Vol. 43 No. 4 SCIENCE IN CHINA (Series D) August 2000

Crustal motion of Chinese mainland monitored by GPS

ZHU Wenyao (朱文耀)[1], WANG Xiaoya (王小亚)[1], CHENG Zongyi (程宗颐)[1], XIONG Yongqin (熊永清)[1], ZHANG Qiang (张 强)[1], YE Shuhua (叶叔华)[1], MA Zongjin (马宗晋)[2], CHEN Junyong (陈俊勇)[3], XU Houze (Houtze Hsu 许 厚 泽)[4], WEI Ziqing (魏子卿)[5], LAI Xi'an (赖锡安)[6], LIU Jingnan (刘经南)[7], JIN Biaoren (金标仁)[7], REN Jinwei (任金卫)[2] & WANG Qi (王 琪)[6]

1. Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China;
2. Institute of Geology, State Seismological Bureau, Beijing 100029, China;
3. National Bureau of Surveying and Mapping, Beijing 100830, China;
4. Wuhan Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China;
5. Xi'an Institute of Surveying and Mapping, Xi'an 710054, China;
6. Institute of Seismology, State Seismological Bureau, Wuhan 430071, China;
7. Wuhan Technical University of Surveying ang Mapping, Wuhan 430070, China

Correspondence should be addressed to Zhu Wenyao (email: zhuw@center.shao.ac.cn)

Received May 25, 1999

Abstract To measure and monitor the crustal motion in China, a GPS network has been established with an average side length of 1 000 km and with more than 20 points on the margins of each major tectonic block and fault zone in China. Three campaigns were carried out in 1992,1994 and 1996, respectively by this network. Here we present, for the first time, the horizontal displacement rates of 22 GPS monitoring stations distributed over the whole China and global IGS stations surrounding China, based on these GPS repeated measurements. From these results by GPS, we have obtained the sketch of crustal motion in China.

Keywords: crustal motion in China, GPS monitoring.

Chinese mainland lies among the Indian plate, the Philippines sea plate, Siberian and Mongolian plate. It has a peculiar tectonic feature. The inter-plate deformation and interaction between blocks are very complicated. Especially, the Qinghai-Xizang plateau, called the world ridge, is the youngest plateau in the world at present. It is the region where the crustal motion is the strongest among the global continents. Therefore, the Chinese mainland is an ideal object for studying intraplate deformation and dynamics, and is regarded as the key to studying the lithospheric dynamics of continents. Due to the limitation of observational accuracy, the quantitative survey of the present-day crustal motion in China is basically the component of vertical motion by means of gravimetric and leveling survey. Although there are data from geology, topology, seismology and some local fault zone monitoring[1—5], the reliable observation of the large scale crustal horizontal motion is not available till now. Hence there is no convincing data of horizontal displacement to study the dynamical mechanism of the crustal motion of the Chinese mainland. Now the development of GPS technique provides a guarantee for directly surveying large scale crustal motion of Chinese mainland[6,7]. A GPS network for measuring and monitoring crustal motion of China has been completed, through which three campaigns have been made in 1992,1994 and 1996 respectively. The GPS network covers the whole mainland of China with 22 points carefully selected by Chinese geologists (see fig. 1). Through repeated measurements for several periods, we expect to resolve the relative crustal horizontal motion with an accuracy better than 5 mm/a. These results will be combined with gravimetric survey, leveling, geological, seismic and geomorphological approaches to gradually establish a quantitative model about large-scale deformation. Using modified GAMIT package[8], we have preliminarily determined the change rates of the station coordinates by repeated measurements in three campaigns. These results may provide convincing information related to the horizontal tectonic motion in Chinese mainland.

