Analysis of positioning deviation between Beidou and GPS based on National Reference Stations in China

Ming Chen[1], Qinglan Zhang[1,2]

[1] National Geomatics Center of China, Beijing, China - (cm,qinglanzhang)@ngcc.cn
[2] GNSS Center, Wuhan University, Wuhan, China

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ABSTRACT:

In order to probe into the characteristics of positioning deviation between Beidou Navigation Satellite System (Beidou) and global positioning system (GPS), and investigate possible contribution of Beidou data to refinement of global coordinate system, refined calculation is made on observation data of 240 national reference stations that are distributed uniformly across China on the whole in this study. These stations support satellite signals of four global navigation satellite systems, including Beidou, GPS, GLONASS and Galileo, and a 5-year time span from 2016 to 2020 is adopted. In this study, PPP is calculated based on GPS data and Beidou single system data in no-difference resolution network mode, and accurate coordinates of national reference stations in two processing modes are obtained. Analysis of difference between the calculations based on Beidou data and on GPS data shows that the consistency between Beidou and GPS positioning results reaches about 5mm in the east and in the north, and about 1.3cm in the height direction.

1. INTRODUCTION

In recent years, global navigation satellite system (GNSS) has developed rapidly. There are four GNSS including US GPS, the Chinese Beidou, the Russian GLONASS and the European Galileo system. Among them, Beidou satellite navigation system has adopted a "three-step" approach to construction, from active to passive and from regional to global. On December 28, 2012, the construction of Beidou-2 system was completed. On July 31, 2020, Beidou-3 system will be officially opened, marking the successful completion of the three-step development strategy of Beidou and a new era of global service.

Constructing a Beidou coordinate frame is prerequisite for precision orbit determination and positioning as well as efficient application of Beidou. Its main purposes are to define coordinate system of the Beidou Satellite Navigation System, research the theories and methods of implementing and maintaining coordinate system in peacetime and wartime, provide solutions to refinement of geocentric coordinates of ground monitoring station of China's global satellite navigation system, determine the conversion relation between China's independent coordinate system and geodetic coordinate systems such as international terrestrial reference frame (ITRF) (Altamimi Z et al.,2011,2016), WGS84, PZ-90, GTRF and so much more and estimate conversion accuracy, to address the needs of navigation, positioning and orbit determination of the Beidou Navigation Satellite System.

Regarding construction and maintenance of Beidou coordinate frame, Chen et al.,(2008) proposed China Geodetic Coordinate System 2000(CGCS2000) and corresponding frame construction method; Liu et al.(2009) considered about updating national geocentric dynamic coordinate frame by constructing national continuously operating reference station (CORS); Wei et al.(2013) proposed to adopt “Beidou coordinate system” for Beidou Navigation Satellite System and gave the definition; Zou(2011) simulated the construction and maintenance of Beidou coordinate frame with data from IGS tracking stations and from some Beidou tracking stations at that time, providing a reference for construction of real Beidou coordinate frame; Wei et al.(2014) preliminarily realized Beidou frame by virtue of GPS data and short-term dual-mode station data, and figured out the speed of 0.3mm/yr in horizontal direction, and 0.9mm/yr in perpendicular direction ; Zeng et al.(2015) discussed construction, connection and data processing of Beidou reference station, and offered some proposals. Shi et al (2017) solely utilized Beidou data to obtain station residual plane repeatability and height repeatability prior to 0.8cm and 1.7cm respectively. The construction and maintenance of Beidou coordinate frame require long-time data accumulation. Beidou data of more than five years can be obtained at present, which lays a foundation for calculating out a long-time reliable and accurate Beidou coordinate frame. It is worth mentioning that since the long-time Beidou data of China's national reference stations is mainly obtained from Beidou-2 and rarely from Beidou-3, the analysis of positioning error of Beidou and GPS in this study is mainly based on Beidou-2 data.

