Precise Orbit and Clock Offset Determination of LEO Navigation Satellites Based on Multi-constellation and Multi-frequency Spaceborne GNSS Data

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Abstract. With massive low earth orbit (LEO) satellites, LEO navigation enhancement system is important to improve the service performance of GNSS system. The high precision orbit and clock offset calculation of LEO satellites is one key to establish the stable and reliable space-time reference. Based on GPS/BDS/GALILEO data measured by LEO navigation satellites, this paper determines the precise LEO orbit and clock offset, and evaluates the precision of LEO orbit and clock offset solution. The orbit determination accuracy using GPS (L1/L2), GPS (L1/L5), BDS (B1C/B2a), and GALILEO (E1/E5a) combination is 2.42, 2.93, 2.67, and 2.87 cm, respectively. The clock offset solution accuracy using the above four combination is 0.167, 0.194, 0.186, and 0.180 ns, respectively. These results can provide high-quality product for navigation enhancement system services.

Keywords: LEO navigation enhancement · Multi-constellation · Orbit · Clock offset

1 Introduction

Global Navigation Satellite System (GNSS) can provide all-day, high-precision positioning, navigation and time (PNT) service, and has become an important infrastructure to safeguard national information security and promote economic development [1]. The GNSS systems represented by GPS/BDS/GALILEO not only keep the stable maintenance, but also improve the service performance through satellite-based, ground-based and other enhancement means. Because of its unique advantages in shortening the precision positioning convergence time and improving the positioning accuracy, LEO navigation enhancement system has become the potential choice to further enhance the GNSS system's service capability [2].

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The precise orbit and clock offset products of LEO satellites provide important space and time benchmarks for LEO navigation enhancement, and their solution accuracy is an prerequisite to ensure their tasks. Many LEO satellites, such as GRACE [3], CHAMP [4], SWARM [5], Fengyun [6] and Haiyang [7], have been launched into orbit continuously. Many achievements have been made in the aspects of perturbation refinement and measurement error modelling related to satellite orbit determination. With the continuous maturity of GPS, BDS, GALILEO and other satellite systems, it is possible to use multi-system data for LEO satellite precise orbit determination (POD). Li et al. [6] analyzed the data quality of onboard GPS and BDS data of FY3C satellite, and carried out POD based on the data of two navigation systems. After disabling BDS GEO data, the orbit accuracy was further improved. Based on the BDS data of Luojia-1 satellite, the final solution accuracy can reach 2 cm by adjusting the weight of GEO satellite data [8]. The POD accuracy using GPS, BDS and GPS/BDS satellites is discussed by using the measured data of Tianping satellite, and the orbit determination accuracy is evaluated by means of overlapping arcs and satellite laser range (SLR) check [9]. Using GPS/GALILEO data of Sentinel-6A satellite, the orbit calculation of single system and multi-systems is realized [10]. Yang [11] discussed the accuracy of LEO satellite clock difference solution based on simulation data, which can be better than 1 ns. Zhang [12] made an in-depth analysis of LEO satellite real-time calculation, prediction and other aspects, and studied the performance of different types of clocks.

Based on the measured GNSS data of LEO navigation satellite, this paper analyzes the influence of antenna phase center deviation (PCO), different code bias (DCB) correction on the orbit accuracy, and discusses the orbit determination accuracy using single system, multi-system processing strategies. LEO satellite clock offset is also an important product of LEO navigation enhancement system. This paper also discusses the accuracy and characteristics of LEO satellite clock offset calculation. Finally, the relevant conclusions are carefully given.

2 Data Source and Calculation Principle

The test data in this paper are from Tianshu-1 (abbreviated as TS01) of Insight Position Digital Intelligence Technology Service Co., Ltd. and one test satellite of a Chinese LEO enhancement system (abbreviated as SH01). The TS01 satellite was launched in October 2021, with an orbital height of about 520 km and an orbital inclination of 97.5°. It can receive L1 and L5 data from GPS satellites and transmit navigation signals to the ground. The SH01 satellite was launched in August 2021, with an orbital height of about 1100 km and an orbital inclination of 86.4°. It mainly verifies the LEO navigation enhancement and communication functions. The SH01 satellite can receive GPS (L1/L2/L5), BDS (B1C/B2a), GALILEO (E1/E5a) data, and broadcast navigation signals.

