GNSS Biases and Research Advances: Postprint

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Abstract

GNSS signals experience equipment delays during the transmission process from satellite emission to receiver reception. Equipment delays are closely correlated with clock biases, ambiguities, and other parameters, making it difficult to completely separate them. Typically, equipment delays are combined with their associated parameters to form different relative equipment delays according to practical requirements. Better classification and distinction of these relative equipment delays would have significant reference value for high-precision GNSS applications. This paper introduces several commonly used biases proposed based on equipment delays: inter-code bias, uncalibrated phase delay, inter-frequency clock bias, and inter-system bias, and elaborates on their concepts, causes, solution strategies, and related research progress.

Full Text

Preamble

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Research Progress on GNSS Biases

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Abstract

GNSS signals experience equipment delays during transmission from satellite transmission to receiver acquisition. These device delays are closely related to clock biases and ambiguities, making complete separation difficult. Typically, device delays are combined with related parameters to form different relative device delays according to practical needs. Better classification and distinction of these relative delays have important implications for high-precision GNSS applications. This paper introduces several commonly used biases based on device delays: differential code bias, uncalibrated phase delays, inter-frequency clock bias, and inter-system bias. Their concepts, causes, solution strategies, and research progress are described in detail.

Keywords: differential code bias; uncalibrated phase delays; inter-frequency clock bias; inter-system bias

1 Introduction

In the development of Global Navigation Satellite Systems (GNSS), the United States and Russia have continuously modernized their satellite navigation systems, while other countries and regions have built their own systems and developed related industries. The mutual integration and learning among different GNSS have greatly promoted technological progress, leading to a qualitative leap in service capabilities. GNSS applications have expanded into indispensable parts of daily life. As applications proliferate, researchers and users increasingly pursue higher quality data, better processing methods, and more precise products. In navigation and positioning applications, correcting, estimating, or completely eliminating various errors during GNSS signal transmission is a prerequisite for obtaining high-precision products, among which device delays caused by GNSS equipment constitute a major error source.

GNSS device delay (or hardware delay) refers to the time delay experienced by GNSS signals during transmission through satellite and receiver equipment channels (e.g., digital filters). The delay from signal generation to the satellite antenna phase center is called satellite transmission device delay, while the delay from receiver antenna phase center to the actual signal processing point is called receiver device delay. In GNSS pseudorange and carrier phase observation equations, device delays typically appear as additional terms including receiver- and satellite-related parameters. However, satellite and receiver device delays are highly correlated with corresponding clock biases, while phase device delays also relate to ambiguities, making complete separation impossible. Therefore, device delays are generally solved as relative biases in data processing. lists four common methods for handling device delay-related biases [**?**].

Table 1 Methods for handling device delay-related biases
1. Complete removal from observation equations, typically using differencing methods
2. Estimation as parameters in observation equations along with other parameters
3. Broadcast correction method: obtaining biases through other methods and broadcasting to users in real-time; these delays remain stable over certain peri-

ods
4. Pre-calculation from other sources and use as constants; these delays generally exhibit long-term stability

Different applications require consideration of slightly different device delays, necessitating classified research based on practical needs. In single GNSS systems, when processing pseudorange observations involving two or more signals, signal-to-signal relative pseudorange device delays must be considered due to different transmission times in channels—this is the differential code bias (DCB). For ambiguity resolution, research on uncalibrated phase delays (UPD) has emerged. When using multiple frequency signals, satellite clock biases differ under different frequency combinations, requiring consideration of inter-frequency clock bias (IFCB). Multi-system joint processing introduces inter-system bias (ISB).

As international research on device delay-related biases increases and applications expand, the International GNSS Service (IGS) established the Bias and Calibration Working Group (BCWG) to conduct related research in the GNSS bias field. Its primary objectives are to investigate existing device delay definitions and impacts, provide appropriate and consistent processing rules, and deliver high-quality products to users. The group also monitors new GNSS systems and signals, continuously updating device delay definitions and improving product services.

This paper provides a detailed introduction to GNSS biases related to device delays.