In the implementation of the Beidou coordinate framework, the observation data of the national reference station supporting the Beidou and GPS dual systems are used, and the GPS and Beidou observation data are used for data processing respectively. The GPS data of IGS station and national reference station are used for precise network solution to obtain the geocentric coordinates of the reference station under ITRF framework, which can be used as the initial implementation of Beidou coordinate framework based on GPS technology.The data processing based on Beidou data can take the coordinates and speed under ITRF framework as constraints, and get the initial implementation of Beidou coordinate framework based on Beidou technology. In this way, the obtained Beidou coordinate framework can meet the high precision of ITRF framework at the same time, and also maintain internal consistency.

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One important task of constructing Beidou coordinate frame is to analyze Beidou positioning accuracy and the difference from GPS positioning error. Shi et al.(2012) systematically analyzed Beidou positioning accuracy and figured out centimeter-level static PPP accuracy, centimeter-level relative positioning accuracy and RTK positioning accuracy as good as 5-10cm; Gao et al.(2012) researched unification of Beidou and GPS spatio-temporal systems and realized Beidou/GPS data integration and joint positioning; Yang et al.(2014) evaluated the performance of Beidou Navigation Satellite System in basic navigation and positioning, and concluded that Beidou is comparable to GPS in respect of pseudo distance and carrier phase measurement accuracy but is still far inferior to GPS concerning single-frequency pseudo distance differential positioning due to multi-path and big error of Beidou GEO satellite pseudo distance; Wang et al.(2014) conducted contrastive analysis of precise point positioning accuracy between Beidou and GPS, and figured out Beidou PPP accuracy of 1-2cm in horizontal direction and 3-4cm in perpendicular direction. Liu et al.(2020) compared the CGCS2000 coordinates calculated from Beidou data of city-class reference stations with the coordinates calculated from GPS data, and obtained RMS values in plane and height direction of 3.1 and 4.2mm respectively.

In order to probe into the characteristics of positioning deviation between Beidou and GPS, and investigate possible contribution of Beidou data to refinement of global coordinate system, in this paper, the observation data of 240 national reference stations in China are calculated accurately, and the differences between the two positioning results are analyzed.

2. MATERIALS AND METHODS

2.1 Data Resources

In 2016, China's national department of surveying, mapping and geographic information completed construction of 240 national satellite navigation and positioning reference stations uniformly distributed across the country, set up a national data center, built a data exchange and sharing platform for reference stations across the country, established 31 data transmission backbone networks between the national data center and provincial data centers, and developed a national satellite navigation and positioning reference service system, which provides a unified authoritative national coordinate frame for domestic satellite navigation and positioning service, and can realize rapid real-time high precision navigation and positioning service at meter level and decimeter level as well as national-local and inter-industry data exchange and resource sharing. The distribution of Chinese national GNSS reference stations is as below:

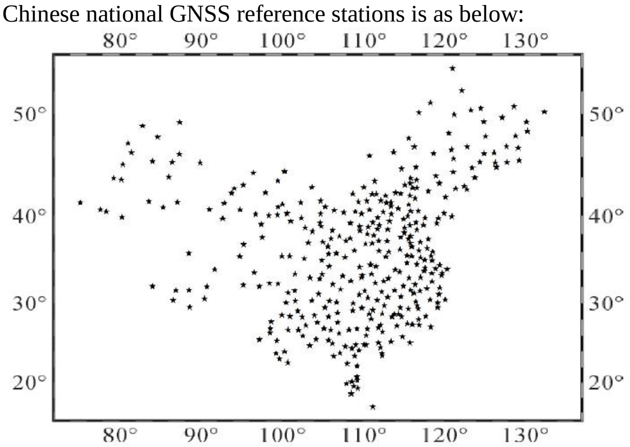

Figure 1. The distribution of Chinese national GNSS reference stations (This figure is a schematic diagram of the topic and does not involve national territory information)

