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Key technologies analysis and design of ultra-clean & ultra-stable spacecraft for gravitational wave detection

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The observation of gravitational wave enables human to explore the origin, formation and evolution of universe governed by the gravitational interaction and the nature of gravity beyond general theory of relativity. The groundbreaking discovery of Gravitational Wave by Laser Interferometer Gravitational-Wave Observatory provides a brand-new observation way. While detecting gravitational wave on ground is limited by noises and test scale, space detection is an optimized alternative to learn rich sources in range of 0.1 mHz–1 Hz. Considering the great significance of space gravitational wave detection, ESA proposed LISA project, CAS also proposed Taiji project. Due to the extremely weak gravitational wave signal and high measurement accuracy requirement, the spaceborne GW observation antenna is accomplished by three spacecrafts constitute isosceles triangle formation intersatellite interferometer. The arm length of the interferometer reaches millions of kilometers between them, and the measurement accuracy reaches pico-meter magnitude. There are many key technologies including pm magnitude space laser interferometer metrology, drag-free control using TM of Gravity Reference Sensor, μN micro thruster, ultra-clean & ultra-stable spacecraft, etc. This paper focuses on key technologies of the ultra-clean & ultra-stable spacecraft, analyzing the design of mechanical, thermal control and magnetic clean. Moreover, it reports the preliminary results of the technological breakthrough.

Keywords: Gravitational waves; ultra-clean & ultra-stable spacecraft; key technologies analysis.

1. Introduction

On February 11, 2016, Laser Interferometer Gravitational-Wave Observatory (LIGO) experimental group announced that gravitational wave was directly detected on ground, providing a brand-new observation way, changing astronomy by opening the window of high-frequency gravitational wave to observe low mass sources at low redshift.[1]

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Ground-based gravitational wave detection is affected by the noises such as surface vibration, gravity gradient, and limited by test scale, causing the detection frequency band to be limited to more than 10 Hz. Since most of the wave sources with larger feature quality and scale are distributed in the middle and low frequency band (0.1 mHz–1 Hz), the arm length of intersatellite laser interferometry must reach the order of millions of kilometers. Restricted by the radius of curvature of the earth and noises such as surface vibration and gravity gradient, the space detection is an optimized alternative to realize high precision interferometers.[2–5]

The earliest space gravitational wave detection project is Laser Interferometer Space Antenna (LISA), which is also the most mature project by far.[6–9] The project was proposed by the European Space Agency (ESA) cooperating with National Aeronautics and Space Administration (NASA) in the 1990s. The recent announcement of the amazing performance of the LISA Pathfinder which launched in 2015, validates the feasibility of some key technologies, clearing away most technical obstacles for LISA.[10,11]

In 2012, the Chinese Academy of Sciences (CAS) proposed "Taiji Project" for space gravitational wave detection, to detect the sources in range of 0.1 mHz–1 Hz band.[12] Taiji project in Space would be accomplished by three spacecrafts maintaining of an equilateral triangle in the Keplerian orbit around the sun, with the arm length of interferometer reaching 3 million km, measuring the distance change between two drag-free controlled Test Masses (TM). Within the detection frequency range, the measurement accuracy of the laser interferometer should reach the order of pm/Hz$^{1/2}$ magnitude, and residual acceleration should reach the order of 10^{-15}ms^{-2}/Hz$^{1/2}$ magnitude.[13,14] However, such high technical targets are extremely difficult to achieve based on existing capabilities.[15,16] Taiji project aims to establish a three-step plan to launch at 2030s. The first step is manufacturing a pilot experimental satellite "Taiji-1" to prepare necessary technology for Taiji project. The Taiji-1 had successful launched in 2019, Fig. 1 displays the artist's view of satellite. Meanwhile, Taiji Collaboration also dedicates to optimize the key technologies like laser Interferometer Measurement System (IMS), Gravity Reference Sensor (GRS), drag-free control, μN micro thruster and

