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A brief analysis to Taiji: Science and technology

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ABSTRACT

The space gravitational wave (GW) antennae is more sensitive to the lower frequency GW signals compare with the ground-based GW detectors. The space mission Taiji is designed to detect the GW sources within frequencies between 0.1 mHz and 1 Hz. A preliminary study of Taiji was started in 2008. Up to now, a sophisticated mission design of Taiji have gradually taken shape. The research and development of the key technologies for Taiji is now officially launched. A brief introduction to the analysis and the pre-work of the Taiji technology are given here.

Brief introduction to space GW antenna

Since the ground-based GW detector LIGO announced its first detection in 2016 [1], the space GW detection missions, the space-borne counterpart of LIGO, have attracted more and more attention. Similar to electromagnetic wave, the GW is a broadband astronomical messenger. Depended on the effective arm-length, the sensitive frequencies of ground-based GW detectors are ranging from 10 Hz to 10 kHz, while the space-borne GW antennae are more sensitive between 0.1 mHz and 1 Hz. The GW signals in the frequency band between 0.1 mHz and 1 Hz are believed to have great astronomical and cosmological significances [2–4].

A Chinese space-borne GW detection mission was started in 2008. In 2016, after years of preliminary study, a complete mission design called "Taiji" gradually came into being and was officially supported by Chinese Academy of Sciences. The space mission Taiji consists of three satellites. Each satellite follows a heliocentric orbit. The three satellites together form a giant equilateral triangle with the side length being approximately three million kilometers. The mass center of the three-satellite-constellation falls on earth orbit and trails earth for 20° or −20°. Taiji plans to detect the low frequency (0.1 mHz–1 Hz) GW sources by using inter-satellite laser ranging interferometer and drag-free control technology [5].

The first proposed space-borne GW detection mission was LISA (Laser Interferometer Space Antenna) [6], a joint ESA-NASA mission. The LISA constellation also consisted of three satellites. The orbital design of LISA was proved to be most suitable for low frequency GW detection and shared by Taiji and other space-borne GW detection missions. The original arm-length of LISA was five million kilometers [7]. In 2011, NASA announced to quit LISA mission due to financial problem and ESA had to turn to a mission descope called eLISA (or NGO) [8]. To reduce the costs, the arm-length of eLISA was decreased to 1 million kilometers. Encouraged by the great success of technology demonstration mission of LISA (which called LISA pathfinder) [9], NASA decided to rejoin LISA mission on 2017, and the LISA arm-length is changed to 2.5 million kilometers [6]. LISA, as the pioneer of the space GW detection missions, has led a clear direction for many other space-borne GW detection missions such as ASTROD [10], DECIGO [11], ALIA [12], BBO [13] Tianqin [14] and Taiji [5,15,16]. LISA also set up a great foundation for space-borne GW detection includes data analysis, GW astronomy, technology anatomy, general relativity test and etc.

Taiji mission design and road map

Taiji constellation consists of three satellites, in Fig. 1 left (not in proportion). The distance between every two satellites is approximate 3 million kilometers. Every satellite exchange laser with the other two to form three Michelson type interferometers. Each satellite carries a pair of laser ranging interferometers and two drag-free control systems. The drag-free control system offers an ultra-stable satellite platform and a sub-femto-g inertial reference for laser ranging interferometer. The laser interferometer needs to reach pico-meter precision to detection the weak GW signals.

Based on the preliminary study and principle demonstration experiments, Taiji decides to take three steps to launch the final three satellites to detect GW (Fig. 2). The first step is to develop and demonstrate the key technologies on ground. Then to launch two satellites

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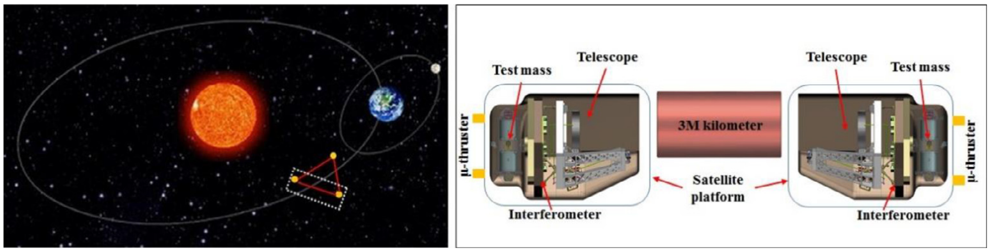

Fig. 1. The schematic diagram of Taiji's orbit and payload.