The national GNSS reference stations run via unattended full-automatic operation of high reliability under guard, incessantly trace and observe satellite signal data around the clock, realize real-time data transmission to data centers via dedicated data transmission networks, and have the functions of data collection from multiple satellite systems, integrity monitoring, reliability analysis and satellite orbit determination. National GNSS reference stations are capable of incessantly collecting data from multiple satellite navigation systems, including Beidou, GPS, GLONASS and Galileo, and providing data services of various satellite ephemeris and clock biases at different grades, which are a key infrastructure supporting the multifunctional navigation application service system. The national GNSS reference stations are uniformly distributed across the country on the whole. Specifically, the distribution in the east is relatively dense at the consideration of current development situation in the east, and in the west is relatively sparse (Chen Ming et al., 2016). Basic information of Chinese national GNSS reference stations is as below:

Content	Indicator	Remark
Coverage	Nationwide	Can be extended to greater coasting area
Number of stations	410	
Shortest edge	41km	Xuzhou to Suzhou
Longest edge	1160km	Mount Qomolangma to Luopu
Mean station distance	200km	
Data transmission network	10Mbps MSTP	Bandwidth of backbone network is 10Mbps
Receiver equipment	Trimble NetR9	Support Beidou, GPS, GLONASS, Galileo systems

Table 1. Basic Information of Chinese National GNSS Reference Stations.

The 240 national GNSS reference stations all are equipped with Trimble NetR9 GNSS receiver and TRM59900.00 GNSS antenna, process observation data of a 5-year period from Jan. 1, 2016 to Dec. 31, 2020, and conduct single-day solution of GPS and Beidou separately. For GPS data processing, 51 IGS core stations are added for joint solution.

2.2 Calculation process

For purpose of this study, the Position and Navigation Data Analyst (PANDA) developed by Wuhan University is employed for data processing. The data calculation process is as Figure 2.

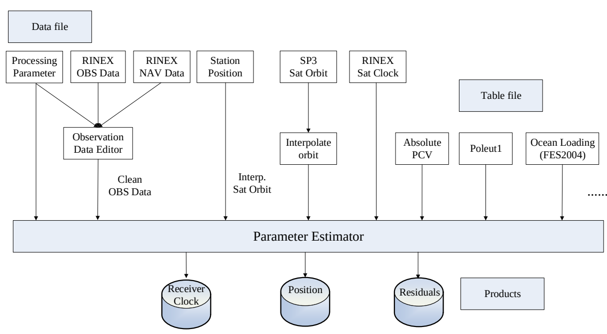

Figure 2. PPP calculation process

In this paper, non difference PPP positioning method is used for data calculation. Firstly, the observation data file, precise ephemeris and clock error file, table file and other data should be prepared, then the data format conversion and data preprocessing should be carried out to get clean data, and then the parameter estimation should be carried out according to the error correction model and calculation strategy to get the calculated unknown parameters. The unknown parameters include station three-dimensional coordinates, receiver clock error, tropospheric delay and ionospheric free combination ambiguity. The least square parameter estimation method is used to estimate the unknown parameters. For the eliminated parameters, the information is not eliminated and still remains in the normal equation, which can be solved by parameter recovery. The data processing strategies are as Table 2.

Item	Description
Processing	PPP
Observations	Ionosphere-free combination of GPS/Beidou
Sampling	30s
Processing sessions	24hours
Elevations cut-off angle	7°,weighted below 30°
Satellite orbits and clocks	Fixed with satellite products from IGS center
ERPs	Fixed with IERs 08 C04 products
Ambiguity	Resolved to integer values (Ge et al.2005)
Tropospheric refraction	A prior model with remaining estimated as piecewise constant
Ionospheric refraction	First order is eliminated by ionosphere-free combination,and higher orders are ignored
Antenna phase center	Corrected with igs08.atx/igs14.atx
Ocean tide	FES2004 model (Lyard et al.2006)
Solid Earth tide	IERS conversion 2010(Petit and Luzum,2010)
Pole tide	IERS conversion 2010(Petit and Luzum,2010)
Atmosphere loading	None

