2016; Pan et al. 2018).

However, traditional method to estimate IFCB is based on single station IFCB solution of all visible satellites and then combined by weighted averaging of all tracked stations for each satellite. In this approach, receiver IFCB is assumed as a constant value and could be eliminated after epoch difference. Li proves that the contribution of receiver IFCB can be ignored (Li et al. 2012). However, this may attribute to the stability averaged receiver IFCB of all tracked stations, while it can't proves the assumption of constancy in receiver IFCB. When few stations are tracked for one satellite, averaged receiver IFCB may be not stable and satellite IFCB would absorb the residual of averaged receiver IFCB. For the estimation of BDS IFCB, MEO satellite would show noisier comparing with GEO and IGSO satellites (Pan et al. 2018), which may attribute to the unstable of averaged receiver IFCB when not enough stations are tracked.

Although IFCB estimation is fully discussed by many researchers, there are not many works on demonstration and effects of IFCB correction in PPP, especially for BDS. Pan investigates the BDS triple frequency PPP performance after correcting IFCB (Pan et al. 2018). However, only one station of one day is used so that the conclusion is not convincing.

In this paper, we propose an improved method to estimate both satellite and receiver IFCB change based on network solution. 55 MGEX station are selected to assess the long term variation of IFCB for BDS, together with IFCB for stations. The estimated BDS IFCB is then corrected in PPP of B1B3 combination to evaluate their effects in PPP.

2 IFCB Estimation

2.1 Traditional Approach of IFCB Estimation

Tradition approach to estimate IFCB is proposed by Montenbruck (Montenbruck et al. 2012). For carrier phase observation of triple frequency in the case of BDS, one can form two ionosphere-free (IF) combinations. The geometry range, troposphere delay and some station depended displacement errors can be removed by subtracting these two ionosphere-free combinations:

$$\mathrm{DIF}(B_1, B_1, B_3) = IF(B_1, B_2) - IF(B_1, B_3) = IFCB^s - IFCB_r + dN \tag{1}$$

where dN is the differenced ambiguity between B1B2 and B1B3 IF combination, $IFCB^s$ and $IFCB_r$ stand for IFCB between B1B2 and B1B3 ionosphere combination on satellite and receiver, respectively.

If no cycle slip occurs between two adjacent epochs, dN could eliminated by epoch differencing. The epoch differenced observation in Eq. (1) could express as:

$$\Delta \mathrm{DIF}(B_1, B_1, B_3) = \Delta IFCB^s - \Delta IFCB_r \tag{2}$$

where Δ is the symbol of epoch differencing.

In traditional method, receiver IFCB is assumed as a constant value and thus $\Delta IFCB_r$ in Eq. (2) becomes zero. So IFCB on satellite is easy to estimate at each station.

For one specific satellite, if it is tracked by n stations, the integrated epoch differenced IFCB could be calculated by weighted averaging of all tracked stations:

$$\Delta IFCB^s = \left(\sum\nolimits_{r=1}^{n} (\Delta IFCB_r^s \cdot w_r) / \sum\nolimits_{r=1}^{n} w_r \right) \tag{3}$$

where w_r is the weight contribution at station r.

After we get epoch differenced IFCB, the accumulated IFCB could be calculated by simple sum up of $\Delta IFCB^s$:

$$IFCB^s(t) = \sum\nolimits_{i=1}^{t} \Delta IFCB^s(i) \tag{4}$$

where $IFCB^s(t)$ is the IFCB at epoch t.

What should be pointed out is that the IFCB at first epoch is assumed as zero, which is obvious not true. Therefore the estimated IFCB in this approach contains a constant bias on each satellite. However, for PPP float ambiguity solution, the constant bias of IFCB would be absorbed by ambiguity. Therefore it would not affect PPP result.

2.2 Improved IFCB Estimation Based on Network Solution

As mentioned in previous sub-section, the IFCB on receiver is assumed as a stable value and is eliminated after epoch difference. However, there is no evidence proving the stability of this value. If IFCB on receiver is not a constant value, then the traditional approach is not theoretical compactness, even receiver IFCB may be very small after station averaging. In other words, the averaged receiver IFCB may not be ignored when there are not many stations tracking one satellite. Results prove that in traditional approach, when satellite average weight is low for one satellite, the estimated IFCB may exhibit higher noise (Pan et al. 2018)

To full consider the variation of receiver IFCB, we propose an improved method based on network solution.