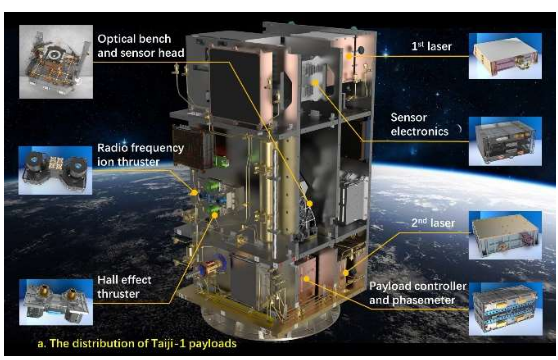

Fig. 1. The artist's view of Taiji-1 satellite (without outer panels).

ultra-clean & ultra-stable spacecraft toward the final Taiji project. This paper analyzes the key technologies of the ultra-clean & ultra-stable spacecraft, reports the design and preliminary results of mechanical design, thermal control, magnetic clean control.

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2. Key Technologies Analysis

As gravitational wave signal is extremely weak, SpaceCraft (S/C) requires high sensitivity, not only for the IMS, GRS and micro thruster, but also for the satellite platform to provide ultra-clean & ultra-stable environment.

Based on the requirements of scientific observation, the three spacecrafts need to be maintained as an equilateral triangle with six laser links. Each spacecraft should establish two interferometer arms between other two spacecrafts with a nominal angle of 60°. Each laser interferometric arm contains one set of laser interferometric measuring instruments and one set of Test Mass in GRS with drag free control. The measurement sensitivity could breakdown to interferometric metrology noise and acceleration noise. The key technology identification of spacecraft is also based on error breakdown.

2.1. *Spacecraft requirement from interferometric measurement system*

The major contributors to IMS sensitivity include readout noise, laser/clock/phasemeter noise, pathlength measurement noise, etc.[17] Among them, the pathlength measurement is directly affected by spacecraft, which arises because thermal induced optical path variations and tilt-to-length coupled into arm length variations. The temperature fluctuations can couple strongly within the pathlength variations, including telescope deformation, optical bench deformation, and parameter variations of optical components. So it is essential to maintain temperature stability of the IMS within the measurement bandwidth. The spacecraft should support ultra-stable thermal control, with the temperature stability supposed to maintain 10 μK/Hz$^{1/2}$. Moreover, the spacecraft structure, especially the interface between S/C and IMS should build with very low thermal expansion coefficient material valuing less than $1\times10^{-7}\,K^{-1}$.

2.2. *Spacecraft requirement from gravity reference sensor*

The GRS is responsible for ensuring that the residual acceleration of two TMs falls below the sensitivity requirements, by providing tight pointing and translational control of the spacecraft and its TM. The highest requirement to GRS is that the amplitude spectral density of the TM acceleration disturbance shall reach the order of 10^{-15}ms^{-2}/Hz$^{1/2}$ magnitude.

The contributors to acceleration noise include electrostatics, magnetic field effects, Brownian noise, self-gravity effects, thermal effects, drag-free and telescope control, etc. The couple between S/C and GRS is complicated, which includes the mechanical & thermal, magnetic field & self-gravity field, AOCS & drag-free control. The design of the spacecraft is driven by the requirement to keep the TM in GRS as undisturbed as possible. Specifically for the negative effects, the mechanical deformation would change

CoM and self-gravity, while the temperature stability would influence electronics, gas pressure fluctuations and thermal gradient effects around GRS, and the magnetic field may contribute to noise. To avoid these possible disturbances, the S/C should be ultra-clean and ultra-stable, and the magnetic field & self-gravity field effect should be controlled as low as possible.

3. Key Technologies Design and Preliminary Results

3.1. *Ultra-stable mechanical design*

The mechanical design is an important part of the ultra-stable spacecraft, it could be divided into two main parts: proper layout to minimize the residual acceleration on the TM, and support stable structure for the payloads and on-board components.

