Chapter 62
GNSS Satellite Clock Real-Time Estimation and Analysis for Its Positioning

Bingbing Duan, Junping Chen, Jiexian Wang, Yize Zhang, Jungang Wang and Li Mao

Abstract Real-time and high-precision Multi-GNSS positioning technical has been playing an important role in the determination of low earth orbiter (LEO) and monitoring of geologic hazards. The key concern should be on the achievement of the high-precision satellite orbit and clock products. In this paper, real-time clock estimation strategy was introduced. Based on the mean square root filtering method, dates via 35 global uniformly distributed IGS observations were used to estimate real-time satellite clock errors of GPS and CLONASS, which was proved 0.2 ns and 0.8 ns respectively. The outcomes were verified again via precise point positioning. Consequently, compared with the positioning accuracy via only GPS, that of GPS and GLONASS improved 26 % in X direction, 40 % in Y direction and 2 % in Z direction. The convergence time shorten 2 to 4 times as well.

Keywords GPS · GLONASS · Real-time clock estimation · Combination positioning · Mean square root filtering

62.1 Instruction

Precise point positioning (PPP) of Global navigation satellite system (GNSS) can achieve centimetre-level accuracy for static positioning and decimetre-level for kinematic respectively. Its precision depends mainly on the quality of satellite orbit

B. Duan (✉) · J. Wang · Y. Zhang · J. Wang · L. Mao
College of Surveying and Geo-informatics Building, Tongji University, Shanghai, China
e-mail: 410_duanbingbing@tongji.edu.cn

J. Chen
Shanghai Astronomical Observatory, Chinese Academy of Sciences, SHAO, ShangHai, China
e-mail: junping.chen@shao.ac.cn

J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2014 Proceedings: Volume III*, Lecture Notes in Electrical Engineering 305,
DOI: 10.1007/978-3-642-54740-9_62,

and clock. At present, the precision of GPS broadcast ephemeris is 7 ns for clock error (http://igscb.jpl.nasa.gov/components/prods.html) while GLONASS is 15 ns, which is far from the requirement of precise positioning [1]. From November 5, 2000 (GPS Week 1087), International GNSS Service(IGS) began to offer ultra-rapid(IGU) services, but the predicting part is still not accurate enough (5 ns). Besides that, RTG (Real-time GIPSY) developed by JPL analysis center could estimate real-time GPS orbit and clock products based on 60 NASA global networks (http://galia.gdgps.net/igds). The precision is 1 ns and has about 4 seconds latency, but the production is secretive [2]. Natural Resources Canada(NRCan, http://www.cdgps.com) can also estimate real-time GPS clock using ultra-rapid orbit but need to be authorised [3]. Till now, almost all the real-time GPS clock products are paid and GLONASS clock products provided by CLONASS control center (MCC, ftp.glonass-iac.ru/MCC) and Shanghai Astronomical Observatory (SHAO, http://202.127.29.4/shao_gnss_ac/) could not satisfy the need of precise positioning. So, real-time clock products are needed for the real-time positioning.

62.2 Real-Time Satellite Clock Error Estimation Module

There are two main roles for clock in GNSS positioning, one is to record the emission time of satellite signal and another is to determine the transmission time between satellite and receiver antenna. For the former effect, we need the absolute time to calculate the orbit position. Thus, a precision better than 10–6 s will be enough [4]. For the latter using, it depends only on relative time and needs to choose a satellite or receiver clock as reference clock.

62.2.1 Observation Module

Ionosphere-free combination of pseudorange and carrier phase observations are used in the estimation of precise satellite clock error. It could be simplified as [5]

$$P_{IF}^{G,R} = \frac{f_1^2}{f_1^2 - f_2^2} P_1 - \frac{f_2^2}{f_1^2 - f_2^2} P_2 = \rho + c(dt_r - dt_s) + d_{trop} + \varepsilon(P_{IF}) \tag{62.1}$$

$$\begin{aligned}\Phi_{IF}^{G,R} &= \frac{f_1^2}{f_1^2 - f_2^2} \Phi_1 - \frac{f_2^2}{f_1^2 - f_2^2} \Phi_2 \\ &= \rho + c(dt_r - dt_s) + d_{trop} + \frac{c(f_1 N_1 - f_2 N_2)}{f_1^2 - f_2^2} + \varepsilon(\Phi_{IF})\end{aligned} \tag{62.2}$$

where G, R denote GPS and GLONASS respectively; $P_{IF}^{G,R}$, $\Phi_{IF}^{G,R}$ are respectively the pseudo-range and carrier phase observation; ρ is geometrical distance; c is light speed; $f_{i=1,2}$ is frequency; dt_r is receiver clock offset; dt_s is satellite clock

Table 62.1 Parameters of clock error estimation

Name	Number	Initial value
Satellite clock error	One at each epoch and each satellite	Broadcast ephemeris
Receive clock error	One at each epoch and each receive	Pseudorange point positioning
Tropospheric delay	One at each receive and each hour	Module
Site coordinate	Each station has three	Pseudorange point positioning
Ambiguity	One at each station and satellite	D-value between Pseudorange and carrier phase observations

offset; d_{trop} is tropospheric delay; N_1, N_2 is the ambiguity of observations; $\varepsilon(P_{IF})$ and $\varepsilon(\Phi_{IF})$ are residuals.

