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Evaluation and analysis of real-time precise orbits and clocks products from different IGS analysis centers

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Abstract

To meet the increasing demands from the real-time Precise Point Positioning (PPP) users, the real-time satellite orbit and clock products are generated by different International GNSS Service (IGS) real-time analysis centers and can be publicly received through the Internet. Based on different data sources and processing strategies, the real-time products from different analysis centers therefore differ in availability and accuracy. The main objective of this paper is to evaluate availability and accuracy of different real-time products and their effects on real-time PPP. A total of nine commonly used Real-Time Service (RTS) products, namely IGS01, IGS03, CLK01, CLK15, CLK22, CLK52, CLK70, CLK81 and CLK90, will be evaluated in this paper. Because not all RTS products support multi-GNSS, only GPS products are analyzed in this paper. Firstly, the availability of all RTS products is analyzed in two levels. The first level is the epoch availability, indicating whether there is outage for that epoch. The second level is the satellite availability, which defines the available satellite number for each epoch. Then the accuracy of different RTS products is investigated on nominal accuracy and the accuracy degradation over time. Results show that Root-Mean-Square Error (RMSE) of satellite orbit ranges from 3.8 cm to 7.5 cm for different RTS products. While the mean Standard Deviations of Errors (STDE) of satellite clocks range from 1.9 cm to 5.6 cm. The modified Signal In Space Range Error (SISRE) for all products are from 1.3 cm to 5.5 cm for different RTS products. The accuracy degradation of the orbit has the linear trend for all RTS products and the satellite clock degradation depends on the satellite clock types. The Rb clocks on board of GPS IIF satellites have the smallest degradation rate of less than 3 cm over 10 min while the Cs clocks on board of GPS IIF have the largest degradation rate of more than 10 cm over 10 min. Finally, the real-time kinematic PPP is carried out to investigate the effects of different real-time products. The CLK90 has the best performance and mean RMSE of 26 globally distributed IGS stations in three components are 3.2 cm, 6.6 cm and 8.5 cm. And the second-best positioning results are using IGS03 products.

Keywords: IGS RTS; Epoch availability; Satellite availability; Accuracy degradation; Latency; Real-time PPP

0. Introduction

Precise Point Positioning (PPP) (Zumberge et al., 1997; Kouba and Héroux, 2001; Ge et al., 2008; Bisnath and Gao, 2009; Bertiger et al., 2010), which can derive centimeter to decimeter level positioning accuracy using a single receiver, becomes a powerful tool in geodetic and geodynamic applications (Ge et al., 2008). High precision satellite orbit and clock products are two major corrections required to conduct PPP. The IGS currently provides precise orbit and clock products for GPS and GLONASS, and further inclusion of other constellations is planned (Dow et al., 2009; Montenbruck et al., 2017). To satisfy the increasing real-time demands, the IGS Real-Time Working Group (RTWG) was established in 2001 (Agrotis et al., 2014; Hadas and Bosy, 2014) and The IGS real-time service (RTS) was officially launched on April 1, 2013 (Hadas and

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Bosy, 2014; Elsobeiey and Al-Harbi, 2016). With the available real-time satellite orbit and clock products, extensive researches have been carried out on real-time PPP including various applications, such as the offshore navigation, precision agriculture and nature hazard monitoring (Gao and Chen, 2004; Yang and Gao, 2017; Yang et al., 2017).

Several RTS products are currently available from IGS to support real-time PPP (Hadas and Bosy, 2014; Elsobeiey and Al-Harbi, 2016; Kazmierski et al., 2017). Positioning performances are different when different RTS products are applied (Krzan, 2015; Elsobeiey and Al-Harbi, 2016). Generally speaking, availability and accuracy are two main major concerns on RTS products as they are affecting positioning accuracy, which will be investigated in detail in this paper.

When it comes to availability to be discussed in this paper, there are two requirements for the RTS products with respect to availability at specific epoch. The first requirement is that the RTS products can be received at that epoch, which is investigated by most researchers. For example, the availability of IGS01 and IGS03 is 92% over one week (Hadas and Bosy, 2014). The other requirement is that latency is smaller than a specific threshold such as 90s, which is rarely discussed in previous papers.

In other words, the latency is also considered as part of the availability in this paper. To investigate accuracy of RTS products, daily comparisons of clock products (Elsobeiey and Al-Harbi, 2016) are carried out by BKG and accuracy of orbit and clock products from RTS streams, namely IGS01 and IGS03 (Hadas and Bosy, 2014), CLK01, CLK81, CLK92, GFZC2 and GFZD2 (Lu et al., 2017) are assessed separately. Since positioning accuracy are affected by the combined effects of satellite orbit and clock products and common errors of radial orbit and clock for all satellites can be absorbed into receiver clock offset (Hauschild and Montenbruck, 2009), combined effects of RTS orbit and clock products should be considered.

Due to the latency or potential outage, the accuracy of RTS products will degrade over time (Hadas and Bosy, 2014). Thus, the degradation of RTS products will be investigated apart from the nominal accuracy. The degradation of orbit IGS01 and IGS03 is compared with IGS final products in various lengths of delay, from 5 s to 10 min (Hadas and Bosy, 2014). Although the evaluation on some RTS products were conducted by researchers (Hadas and Bosy, 2014; Krzan, 2015; Elsobeiey and Al-Harbi, 2016), the work was mainly limited to special IGS products, namely the IGS01/IGC01, IGS02 and IGS03. So far there are very limited discussions on the evaluation of many other real-time products available from IGS real-time Analysis Centers (ACs) systematically. Meanwhile, it is very difficult for real-time PPP users to select a suitable RTS product without a good understanding of the availability and accuracy as well as the positioning performance of different RTS products.

To solve the above problems, this paper will evaluate and analyze the availability and accuracy of RTS products from different ACs, which include nine products listed in Table 1. Because multi-GNSS products are not provided by all RTSs, only GPS products are analyzed. The RTS products are firstly described in Section 1. Then availability of RTS products is discussed in Section 2. In Section 3, the evaluation of RTS products is first carried out by comparing to the IGS final products and the PPP based positioning is then conducted to further assess the quality of the RTS products. Conclusions and discussions are included in Section 4.

1. IGS real-time service products

There are several RTS products can be real-time received via the Internet from IGS and nine RTS products will be investigated in this paper, namely IGS01, IGS03, CLK01, CLK15, CLK22, CLK52, CLK70, CLK81 and CLK90, as listed in Table 1. IGS01 and IGS03 are two combined RTS products mostly used by real-time PPP users, which are firstly generated by individual real-time ACs and combined by European Space Agency's Space Operations Centre (ESA/ESOC) and BKG correspondingly. RTS products generated by individual real-time ACs, such as CLK01, CLK15, CLK22, CLK52, CLK70, CLK81 and CLK90, are broadcasted to real-time users directly.