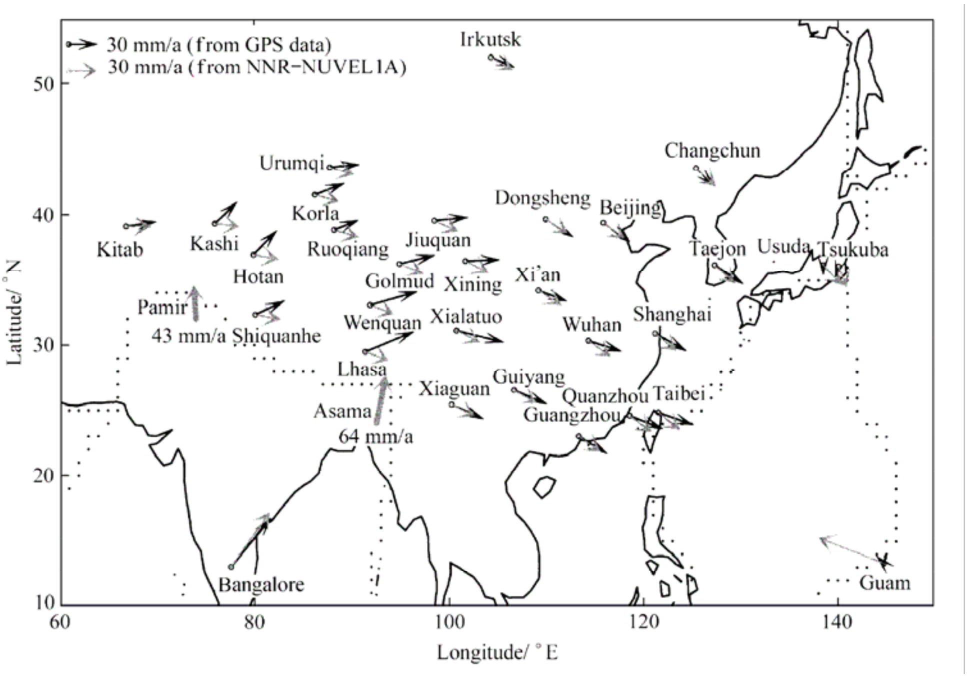

Fig. 1. The horizontal site velocity of China from GPS and NNR-NUVEL1A.

1 Campaigns and data processing

In October, 1991, a group, in charge of the task of “Investigation on Present Crustal Motion and Geodynamics in China” under a key basic research program, invited specialists concerned in geology, geodynamics and geodesy all over the country to discuss a plan for establishing a GPS crustal motion monitoring network in China. It has been proposed to establish a GPS network with an average side length of 1 000 km and more than 20 points on the margins of each major tectonic block and fault zone in the mainland. Subsequently, three campaigns by the Chinese GPS network were carried out in 1992,1994 and 1996 respectively. Owing to the conditions at that time, the first observation campaign was only performed in the some areas of the Qinghai-Xizang Plateau with 4 sets of Leica 200 GPS receivers during Oct. 8—Oct. 12, and Oct. 21—Oct. 24. The last two campaigns spread over the whole mainland. The second campaign, employing 15 sets of Leica 200 GPS receivers, was divided into two sections: eastern section from Aug. 15 to Aug. 20 and western section from Aug. 28 to Sept. 2. These two sections, where Urumqi, Golmud and Xiaguan stations were regarded as three common points, consist of 15 and 10 stations respectively. The third campaign was operated on the 22 stations in the same period from July. 25 to Aug. 3 with such three kinds of receivers as Ashtechz12, Rogue SNR 8000 and Leica 200. There were seven common baselines in the Qinghai-Xizang area to be repeatedly measured in the three campaigns. They are Lhasa-Wenquan, Golmud-Wenquan, Golmud-Xining, Lhasa-Xiaguan, Golmud-Xialatuo, Wenquan-Xiaguan and Xining-Xialatuo.

In order to maintain the unity and self-consistency of the terrestrial reference frame during the three campaign observations and to study the background of crustal motion of Chinese mainland, we chose the following international terrestrial reference frame (ITRF) sites as fiducial ones whose data were processed simultaneously together with our network data: ALGO, ALBH, TAIW, TSKB, GOLD, FAIR, KOKB, ONSA, MASP, HART, SANT, WETT, HERS, PAMA, KWJ1, YAR1, YELL, MAC1 and so on. In addition, five IGS stations surrounding China, TAEJ, GUAM, KIT3, IRKT and IISC, were added in the 1996 data processing.

The observations in integrated adjustment for the whole network are daily baseline solutions. The adjustments for multi-day data were combined by using their variance-covariance matrices with the Kalman filter program GLOBK package in ITRF96 with more than 20 global GPS sites being fiducial.

The method of data processing for daily baseline solution is summarized as follows:

Software used	Modified GAMIT
Measurement model	
Basic observables	L1, L2 two frequency carrier phases; P code only for receiver clock and ambiguity estimation; elevation angle cutoff is 15 degrees; sampling interval is 60 s; weighting is uniform.
Modeled observables	Double difference ionosphere-free linear combination
Troposphere	*A priori* Saastamoinen atmospheric correction model
Tidal displacements	Displacements due to solid earth tidal and ocean loading come from IERS standard (1995); atmospheric load and polar tides are not considered.
Satellite orbits	IGS precise ephemerides for 1994,1996, and GFZ for 1992
EOP	IGS EOP series for 1994 and 1996, and GFZ EOP series for 1992
Estimated parameters	
Station coordinates	To select IGS stations as the fiducial points, its daily coordinate updates to be from its coordinates and velocities in ITRF96 were assigned the *a priori* constraint 1σ (from ITRF96) in the estimation.

