Chapter 2
Study on the Earth's Volume Change by Using Space Observed Technology

Xinhui Zhu, Fuping Sun and Ren Wang

Abstract Although plate tectonics already being the studying basis and mainstream of global tectonics nowadays, theories of expanding or compressing about the Earth have not been ceased in deed, which were still the main objects of investigating and searching proofs for many geoscientists. In the research of plate tectonics, a basic hypothesis which has been used until now is that the solid Earth's volume (or radius) keeps unchanging because the lithosphere's expanding and compressing could be compensated mutually. Whether and in which time scale these hypothesizes is correct or not, that has not been proved rigorously. Along with the development of space techniques and improvement of geodetic precision, it is possible to detect and resolve above problems in the help of more and higher precision observations and stations distributing globally. The earth's unsymmetrical phenomenon and the doctrine of its expansion and compression was discussed and expounded. After a detailed analysis of the status of global change phenomena research, one data processing method by unifying the global vertical velocity to the optimal global crustal vertical motion reference datum was put forward. Then the solid earth's volume and radius change were detected by using Delaunay arithmetic and plate motion model interpolation method. The result shows that the earth volume's change rate is $(-0.0379 \pm 0.0902) \times 10^3 km^3/a$, which is similar to (-0.1 ± 0.2) mm/a after being converted to the change of the earth's radius, and is close to the result (near to -0.24 mm/a) by using global observed station's radial velocity. The conclusion is that the radius of the earth cannot be considered changed in the range of one time mean error, which is corresponded to the results of others by using space observed data and physical geography information.

Keywords Space-geodetic data · Earth · Asymmetrical deformation · Delaunay triangle gridding · Reference datum of global vertical crustal motion

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2.1 Introduction

The shape of the Earth and its changes are still ancient pending scientific issues, not only lively discussion by many domestic and foreign scholars and Earth science enthusiasts, but also good for geophysical mechanism for analysis and detection, use of space observation technology experimental verification, given different results and conclusions.

As early as in the mid-90s of the last century, domestic scholars in China have carried out the first research based on space geodetic measured global tectonic changes, Sun [1, 2] qualitatively validated unsymmetrical global detection of north hemisphere expending and south hemisphere shortening by using North and South mid-latitude belts changing rate observed by VLBI and SLR respectively; while its quantitive results were also gotten by those of the integration of GPS, VLBI and SLR stations geodesic variation rate and station speed measurement in Sun et al. [3], which pointed out that the northern hemisphere latitudes compressed change in magnitude of around 8–10 mm/a, the southern hemisphere middle-latitude belt expansion change about 12–14 mm/a. Subsequently, Ma [4, 5], Huang [6], Jin [7], Sun [8] equality using tectonics and space geodetic data confirms the earth exists south up north shrinkage asymmetric global tectonic change. Sun et al. [9, 10] used the geodetic data updated to 2003 from more than 700 stations all over the world to detect the changing of the solid earth's volume and radius, pointed out that the earth may be in a state of compression which means a 3–4 mm decrease of radius per year, while Shen et al. [11–13] showed that the earth may be expanding at the same time. There is nothing strange about this; a study made by some overseas researchers in 2007 came up the different result either. Russian scientists' study based on SLR [14] showed that the radius of earth is increasing in 1 mm per year; while German scientists [15] used VLBI find out that the radius of earth is decreasing in 0.5 mm/a. Wu et al. [16] made full use of the accurate station position and velocity fields under ITRF2008 frame, combined with gravity data from Gravity Recovery and Climate Experiment (GRACE) and Linear changing data from two Ocean Bottom Pressure (OBP) models, researched the movement of the origin of ITRF2008 frame and the changing of the earth radius, the result shown that the earth radius is changing in 0.1 ± 0.2 mm/a, which means the radius of the earth cannot be considered changed in the range of one time mean error.

Why could this situation happen? According to our analysis, there maybe have several aspects of reasons, as the followings: (1) Precision of geodetic data. As everybody knows, the precision of crustal movement that space geodesy techniques surveyed is closely related to terms that stations survey continuously, the longer the surveying time, the higher the accuracy of data. Generally speaking, data used of above research results were almost surveyed to 2003 or 2004, the precision of crustal movement is superior to 1–2 mm/a barely. (2) Numbers and distribution of stations. In early days, the high-quality stations were less, the stations of VLBI and SLR only has a few, and is distributed unevenly; In southern hemisphere, there has a few stations, in northern hemisphere, there has none. Taking a consideration of influence

of ocean, the problem of stations of the numbers and distribution, there could have great influence on test result. (3) Data preprocessing. Between different technologies, different batches of solving velocity field of crustal movement, there usually have systemic bias as a result of the different of vertical crustal movement reference; these deviations would usually be ignored. Specifically, vertical crustal movement reference datum's bias will have an influence on the estimation result of the earth volume change directly. (4) Detection method. Because different researchers adopt different detection method, there will have biased estimate. (5) The earth volume almost doesn't change, theoretical result is near zero, and then, estimation result will have positive and negative.