More specifically, IGS01 is a single-epoch combined product with update rate at 5 s for both orbit and clock, which is produced using software developed by ESA/ESOC (Rülke and Agrotis, 2016). The satellite clock products of IGS03 is a Kalman filter combined product using BNC developed by BKG, in which three kinds of parameters, AC special offset, satellite and satellite and AC special offset and actual satellite clock correction, are estimated in Kalman filter. AC special offset is assumed to be static parameters while satellite and AC specific offset and satellite clock correction are stochastic parameters with appropriate white noise in processing (Mervart and Weber, 2011). Meanwhile, the orbit products of IGS03 is extracted from one of incoming individual RTS products while the orbit and clock update rates are 60 and 10 s respectively.

The other seven RTS products are generated by individual ACs with different software. IGS Ultra Rapid (Griffiths and Ray, 2009; Choi et al., 2013), CODE Ultra Rapid (Dach et al., 2009) or Internal Ultra Rapid orbit products are adopted as a priori information by ACs. When clock corrections are estimated, orbit is often fixed. However, For CLK90, orbit corrections are estimated with clock corrections simultaneously. Latencies of individual ACs products are less than 10 s (Agrotis et al., 2010; Laurichesse et al., 2013; Rülke et al., 2016). All above mentioned RTS products can be real-time received via Networked Transport of RTCM via Internet Protocol (NTRIP) (Weber et al., 2005) after registration.

Table 1
Brief description of nine RTS products.

Products	Generating agency	GPS update rate (orbit/clock)	Orbits	Orbit reference point	Software	Latency(s)
IGS01	ESA/ESOC	5/5	Combined	APC	RETINA	24–28
IGS03	BKG	60/10	Combined	APC	BNC	~27
CLK01	BKG	60/ 5	GPS + GLONASS RT orbits and clocks using IGU orbits	CoM	BNC	
CLK15	WUHAN	5/5	GPS orbits and clocks based on IGU orbits	CoM	PANDA	
CLK22	NRCan	5/5	GPS orbits and clocks using NRT batch orbits	APC	HPGNSSC	~3
CLK52	ESA/ESOC	5/5	RT orbits and clocks using NRT batch orbits	CoM	RETINA	<10
CLK70	GFZ	10/5	RT orbits and clocks and IGU orbits	APC	EPOS-RT	
CLK81	GMV	5/5	RT orbits and clocks based on NRT orbit solution	CoM	magicGNSS	
CLK90	CNES	5/5	GPS + GLONASS orbits and clocks	CoM	PPP-WIZARD	~8

Note: GPS: Global Positioning System.
ESA/ESOC: European Space Agency's Space Operations Centre.
BKG: Bundesamt für Kartographie und Geodäsie.
WUHAN: Wuhan University.
NRCan: Natural Resources Canada.
GFZ: DeutschesGeoForschungsZentrum.
GMV: GMV Aerospace and Defense.
CNES: Centre National d'Etudes Spatiales.CODE: Center for Orbit Determination in Europe.APC: Antenna Phase Center.
CoM: Center of Mass.

2. Evaluation and analysis of RTS product on availability

The availability of RTS products is discussed with a new perspective in this section. When it comes to the definition of availability, there are two basic requirements for the RTS products to be considered as available at a specific epoch. The first one is that the RTS products can be real-time received at that epoch through internet or communication satellite. The availability can't be confirmed with only the first requirement because the latency of RTS products also needs to be considered at the same time, which is usually missed by the other researchers. The second requirement is that the latency of the received RTS products is smaller than a specific threshold, such as 90 s in this experiment. Thus, the availability can vary with different thresholds of latency. In other words, the latency is actually considered as part of the availability. The RTS products can be only considered as available for that epoch once both requirements can be met.

More specifically, the availability of RTS products is investigated in two different levels. The first level denotes epoch availability, indicating whether RTS products are received for the epoch, which is mostly discussed by previous researchers. But very few investigations have been carried out about the second level, i.e. satellite availability (the available satellite number at each epoch). The satellite availability is very important for positioning applications which determines the positioning geometry.

Nine RTS products are analyzed which were collected through the Internet in Calgary, Canada from June 15, 2017 (Day of Year (DOY) 166) to Jun 21, 2017 (DOY 172). The epoch availability results are shown in Fig. 1. As we can see that the daily epoch availabilities of all RTS products are very high, which can reach more than 90%. For different RTS products, the epoch availability can be quite different. For example, the availability differences between CLK70 and other RTS products on DOY 170 of 2017 are more than 5%. Meanwhile the daily epoch availability of a RTS product can also change significantly. For example, the CLK70 shows the largest fluctuation in its daily epoch availability.

For the satellite availability, the results are shown in Fig. 2. We can see that the satellite availability of the nine RTS products is very high where even the minimum daily average number of available satellites is more than 29. The average number of available satellites ranges from 29 to 31 during the period. Similarly, the satellite availability of different RTS products is not the same which varies with time for a RTS product.

To investigate the latency of RTS products, the RTS products are collected on June 21, 2017 (DOY 172). The statistic results for the whole day are shown as the following Fig. 3. We can see that, the IGS01 and IGS03 have latency at 28 s and 26 s, respectively, which are much larger than the other seven RTS products due to time taken to combine individual products. Among all nine RTS products, the CLK22 has the shortest latency at 3 s. The latency of CLK01, CLK15, CLK52, CLK81 and CLK90 are between 5 s and 11 s. CLK70 gets the longest latency apart from IGS01 and IGS03 and the value is 13 s. Meanwhile, the standard deviation of the latency over one day for each RTS product is also calculated and shown in a red line in Fig. 3. The smallest standard deviation is 0.5 s for CLK01, CLK81 and CLK90 and the largest one is 4.5 s for IGS01.

3. Evaluation and analysis of RTS products on accuracy

Actually, the true accuracy of RTS products can be divided into two aspects, namely the nominal accuracy of the RTS products and the accuracy degradation over time. For the first part, the nominal accuracy is analyzed in an ideal situation without considering the latency and potential outage, which is not uncommon as shown in previous discussions. The IGS final products can be used as the reference for the computation of the nominal accuracy. In fact, all RTS products will experience latency and potential outage, so the accuracy degradation over time need to be investigated in the second part. Lately the PPP experiments will be carried out to check the accuracy of RTS products in position domain. The experiment data are the RTS products received on June 21, 2017 (DOY 172).

3.1. Analysis of the nominal accuracy

As the orbit reference centers for the nine RTS products are different, the IGS antenna file is used for applying the satellite phase center offset (Schmid et al., 2016) for products with APC referred center, such as IGS01, IGS03, CLK22 and CLK70. The RTS orbit products are defined in the International Terrestrial Reference Frame 2014 (ITRF2014) (Altamimi et al., 2016). The IGS final products are used as the reference for the comparisons and Root-Mean-Square Error (RMSE) of every satellite in three components is calculated for each RTS product on June 21, 2017 (DOY 172). The mean RMSE values of satellites are shown as following Fig. 4.

