WHU Real-time Clock Products: Aiming at Better Timing Performance and Multi-GNSS Time Interoperability

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Feiyu Mao, Xiaopeng Gong, Shengfeng Gu, Yidong Lou
GNSS Research Center, Wuhan University

Introduction

Since the end of 2018, we have provided Real-time (RT) clock products on behalf of Wuhan University (WHU) RT Analysis Center (AC) using the FUSING software. Currently, most RT clocks only focus on the accuracy and positioning performance. In the past two years, we are devoted to improving the performance of real-time clocks in multi-GNSS time interoperability and timing service to provide all-around clock products. Our work mainly focuses on three aspects: (1) maintaining stable system time offsets (STO) to make it easier for users to fix ISB value, (2) adopting the clock model rather than white noise model for satellite clock parameters to improve frequency stabilities, (3) utilizing the UTC(k) as the reference time to support UTC access.

Methodology

Conventional Method

Generally, satellite clock estimation adopts white noise model for clock parameters. The satellite and receiver clock parameters are linearly dependent, which means that there is a rank deficiency in the observation model for clock estimation. Therefore, additional constraints must be introduced. For WHU conventional method, broadcast clocks are used to establish the constraint equation with:

$$\begin{cases}\dfrac{1}{n^X}\sum\limits_{s=0}^{n^X}\left(d\tilde{t}^s_{\mathrm{BRDC}} - d\tilde{t}^s_{\mathrm{IF}}\right) = 0\\ \dfrac{1}{n^Y}\sum\limits_{s=0}^{n^Y}\left(d\tilde{t}^s_{\mathrm{BRDC}} - d\tilde{t}^s_{\mathrm{IF}}\right) = 0\end{cases}$$

X, Y: constellation identifier
n^X, n^Y: number of satellite clocks
$d\tilde{t}^s_{\mathrm{BRDC}}$: broadcast clocks
$d\tilde{t}^s_{\mathrm{IF}}$: estimated clocks

New Method

In recent years, GNSS atomic clocks have a great improvement in short-term stabilities. The white noise model might cover the high short-term stabilities. Additionally, the system time offset (STO) of estimated clocks will vary as that of broadcast clocks. Many studies have shown that the receiver hardware delay is stable over a long period. Consequently, we adopt three-state clock model for clock parameters and utilize the stable hardware delay difference to maintain stable STO values of multi-GNSS satellite clocks in the new method. The inter-system bias (ISB) contains hardware delay difference and the STO, which can be expressed as:

$$ISB^{(X,Y)}_{r,\mathrm{IF}} = d\tilde{t}^Y_{r,\mathrm{IF}} - d\tilde{t}^X_{r,\mathrm{IF}} = \Delta d^{(X,Y)}_{r,\mathrm{IF}} - STO^{(X,Y)}$$

To use the stable hardware delay difference, we established ISB models with unified STO values. Suppose X is the reference constellation, then the constraint equation for other constellations is changed to:

$$\frac{1}{n_r}\sum_{r=1}^{n_r}\left(\widehat{\mathrm{ISB}}^{(X,Y)}_{r,\mathrm{IF}} - \widetilde{ISB}^{(X,Y)}_{r,\mathrm{IF}}\right) = 0$$

$\widehat{\mathrm{ISB}}$: ISB estimation values
$\widetilde{ISB}$: ISB model values

There are some IGS stations using UTC(k) as receiver clocks. In the new method, we replace broadcast clocks with UTC(k) as the reference time. Then users are able to access the UTC using WHU real-time clocks.

Results

Real-time clocks (CONV: conventional method, NEW: new method) and 30 multi-GNSS station observations from DoY 099 to 146, 2024 are collected for validation. For the new method, GPS is selected as the reference system.

Satellite Clock Accuracy

The accuracy of RT clocks are evaluated by comparing with GFZ MGEX clock products. Both methods show similar performance in clock STD values.

Table 1 STD of satellite clocks

System	CONV	NEW
GPS	0.121	0.110
GLONASS	0.256	0.242
BDS-3	0.166	0.170
Galileo	0.099	0.095

