Impact of Sampling Rate of IGS Satellite Clock on Precise Point Positioning

GUO Fei, ZHANG Xiaohong, LI Xingxing, CAI Shixiang
School of Geodesy and Geomatics, Wuhan University, 129 Luoyu Road, Wuhan 430079, China.

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Abstract Both static and kinematic testings are investigated by using IGS 5min, 30s and 5s-interval precise satellite clock products in precise point positioning (PPP) solution. Test results show that the sampling rate of IGS satellite clock has very little effect on the static PPP solution. All the three types of sampling intervals of precise satellite clock can satisfy mm-cm level of positioning accuracy; higher sampling rate has no significant improvement for PPP solution. However, in kinematic PPP, sampling rate of satellite clock has a significant impact on the PPP solution. The higher the interval of satellite clock, the better the accuracy achieved. The accuracy of kinematic PPP achieved by using 30s-interval precise satellite clock is improved by nearly 30-50 percent with respect to the solution by using 5min-interval precise satellite clock, but using 5s and 30s-interval satellite clock can almost produce the same accuracy of kinematic solution. Moreover, the use of precise satellite clock products from different analysis centers may also produce more or less effect on the PPP solution.

Keywords precise satellite clock error; sampling rate; precise point positioning; accuracy

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Introduction

Precise Point Positioning (PPP) has been widely applied in many fields such as precise orbit determination of LEO (Low Earth Orbit), aerial surveying, hydrographic surveying, etc. The so-called PPP is an absolute positioning method that uses a standalone receiver and one-way phase observations, taking precise correction models for all error sources into account, and adopting both precise orbit and precise satellite clock generated by IGS or other communities. Now, more and more researchers focus on PPP development, mainly concentrating on the theoretical model, algorithm and software, experimental results analysis as well as practical applications, etc.[1-7]. At present, PPP users can achieve mm-cm level of accuracy in static mode and cm-dm level of accuracy in kinematic mode.

In PPP, the orbit and satellite clock corrections are interpolated at the corresponding time of observation. The error from orbit interpolation is negligible because the orbit has very smooth behavior. Presently, the sampling rate of the IGS final orbit is 15min with a high accuracy of within 5 cm. In practice, since the sampling rate of GPS observations is higher than the precise products, interpolation is required to obtain the exact position of satellites when the signals are sent [8]. Usually, the use of polynomial interpolation or Lagrange interpolation can satisfy mm-level accu-
racy, which is far beyond the precision of precise satellite orbit itself. Conversely, the clock interpolation is critical because the satellite clock corrections lack any smooth trend. Accordingly, there is a strong demand for high rate clock correction in PPP solution. In contrast to the orbit interpolation, the satellite clock corrections interpolation may not be accurate because of the high level of irregularity. This irregularity cannot be attributed to the defect of the interpolation strategy but to the nature of clock corrections. Though the precise ephemeris formatted in SP3 also contains 15 min-interval precise satellite clock error information, the satellite clock is so irregular that we cannot get an accurate interpolation clock with 15 min-interval precise satellite clock. Consequently, 5 min and 30 s-interval precise satellite clock products have been generated in succession by IGS analysis centers. From April of 2008, CODE began to publish the 5s-interval precise satellite clock products [9], which provide us an extra selection for PPP solution. In total, there are 15 min, 5 min, 30 sec, 5 sec-interval satellite clocks available for PPP users. In this paper, the effect of the sampling rate of precise satellite clock products on PPP solution will be extensively investigated by full comparisons with the ground truth. Because the interpolation from 15 min-interval satellite clock cannot satisfy the requirement of PPP, we will not take the 15 min-interval satellite clock into consideration in the following discussion. We mainly discuss the impact of IGS satellite clock products on the accuracy of PPP with intervals of 5 min, 30 s and 5 s, respectively. Presently, only CODE provides 5s-interval precise satellite clock error products, so we choose the 5s-interval and the 30s-interval precise satellite clock error products from CODE, while the 5 min-interval precise satellite clock product is provided by IGS. In order to have comparability of the precise clock products from different analysis centers, both the IGS 30s-interval and CODE 30s-interval precise clock error products are used for comparison.

