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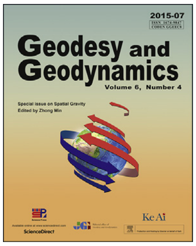

Progress on the use of satellite technology for gravity exploration

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ABSTRACT

In this paper, the technological progress on Chinese gravity exploration satellites is presented. Novel features such as ultra-stable structure, high accurate thermal control, drag-free and attitude control, micro-thrusters, aerodynamic configuration, the ability to perform micro-vibration analyses, microwave ranging system and mass center trimmer are described.

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1. Introduction

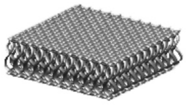
In China, studies for the preparation of gravity satellite missions, in addition to research and development of new technologies, scientific instruments and spacecrafts, began more than 15 years ago. Under the guidance of the China National Space Administration, satellite gravity measurement missions have been conducted. Certain key research projects related to the development of scientific instruments and spacecrafts have been funded. This paper highlights the technological progress that has been observed to date.

2. Ultra-stable material and structure

2.1. *Near-zero CTE carbon–carbon composite material*

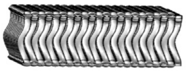
Carbon–carbon composite materials were selected for the fabrication of key bench sustaining payloads. The advantages of carbon–carbon composite structure include near-zero coefficient of thermal expansion (CTE), low moisture sensitivity, and high specific stiffness.

To simultaneously realize near-zero CTE in X, Y, Z directions, the bench thickness direction should also have a near-zero CTE. Taking into consideration the two preferential qualities (i.e., rigidity and minimal weight), four types of carbon–carbon structures were developed as potential prototypes of the final bench structure. Figs. 1–4 illustrate the three-dimensional (3D) woven integrated, truss core, carbon honeycomb core, and carbon honeycomb core sandwich structures that were proposed.



a-Profile

b-Warp direction



c-Weft direction

Fig. 1 – 3D woven integrated sandwich structure.

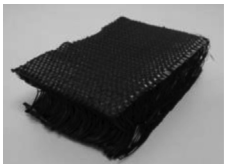


Fig. 2 – Sample of 3D structure.

a-Straight rods truss core

b-Inclined rods truss core

c-Pyramidal truss core

Fig. 3 – Truss core sandwich structure.

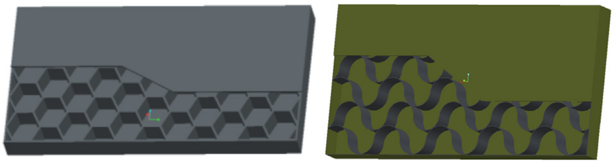


Fig. 4 – Carbon honeycomb core sandwich structure.

2.2. *A composite truss structure model*

Satellites that are designed for gravity measurement missions need to maintain orbital stability to ensure a relatively fixed position and pointing of each precise payload stable. Fig. 5 provides an example of a truss structure model. The low thermal expansion coefficient that characterizes composite truss structure designs compromises the payload. Fig. 6 illustrates a finite element-based (FE) model of the truss structure that was built to facilitate thermal distortion analysis.

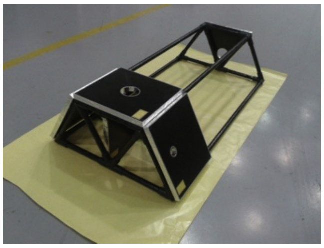


Fig. 5 – The model of truss structure.

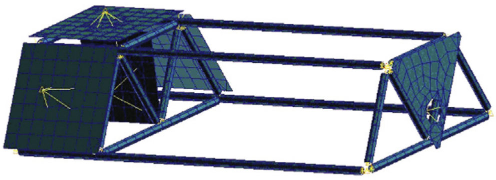


Fig. 6 – The FE model of composite truss structure.

3. Precise thermal control

3.1. *Grading thermal control design method*

The grading thermal control design method was studied. Satellite thermal design adopts the subdistrict thermal control design mode in accordance to the requirement for satellites' high-precision temperature control.

