Chapter 41
BeiDou Positioning and Multipath Analysis for Short Baselines

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Abstract In this paper, we carried out GPS and BeiDou relative positioning with our developed software using the real data collected in Beijing and Shanghai, respectively, and assessed the accuracy of single epoch baseline solution of the two systems. For short baseline, the relative positioning accuracies of the two systems are basically the same, and the vertical accuracy of the baseline of BeiDou is better than that of GPS. The solved time series errors mainly contain the multipath error and random noise. We used wavelet filtering to extract multipath error according to the frequency characteristics of the random noise and multipath errors. Subsequently, the analysis of GPS and BeiDou multipath was carried out to find the differences between them. Finally, sidereal filtering based on the orbit characteristics of BeiDou was used to eliminate multipath error and improve the relative positioning accuracy. The results showed that the accuracy of relative positioning for short baselines can improve up to 10 % after the multipath error is filtered out.

Keywords BeiDou · GPS · Relative positioning · Multipath effects · Sidereal filtering

41.1 Introduction

BeiDou Navigation Satellite System is China's global navigation satellite system which has been developed independently. By the end of 2012, a regional navigation satellite system providing service for areas in China and its surrounding areas has

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2013 Proceedings*, Lecture Notes in Electrical Engineering 243,
DOI: 10.1007/978-3-642-37398-5_41,

been established and there are 14 satellites in orbit including 5 geostationary orbit (GEO) satellites, 5 inclined geostationary orbit (IGSO) satellites and 4 median elevation orbit (MEO) satellites. The open service is free to all users with point positioning accuracy of 10 m, timing accuracy of 20 ns and velocity accuracy of 0.2 m/s currently [1]. BeiDou works as the third mature navigation satellite system following the former GPS and GLONASS. With the construction and development of BeiDou system, its data processing and application becomes a hot spot and focus of GNSS positioning. In recent years, numerous studies related to positioning and its error sources using BeiDou system have been carried out by many institutions and scholars. For instance, the error sources such as satellite clock error, ionosphere delay, troposphere delay and multipath error were analyzed and single point positioning was carried out after correcting these errors [2]. Performance of precise point positioning and relative positioning based on BeiDou system were initially assessed and the results are compared and analyzed using real GPS/BeiDou data collected from UR240-CORS Dual-System receivers [3, 4]. In this paper, we carry out GPS and BeiDou relative positioning with our developed software using the real data collected in Beijing and Shanghai, respectively, and assessed the accuracy of single epoch baseline solution using the two systems. Subsequently, sidereal filtering based on the orbit characteristics of BeiDou system are carried out and the positioning accuracy is significantly improved.

41.2 GNSS Baseline Solution Principle

The accuracy of GNSS point positioning will be affected by many factors such as satellite orbit errors, clock errors and signal propagation errors. The relative positioning, which is widely used in precision positioning, can effectively weaken the impact of these errors. The receiver and satellite clock biases can be eliminated using double differenced observations, the equations of pseudo-range and carrier phase read [5]

$$P_{AB}^{ij} = \rho_{AB}^{ij} + (l_B^j - l_B^i)dX_B + (m_B^j - m_B^i)dY_B + (n_B^j - n_B^i)dZ_B + I_{AB}^{ij} + T_{AB}^{ij} + M_P + \varepsilon_P \quad (41.1)$$

$$L_{AB}^{ij} = \rho_{AB}^{ij} + (l_B^j - l_B^i)dX_B + (m_B^j - m_B^i)dY_B + (n_B^j - n_B^i)dZ_B + \lambda_f N_{AB}^{ij} - I_{AB}^{ij} + T_{AB}^{ij} + M_L + \varepsilon_L \quad (41.2)$$

where, P_{AB}^{ij} and L_{AB}^{ij} are the double differenced pseudo-range and carrier phase measurements, the subscript A, B represent stations and superscript i, j represent satellites, A denotes the reference station and i is the reference satellite. dX, dY and dZ represent three coordinate corrections of baseline vectors; l, m and n represent direction cosines of three coordinate components; λ_f is wavelength of f frequency,

