

Article

Impact of Latency and Continuity of GNSS Products on Filter-Based Real-Time LEO Satellite Clock Determination

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Abstract: High-precision Low Earth Orbit (LEO) satellite clocks are essential for LEO-augmented Positioning, Navigation, and Timing (PNT) services. Nowadays, high-precision LEO satellite clocks can be determined in real-time using a Kalman filter either onboard or on the ground, as long as the GNSS observations collected onboard LEO satellites can be transmitted to the ground in real-time. While various real-time and high-precision GNSS products are available nowadays in the latter case, their continuity and latencies in engineering reality are not as perfect as expected and will lead to unignorable impacts on the precision of the real-time LEO satellite clocks. In this study, based on real observations of Sentinel-3B, the impacts of different latencies and continuity of the real-time GNSS products on LEO real-time clocks are determined and discussed for two scenarios, namely the “epoch estimation” and “arc estimation” scenarios. The former case refers to the traditional filter-based processing epoch-by-epoch, and the latter case connects LEO satellite clocks from different rounds of filter-based processing under a certain arc length. The two scenarios lead to the “end-loss” and “mid-gap” situations. Latencies of the real-time GNSS products are discussed for the cases of orbit-only latency, clock-only latency, and combined forms, and different handling methods for the missing GNSS satellite clocks are discussed and compared. Results show that the real-time LEO satellite clock precision is very sensitive to the precision of real-time GNSS satellite clocks, and prediction of the latter becomes essential in case of their latencies. For the “end-loss” situation, with a latency of 30 to 120 s for the GNSS real-time clocks, the LEO satellite clock precision is reduced from about 0.2 to 0.28–0.57 ns. Waiting for the GNSS products in case of their short latencies and predicting the LEO satellite clocks instead could be a better option. For “arc-estimation”, when the gap of GNSS real-time products increases from 5 to 60 min, the real-time LEO clock precision decreases from 0.26 to 0.32 ns.

Keywords: LEO; real-time; satellite clocks; GNSS products; latency; gap



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1. Introduction

Satellite-based Positioning, Navigation, and Timing (PNT) is nowadays utilizing signals from satellites at various orbital heights, such as Geostationary Orbit (GEO), Medium Earth Orbits (MEOs), Inclined Geosynchronous Orbits (IGSOs), and Low Earth Orbits (LEOs). Among them, and benefiting from the low altitudes and the fast speeds of the LEO satellites, the feasibility of LEO/GNSS-integrated PNT services has been highlighted in recent years [1–7]. LEO satellites will serve as navigation satellites and be applied to

fields such as unmanned driving and artificial intelligence to achieve precise, real-time, dynamic, and global PNT services. High-precision real-time LEO satellite products are indispensable for achieving single-receiver-based cm-level accuracy in LEO-augmented PNT services.

The use of GNSS observations collected onboard LEO satellites has been reliably validated and utilized in LEO satellite Precise Orbit Determination (POD) and clock determination for many years [7–10]. Research has shown that LEO orbit determination using dual-frequency, multi-constellation GNSS with a batch least-squares reduced-dynamic model can achieve RMS of about 1.5 cm in post-processing mode [8] and real-time LEO satellite POD with a latency of a few minutes could also be achieved with an Orbital User Range Error (OURE) of 2–4 cm [11]. The filter-based model was also studied for the LEO satellite POD [9]. Combined with dynamic models, sub-dm to dm accuracy can be achieved. Even without any dynamic model, filter-based kinematic LEO satellite POD can also achieve accuracy at a similar level [10].

Like the real-time LEO satellite POD, GNSS observations combined with a reduced dynamics model or kinematic model can also be used to determine the LEO satellite clocks in real-time. When employing batch least-squares adjustment in the reduced-dynamic model to determine LEO satellite clocks, near-real-time clock precision of approximately 0.15 ns can be attained when using high-quality GNSS real-time orbital and clock products [12]. Nonetheless, this entails a processing duration of roughly 5 min for a 24 h processing cycle with a 30 s sampling interval, even with a modern processing unit. In such a case, a clock prediction of at least 10 min is needed to catch up with the real-time applications. This introduces prediction loss of a few sub-nanoseconds due to the complicated systematic effects contained in the LEO satellite clock estimates [12–14].

LEO satellite clocks can be determined more efficiently in a filter-based manner, yet less precise compared to the Batch Least-Squares (BLS) processing. Using triple-frequency GPS/Galileo observations from Sentinel-6A and broadcast ephemerides, a 14-day continuous evaluation of actual flight data showed that a 0.9 ns real-time clock standard deviation can be achieved [15]. Wu et al. have introduced and implemented a method for real-time determination of LEO satellite clocks [16]. This approach involves near-real-time clock determination combined with ultra-short-term clock prediction. It employs Kalman-filter-based processing but allows for restarts at predefined times, thereby preventing continuous bias propagation and accumulation from earlier epochs. Using dual-frequency, real observations from Sentinel-3B and real-time GNSS products from the National Center for Space Studies (CNES) in France [17], the near-real-time GNSS clocks have a precision of about 0.2–0.3 ns, then by predicting for a short period (up to 120 s), a real-time clock precision of about 0.3 ns was achieved [16]. Integrating ground observations from a simulated regional network with onboard GNSS observations was also studied, with a precision of about 0.15 ns in the post-processing mode [18].

While most studies for real-time LEO satellite clock determination used real-time GNSS products either collected in good conditions or directly archived on the FTP server of the service provider, in-depth study of the impact of the continuity and latencies of the real-time GNSS orbits/clocks on real-time LEO satellite clock determination was rarely performed. Hadas et al. concluded a latency of about 31 s for the IGS03 stream and 28 s for the IGS01 stream [19]. Lv et al. also showed the loss rates of the IGS real-time products ranging from about 3% to 45% and pointed out that the loss of GNSS products significantly impacts real-time Precise Point Positioning (PPP) applications [20]. The latencies and continuity of the real-time GNSS products would, without a doubt, lead to unignorable impacts on the real-time LEO satellite clock estimates, sometimes even greater than the precision of the real-time GNSS products themselves. In [21], the impacts of the continuity and latency of the real-time GNSS products on LEO satellite POD are presented. In this study, the focus is on the LEO satellite clocks, which are a limiting factor for the LEO satellite Signal-in-Space Ranging Error (SISRE). Different situations of the discontinuity and latencies of the real-time GNSS products, the strategies to deal with

these situations, and the resulting impacts on the real-time LEO satellite clock precision are discussed in the frame of this contribution. In addition to orbit and clock products, other factors like the yaw attitude of GNSS satellites could also influence the LEO satellite clock precision [22], but this effect will not be addressed in this study.

The paper starts with a general overview of the GNSS products used in the LEO clock determination in this contribution. Afterward, the methodology for LEO clock determination based on using the Kalman filter is described. Subsequently, the impacts of the latency and continuity of GNSS real-time products on the LEO satellite clock determination are discussed in detail. The conclusions and discussions are given at the end.

2. GNSS Products

The International GNSS Service (IGS) [23] has ensured the availability of open-access, high-quality GNSS orbital and clock data products since 1994 [24]. The post-processed products of IGS include Final products, Rapid products, Ultra-Rapid (observed half), and Ultra-Rapid (predicted half) products, with latencies of 12–19 days, 17–41 h, 3–9 h, and real-time, respectively. Due to the long delays, none of the first three can be used for real-time LEO satellite clock determination. Therefore, available real-time GNSS products are limited to the Ultra-Rapid (predicted half), the broadcast ephemeris, and the real-time stream products provided by IGS Real-Time Service (RTS). Taking the GPS satellite clock as an example, the STD of broadcast ephemeris and Ultra-Rapid (predicted half) is about 2.5 and 1.5 ns, respectively, which limits their applications for high-precision real-time LEO satellite clock determination.

