GEODYNAMICS & TECTONOPHYSICS

PUBLISHED BY THE INSTITUTE OF THE EARTH'S CRUST
SIBERIAN BRANCH OF RUSSIAN ACADEMY OF SCIENCES

2015 VOLUME 6 ISSUE 1 PAGES 45–61 ISSN 2078-502X

http://dx.doi.org/10.5800/GT-2015-6-1-0171

Recent Geodynamics

ESTIMATION OF THE ASYMMETRIC VERTICAL VARIATION OF THE SOUTHERN AND NORTHERN HEMISPHERES OF THE EARTH

Wen-Bin Shen[1, 2], Rong Sun[1], Yuri V. Barkin[3], Zi-Yu Shen[1]

[1] *Department of Geophysics, School of Geodesy and Geomatics / Key Laboratory of Geospace Environment and Geodesy of Ministry of Education, Wuhan University, Wuhan, China*

[2] *State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China*

[3] *Sternberg Astronomical Institute of Moscow State University, Moscow, Russia*

Abstract: In previous studies, the northern hemisphere of the Earth is considered to be in compression while the southern one is in expansion. In this study, based on three different methods, we calculate average vertical variations of the two hemispheres from velocity field data under the ITRF2008 (International Terrestrial Reference Frame 2008) solution. Results show that the northern hemisphere is in expansion at the rate about 1 mm/yr, while the compression rate of the southern hemisphere is one order smaller than the expansion rate of the northern one. After the post glacial rebound effect is subtracted, results show that the expansion and compression rates of the northern and southern hemispheres are 0.46 mm/yr and –0.19 mm/yr, respectively. Transformation between the velocity fields under ITRF2008 and ITRF2000 can explain why different authors have different conclusions about the expansion/compression pattern of one hemisphere or the other. Anyway, the entire Earth is expanding at a rate about 0.2 mm/yr, and this estimation coincides with results of our previous studies. The mean variation rates of the radii at different latitudes have been calculated.

Key words: reference systems, tectonic deformation, space geodetic datasets, expansion, compression.

Recommended by V.A. San'kov

For citation: *Shen W.-B., Sun R., Barkin Yu.V., Shen Z.Y.* 2015. Estimation of the asymmetric vertical variation of the southern and northern hemispheres of the Earth. *Geodynamics & Tectonophysics* 6 (1), 45–61. doi:10.5800/GT-2015-6-1-0171.

ОЦЕНКА АСИММЕТРИЧНОГО ВЕРТИКАЛЬНОГО ИЗМЕНЕНИЯ ЮЖНОГО И СЕВЕРНОГО ПОЛУШАРИЙ ЗЕМЛИ

Вэнь Бинь Шень[1, 2], Жун Сунь[1], Юрий Баркин[3], Зи-Ю Шень[1]

[1] *Отделение геофизики, школа геодезии и геоматики / Лаборатория Геокосмических окружающей среды и геодезии Министерства образования, Университет города Ухань, Ухань, Китай*

[2] *Государственная лаборатория информационной техники в геодезии, картографии и дистанционном зондирования, Университет города Ухань, Ухань, Китай*

[3] *Государственный астрономический институт им. П.К. Штернберга Московского государственного университета им. М.В. Ломоносова, Москва, Россия*

Аннотация: В предыдущих геодезических исследованиях считалось, что Северное полушарие испытывает тенденцию сжатия, а Южное полушарие, наоборот, расширения. В данной работе аналогичные исследования были проведены на основе трех различных методов. Для расчета средних вертикальных изменений этих двух полушарий мы использовали поле скоростей в Международной земной системе координат (ITRF) в эпоху 2008. Наши результаты показали, что в Северном полушарии из-за деформации происходит расширение со средней скоростью около 1 мм/год, а Южное полушарие испытывает сжатие со скоростью на порядок меньше скорости расширения. После исключения из рассмотрения эффекта постледникового отскока было установлено, что темпы расширения и сжатия Северного и Южного полушарий составляют 0.46 мм/год и –0.19 мм/год, соответственно. Преобразование между полями скоростей для двух международных систем координат ITRF 2008 и ITRF 2000 может объяснить, почему разные авторы делают различные выводы о характере расширения / сжатия Северного и Южного полушарий. Тем не менее, в целом, Земля расширяется со скоростью около 0.2 мм/год, что совпадает с нашими предыдущими исследованиями. Были рассчитаны также средние скорости изменения радиуса Земли в зависимости от широты.

Ключевые слова: земные системы координат, тектонические деформации, космические геодезические наборы данных, расширение, сжатие.

1. Introduction

Based on different methods and different datasets, it is found that the expansion/compression patterns of the northern and southern hemispheres of the Earth are different. Based on geophysical methods and the tectonic structure, *Ma* and *Chen* [*1988*] and *Ma et al*. [*2002*] declared that the northern hemisphere is in compression, while the southern one is in expansion. *Sun et al*. [*2000*] calculated the length variation of the latitude circle in the northern hemisphere and southern hemisphere and found that the compression rate of the northern hemisphere amounts to –8 ~ –10 mm/yr, and the expansion rate of the southern hemisphere is 12~14 mm/yr. *Jin* and *Zhu* [*2003*] calculated the length variation of the latitude circle in the southern hemisphere based on the velocity field under the International Terrestrial Reference Frame in datum epoch 2000 (ITRF2000) and also found that the southern hemisphere is in expansion. Besides, they calculated the relative speed of movements of different plates by Euler's theorem based on the plate model derived from space geodetic data and concluded that the southern hemisphere is stretching at a slowing-down speed. *Huang et al*. [*2002*] also used the velocity field under ITRF2000 to estimate volume variations of the northern and southern hemispheres and concluded that the volume variations of the northern and southern hemispheres are -1.57×10^3 km^3/yr and 0.936×10^3 km^3/yr, respectively, which correspond to the compression rate of the northern hemisphere at –6.2 mm/yr and the expansion rate of the southern hemisphere at 3.5 mm/yr. Furthermore, *Sun et al*. [*2006*] obtained similar results by using Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS) solutions provided by the International Earth Rotation Service (IERS), and they concluded that the variation rates of the volume in the northern and southern hemispheres are -2.5428×10^3 km^3/yr and 0.6641×10^3 km^3/yr, respectively, resulting in a total volume variation of -1.8787×10^3 km^3/yr. Based on data from 617 space geodetic stations under ITRF2000, *Shen* and *Zhang* [*2008*] found that the volume variation rates of the northern and southern hemispheres are -1.3765×10^3 km^3/yr and 1.6517×10^3 km^3/yr, respectively.

Note also that the possible asymmetry in deformation of the northern and southern hemispheres provides evidence of the variability of the mean radius of the Earth. One of the first estimates of the secular increase in the average radius of the Earth in the modern era was 0.22–0.23 mm/yr [*Barkin*, *Shuanggen*, *2007*], which to some extent will announce a more modern determination of the characteristics [*Shen et al*., *2011*; *Wu et al*., *2011*]. Based on multiple precise geodetic data sets and simultaneous estimations of multi-parameters, *Wu et al.* [*2011*] stated that, the ITRF2008 origin is consistent with the mean position of the Earth center of mass (at the level of 0.5 mm yr^{-1}), and the mean radius of the Earth is not changing within 1 σ measurement uncertainty of 0.2 mm yr^{-1}. In this regard, of particular interest is the rate of secular change of average radii of the northern and southern hemispheres of the Earth in the light of the expected changes in their contrast in view of the preliminary conclusions on the basis of the geomodel of the forced displacement and oscillations of the planet's core and mantle [*Barkin*, *2002*]. It is the main problem of our study presented in this paper.

The geodetically observed length variations of latitude circles of the Earth testify an asymmetry shape

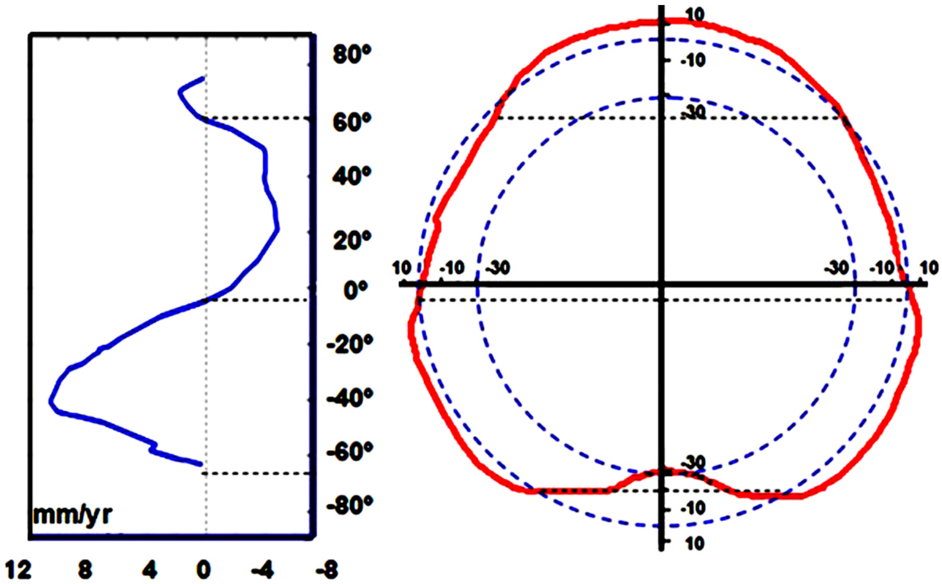


Fig. 1. Rates of secular change in the lengths of latitudinal circles around the Earth from satellite observations (left graph) [*Barkin, Shuanggen, 2006, 2007*] and their correlation with the geometrical shape of the geoid (right graph) [*Barkin, 2011*].

