Accuracy Evaluation of BeiDou Coordinate System Alignment to ITRF Using BDS Single-System Observation Data: Postprint

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Abstract

Using BeiDou observation data from October 2019 to March 2020, daily station coordinates were obtained to realize the BeiDou Coordinate System (BDCS) and align it with ITRF2014. The accuracy of the BDS observation data processing results was evaluated using station coordinates derived from single-day GPS observation data and those provided by the International GNSS Service (IGS). The comparison results indicate that the mean RMS difference between station coordinates solved using BDS data and the single-day station coordinates provided by IGS is less than 1 cm, while the mean RMS difference with station coordinates solved from single-day GPS data is less than 1.5 cm. The dispersion of station coordinate time series solved using BDS data is relatively large, and a preliminary analysis of its causes was conducted. Additionally, GPS observation data was employed to preliminarily estimate the velocity field of monitoring stations in the China region. With the stable operation of the BeiDou Navigation Satellite System and the accumulation of BeiDou observation data in the future, it is expected that higher-precision station coordinates and velocities, as well as improved alignment of BDCS to ITRF, will be obtained.

Full Text

Accuracy Evaluation of Aligning the BeiDou Coordinate System to ITRF2014 Using BeiDou Single-System Observation Data

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Abstract

Using BeiDou observation data from October 2019 to March 2020, we obtained daily station coordinates and realized the BeiDou Coordinate System (BDCS) aligned to ITRF2014. The accuracy of the BDS-based solutions was evaluated using both GPS-derived station coordinates and IGS-provided station coordinates. The results show that the root-mean-square (RMS) of coordinate differences between BDS solutions and IGS-provided coordinates is less than 1 cm, while the RMS difference between BDS and single-system GPS solutions is less than 1.5 cm. The coordinate time series derived from BDS data exhibit relatively large scatter, for which we provide a preliminary analysis. Additionally, we preliminarily estimated the velocity field for Chinese regional monitoring stations using GPS observations. With the stable operation of the BeiDou Navigation System and continued accumulation of BeiDou observation data, higher-precision station coordinates, velocities, and BDCS alignment to ITRF are expected in the future.

Keywords: BeiDou Navigation Satellite System; BeiDou Coordinate System; International Terrestrial Reference Frame

1 Introduction

On July 31, 2020, the BeiDou Navigation Satellite System (BDS) began providing seven types of services globally and in surrounding regions [?]. Satellite-broadcast navigation services include meter-level positioning, navigation, and timing (PNT) services globally; decimeter-level satellite-based augmentation services; and decimeter-to-centimeter-level precise point positioning services in China and surrounding areas [?, ?, ?, ?]. Unlike other GNSS systems, the BeiDou-3 ground monitoring stations are primarily distributed within China, meaning their geographic coverage cannot span the globe, which affects satellite orbit determination, timing, and global service provision. To address this, inter-satellite link equipment is installed on satellites to utilize bidirectional inter-satellite measurements that separate relative satellite clock errors from relative geometric distances, decoupling satellite orbits and clock errors. These inter-satellite distances are then used as observations, combined with ground measurements, for joint satellite-ground and inter-satellite orbit determination, thereby achieving measurements beyond Chinese territory [?, ?, ?, ?, ?]. Chen et al. [?] evaluated the BeiDou-3 basic navigation service performance, showing that with inter-satellite link data, broadcast ephemeris user range error is better than 0.1 m, broadcast clock parameter prediction accuracy is better than 1.5 ns, and space signal accuracy is better than 0.6 m.

High-precision stable services and interoperability of navigation systems depend on the accuracy of reference frame realization and maintenance. Typically, satellite navigation systems use observation data from ground monitoring stations for precise satellite orbit determination and time synchronization processing to generate navigation messages and provide global PNT services. The purpose of establishing and maintaining a navigation system space datum is to accurately determine and predict the positions and velocities of monitoring stations in a unified Earth reference frame. This is achieved by using space geodetic methods to obtain precise epoch coordinate estimates for monitoring stations, then using time series analysis methods to model station motion and estimate linear and nonlinear model parameters to maintain the terrestrial reference frame. The accuracy of epoch coordinate estimation is related to satellite orbit precision and measurement models, while reference frame maintenance accuracy depends on station motion modeling precision.