In 2013, IGS RTS was established to meet the demands of various real-time applications. Currently, four IGS-SSR streams are disseminated, named SSRA02IGS, SSRC02IGS1, SSRA03IGS1, and SSRC03IGS1, which are weighted averages of products of different Analysis Centers (ACs). Besides that, some ACs also provide individual RTS products [17,25,26]. For GPS satellites, the clock precision is typically good, ranging from 0.1 to 0.2 ns, and the orbital accuracy is generally within 5 cm in each direction, compared with COM final products, respectively [27,28]. As such, IGS RTS provides the necessary product assurance for determining real-time LEO satellite products when using GNSS observations.

In this study, real-time GNSS satellite products from four different analysis centers, CNE, GFZ, GMV, and WHU, were collected using the BKG Ntrip Client (BNC) Version 2.12.18 [29] from Day-Of-Year (DOY) 119–225, 2024. Figure 1 shows the continuity of GPS satellite products during the test period with a sampling interval of 30 s for the clocks and 5 min for the orbits. It can be seen that all products exhibit small data gaps, which could be caused by various reasons, including the internet connection and the server connection status.

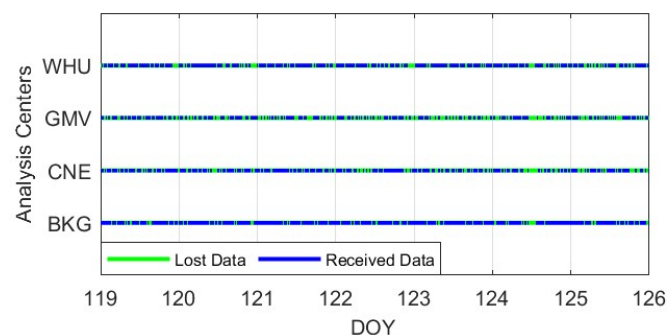


Figure 1. The continuity of the received real-time GPS satellite clocks from four analysis centers.

Table 1 displays the continuity and latency of these products during the test period. The latency varies from 5 to 30 s. Most of the ACs adopt their own ultra-rapid orbits or IGS ultra-rapid orbits to generate the RTS orbit corrections, while the satellite clock offsets are estimated by introducing the predicted orbits [17,19]. Therefore, in the process of generating RTS products, the steps that may cause delays include collecting network

observations, estimating the clocks, and disseminating clocks and orbits over the network. The internet status of the service provider, the transmission caster, and the user could also cause data gaps and delays.

Table 1. The continuity and latency of the received real-time GPS satellite clocks from different analysis centers.

ACs	Continuity	Latency
WHU	80.69%	≤ 5 s
GMV	67.53%	≤ 30 s
CNE	78.07%	≤ 20 s
BKG	87.60%	≤ 20 s

The continuity or latency of the real-time GNSS product would directly influence the precision and continuity of the LEO satellite clock determination. This will be discussed in the next section.

3. Processing Methods

This section will first introduce two methods for determining the LEO satellite clocks using a Kalman filter, i.e., the epoch-processing and the arc-processing. Next, the impacts of the latency and continuity of the GNSS real-time products on the LEO satellite clocks determination will be explained analytically.

3.1. Filter-Based Real-Time LEO Satellite Clock Determination

In this study, the LEO real-time clock is determined using a kinematic model processed using a Kalman filter to achieve both high precision and high computational efficiency. The orbits can be estimated together with the clocks or introduced based on a short-term prediction [30]. This study employs the former case. The Observed-Minus-Computed (O-C) terms of the Ionosphere-Free (IF) pseudo-range and carrier phase GNSS observations collected onboard LEO satellites can be expressed as follows:

$$P_{IF} = A_x \Delta r_K + c \times d\bar{t}_r + \varepsilon_{P_{IF}} \quad (1)$$

$$L_{IF} = A_x \Delta r_K + c \times d\bar{t}_r + \lambda \bar{N}_{IF} + \varepsilon_{L_{IF}} \quad (2)$$

with

$$d\bar{t}_r = dt_r + \frac{d_{r,IF}}{c} + d_{rel} \quad (3)$$

$$\Delta r_K = [\Delta r_x, \Delta r_y, \Delta r_z] \quad (4)$$

$$\lambda_{IF} = \frac{c}{f_1 + f_2} \quad (5)$$

$$\bar{N}_{IF} = \frac{f_1^2}{f_1^2 - f_2^2} N_1 - \frac{f_2^2}{f_1^2 - f_2^2} N_2 + b_{r,IF} - b_{IF}^s - \frac{d_{r,IF}}{\lambda_{IF}} \quad (6)$$

where the pseudo-range and phase observations O-C terms for the IF combinations are represented by P_{IF} and L_{IF} , respectively. f_1 and f_2 correspond to the first and the second frequencies used, respectively. A_x is the design matrix containing partial derivatives of the observations with respect to the orbital coordinates. Δr_K is the kinematic orbital correction vector based on the initial orbits, with Δr_x , Δr_y , and Δr_z representing the increments of the LEO satellite position in the X, Y, and Z directions of the Earth-Centered Earth-Fixed (ECEF) system, respectively. No dynamic model is applied to the orbit. $d\bar{t}_r$ represents the estimable receiver clocks with the inclusion of the IF receiver code bias $d_{r,IF}$ and the relativistic effects d_{rel} . Recall that dt_r denotes the LEO satellite clocks. Note that $d\bar{t}_r$ is estimated as independent epoch-by-epoch parameters without applying constraining clock models. It is assumed here that the IF code hardware delay of the GNSS satellite is already

included in the GNSS satellite clock products. Depending on the systems and types of signals used, Differential Code Bias (DCB) and Inter-System Biases (ISBs) may apply [5,25]. Compared to the stricter data preprocessing approach in the BLS-based reduced-dynamic model, in the Kalman filter-based kinematic model, cycle slip detection is performed using only the GF combination, with the threshold set to 0.05 m. Once a cycle slip is detected, the ambiguity parameters are reset.

The above-mentioned LEO satellite clocks are determined in two ways in this study; the first method involves continuous filtering calculations, as seen in the left panel of Figure 2, while the second method periodically starts the filtering process for a certain arc length and connects different rounds of real-time clock products based on near-real-time determination and short-term prediction [18], as seen in the right panel of Figure 2.

