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Precise orbit determination of Beidou Satellites with precise positioning

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Chinese Beidou satellite navigation system constellation currently consists of eight Beidou satellites and can provide preliminary service of navigation and positioning in the Asia-Pacific Region. Based on the self-developed software Position And Navigation Data Analysis(PANDA) and Beidou Experimental Tracking Stations (BETS), which are built by Wuhan University, the study of Beidou precise orbit determination, static precise point positioning (PPP), and high precision relative positioning, and differential positioning are carried out comprehensively. Results show that the radial precision of the Beidou satellite orbit determination is better than 10 centimeters. The RMS of static PPP can reach several centimeters to even millimeters for baseline relative positioning. The precision of kinematic pseudo-range differential positioning and RTK mode positioning are 2–4 m and 5–10 cm respectively, which are close to the level of GPS precise positioning. Research in this paper verifies that, with support of ground reference station network, Beidou satellite navigation system can provide precise positioning from several decimeters to meters in the wide area and several centimeters in the regional area. These promising results would be helpful for the implementation and applications of Beidou satellite navigation system.

compass/Beidou, PANDA, precise orbit determination (POD), Beidou difference

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The Beidou Navigation Satellite System is a global satellite navigation system, which is independently developed, deployed, and operated by China and still in progress. According to its overall planning schedule, the system will be able to provide PNT and short message communication services in the Asian-Pacific region by about 2012; by 2020, a Beidou Navigation Satellite System with global coverage will be in place [1]. Users will have access to integrated services of PNT and short message communication from the full-fledged Beidou system and can also take advantage of the compatibility and interoperability between Beidou and other GNSS systems to utilize multi-GNSS observation data, greatly improving observation redundancy and the accuracy of navigation and positioning services [2] . The tenth Beidou navigation satellite was launched successfully on December 2nd, 2012, symbolizing both an important advance in the development of regional Beidou Navigation Satellite System and a new phase in the deployment of our nation's independent satellite navigation system (http://www.beidou.gov.cn/[EB]). Although regional constellation deployment of the Beidou Navigation Satellite System is still not yet completed, initial PNT services in the Asian-Pacific region have already taken shape.

The key to enhancing satellite navigation system's PNT performance lies primarily in two aspects: on the one hand,

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increasing the number of navigation satellites and optimizing spatial geometric configuration, that is, improving satellites' geometric observation condition at the ground terminal; on the other hand, improving the accuracy of satellite ephemeris, clock offset and relevant model parameters, which means improving accuracy of the system's spatial signals. Taking the limited number of satellites into account, obtaining precise orbit and clock offset of the navigation satellites comes as a top priority when we endeavor to enhance precise positioning ability of satellite navigation systems [3]. Integrated procession of multi-mode data is an effective tool for the determination of precise orbit and clock offset parameters of a new satellite navigation system as it can make the most of precise spatial and time references of the legacy navigation systems [4, 5]. In view of this, Wuhan University sets out to establish a continuous observation reference network called BEIDOU Experimental Tracking Stations (BETS) for the Beidou Navigation Satellite System in the Asian-Pacific region from the beginning of 2011 and now preliminary BETS has been formed.

Researches in this paper are based on Beidou/GPS dual-mode observation data from BETS tracking. And PANDA, integrated satellite navigation data processing software independently developed by Wuhan University, is adopted in data processing and analysis [6–8]. Orbit and clock offset parameters for Beidou satellites are first obtained through combined precise orbit determination with Beidou/GPS dual-mode data. Then by using these precise orbit and clock offset products, the Beidou Navigation Satellite System's ability to provide precise point positioning service is analyzed. Meanwhile, precise relative positioning on short baseline is carried out to test the effect of GPS data fusion on the accuracy improvement in precise relative positioning. In order to verify the performance of the Beidou Navigation Satellite System's real-time precise positioning service, real-time differential relative positioning with Beidou's carrier phase as well as pseudorange observation data is also discussed. Precise orbit and clock offset products as well as precise point positioning results in this paper suggest the potential capability of the Beidou Navigation Satellite System to offer wide-area precise positioning services, whereas the findings in post and real-time precise relative positioning can serve as references when setting up centimeter-level regional ground augmentation service systems with the Beidou Navigation Satellite System.