Table 2. PPP calculation strategies

For the table above, different precision satellite orbit and atx products from IGS data centers were adopted depending on the actual situation in different periods. Concerning GPS data processing, igs08_wum.atx was employed from Jan. 1, 2016 until Jan. 28, 2017, and igs14.atx from Jan. 29, 2017 until Dec. 31, 2020, and igswwwwd.sp3 file (precision satellite orbit) had been being employed (wwww refers to GPS week, and d to day of the week). Concerning Beidou data processing, igs08_wum.atx was employed from Jan. 1, 2016 until Jan. 28, 2017, igs14_wum.atx from Jan. 29, 2017 until Dec. 31, 2018, and igs14.atx during the 2019-2020 period. The calculation of BDS data in this study is based on B1 and B2 data. To maintain data source consistency of satellite orbit determination and reference station positioning calculation, it is suggested to employ precision satellite orbit products developed on the basis of B1 and B2 for Beidou calculation as far as possible. In view of this, wumwwwwd.sp3 released by Wuhan University was employed from 2016 until 2018, and codwwwwd.sp3 developed on the basis of B1 and B2 data was chosen for calculation of 2019-2020 Beidou data despite that the basis on which the orbit products released by most IGS data centers including Wuhan University changed into B1 and B3 data since 2019.

3. RESULTS AND DISCUSSION

3.1 Station Coordinates Residual

Since precise point positioning solution in this study is conducted on the basis of observation data of a continuous 5-year period from 2016 to 2020 from Chinese national GNSS reference stations and the time span is large, linear variation is unavoidable for the calculated station coordinates. Table 3 shows RMS values of time series of coordinates of Chinese national GNSS reference stations after elimination of linear velocity. As shown, the RMS values based on GPS data are 0.27cm and 0.28cm respectively in directions E and N, and 0.77cm in direction U. The RMS values of coordinates residual based on BDS data all are obviously larger than that based on GPS data approximately by quadruple in direction E and triple in directions N and U. Reason analysis shows that repeatability accuracy of station coordinates is inversely proportional to time span due to imperfection of Beidou error correction model.

Stations	RMS(cm)		
	E	N	U
GPS	0.27	0.28	0.77
Beidou	1.14	0.79	2.27

Table 3.RMS of Time Series of Coordinates of Chinese National GNSS Reference Stations

Since two different precision satellite orbit products were employed for BSD data calculation before and after Jan. 1, 2019, statistics of coordinate repeatability for the two periods were developed respectively. The results show that the RMS values in the three directions are 1.38cm, 0.91cm and 2.61cm in the first period respectively, and 0.61cm, 0.57cm and 1.54cm in the second period respectively. In the second period, the Beidou-based RMS values are approximately twice of GPS-based RMS values. In the first period, the Beidou-based RMS values are about triple of GPS-based RMS values in directions N and U and quadruple in direction E. This is mainly because different precision satellite orbit products were employed.

To visually present the characteristics of time series residual of coordinates based on GPS data and on BSD data, national GNSS reference stations AHBZ (first stations of all national GNSS reference stations in alphabetical order, located in Anhui Province, China) were selected at random for mapping. Figure 3 shows time series of coordinates calculated from GPS data and from BSD data respectively. It is observed that the coordinates calculated from GPS data are obviously better than that from BSD data in respect of repeatability, and show significant linear variation in directions E and N and relatively seasonal variation in direction U in addition to subsidence. Coordinates calculated from BSD data and that from GPS data take on a consistent trend at a close linear velocity with a slightly large difference in the height direction. It is also observed that the coordinates calculated from BDS data after 2019 is superior to that before 2019 in respect of repeatability due to difference in precision satellite orbit.

