ICFP2026

Advances in the Taiji Program for Gravitational-Wave Detection

Ziren Luo *on behalf of*

Taiji Collaboration

2026-10-25

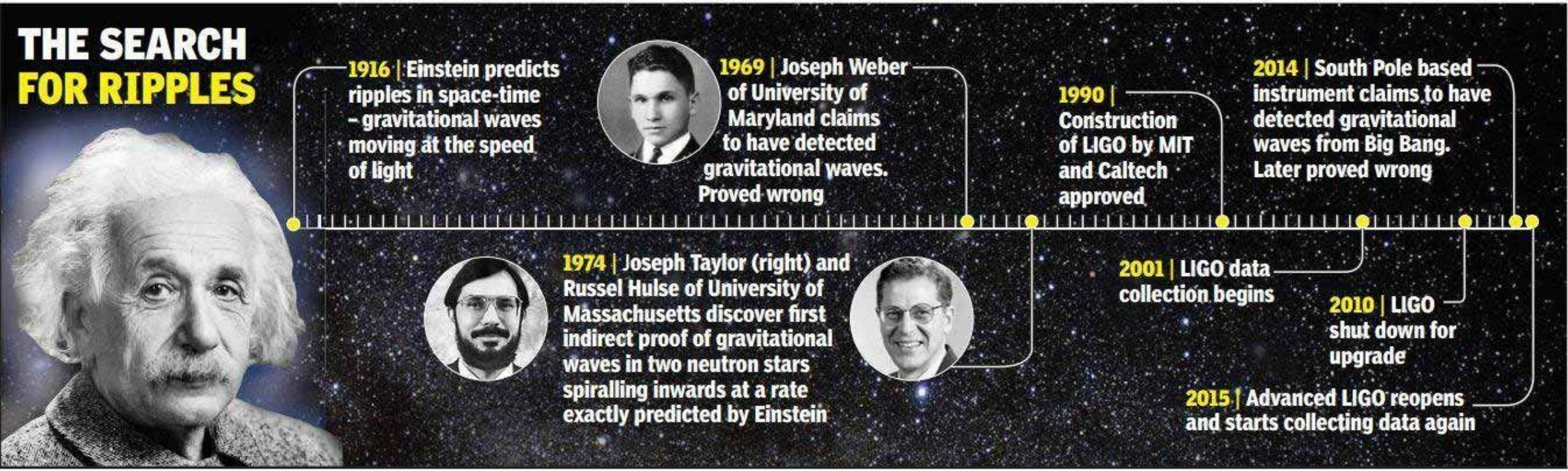
Huairou，Beijing



Outline

- The background
- The Taiji-1
- The Taiji-2 R&D
- The progress

Hundred years of GW detection

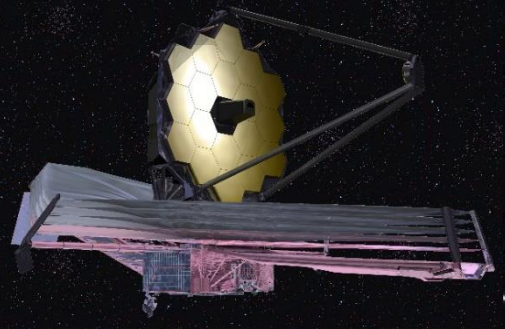


In 2016, LIGO directly detected the Gravitational wave. The existence of GW was confirmed, and proved that:

Einstein was right AGAIN

GWs opened a new window

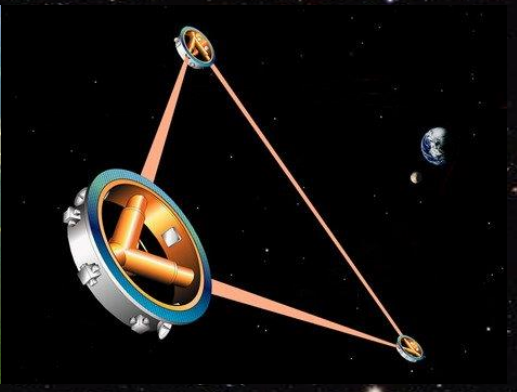
EM wave telescope





GW antenna





New messenger to study the dark side of the Universe

Why space?

From ground to space

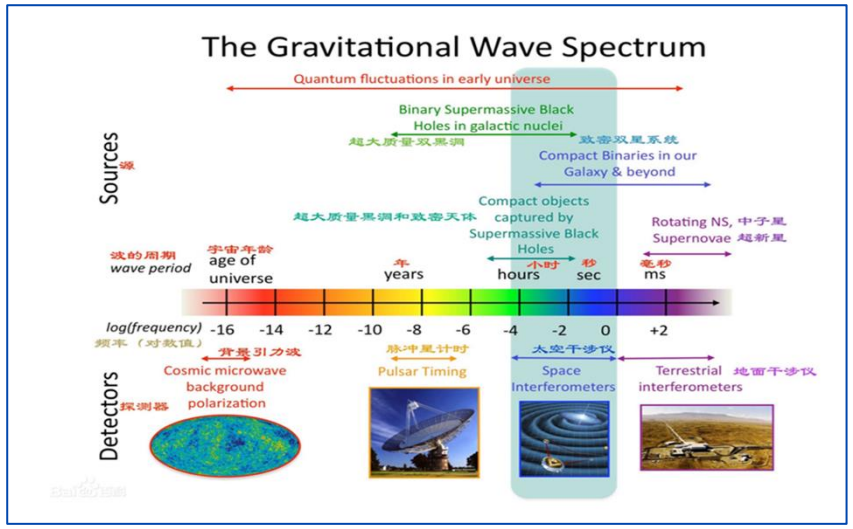


Different frequencies

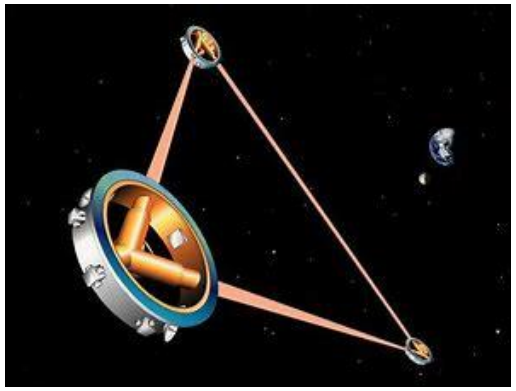
↳ **Different sources**

↳ **Different sciences**

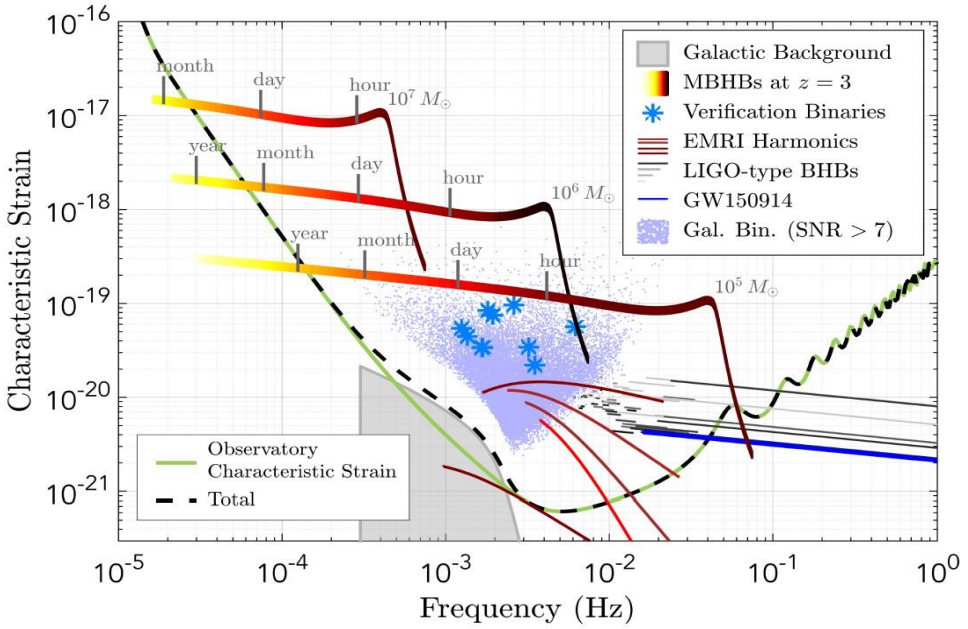
complementary



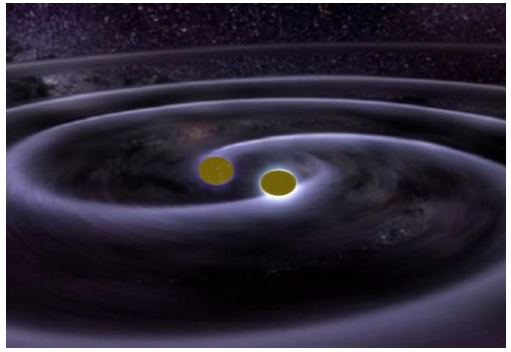
Introduction of space-borne detectors



- 3 satellites
- Laser link
- From 10^5 to 10^6 to 10^8 km
- Geo- or Helio- centric orbit
- From deci-hertz to milli-hertz to micro-hertz
- From 10^2 to 10^8 ⊙