Currently, the four major satellite navigation systems (GPS, GLONASS, Galileo, and BDS) all use satellite geodetic techniques for monitoring station coordinate estimation and achieve high-precision space datum and system interoperability through periodic alignment with the International Terrestrial Reference Frame (ITRF) [?]. Due to differences in ground station distribution, station construction conditions, and observation methods among navigation systems, specific methods for space datum realization and maintenance vary. The U.S. GPS coordinate system WGS84 benefits from globally uniform station distribution and mature GPS measurement and dynamic models. Global uniform station distribution helps eliminate the impact of regional overall motion on global reference frame maintenance accuracy, while mature GPS processing methods include unified system parameters and refined antenna phase center models. These comprehensive reference frame processing methods ultimately achieve high-precision alignment and long-term maintenance between WGS84 and ITRF, with differences between WGS84 (G1762) and ITRF2008 at the 1 cm level [?, ?]. The Galileo coordinate system GTRF20V02 (Galileo Terrestrial Reference Frame) aligns with ITRF2014 with accuracy better than 1 cm [?, ?, ?]. The GLONASS coordinate system PZ-90 (Parametry Zemli 1990) aligns with ITRF2014 with accuracy better than 2 cm [?, ?, ?, ?].

Since 2013, the BeiDou Satellite Navigation System has used the China Geodetic Coordinate System 2000 (CGCS2000) [?, ?, ?]. With the construction of the global BeiDou system, BeiDou service expanded from regional to global coverage. Beginning in December 2017, the BeiDou Navigation System adopted the BeiDou Coordinate System (BDCS) [?]. Wei et al. [?] and Wu [?] conducted four separate GPS observation campaigns at BeiDou monitoring stations, using GPS data from 64 globally distributed IGS stations and 8 Chinese regional stations to first realize BDCS and align it with ITRF2014, achieving 1 cm station coordinate accuracy and 2 mm/yr velocity accuracy. Shi et al. [?] used combined GPS and BDS data from the IGS/MGEX global observation network to study BDCS establishment and maintenance methods, achieving millimeter-level station coordinate estimation using BeiDou-2 observation data. The BeiDou-2 system primarily provided positioning, velocity measurement, timing, and short-message communication services for the Asia-Pacific region, with 5 GEO, 7 IGSO, and 3 MEO satellites, covering mainly the Asia-Pacific region.

With the launch of BeiDou-3 global services, the number of satellites in orbit has increased to 3 GEO, 3 IGSO, and 24 MEO satellites, with coverage extended globally. Therefore, the feasibility and accuracy of realizing BDCS using BeiDou single-system satellite data require further investigation. From January 1 to March 31, 2019, GPS observations from over 120 globally distributed stations (including IGS stations and BeiDou regional monitoring stations) were used to realize and align with ITRF2014 at millimeter-level accuracy [?, ?, ?, ?]. Since the current observation data time span is short (< 2.5 years), precise station velocities cannot be estimated [?]. Therefore, BDCS adopts a high-frequency update cycle (1 year), continuously monitoring each monitoring station during the update period to maintain millimeter-level BDCS accuracy.

Currently, both CGCS2000 and BDCS are realized and maintained through GPS observation data rather than relying on BeiDou single-system observations. Based on this, we first use single-system GPS observations from BeiDou regional monitoring stations, China Mainland Tectonic Environment Monitoring Network (CMONOC) stations, and globally distributed IGS and iGMAS stations from January 2019 to April 2020 to realize a global reference frame aligned with ITRF2014. IGS-provided daily station coordinates are used to validate the calculation method. Then, using single-system BeiDou observations from BeiDou regional monitoring stations and globally distributed IGS and iGMAS stations from October 2019 to March 2020, we preliminarily attempt to obtain precise epoch station coordinate estimates, realize BDCS, and align it with ITRF2014. The accuracy is assessed using both GPS-derived station coordinates and IGS-provided coordinates.

