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Future dedicated Venus-SGG flight mission: Accuracy assessment and performance analysis

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Abstract

This study concentrates principally on the systematic requirements analysis for the future dedicated Venus-SGG (spacecraft gravity gradiometry) flight mission in China in respect of the matching measurement accuracies of the spacecraft-based scientific instruments and the orbital parameters of the spacecraft. Firstly, we created and proved the single and combined analytical error models of the cumulative Venusian geoid height influenced by the gravity gradient error of the spacecraft-borne atom-interferometer gravity gradiometer (AIGG) and the orbital position error and orbital velocity error tracked by the deep space network (DSN) on the Earth station. Secondly, the ultra-high-precision spacecraft-borne AIGG is propitious to making a significant contribution to globally mapping the Venusian gravitational field and modeling the geoid with unprecedented accuracy and spatial resolution through weighing the advantages and disadvantages among the electrostatically suspended gravity gradiometer, the superconducting gravity gradiometer and the AIGG. Finally, the future dedicated Venus-SGG spacecraft had better adopt the optimal matching accuracy indices consisting of $3 \times 10^{-13}/s^2$ in gravity gradient, 10 m in orbital position and 8×10^{-4} m/s in orbital velocity and the preferred orbital parameters comprising an orbital altitude of 300 ± 50 km, an observation time of 60 months and a sampling interval of 1 s.

Keywords: Venus-SGG mission; Analytical error model; Atom-interferometer gravity gradiometer; Deep space network; Venusian gravitational field recovery

1. Introduction

Until now, more than 40 Venus probes have been launched by the Soviet Union, the United States, Europe, Japan, etc. in the interest of carrying out the extensive and intensive scientific investigations on the Venus (e.g., Taguchi et al. (2007), Russell et al. (2008), Chassefière et al. (2009), Kappel et al. (2012), and Withers et al. (2013)). However, there still have no active plans to implement the dedicated Venusian spacecraft gravity mission which is a multi-disciplinary and high-tech systems engineering by far (Zheng et al., 2014a). On account of many similarities between the Earth and the Venus, scientific information of the cause, evolution and structure regarding the Venus not only is helpful for investigating the origin, development and evolution of the Earth (e.g., Kaula (1990)), but also makes for substantially improving the understanding and cognition on the characteristics of the origin and evolution concerning the Moon (Zheng et al., 2011a, 2015a; Maghrabi, 2014; Califorrniaa, 2015), the Mars (Zheng et al., 2011b, 2013a; Beaudet, 2013; Moores et al., 2015), the Mercury (Yoshioka et al., 2008; Sauvaud et al., 2010; Noyelles and Lhotka, 2013), and so on.

As shown in Table 1, the European Space Agency (ESA) successfully executed the first-stage satellite gravity

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Table 1
A comparison of the implemented Earth's GOCE program, the past lunar GRAIL project and the future Venus-SGG mission.

Parameters		Spacecraft gravity missions		
		GOCE (Earth)	GRAIL (Moon)	Venus-SGG (Venus)
Orbital indices	Research institute	ESA	JPL	CAS
	Launching time	2009-03-17–2013-11-10	2011-09-10–2012-12-17	2020–2030 yrs
	Orbital altitude	250 km	55 km (Primary program) 23 km (Extended program)	300 ± 50 km
	Orbital inclination	96.5° (Sun-synchronous)	89.9° (near-polar)	90° (polar)
	Orbital eccentricity	<0.001 (almost-circular)	<0.001 (almost-circular)	<0.001 (almost-circular)
	Flight lifetime	>4 yrs	>1 yr	>5 yrs
	Number of spacecrafts	Single	Twin (Collinear formation)	Single
	Tracking mode	SST-HL/SGG	SST-HL/LL	DSN-SGG
	Sampling interval	1 s	5 s	1 s
Instrument errors	Gravity gradient	$3 \times 10^{-12}/s^2$ (Electrically-suspended gravity gradiometer)	–	10^{-13}–$10^{-14}/s^2$ (AIGG)
	Inter-satellite range-rate	–	10^{-7}–10^{-8} m/s (LGRS)	—
	Orbital position	1 cm (GPS/GLONASS)	10–100 m (DSN)	1–100 m (DSN)
	Orbital velocity	10^{-5} m/s (GPS/GLONASS)	10^{-3} m/s (DSN)	10^{-3}–10^{-4} m/s (DSN)
Gravity models	Satellite-only (Optimal)	GO_CONS_GCF_2_TIM_R5 ($L = 280$) (Pail et al., 2011)	GL0900D ($L = 900$) (Konopliv et al., 2014)	$L \geqslant 360$