To sum up, We believe that (1) the earth's south up north shrinkage asymmetric global geodetic changes have been confirmed by tectonics and space geodetic results; (2) the earth volume is compressed, expansion, or unchanged, has not yet been confirmed, the causes has been analyzed at the head, this problem is still necessary to further study; (3) To determine the earth's shape, size and its change is the basic task of geodesy, with stations increases and the improvement of observation precision, Global tectonic change research which is based on the spatial geodetic data is becoming research frontier and hot point in the field of domestic and international. Consequently, a high accuracy of geocentric coordinates global crustal motion velocity field would be built by using the data of the latest global ITRF2008 international terrestrial reference frame, whose station accuracy is better than 0.3 mm/a, datum reference is completely unified, and which was used to study on global tectonic change phenomenon, such as the compression or expansion of the solid earth, asymmetry between the southern and northern hemispheres structure change and so on and give quantitative estimation, according to global data to discuss the possible mechanisms about these global tectonic change.

2.2 Data-Processing

The data comes from ITRF2008. Because most DORIS stations of geocentric coordinate velocity precision is under 0.3 mm/a, we only use GPS, VLBI and SLR data sequence in ITRF2008. In order to build a global relatively uniform distribution, precision is better than 0.3 mm/a, a completely unified global reference of high accuracy of geocentric coordinates global crustal motion velocity field, we need to do some data processing work.

First of all, some stations that geocentric coordinate velocity error more than 0.3 mm per year should be eliminated in order to ensure the accuracy of data calculation.

Secondly, systematic bias solved by using different techniques between the co-location station and the common station velocity field, should be using to unify those three kinematics technique data reference. Among them, the vertical direction reference datum, presented by Zhu [17] determined global vertical crust

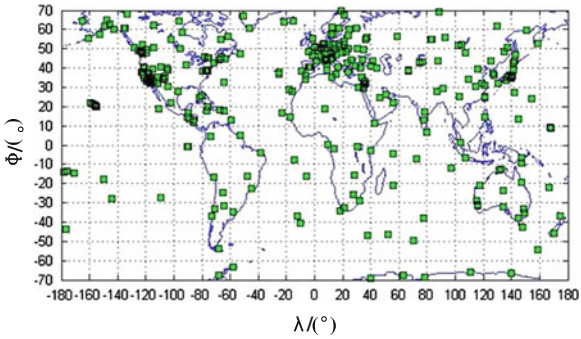

Fig. 2.1 Distribution of sites in ITRF2008 after pre-processing

movement reference, the geocentric coordinate velocity field is converted to a site-centric coordinate velocity field, and GPS and VLBI vertical velocity are converted to a unified global vertical crustal movement reference.

Finally, these 3 kinds' data would be used synthetically. To the different technology between the co-location stations, you can choose the station coordinate and velocity which keep the highest accuracy.

After above three steps of data pretreatment, 337 effective stations were choose whose precision is better than 0.3 mm/a, and reference datum completely unified of global crustal motion velocity field of geocentric coordinates, the distribution of stations such as shown in Fig. 2.1.

2.3 Detection Method

Inscribed polyhedron can always be formed with N (number) points for vertex that distributed in a sphere. As long as these vertex coordinates are defined, the polyhedron volume can be calculated. If the vertex coordinates changed, the polyhedral volume has always been changed. Based on this idea, we adopt three stations (assuming called A and B, C station) on the earth's surface with the Earth's core to constitute a tetrahedron O-ABC, as shown in Fig. 2.2, with a series sum of tetrahedral volume to approximate the total volume of the earth. Then the earth's surface shall surrounded by a series of triangle mesh, the triangular grid should be satisfied with neither overlap nor no crack condition [9, 10].

