Detection of unsymmetrical global tectonic change by using space geodetic data

SUN Fuping[1], ZHAO Ming[2], NING Jinsheng[3] & CHAO Dingbo[3]

1. Zhengzhou Institute of Surveying and Mapping, Zhengzhou 450052, China;
2. Shanghai Observatory, Chinese Academy of Sciences, Shanghai 200030, China;
3. Wuhan Technical University of Surveying and Mapping, Wuhan 430070, China

Abstract The global tectonic change deduced from geophysical research was first identified by space geodetic data from VLBI, GPS and SLR measurements. Whether using geodesic rates or using vertical velocities of stations, three kinds of data and their integration give consistent results: within the mid-latitude belt on the Northern Hemisphere there may be about 8 — 10 mm/a contracting change; within the mid-latitude belt on the Southern Hemisphere there may be about 12—14 mm/a expanding change. This result not only validates the reverse global tectonic change in the Southern and Northern Hemispheres of the Earth, but also gives relatively precise quantative estimations.

Keyworkds: space geodesy, measuring site velocities, global tectonic change.

According to geophysical research, Ma et al.[1,2] indicated that the reverse global tectonic change in the Northern and Southern Hemispheres may exist, that is, the Northern and Southern Hemispheres may be contracting and expanding respectively. The geophysical evidence of the inference is: (i) the geoid with pear shape shows that the Northern Hemisphere may be caving in, and the Southern Hemisphere may be sticking out along the middle latitude belts (±20° — ±50°); (ii) about 3/4 of compressing and spreading tectonic boundaries are in the Northern and Southern Hemispheres respectively; (iii) according to the seismological wave measurements, S waves move more slowly in the Southern Hemisphere than in the Northern Hemisphere, indicating that the Southern and Northern Hemispheres are relatively hot and cold zones respectively.

Based on recent 15-year Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) measurements, and recent 5-year Global Positioning System (GPS) measurements, the site velocities of more than 150 stations in global distribution have been estimated at precision level of better than 3—5 mm/a. The above-mentioned global tectonic change will be demonstrated in the relative motions of the stations, so it has been possible to detect the global tectonic change by using space geodetic measurements. In this note, the above-mentioned global tectonic change was estimated by using the site velocities of VLBI, SLR and GPS stations, and the detecting results were discussed.

1 Data

The VLBI data come from the SSC (GSFC) 96R01 solution given by NASA Godard Space Flight Center (GSFC). The solution used global VLBI measurements during 1979—1996, and derived geocentric coordinates and site velocities of more than 100 VLBI stations. The precision of site velocities of about 50 stations are better than 3 mm/a. The SLR data come from the SSC (CSR) 96L01 solution given by the Center of Space Research (CSR) in Texas University. The solution used global SLR measurements during 1980—1996, and derived geocentric coordinates of 100 SLR stations and site velocities of about 50 SLR stations. The precision of site velocities of more then 20 stations is better than 5 mm/a. The GPS data come from the SSC(JPL) 96P01 solution given by the Jet Propulsion Laboratory (JPL) of California Institute of Technology, USA. The solution used global GPS measurements during 1991—1996, and derived geocentric coordinates and site velocities of more than 100 GPS stations. The precision of site velocities of most stations is better than 3 mm/a.

Because the global tectonic change is very small geodynamic activity, the data used in detection must have higher precision and better distribution. Accordingly, we select 83 VLBI, SLR and GPS stations within the mid-latitude belts (±20° —±50°) of the Earth to estimate the global tectonic change. Fig. 1 shows the global distribution of these stations. Most of the stations have standard error better