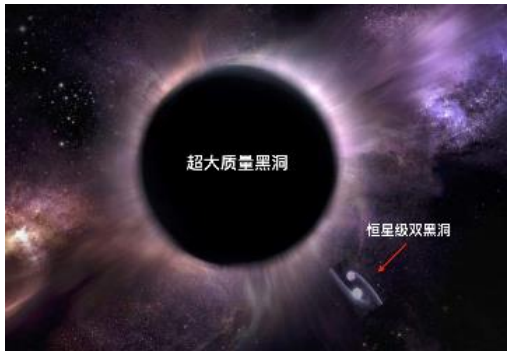
Major scientific objectives

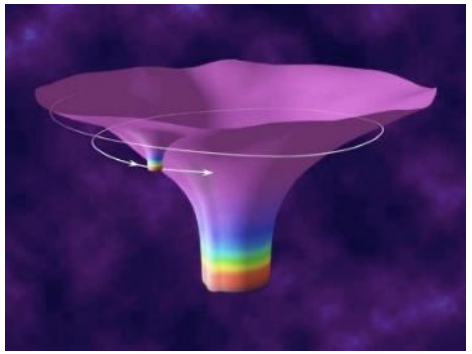




Cover intermediate- and super- massive black hole merger

- **Relic of Pop III stars**
- **Structure formation**
- **Standard siren ……**

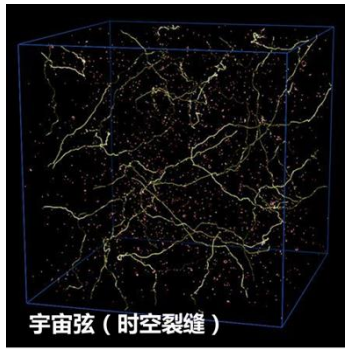


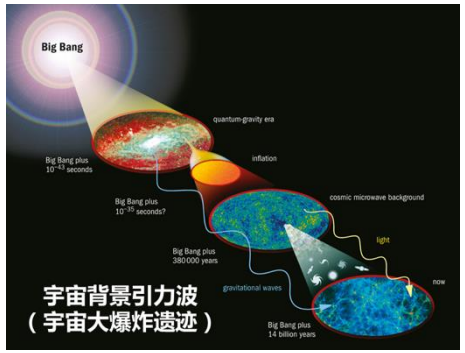


Cover intermediate- and extreme- mass ratio in-spiral

- **Horizon probe**
- **No hair theorem**
- **Galactic Nuclei ……**







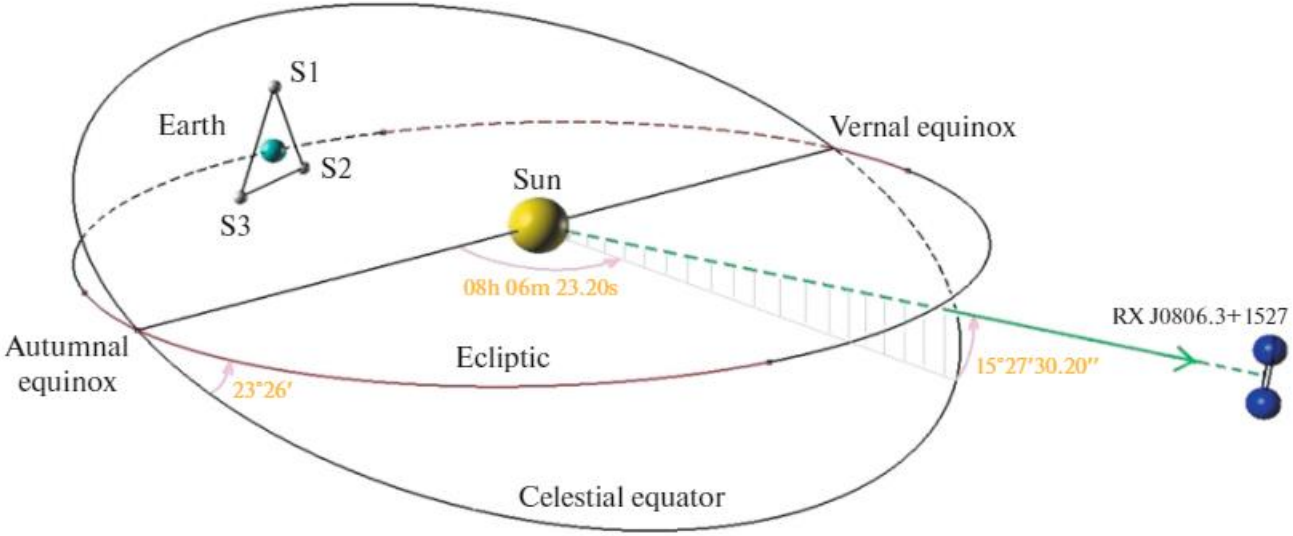
Galactic binary, cosmic string, stochastic background from big bang

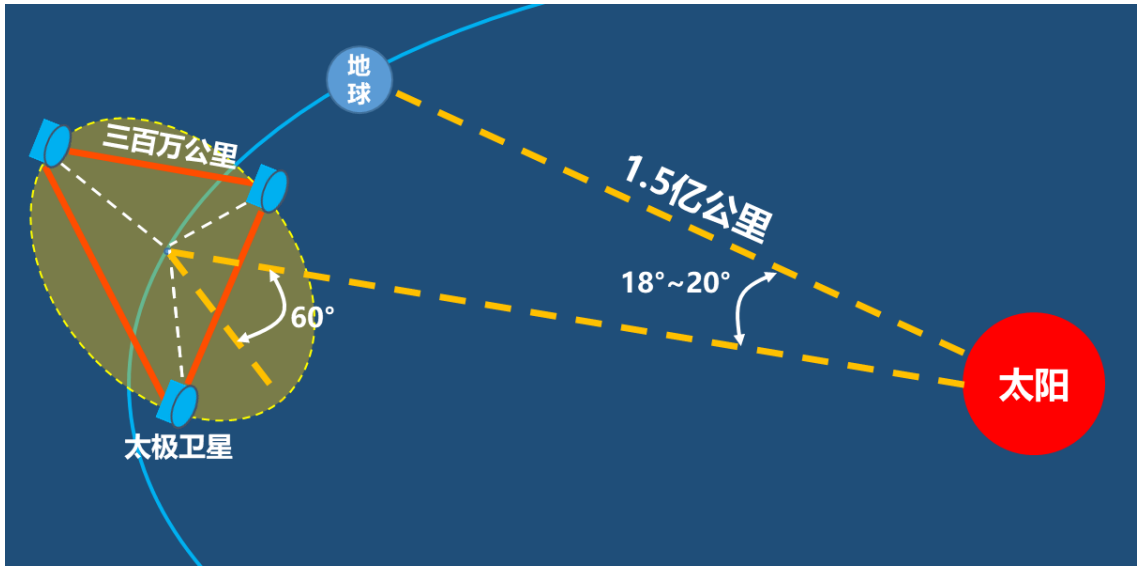
- **State fuction of white dwarf, topology of cosmos, Physics of very early universe ……**

Space GW detection in China

TianQin

- Geocentric orbit, 0.17 million km arm-length
- Leading by SYSU and HUST



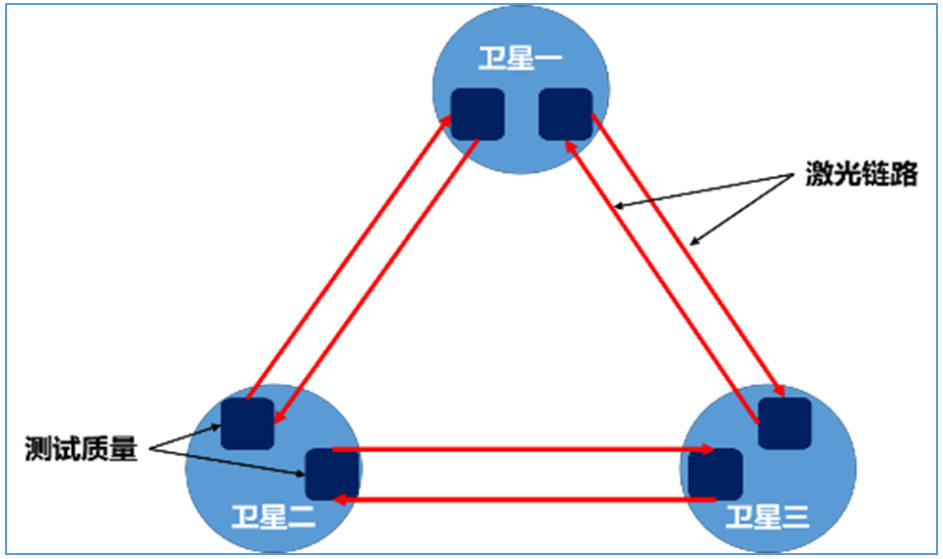


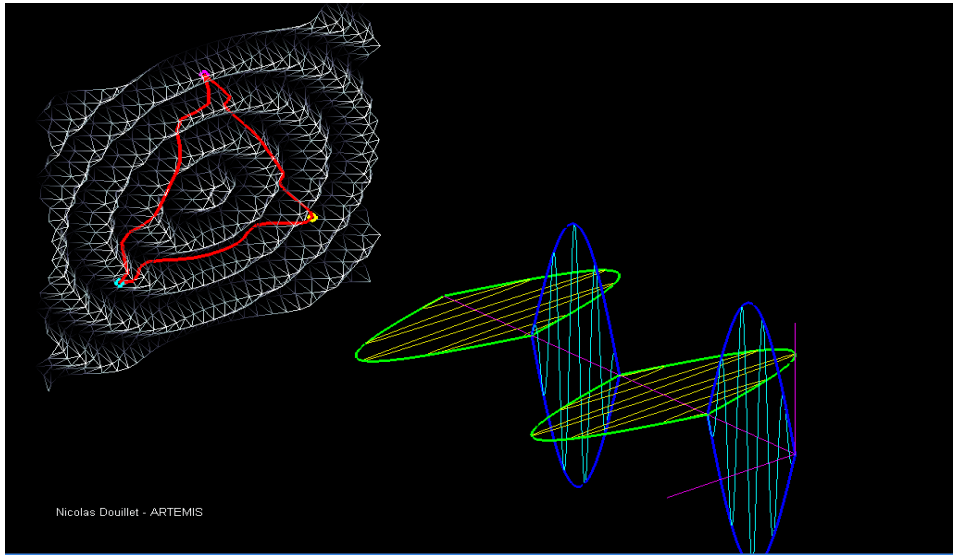
Taiji

- Heliocentric, 3 million km, 1AU from the Sun
- Leading by CAS

Principle

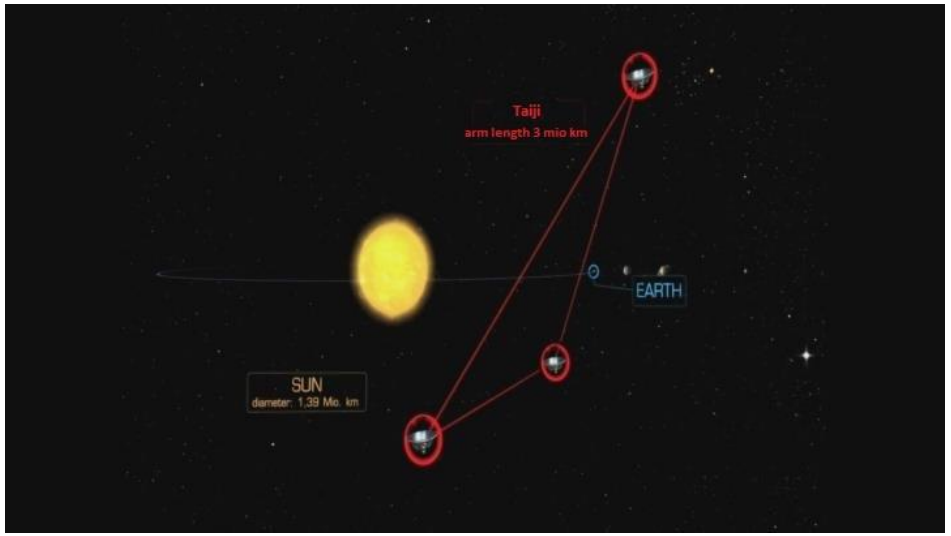
- The GW train passing by were sensed by the test masses, induced light pathlength changing between TMs, these changes were measured by lase interferometer