The LEO satellite POD software used in this paper is SHAOOD (Shanghai Astronomical Observatory Orbit Determination) developed by Shanghai Astronomical Observatory, Chinese Academy of Sciences, and its accuracy can reach 2 ~ 3 cm [13]. The date of TS01 satellite test data in this paper is December 2021, and SH01 is February 2022. The GNSS product is the precise product of Wuhan University (WUM). More detailed processing strategies are given in Table 1.

Table 1. Precision orbit and clock offset determination strategy of LEO satellite

Model	Description
Measurement model	
Observation	Non-differentiated ionosphere-free linear combination
Arc length and interval	12 h, 10 s
Weighting strategy	PC (a priori sigma of 1 m), LC (a priori sigma of 1 cm)
GPS products	WUM final products
Elevation cut-off angle	5°
GNSS PCO	igs14.atx
LEO PCO	Discussed
Dynamic model	
Earth gravity	EIGEN_GL04C, 120 × 120
N-body	JPL DE405
Relativity	IERS 2010
Solid earth tide and pole tide	IERS 2010
Ocean tides	FES 2004 (30 × 30)
Solar radiation pressure	Cannonball model
Atmospheric drag	NRLMSISE-00
Empirical forces	Piecewise periodical estimation of the sin and cos coefficients in the track and normal directions
Estimated parameters	
LEO initial state	Position and velocity at the initial state
Receiver clock	Epoch-wise estimated
Ambiguities	Floated solution
Solar coefficients	One per 3 h
Drag coefficients	One per 3 h
Empirical coefficients	One per 3 h

3 Precision Orbit Determination Analysis

3.1 PCO Estimation

Accurate phase center of LEO satellite antenna is an important prerequisite for POD. Although a group of PCO values need to be calibrated before the satellite is launched, the real PCO deviates from the ground calibration values due to mass changes, environmental anomalies, and other reasons. Therefore, the PCO estimation is one of the important links of LEO satellite POD. Since it is necessary to apply empirical force in the T and N directions to compensate the force that has not been modeled, the related PCO components in the X and Y directions are often estimated incorrectly [13], so this paper only estimates the PCO in the Z direction. Here, both ground calibration and on-orbit estimation values are used for POD to analyze the influence of PCO on orbit determination accuracy.

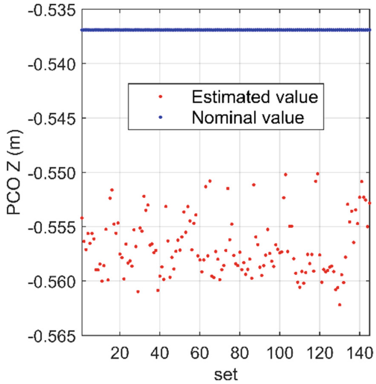


Fig. 1. Estimation results of SH01 satellite PCO-Z (GPS: L1/L2)

Figure 1 shows the estimation of PCO-Z component of SH01 satellite. Compared with the ground calibration value, PCO-Z has changed about 2 cm after the satellite entered orbit. Similarly, the PCO-Z of TS01 satellite changed from −0.2936 m (the nominal PCO) to −0.2742 m (the estimation PCO). Without correction, this PCO error will be obviously reflected in the orbit determination results, especially the phase residuals. The root mean square (RMS) of SH01 satellite POD phase residuals using the ground nominal values is 11.03 mm, while the RMS using the estimated PCO values is 10.63 mm. The RMS of TS01 satellite POD phase residuals using nominal and estimated PCO values is 10.33 mm and 8.47 mm, respectively. Solar storms, fuel changes, orbital maneuvers and other special circumstances may lead to abnormal jumps of PCO [7]. Therefore, it is of great significance to strengthen the on-orbit monitoring of PCO to ensure the satellite orbit accuracy.