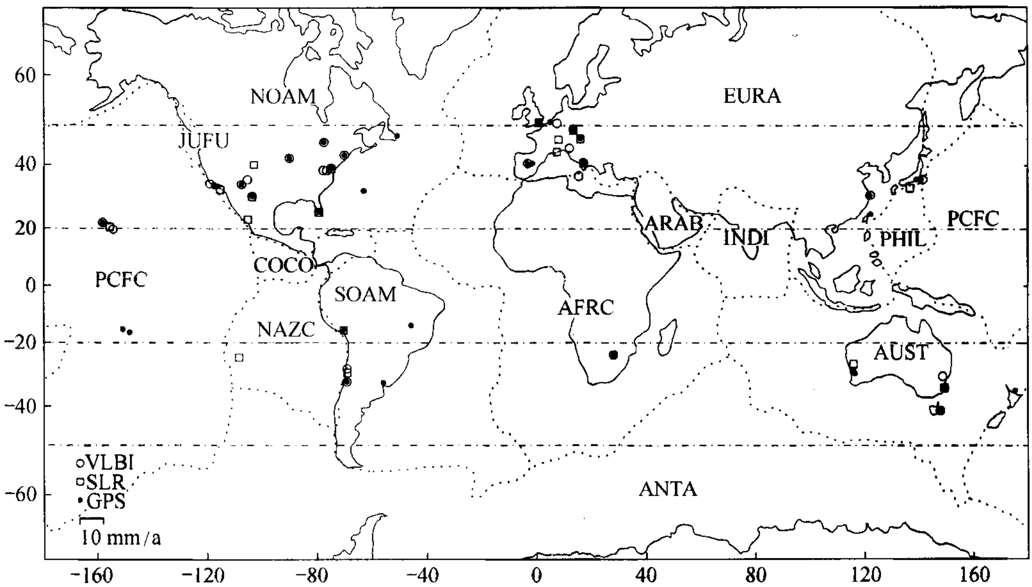

Fig. 1. Global distribution of VLBI, SLR and GPS stations. The solid lines show the continent boundaries, the dot lines plate boundaries, the dot-dashed lines the middle latitude belts. EURA, Eurasia plate; PCFC, Pacific plate; NOAM, North America plate; SOAM, South America plate; AFRC, Africa plate; AUST, Australia plate; ANTA, Antarctic plate; NAZC, Nazca plate; PHIL, Philippine plate; INDI, India plate; ARAB, Arab plate; COCO, Cocos plate; CARB, Caribbean plate; JUFU, Juan de Fuca plate.

than 2 mm/a except for several SLR stations. We have to use several stations with low latitude due to less stations in the Southern Hemisphere

2 Methods

(i) Detection by using geodesic change rates. According to the basic principle of plate tectonics, the large-scale horizontal movements of lithosphere plates on the Earth could be described as a kind of rotating motion along an axis on a sphere; globally, the spreading part of plate along separating boundaries would be equal to the missing part of plate along compressing boundaries, so the radius of the Earth will keep unchanged. Based on this principle, the geological plate motion model, for xample, NUVEL-1A[3,4], could be derived from geological data through constraining the plate circuit to be closed on the predicting model. Therefore the model illustrates the averaged plate motions on the Earth with an unchanged radius. Space geodetic site velocities show the global tectonic motions occurring presently, if the global tectonic change exists, the change must be reflected by the differences between space geodetic motions and geological model predictions. This is a theoretical proof of our method. The observations used to establish the geological plate motion model, such as sea floor spreading rates and transform fault azimuth, are average values during recent several million years[3,4], so the results given by the geological plate motion model are average plate motions in recent several million years, which can be thought as the predictions relative to the long stillness Earth (with unchanged radius). In addition, the accuracy of plate motions given by the geological model is better than 3 mm/a[3,4]. Therefore, we think that the results based on the above detecting methods should be reliable.

If the above-mentioned reverse global tectonic change in the Northern and Southern Hemispheres really exists, the closed difference W of latitudinal circle between space geodetic rates and model predictions along mid-latitude belts would not be equal to zero. W should be negative if the Northern Hemisphere is contracting and positive if the Southern Hemisphere is expanding. On these grounds, the measured site velocities were processed to detect the global tectonic change.