2 Differential Code Bias

DCB arises from inconsistent equipment delays during ranging code transmission or reception, appearing as device delay differences between different frequencies or between different ranging codes on the same frequency at the same epoch [?]. DCB represents the difference in device delays between two signals, with values reaching several nanoseconds or even tens of nanoseconds depending on signal channel characteristics [?]. Based on signal mechanisms, DCB can be classified as intra-frequency DCB (caused by different ranging codes on the same carrier frequency) or inter-frequency DCB (caused by different carrier frequencies) [?]. According to delay location, DCB is further divided into receiver DCB and satellite DCB [?].

DCB is a major error source in ionospheric total electron content (TEC) retrieval [?]. As early as 1991, Coco et al. identified device delay-related biases between L-band signals when determining GPS ionospheric delay accuracy, concluding that these biases must be removed from GPS observations for TEC determination [?]. DCB must also be considered in GNSS precise point positioning and time synchronization applications [?], making it essential for any pseudorange observation processing involving two or more signals [?]. Additionally, since receiver DCB is closely related to receiver performance, long-term analysis of receiver DCB values facilitates receiver performance monitoring [?].

With the widespread application of high-precision GNSS, DCB research has become increasingly sophisticated and indispensable. Processing methods differ between intra-frequency and inter-frequency DCB.

Intra-frequency DCB can be solved directly through pseudorange observation differencing [?]. Since two code signals are modulated on the same carrier frequency, ionospheric effects can be neglected. The pseudorange observation equation is given by Equation (1):

$$P = \rho + c(dtr - dts) + (dr - ds) + T + I + \epsilon_P$$

Differencing pseudorange observations from two codes P_1, P_2 yields DCB [?], as shown in Equation (2):

$$P_1 - P_2 = (dr_{;1} - dr_{;2}) + (ds_{;1} - ds_{;2}) + \epsilon_P$$

where P represents pseudorange observation, ρ is the geometric distance between receiver and satellite, dtr and dts are receiver and satellite clock biases, dr and ds are receiver and satellite pseudorange hardware delays, T is tropospheric delay, I is ionospheric delay, and $\epsilon_{P1}, \epsilon_{P2}$ are pseudorange noise corrections. Since pseudorange observations have relatively large noise, the equation can be averaged over one day to reduce noise and obtain integrated DCB observations.

Intra-frequency DCB parameters remain stable over periods (e.g., one month) and can be treated as constants [?]. Since 2010, the Center for Orbit Determination in Europe (CODE) has used this method to calculate GPS and GLONASS DCB products for users. [Figure 1: see original paper] shows monthly mean values of satellite and receiver intra-frequency DCB for January 2019, while [Figure 2: see original paper] presents time series of intra-frequency DCB for satellites G02, G08 and stations ALRT, COCO during the same period.

Inter-frequency DCB can be obtained through pre-launch calibration or software estimation [?]. Satellite and receiver equipment delays are typically calibrated before launch for direct user application. However, as equipment ages, hardware performance changes, and environmental factors cause deviations between actual and calibrated values [?]. Coco et al. compared pre-launch calibration values with estimated values, finding excellent agreement for two of four satellite pairs but significant differences for the other two, suggesting cautious treatment of pre-launch values [?]. Consequently, more researchers and users calculate inter-frequency DCB from GNSS measurements, using these solutions to monitor calibrated values [?].

Current inter-frequency DCB estimation methods include: (1) solving DCB parameters simultaneously with ionospheric TEC modeling [?, ?]; and (2) applying empirical or existing ionospheric models for delay correction before calculating DCB parameters [?]. Method 2' s DCB quality heavily depends on the selected ionospheric model' s accuracy [?], but allows calculation of DCB for any system at any time, greatly improving efficiency [?]. The German Aerospace Center uses Method 2, applying Global Ionospheric Maps (GIM) to directly remove ionospheric TEC and obtain combined satellite and receiver DCB, then separating them using zero-mean baseline constraints [?]. The drawback is reduced DCB accuracy in regions with significant ionospheric variations (e.g., equatorial areas) [?]. Method 1 simultaneously solves DCB with ionospheric model coefficients, making results dependent on ionospheric solution accuracy and requiring reasonably distributed GNSS stations [?].