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2 Data Processing Methods

We use the GAMIT/GLOBK software [?] for GNSS data processing. Stations are divided into several subnets, with a certain number of stable stations selected as common stations in each subnet. Each subnet estimates parameters including satellite precise orbits, atmospheric parameters, polar motion, UT1, and coordinates to obtain daily station coordinate solutions. For IGS stations with ITRF2014 coordinates, these are used as initial coordinates; other stations use single-point positioning coordinates as initial values. The a priori precision of IGS core stations is 5 cm, while other stations have 100 m a priori precision. After obtaining daily loose solutions from all subnets, we employ an instantaneous epoch alignment method based on Kalman filtering [?] to combine daily loose solutions from all subnets through a minimum constraint approach for each epoch, obtaining precise station epoch coordinate estimates and realizing the instantaneous epoch BeiDou coordinate system. By constraining IGS core station ITRF2014 coordinates, station coordinates are aligned to ITRF2014. The minimum constraint method ensures no overall translation, rotation, or scale change between reference station coordinate differences and prior coordinates in the least squares sense [**?**]. Helmert transformation is typically used for conversion between different reference frames. Whether to use 7/14 parameters or 6/12 parameters for transformation between different reference frames remains internationally debated [**?**, **?**]. Considering that other navigation systems use 7 parameters, we adopt 7 parameters for system compatibility and interoperability. The instantaneous epoch frame alignment to ITRF process is shown in Figure 1 [Figure 1: see original paper], and the analysis models used in GAMIT/GLOBK are listed in Table 1 .

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3 Accuracy Assessment of Global Reference Frame Alignment to ITRF2014 Using GPS Data

To verify the accuracy and reliability of the single-system BDS results presented in Chapter 4, we first use single-system GPS data from globally distributed stations to estimate precise epoch station coordinates and velocities, realizing a global reference frame aligned with ITRF2014. The accuracy is evaluated using IGS-provided station coordinate series.

3.1 Data and Station Distribution GPS data from 220 stations were used from January 1, 2019 to April 20, 2020, including BeiDou regional monitoring stations, globally distributed IGS stations, CMONOC stations, and iGMAS stations. The station distribution is shown in Figure 2 [Figure 2: see original paper]. For long-term monitoring of regional stations, collocated CMONOC and iGMAS stations near each regional monitoring station were also included in the solution. Based on the observation stations used in BDCS (2019V01), additional IGS stations capable of receiving BeiDou-3 satellite observations were added. Precise orbit and clock files were obtained from IGS (https://cddis.nasa.gov/). The 220 stations were divided into 6 subnets, with 40 stable IGS core stations as common stations in each subnet. The loose constraint solution method, models, constraint standards, and ITRF2014 alignment method are as described in Chapter 2. Figure 3 [Figure 3: see original paper] shows the daily number of effective stations, the number of constrained stations for ITRF2014 alignment, and the number of observed satellites. The number of daily observed stations was about 160 in early 2019, increasing to about 200 by March 2020. From August 2019, the number of stations increased because some BeiDou regional stations were initially unstable, but as they became stable over time, more regional stations and observation data participated in the solution. The smaller number of effective observed stations (<150) in some epochs was also caused by fewer regional stations. The number of effective daily ITRF2014-constrained stations is 25-40, and the number of observed satellites is 30, 31, or 32.

3.2.1 Coordinate Time Series of Collocated Stations From 260 CMONOC GNSS stations, the station nearest to each regional monitoring station was selected as a collocated station to assess the long-term stability of regional stations. Taking the Beijing area as an example, there are 4 collocated stations in this region. Figure 4 [Figure 4: see original paper] shows the coordinate time series for each station, where BJFS (SHAO) is the BJFS station from this solution, BJSH is a CMONOC station, BJF1 is an iGMAS station, 3012 is a regional monitoring station, and BJFS (IGS) is the BJFS station from IGS solutions. For easy comparison, each station is offset by 10 mm in the horizontal direction and 20 mm in the vertical direction. The figure shows good consistency in horizontal and vertical coordinate time series among the 5 stations, with obvious trend changes in the horizontal direction. Figure 5 [Figure 5: see original paper] shows coordinate time series for 4 collocated stations in Inner Mongolia, where the vertical direction exhibits nonlinear characteristics.

3.2.2 Station Coordinate Residual RMS IGS-provided daily station coordinate values (https://cddis.nasa.gov/) from January 1, 2019 to April 19, 2020 were used to verify the accuracy of the 98 IGS station coordinates from this solution. Figure 6 [Figure 6: see original paper] a) shows the time series of the ABPO station coordinates from this solution and IGS-provided daily solutions; Figure 6 b) shows the coordinate differences between the two series, which agree well. Figure 7 [Figure 7: see original paper] shows the RMS statistics of coordinate differences in E, N, and U directions for 98 stations, with mean RMS values of 1.8 mm in the E direction, 1.8 mm in the N direction, and 4.3 mm in the U direction. These results demonstrate that the repeatability of IGS station coordinates from GPS data is better than 1 cm.