Every tetrahedron's volume can be obtained as sixth of mix product of those three independent vectors by using analytic geometry knowledge [6, 7, 12]. The tetrahedron is shown in Fig. 2.2, where point A, B and C are three peaks of spherical triangle, namely three stations distributed in the earth's surface. Supposed r_A, r_B, r_C as three station's position vector respectively, so tetrahedron O-ABC volume can be obtained by formula (2.1):

$$V = \frac{1}{6} r_A \cdot (r_B \times r_C) \tag{2.1}$$

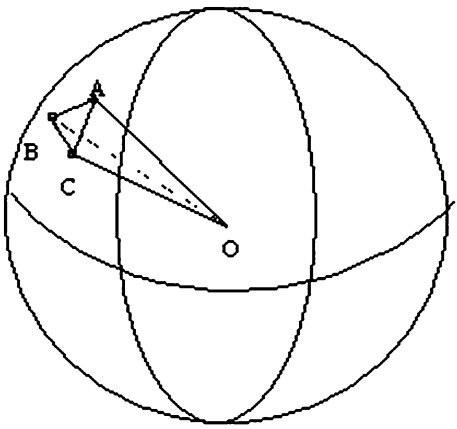

Fig. 2.2 Sketch map of tetrahedron from 3-sites and the earth's core

The change of volume can also be gotten by differential of time t as both sides of above formula. Polyhedron volume changes can be quite well reflecting part of the earth's volume change of different area [6].

Based on the coordinates, velocities and their error estimations of GPS and VLBI stations in 2003, using Delaunay arithmetic forming series of triangles to approach the surface of the Earth, the Earth's area, volume and their changes were studied [9, 10]. That's to say, the solid Earth's volume change can be acquired from Delaunay algorithm to make all global station form a continuous Delaunay triangulation grids, where all triangles of the grid with the earth's core constitute a geometric polyhedron, whose change of all geometry polyhedral can be calculated by all station's geocentric coordinate velocity. And the accumulation is the solid earth volume change which can be regarded as the change of solid earth's radius change. The idiographic methods are shown in reference [9, 10].

For the quantitative estimation of earth's radius change, this paper proposes the following method. First we are going to build High precision geocentric coordinates and speed fields, and convert it into topocentric coordinate velocity field, then make all station's radial velocity unified to the global vertical crustal motion's reference datum [17], finally make all the station's vertical velocity after unified to a weighted average, the earth radius change rate can be obtained.

In order to be able to use Delaunay algorithm to realize triangular mesh change, it is necessary to project all stations into one plane. If the equator as the boundary, then the earth is divided into north and south hemisphere; if the longitude line of 0–180° is taken as the boundary, the earth is divided into East and West hemisphere; if the longitude line of 90–270° as the boundary, the earth is divided into Pacific and Atlantic hemisphere (which include the Pacific Ocean and Atlantic Ocean respectively) [9, 10]. Here we only take the most representative of the north and south hemispheres as an example, to analyze the solid earth's asymmetrical detected change. Then the volume change of north and south hemisphere would be calculated respectively, and which characteristics of asymmetrical change could also be analyzed.

By measuring technique, measurement instrument and other objective factors limit, and few observed stations in some parts of the region, global stations were distributed unevenly, which can also be seen from Fig. 2.1. According to the vertical projection way, if hemisphere is regular, the graphics that projected to one plane should be close to an ellipse. That is to say, if station's distributed density around the equator are enough, the graphics that projection to the equatorial plane also ought to be an elliptic [6], while the actual observed station can't meet this condition, so the calculation on the area that there is few station should be for interpolation processing, increase of virtual stations, and calculates the movement rate of these new stations.

For the interpolation principle of interpolation points, scholars have done some research, summarizes several interpolation methods. A kind of method is: if in a Delaunay triangle meet any two vertex to sphere core have open angle is greater than 5°, then it can be taken its geometric center of this Delaunay triangle as the interpolation point. After interpolation, the original Delaunay triangle will be divided into three Delaunay triangles, and so on, until every Delaunay triangle to sphere core of opening angle is no more than 5° [12]. After inspection by a lot of data, this method had been detected that the interpolation effect of parts of the southern hemisphere is not ideal, its effect is bad is likely to be due to the influence of long and narrow triangles. Now improve the method further, and made some adjustments to the restrictions, that's to make the original angle to be greater than 5° to exchange the three angles that greater than 30°. This restriction conditions may be too strict to lead to the interpolation effect is not very ideal. If taking each Delaunay triangular surface area as a basis for judgment, we arrange the existing Delaunay triangular surface area by area values in descending order, and choose a standard area values as needing to interpolation control range. Thereby controlling the insertion point in the number and approximate position, such adjustments can make the global distribution of stations seem relatively uniform, and here we adopt this method. After interpolation, the stations distributions are shown in Fig. 2.3.