Рис. 1. Скорость векового изменения длины широтных окружностей Земли по спутниковым данным (график слева) [*Barkin, Shuanggen, 2006, 2007*] и корреляция колебаний с геометрической формой геоида (график справа) [*Barkin, 2011*].

variations of the northern and southern hemispheres as an important consequence of the mantle deformation due to gravitational action of the drifting core of the Earth [*Barkin, 2002; Barkin, Shatina, 2005; Barkin, Shuanggen, 2006*]. The circles are pulled together in the southern hemisphere and stretched in the northern hemisphere. Meanwhile, this phenomenon is also supported by the secular radial motions of geodetic observations and the secular geocenter motion trend towards the Sorth Pole of the Earth. These relative motions of the Earth shells lead to inverse changes of the Earth shape which are manifested as formation of fluxes on the Earth surface as well as the intensity of many natural processes in the hemispheres [*Barkin, 2002; Barkin, Shatina, 2005*]. The secular asymmetrical change of the Earth hemispheres is an important signal to the Earth interior activities, such as relative oscillations or deformations of the core and mantle induced by the forced core-mantle interaction. The main consequence of the relative displacement is evidenced in contrasting changes of tension states of the mantle layers in the hemispheres. The inertia moment with respect to the polar axis of the Earth is increasing in the northern hemisphere and decreasing in the southern hemisphere. Furthermore, due to the mantle deformation under a gravitational action of the displaced core, the centre of the Earth mass tends to move towards the South Pole with a velocity of 0.9±0.2 mm/yr [*Jin, Barkin, Park, 2007*]. These secular differences or drifts result in secular redistribution of masses in the Earth hemispheres, increasing in the northern hemisphere and decreasing in the southern hemisphere.

Deviations of the geoid form relative to the surface of the ellipsoid (right graph in Fig. 1) are shown in meters and in the conventionally enlarged scale with respect to the actual dimensions. Noticeable is the correlation curve (left graph in Fig. 1) with the shape of the geoid. Theoretical values of the rates of secular lengthening of latitude circles are determined by the following equation [*Barkin, Shatina, 2005; Barkin, 2007*].

$$\dot{L}_{\varphi} = 2\pi\dot{u}_{\rho} = -\dot{\rho}\cdot 0.304469\cdot sin\varphi cos\varphi =$$
$$= (-5.47\pm 0.16)\cdot sin2\varphi\; mm/yr. \qquad (1)$$

According to geodynamic concepts [*Barkin, 2002*] of changes in the shape of the Earth, its pear-shaped form is caused by deformations of the mantle due to relative displacements and oscillations of the planet's core and mantle [*Barkin, 2002*]. Asymmetry in variations of lengths in the southern and northern hemispheres (right graph in Fig. 2) may be caused by the influence of another dynamical mechanism, such as spreading of the lithospheric plates which is most active in the southern hemisphere. This geomodel provides clear explanations of a number of geodynamical phenomena, such as observed secular variations of lengths

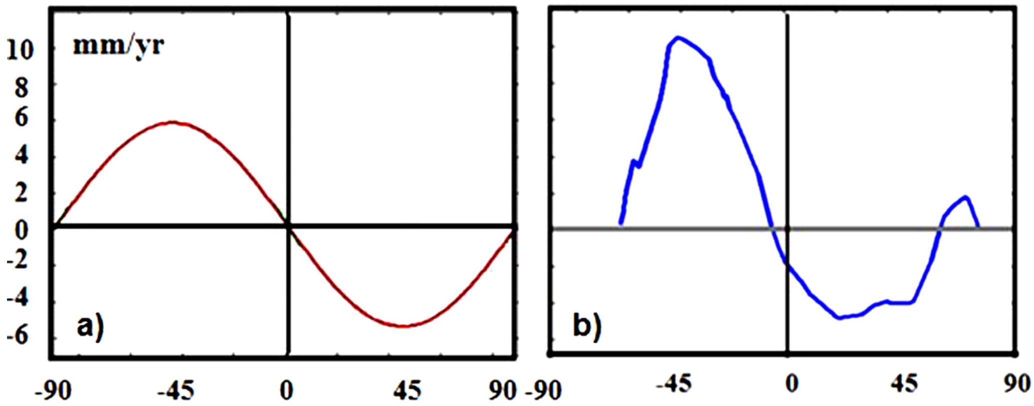


Fig. 2. Velocities of secular variations of lengths of latitudinal circles of the Earth versus latitudes, according to satellite observations data (*b*), and a theoretical dependence (*a*) obtained on the basis of the solution of the problem of elasticity concerning elastic mantle deformations under gravitational effect of drifting of the Earth's core to the north.

Рис. 2. Скорости вековых вариаций длины широтных кругов Земли в зависимости от широты по данным спутниковых наблюдений (*b*) и теоретическая зависимость (*a*) вариаций, полученная на основе решения задачи теории упругости об упругих деформациях мантии под действием гравитации при смещении коры Земли на север.

of latitudinal circles, meridional displacements of points of the Earth's surface to the north, non-polar latitude variations, mechanism of formation of low-velocity zones (LVZ) and their layered structures (Earth: an average depth of about 145 km; Mars: an average depth of about 290 km) [*Barkin et al., 2012a, 2012b*] and other phenomena.

The dynamic theory [*Barkin, 2002*] predicts another subtle effect – contrasting secular variations of the northern hemisphere average radii (slow growth with velocity) and the southern hemisphere average radii (slow down) by deformation of the Earth's mantle [*Barkin, Shatina, 2005*]. The dynamic effect is very small and corresponds to the maximum value of the strain rate of the hemispheres (near the poles) at about 0.033 mm/yr [*Barkin, 2011, 2013; Barkin et al., 2013a, 2013b*]. For the secular change of the mean radius of the latitudinal circle (in dependence from latitude, φ and for the accepted velocity of the polar drift of the core, $\dot{\rho} = 27.4 \pm 0.8\, mm/yr$), the following equation was derived [*Barkin, 2011*]:

$$\dot{R}_{\varphi} = \dot{\rho} \cdot 0.001203 \cdot sin\varphi = \\ = (0.03296 \pm 0.00096) \cdot sin\varphi\, mm/yr. \qquad (2)$$

There is another effect of changes in the average radii of the hemispheres – a kinematic effect, which reflects the secular drift of the ITRF2008 origin. The kinematic effect is significant and depends on the velocity of the secular drift of the ITRF origin. In this paper, a conventional maximum rate of increase of the mean radius of the northern hemisphere is about 1.8 mm/yr, and a similar decrease of the mean radius of the southern hemisphere corresponds to this effect. Actually, a relative motion of ITRF2008 with respect to ITRF2000 is considered mainly along negative direction of polar axis Z. On the basis of these characteristics, the surface deformations calculated in this study are in agreement with our preliminary theoretical estimations. Therefore, this approach to analyses of deformations of the Earth surface proves correct.

Note that here we do not directly consider the secular drift of the center of mass of the Earth and operate with the base coordinate systems ITRF2000, 2005, 2008. However, based on analysis of satellite observation data from DORIS system, we obtained an estimate of the polar drift velocity of the Earth center of mass relative to its mantle (to DORIS base reference system) at 5.29 mm/yr [*Zotov et al., 2009; Barkin, 2010a, 2010b*]. Formally, it suggests that ITRF DORIS moves to the south with respect to ITRF2000 with a velocity about 3.5 mm/yr. And the main reason for these discrepancies of the coordinate systems may be due to heterogeneity of the observational data obtained by other techniques. These important questions about the reference frames will be considered in our future works.

This work aims to study the problem of modern space geodesy in view of identification and determination of the secular variations of the mean radii of the northern and southern hemispheres of the Earth due to deformation of its surface. Theoretical estimates based on the dynamics of the forced relative displacements of the core and mantle show that the effect of the radial deformation of the Earth caused by the secular drift of the core relative to the elastic mantle is small, but obtaining its exact determination is currently very challenging. However, our research has confirmed

Т a b l e 1. **Asymmetric average vertical motion between the northern and southern hemispheres of the Earth**

Т а б л и ц а 1. **Асимметричные средние вертикальные движения между Северным и Южным полушариями Земли**

Method	Average vertical variation rate of the radius of the northern hemisphere, mm/yr (461 stations)		Average vertical variation rate of the radius of the southern hemisphere, mm/yr (168 stations)		Average vertical variation rate of the radius of the whole Earth, mm/yr (629 stations)	
	PGR not subtracted	PGR subtracted	PGR not subtracted	PGR subtracted	PGR not subtracted	PGR subtracted
Shen et al. [*2011*]	–	–	–	–	0.539±0.052	0.238±0.037
Area method	1.003±0.073	0.490±0.050	0.038±0.050	–0.034±0.048	0.539±0.052	0.238±0.037
Virtual equator station method	1.140±0.074	0.531±0.050	0.029±0.047	–0.074±0.042	0.604±0.050	0.239±0.035
Griding method (1°×1°grid)	0.955±0.010	0.462±0.007	–0.125±0.005	–0.194±0.004	0.386±0.008	0.117±0.006
Weighted average	0.959±0.017	0.464±0.012	–0.122±0.009	–0.192±0.007	0.395±0.014	0.123±0.010

correctness of the basic conclusions concerning the discussed phenomena: 1. The Earth's surface deformation at the level of order 0.2 mm/yr (Table 1); 2. Contrast surface deformations of the Earth's northern and southern hemispheres (Table 2); 3. A curve of changes of mean radii of latitudinal circles, which is constructed on the basis of observation data. The obtained results reveal new features in the geodesic changes of the Earth shape and provide an important confirmation of the considered basic geodynamic model of forced displacements and relative oscillations of the Earth's core and mantle [*Barkin, 2002*].