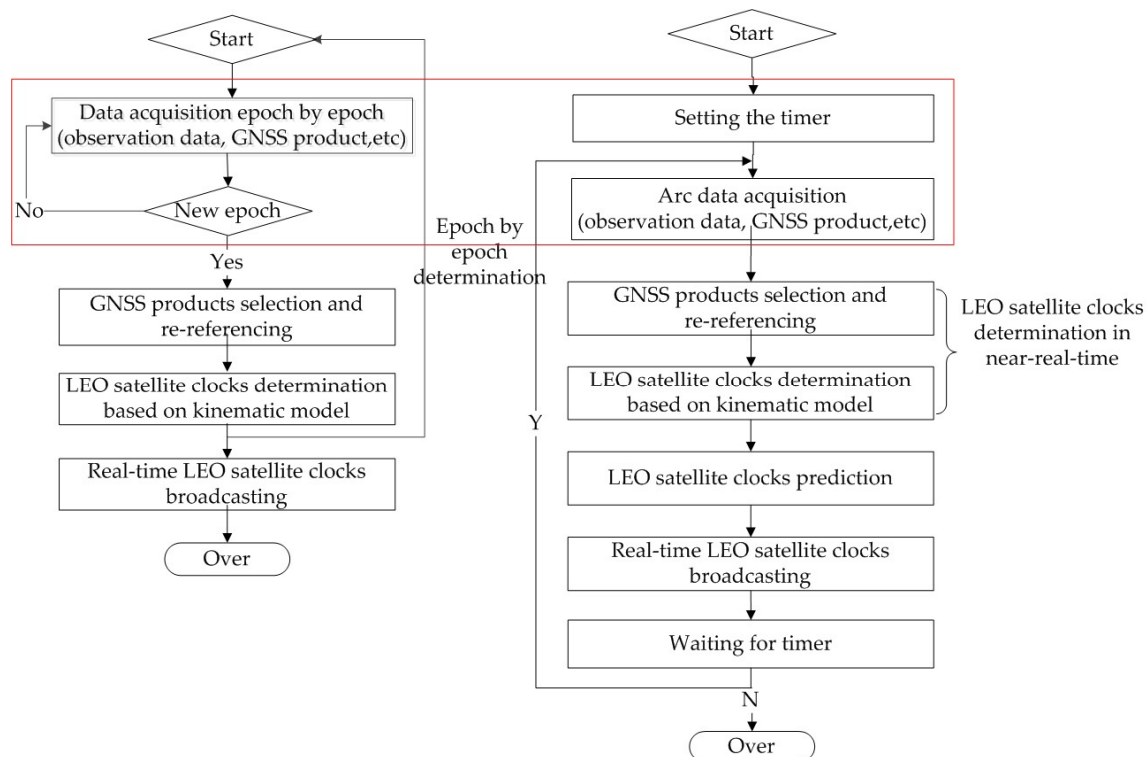


Figure 2. Epoch-processing (left) and arc-processing (right) of real-time LEO satellite clock determination based on the kinematic model using the Kalman filter.

The difference between the two methods lies in the observation data input, as shown in the contents within the red box in Figure 2. The left panel of Figure 2 describes the traditional Kalman filtering process, where the observation data are input epoch by epoch, and the clocks are estimated epoch by epoch, referred to as “epoch-estimate” in this study. In the right panel of Figure 2, a segment of observation data is input at pre-defined intervals, and the clocks of this arc are estimated, referred to as “arc-estimation” in this study.

The time required to estimate the parameters differs between the two methods due to the difference in the amount of processing data. When data are input epoch by epoch in the epoch-processing method, the time required to estimate the clocks for a single epoch is usually less than 1 s, with the filter running forward continuously. Due to the longer length of the observation arc in the arc-processing method, the time required to periodically estimate the LEO satellite clocks is longer, which implies a slightly longer prediction time (e.g., 60 s). However, the latter method can hamper bias propagation and accumulation from previous epochs and can handle situations with poor network quality, thereby improving the stability of the LEO satellite clocks [16].

Figure 3 depicts a processing timeline of these two methods for the real-time LEO satellite clock determination. T_0 is the initial time of the entire process. In the method where

LEO clocks are calculated epoch by epoch, the time required to estimate a single epoch, T_{epoch} , represents the latency of the LEO satellite clock products generated in this scenario. For “arc-estimation”, ΔT denotes the time interval between the launching of two subsequent processing sessions. Point A marks the beginning of the near-real-time LEO clock arc, B marks the end of the near-real-time LEO clock arc, and C represents the time point when the near-real-time clock determination and prediction are completed. D signifies the end of the prediction arc. As depicted by the blue lines, T_{arc} (between B and C) for processing one arc is longer than T_{epoch} for processing one epoch (typically shorter than 1 s). Consequently, the prediction arc (BD) needs to be longer to fulfill the needs of real-time applications.

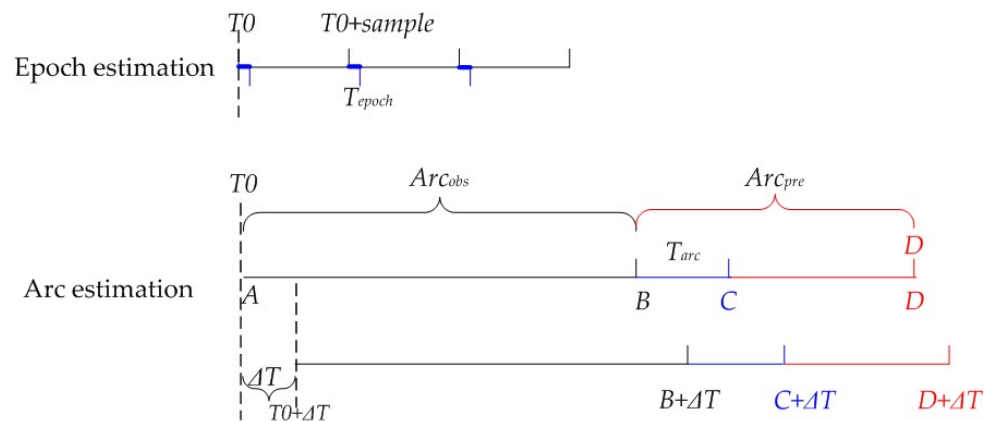


Figure 3. Processing timelines of the two methods for real-time LEO satellite clocks determination based on the kinematic model and using the Kalman filter.

Table 2 lists the strategies of filter-based real-time LEO satellite clock determination. The length of observation depends on whether it is “epoch estimation” or “arc estimation”. The choice relates mainly to whether the GNSS observations onboard LEO satellites can be obtained for processing in real time. Additionally, the attitude of GNSS satellites is considered stable, and its impact on the LEO satellite clocks is negligible.

Table 2. The strategies of filter-based real-time LEO satellite clock determination.

Parameters	Processing Strategies
Observations	Undifferenced IF code and carrier phase combination (GPS: L1/L2)
Length of observation	Arc-estimation: 6 h/Epoch estimation: 30 s
Sampling	30 s
Elevation cut-off angle	3°
GNSS orbits and clocks	CNES real-time products
GNSS satellite antenna PCO/PCVs	igs20.atx
LEO satellite antenna PCO/PCVs	Operator supplied
Phase wind-up	Corrected
Estimator	Extended Kalman filter, Kinematic

3.2. Impacts of the Latency and Continuity of GNSS Real-Time Products on the LEO Satellite Clock Determination

For the LEO satellite constellation, a communication network can be constructed through inter-satellite links to enable real-time downlink of onboard GNSS observation data [4]. Typically, the data downlink delay can be limited to a few seconds or even shorter. However, as shown in Table 1, the latency for receiving real-time GNSS products could be 20–30 s. As a result, when estimating LEO satellite clocks in real-time with the epoch-processing method, as depicted in the left panel of Figure 2, there arises a situation

where the observation data precede the availability of GNSS real-time products. In other words, GNSS real-time products may not be available due to their latency to determine the LEO satellite clocks at the final epoch of the observation period. In this study, we indicate this situation as “end-loss”.

When employing the arc-processing method, as shown in the right panel of Figure 2, it is necessary to consider the discontinuity of the GNSS real-time products in the near-real-time processing arc (the black line in the lower part of Figure 3), which is labeled as “mid-gap”. In this method, attention needs to be paid to the place and duration of the appeared gaps, which will influence the subsequent LEO clock predictions.

As explained above, the latency of the GNSS products leads to the problem of “end-loss”, and discontinuity of the GNSS products leads to the problem of “mid-gap”. When performing filter-based real-time LEO satellite clock determination, the GNSS product loss can be handled as follows:

- In real-time processing mode, when “end-loss” occurs due to the latency of the GNSS products. The orbits are tested for two scenarios: (1) Orbit extrapolation based on the available real-time orbital information using the 9th-order Nevil model [31]; (2) using the ultra-rapid orbits employed for estimating the clocks, i.e., only the clocks are considered delayed (see Scenarios C and E in Table 2). For the delayed real-time GNSS satellite clocks, two scenarios are tested as well: (1) Employing the last-epoch clock that is available in the real-time products. For example, the software RTKlib Version 2.3.4 [31] utilizes this strategy; (2) predicting the clocks based on linear extrapolation of the last N epochs, and N is the value of the “end-loss” duration divided by the GNSS clock sample.
- In near-real-time processing mode or post-processing mode, when “mid-gap” occurs during the LEO satellite clocks determination, linear interpolation of GNSS satellite clocks is performed using the last epoch before the clock product interruption and the first epoch after the interruption. The interpolation method is performed as follows:

$$dt^g = \frac{dt_2^g \times \Delta t_1 + dt_1^g \times \Delta t_2}{\Delta t_2 - \Delta t_1} \quad (7)$$

with

$$\Delta t_2 = t_2 - t \quad (8)$$

$$\Delta t_1 = t - t_1 \quad (9)$$

where t_1, t_2 is the last epoch before the clock product interruption and the first epoch after the interruption, respectively; t is the epoch to be interpolated at; dt_1^g and dt_2^g is the GNSS clocks at t_1, t_2 ; dt^g is the GNSS clock at t to be interpolated.