For BeiDou regional monitoring stations, since the observation time span is short (<2.5 years), we analyze station coordinate accuracy by removing linear trend terms. Figure 8 [Figure 8: see original paper] shows the coordinate time series for a regional monitoring station (3172). Figure 9 [Figure 9: see original paper] shows the RMS statistics of residuals after trend removal for 35 regional monitoring stations, with mean RMS values of 1.9 mm in the E direction, 2.2 mm in the N direction, and 8.2 mm in the U direction. These results indicate that the repeatability of regional monitoring station coordinates from GPS data is better than 1 cm.

3.3 Station Velocity Field The GPS observation data used in this study span a short period (470 days), so only linear terms are considered to obtain station velocities through linear fitting. IGb14 station velocities are derived from over 20 years of GPS observations, with nonlinear modeling accounting for annual, semi-annual, seismic, receiver, and antenna changes to obtain precise station velocities. Therefore, we use IGb14-provided station velocities as the standard to evaluate the accuracy of the 98 IGS station velocities from this solution. Figure 10 [Figure 10: see original paper] shows velocity differences for 98 stations, where vSHAO represents velocities from this study, vIGS represents velocities from linear fitting of IGS-provided daily coordinate series, and vIGb14 represents IGb14-provided velocities. The RMS difference between vSHAO and vIGS is within 2 mm/yr, while the difference with vIGb14 is within 2 mm/yr horizontally and about 3 mm/yr vertically. In Figure 10 b), stations KOUR (sta = 40) and OUS2 (sta = 60) show large horizontal velocity differences from IGb14, primarily due to receiver changes on October 9, 2019 and September 25, 2019, respectively.

For BeiDou regional monitoring stations, since collocated stations from other observation networks near them also participated in the solution, we assess regional monitoring station velocity accuracy through collocated station velocities. Table 2 shows velocity values for collocated stations in the Beijing area, including BJSH (CMONOC station velocity), BJF1 (iGMAS station velocity), BJFS (IGS) (velocity from linear fitting of IGS-provided daily coordinate series), 3012 (regional monitoring station velocity), BJFS (SHAO) (BJFS station velocity from this solution), BJFS (ITRF2014) (ITRF2014-provided BJFS velocity), and BJFS (IGb14) (IGb14-provided BJFS velocity). Comparisons of BJFS (SHAO) with BJFS (ITRF2014) and BJFS (IGb14) show that the short observation time span affects velocity estimation accuracy by about 1 mm/yr horizontally and 2 mm/yr vertically. The difference between BJFS (SHAO) and BJFS (IGS) is about 1 mm/yr in the N direction and about 2 mm/yr in the E and U directions. Stations 3012 and BJF1 have relatively poor velocity accuracy in the E and U directions due to missing observation data and lack of analysis and modeling of nonlinear motion in the station series.

Figure 11 [Figure 11: see original paper] shows the horizontal velocity field for collocated stations in China (blue and red arrows represent stations from two different observation networks). Most stations show good consistency in horizontal velocity trends, with relatively large differences at some stations caused by short observation time spans. For example, in the upper left blue box, the red arrow station has 450 days of observations while the blue arrow station has only 105 days.

Station velocity comparisons show differences between this solution's velocity field and IGb14 and ITRF2014 velocities. A primary reason is the short observation time span (470 days) and the fact that seasonal terms, jumps from tectonic and non-tectonic movements, post-seismic deformation, and other deformations were not considered in velocity calculations. Blewitt and Lavallee [?] demonstrated that observation data must span at least 2.5 years to obtain precise station velocities. Therefore, as observation data increase and various nonlinear factors are precisely considered for each station, velocity accuracy will improve.

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4 Accuracy Assessment of BDCS Alignment to ITRF2014 Using BeiDou Single-System Data

Using BeiDou observations from globally distributed stations from October 1, 2019 to March 19, 2020, we realized BDCS aligned to ITRF2014 and compared the results with the single-system GPS solutions from Chapter 3 and IGS-provided station coordinates.

4.1 Data and Station Distribution When processing BeiDou single-system observations, orbit and clock products were obtained from iGMAS (http://www.igmas.org/). Since precise clock products for BeiDou B1I and B3I signals were not available before October 1, 2019, we selected 209 globally distributed stations capable of receiving BeiDou B1I and B3I frequency observations from October 1, 2019 to March 19, 2020, including BeiDou regional monitoring stations, globally distributed IGS core stations, and iGMAS stations, as shown in Figure 12 [Figure 12: see original paper].