First, the site velocities were used to compute baseline length rates among stations on different plates. Second, the length rates of baseline were transformed to geodesic rates and the geodesic rate differences x_{ij} between measured rates and predicted ones can be given as

$$X_{ij} = \dot{S}_{ij}^{\text{obs}} - \dot{S}_{ij}^{\text{pre}} = (\dot{B}_{ij}^{\text{obs}} - \dot{B}_{ij}^{\text{pre}}) / \sqrt{1-(B_{ij}/2R)^2} - \dot{R}\left(B_{ij} / \sqrt{(2R)^2 - (B_{ij})^2} - \arcsin(B_{ij}/2R) \right), \quad (1)$$

where B_{ij} is baseline length, $\dot{S}_{ij}^{\text{obs}}$ and $\dot{S}_{ij}^{\text{pre}}$ are geodesic rates from space geodetic measurements and geophysical model predictions respectively, $\dot{B}_{ij}^{\text{obs}}$ and $\dot{B}_{ij}^{\text{pre}}$ are the baseline change rates from space geodetic measurements and geophysical model predictions respectively, R and $\dot{R}$ are radius of the Earth and its change rate, in computation, we use $(V_i^r + V_j^r)/2$ instead of $\dot{R}$, here V_i^r, V_j^r are vertical site velocities of ith and jth stations respectively. Second, the weighted average $\left(U_{ij} = \sum P_{ij} X_{ij} / \sum P_{ij}\right)$ of all geodesic rate differences in an arc is computed, which is called arc difference and reflects the latitudinal tectonic change of an arc within the middle latitude belts, here P_{ij} is given by the transmit rule of weight reciprocal from formula (1). Then the summation (closed difference $W1=U_{ij}+U_{jk}+U_{kl}+U_{li}$) of arc differences within the middle latitude belts is computed. In another way, at first the single circle closed difference ($W_{ij}^{kl} = X_{ij} + X_{jk} + X_{kl} + X_{li}$) are computed, then the total circle closed difference $\left(W2 = \sum P_{ij}^{kl} W_{ij}^{kl} / \sum P_{ij}^{kl}\right)$ is computed, here P_{ij}^{kl} is given by the transmit rule of weight reciprocal from the formula ($W_{ij}^{kl} = X_{ij} + X_{jk} + X_{kl} + X_{li}$). Finally, the closed difference W is the estimations of global tectonic change. If W is negative, the related hemisphere is compressing, otherwise, it is swelling. Due to the poor distribution of observing stations on global plates, the circle closed difference only consists of four arcs. In future, with increase of observing stations, the circle closed difference will consist of more than four arcs, the more accurate detecting results will be obtained.

(ii) Detection by using vertical site velocities. In order to illustrate motions of stations audio-visually, the geocentric site velocities usually are transformed to topocentric site velocities. The topocentric site velocities of any station include east, north and vertical velocities, the east and north velocity is no contribution to contracting and expanding change of the Earth, the vertical velocities can be directly used to compute the global tectonic change. If the ith and jth stations are located in the same latitudinal circle, their latitude $\varphi = \varphi_i = \varphi_j$, their longitude difference $\alpha_{ij} = \lambda_j - \lambda_i$, then the latitudinal arc length S_{ij} is $S_{ij} = R\cos\varphi \cdot \alpha_{ij}$, so the arc length rate caused by the global tectonic change is $\dot{S}_{ij} = \dot{R}\cos\varphi \cdot \alpha_{ij}$. In computation, we use $(V_i^r + V_j^r)/2$ instead of $\dot{R}$, then we get