4. Tests and Results

A detailed analysis is conducted on the impact of the continuity and latency of GNSS real-time products on LEO satellite clocks, focusing on the occurrences of “end-loss” and “mid-gap” during the determination of LEO satellite clocks when using the “epoch-estimation” or “arc-estimation” methods.

Using real data collected onboard Sentinel-3B on DOY 227, 2018, and the CNES real-time satellite orbital and clock products with different latencies or gaps, LEO satellite clocks are determined and analyzed. For comparison purposes, Sentinel-3B clocks estimated using a Kalman filter-based kinematic model with the CNES real-time products without latency and gap are evaluated as well. The Sentinel-3B clocks determined based on a BLS reduced-dynamic model using the final products provided by the Center for Orbit Determination in Europe (CODE) [32] are used as the reference to calculate the clock precision of the above-mentioned scenarios. As ΔT in Figure 3 of the manuscript is set to 120 s, each day’s results contain 720 sessions.

Figure 4 displays the real-time clocks of Sentinel-3B estimated in a Kalman filter using the CNES real-time products without latency, denoted as K (see the blue line in the top

panel of Figure 4), and the corresponding clocks determined based on BLS and CODE final products, denoted as R (see the red line in the top panel of Figure 4). The difference between the two products (after unifying the time reference) is shown in the bottom panel. It can be seen that the precision of the real-time LEO satellite clocks without latency and gaps in GNSS real-time products amounts to about 0.2 ns.

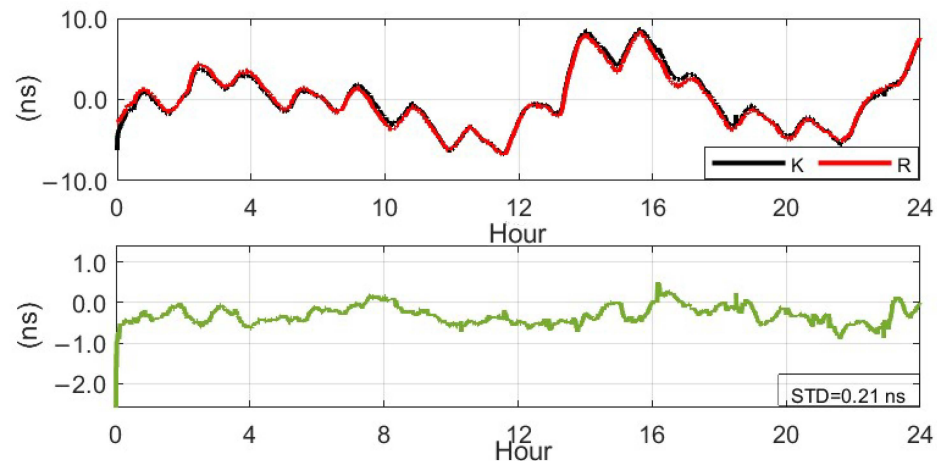


Figure 4. (Top): Sentinel-3B satellite clocks determined using the Kalman filter-based kinematic model with the CNES real-time products without latency (blue line) and using the BLS-based reduced-dynamic model with the CODE final products (red line); (Bottom): differences between the two sets of clocks (real-time and final) in the top panel after unifying the time reference.

4.1. “End-Loss” Scenario

Under normal circumstances, GNSS real-time orbits and clocks are received via the internet in State Space Representation (SSR) format. Depending on the network quality, the GNSS orbits and clocks are assumed to be delayed with the same latency. However, due to the varying prediction accuracy loss of GNSS orbits and clocks, it is necessary to analyze not only the impact on LEO satellite clocks when both GNSS orbits and clocks are missing but also the impact when each is lost separately.

The five scenarios of “end-loss” are detailed in Table 2. Scenarios A and B involve the loss of both the GNSS clocks and orbits; while the orbits are extrapolated using the Nevil model, the clocks of the last available epoch are used for Scenario A and linearly extrapolated in Scenario B. Scenarios C and E assume only the delay of the GNSS real-time clocks, with the clocks of the last available epoch used in Scenario C and linearly extrapolated in Scenario E. To compare the impacts of the clock and orbit loss, Scenario D assumes the latency of only the orbits. It is worth noting that real-time GNSS satellite clocks with an unstable time reference can be re-referenced to the clocks of a selected GNSS satellite before predicting the GNSS clocks. Assuming that the latency of GNSS real-time products typically does not exceed 120 s, the latency is set to 30, 60, 90, and 120 s for further evaluation.

The analysis started from scenario A. Figure 5 illustrates the comparison between the real-time Sentinel-3B satellite clocks determined using the CNES real-time products with different latencies (Scenario A in Table 3). The real-time clocks using the CNES products without latency are used as a reference in Figure 5 to illustrate the precision loss caused by only the latencies. It can be inferred that as the latency of the GNSS product loss increases from 30 to 120 s, the fluctuation in the clocks visibly increases.

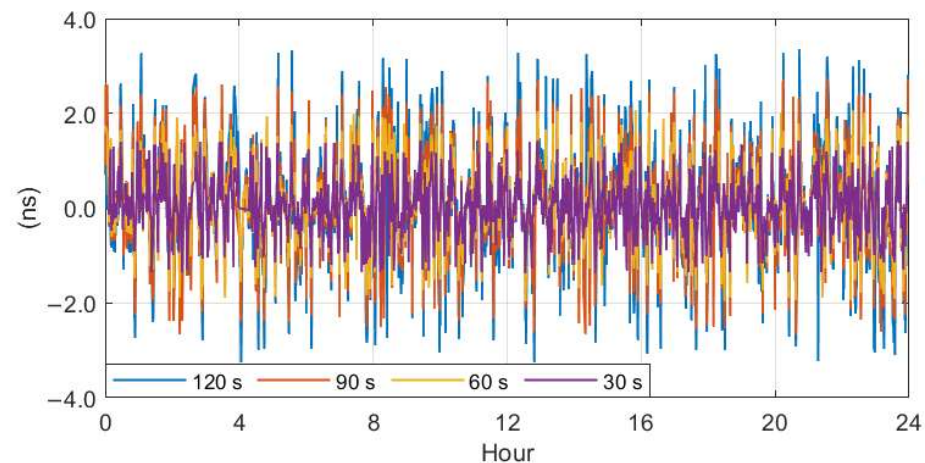


Figure 5. Sentinel-3B clocks determined using the Kalman filter-based kinematic model and CNES real-time products with different latencies for Scenario A. The clocks using CNES real-time products without loss at the end are used as the reference.

Table 3. Five scenarios of “end-loss” situation.

Scenario	Lost Products	Lost Duration (s)
A	Clocks and orbits (predicted)	30/60/90/120
B	Clocks (predicted) and orbits (predicted)	30/60/90/120
C	Clocks	120
D	Orbits (predicted)	120
E	Clocks (predicted)	30/60/90/120

When using the BLS clocks and employing the CODE final products as the reference, the four cases in Figure 5, together with the case without latency in the GNSS products, are shown in Figure 6 (for Scenario A in Table 3). Comparing the dark blue line with the other lines, it can be seen that the degradations caused by latencies of the GNSS products, even at 30 s, are significant. The degradation increases with the latency of the GNSS products.

