ORIGINAL ARTICLE

Real-time service performances of BDS-3 and Galileo constellations with a linear satellite clock correction models

Haojun Li[1*], Danzeng Luojie[1] and Huimin Ding[1]

Abstract

In order to facilitate high-precision and real-time Precise Point Positioning (PPP), the International GNSS (Global Navigation Satellite System) Service (IGS), BDS-3 (BeiDou-3 Navigation Satellite System), and Galileo navigation satellite system (Galileo) have provided real-time satellite clock correction, which is updated at a high-frequency. However, the frequent updates pose the challenges of increasing the computational burden and compromising the timeliness of these correction parameters. To address this issue, an improved Real-Time Service (RTS) method is developed using an extrapolation algorithm and a linear model. The results indicate that a 1 h arc length of the satellite clock correction series is optimal for fitting a linear model of the RTS. With this approach, the 1 h extrapolation results for BDS-3 and Galileo are superior to 0.09 ns. Moreover, when these model coefficients are transmitted and updated at the intervals of 1, 2, 5, and 10 min, the corresponding PPP can converge at the centimeter-level. It is evident that these improved RTS methods outperform the current approach with high-frequency interval transmission, as they effectively mitigate the challenges associated with maintaining the timeliness of correction parameters.

Keywords Precise point positioning, Satellite clock correction, Real-time service

Introduction

A satellite of the Global Navigation Satellite System (GNSS) carries a clock, which serves as the time reference for distance measurement. Satellite clock error is a significant factor that affects positioning accuracy, while delivering a high-precision positioning service is a routine task. Originally, the GNSS provided this service by transmitting the corresponding parameters generated using an extrapolation method. This service, known as broadcast ephemeris, was designed to meet the meter-level Single Point Positioning (SPP) requirement (Leick et al., 2015). However, the age of the satellite clock parameter in the GNSS broadcast ephemeris is limited due to the poor long-term extrapolation performance of GNSS satellite clocks. Consequently, the satellite clock parameter in the broadcast ephemeris requires frequent updating. The update intervals for different GNSSs, including Global Positioning System (GPS), GLObal NAvigation Satellite System (GLONASS) and BeiDou Navigation Satellite System (BDS), are presented in Table 1. The table indicates that the update interval for satellite clock correction parameters in the BeiDou-3 Navigation Satellite System (BDS-3) broadcast ephemeris is six times longer than that of the Galileo navigation satellite system (Galileo).

The high-precision satellite clock products with different updating intervals have been provided by the International GNSS Service (IGS) since the time when the Precise Point Positioning (PPP) was proposed (Malys & Jensen, 1990; Zumberge et al., 1997), as discussed by Dow et al. (2009). Initially, the IGS offered the final satellite clock products with a delay of approximately 15 d, which are mainly used for the

*Correspondence:
Haojun Li
lhjch@tongji.edu.cn
[1] College of Surveying and Geo-Informatics, Tongji University, Shanghai 200092, People's Republic of China

Li *et al. Satellite Navigation*   (2023) 4:23

Page 2 of 10

Table 1 Update intervals of the satellite clock correction parameters in broadcast ephemeris for the different GNSS systems

GNSS	GPS	GLONASS	BDS	Galileo
Update interval (min)	120	30	60	10–100

post-processing applications of PPP. However, due to the increasing demand for real-time PPP in the fields such as weather forecasting (Li et al., 2012) and earthquake magnitude determination (Fang et al., 2014; Geng et al., 2010), the real-time satellite clock estimation and services have been studied. In real-time scenarios, the estimation of satellite clocks is typically performed using dual-frequency ionosphere-free linear combinations (Bock et al., 2009; Ge et al., 2012; Hauschild & Montenbruck, 2009; Li et al., 2010a, b; Zhang et al. 2011). To accommodate various observation requirements, the impact of GNSS satellite biases on satellite clock correction was investigated (Li et al., 2017). Additionally, the studies have explored the satellite Inter-Frequency Clock Bias (IFCB) (Cai et al., 2016; Li et al., 2013, 2016; Montenbruck et al., 2012; Pan et al., 2017) to compute triple-frequency satellite clocks (Li et al., 2018).

Real-time PPP processing is crucial for the users who require the most up-to-date satellite clock products. Therefore, the Real-Time Service (RTS) for satellite clock correction plays a vital role in maintaining accuracy while simplifying delivery. The International GNSS Service (IGS) Real-Time Working Group was established in 2011 to provide real-time satellite clock corrections relative to the broadcast ephemeris (Elsobeiey & Al-Harbi, 2016). The IGS RTS updates satellite clock parameters at 6-s intervals. However, the frequent updating of satellite clock correction imposes a burden on the service. To address this issue, researchers investigated the methods to improve the RTS for BDS-3 and Galileo systems. These studies, conducted by Yang et al., (2020, 2022), Wu et al. (2020), Li et al., (2022a, b), and Feng et al. (2023), aim to prolong the update interval and enhance the service capabilities. However, these methods often use high-order polynomials and harmonic-based functions, which require the broadcast of multiple parameters and can complicate the RTS method. To leverage the favorable characteristics of Galileo and BDS-3 satellite clocks, which are equipped with stable Passive Hydrogen Maser (PHM) clocks (Jaduszliwer & Camparo, 2021), a new RTS method is developed in this paper, which utilizes linear functions to simplify the process. Additionally, the PPP performance with this method is thoroughly analyzed.

Method

The RTS of satellite clock errors is a precondition for RT PPP processing. To develop an RTS method, the parameters that aim to extrapolate real-time GNSS satellite clock correction variations are updated at different intervals. These parameters and the intervals are typically generated based on the satellite clock performance and the PPP user's accuracy requirements. The extrapolation algorithm typically estimates the coefficients of a function fitting to the computed satellite clock correction series, which are then used for the positioning application for the next time span. It is evident that the arc length of the used satellite clock correction series is directly related to the timeliness of the fitting coefficients in the extrapolation algorithm. A linear model offers simple coefficients, which facilitates delivery. Therefore, the construction of an RTS method using the linear model is discussed.