1 BEIDOU experimental tracking stations

To carry out comprehensive scientific and application studies about the Beidou Navigation Satellite System, Wuhan University set out to establish the BEIDOU experimental Tracking Stations (BETS) worldwide at the beginning of 2011. Currently, a continuous tracking network for Beidou in-orbit satellites has been basically formed. The network now consists of six offshore as well as nine domestic continuous tracking stations while at the same time the domestic tracking stations also constitute a wide-area differential network for the Beidou Navigation Satellite System. The BETS network is equipped with UR240-CORS, a kind of Beidou/GPS dual-mode receiver, which is independently developed by China and supports Beidou/GPS dual system quadruple frequency high-accuracy receivers. Its carrier phase observation accuracy can achieve millimeter level. A distribution map of the BETS tracking network is shown in Figure 1.

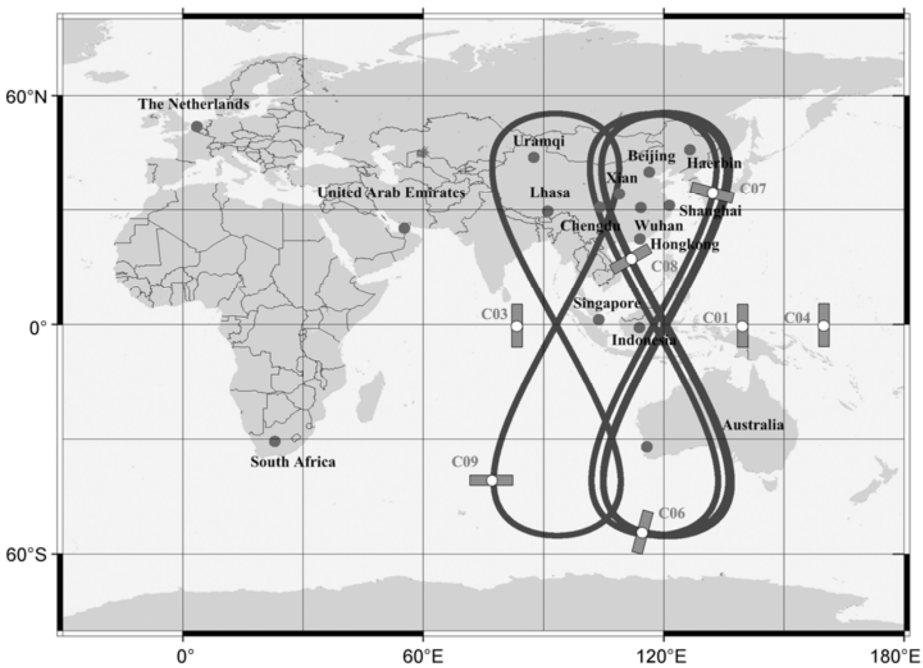

Figure 1 BEIDOU Experimental Tracking Stations (BETS).

2 Precise orbit determinations and PPP of Beidou satellites

In precise orbit determination for Beidou satellites, Beidou/GPS dual-mode observation data from BETS are adopted. BETS can obtain observation data from both GPS and the Beidou Navigation Satellite System simultaneously, thus making it possible to use GPS data in precise positioning and time synchronization for ground stations and further precise orbit determination for Beidou satellites. The strategy for precise orbit determination of Beidou satellites is as follows: firstly, resolving coordinate, clock offset and zenith tropospheric delay (ZTD) parameters for ground stations; then fixing ground receivers' clock offset and ZTD parameters and resolving the initial position of each of the six Beidou satellites, as well as satellite clock offset and nine light pressure parameters. In addition, time bias will exist when BETS receivers collect signals from two different navigation systems. As clock offsets of the receivers are calculated with GPS observation, it is essential to estimate this time bias between these two satellite systems in orbit determination of Beidou satellites for each station in BETS after getting all stations' clock offsets. For more detailed processing procedures, please see Reference [9].

Observation data from September 1st to September 10th, 2011 (DOY 244–253) are processed in this paper. Precise orbits of Beidou satellites are determined with every three successive days as an arc segment. The overlapping sections (24 hours) between these arc segments during seven successive days (DOY 245–251) are calculated as indicator of orbit difference. Statistical accuracy of these overlapping differences for five operational Beidou Navigation Satellite System satellites (C01, C04, C06, C07, C08) during this period is presented in Figures 2 and 3.