	Other station coordinates were estimated without *a priori* constraints
Satellite orbits	To adopt loose constraints 10^{-7} for the initial state vectors of satellite orbits and 10% for three scale factors of solar radiation pressure
Troposphere	Zenith delay estimated once two hours for each station
Ambiguity	Estimated as real values without a *priori*
Station clock bias	Station clock biases including epoch, rate and acceleration are estimated during the preprocessing using P code measurements.

Averaged repeatabilities in daily solution of site coordinates for latitudinal, longitudinal and radial components are listed below.

	Latitude /10^{-4} s	Longitude/10^{-4} s	Radial/10^{-3} m
1992	2.33.0	24.3	
1994	1.6	2.1	22.1
1996	1.5	2.0	18.4

2 Results and analysis

The results of horizontal site velocities for GPS crustal motion monitoring network in China are shown in table 1.

Table 1 Horizontal site velocities for GPS crustal motion monitoring network in China

Sites	Lati. / (°)	Long. / (°)	Nrate	Erate	Nrate	Erate	Nrate	Erate
			/mm • a^{-1} (by GPS)		/mm • a^{-1} (by NNR-NUVEL1A)		/mm • a^{-1} (WRT Eurasian plate)	
Lhasa	29.50	91.36	15.5±1.7	50.4±2.3	−6.6	25.1	22.1	25.3
Wenquan	33.05	91.86	10.4±1.8	48.9±2.4	−6.7	25.1	17.1	23.8
Golmud	36.25	94.88	6.7±1.5	36.8±2.2	−7.5	24.9	14.2	11.9
Xining	36.48	101.65	1.1±1.8	35.6±2.5	−9.2	24.3	10.3	11.3
Jiuquan	39.57	98.50	2.6±2.0	34.3±2.7	−8.4	24.5	11.0	10.8
Xialatuo	31.13	100.75	−9.0±1.8	49.0±2.4	−9.0	24.4	0.0	24.6
Xiaguan	25.46	100.25	−11.1±1.5	33.1±2.2	−9.2	24.1	−1.9	9.0
Kashi	39.33	75.92	16.5±2.1	23.4±2.7	−2.4	25.9	18.9	−2.5
Hotan	36.93	79.93	18.5±2.1	24.1±2.7	−3.5	25.7	22.0	−1.6
Ruoqiang	38.85	88.02	7.7±2.2	25.5±2.7	−5.8	25.3	13.5	0.2
Shiquanhe	32.33	80.10	10.5±3.4	30.1±3.9	−3.5	25.6	14.0	4.5
Korla	41.50	86.17	8.8±2.3	30.7±2.7	−5.2	25.4	14.0	5.3
Urumqi	43.62	87.71	2.3±1.7	31.2±2.3	−5.6	25.2	7.9	6.0
Dongsheng	39.68	109.96	−13.9±2.1	28.5±2.8	−11.2	23.3	−2.7	5.2
Guiyang	26.57	106.68	−10.8±2.1	34.4±2.7	−10.4	23.7	−0.4	10.7
Changchun	43.60	125.44	−13.9±2.1	19.2±2.8	−13.9	20.6	0.0	−1.4
Beijing	39.42	115.89	−14.9±2.3	26.6±3.0	−12.3	22.5	−2.6	4.1
Wuhan	30.50	114.25	−8.3±1.8	34.5±2.5	−12.4	22.8	4.1	11.7
Guangzhou	23.03	113.34	−13.4±2.2	29.7±2.9	−11.8	23.0	−1.6	6.7
Quanzhou	24.63	118.60	−10.3±2.4	34.1±3.1	−13.3	22.3	3.0	11.8
Shanghai	31.10	121.20	−13.4±1.4	32.5±2.0	−13.3	22.3	0.1	10.2

In order to study the background field of Chinese crustal motion, from May 1995 to June 1998, we also carried out successive measurements of displacement velocities of 12 IGS sites distributed in China and its neighborhood, including Shanghai, Lhasa, Taibei, Wuhan, Xi’an, Irkutsk, Kitab, Taejon, Tsukuba, Usuda, Bangalore and Guam. The results are shown in table 2 [9], where corresponding results from ITRF96 are also listed for comparison. For the sake of intuitions, we also give fig. 1 showing these horizontal site velocities estimated by GPS and NNR-NUVEL1A.