PPP

Assuming the station coordinates and satellite clock and orbit products remain fixed, the linearized ionosphere-free carrier phase and code combinations at epoch i can be expressed as follows:

$$\begin{cases} l_r^s(i) = \rho_r^s(i) + \delta_r(i) + a_r^s(i) - T_r^s(i) \\ p_r^s(i) = \rho_r^s(i) + \delta_r(i) - T_r^s(i) \end{cases} \tag{1}$$

where $l_r^s(i)$ and p_r^s are the phase and code observations, respectively; ρ_r^s is the range from the satellite to the receiver; δ_r is the receiver clock error; a_r^s is the ambiguity of the ionosphere-free carrier phase combinations of satellite s at receiver r; and T_r^s is slant tropospheric delay. An estimator of Least Squares (LS) and an elevation-dependent weight are used in computing these biases. The elevation-dependent weight is written as follows:

$$w_i = \begin{cases} 1/\sigma^2 & 30^0 \le \theta_i \le 90^0 \\ 2\sin(\theta_i)/\sigma^2 & 7^0 \le \theta_i < 30^0 \end{cases} \tag{2}$$

where σ^2 is the variances of carrier phase and code observations, respectively; and θ_i is the elevation at i epoch.

Linear model

The PPP processing relies on the service of satellite orbit and clock error. As the estimation methods for these parameters have developed, the corresponding RTS is a routine task implemented by IGS and GNSS systems. The RTS method must consider the timeliness and age of satellite parameters. Polynomial functions are commonly used to model and extrapolate satellite clock corrections (Leick et al., 2015). However, the linear model, which considers satellite clock variation

Li *et al. Satellite Navigation*   (2023) 4:23

Page 3 of 10

and has a small number of parameters, is an alternative option. The linear model can be expressed as follows:

$$\delta(t) = a_0 + a_1 \times (t - t_0) \tag{3}$$

where t is observation time and t_0 is reference time; $\delta(t)$ is the satellite clock correction at t, a_0 and a_1 are coefficients.

In GNSS satellite clock parameterization, the linear model is typically employed to construct the broadcast ephemeris, which has an age in the order of hours. Because of the long term of prediction, the accuracy of the satellite clock correction is only sufficient for meter-level positioning. Nevertheless, the linear model with its two coefficients can easily capture decimeter-level satellite clock variations. Therefore, it is essential to examine the performance of the linear model in constructing RTS for BDS-3 and Galileo satellite clock corrections.

RTS strategy

A good RTS method should consider both the timeliness and accuracy of the broadcasted parameters. For BDS-3, a difference in the satellite clock correction between the broadcast ephemeris and estimated values is directly broadcasted (Li et al., 2022b). It is clear that the arc length of the observations used to estimate the satellite clock correction affects the timeliness of the broadcasted parameters, as computation is required. Therefore, it is important to use an appropriate arc length for the satellite clock correction and extrapolation algorithm. The extrapolation algorithm is particularly useful in saving time and maintaining the timeliness of the broadcasted parameters. Considering these factors, the flow chart of the proposed RTS method is shown in Fig. 1.

Data processing

To evaluate the performance of the linear model in its corresponding RTS method, we used one-month (May 1–31, 2021) IGS BDS-3 and Galileo satellite clock correction products (ftp://ftp.gfz-potsdam.de/pub/GNSS/products/mgnss) of GeoForschungsZentrum (GFZ) to simulate the RT experiment. Additionally, we employed 10 IGS stations to test the proposed RTS method. The PPP processing strategy used is outlined in Table 2. We analyzed the positioning accuracy and convergence time. The convergence time is defined as the elapsed time when the PPP coordinate errors for all consecutive epochs in the north, east, and up directions are less than 10 cm.

Extrapolation of the linear model

Extrapolation is a key component of the RTS method, where a function is fitted to a set of observed satellite clock correction series and then used to predict future values. In this study, we used IGS satellite clock correction series of different arc lengths to analyze the performance of the linear model in extrapolating satellite clock corrections for BDS-3 and Galileo. The coefficients of the linear model were fitted using different arc lengths of satellite clock correction series, and the extrapolated values for the next time spans were obtained using the fitting

Table 2 PPP processing strategy

| Item	Strategy
Data	10 IGS stations, May 1–31, 2021
Estimator	Least squares (Chang, 2015)
Sampling	30 s
Elevation cut-off	10°
Satellite clock	(1) IGS; (2) Improved RTS, which transmits the linear coefficient at different intervals
Satellite orbit	IGS product of GFZ
Tropospheric delay	Saastamoinen model for the dry delay and estimation for the wet component
Ionospheric delay	Ionosphere-free
Relativistic effect; Sagnac effect; phase wind-up effect; tide effect	Corrected model (Petit & Luzum, 2010)
Station coordinates	Estimated
Receiver coordinates	Static and kinematic modes
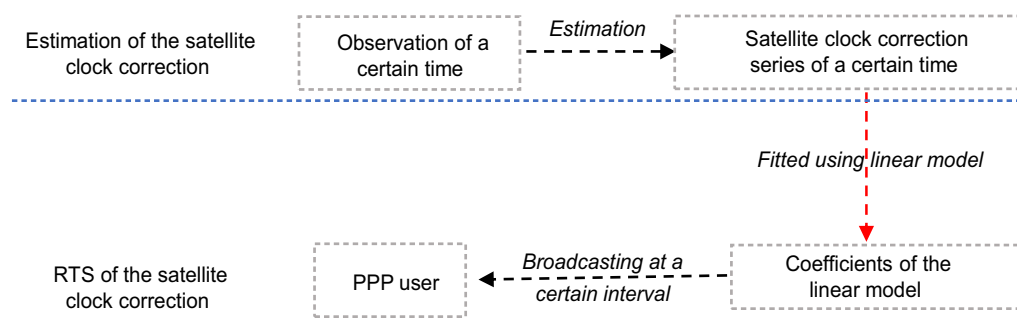
Fig. 1 Flow chart of the presented RTS strategy

