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Precision Processing and Accuracy Evaluation of BeiDou-3 System Data in Beijing

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In response to the current situation where Beijing's benchmark maintenance relies solely on GPS data, we conduct in-depth research on the positioning accuracy of different dual frequency and orbit combinations of the BeiDou system. Gamit software is used to calculate the benchmark station data for seven consecutive days, and we compared the positioning performance characteristics of the BeiDou and GPS systems with different frequency and orbit combinations. The positioning accuracy of the BeiDou system is evaluated from three aspects: standardized root mean square error, baseline repetition rate, and coordinate difference. The results show that in the Beijing area, the positioning accuracy of different frequency combinations of the BeiDou-3 satellite system is higher than that of the BeiDou-2 system. The B1C/B2a frequency positioning accuracy of BeiDou-3 is higher than that of B1I/B3I frequency points, and the orbit combination of MEO+IGSO has the highest positioning accuracy among all combinations. This discovery not only provides new technological options for our city's benchmark maintenance work, but also provides more scientific and accurate surveying and mapping benchmark support for geographic spatial analysis and natural resource management.

1. Introduction

After three important development processes of the BeiDou-1 navigation satellite system (BDS-1), BeiDou-2 navigation satellite system (BDS-2), and BeiDou-3 navigation satellite system (BDS-3), China's independently developed BeiDou Navigation Satellite System (BDS)(1) officially completed the final stage of global network deployment on June 23, 2020, marking the official entry of the BDS system into a new era of global services.(2) The continuous improvement of the BDS system is reflected not only in the combination of different orbit constellations and the upgrading of system composition,(3) but more significantly in the richness and increase of service signals. Compared with the BDS-2 system, which only uses B1I/B2I/B3I frequency signals, the BDS-3 system not only retains the B1I and B3I signals but also introduces new B1C/B2a/B2b frequency signals.(4,5) This change provides a more solid data foundation for multifrequency combination, making the selection of positioning methods more diversified. In

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addition, compared with the BDS-2 constellation, the BDS-3 system significantly increases the number of medium orbit Earth (MEO) satellites. The MEO satellites, with their high-precision orbit determination capability, lower orbital altitude, and rapid changes in satellite geometry,(6) effectively improve the positioning accuracy of the BDS-3 system and provide users with more accurate and reliable navigation and positioning services.(7,8)

Currently, domestic and foreign scholars have analyzed and verified the signal quality, orbit, and positioning performance of BDS systems. Li *et al.*(9) and Yin *et al.*(10) conducted a comprehensive analysis of the B1C/B2a signals of the BDS-3 system satellite and compared them with those of GPS and the Galileo satellite navigation system (Galileo). Guo *et al.* proposed an indicator system for the BDS-3 system that covers four aspects: spatiotemporal benchmark, spatial signal quality, spatial signal accuracy, and service performance.(11) Wang *et al.* used Multi-GNSS system data from tracking stations for data processing, compared and analyzed with GPS and BDS in terms of internal and external compliance accuracy.(12)

As the core support of the capital's basic geographic information framework, the Continuously Operating Reference Stations(13) (CORS) system in Beijing not only undertakes the task of building and maintaining high-precision surveying and mapping benchmarks in the Beijing area, but also provides high-precision location services to users of the city's Real-time Kinematic (RTK) network. In 2022, Beijing successfully completed the BeiDou upgrade and transformation project.(14) This milestone enabled the CORS service system to comprehensively receive, efficiently process, and provide accurate location services for GPS, BDS, and four-system data, greatly enhancing its BeiDou high-precision positioning service capability and level. However, the current data processing for benchmark maintenance in Beijing still mainly relies on GPS single-system data, which, to some extent, limits the timeliness of data and the breadth of services. In view of this, conducting in-depth research on the combination of BDS systems in the field of benchmark maintenance will inject cutting-edge technological power into Beijing's benchmark maintenance system, not only opening up innovative technological paths and solutions, but also significantly improving the accuracy and scientificity of surveying and mapping benchmarks for geographic spatial analysis and natural resource management in Beijing.