The spacecraft layout should ensure that the external forces, both gravitational and magnetic, on the TM are minimized. The Center of Mass (CoM) of the spacecraft is designed at the midpoint of the line between two TMs, as close as possible to the TMs. And the electronic component with large magnetic magnitude such as power switching & distribution unit, transponders, and laser should be placed as far as possible. The Fig. 2 is the preliminary design of Taiji spacecraft. To avoid the CoM drastic changed after long time orbital shift, the spacecraft designs separable science module and propulsion module, but only science module works in the mission orbit. Flexible and deployable appendages also should be avoided to minimize disturbances.

The self-gravity effect of spacecraft also needs to be carefully considered. As self-gravity cannot be directly measured on the ground, the accurate simulation analysis method is proposed to estimate the center of self-gravity and gravity gradient. To reach gravitational balance, multiple iterations of the layout and simulation shall be done. The simulation analysis is divided into the following steps: (1) Based on the finite element method, building different discrete mesh model adopted for different shape of units, set different mesh cell size based on the distance to the TM. (2) Study the gravity calculation formulas of three-dimensional blocks with different densities and shapes, such as upright

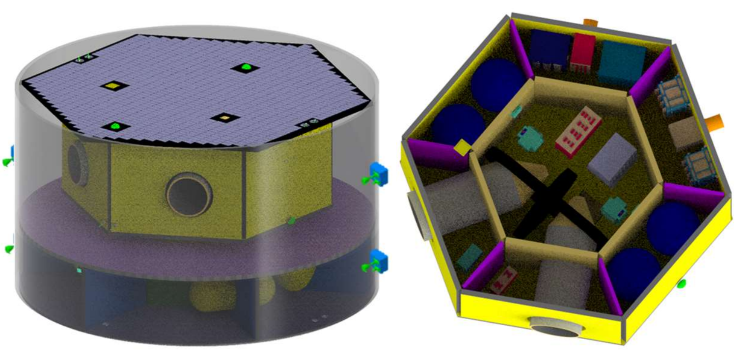

Fig. 2. The configuration design and layout of science module.

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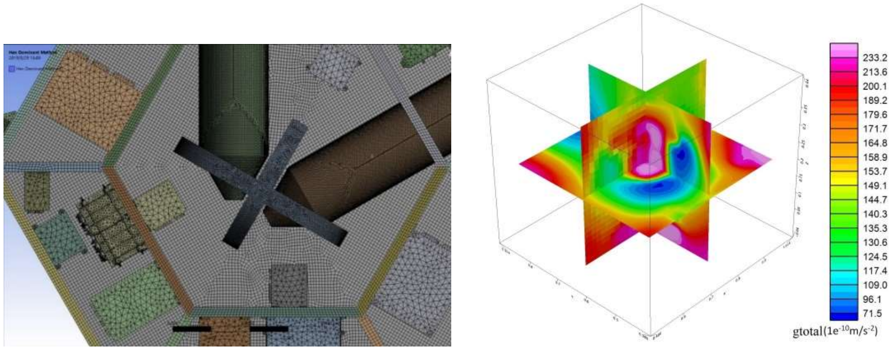


Fig. 3. The meshing example and gravitational value diagram.

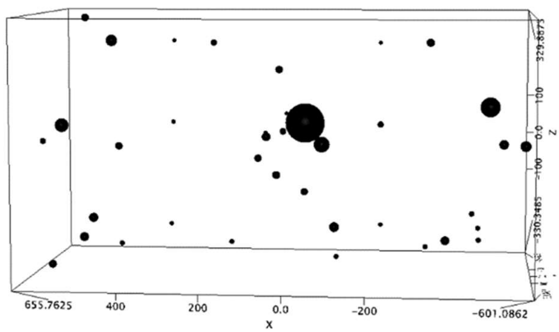
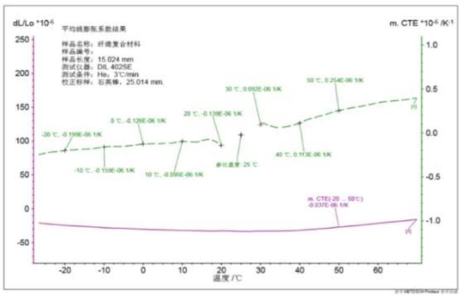


Fig. 4. The three-dimensional mass distribution of Taiji-1 satellite.