Li *et al. Satellite Navigation*   (2023) 4:23

Page 4 of 10

coefficients. The 24 h satellite clock corrections were generated using the analogous procedure. The Root Mean Square (RMS) of the difference between the extrapolated and IGS values were computed. The one month mean RMS values of min-level extrapolation results for BDS-3 and Galileo are plotted in Figs. 2 and 3, respectively. These figures show the min-level extrapolation

results decrease as the extrapolation time increases and the accuracy for Galileo is better than that of BDS-3. It is also observed that the min-level extrapolation RMS results are less than 0.09 ns.

The one month mean RMS values of hour-level extrapolation results for BDS-3 and Galileo are given in Figs. 4 and 5, respectively. It is obvious that the hour-level
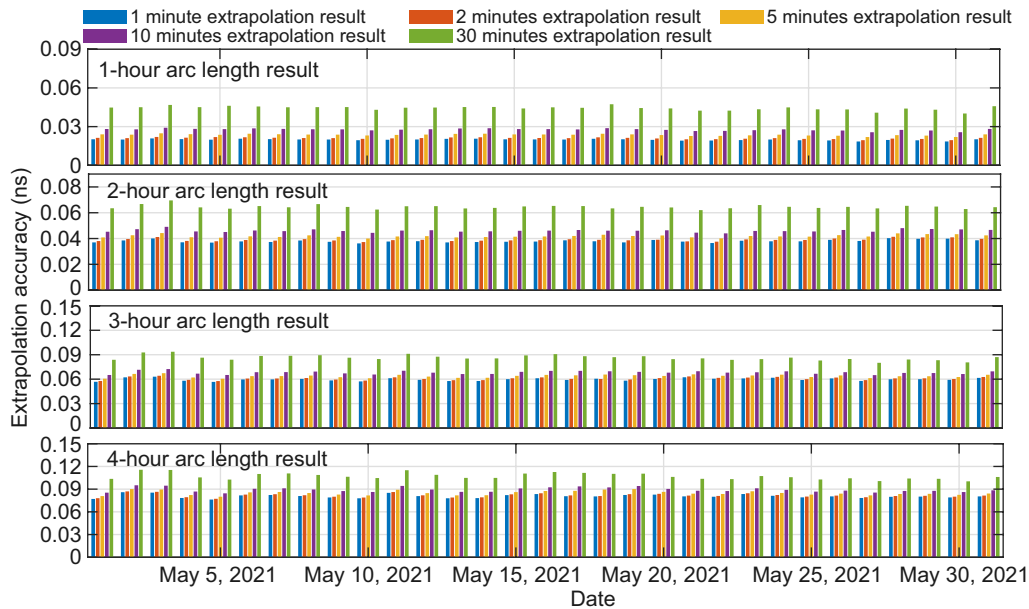
Fig. 2 Mean RMS for BDS-3 min-level extrapolation results
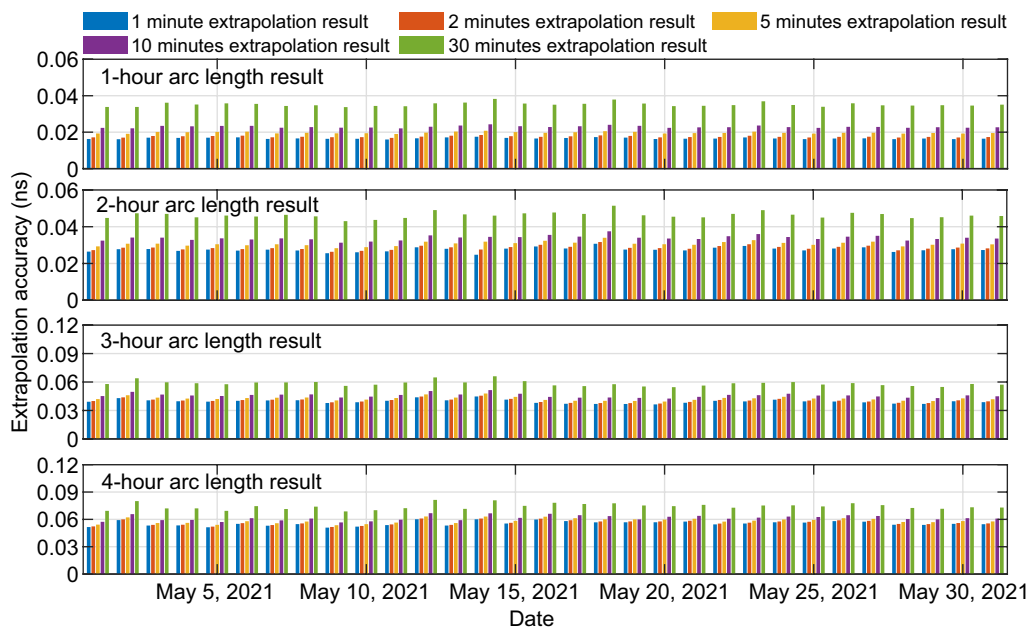
Fig. 3 Mean RMS for Galileo minute-level extrapolation results
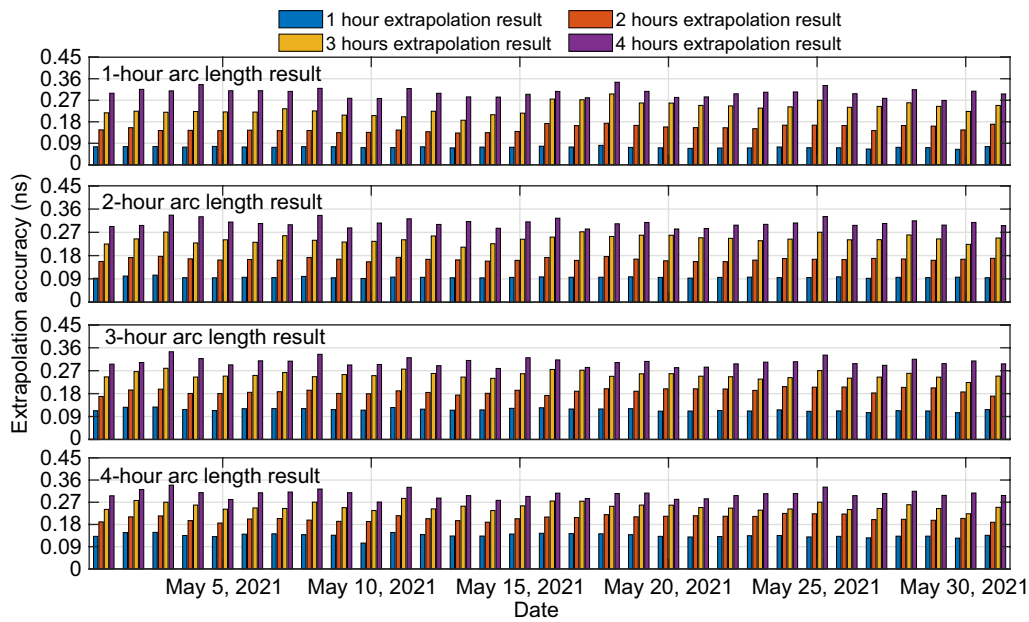
Fig. 4 Mean RMS for BDS-3 h-level extrapolation results
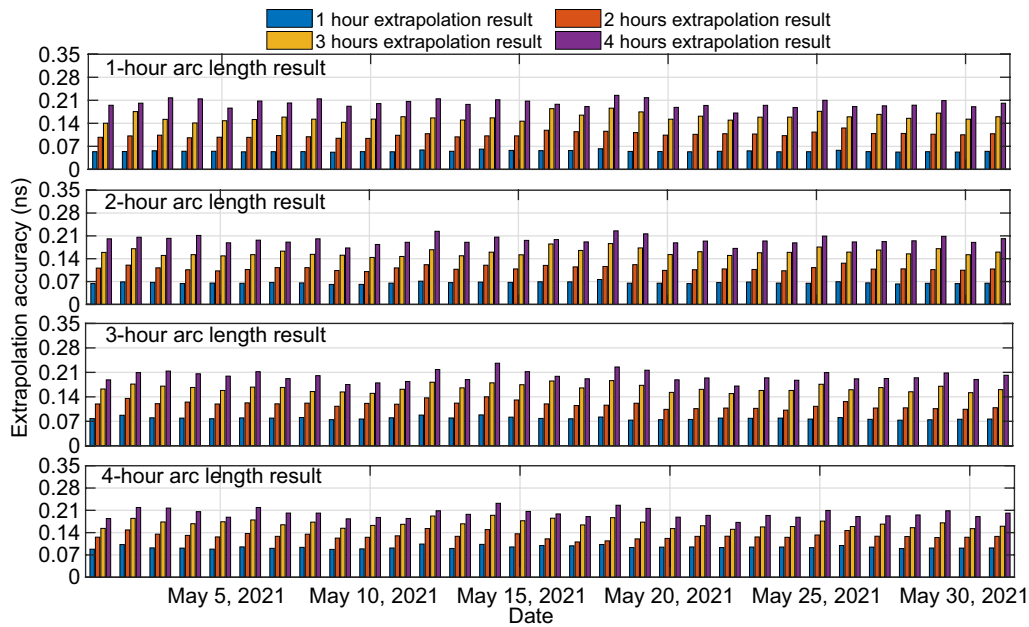
Fig. 5 Mean RMS for Galileo hour-level extrapolation results

