

Chapter 18

Realization of High-Precision Relative Positioning Using Beidou Regional Navigation Satellite System

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Abstract Based on Beidou regional navigation satellite system in the phase of 4GEO + 5IGSO constellation, systematic research on Beidou high-precision relative positioning has been carried out by sufficient measured data from Beidou test network. A comparison scheme with Beidou/GPS dual-mode data is designed, and feasibility and attainable precision of Beidou relative positioning have been verified effectively. As shown in results: coordinate accuracy realized by Beidou relative positioning has achieved centimeter level, and baseline repeatability has reached millimeter level, which are equivalent to GPS high-precision relative positioning level. For short baseline, coordinate repeatability in the North, East and Up direction is respectively better than 0.5, 1.3 and 2.9 mm, and absolute error of coordinate is respectively better than 0.2, 0.6 and 1.7 mm by comparison with GPS; for medium/long baseline, the coordinate repeatability in the NEU direction is respectively better than 2.1, 5.9 and 7.3 mm, and absolute error of coordinate is respectively better than 1.6, 1.3 and 2.2 mm; for long baseline over 1000 m, NEU coordinate repeatability is respectively better than 8.4, 14.6 and 21.3 mm, and absolute error is respectively better than 1.5, 1.5 and 14.5 mm, and baseline repeatability is approximately 0.003 ppm. The conclusion

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from the article provides technical criteria for widespread use of Beidou in the high precision application fields, and makes sense for promotion of application prospect and enhancement of usage confidence with Beidou.

Keywords Beidou navigation system · Relative positioning · Ambiguity · Baseline · Repeatability · ppm

18.1 Forewords

The relative positioning technology based on carrier phase observable is an important mode in GNSS application, therefore, the precision of relative positioning has become an major indicator used to evaluate performance of navigation satellite system. In 1984, Dr B.W. Remondi had proposed mathematical model and processing method of high precision relative positioning by the carrier phase observables form two GPS receivers synchronously, conducted initial verification by baseline with the length of 100 m, and achieved the precision of mm level by relative positioning [1]. In the GPS test campaign in 1993, measuring accuracy can be achieved 0.001 ppm order of magnitude for baseline of 3,000 km by GPS relative positioning technology [2]. The development of IGS has tremendously propelled the application of GPS, at present, the technologies of network RTK and virtual reference station based on the prototype of relative positioning have been gradually mature, and realized real-time, high precision, and dynamic positioning [3]. The relative positioning technology has become one of the most important work mode, and plays an important role in fundamental research of high-precision surveying and mapping, atmospheric science, geosciences and so on. After several decades of development, GPS has dominated high-precision GNSS application market both at home and abroad [4–6].

Whole Beidou constellation had been completed in October 2012, which symbolizes that the construction of China independent navigation satellite system has entered a new development phase. As a strategic national infrastructure, the promotion in application field of Beidou satellite navigation system in key fields of national economy of China plays an important strategic role [7]. There are differences between Beidou regional navigation satellite system and GPS in terms of constellation distribution, character of signal, satellite orbit precision and observation data quality [8], so it is essential to research feasibility and precision of high-precision relative positioning using Beidou regional navigation satellite system.

Based on actual measured data form Beidou test network, large scope of Beidou relative positioning test has carried out, systematic research under condition of short, medium and long baseline. The results show that coordinate precision realized by Beidou relative positioning has reached centimeter level, and baseline repeatability has reached millimeter level, which are equivalent to GPS level of high-precision relative positioning precision.

18.2 Relative Positioning Strategy of Beidou

In this section, we first give the selection of model and parameter estimation, and then perform data processing procedure in detail.

18.2.1 Ambiguity Fixing Strategy

Determination of integer cycle ambiguity is a critical technology of relative positioning, after determination of ambiguity, observed value of phase will be transformed as precise range observation. Therefore, ambiguity fixing plays an important role for enhancement of positioning precision and positioning efficiency [9]. Determination of ambiguity is divided into two steps: firstly calculate the float solution of ambiguity, and then restrict float ambiguity to fixed one by covariance information [10, 11]. Under the condition of poor pseudo-range precision of dual-frequency, QIF method can be used for long baseline ambiguity resolving, and good result have been achieved in Bernese software [12], and it applies to long baseline data processing. For detailed algorithm about QIF, please refer to the literature 12.