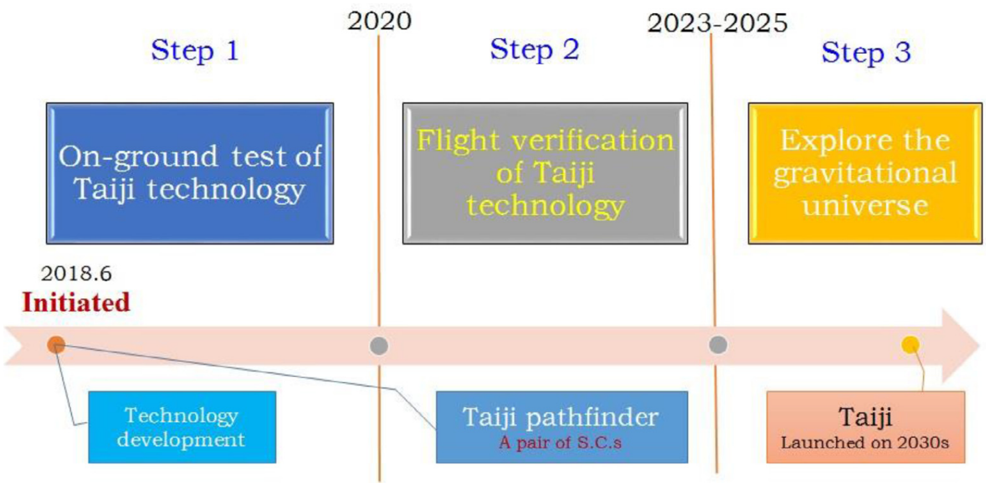

Fig. 2. The roadmap of Taiji.

to verify the Taiji technology in space. Taiji will be launched on 2030s at last.

Chinese Academy of Sciences has decided to support Taiji mission by initiating two projects "Taiji technology development" and "Taiji pathfinder" on 2018. The goal of "Taiji technology development" is to study and develop the key technologies to meet the requirement of Taiji. "Taiji pathfinder" is going to launch two satellite to verify long baseline interferometry in space.

The Taiji pathfinder will take the same orbit as Taiji only with a shorter arm-length (half million kilometers, to be further determined). The satellite and payload design are also as same as Taiji, however one satellite only contains one laser ranging interferometer and one drag free control system, with the other slot installed by dummy mass.

Taiji once launched will maintain scientific running for about 5 years. The goals and targets of different stages of Taiji are listed in Table 1.

The scientific objectives of Taiji

The most interesting GW source of Taiji is super (intermediate) mass black hole merger. According to the hierarchical growth model of cold and dark matter, the galaxies from its formation to now are usually harbored by central massive black holes and surrounded by dark matter halos. The GW events of super (intermediate) mass black hole mergers can help us to trace how the seed black hole merges each other and slowly grow up into super massive black holes. While the seed black holes grow in the evolution towards further inhomogeneity, they accrete and merge in accompany with the merge of host galaxies and dark matter halos [17]. Thus it may help to explain how the big structure of the observed universe forms.

The other problem is the so called M-σ relation. Observations indicate that the supermassive black holes exist in the centers of almost every galaxy, and the velocity dispersion of stars in the galactic bulge is closely correlated with the mass of the supermassive black hole in the galactic center, i.e, the M–σ relation [18]. The observation of super (intermediate) mass black hole merger together with the hierarchical model of cold and dark matter, the co-evolution history between the galaxy and its central black hole could be revealed which lead to a better understanding to M–σ relation.

The origin of the seed black holes of the hierarchical model is another interesting topic. Light seed model indicates that the seed black holes may come from the remnants of the 1st generation stars. Because there is no metal abundance, the 1st generation stars are very massive and the stellar wind loss caused by radiation may be neglected. That when the 1st generation star of 140 to 260 solar mass meet its end it will collapse into black hole with a mass greater than one half of the original stellar mass [19]. Other theory shows that the original gas clouds may directly collapse to form the seed black holes with a mass larger than 10^4 solar mass through an effective angular momentum transfer, and the collapse of stellar cluster nuclei may also form the seed black holes of 10^3 to 10^4 solar mass [20,21].