gradiometry program named Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) dedicated to mapping in detail the Earth's gravitational field in the medium-short-wavelength band. The GOCE satellite around the Earth flies in a near-polar, almost-circular, Sun-synchronous and low-altitude orbit, and adopts the satellite-to-satellite tracking in the high-low associated with satellite gravity gradiometry (SST-HL/SGG) mode. Aside from continuously tracking the low-orbiting GOCE satellite making use of the high-orbiting American Global Positioning System combined with Russian GLObal NAvigation Satellite System (GPS/GLONASS) (Bock et al., 2007), the second-derivatives of the Earth's gravitational potential are accurately measured by the spacecraft-borne electrically-suspended gravity gradiometer (Visser, 2007) located at the centroid of the GOCE satellite and the non-conservative forces acting on the GOCE satellite are compensated in real time using the drag-free and attitude control system (DFACS) (Canuto, 2008). Since the idea of the satellite gravity gradiometry was initially applied to acquiring gravity information in the early 1980s, many scientific institutions have carried out the comprehensive and in-depth investigations with regard to precisely detecting the near-global gravity field by the satellite gravity gradiometry techniques up to now (Zheng et al., 2011c, 2012a, 2013b; Yi, 2012). Because the negative influences of the signal attenuation of the Earth's gravitational field are apt to be exponentially aggravated with the gradual increase in the orbital altitude of the satellite, the medium-long-wavelength components of the Earth's gravitational field are only able to be efficiently gained through the satellite-to-satellite tracking mode (e.g., the current Earth's Gravity Recovery and Climate Experiment (GRACE) mission at an orbital altitude of about 500 km, which has been cooperatively performed by the American Jet Propulsion Laboratory, National Aeronautics and Space Administration (NASA's JPL) and the German GeoForschungsZentrum Potsdam (GFZ) on March 17, 2002 (Zheng et al., 2011d, 2012b, 2012c, 2015b; Bezděk et al., 2014)). However, the satellite gravity gradiometry principle is conducive to directly determining the second-order gradients of the geopotential of the Earth, and then substantially mitigating the signal attenuation of the Earth's gravitational field recovery. Accordingly, the GOCE satellite is propitious to achieving the detailed global gravity maps in the medium-high-frequency range. The mission objectives of the GOCE satellite around the Earth are to determine gravity-field anomalies with an accuracy of 10^{-5} m/s^2, to determine the geoid with an accuracy of 1–2 cm and to achieve the above at a spatial resolution better than 100 km (Rummel et al., 2002). The scientific goals of the GOCE program aim to offer the better understanding of the physics of the Earth's interior to gain new insights into the geodynamics associated with the lithosphere, mantle composition and rheology, uplift and subduction processes; the better understanding of the ocean currents and heat transport; the global height-reference system, which can serve as a reference surface for the study of topographic processes and sea-level change; and the better estimates of the thickness of polar ice-sheets and their movement (Johannessen et al., 2003).

As displayed in Table 1, in consideration of the outstanding performances of the implemented Earth-monitoring satellite gravity programs (namely CHAMP (CHAllenging Minisatellite Payload), GRACE and GOCE), the NASA's JPL has triumphantly sent a pair of dedicated Gravity Recovery and Interior Laboratory (GRAIL-A/B) spaceships to the low-Moon orbit aiming to explore the detailed maps of the lunar gravitational field by the satellite-to-satellite tracking in the high-low/low-low (SST-HL/LL) principle (Zheng et al., 2011a, 2012d,e, 2015b; Andrews-Hanna et al., 2013; Wieczorek et al., 2013). The lunar GRAIL project, operating in an