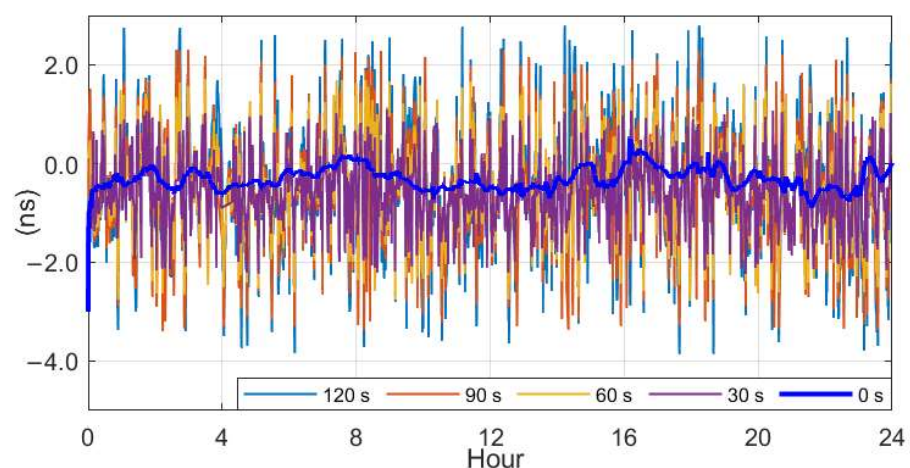


Figure 6. Sentinel-3B clocks determined using the Kalman filter-based kinematic model and CNES real-time products with different latencies for Scenario A. The BLS clocks using the CODE final products are used as the reference.

Taking the CNES real-time products with 120 s loss at the end as an example, Figures 7 and 8 illustrate the LEO satellite clock errors in the five scenarios in Table 3 compared with the case without latency in the CNES real-time products, as shown in Figure 7, and those

compared with the BLS clocks using the CODE final clocks, as shown in Figure 8. It can be clearly seen that when only the GNSS orbits are lost (seen in the green lines for Scenario D), the LEO satellite clocks experience the least precision loss. This is partly due to the relatively smaller prediction loss of orbits compared to clocks. Comparing scenarios A and E, it can be seen that when “end-loss” occurs in the GNSS clocks, whether it is predicted or not, it significantly impacts the determination of the LEO satellite clocks.

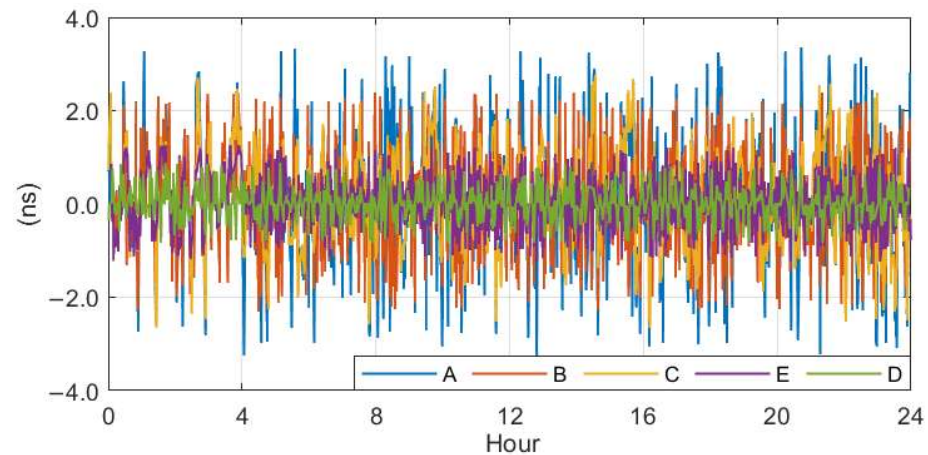


Figure 7. Sentinel-3B clocks in the five scenarios (see Table 3) with a latency of 120 s compared with the clocks estimated using the CNES real-time products without latencies.

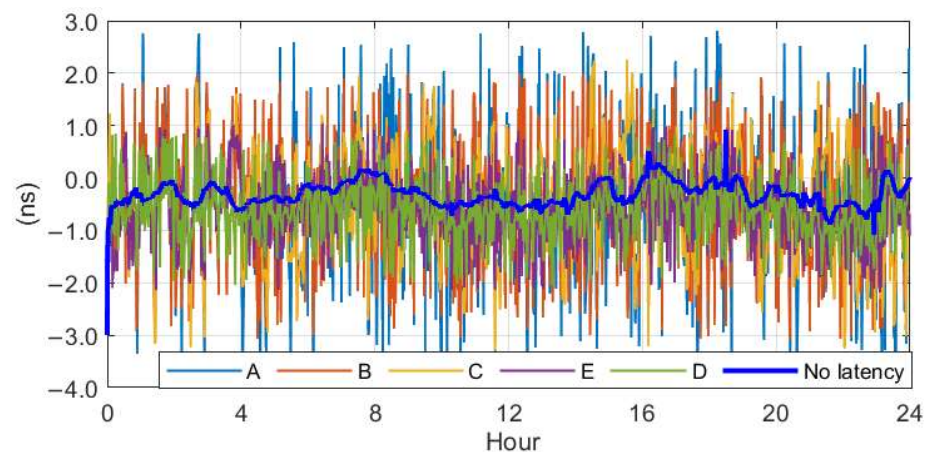


Figure 8. Sentinel-3B clocks in the five scenarios (with a latency of 120 s, see Table 3) and the clocks without latencies in the CNES products, compared with the BLS clocks using the CODE final products.

Table 4 displays the error budget for LEO satellite clocks resulting from various scenarios of the “end-loss” situations of the GNSS real-time products due to latency. It can be observed that when both the GNSS orbital and clock products are lost for durations between 30 and 120 s and no prediction is performed for the GNSS satellite clocks, the precision of the LEO satellite clocks degrades from 0.2 ns without latency to 0.61–1.15 ns. Comparing Scenario A with C and D, it can be seen that the GNSS clock latency is the major cause of this degradation. In Scenario B, the missing GNSS clocks are extrapolated, which reduces the degradations by about 10–20%. Still, with a latency of 30, 60, 90, and 120 s, one needs to expect a degraded precision of 0.53, 0.72, 0.85, and 0.93 ns, respectively. In scenario E, only the GNSS satellite clocks are considered delayed and then predicted. As shown in Table 5, the precision of the predicted GNSS clocks varies from 0.1 to 0.16 ns for latencies from 30 to 120 s. Correspondingly, the precision of the LEO satellite clocks is degraded to 0.28–0.57 ns for a latency of the GNSS clocks from 30 to 120 s. Comparing Scenarios C and E, it can be seen that linearly extrapolating the GNSS satellite clocks significantly reduces the degradation in the LEO satellite clock prediction.

Table 4. The STDs of Sentinel-3B satellite clocks in different scenarios. K represents the reference clocks determined by Kalman filtering utilizing the CNES real-time products, and R denotes another reference clock estimated by using BLS and utilizing the CODE final products.

Scenario	Latency (s)	STD (vs. K) (ns)	STD (vs. R) (ns)
No latency	0	—	0.21
A	30	0.53	0.61
	60	0.72	0.78
	90	0.95	0.95
	120	1.15	1.15
	30	0.48	0.53
B	60	0.64	0.72
	90	0.75	0.85
	120	0.87	0.93
	120	0.85	0.90
C	120	0.32	0.53
E	30	0.13	0.28
	60	0.26	0.36
	90	0.34	0.47
	120	0.47	0.57

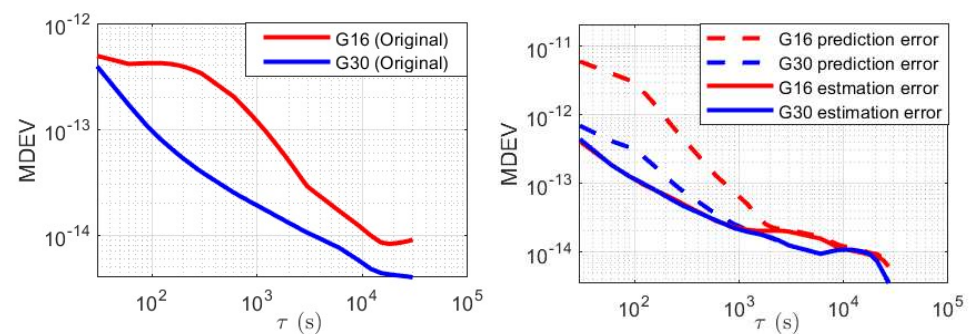
Table 5. The prediction precision of CNES GPS satellite clocks and the precision of Sentinel-3B clocks in scenario E.