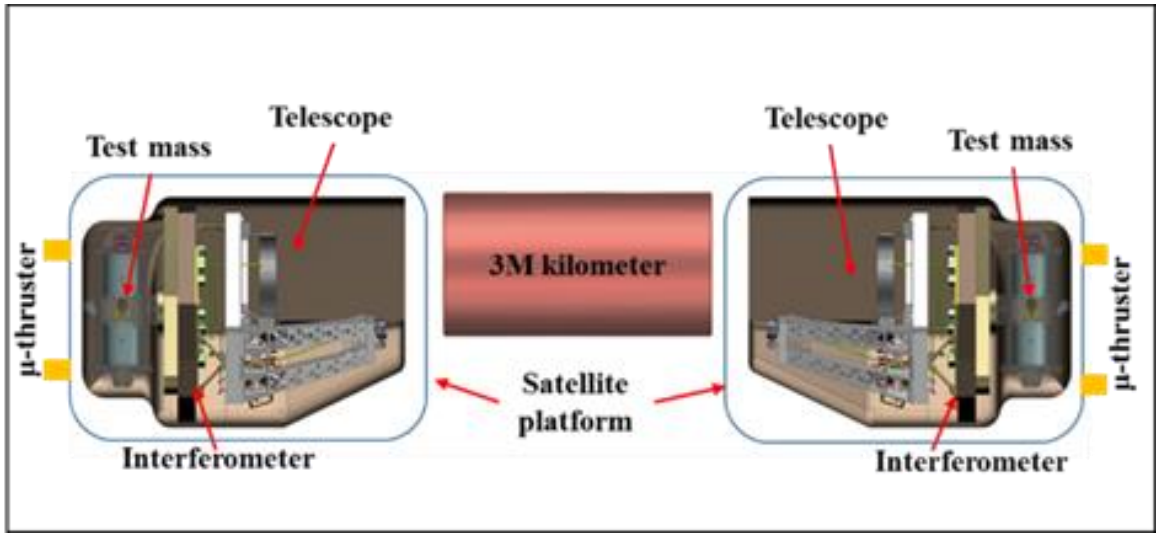




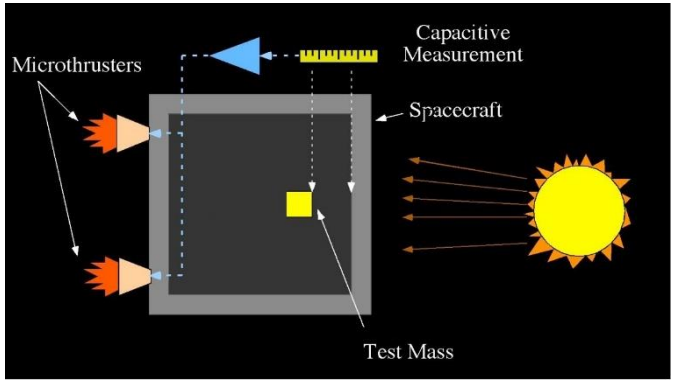
- Difficulties: weak signal、long baseline、various disturbance

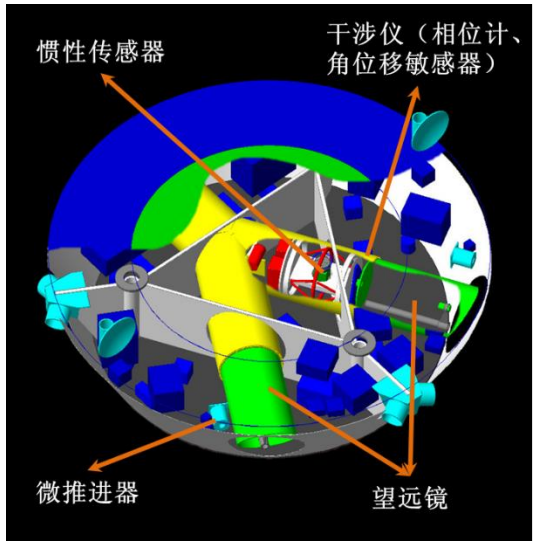
Challenges





- Inter-satellite inteferometry （10^{-20}~$^{-21}$）
  - ➢ Picometer displacement in 10^{5-6} Km
  - ➢ Pointing accuracy and stability 1nrad
- Drag-free control (57 DOFs)
  - ➢ TMs disturbing acceleration $10^{-15}ms^{-2}$
  - ➢ Micro newton thruster 0.1μN





Taiji-1

From Taiji-1 heritage to full-mission preparation

1

2008–2016

Early studies and mission formulation

concept · proposal · public introduction

2

2018–2019

Taiji-1 in-orbit heritage

technology demo · launch · in-orbit validation



3

2020–2023

Key technology maturation

drag-free · laser interferometry · phasemeter · grav. reference sensor

4

2024–2026

Full-mission engineering preparation

integration · verification · data challenges



Ground-based drag-free spacecraft simulator for semi-physical verification

Roadmap **evolution**

The historical Taiji-1/2/3 roadmap has evolved toward full-mission engineering, integration, verification, and science-data readiness.

Possible timetable

Taiji-2 2030

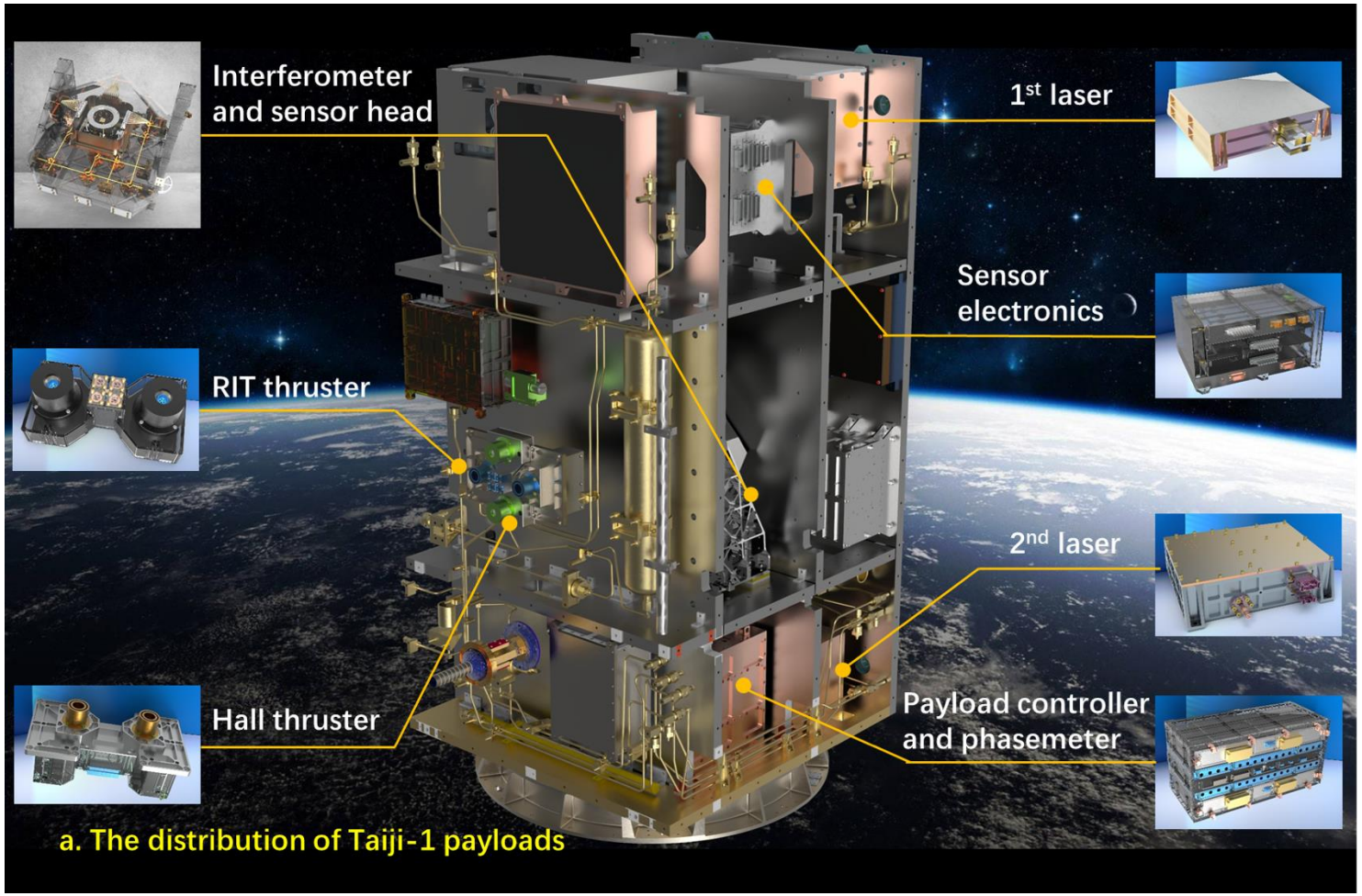
Taiji-3 2035

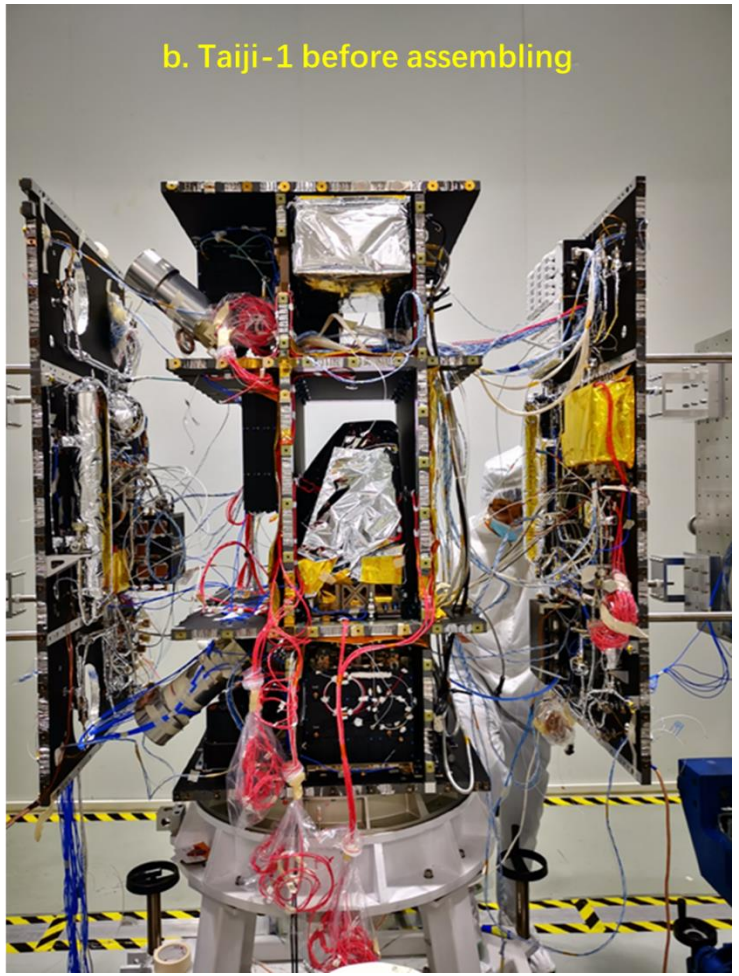
Taiji-1



- 2018-8-30, mission adopted, started mission formulation review
- 2018-12-17, started flying model manufacturing
- 2019-4-30, payload delivered to satellite company, started implementation and test
- 2019-8-1, started satellite-rocket docking and test
- 2019-8-15, shipped to launching site
- 2019-8-31, launched