2. Data Calculation

2.1 Observation equation

In actual measurement, the error sources that affect positioning accuracy mainly include errors related to the satellites, errors related to signal propagation, and errors related to receivers.(15) In high-precision Global Navigation Satellite System (GNSS) positioning, carrier phase differential measurement is usually used for baseline processing, and double difference observation is used to establish error equations. Double difference observation can eliminate receiver and satellite clock biases, and weaken the effects of tropospheric delay, ionospheric delay, and satellite ephemeris error, while retaining the integer ambiguity of the carrier phase and eliminating calculation parameters, thus shortening the calculation time, especially for short baselines where the atmospheric error reduction effect is significant.(16) Therefore, on the basis of the characteristics of the carrier signal and the effect of errors, the observation equation for carrier phase measurement can be set as

$$L_k^j(t) = \frac{f}{c}\rho_k^j(t) - f[\partial t_k(t) - \partial t^j(t)] - \frac{f}{c}[I_k^j(t) - T_k^j(t)] + N_k^j(t), \tag{1}$$

where j is the satellite, k is the receiver, t is the epoch moment, f is the frequency of the carrier phase, L is the carrier phase observation value, c is the speed of signal propagation (the speed of electromagnetic wave propagation in vacuum is the speed of light), ρ is the geometric distance between the receiver and the satellite, and δt_k, ∂t^j, T_k^j, I_k^j, and N are the receiver clock bias, satellite clock bias, ionospheric delay, tropospheric delay, and integer ambiguity, respectively.

2.2 Experimental design

In our experiment, 17 benchmark stations in the CORS system of Beijing were selected and preprocessed using self-developed preprocessing software. The original T02 format data was converted into Receiver Independent Exchange Format (RINEX) 3.04 version data, conducting quality inspection and analysis at the same time, with a sampling interval of 30 s and a time period of 7 days from July 30 to August 5, 2023.

On the basis of the characteristics of the signal and system compositions of the BeiDou system, combined with the advantages of GAMIT software, high-precision data processing was carried out. Eight control experiments were set up, as shown in Table 1, and experiment 8 (GPS) was introduced as an external comparison to verify the positioning and calculation accuracies of the BeiDou system at different frequencies and orbits. Among them, B1I/B3I frequency points were used in experiments 1, 2, and 4, and all B1c/B2a frequency points were used in experiments 3, 5, 6, and 7. Three inclined geosynchronous orbit (IGSO) satellites, C38, C39, and C40, were removed in experiment 6, and two geosynchronous orbit (GEO) satellites, C59 and C60, were removed in experiment 7.

Table 1
Experiment plan.

Experiment	Satellite system	Frequency combination	PRN number
Experiment 1	BDS-2 system	B1I/B2I	1–16
Experiment 2	BDS-3 system	B1I/B3I	17–60
Experiment 3	BDS-3 system	B1c/B2a	17–60
Experiment 4	BDS-2/3 system	B1I/B3I	1–60
Experiment 5	BDS-2/3 system	B1c/B2a	1–60
Experiment 6	BDS-3 system MEO+GEO	B1c/B2a	17–60 except C38, C39, C40
Experiment 7	BDS-3 system MEO+IGSO	B1c/B2a	17–60 except C59, C60
Experiment 8	GPS system	L1/L2	1–32

2.3 Solution strategy

We use the high-precision GNSS data processing software GAMIT (v10.76) for baseline processing. Because the software is not yet able to process multiple system data simultaneously, the same processing parameters are used for the baseline processing of GPS and BDS single systems separately. After the baseline calculation is completed, network adjustment is carried out in conjunction with Wuhan University's COSA software to obtain the relative positioning results of the eight experiments.

3. Precision Analysis

3.1 Normalized root mean square error (NRMSE)

NRMSE can describe the degree of deviation between the baseline solution value and its weighted average per unit time.[17] From the data in Fig. 1, it can be concluded that Experiment 4 [BDS system (B1I/B3I)] has the smallest root mean square error and a higher starting accuracy, followed by Experiment 2. The results show that the NRMSE of B1I/B3I signals is lower than that of B1c/B2a. The NRMSEs of all experiments were less than 0.24, indicating that the BDS system achieved the expected solution quality, the set solution strategy was correct, and there were no issues such as a large number of unrepaired cycle jumps or incorrect starting coordinates of the measurement station.