3.2 DCB Correction

For the purpose of improving system service performance and meeting various user needs, GPS/BDS/GALILEO and other navigation systems gradually broadcast navigation signals of various frequencies. The POD of LEO satellite using navigation data of multiple frequency combinations has become a new processing method. However, the GNSS clock offset products provided by GNSS analysis centers often use fixed frequency pseudo range data as the benchmark, such as L1/L2 combination for GPS, B1I/B3I for BDS, and E1/E5a combination for GALILEO. Therefore, it is necessary to consider the pseudo range reference deviation between navigation data and satellite clock difference. The DCB correction product used in this paper is from the Aerospace Information Research Institute, Chinese Academy of Sciences [14].

Figure 2 shows the impact of DCB on SH01 satellite orbit determination residuals. The RMS of SH01 satellite pseudo range residuals without and with DCB correction are

2.83 m and 1.00 m respectively, while the RMS of TS01 satellite pseudo range residuals without and with DCB correction are 3.54 m and 0.66 m, respectively. Obviously, ignoring the DCB correction will have a significant impact on POD.

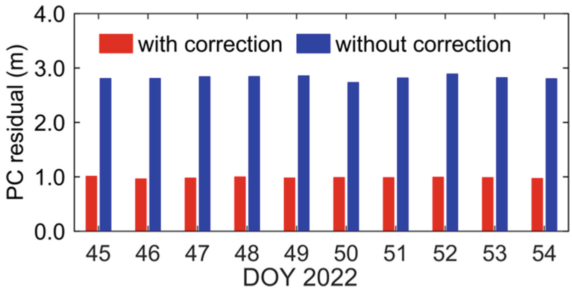


Fig. 2. Effect of DCB correction on SH01 orbit determination accuracy

3.3 Orbit Accuracy

This paper mainly analyzes the orbit determination accuracy using multi-system and multi-frequency navigation data, and TS01 satellite can only receive GPS L1/L5 data. As a result, SH01 satellite is selected as the analysis object in this section and Sect. 4. Due to the lack of external precision orbit and SLR data, overlap arc comparison (10 h) are used to evaluate the orbit quality.

Figure 3 shows the overlapping orbit accuracy of SH01 satellite using GPS (L1/L2), GPS (L1/L5), BDS (B1C/B2a), GAL (E1/E5a) data, and Table 2 shows the POD accuracy of single- and multi-systems. First, the orbit determination accuracy of both single- and multi-system solutions is better than 3 cm, which shows the processing strategy and orbit determination results in this paper are reliable. Second, compared with the single system results, the multi-system orbit determination strategy has more observation data, which increases the reliability of parameter estimation. Therefore, the accuracy of multi-system orbit determination results is generally higher. The orbit determination accuracy of GPS (L1/L2)/BDS, GPS (L1/L2)/GAL, BDS/GAL, GPS/BDS/GAL is 2.28 cm, 2.30 cm, 2.36 cm, and 2.21 cm, respectively. However, it must be noted that the adoption of multi-system data also has more observation data and parameters to be estimated, which will increase the calculation pressure in POD.

4 Precision Clock Determination Analysis

When using GPS/BDS/GALILEO data for POD, inter system bias (ISB) of different navigation systems must be considered [15]. Generally, we have two methods to handle ISB parameter. First, one system can be selected as the reference system, and an ISB parameter to be estimated can be added when other system data is used. The other way is that the LEO clock offset calculated by different navigation systems can be estimated separately. The second method is adopted in this paper. Figure 4a shows the SH01 clock