Taiji-1

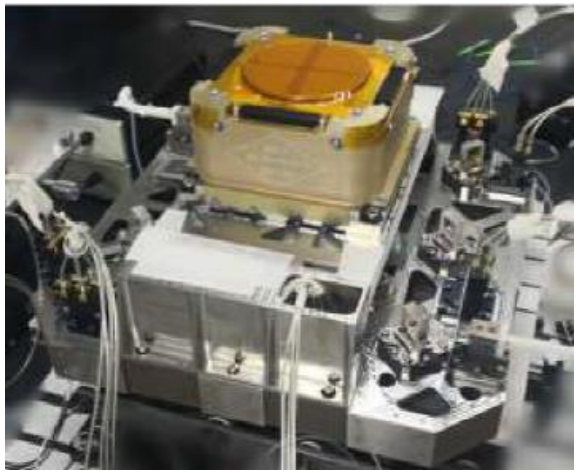


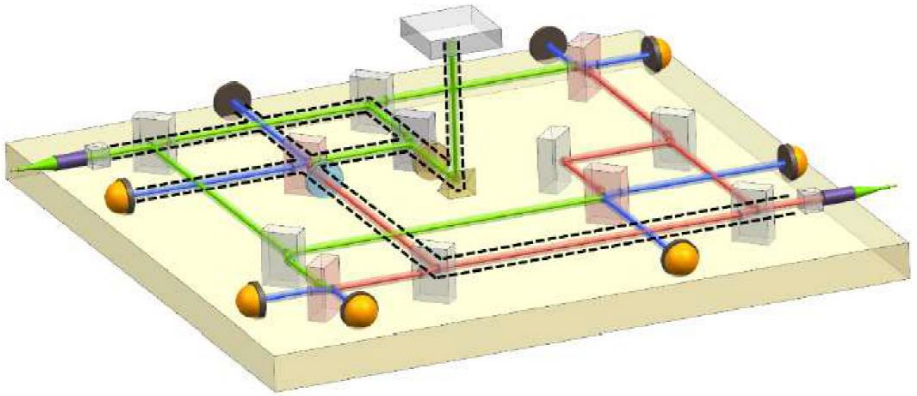


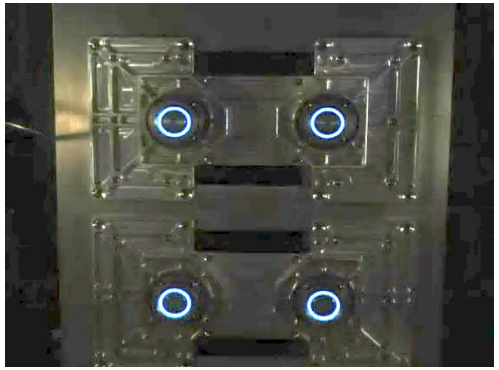
Yue-Liang Wu and etc., Communications Physics, 4, 34 (2021). https://doi.org/10.1038/s42005-021-00529-z

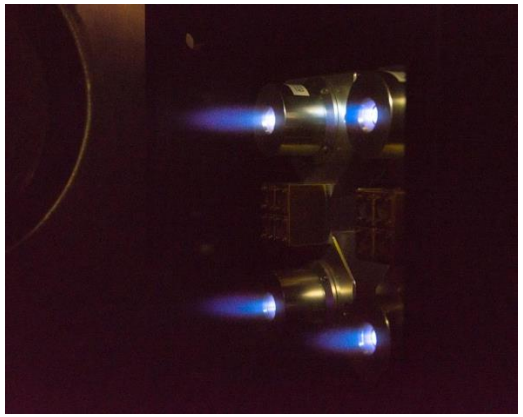
Taiji-1

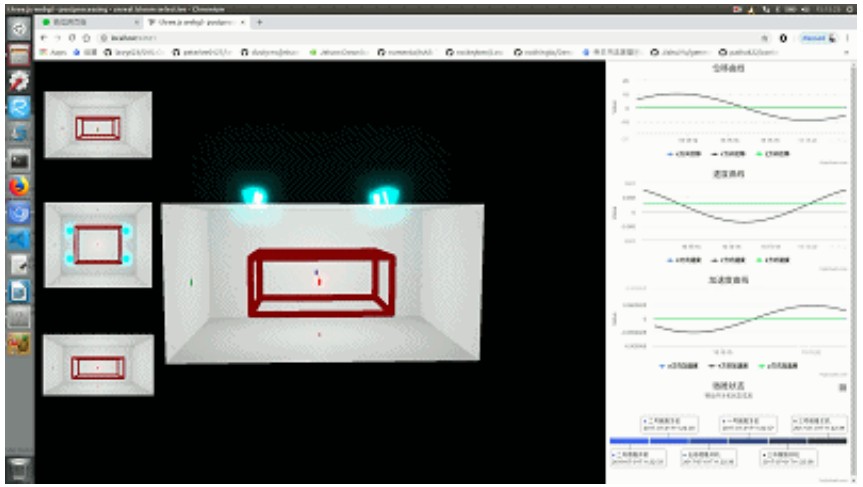
- **Optical readout gravitational reference sensor, drag-free control, etc**
- **Manufacturing Process & Machining Technique of the Key Payload**

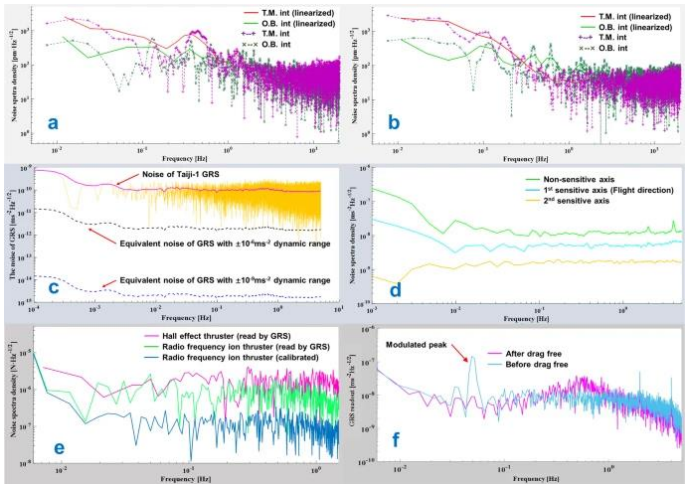








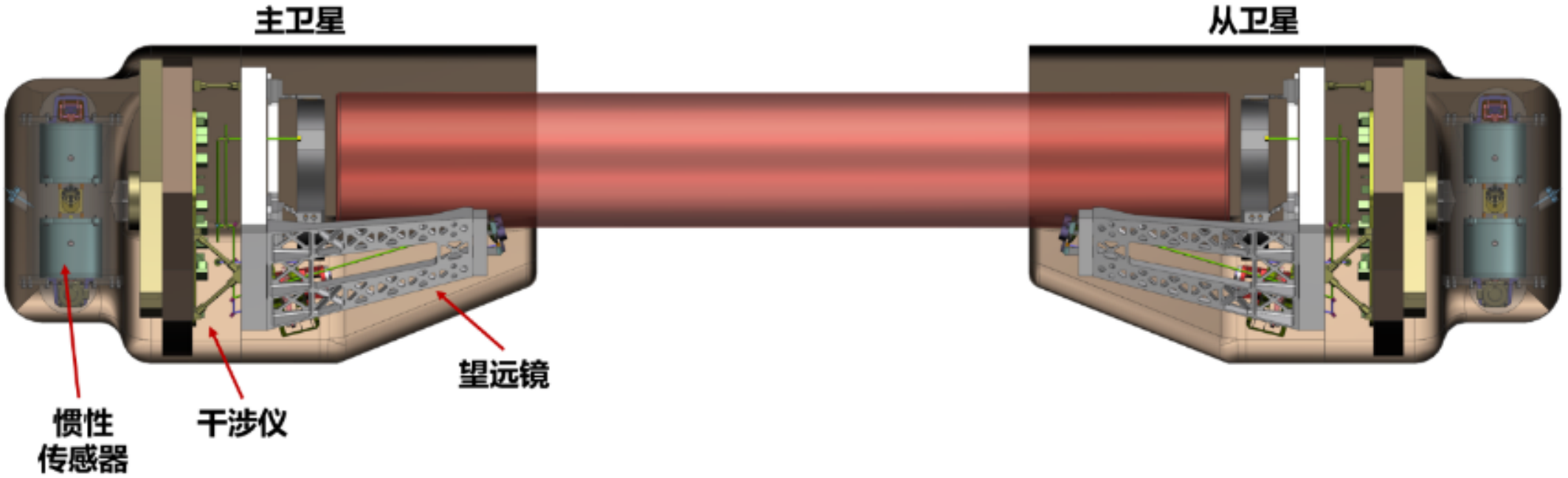




Taiji-2 R&D

Taiji-2

The technology development is still a few step away from Taiji-3
However, it meets the requirement of Taiji-2



Two satellites, heliocentric orbit, trailing earth 5-10 degree, 1 million km arm

From key technologies to full-mission engineering readiness

One mission-design track and three system-verification tracks

Mission and engineering design

01

Launch · orbit · transfer · TT&C · spacecraft–payload interfaces · science operations · data-processing design

MISSION DESIGN

Core measurement-system integration

02

MOSA-level integration of GRS, optical metrology, laser-link acquisition, and pointing subsystems

PAYLOAD INTEGRATION

Drag-free closed-loop dynamics verification

03

Spacecraft–test-mass dynamics · drag-free control · pointing/control coupling · semi-physical closed-loop tests

CLOSED-LOOP VERIFICATION

Scientific interferometer full-chain verification

04

Three-arm interferometry · inertial reference · ranging / optical-path simulation · TDI-related noise suppression · long-duration stability

FULL-CHAIN VERIFICATION

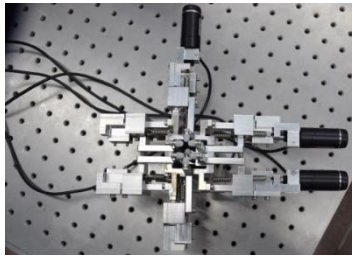
SUPPORTING KEY TECHNOLOGY

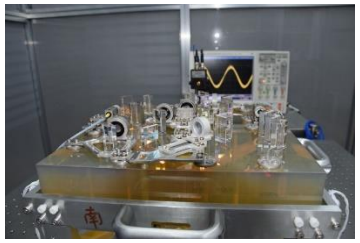
GRS / electrostatic suspension	TRL 5
Drag-free control	TRL 6
Laser-link acquisition & tracking	TRL 5
Laser interferometry	TRL 5
Unltra-stable plaform	TRL 5
Cold-gas micro-propulsion	TRL 6-7
End-to-end dynamic simulation	under validation
Noise suppression & signal inversion	under validation

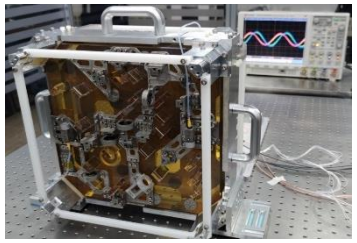
Take-away: System-level verification is the bridge from key-technology maturity to full-mission readiness.

