Cheng *et al. Satell Navig* (2021) 2:2
https://doi.org/10.1186/s43020-020-00032-w

Satellite Navigation
https://satellite-navigation.springeropen.com/

ORIGINAL ARTICLE **Open Access**

Update China geodetic coordinate frame considering plate motion

Pengfei Cheng[1], Yingyan Cheng[1*], Xiaoming Wang[2] and Yantian Xu[1]

Abstract

China Geodetic Coordinate System 2000 (CGCS2000), as the formal national coordinate reference frame, has been used for 20 years. The coordinates of all Global Navigation Satellite System (GNSS) stations in China need referring to this system. To this end, the first step is to align the coordinates of all stations, usually included in a regional GNSS network, with a given International Terrestrial Reference Frame (ITRF), then these coordinates are corrected to the CGCS2000 in consideration of plate movement. For a better alignment result, regional control stations are needed and their coordinates were estimated from the combination of constraint-free normal equation systems provided by several International GNSS Service (IGS) analysis centers. The effect in using these refined coordinates, which determine a regional coordinate datum, on the alignment result should be evaluated by the coordinate corrections of the regional control stations to the regional coordinate datum, i.e. smaller corrections mean better alignments of the two associated frames. The test results show that the refined coordinates are more accurate than the ones calculated from the station's velocity, and are well aligned with the ITRF2005. Moreover, for obtaining the coordinates of GNSS stations in an updated CGCS2000 frame, a gridded linear velocity field based on the estimated velocities at 1025 CGCS2000 stations was generated for mainland China using the optimal interpolation method, the inverse distance weighting, which is selected from five interpolation methods. The overall precisions of the constructed velocity field at all stations in the East (*E*) and, North (*N*) directions are 0.78 mm/a and 0.95 mm/a, respectively. For evaluating the accuracy of the updated CGCS2000 frame, monthly solutions for the coordinates of some CGCS2000 CORS stations in the ITRF2014 during the period from 2000.0 to 2018 were obtained and the Root Mean Square (RMS) of the differences between the coordinates corrected to the CGCS2000 and the known coordinates at these stations are about 2–3 cm.

Keywords: Optimal reference frame alignment, Frame agreement, China's grid velocity, CGCS2000 update

Introduction

China Geodetic Coordinate System 2000 (CGCS2000) was released on July 1, 2008 (Chen 2008) as the formal national reference frame. It was defined in the International Terrestrial Reference Frame (ITRF) 97 at the reference epoch 2000.0 and maintained using 2600 Global Navigation Satellite System (GNSS) geodetic reference stations distributed over China (Cheng et al. 2008). There are several newer ITRFs (Altamimi et al. 2002, 2012), shown in Table 1, which need to be considered in the CGCS2000 transformation. The CGCS2000 is a static frame and maintained by the coordinates of all GNSS stations, which are usually estimated from the observations in different times and referred to different ITRFs, transformed to the CGCS2000 frame.

A few approaches have considered the plate motions in the transformation of the coordinates of a regional GNSS network from an ITRF to the CGCS2000. Two common ones are as below. The first approach is using the seven transformation parameters at a given epoch, obtained from the parameters at the reference epoch, and their rates between the ITRF and ITRF97 (Wang 2020), together with the movement velocities of the selected stations. The second one is tightly constraining the coordinates of some stations to their known coordinates in the

---

*Correspondence: 504827709@qq.com; yycheng@casm.ac.cn
[1] Chinese Academy of Surveying and Mapping, 28 Lianhuachi West Road, Beijing 100036, China
Full list of author information is available at the end of the article

Table 1 Information on the ITRFs released after the ITRF97

Version	GPS week	Duration
ITRF2000	1043–1399	12 2 2001–11 4 2006
ITRF2005	1400–1585	11 5 2006–5 30 2010
ITRF2008	1586–1800	5 31 2010–1 20 2016
ITRF2014	1801–	1 21 2016–

CGCS2000 (Liu et al. 2014). The first approach cannot achieve high accuracy of the transformed coordinates, because of the limited velocity precision of the stations. The second approach does not consider plate motions, leading to some distortion of the regional network.

In this study, to obtain accurate positions of GNSS stations in the CGCS2000, two steps are normally carried out. The first step is to process the observations of the GNSS stations to obtain their coordinates at the observation epoch in their associated ITRF. The second step is to correct the coordinates obtained above to the reference epoch 2000.0 using a plate motion model or a linear velocity field in mainland China. If the above ITRF is not the ITRF97, additional transformation into the ITRF97 is needed using the transformation parameters at the epoch 2000 and their rates between the two ITRFs.

In the first step, for the alignment of a regional GNSS network with an ITRF, regional control stations are needed. Currently, the most common method is to select the International GNSS Service (IGS) stations in the region and its surrounding areas, even their movement trends do not agree with the corresponding plates. Moreover, the coordinates of the regional control stations at the observation time are obtained based on their velocities provided in ITRF documentation. Thus the obtained coordinates are the mean positions of the stations in the period from the reference epoch to the observation epoch, which are likely different from the real positions of the stations at the observation time.

In the second step, to obtain the coordinates of GNSS stations in the CGCS2000, the quasi-stable adjustment method is used, which uses some selected CGCS2000 reference stations as the control stations for strongly tying the two associated frames. However, if a regional GNSS network covers different plates, which have different movement directions and magnitudes, the above adjustment can distort the network. To overcome this problem, the following procedure of three steps was carried out in this study. The first step is determining the criteria for the selection of global control stations for the quasi-stable adjustment in the ITRF, which only selects the stations that well represent the geometric relationship between the two associated frames. The second step is estimating the positions of the selected control stations at the observation epoch from a combined adjustment based on the constraint-free normal equation systems provided by several IGS analysis centers, for a better alignment between the two associated ITRFs with the GNSS stations and the control stations. The third step is correcting the above-obtained coordinates to the reference epoch 2000.0 using a plate motion model or the linear velocity field in mainland China developed in this study.

The purpose of this paper is to introduce optimal methods or strategies for aligning a regional network to an ITRF and updating the CGCS2000 coordinates of stations by considering plate movement, to avoid the network distortion due to incorrect method. The detailed procedure for aligning the regional network with an ITRF includes two steps. The first step is to select control stations considering consistent of their movement with their corresponding plate. The second step is to obtain the coordinates of the stations of the regional network in the associated ITRF under control of the selected control stations. For updating the regional CGCS2000 frame, additional step is needed, to transform the coordinates of the stations in the ITRF to the CGCS2000 using their velocities and seven transformation parameters between the associated ITRFs.