Current ionospheric modeling assumes daily stability of receiver DCB, estimating one parameter per day [?]. This approach is reasonable for code division multiple access (CDMA) systems like GPS, Galileo, and BDS. However, GLONASS uses frequency division multiple access (FDMA) to separate satellite signals [?]. In this multiplexing technique, adjacent frequencies within L1 and L2 bands are assigned to different satellites, causing different processing delays in receiver channels that vary with frequency [?]. Therefore, the device delay difference caused by different carrier frequencies in GLONASS transmission or reception channels is called inter-frequency bias (IFB) [?]. GLONASS satellite IFB values vary significantly and require different processing than inter-frequency DCB, necessitating solution of IFB for each receiver channel. Currently, IGS analysis centers do not include IFB in their DCB products.

3 Uncalibrated Phase Delays

Similar to pseudorange, carrier signals are affected by various biases during transmission and reception [?]. Under the influence of initial phase, satellite and receiver device delays, and other factors, non-differentially processed carrier phase ambiguities absorb additional biases, represented as UPD [?]. Since integer ambiguity counts are ambiguous, the integer part of UPD parameters couples completely with ambiguities and cannot be separated. Only the fractional part (less than one carrier signal cycle) can be determined, called fractional cycle biases (FCB) [?]. Some scholars occasionally use UPD directly instead of FCB.

Precise Point Positioning (PPP), a common absolute positioning method in non-differential data processing, frequently requires UPD consideration. PPP utilizes precise orbit and clock products, comprehensively considers various error corrections, and employs reasonable parameter estimation methods (least squares or Kalman filtering) to achieve absolute positioning using a single GNSS receiver [?]. Since PPP uses non-differential observations, many errors cannot be reduced or eliminated through differencing, requiring consideration of all error sources. Fixing carrier phase ambiguities can improve PPP accuracy and convergence speed [?]. PPP technology has been successfully applied in atmospheric delay retrieval, dynamic precise positioning, crustal motion and ocean tide monitoring, precise timing, and precision agriculture. Better and faster ambiguity fixing is crucial for PPP development.

However, directly calculated ambiguities lack integer characteristics, yielding float solutions due to UPD from three main sources [?]: (1) Carrier signals from satellites and receivers do not start from zero phase, with unknown initial phases that cannot be separated from ambiguities. (2) Different signals experience different device delays during satellite and receiver transmission, which couple with ambiguities. (3) PPP uses precise clock products from IGS or similar solutions, typically based on ionosphere-free combinations and pseudorange clock biases. With only centimeter-level accuracy, these clock biases cause ambiguities to absorb partial clock errors in carrier phase observation equations.

Compared with float PPP solutions, integer PPP solutions offer two advantages: improved positioning accuracy and reduced convergence time. Li et al. [?] noted that float PPP requires several hours of observation to achieve centimeter or millimeter accuracy, with lower precision and reliability than double-difference fixed solutions. Recent international research has shifted toward PPP fixed solutions, focusing on restoring integer characteristics of non-differential ambiguities through FCB separation methods [?].

Increasing research uses FCB calculation for ambiguity fixing, with the most common methods being inter-satellite single-difference estimation and integer clock methods. The inter-satellite single-difference method was proposed by Cabor [?] and improved by Ge et al. [?]: first calculating non-differential ambiguity float solutions using approximately 100 IGS ground stations, then differencing between satellites to eliminate receiver FCB; next estimating wide-lane ambiguities using MW combinations to obtain wide-lane FCB corrections; finally introducing wide-lane ambiguities into ionosphere-free combinations to fix narrow-lane ambiguities and separate narrow-lane FCB corrections. The integer clock method calculates non-differential wide-lane FCB corrections to fix wide-lane ambiguities, then estimates satellite clock biases containing narrow-lane FCB [?]. After obtaining FCB, ionosphere-free wide-lane and narrow-lane ambiguities can be directly fixed to obtain PPP integer solutions with high-precision results for practical applications [?].

The Wuhan University PRIDE (Positioning Racers to Image and Decipher the Earth) research group currently provides GPS C1W/C2W/L1C/L2C satellite FCB data with one value per signal per satellite per day [?]. [Figure 3: see original paper] shows FCB values for all GPS satellites across four signals on January 1, 2020, demonstrating significant differences between satellites and signals on the same day. [Figure 4: see original paper] presents time series for satellites G01 and G10 during January 2020, showing relatively stable variations for the same satellite and signal during this period. The French CNES analysis center also provides wide-lane FCB, primarily solved using the integer clock method.