extrapolation results are worse than the min-level results, and the 4 h results of BDS-3 and Galileo reach a mean accuracy of 0.3 ns and 0.2 ns, respectively. Similar to the min-level extrapolation results, the hour-level extrapolation accuracy decreases as the arc length increases and the 4 h extrapolation results for 1 h arc length is better than that of 4 h arc length. The mean accuracies for

different arc length and different extrapolation times are computed and provided in Fig. 6. This figure shows that the results become worse with increasing arc length of the satellite clock correction series and the optimal arc length for the satellite clock correction series is 1 h. From Fig. 6, the minute- and hour-level extrapolation results for BDS-3 and Galileo are better, and the mean
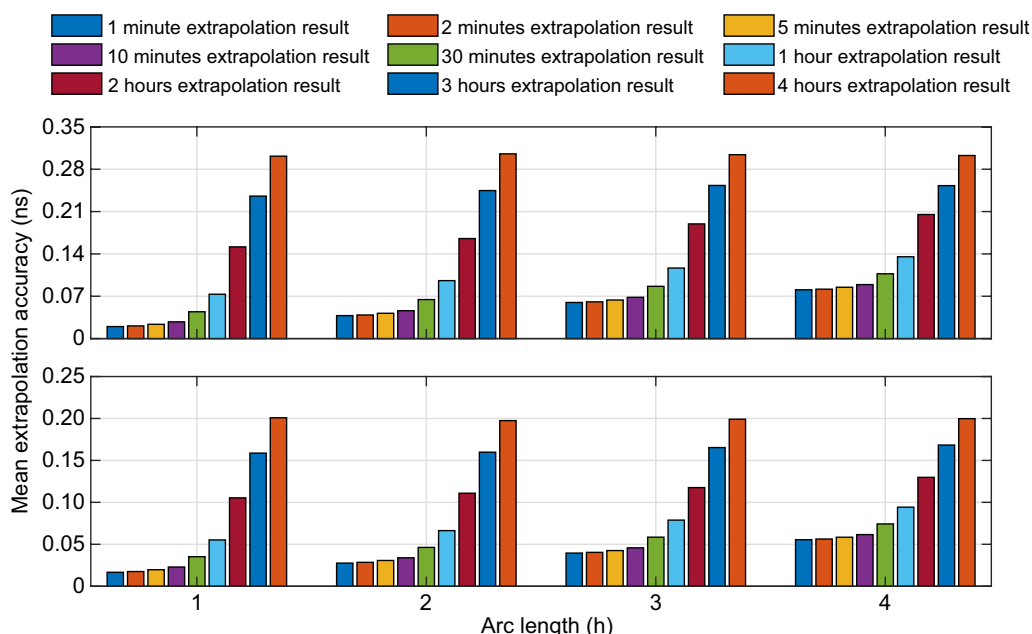
Fig. 6 Mean accuracies of BDS-3 (Up) and Galileo (Down) for different arc length and different extrapolation times