In this paper, the position and velocity data obtained from the stations under ITRF2008 are used to estimate average vertical variation rates for both hemispheres. After introducing the datasets used in this study in Section 2, we describe the method for estimating the average vertical variation rates for the hemispheres in Section 3. The results and relevant discussions are presented in Section 4, and the conclusion is stated in Section 5.

2. Data

In this study, the velocity field of the Earth surface is given according to ITRF2008 [*Altamimi et al., 2011*]. ITRF provides information on positions and velocities of a set of stations. The techniques include GPS, VLBI, Satellite Laser Ranging (SLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). The latest version of ITRF is ITRF2008, including 1572 station records. However, some of these records belong to a same station, and in fact data from only 935 different stations are available. In addition, to transform the coordinates between terrestrial reference frames set up by different techniques, some stations are set up in a very small area. In our study, these stations are viewed as one station, i.e. a representative station, the position and velocity of which are determined by the weighted average of all the records at such stations. After such preprocessing, data from 845 stations are under study [*Shen et al., 2011*]. Furthermore, stations located in the orogen belts are not used. The information about the orogen belts considered in this study is from PB2002 [*Bird, 2003*] plate model, which includes 13 orogen belts. Besides, stations that have absolute vertical velocity larger than 0.02 m/yr are removed since so large vertical motions are considered as having nothing to do with the global-size movement [*Shen et al., 2011*]. Thus, data from 629 stations are used for further calculations.

The post-glacial rebound (PGR) has contribution to the vertical movements of the stations. The PGR data used in this study are taken from website (http://grace.jpl.nasa.gov/data/pgr/) [*Paulson et al., 2007*]. For each station on the surface of the Earth, its vertical motion due to PGR is calculated as follows:

$$v_{PGR} = \sum \bar{C}^P_{n0}\,\bar{P}_{n0}(\theta) + \sum_n \sum_m (\bar{C}^P_{nm} \cos m\lambda + \\ + \bar{S}^P_{nm} \cos m\lambda)\,\bar{P}_{nm}(\theta), \qquad (3)$$

where $\bar{C}^P_{n0}$, $\bar{C}^P_{nm}$ and $\bar{S}^P_{nm}$ are spherical harmonic coefficients obtained from the grid value of the uplift rate in the PGR model (from website http://grace.jpl.nasa.gov/data/pgr/; see *Paulson et al.* [*2007*]), $\bar{P}_{n0}(\theta)$ and $\bar{P}_{nm}(\theta)$, are normalized Legendre functions. Estimation of PGR effects based on the PGR model is described in detail in [*Shen et al., 2011*].

3. Methods

To estimate the average vertical velocity of each hemisphere, three different methods are used: (1) area

Table 2. **Mean variation rate of radius at different latitude**

Таблица 2. **Средняя скорость вариаций радиуса на разных широтах**

Latitude (degree)	Average vertical variation over latitude circle	
	PGR not subtracted (mm/yr)	PGR subtracted (mm/yr)
90	4.073±0.085	2.129±0.085
80	3.741±0.102	2.637±0.103
70	2.730±0.101	1.832±0.057
60	1.986±0.177	0.192±0.076
50	0.340±0.088	–0.080±0.081
40	0.123±0.055	0.487±0.058
30	–0.326±0.045	–0.114±0.040
20	–0.186±0.087	0.072±0.090
10	–0.279±0.093	–0.074±0.095
5	–0.237±0.084	–0.058± 0.085
–5	–0.282± 0.071	–0.158±0.070
–10	–0.368±0.068	–0.275±0.066
–20	0.198±0.031	0.265±0.028
–30	0.247±0.047	0.266±0.043
–40	–0.389±0.065	–0.444±0.056
–50	–0.501±0.046	–0.501±0.040
–60	0.512±0.080	0.267±0.067
–70	–0.106±0.057	–0.488±0.060
–80	–1.369±0.033	–2.431±0.025
–90	–3.005±0.418	–4.251±0.418

method; (2) virtual equator station method; (3) gridding method.

3.1. Area method

For each small spherical triangle, its representative velocity v_{tr} is calculated as follows:

$$v_{tr} = \frac{v_A+v_B+v_C}{3}, \tag{4}$$

where v_A, v_B, v_C are vertical velocities of three end nodes of the given spherical triangle. The variance $m^2_{v_{tr}}$ of v_{tr} is calculated based on the error propagation law.

To estimate the average vertical velocity of a hemisphere, SDTIN (Spherical Delaunay Triangular irregular network) is set up for the space geodetic stations [*Renka, 1997*]. The triangles thus formed can be classified into three types:

Type 1: All nodes are located in the northern hemisphere (888 spherical triangles, accounting for 70.8 % of the total number of spherical triangles);

Type 2: All nodes are located in the southern hemisphere (300 spherical triangles, accounting for 23.9 % of the total number of spherical triangles);

Type 3: Nodes are located at both sides of the equator (66 spherical triangles, accounting for 5.3 % of the total number of spherical triangles).

To calculate the average vertical motion $v_{northern}$ of the northern hemisphere, for example, triangles of Type 1 and Type 3 are used, and the equation is as follows:

$$v_{northern} = \frac{\sum_i P_i^N v_i}{\sum_i P_i^N}, \quad P_i^N = \frac{S_i^N}{m^2_{v_i}}, \tag{5}$$

where S_i^N is the spherical area of the i-th triangle; $m^2_{v_i}$ is the variance of the i-th triangle; P_i^N is the weight of the i-th triangle; v_i is the average vertical velocity calculated from vertical velocities at three endpoints of this spherical triangle. It should be noted that if triangle of Type 3 is used in equation (5), S_i^N is the area occupied by the given triangle in the northern hemisphere. The average vertical motion of the southern hemisphere is calculated by the same process.

3.2. Virtual equator station method

In the virtual equator station method, each spherical triangle of Type 3 mentioned above is further divided into four small triangles, each being of Type1 or Type 2. Then all the triangles of Type 3 are transformed to triangles of Type 1 or 2, and each hemisphere is thus covered by one SDTIN. The process to calculate the general vertical motion of a hemisphere is thus similar to the calculations of the general vertical motion of the whole Earth, although SDTIN used here covers one hemisphere instead of the globe.

To divide a triangle of Type 3 into triangles of Type 1 or 2, virtual stations are added in each triangle of Type 3 (Fig. 3). The position of each virtual station is obtained by calculating the crossing point of one spherical line of this triangle and the equator. In each triangle of Type 3, only two spherical lines will cross the

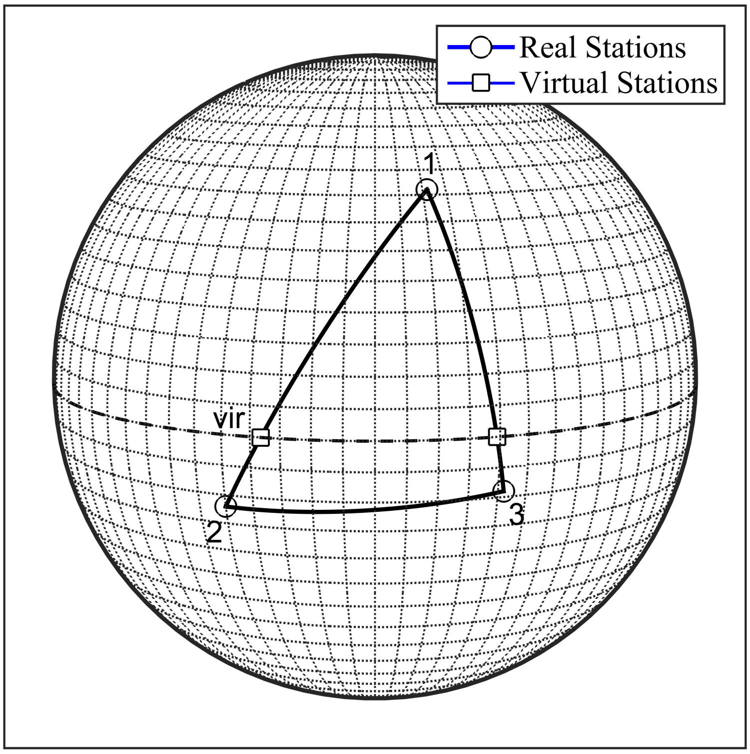


Fig. 3. Spherical triangle. Real stations are shown by circles, and virtual stations are shown by squares.

Рис. 3. Сферический треугольник. Реальные станции показаны кружочками, виртуальные – квадратиками.

equator, and the third spherical line does not cross the equator (Fig. 3), except for the case that one spherical line coincides with the equator (but in this case the triangle belongs to Type1 or 2). The vertical velocity for each virtual station is obtained by interpolation from the vertical velocity of endpoints of the spherical line on which the virtual station is located (Fig. 3):

$$v_{vir} = \frac{l_1 v_1 + l_2 v_2}{l_1 + l_2}, \quad (6)$$

where 1 and 2 represent the two end points of the spherical line; *vir* means a virtual station; v_{vir} is the vertical velocity of the virtual station; v_1 and v_2 are vertical velocities of two endpoints on the spherical line; l_1 and l_2 are lengths along the great circle between the virtual station and endpoints 1 and 2, respectively.