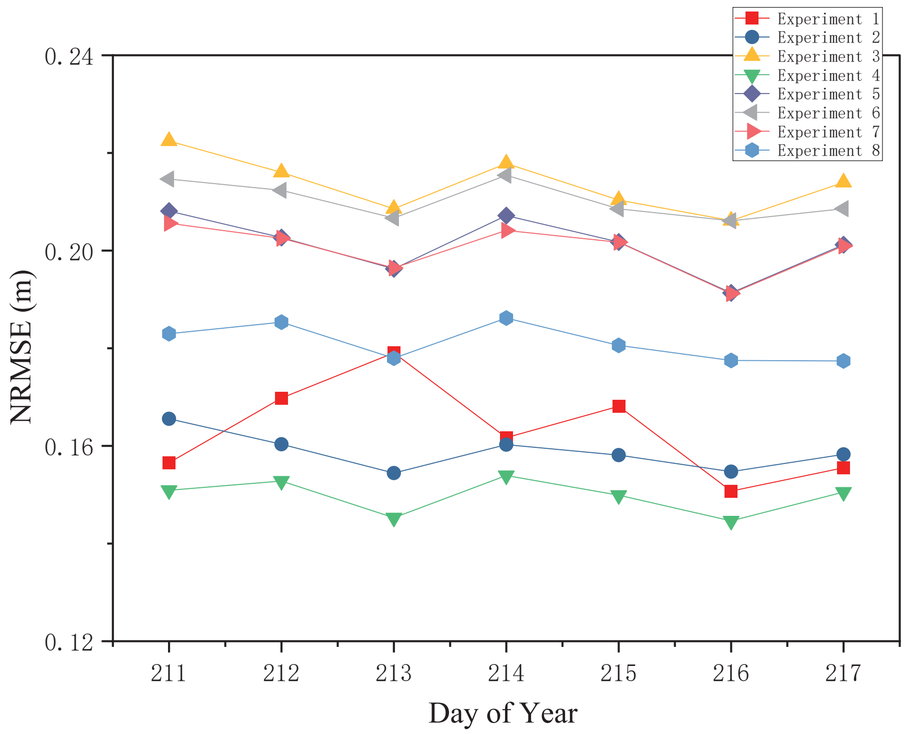

Fig. 1. (Color online) NRMSEs of different schemes.

3.2 Baseline repeatability test

The baseline repetition rate R is an important indicator for evaluating baseline solutions and reflects the accuracy of baseline compliance. The smaller its value, the higher the accuracy of baseline compliance and the higher the baseline quality. Conversely, the lower the accuracy of baseline compliance, the worse the quality.(18)

$$R = \sqrt{\left[\frac{\frac{n}{n-1}\sum_{i=1}^{n}\frac{(C_i - C_m)^2}{\sigma_{C_i}^2}}{\sum_{i=1}^{n}\frac{1}{\sigma_{C_i}^2}}\right]} \tag{2}$$

Here, n is the total number of observation periods for the same baseline, C_i is a component or edge length of the baseline for a certain period of time, $\sigma_{C_i}^2$ is the variance of the C_i component corresponding to the time period i, and C_m is the weighted average of each time period.

Table 2 shows the fixed and proportional errors for the eight experiments. Among all directions, experiment 7 [BDS3 system MEO+IGSO orbit (B1c/B2a)] had the smallest average values, which were 1.34, 1.49, 6.33, and 1.47 mm, respectively. Experiment 5 had the second highest average values, which were 1.53, 1.69, 6.75, and 1.68 mm, respectively. The values in experiment 1 (BDS-2) were significantly larger than those in the other experiments and not of the same order of magnitude, indicating that the accuracy of the BDS-2 baseline solution was the lowest. The baseline repetition rates in the six experiments with the BDS-3 system were at the millimeter level in both horizontal and length components, while in the vertical component, it was slightly less accurate, with most of the baselines having slightly lower accuracies. The repetition rate can reach the centimeter level, which is comparable to the accuracy of GPS systems. Therefore, according to the baseline component repetition rate results, all eight experiments meet the requirements for baseline solution accuracy.

Table 2
Baseline repetition rates.