accuracies of minute-level results for BDS-3 and Galileo are better than 0.044 ns and 0.035 ns, respectively, when a 1-h arc length for the satellite clock correction series is used. This highlights the importance of selecting an appropriate satellite clock correction series estimated using observations to construct the RTS method. A satellite clock correction series with a long arc length can waste time for estimation and affect the timeliness of the RTS.

RTS performance
The advantage of the extrapolation algorithm in preserving the timeliness of broadcast RTS parameters is apparent. Following the procedure depicted in Fig. 1, a 1 h estimated satellite clock correction series is utilized to determine the parameters of the linear model. These parameters are subsequently transmitted and updated at the minute level. The analysis of PPP performances for various strategies aims to determine the optimal RTS method. In PPP processing, the IGS orbit of the corresponding satellite clock products is utilized. This approach aligns with the common strategy. The convergence time and positioning error of BDS-3 and Galileo for different strategies are assessed over a one-month period. Figure 7 illustrates the computed one-month convergence time of BDS-3 and Galileo for different static PPP strategies. It is evident from the figure that the convergence time of both Galileo and BDS-3 under different RTS strategies can reach a centimeter-level accuracy, albeit taking longer than the IGS standard. The static PPP

positioning of Galileo and BDS-3 also achieve centimeter-level precision, with the mean convergence time of 57 and 53 min, respectively, even when the linear model parameters are broadcasted and updated every 10 min. The decreasing trend in convergence time suggests the accuracy of the extrapolated Galileo and BDS-3 satellite clock error is improved. As a result, users have the flexibility to choose their preferred strategy based on their specific requirements.

The one-month static and kinematic PPP processing results are analyzed, and the mean positioning errors are calculated and presented in Figs. 8 and 9, respectively. It is evident from these figures that the static positioning results outperform the kinematic results. The static PPP using RTS intervals of 1, 2, 5, and 10 min in the North, East, and Up directions achieve centimeter-level accuracy. This indicates that the static PPP approach yields better results compared to the kinematic approach in various strategies and directions. It is evident that the positioning accuracy in North and East directions is better than that in Up direction. Figures 10 and 11 present the static and kinematic positioning results for BDS-3 and Galileo at 10 observation stations using a 10 min RTS strategy. Remarkably, all observation stations achieve centimeter-level positioning accuracy, despite the linear model parameters being updated at 10 min intervals. These results highlight the effectiveness of the linear model in establishing a better RTS, especially when considering timeliness and simplicity. The simplicity and suitability make the linear model a favorable choice for
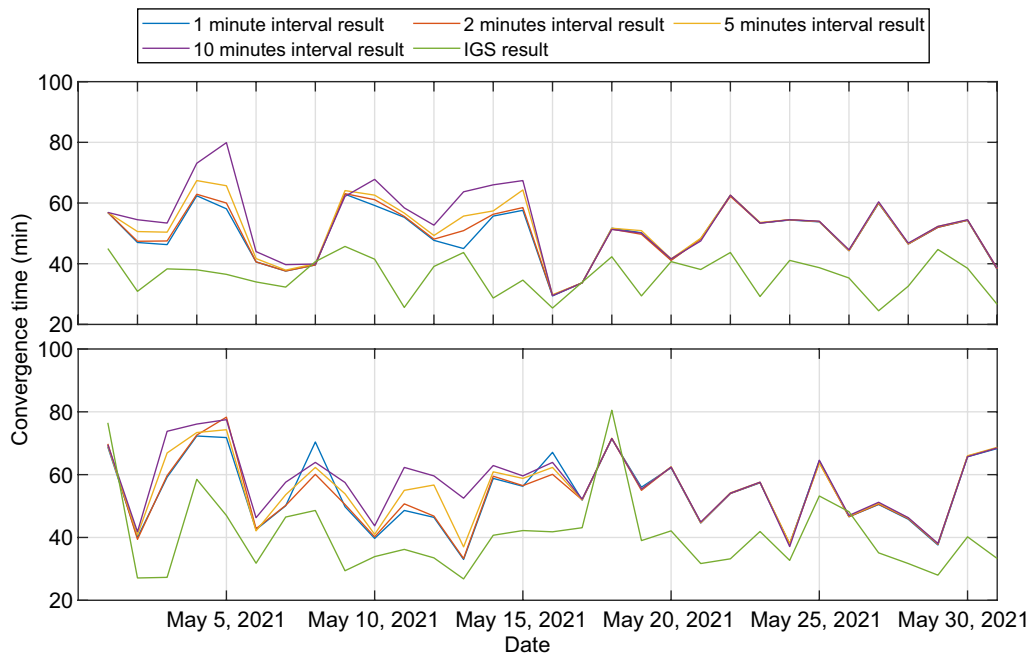
Li *et al. Satellite Navigation*   (2023) 4:23