Satellite Clock Stabilities

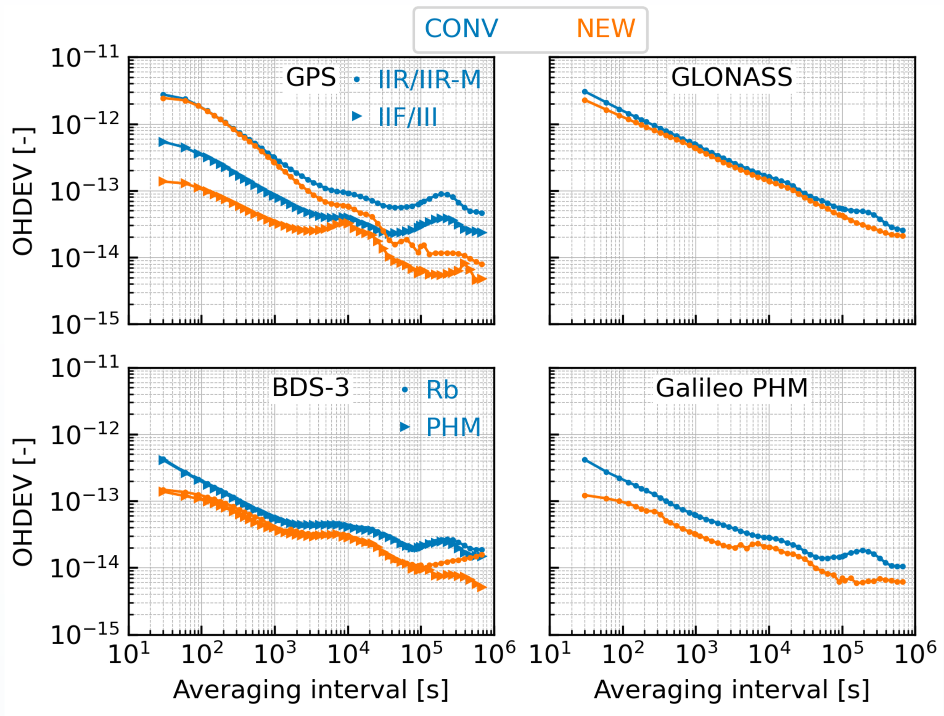

Figure 1. Satellite clock stabilities

- For clocks of GPS Block IIF/III, BDS-3 and Galileo, the new method can significantly improve the stabilities.
- For GLONASS clocks, the results of both methods show almost identical stabilities.

PPP One-Way Timing

Four stations with UTC(k) are processed in static mode to analyze PPP one-way timing performance. UTC access errors are analyzed through comparing with UTCr.

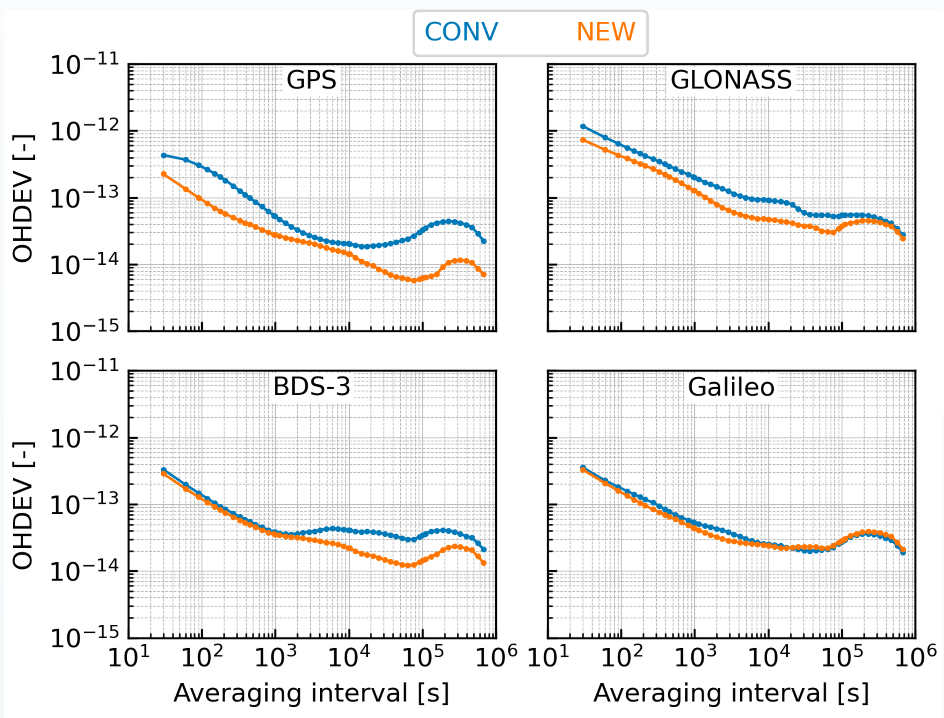

Figure 2. PPP one-way timing stabilities

- The clocks with new method show improved performance in PPP timing stabilities and UTC access.