The interpolation theory has been explained in reference [9, 10] more detail, which applying interpolation to the stable plates, it doesn't affect the plate's motion trend after interpolations. Thus, according to stable plates Euler vector of plate motion model ITRF2008VEL in reference Zhu [17] and formula (2.2), we can solve the interpolation points movement rate, thereby solving the whole earth volume and its change.

$$\begin{bmatrix} V_i^x \\ V_i^y \\ V_i^z \end{bmatrix} = \begin{bmatrix} 0 & R\sin\phi_i & -R\cos\phi_i\sin\lambda_i \\ -R\sin\phi_i & 0 & R\cos\phi_i\cos\lambda_i \\ R\cos\phi_i\sin\lambda_i & -R\cos\phi\cos\lambda_i & 0 \end{bmatrix} \begin{bmatrix} \Omega_k^x \\ \Omega_k^y \\ \Omega_k^z \end{bmatrix} \tag{2.2}$$

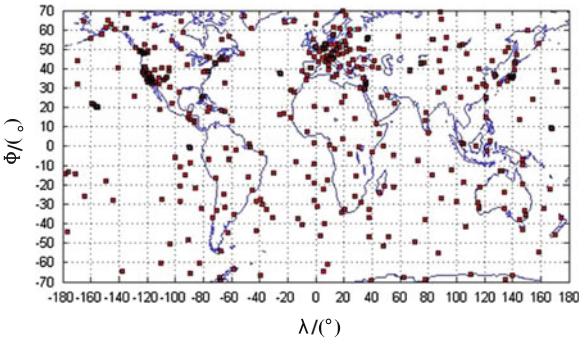

Fig. 2.3 Distribution of global sites after interpolation

2.4 Results and Discussions

After interpolations of the original 337 stations, a total of 450 groups of station data were received, which includes 155 of southern hemisphere and 295 of northern hemisphere respectively. There were formed 812 Delaunay triangles by using after interpolated data, wherein 257 of southern hemisphere and 555 of Northern Hemisphere respectively. The interpolation effects are shown as below (Figs. 2.4, 2.5, 2.6).

The results of two methods in reference [9, 10] and [6, 12] respectively were similar, which showing those two methods have no big difference theoretically. The results are shown in Table 2.1.

From the results in Table 2.1, we can include that the Earth is in asymmetrical change detected by ITRF2008 data, the north hemisphere is compressing and the south expending, which is in consistent with reference [2, 3, 6, 8–10] and Shen [12], that's to say, the Earth is still in south up north shrinkage asymmetrical change, this point has been verified by space observed data.

If the earth is taken as a regular sphere, the earth radius is 6366.740 km, the earth's total volume is $V0 = 4\pi R^3/3 = 1.01 \times 10^{12}\text{km}^3$, if the radius of the earth changes in 1 mm, earth volume change rate is $dV = 0.510 \times 10^3\text{km}^3/\text{a}$. The calculation results detected by observed data show the earth volume change rate was $(-0.0379 \pm 0.0902) \times 10^3\text{km}^3/\text{a}$, converted to the Earth radius change approximate to (-0.1 ± 0.2) mm/a, the conclusion is similar to reference [16], i.e., the radius of the earth cannot be considered changed in the range of one time mean error.

For the quantitative estimation of the Earth radius change, here we take observed site's velocity as base. Viz. building high accuracy geocentric coordinates and speed fields, converting into topocentric coordinate velocity field, and then make all station's radial velocity unified to the global vertical crustal motion's reference datum [17], finally make all the station's vertical velocity after unified to a weighted average, the earth radius change rate could be approximate to -0.24 mm/a, which was corresponding to above results.