Page 7 of 10

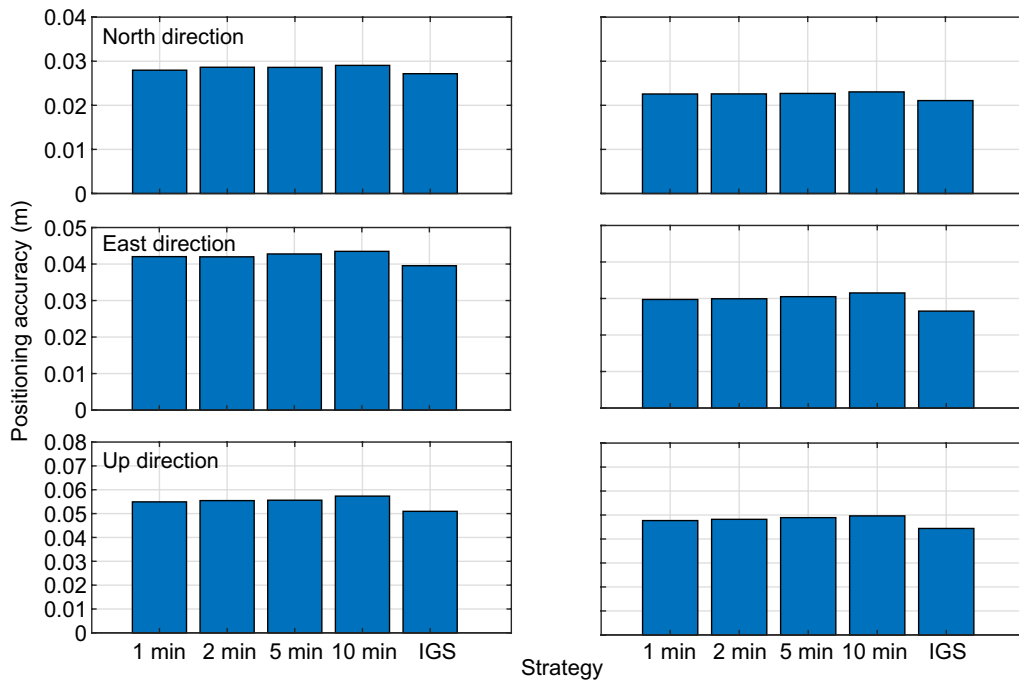**Fig. 7** Mean convergence time of BDS-3 (Up) and Galileo (Down)

Fig. 8 Static positioning of BDS-3 (Left) and Galileo (Right) for different strategies

constructing BDS-3 and Galileo RTS for satellite clock correction.

Conclusion

The provision of highly accurate RTS for satellite clock correction, orbit, and bias is crucial for high-precision and real-time PPP processing. The IGS, BDS-3, and
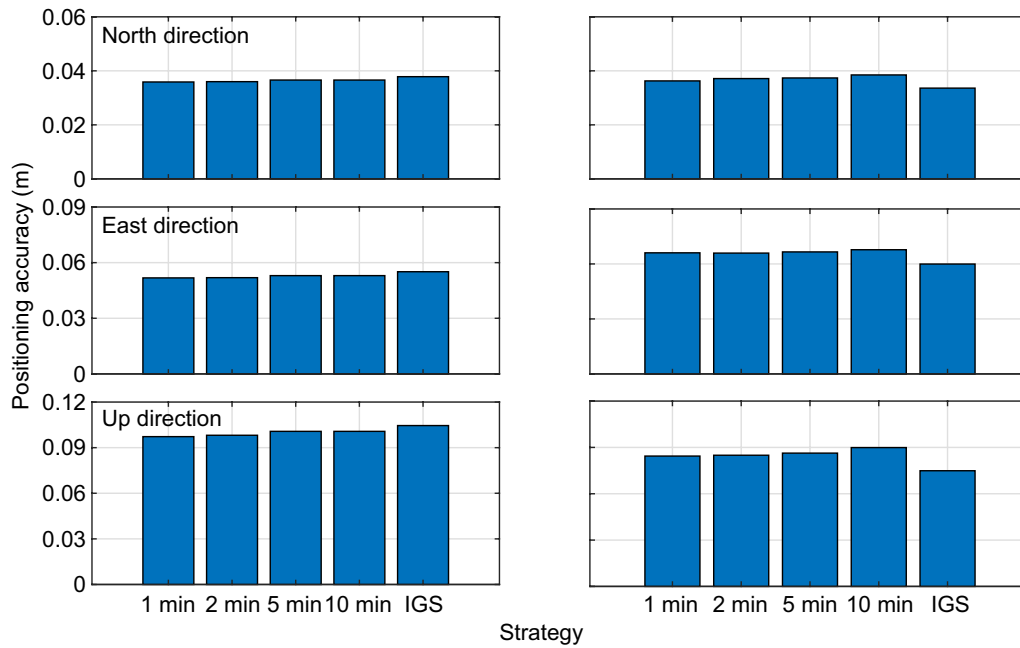
Fig. 9 Kinematic positioning of BDS-3 (Left) and Galileo (Right) for different strategies
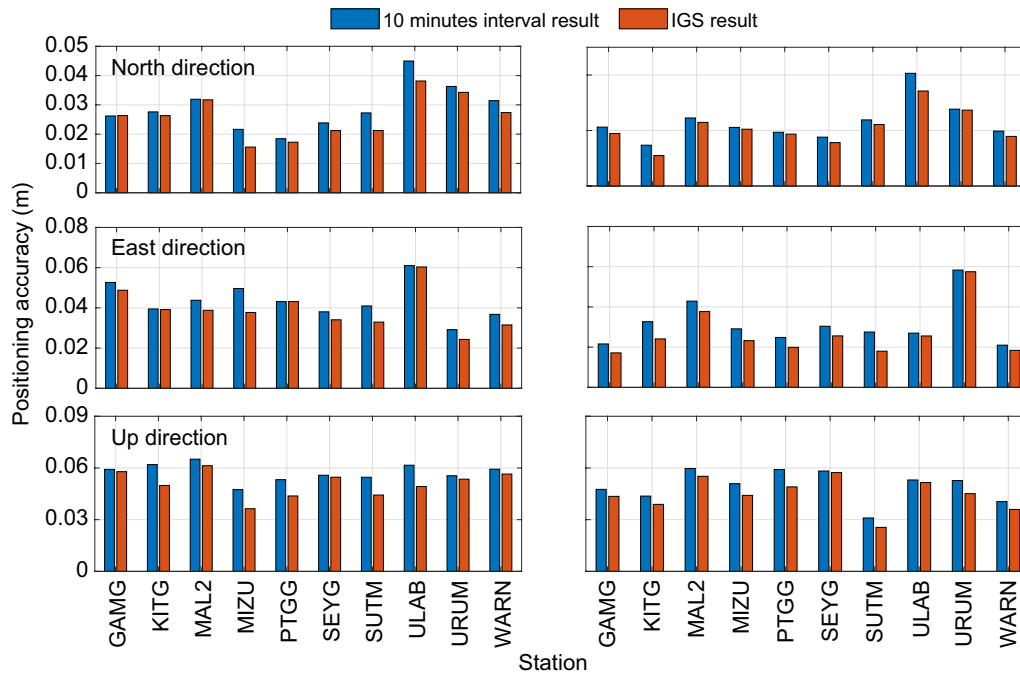
Fig. 10 BDS-3 (Left) and Galileo (Right) PPP static positioning results of IGS and 10 min strategy