High-precision temperature control can be achieved by multi-grading thermal control design. Three-grading thermal control designs were used in this study to initiate the investigation into ways to maintain high-precision temperature controls by applying the grading thermal control design method. The thermal control district is divided into three parts; these are identified as the core thermal, the transition thermal and the periphery thermal control districts. Among the three districts, equipments that require the most stable temperatures and the narrowest viable temperature ranges are placed in the core thermal control district. Equipments that have the same but relatively less demanding temperature requirements are placed in the transition thermal control district and equipments that do not share the aforementioned requirements are placed in the periphery thermal control district. Strict heat insulation and independent temperature controls were designed to meet specific requirements for each of the different districts to reduce interacting influence among them [1,2].

3.2. *Digital proportional-integral-derivative control*

Thermal regulation is based on a proportional-integral-derivative (PID) [3]. The associated algorithm supports the execution of rapid reactions to any kind of perturbations; this is imperative to ensure the maintenance of the structures and temperatures of electronic elements as close to the defined temperature as possible (Fig. 7).

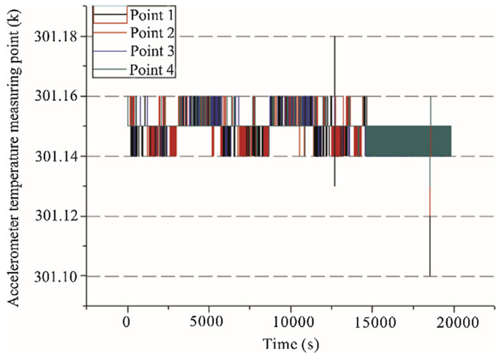


Fig. 7 – Curves of thermal control experiment results.

4. Attitude and orbit control

4.1. *Drag-free and altitude control design*

Known limitations of the embedded-model-based drag-free and altitude control (DFAC) include the effect of stochastic noises and an incomplete understanding of disturbances on its performance. As a result, a logical-derivative-based DFAC was proposed. It offers comparative advantages to the traditional design; these advantages are attributed to its robustness against noises and sources of disturbance. The logical derivative controller was introduced in the last century and has been applied in many engineering fields, such as satellite attitude control and chemical temperature control. The logical derivative controller can achieve better transient responses than the general linear derivative control [4,5]. On the basis of the simulation results, the designed logical-derivative-based DFAC can achieve better control performance (Fig. 8).

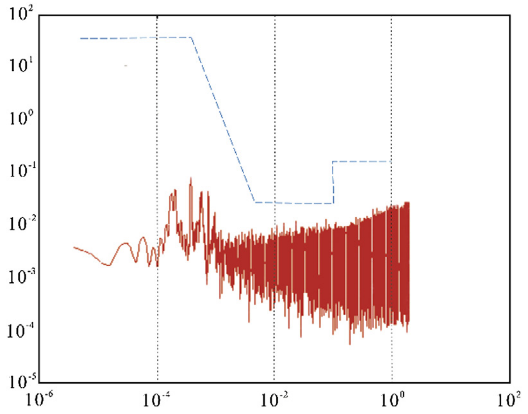


Fig. 8 – The linear acceleration under logical-derivative-based DFAC.

4.2. *Control technology for LL-SST gravity measurement satellites and its physical experiments*

The control subsystem of satellites that are tasked to acquire gravity measurements based on low–low satellite-to-satellite tracking (LL-SST) data is responsible for these satellites' orbit, altitude dynamics and control. The optimization of this control subsystem was explored; corresponding semi-physical and principle full-physical simulation experiments were performed. Schematics illustrating the components of the simulation system are presented in Figs. 9 and 10.

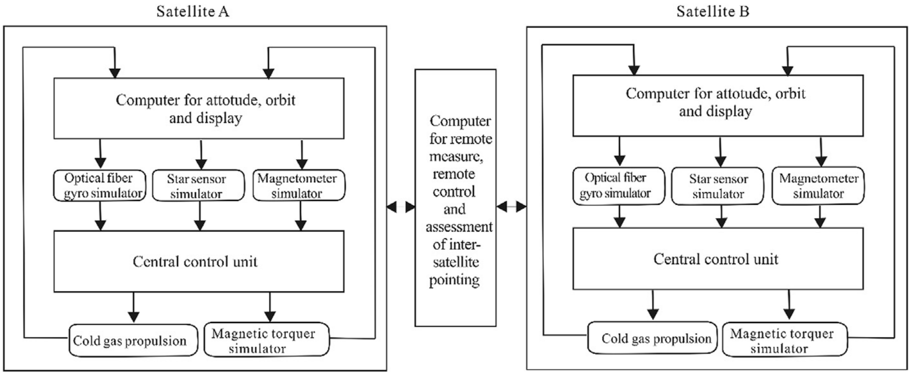


Fig. 9 – Schematic diagram of semi-physical simulation system for altitude and orbit control.