Experiment	Fixed error *a* (mm)				Scale error *b*			
	N	E	U	L	N	E	U	L
Experiment 1	4.45	6.94	20.11	5.65	9.4×10^{-9}	2.3×10^{-9}	9.7×10^{-8}	4.8×10^{-10}
Experiment 2	2.19	2.27	7.89	2.37	3.6×10^{-9}	7.8×10^{-9}	1.0×10^{-8}	4.8×10^{-9}
Experiment 3	2.05	2.17	7.38	2.27	3.9×10^{-9}	6.8×10^{-9}	9.9×10^{-9}	4.4×10^{-9}
Experiment 4	1.70	2.10	6.69	2.09	3.8×10^{-9}	5.9×10^{-9}	1.3×10^{-8}	4.1×10^{-9}
Experiment 5	1.53	1.69	6.75	1.68	4.3×10^{-9}	3.1×10^{-9}	1.1×10^{-8}	3.0×10^{-9}
Experiment 6	1.76	2.30	6.73	2.16	4.5×10^{-9}	6.3×10^{-9}	6.8×10^{-9}	4.8×10^{-9}
Experiment 7	1.34	1.49	6.33	1.47	4.3×10^{-9}	3.7×10^{-9}	9.9×10^{-9}	2.8×10^{-9}
Experiment 8	1.63	2.49	7.05	2.23	4.8×10^{-9}	1.3×10^{-9}	2.1×10^{-8}	1.5×10^{-9}

3.3 Evaluation of mean square error in coordinate points

Considering that some benchmark stations in Beijing are located in subsidence areas and their coordinates do not have long-term stability, in this study, we consider the positioning results of the GPS system as reference truth values and calculate the difference between them and the coordinates adjusted by various experiments. Subsequently, the maximum, minimum, and average values in the *X*, *Y*, and *Z* directions were calculated, and the root mean square error was further used to analyze the positioning accuracy of each benchmark station. Table 3 shows the differences in location between 17 benchmark stations and GPS systems in seven experiments, with data measured in millimeters.

From the analysis results of three sets of experimental data (Experiment 1: BDS-2 system; Experiment 2: BDS-3 system; Experiment 4: BDS system; all based on B1I/B3I frequency points), it can be clearly observed that the BDS-3 system exhibits a significantly higher positioning accuracy than the BDS-2 system at most stations. Specifically, the maximum point difference of the BDS-2 system at the XIJI station reached 42.12 mm, while the average value of the overall measurement station was 17.09 mm. In contrast, the BDS-3 system had a significantly improved positioning accuracy, with an average difference reduction of 37.21% and a root mean square error reduction of 40.87%. However, when the BDS-2 and BDS-3 systems were used in combination in Fig. 2, although the number of observed satellites increased, this did not lead to further improvement in accuracy. Instead, it resulted in a 16.40% increase in average difference

Table 3
Accuracy evaluation of point mean square error.

Station	Experiment 1 (mm)	Experiment 2 (mm)	Experiment 3 (mm)	Experiment 4 (mm)	Experiment 5 (mm)	Experiment 6 (mm)	Experiment 7 (mm)
BISM	12.73	14.64	4.71	10.66	4.37	4.21	4.11
BJCP	11.45	14.01	3.91	14.64	3.23	4.18	3.90
BJHR	23.53	11.65	3.83	14.46	5.60	3.83	5.93
BJTZ	18.57	10.52	1.97	13.32	3.13	1.88	3.59
CHAO	41.63	24.41	4.18	25.74	4.93	3.40	4.43
CHPN	6.48	4.92	15.61	5.30	16.54	14.58	15.99
DAXN	9.65	14.80	18.64	21.88	13.36	18.32	12.63
DSQI	9.11	10.33	12.69	6.57	8.69	11.90	7.62
MYUN	26.82	11.08	3.65	11.86	4.32	3.23	4.70
NKYU	8.42	15.40	3.90	23.51	8.77	3.35	8.27
NLSH	6.65	3.14	14.94	4.94	15.47	15.07	15.74
PING	18.64	1.53	3.94	1.69	4.92	3.85	5.07
SHIJ	22.04	8.99	3.67	9.57	3.11	3.95	3.81
XIJI	42.12	7.72	21.85	12.43	8.40	18.42	6.66
XNJC	6.02	9.38	3.43	11.67	2.12	2.66	1.33
YIZH	12.72	14.32	3.80	17.98	4.63	3.44	4.60
YQSH	13.90	5.53	4.25	6.06	4.35	4.65	4.30
Maximum	42.12	24.41	21.85	25.74	16.54	18.42	15.99
Minimum	6.02	1.53	1.97	1.69	2.12	1.88	1.33
Average	17.09	10.73	7.59	12.49	6.82	7.11	6.63
Root mean square error	20.26	11.98	9.79	14.12	8.07	9.12	7.81