$$\dot{S}_{ij} = (V_j^r + V_i^r)\cos\varphi(\alpha_{ij}/2). \quad (2)$$

The weighted average $\left(U_{ij} = \sum P_{ij} \dot{S}_{ij} / \sum P_{ij}\right)$ of all latitudinal length rates in an arc is computed, which is called arc difference and reflects the latitudinal tectonic change of an arc within the middle latitude belts, here P_{ij} is given by the transmit rule of weight reciprocal from formula (2). Finally the summation (closed difference $W1=U_{ij}+U_{jk}+U_{kl}+U_{li}$) of arc differences within the middle latitude belts is computed. In another way, at first the single circle closed difference $W_{ij}^{kl} = \dot{S}_{ij} + \dot{S}_{jk} + \dot{S}_{kl} + \dot{S}_{li}$ are computed, then the total circle closed difference $\left(W2 = \sum P_{ij}^{kl} W_{ij}^{kl} / \sum P_{ij}^{kl}\right)$ is computed, here P_{ij}^{kl} is given by the transmit rule of weight reciprocal from the formula $W_{ij}^{kl} = \dot{S}_{ij} + \dot{S}_{jk} + \dot{S}_{kl} + \dot{S}_{li}$. Principally, if the Earth has no compressing or swelling change, the vertical velocities must be zero, so W should be zero; otherwise, W should not be zero. When the vertical velocities are negative, W must be negative, showing that the Earth is contracting along the latitudinal circle; conversely, W must be positive, showing that the Earth is expanding along the latitudinal circle. Therefore, the vertical velocities of stations can be directly used to estimate compressing and swelling velocities of the Earth. Usually, the stations do not rigorously lie on the same latitudinal circle, in application, we use the averaged latitude φ_{ij} ($\varphi_{ij} = (\varphi_i + \varphi_j)/2$) of two stations instead of φ.

Because VLBI, SLR and GPS site velocities were derived by different international analysis centers, their kinematics reference frames would be different. In order to integrate three kinds of data, it is necessary to unify them into the same kinematics reference frame. The GPS and SLR data were transformed into VLBI kinematics reference frame by using site velocities of 20 VLBI and SLR co-location stations and 28 VLBI and GPS co-location stations.

Theoretically, the vertical motion of station should be defined as the motion relative to geocenter, but in fact the vertical kinematic datum of the velocity fields is not geocentric datum. So before we use the vertical velocities to detect global tectonic change, they should be transformed into a geocentric datum. Here we assume the geophysical model (ICE-4G) of postglacial rebound providing us a geocentric kinematic datum[5], we transformed the unified VLBI, SLR and GPS frame into the ICE-4G frame by deleting systematic deviation between VLBI and ICE-4G frames. In practice, the systematic deviation was derived from the differences between VLBI and ICE-4G vertical velocities of 10 stations in northern Europe and America by using the following formula:

$$\sum_{i=1}^{m} \left[\left(V_i^{\text{obs}} - S - V_i^{\text{pre}}\right) \cdot \hat{X}_i\right]^2 = \min, \qquad (3)$$

where V_i^{obs} and V_i^{pre} are projecting vectors of VLBI and ICE-4G vertical velocities in geocentric velocity field respectively, S is vector of systematic deviation, $\hat{X}_i$ is unit geocentric vector of ith station, m is the number of stations.

3 Results and discussion

Within the mid-latitude belt on the Northern Hemisphere, we select some stations located on North America, Europe, East Asia, Pacific to form 4 latitudinal arcs, the longitude differences between any two stations for every arc are smaller than 120°, most of latitude differences are within 20°. We used the above methods to estimate the compressing change rates occurring in the north half of the Earth from VLBI, GPS, SLR and their integrated site velocities respectively, and the results are given in table 1.

Table 1 Detecting results in the Northern Hemisphere (mm/a)

Tech.	Method	PCFC-NOAM	NOAM-EURA	EURA-SOCH	SOCH-PCFC	*W*1	*W*2
VLBI	M1	1.8±1.0	−1.7±1.0	3.9±1.5	−14.5±1.6	−10.6±2.6	−10.9±2.7
	M2	−0.9±0.5	−1.1±0.6	−2.3±0.8	−3.3±0.8	−7.9±1.4	−10.1±1.5
GPS	M1	0.6±0.6	−1.1±0.5	5.0±1.0	−15.1±1.1	−10.6±1.7	−6.8±1.8
	M2	−0.2±0.2	−0.6±0.3	−3.5±0.6	−4.5±0.7	−8.8±1.0	−8.7±1.0
SLR	M1	−0.9±2.0	1.6±3.3	−25.1±3.0	15.5±2.1	−8.9±5.3	−7.9±5.3
	M2	−0.5±1.0	−1.5±2.0	−2.3±1.9	−3.7±1.1	−8.0±3.1	−7.7±3.2
Inte.	M1	1.0±1.2	−1.3±1.7	4.2±1.5	−15.0±1.8	−11.1±3.1	−8.6±3.2
	M2	−0.5±0.6	−0.9±1.1	−3.1±1.0	−4.0±1.0	−8.5±1.9	−9.4±1.8