The extreme(intermediate) mass ratio inspiral is another important GW source of Taiji. It is a two-body inspiral systems of star-mass black holes or neutron stars, white dwarfs revolving continuously on the innermost stable circular orbits (ISCOs) around the super(intermediate) massive black holes in the galactic centers. Because the gravitational region involved by such a GW source is close to the horizon of the central black hole, and the accumulated time of signals is long enough, the detection of gravitational waves from this system provides a perfect method for studying and inverting the galactic central environment and dynamic evolution in a small area where is hard to resolve by electromagnetic waves. From the data of gravitational waves, we can derive the orbits of small compact celestial bodies in the extreme strong gravitational field of the central black hole, map and study the gravitational field of the central black hole in a very precise manner [16].

The GW signals from compact binary stars in the Milk Way form a foreground noise to Taiji and only a few of them could be resolvable. However, the strength, spectral shape and annual variation of the

Table 1
The aims and purposes of Taiji's different stages.

Stage	Goal	Target		Relevancy
		Displacement noise: $pm/Hz^{1/2}$	Acceleration noise: $m/s^2/Hz^{1/2}$	
Taiji technology development	Develop the technology to meet Taiji's requirement	8	$3*10^{-15}$	● Also covers the requirement of Taiji pathfinder ● Also includes Taiji's system study and end-to-end simulation
Taiji pathfinder	Space verification of Taiji technology	200	$3*10^{-13}$	● Flight test for individual technology is considered ● Engineering phase will be started on 2019 ● Covers all the Taiji's technologies except time delay interferometer
Taiji	Study the gravitational universe	8	$3*10^{-15}$	● Systematic study of noise models ● Detect GW ● Life time ~5 years

unresolvable binary stars in the Milk Way can be used to constrain the distribution of the compact binary stars, the stellar evolution history and formation mechanism [22]. Other GW sources such as stochastic GW background and un-modelled sources are all Taiji's objective sources, which can help to tackle the challenging problems: gravitational physics and cosmology, such as electroweak phase transition and property of dark energy, and the nature of gravity [5,16,23,42].

To ensure a reasonable event rate for Taiji mission and to make it realizable for technology development, a detailed analysis of the baseline design was performed [16,24]. One of the baseline was selected which was listed in Table 2. The corresponding sensitivity curve is plot in Fig. 3.

The recent progress of Taiji technology development

During ten years' preliminary study and principle demonstration experimental, great progress for Taiji key technology development is made and will be presented below.

Laser ranging interferometer

The laser ranging interferometer system consists of three parts: the laser source, the telescope and the interferometer.

The laser for Taiji and Taiji pathfinder is 1064 nm and the prototype have already been built in Chinese Academy of Sciences. By changing the pumping laser from 808 nm to 885 nm, the energy efficiency of the laser head is improved to 50.7% (Fig. 4 left) [25]. The same series of the laser head (with different wavelength) have already been used in Chinese satellite missions such as Change and Fengyun. The frequency stability of the laser for Taiji and Taiji pathfinder is 30 $Hz/Hz^{1/2}$ that a stable FP cavity as laser frequency reference is needed to lock the laser frequency with Pound-Drever-Hall method. A prototype of the FP cavity has been built (Fig. 4 right) and successfully passed the vibration and radiation test. The frequency stability of the laser locked on it has been achieved 30 $Hz/Hz^{1/2}$ [26], which based on a simulation study should meets both first-generation and second-generation numerical TDI's of Taiji [40].

The telescope is the laser transmitting-receiving device. A preliminary design of Taiji telescope has been finished. A simulation analysis of the far-field wave-front, the optical path-length stability, scattering light and on-orbit performance has already been carried out [27]. An aluminum model of this telescope has been made to verify the low stress structure design. An all-SiC prototype is now under construction (Fig. 5). Meanwhile, another model with ultra-low-expansion mirror and invar-steel structure is also under preparation as a backup.

The interferometer is the place where the interferometric beat notes generated. The prototype of Taiji interferometer has been built, and the main functionalities have also been tested [28–31]. The displacement measurement precision achieves 15 $pm/Hz^{1/2}$, differential wave front sensing achieves 8 $nrad/Hz^{1/2}$, 1064 nm laser phase locking achieves 20 $pm/Hz^{1/2}$ and phasemeter readout precision reaches 2π $\mu rad/Hz^{1/2}$. Refer to the solid design of LISA interferometer [6,32], A preliminary design for Taiji interferometer, which will be test in Taiji pathfinder, is given in Fig. 6. A prototype by using optical bonding technics is built and tested (Fig. 6 right). Besides the scientific interferometers, the Taiji interferometer also has other auxiliary functionalities, such as acquisition, pointing, weak light phase locking, clock noise transferring, clock synchronization, inter-satellite ranging, communication, arm locking and et al.

