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ORIGINAL ARTICLE

A computationally efficient approach for estimating high-rate satellite clock corrections in realtime

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Abstract Realtime satellite clock corrections are usually estimated using undifferenced phase and range observations from a global network. Because a large number of ambiguity parameters must be estimated, the computation is time-consuming. Consequently, only a sparse global network of limited number of stations is processed by most IGS Realtime Analysis Centers with an update rate of 5 s. In addition, it is very desirable to build the capability to simultaneously estimate clock corrections for multi-GNSS constellations. Although the estimation can be sped up by epoch-differenced observations that eliminate ambiguities, the derived clocks can contain a satellite-specific bias that diminishes the contribution of range observations. We introduce a computationally efficient approach for realtime clock estimation. Both the epoch-differenced phase and undifferenced range observations are used together to estimate the epoch-differenced satellite clocks and the initial clock bias for each satellite and receiver. The biased clock corrections accumulated from the estimated epoch-differenced clocks are then aligned with the estimated clock biases and provided as the final clock corrections to users. The algorithm is incorporated into the EPOS-RT software developed at GFZ (GeoForschungsZentrum) and experimentally validated with the IGS global network. The comparison with the GFZ rapid products shows that the accuracy of the clock estimation with the new approach is comparable with that of the undifferenced approach, whereas the computation time is reduced to one-tenth. As a result, estimation of high-rate satellite clocks from a large reference network and tracking satellites of multi-GNSS constellations becomes achievable.

Keywords Realtime clock estimation · High-rate satellite clock · Precise point positioning · Global precise positioning services

Introduction

In order to provide precise point positioning (PPP) services, precise satellite clocks and orbits have to be estimated and disseminated to users in realtime (Bar-Sever et al. 2001, 2003; Collins et al. 2005; Dixon 2006; Pérez et al. 2006; Mireault et al. 2008; Ge et al. 2009; Hauschild and Montenbruck 2009; Melgard et al. 2009). Usually, predicted orbits over a few hours are considered known in the clock estimation because the errors of these orbits are rather small and can even be absorbed by the estimated clocks. Since the procedure to obtain such predicted orbits is exactly the same as generating IGS ultra-rapid products, most of the efforts are made on the realtime clock estimation in order to provide global precise positioning services. Normally, satellite clocks are estimated using undifferenced phase and range observations of a global network. Because a large number of ambiguities have to be estimated together with clock parameters, the computation is time-consuming. Consequently, only a sparse global network of limited number of stations is processed for realtime clock solutions by most of the IGS Realtime Analysis Centers under the IGS Real-Time Pilot Project launched in 2007 (http://www.rtigs.net). Still, the current realtime clock estimates can only be updated every 5 s due to the heavy computation load. A denser

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network would provide more observations to estimate the clock parameters and thus provide clock estimates of higher quality. Recent research has proven that ambiguity fixing can reduce the convergence time and improve the accuracy of realtime kinematic PPP significantly (Ge et al. 2008; Collins 2008; Laurichesse et al. 2008; Geng et al. 2010). For fast and reliable ambiguity fixing, the short-term clock accuracy should be better than 3 cm because the narrow-lane ambiguity has a wavelength of only 10 cm. Therefore, a denser network might be more desirable. Although the estimation can be accelerated by epoch-differenced observations (Zhang et al. 2007; Mervart et al. 2008; Ge et al. 2009) since ambiguities are eliminated, the derived clocks are biased by initial clock offsets. These satellite-specific biases must be removed correctly, so that range observations can be used with low-cost receivers as well as with geodetic receivers to shorten the initialization time. There are several approaches to align such satellite-specific biases. The major idea is to have two parallel processes. In the first one, undifferenced observations are used to estimate most of the desired parameters such as ambiguities, station coordinates, and even satellite orbits. The update rate is low, for example 5 min or even longer. The second process uses the same configuration, but the slowly changing parameters are fixed to the estimates from the first process; only receiver and satellite clocks are estimated so that the process can be updated very fast (Zhang et al. 2010).

We introduce an alternative approach for fast clock estimation in realtime. The epoch-differenced phase and undifferenced range observations are used in the estimation process. We estimate not only epoch-differenced satellite clocks but also the clock bias for each satellite and receiver. The clock corrections accumulated from the estimated epoch-differenced clocks are aligned with the estimated clock biases and provided as the final clock corrections to users. The algorithm is implemented within the EPOS-RT software developed at GFZ (Ge et al. 2009) for validation. A global network of about 100 IGS stations is used to simulate the realtime clock estimation using undifferenced and epoch-differenced observations and the new approach. Comparison with the GFZ rapid products shows that the new method has a comparable accuracy to the undifferenced approach, whereas the computation time is reduced dramatically. In general, the new approach demonstrates a promise to generate satellite clock solutions in realtime from a large number of reference stations tracking satellites of multi-GNSS constellations.