3.3. Gridding method

In the gridding method, a global SDTIN is set up similar to the two methods described above. A grid network is set up with an equal longitude/latitude interval (Fig. 4). At each grid point, a virtual station is added. Its vertical velocity is calculated from vertical velocities of the three endpoints of the spherical triangle in which the virtual station is located (Fig. 5). Then, the average vertical motion of the surface of the globe or a hemisphere is calculated on the basis of the vertical velocities of all the grid points.

Interpolation of the vertical velocity of a grid point in a spherical triangle is similar to interpolation of the vertical velocity of a virtual station on a spherical line:

$$v_{grid} = \frac{l_1 v_1 + l_2 v_2 + l_3 v_3}{l_1 + l_2 + l_3}, \quad (7)$$

where v_{grid} is the vertical velocity of the grid; v_1, v_2 and v_3 are vertical velocities of the three endpoints of the spherical triangle; l_1, l_2 and l_3 are length weight factors related to the distance between the endpoint *i* (*i*=1,2,3) and the grid point (Fig. 5). The determination of the length weight factors are described in the sequel.

Real stations are denoted by circles, and a virtual station (the grid node as shown in Fig. 5) is denoted by a square. A line connecting real station 1 and virtual station 'x' on the surface of the sphere forms a great circle arc. Intersection between this great circle arc and the great circle arc connecting endpoints 2 and 3 is denoted as point 4.

We take l_1 as an example. A line connecting endpoint 1 and gird point 'x' forms a great circle arc (Fig. 5). A line between endpoints 2 and 3 forms the second great circle arc. The extension of the first great circle arc crosses the second great circle arc since the grid

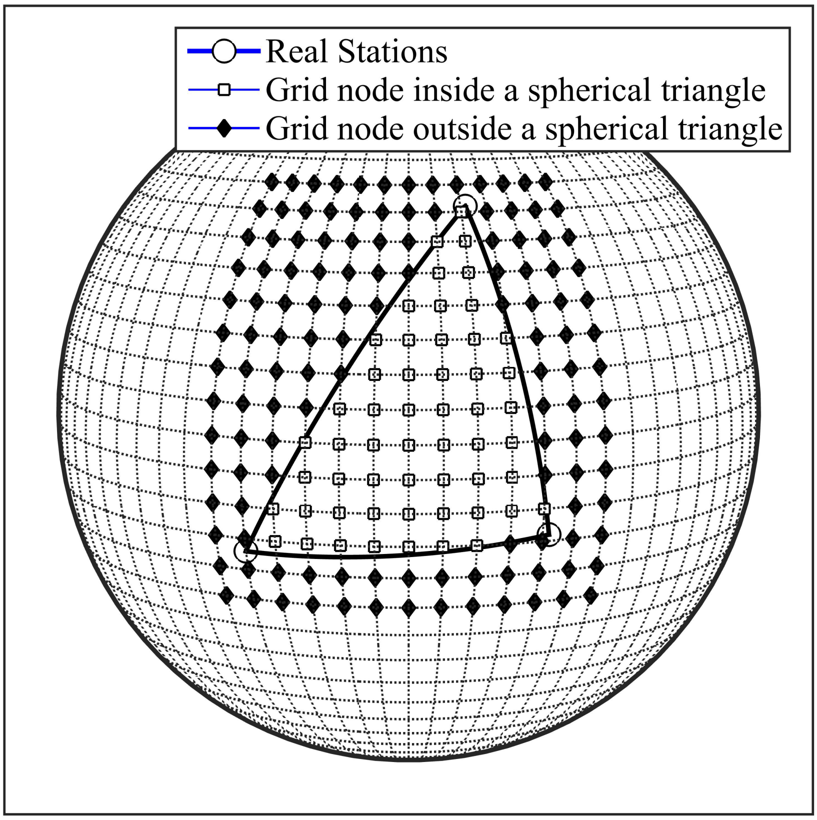


Fig. 4. Grid network and spherical triangle.

Рис. 4. Решетчатая сеть и сферический треугольник.

point is located inside the spherical triangle. Denoting the crossing point as point 4, the length of the great circle arc between endpoint 1 and point 4 is denoted as l_{14}, and the length of the great circle arc between grid point 'x' and point 4 is denoted as l_{x4}. Then, l_1 is calculated as follows:

$$l_1 = \frac{l_{x4}}{l_{14}}. \tag{8}$$

After a grid network is generated, the average vertical motion $\bar{v}$ of the surface of the globe or a hemisphere can be calculated as follows:

$$\bar{v} = \frac{\sum_i P^i_{grid} v^i_{grid}}{\sum_i P^i_{grid}}, \quad P^i_{grid} = \frac{S^i_{grid}}{m^2_{v^i_{grid}}}, \tag{9}$$

where v^i_{grid} is the vertical velocity of the i-th grid given by equation (7); $m^2_{v^i_{grid}}$, S^i_{grid} and P^i_{grid} are respectively the covariance of the vertical velocity, the spherical area and the weight of this grid. The region represented by the grid is a spherical parallelogram bounded by two neighboring longitude lines and two neighboring parallel latitude lines (see Fig. 4).

4. Results of the asymmetric vertical variation

4.1. Expansion in the northern hemisphere and compression in the southern hemisphere

The average vertical variations of the northern and southern hemispheres are estimated using the vertical velocities recorded at 629 stations, and based on the methods described in Section 3, we calculated expansion/compression rates for the two hemispheres of the Earth (see Table 1).

Calculations by the three different methods yield consistent average variation rates of the radius of the northern hemisphere. This suggests that the general vertical variation of the northern hemisphere is around 1 mm/yr, which reduces to 0.5 mm/yr after the PGR effect is subtracted. Our calculations also show that the general vertical variation rates of the southern hemisphere based on the three different methods are method-dependent (see Table 1), which might be due to the fact that the stations in the southern hemisphere are few in number and uneven in distribution. However, the average vertical variation rate of the southern hemisphere suggests that the southern hemisphere is in compression, with a magnitude one order smaller

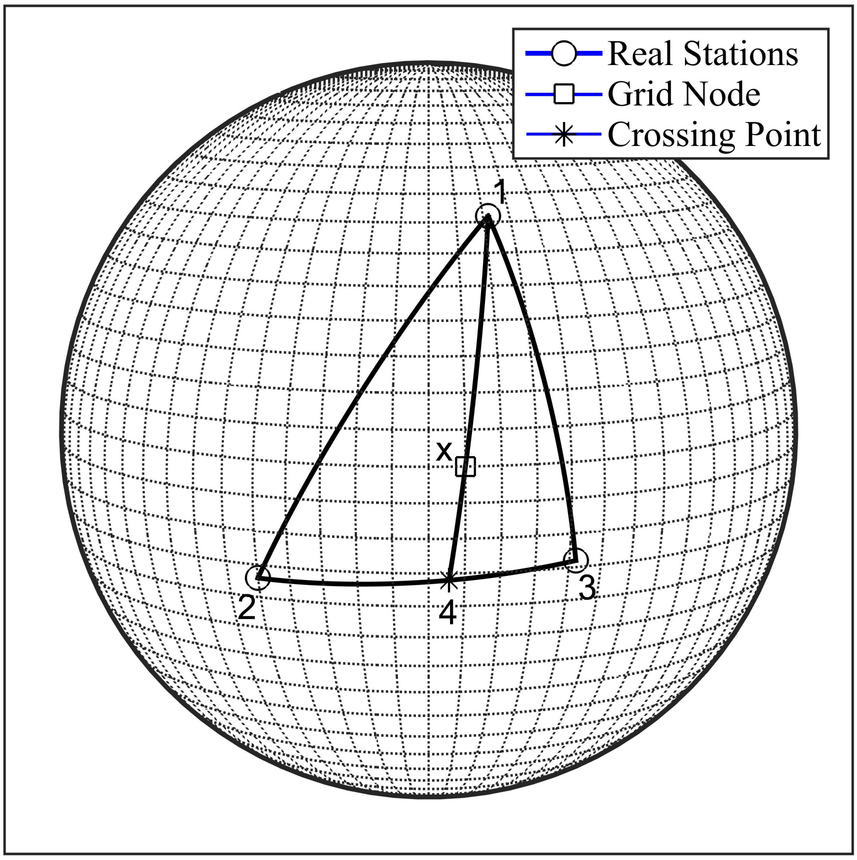


Fig. 5. Interpolation of the vertical velocity for the grid point inside the spherical triangle 1-2-3.

Рис. 5. Интерполяция вертикальной скорости для точки сети внутри сферического треугольника 1-2-3.

than the expansion rate in the northern hemisphere. However, regardless of the calculation method, it is noted that the entire Earth is in expansion. The expansion rate of the entire Earth, which is calculated by either the area method or the virtual equator station method, is very close to the result published in [*Shen et al., 2011*], which is obtained by the gridding method and is slightly lower than the rates obtained by the other two methods. This demonstrates that different methods may give different results, but in the same magnitude (see Table 1).

In the previous studies related to the average vertical variation rates of the two hemispheres, the southern hemisphere is considered in expansion, while the northern one is in compression [*Jin, Zhu, 2003; Shen, Zhang, 2008; Sun et al., 2000, 2006*]. Such a difference might be caused by the difference in time spans represented by the available data. A possible explanation might be that the northern hemisphere experienced the impacts from compression to expansion, while the southern one experienced the opposite process. This also explains why the expansion rate in the southern hemisphere is slowing down as noted in the previous studies [*Jin, Zhu, 2003*]. A more detailed discussion is given in Section 4.3. In section 4.2, we first discuss the dependence between the mean radii secular changes of latitude circles and latitudes.