This paper is organized as follows. Section 2 introduces the strategies for aligning the Chinese regional GNSS network with the ITRF2005, including the determination of the criteria for the selection of GNSS reference stations as the control stations of the Chinese regional network and the refinement of the coordinates of the selected reference stations in the ITRF2005. In Sect. 3, the common interpolation methods for constructing a new gridded velocity field in mainland China are compared and analyzed, and the accuracy of the updated CGCS2000 based on the movements obtained from the newly constructed gridded velocity field is evaluated. Section 4 gives summary and conclusions.

Strategy for aligning the Chinese regional GNSS network with an ITRF

In GNSS data processing, the single-day solutions are obtained using the GAMIT or Bernese software, then some reference stations are selected as control stations and used in a multi-day combined adjustment for aligning a regional network with an ITRF. Since GNSS single-day solutions can be obtained with most of the professional software packages, in this section we focus on the strategies for selecting control stations and obtaining their refined coordinates.

Selection of control stations

It is the common practice that a new ITRF is aligned with its previous one by applying the no-net-translation and no-net-rotation conditions from transformation parameters in the global well distributed core stations that are commonly used for the maintenance of the two ITRFs, and then the coordinates of these stations in the new ITRF are estimated by a combined adjustment with the minimal constraints. The seven transformation parameters and their rates between the two ITRFs are estimated by the least squares method based on the coordinates of these core stations. However, if the frame of a regional GNSS network is aligned with an ITRF, it is unlikely to use the same core stations as the ones used in the ITRF, e.g. like the case that some of the core stations have no observations or have bad observations during the period of investigation. Thus the global control stations, which determine a reference coordinate datum, are selected to better represent the relationship between the two frames. These global control stations are used as control stations for a global combined adjustment to estimate the coordinates of all the global stations used in the adjustment for the ITRF construction. To align the regional GNSS network tightly with the ITRF, regional control stations can be selected from the global control stations selected above for a regional combined adjustment. The strategy for the selection of such a group of global control stations is proposed in this study. Since the International Terrestrial Reference System (ITRS) is defined as an earth-fix coordinate system, all GNSS stations are assumed to fix on the earth crust and have the same movements theoretically. However, the earth crust comprises several plates, which have different movement trends and magnitudes, thus regional GNSS stations are most likely to move with their corresponding plates. Based on this reasoning, a plate-fixed coordinate system is proposed in this study for a better alignment of a regional GNSS network with the ITRF. In contrast to the general criteria for the selection of the ITRF stations, i.e. only based on the precisions of the coordinates and/or velocities of the stations, we take into account the characteristics of the plate movements in addition to applying the general criteria for selecting initial candidates. Among the initial candidate stations only those whose motions are consistent with the corresponding plate movements are selected as the global control stations. A statistic method, called supervised clustering, is employed to identify the consistency between the movements of the stations and the plate. This can ensure that all selected control stations are in a stable area of the plate so that they can well represent the real movement of the plate.

The procedure for the selection of global control stations is as follows. Two sets of velocity data, one obtained from the NNR-NUVEL-1A model and the other from an ITRF combined solution, which can be downloaded from the ITRF website, are used to estimate the seven transformation parameters for each plate between the two associated frames with the two sets of data using the least squares method; then the supervised clustering method is used to identify the stations to be excluded, whose velocity or azimuth residuals are larger than their two sigma values. A test on the selection of Chinese national control stations was conducted. 92 stations were selected from the initial 126 global IGS candidate stations and used in the estimation of the refined coordinates of the global GNSS network, from which the regional control stations were further selected for the estimation of Chinese national velocity field. Figure 1 shows the distribution (red stars) of the 92 stations, along with the other global IGS stations (blue dots) in the ITRF2005 frame. For the detailed procedure refers to (Cheng et al. 2020).

Coordinate refinement of regional control stations

Similar to the selection of global control stations for the determination of the coordinate datum of a global GNSS network, regional control stations are needed in multi-day combined adjustments for the regional network and aligning the regional network with the associated ITRF. In this study, for the adjustment of the Chinese GNSS network, among the 92 global control stations selected above, only the stations within the Chinese region and its surrounding areas were chosen as the regional control stations. For the evaluation of the alignment of the regional network with the ITRF, the corrections of the coordinates of these regional control stations with respect to their prior coordinates, i.e. the known coordinates were used as an indicator. In this study the known coordinates were referred to the refined coordinates of the stations estimated in the global combined adjustment. The smaller the corrections, the better the alignment accuracy is. The coordinates of the regional control stations, which determine the regional coordinate datum for the regional combined adjustment, can be estimated through the combination of constraint-free normal equation systems obtained from several IGS analysis centers, or obtained based on the station velocities at the reference epoch, provided in ITRF documentation. Hereafter, the two datum or frames constructed are named Epoch Reference Frame (ERF) and Derived Reference Frame (DRF), respectively. The former represents the real position of each station at a given epoch, while the latter is the mean position of the station in a period of time, and their differences can reach several centimeters. The differences are mainly caused by the site's non-linear movement driven by geophysical mechanism, such as seasonal changes, position jumps, high-frequency loads

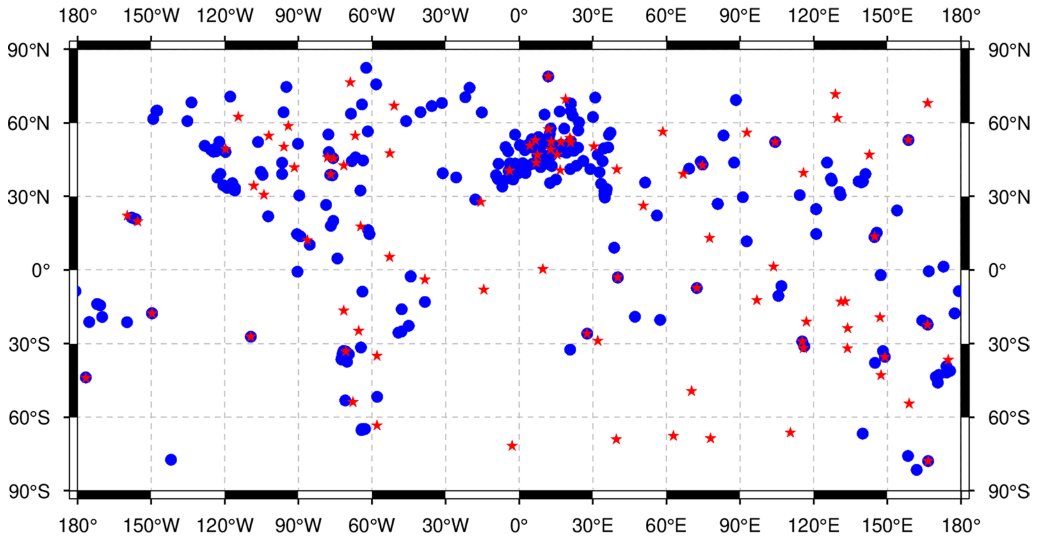

Fig. 1 Distribution of all global IGS stations, of which 92 were selected as the GNSS control stations (red stars) for the estimation of the national velocity field in China