The new approach

For the convenience of description, we first introduce the undifferenced and epoch-differenced approaches. The new approach is then developed naturally as an appropriate combination of these two existing approaches.

The undifferenced method

Assuming that station coordinates and satellite orbits are known and can be fixed in the clock estimation, the linearized observation equations of the ionosphere-free phase and range combinations can be expressed as

$$\begin{aligned} v_{\mathrm{Lc}}(i) &= \delta t_{\mathrm{r}}(i) - \delta t_{\mathrm{s}}(i) + m(i)\delta T(i) + B + l_{\mathrm{Lc}}(i) \\ v_{\mathrm{Pc}}(i) &= \delta t_{\mathrm{r}}(i) - \delta t_{\mathrm{s}}(i) + m(i)\delta T(i) + l_{\mathrm{Pc}}(i) \end{aligned} \tag{1}$$

where i is the epoch number; δt_{r} and δt_{s} are receiver and satellite clock parameters; and δT and m represent the zenith total delay (ZTD) parameter and its mapping function. The symbol B denotes the ambiguity of the ionosphere-free phase observations. The post-fit and pre-fit residuals of the phase and range observations are v_{Lc}, l_{Lc} and v_{Pc}, l_{Pc}.

In order to obtain the satellite clock solutions from (1), it is necessary to estimate all parameters. For a network of about 50 stations and a constellation of about 30 satellites, each station tracks about eight satellites simultaneously on average. There are about 400 ambiguity parameters, 50 receiver clocks, 30 satellite clocks, and 50 ZTD parameters. There are about three to four times as many active ambiguity parameters as there are other parameters, which is the reason why the computation time for estimation of all parameters is about nine to sixteen times longer than estimation without ambiguities.

This problem worsens if the number of stations and satellites increases since the number of ambiguities increases significantly faster than the other parameters. Figure 1 shows the growth of the number of parameters with the number of stations for the GPS constellation, while Fig. 2 shows a more dramatic increase in the number of parameters when the satellite number increases from 30 to 120 for a network with 50 stations. Due to the heavy computation burden, most of the IGS Realtime Analysis Centers process only a sparse network of about 50 stations and provide realtime clock estimates only every 5 s instead of a shorter interval.

In realtime GNSS clock estimation, phase and range observations contribute to clock solutions in different ways. The highly precise phase observations determine only accurate temporal change of clock biases because of the existence of phase ambiguities, whereas the range observations determine best the constant offset of each clock. The latter is necessary to align the clock to the time reference. Because of lower weighting due to the relatively high noise level, the range observations barely contribute to the temporal clock change. A well-known example for this

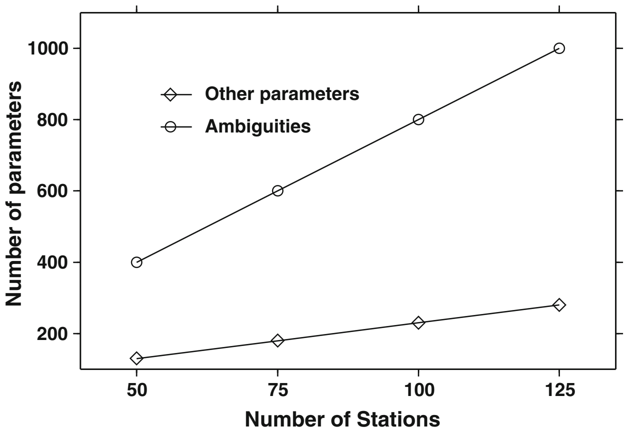

Fig. 1 Growth of the number of ambiguities and the other parameters versus the increase in the number of stations tracking a constellation of 30 satellites