4.2. Variation of the radius with respect to latitude circles

To further explore the details of the general vertical motion of the two hemispheres, the variation rate of the Earth's radius is calculated with respect to the variations of the latitude circles. Previously, similar studies [*Jin, Zhu, 2003; Sun et al., 2000; Barkin, Shuanggen, 2006, 2007*] have addressed the calculations of the length variation of a latitude circle. Since the distribution of the stations on the Earth surface is very uneven, not enough stations are located on or near a given latitude circle. In this study, we apply the grid network of the virtual stations constructed in Section 3.3. Since the grid network is generated equidistant along latitude direction, and the average vertical variation rate along this latitude circle can be easily calculated by the weighted average of the vertical velocities of all of the grid-crossing points on this latitude circle. Applying the method described by *Sun et al.* [*2000*] and *Jin* and *Zhu* [*2003*] will

T a b l e 3. **Transformation parameters concerning different ITRFs**

Т а б л и ц а 3. **Параметры трансформации для разных ITRF**

Transformation parameters From	To		T1(mm)	T2(mm)	T3(mm)	D(10⁻⁹)	R1(mas)	R2(mas)	R3(mas)
ITRF2008	ITRF2005	Value	–0.5	–0.9	–4.7	0.94	0.000	0.000	0.000
		Uncertainty	±0.2	±0.2	±0.2	±0.03	±0.008	±0.008	±0.008
		Variation rate/yr	0.3	0.0	0.0	0.00	0.000	0.000	0.000
		Uncertainty of variation rate/yr	±0.2	±0.2	±0.2	±0.03	±0.008	±0.008	±0.008
ITRF2005	ITRF2000	Value	0.1	0.8	–5.8	0.40	0.000	0.000	0.000
		Uncertainty of value	±0.3	±0.3	±0.3	±0.05	±0.012	±0.012	±0.012
		Variation rate/yr	–0.2	0.1	–1.8	0.08	0.000	0.000	0.000
		Uncertainty of variation rate/yr	±0.3	±0.3	±0.3	±0.05	±0.012	±0.012	±0.012

N o t e. The transformation parameters from ITRF 2008 to ITRF 2005 are from *Altamimi et al.* [*2011*]. The reference epoch for this transformation is 2005.0. The transformation parameters from ITRF 2005 to ITRF 2000 are from http://itrf.ensg.ign.fr/ITRF_solutions/index.php. The reference epoch is 2000.0.

П р и м е ч а н и е. Параметры преобразования из ITRF 2008 в ITRF 2005 взяты из работы [*Altamimi et al.*, *2011*]. Контрольная дата для этого преобразования – 2005.0. Параметры преобразования из ITRF 2005 в ITRF 2000 взяты с сайта http://itrf.ensg.ign.fr/ITRF_solutions/index.php. Контрольная дата – 2000.0.

not change the result because the grid-crossing points are equidistant on the latitude circle.

Without loss of generality, the average vertical variation rate along a latitude circle is estimated based on the vertical variation of the 1×1 grid network (Table 2, Fig. 6).

Both large expansion and compression regions are revealed in the high latitude areas in northern hemisphere and southern hemisphere respectively, and smaller expansion/compression regions are revealed in the low latitude areas. It can thus be generally concluded that expansion/compression is not uniform considering the entire Earth.

4.3. Movement of the ITRF reference frame as a motion of the mantle relative to the Earth center of mass

Each ITRF is set up by using certain stations in a specified time periods. So the variation of the Earth's surface can be estimated by comparing different ITRFs if a certain approach is applied. The seven transformation parameters (three translation-, three rotation-, and one scale-factor parameters) between ITRF2000 and ITRF2005 and those between ITRF2005 and ITRF2008 are listed in Table 3 (according to website http://itrf.ensg.ign.fr/ITRF_solutions/index.php).

From Table 3, we find that the magnitude of T3 (translation in Z direction) is negative either in the transformation parameters from ITRF2008 to ITRF2005 or from ITRF2005 to ITRF2000, and it is about –5 mm. However, the variation rate of T3 is zero from ITRF2008 to ITRF2005 and negative from ITRF2005 to ITRF2000.

From Table 3 we can see the relative positions and displacements of the terrestrial coordinate systems ITRF2000, ITRF2005, and ITRF2008. Coordinate system transformations are regarded as translational displacement of the position of coordinate system ITRF2000 against coordinate system ITRF2005, coordinate system ITRF2005 position against coordinate system ITRF2008, along the polar axis of the Earth with velocities estimated as 1.8 mm/yr and zero, respectively.

If the ITRF2008 origin is compared to the Earth center of mass, according to our geomodel, the Earth's mantle moves northward relative to the Earth center of mass at a velocity estimated as 5.29 mm/yr [*Zotov et al., 2009*]. For the analysis of changes in the Earth's mantle deformation, the radial velocity components at the stations due to the drift of the Earth center of mass, $V_C cos\theta_i$ should be subtracted from the radial components of the velocity field at stations under ITRF2008.This yields the calculated radial velocity at the stations due to the secular drift of the center of mass:

$$V_{i,2008}^{(d)} = V_{i,2008} - V_C cos\theta_i \,. \tag{10}$$

After subtracting the drift influence due to the mass center motion, we obtain the corresponding model surface deformations of the Earth.

Changes of the Earth shape lead to two effects, including the kinematic effect caused by secular southern drift of the Earth center of mass relative to the mantle. It is fully described, if given the drift velocity center of mass relative to the mantle at given epoch. This is given in the parameters of the relative translational displacements of systems ITRF2000, 2005, 2008 and

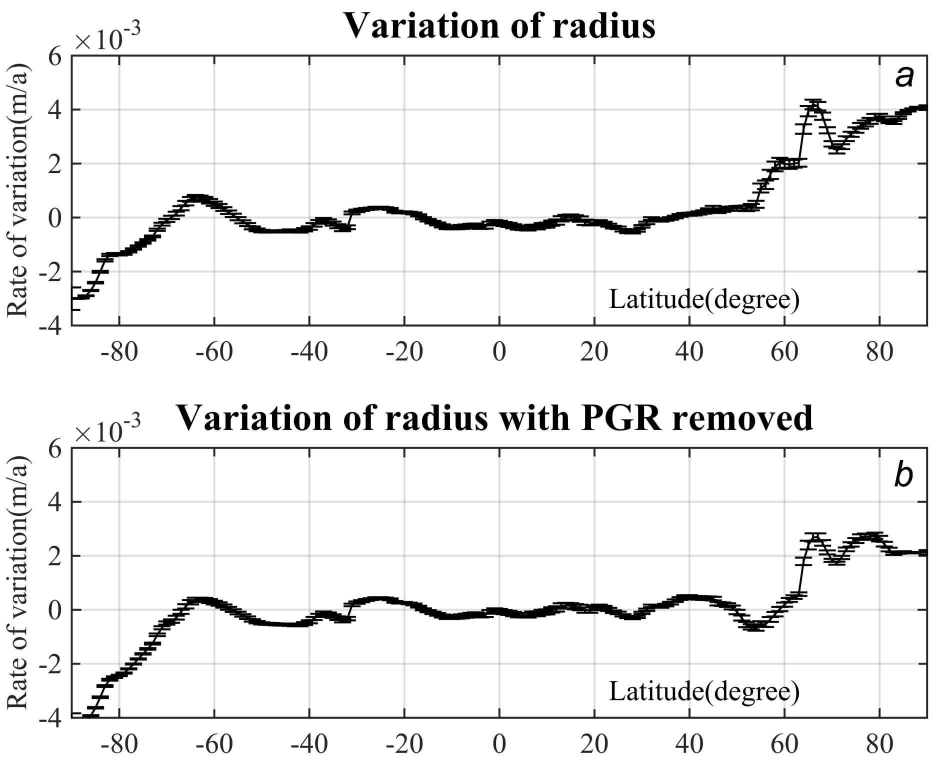


Fig. 6. Variation of the radius with respect to the variation of the latitude circle.

Large uplift is found in the high latitude area in the northern hemisphere, while large decline is found in the high latitude area in the southern hemisphere. The results for the low latitude area reflect small vertical movements. Vertical variations of the radius along the latitude circle: (*a*) without considering the PGR effect, and (*b*) after the PGR effect is subtracted.

Рис. 6. Вариации радиуса относительно вариаций широтного круга.

Сильное увеличение установлено в районе высоких широт в Северном полушарии, при этом сильное снижение установлено в районе высоких широт в Южном полушарии. Результат по району низких широт отражает мелкие вертикальные движения. Вертикальные вариации радиуса по широтному кругу: (*а*) постледниковый отскок не удален; (*b*) постледниковый отскок удален.

adopted in this paper as approximately equal to 1.8 mm/yr (Table 3). Determination of the velocity of the Earth center of mass relative to its mantle by a different approach gives a higher value about 5.29 mm/yr [*Zotov et al., 2009*]. In this case, the displacement of the center of mass is determined with respect to the reference coordinate system of the mantle.

One may consider the second effect of the change in the mean radii of the Earth hemispheres, which is caused by deformation of the surface of the mantle due to the gravitational effect of displacement of the center of mass [*Barkin, Shatina, 2005*]. According to our theoretical (dynamic) estimates, this effect is very small, about 0.014 mm/yr in the northern hemisphere, and about –0.014 mm/yr in the southern hemisphere (near the poles).