As we can see that the average 3D orbit (RMSE) for all satellites over one day for nine RTS products range from 3.8 cm to 7.5 cm. For CLK01, CLK15, CLK52 and CLK90, the RMSE are around 4 cm. The accuracy is less than 2 cm in radial component for all products except IGS01 and CLK22, which affect the positioning mostly due to the radial direction is closest to the line of sight direction.

RMSE values of satellites in radial, along-track and across-track directions are shown in Fig. 5. As we can see that, the orbit of different satellites from the same RTS products share similar accuracy. For CLK01, CLK15, CLK52 and CLK90, RMSE of most satellites in all three directions are less than 5 cm. The satellite orbit errors in radial direction for IGS01 and CLK22 are much larger than the other RTS products. For IGS03, CLK70 and CLK81, the satellite orbit errors in the along-track and across-track directions are much larger than the other RTS products.

In order to assess the accuracy of satellite clock products, the RTS products on June 21, 2017 (DOY 172) are collected. We downloaded the IGS final clock products with 30 s interval and the update rates of RTS products are 5 s or 10 s. In this experiment, comparison interval with 30 s is applied to avoid the effect of the interpolation. Double-difference will be carried out for the comparison and the equation (Chen et al., 2017) can be written as,

$$\begin{aligned} \Delta CLK(k)_i^j &= CLK(k)_i^j - CLK(k)_{final}^j \\ \nabla\Delta CLK(k)_i^j &= \Delta CLK(k)_i^j - D(k)_i \end{aligned} \tag{1}$$

where superscript j denotes the satellite and subscript i denotes the RTS product. k here means the epoch and $CLK(t)_i^j$ is satellite clock bias of RTS product and $CLK(t)_{final}^j$ is clock bias of IGS final product. $\Delta CLK(k)_i^j$ is the single difference between the RTS products and IGS final products; and $\nabla\Delta CLK(k)_i^j$ are double-differenced results by removing the common offset for all satellites between RTS products and IGS final products. $D(k)_i$ here

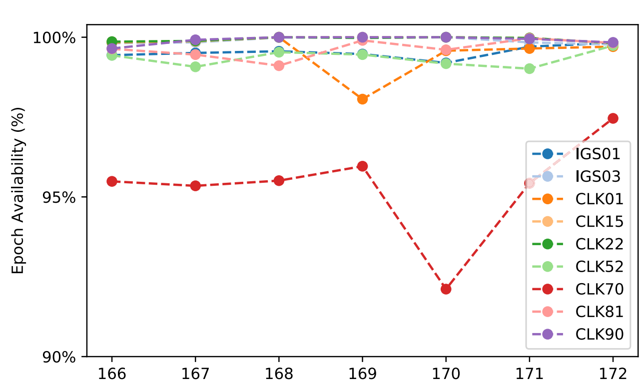

Fig. 1. Epoch availability of nine RTS products from DOY 166 to DOY 172 of 2017.

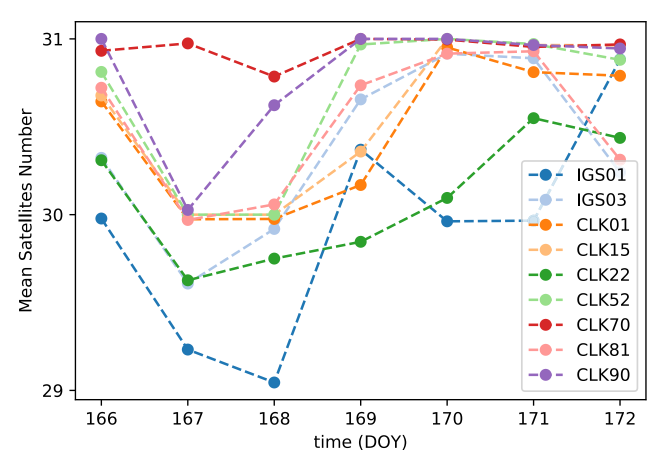

Fig. 2. Satellite availability of nine RTS products from DOY 166 to DOY 172 of 2017.

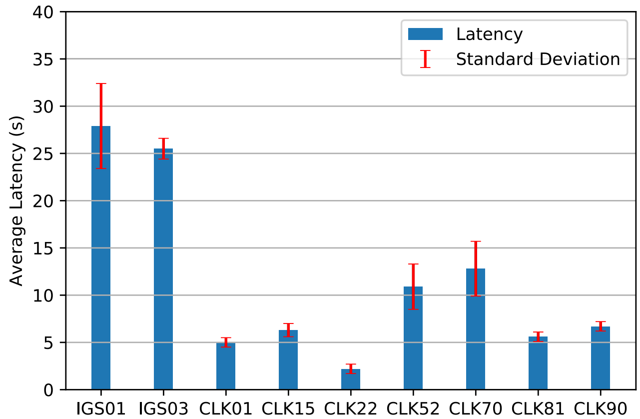

Fig. 3. Latencies of nine RTS products on DOY 172.

denotes the common offset between RTS product and IGS final product at this epoch, which can be calculated by

$$D(k)_i = \frac{1}{N}\sum_{j=1}^{N}\Delta CLK(k)_i^j, j = 1,\cdots N.$$

where N is common satellites number.

The mean Standard Deviations of Errors (STDE) of all satellites for RTS clock products are shown in Fig. 6. As we can see, the STDE of nine RTS products are in range of 1.9 cm–5.6 cm. The largest STDE is from CLK22 and smallest one is form CLK90. Mean STDE of IGS03 is slightly larger than CLK90 and a little smaller than CLK52. The mean STDE of CLK01, CLK15, CLK70 and CLK81 are between 4 cm and 5 cm. More detailed STDE values for each satellite are shown in Fig. 7. The STDE of satellites from same RTS products are similar. For CLK90 and IGS03, STDE of most satellites are less than 3 cm, which are the best two and followed by CLK52. The STDE of some satellites such as PRN24 and PRN26 from CLK22 are more than 10 cm.

The Signal In Space Range Error (SISRE) has often been used to gain a coarse estimate of the expected positioning accuracy (Warren and Raquet, 2003; Hauschild and Montenbruck, 2009; Heng, 2012; Montenbruck et al., 2014). In this paper, we use the modified SISRE to avoid radial orbit errors or clock errors, which are common to all satellites. In a navigation solution, these common errors would be absorbed into the user clock correction and do not affect the position (Hauschild and Montenbruck, 2009). The modified SISRE is calculated by

$$SISRE_{modified} = \sqrt{[rms(\Delta e_{RC} - \overline{\Delta e_{RC}})]^2 + w_{A,C}^2(A^2 + C^2)} \quad (2)$$

where $SISRE_{modified}$ is the modified SISRE; rms means the root-mean-square. Δe_{RC} is combined radial orbit and clock error, and $\overline{\Delta e_{RC}}$ is the mean of Δe_{RC}. $w_{A,C}^2$ is weight factor and for GPS the value is $1/49$. $A = rms\Delta r_A$ and $C = rms\Delta r_C$. Δr_A and Δr_C are orbit errors in the along-track and cross-track directions. RTS products received on June 21, 2017 (DOY 172) are used here. Modified SISRE of all nine RTS products are presented in Fig. 8. As we can see, the average modified SISRE of all satellites for all nine RTS products are smaller than 6 cm. The largest mean SISRE of nine products is 5.5 cm for CLK22 and the smallest is 1.3 cm for CLK90. The second and third smallest mean SISRE are from CLK52 and IGS03. The standard deviation of each product is also calculated and shown as the red line, for all products is less than 2.2 cm. CLK90 get the smallest standard deviation, which is 0.9 cm.