Compared with GPS-only FCB methods, estimating FCB values for multiple systems yields faster and better positioning results. The Wuhan University School of Geodesy and Geomatics is also researching multi-GNSS FCB products, including GPS, Galileo, BDS, and QZSS systems [?]. Although FCB research is maturing, it remains developmental with gradually improving products.

4 Inter-Frequency Clock Bias

GPS, Galileo, QZSS (Quasi-Zenith Satellite System), and BDS all provide multi-frequency signal services, further advancing GNSS development. Multi-frequency signals improve positioning accuracy and ambiguity resolution speed. Compared with dual-frequency signals, triple-frequency signals offer advantages including increased observable wavelengths, reduced noise, and decreased ionospheric effects [?]. Triple-frequency signals enable cycle slip detection and repair, ambiguity fixing, and other applications promoting high-precision navigation. However, satellite and receiver hardware delays and space environment effects cause differences in satellite clock biases solved using different frequency observations and combinations [?]. Montenbruck et al. identified differences between clock biases estimated from different frequency ionosphere-free combinations when studying GPS Block IIF satellites, defining them as inter-frequency clock bias (IFCB) with maximum values reaching 15 cm [?]. They also found IFCB variation periods correlate with satellite elevation angles relative to the Sun [?]. Li et al. calculated IFCB for PRN25 and PRN01 satellites, proposed methods for solving inter-frequency phase bias, and found IFCB variations affect PPP convergence time and positioning accuracy for different frequency ionosphere-free combinations [?].

In triple-frequency processing, GNSS triple-frequency observations can form two ionosphere-free combinations [?]:

$$\begin{cases} P_{IF}^{1,2} = \rho + (cdtr + dr^{1,2}) - (cdts + ds^{1,2}) + T + \epsilon_P^1 \\ L_{IF}^{1,2} = \rho + (cdtr + dr^{1,2}) - (cdts + ds^{1,2}) + (br^{1,2} - dr^{1,2} - bs^{1,2} + ds^{1,2}) + \lambda^{1,2} N^{1,2} + T + \epsilon_L^1 \\ P_{IF}^{1,5} = \rho + (cdtr + dr^{1,5}) - (cdts + ds^{1,5}) + T + \epsilon_P^2 \\ L_{IF}^{1,5} = \rho + (cdtr + dr^{1,5}) - (cdts + ds^{1,5}) + (br^{1,5} - dr^{1,5} - bs^{1,5} + ds^{1,5}) + \lambda^{1,5} N^{1,5} + T + \epsilon_L^2 \end{cases}$$

where 1, 2, 5 represent frequencies, P_{IF} and L_{IF} are ionosphere-free pseudorange and carrier phase observations, ρ, dr, ds are as in Equation (2), br, bs are receiver and satellite phase hardware delays, λ is the ionosphere-free combination wavelength, N is phase ambiguity, and ϵ_L is phase noise correction.

When solving satellite clock biases using two ionosphere-free combinations, parameterized satellite and receiver clock biases absorb corresponding hardware biases, producing two sets of clocks. Let $cdtr + dr^{1,2}$ be the receiver clock bias solved from frequencies 1 and 2, denoted as $\delta_r^{1,2}$; $cdts + ds^{1,2}$ as the satellite clock bias solved from frequencies 1 and 2, denoted as $\delta_s^{1,2}$; $cdtr + dr^{1,5}$ as the receiver clock bias from frequencies 1 and 5, denoted as $\delta_r^{1,5}$; and $cdts + ds^{1,5}$ as the satellite clock bias from frequencies 1 and 5, denoted as $\delta_s^{1,5}$. Simultaneously solving two sets of receiver and satellite products increases time and computational costs [?]. To improve efficiency, a method eliminating clock product inconsistencies was proposed—solving IFCB. The main concept solves clock biases for one frequency combination as a reference, expressing other clocks as this reference plus IFCB [?]:

$$IFCB^s = \delta_s^{1,5} - \delta_s^{1,2} IFCB^r = \delta_r^{1,5} - \delta_r^{1,2}$$