The 209 stations were divided into 5 subnets, with 40 IGS14 core stations capable of receiving BeiDou-3 observations selected as common stations in each subnet. The loose constraint solution method, models, constraint standards, and ITRF2014 alignment method are as described in Chapter 2. Figure 13 [Figure 13: see original paper] shows the number of effective stations per epoch, the number of constrained stations for ITRF2014 alignment, and the number of observed satellites. In October 2019, about 150 stations were effectively observed per epoch, increasing to about 200 by March 2020. The number of ITRF2014-constrained stations increased from about 25 to about 40, and the number of observed satellites increased from about 20 to about 30. These statistics indicate that as time progresses, more global stations can receive BeiDou-3 satellite observations, and more effective observation data and satellites are available.

4.2.1 Regional Monitoring Station Coordinate Residual RMS We analyzed the coordinate accuracy of 31 regional monitoring stations using the RMS of residuals after removing linear terms from station coordinate time series. Figure 14 [Figure 14: see original paper] a) shows the coordinate time series and fitted linear trend for station 3172, while Figure b) shows the residual time series after trend removal. Figure 15 [Figure 15: see original paper] shows the RMS statistics of residuals after linear term removal for 31 regional monitoring stations. Most stations have horizontal RMS less than 5 mm and vertical RMS less than 8 mm, with mean RMS values of 4.4 mm in the E direction, 3.4 mm in the N direction, and 7.9 mm in the U direction. These results demonstrate that the repeatability of regional monitoring station coordinates from BeiDou single-system data is better than 1 cm.

4.2.2 IGS Station Coordinate Residual RMS We evaluated the accuracy of IGS station coordinates using IGS-provided station coordinates. Figure 16 [Figure 16: see original paper] shows the time series of ABPO station coordinates from this solution, IGS-provided daily solutions, and the coordinate differences between them. The two time series show consistent trends, but the scatter of station coordinate time series from BDS data is significantly larger. Figure 17 [Figure 17: see original paper] shows the RMS of coordinate differences between the 126 IGS stations from this solution and IGS-provided coordinates, with mean RMS values of 5.96 mm in the E direction, 4.5 mm in the N direction, and 12.5 mm in the vertical direction. These results indicate that the repeatability of IGS station coordinates from BeiDou single-system observations is about 1 cm.

In addition to evaluating IGS station coordinate accuracy using IGS-provided coordinates, we assessed the BDS results using GPS-derived station coordinates from Chapter 3. Figure 18 [Figure 18: see original paper] shows the time series of ABPO station coordinates from BDS and GPS data and their differences. The two time series show consistent trends, but the scatter of BDS-derived station coordinate time series is larger. Figure 19 [Figure 19: see original paper] shows the RMS statistics of coordinate differences between 106 stations (IGS and regional monitoring stations) from BDS and GPS data. Most stations have coordinate difference RMS less than 1 cm horizontally and less than 2 cm vertically, with mean RMS values of 7.0 mm in the E direction, 4.8 mm in the N direction, and 13.8 mm in the U direction. These results indicate that the difference between single-system BDS and single-system GPS station coordinate solutions is better than 1.5 cm.

As noted, Figures 16 and 18 show that BDS-derived station coordinate time series match well with both GPS-derived and IGS-provided daily coordinate time series in terms of trends, but the scatter is larger. To explain this, we conducted comparative analyses using several different observation datasets and precise orbit products, as shown in Table 3 . Case 1 uses BDS observations from 209 stations with BDS precise orbit products from iGMAS (the method used in this section). Case 2 uses GPS observations from the same stations and time span as Case 1, with GPS precise orbit products from iGMAS. Case 3 uses GPS observations from the same stations and time span as Case 1, with GPS precise orbit products from IGS. Case 4 uses IGS-provided daily station coordinate solutions (SINEX format) as a reference standard to evaluate the other three solutions.