N represents ambiguity; I and T represent ionosphere and troposphere delays respectively, which can be neglected when the baseline is short. The double differenced constant term

$$\rho_{AB}^{ij} = \rho_{AB}^{j} - \rho_{AB}^{i} = \rho_{B}^{j} - \rho_{A}^{j} - \rho_{B}^{i} + \rho_{A}^{i} \tag{41.3}$$

where, ρ is the distance between station and satellite. M_P and M_L represent multipath of pseudo-range and phase, respectively. ε_P and ε_L represent the pseudo-range and carrier phase measurement errors respectively. The weight matrix of double differential observations is [6]:

$$\mathbf{P}_s = \frac{1}{2n_s}\left(n_s\mathbf{I}_{n_s-1} - \mathbf{e}_{n_s-1}\mathbf{e}_{n_s-1}^T\right) \tag{41.4}$$

where, **I** and **e** denote diagonal matrix and unit matrix correspondingly. s represent the observation type and n_s represent satellite number of this observation type.

41.3 Data Processing and Analysis

41.3.1 Data Collection

We collected two short baselines data using UB240-CORS BD-2/GPS Dual-System Quad-Frequency (GPS: L1, L2; BD-2: B1, B2) receivers produced by UNICORE Communications Incorporation. One ultra-short baseline in Beijing is 3.0669 m and the observation period is from Nov 8, 2012 to Nov 10, 2012. Another short baseline in Shanghai is 470.3009 m and the observation period is from Nov 8, 2012 to Nov 15, 2012. The sampling interval of all the data is 1 s.

41.3.2 Analysis of Baseline Solution Results Based on Different Systems

By using self-developed BeiDou/GPS data processing software, we calculated all the data. Meanwhile, we also computed the baseline with all the GPS data using Bernese software, which are used as reference values for analyzing the accuracy of our epoch-wise solutions. Figure 41.1 presents the error time series for the short baselines of both BeiDou and GPS in Shanghai at Nov 08, 2012.

The root mean squared (RMS) errors, which are calculated from the error time series of the BeiDou system in Fig. 41.1, are 0.41, 0.30 and 0.71 cm respectively for north (N, *blue*), east (E, *red*) and up (U, *green*) coordinate components; and the RMS errors for the GPS system are 0.33, 0.28 and 1.26 cm respectively. Figure 41.2 illustrates the RMS errors of all day's solutions for the short baselines

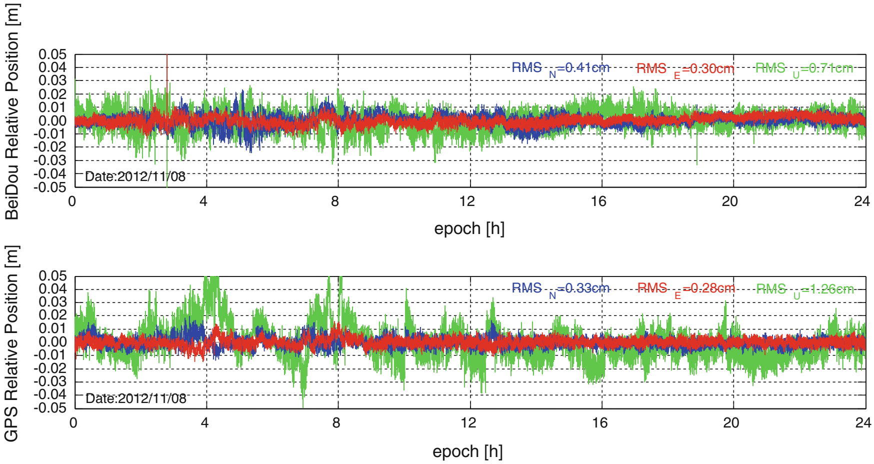

Fig. 41.1 Error time series of BeiDou, GPS baseline of Shanghai station (2012/11/08, 86400 epochs)