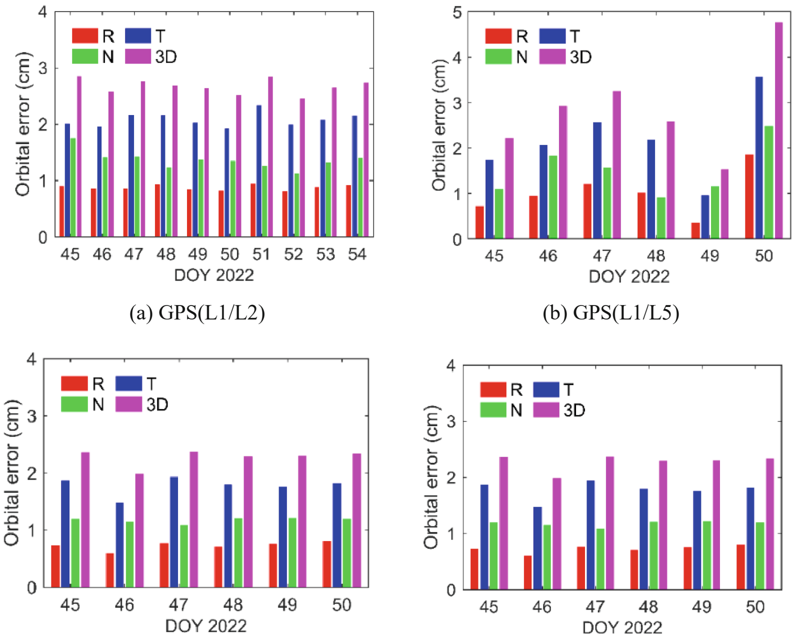
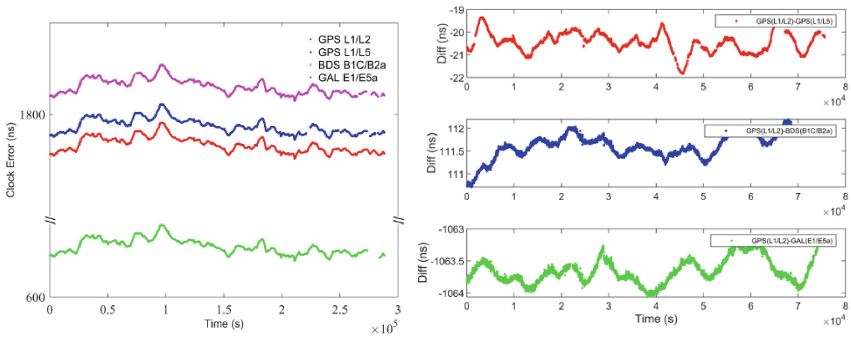


Fig. 3. Overlapping orbit comparison results of SH01 Satellite

Table 2 POD Results of SH01 Satellite using single and multi-system

Data	R/cm	T/cm	N/cm	3D/cm
GPS(L1/L2)	0.80	1.86	1.27	2.42
GPS(L1/L5)	1.00	2.18	1.62	2.93
BDS(B1C/B2a)	0.88	2.08	1.37	2.67
GAL(E1/E5a)	1.02	2.18	1.51	2.87
GPS(L1/L2)/BDS	0.73	1.78	1.18	2.28
GPS(L1/L2)/GAL	0.75	1.75	1.23	2.30
BDS/GAL	0.78	1.83	1.22	2.36
GPS/BDS/GAL	0.71	1.71	1.18	2.21

offset calculated in one day using GPS (L1/L2), GPS (L1/L5), BDS (B1C/B2a), GAL (E1/E5a) combinations. The LEO clock offset calculated by each combination has a relatively stable consistency. However, it can be seen from Fig. 4b that the difference between SH01 satellite clock offset calculated by different combination data is not very stable, even up to 1–2 ns, and shows a certain period. This may be due to the simultaneous calculation of satellite orbit and satellite clock offset, resulting in the difference between SH01 satellite clock offset related to the orbital period. This phenomenon is also found in Sentinel-6A [10].



(a) SH01 clock offset (b) The difference of SH01 clock offset

Fig. 4. Results of SH01 satellite clock offset of SH01 satellite calculated by different navigation systems data

Due to the lack of external stable and accurate LEO satellite clock offset, overlapping clock offset comparison strategy is adopted when evaluating SH01 satellite clock offset accuracy. Figure 5 shows the clock offset overlapping accuracy of LEO satellite calculated with GPS (L1/L2), GPS (L1/L5), BDS (B1C/B2a), GALILEO (E1/E5a) data. The RMS are 0.167, 0.194, 0.186 and 0.180 ns, respectively. The calculation accuracy of each day is relatively stable, which can provide precise clock offset products for LEO navigation enhancement system.

