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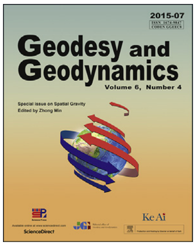

Progress in satellite gravity recovery from implemented CHAMP, GRACE and GOCE and future GRACE Follow-On missions

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ABSTRACT

Firstly, the Earth's gravitational field from the past Challenging Minisatellite Payload (CHAMP) mission is determined using the energy conservation principle, the combined error model of the cumulative geoid height influenced by three instrument errors from the current Gravity Recovery and Climate Experiment (GRACE) and future GRACE Follow-On missions is established based on the semi-analytical method, and the Earth's gravitational field from the executed Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission is recovered by the space-time-wise approach. Secondly, the cumulative geoid height errors are 1.727×10^{-1} m, 1.839×10^{-1} m and 9.025×10^{-2} m at degrees 70,120 and 250 from the implemented three-stage satellite gravity missions consisting of CHAMP, GRACE and GOCE, which preferably accord with those from the existing earth gravity field models involving EIGEN-CHAMP03S, EIGEN-GRACE02S and GO_CONS_GCF_2_DIR_R1. The cumulative geoid height error is 6.847×10^{-2} m at degree 250 from the future GRACE Follow-On mission. Finally, the complementarity among the four-stage satellite gravity missions including CHAMP, GRACE, GOCE and GRACE Follow-On is demonstrated contrastively.

1. Introduction

The 21st century is a new epoch that we upgrade the cognitive capabilities to the digital earth using the satellite-to-satellite tracking in the high-low mode (SST-HL), the satellite-to-satellite tracking in the high–low/low–low mode (SST-HL/LL) and the satellite gravity gradiometry (SGG) [1]. The global static and time-varying gravitational field can reflect the spatial distribution, movement and variation of materials on and inside the Earth, and can dominate the undulation and

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change of the geoid. Accordingly, the investigations on the fine configuration and time-variable characteristics of the Earth's gravitational field not only are requirements for geodesy, solid earth geophysics, oceanography, hydrology, glaciology, space science, etc., but also will provide important information for resource exploration, environmental protection and disaster monitoring [2–8].

As shown in Table 1, the successful launch of the past CHAMP satellite, the current twin GRACE satellites and the executed GOCE satellite, and the upcoming implementation of the future twin GRACE Follow-On satellites [9–17] declare that we will meet the era of the unprecedented satellite gravity exploration.

The Earth's gravitational field from the past CHAMP, current GRACE, executed GOCE and future GRACE Follow-On missions are, respectively, recovered making use of three different methods comprising the energy conservation principle, the semi-analytical method and the space-time-wise approach, and the advantages and disadvantages from the four-stage satellite gravity missions are in detail discussed in this study. This work not only is propitious to providing the theoretical and methodological basis for mapping the next-generation Earth gravity field model with high accuracy and spatial resolution, but also has the reference significance for the development direction of the future deep space satellite gravity missions (e.g. Moon [18,19], Mars [20]).

2. Methods

2.1. Past CHAMP mission

The energy conservation principle [21–31] is one of the efficient approaches to recover the CHAMP Earth's gravitational field complete up to degree and order 70. The advantage is that the Earth's gravitational field is in favor of being easily recovered because the energy observation equation has a linear relationship between the spherical harmonic coefficients of the geopotential and the Earth's disturbing potential. The disadvantage is that the determination accuracy of the Earth's gravitational field is sensitive to the observation error in the orbital velocity.

In the Earth-centered inertial (ECI) frame, the energy observation equation of the single satellite is defined as

$$\mathbf{T} = \mathbf{E}_k - \mathbf{E}_f + \mathbf{V}_\omega - \mathbf{V}_T - \mathbf{V}_0 - \mathbf{E}_0 \tag{1}$$

where $\mathbf{T}$ represents the Earth's disturbing geopotential,

$$T(r,\theta,\lambda) = \frac{GM}{r}\sum_{l=2}^{L}\sum_{m=0}^{l}\left[\left(\frac{R_e}{r}\right)^l (C_{lm}\cos m\lambda + S_{lm}\sin m\lambda)\overline{P}_{lm}(\cos\theta)\right]$$

where r shows the distance from the satellite's centroid to the geocenter, θ and λ display the geocentric colatitude and geocentric longitude, GM denotes the product of the gravitational constant G and the Earth's mass M, R_e presents the Earth's mean radius, $\overline{P}_{lm}(\cos\theta)$ denotes the normalized Legendre polynomials with degree l and order m, and C_{lm}, S_{lm} express the estimated geopotential coefficients.