Prediction Period (s)	STD of CNES GPS Satellite Clocks (vs. COM Final Clock) (ns)	STD of Sentinel-3B Clocks (vs. R) (ns)
0	0.079	0.21
30	0.104	0.28
60	0.120	0.36
90	0.135	0.47
120	0.155	0.57

Predicting the LEO satellite clocks instead of the GNSS orbits and clocks is another way to solve the problem of delays of the products. LEO satellite clocks can be predicted with periodic terms and polynomials, as expressed in [25]. The error budget of the LEO clock prediction errors is summarized in Table 6. From Tables 4–6, it can be seen that the precision of the LEO satellite clocks is very sensitive to the precision of the GNSS satellite clocks. Comparing Tables 4 and 6, it can be concluded that for latency of the real-time GNSS products within 2 min, better results can be achieved when waiting for the GNSS real-time products, processing the near-real-time LEO satellite clocks, and performing a LEO satellite clock prediction over this ultra-short period. The short-term predicted clocks for certain GPS satellites show larger noise than the predicted Sentinel-3B clocks connected with an Ultra-Stable Oscillator (USO) that exhibits rather good short-term noise [33]. This cannot be completely reflected in the STDs in Table 5 but can be reflected in the Modified Allan Deviations (MDEVs) [34], as shown in Figure 9. In contrast, the good short-term stability of the USO in Sentinel-3B leads to much smaller degradations for short-term prediction, as shown in Table 6.

Table 6. Prediction precision of Sentinel-3B satellite clocks.

Prediction Period (s)	STD (vs. K) (ns)	STD (vs. R) (ns)
30	0.042	0.222
60	0.055	0.224
90	0.064	0.230
120	0.081	0.232

**Figure 9.** The MDEVs of the satellite clocks (**left**) and the clock estimation errors and prediction errors over 120 s (**right**) for G16 and G30.

As representative examples, the left panel of Figure 9 shows the MDEVs of the GPS clocks (re-referenced to a stable reference) for G16 (Block IIR) and G30 (Block IIF) before (left panel) and after (right panel) prediction for 120 s. The G16 clocks exhibit a worse short-to mid-term stability than the G30. The right panel of Figure 9 shows the clock estimation errors (without latency) and clock prediction errors (with a latency of 120 s) for these two clocks. It can be seen that while both clocks are precisely estimated, the short-term noise of the prediction errors of G16 are significantly larger than those for G30. This is caused by the worse short-term stability of the G16 clocks, as shown in the left panel of Figure 9.

4.2. “Mid-Gap” Scenario

As previously discussed, the “mid-gap” case of GNSS real-time products primarily impacts the near-real-time estimation aspect of the “arc-estimation”, as illustrated in the right panel of Figure 2. This, in turn, influences the subsequent short-term prediction of LEO satellite clocks, ultimately affecting the precision of the real-time clocks.

When employing the arc-processing method to determine near-real-time LEO clocks, as illustrated in Figure 3, it is crucial to minimize T_{arc} (BC) to shorten the prediction arc (CD), which helps minimize precision loss during prediction, thus achieving high-precision real-time clocks. Based on the existing analysis [16], setting ΔT to 120 s and the near-real-time determination arc to 4 h is the preferable choice.

Figure 10 displays the real-time clocks of Sentinel-3B estimated in a Kalman filter using the CNES real-time products without latency, denoted as K (see the black line), the corresponding clocks determined based on BLS and CODE final products, denoted as R (see the red line), and the connected near-real-time clocks (shifted by 5 min each session) estimated in a Kalman filter using the CNES real-time products without gaps, denoted as C (see the blue line). The differences between the C and K clocks are displayed in the top panel of Figure 11, and those between the C and R clocks are illustrated in the bottom panel. From Figures 10 and 11, it can be seen that the clock connection between different sessions does not significantly influence the clock performance, leading only to a 0.02 ns difference, as shown in the top panel of Figure 11. The precision of such a real-time clock estimation amounts to about 0.23 ns without gaps (see the bottom panel of Figure 11).

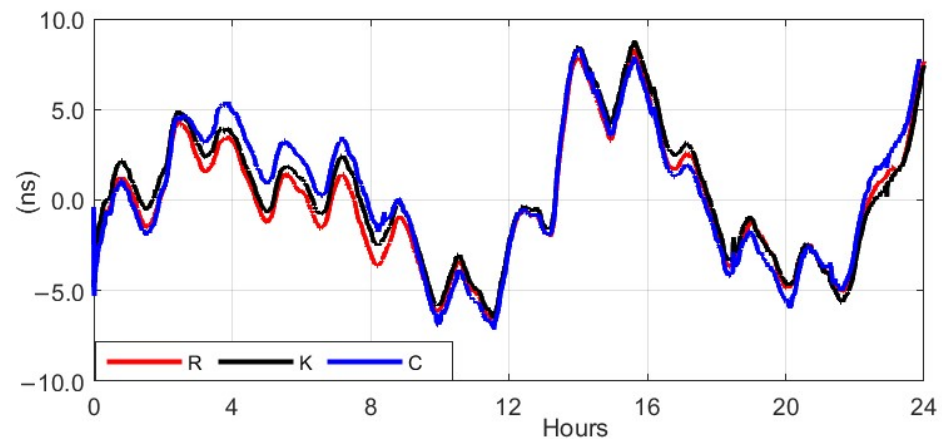


Figure 10. Sentinel-3B satellite clocks determined using the Kalman filter-based kinematic model with the CNES real-time products without latency (black line); using the BLS-based reduced-dynamic model with the CODE final products (red line); the connected near-real-time clocks estimated in a Kalman filter using the CNES real-time products without gaps (blue line).

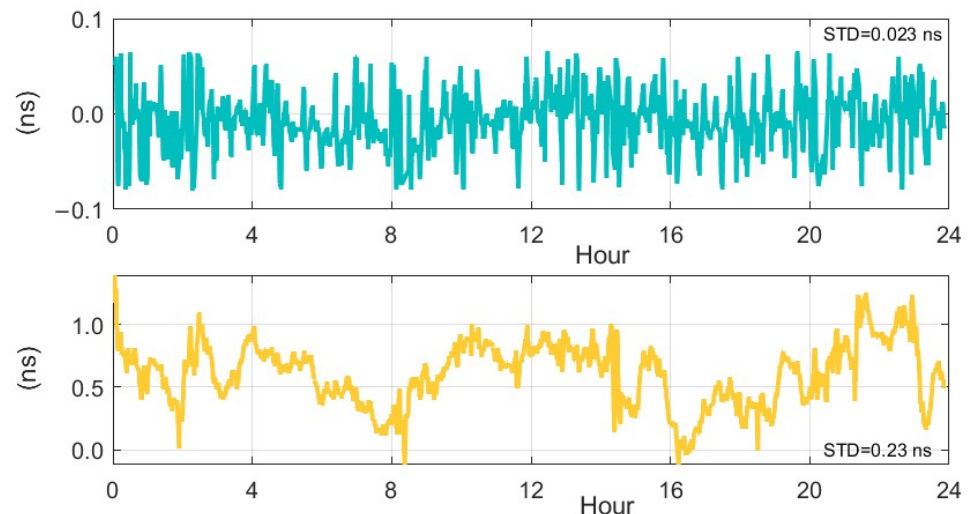


Figure 11. Differences between the C and K clocks (**top**) and C and R clocks (**bottom**) for Sentinel-3B. The explanations of C, K, and R clocks are given in Figure 10.