Within the mid-latitude belt on the Southern Hemisphere, because of less number and poor distribution of stations, we had to use some stations with low latitude. The different techniques would form different latitudinal arcs, for example, GPS stations located on Australia, Africa, South America, South Pacific can form 4 latitudinal arcs, VLBI stations located on Australia, Africa, South America can only form 3 latitudinal arcs, and SLR stations cannot form a closed latitudinal circle because the site velocity precision of stations on Africa is very poor. The results are given in table 2. The standard error of each arc difference U_{ij} in tables 1 and 2 is the root of mean square of the standard errors of X_{ij} or $\dot{S}_{ij}$. If we use the transmit rule of error to compute standard errors of U_{ij}, it would be too small and show too optimistic precision. The standard error of *W*1 is computed by using the standard errors of U_{ij} based on the transmit rule of error. The standard error of *W*2 is the root of mean square of the standard errors of all W_{ij}^{kl}, and the standard error of each W_{ij}^{kl} is computed by using standard errors of X_{ij} or $\dot{S}_{ij}$ based on the transmit rule of error. In tables 1 and 2, M1 means the results by using the method described in section 2(i), and M2 the results by using the method described in section 2(ii).

Table 2 Detecting results in the south half of the Earth (mm/a)

Tech.	Method	AFRC-AUST	AUST-PCFC	PCFC-SOAM	SOAM-AFRC	W1	W2
GPS	M1	5.1±1.7	−0.8±0.9	18.9±1.6	−7.8±1.7	15.4±3.0	11.9±3.0
	M2	0.7±1.0	2.8±0.4	6.7±1.0	4.5±0.8	14.7±1.7	13.1±1.7
VLBI	M1	−0.2±1.9	15.4±3.6		−9.7±2.5	5.5±4.7	4.0±4.8
	M2	1.6±1.1	4.6±2.2		2.6±1.5	8.8±2.9	7.8±2.9
Inte.	M1	3.5±1.8	1.2±1.1	19.4±2.3	−7.9±3.0	16.2±4.3	12.7±4.3
	M2	1.1±1.0	3.1±0.5	6.6±1.4	4.1±1.6	14.9±2.4	13.4±2.5

From tables 1 and 2 we can see, whether using data from different techniques or using different methods, all give consistent detecting results. Within the mid-latitude belt on the north half of the Earth, the closed differences (*W*) derived by two methods are all negative; within the mid-latitude belt on the south half of the Earth, the closed differences (*W*) are all positive. If the detecting methods have no problems, this result would show that the reverse global tectonic change in the north and south half of the Earth probably exists. The size of the change could be determined by VLBI and GPS detecting results due to their higher precision measurements, larger number and better distribution of stations. The compressing change in the Northern Hemisphere of the Earth is about 8—10 mm/a, the swelling change in the south half of the Earth is about 12—14 mm/a, the latter result may have larger error due to less number and poor distribution of stations in the south half of the Earth.

References

1. Ma, Z., Chen, Q., Global seismotectonic system and asymmetry of the Earth, Science in China, Ser. B (in Chinese), 1988 (10): 1092.
2. Ma, Z., Gao, X., Ren, J., The features of contemporary global tectonics and its dynamic explanation, Quaternary Science (in Chinese), 1992(4): 293.
3. DeMets, C., Gordon, R. G., Argus, D. F. et al., Current plate motions, Geophys. J. Int., 1990(101): 425.
4. DeMets, C., Gordon, R. G., Argus, D. F. et al., Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, Geophys. Res. Lett., 1994(21): 2191.
5. Argus, D. F., Post-glacial rebound from VLBI geodesy: on establishing vertical refernece, Geophys. Res. Lett., 1996(23): 973.

(Received June 3, 1999)