18.2.2 Parameter Estimation Strategy

The important details on selection of parameter and model adopted in paper such as ionosphere and troposphere involved in resolution are listed in Table 18.1.

Table 18.1 Strategy of model selection and parameter estimation in baseline processing

Parameter	Selection of parameter and model
Basic observables	Ionosphere-free combination
Satellite ephemeris	Post-processed Satellite orbit
Difference strategy	Maximum of observation time
Ionosphere model	TEC model of China region
Troposphere model	Niell model (moisture content per hour) [11]
Troposphere mapping function	Gradient is LINEAR
Ambiguity resolution method	QIF
Network solution strategy	Fixing constraint of one station
Tide model	Hans-Georg Scherneck
Earth rotation parameter	IGS ERP
Earth gravity field	JGM3
Reference framework	IGS 05

18.2.3 Data Processing Procedure

Detailed processing procedure of Beidou relative positioning is as follows: (1) pre-processing of original data: firstly, by performing pre-processing of zero-difference data, clean phase observation value is acquired through detection of gross error and cycle slip of phase observables, cycle slip detection of zero-difference observables adopts Blewitt method [13]; (2) time synchronization and formation of single-difference: using pseudo range observables for single epoch positioning, receiver clock error is obtained, then we acquire single-difference observables with zero-difference observables in observation network as certain rules and algorithm, takes observables maximization as rules this article; (3) data pre-processing in the triple-difference mode: adopt triple-difference observables combination to get certain precise station coordinate, perform further cycle slip detection through assumption inspection method of ionosphere-free combination residual error; (4) residual error editing: under condition of mandatory constraint of prior coordinate, we get positioning residual error by using phase ionosphere-free combination, proceed with residual error editing, and further eliminate the gross error of observation data, therefore pre-processing of observation data is completed; (5) getting the first network solution using observation data after residual error editing, meanwhile, the troposphere parameter is estimate; (6) ambiguity fixing: using ionosphere model as prior constraint, to get the estimated value of wide-lane ambiguity, use ionosphere-free combination to get and save the estimated value of narrow-lane ambiguity with QIF method; (7) final result estimation: introduce the fixed double-difference ambiguity into ionosphere-free combination observables, so as to enhance precision of estimated parameter and get the fixed solution of observation network. The processing procedure is shown in Fig. 18.1.

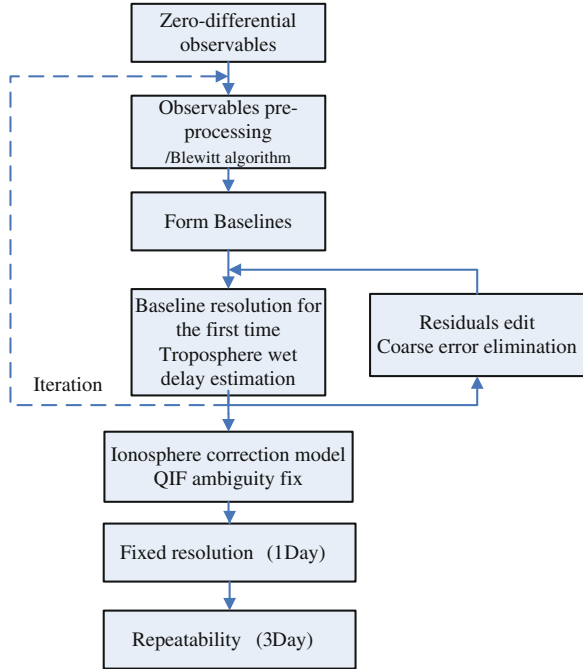
There are two schemes to detect the precision of Beidou relative positioning, one is to use the precise coordinate acquired through GPS as reference, the other is to use repeatability of multiple single-day solutions as evaluation index.