The first term $\mathbf{E}_k = \frac{1}{2}|\dot{\mathbf{r}}|^2$ on the right-hand side of equation (1) is the kinetic energy, where $\dot{\mathbf{r}}$ represents the orbital velocity vector. The second term $\mathbf{E}_f = \int \dot{\mathbf{r}}\mathbf{f}\, dt$ is the dissipative energy, where $\mathbf{f}$ shows the non-conservative force (e.g., atmospheric drag, solar radiation pressure, the Earth's albedo, orbital altitude and attitude control forces, etc.). The third term $\mathbf{V}_\omega = -\omega_e(x\dot{y} - y\dot{x})$ is the geopotential rotation, where ω_e denotes the Earth's angular rotation rate. The fourth term $\mathbf{V}_T$ is the three-body disturbing potential (e.g., lunisolar gravitation, Earth's solid tides, ocean tides, principle of relativity effect, etc.). The fifth term $\mathbf{V}_0 = GM/r$ is the geocentric potential. The last term $\mathbf{E}_0$ is the energy constant derived from the initial orbital position and orbital velocity vectors.

2.2. Current GRACE and future GRACE Follow-On missions

The semi-analytical method [32–37] is an efficient method for estimating the accuracies of the Earth's gravitational field from the current GRACE and future GRACE Follow-On missions. The principle of the semi-analytical method is that the accuracy of the Earth's gravitational field is estimated using the error model of the satellite observation equation established by the relationship between the cumulative geoid height error and the measurement error of the space-borne instruments. The advantages are that the establishment of the high-degree earth gravity field model is rapid, the physical

Table 1 – A comparison of the past CHAMP, current GRACE, executed GOCE and future GRACE Follow-On missions.

Parameters	Satellite gravity missions			
	CHAMP	GRACE	GOCE	GRACE Follow-On
Scientific institution	GFZ[a]	NASA[b] and DLR[c]	ESA[d]	NASA
Mission lifetime	2000-07-15–2010-09-19	2002-03-17	2009-03-17–2013-11-10	2016–2020
Orbital altitude	454–300 km	500–300 km	250–240 km	about 250 km
Orbital inclination	87°	89°	96.5°	89°
Orbital eccentricity	<0.004	<0.004	<0.001	<0.001
Inter-satellite range	—	220 km	—	50 km
Tracking mode	SST-HL	SST-HL/LL	SST-HL/SGG	SST-HL/LL
Spatial resolution	285 km	166 km	80 km	55 km

[a] GFZ: GeoForschungsZentrum, Potsdam, Germany.
[b] NASA: National Aeronautics and Space Administration, USA.
[c] DLR: Das Deutsche Zentrum für Luft-und Raumfahrt, Germany.
[d] ESA: European Space Agency.

significance of the satellite observation equation is definite, and the error analysis is easy. We created the combined error model of the cumulative geoid height influenced by the measurement errors in the satellite-borne payloads using the semi-analytical approach. Accordingly, the accuracies of the Earth's gravitational field from GRACE and GRACE Follow-On can be accurately and rapidly estimated based on the combined error model of the cumulative geoid height.

The combined model of the cumulative geoid height error δN impacted by three error sources including the inter-satellite range-rate $\delta\dot{\rho}_{12}$, orbital position δr and non-conservative force δf is established as

$$\delta N = R_e\sqrt{\sum_{l=2}^{L}\left[\frac{1}{1-P_l(\cos\theta)}\frac{R_e}{GM}\left(\frac{r}{R_e}\right)^{2l+1}\sigma_l^2(\delta\eta)\right]} \tag{2}$$

where $\delta\eta = \sqrt{\sigma_l^2(\delta\dot{\rho}_{12}) + \sigma_l^2\left(\sqrt{\frac{4GM\tan^2(\theta/2)}{r^3}}\delta r\right) + \sigma_l^2(\int \delta f dt)}$.

The calculational processes of estimating the cumulative geoid height error using the combined error model are depicted as follows (e.g. future GRACE Follow-On mission).

Firstly, the random white noises $\delta\eta$ of the normal distribution with an observation period of 30 days and a sampling interval of 10 s are produced.

Secondly, the orbital position of the future twin GRACE Follow-On satellites are simulated based on the numerical integration formulas of the 9th-order Runge–Kutta linear single-step method associated with the 12th-order Adams-Cowell linear multi-step method. The simulation parameters of the satellite orbit are listed in Table 1.