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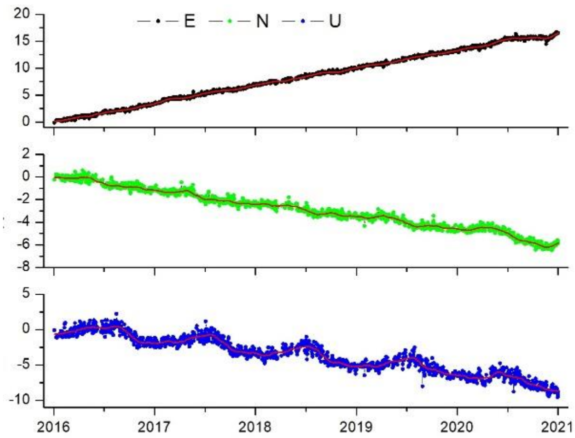
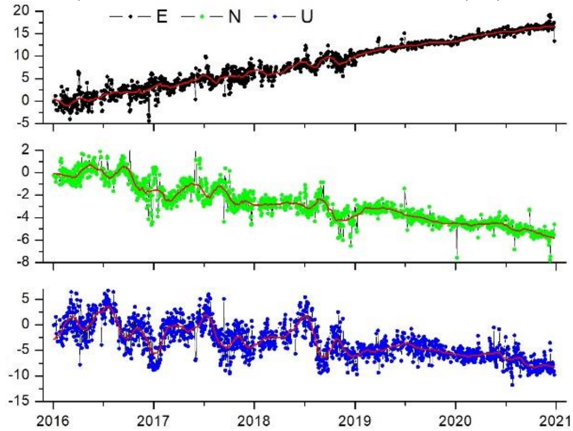


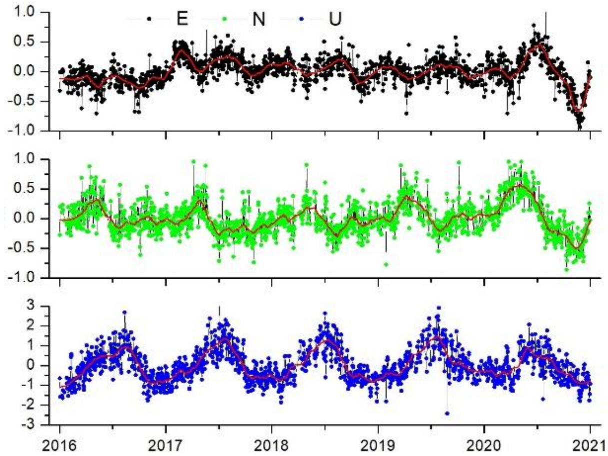
a) Coordinates calculated from GPS data(cm)



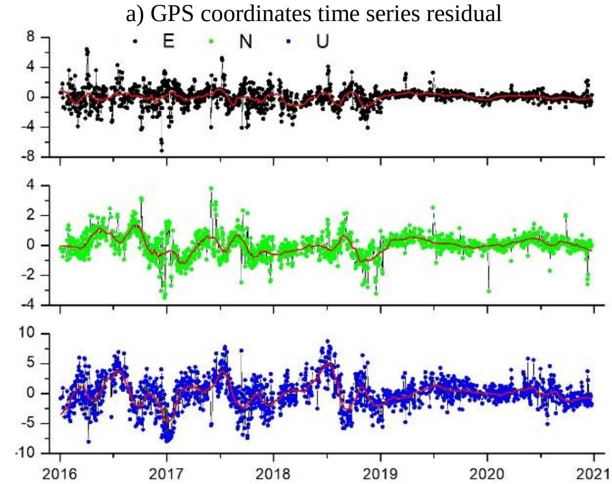
b) Coordinates calculated from BDS data(cm)

Figure 3. Comparison of Linear Velocity of Time Series Residual of Station Coordinates

To analyze seasonal variation of station coordinates, the linear velocity of time series of coordinates of stations AHBZ is eliminated, as shown in Figure 4. Figures 4 a) and 2 b) show time series residual of station coordinates calculated from GPS data and from BDS data after elimination of linear velocity respectively. It is observed that the GPS results show better repeatability, with residual repeatability better than 1cm in directions E and N and better than 3cm in direction U, and taking on obvious seasonal variation on yearly basis (especially obvious in height direction). The overall trend of coordinates calculated from BDS data is consistent with that from GPS data. Concerning seasonal variation, the coordinates calculated from BDS data is slightly inferior to that from GPS data in respect of repeatability accuracy and seasonal variation although the trend is presented roughly.



a) GPS coordinates time series residual



b) Beidou coordinates time series residual

Figure 4. Comparison of time series residual of coordinates after elimination of linear velocity(cm)

Table 4 show time series RMS of coordinates of stations AHBZ after elimination of linear velocity, which indicates that the RMS values in the three directions of time series of coordinates calculated from BDS data from 2019 until 2020 are approximately twice of that from GPS data. For a 5-year time span, the repeatability accuracy of time series of coordinates calculated from BDS data of the first three years is poor (about triple of that calculated from GPS data in directions N and U and quadruple in direction E), which is comparable to the RMS of all national GNSS reference stations.