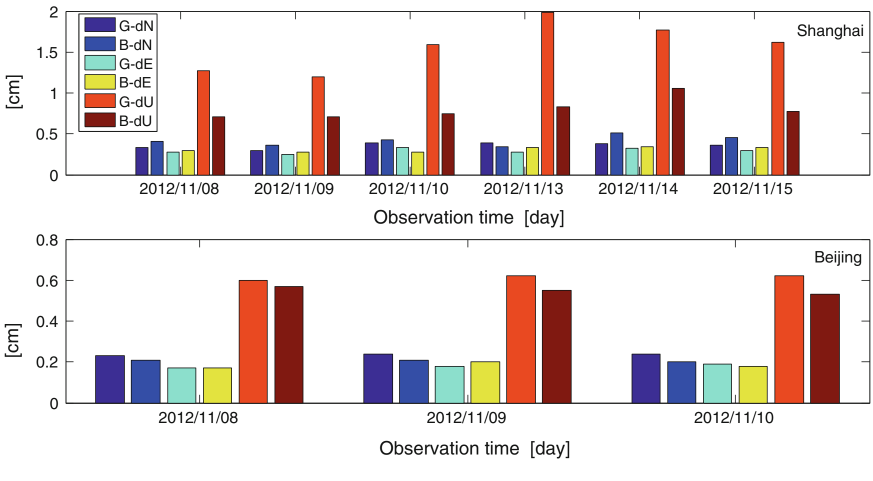

Fig. 41.2 RMS errors of each coordinate components for the baselines in Shanghai (*Up*) and Beijing (*Down*)

both in Shanghai and Beijing. The average RMS errors of the short baseline in Shanghai are 0.36, 0.29, 1.57 cm and 0.42, 0.31, 0.80 cm for the N, E and U coordinate components of GPS and BeiDou systems, respectively. The average RMS errors of the short baseline in Beijing are 0.24, 0.18, 0.61 cm and 0.21, 0.18, 0.55 cm for N, E and U coordinate components of GPS and BeiDou systems, respectively. We find that the relative positioning errors of the two systems are basically at the same level. For the baseline in Shanghai, GPS performs better than BeiDou for the N, E coordinate components but inferior to BeiDou for the U coordinate component; for the baseline in Beijing, BeiDou performs slightly better than GPS for the N, U coordinate components and almost the same for the E coordinate component. In summary, for short baseline, the relative positioning errors of the two systems are basically at the same level for the N, E coordinate components, and the accuracy of BeiDou is better than that of GPS for the U coordinate component, especially in Shanghai, the lower latitude area.

41.3.3 Analysis of DOP Value for Different Systems

In order to compare the difference of satellite constellations between GPS and BeiDou system, we count visible satellites and DOP values of GPS and BeiDou in Shanghai and Beijing on Nov 8, 2012, respectively. The results are shown in Fig. 41.3.

As can be seen from Fig. 41.3, the number of visible satellites of BeiDou (*green*) in Shanghai and Beijing areas are from 6 to 11 and the average numbers are 8 and 7 in Shanghai and Beijing, respectively. While the average numbers of GPS (*blue*) are 8.5 and 9 respectively in Shanghai and Beijing. The number of BeiDou satellites is less than that of GPS, especially in the higher latitudes areas. Because BeiDou constellation consists of three different types of satellites: GEO, IGSO and MEO satellites, there are only two MEO satellites providing services at present and we carried out positioning using GEO + IGSO satellites mode in most times, which causes less visible satellites in higher latitudes areas. The total visible satellites of the two systems (*red*) in Shanghai and Beijing areas are from 13 to 20, therefore, the satellites constellation will be significantly improved when we carry out integrated positioning by using the GPS/BeiDou systems.