Thirdly, the grids with a $1^\circ \times 1^\circ$ resolution are plotted on the Earth's surface of longitude $\lambda(0^\circ-360^\circ)$ and latitude $\phi(-90^\circ-90^\circ)$, and $\delta\eta(\phi,\lambda)$ is put in the track position of the satellite orbit on the Earth's surface.

Finally, according to the spherical harmonic expansion, $\delta\eta(\phi,\lambda)$ is displayed as

$$\delta\eta(\phi,\lambda) = \sum_{l=0}^{L}\sum_{m=0}^{l}\left[\left(C_{\delta\eta_{lm}}\cos m\lambda + S_{\delta\eta_{lm}}\sin m\lambda\right)\overline{P}_{lm}(\sin\phi)\right] \tag{3}$$

where $C_{\delta\eta_{lm}}, S_{\delta\eta_{lm}}$ denote the expansion coefficients of $\delta\eta(\phi,\lambda)$.

$$\left(C_{\delta\eta_{lm}}, S_{\delta\eta_{lm}}\right) = \frac{1}{4\pi}\iint \delta\eta(\phi,\lambda)\overline{Y}_{lm}(\phi,\lambda)\cos\phi d\phi d\lambda \tag{4}$$

The variance of $\delta\eta$ at every degree is expressed as

$$\sigma_l^2(\delta\eta) = \sum_{m=0}^{l}\left(C_{\delta\eta_{lm}}^2 + S_{\delta\eta_{lm}}^2\right) \tag{5}$$

Substituting equation (5) into (2), the accuracy of the Earth's gravitational field is conducive to being precisely and rapidly estimated.

2.3. *Executed GOCE mission*

The core ideas of the Earth's gravitational field recovery from the executed GOCE mission adopting the space-time-wise approach are described as follows [38]. Firstly, the four equidistant and regular reference spherical surfaces with the center of sphere located at the geocenter are designed and the GOCE satellite orbit is located between the second and third reference spherical surfaces. The gridding is averagely measured off according to the longitude and latitude on the every reference spherical surface. Secondly, the satellite gravity gradient data are rapidly calculated by the fast Fourier transform (FFT) on each reference spherical surface and are transformed from the reference spherical surfaces to the satellite orbit by the three-dimensional interpolation (Space-wise approach). Finally, equation (6) is solved at the satellite orbit, and the geopotential coefficients are derived from the least-squares procedure (Time-wise approach).

In the Earth-centered inertial frame, the observation equation of the satellite is defined as

$$\mathbf{y}_{m\times 1} = \mathbf{A}_{m\times n}\overline{\mathbf{x}}_{n\times 1} \tag{6}$$

where $\mathbf{y}_{m\times 1}$ denotes the gravity gradients at satellite orbit, m represents the number of the satellite gravity gradients; $\mathbf{A}_{m\times n}$ displays the design matrix with rows m and columns $n = L_{\max}^2 + 2L_{\max} - 3$, L_{max} is the maximum degree of the spherical harmonic function; and $\overline{\mathbf{x}}_{n\times 1}$ expresses the estimated earth's geopotential coefficients.

Because equation (6) is the overdetermined large-scale system of equations, it does not have an exact solution, but a least-squares solution. Multiplying equation (6) by $\mathbf{A}^T\mathbf{E}^{-1}$ on both sides at the same time yields

$$\mathbf{A}^T\mathbf{E}^{-1}\mathbf{y} = \mathbf{A}^T\mathbf{E}^{-1}\mathbf{A}\overline{\mathbf{x}} \tag{7}$$

where $\mathbf{E}$ represents the error covariance matrix of the satellite gravity gradients. In this study, the random white noises of normal distribution are introduced into the satellite gravity gradients during the numerical simulation process.

When the spherical harmonic degree of the Earth's gravitational field recovery is higher ($L_{\max}$>150), $\mathbf{A}^T\mathbf{A}$ is an ill-conditioned matrix, and the ill condition is apt to be sharply intensified with the increase in the spherical harmonic degree. Because the ill condition will lead to decrease the accuracy of the Earth's gravitational field recovery, the regularization will play a significant role in the satellite gravity recovery step. The main effect of the regularization is to reduce ill condition and suppress the high-frequency noise of the Earth's gravitational field determination [39]. The Kaula regularization can be defined as

$$\mathbf{K} = K_0 K_1 \tag{8}$$

where K_0 represents the Kaula regularization parameter. As for recovering the GOCE Earth's gravitational field complete up to degree and order 250, $K_0 = 2\times 10^{-10}$. K_1 denotes the Kaula regularization function,

$$K_1 = \delta_{ij}\, l^4(i) \tag{9}$$

where δ_{ij} denotes Kronecker symbol, and $l(i)$ shows the spherical harmonic degree of the Earth's potential coefficients corresponding to the row (column) number i.