In this paper, we consider that the vertical displacements of the surface points under coordinate system ITRF2008 are mobile and closely related to the drifting center of mass of the Earth relative to the mantle. To consider only the effects of the surface deformation, we have to subtract radial components caused by the secular drift of the Earth center of mass from vertical components of the velocities of all points on the surface (ITRF2008 against ITRF2000).

A simple equation is used:

$$V_i = V_C cos\theta_i = 1.8 \cdot cos\theta_i \text{ mm/yr},$$

where angle θ is a co-latitude; i is station's number. With such adjustments in the vertical components, we obtain parameters of changes of the Earth surface in some of the original coordinate system (in our case, in ITRF2008 (d)). As a result, we can determine the average vertical velocity of points on the Earth surface in the northern and southern hemispheres, and construct a curve of the vertical components versus latitudes.

Radial velocity components of stations P_i with respect to the two coordinate systems, i.e. ITRF2008 (d) (actual starting at the center of the Earth at given epoch) and ITRF2008 (actually with the origin at the center of the Earth at epoch 2008.0), are related by equation (10). Radial velocities of the stations under ITRF2008 (d), $V_{i,2008}^{(d)}$, represent the sum of two components. One of them corresponds to the observed changes in the Earth surface, $V_{i,2008}$, and the second is related to the drift of the center of mass of the Earth. Our task – to study the velocity field $V_{i,2008}^{(d)}$ – focuses on the northern and southern hemispheres. $V_{i,2008}$ are observed velocities of the stations. They are known for certain errors. With respect to ITRF2000, the origin of ITRF2008 is characterized by a permanent southern trend with velocity V_C = –1.8 mm/yr (see ITRF website). Thus, the radial velocities of the monitoring stations under ITRF2008 (d) describe the changes in the Earth shape, but with respect to the moving coordinate system ITRF2008, the origin of which can be approximated to match the center of mass of the Earth in a certain era as close to the average in 2008 [*Wu et al., 2011*].

We can formulate an additional task of determining the velocity of the center of mass from geodetic data on the secular vertical velocities of the stations under ITRF2008, i.e. determining velocity V_C under conditions that the average rate of change of the radii of the hemispheres is negligible, as mentioned above, i.e. $0 = V_{i,2008} - V_C \cos\theta_i$.

In accordance with our constructions and the model ITRF2008, the Earth mantle is moving along the Z direction to the north with a constant velocity of 1.8 mm/yr with respect to the center of mass of the Earth. Such motion will not affect the result whether the entire Earth is in expansion or compression since the contribution to the volume variation of the entire Earth at any point due to the motion of this point can be compensated by the contribution to the volume variation due to the motion of the opposite point. Yet the average vertical variation of each hemisphere will be influenced. Since there is a general motion of the Earth mantle to the north relative to the Earth center of mass, we can explain why our conclusions (expansion in the northern hemisphere and compression in the southern hemisphere) are different from those in the previous studies.

Suppose there is a moving trend of the Earth's mass center to the south in Z direction relative to the mantle, and the magnitude of that motion is 1.8 mm/yr (Table 3). Such a magnitude is also found reasonable as shown in Fig. 6. If the Earth's mass center is indeed moving along the negative Z direction relative to the Earth mantle, the high latitude area in the northern hemisphere is in uplift, while the high latitude area in the southern hemisphere is in decline.

One should also consider a model with translational displacement of the Earth center of mass to the south with velocities of 1.8 mm/yr and 5.29 mm/yr. Also, determination of the velocity of the Earth center of mass relative to the mantle suggests slight deformations in the hemispheres. It is assumed that the discussed phenomena of deformations of the hemispheres are due to kinematic effects of relative offset of the mantle to the Earth center of mass.

Obviously, vertical variation (along the plumb line) caused by the Z-direction motion becomes smaller and smaller from higher to lower latitude areas if the volume of the entire Earth holds invariant. Hence, due to the above mentioned moving trend (1.8 mm/yr) of the Earth's mantle along the Z direction with respect to the Earth center of mass, calculations show that the northern hemisphere is in expansion at a maximum rate of 0.9 mm/yr, and the southern hemisphere is in compression at a rate of –0.9 mm/yr. There are other deformations caused by other processes. Now, we find that, in one system, the northern hemisphere is in expansion and the the southern hemisphere is in compression, while in another system, the northern hemisphere is in compression and the southern hemisphere is in expansion. Hence, we can conclude that considering the expansion/compression pattern of one hemisphere is irrelevant.

To further confirm our conclusion, we recalculate the average vertical variation along the latitude following the method described in Section 4.2. This time we subtract the quantity of 1.8 mm/yr from the velocity field in Z direction for every station. Then, the average vertical variation along the latitude will be changed, as shown in Fig. 7, from which we can see that the northern hemisphere is in compression, while the southern hemisphere is in expansion. This conclusion is in accordance with results published in [*Jin, Zhu, 2003; Shen, Zhang, 2008; Sun et al., 2000, 2006*].

Exactly to say, after a trend in the velocity in Z direction of about 1.8 mm/yr is removed, the southern hemisphere is in expansion at a rate of 0.708±0.007 mm/yr, while the northern hemisphere is in compression at a rate of –0.436±0.012 mm/yr. This is in accordance with the conclusions stated in the majority of the previous studies [*Jin, Zhu, 2003; Sun et al., 1997, 2000, 2006*]. Hence, the different expansion/compression patterns given in this study and the previous studies may be attributed to the average motion in Z direction of the Earth mantle with respect to the Earth center of mass. Although the previous studies show that the southern hemisphere is in expansion, the expansion rate is found to be slowing down. If this trend is kept for a certain period, the southern hemisphere would be found in compression as concluded in this study. The case for the northern hemisphere may just be the opposite. One may explain the asymmetric expansion of the two hemispheres by the relative drift between the core and mantle [*Barkin, 2010a, 2010b;*

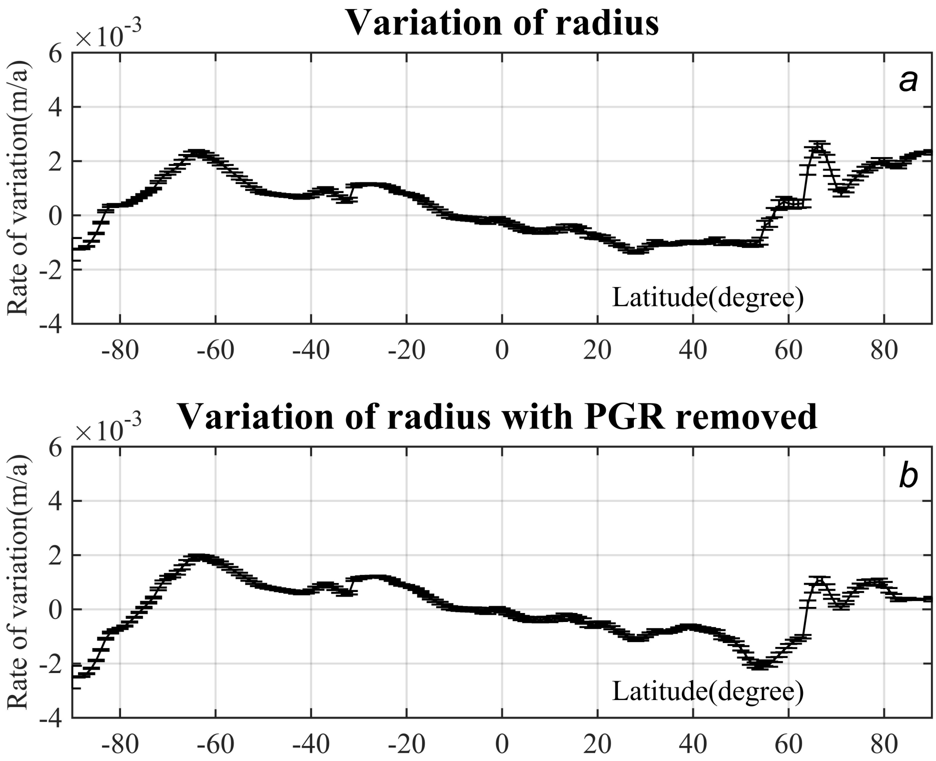


Fig. 7. Variation of the radius after a trend in Z direction is removed.

Large uplift can be found in the southern hemisphere, while large decline can be found in the northern hemisphere. Vertical variations of the radius along a latitude circle: (*a*) without considering the PGR effect, and (*b*) after the PGR effect is subtracted.

Рис. 7. Вариации радиуса после удаления тренда в направлении Z.

Сильное увеличение можно обнаружить в Южном полушарии и сильное снижение в Северном полушарии. Вертикальные вариации радиуса по широтному кругу: (*a*) постледниковый отскок не удален; (*b*) постледниковый отскок удален.

Barkin, Shuanggen, 2006, 2007; Goncharov et al., 2012, 2014], but we left this problem as open.

Here we note that this study only considered the translation parameters listed in Table 3, because the consideration here focuses on the possible explanation for the expanding northern hemisphere and the compressing southern hemisphere instead of the opposite expansion/compression pattern described in the previous studies [*Jin, Zhu, 2003; Shen, Zhang, 2008; Sun et al., 2000, 2006*]. As a remark, the variation of scale factor D (see Table 3) may also influence the magnitude of expansion/contraction of the two hemispheres. However, the contribution to expansion/contraction caused by the scale variation is too small to be considered at present.