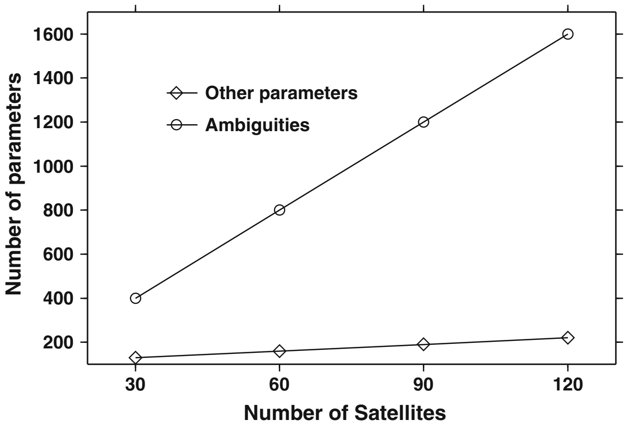

Fig. 2 Increase in the number of ambiguities and the other parameters against the number of satellites tracked by a network of 50 stations

fact is the impact of the differential code bias (DCB) corrections (Schaer and Steigenberger 2006). The temporal variations in the estimated clocks with and without DCB corrections are almost the same, but the clock offsets are changed from satellite to satellite. Conversely, the biased clock offset does not affect the modeling of phase observations because it will be absorbed by the corresponding ambiguity parameter. However, the range observations must be down-weighted accordingly in order to avoid the contamination of such biases.

Epoch-differenced approach

The epoch-differenced observations are used in the estimation with the following observation equations based on (1) (Zhang et al. 2007; Mervart et al. 2008),

$$\begin{aligned} v_{\Delta \mathrm{Lc}}(i) &= \Delta\delta t_{\mathrm{r}}(i) - \Delta\delta t_{\mathrm{s}}(i) + \Delta m(i)\delta T(i) + \Delta l_{\mathrm{Lc}}(i) \\ v_{\Delta \mathrm{Pc}}(i) &= \Delta\delta t_{\mathrm{r}}(i) - \Delta\delta t_{\mathrm{s}}(i) + \Delta m(i)\delta T(i) + \Delta l_{\mathrm{Pc}}(i) \end{aligned} \qquad (2)$$

where Δ is the difference operator between two adjacent epochs; for example, the differenced clock is $\Delta\delta t(i) = \delta t(i) - \delta t(i-1)$. The ambiguity parameters are removed in the epoch-differenced observations; therefore, only differenced clocks and ZTDs remain. Numerical tests show that the computation time for each epoch is reduced to 0.25 s for a network with about 50 stations. However, instead of clock corrections, the epoch-differenced clocks are estimated which must be accumulated in order to obtain clock corrections. According to the definition of $\Delta\delta t(i)$, we have

$$\delta t(i) = \delta t(i_0) + \sum_{j=i_0+1}^{i} \Delta\delta t(j) \qquad (3)$$

Although the clock changes and therefore the accumulated clock corrections can be estimated rather precisely, they are biased by the clock offset $\delta t\ (i_0)$ at the starting epoch i_0. The amplitude of this bias depends on where the initial clock is retrieved from. It can reach tens of nanoseconds when broadcast navigation information is used. If a cycle slip occurs at a phase observation, no epoch-differenced observation can be formed between this observation and that of the previous epoch. If all stations lost tracking of a satellite, there are no observations contributing to the epoch-differenced clock parameter of this satellite, and thus, its clock change cannot be propagated forward. Similarly, the propagation of a receiver clock change is broken if the receiver has lost tracking to all satellites. In these cases, there will be no clock difference estimated between the adjacent epochs and a new clock offset must be introduced according to (3).

It is noted that the epoch-differenced tropospheric delays cannot be ignored, although they are very small for high-rate data. The major reason is that the remaining tropospheric delays have a systematic effect because the epoch-differenced mapping function is always positive for descending and negative for ascending satellites. Ignoring this term will cause biases in the estimated clock changes which could accumulate into a significant bias, although for retrieving high-rate satellite clock corrections in post-processing mode the accumulation can be controlled by using clocks already estimated at a lower sampling rate as control points (Bock et al. 2009).

The new approach

As mentioned earlier, the constant clock biases are determined by range observations. We thus propose to combine epoch-differenced phase observations and undifferenced range observations to estimate clocks, so that both clock change and clock offset can be estimated precisely while maintaining the computational efficiency of the epoch-differenced method.