18.3 Processing Scheme of Beidou Relative Positioning

18.3.1 Design of Comparison Scheme

In order to verify relative positioning precision of Beidou reasonably, a detailed schemes are designed, and flow chart is showed in Fig. 18.2. Firstly, we estimate station coordinate with confederative GPS data from both Beidou/GPS dual-mode receiver and IGS core stations (see yellow parts in Fig. 18.2), fix one IGS core station for constrained adjustment, and unify reference framework to IGS05.

Fig. 18.1 Flow chart of data processing with Beidou



In this way, precision coordinates of dual-mode station may be gotten, and then they are used to reference for testing the precision of Beidou relative positioning which are estimated with only Beidou data (see grey parts in Fig. 18.2). So coordinates that come from different navigation system may be compared to evaluate performance of Beidou.

18.3.2 Observation Data

The actual measurement data between June 18 2012 and June 20 (day of year 170–172) are processed, all stations are equip with Beidou/GPS dual-mode receivers which can receive of Beidou and GPS data simultaneously. The data sampling interval is 30 s, B1I and B2I carrier phase data are selected. The on-orbit satellites of Beidou during the period of time are 4GEO + 5IGSO constellation (C01, C3, C04, C5, C06, C07, C08, C09 and C10). Distances between each stations are showed in Table 18.2.

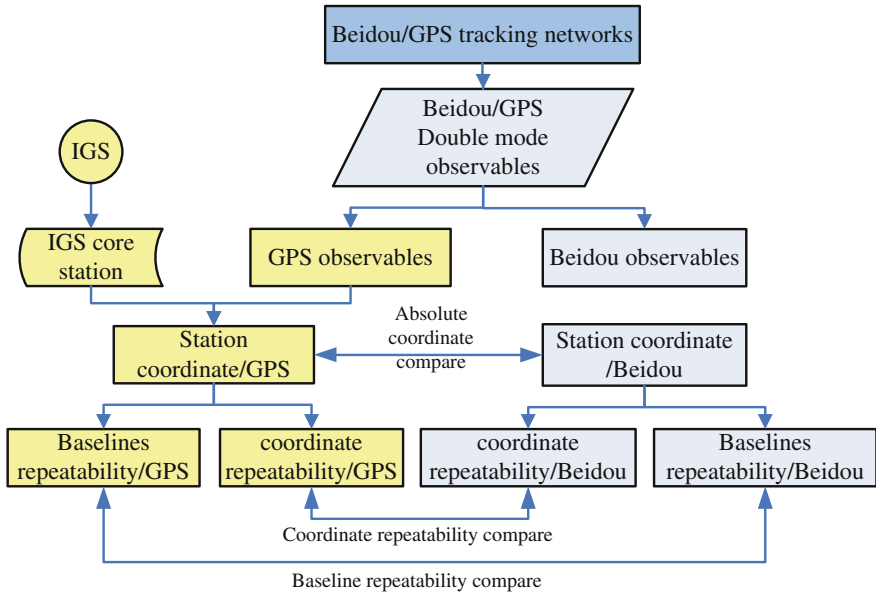


Fig. 18.2 Data processing scheme

Table 18.2 Distance between stations (unit : km)

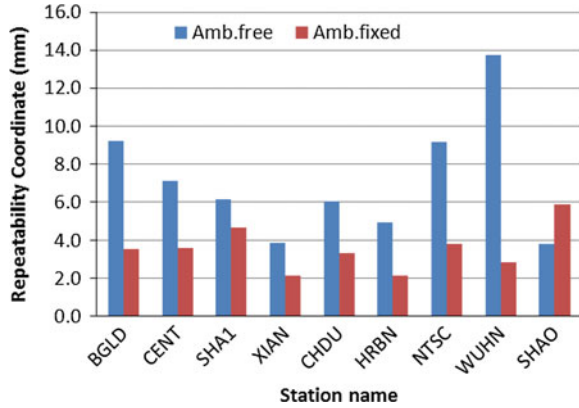
	CENT	SHA1	XIAN	CHDU	HRBN	NTSC	WUHN	SHAO
BGLD	652	1225	0.786	605	1958	28	652	1196
CENT		687	652	987	1986	643	0.43	657
		SHA1	1225	1663	1679	1205	687	30
			XIAN	604	1959	30	652	1197
				CHDU	2551	633	987	1634
					HRBN	1931	1986	1686
						NTSC	643	1177
							WUHN	657