In Eq. (62.2), clock parameter and ambiguity parameter are related and can not be estimated directly, but we can get satellite clock error through pseudorange equation. However, it could not be precise enough due to the precision of pseudorange observation. So, different weight should be given to the two kinds observations.

62.2.2 Error Correction and Pre-processing

Some errors need to be corrected in the precise point positioning. We eliminate the ionosphere error using ionosphere-free combination; For troposphere correction, we calculate an initial value at the Zenith direction using Saastmoinen module and regard the residual error as parameter in the normal equation; Using GMF (Global mapping function) as Mapping function [6]; For Antenna phase center correction, we use absolute phase center correcting module [7]; Then, Solid tide, pole tide, ocean tide and relativity effect, this paper refers to the International Earth Rotation Service (IERS); finally, wind up correction, We refer to the IGS standard module [8].

In the pre-processing we will come across ms jump correction, cycle slip and the estimation of initial value. For some GPS receivers, the time scale will drift due to the unstable of frequency. In order to keep the consistency of observations and time scale, we have to modulate the time scale of the receiver. Then, in order to detect whether there is any ms jump, we compare the D-value of pseudorange and carrier phase observations between epochs. Besides, we use LW and LG combination to detect cycle slips and use Bancroft method to estimate initial value based on pseudorange observations. The calculation parameters are shown in Table 62.1.

62.2.3 Method of Parameter Estimation

Least square estimation and kalman filtering theory are the most common methods for GNSS parameter estimation and the latter is more suitable for kinematic positioning. However, researches have shown that the Kalman filter algorithm is sensitive to computer roundoff and that numeric accuracy sometimes degrades to the point where the results cease to be meaningful. we put the mean-root-square filtering method into GNSS parameter estimation and find out that it is more elegant in parameter estimation.

Recall the least square performance functional from document [5].

$$J(x) = \|A_i \delta x - l_i\|_2 = \min \tag{62.3}$$

Let H be an orthogonal matrix. Because of the property of orthogonal matrix, we can write

$$J(x) = \|HA_i \delta x - Hl_i\|_2 = \min \tag{62.4}$$

In fact, $J(x)$ is independent of H and this can be exploited. We shall show how H can be chosen using Household transformation in bibliography [9].

For an arbitrary matrix $A \in R^{m \times n} (m \geq n)$, there exists an orthogonal transformation $H \in R^{m \times m}$ such that

$$HA = \begin{bmatrix} s & \vdots & \\ & \vdots & \tilde{A} \\ 0 & \vdots & \end{bmatrix} \tag{62.5}$$

where s and $\tilde{A}$ are computed directly from A, and the matrix H is only implicit, computer mechanization requires no additional computer storage other than that used for A. We use the properties of the elementary Household transformation H that

$$Hl_i = l_i - \gamma \bar{u} \qquad \gamma = (l_i^T \bar{u})\bar{u} + v \tag{62.6}$$

where $\bar{u}$ is a unit vector of u, and u is the normal to the reference plane. v is that part of l_i that is orthogonal to u.This formula shows that storage of the matrix H is not necessary. So formula (62.4) can write

$$J(x) \left\| \begin{bmatrix} R \\ 0 \end{bmatrix} \delta x - \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \right\|_2 = \min \tag{62.7}$$

where $R \in R^{n \times n}$, is an upper triangular matrix, $Hl_i = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}$, $z_1 \in R^n$, $z_2 \in R^{m-n}$.

By reducing the least square performance functional to the form (62.5), we can see that the minimizing δx must satisfy

$$R\delta x - z_1 = 0 \tag{62.8}$$

These results are more elegant than is the brute force construction via the normal equation. More importantly, the solution using orthogonal transformation is less susceptible to errors due to computer roundoff.