From Figure 3, it can be observed that as the sliding window continuously moves (with ΔT interval), the obtained near-real-time clocks can be added over the interval $[B, B + \Delta T]$ to the clocks processed in the previous session. Starting from 4:00 (GPST) on the test day, different lengths of mid-gap periods are set to discuss their impact on the LEO satellite clocks.

As the sliding window continuously moves, when the end epoch of the LEO observation data falls within the “mid-gap” duration, the LEO satellite clock is determined by using the predicted GNSS clocks and orbits. Based on the analysis in the previous section, GNSS clock prediction will lead to a sharp degradation in LEO satellite clock determining precision, as shown in the top panel of Figures 12–14, especially when the prediction duration is tens of minutes. Therefore, the near-real-time LEO satellite clocks estimated based on extrapolated GNSS products are not included in the statistical analysis. When the end epoch of the observation data exceeds the mid-gap, the GNSS clocks and orbits used to determine the LEO satellite clocks are obtained through linear interpolation. In comparison, the GNSS satellite clocks are interpolated with a precision loss depending on the gap period, i.e., about 0.01, 0.013, and 0.015 ns for gaps over 5, 10, and 15 min, respectively.

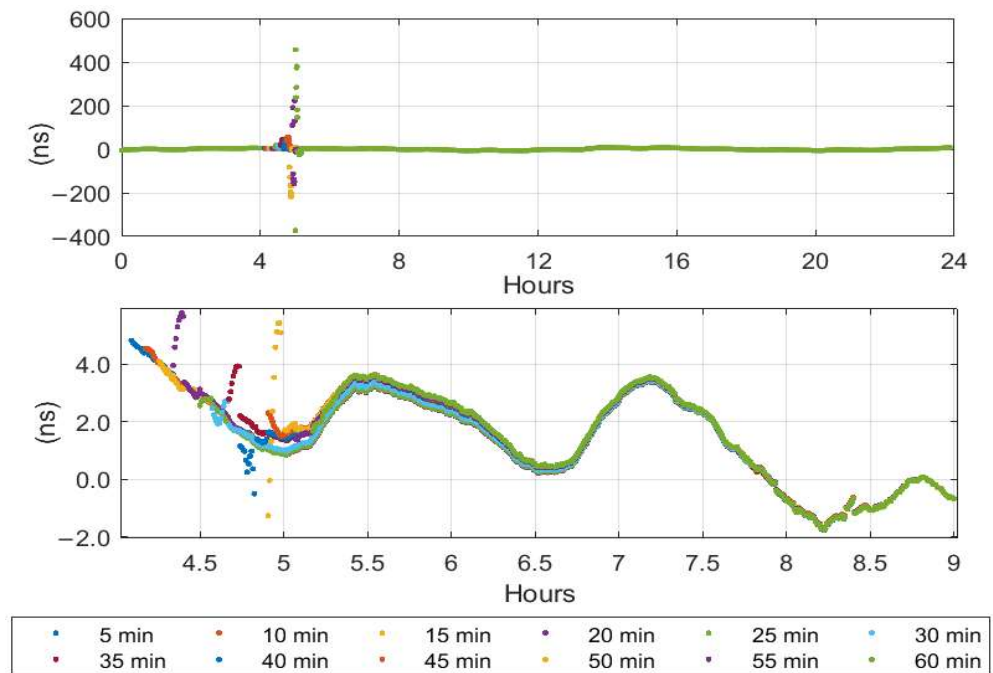


Figure 12. Near-real-time Sentinel-3B clocks based on a Kalman filter-based kinematic model, using CNES products with different “mid-gap” durations. **(Top):** Sentinel-3B clocks for the entire day; **(Bottom):** Sentinel-3B clocks from the first epoch affected to the last epoch affected.

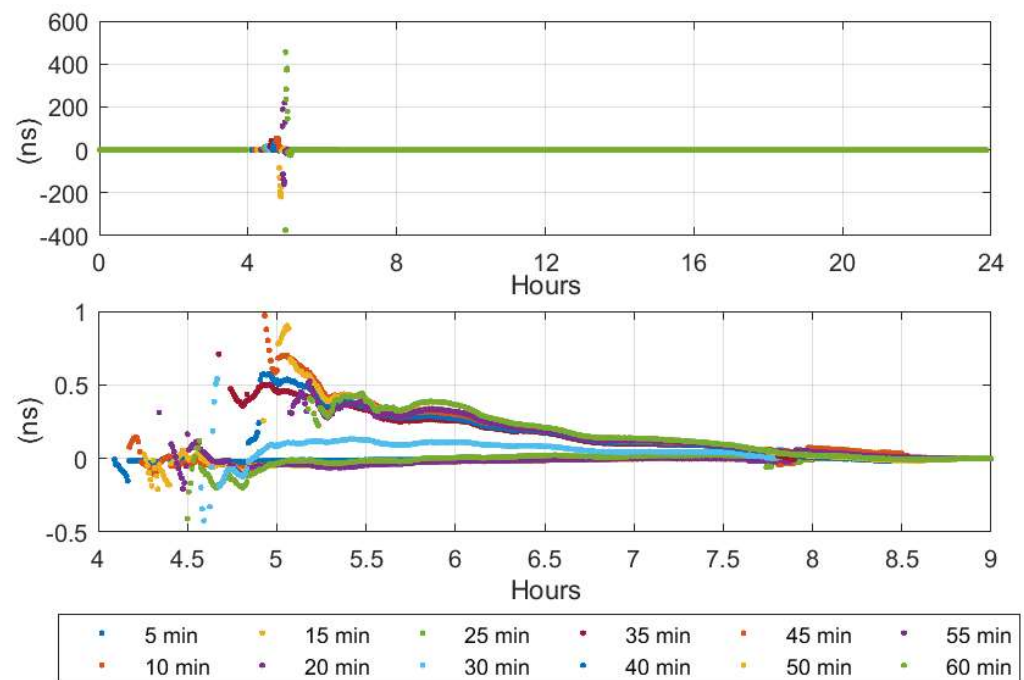


Figure 13. Near-real-time Sentinel-3B clock errors using the Kalman filter-based kinematic model with the CNES real-time products suffering from different “mid-gap” durations, compared with those using continuous CNES real-time products. **(Top):** Sentinel-3B clocks for the entire day; **(Bottom):** Sentinel-3B clocks from the first epoch affected to the last epoch affected.