3.2. Analysis of accuracy degradation over time

In order to investigate the true accuracy of the RTS products, the analysis of accuracy degradation over time need to be carried out due to the combined effect of latency and potential outage.

As we know that RTS products include the corrections and correction rates for the broadcast ephemeris and the accuracy depends on the difference between the reference time and the applied time. The accuracy will degrade with the increase of the time difference, so the RTS products are usually updated with very high update rates such as 5 s or 10 s. The analysis of degradation of the RTS products over time are carried out in terms of orbit and clock separately.

In order to show the satellite orbit degradation over time for all nine RTS products, the contribution of the satellite orbit to SISRE is calculated as the following equation,

$$SISRE(orb) = \sqrt{w_R^2 R^2 + w_{A,C}^2(A^2 + C^2)} \quad (3)$$

where w_R^2 and $w_{A,C}^2$ are weight factors and for GPS values are 0.98^2 and $1/49$. R, A and C are orbit RMSE in the radial, along-track and cross-track directions; $SISRE(orb)$ is the contribution of orbit to SISRE.

RTS products on June 21, 2017 (DOY 172) are adopted in the experiment. IGS final products are used as reference and the interval of the comparison is 30 s. Results show that all satellites are similar behaviors for the degradation.

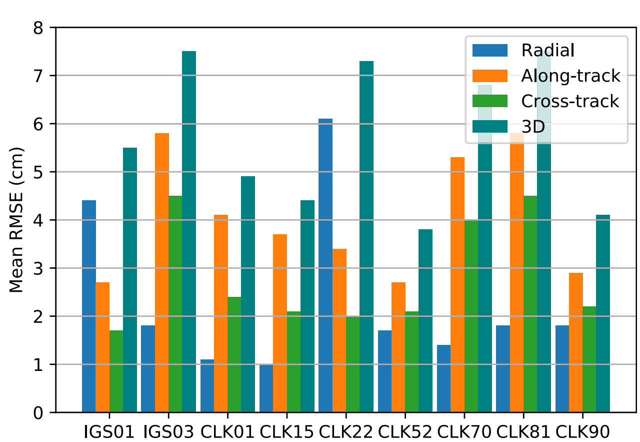

Fig. 4. Mean RMSE of satellite orbit of nine RTS products on DOY 172, 2017.

Fig. 5. Orbit RMSE of satellites of nine RTS orbit products on DOY 172, 2017.

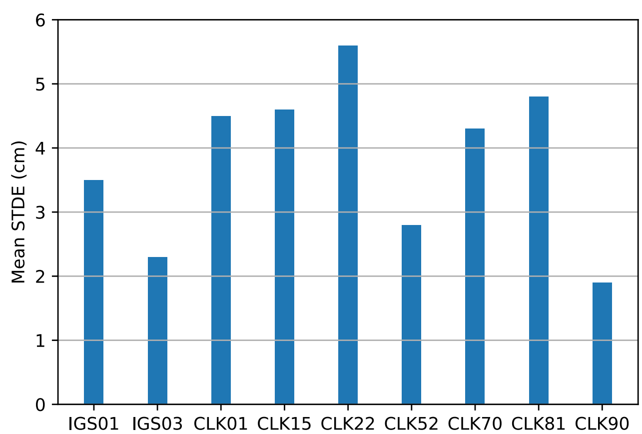

Fig. 6. Mean STDE of satellite clocks of nine RTS products on DOY 172, 2017.

PRN01, PRN05, PRN08 and PRN19 are selected to represent the whole constellation and the satellite orbit degradation over time of the nine RTS products are shown in Fig. 9. As we can see, the orbit degradation of all nine RTS products show linear trend over 10 min and the degradation for most RTS products are less than 10 cm over 10 min.

The more detailed statistics of the orbit degradation are given in the following Table 2. The degradation over 1 min can be considered as the degradation rate if we assume degradation is with linear mode. As we can see that the maximum degradation are 0.7 cm and 1.1 cm in one minute for PRN01 and PRN05. For PRN19 and PRN08, the maximum orbit degradation is 0.4 cm in one minute. When it comes to the comparison of different RTS products, we can see that CLK22 and CLK81 have the minimum degradation while CLK90 gets the maximum degradation. The main reason for the different performance is due to the different satellite orbit correction rates in different RTS products. Since the satellite orbit degrades quite slow, so the update rate of the orbit part in RTS products are normally slower than the clock part.

According to the block-type and clock type, the current GPS satellite clocks can be divided into 4 groups as Table 3 (Langley, 2017).

To investigate the degradation of clock products over time, IGS final products can be used for reference and RTS clock products with various lengths of delay can be compared, from 5 s to 10 min (Hadas and Bosy, 2014). The degradation of clock products can be expressed as following,

$$\delta e(t) = e(t) - e(t_0) \tag{4}$$

where $\delta e(t)$ is the degradation at epoch t compared with the epoch t_0, $e(t)$ and $e(t_0)$ are the clock difference of RTS