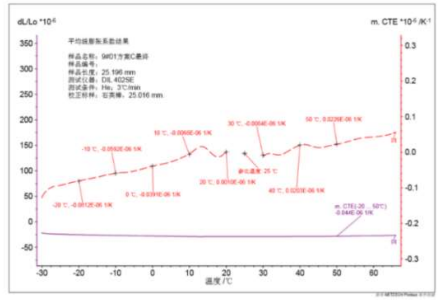
rectangular solids, spheres, cones, to calculate the gravity contribution of discretized grid unit to the TM. Figure 3 shows the meshing example of Taiji spacecraft and one of the total gravitational value calculation result. The simulation accuracy of self-gravity is better than 10^{-10} ms^{-2}. The accuracy is still need to optimize considering the goal of measurement accuracy is 10^{-16} ms^{-2}.

The method of self-gravity simulation has also been applied in Taiji-1 satellite and guides the layout design. Figure 4 displays the three-dimensional mass distribution of Taiji-1 satellite. The size of sphere indicates the value of mass. The center of the biggest sphere is the TM, also the CoM of the satellite.

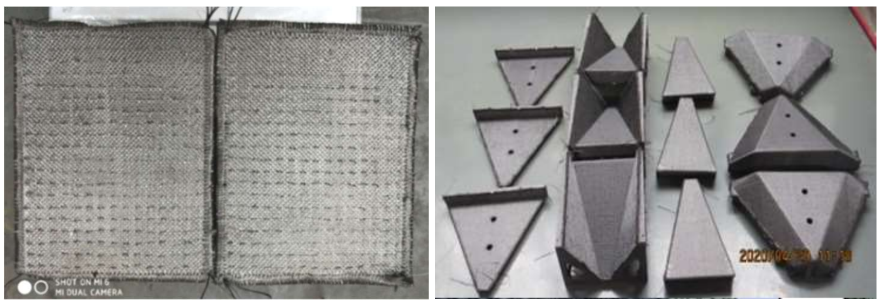
The very low Coefficient of Thermal Expansion (CTE) material is also a key point to keep spacecraft stable. To minimize the noise lower than the measurement accuracy, Taiji project requires the structural deformation reaching the order of pm/Hz$^{1/2}$, corresponding to CTE of the structure less than 1×10^{-7} K^{-1}. The continuous fiber reinforced Ceramic Matrix Composites (CMCs) material seems a good choose due to their low density, high strength and excellent thermal stability. The CTE of CMCs



(a) The CTE of CMC: ≤ 5×10^{-7} K^{-1}



(b) The CTE of CMC after optimized: ≤ 1×10^{-7} K^{-1}



(c) The structural molding of CMC materials

Fig. 5. The CTE test result of optimized CMC materials and structural molding.

usually between 5–12×10^{-7} K^{-1}. To reach lower CTE value, SiBC matrix is introduced into C/SiC by liquid silicon infiltration.[20] The optimized CMC material is designed with high modulus filament carbon fiber and C/SiC-SiBC substrate, and pyrolytic carbon used as interface layer. Based on the performance of the optimized material, it is considered as a feasible solution, and had been verified by linear expansion coefficient test on ground. The test result is shown in Fig. 5, the CTE meets the expected target. Now, the optimized CMC materials are used for structural molding, and the further test for structure will be done soon.

3.2. *High precision and stability thermal control design*

Thermal control is designed for ultra-stable spacecraft to achieve high precision temperature measurement and high stability thermal fluctuation control.