Inertial sensor

The inertial sensor is to measure the relative displacement between the spacecraft and the test mass, and then feed to drag-free controller. Based on the successful experience of LISA pathfinder [9,33–35], the previous noise analysis and the mathematic modeling, the following

Table 2
Baseline design parameters for Taiji.

Armlength (m)	Laser Power (W)	Telescope diameter (m)	1-Way position noise ($pm/Hz^{1/2}$)	Acceleration noise ($ms^{-2}/Hz^{1/2}$)
3×10^9	2	0.4	8 (1 mHz–1 Hz)	3×10^{-15} (1 mHz–1 Hz)

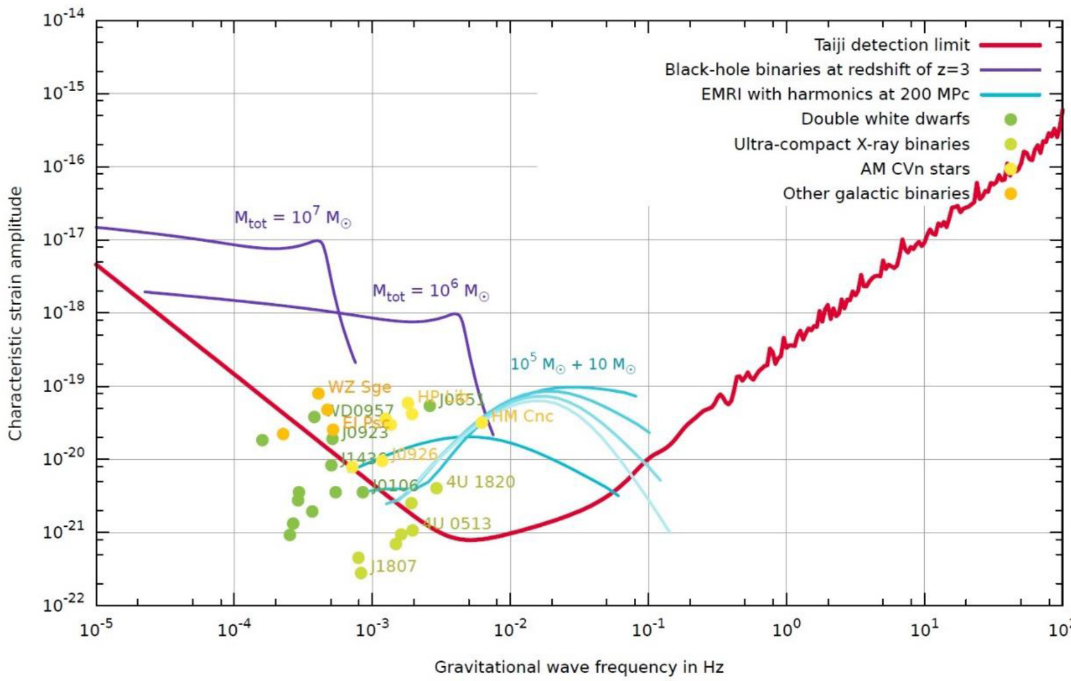

Fig. 3. The sensitivity curve of Taiji.

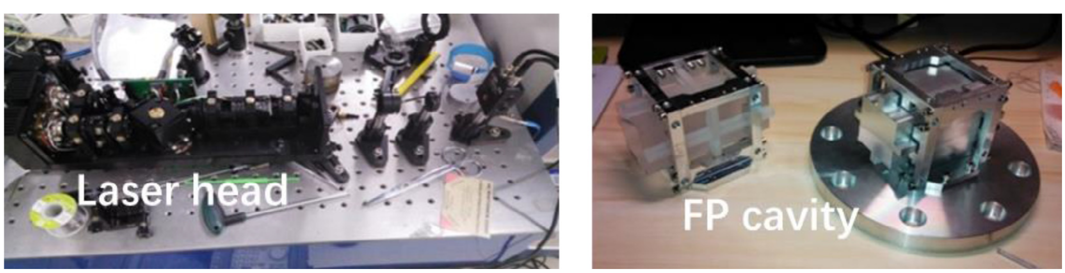

Fig. 4. The toy model of the super stable laser.

studies have been carried out, includes aluminum model manufacture, capacitive sensing and electrostatic force control, launch locking and releasing mechanism, vacuum system, charge management and torsion balance test platform.