Table 2 Horizontal velocities for some IGS sites in China and its neighbourhood by crustal motion monitoring network in China

Sites	Nrate	Erate	Nrate	Erate	Nrate	Erate
	/mm • a^{-1}		/mm • a^{-1}		/mm • a^{-1}	
	(by GPS)		(From ITRF96)		(WRT Eurasian plate)	
IISC	37.3±0.6	41.0±1.2	36.4	38.7	40.1	18.2
GUAM	5.6±0.4	−7.5±0.6	4.4	−9.4	21.5	−29.9
IRKT	−7.6±0.5	24.6±0.7	−6.7	25.1	2.2	1.8
KIT3	3.6±0.3	31.0±1.0	4.1	29.9	1.2	5.1
LHAS	18.1±0.3	46.6±0.9	17.3	44.4	24.7	20.5
SHAO	−11.8±0.3	33.1±0.8	−13.4	32.5	0.5	10.8
TAEJ	−14.6±0.2	28.9±0.6	−15.4	29.8	−0.4	7.8
TAIW	−9.6±0.3	36.4±0.8	−11.2	36.5	3.7	14.1
TSKB	−9.5±0.3	−5.6±0.8	−10.7	−2.0	6.2	−22.8
USUD	−8.0±0.2	−0.1±0.7	−6.9	2.6	7.6	−19.4
WUHN	−8.3±0.3	31.3±0.8	−7.4	36.6	4.1	8.4
XIAN	−8.1±0.3	29.4±0.8	−12.1	23.8	3.7	6.2

The station LHAS in table 2 is different from that in table 1, they are 20 km apart.

Measurement precision for horizontal site velocity (north component and east component) in the tables is estimated by

$$\sigma_v = \frac{\sigma_r}{T}\sqrt{\frac{12(n-1)}{n(n+1)}}\ ,$$

where σ_r is the standard deviation of single solution of site coordinate components, n the number of single solutions, and T the span of the whole observations in unit of year[10].

From the results in tables 1, 2 and fig. 1, we may see the sketch of crustal motion of Chinese mainland in the Eurasian plate.

1) The consistency of the size and the direction of the horizontal velocities from GPS data and NNR-NUVEL1A for three IGS stations IISC, KIT3 and IRKT, which are situated to the south, west and north of China respectively, suggests that the effects of the Indian plate, Eurasian plate and the Siberian blocks on Chinese mainland have been stable in the past one million years.

2) Due to the complicated tectonic structure of the mainland crust, its horizontal motion appears to be apparently inhomogeneous. Observational results indicate that the crustal motion between the east and west of China has an explicit difference. Taking Longmen fault zone and Anning river-Xiaojiang zone (N-S seismic zone of China) on the eastern fringe of the Qinghai-Xizang plateau as a boundary, the effect of the Indian plate on the crustal deformation in the east of China is by far weaker than that in the west of China. The relative crustal motion in the whole west of China under the effect of the strong northward propulsion by the Indian plate ap-

pears to shorten in north-south direction and lengthen in east-west direction, and what is more, the latter is larger than the former. Stations located in the east part of the west of China, such as Lhasa,Wenquan, Golmud, Xining and Jiuquan, have an explicit north-eastward motion with respect to Eurasian plate and their moving rates gradually reduce from south to north. However, Kashi and Hotan stations in the west part have only a northward motion and no explicit eastward motion. For the first time, these results have provided a direct observational proof in support of such an important geological inference that “the northward push-pressing of the Indian plate has two prominent sections: the Pamir wedge in the west and the Asama wedge in the east. These two wedges advance northward at different velocities. The Pamir wedge deeply penetrates into the Eurasian plate at a northwestward velocity of 43 mm/a; while the Asama wedge dives deeply into the Eurasian plate at a northeastward velocity of 64 mm/a”[1, 11].

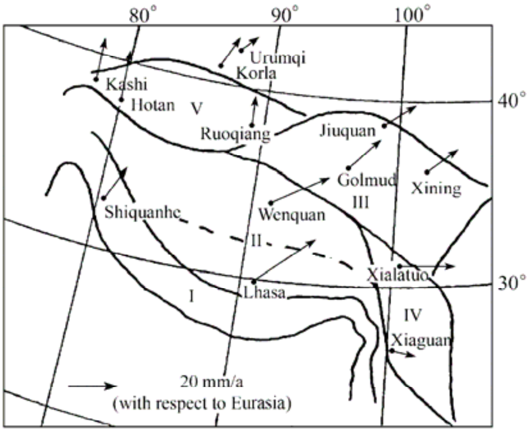

Fig. 2. The major tectonic blocks and horizontal site velocity in west China. I. Himalaya block; II, Xizang block; III. Gan-Qing block; III, Chuan-Dian block; V. Tarim block.