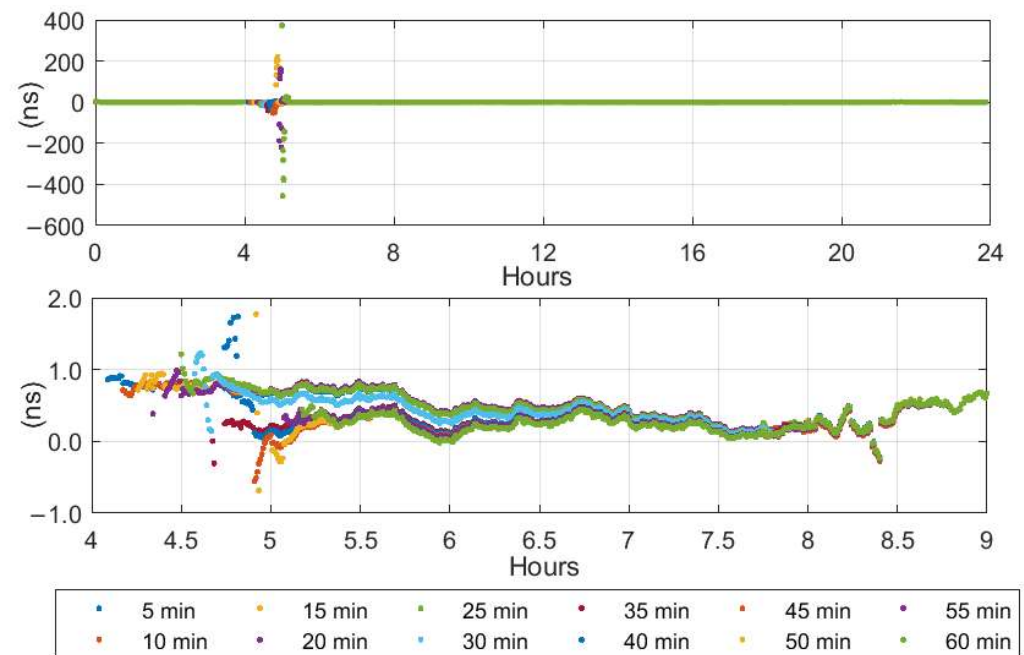


Figure 14. Near-real-time Sentinel-3B clock errors determined using the Kalman filter-based kinematic model with CNES products of different “mid-gap” durations, compared with the BLS clocks determined using the CODE final products. **(Top):** Sentinel-3B clocks for the entire day; **(Bottom):** Sentinel-3B clocks from the first epoch affected to the last epoch affected.

As inferred from Figure 3, to generate LEO satellite clocks for a full day of 86,400 s, the number of sessions that need to be initiated periodically is $86,400/\Delta T$. If the arc length of the mid-gap period is M , then the number of affected sessions is $((AB) + M)/\Delta T$, where (AB) is the length of the near-real-time processing arc. The first epoch of the LEO satellite clocks affected is the epoch when “mid-gap” begins, while the last epoch affected for the LEO satellite clock determination is the moment when “mid-gap” ends, extended by the length of near-real-time determination arc (AB) . For example, assuming that each processing arc is 4 h, ΔT is set to 120 s, and the “mid-gap” starts from 4:00, as mentioned before; when the mid-gap duration is 60 min, the number of affected sessions is 150. The first affected epoch is 4:00, and the last affected epoch is 9:00.

The top panel of Figure 12 displays the near-real-time Sentinel-3B clocks based on the kinematic model with Kalman filter, using CNES products with different “mid-gap” durations. The bottom panel shows the Sentinel-3B clocks from the first affected epoch to the last affected epoch (with a “mid-gap” duration of 5 min up to 60 min), with the clocks during the mid-gap period removed. It can be seen that as the “mid-gap” duration increases, the number of gross errors in the Sentinel-3B clocks increases, and the fluctuation range becomes larger. After the gap period, the LEO satellite clocks are no longer affected.

Figure 13 illustrates the near-real-time Sentinel-3B satellite clocks determined based on the use of the Kalman filter-based kinematic model and using the CNES real-time products with different “mid-gap” durations compared with those determined using the CNES real-time products without gaps. Figure 14 illustrates its counterparts compared with the BLS clocks determined using the CODE final products. As shown in Figures 13 and 14, the clock errors become larger as the mid-gap duration increases.

Based on the analysis presented in [16], with ΔT set to 120 s and the near-real-time processing arc set to 4 h, the prediction arc (BD) needs to be set to at least 150 s to ensure supporting real-time applications. Table 7 illustrates the error budget of near-real-time clocks and the predicted clocks, compared to the Sentinel-3B clocks based on the Kalman filter-based kinematic model using the CNES real-time products without loss (denoted as “K”) and the BLS Sentinel-3B clocks processed using the CODE final products (denoted as “R”).

Table 7. The error budget of the connected Sentinel-3B clocks processed with a Kalman filter-based kinematic model with CNES real-time products with different “mid-gap”.

Gap Length	Near-Real-Time Clocks		Real-Time Clocks	
	VS. K (ns)	VS. R (ns)	VS. K (ns)	VS. R (ns)
0 min	0.0230	0.2345	0.0871	0.2609
5 min	0.0249	0.2435	0.0881	0.2610
10 min	0.0262	0.2598	0.0901	0.2630
15 min	0.0265	0.2610	0.0906	0.2664
20 min	0.0268	0.2615	0.0917	0.2677
25 min	0.0279	0.2638	0.0919	0.2689
30 min	0.0331	0.2670	0.0925	0.2765
35 min	0.0332	0.2738	0.0984	0.2936
40 min	0.0326	0.2801	0.1158	0.2959
45 min	0.0334	0.2810	0.1159	0.2958
50 min	0.0340	0.2827	0.1161	0.2990
55 min	0.0345	0.2834	0.1171	0.3132
60 min	0.0346	0.2338	0.1174	0.3182

As shown in Table 7, when the mid-gap duration increases from 5 to 60 min, compared to the LEO satellite clocks determined with continuous CNES real-time products, the precision of the near-real-time clocks decreases from 0.023 to 0.035 ns, and the precision loss in prediction increases from 0.087 ns to about 0.11 ns. While compared to the BLS LEO satellite clocks using the CODE final products, the near-real-time clock precision decreases from approximately 0.23 to 0.28 ns, and the precision of the real-time clocks achieved by the user (after the prediction) decreases from about 0.26 to 0.32 ns.

Therefore, when generating LEO satellite clocks using “arc-estimation”, if a “mid-gap” situation occurs in the GNSS products during the near-real-time determination arc, the precision of the real-time LEO satellite clocks decreases. When a “mid-gap” occurs, one option is to stop the Kalman filter and let it re-converge. However, considering that re-convergence can take a long time, e.g., tens of minutes, if the mid-gap duration is less than one hour, continuing to estimate LEO clocks based on interpolated GNSS products is a better choice.

5. Discussion and Conclusions

In the future, it is expected that LEO constellations will collaborate with GNSS satellite constellations to provide LEO-augmented PNT services for GNSS-challenging environments and autonomous driving. High-dynamic, high-precision, and real-time PNT services require the support of high-precision real-time LEO satellite products, such as high-precision real-time LEO satellite clocks.

Currently, the determination of LEO clocks is mainly based on GNSS observations onboard LEO satellites. Therefore, GNSS real-time products are crucial for the precision of the real-time LEO satellite clock estimates, not only with regard to their accuracy but also to their latency and continuity. To address this issue, this study analyzes the impact of the latency and continuity of the GNSS real-time products on LEO satellite clocks, employing two methods of real-time LEO satellite clock determination.

For the “arc-estimation” and “epoch-estimation” methods of determining LEO clocks, the loss of the GNSS real-time products was classified into the “end-loss” and “mid-gap” scenarios. Tests were conducted for these two scenarios using Sentinel-3B’s GPS L1/L2 onboard observation data and the CNES real-time products. Results showed that as the loss duration increases, both the “mid-gap” or “end-loss” situations would lead to unignorable

degradations in the precision of LEO satellite real-time clocks. For the “epoch-estimation” method, when the “end-loss” duration of both GNSS clocks and orbits increases to 120 s in different scenarios, the precision of LEO clocks decreases from 0.2 ns to around 1 ns when not extrapolating the GNSS satellite clocks, and to 0.93 ns when extrapolating the GNSS clocks. If ultra-rapid GNSS orbits are used instead of considering the orbits as delayed, with the GNSS clocks extrapolated over the latency period, the real-time LEO satellite clock precision amounts to around 0.5 ns for a latency of 120 s. When directly predicting LEO satellite clocks for 120 s, the prediction precision decreases from 0.21 to 0.23 ns. For the “arc-estimation” method, when the “mid-gap” duration increases from 5 to 60 min, the real-time clock precision achieved by the user decreases from 0.26 to 0.32 ns.

In summary, the latency and continuity of GNSS products significantly impact the filter-based real-time LEO satellite clock determination. Using appropriate methods to improve the GNSS orbit and clock prediction or interpolation methods in real-time, or shorten the latency and gaps, would be essential to guarantee high precision of the real-time LEO satellite clocks.

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