1 Precise satellite clock products and interpolation method

The precise satellite clock error is one of the products released by IGS to global GPS users. The 5 min-interval precise satellite clock error products were first released at the 1085th GPS week (October 2000). Until the 1406th GPS week (December 2006), the 30s-interval precise satellite clock error products are delivered by some IGS analysis centers such as CODE and MIT. Recently, CODE began to release 5 s-interval precise satellite clock error products from the 1478 th GPS week (May 2008). Table 1 lists the specifications of the three types of sampling rates of clock available for PPP solution [9-10].

| Product         | Interval | Accuracy | Latency       | Update       |
|-----------------|----------|----------|---------------|--------------|
| Rapid(IGR)      | 5 min    | 0.1 ns   | 17 hours      | Daily        |
| Post (IGS)      | 5 min    | 0.1 ns   | Up to 13 days | Weekly       |
| Post (IGS/CODE) | 30 s     | 0.1 ns   | Up to 13 days | Weekly       |
| Post (CODE)     | 5 s      | 0.1 ns   | Up to 13 days | Weekly       |

IGS precise clock is available at a typical rate of 5 min, 30 sec and 5 sec. Unfortunately, the observation sampling rate is higher than IGS satellite clock sampling rate in many GPS applications [11]. The sampling interval of the observation ranges from 30 s to 0.1 s, or even denser. In PPP, the interpolation is made to compute the precise satellite clock correction at observation time with the IGS satellite clock products. The commonly used interpolation methods include the linear interpolation, binomial interpolation, Lagrange interpolation and cubic spline interpolation, etc. The method adopted to get the best results totally depends on the characteristics of satellite clock behavior as well as the feature of the interpolation itself. A detailed comparison and analysis for the performance of the above mentioned interpolation methods have been investigated by Ye et al. [12]. The authors concluded that the higher the rate of the clock, the higher the accuracy of interpolation achieved. The interpolation error of 5-min clock error product can reach 0.11 to 0.38 ns, while the interpolation error using 30-s clock can reach 0.10–0.15 ns. We also do similar comparisons and draw the same conclusion that the above 4 interpolation methods are basically equivalent for short interval clock products (e.g. 30 s- interval). The precision of linear interpolation is relatively
better while Lagrange interpolation is relatively poorer. Therefore, we adopt linear interpolation to compute the precise satellite clock error correction in PPP solution.

2 Impact of precise satellite clock interval on PPP solution

2.1 Impact on static solution

We download the 30 s-interval observation data of April 27th 2008 from ALGO, an IGS tracking station with high rate observations, and then download the 5 min and 30 s-interval precise satellite clock files from IGS; meanwhile the 30 s and 5 s-interval precise satellite clock files are taken from CODE (ftp://ftp.unibe.ch/aiub/CODE/2008/). After all the necessary data are prepared, we use TriP, a PPP software developed by WUHAN University[3], to process the GPS data with different precise clock products respectively, and then find differences between solutions and known coordinates in NEU components. Results are summarized in Table 2.

| Sample interval of satellite clock | ALGO Truth-Value from PPP Solution | Position error in NEU (m) | Residual RMS (m) |
|-----------------------------------|-----------------------------------|--------------------------|-----------------|
| B(deg)                            | L(deg)                            | H(m)                     | dN | dE | dU |                      |
| 5 min/IGS                         | 45.955800042                      | ~78.07136880             | 200.9194 | ~0.020 | 0.002 | ~0.014 | 0.017 |
| 30 s/IGS                          | 45.9558000240                     | ~78.071368778            | 200.9331 | ~0.022 | 0.001 | ~0.017 | 0.007 |
| 30 s/CODE                         | 45.9558000225                     | ~78.071368793            | 200.9360 | ~0.019 | ~0.004 | ~0.019 | 0.007 |
| 5 s/CODE                          | 45.9558000251                     | ~78.071368854            | 200.9385 | ~0.019 | ~0.004 | ~0.019 | 0.007 |

From Table 2 we can conclude that the above four types of clock products produce almost the same accuracy in each component. There is no remarkable difference among the results of static PPP by adopting different sampling rates of clock products. Using the same sampling rate of precise satellite clock error products from different organizations will also generate a 2-3 mm of difference between each other. However, using higher rate of precise satellite clock error products makes a significant improvement for the precision of PPP.