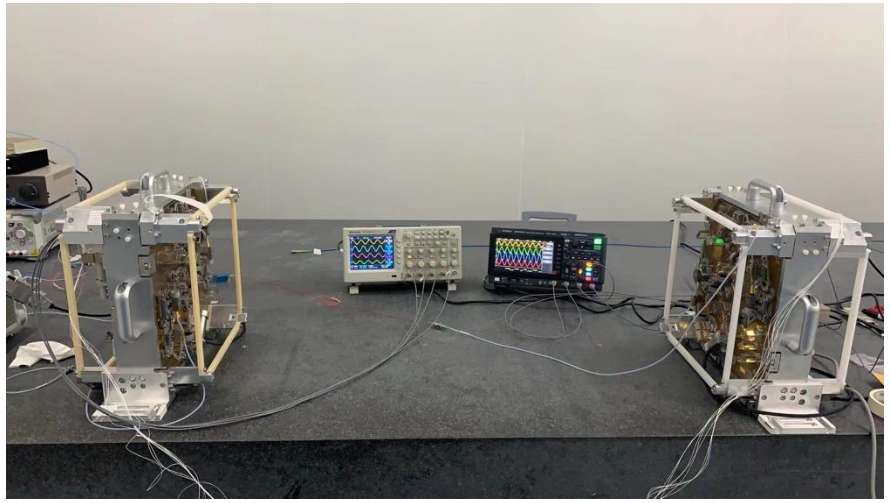
Taiji R&D progress —— Interferometer



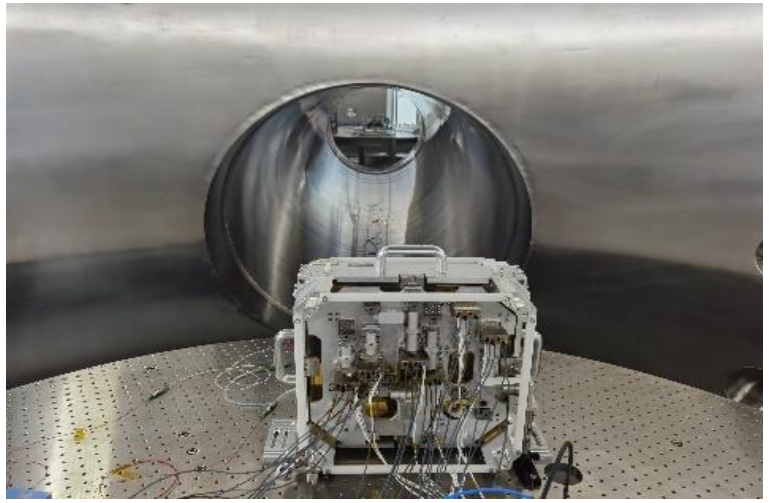








- Optical bonding
- Precise positioning
- Two 1:1 models
- Establishing laser link and test
- Phase-meter



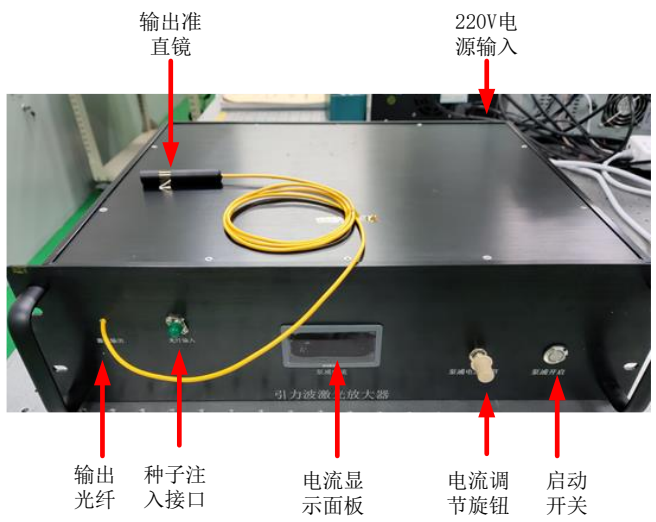


Deviation: 42 μrad, 9 μm

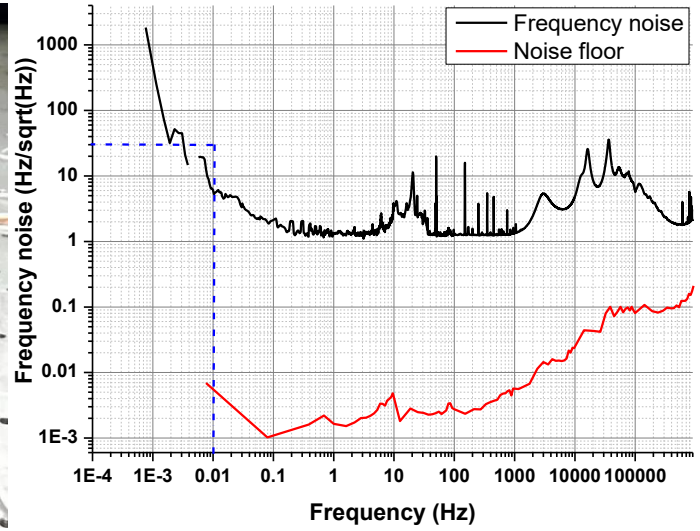
Noise PSD: 6pm/Hz$^{1/2}$

Phase meter: 1μrad/Hz$^{1/2}$

Taiji R&D progress —— Interferometer



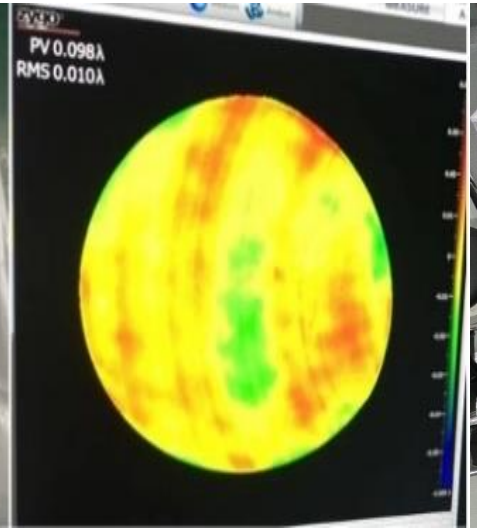




- **Laser head, amplifier, FP locking**

$6Hz/Hz^{1/2}$, 4W, $10^{-4}/Hz^{1/2}$



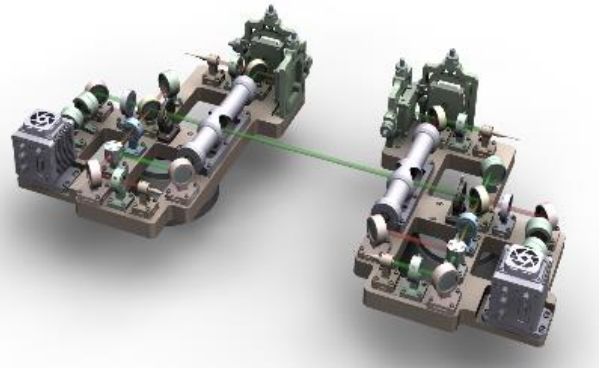


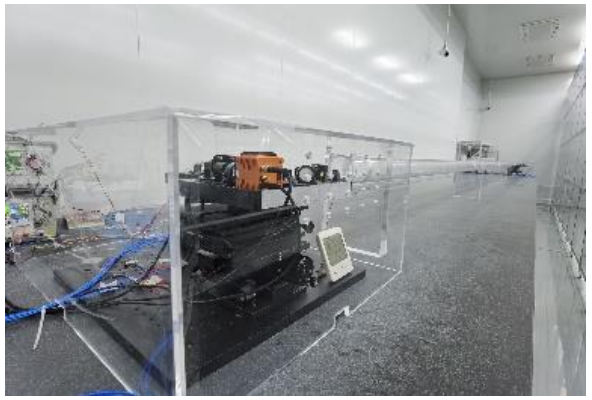


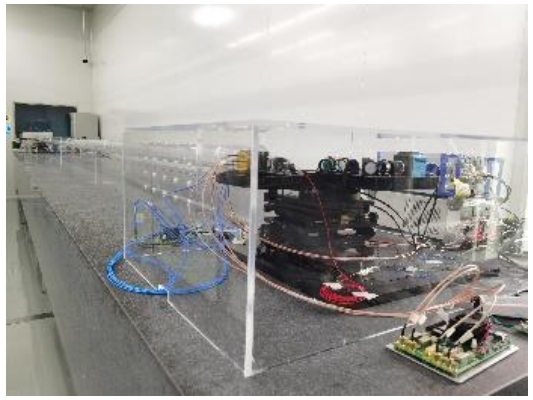
- **Mirror**
- **Structure**
- **Invar steel, silicon carbide ……**

$\lambda/100$, $10pm/Hz^{1/2}$

Taiji R&D progress —— ATP

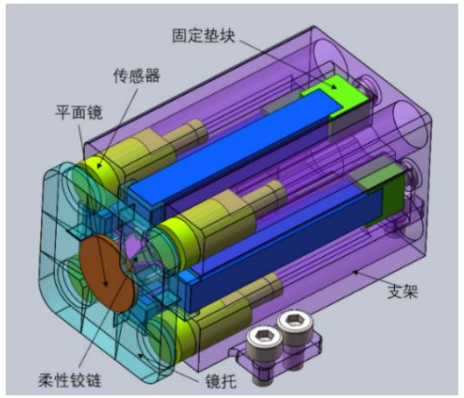


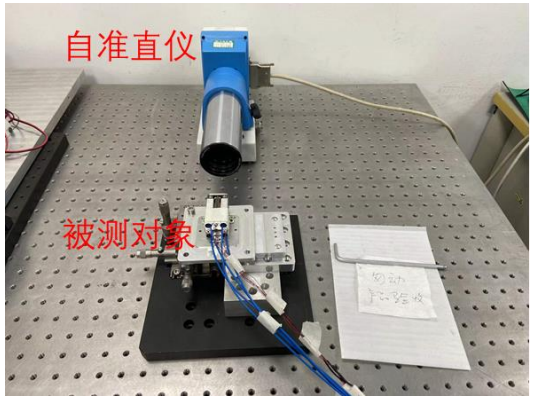


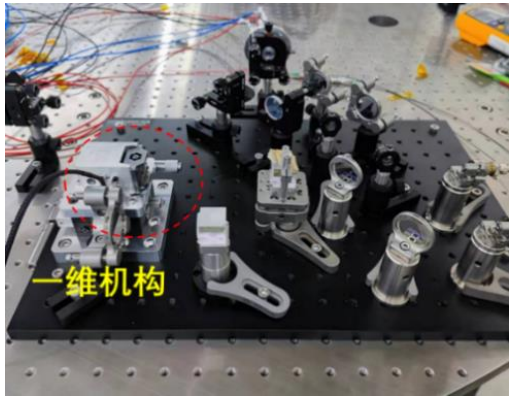


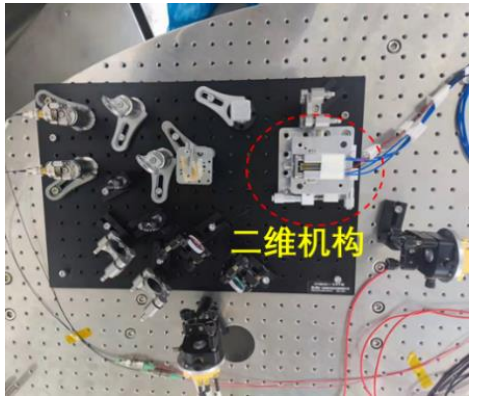
- Acquisition with camera
- Pointing with DWS
- Archimedes spiral