As the thermal stability requirement is 10 μK/Hz$^{1/2}$, the temperature measurement resolution needs to be maintained as one order of higher magnitude, achieving 1 μK/Hz$^{1/2}$@1 mHz. Two high-resolution temperature measurement strategies are designed for measuring temperature, using high-precision bridge and multiple platinum resistors series connection separately. For the bridge method, the core circuit principle prototype

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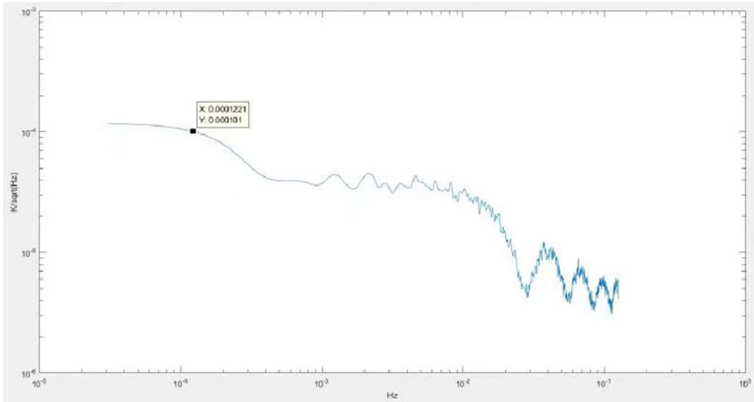

Fig. 6. The temperature measurement result with multiple platinum resistors series connection method.

has been finished and tested. While the measurement strategy seems proper for the gravitational wave detection mission, the noise of the whole temperature measurement system still needs to be optimized and verified. For the multiple platinum resistors series connection method, the series connection improved signal-to-noise ratio. Now, the measurement resolution is 30 μK, the test data curve is displayed in Fig. 6. 30 μK resolution is still a gap to the target resolution.

Taiji spacecrafts will be on heliocentric orbit. Although the environment of external heat flow on the orbit is stable, the thermal stability specification would still be a great challenge. The technical tackling strategy is to combine active and passive temperature control and applying graded control. As Fig. 7 displays, a three-level thermal control strategy is designed for the Taiji S/C.

For the first level area, the spacecraft internal thermal control is precisely designed with proper radiator surfaces and solar array panel which is thermally isolated, minimizing the interference of external heat flow. The internal heat transfer coefficient of the structure panels is optimized to improve the uniform temperature. The active thermal compensation is carried out and the ripple of power supply bus is controlled to reduce the transient interference.

For the second level area, a heat shield is built between second and third level. The heat shield is composed of insulation materials, Multi-Layer Insulation (MLI), heat conduction structure, etc. Outer layer uses insulation materials and MLI to isolate heat conduction and heat radiation. Internal layer uses aerogel and coating to isolate radiation. The high precision closed-loop PID control is applied to the second level area, controlling the thermal fluctuation to be smaller than 1 mK.

For the third level area, which is also the core area to place payload components with high thermal stability requirement, passive thermal control is used with the goal of 10 μK.

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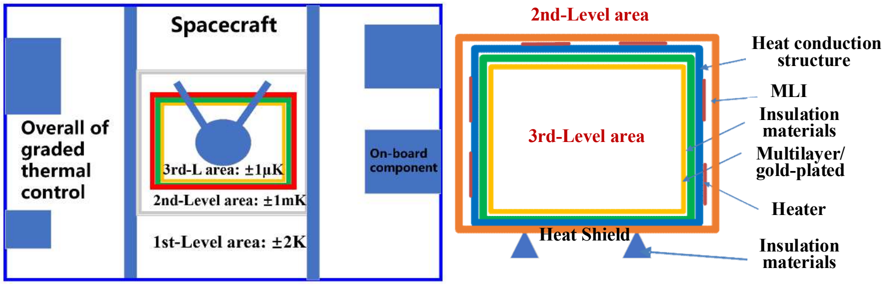

Fig. 7. The three-level temperature control: overall (Left) and core area (Right).