Figure 2 demonstrates overlapping accuracy in the radial direction for each of the satellites. It can be seen that radial overlapping accuracy can reach the order level of 10 cm,

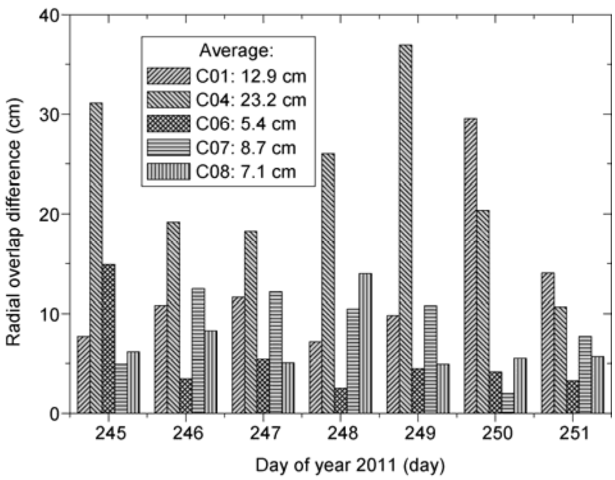

Figure 2 Radial overlapping difference of BEIDOU satellites.

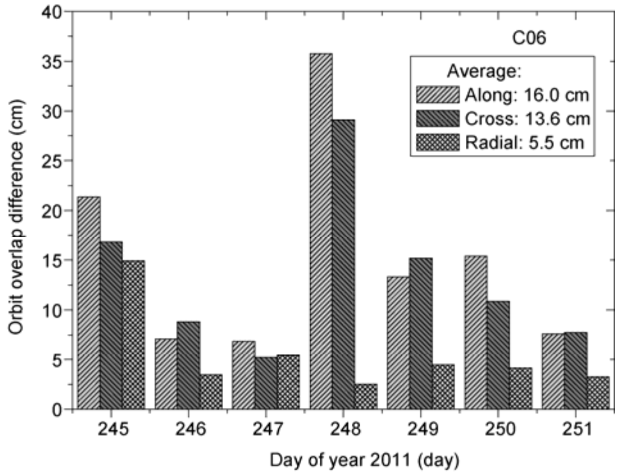

Figure 3 Orbit overlapping difference of BEIDOU C06.

basically similar to that of current Galileo experimental satellites [10]. And radial overlapping accuracy of IGSO satellites (C06, C07, C08) is higher than that of GEO satellites (C01, C04) on account of the GEO's geostationary feature.

Overlapping accuracy in all the three directions for Beidou satellite C06 is illustrated in Figure 3. Its radial, tangential and normal overlapping accuracy are all within 10–20 cm, also equal to those of current Galileo experimental satellites.

Researches on PPP application based on the Beidou Navigation Satellite System are conducted to analyze Beidou's high-accuracy positioning performance and test the precise orbit and satellite clock offset products for Beidou satellites generated by PANDA at the same time.

Observation data during September 1st and 5th (DOY 244–248) are selected for the PPP experiments. In statistic PPP of BETS, every computational arc segment covers the 24 hours in a single day and parameters to be estimated include reference station coordinate (with coordinate obtained through pseudo range positioning as the prior value and its accuracy is set as 20 m), receiver clock offset, troposphere parameters, etc. Precise orbit and clock offset of Beidou satellites used are the products generated by PANDA.

High-accuracy coordinates of the dual-mode tracking stations in BETS can be calculated with their GPS observation data, so PPP accuracy of the Beidou Navigation Satellite System can be directly evaluated through coordinate comparison with high-accuracy GPS positioning results. The accuracies of PPP solely with the Beidou Navigation Satellite System of 10 stations after simultaneous observation on DOY 245 are listed in Table 1.

Results in Table 1 indicate that horizontal accuracy of statistic PPP only with the Beidou Navigation Satellite System can achieve 5 cm while accuracy in the elevation direction can reach 10cm; corresponding RMS is 2 and 7 cm respectively. This also proves that the Beidou Navigation Satellite System has been preliminarily qualified to provide

Table 1 PPP precision by BEIDOU

Station name	East (cm)	North (cm)	Up (cm)
BJF1	−2.18	−1.08	11.57
CENT	−0.73	−0.15	2.12
CHDU	−1.71	−0.15	2.93
HKTU	0.06	−0.17	−0.09
HRBN	1.12	3.20	−7.52
LASA	0.22	0.47	0.86
PETH	−3.24	−2.17	−2.40
SHA1	0.14	0.05	-0.77
SIGP	0.62	0.08	7.15
URMQ	−1.54	4.09	−17.31
RMS	1.51	1.82	7.4

high-accuracy positioning and navigation services.