In the improved approach, receiver IFCB is not regarded as a constant value in Eq. (2). Therefore $\Delta IFCB_r$ is not zero and should also estimate together with $\Delta IFCB^s$, which is impossible to estimate within a single station. Fortunately, $\Delta IFCB_r$ is same for all satellite at the same station, so we can solve the epoch differenced satellite and receiver IFCB base on a network solution.

For all stations and all satellites, we can form the network observation as:

$$\begin{bmatrix} 1 & 0 & \cdots & -1 & 0 & \cdots \\ 1 & 0 & \cdots & 0 & -1 & \cdots \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 1 & \cdots & -1 & 0 & \cdots \\ 0 & 1 & \cdots & 0 & -1 & \cdots \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} \Delta \mathrm{IFCB}^1 \\ \Delta \mathrm{IFCB}^2 \\ \vdots \\ \Delta \mathrm{IFCB}_1 \\ \Delta \mathrm{IFCB}_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} \Delta \mathrm{DIF}_1^1 \\ \Delta \mathrm{DIF}_1^2 \\ \vdots \\ \Delta \mathrm{DIF}_2^1 \\ \Delta \mathrm{DIF}_2^2 \\ \vdots \end{bmatrix} \quad (5)$$

For the solution of Eq. (5), the normal equation is rank defected as there is no defined datum. To overcome this problem, we define the averaged epoch differenced IFCB for all satellite is zero. Then by using Least Square or Kalman Filter, one can estimate the epoch differenced IFCB for all satellite and receiver.

After epoch differenced IFCB is estimated, we can use Eq. (4) to get IFCB at each epoch.

3 Experiment Setup

To validate the proposed approach, 55 MEGX stations that can track triple frequency signal of BDS are selected, which are shown in Fig. 1. To assess the long term performance IFCB for BDS, we choose 60-days of data from day of year (DOY) 180～239 in 2017.

For estimation of BDS IFCB, we assume the averaged epoch differenced BDS IFCB is zero in the improved approach.

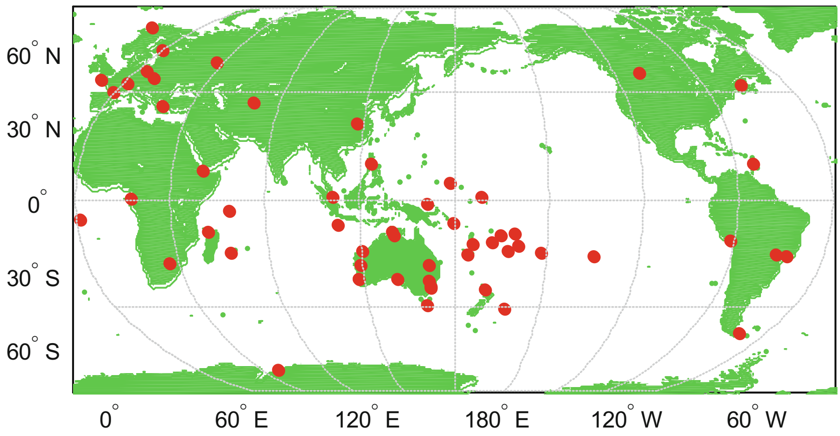

Fig. 1. 55 Selected MGEX stations for the estimation of BDS IFCB

4 IFCB Results and Analysis

4.1 BDS IFCB and Station IFCB

By using the proposed IFCB estimation approach, we can get the IFCB variation of BDS satellites. Figures 2, 3 and 4 shows the long term variation of IFCB C03, C04, C08, C09, C11, C12, which represents GEO, IGSO and MEO satellites, respectively.

From the figures we can obviously see that the daily BDS IFCB change is always within 10 cm and it shows a quite good periodic characteristic of 24 h. Comparing our result with previous result using traditional method (Pan et al. 2018), we can know that the magnitude is similar but the IFCB noise for MEO satellite is similar with GEO and IGSO satellites, which shows much smaller noise than precious research (Pan et al. 2018). This may attribute to that in the improved approach, the IFCB of one satellite doesn't affect by tracked station number as it is connected with receiver and other satellite IFCB.