By adopting the Kaula regularization, equation (7) can be modified as

$$\mathbf{A}^T\mathbf{E}^{-1}\mathbf{y} = \left(\mathbf{A}^T\mathbf{E}^{-1}\mathbf{A} + \mathbf{K}\right)\overline{\mathbf{x}} \tag{10}$$

Assuming $G = A^T E^{-1} y$, $N = A^T E^{-1} A + K$, equation (10) can be rewritten as

$$G_{n\times 1} = N_{n\times n}\overline{x}_{n\times 1} \tag{11}$$

In general, $A_{m\times n}$ is a large-scale design matrix. Due to consuming a large number of the memory space, it is very difficult to store $A_{m\times n}$. Although the normal matrix $N_{n\times n}$ is much smaller than $A_{m\times n}$, large numbers of the memory space (about 12 Gb) is required to store $N_{n\times n}$. $N_{n\times n}$ is a block-diagonally dominant matrix.

The pre-conditioned conjugate-gradient iterative approach (PCCG) is one of the most efficient methods to solve the large-scale linear system of equations. During solving equation (11), the block-diagonal part of $N_{n\times n}$ is chosen as $P_{n\times n}$, and the off-block-diagonal part of $P_{n\times n}$ is zero. Thereby, $P_{n\times n}$ maintains the characteristics of $N_{n\times n}$, and the computation of $P_{n\times n}^{-1}$ is much easier than $N_{n\times n}^{-1}$. In a word, the number of iterations can be substantially reduced by the appropriate choice of $P_{n\times n}$ (reducing approximately 1000 times as compared to the direct least-squares method).

3. Results

As illustrated in Fig. 1, the asterisk, solid bold, dashed slim and solid slim lines respectively express the cumulative geoid height errors based on the accuracy indexes of the space-borne instruments (Table 2) from the past CHAMP, current GRACE, executed GOCE and future GRACE Follow-On missions. At degrees 70,120 and 250, the cumulative geoid height errors are 1.727×10^{-1} m, 1.839×10^{-1} m and 9.025×10^{-2} m from the implemented CHAMP, GRACE and GOCE missions, which basically are in agreement with the existing Earth gravity field models EIGEN-CHAMP03S, EIGEN-GRACE02S and GO_CONS_GCF_2_DIR_R1. At degree 250, the cumulative geoid height error is 6.847×10^{-2} m from the future GRACE Follow-On mission. The statistic results of the cumulative geoid height errors from the four-stage satellite gravity missions at every degree are listed in Table 3.

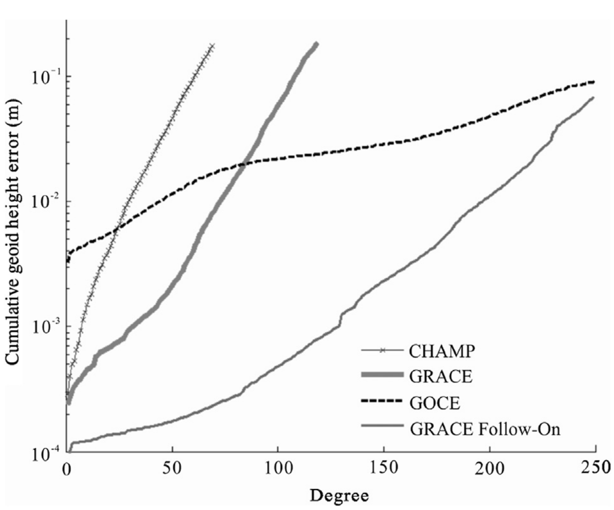

Fig. 1 – Comparison of cumulative geoid height errors from the implemented CHAMP, GRACE and GOCE and future GRACE Follow-On missions.

According to Fig. 1 and Table 3, the research results are stated as follows.

(1) The utmost ability from the past CHAMP mission to recover the global gravitational field using the SST-HL mode is about 70 degrees. Due to the limitations regarding the orbital altitude, instrument noises, tracking mode, etc., CHAMP satellite is only fit for measuring the Earth's long-wavelength gravitational field. Therefore, the CHAMP mission is just an exploratory experimentation for high-accurately determining the Earth's gravitational field using the first-stage dedicated gravity satellite, and makes for sufficiently improving the accuracy of the earth's potential coefficients and enhancing the dependability of the Earth gravity field model.