Till now, the aluminum model has been completed, the perpendicularity of the assembly precision was measured to be 10 μrad and the roughness of the test mass surfaces was reached to be 8 nm (Fig. 7). The PCB board for capacitive sensing is designed and under construction. The design of launch locking and releasing mechanism is finished, a numerical simulation indicates that 5 μm/s releasing linear velocity and 100 μrad/s releasing angular velocity can be met. A torsion balance to test the inertial sensor on ground is also designed.

Drag-free and μ-thruster

An elementary study of Taiji drag-free control scheme has been carried out during last few years, which includes a mathematical simulation of single satellite drag free control (6 degree of freedoms) and a systematic analysis of satellite-satellite tracking drag-free control (one degree of freedom). The basic understanding of noise analysis, control algorisms, control loop design and mathematical modeling of Taiji drag-free control is collected. And this control scheme is planning to be tested in space within two years.

The prototypes of three type of μ-thruster were made, see Fig. 8, which were radio-iron-thruster (R.I.T.), cold gas thruster and Hall effect thruster. Particularly, the force resolution of the R.I.T. prototype is 0.5 μN and its noise level is 0.4 $\mu N/Hz^{1/2}$. The neutralizer for the R.I.T. prototype has also been built recently [36,37]. The μ-Hall thruster is also under construction, and a flight test for this thruster is planned in next year. The 1 mN cold gas thruster has passed the pre-launch testing, the μN cold gas thruster is also now under development.

Ultra-stable platform

The previous study of the ultra-stable platform focuses on three problems (Fig. 9). The first is self-gravity. A self-gravity model of Taiji satellite is constructed to study the coupling stiffness between the proof mass and the spacecraft. The bias acceleration acts on the proof mass by

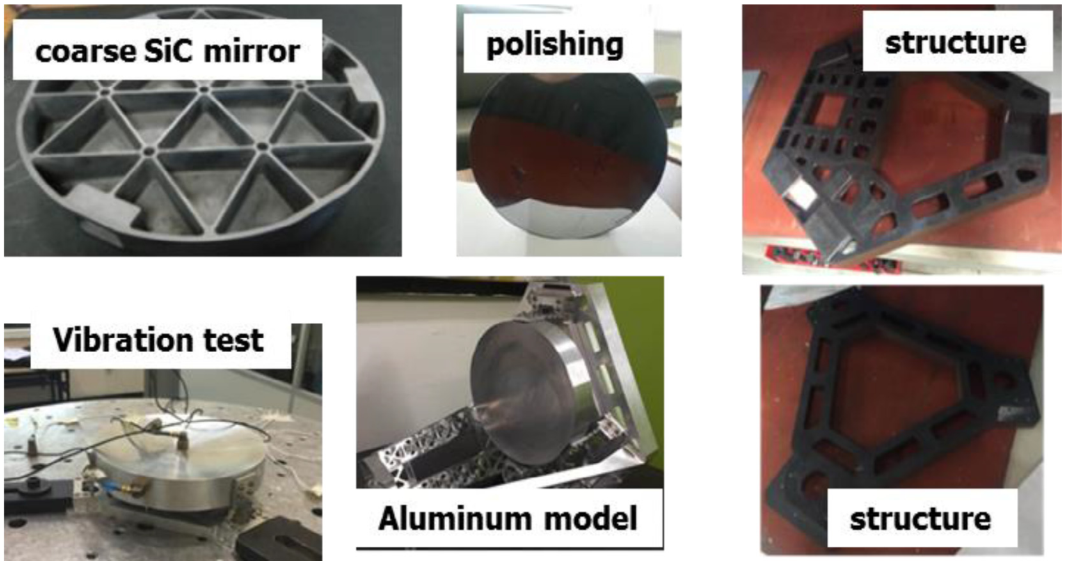

Fig. 5. The development of telescope (up left is the coarse SiC primary mirror, up middle is the polished SiC primary mirror, up right and down right is the SiC telescope structure, down middle is the aluminum telescope model, down left is the vibration test of the aluminum model).

spacecraft mass distribution can also be studied with this model. The micro-Kalvin thermal control scheme for inertial sensor and interferometer is studied with a thermal diagnostic model. While a simulation of magnetic cleanliness for Taiji spacecraft is also carried out to make sure the residue magnetic field and its fluctuation does not exceed the requirement.