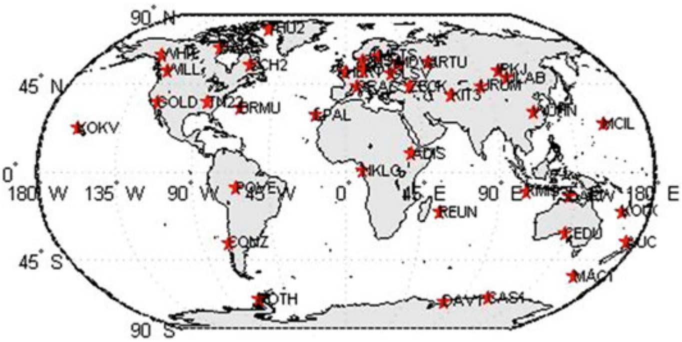

Fig. 62.1 Distribution of IGS station

62.3 Analysis of Examples

In the calculation, 35 global uniformly distributed IGS stations are used (Fig. 62.1) at 300 day, 2012. We fix the station coordinates refer to the snx file, use ultra-rapid orbit. The sampling interval is 30 s and satellite cutoff is 7°. All the calculation is based on the LTW_BS software that developed by SHAO.

We choose a atomic clock as reference clock in the estimation. So, when evaluate the precision of estimated clock error we have to compare the D-value of one reference satellite to others.

Figure 62.2 is a comparison of GPS clock estimation between single and multi-system, which shows that RMS of GPS clock could be 0.2 ns and the result are almost the same for the two situations. Figure 62.3 is the estimation of GLONASS clock error, which could easily find that RMS of GPS clock could be 0.8 ns and satellite R10, R11, R12 own a bad precision because of the their observations.

62.4 Real-Time Precise Point Positioning

In order to certify the reliability of the estimated satellite clock, we put the result together with orbit product from IGU into real-time precise point positioning.

Figures 62.4 and 62.5 depend on single system's estimated clock and multi-system estimated clock respectively, we can find that there is no obvious difference. Figure 62.6 is the result of combination of GPS and GLONASS, which denotes that the convergence time decreases a lot.

Table 62.2 is the result of 10 stations for real-time positioning, where we can find that result from GPS + GLONASS combination improved 26 % in X, 40 % in Y and 2 % in Z compared to that from single GPS system, and convergence time shorten 2 to 4 times.

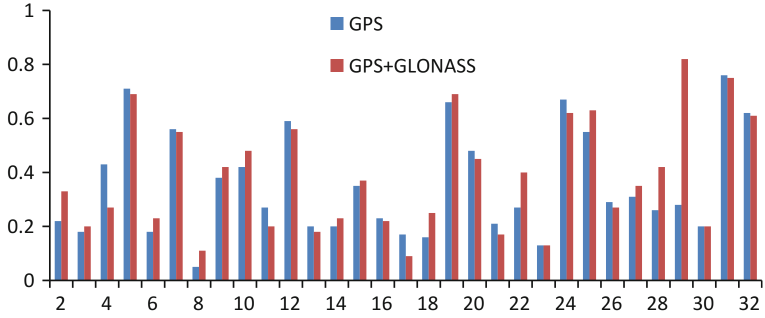

Fig. 62.2 Comparison of GPS clock estimation between single and multi-system RMS (ns)

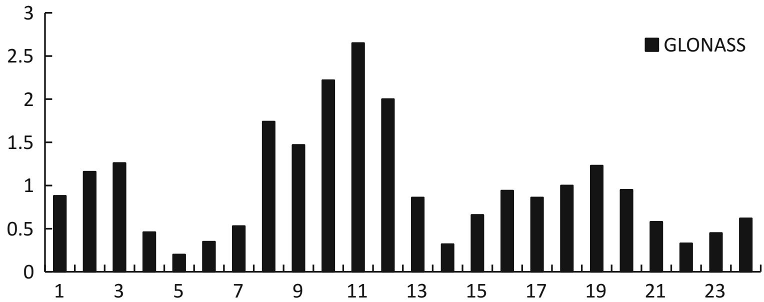

Fig. 62.3 Result of GLONASS clock estimated by multi-system

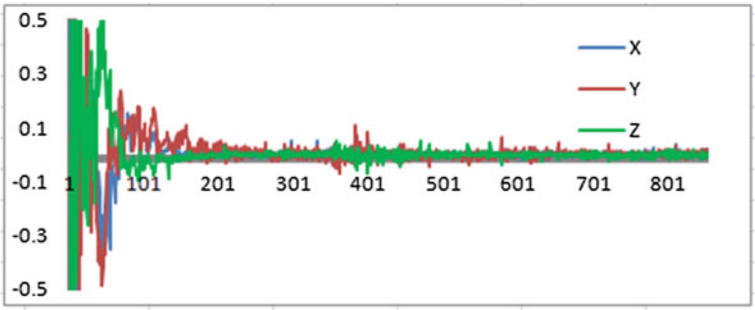

Fig. 62.4 GPS positioning based on single system's clock (m)