From (1) and (2), the observation equations of the epoch-differenced phase and undifferenced range are

$$v_{\Delta \mathrm{Lc}}(i) = \Delta\delta t_{\mathrm{r}}(i) - \Delta\delta t_{\mathrm{s}}(i) + \Delta m(i)\delta T(i) + \Delta l_{\mathrm{Lc}}(i) \tag{4a}$$

$$v_{\mathrm{Pc}}(i) = \delta t_{\mathrm{r}}(i) - \delta t_{\mathrm{s}}(i) + m(i)\delta T(i) + l_{\mathrm{Pc}}(i) \tag{4b}$$

Substituting the clock corrections $\delta t_{\mathrm{r}}(i)$ and $\delta t_{\mathrm{s}}(i)$ in (4b) by (3), accumulated from epoch i_{r0} and i_{s0}, we have

$$\begin{aligned} v_{\mathrm{Pc}}(i) = {} & \Delta\delta t_{\mathrm{r}}(i) - \Delta\delta t_{\mathrm{s}}(i) + m(i)\delta T(i) + \delta t_{\mathrm{r}}(i_{\mathrm{r0}}) - \delta t_{\mathrm{s}}(i_{\mathrm{s0}}) \\ & + l_{\mathrm{Pc}}(i) + \sum_{j=i_{\mathrm{r0}}+1}^{i-1} \Delta\delta t_{\mathrm{r}}(j) - \sum_{j=i_{\mathrm{s0}}+1}^{i-1} \Delta\delta t_{\mathrm{s}}(j) \end{aligned} \tag{5}$$

The last two terms in (5) can be replaced by clock differences estimated at past epochs. Denoting the sum of the last three terms of the range observation equation as $\bar{l}_{\mathrm{Pc}}(i)$, Eq. (5) becomes

$$\begin{aligned} v_{\mathrm{Pc}}(i) = {} & \Delta\delta t_{\mathrm{r}}(i) - \Delta\delta t_{\mathrm{s}}(i) + m(i)\delta T(i) + \delta t_{\mathrm{r}}(i_{\mathrm{r0}}) \\ & - \delta t_{\mathrm{s}}(i_{\mathrm{s0}}) + \bar{l}_{\mathrm{pc}}(i) \end{aligned} \tag{6}$$

The initial clock biases for each station and satellite are estimated with (4a) and (6). For the network with 50 stations, the total number of parameters reduces from 530 to 210, which is merely 80 more than for the epoch-differenced approach.

From the experience, we know that clock changes and ZTDs can be estimated rather precisely with the epoch-differenced method (Zhang et al. 2007, Mervart et al. 2008, Ge et al. 2009). We can first estimate the clock differences and ZTDs at each epoch using only the epoch-differenced phase observations (4a). Next, these estimates are used to correct the range observations so that only the initial clock biases remain in the range observations. The corresponding observation equations can be obtained from (5) by putting the clock difference parameters at epoch i into the accumulated clocks as follows,

$$\begin{aligned} v_{\mathrm{Pc}}(i) = {} & \delta t_{\mathrm{r}}(i_{\mathrm{r0}}) - \delta t_{\mathrm{s}}(i_{\mathrm{s0}}) + l_{\mathrm{Pc}}(i) \\ & + \sum_{j=i_{\mathrm{r0}}+1}^{i} \Delta\delta t_{\mathrm{r}}(j) - \sum_{j=i_{\mathrm{s0}}+1}^{i} \Delta\delta t_{\mathrm{s}}(j) + m(i)\delta T(i) \end{aligned} \tag{7}$$

Denoting the sum of the last four terms by $\tilde{l}_{\mathrm{Pc}}(i)$, Eq. (7) becomes

$$v_{\mathrm{Pc}}(i) = \delta t_{\mathrm{r}}(i_{\mathrm{r0}}) - \delta t_{\mathrm{s}}(i_{\mathrm{s0}}) + \tilde{l}_{\mathrm{Pc}}(i) \tag{8}$$

With this reformulation, the data processing at each epoch can be divided into two steps: the estimation of differenced clock and ZTD parameters using epoch-differenced phases with (4a) and the estimation of the initial clock biases using undifferenced ranges with (8). The two steps can be realized by two estimators running parallel for further reduction in computation time.

It is noted that the second estimator is very similar to taking the time average of the range residuals computed with precisely estimated clock changes. Therefore, the estimates should be very stable after a certain time period. This also means that the second estimator does not have to be continued if the initial clock parameters are sufficiently stable and approximately better than range accuracy. An initial clock parameter is required if the related clock change cannot be estimated due to equipment failure. For example, all receivers have lost track on a satellite or a receiver has lost track on all satellites. Furthermore, the initial clock biases should not be used before they have converged to accuracy comparable with the range quality. Also, based on (6), the computation time could be reduced even further by forming the difference between satellites to remove receiver clocks and their initial biases (Zhang et al. 2007).