In precise orbit determination of Beidou satellites, CHDU station is excluded from parameter estimation so as to analyze systematic error that may exist between different navigation systems (here as Beidou and GPS). PPP of CHDU is carried out using precise orbit and clock offset of Beidou satellites calculated with other stations. Positioning results of five successive days are depicted in Figure 4.

From Figure 4, it can be observed that although excluded from precise orbit determination, CHDU station's positioning accuracy can also reach 2 and 5 cm in the horizontal and elevation direction respectively. The possible systematic error between different navigation systems (here as Beidou and GPS) of the terminal equipment also can be perceived notably in this chart. This kind of error can be attributed to the satellites' geometry configuration, frequency difference and many other factors. In general, high-accuracy orbit and clock offset parameters of the Beidou Navigation Satellite System can be gained through more densely-distributed ground reference stations, thus serving for provision of wide-area PPP services for the users.

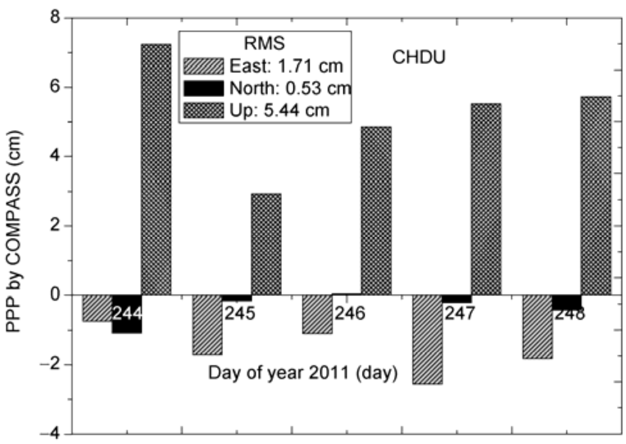

Figure 4 PPP precision of CHDU station.

3 High-accuracy relative positioning of the Beidou Navigation Satellite System

3.1 Precise Relative Positioning on short baselines

Currently, relative positioning is still a major method in sub-millimeter/millimeter level high-accuracy coordinate resolving. On the basis of the BETS network, a 436-meter short baseline is selected in this paper to carry out experiments of baseline measurement with the Beidou Navigation Satellite System. Reference coordinate of this baseline is calculated with GPS data and TGO—a commonly-used GPS data processing software.

Strict and reliable preliminary Beidou/GPS data processing is a guarantee for high-accuracy Beidou/GPS combined baseline solution. The automatic cycle slip detection and repairing method proposed in Reference [11], capable of detecting cycle slips as small as one cycle, is adopted in preliminary data processing here. In the parameter resolution process, ambiguity parameters are fixed with a method based on MLAMBDA as presented in Reference [12], the searching efficiency of which is remarkably enhanced than the frequently used LAMBDA method. Baseline resolution results obtained through GPS, BEIDOU and GPS/BEIDOU respectively are finally analyzed in a statistical manner.

Average results of both statistic and kinematic modes during the whole week from June 19th to 25th, 2011 (DOY 170–176) are shown in Table 2. Reference baseline components of all of the three methods (GPS, BEIDOU, GPS+GLONASS) are those processed with the commercial software TGO.

In the static mode, GPS baseline components calculated with PANDA are quite similar to those reference ones processed by TGO (difference in the east, north and elevation direction is 0.80 mm, −1.60 and 1.20 mm respectively). When only data from the Beidou Navigation Satellite System are used, baseline accuracy can also achieve millimeter level—slightly lower than that of GPS (as 6.20, 0.70 and −5.00 mm in the east, north and elevation direction respec-

Tabale 2 Statistic results of GPS and BEIDOU baseline solutions

	Statistic mode			Kinematic mode		
	East (mm)	North (mm)	Up (mm)	East (mm)	North (mm)	Up (mm)
GPS	0.80	−1.60	1.20	9.10	7.40	16.70
BEIDOU	6.20	0.70	−5.00	4.50	13.40	31.90
GPS+BEIDOU	2.40	−0.90	1.10	5.90	4.70	11.50

tively). And there is also an evident systematic error, which may result from phase center error of the receiver's antenna. For baseline accuracy of each day during this period, refer to Figure 5.