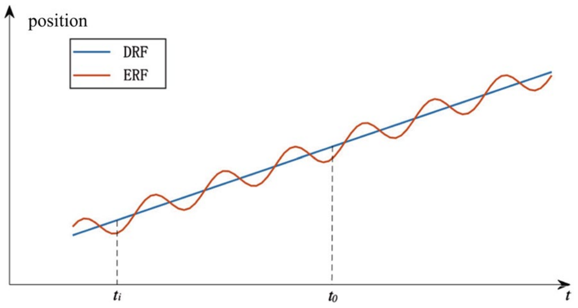

Fig. 2 Position of a station in two frames in a 2-year period

or post-seismic behavior. To clarify this, Fig. 2 shows the positions of a station in the ERF (red curve) and DRF (blue straight line) in a 2-year period.

Another strategy for a better alignment of a regional network with an ITRF is also proposed in this study. The coordinates of the regional control stations at the observation epoch, which were estimated through the combination of constraint-free normal equation systems from seven IGS analysis centers under the control of the aforementioned 92 global control stations, were used for the determination of the regional coordinate reference datum.

For a regional combined adjustment, as an example, one-month observations in May 2015 at 148 Continuously Operating Reference Stations (CORS) in Shandong Province (SDCORS) were processed and analyzed. From the 92 global control stations mentioned above, 10 IGS stations in China and its surrounding area were selected as the regional control stations of SDCORS, see Fig. 3 for their distribution. Figure 4 shows the differences in the coordinates of the same station in the above two frames, denoted by P_{DRF} and $P_{\mathrm{ERF,}}$ at the epoch 2015.412. We can see from the figure that the differences between the P_{DRF} and P_{ERF} at the BJFS, DAEJ, IISC, WUHN and YSSK stations in the X and Y components are in the range of 2–4 cm.

Figure 5 shows the differences between the coordinates of each SDCORS station at the epoch 2015.412 in the ITRF2005 aligned from the ERF and DRF frames. The average differences are about 1.2 cm, 1.0 cm and − 3.0 mm in the Y, X and Z components respectively. Table 2 lists the statistics of all the results shown in Fig. 5, which indicates the maximum, minimum and mean values in the X and Y components are significantly larger than that of the Z component.

To evaluate how well the above regional network in the two frames is aligned with the ITRF2005, we selected 10 regional control stations, and computed their coordinate corrections at the epoch 2015.412, which were obtained from the combined adjustment to its known coordinates. The results are listed in Table 3. We can see that the P_{ERF} values of the most stations are much smaller than the P_{DRF} counterparts, meaning that the accuracy of the alignment from the ERF frame is significantly better. The ERF results show that the corrections in the N, E components of all the stations, except for WUHN is 4.39 mm in the N component, are all below 4 mm; while the DEF results indicate that the coordinate corrections at all the stations in the H component are about 1 cm, and the most corrections in the three components are in the range of 1–3 cm.

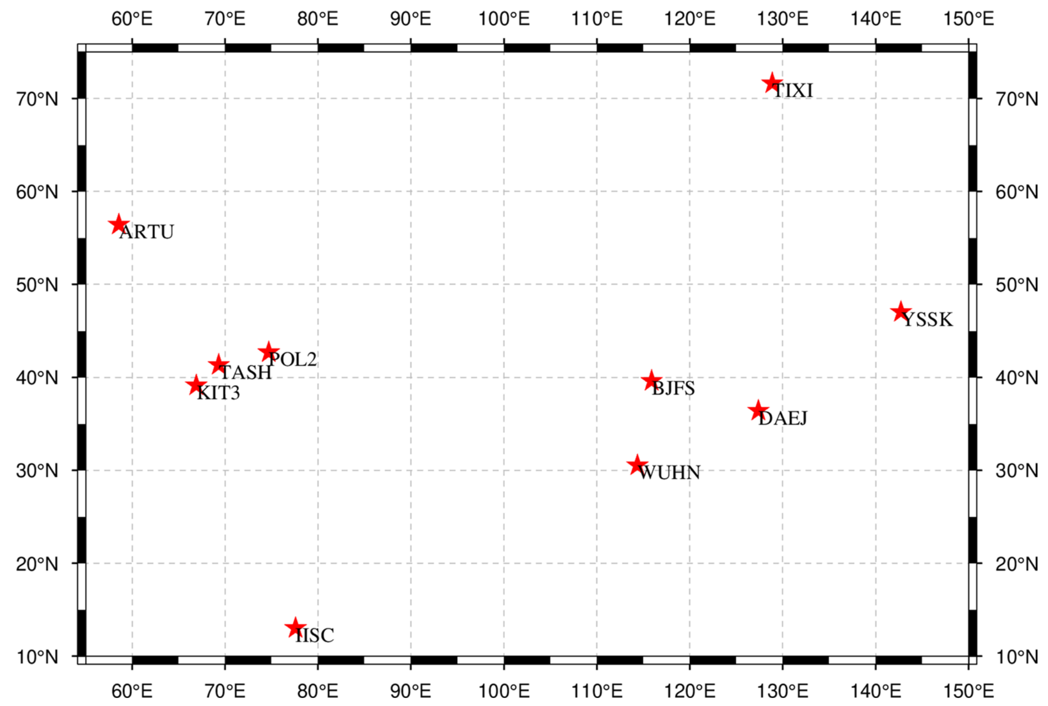

Fig. 3 Distribution of 10 selected regional reference control stations for SDCORS

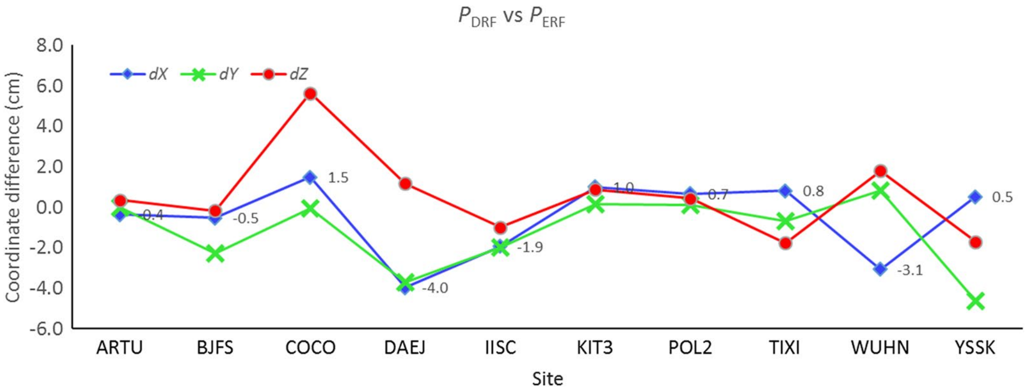

Fig. 4 Differences between P_{DRF} and P_{ERF} at the epoch 2015.412 at 10 reference stations (unit: cm)

