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# Handling the satellite inter-frequency biases in triple-frequency observations

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## Abstract

The new generation of GNSS satellites, including BDS, Galileo, modernized GPS, and GLONASS, transmit navigation sdata at more frequencies. Multi-frequency signals open new prospects for precise positioning, but satellite code and phase inter-frequency biases (IFB) induced by the third frequency need to be handled. Satellite code IFB can be corrected using products estimated by different strategies, the theoretical and numerical compatibility of these methods need to be proved. Furthermore, a new type of phase IFB, which changes with the relative sun–spacecraft–earth geometry, has been observed. It is necessary to investigate the cause and possible impacts of phase Time-variant IFB (TIFB). Therefore, we present systematic analysis to illustrate the relevancy between satellite clocks and phase TIFB, and compare the handling strategies of the code and phase IFB in triple-frequency positioning. First, the un-differenced L1/L2 satellite clock corrections considering the hardware delays are derived. And IFB induced by the dual-frequency satellite clocks to triple-frequency PPP model is detailed. The analysis shows that estimated satellite clocks actually contain the time-variant phase hardware delays, which can be compensated in L1/L2 ionosphere-free combinations. However, the time-variant hardware delays will lead to TIFB if the third frequency is used. Then, the methods used to correct the code and phase IFB are discussed. Standard point positioning (SPP) and precise point positioning (PPP) using BDS observations are carried out to validate the improvement of different IFB correction strategies. Experiments show that code IFB derived from DCB or geometry-free and ionosphere-free combination show an agreement of 0.3 ns for all satellites. Positioning results and error distribution with two different code IFB correcting strategies achieve similar tendency, which shows their substitutability. The original and wavelet filtered phase TIFB long-term series show significant periodical characteristic for most GEO and IGSO satellites, with the magnitude varies between – 5 cm and 5 cm. Finally, BDS L1/L3 kinematic PPP is conducted with code IFB corrected with DCB combinations, and TIFB corrected with filtered series. Results show that the IFB corrected L1/L3 PPP can achieve comparable convergence and positioning accuracy as L1/L2 combinations in static and kinematic mode.

*Keywords:* Precise satellite clock; GNSS biases; Inter-frequency clock bias; Differential code biases; BeiDou Navigation Satellite System

## 1. Introduction

Global Navigation Satellite System (GNSS) measurements are affected by systematic delays related to the signal generation and processing chain. The resulting code and phase observations are affected by frequency- and signal-dependent biases. In relative positioning applications, most receiver- and satellite-related biases can be eliminated by forming double difference. However, in un-differenced precise point positioning (PPP) (Zumberge et al., 1997), the biases must be accounted to achieve centimeter positioning accuracy. Recently, GNSSs are developing towards the fusion of multi-constellation and multi-frequency. GPS is introducing new Block-IIF satellites transmitting the third civil signal L5 signal. The Europe Galileo system can provide in a total of four frequencies for commercial and

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civilian use. The Chinese BeiDou Navigation Satellite System (BDS) has already transmitted triple-frequency signals. The Multi-GNSS Experiment (MGEX) has launched by the International GNSS Service (IGS) to support multi-GNSS processing (Dow et al., 2008, 2007; Steigenberger et al., 2015). The advent of the extra frequency have been demonstrated to benefit precise GNSS data processing, such as ambiguity resolution (Geng and Bock, 2013) and robust kinematic precise positioning (Guo et al., 2016a, 2016b). However, biases induced by new systems and frequencies need to be handled.

Apart from the intra- and inter-system biases (Willis, 2011) and inter-satellite-type biases for BDS ((Nadarajah et al., 2013, 2015), satellite inter-frequency bias (IFB) within single GNSS system need to be corrected. Satellite IFB is induced due to the inconsistency of the observations used for clock estimation and PPP processing. In the case of dual-frequency data processing, only one ionosphere-free combination is employed, the bias can be fully absorbed by clock parameters. Therefore, they do not affect the positioning result if the estimated clocks are used in PPP. However, in triple frequency data processing, two ionosphere-free observations are involved, the clock parameters cannot absorb the biases in the two ionosphere-free observations if they are not the same. Though the estimability of the biases in the satellite clocks has already been developed and discussed (Khodabandeh and Teunissen, 2015; Odijk et al., 2016), there are still confusion and unresolved issues in the choice and usage of the IFB correcting model.