Highly coupled complex system

Taiji is also a highly coupled complex science mission. All the interfaces between systems (and their subsystems), include mission design, scientific requirement, laser ranging interferometer, inertial sensor, drag-free control, μ-thruster system, ultra-stable platform, orbital design and space environment are traced, over hundreds coupling relations have been found.

To solve the problems given by the highly coupled complexness of Taiji, many tasks are started in advance. The template bank begins to be built, especially the waveform of extreme (and intermediate) mass ratio in-spirals. A new G.W. source called b-EMRI is discovered and studied by Taiji collaboration [38]. The b-EMRI is such system that the small part in EMRI in fact is a binary black holes. Though b-EMRI is low in event rate, the coalescence generates not only Taiji band GW but also high-frequency ($\sim 10^2$ Hz) GW detectable by ground-based observatories, making these binary-EMRIs ideal targets for future multi-band GW observations. A program of matched filtering including particle swarm optimization and Monte Carlo Markov Chain algorism is established. The processing procedure for 1A data is also studied [39]. An end-to-end simulation for Taiji mission has been started based on the coupling relation mentioned above. Some key ideas of satellite design for Taiji will be tested on upcoming Chinese satellite missions such as SVOM, SMILE, EP and ASO-S.

Problems to be studied

The problems need to be studied in the stage of “Taiji technology development” is listed in Table 3.

To tackle the above problems some preliminary thoughts are discussed below. An overall consideration of the seed laser, the laser power amplifier, the FP cavity and the control modular will help us to improve the laser intensity stability and locking loop stability. The telescope on-orbit stability could be improved by adopting a thermal compensating structure design. An optimization of telescope optical design and sub-nanometer polishing may reduce the scattering light. A complete noise model analysis and high integration will help to build

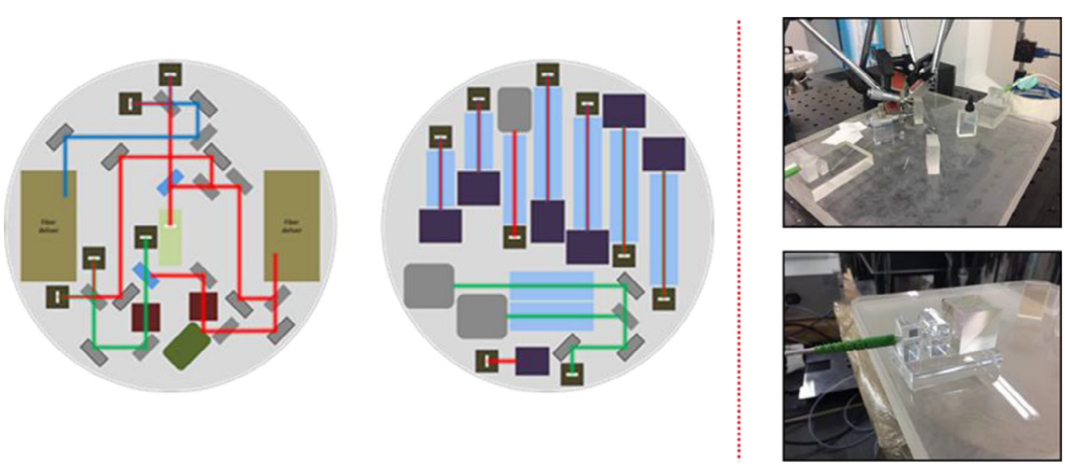

Fig. 6. The optical design and an optical bonding prototype of Taiji’s interferometer (left is the front of the interferometer, middle is the back of the interferometer, right is optical bonding test).