Validation and results

The new processing approach has been incorporated into the EPOS-RT software that is running operationally at GFZ for estimating realtime clocks from a global network. That solution is being incorporated in the IGS realtime combination (Agrotis et al. 2010) and the online PPP test service (http\\igs.bkg.bund.de/ntrip/ppp). We process data in a simulated realtime mode, i.e., the data are read from RINEX files instead of capturing from realtime streams. The GFZ rapid orbits and related clock products are used as reference for assessing the quality of estimated clocks.

Three global networks with 50, 75, and 100 stations are defined by the GFZ rapid network, which is shown in Fig. 3. Data from days 151 and 152 of 2010 are processed using a priori STDs for range and phase observations of 2 m and 0.02 cycles, respectively. The undifferenced and epoch-differenced observations are treated as stochastically independent. The tropospheric model and other parameters are kept the same as implemented in the routine processing.

The averaged computation times for a single epoch for the undifferenced range and phase (UD), epoch-differenced range and phase (ED), and mixed undifferenced range and epoch-differenced phase (MD) approaches are compared. The estimated initial clock offsets by the MD approach are also presented and validated. The computations are carried out on an Authentic AMD personal computer with four 2.512-GHz processors.

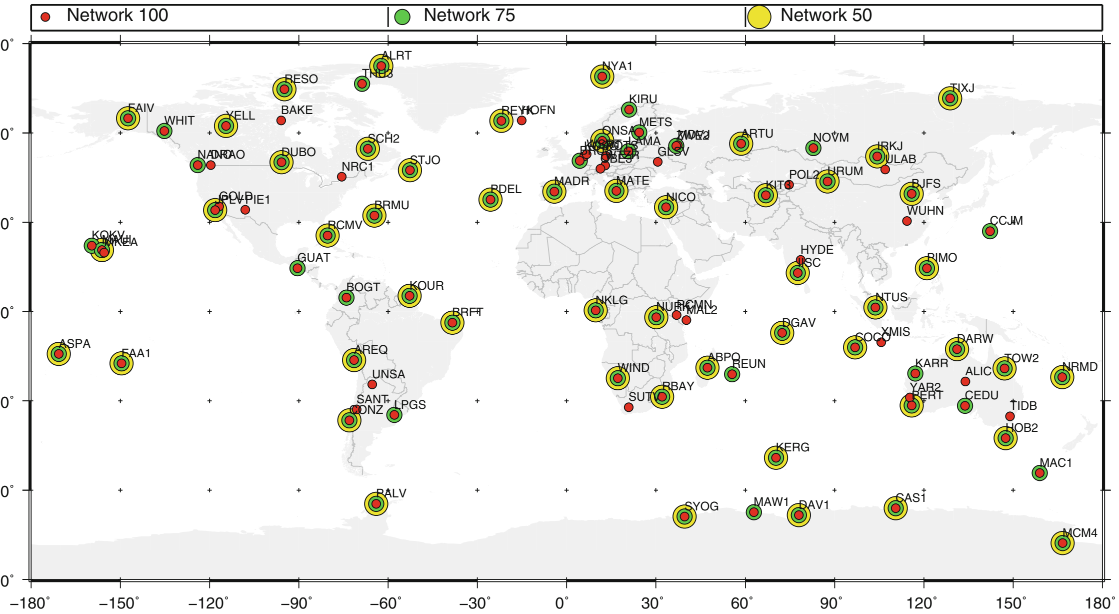

Fig. 3 Three global testing networks consisting of 50, 75, and 100 stations, (large *yellow dots*, *green dots*, and small *red dots*)

Computation time

Figure 4 shows the averaged computation time for a single epoch for the three station sets. The UD approach needs about 4, 15, and 36 s. This is approximately 10–20 times as long as needed for ED, whereas the respective factor for the MD approach generally is less than two. The single-epoch processing time needed increases significantly with the number of stations for UD, but remains very flatly for the other two. The MD approach is able to update clocks within 0.5, 0.8, and 2.5 s for the three test networks.

Estimated clocks

We calculate the differences between the estimated clocks and the GFZ rapid clocks. Following the standard practice in IGS clock comparisons, the resulted time series are aligned to a reference satellite in order to remove systematic biases (Agrotis et al. 2010). The bias and STD of each satellite clock are computed. In addition to the STDs of all satellites, we also use the RMS of the clock differences as quality indicators to measure the satellite-specific bias of the clock estimates. The larger RMS indicates a worse consistency of clock biases, which directly propagate into the range modeling.