Maintenance of the CGCS2000 with a linear velocity model

All the ITRFs, except for the ITRF2014, were established based on a linear model fitting the coordinates of geodetic reference sites (Altamimi et al. 2002, 2012). The linear assumption is significant for tectonic interpretations. However, the stations that have non-linear motions have their residuals up to a few centimeters, especially when loading effects are neglected (Bennett 2008; Blewitt and Lavalée 2002; Collilieux et al. 2010). The latest release of an ITRF, the ITRF2014, was generated with an enhanced model based on the assumption of nonlinear station motions, including seasonal (annual and semiannual) signals (Davis et al. 2012) and post-seismic deformations for those sites subject to major earthquakes. Due to the longer time series of the inputs and more accurate mathematical model, the ITRF2014 has demonstrated its superiority to its previous ITRF releases (Altamimi et al. 2016).

There are two ways to maintain a reference frame with linear movement. One is using an improved plate motion model to construct a linear velocity model (Gan 2007)

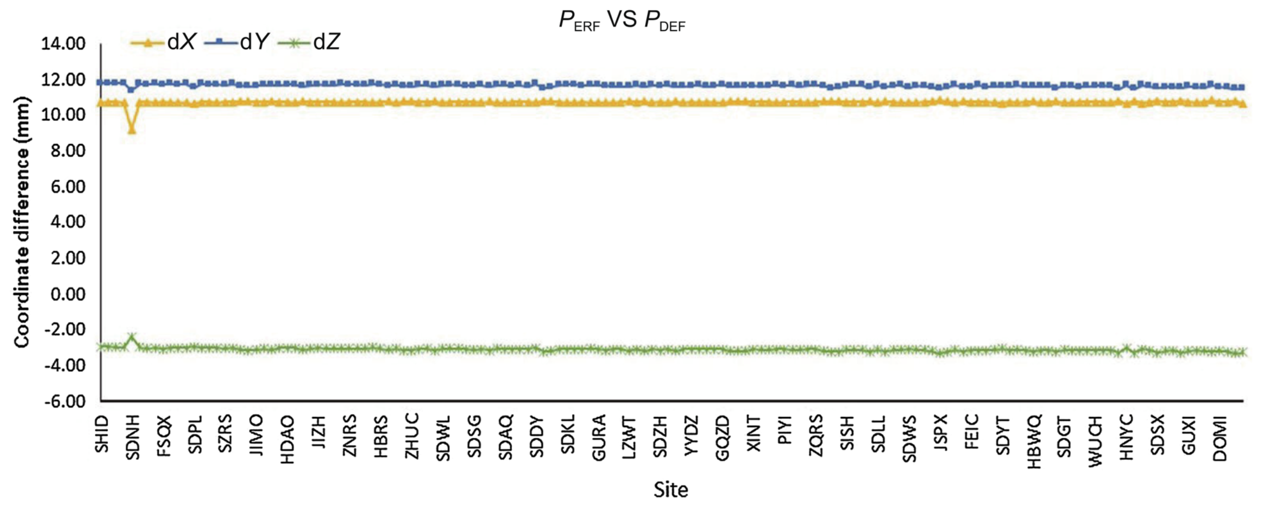

Fig. 5 Differences between the coordinates at each SDCORS station at the epoch 2015.412 in the ITRF2005 aligned from the ERF and DRF frames

Table 2 Statistics of all results shown in Fig. 5

Statistic	P_{DRF}–P_{ERF} (mm)		
	ΔX_1	ΔY_1	ΔZ_1
Max	10.84	11.79	− 2.39
Min	9.21	11.38	− 3.32
Mean	10.73	11.65	− 3.10
Std	0.13	0.07	0.10

and the other is constructing a non-linear site movement model for each reference station. A plate motion model is developed using the linear velocities at all reference stations on the plate for transforming the coordinates of a station to the epoch required. It can only achieve a cm-level accuracy due to its neglect of nonlinear movement. However, a nonlinear site movement model can achieve a mm-level accuracy, and is suitable for the accurate maintenance of the Chinese national reference frame in future. For regional CGCS2000, especially provincial CGCS2000, linear maintenance is still the major option at present.

Gridded horizontal velocity field in China

Selection for an optimal interpolation method

Under the control of the selected regional GNSS control stations for the Chinese national GNSS network, the coordinates and velocities at all the network stations were estimated based on the observations during the period from 1998 to 2010. A gridded velocity field for mainland China is to be determined and its database is provided to the general public to update the coordinates

Table 3 Coordinate corrections at each regional reference station at the epoch 2015.412 obtained from the combined adjustments in the two frames

Site	P_{DRF} (mm)			P_{ERF} (mm)		
	d*E*	d*N*	d*H*	d*E*	d*N*	d*H*
YSSK	14.65	8.61	− 29.97	− 2.80	− 2.30	6.78
TIXI	− 17.00	− 1.58	− 16.14	0.78	− 2.08	5.15
DAEJ	38.77	7.78	− 1.41	0.49	− 1.01	− 4.71
BJFS	2.30	2.72	− 18.75	2.46	− 1.34	− 6.24
WUHN	12.34	4.02	32.30	2.27	4.39	2.27
IISC	8.74	− 7.34	− 9.83	− 1.09	0.82	6.07
POL2	− 11.27	− 11.24	11.40	0.17	− 1.19	− 0.31
KIT3	− 17.87	− 10.32	25.79	− 3.64	− 2.14	8.49
ARTU	− 1.81	− 10.43	5.84	− 1.72	0.16	− 0.95

of any GNSS stations at the observation epoch to the CGCS2000 frame.

A gridded horizontal velocity field is constructed using an interpolation method, but different methods perform differently. In this study, we aim at the selection of an optimal method. Five interpolation methods were tested, including Inverse Distance Weighting (IDW), Block Euler Vector (BEV), Least Squares Collocation (LSC), Local Euler Vector (LEV) and Finite Element (FE), using the velocity components at the aforementioned 1025 GNSS stations (Cheng at al. 2020). More specifically, the velocities for all the stations in each of the 20 subplates were interpolated with the above five methods. The method that achieved the highest accuracy was regarded as the optimal one and was employed to construct the gridded velocity field. For the detailed information on the 20 subplates, one can refer to China Plate Model (CPM) for CGCS2000 (CPM-CGCS2000) (Cheng et al. 2013). The CPM-CGCS2000 was developed for the maintenance of the CGCS2000 dynamic reference frame. Table 4 gives the 20 subplates or blocks.