4.4. Variations of the mean radius in latitudinal belts, depending on latitudes

Asymmetric expansion is noted in variations of the mean radius of the planet in individual latitude belts towards the northern and southern hemispheres. For the wide area of equatorial and mid-latitudes, the secular medium velocity of radii of latitudinal belts is small, and in the polar regions, there is a tendency of increasing velocities (in absolute value)with trends of opposite signs for the northern and southern hemispheres. Velocities in the circumpolar regions of the northern hemisphere grow in accordance with the increase of the mean radii, and vice versa in the southern hemisphere, in accordance with the decrease of the mean radii (Fig. 7).

There is no complete agreement between the theoretical estimates of average rates of slow changes in the mean radii of the northern and southern hemispheres with the values obtained from observation data (see Table 1). However, the smallness of the effect is actually confirmed in the secular variation of the radius, for example, compared with secular changes in the lengths of latitudinal circles. To obtain more precise determinations of the considered characteristics, longer series of observations and further research are required.

A good correlation is revealed for the latitudinal secular variations of the mean radii of the circles, both theoretical and observed, for field latitudes 60S – 60N. However, at the high latitudes (polar regions), the observed contrasting (opposite sign) changes in the average radii of the circles of the latitude appear in the range of velocities about 2–4 mm/yr (Figures 6 and 7).

Thus, the predicted theoretical phenomena associated with the radial Earth surface changes are explained in general. In future studies, the conclusions presented here will be further developed with reference to updated and more accurate observation data and improved models showing deformation of the Earth's surface.

5. Conclusion

Many processes contribute to movements of the Earth surface. Expansion/compression patterns of the northern and southern hemispheres attract attention of many scientists. In this study, we use the velocity field under ITRF2008 to estimate the vertical variation of the surface of the two hemispheres.

Our research has confirmed that the basic conclusions on the discussed phenomena are correct: 1. The Earth's surface deformation about 0.2 mm/yr (see Table 1); 2. Contrasting deformations of the Earth surface in the northern and southern hemispheres, i.e. slow increase in the mean radius of the northern hemisphere and slow decrease of the average radius of the southern hemisphere (see Table 2); 3. The established curve of changes of the mean radii of the latitudinal circles based on the observation data agrees qualitatively with the previously constructed theoretical curve (see Fig. 6).

In this study, the obtained results reveal new features in geodesic changes of the Earth shape and provide an important confirmation of the considered basic geodynamic model of the forced displacements and the relative oscillations of the Earth core and mantle [*Barkin, 2002*].

In contradiction to the conclusions made in the previous studies, we found that the northern hemisphere is in expansion at a rate of 1 mm/yr, while the southern hemisphere is in compression at a rate one order smaller than the expansion rate of the northern hemisphere. Besides, when the PGR effect is considered, the expansion rate of the northern hemisphere amounts to 0.464±0.012 mm/yr, and the compression rate of the southern hemisphere is –0.192±0.007 mm/yr. As a whole, the Earth is expanding, and this conclusion correlates with the previous study by *Shen et al.* [*2011*]. The different expansion/compression patterns described in this study and the previous studies may be attributed to the general motion of the Earth's surface in Z direction relative to the center of the Earth. For instance, concerning that *Shen* and *Zhang* [*2008*] used the coordinates and velocities of the stations under ITRF2000, and referring to Table 3 and the above discussions, it is clear why they concluded that the southern hemisphere is in expansion and the northern hemisphere is in compression.

The general motion of the Earth's surface along the positive Z direction with respect to the Earth center of mass may be viewed as an observable effect resulting from expansion in the northern hemisphere and compression in the southern hemisphere. Variation of the transformation parameters may be attributed to many different sources, such as the distribution of stations and actual movement of the Earth surface in a certain period, and the center variation of the Earth. In this study, we have tried to explain the variation of the transformation parameters by suggesting a possibility of expansion in the northern hemisphere and compression in the southern hemisphere at present, although it contradicts with the results of the previous studies [*Jin, Zhu, 2003; Shen, Zhang, 2008; Sun et al., 2000, 2006*]. However, as pointed out previously, a consideration of expansion/compression of one hemisphere rather than those of the entire Earth is hardly significant.

Based on this study, the entire Earth is expanding at a rate about 0.2 mm/yr, and this conclusion coincides with the previous studies [*Chen, 2000; Shen et al., 2011*]. However, the above mentioned space geodetic calculation approach [*Altamimi et al., 2011*] might be only suitable in land area. We have just tried to extend the datasets to ocean region by interpolation. Since some stations are located quite far from each other, interpolation of the velocity in the ocean area based on the stations located on land may induce possible bias. Whether such interpolation is valid should be confirmed by other methods. Another study of us [*Shen et al., 2012*] confirmed the validity of the velocity interpolation over the ocean region using the evidences of the sea level rise observations and thermal expansion estimate of the ocean, which suggests that the expansion rate in the ocean area is about 0.71±0.65 mm/yr. The accuracy is very poor, due to the fact that the present observations of the sea level rise are relatively rough [*Nicholls, Cazenave, 2010*], the estimates of the sea level rise caused by the temperature variation of the ocean water [*Albritton et al., 2001*] are not accurate enough, and many uncertain factors are beyond considerations. Detailed investigations about the expansion in oceanic areas are beyond the scope of this study.

Finally, as a remark, we note that *Wu et al.* [*2011*] stated that the Earth does not expand because they provided an estimate of the Earth expansion rate at 0.1±0.2 mm/yr. However, *Wu et al.* [*2011*] used a different approach compared to the one used by *Shen et al.* [*2011*] and in the present study. They used observations (VLBI, SLR, GPS) to estimate multi-parameters (including for instance the motion of MC, rotations of plates, Love numbers, etc.) simultaneously, and the 'expansion rate' is only one of the multi-parameters. Hence, the accuracy of the parameter termed 'Earth expansion rate' is severely compromised. In our study, it is assumed that the expansion of the Earth is global. Every vertical movement of any station has its contribution. With the increase of the measurements globally, the accuracy of the estimated average global vertical movement will be gradually improved. In our opinion, since the focus of the study by *Wu et al.* [*2011*] is on estimating mass center motion, Earth expansion rate, motion of plates, and other parameters simultaneously, using the observed velocity field on solid Earth surface, the accuracy of the Earth expansion rate is severely compromised as mentioned above. However, if we only concentrate on estimating the Earth expansion (just like *Shen et al.* [*2011*] and the present study), using the same observations, the accuracy will be much higher. This is the reason why the accuracy of our results is much higher than that in [*Wu et al., 2011*]. For instance, suppose the mass center (MC) has no motion, but the Earth expands, and we have only stations distributed in the northern hemisphere, then, according to *Wu et al.* [*2011*], estimations will show that there is a motion of MC due to observation uncertainty, and at the same time, the estimated expansion rate will be quite inaccurate, because parts of the vertical motions are attributed to the MC motion (which is not real) rather than expansion of the Earth.

6. Acknowledgments

We are grateful to the anonymous reviewers and associate editor for their valuable comments and suggestions, which largely improved the manuscript. This work was supported by National 973 Project China (Grants 2013CB733301 and 2013CB733305) and NSFC (Grants 41174011, 41429401, 41210006, 41128003, and 41021061).

7. References

Albritton D.L., Meira Filho L.G., Cubasch U. et al., 2001. Technical Summary. IPCC Third Assessment Report – Climate Change 2001 IPCC.

Altamimi Z., Collilieux X., Métivier L., 2011. ITRF2008: an improved solution of the international terrestrial reference frame. *Journal of Geodesy* 85 (8), 457–473. http://dx.doi.org/10.1007/s00190-011-0444-4.

Barkin Yu.V., 2002. Explanation of endogenous activity of planets and satellites and its cyclicity. In: Proceedings of the Earth Sciences Section of the Russian Academy of Natural Sciences. Issue 9. VINITI, Moscow, p. 45–97.

Barkin Yu.V., 2007. Trend and periodic variations of lengths of latitudinal circles of the Earth. *Geophysical Research Abstracts* 9, 08467. Available from: http://meetings.copernicus.org/www.cosis.net/abstracts/EGU2007/08467/EGU2007-J-08467.pdf.

Barkin Yu.V., 2010a. Forced relative displacements of the core and mantle as the basic mechanism of secular changes of the Earth shape and lithosphere plates tectonics. *Geophysical Research Abstracts* 12, EGU2010-13792. Available from: http://meetingorganizer.copernicus.org/EGU2010/EGU2010-13792.pdf.

Barkin Yu.V., 2010b. The drift of the center of mass of the Earth and the secular variations of gravity. *Geofizicheskiye Issledovaniya* 11 (Special Issue), 18–31 (in Russian) [*Баркин Ю.В.* Дрейф центра масс Земли и вековые вариации силы тяжести // *Геофизические исследования*. 2010. Т. 11. Спецвыпуск. С. 18–31].

Barkin Yu.V., 2011. Secular variation of the Earth figure in the modern era. In: Proceedings of the International Conference dedicated to the memory of Victor Efimovich Khain, Moscow, February 1–4, 2011. Publishing House of the Faculty of Geology, Lomonosov Moscow State University, Moscow, p. 183–188 (in Russian) [*Баркин Ю.В.* Вековые вариации фигуры Земли в современную эпоху // Современное состояние наук о Земле: Материалы международной конференции, посвященной памяти Виктора Ефимовича Хаина. М.: Изд-во Московского государственного университета им. М.В. Ломоносова, 2011. С. 183–188].