Table 1 also summarize the RMS of BDS IFCB, it can be seem that the RMS is within 3 cm for all BDS satellites, which is comparable with other results (Pan et al. 2018).

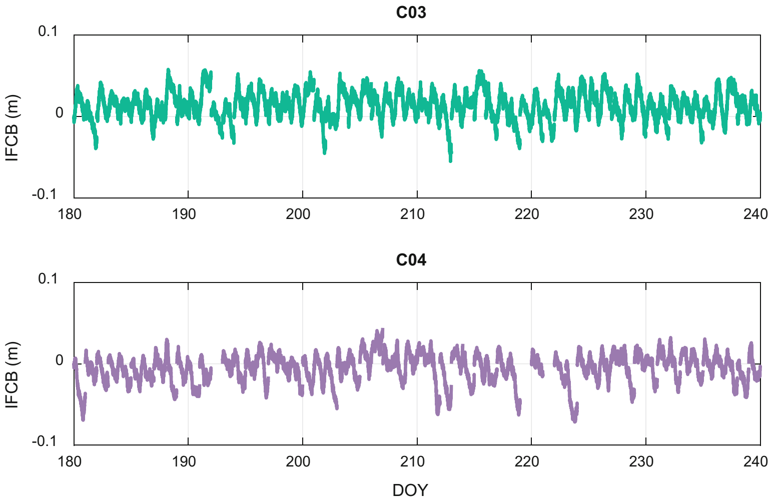

Fig. 2. Long term variation of IFCB for BDS GEO satellites (C03/C04, DOY180～DOY239)

In the improved approach, station IFCB can also derived. Figure 5 shows the estimated station IFCB at station CUT0 and DARW. We can see that IFCB is actually not stable and it also has a periodic characteristic of 24 h, which proves that the assumption of stability for receiver IFCB is not true.

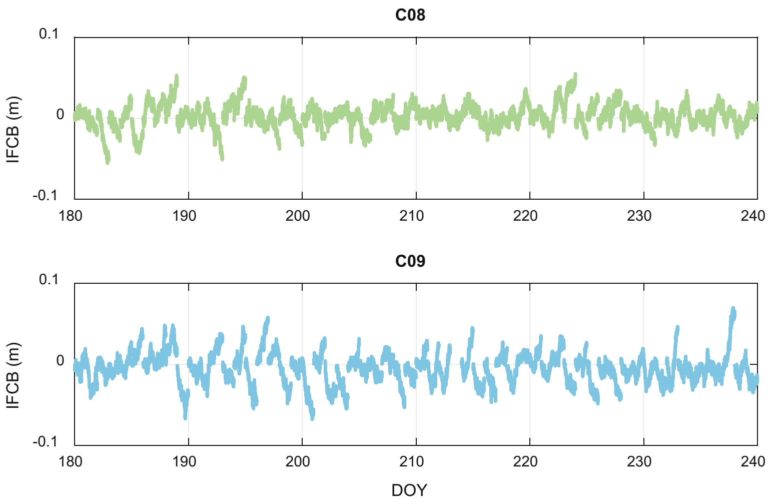

Fig. 3. Long term variation of IFCB for BDS IGSO satellites (C08/C09, DOY180～DOY239)

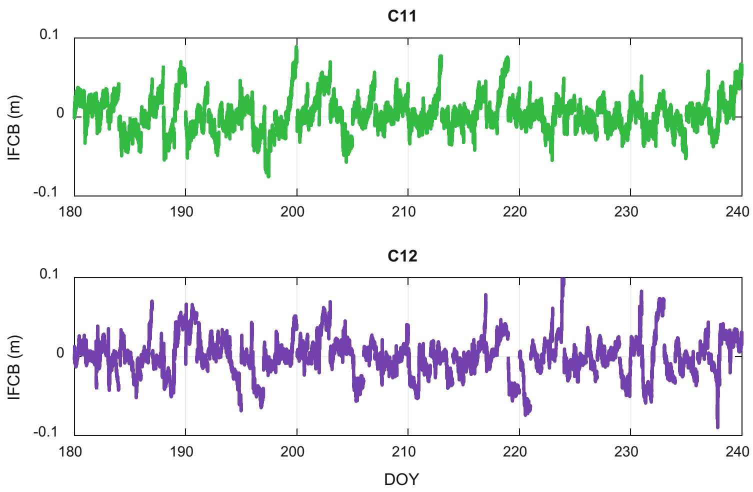

Fig. 4. Long term variation of IFCB for BDS MEO satellites (C11/C12, DOY180～DOY239)