It can also be known from Table 2 that average accuracy of kinematic GPS baseline independently resolved with PANDA is 9.10, 7.40 and 16.70 mm in the east, north and elevation direction respectively. With current small number of satellites and uneven constellation configuration, the corresponding kinematic resolution accuracy of the Beidou Navigation Satellites System is lower (with 4.50, 13.40 and 31.90 mm in the east, north and elevation direction respectively).

Although in statistic baseline resolution, there is no obvious effect of Beidou/GPS combined method in comparison with simple GPS method, the baseline accuracy obtained with Beidou/GPS combined data is significantly improved in kinematic resolution. As presented in Figure 6, compared with single GSP resolution, daily baseline accuracy of the Beidou/GPS combined method during this period has improved by 33.3%, 28.6% and 29.4% in the east, north and elevation direction respectively. The reason lies mainly in the increase in observation data redundancy and strengthening of the geometric observation structure.

The kinematic baseline processing results of GPS and Beidou/GPS on DOY 171, 2011 are given in Figure 7. It can be seen that dE、dN and dU accuracy of GPS kinematic baseline resolution is 0.6, 0.5 and 1.4 cm respectively whereas those of GPS/BEIDOU are 0.3, 0.4 and 1.0 cm respectively. Therefore, it can be concluded that integration of Beidou data results in obvious improvement of kinematic results during this period, especially in the elevation direction.

3.2 Beidou pseudorange and carrier phase differential positioning

The application of GPS differential positioning is quite

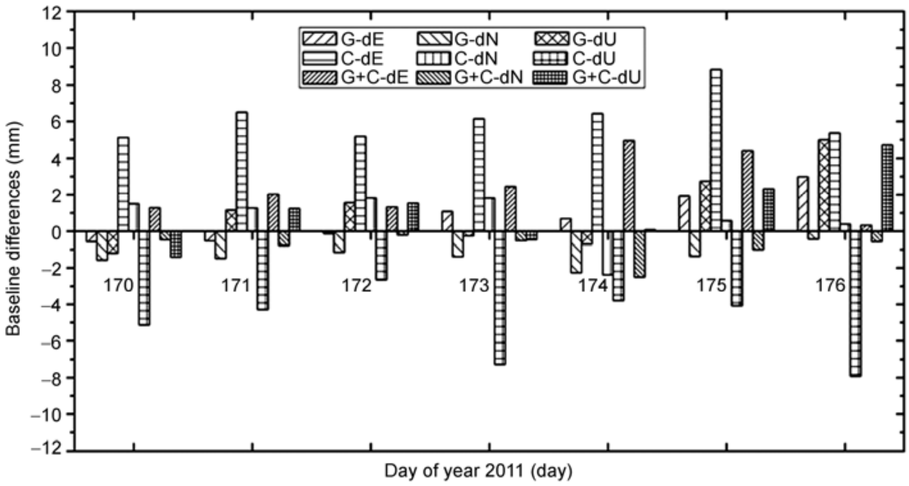

Figure 5 Static mode baseline solutions day by day.

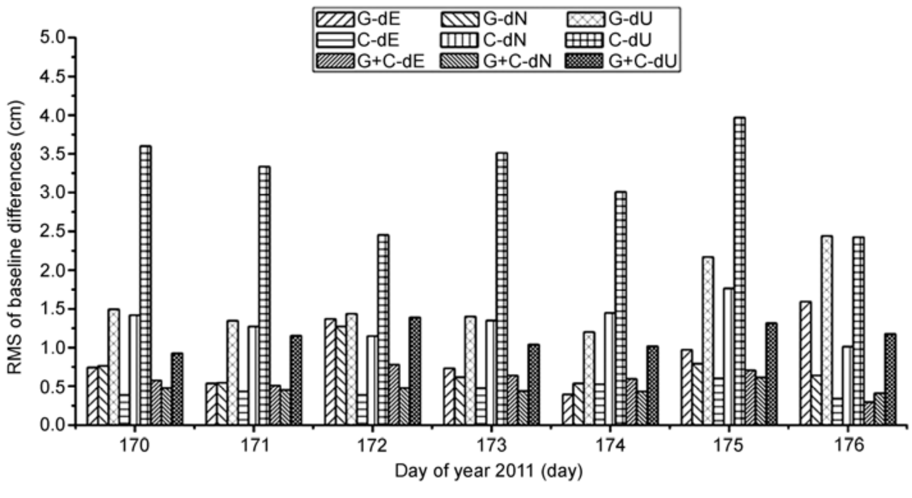

Figure 6 Kinematic mode baseline solutions day by day.