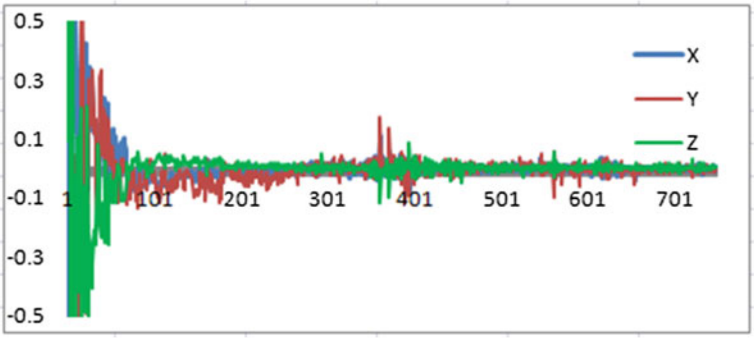

Fig. 62.5 GPS positioning based on multi-system's clock (m)

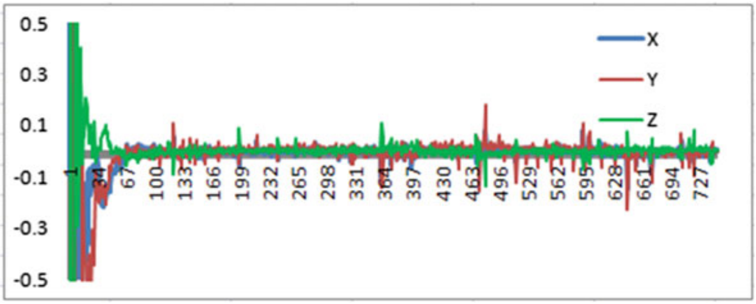

Fig. 62.6 GPS + GLONASS positioning based on multi-system's clock (m)

Table 62.2 Real-time kinematic positioning

站名	GPS (RMS)			GPS + GLONASS (RMS)			收敛至 0.1 m 时间(历元)	
	X	Y	Z	X	Y	Z	GPS	GPS + GLONASS
GOLD	0.043	0.046	0.040	0.017	0.024	0.017	120	33
GRAS	0.019	0.019	0.010	0.013	0.007	0.014	32	20
IRKJ	0.017	0.010	0.010	0.007	0.010	0.014	83	35
JPLM	0.025	0.043	0.024	0.015	0.019	0.014	55	36
KIT3	0.023	0.016	0.017	0.015	0.016	0.018	64	28
KOKV	0.017	0.041	0.009	0.025	0.023	0.017	48	29
KOSG	0.018	0.054	0.023	0.013	0.006	0.014	91	36
XMIS	0.011	0.012	0.016	0.009	0.008	0.011	78	38
THU2	0.010	0.009	0.018	0.009	0.006	0.021	103	32

62.5 Conclusion

This paper elaborates the observation modules, error correction modules, preprocessing and parameter estimation of GNSS clock estimation. First, do some experiment in the estimation of GPS and GLONASS clock error based on single and multi-system, and find that clock from single system and multi-system is almost the same in precision. Then, put the estimated clock products into real-time precise point positioning and conclude that result from GPS + GLONASS combination improve 26 % in X, 40 % in Y and 2 % in Z compared to that from single GPS system. Besides, the convergence time shorten 2 to 4 times.

Acknowledgements This paper is supported by the 100 Talents Programme of The Chinese Academy of Sciences, the National High Technology Research and Development Program of China (Grant No. 2013AA122402), the National Natural Science Foundation of China (NSFC) (Grant No. 11273046 and 40974018), the Shanghai Committee of Science and Technology(Grant Nos. 12DZ2273300,13PJ1409900) and National Natural Science Foundation of China (NSFC) (Grant NO. 41174023).

References

1. Guo J, Meng X, Li Z (2011) Accuracy analysis of GLONASS satellites broadcast ephemeris. J Geodesy Geodyn 31(1):12–16
2. Dach R, Hugentobler U et al (2007) Bernese GPS software version 5.0. Astronomical Institute, University of Bern, Bern, Switzerland
3. Dettmerring (2006) Real-Time GNSS-Policy Aspects[R].BKG, Frankfurt, Germany
4. Yidong Lou (2008) Research on real-time precise GPS orbit and clock offset determination. WuHan University, WuHan
5. Jiexian Wang (1997) GPS precise orbit determination and positioning. Tongji University Press, Shanghai
6. Boehm J, Niell AE, Tregoning P et al (2006) The global mapping function (GMF): a new empirical mapping function based on data from numerical weather model data. Geophys Res Lett 33(4):13–15
7. Dow JM, Neilan RE et al (2007) Galileo and the IGS:taking advantage of multiple GNSS constellations. Adv Space Res 39(10):1545–1549
8. Wu JT, Wu SC, Hajj GA et al (1993) Effects of antenna orientation on GPS carrier phase. Manuscripta Geod 18:91–93
9. Boehm J, Niell AE, Tregoning P, et al (2006b). The Global Mapping Function (GMF): a new empirical mapping function based on data from numerical weather model data. Geophys Res Lett 33(4):48–52