The velocities interpolated with each of the five selected methods at all stations in each subplate were validated using the cross-validation method, referring to (Chen 2013) for the detailed information. The Root Mean Square Error (RMSE) was calculated from the differences between the interpolated and the reference velocities at all stations in each of the 20 subplates in the two horizontal directions, as shown in Fig. 6. Table 5 shows the RMSs of the velocities interpolated for all the 1025 stations with each method. One can see that the IDW model significantly outperformed all the other models in all the 20 subplates, except the South China Sea subplate, where the IDW was slightly worse than the others. Thus this method was the optimal model.

Table 4 Information on 20 subplates, and the stations in the last column were selected for testing

Serial	Subplate	Abbr	Station for testing
1	Altai	Alt	
2	Alashan	Alsh	
3	Bayan Har	BnHr	
4	North China	NChn	BJFS
5	Eastern Shandong	Eshd	SHAO
6	South China	SChn	WUHN
7	Lhasa	Lhsa	LHAS
8	Junggar	JnGr	URUM
9	ChuanDian	ChnD	KUMN
10	Qaidam	Qdm	
11	Southwestern Yunnan	SwYn	
12	Qiangtang	QTng	
13	Qilian	Qln	
14	South China Sea	SChs	
15	Tianshan	TShn	
16	Mongolia and China	MngC	
17	Tarim	Trim	
18	Korea and China	KrCh	
19	Ordos	Ords	
20	Yanshan	YShn	

Table 5 RMS of the velocities interpolated for all the 1025 stations in the 20 subplates from each model in the East and North directions (unit: mm/a)

Method	*E* direction	*N* direction
IDW	1.06	1.16
BEV	1.81	1.65
LEV	1.22	1.20
FE	1.64	1.58
LSC	1.22	1.16

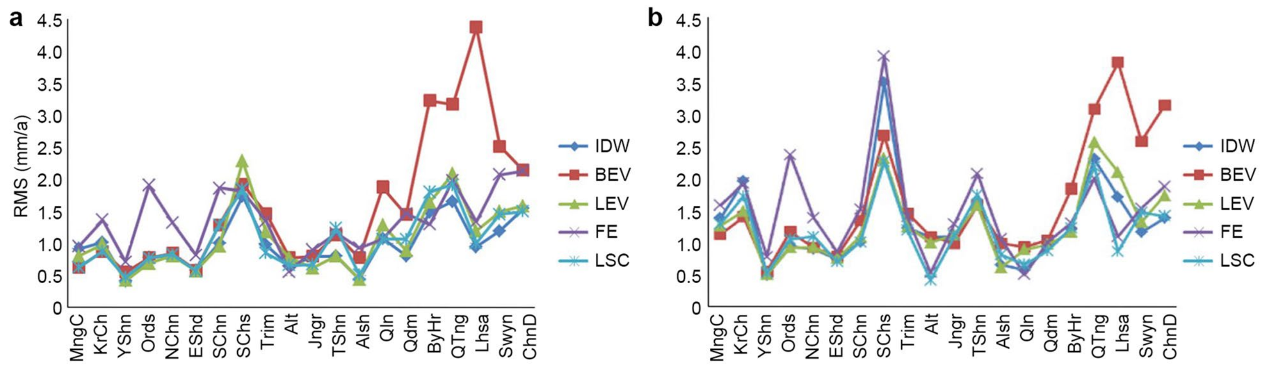

Fig. 6 RMSE of the velocities interpolated for all stations in each of the 20 subplates from each method in (**a**) the East direction and (**b**) the North direction

Construction of a gridded horizontal velocity field

The selection of sample points is important to the IDW performance. Usually at least four sample points that are surrounding and closest to the point of interest are selected. Two common methods for searching such sample points are the linear search and the area search. In this study the circle search method, which belongs to the category of area search, was used. According to the distribution of the sample points used in this study, most of them were within the circle with a radius from 1° to 3°. Thus the searching process started from the radius of 1°. If there were more than four sample points within the circle, the interpolation was performed, otherwise the searching process continued with the search radius of 2°, then 3° if needed. Generally, the larger the radius of searching circle, the weaker the correlation between the sample points and the interpolation point and the poorer the accuracy of the interpolated result will be.

The results of a 1° × 1° gridded velocity field in mainland China were constructed using the above procedure. It should be mentioned that in some complicated geological areas, such as the Chuandian and Qinhai Tibet subplates, higher grid resolutions of $30' \times 30'$ and $15' \times 15'$ were applied. The precisions of the whole velocity field in the E, N directions were 0.78 mm/a and 0.95 mm/a, respectively.

Maintenance of the CGCS2000 with a linear velocity field

Effect of inconsistent frames on a multi-day solution

Generally, GNSS observations are processed in a ground-based frame that is consistent with the space-based frame that GNSS satellites are associated with. The ground-based frame is determined by the control points selected from the reference stations used in the construction of an ITRF. The space-based frame is determined by the earth-fixed coordinates of GNSS satellites in different ITRFs (see Table 1), and provided in IGS satellite ephemerides. When a solution is to be obtained from multi-day GNSS observations, the common practice is to obtain single-day solutions first, then all single-day solutions are combined in the final adjustment. If the combination of these daily solutions cannot remain the consistent between the space-based frame and the ground-based frame,