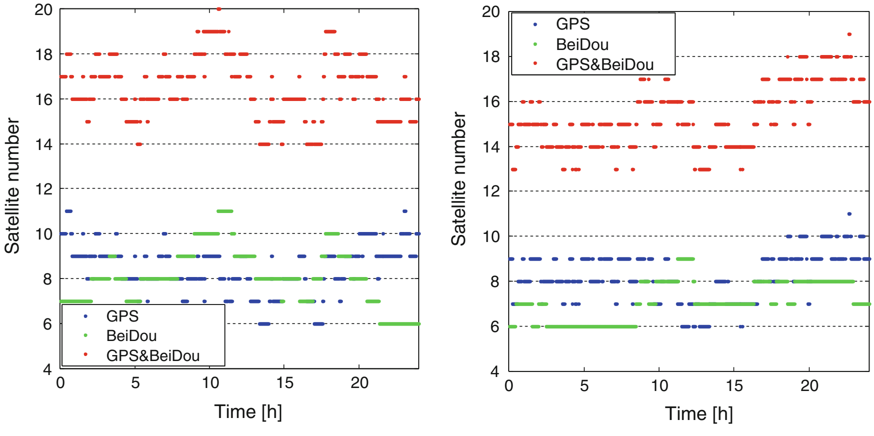

Fig. 41.3 Visible satellite statistics of different systems for Shanghai (*Left*) and Beijing (*Right*) areas

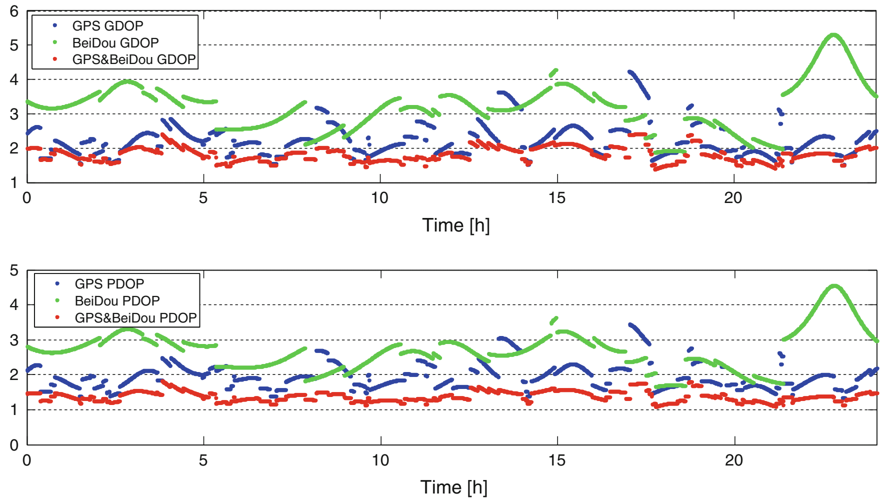

Fig. 41.4 DOP value condition of Shanghai area

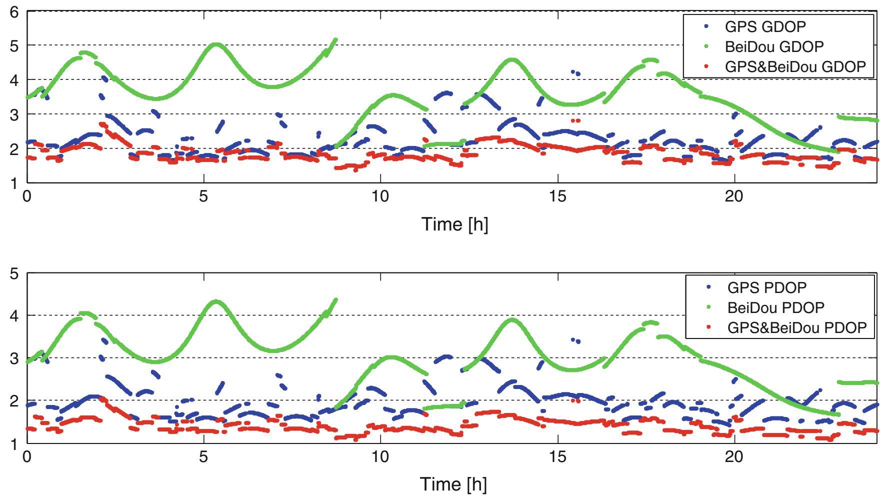

Fig. 41.5 DOP value condition of Beijing area

The DOP values in Shanghai and Beijing areas of the two systems are drawn in Figs. 41.4, 41.5, respectively. Comparing Figs. 41.4 and 41.5, we can find that both the GDOP and PDOP values of BeiDou are larger than that of GPS. The DOP values of BeiDou is large but the alteration trend smooth and consecutive. When a IGSO satellite arise or fall down, the DOP value will vary significantly (As shown 9:00 am in Figs. 41.3 and 41.5).The DOP value will be significantly improved when combine the two systems.