4.2 Effect of IFCB on PPP

To evaluate the estimated IFCB, we perform kinematic PPP solution using B1B3 ionosphere-free combination by correcting and not correcting IFCB. To have a better understanding and comparison of B1B3 based PPP, traditional B1B2 ionosphere-free based kinematic PPP solution is also calculated. 13 MGEX stations on DOY 201, 2017 are selected and statistical RMS of kinematic PPP are presented in Table 2. The convergence period of kinematic PPP is set as 30 min therefore the first 30 min PPP error is not included in the statistical RMS.

Table 1. RMS of BDS IFCB (DOY180～DOY239)

PRN	RMS(m)	PRN	RMS(m)
C01	0.016	C08	0.015
C02	0.018	C09	0.020
C03	0.021	C10	0.019
C04	0.019	C11	0.022
C05	0.026	C12	0.024
C06	0.024	C13	0.019
C07	0.015	C14	0.023

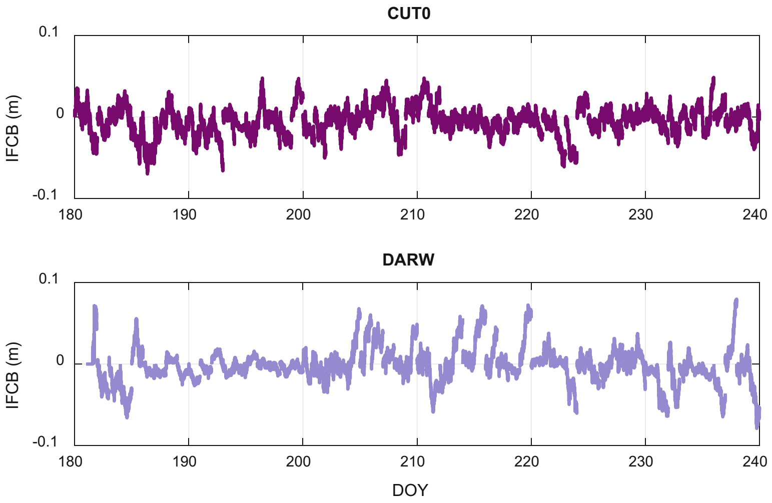

Fig. 5. Long term variation of IFCB at station CUT0 and DARW (DOY180～DOY239)

We can see that the mean accuracy of B1B3 PPP after IFCB correction is 0.081 m in horizontal and 0.121 m in vertical, while it is 0.087 in horizontal and 0.126 in vertical, which indicates a slight improvement of about 0.5 cm in horizontal and vertical, respectively. However, both solutions in B1B3 are worse than traditional B1B2 based PPP solution. The improvement after IFCB correction is not so obvious, which may due to the reason that the estimated RMS of IFCB is only within 3 cm, and when cycle slip occurs on a satellite, the ambiguity solution would re-initialize so that the mean value of IFCB would absorbed into ambiguity.

To take a detailed view of PPP performance after IFCB correction, we select result at station of XMIS as example, the B1B3 based kinematic PPP with and without IFCB correction is shown in Fig. 6. We can clearly see the improvement of PPP performance after IFCB correction. Figure 7 shows the histogram of positioning residuals for carrier phase. With more positioning residuals gather in the center of zero, it proves slightly better performance after IFCB correction.

Table 2. Kinematic PPP performance of B1B2 and B1B3 combination (H means horizontal and V means vertical)

Station	B1B3 IFCB uncorrected		B1B3 IFCB corrected		B1B2	
	H (m)	V (m)	H (m)	V (m)	H (m)	V (m)
CEDU	0.045	0.099	0.057	0.084	0.045	0.090
CUT0	0.050	0.082	0.030	0.079	0.029	0.062
DARW	0.051	0.074	0.036	0.082	0.041	0.064
KARR	0.034	0.058	0.030	0.070	0.028	0.054
KAT1	0.053	0.092	0.062	0.081	0.053	0.062
KITG	0.353	0.287	0.336	0.266	0.236	0.155
MCHL	0.089	0.125	0.096	0.125	0.098	0.110
MRO1	0.033	0.060	0.035	0.056	0.028	0.045
PNGM	0.055	0.122	0.055	0.141	0.051	0.122
SIN1	0.052	0.109	0.048	0.102	0.039	0.104
STR1	0.102	0.189	0.095	0.190	0.126	0.168
STR2	0.141	0.191	0.133	0.190	0.109	0.166
XMIS	0.076	0.143	0.066	0.132	0.051	0.110
Mean	0.087	0.126	0.081	0.121	0.072	0.101