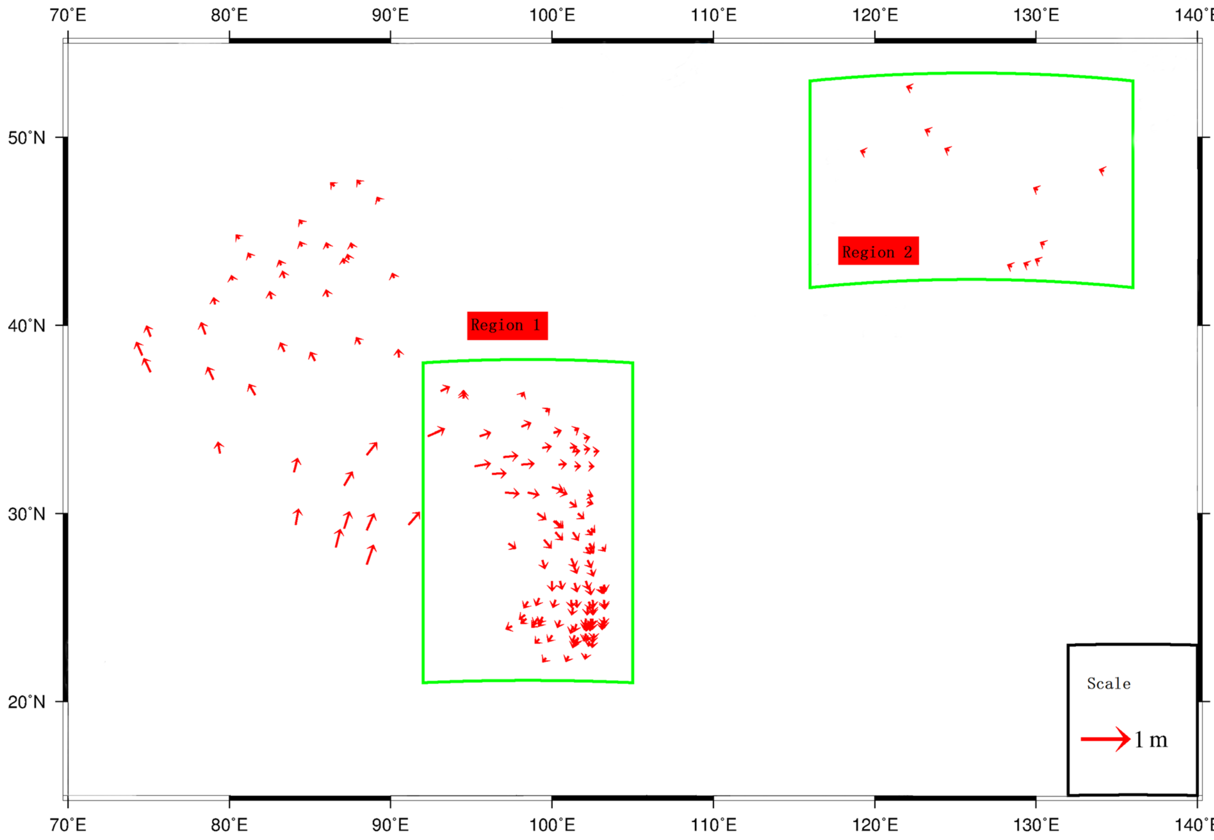

Fig. 7 Vectors of the differences in the coordinates at the national GNSS stations that have the value larger than 10 cm obtained from the quasi-stable adjustment and plate movement

especially in the alignment of a regional reference frame with the CGCS2000 to obtain the positions of the GNSS stations in the CGCS2000, the regional network can be distorted.

Currently, two common methods for correcting the coordinate of a GNSS station from the observation epoch to the CGCS2000 reference epoch are the quasi-stable adjustment under the CGCS2000 and the plate movement correction (Cheng 2017). In the first method, the single-day normal equations are adjusted by tightly constraining some of the GNSS stations, which are used as quasi-stable reference stations, to their known CGCS2000 coordinates, and in the second method, the coordinates derived from these normal equations in the current ITRF are corrected to the CGCS2000 using a plate motion model.

To analyze the coordinate differences at GNSS stations in mainland China due to different correction methods used, observations over a 30-day period from 1 to 31 August, 2015, in a network of about 1800 nationwide GNSS stations were processed in the ITRF2005. The aforementioned two methods were applied to obtaining two sets of coordinates in the CGCS2000, i.e. one set from a quasi-stable adjustment in the CGCS2000 (ITRF97), and the other set from a combined adjustment of multi-day solutions in the ITRF2005, and then correcting the coordinates from the ITRF2005 to the CGCS2000 with plate movement corrections. The difference in the two sets of coordinates at the same station was calculated and the results expressed in vectors are shown in Fig. 7. Note that only the stations that have the differences larger than 1 dm are shown in this figure. From Fig. 7 we can see that inappropriate corrections result in the wrong tie to the CGCS2000, causing the GNSS network distortion, especially in southwest China and northeast China. The directions of the vectors agree well with the movement directions of the plate where the stations are located, and larger differences occurred in the subplates whose motion is inconsistent with that of the subplates in middle China.

Figure 8 shows another case, a regional GNSS network in Shandong province, for a further comparison of the differences resulting from the above two methods. The observations were from 154 well distributed GNSS stations over the 30-day period in April 2015. From this figure, a small but noticeable rotation angle among these vectors can be seen, although the absolute magnitudes of the vectors are not large (under 2 cm). If these stations were used as control points in the later adjustment of the network, it would lead to a rotation of the whole network.

Accuracy of the CGCS2000 linear maintenance

The CGCS2000 has been used for nearly 20 years. To evaluate the accuracy of the CGCS2000 linear maintenance, the results from the six stations listed in the last column in Table 2 were used for the six corresponding subplates. These subplates were further grouped into stable and unstable areas. The stable area was in the middle of China including the south China, eastern Shandong, north China subplates. while the unstable area was in the west or southwest China including the Chuandian, Junggar and Lhasa subplates. The coordinates of these

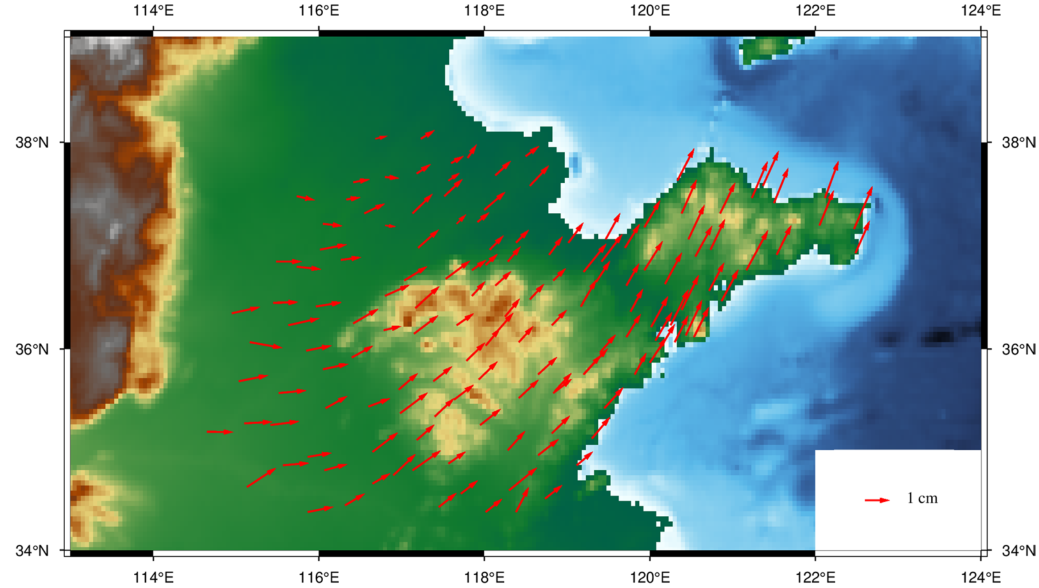

Fig. 8 Vectors of the differences in the plane coordinates with two methods in Shandong province