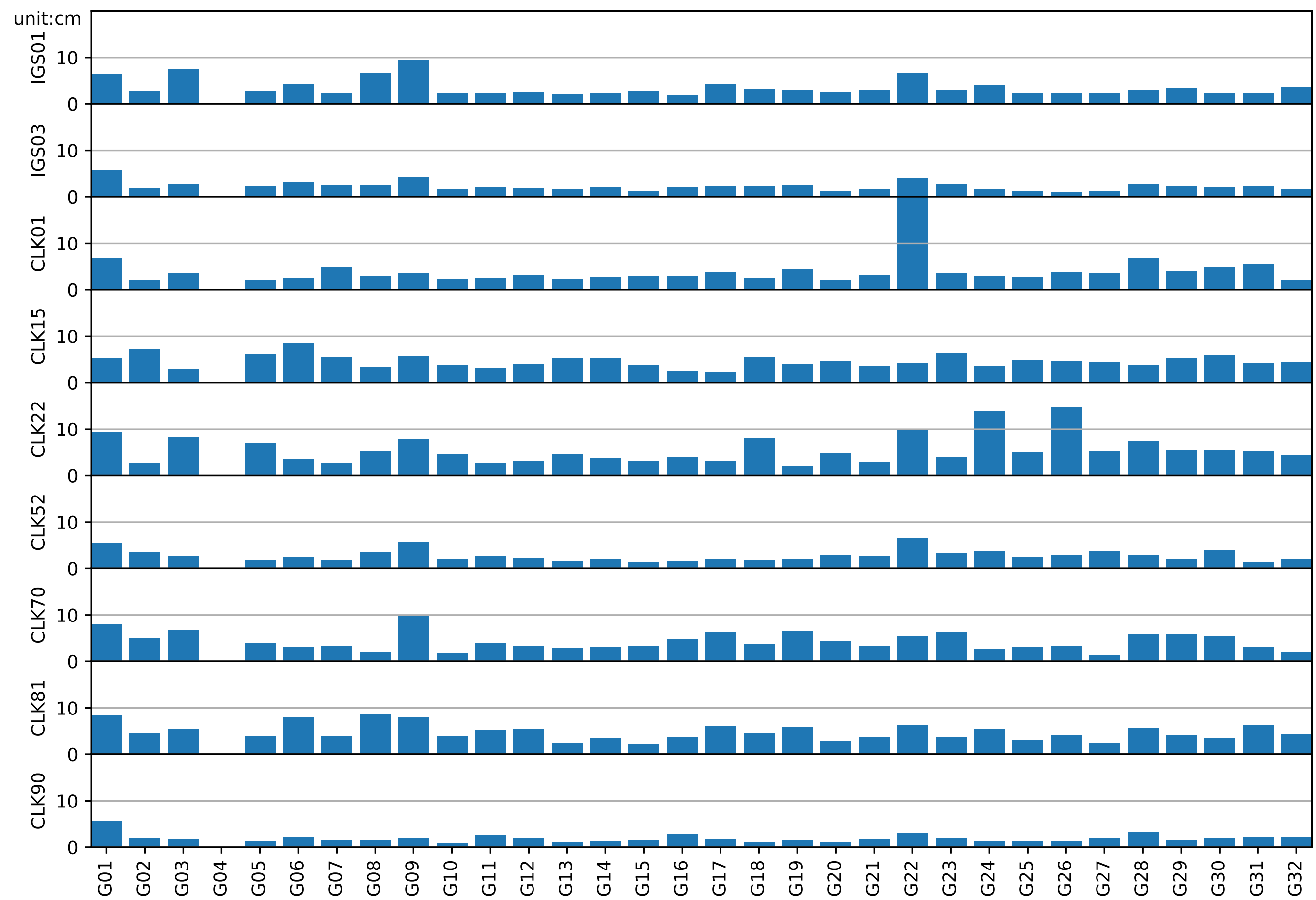

Fig. 7. STDE of satellites clocks of nine RTS products on DOY 172, 201.

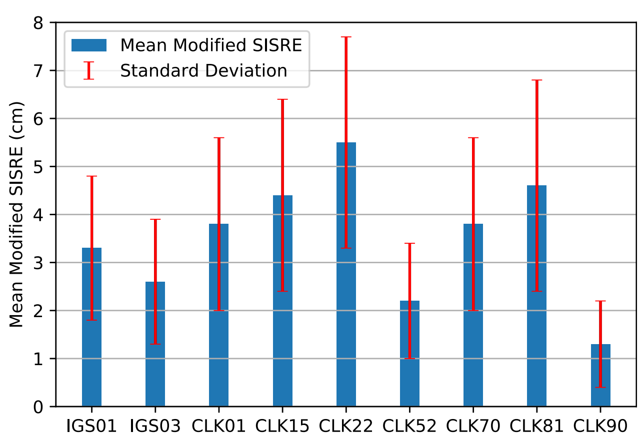

Fig. 8. Mean modified SISRE of RTS products on DOY 172.

products compared with IGS final clock products at epoch t and t_0, which can be computed as,

$$e(t) = CLK(t) - CLK(t)_{final}$$
$$e(t_0) = CLK(t_0) - CLK(t_0)_{final} \quad (5)$$

where t_0 is the reference epoch of RTS product.

The degradation of different satellite clocks is presented in Fig. 10. As we can see that the satellite clock degradation for different types are quite different. The Rubidium (Rb) clocks on board of GPS IIF satellites have the smallest degradation rate less than 3 cm over 10 min and the Cesium (Cs) clocks on board of GPS IIF have the largest degradation rate larger than 10 cm over 10 min. The main reason is different stability of different types of satellite clocks (Yang et al., 2017).

For the satellite clock, the degradation of different RTS products are exactly the same due to the RTS corrections for clock drift and clock drift rate are all set as zero currently. Thus, the satellite clock degradation indicates the discrepancy between the satellite clock drift broadcast ephemeris and the actual satellite clock drift in the IGS final products.

3.3. Analysis in position domain with PPP

PPP will be carried out in this section to evaluate the RTS products in position domain. GNSS observation data of 26 globally distributed IGS stations on June 21, 2017 (DOY 172) are collected and the distribution of the stations is shown as following Fig. 11.

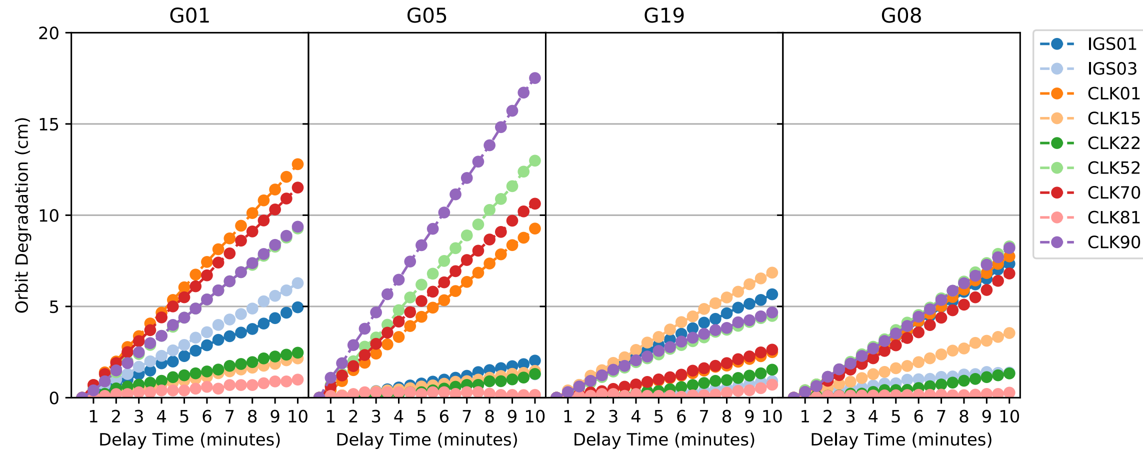

Fig. 9. Orbit degradation of satellite PRN01, PRN05, PRN08 and PRN19 over 10 min.

Table 2
Degradation of satellite orbit for PRN01, PRN05, PRN19 and PRN08 in 1 min (unit: cm).