The same graded thermal control strategy has already been applied to Taiji-1 satellite. Although not as many isolated as the final Taiji spacecraft, on-board data shows that the core area has achieved the temperature stability of ±5 mK and reached the leading level in China.[19]

3.3. *Magnetic simulation and magnetic clean control*

Magnetically driven forces play a key role in the instrument sensitivity in the low-frequency regime (mHz and below), which is overlapping with the Taiji project measurement band.[20,21] The magnetic field can couple the magnetic susceptibility and remanent magnetic moment from the TMs. So, it is important to consider the S/C and payload design. To control the magnetic clean, no ferromagnetic materials shall be used near the TM. The residual magnetism of S/C components is controlled, and time-varying magnetic field needs real-time monitoring. It is also necessary to have a stable electromagnetic environment, with no spurious frequencies especially within the measurement bandwidth.

The ground direct measurement of the magnetic field on the TM is difficult and easily disturbed by geomagnetism. Therefore, it is necessary to use accurate magnetic simulation while designing. The strategy is combined with the magnetic test results of S/C component and multi-dipole approximation method for magnetic field simulation to achieve precise estimation. Comparing the measurement of the whole S/C, the measurement of each component's magnetic field characteristic is easier. The omnidirectional and solid angle test should be carried out to collect detailed information for magnetic property inversion and simulation analysis of the whole S/Cs magnetic characteristics. To simulate the S/C magnetic field source based on the test results, each component can be equivalent to a single dipole or multiple magnetic dipoles.

As there is no accurate magnetic data of Taiji project yet, the data of magnetic source of LISA pathfinder is used to verify the developed magnetic field simulation algorithm.[22] The data from LPF provides the position of the magnetic dipole and dipole momentum, but the information of the momentum direction is unknown. As a result, sources with random directions have to be used to deduce. The deduction includes two steps. First, the random direction of the magnetic moment for each magnetic dipole is given. Then the

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superimposed magnetic field component of all magnetic dipole at TM position would be calculated. One thousand times random magnetic field component is calculated. The calculation results are averaged to get more accurate magnetic field distribution.

Considering the geometric distribution of the magnetic field *X*, *Y*and *Z* component in a certain XY plane which TM is placed, the formula as is shown following. Character m_x, m_y and m_z are the components of the magnetic moment in the *X*, *Y* and *Z* directions, *R* is the distance from the field point to the magnetic source, ΔX, ΔY, ΔZ are the components of *R* on *X*, *Y*, *Z* axis.

$$B_x = \frac{\mu_0}{4\pi} \cdot \left[\frac{3(m_X\Delta x + \mathrm{m}_Y\Delta Y + m_Z\Delta Z)\Delta X}{R^5} - \frac{m_x}{R^3}\right], \quad (1)$$

$$B_Y = \frac{\mu_0}{4\pi} \cdot \left[\frac{3(m_X\Delta x + m_Y\Delta Y + m_Z\Delta Z)\Delta Y}{R^5} - \frac{m_Y}{R^3}\right], \quad (2)$$

$$B_Z = \frac{\mu_0}{4\pi} \cdot \left[\frac{3(m_X\Delta x + m_Y\Delta Y + m_Z\Delta Z)\Delta Z}{R^5} - \frac{m_Z}{R^3}\right]. \quad (3)$$

Some of the simulation results display in Fig.8. The magnitude of the magnetic field distribution and gradient is the same as what LPF has reported, which means that the effectiveness of the algorithm is verified.

The magnetic field distribution of LISA-Pathfinder is also calculated by Comsol multiphysics simulation software as displayed in Fig. 9. Cylinder with uniform magnetic moment is used to replace the magnetic source. Random magnetic moment direction is used to simulate.