Figure 20 [Figure 20: see original paper] shows the ABPO station coordinate time series from Cases 2, 3, and 4. The scatter of station coordinate time series for both Case 2 and Case 3 is slightly larger than for Case 4. Figure 21 [Figure 21: see original paper] a) shows the RMS statistics of coordinate time series differences between Cases 2 and 3 for 140 IGS stations, with mean RMS less than 4 mm horizontally and 5.3 mm vertically. Cases 2 and 3 use the same GPS observations but different precise orbit products from iGMAS and IGS, respectively. The results indicate that iGMAS orbit products have comparable accuracy to IGS orbit products, consistent with iGMAS evaluation results [**?**]. Figure 21 [Figure 21: see original paper] b) shows the RMS statistics of coordinate time series differences between Cases 3 and 4 for 125 IGS stations, with mean RMS less than 4 mm horizontally and 6.2 mm vertically. Cases 3 and 4 use the same GPS observations and IGS precise orbits, but IGS uses relatively more stations, and each analysis center simultaneously solves for satellite orbits and clocks, with gross errors eliminated through IGS analysis center combination. Therefore, the scatter of Case 4 station coordinate time series is relatively smaller.

Figure 22 [Figure 22: see original paper] a) shows the ABPO station coordinate time series from Cases 1 and 2. The scatter of both time series is larger than for Case 4, with a relatively larger difference between Case 1 and Case 4. Cases 1 and 2 use BDS and GPS observations, respectively, with precise orbits both from iGMAS. Therefore, the differences primarily arise from different satellite system data and corresponding analysis models. Figure 22 [Figure 22: see original paper] b) shows the RMS statistics of coordinate differences between Cases 1 and 2 for 140 IGS stations, with mean RMS within 7 mm horizontally and 13.7 mm vertically. This indicates that BeiDou system analysis models, observation data quality, satellite coverage, and relatively fewer available satellites are additional reasons for the larger scatter in station coordinate time series. As more BeiDou observation data and available satellites become available, we will conduct more detailed and in-depth analyses of the specific reasons.

4.2.3 Helmert Transformation Parameters Analyzing Helmert transformation parameters between a reference frame and ITRF can investigate the self-consistency and stability of reference frame alignment. Figure 23 [Figure 23: see original paper] shows the 7-parameter time series for each epoch's reference frame alignment to ITRF2014, obtained by constraining IGS core stations using both BDS and GPS data. In Figure 23 a), Tx, Ty, and Tz are translation parameters, and the bottom panel shows the scale time series. Figure 23 b) shows the three rotation parameter time series. The 7-parameter time series from single-system GPS data is more stable, while that from BDS data shows larger scatter, particularly during October and November 2019. This may be due to the early operational stage of BeiDou-3, with relatively few available satellites and observation data, or may be caused by current errors in the BeiDou navigation system, such as satellite phase center models and solar radiation pressure models, introducing unstable errors into the 7 parameters. As the BeiDou system operates more stably and observation data accumulate, we will conduct more detailed and precise analyses of the seven transformation parameters.

5 Conclusions

Using BeiDou observations from BeiDou regional monitoring stations and IGS stations from October 1, 2019 to March 19, 2020, we preliminarily attempted to realize epoch BDCS aligned to ITRF2014 and estimate precise station coordinates for each epoch. Using GPS observation results from January 1, 2019 to April 20, 2020 and IGS-provided daily station coordinate time series, we evaluated station coordinate accuracy. The main results are as follows:

1. The repeatability of IGS and regional monitoring station coordinates from single-system GPS data is better than 1 cm.
2. The mean RMS of coordinate differences between BeiDou single-system solutions and IGS daily solutions is less than 1 cm, while the mean RMS of coordinate differences between single-system BDS and GPS solutions is less than 1.5 cm. The coordinate time series show consistent trends. For regional monitoring station coordinate time series from BeiDou single-system data, the mean RMS of residuals after removing linear velocities is better than 1 cm.
3. The scatter of station coordinate time series from BeiDou single-system data is relatively large, which may be related to frame station distribution and BDS satellite data quality. The epoch 7-parameter time series for BDCS alignment to ITRF2014 from BeiDou single-system data also shows large scatter, possibly due to errors in the BeiDou navigation system, limited available satellites, and insufficient observation data. As the BeiDou system operates more stably and observation data accumulate, more detailed analyses will be conducted.
4. We preliminarily realized regional station velocity field estimation using GPS data. With data accumulation, high-precision velocity estimation using BeiDou single-system data is expected.
5. With stable BDS operation, we anticipate achieving higher-precision and more stable reference frames by comprehensively using BDS, GPS, and Galileo data in the future.

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Note: Figure translations are in progress. See original paper for figures.