Barkin Yu.V., 2013. The modern space geodesy data indicate northern polar drift of the Earth's core relative to the mantle. In: Lomonosov Readings 2013. Physics Section. Book of Abstracts. Faculty of Physics, Moscow, p. 209–212 (in Russian).

Barkin Yu., Hanada H., Sasaki S., Barkin M., 2012a. About some inner structures of the Earth, the Moon and Mars as geodynamical consequences of the action of mechanism of the forced relative oscillations of their core and mantle. In: The third Moscow Solar System Symposium (SM-S3) (8–12 October 2012, Moscow, Russia). Book of Abstracts. Abstract 3MS3-PS-52, p. 244–245.

Barkin Yu., Hanada H., Sasaki S., Barkin M., 2012b. Prediction of the existence of the zone of lower seismic velocities of Mars at depth 300 km and mechanism of its formation. In: The 118th Meeting of the Geodetic Society of Japan, Sendai, Japan, (29 October – 2 November 2012, Sendai). Book of Abstracts, p. 147–148.

Barkin Yu.V., Shatina A.V., 2005. Deformation of the Earth's mantle due to core displacements. *Astronomical and Astrophysical Transactions* 24 (3), 195–213. http://dx.doi.org/10.1080/10556790500496339.

Barkin Yu., Shen W.-B., Shuanggen J., 2013b. Geodetic consequences of the northern drift of the Earth's core and their confirmations in the space geodesy data: the expected related phenomena on the Moon and Mars. In: Japan Geoscience Union Meeting (19–24 May 2013, Makuhari Messe, Chiba, Japan). Abstracts, P-PS03-P09. Available from: http://www2.jpgu.org/meeting/2013/session/PDF_all/P-PS03/PPS03_O_e.pdf.

Barkin Yu.V., Shuanggen J., 2006. Kinematics and dynamics of the Earth hemispheres. *Geophysical Research Abstracts* 8, 01680. Available from: http://meetings.copernicus.org/www.cosis.net/abstracts/EGU06/01680/EGU06-J-01680-1.pdf.

Barkin Yu.V., Shuanggen J., 2007. On variations of the mean radius of the northern and southern hemispheres of the Earth. *Geophysical Research Abstracts* 9, 08183. Available from: http://meetings.copernicus.org/www.cosis.net/abstracts/EGU2007/08183/EGU2007-J-08183.pdf.

Barkin Yu., Shuanggen J., Shen W.-B., 2013a. Theoretical prediction and observation evidences on the northward drift and annual oscillation of the Earth's core from space geodes. In: International Symposium & Summer School on Planetary Science (IAPS 2013) July 1–7, 2013, Shanghai, China. Available from: http://202.127.29.4/meetings/iaps2013/Program_IAPS2013.pdf.

Bird P., 2003. An updated digital model of plate boundaries. *Geochemistry Geophysics Geosystems* 4 (3), 1027. http://dx.doi.org/10.1029/2001GC000252.

Chen Z.G., 2000. The evolution model of the Earth's limited expanding. *Chinese Science Bulletin* 45 (4), 304–313. http://dx.doi.org/10.1007/BF02909758.

Goncharov M.A., Raznitsin Yu.N., Barkin Yu.V., 2012. Specific features of deformation of the continental and oceanic lithosphere as a result of the Earth core northern drift. *Geodynamics & Tectonophysics* 3 (1), 27–54 (in Russian) [*Гончаров М.А., Разницин Ю.Н., Баркин Ю.В.* Особенности деформации континентальной и океанической литосферы как следствие северного дрейфа ядра Земли. *Геодинамика и тектонофизика*. 2012. Т. 3. № 1. С. 27–54]. http://dx.doi.org/10.5800/GT-2012-3-1-0060.

Goncharov M.A., Raznitsyn Y.N., Barkin Y.V., 2014. The northward continental drift component in the Phanerozoic, its possible cause, and structural consequences. *Doklady Earth Sciences* 455 (2), 383–385. http://dx.doi.org/10.1134/S1028334X14050031.

Huang L.R., Ma Z.J., Zhu J.X., 2002. The newest observational evidence on asymmetrical deformation of the Earth. *Acta Seismologica Sinica* 15 (2), 210–213. http://dx.doi.org/10.1007/s11589-002-0010-5.

Jin S., Barkin Yu., Park J., 2007. Earth's shape variations: Geodetic observations and Crust-Mantle-Core rotation modeling. In: American Geophysical Union, Spring Meeting 2007, Abstract #G42A-05. Available from: http://adsabs.harvard.edu/abs/2007AGUSM.G42A..05J.

Jin S., Zhu W., 2003. Quantitative analysis of the slowing expansion in the southern hemisphere. *Chinese Journal of Geophysics* 46 (6), 760–766.

Ma Z., Chen Q., 1988. Global earthquake tectonic system and asymmetry of the Earth. *Science in China Series B: Chemistry*, 1092–1099.

Ma Z., Song X., Du P., Fu R., Sun F., Wang Y., 2002. Asymmetry between the southern and northern hemispheres of the Earth. *Chinese Journal of Geophysics* 45 (1), 26–33.

Nicholls R.J., Cazenave A., 2010. Sea-level rise and its impact on coastal zones. *Science* 328 (5985), 1517–1520. http://dx.doi.org/10.1126/science.1185782.

Paulson A., Zhong S., Wahr J., 2007. Inference of mantle viscosity from GRACE and relative sea level data. *Geophysical Journal International* 171 (2), 497–508. http://dx.doi.org/10.1111/j.1365-246X.2007.03556.x.

Renka R.J., 1997. Algorithm 772: STRIPACK: Delaunay triangulation and Voronoi diagram on the surface of a sphere. *ACM Transactions on Mathematical Software* (*TOMS*) 23 (3), 416–434.

Shen W.B., Shen Z.-Y., Sun R., 2012. The expanding Earth confirmed by geodetic observations and sea level rise. In: JpGU International Symposium, Chiba, Japan, 20–25 May, 2012.

Shen W.B., Sun R., Chen W., Zhang Z., Li J., Han J., Ding H., 2011. The expanding Earth at present: evidence from temporal gravity field and space-geodetic data. *Annals of Geophysics* 54 (4), 436–453. http://dx.doi.org/10.4401/ag-4951.

Shen W.B., Zhang Z.G., 2008. Detecting the Earth expansion effect based on space-geodetic data. *Science of Surveying and Mapping* 33 (3), 5–6.

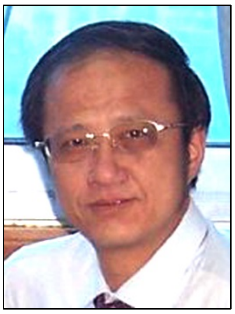
Sun F.P., Ning J., Chao D., Zhao M., Qian Z., 1997. Space geodetic detection of postglacial rebound. *Acta Geodaetica et Cartographica Sinica* 26 (4), 283–288.

Sun F.P., Zhao M., Ning J., Chao D., 2000. Detection of unsymmetrical global tectonic change by using space geodetic data. *Chinese Science Bullentin* 45 (7), 639–643. http://dx.doi.org/10.1007/BF02886042.

Sun F.P., Zhu X.H., Wang R., Li J.T., 2006. Detection of changes of the Earth's volume and geometry by using GPS and VLBI data. *Chinese Journal of Geophysics* 49 (4), 900–906. http://dx.doi.org/10.1002/cjg2.910.

Wu X., Altamimi X., Vermeersen B.L.A., Gross R.S., Fukumori I., 2011. Accuracy of the International Terrestrial Reference Frame origin and Earth expansion. *Geophysical Research Letters* 38 (13), L13304. http://dx.doi.org/10.1029/2011GL047450.

Zotov L.V., Barkin Yu.V., Lubushin A.A., 2009. Geocenter motion and its geodynamical contents. In: Space geodynamics and modeling of the global geodynamic processes, Novosibirsk, Russia, 22–26 September, 2008, Trofimuk Institute of Petroleum-Gas Geology and Geophysics SB RAS. GEO Academic Publishing House, Novosibirsk, p. 98–101 (in Russian).



Wen-Bin Shen, Ph.D. in Physical Geodesy
Department of Geophysics, School of Geodesy and Geomatics /
Key Laboratory of Geospace Environment and Geodesy of Ministry of Education, Wuhan University
Wuhan 430079, China
✉ e-mail: wbshen@sgg.whu.edu.cn

Rong Sun, Ph.D.
Department of Geophysics, School of Geodesy and Geomatics /
Key Laboratory of Geospace Environment and Geodesy of Ministry of Education, Wuhan University
Wuhan 430079, China
e-mail: rsun@whu.edu.cn

Баркин Юрий Владимирович, д.ф.-м.н., профессор, в.н.с.
Государственный астрономический институт им. П.К. Штернберга,
Московский государственный университет им. М.В. Ломоносова
119992, Москва, Университетский пр-т, 13, Россия
Тел.: (495)-939-50-24; e-mail: barkin@inbox.ru

Barkin, Yuri V., Doctor of Physics and Mathematics, Professor, Lead Researcher
The Sternberg Astronomical Institute, Lomonosov Moscow State University
13 Universitetsky prospect, Moscow 119992, Russia
Tel.: (495)-939-50-24; e-mail: barkin@inbox.ru

Ziyu Shen, B.S. degree in Metallurgical Engineering
Department of Geophysics, School of Geodesy and Geomatics /
Key Laboratory of Geospace Environment and Geodesy of Ministry of Education, Wuhan University
Wuhan 430079, China