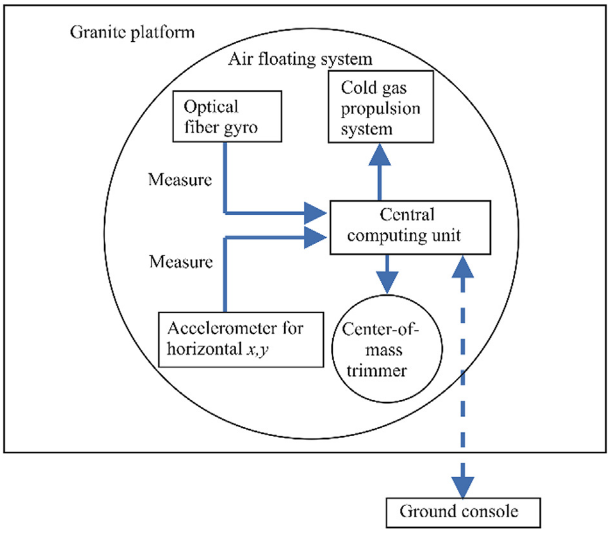
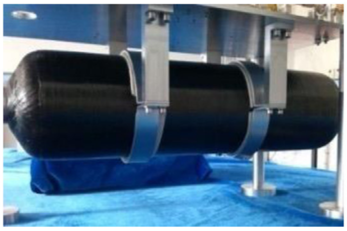


Fig. 10 – Schematic of the full-physical simulation experiment system.

4.3. *Cold gas micro propulsion*

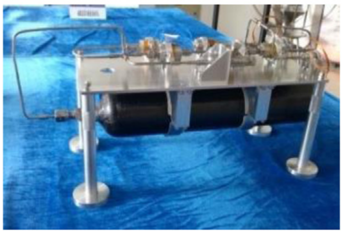
The Beijing Institute of Control Engineering developed a very high pressure cold gas propulsion system in 2012; it is capable of handling storage pressures of up to 60 MPa. The tank is wrapped in titanium fiber, which maintains a notably smaller and lighter unit. The system is also equipped with a mechanical pressure regulator. The regulator has two stages with a small container positioned between them. N_2 is used as a propellant, the pressure can be adjusted to 0.1 MPa, the total weight of the system is less than 2 kg, the total impulse reaches 930 Ns and the average power that is wasted over long periods is less than 1W. 10 and 200 mN thrust options are also available.

Fig. 11 shows the titanium fiber wrapped around the propellant tank, the two-stage regulator and the cold gas propulsion system model.



a– Tank wrapped with titanium fiber

b– Regulator assembly



c– System model

Fig. 11 – Very high pressure micro cold gas propulsion system.

4.4. *Ion electric propulsion*

The Lanzhou Institute of Physics (LIP) has been developing a 10 cm diameter Kaufman ion thruster, named LIPS-100. The design and evaluation of the model prototype (i.e., LIPS-100P) was successfully completed when all of the design goals were met. The program has continued with the design, manufacture, and assessment of the engineering model (i.e., LIPS-100E). These are shown in Figs. 12–14 and the performance parameters are summarized in Table 1.

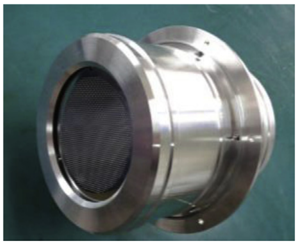


Fig. 12 – LIPS-100P thruster.

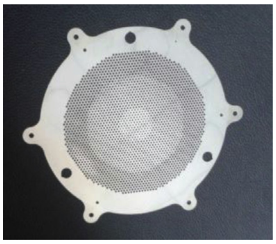


Fig. 13 – The screen grid.

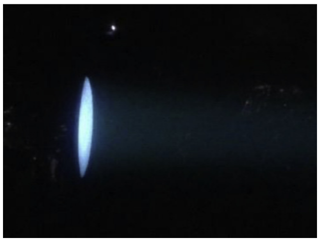


Fig. 14 – LIPS-100P thruster operating.

Table 1 – Performance parameters of the LIPS-100 thruster.