Acquisition 0.1μrad
Pointing 20.25nrad/Hz$^{1/2}$







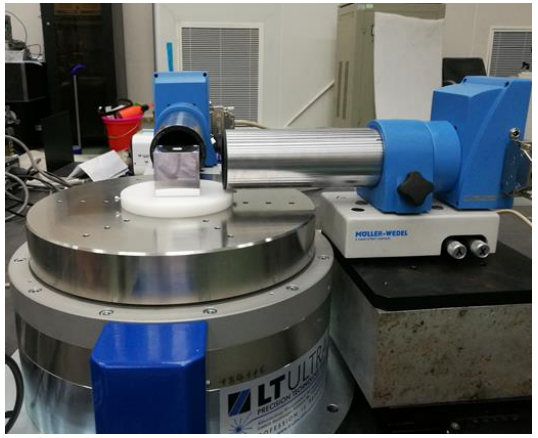


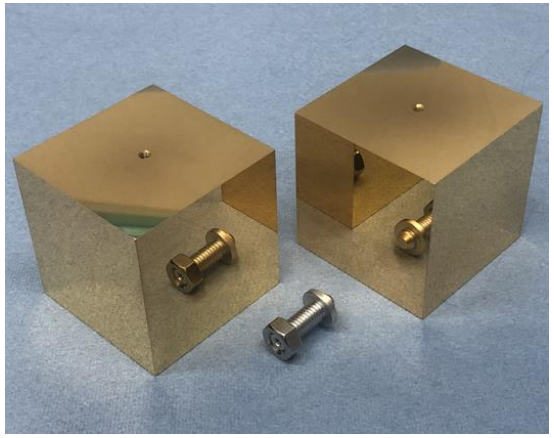
- Pointing ahead angle mechanism (1 dimensional & 2 dimensional)

Field (out of telescope 100×) 6.23μrad (1d), 5.4μrad (2d); θ deviation (out of telescope 100×) 4.4 nrad(1d), 6.8nrad(2d); longitudinal noise 8.3pm/Hz$^{1/2}$ (1d), 8.5pm/Hz$^{1/2}$ (2d)

Taiji R&D progress —— Inertial sensor

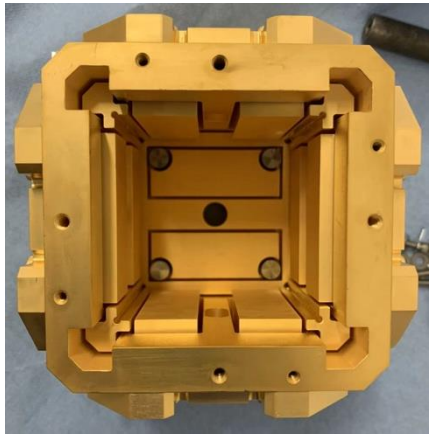


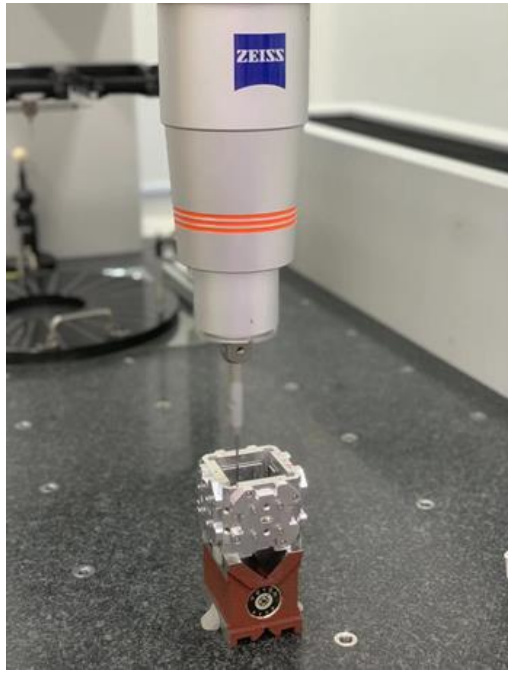




- TM machining, coating
- Cage manufacture, assemble, measuring
- Sensor head integrating
- 1:1 model







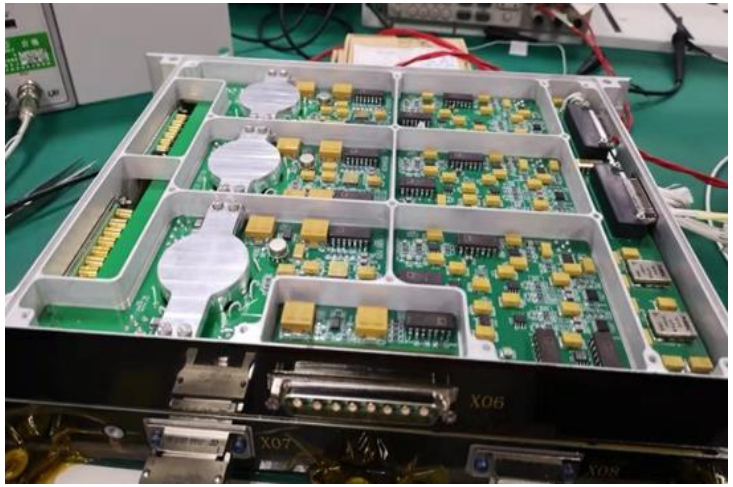
Parallelism and perpendicularity 9×10^{-5}rad

Electrode symmetry 15μm

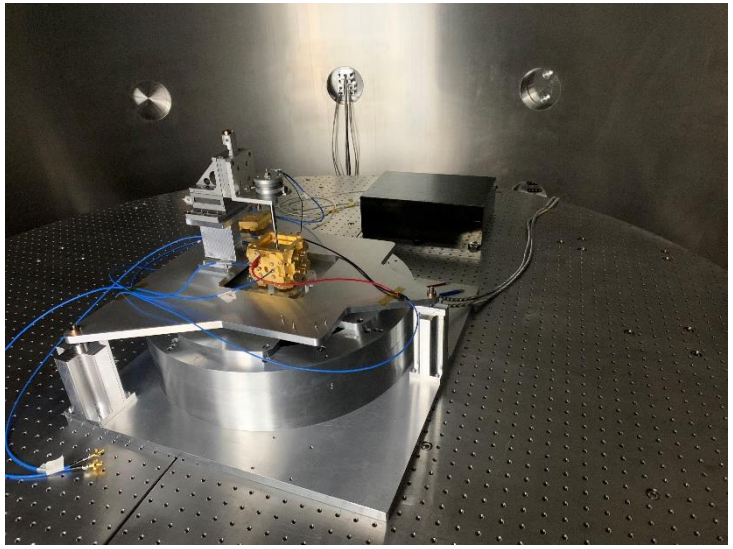
Magnetic susceptibility 4×10^{-6}

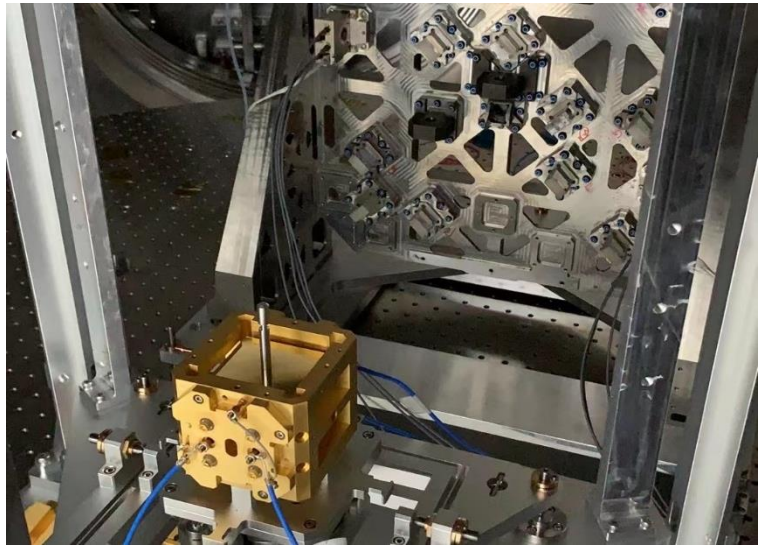
Gold platinum alloy

Taiji R&D progress —— Inertial sensor









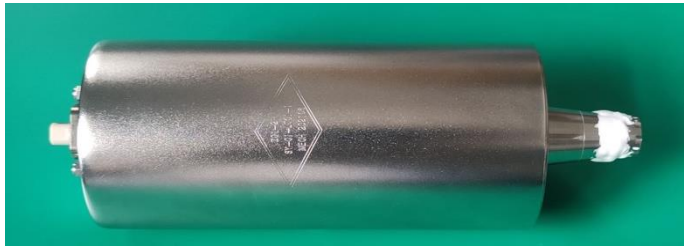
- Capacitive sensing
- Electrostatic driving
- 1:1 model
- Test with sensor head
- Test with interferometer

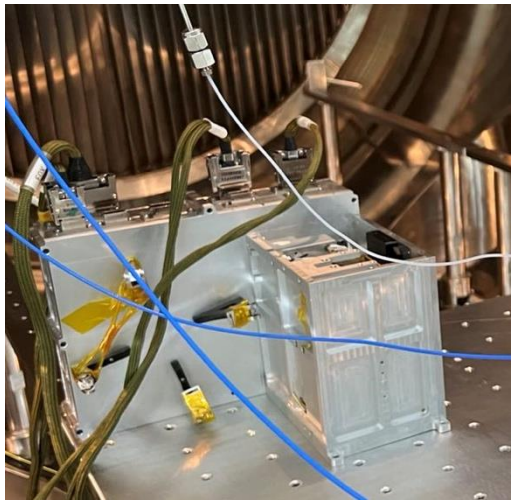
Displacement 1.7nm/Hz$^{1/2}$

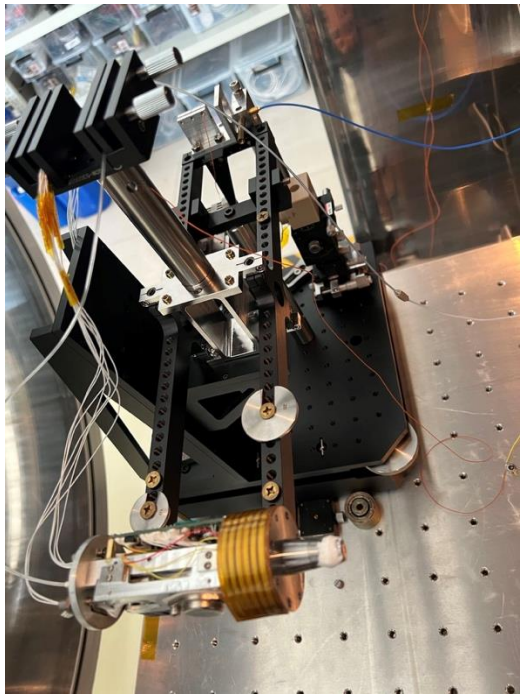
Driven voltage fluctuation 5ppm/Hz$^{1/2}$

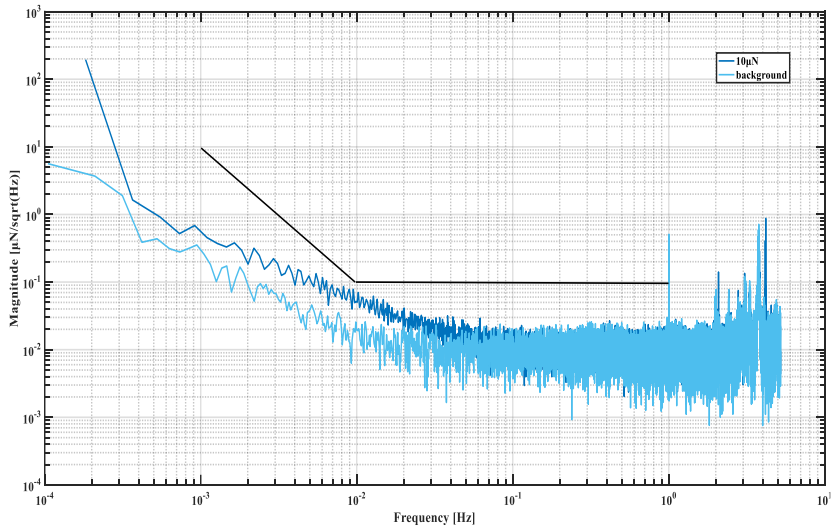
Taiji R&D progress —— Drag-free and thruster











Ion thrusters already flight with Taiji-1

Cold Gas Thruster

- Thruster head
- Electronics and controller
- propulsive force calibration torsion pendulum (Electrostatic comb)

Specific impulse ＞ 53s

Resolution 0.1μN

Noise 0.1μN/Hz$^{1/2}$

Response time 110ms(rising up) 120ms (falling down)

Fly tested on 2025!