Galileo systems have provided these RTS, with the satellite clock correction being transmitted and updated at high-frequency. However, frequent updating of the correction parameters can increase the computational burden and compromise the timeliness of these parameters. To address this issue, an improved RTS is established using the extrapolation algorithm and a linear model. The results indicate that a 1 h arc length of the

Li *et al. Satellite Navigation*   (2023) 4:23

Page 9 of 10
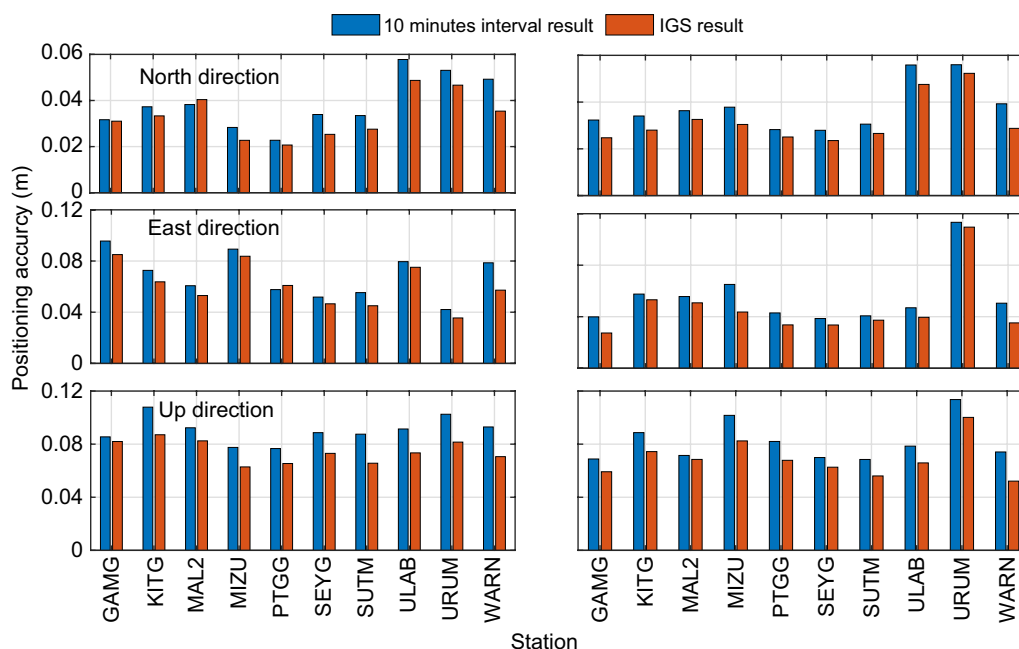
Fig. 11 BDS-3 (Left) and Galileo (Right) PPP kinematic positioning results of IGS and 10 min strategy

satellite clock correction series is optimal for fitting a linear model of the RTS. With this approach, the 1 h extrapolation results for BDS-3 and Galileo are better than 0.09 ns. Furthermore, when these coefficients are updated at intervals of 1, 2, 5, and 10 min, the corresponding PPP positioning can converge at the centimeter-level. It is evident that these improved RTS methods outperform the current approaches that transmit and update the coefficients at high-frequency, as they struggle to maintain the timeliness of these correction parameters.

References
Bock, H., Dach, R., Jäggi, A., & Beutler, G. (2009). High-rate GPS clock corrections from CODE: support of 1 Hz applications. *Journal of Geodesy, 83*(11), 1083–1094.

Cai, C., He, C., Santerre, R., Pan, L., Cui, X., & Zhu, J. (2016). A comparative analysis of measurement noise and multipath for four constellations: GPS, BeiDou, GLONASS and Galileo. *Survey Review, 48*(349), 287–295.