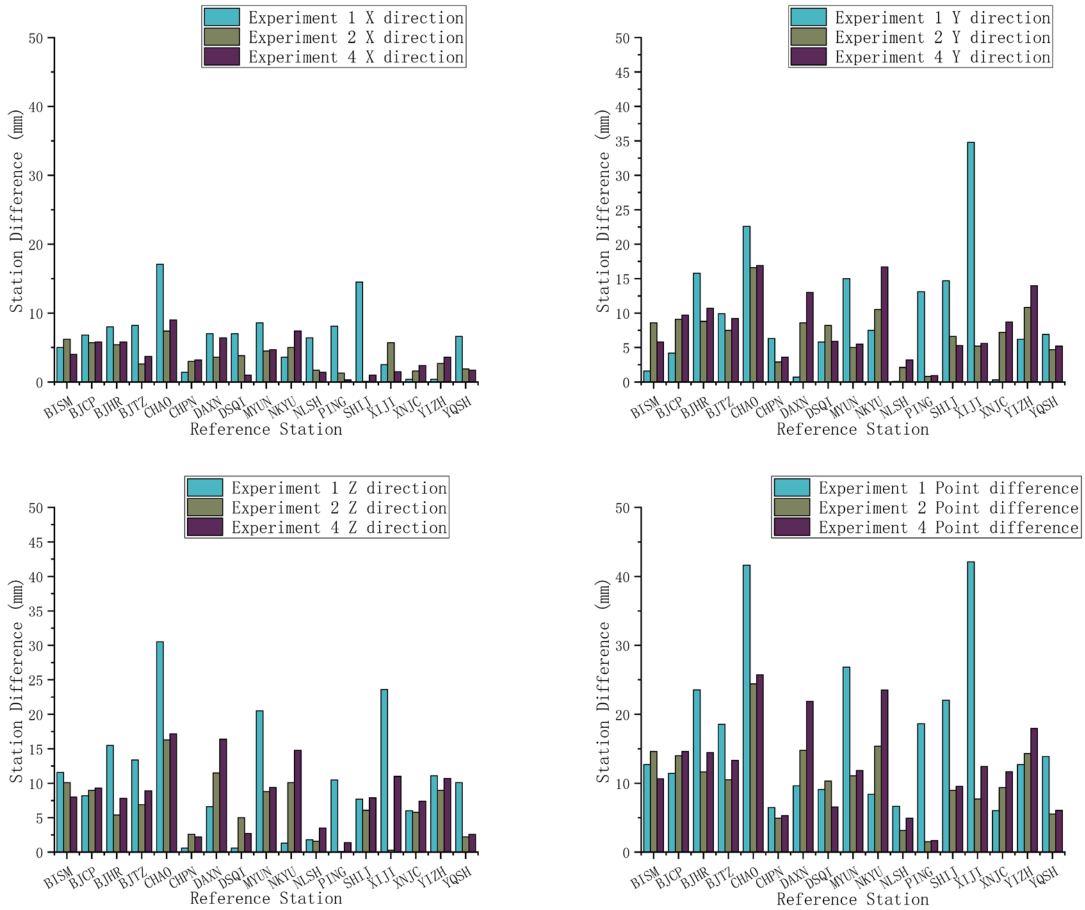

Fig. 2. (Color online) BDS system difference statistics.

and a 17.86% increase in root mean square error compared with using the BDS-3 system alone. This result indicates that in the Beijing area, the BDS-3 satellite system has a higher positioning accuracy for different frequency combinations than does the BDS-2 system.

Some scholars have tested the data quality and positioning performance of the BeiDou-3 positioning system at different frequencies, and the results show that the B1C/B2a dual-frequency ionospheric free combination positioning is superior to the B1I/B3I dual-frequency positioning.[19,20] From the data in Fig. 3, two sets of experimental data were selected for this study, it can be clearly observed that the B1c/B2a frequency points exhibit a significantly higher positioning accuracy than the B1I/B3I frequency points in most measurement stations. The maximum point difference of B1I/B3I frequency points at the CHAO station reached 24.41 mm, while the average value of the overall measurement station was 10.73 mm with a root mean square error of 11.98 mm. In comparison, B1c/B2a frequency points improved the positioning accuracy, with an average difference reduction of 29.26% and a root mean square error reduction of 18.28%. The results indicate that in the Beijing area, the B1c/B2a frequency signals of the BDS-3 system have a stronger anti-interference ability and a higher positioning accuracy.