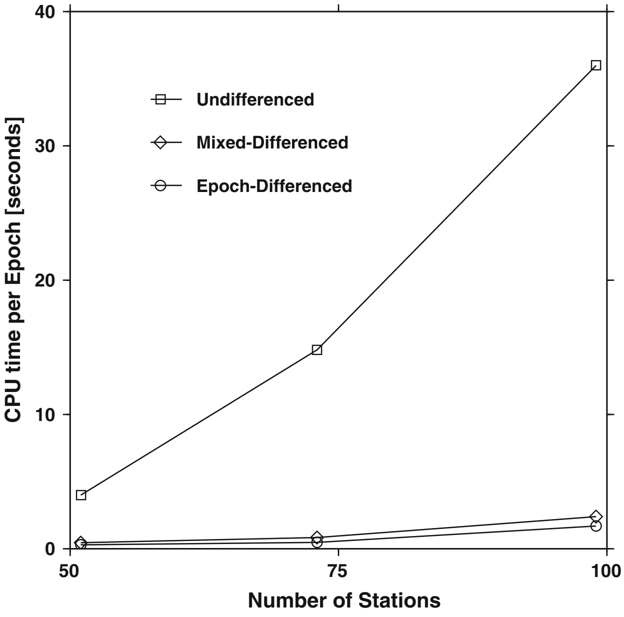

Fig. 4 Averaged computation time for a single epoch processed with undifferenced, epoch-differenced, and mixed-differenced observations as a function of the number of stations

Table 1 summarizes the results for the two quality indicators mentioned earlier. The results of the three networks processed with the same approach vary slightly. The RMS of the ED approach is about 4 ns, which is significantly larger than expected due to the poor quality of the broadcast clock used as initial values. The 4-ns RMS leads to about 1.2-m noise in the modeling of range observations and respective poor positioning results if the ranges are used only. Both the MD and UD approaches result in very small RMS of about 0.20 and 0.33 ns. The corresponding range noises are about 6 and 10 cm, which are negligible compared with the range noise of current receivers. The ED approach has the smallest STD, UD the largest, and the MD value falls in-between, although the difference is

Table 1 RMS and STDs of the estimated clocks compared with GFZ rapid products; the unit is ns

Number of stations	Undiff.		Epoch-diff.		Mixed diff.	
	RMS	STD	RMS	STD	RMS	STD
50	0.22	0.11	4.07	0.09	0.32	0.11
75	0.20	0.10	4.08	0.09	0.33	0.10
100	0.19	0.09	4.08	0.08	0.33	0.09

negligible compared with the STD values. The STDs decrease slightly with increasing the number of stations.

Figure 5 illustrates the clock biases for each satellite for the different test networks and approaches. There are almost no differences between the three networks in regard to the same method, but significant difference exists between MD and ED, and UD and ED. The bias of ED approach reaches up to 13 ns, which corresponds to a range error of 4 m.

Figure 6 shows the satellite-specific STD of the clock estimates. The figure indicates large STD in several satellites, for example G10 and G32. These two Block IIA satellites were in eclipse, and inconsistent attitude modeling resulted in this large difference (Kouba 2009). The ED and MD approaches can reduce this impact because the differences in the attitude modeling most likely cancel in the epoch-differenced observations. Comparison with GFZ rapid products shows that the MD approach can reduce the clock RMS significantly from 4 ns (ED) to 0.33 ns, which is very close to 0.20 ns obtained for UD. The STDs of the clock estimates are between those of ED and UD.

Estimated initial clock biases

Figure 7 shows sample time series of the estimated initial biases of satellite clocks after removal of the satellite-specific mean value. The systematic change along with time can be interpreted as an epoch-wise clock offset for all satellites, which has no effect in user positioning. A convergence period of about 1 h (120 epochs) is needed to achieve values smaller than 10 cm in amplitude. After 1.5 h, this amplitude is less than 4 cm and remains the same afterward. Since the initial clock bias is only important for range observations, an accuracy of 10 cm might be sufficient given the range accuracy of about 0.3 m for current generation of receivers.

The initial clock bias parameter can be removed from the filter after its convergence so that the computation time in each epoch can be further reduced. Moreover, using a well-estimated initial clock bias will also avoid the effect of possible poor range observations on clock changes.