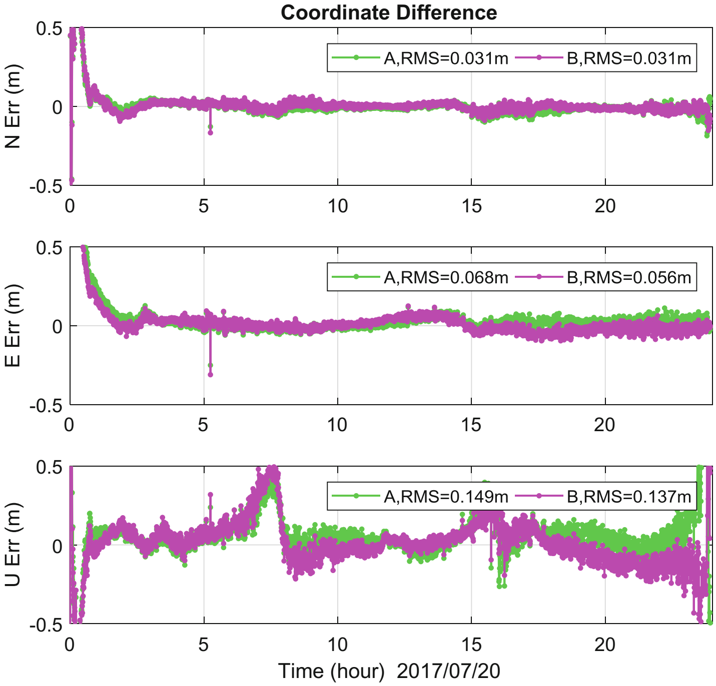

Fig. 6. Kinematic PPP performance with and without IFCB correction at station of XMIS (A means IFCB uncorrected and B means IFCB corrected)

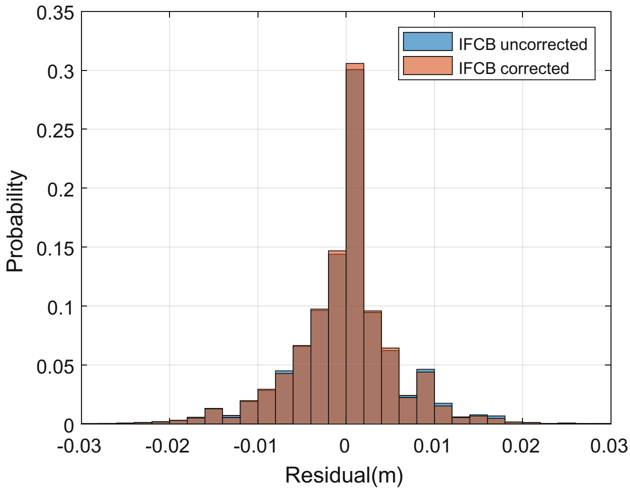

Fig. 7. Histogram of positioning residuals of carrier phase with and without IFCB correction at station of XMIS

5 Conclusions

In this paper, we propose an improved IFCB estimation approach based on network solution. In this method, the satellite and station IFCB are estimated together under the zero mean constraint epoch differenced satellite IFCB. To validate this method, 60-days of global MGEX data are used to estimate BDS IFCB between B1B2 and B1B3. Results show that:

(1) BDS IFCB is within 10 cm and the RMS for all satellites are within 3 cm with a periodic characteristic, and the estimated IFCB based on network solution have a smaller noise compared with traditional method.
(2) For station IFCB, it has a similar periodic performance as satellite.
(3) After correcting IFCB in kinematic PPP in B1B3 combination, statistical results among 13 MGEX stations show about 0.5 cm improvement in horizontal and vertical comparing with uncorrected IFCB PPP solution.

This method could apply in the estimation of other GNSS system and the new BDS-3 satellite.

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