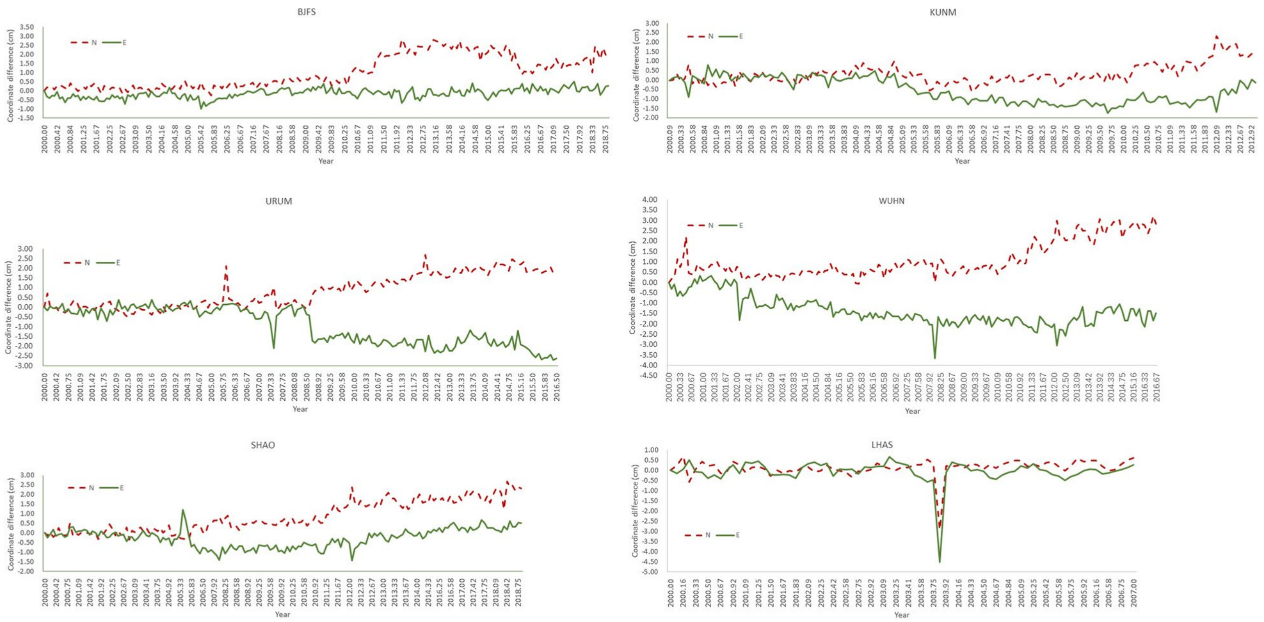

Fig. 9 Time series of the differences between the transformed and reference coordinates at six stations located in six subplates in China, where the red dashed lines are for the N component and green solid lines for the E component

stations were obtained from the monthly solutions of the observations in the period from 2000.0 to 2018 (except the LHAS station which had a short period data from 2000.0 to 2007.0) in the ITRF2014. They then were transformed to the CGCS2000. The time series of the differences between the transformed coordinates and the CGCS2000 coordinates (as the references) at the six stations in the *N*, *E* directions are shown in Fig. 9.

As it is known, a plate motion mainly occurs horizontally, thus the plate motion corrections are only for the horizontal coordinates of the stations, keeping the height components unchanged. This is also the reason why we focus on the transformed horizontal coordinates in the CGCS2000 maintenance for the performance evaluation in this section. The differences of the horizontal coordinates at some stations shown in Fig. 9 present a trend of increase with time, and the differences at all the six stations are in the range about 2–3 cm. Different stations at the same time have different corrections as they are in different subplates. At the sites in the stable area, such as the SHAO (the middle left subfigure) and WUHN stations (the upper right subfigure), their differences are all around 2 cm with little fluctuations. The difference time series at the BJFS station shows some fluctuations in the N direction. The differences at the three stations show an increase trend from 2010. In the unstable area, the differences at KUNM and URUM are large and have large temporal variations, but the results at the LHAS station are not the same due to its short period data. The differences at the URUM and KUNM stations show an increase trend from 2008 and 2007.16, respectively. The difference vectors (formed by the *N* and *E* components) show the positions of KUNM and URUM deviate from their positions in the CGCS2000 and are becoming bigger and bigger, and their movement direction is similar to that of their subplate.

Generally, there are three causative reasons for the differences between the transformed and the CGCS2000 reference coordinates of a site. The first is the temporal variation in the movement trend, like KUNM; the second one is the position jumps triggered by the events, such as periodical motions, post-seismic deformation, or changes in the GNSS receiver's antenna height, like LHAS, URUM; and the third one is the nonlinear movements due to atmospheric or hydrological environmental loads. The temporal variation in a movement trend is dependent of both the subplate's movement rate and the interval between the observation time and the CGCS2000 reference epoch. The longer the interval, the greater the difference will be.

Conclusion

For maintaining China's reference frame CGCS2000 or updating China's dynamic reference frame, several topics are discussed in this paper, including the strategy for better aligning a regional GNSS network with an ITRF, the evaluation of the accuracy of the alignment using the designed strategy, and the approach of considering plate motion in updating the CGCS2000 and its accuracy evaluation. These approaches and test results are summarized below:

1. For selecting global control stations, a more rigid criterion was proposed and implemented using a statistic method called the supervised clustering based on the plate-fixed coordinate system to identify and select the stations whose movements agreed well with the movement of the corresponding plate. This criterion and the supervised clustering were applied to the selection of the stations whose velocity and azimuth residuals were both under their two sigma standards. From the initial 126 global candidate stations, 92 IGS stations were selected as the global control stations.
2. For a better alignment of the Chinese regional network with the ITRF2005, ten out of 92 IGS stations in China and its surrounding area were used as the regional control stations and their coordinates were obtained from a global combined adjustment under the control of the 92 global control stations. The results indicated the accuracy of the alignment of the 10 regional control stations with the ITRF2005 was improved from a cm-level to a mm-level, compared with the coordinates of these stations obtained from the velocities provided in the ITRF documentation.
3. To evaluate how well a regional network is aligned with an ITRF, the magnitudes of the coordinate corrections at the 10 regional control stations were used as the indicator. The smaller the correction value, the better the agreement of the two frames is. For testing, one-month observations from 148 SDCORS were processed and analyzed. The results show a noticeable systematic deviation between the P_{DRF} and P_{ERF} regional reference datum, and the average differences at the 148 stations in the Y, X and Z components are about 1.2 cm, 1.0 cm and − 3 mm respectively. The alignment of the P_{ERF} with the ITRF is better than that of the $P_{\mathrm{DRF.}}$
4. The velocities at 1025 Chinese national GNSS reference stations were obtained by a least squares estimation with the mean precisions in the N, E, U components being $\pm$ 0.124, $\pm$ 0.127 and $\pm$ 0.563 mm/a, respectively. They were the sample data, to construct a $1^\circ \times 1^\circ$ gridded velocity field in mainland China using the inverse distance weighting interpolation method. The overall precisions of the constructed velocity field in the E, N components were 0.78 mm/a and 0.95 mm/a, respectively.
5. Currently, the accuracy of the CGCS2000 frame maintenance based on a linear velocity model is at a 2–3 cm level, and poorer in western China, especially in those complicated geological areas. The longer the time from the CGCS2000 reference epoch, the larger the differences between the transformed coordinates with the linear velocity model and the CGCS2000 reference coordinates will be.