18.4 Processing Results and Discussion

18.4.1 GPS Relative Positioning Test of Beidou/GPS Dual-Mode Receiver

The purpose of this test is to acquire GPS relative positioning criterion, so as to get precise coordinate of dual-mode receiver for comparison with Beidou positioning results later. The GPS data form three IGS core stations including BJFS, WUHN and from seven Beidou/GPS trace SHAO of IGS are selected, and form including CENT, SHA1, XIAN, CHDU, HRBN, NTSC and BGLD of are together process,

Fig. 18.3 Coordinate repeatability with GPS data



processing strategy in Sect. 18.3 is adopted, and BJFS is deemed as fixed station constraint, coordinate repeatability of the other stations are shown in Fig. 18.3. As shown in results, with the exception of slightly large statistics value of WUHN, coordinate floating solution repeatability of all stations are better than 1.0 cm, and fixed solutions are better than 6 mm.

Altogether 28 independent baselines have been formed from observation data of 3 days, and 2998 ambiguity parameters have been estimated, and 2318 parameters have been successfully fixed, the average success rate is 77.3 %, as the statistics characteristics of wide-lane and narrow-lane ambiguity, the residual error should comply with normal distribution [14]. Figure 18.4 shows that wide-lane ambiguity statistics in scope of 0.5 cycle, which complies with normal distribution well.

Analysing relative positioning residual error, Fig. 18.5 shows time series of baseline of BJFS-SHA1 in one day, and Fig. 18.6 shows statistics of all double difference observable. The result shows that GPS relative positioning residual error is approximately 0.0015 m.

Relative positioning mainly measures coordinate difference between two stations, therefore baseline repeatability is especially important, for the sake of

Fig. 18.4 Distribution of fractional part of GPS wide-lane ambiguity

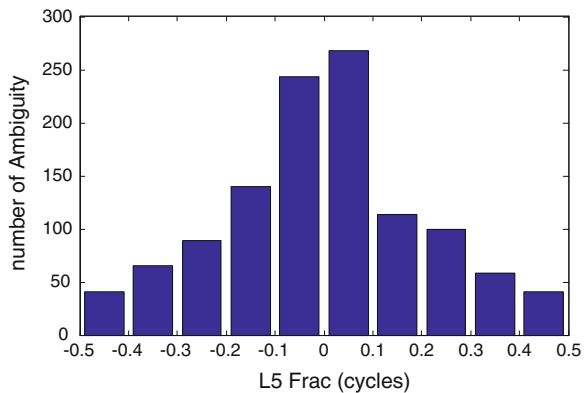


Fig. 18.5 Time series of relative positioning residual error with GPS

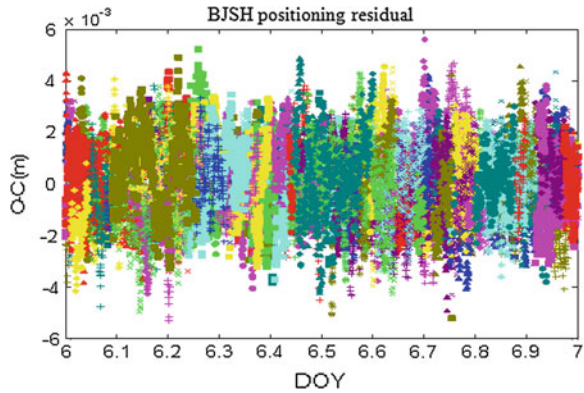
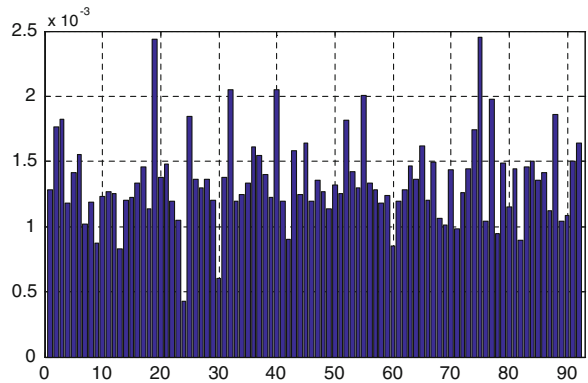