The upper panel of Fig. 8 shows the estimated initial clock biases using data of 24 h and data of the first 1.5 h for the MD approach, and the clock biases of the ED-approach, all with respect to the GFZ rapid products. The lower panel shows the differences in ED clock biases and the estimated initial clock biases. The upper panel shows that in both cases the estimates of the initial clock biases are able to calibrate the clock biases in the ED approach precisely. From the lower panel, it is seen that for most of the satellites, the estimated biases are almost of the same quality; large differences occur at satellites G04, G05, G10, G17, and G32. Further investigation confirms that most of these satellites are in eclipse. Still, the 1.5-h result is better than 0.3 ns, which corresponds to range noise of 10 cm and can be neglected compared with the quality of the range observations available currently.

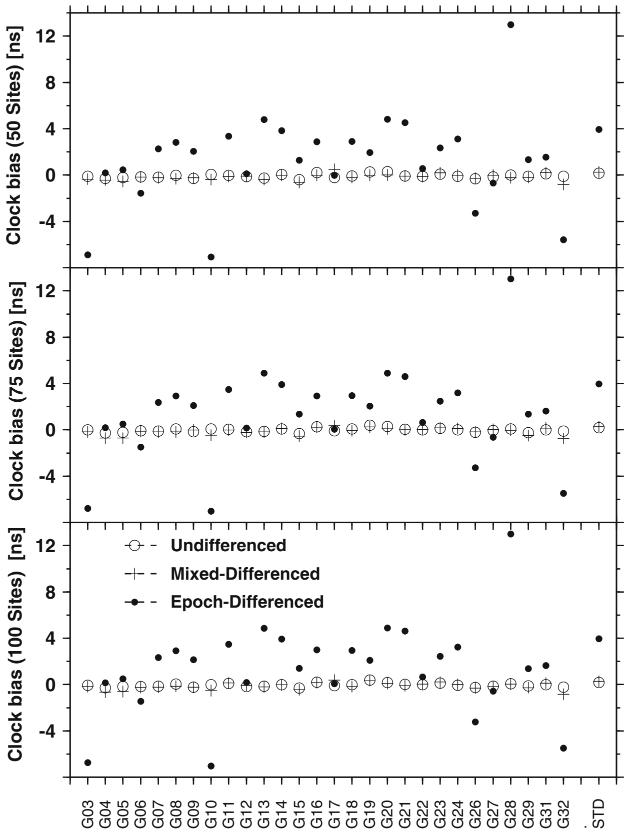

Fig. 5 Satellite-specific biases of clocks estimated by ED, MD, and UD for the three networks compared with the clocks of GFZ rapid products. The STDs of the biases are listed last to the right. G02 is the reference satellite

Conclusions

We have developed a new approach for fast estimation of satellite clocks in realtime. The new approach properly makes use of combined epoch-differenced phases and undifferenced ranges instead of treating epoch-differenced or undifferenced phases and ranges separately. The advantage

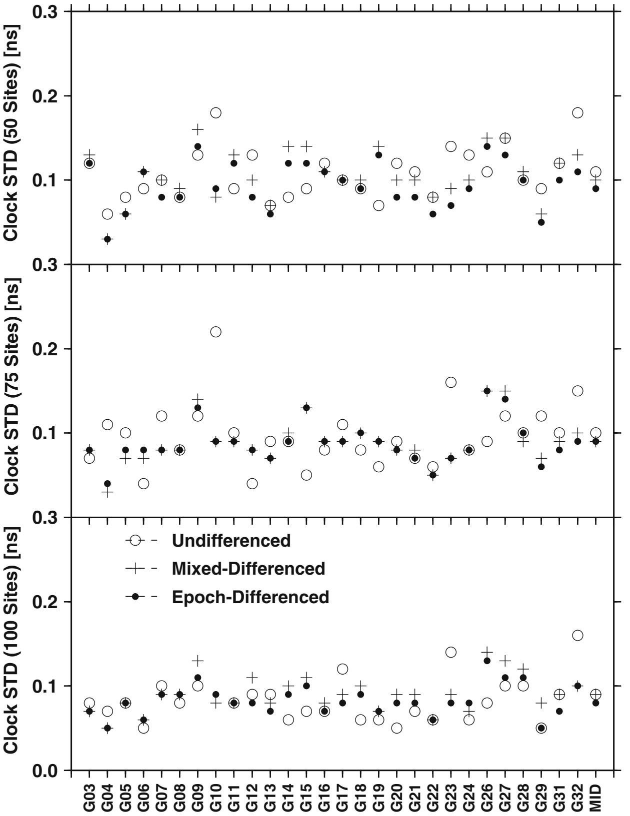

Fig. 6 Satellite-specific STDs of clock estimates compared with the clocks of GFZ rapid products. The mean values of the STDs are also plotted near the right edge of each panel. G02 is the reference satellite