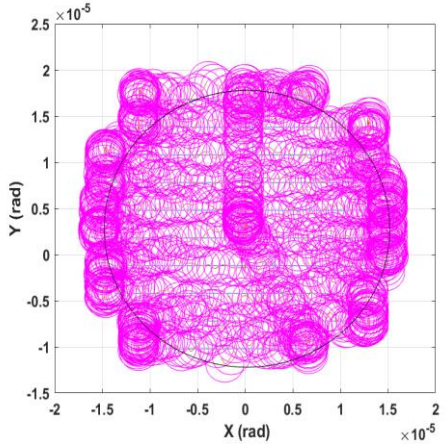
Taiji R&D progress —— Drag-free and thruster

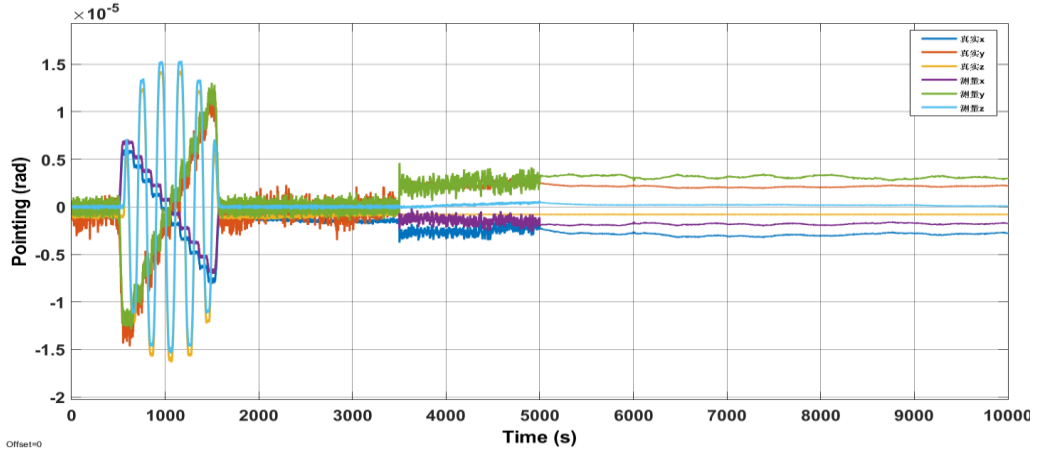


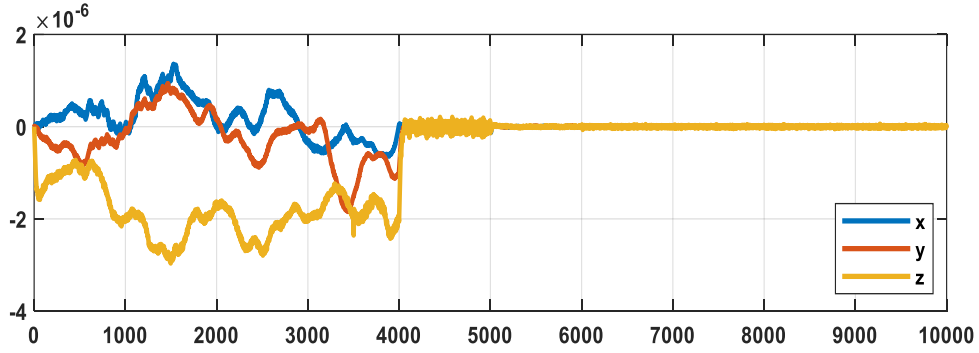


- **Payload simulator quasi-physical (electrical interface, data flow)**
- **Drag-free controller (1:1)**
- **From laser link establishing to scientific operation**

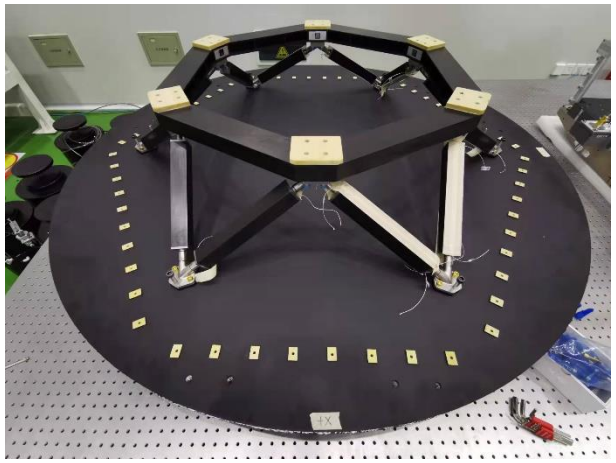
Residue jitter 8nrad/Hz$^{1/2}$, 7nm/Hz$^{1/2}$

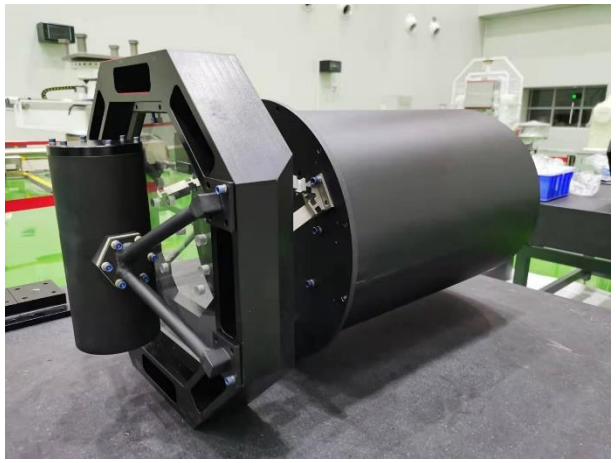




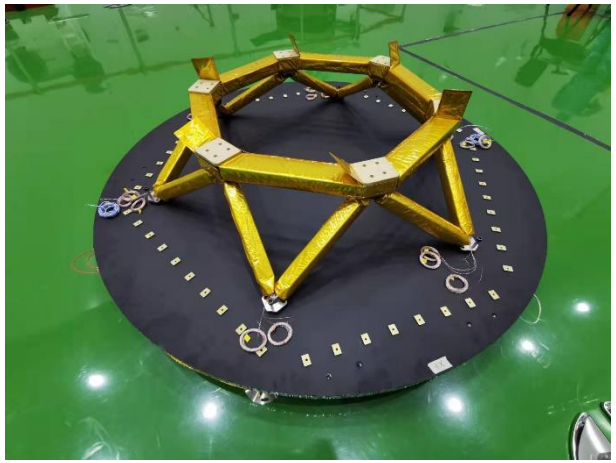


Taiji R&D progress —— stable platform

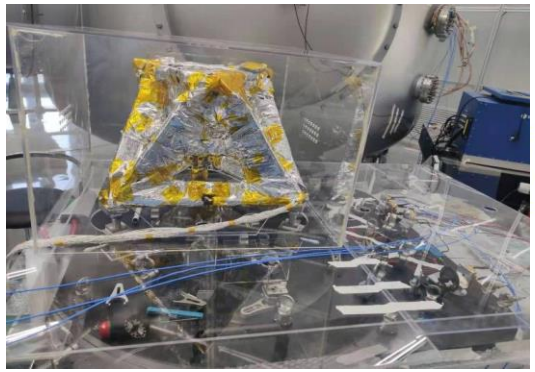


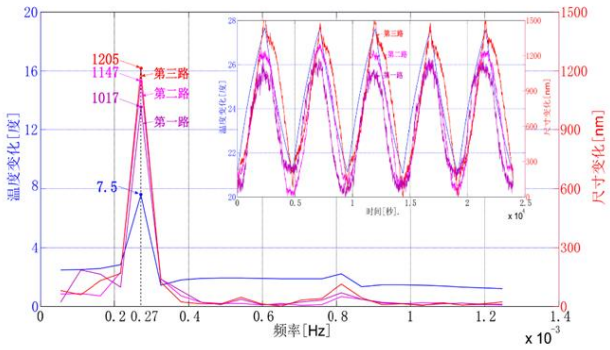












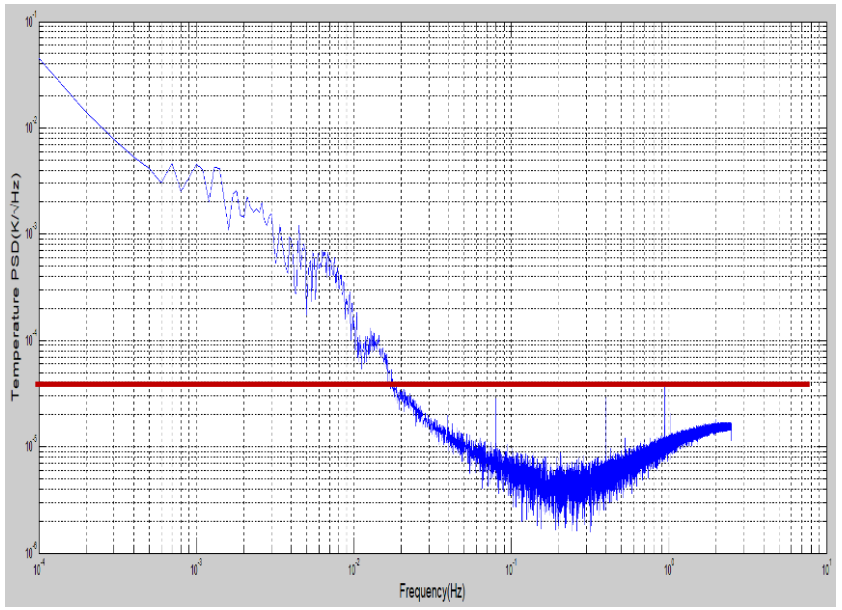
- **Model prototype of taiji satellite**
- **Ultra stable structure**

CTE 0.58×10^{-7}/K (bar), 2.38×10^{-7}/K (structure)