Parameter name	Nominal value	Test result
Thrust (mN)	1–15	2–15.8
Impulse (s)	Approximately 3000	Approximately 3204
Total power (W)	≤450	438
Discharge loss (W/A)	≤280	265
Mass utilization efficiency (η_m)	5%–85%	10%–82.3%
Electric efficiency (η_e)	75%	76.3%
Total efficiency (η_T)	60%	62.8%

4.5. *Cusped field thruster*

The prototype of cusped field thruster (CFT) that was developed for the gravity mission is shown in Fig. 15. The thruster's main structure consists of permanent, modular magnets, a ceramic channel wall, a protective plate, an anode, magnetic-guiding rings, locating rings and a cooling shell. The variable magnet length was the most significant factor that was considered in the design.

Fig. 15 – Prototype of CFT for gravity explorer missions.

5. The GNSS receiver

The defined performance parameters of the Global Navigation Satellite System (GNSS) receiver are summarized in Table 2.

6. Microwave ranging system

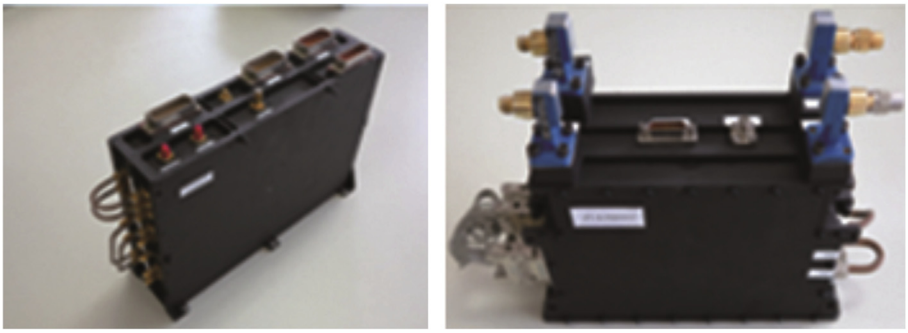
On the basis of a dual, one-way ranging system framework, an experimental, K-band ranging system prototype that includes antennas, microwave units, signal processing terminals (i.e., a K-band ranging receiver and GNSS signal processors) and Ultra Stable Oscillator (USO) were developed [6–8]. Lab based demonstrations and verification of the proposed system was conducted by the China Academy of Space Technology located in Xi'an in recent years. Fig. 16 presents photos of selected hardware components of the prototype and the results of the lab based performance evaluation results are summarized in Table 3.

7. Mass center trimmer

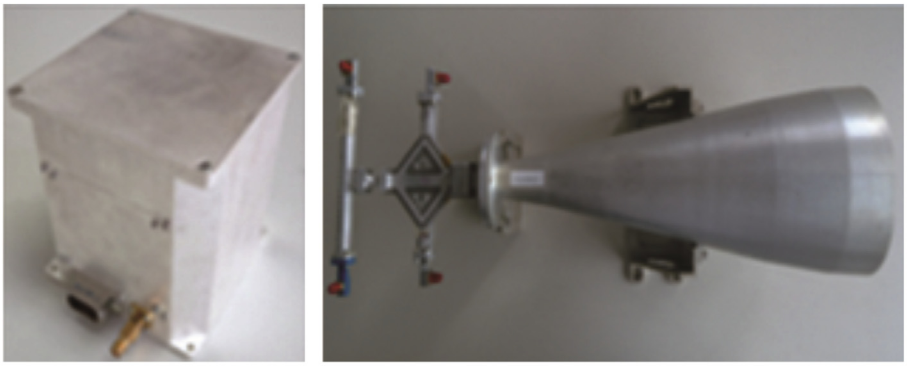
The Lanzhou Institute of Physics studied theories and methods that were pertinent to the regulation of satellite centroids in-orbit, proposed key techniques, developed a mass trim mechanism (MTM) and a mass trim electronic (MTE) prototype and performed MTM environmental adaptability tests. The correlation tests demonstrated that the technical capabilities of the MTM satisfy the defined mission requirements (Fig. 17 and Table 4).

Table 2 – Performance parameters of GNSS receiver.