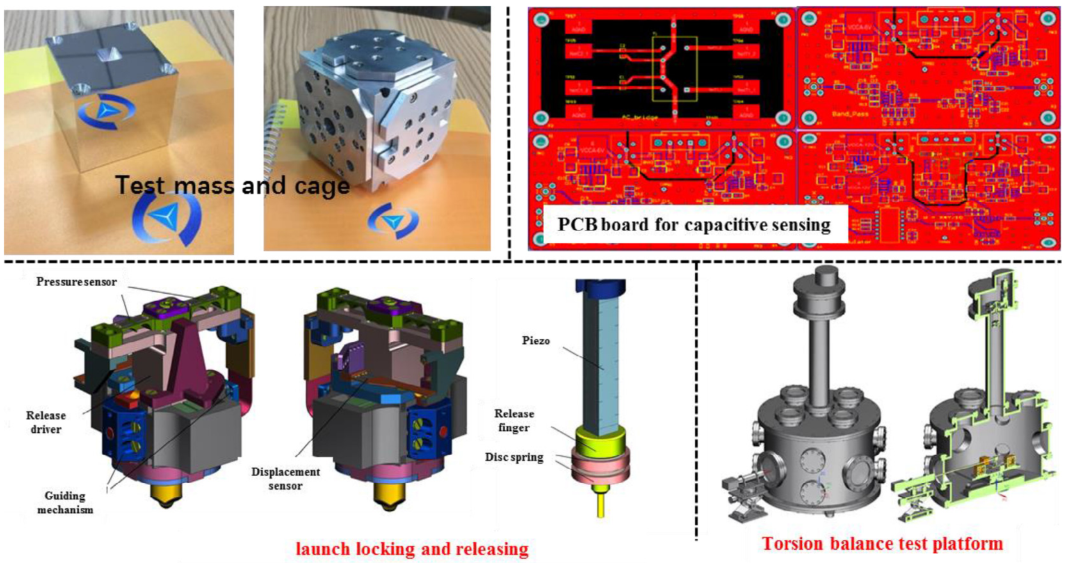

Fig. 7. The development of the inertial sensor (up left is the aluminum model of the sensor head, up right is the PCB board design, down left is the design of the locking and releasing mechanism, down right is the design of torsion balance).

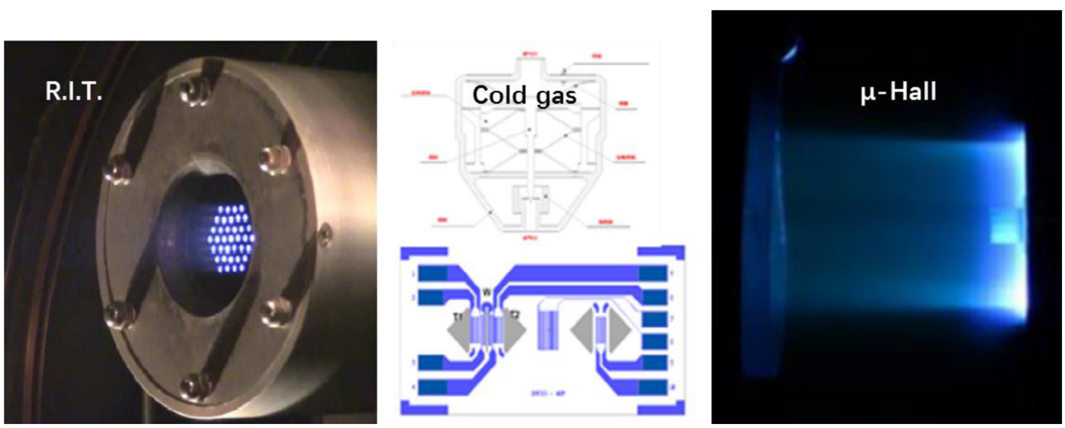

Fig. 8. The three micro-thruster candidates.

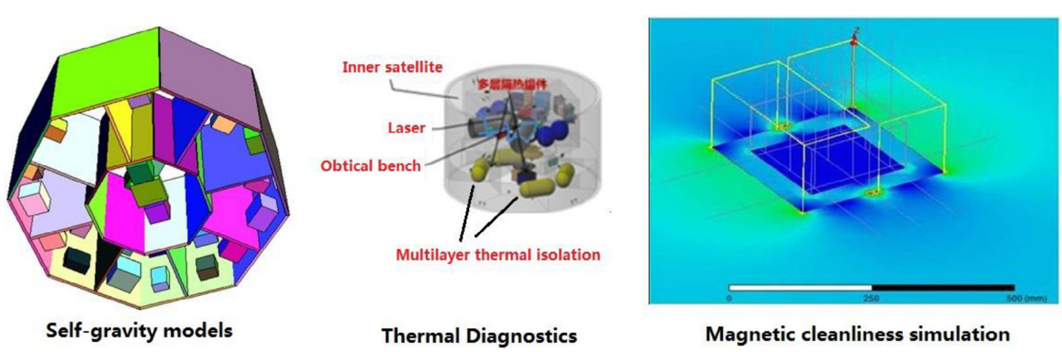

Fig. 9. Ultra-stable satellite platform.