Fig. 18.6 Statistics of relative positioning residual error with GPS (unit : m)



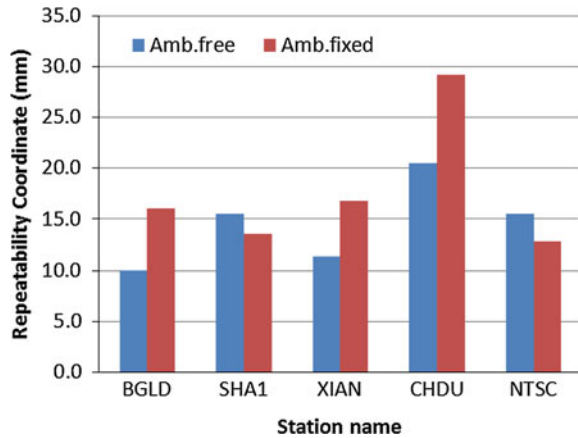
correspondence with comparison with Beidou baseline repeatability later, 9 among 28 baselines are selected to analyze repeatability of three-days solution, as shows in Table 18.3, baseline repeatability is related to baseline length, for long baseline up to one thousand kilometres, the repeatability of GPS baseline is approximately 0.001 ppm.

18.4.2 Beidou Relative Positioning Test of Beidou/GPS Dual-Mode Receiver

Scheme II realized relative positioning by Beidou observational data acquired from dual-mode receiver, configuration of parameter is identical with scheme I, CENT station is the restriction of fixed station. Figure 18.7 shows coordinate repeatability of BGLD, SHA1, XIAN, CHDU and NTSC involved in positioning resolution, as shown in the results, coordinate repeatability of five stations are

Table 18.3 Repeatability of baselines by GPS

Baseline	Baseline length/m	D(LGT)	D(LGT) (ppm)
BGLD-SHA1	1225216.7	0.0006	0.001
BGLD-CHDU	605095.4	0.0010	0.002
BGLD-NTSC	28481.5	0.0010	0.035
SHA1-XIAN	1225641.0	0.0002	0.001
SHA1-CHDU	1663819.5	0.0004	0.001
SHA1-NTSC	1205323.7	0.0006	0.001
XIAN-CHDU	604313.9	0.0006	0.001
XIAN-NTSC	29250.1	0.0008	0.028
CHDU-NTSC	633341.0	0.0010	0.002

Fig. 18.7 Repeatability of 3D position with Beidou

better than 2 cm, and the accuracy of coordinate is not improved dramatically after ambiguity fixing.

Due to the fact that the number of Beidou satellite is fewer than GPS, furthermore, GEO satellite in Beidou constellation is always visible to observation station and IGSO satellite regression cycle is one day, the number of satellite rises and falls is fewer, so the number of ambiguities during three-day observation period is relatively small, altogether there are 658 ambiguity parameters resolved, 326 parameters are successfully fixed and success rate is 55.0 %. The residual error of wide lane ambiguity is shown in Fig. 18.8.

The observation residuals are analysed, the time serie of residual error of CENT-SHA1 baseline is shown in Fig. 18.9, and the statistics results is given in Fig.18.10 according to different baselines of Beidou, as seen from the above results, most residual error of baselines are smaller than 0.0015 mm, and the longer the baseline, the greater the residual.