Assuming phase device delays are absorbed by ambiguities, differencing different frequency combinations (1/2 and 1/5) eliminates geometric distance and tropospheric delay, leaving only ambiguity terms and IFCB for phase, and only IFCB for pseudorange, as shown in Equation (5):

$$PDIF^{1,2,5} = P_{IF}^{1,5} - P_{IF}^{1,2} = IFCB^r - IFCB^s + \epsilon_P^3 LDIF^{1,2,5} = L_{IF}^{1,5} - L_{IF}^{1,2} = IFCB^r - IFCB^s + \lambda^{1,5} N^{1,5} - \lambda^{1,2} N^1$$

where $N^{1,2}$ and $N^{1,5}$ are ambiguities absorbing phase device delays for frequency combinations 1/2 and 1/5. Research suggests receiver IFCB is constant, while satellite IFCB contains both constant and variable components [?, ?]:

$$IFCB^s = \delta_s + ifcb_s$$

where δ_s represents the variable component and $ifcb_s$ the constant component. The variable component can be solved using phase observation equations. When no cycle slips occur between epochs, epoch-differencing the carrier phase observation equation in Equation (5) eliminates integer ambiguities and constant IFCB components. Using a single station across multiple epochs (e.g., k epochs), the variable component for each epoch is:

$$m = LDIF^{1,2,5}(m) - \frac{1}{k}\sum_{i=1}^{k} LDIF^{1,2,5}(i)$$

The ambiguity-absorbed portion can be solved using pseudorange observation equations. Direct epoch averaging yields the sum of satellite and receiver constant components. To obtain the $ifcb_s$ component while eliminating the receiver portion, a reference satellite can be selected for solving.

Satellite IFCB variation exhibits time-varying characteristics that can be modeled as periodic functions related to the Sun-satellite-Earth angle, while receiver IFCB can be treated as constant [?]. Therefore, IFCB can be predicted in advance for application in related fields.

5 Inter-System Bias

Inter-system bias must be considered when multiple satellite navigation systems are jointly used for navigation and positioning [?]. Different GNSS systems adopt different coordinate and time references, with varying signal structures and systems [?], causing receiver equipment-related delay biases when different GNSS signals transmit through multi-GNSS receiver channels. These systematic biases must be considered when fusing multi-GNSS data [?].

ISB is generally considered a correction needed when observations from one satellite system (e.g., BDS) are processed together with those from a reference system (e.g., GPS) [?]. In practice, coordinate reference differences between systems mainly manifest in satellite positions and are generally converted to the same coordinate system during multi-GNSS data processing, making their impact on ISB negligible. Thus, ISB primarily includes time reference differences and receiver device delays [?].

With the emergence of multiple GNSS systems, many scholars have studied multi-GNSS navigation and positioning methods [?, ?], generating corresponding ISB research. Addressing ISB enables better joint application of multi-GNSS systems, dramatically increasing available satellite numbers and improving satellite geometry, which reduces position dilution of precision and benefits navigation in harsh environments with limited visible satellites [?, ?].

Current ISB research includes processing methods, source and characteristic studies, and modeling/prediction [?]. ISB exists in both pseudorange and carrier phase observation equations [?], though definitions vary by context. In multi-GNSS joint network solutions, only one reference clock bias is estimated for the entire network. However, different signal frequencies and satellite systems produce different device delays absorbed by receiver clock biases, creating actual differences between systems' receiver clock biases [?]. Therefore, bias parameters must be introduced for different systems. For example, when jointly processing GPS (denoted G) and BDS (denoted C), GPS receiver clock bias is typically used for both systems, expressed as $cdtr + dr_G$, with the introduced bias parameter ISB. The ionosphere-free combined observation equations for the two systems become [?]:

$$\begin{cases} P_{IF} = \rho_G + (cdtr + dr_G) - (cdt_G + d_G) + T + \epsilon_{PG} \\ L_{IF} = \rho_G + (cdtr + dr_G) - (cdt_G + d_G) + (br_G - dr_G - b_G + d_G) + \lambda N_G + T + \epsilon_{LG} \\ P_{IF} = \rho_C + (cdtr + dr_C) - (cdt_C + d_C) + ISB + T + \epsilon_{PC} \\ L_{IF} = \rho_C + (cdtr + dr_C) - (cdt_C + d_C) + ISB + (br_C - dr_C - b_C + d_C) + \lambda N_C + T + \epsilon_{LC} \end{cases}$$

ISB represents the inter-system bias of system C relative to system G. Considering time reference differences between systems, ISB also contains a constant bias parameter [?], denoted as D:

$$ISB = (dr_C - dr_G) + D$$

The above ISB formula applies to CDMA-based GNSS systems. For FDMA-based GLONASS, ISB also includes inter-frequency biases for different satellites [?], requiring either one ISB value per satellite or removal of each satellite' s inter-frequency bias. Notably, rank deficiency occurs when ISB parameters are jointly solved with orbit products, requiring additional constraints [?]. Two constraint methods exist: (1) setting ISB to zero for a specific station, or (2) constraining the sum of ISB across the station network to zero.