Differential code bias (DCB) products, which is defined as the differential hardware delay that occurs between two different code observations, is actually the satellite code IFB. PPP users can calibrate pseudorange observations to keep compatibility with IGS precise clock model by applying DCB corrections (Jefferson et al., 2001). Triple-frequency users can correct the satellite code IFB by a linear transformation of the DCB products, which will be called “DCBCorr” method hereafter. Though accurate multi-GNSS and multi-frequency DCBs products for different observation types are provided in GNSS community (Fan et al., 2017; Montenbruck et al., 2014), the DCB estimates are subject to the accuracy of ionosphere mode. Furthermore, a linear transformation of L1/L2 and L1/L3 DCB to triple-frequency DCB cannot ensure its consistency with the directly estimated L1/L2-L1/L3 DCB products. Alternatively, Li et al. (2015) proposed a method to estimate the P1/P2-P1/P3 code IFB with a geometry-free and ionosphere-free transformation, which will be called “GFIFCorr” method hereafter. Therefore, it is necessary to compare the feasibility and the impact of two different code IFB correction methods.

Satellite phase IFB is usually regarded as constant and can be absorbed by the ambiguities in PPP. However, a new type of phase Time-variant IFB (TIFB), which is also called inter-frequency clock bias (IFCB) by Montenbruck et al. (2012), for triple-frequency observation has been observed. The TIFB is defined as the phase biases difference between the current clock products computed with L1/L2 and the satellite clocks computed with L1/L5. Extensive research has been conducted to model the behavior of TIFB (Li et al., 2015, 2013, 2012; Pan et al., 2016). Pan et al. (2016) conduct experiment to analysis the phase TIFB of different stations, and conclude that the TIFB might originate from phase hardware delay of the satellite. However, theoretical analysis is required to identify the relationship between the phase TIFB and the precise satellite clock products.

We aim at conducting theoretical and experimental analysis to compare the different code IFB correction methods and clarify the cause and impacts of phase TIFB. In Section 2, we will first present the mathematical models to study the biases in satellite clocks, and then analysis the IFB induced to triple-frequency observation models. Furthermore, different methods used to correct the satellite IFB are analyzed. Then Section 3 will present the experimental validation to illustrate the corrections for code and phase IFB employing the BDS triple-frequency observations. Finally, the main points and conclusions are summarized in Section 4.

## 2. Mathematical models

In this section, we present basic GNSS observations for uncombined and ionosphere-free (IF) PPP model. The undifferenced clock estimation methods considering the hardware biases are derived. Besides, the biases induced by clocks in triple-frequency observations are analyzed in detail.

### 2.1. Basic GNSS observations

The basic observations of the GNSS pseudorange and carrier phase on frequency $i$ between receiver $r$ and satellite $s$ at a particular epoch can be expressed as follows:

$$\begin{aligned} P^s_{r,i} &= \rho^s_r + dt_r - dt^s + T^s_r + \mu_i \cdot I^s_{r,1} + b_{r,i} - b^s_i + \varepsilon^s_{i,P} \\ L^s_{r,i} &= \rho^s_r + dt_r - dt^s + T^s_r - \mu_i \cdot I^s_{r,1} + N^s_{r,i} + B_{r,i} - B^s_i + \varepsilon^s_{i,\Phi} \end{aligned} \tag{1}$$

where $P$ and $L$ are pseudorange and carrier phase observations in length, respectively; $\rho$ is the satellite-to-receiver range; $dt_r$ and $dt^s$ are the receiver and satellite clock errors in meter; $T$ is tropospheric delay; $I$ denotes the ionospheric delay on the first frequency, $\mu_i = f_1^2/f_i^2$ is the frequency-dependent multiplier factor; $N$ is the ambiguity in meters; $\varepsilon_P$ and $\varepsilon_\Phi$ are the corresponding noises. Further, $b_r$ and $b^s$ are the receiver and satellite pseudorange hardware biases; $B_r$ and $B^s$ are the receiver and satellite carrier-phase hardware biases. Note that the hardware biases differ for different measurement types and signal frequencies. Though the hardware biases are known to slowly vary in time (Gabor & Nerem, 1999), their temporal behavior can also be modeled by a random-walk process (Wen et al., 2011). Due to