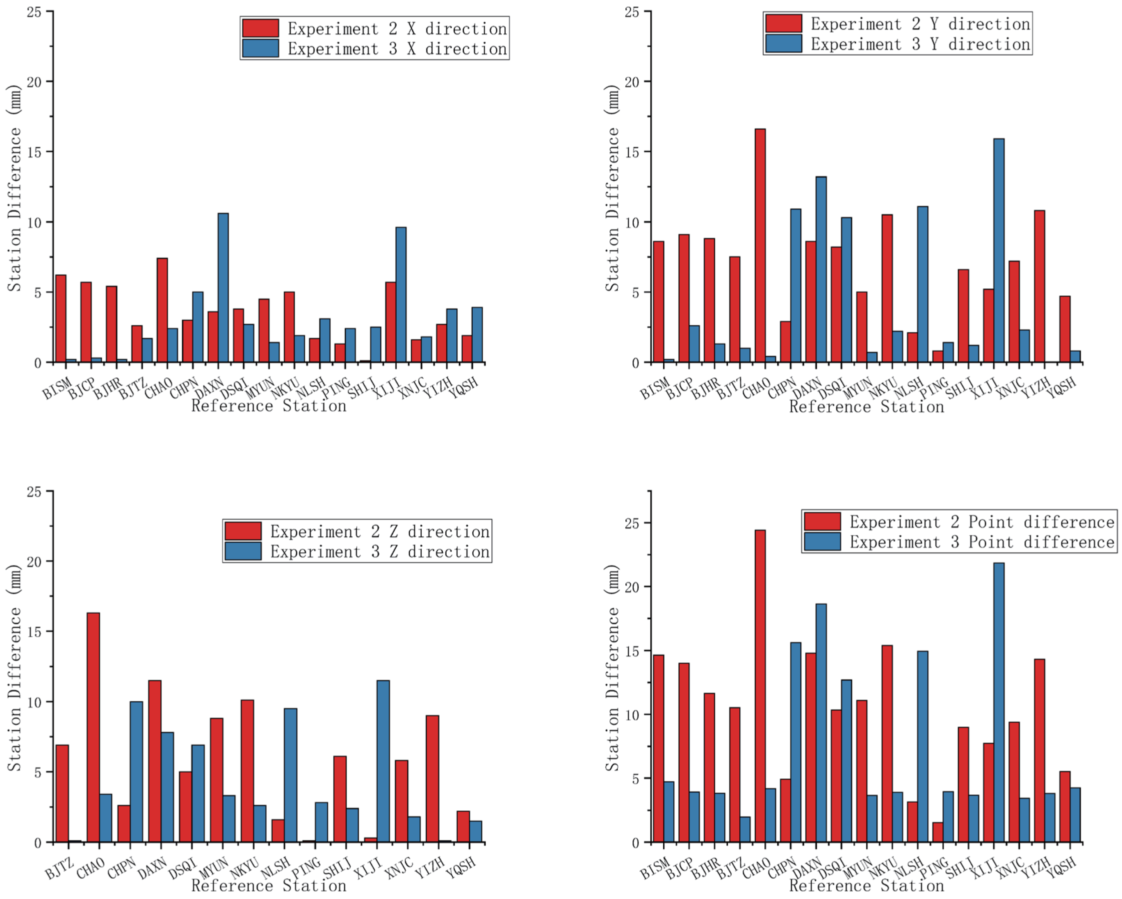

Fig. 3. (Color online) Statistics of differences between different frequency points.

After a detailed comparison of three sets of experimental data (experiment 3: MEO+IGSO+GEO of the BDS-3 system; experiment 6: MEO+GEO of BDS-3 system; experiment 7: MEO+IGSO of BDS system; all based on B1c/B2a frequency points), it was found that the root mean square error of all experiments remained below 8 mm. Although the MEO+GEO+IGSO combination produced the maximum point difference (21.85 mm) at the XIJI station, the average point difference of the overall station was 7.59 mm and the root mean square error was 9.79 mm. From the data in Fig. 4, compared with the MEO+GEO combination, although the positioning accuracy was not improved significantly, the average difference decreased by 6.32% and the root mean square error also decreased by 6.84%, demonstrating a certain optimization effect. Therefore, the MEO+IGSO combination performed the best in positioning accuracy, with an average difference reduction of 6.75% and a root mean square error reduction of 14.36%.