3) It is indicated by these GPS measurement results that there are obvious block characteristics for the crustal motion in the west of China. Fig.2 shows the locations of the major tectonic blocks and horizontal velocities of observing sites in the west of China. There are the largest northward and eastward movements for both Lhasa and Wenquan sites located in the Xizang block of Qinghai-Xizang subplate. That the moving rate of Wenquan site is less than that of Lhasa site indicates that the effect of the push-pressing coming from the Indian plate gradually reduces from south to north. In fact, ref. [1] indicates that taking Bangongcuo-Nujiang suture zone as a boundary by dashed line in fig. 2, the Xizang block can be divided into two tectonic subblocks. Lhasa and Wenquan sites are situated respectively on these blocks in the south and north. Golmud, Xining and Jiuquan stations are located in the Ganqing block of the Qinghai-Xizang subplate. They possess the northward and eastward movement at almost the same velocity, which is weaker than that of Lhasa and Wenquan sites. The small differences of the velocities among these sites also appear to gradually diminish northwards and eastwards, and may reveal that the Ganqing block is not a rigid one. In the west, there are two blocks whose crustal motion is special. One is located in the west of Yunnan Province, which is a rhombic block enclosed by Jinshajiang River, Red River fault zone and a series of north-south directional fault zone in the south part of north-south seismic zone. Xialatuo and Xiaguan stations belong to this block. With small southward slip, the north part of the block (Xialatuo station) has an explicit eastward motion due to the push of the west Xizang block. This results in an apparent dextral motion. The other block, which includes Kashi, Hotan and Ruoqiang

stations, is Tarim block in the south of Xinjiang block. In this block, on one hand, northward motion of its west part (Kashi and Hotan stations) is much greater than that of its east part (Ruoqiang station) caused by the Pamirs' northward push in the Indian plate; on the other hand, this block penetrates into the neighboring blocks like a wedge. Its motion is different from the eastward motion of the surrounding blocks. It is the only block without eastward motion in the mainland of China.

Acknowledgements This work was supported by the National Climbing Project of China (Grant No. 970231003), the National Important Basic Research Project (Grant No. G1998040703) and the Major Project for Basic Research of the Chinese Academy of Sciences (Grant No. KJ951-1-304).

References

1. Editorial Board of "Atlas of Lithospheric Dynamics in China" (eds.), Introduction of Lithospheric Dynamics in China (in Chinese), Beijing: Seismological Press, 1991.
2. Avouac, J. P., Tapponnier, P., Bai, M. et al., Active thrusting and folding along the Northern Tien Shan and Late Cenzoic rotation of Tarim relative to Dzungaria and Kazakhotan, J. Geophys. Res., 1993: 6755.
3. Bilham, R., Larson, K., Freymueller, J., GPS measurements of present-day convergence across the Nepal Himalaya, Nature, 1997, 386: 61.
4. Holt, W. E., Ni, J. F., Wallace, T. C. et al., The active tectonics of the Eastern Himalayan syntaxis and surrounding regions, J. Geophys. Res., 1991, 96 (B9): 14595.
5. Molnar, P., Caen, H. L., Fault plane solutions of earthquakes and active tectonics of the Tibetan Plateau and its margins, Geophys. J. Int., 1989, 123.
6. Dong, D.N., Bock, Y., GPS network analysis with phase ambiguity resolutions applied to crustal deformation studies in California, J. Geophys. Res., 1989, 94: 3949.
7. Zhu Wenyao, Cheng Zongyi, Xiong Yongqing et al., Preliminary results of measuring the crustal deformation in Qinghai-Xizang area using GPS technique, Science in China, Ser. D, 1998, 41(3): 314.
8. King, R. W., Bock, Y. (eds.), Documentation for the GAMIT GPS analysis software, release 9.6, Cambridge: Mass. Instit. Tech., 1997.
9. Zhu Wenyao, Cheng Zongyi, Wang Xiaoya et al., Background of crustal movement of Chinese mainland, Chinese Science Bulletin, 2000, 45(6): 557.
10. Cruttal Dynamics Project Preprint No.51, NASA/GSFC 1985.
11. Ye, S. H. , ed., Earth in Motion——Present-day Crustal Motion and Geodynamical Researches and Applications (in Chinese), Changsha: Hunan Science and Technology Press, 1996.