Table 41.1 Statistic of the multipath correlation delay for BeiDou and GPS (Beijing and Shanghai area)

System	Relevant date	Direction	Beijing area		Shanghai area	
			Correlation lag (s)	Max. corr. coefficient	Correlation lag(s)	Max. corr. coefficient
BeiDou	Day1-Day2	N	244	0.513	252	0.622
		E	253	0.455	239	0.573
		U	247	0.469	245	0.501
	Day2-Day3	N	243	0.598	241	0.575
		E	246	0.623	243	0.592
		U	242	0.590	245	0.611
	Day1-Day3	N	491	0.410	490	0.584
		E	487	0.396	483	0.416
		U	488	0.322	485	0.409
GPS	Day1-Day2	N	245	0.712	250	0.663
		E	245	0.675	246	0.683
		U	248	0.757	247	0.766
	Day2-Day3	N	250	0.697	248	0.717
		E	247	0.657	249	0.632
		U	248	0.743	243	0.710
	Day1-Day3	N	488	0.677	485	0.579
		E	491	0.623	493	0.634
		U	488	0.732	487	0.601

41.3.4 Multipath Error Analysis for BeiDou and GPS

The error time series mainly contain the multipath error and random noise. We extract the multipath errors of GPS and BeiDou measurements by using wavelet filtering according to the frequency characteristics of the random noise and multipath errors. Since the observation environment of the permanent stations are not change, the multipath errors must be periodic. We can improve the accuracy of daily baseline solution by filtering the periodic multipath errors. In this example, the single epoch solution of the two systems for Beijing and Shanghai has been carried out using three consecutive days' measurements from Nov 8 to Nov 10, 2012. We use the 10 order daubechies (db10) wavelet to extract the multipath errors according to the low-frequency characteristics from three days' error time series of the N, E and U coordinate components, respectively.

The cross-correlation lags and coefficients between pairs of results are shown in Table 41.1. The cross-correlation lags indicate the shifts from ~239 to 253 s. These shifts are roughly indicative of the sidereal repeat period (~236 s less than 1 solar day), which indicate that the multipath errors significantly exist. As shown in Table 41.1, the correlation coefficients of BeiDou are smaller than that of GPS, which indicates that the change of constellation geometry of BeiDou is more significant than that of GPS. The cross-correlation lag of BeiDou are slightly shorter than that of GPS, and the cross-correlation lag between the adjacent two days is centered at about 240 s, which is longer than the theoretical value 236 s. With the increase of interval days, the max correlation coefficient decrease gradually [7]. For instance, the max correlation coefficient of day1 and day3 is smaller than that of day1 and day2 or day2 and day3. It indicates that the geometry structure of satellites will change at the same place as the increase of interval days.

41.4 Sidereal Filtering Based on Orbit Characteristics of BeiDou

41.4.1 Multipath Period of BeiDou

For a fixed station, the period of satellite-receiver geometry mainly depends on satellites orbit period. We can calculate satellite orbit period according to the broadcast ephemeris, the equation is [8]

$$\begin{aligned} n &= \sqrt{GM}/a^{\frac{3}{2}} + \Delta n \\ T &= 2\pi/n \end{aligned} \tag{41.5}$$

where, $\sqrt{GM}$ is the Earth, a and Δn are the semi-major axis of orbit ellipse and the perturbation of mean velocity, T is orbit period.