Chang, G. (2015). On least-squares solution to 3D similarity transformation problem under Gauss-Helmert model. *Journal of Geodesy, 89*(6), 573–576. https://doi.org/10.1007/s00190-015-0799-z

Dow, J., Neilan, R., & Rizos, C. (2009). The International GNSS service in a changing landscape of Global Navigation Satellite Systems. *Journal of Geodesy, 83*(3–4), 191–198. https://doi.org/10.1007/s00190-008-0300-3

Elsobeiey, M., & Al-Harbi, S. (2016). Performance of real-time precise point positioning using IGS real-time service. *GPS Solutions, 20*, 565–571.

Fang, R., Shi, C., Song, W., Wang, G., & Liu, J. (2014). Determination of earthquake magnitude using GPS displacement waveforms from real-time precise point positioning. *Geophysical Journal International, 196*(1), 461–472.

Feng, B., Chen, J., Ding, H., & Zhu, W. (2023). Kang Q (2023) Improved service method and its positioning performance of the Galileo satellite clock correction. *Advances in Space Research, 71*(10), 4045–4054. https://doi.org/10.1016/j.asr.2022.12.052

Ge, M., Chen, J., Dousa, J., Gendt, G., & Wickert, J. (2012). A computationally efficient approach for estimating high-rate satellite clock corrections in realtime. *GPS Solutions, 16*, 9–17.

Geng, J., Meng, X., Dodson, A. H., & Teferle, F. N. (2010). Integer ambiguity resolution in precise point positioning: Method comparison. *Journal of Geodesy, 84*, 569–581.

Hauschild, A., & Montenbruck, O. (2009). Kalman-filter-based GPS clock estimation for near realtime positioning. *GPS Solutions, 13*, 173–182.

Jaduszliwer, B., & Camparo, J. (2021). Past, present and future of atomic clocks for GNSS. *GPS Solutions, 25*, 27.

Leick, A., Rapoport, L., & Tatarnikov, D. (2015). *GPS satellite surveying* (4th ed.). Wiley.

Li, H., Chen, J., Wang, J., Hu, C., & Liu, Z. (2010a). Network based real-time precise point positioning. *Advances in Space Research, 46*(9), 1218–1224.

Li, H., Chen, J., Wang, J., & Wu, B. (2012). Satellite- and epoch differenced precise point positioning based on regional augmentation network. *Sensors, 12*(6), 7518–7528.

Li, H., Ding, H., Feng, B., & Kang, Q. (2022). Improved method for BDS-3 satellite clock parameterization in the broadcast ephemeris, real-time service (RTS) and IGS final products. *Measurement, 204*, 112059. https://doi.org/10.1016/j.measurement.2022.112059

Li, H., Li, B., Lou, L., Yang, L., & Wang, J. (2017). Impact of GPS differential code bias in dual- and triple-frequency positioning and satellite clock estimation. *GPS Solutions, 21*(3), 897–903.

Li, H., Li, B., Xiao, G., Wang, J., & Xu, T. (2016). Improved method for estimating the inter-frequency satellite clock bias of triple-frequency GPS. *GPS Solutions, 20*, 51–760.

Li, H., Li, X., & Gong, X. (2022a). Improved method for the GPS high-precision real-time satellite clock error service. *GPS Solutions, 26*, 136.

Li, H., Wang, J., Chen, J., Hu, C., & Wang, H. (2010). The realization and analysis of GNSS Network based Real-time Precise Point Positioning. *Chinese Journal of Geophysics-Chinese Edition, 53*(6), 1302–1307.

Li, H., Wu, B., & Zhou, X. (2013). Fast estimation and analysis of the inter-frequency clock bias for the Block IIF satellites. *GPS Solutions, 17*(3), 347–355.

Li, H., Zhu, W., Zhao, R., & Wang, J. (2018). Service and evaluation of the GPS triple-frequency satellite clock offset. *Journal of navigation, 71*(5), 1263–1273.

Malys, S., & Jensen, P. (1990). Geodetic point positioning with GPS carrier beat phase data from the CASA UNO experiment. *Geophysical Research Letters, 17*, 651–654. https://doi.org/10.1029/GL017i005p00651

Montenbruck, O., Hugentobler, U., Dach, R., Steigenberger, P., & Hauschild, A. (2012). Apparent clock variations of the Block IIF-1 (SVN62) GPS satellite. *GPS Solutions, 16*(3), 303–313.

Pan, L., Zhang, X., Li, X., Liu, J., & Li, X. (2017). Characteristics of inter-frequency clock bias for Block IIF satellites and its effect on triple-frequency GPS precise point positioning. *GPS Solutions, 21*(2), 811–822.

Petit G, Luzum B (2010) IERS Conventions (2010). IERS technical note.

Wu, W., Guo, F., & Zheng, J. (2020). Analysis of Galileo signal-in-space range error and positioning performance during 2015–2018. *Satellite Navigation, 1*, 6. https://doi.org/10.1186/s43020-019-0005-1

Yang, Y., Ding, Q., Gao, W., Li, J., Xu, Y., & Sun, B. (2022). Principle and performance of BDSBAS and PPP-B2b of BDS-3. *Satellite Navigation, 3*, 5. https://doi.org/10.1186/s43020-022-00066-2

Yang, Y., Mao, Y., & Sun, B. (2020). Basic performance and future developments of BeiDou global navigation satellite system. *Satellite Navigation, 1*, 1. https://doi.org/10.1186/s43020-019-0006-0

Zhang, X., Li, X., & Guo, F. (2011). Satellite clock estimation at 1 Hz for real time kinematic PPP applications. *GPS Solutions, 15*(4), 315–324. https://doi.org/10.1007/s10291-010-0191-7

Zumberge, J. F., Heflin, M. B., Jefferson, D. C., Watkins, M. M., & Webb, F. H. (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research, 102*, 5005–5017. https://doi.org/10.1029/96JB03860

Publisher's Note