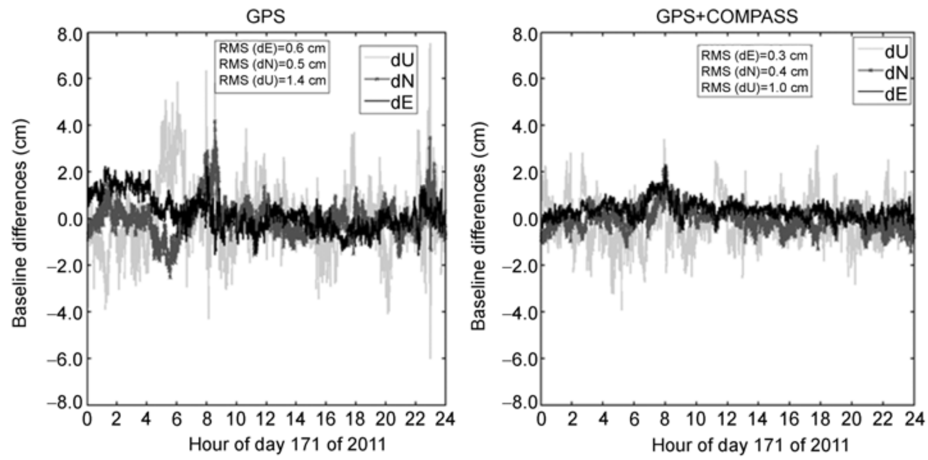

Figure 7 Kinematic mode baseline solutions of Day 171.

broad as it can eliminate or dramatically reduce multiple kinds of error sources in satellite navigation and positioning such as clock offsets of receivers and satellites, and the ambiguity of double-differenced carrier phase observation is integral [13]. Pseudorange differential positioning, usually with meter-level accuracy, can only be applied in navigation and other fields that do not have requirements of high accuracy; real-time carrier phase differential positioning, the accuracy of which can achieve centimeter-level, is often used in surveying and mapping and other high-accuracy fields. To test the accuracy as well as reliability of the Beidou Navigation Satellite System in the current stage, two sets of data are selected for analysis in this section.

(1) Pseudo range and Carrier Phase Differential Positioning in Urban Area (20–30 km)

This experiment uses data from reference stations in the regional trial network of Wuhan. Distribution of these reference stations and the path of the roving station are illustrated in Figure 8.

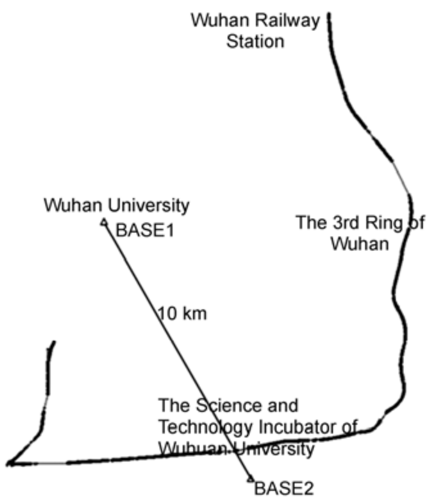

Figure 8 Sites of Reference Stations and the track of the Rover.

Real-time and post resolutions are finished independently as two positioning modes. Accuracy of the resolved coordinates is evaluated with GPS RTK results (horizontal accuracy of 3 cm and elevation accuracy of 5 cm) as reference. Table 3 shows the accuracy of pseudorange and carrier phase differential positioning.

(2) Trans-Provincial (240 km) Pseudo range Differential Positioning Test

Reference station of this test is located at Wuhan University whereas the roving station is vehicle-borne. The basic information of test data is listed in Table 4 and trial of the test path is shown in Figure 9.

Data from the vehicle-borne roving station and reference station are resolved by pseudo range differential positioning and point positioning independently. The results are compared with those of GPS PPP/INS combined method (accuracy of 0.2 m). Accuracy of results in this test is 2.53 m in the horizontal direction and 2.86 m in elevation. The error distribution is given in Figure 10.