Product	G01	G05	G19	G08
IGS01	0.2	0.1	0.3	0.3
IGS03	0.4	0.1	0.1	0.1
CLK01	0.7	0.4	0.1	0.4
CLK15	0.1	0.1	0.4	0.2
CLK22	0.1	0.1	0.1	0.1
CLK52	0.5	0.7	0.2	0.4
CLK70	0.7	0.6	0.1	0.3
CLK81	0.1	0.1	0.1	0.1
CLK90	0.4	1.1	0.3	0.3
Min	0.1	0.1	0.1	0.1
Max	0.7	1.1	0.4	0.4

RTKLIB (Takasu et al., 2007) is used in the PPP experiment. The detailed kinematic PPP settings is listed as Table 4 and the ionosphere free combination is used.

Coordinates of the IGS stations are downloaded from Scripps Orbit and Permanent Array Center (SOPAC) and used as the reference.

The daily mean RMSE of all stations are presented in Fig. 12. The maximum PPP RMSE of nine products are 6.6 cm in north direction, 11.8 cm in east direction and 15 cm in vertical direction. Among all nine RTS products, CLK90 has the best performance followed by IGS03. The PPP RMSE with CLK15 and CLK22 are largest two while the IGS01, CLK01, CLK52, CLK70 and CLK81 have similar performance. Mean RMSE in three components are 3.2 cm, 6.6 cm and 8.5 cm for CLK90.

Table 3
Block-type, PRN and clock type of GPS.

Group	Block-type	Clock type	Satellite PRN
1	IIR	Rb	16, 28, 20, 19, 2, 21, 11, 22, 18, 14, 23, 13
2	IIR-M	Rb	31, 7, 12, 29, 17, 5, 15
3	IIF	Rb	30, 25, 26, 27, 1, 6, 3, 10, 9, 32
4	IIF	Cs	24, 8

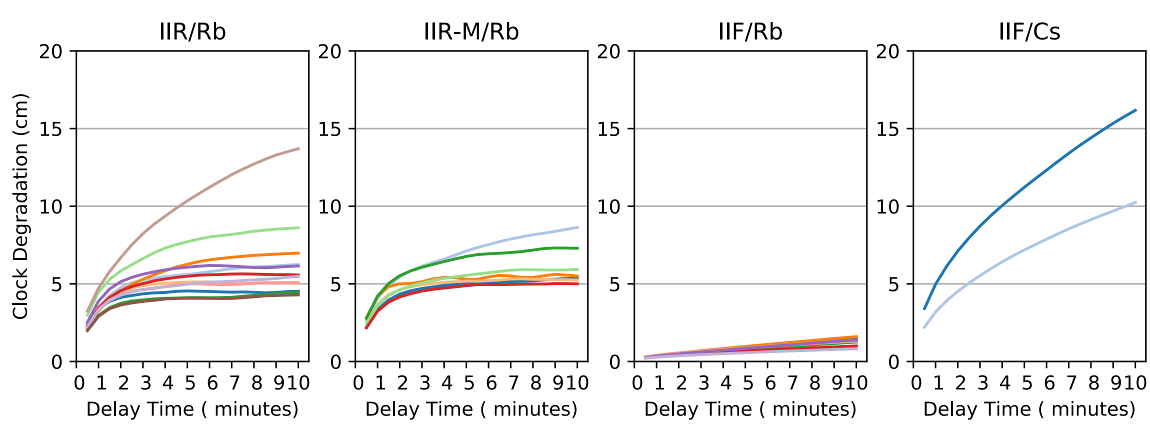

Fig. 10. Satellite clock degradation over time of nine RTS products.

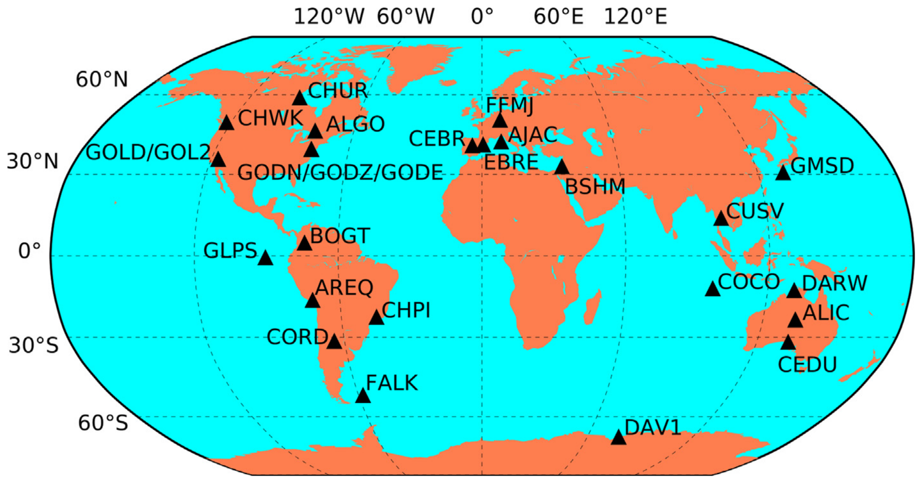

Fig. 11. 26 globally distributed IGS stations for PPP experiment.

Table 4
Kinematic PPP settings.

Options	Settings
Constellation	GPS satellites
Combination mode	Ionosphere-free phase and code combinations
Positioning mode	Kinematic
Frequencies	L1, L2
Sampling rate	1 s
Elevation mask	7°
Tropospheric zenith hydrostatic delay	GPT model (Boehm et al., 2007)
Tropospheric zenith wet delay	Initial model + estimated (random walk process)
Tropospheric mapping function	GMF (Boehm et al., 2006)
Phase wind-up	Corrected
Sagnac effect, relativistic effect	IS-GPS-200 (GPS ICD, 2010)
Satellite/receiver phase center correction	Corrected with IGS absolute correction model
Receive clock	IERS conventions (Petit and Luzum, 2010)
Station coordinates	Estimated

Kinematic PPP RMSE of 26 IGS stations are shown in Fig. 13. As we can see, the RMSE for all stations using CLK90 are smallest among all nine RTS products and the IGS03 get similar performance. The RMSE of the horizontal directions of most stations using CLK15 are larger than 10 cm.

Convergence time is an important factor for PPP. Statistics of convergence time with 26 stations are calculated and shown in Table 5. As we can see, for the nine RTS products, the maximum convergence time is in range of 450 min to 607 min and the minimum convergence time is in range of 4 min to 15 min. The mean convergence time of 26 stations ranges from 101.1 min to 131.0 min. Meanwhile, the median ranges from 47 min to 65 min. Although there are slight differences among the nine RTS products, convergence time of PPP with the nine RTS products is similar.

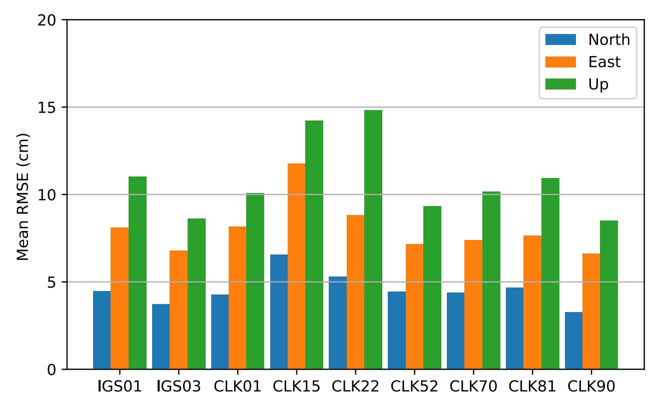

Fig. 12. Mean STDE of kinematic PPP errors of 26 globally distributed IGS stations.