Station	RMS(cm)		
	E	N	U
GPS	0.24	0.28	0.82
BDS(2016-2020)	1.17	0.78	2.49
BDS(2016-2018)	1.43	0.92	2.96
BDS(2019-2020)	0.50	0.45	1.46

Table 4. RMS of time series residual of coordinates of stations AHBZ after elimination of linear velocity

3.2 Station Coordinates Difference

The RMS values in directions E, N and U of time series residual of coordinates calculated from BDS data and from GPS data by subtracting coordinates calculated from GPS data from that calculated from BDS data are 1.49cm, 0.95cm and 2.66cm respectively. Calculations are conducted for two periods before and after Jan. 1, 2019. The RMS values in directions ENU are

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1.73cm, 1.06cm and 3.06cm in the first period, and 0.81cm, 0.69cm and 1.91cm in the second period.

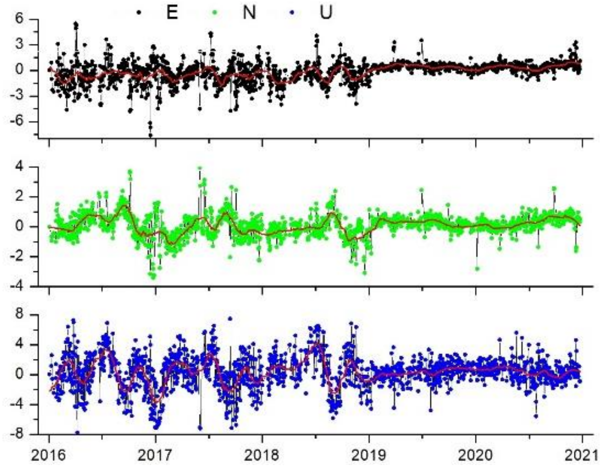

Figure 5. Station coordinates difference calculated from GPS data and from Beidou data

Figure 5 is developed based on stations AHBZ to show time series of coordinate difference calculated from GPS data and from BDS data. The RMS values of residual of AHBZ coordinates in directions ENU are 1.25cm, 0.78cm and 2.25cm respectively. Figures 4 and 5 indicate that the coordinate residual before 2019 is larger than that after 2019. Statistics of coordinates residual for the two periods before and after 2019 shows that the RMS values in the three directions are 1.43cm, 0.90cm and 2.69cm respectively in the first period, and 0.54cm, 0.46cm and 1.29cm respectively in the second period, the difference in the second period is obviously smaller than that in the first period, and the repeatability in the second period is better as shown in the time series chart of coordinates calculated from BDS data.

4. CONCLUSION

Based on GPS data and BDS data of the national GNSS reference stations uniformly distributed across China, precise point positioning is calculated, and the difference in station coordinates calculated from GPS data and BDS data is analyzed, which provides a reference for data processing for construction and maintenance of Beidou coordinate frame. Calculations show that the repeatability of station coordinate residual calculated from GPS data is superior to that calculated from BDS data on the whole. The repeatability values of reference station residual in directions ENU solely based on BDS data are about 1.2cm, 0.8cm and 2.3cm respectively, which were improved to 0.6cm, 0.6cm and 1.5cm respectively during 2019-2020 period since the adoption of code precision satellite orbit products. With good satellite orbit accuracy and good reference station data quality, the difference RMS values between coordinates calculated from GPS data and that from BDS data can reach 0.5cm, 0.5cm and 1.3cm. On the whole, the BSD data based on national GNSS reference stations can meet the needs of constructing and maintaining a centimeter-level Beidou coordinate frame.

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