Taiji interferometer. A low noise voltage reference and a detailed mathematical modeling of the circus will improve the voltage noise, applied electrostatic force noise and resolution of capacitive sensing. The robustness of the drag-free controller can only be achieved by a concrete study of on-orbit disturbance, inertial sensor noise model and μ-thruster noise. While the resolution and noise level of μ-thruster can be improved by the improvement of micro flow measurement, stable pressure control, proportional control valve and micro-nozzle manufacturing. A high precise on-ground calibration system is needed to test and verify the effects due to self-gravity, thermal fluctuation and residue magnetic field. The computational efficiency of matched filtering will be improved by employing an optimized parameter searching algorism. A multi granularity modeling method will be used for Taiji end-to-end simulation. A holistic mathematical model for platform and payload will be constructed soon to solve the problems of platform design. An on-ground experimental setup to simulate the complete Taiji optical system will be constructed which will help to find possible solution to 2nd generation TDI variable.

Table 3
The recent progress and research problems of Taiji's technology.

Taiji Technology	Recent progress	Research problems
Laser ranging interferometer	Prototype built; laser frequency stability: 30 Hz/Hz$^{1/2}$; telescope simulation done; Interferometer precision: 15 pm/Hz$^{1/2}$; DWS readout: 8 nrad/Hz$^{1/2}$.	Laser: Stability and reliability of frequency locking loop; Telescope: on-orbit stability and scattering problem; Interferometer: multi-functionality and precision improvement.
Inertial sensor	Design of capacitive sensing and electrostatic force control, design of launch locking and releasing mechanism, design of torsion balance test platform; Aluminum prototype: constructed.	Capacitive sensing: aF; Voltage control: μV/Hz$^{1/2}$; Electrostatic force control; Torsion balance construction.
Drag-free and μ-thruster	Drag-free: mathematical simulation Gold gas: 1mN resolution prototype; R.I.T. prototype: 0.5 μN resolution, 0.4 μN/Hz$^{1/2}$ noise.	Drag-free: robust design; Thruster: improvement of stability, resolution and noise level.
Ultra-stable platform	Satellite models: self-gravity, thermal diagnostic, magnetic cleanliness.	High resolution thermal-meter; Experimental verification of self-gravity model; Precise measurement of structure distortion.
Source and template	Matched filtering: PSO, MCMC; Template: EMRI.	Template bank building; Improve computational efficiency.
Constellation optimization	Highly coupled system modeling; Complex system simulation.	End-to-end mission simulation; Global optimization.
platform design optimization and simulation	Experience from "Mozi" and "Wukong"; Opportunities for practice: SVOM, SMILE, EP, ASO-S.	Holistic analysis of platform and payload; Overall design and optimization.
TDI and data analysis	1A data processing	2nd TDI algorism; Data analysis assembly.

Conclusion and perspectives

With the detailed study of Taiji mission design and the anatomy of Taiji key technologies, the Taiji collaboration will deepen the Taiji science, optimize the Taiji system design and further develop the laser ranging interferometer, inertial sensor, drag-free and μ-thruster, and ultra-stable platform. A systematic flight test of Taiji technology is going to be made via Taiji pathfinder.

The individual technology will be flying tested earlier by other satellite missions. The Taiji-1 was such a satellite which was launched in August 2019 to test the laser interferometer, accelerometer, μ-thruster and drag-free control. The first stage test in orbit was completed [41], and set a solid foundation for Chinese future gravitational wave observation in space.

CRediT authorship contribution statement

Ziren Luo: Data curation, Formal analysis, Investigation, Methodology, Validation, Resources, Software, Visualization, Writing - original draft, Writing - review & editing. **ZongKuan Guo:** Data curation, Formal analysis, Investigation, Methodology, Validation. **Gang Jin:** Funding acquisition, Project administration. **Yueliang Wu:** Conceptualization, Supervision, Funding acquisition, Project administration, Data curation, Formal analysis, Investigation, Methodology, Validation. **Wenrui Hu:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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