In order to investigate the influence of different sampling rate of satellite clock products on PPP solution, the higher sample (1 s-interval sampling rate) of GPS observation from ALGO were processed in static PPP solution with the same strategy as above, the similar results are listed in Table 3, from which we can draw a similar conclusion as above. The static positioning error with different types of precise clock products is substantially the same. 5 min sampling rate clock is dense enough to satisfy the static PPP solution. However, the residuals RMS of 5 min sampling rate clock is much larger than that of 30 sec or 5 sec sampling rate clock even if higher sampling rate (such as 30 s, 5 s-interval) can hardly improve the PPP results. It may be explained that the interpolation error with high rate clock is smaller than that of lower rate clock, and the interpolation error keeps in random behavior, the larger interpolation error could only make the residual RMS bigger, while the position error from clock interpolation error may be averaged to be negligible in static PPP solution.

| Sampling interval of satellite clock error | ALGO Truth-Value from PPP Solution | Position error in NEU (m) | Residual RMS (m) |
|-------------------------------------------|-----------------------------------|--------------------------|-----------------|
| B(deg)                                    | L(deg)                            | H(m)                     | dN | dE | dU |                      |
| 5 min/IGS                                 | 45.9558000232                     | ~78.071368809            | 200.9348 | ~0.021 | ~0.001 | 0.015 | 0.016 |
| 30 s/IGS                                  | 45.9558000219                     | ~78.071368809            | 200.9357 | ~0.022 | ~0.001 | 0.016 | 0.006 |
| 30 s/CODE                                 | 45.9558000247                     | ~78.071368856            | 200.9377 | ~0.019 | ~0.004 | 0.018 | 0.006 |
2.2 Impact on kinematic solution

To analyze the impact of precise satellite clock error of different sampling rates on kinematic PPP solution, a straightforward method is to process the observation of the IGS tracking station (the coordinates are precisely available) epoch by epoch in kinematic mode, and then we compare the epoch-by-epoch solution with the known coordinate of the selected IGS station to calculate the position error of each epoch. Here, GPS data with 1s-interval sampling rate from ALGO is used to investigate the impact of different precise satellite clock products on kinematic PPP solution. Fig.1 illustrates the kinematic positioning error of PPP by using IGS satellite clock product with different sampling rates. The horizontal axis represents GPS time in second; the vertical axis indicates the NEU component of positioning error. Figure 1 indicates that the positioning error in the component of N and E distributes within ±0.2 m, while the positioning error in vertical component is relatively larger, distributing mostly around ±0.2 m except Fig.1(a). From the following Figures, we can see that the fluctuation amplitude of positioning error in Fig.1(d) with 5 sec clock products is smoother than the other three ones while the error curve in Fig.1(a) with 5 min clock is noisier, which means that using the 5 s sample interval precise satellite clock products provided by CODE could get the most stable results while using the 5 min precise satellite clock products provided by IGS gives the biggest noisy positioning. Finally, the solution of PPP using precise satellite clock error products of same sample interval, whether provided by CODE or IGS, brings us almost the same accuracy.

![Figure 1](image1.png)

Fig.1 Kinematic positioning error of PPP by using IGS satellite clock products of different sampling rates

Furthermore, the quantitative analysis based on statistical calculation of precision of kinematic PPP is made based on the positioning error of different sampling rates of precise satellite clock products. The
following items including the maximum, minimum, mean, standard deviation (STD), and Root Mean Square (RMS) indicators of the positioning error in NEU components are listed in Table 4.