In summary, although there are slight differences in errors under different track combinations, the overall performance of each station shows a high degree of stability. In the Beijing area, the MEO+IGSO combination, in particular, stands out with the highest positioning accuracy and is the optimal track combination choice.

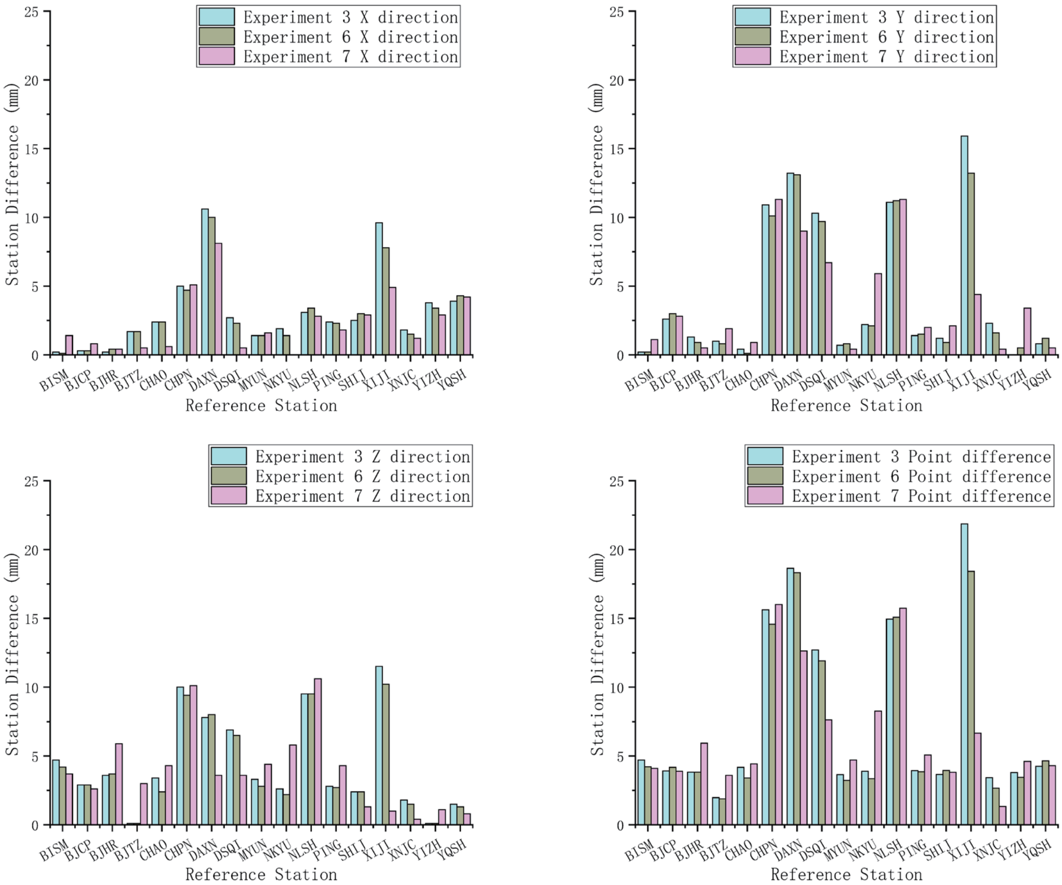

Fig. 4. (Color online) Statistics of differences in different orbits.

4. Conclusion

We deeply explored the characteristics of the BeiDou satellite system in multifrequency and multiorbit fusion applications. By using GAMIT and COSA software to evaluate the eight sets of experimental data, the relative positioning accuracy of the BDS system under different frequency settings and orbit types is comprehensively evaluated from three aspects: NRMSE baseline repeatability, and GPS coordinate difference. The comprehensive analysis results showed that in the Beijing area, the BDS-3 system demonstrated a significantly superior positioning accuracy with its more abundant observation satellite resources. Specifically, the B1c/B2a frequency signals of the BDS-3 system, with their enhanced anti-interference ability, further improved the accuracy of positioning. In addition, although different track combinations exhibited slight differences in station errors, the overall performance was stable and reliable. The MEO+IGSO combination stood out among all tested track combinations and was the optimal track combination choice.

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