General performance		Navigation		Time tag measurement		Startup time		Post-process performance	
Type of service	Standard position service, real-time orbit determination	Absolute position, velocity	10 m, 0.05 m/s	1PPS precision	100 ns	Code	2 min	Post precise orbit determination	5 cm, 0.001 m/s
Number of simultaneous antennas	1 or 2	Real-time orbit determination	3 m, 0.01 m/s			Warm	1 min	Relative clock offset error	0.1 ns
Frequencies	GPSL1, L2, BDB1/B2/B3	Clock offset solution error	50 ns						
Number of channels	24								
Pseudo-range	40 cm								
Carrier phase	2 mm								
Signal power	−133 dBm min								
Operation period	5 years								



a-Signal process terminal b-Microwave unit



c-USO d-K/Ka antenna

Fig. 16 – The hardware of the experimental prototype.

Table 3 – Performance test results in the laboratory.

Test items	Test results	Conditions
Biased ranging accuracy (μm)	3.10	1. Relative movement between two K/Ka antennas. 2. Simulative 170 km–270 km 3. 0.0001 Hz–0.1 Hz.
Ranging rate accuracy (μm/s)	0.30	4. Allan variance of the USO is better than 3×10^{-13} @1s.
The source of error affecting the observable range due to changes in the temperature of the components (μm/0.1K)	4.96	The simultaneous change in temperature of the components.

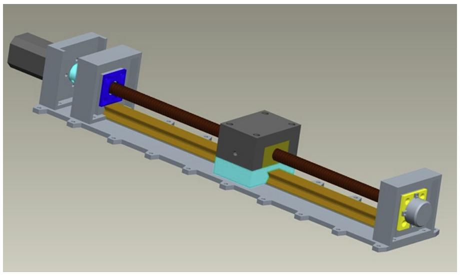


Fig. 17 – MTM design.

Table 4 – MTM engineering prototype capabilities.

Item	Value
Movable mass	2.5 kg
The max travel distance	±200 mm
Movable mass movement precision	0.47 mm
Movable mass self-locking precision	0.31 mm
Total quality	7.7 kg
Power	5.02 W
Volume	≤650.5 mm × 124 mm × 86 mm
Intermittent working time	> 50 times
Total working hours	> 105 h

8. Aerodynamic and micro-vibration analysis

8.1. *Method for accurate aerodynamic modeling*

Aerodynamic modeling of satellites involves an atmospheric model of the Earth, knowledge of satellite surface characteristics and gas-surface interactions. Some efforts have focused on methods to improve upon the accuracy of modeling processes. Requirements include the need to address the needs under different scenarios, to investigate the validity of assumptions that are required when creating atmospheric models and gas-surface interaction models, associated with uncertainty factors and boundary limitations, to determine the impact of potential errors and rules that govern model selection. Furthermore, additional requirements are necessary to solve the problems of complex gas-surface interactions, including surface shielding and multiple molecular reflections, the incorporation of ray-tracing and test-particle monte carlo (TPMC) methods and the establishment of appropriate simulation algorithms for free molecular flow. Finally, it is necessary to integrate information from multiple disciplines and to propose a modeling method based on discrete elements and master-model technology [9,10].

8.2. *Micro-vibration analysis*

A roadmap for micro-vibration control and a backup plan was established. The key steps included the identification of needs and resources, the analysis of vibration transfer behavior, the allocation of system budgets, the design of ultra-silent components and final systems validation. The schematic of the roadmap is illustrated in Fig. 18.

On the basis of the finite elements of the satellite model, the vibration transfer behavior of structure was analyzed. The sources of disturbance were identified as the magnetic rods, the thruster for cold gas, the latching valve and the power control and distribution unit (PCDU). Transfer functions from the source to the accelerometer sensor head and the associated response were determined. These results can be used to evaluate the impact of the disturbances and can be used to carry out measurements for vibration reduction.

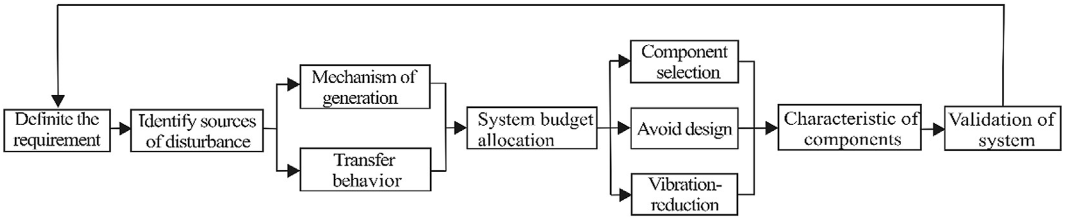


Fig. 18 – Overview of roadmap for micro-vibration control.