It can be drawn from the above tests and positioning results that the accuracy of pseudo range differential positioning of the Beidou Navigation Satellite System is greatly

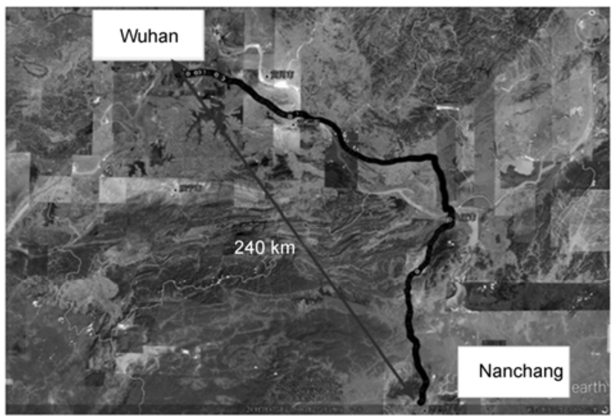

Figure 9 Sites of Reference Stations and the Track of the Rover.

Table 3 Statistic results of differential positioning precision (mean square error as limit error)

Positioning type		Effective/total epochs	Accuracy (m)		
			Horizontal	Elevation	3D
Beidou pseudorange differential positioning	Real-time	956/1255	1.87	3.39	4.10
	Post	2620/2907	0.91	2.31	2.57
Beidou carrier phase differential positioning	Real-time	680/1652	0.04	0.07	0.07
	Post	1930/2907	0.02	0.05	0.06
Post GPS pseudorange positioning		2906/2907	0.66	1.24	1.51

Table 4 Description of test data[a)]

Information	Description	
Reference station	Place	Wuhan
	Receiver	Unicore UB240-CORS
Roving station	Place	Express way from Wuhan to Nanchang
	Receiver	Unicore UB240-CORS
	Motion state	Vehicle-Borne

a) Observation time: 2011-09-15, 9:00 to 20:00.

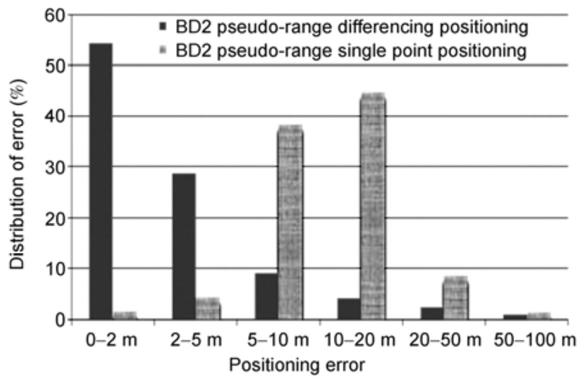

Figure 10 Distribution of the error of pseudo-range differential positioning and SPP.

improved compared to that of pseudo range point positioning in the current stage. Accuracy of Beidou pseudorange differential positioning is better than 2 and 4 m in the horizontal and elevation direction respectively, superior to the 4-m–20-m navigation accuracy of ordinary GPS services. During the initial deployment period of regional Beidou Navigation Satellite System, it is still quite difficult to eliminate various kinds of error sources, so pseudo range and carrier phase differential positioning is an effective tool for improving precise navigation and positioning services of Beidou users.

4 Conclusions

High-accuracy orbit determination as well as navigation and positioning based on the Beidou Navigation Satellite System is realized in this paper with observation data from ‘BEIDOU Experimental Tracking Stations’ and our nation’s independently developed precise data processing software PANDA. The results reveal that radial accuracy of precise orbit determination for Beidou satellites is better than 10 cm; the accuracy of real-time kinematic pseudo range differential positioning can reach 2–4 m, capable of meeting the demands of our domestic navigation users in the near future; the accuracy of statistic PPP, relative baseline positioning and kinematic RTK positioning can achieve centimeter-level, millimeter-level and 5–10 cm respectively, able to satisfy the domestic professional users’ needs in surveying and mapping, national land resources surveying and other fields.

In conclusion, with ground reference network augmentation, the Beidou Navigation Satellite System can provide high-accuracy navigation and positioning that are superior to average GPS services within our nation’s territory. Therefore, it is of critical strategic significance to take full advantage of our nation’s ground satellite navigation reference stations and to set up ground-based augmentation service system for the Beidou Navigation Satellite System.

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