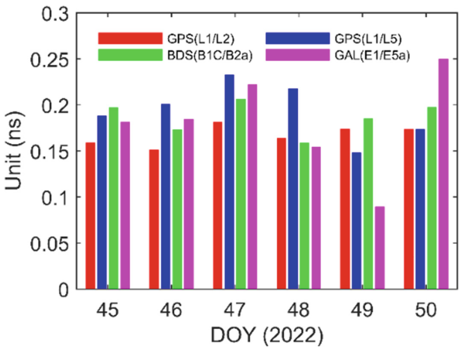


Fig. 5. Calculation accuracy of SH01 clock offset

5 Conclusion

In this paper, the accuracy of orbit determination using single and multi-system data is further improved by estimating the PCO value and applying DCB correction. The clock offset calculated based on different GNSS data has obvious inter system deviation, and presents a certain periodic term. Using multi frequency and multi-system data for precise orbit and clock offset calculation not only expands the understanding of fusion LEO satellite data processing theories and methods, but also ensures that the LEO augmentation system can provide stable and reliable PNT services.

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References

1. Yang Y, Mao Y, Sun B (2020) Basic performance and future developments of BeiDou global navigation satellite system. Satell Navig 1(1):1–8
2. Hein GW (2020) Status, perspectives and trends of satellite navigation. Satell Navig 1(1):1–12. https://doi.org/10.1186/s43020-020-00023-x
3. Kang Z, Nagel P, Pastor R (2003) Precise orbit determination for GRACE. Adv Space Res 31(8):1875–1881
4. Montenbruck O, Kroes R (2003) In-flight performance analysis of the CHAMP BlackJack GPS receiver. GPS Solut 7(2):74–86
5. Oliver M, Stefan H, Jose V et al (2018) Reduced dynamic and kinematic precise orbit determination for the Swarm mission from 4 years of GPS tracking. GPS Solut 22(3):79
6. Li W, Li M, Zhao Q et al (2018) FY3C satellite onboard BDS and GPS data quality evaluation and precise orbit determination. Acta Geod Cartogr Sin 47(S0):9–17
7. Guo J, Zhao Q, Xiang G et al (2015) Quality assessment of onboard GPS receiver and its combination with DORIS and SLR for Haiyang 2A precise orbit determination. Sci China Earth Sci 58(1):138–150
8. Wang L, Xu B, Fu W et al (2020) Centimeter-level precise orbit determination for the Luojia-1A satellite using BeiDou observations. Remote Sens 12(12):2063
9. Zhao X, Zhou S, Ci Y et al (2020) High-precision orbit determination for a LEO nanosatellite using BDS-3. GPS Solut 24(4):102
10. Montenbruck O, Hackel S, Wermuth M et al (2021) Sentinel-6A precise orbit determination using a combined GPS/Galileo receiver. J Geodesy 95(9):109
11. Yang Z, Liu H, Qian C et al (2020) Real-time estimation of Low Earth orbit (LEO) satellite clock based on ground tracking stations. Remote Sens 12(12):2050
12. Zhang HC (2021) Method and application of real-time clock bias estimation for LEO-based navigation augmentation GNSS receiver (in Chinese). Wuhan University
13. Yuan J, Zhou S, Hu X et al (2021) Impact of attitude model, phase wind-up and phase center variation on precise orbit and clock offset determination of GRACE-FO and CentiSpace-1. Remote Sens 13:2636
14. Wang N., Yuan Y, Li Z, Montenbruck O, Tan B (2015) Determination of differential code biases with multi-GNSS observations. J Geodesy 90(3): 209–228
15. Mowafy A, Deo M, Rizos C (2016) On biases in precise point positioning with multi-constellation and multi-frequency GNSS data. Meas Sci Technol 27(3):035102