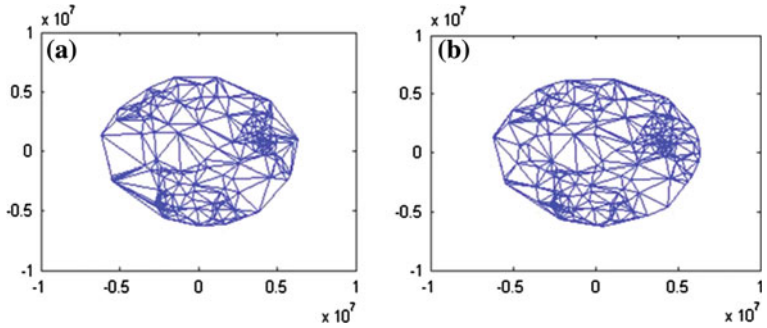

Fig. 2.4 Distribution of delaunay triangle in north-hemisphere before (**a**) and after (**b**) interpolation

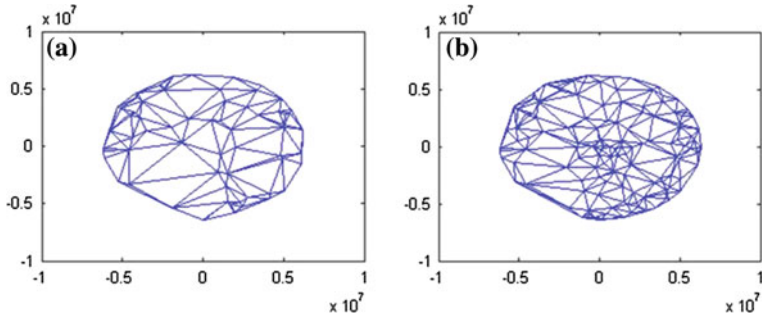

Fig. 2.5 Distribution of delaunay triangle in south-hemisphere before (**a**) and after (**b**) interpolation

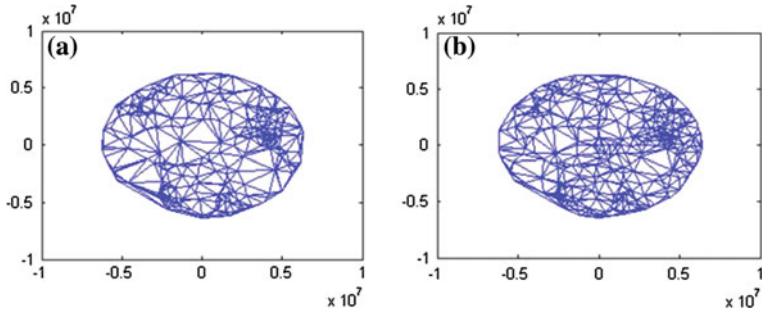

Fig. 2.6 Distribution of delaunay triangle in the earth before (**a**) and after (**b**) interpolation

Table 2.1 The Earth volume and its changing rates

Title	Volume [10^{12}km^3]	Changing rate [km^3·a^{-1}]	Error [km^3·a^{-1}]	Stations number	Delaunay triangles number
North	0.4206	−1.3724	0.0851	295	555
South	0.4147	1.3345	0.0299	155	257
Global (NS)	0.8353	−0.0379	0.0902	450	812

2.5 Conclusions

Compared above results detected by space observed techniques with such reference [6, 9, 10] and Shen [12], there were three points cannot but put forward.

Firstly, it is the problem of data precision. Here, we all chose the observed data that its geocentric coordinate is excelled 0.3 mm/a, while in reference [9, 10], which is under 5 mm/a, obviously higher quality data is better to reflect the results reliability.

Secondly, in data preprocessing, we unified all stations vertical velocity to the global vertical crustal motion reference datum, which is not appeared or discussed in current kindred references. For the necessary of unifying the vertical datum, Zhu [17] had been discussed and explained, so we have reason to believe that unifying vertical velocity is necessary, as well as providing the reliable basis of the main results of this paper. At the same time, the results here are similar to Wu et al. [16] which both using space observation data and geophysical information, which shown that it's reliability and dependability to estimate the Earth's change trend here.

Thirdly, this paper used ITRF2008 data to detect that the earth is still in south up north shrinkage asymmetric change, which is corresponding to the author's before work and the related literature, that's shown that the earth changes have been confirmed by space observations. In addition, because of emphasizing data's high precision and high quality, it is inevitable to delete more stations in the data pretreatment; while the distribution of global station is essentially uneven, some marine station is few and quality is not high, so we adopted reference Zhu [9], proposed the method of plate motion model interpolation The stable plate were interpolated, and the interpolation principle and conditions also made some modified and improved, the interpolation effect could even more improve global station distribution, and interpolated station does not affect the whole plate motion trend, and then the Earth change would not be affected.

In short, for the precise estimation of global change phenomena, it will depend on the higher quality data, more uniform distribution of stations and more reliable estimated method. With the rapid development of space technology and the progress of science, we have the reason to believe that those can be achieved.

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