Table 4 indicates that using 5 min precise satellite clock products generates much larger positioning error than using 30 sec and 5 sec satellite clock in kinematic PPP solution. When using 5 min precise satellite clock products in PPP, the maximum horizontal positioning error reaches around 1 m and the vertical positioning error is up to 1.5 m. The horizontal mean bias is around 2 cm, the standard deviation and RMS are about 7 cm, while the vertical mean deviation is around 7 cm, the standard deviation and RMS is up to 0.165 m and 0.181 m, respectively. When 30 or 5 s sampling rate satellite clock is used in kinematic PPP solution, the positioning error decreases significantly. The mean bias, standard deviation and RMS, especially RMS in the direction of NEU, are decreased by 30% or even more. However, the positioning error by using 30 s sample interval of precise satellite clock is at the same level as that of using 5 s sample interval of precise satellite clock in kinematic PPP; there is only a few millimeters of difference between each other. At the same time, there is almost no obvious difference of the impacts on kinematic PPP by using 30 s sample interval of satellite clock products from IGS and CODE, respectively. Precise satellite clock products with 30 s or 5 s sampling rate of satellite clock can generate higher accuracy than that of 5 min sampling rate clock.

The above kinematic test is simulated by processing the IGS static data epoch by epoch, and then compares the result with the known coordinates published by ITRF; it is not the case of real kinematic investigation. Because the data quality of the real kinematic GPS observation is possibly worse than that of static observation, it is necessary to further analyze the impact of sampling rate of satellite clock on PPP solution using real kinematic GPS data. The following test presents a kinematic experiment in which a ship-borne GPS data is taken for example. Similarly, we process the real kinematic GPS data by using IGS5min, IGS30s, CODE30s, CODE5s satellite clock products, respectively, in the PPP solution, and then compare the PPP solution with those of GSurvey double-difference solution, which can be used as ground truth as the distance between the rover and reference station is no more than 10 km. The differences between PPP solution and GSurvey double-difference solution can be considered as the positioning error of kinematic PPP, which are shown as error curves in Fig.2.

In the same way as we previously do, the quantitative analysis based on statistical calculation of precision of kinematic PPP is made based on the positioning error of different sampling rates of precise satellite clock products. The statistical accuracy is presented at the right and bottom edge of each graph. Fig.2 indicates that the precise satellite clock products with different sampling rates can satisfy the kinematic positioning accuracy at sub-dm or dm level; the precise satellite clock products with 30 s or 5 s sampling rate can produce higher positioning accumu-
cy than that of 5 min sampling rate, and especially in the directions of N and U components, the accuracy could be improved by 30-50%. Furthermore, using precise satellite clock products with 30 s or 5 s sampling rate makes no remarkable difference to the results of kinematic PPP solution.

Just as the simulated kinematic experiment reflects, there is a relatively great difference between the PPP solution by using 30 s-interval and 5 min-interval precise satellite clock products, reaching at about dm level. However, precise satellite clock product with 30s-interval and that of 5 s-interval almost produce the same accuracy. The differences caused by using different sampling rates of precise satellite clock product in kinematic PPP solution mainly depend on the interpolation precision of satellite clock correction and independent of the dynamic state of the GPS antenna.

3 Conclusions and remarks

(1) Though the variation of satellite clocks is of high frequency dithering for a long time, it varies relatively smooth in a short time scale such as the 30 s-interval. Linear interpolation or binomial interpolation is precise enough to interpolate the precise satellite clock correction at a given time, thus, it can satisfy the PPP solution.

(2) The accuracy of PPP can reach mm-cm level in static mode and cm-dm level of accuracy in kinematic mode using any of the 5 min, 30 s, or 5 s-interval precise satellite clock products. For static PPP, the precise satellite clock product at 5 min-interval is dense enough to satisfy the mm-dm level of precision. For kinematic PPP, compared with the 5 min-interval precise satellite clock product with 30 s or 5 s interval could improve the positioning accuracy by 30% or even more. There is no significant difference between the PPP solution by using 30 s or 5 s sampling rate in both kinematic and static mode.

(3) It is suggested that in practical application, the precise satellite clock product of 5 min or 30 s interval is dense enough for static PPP. As for kinematic PPP, the precise satellite clock product of 30s or 5s is required to satisfy the desired accuracy. The precise satellite clock product with higher sampling rate can improve the positioning accuracy a little. Meanwhile, we should take note that the precise satellite clock...
products from different analysis centers of IGS could result in some difference between each other.

Therefore, the latest delivered 5 s-interval satellite clock product provided by CODE hardly makes a great effect on the improvement of PPP accuracy. However, possibly the 5 s-interval precise satellite clock product could accelerate the convergence of PPP. It should be investigated further.

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