Similarly, Repeatability of the nine baselines of Beidou is given, and the results are shown in Table 18.4. Compared with the results in Table 18.3 obtained from

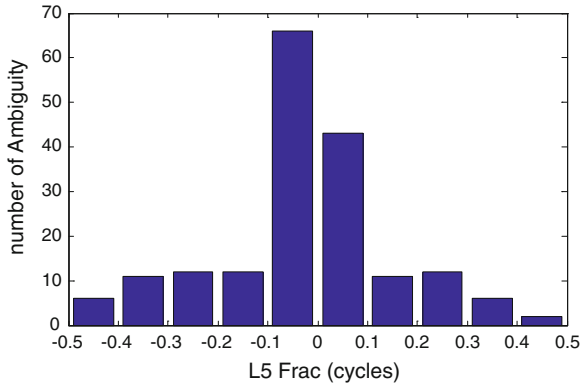


Fig. 18.8 Distribution of fractional part of Beidou wide-lane ambiguity

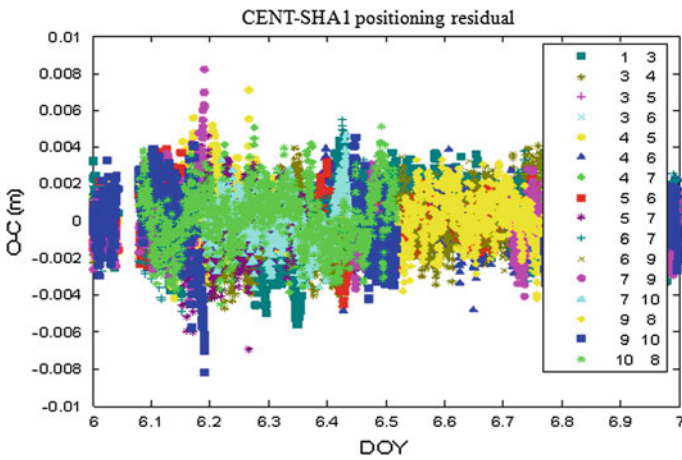


Fig. 18.9 Time series of Beidou relative positioning residual error

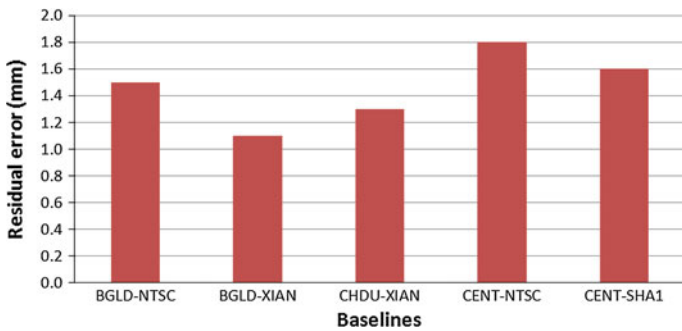


Fig. 18.10 Statistics of relative positioning residual error according to baselines with Beidou

Table 18.4 Repeatability of baselines by Beidou

Baseline	Baseline length/m	D(LGT)	D(LGT) (ppm)
BGLD-SHA1	1225216.7	0.0039	0.003
BGLD-CHDU	605095.4	0.0026	0.004
BGLD-NTSC	28481.5	0.0025	0.087
SHA1-XIAN	1225641.0	0.0049	0.004
SHA1-CHDU	1663819.5	0.0053	0.003
SHA1-NTSC	1205323.7	0.0045	0.004
XIAN-CHDU	604313.9	0.0056	0.009
XIAN-NTSC	29250.1	0.0007	0.025
CHDU-NTSC	633341.0	0.0047	0.007

the GPS, The results show that the repeatability of Beidou is an order of magnitude with GPS, but the accuracy is slightly lower.