The key role of the CGCS2000 maintenance lies in obtaining high-accuracy positions at any epoch. This research indicated that various strategies should be developed to improve the accuracy of the CGCS2000 frame construction and maintenance. However, for a long-term maintenance, the accuracy of the CGCS2000 frame based on a linear velocity model may be at a level of 2–3 cm, or even worse, especially in those unstable areas. If the accuracy cannot meet the requirements for some applications, e.g. accurate local monitoring networks and regional reference frames for large-scale mapping, the continuous observations for several years at the Chinese national GNSS stations are needed to improve the accuracy of the velocity field, or the CGCS2000 frame is to be updated.

Acknowledgements
We are grateful to professor Suqin Wu at China University of Mining and Technology for useful discussion and suggestions. This work was also supported by the team members, Xin Chen, Le Gao and Jun Wan who are master students.

Authors' contributions
PC proposed the research and supervised the experiments. YC performed the research, analyzed the data and wrote the paper. XW processed the GNSS data and estimated the velocities of stations. YX developed the software of correcting GNSS position to CGCS2000. All authors read and approved the final manuscript.

Funding
This study is supported by the National Key Research and Development Program of China (2016YFB0501405) and Natural Resources Innovation Platform Construction and Capacity Improvement (A19090).

Availability of data and materials
All the data used in this project, including the observations of a period of 10 years at GPS stations CMONOC, GPS time series from Scripps Orbit and Permanent Array Center website and local CORS observations in Shandong province.

Competing interests
The authors declare that they have no competing interests.

Author details
[1] Chinese Academy of Surveying and Mapping, 28 Lianhuachi West Road, Beijing 100036, China. [2] Aerospace Information Research Institute, Chinese Academy of Sciences, No. 9 Dengzhuang South Road, Haidian District, Beijing 100094, China.

Received: 27 July 2020 Accepted: 1 December 2020

References

Altamimi, Z., Métivier, L., & Collilieux, X. (2012). ITRF2008 plate motion model. *Journal of Geophysical Research, 117*, B07402. https://doi.org/10.1029/2011JB008930.

Altamimi, Z., Rebischung, P., Métivier, L., & Xavier, C. (2016). ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *Journal of Geophysical Research: Solid Earth*. https://doi.org/10.1002/2016JB013098.

Altamimi, Z., Sillard, P., & Boucher, C. (2002). ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. *Journal of Geophysical Research, 107*(B10), 2214.

Amiri-Simkooei, A., Tiberius, C., & Teunissen, S. P. (2007). Assessment of noise in GPS coordinate time series: Methodology and results. *Journal of Geophysical Research, 112,* B07413. https://doi.org/10.1029/2006JB004913.

Bennett, R. A. (2008). Instantaneous deformation from continuous GPS: Contributions from quasi-periodic loads. *Geophysical Journal International, 174,* 1052–1064.

Blewitt, G., & Lavalée, D. (2002). Effect of annual signals on geodetic velocity. *Journal of Geophysical Research, 107*(B7), 2145. https://doi.org/10.1029/2001JB000570.

Chen, J. (2008). Chinese modern geodetic datum—The China geodetic coordinate system 2000 (CGCS2000) and its framework. *Actageodaeticet Cartographica Sinica, 37,* 3.

Chen, X. (2013). Method for constructing the velocity field model of the Chinese mainland crust movement. Master's thesis. (in Chinese).

Cheng, P., Cheng, Y., et al. (2008). *The user guide of the China Geodetic Coordinate System 2000*. Beijing: Surveying and Mapping Press. (in Chinese).

Cheng, P., Cheng, Y., Bei, J., et al. (2013). CGCS2000 plate motion model. *Acta Geodaetica et Cartographica Sinica, 42*(2), 159–167. (in Chinese).

Cheng, P., Cheng, Y., Wang, X., Wu, S., & Xu, Y. (2020). Realization of an optimal dynamic geodetic reference frame in China: methodology and applications. *Engineering*, *6*(8), 879–897.

Cheng, Y., Dang, Y., Bei, J., et al. (2017). CGCS2000 maintain methods analysis. *Geomatics and Information Science of Wuhan University, 42,* 4.

Collilieux, X., Altamimi, Z., Coulot, D., van Dam, T., & Ray, J. (2010). Impact of loading effects on determination of the International Terrestrial Reference Frame. *Advances in Space Research, 45,* 144–154. https://doi.org/10.1016/j.asr.2009.08.024.

Davis, J. L., Wernicke, B. P., & Tamisiea, M. E. (2012). On seasonal signals in geodetic time series. *Journal of Geophysical Research, 117,* B01403. https://doi.org/10.1029/2011JB008690.

Gan, W., Zhang, P., Shen, Z.-K., Niu, Z., Wang, M., Wan, Y., et al. (2007). Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements. *Journal of Geophysical Research, 112,* B08416. https://doi.org/10.1029/2005JB004120.

Gross, R., Beutler, G., & Plag, H. P. (2009). Integrated scientific and societal user requirements and functional specifications for the GGOS. *Global Geodetic Observing System* (pp. 209–224). Dordrecht: Springer.

Li, Z. (2003). Research on global tectonic features using space earth observation technology. PhD thesis. (in Chinese).

Liu, H., Jiang, W., Wang, Y., Chen, H., & Wu, Y. (2014). Research on joint data processing method using regional CORS in CGCS2000. *Geomatics and Information Science of Wuhan University, 39*(2), 161–165. (in Chinese).

Wang, Z., Chen, P., Sun, X., Hu, Y., & Meng, Q. (2020). Research and accuracy analysis of coordinate transformation method from ITRF2014 to CGCS2000. *Urban Geotechnical Investigation & Surveying, 2020*(2), 119–122. (in Chinese).

Wei, Z., Liu, G., & Wu, F. (2011). The China geodetic coordinate system 2000: —China velocity field. *Actageodaeticaet Cartographica Sinica, 40,* 4. (in Chinese).

Publisher's Note