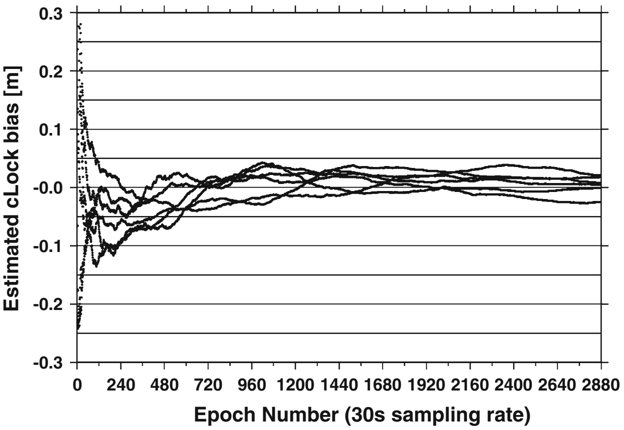

Fig. 7 Estimated initial satellite clock biases. After 1.5 h of convergence time, the amplitude of the inconsistent change in the clock biases is smaller than 4 cm, and the STD is about 1 cm

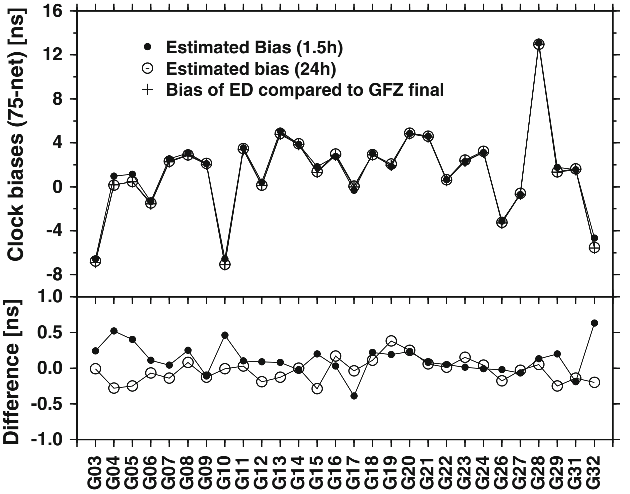

Fig. 8 Comparison of estimated initial clock biases using 24-h data (*open circles*) and 1.5-h data (*black dots*) from the MD approach and the clock biases of the ED approach with respect to the GFZ rapid products (*crosses*). The *bottom panel* shows the differences in ED clock biases with respect to the two sets

of the new approach is twofold: (1) the ambiguity parameters are removed from the epoch-differenced phases and thus increasing the computational efficiency and (2) the clock biases in the ED approach are corrected precisely by the estimated initial clock biases. Therefore, the new approach can provide precise clocks in a computational efficient way.

The new approach has been validated by comparing its clock estimates with the values obtained using undifferenced and epoch-differenced observations from three global networks with 50, 75, and 100 stations. The computation time is about one-tenth to one-twentieth of the UD approach and comparable with that of the ED approach. For the network with around 75 stations, real-time clocks can be updated at the rate of 1 Hz.

The STDs of clock solutions with respect to the GFZ rapid products are about 0.09 ns, which is equivalent to the STDs from the ED and UD approaches. The clock RMS are at the level of 0.33 ns, corresponding to a 10-cm range noise, which is well within the noise level of range observations, although it is not as good as the 0.20 ns of the UD approach. The major differences occur when satellites are in eclipse. The cause is most likely inaccurate modeling of the satellite attitude during the eclipse time in the ED approach. More investigation will be carried out in order to obtain a consistent result.

The new approach has overcome the major drawback of the ED approach, where the initial clock biases of several nanoseconds are present and affect the use of range observations, and it retains the computational efficiency of the ED approach. The effective removal of the initial clock biases makes the clock products more usable for applications with various accuracy levels and receiver quality. The significantly improved computation performance makes realtime clock estimation from a denser reference network at a high clock update rate possible. The technique applies to GPS and multi-GNSS constellations.

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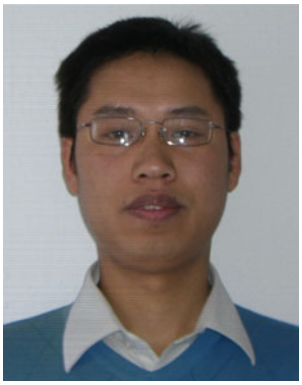

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