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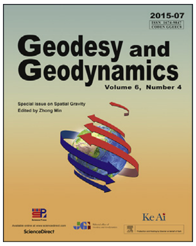

Progress in satellite gravity recovery from implemented CHAMP, GRACE and GOCE and future GRACE Follow-On missions

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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

$$\mathbf{T} = \mathbf{E}_{\mathrm{k}} - \mathbf{E}_{\mathrm{f}} + \mathbf{V}_{\omega} - \mathbf{V}_{\mathrm{T}} - \mathbf{V}_{0} - \mathbf{E}_{0} \tag{1}$$

where $\boldsymbol{T}$ 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 $\boldsymbol{E}_k = \frac{1}{2}|\dot{\boldsymbol{r}}|^2$ on the right-hand side of equation (1) is the kinetic energy, where $\dot{\boldsymbol{r}}$ represents the orbital velocity vector. The second term $\boldsymbol{E}_f = \int \dot{\boldsymbol{r}}\boldsymbol{f}\, dt$ is the dissipative energy, where $\boldsymbol{f}$ 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 $\mathbf{V}_{\mathrm{T}}$ is the three-body disturbing potential (e.g., lunisolar gravitation, Earth's solid tides, ocean tides, principle of relativity effect, etc.). The fifth term $\mathbf{V}_0 = \mathrm{GM}/r$ is the geocentric potential. The last term $\boldsymbol{E}_0$ 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.