To investigate positioning accuracies of short observation durations, PPP experiments, restarted every 1 h, are carried out. Accuracies of the last 5 min in each 1 h are calculated and shown in Table 6. As we can see, accuracies in north component is in range of 8 cm–12 cm, north is in range of 18 cm–27 cm and Up is in range of 16 cm–22 cm. CLK90 gets the best performance among the nine RTS products.

To investigate performance of static PPP with RTS products, static PPP experiments are carried out. Positioning results of AJAC, CHPI and GLPS are presented in Figs. 14–16. As we can see, shapes of convergence curves are also similar in PPP results when different RTS products are applied. For station AJAC, the best performance is CLK90 in accuracy aspect. For station CHPI, IGS01, IGS03, CLK52, CLK70 and CLK90 are better. Meanwhile, for station GLPS, the best two RTS products are CLK90 and IGS03. Convergence time is not consistent for the same RTS products with different stations due to different geometry. The static PPP results are quite similar for the same station when adopting different RTS products and CLK90 is the best in terms of convergence.

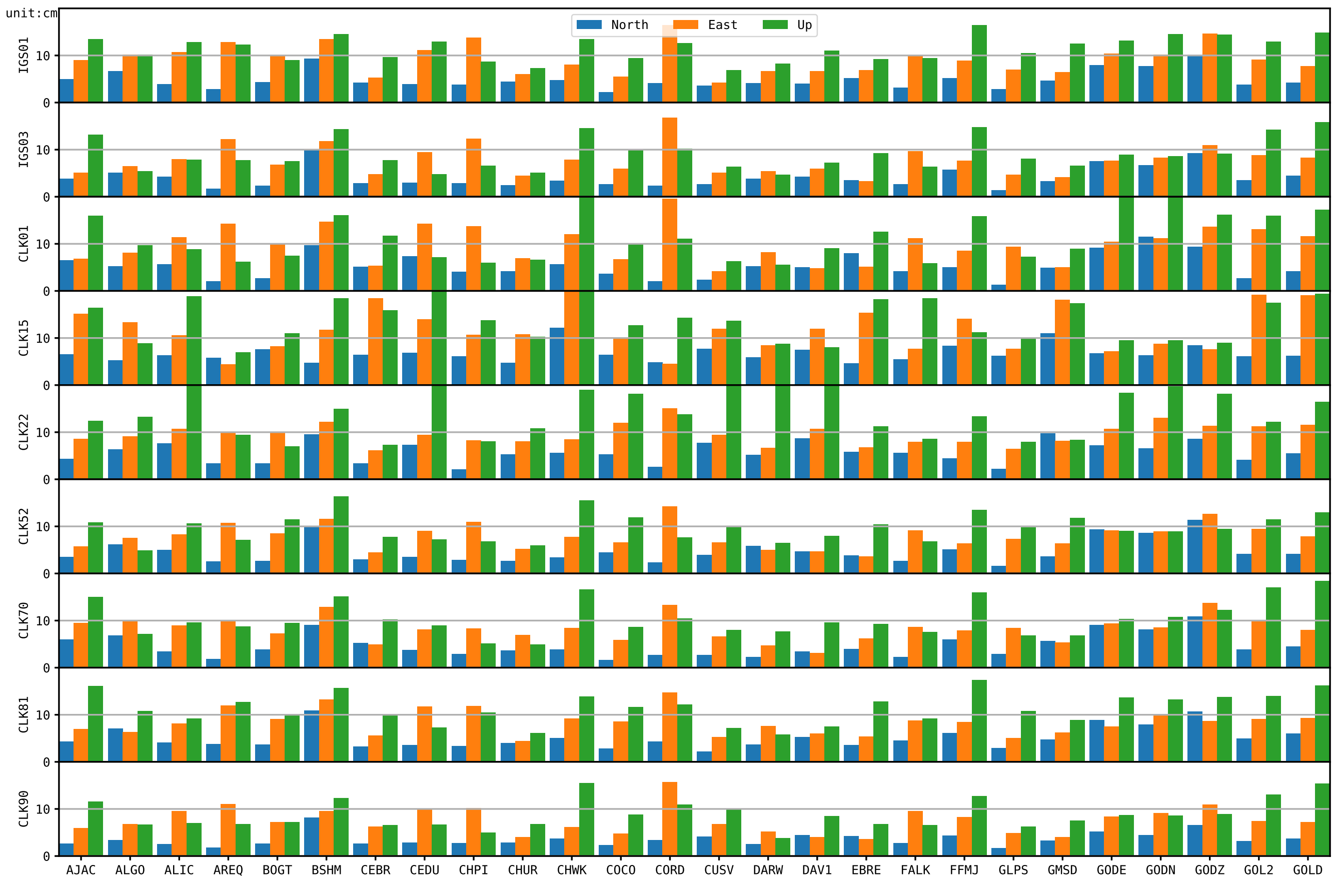

Fig. 13. Positioning accuracy of 26 globally distributed IGS stations on DOY 172 with nine RTS products.

Table 5
Statistics of convergence[a] time (unit: minute).

Products	Maximum	Minimum	Mean	Median
IGS01	473	9	123.1	52
IGS03	488	4	119.9	56
CLK01	493	5	120.9	51
CLK15	607	14	131.0	72
CLK22	457	5	101.1	47
CLK52	450	9	113.9	65
CLK70	456	4	102.7	55
CLK81	470	4	113.3	61
CLK90	477	6	113.4	51

[a] 25 cm for horizontal direction and 50 cm for vertical direction.

Table 6
Accuracies with one-hour resetting (unit: cm).

Products	North	East	Up
IGS01	10	19	20
IGS03	8	18	18
CLK01	10	21	20
CLK15	12	27	22
CLK22	9	19	21
CLK52	8	18	18
CLK70	8	19	19
CLK81	8	18	19
CLK90	7	18	16

4. Conclusions

In this paper, the nine RTS products, namely IGS01, IGS03, CLK01, CLK15, CLK22, CLK52, CLK70, CLK81 and CLK90, is investigated in terms of availability, degradation over time and accuracy.

For the availability, the discussion is carried out in a new way in terms of epoch availability and satellite availability, and the average epoch availability is more than 99.3% for all RTS products except CLK70 and the average satellites number is greater 30 for all RTS product. Latency is unavoidable for real-time products and is considered as part of the availability in this paper. The results show the longest latency is from IGS01 at 28 s and the shortest latency is form CLK22 at 3 s.