GPS constellation only consists of several MEO satellites; the orbit period, which can be calculated with (41.5), is 11 h 58 m. For a fixed station on the Earth, the visible satellites in the sky will be exactly the same after 23 h 56 m 4 s (the sidereal day). Since the multipath errors are related to satellite-receiver geometry, we can mitigate these errors by correct them according to the periodic characteristics, we call this method sidereal filtering [7]. The sidereal filtering has two steps and its implementation requires two or more day's data. The first step is to estimate multipath errors with the measurement of the first day, the second step is to subtract the estimated multipath errors, shifted by one sidereal period (23 h 56 m 4 s), from the estimated positions of the second day [9–11].

We calculate orbit repeat times for all BeiDou satellites with the broadcast ephemerides from Jul. 13 to Aug. 1, 2012, the results are shown in Fig. 41.6.

In Fig. 41.6, the SatID 1-5, SatID 6-10 and SatID 11, 12 are GEO, IGSO and MEO satellites, respectively. We can find that orbit periods of each kind satellite are different, and for one satellite, each day's orbital period is also different. The orbit periods of GEO, IGSO and MEO satellites are 86163, 86162 and 46391 s, respectively, which basically coincide with that of the multipath periods [12]. Namely, GEO, IGSO and MEO satellites appear a period ahead of time 237, 238 and 245 s every day (MEO satellites orbit around the earth 13 cycles every week, taking the 1715 s shift-seconds relative to one week into account, average 245 s for one day and it is basically consistent with the results of GPS).

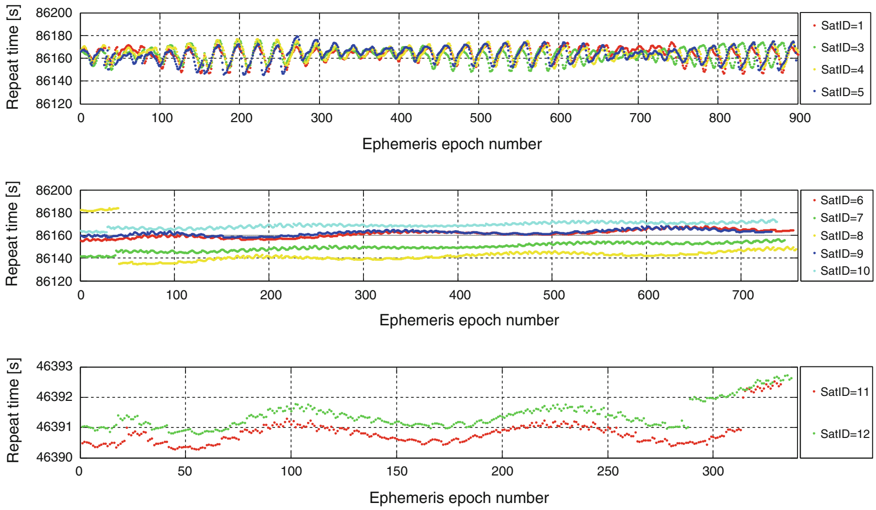

Fig. 41.6 Orbit repeat times found from the broadcast ephemerides of all BeiDou satellites from Jul. 13st to Aug. 1st, 2012 (The broadcast ephemerides interval of BeiDou is 1 h, the ephemerides epoch number in one day are about 24, 19 to 21, 8–10 for GEO, IGSO and MEO satellites, respectively)

41.4.2 Sidereal Filtering Based on Multipath Error Periods of BeiDou

The satellite constellation of BeiDou consists of three different types of satellites: GEO, IGSO and MEO satellites, it contributes to the different orbit periods. So the sidereal filtering based on GPS constellation is not suitable for BeiDou.

We carried out sidereal filtering for baseline solution according to the average orbit period previously obtained. In this example, two consecutive days' dating from Nov 13 to Nov 14, 2012 single epoch baseline solution for the short baselines in Beijing and Shanghai were carried out with BeiDou measurements. The error time series of N, E, and U coordinate components before and after sidereal filtering (2012/11/14) are drawn in Fig. 41.7, and the statistics of baseline solution in Shanghai and Beijing are listed in Tables 41.2 and 41.3 respectively.