Table 2 RMS (ns) of UTC access

System	CONV	NEW
GPS	3.6	3.1
Galileo	5.5	4.8

ISB Series

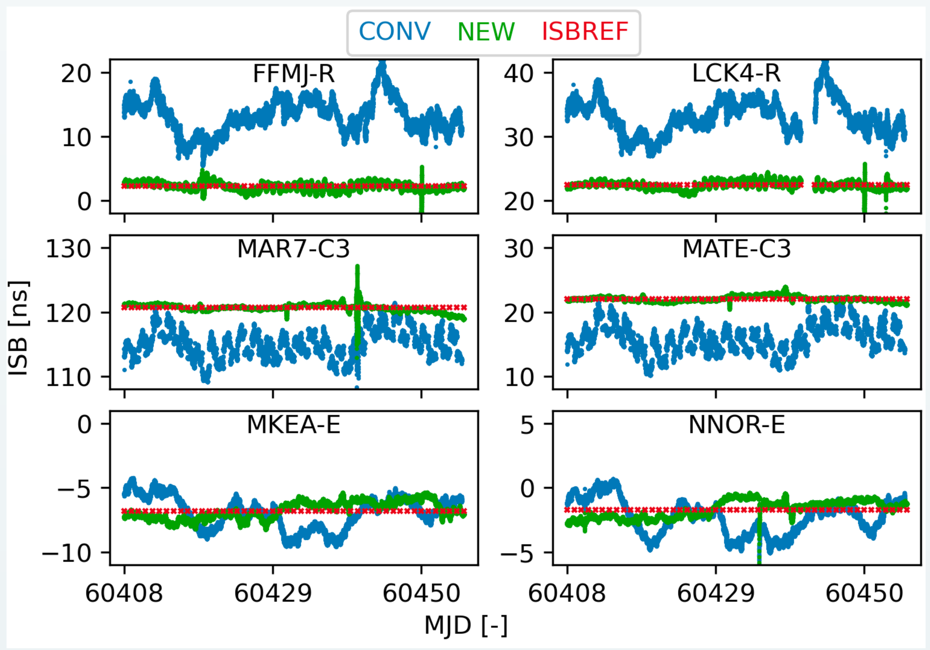

Figure 3. ISB series. ISBREF indicates ISB model values

- Compared with CONV results, NEW results have more stable ISB series, particularly for GLONASS and BDS-3 w.r.t. GPS.
- The real-time results are worse than the simulated real-time test results, which needs to be improved in the future.

Kinematic PPP

One-hour kinematic PPP solutions are performed to analyze the performance of fixing (ISBFIX) and estimating (ISBEST) ISB using the clocks with the new method.

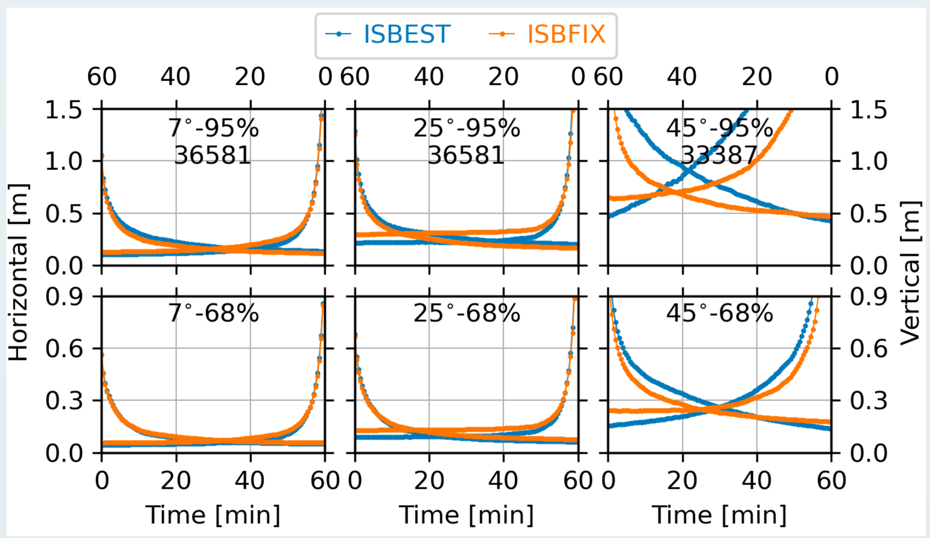

Figure 4. Positioning error series for 95% and 68% levels. The number of analyzed solutions is given in the top

- Positioning errors are slightly larger for ISBFIX when cut-off angles are 7° and 25°, which should be caused by the offset between actual and model values of ISB.
- For 45 ° cut-off angle, fixing the ISB can increase the availability, by 13.1%, and improve the horizontal and vertical positioning accuracy by 16.9% and 28.5%, respectively.

Table 3 RMS and availability of kinematic positioning

Cut-off Angle (°)	H-RMS (cm)		V-RMS (cm)		Availability (%)	
	CONV	NEW	CONV	NEW	CONV	NEW
7	6.2	6.1	5.0	6.1	100.0	100.0
25	7.7	8.2	9.2	10.6	100.0	100.0
45	26.8	22.2	44.6	31.9	86.7	99.8

References

- Gu S, Mao F, Gong X, Lou Y, Shi C (2023) Improved short-term stability for real-time GNSS satellite clock estimation with clock model. J Geod 97(6):61.
- Mao F, Gong X, Gu S, Zheng F, Lou Y, Shi C (2024) Real-time clock estimation using system time offset maintenance aiming at multi-GNSS time interoperability. Measurement 224:113929.