The simulation result shows that the position and direction of the magnetic field will directly affect the interference on TM. Accurate simulation could guide the component layout to reduce interference. In addition, the following points can be optimized to control the magnetic clean during the design: (1) Propose magnetic budget requirement for the components and subsystems of S/C, based on the simulation results. (2) Avoid using permanent magnet. (3) Restrict the use of soft magnetic materials. (4) Uniform design of current conductors and grounding to avoid the stray magnetic fields. (5) Carry out the omnidirectional and solid angle test of each component. (6) Apply nonmagnetic

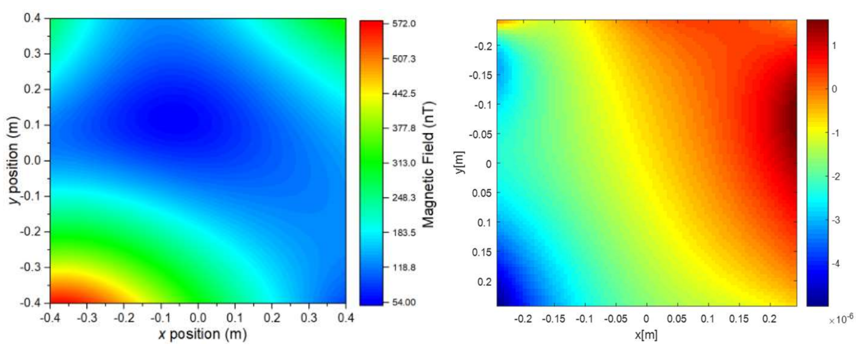

Fig. 8. The dipole approximation result of magnetic field distribution (left) and gradient (right) at TM.

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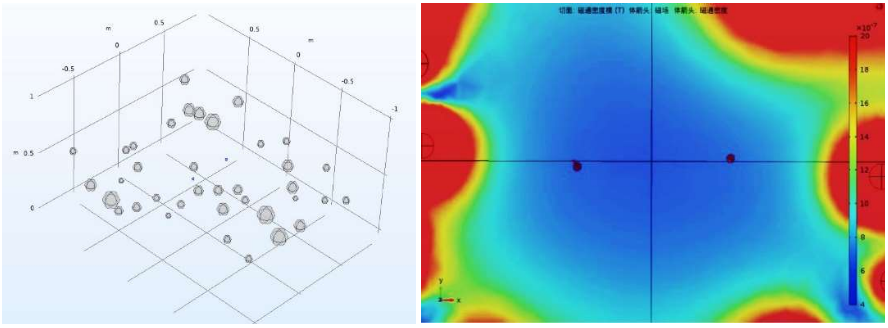

Fig. 9. Spatial distribution map of magnetic field source (left) simulation results of magnetic field distribution near TM (right).

design or magnetic shielding, for components with strong magnetic fields, such as solar panels, switching & distribution unit, laser, etc.

4. Conclusion

CAS proposed to launch Taiji project in the 2030s for the space gravitational wave detection. This paper focuses on the key technologies of ultra-clean & ultra-stable spacecraft, reports preliminary results of the three key points (mechanical design, thermal control and magnetic clean).

For mechanical design of ultra-stable spacecraft, the preliminary design of the configuration and layout of Taiji spacecraft is displayed. The self-gravity simulation analysis method has been proposed and applied in Taiji-1 and the low coefficient of thermal expansion material has been optimized and verification, with the CTE achieving less than 1×10^{-7} K^{-1}. The accuracy of self-gravity simulation achieving 10^{-10} ms^{-2} but still needs to be improved, and the low CTE material needs molding and further test. The temperature measurement resolution can reach 30 μK, but there is still a gap with the final target. The three-level thermal control strategy is designed and applied on the Taiji-1, achieving the temperature stability ±5 mK. For the magnetic clean control, the first step magnetic simulation has already output and verified with LPF report results.

Taiji is a long-time project and there are still many obstacles about key technologies to overcome. This paper aims to support future work with the above analysis.

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