The accuracy of RTS products are discussed on nominal accuracy and accuracy over time. The latency and potential outage are not considered in the nominal accuracy analysis. RMSE of orbits ranges from 3.8 cm to 7.5 cm for different RTS products. The mean STDE of clocks range from 1.9 cm to 5.6 cm. The modified SISRE for all products are from 1.3 cm to 5.5 cm. The CLK90 has the smallest modified SISRE followed by CLK52 and IGS03. The accuracy degradation of the orbit has the linear trend for all RTS products and the satellite clock degradation is dependent on the satellite clock types. The orbit degradation are 0.7

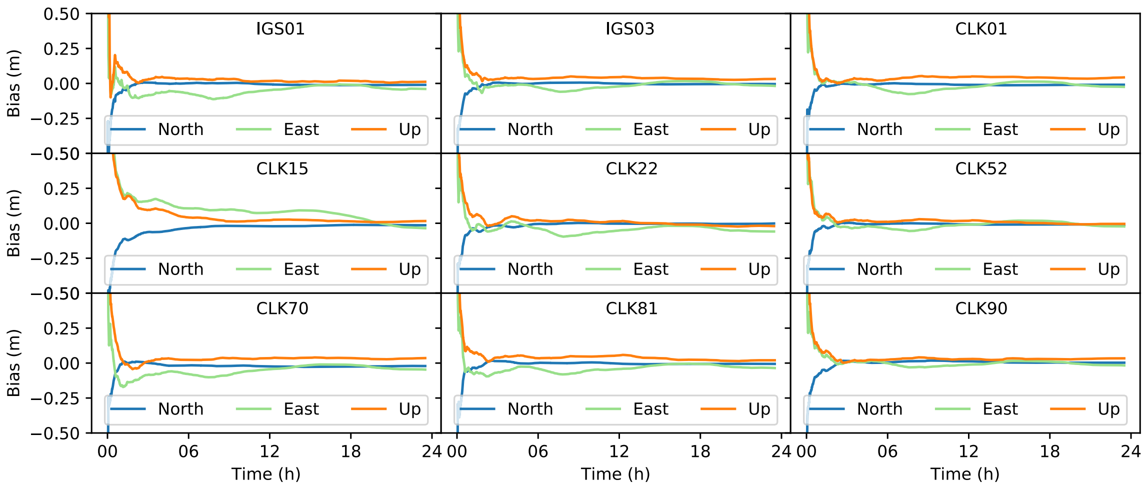

Fig. 14. Static PPP results of station AJAC.

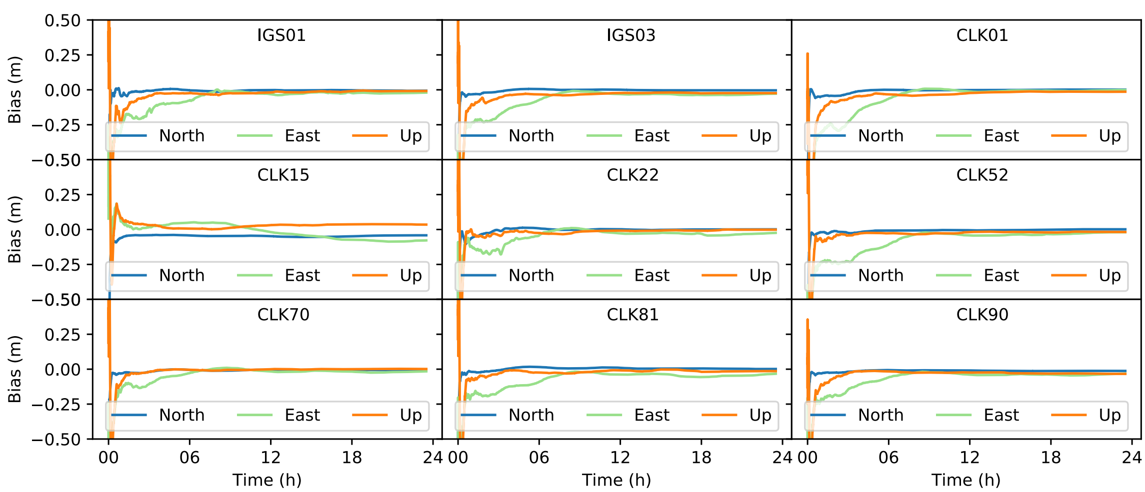

Fig. 15. Static PPP results of station CHPI.

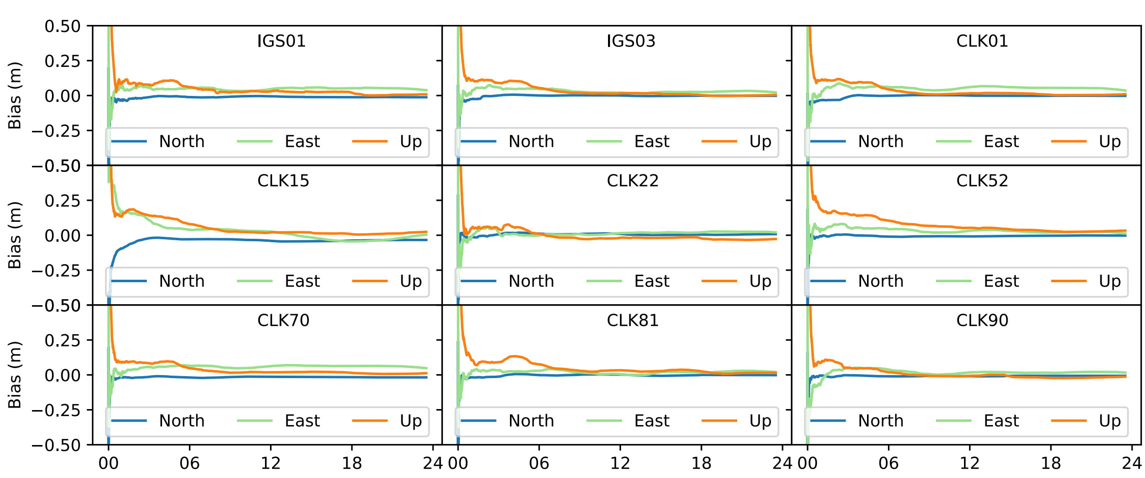

Fig. 16. Static PPP results of station GLPS.

cm and 1.1 cm in one minute for PRN01 and PRN05. The Rb clocks on board of GPS IIF satellites have the smallest degradation rate of less than 3 cm over 10 min and the Cs clocks on board of GPS IIF have the largest degradation rate of more than 10 cm over 10 min.

For daily accuracies of kinematic PPP results of 26 globally distributed IGS stations, the CLK90 has the best performance and mean RMSE in three components are 3.2 cm, 6.6 cm and 8.5 cm. And the second best positioning results are using IGS03 products. There are no signification differences in convergence time for different RTS products. However, in short observation durations experiments, CLK90 get the best accuracies with RMSE values 7 cm, 18 cm and 16 cm in three components.

For discussed above, all products have good performance on availability and accuracy. The individual RTS product CLK90 and combined product IGS03 prove to have the best quality, which are recommended for real-time PPP users.

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