(2) The topmost ability from the current GRACE mission to map the Earth's gravitational field using the SST-HL/LL mode is approximately 120 degrees. The cognitive capability to the Earth's gravitational field is upgraded by an unprecedented level owing to the successful launch of the twin GRACE satellites. The new Earth gravity field model will be produced by every 15–30 days from the GRACE mission, and the contributions to measure the high-accuracy and high-resolution Earth's gravitational field even exceed the total of information in the past 30 years. The twin GRACE satellites not only include two groups of SST-HL mode, but also determine the mutual movements of two low-orbiting satellites based on the differential principle. Accordingly, the recovery accuracy of the static and time-variable Earth's gravitational field from GRACE is at lowest one order of magnitude higher than that from CHAMP.

(3) The top-flight ability from the GOCE mission to determine the Earth's gravitational field using the SST-HL/SGG mode is near 250 degrees. Due to the sharp signal attenuation $(R_e/r)^l$ of the Earth's gravitational field with the increase in the orbital altitude of the satellite, the orbit perturbation analysis is only appropriate to measure the Earth's gravitational field in the medium-long wavelength band. However, the second-order derivatives of the Earth's gravitational potential can be directly determined by the satellite gravity gradiometry technique and the spherical harmonic coefficients are enlarged by l^2 times. Hereby, the satellite gravity gradiometry is in favor of efficiently suppressing the signal attenuation of the Earth's gravitational potential with the increase in the orbital altitude and precisely determining the Earth's gravitational field in the medium-short wavelength range [40].

(4) The uppermost ability from the future GRACE Follow-On mission to measure the Earth's gravitational field using the SST-HL/LL mode is almost 250 degree. The crucial reasons why the accuracy of the Earth's gravitational field from the future GRACE Follow-On mission is at least 10 times higher than that from the current GRACE mission are analyzed as follows. Firstly, the orbital altitude of the twin GRACE Follow-On satellites is sharply decreased, and the signal attenuation of the Earth's gravitational field with the increase of orbital altitude is efficiently mitigated. Secondly, the GRACE Follow-On mission thoroughly improves the measurement accuracy of the inter-satellite range-rate by the interferometric laser ranging system. Finally, the twin GRACE Follow-On satellites

Table 2 – Accuracy indexes of key payloads from the implemented CHAMP, GRACE and GOCE and future GRACE Follow-On missions.

Key payloads	Measurement accuracy			
	CHAMP	GRACE	GOCE	GRACE follow-on
GPS receiver	1×10^{-1} m	3×10^{-2} m	1×10^{-2} m	1×10^{-3} m
Accelerometer	3×10^{-9} m/s^2	3×10^{-10} m/s^2	—	3×10^{-11} m/s^2
Inter-satellite ranging system	—	1×10^{-6} m/s	—	1×10^{-7} m/s
Gradiometer	—	—	3×10^{-12}/s	—

Table 3 – Statistical results of the cumulative geoid height errors from the implemented CHAMP, GRACE and GOCE and future GRACE Follow-On missions.

Degrees	Cumulative geoid height errors (m)			
	CHAMP	GRACE	GOCE	GRACE Follow-On
20	3.732×10^{-3}	6.625×10^{-4}	5.373×10^{-3}	1.355×10^{-4}
50	4.226×10^{-2}	1.997×10^{-3}	1.129×10^{-2}	1.739×10^{-4}
70	1.727×10^{-1}	8.061×10^{-3}	1.668×10^{-2}	2.317×10^{-4}
90	—	2.685×10^{-2}	2.066×10^{-2}	3.617×10^{-4}
120	—	1.839×10^{-1}	2.392×10^{-2}	7.989×10^{-4}
200	—	—	4.723×10^{-2}	1.072×10^{-2}
250	—	—	9.025×10^{-2}	6.847×10^{-2}

are equipped with the drag-free control system for accurately compensating for the non-conservative force.

4. Conclusions

This research focuses principally on demonstrating contrastively the complementarity among the past CHAMP, current GRACE, executed GOCE and future GRACE Follow-On missions based on three different methods consisting of the energy conservation principle, the semi-analytical method, and the space-time-wise approach. Due to aiming to measure the Earth's gravitational field in different wavelength bands, the four-stage satellite gravity missions have different scientific applications. Because the implemented CHAMP, GRACE and GOCE and future GRACE Follow-On missions are respectively sensitive to Earth's gravitational field in the long-wavelength, medium-long-wavelength, medium-short-wavelength and short-wavelength bands, they are not competitive but complementary with one another. Therefore, the combination of the four-stage satellite gravity missions is helpful for producing the Earth gravity field model with unprecedented accuracy and resolution.

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