The iGMAS Shanghai Astronomical Observatory Analysis Center uses the second method to solve ISB for BDS/GPS, Galileo/GPS, and GLONASS/GPS. [Figure 5: see original paper], [Figure 6: see original paper], and [Figure 7: see original paper] show pseudorange ISB time series for 10 common stations from September 17, 2018 to September 19, 2019. Galileo/GPS and GLONASS/GPS ISB values remain very stable, while BDS/GPS stability is slightly poorer.

Multi-GNSS positioning research includes relative positioning and point positioning, with slightly different ISB processing strategies.

In relative positioning, time reference biases are eliminated through double-differencing, but relative receiver device delays remain, preserving ISB [?]. Two cases exist: (1) When systems share the same frequency, tight combination models maintain integer ambiguity characteristics [?] but require identical frequencies between systems, effectively treating them as a single system. (2) When frequencies differ, loose combination models independently solve each GNSS system without cross-system processing, eliminating both pseudorange and phase ISB [?]. GPS and Galileo often use tight combination due to shared frequencies (L1/E1, L5/E5a) [?], while GPS/BDS typically uses loose combination [?, ?]. GPS/Galileo relative positioning studies show minimal ISB differences for identical receivers but large pseudorange ISB differences (up to hundreds of nanoseconds) for different receivers [?].

In point positioning, ISB can be estimated as an additional parameter, though constraints are typically needed due to numerous unknowns [?]. Different constraints produce different ISB values. Static point positioning using precise ephemerides and satellite clocks yields ISB without time reference differences, while dynamic positioning using broadcast ephemerides includes time reference differences [?]. For PPP, phase ISB cannot be separated from ambiguities and is solved together with float ambiguities [?].

Although ISB processing varies by application, many studies agree that receiver and antenna types affect ISB values, which remain stable in the short term [?, ?]. Jiang [?] and Zhang [?] modeled ISB, predicting one-day ISB values from one-week values with satisfactory results, demonstrating certain predictability.

Currently, ISB is primarily a byproduct of multi-GNSS data processing, with few dedicated studies. When multi-system joint processing is needed, researchers generally process ISB according to their own understanding without fully consistent concepts. Different constraints produce different ISB values, limiting user applications. For dynamic positioning, ISB prediction would greatly improve solution efficiency. However, ISB research remains limited, with few long-term characteristic analyses. As a necessary bias in multi-GNSS joint applications, better ISB understanding would facilitate multi-system data fusion.

6 Summary

This paper introduced four device delay-related biases in GNSS data processing (differential code bias, uncalibrated phase delays, inter-frequency clock bias, and inter-system bias), discussing their definitions, calculation methods, and research status. The origins of these biases and their impacts on GNSS applications were examined, with detailed processing methods for each bias in practical applications.

DCB can be considered as the combination of pseudorange device delays for two signals. When using two signals, pseudorange observations are inevitably affected by signal- and frequency-related DCB, requiring its consideration. DCB is currently the most developed bias, widely used in many applications. Uncalibrated phase delays were proposed primarily for fixing integer ambiguities, generally studying their fractional part (FCB), which arises because phase device delays cannot be completely separated from ambiguities. To better utilize triple-frequency data, one satellite clock bias is used as a reference, with other clock biases converted using inter-frequency phase bias. Inter-system bias is a systematic bias arising from differences in reference frames and signal systems between GNSS when combining multiple systems, representing a device delay-related relative bias.

With rapid multi-GNSS development and increasing application demands, research on GNSS-related biases has gained importance. Calibration, monitoring, and proper processing of these device delay-related biases are crucial for improving high-precision GNSS service performance. International bias definitions continue to be revised and improved. Systematic integration and classification of these device delay-related biases, with clear definitions of their differences and connections, will greatly facilitate future research in related fields.

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Note: Figure translations are in progress. See original paper for figures.