9. Numerical simulation

A system used to simulate measurements of the Earth's gravity field was developed by DFH Company. It is equipped with two formation-flying small satellites on low-Earth orbits and was designed to support the exploration of data flows from in-situ detectors to processed data packages. The system also provides a realistic source of data for the gravity field modeling. The application of such a simulation system is based on the understanding of underlying scientific principles of space-borne gravity field measurements and on the successful verification of the space segment design (Figs. 19 and 20).

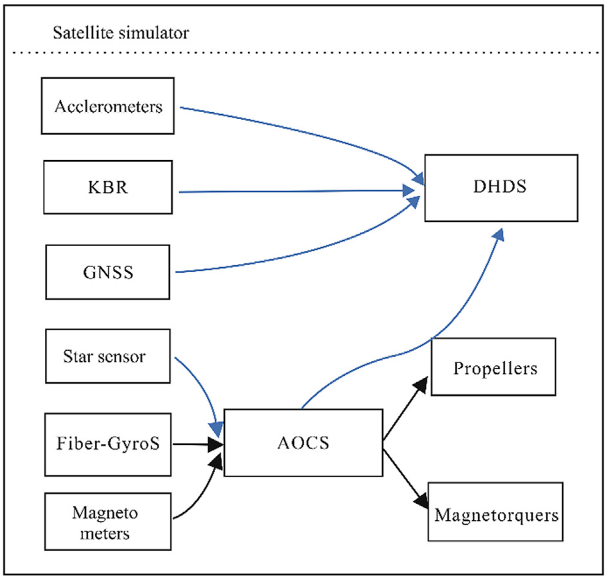


Fig. 19 – Sketch of satellite components.

Fig. 20 – Photo of the satellite simulator A/B.

10. Summary

Research and development on satellite gravity exploration missions and gravity satellite technologies have been conducted in China for more than 15 years already. With financial support from the Chinese National Space Administration, a series of key points has been identified for further evaluation, including those related to direct applications and the improvement of scientific instruments and spacecrafts. As a result of these academic and technical activities, the sound basis has been established to further the development of China's gravity satellites.

Acknowledgments

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REFERENCES

[1] Cheng Wenlong, Liu Na, Wu Wanfan. Studies on thermal properties and thermal control effectiveness of a new shape-stabilized phase change material with high thermal conductivity. Appl Therm Eng 2012;36:345–52 [in Chinese].

[2] Valentini David, Vacance Michel, Battaglia Domenico, Pieper Bernd, Niot Jean-Michel. GOCE instrument thermal control. SAE International; 2006.

[3] Deng Wei, Zhang Yi, Chen Jiehua, Dian Yuan, Wu Hongwei, Gu Sihong. Optimization and realization of digital temperature control system for CPT atomic frequency standard. Acta Electron Sin 2012;40(9):1889–92 [in Chinese].

[4] Canuto Enrico, Massotti Luca. All-propulsion design of the drag-free and attitude control of the European satellite GOCE. Acta Astronaut 2009;64:325–44.

[5] Canuto Enrico. Drag-free and attitude control for the GOCE satellite. Automatica 2008;44:1766–80.

[6] Dunn Charles, Bertiger Willy, Franklin Garth. The instrument on NASA's GRACE mission: augmentation of GPS to achieve unprecedented gravity field measurements. ION GPS 2002:24–7.

[7] Kim J, Tapley BD. Simulation of dual one-way ranging measurements. J Spacecraft Rockets 2003;3(4):419–25.

[8] Dunn CE, Lichten S, Jefferson David, Border JS. Sub-Nanosecond clock synchronization and precision deep space tracking. In: Proceedings of the 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, NASA Conference Publication 3159, Pasadena, California; 1992. p. 89–101.

[9] Eshagh M, Sjoberg Lars E. Atmospheric effects on satellite gravity gradiometry data. J Geodyn 2009;47(1):9–19.

[10] Mazanek Daniel D, Kumar Renjith R, Qu Min, Seywald H. Aerothermal analysis and design of the gravity recovery and climate experiment (GRACE) spacecraft. NASA/TM-2000–210095:1-43.

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