18.4.3 Analysis of Relative Positioning Precision of Beidou Individual Baseline

In order to further verify precision of Beidou relative positioning, three individual baselines with different length, take BGLD as fixed station, and the other three stations are XIAN, NTSC and SHA1, the formed baseline length are respectively 0.78, 28 and 1225 km, which covering short, medium and long baseline, the coordinate repeatability of all baseline for 3 days are calculated (Fig. 18.11). By comparing the coordinate of 3 days with ones by using GPS, the results are shown in Table 18.5. For short baseline, coordinate repeatability in the North, East and Up direction is respectively better than 0.5, 1.3 and 2.9 mm, and absolute error of

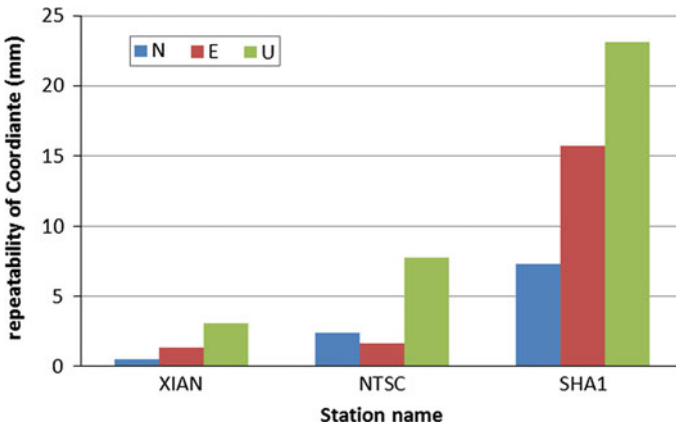


Fig. 18.11 Coordinate repeatability with different length

Table 18.5 Comparisons of coordinates between Beidou and GPS (mm)

Station	Direction	170 day	171 day	172 day
XIAN 786 m	N	0.3	0.0	-0.2
	E	0.7	0.0	-0.6
	U	-1.2	0.5	1.7
NTSC 28 km	N	0.5	-1.6	0.5
	E	-5.3	-1.3	0.4
	U	-5.5	2.2	-2.1
SHA1 1225 km	N	-1.5	-10.9	-7.3
	E	1.5	-6.3	-4.0
	U	-14.5	8.5	-7.9

Table 18.6 Repeatability of single baseline (mm)

Baselines	Baseline length/km	D(LGT) (ppm)
BGLD-XIAN	0.786	1.627
BGLD-NTSC	28.0	0.062
BGLD-SHA1	1225.0	0.003

coordinate is respectively better than 0.2, 0.6 and 1.7 mm by comparison with GPS; for medium/long baseline, NEU direction coordinate repeatability is respectively better than 2.1, 5.9 and 7.3 mm, and absolute error of coordinate is respectively better than 1.6, 1.3 and 2.2 mm; for baseline over 1,000 m, NEU direction coordinate repeatability is respectively better than 8.4, 14.6 and 21.3 mm, and absolute error is respectively better than 1.5, 1.5 and 14.5 mm.

Baseline repeatability is related to baseline length, Table 18.6 shows repeatability results of short, medium and long baseline, short baseline BGLD-XIAN is approximately 1.627 ppm, medium baseline BGLD-NTSC is approximately 0.062 ppm and short baseline BGLD-SHA1 is approximately 0.003 ppm. It can be seen from comparison between the baseline repeatability Beidou and GPS in Table 18.3 that Beidou is at a magnitude same with GPS baseline repeatability, with slightly lower precision, the potential reason may be no precise calibration of correction of antenna phase center, furthermore, the conclusion of this article are drawn when Beidou is in the phase of incomplete 4GEO+5IGSO constellation.

18.5 Summary

Utilizing the 4GEO/5IGSO constellation during initial operation phase of Beidou regional navigation satellite system, The method is systematically researched on Beidou relative positioning, and then a large scope adjustment of Beidou control network is carried out firstly, and the precision of short, medium and long baseline based on Beidou are verified, as shown in the research results, coordinate accuracy

of Beidou regional satellite navigation system has reached centimeter level, baseline repeatability has reached millimeter level, and can be widely used in scientific research and engineering application.

The conclusions obtained in this study provide the technical basis for the use of Beidou in the field of high precision applications fields. Although the accuracy of current Beidou relative positioning is slightly lower than GPS, it has room for further improvement. We should continue to strive to improve the Beidou orbital accuracy, calibrate antenna phase center of the satellite and receiver. In addition, the results of this paper is confined to incomplete 4GEO/5IGSO constellation, when the constellation is completed, the relative positioning accuracy could be further enhanced necessarily.

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