From the results, we can find that sidereal filtering partly eliminate period errors related to satellite-receiver geometry, the accuracy of relative positioning for short baselines is significantly improved. This illustrates that this sidereal filtering based on orbit characteristic of BeiDou is useful for improving the daily BeiDou solution of fixed stations.

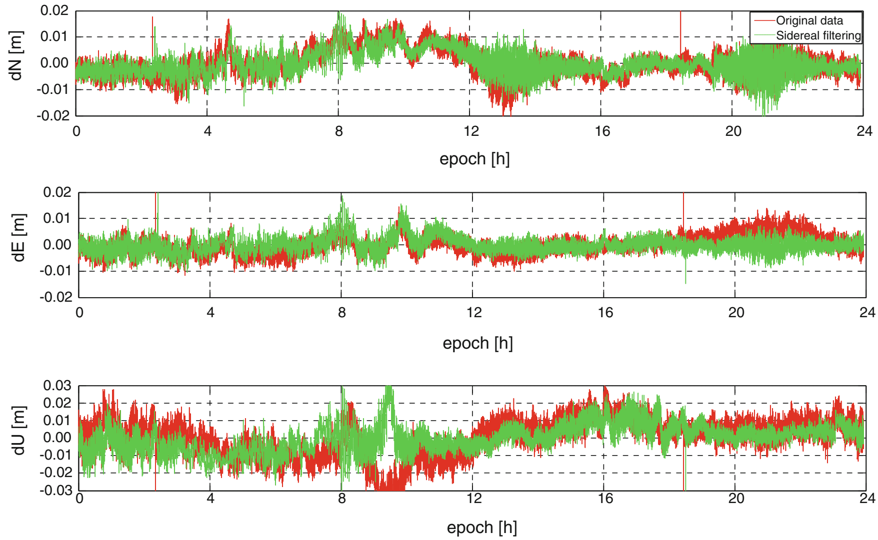

Fig. 41.7 Time series of coordinate error in each orientation before and after sidereal filtering (2012/11/14, Shanghai)

Table 41.2 Results statistics before and after sidereal filtering of Shanghai station

	RMS N (cm)	RMS E (cm)	RMS U (cm)
Original results	0.51	0.34	1.06
Sidereal filtering results	0.43	0.27	0.82
Improvement proportion (%)	15.69	20.59	22.64

Table 41.3 Results statistics before and after sidereal filtering of Beijing station

	RMS N (cm)	RMS E (cm)	RMS U (cm)
Original results	0.23	0.20	0.62
Sidereal filtering results	0.19	0.18	0.55
Improvement proportion (%)	17.39	10.00	11.29

41.5 Conclusions

In this paper, we carry out GPS and BeiDou relative positioning using the real data and assess the positioning performance of the two systems in China. Subsequently, sidereal filtering based on the orbit characteristics of BeiDou is used to eliminate multipath error and improve the accuracy of relative positioning. We can draw the following conclusions from our results:

1. For the two short baselines calculated in this paper, the relative positioning accuracies of the two systems are basically at the same level; the BeiDou can get better accuracy for U coordinate component than GPS.
2. Currently, BeiDou has been able to provide high-precision positioning, its visible satellites keeps about 6–11. Since BeiDou constellation is not yet completed, the average visible satellites are less than that of GPS, and the DOP conditions are inferior to GPS as well.
3. The multipath effect correlation characteristics of BeiDou and GPS are similar to some extends. The periods of multipath of the GEO, IGSO and MEO satellites are 86163, 86162 and 46391 s respectively, which are basically consistent with their orbit periods.
4. Under the circumstance of heavy multipath effect, sidereal filtering based on orbit periods characteristic of BeiDou can significantly improve the accuracy of positioning, which is meaningful to its data processing.

Acknowledgments This work was sponsored by Natural Science Foundation of China (Projects: 41074018). Thanks Li Jianwen, Li Bofeng and Zhu Yongxing for the great support of this paper. Liu Weizhou and Tang Chengpan provided useful guidance during data processing and paper writing. The writers thank UNICORE company for their relevant hardware support.

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