Carbon fiber ceramics

Taiji R&D progress —— stable platform

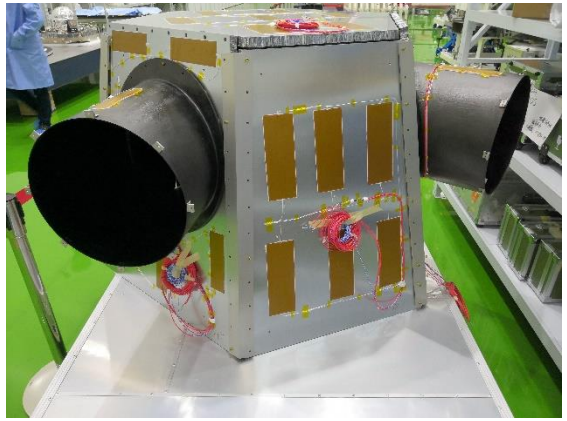




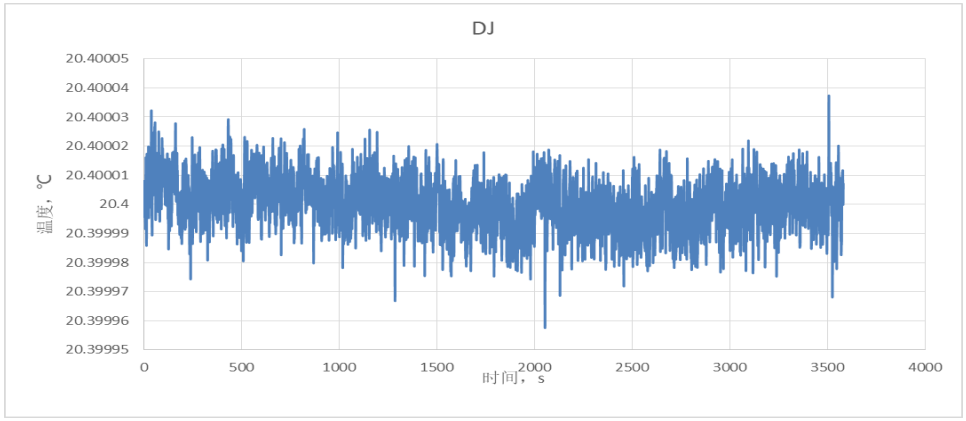
- Thermal meter
- Active-passive thermal control

measurement 30μK/Hz$^{1/2}$

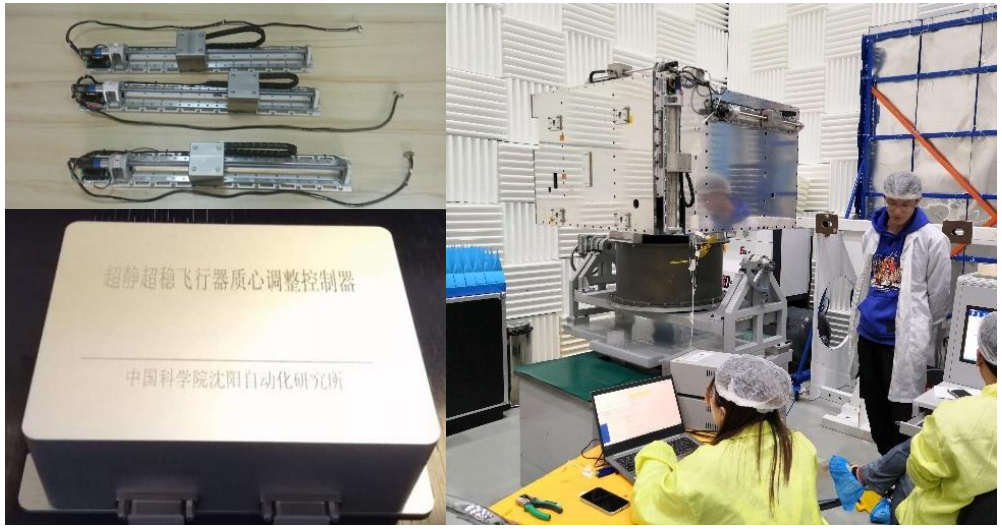
control 30μK

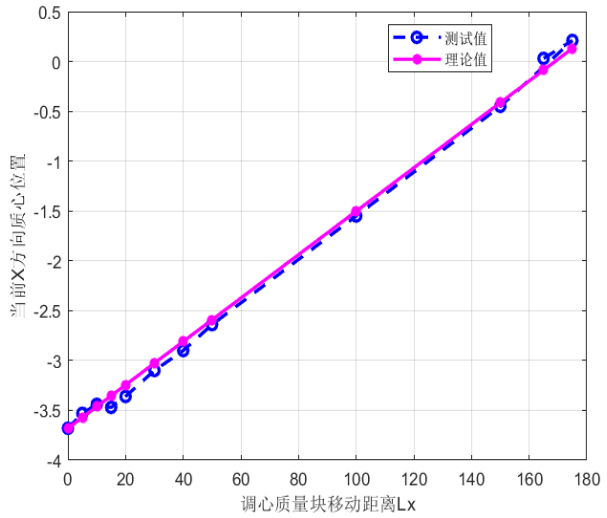


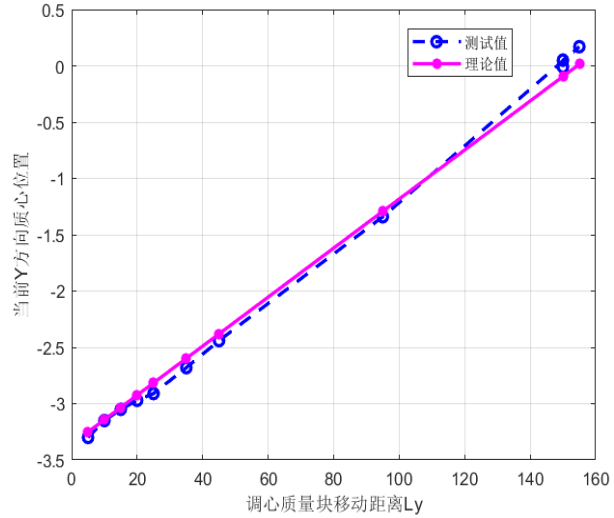


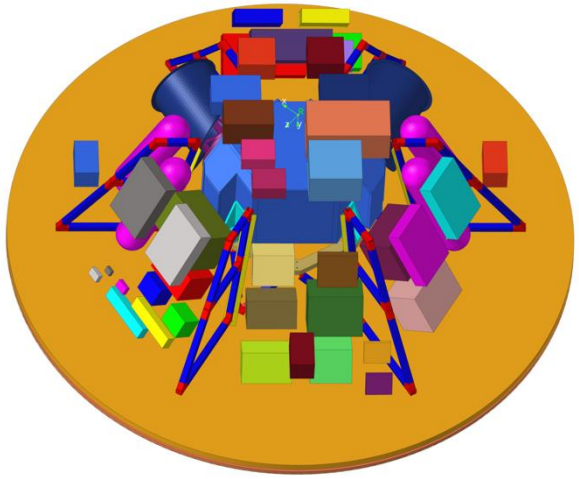


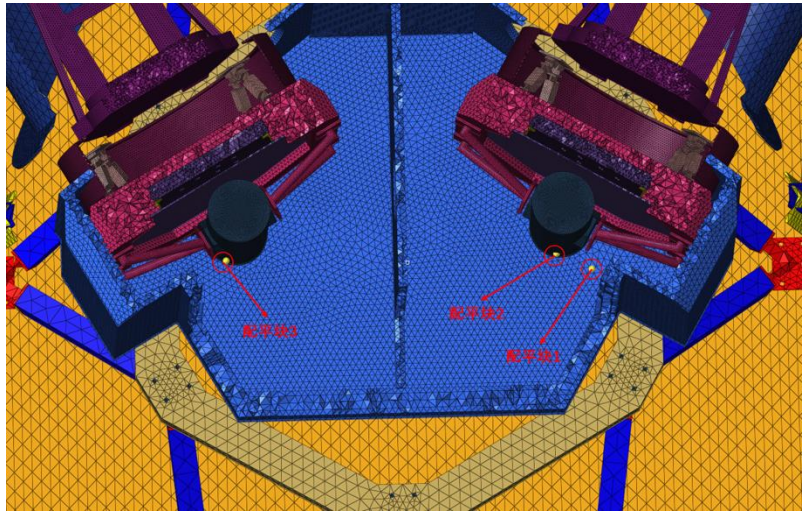
Taiji R&D progress —— stable platform











- **Center of mass actuation (test on Taiji-1)**

  Deviation (x and y) ±0.1mm

- **Self gravitational force simulation**

  TM DC acceleration $3.75\times10^{-10} ms^{-2}/Hz^{1/2}$

  Stiffness $4x10^{-7}/s^2$

Taiji R&D progress —— Taiji simulator

1、Simulation software

- Demonstration project process:
  Escaping, transferring, science operation.
- Providing parameters configuration.
- Generating Mock data.



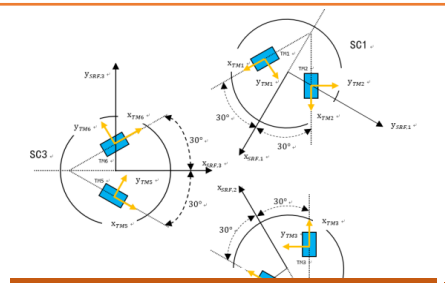
Project process demonstration



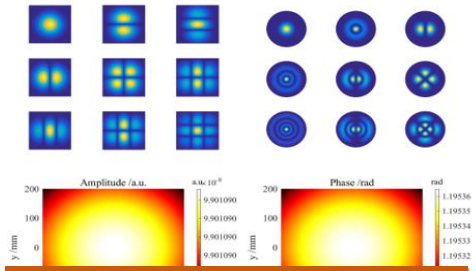
Parameters configuration&Mock Data

2、Full-link Modeling

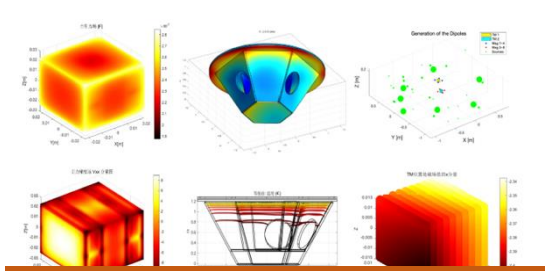
- Formation and orbital dynamics modeling.
  position simulation error: **0.03pm in six years**
- Split interferometry ranging system modeling.
  Computational accuracy 10^{-13}m/Hz$^{1/2}$
- Inertial sensor system modeling and analysis.



Global dynamics of detecting formation



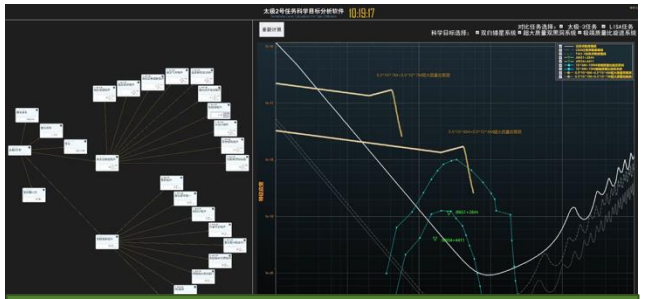
3Mkm diffraction transmission by MEM



Self gravitation、temperature、magnetic field simulation

3、Sensitivity analysis and index system

- Instrument sensitivity calculation and analysis.
- Index system construction for Taiji Program: including **9 types** of displacement noise and **10 types** of acceleration noise, total of hundreds of indicators



Scientific objectives analysis

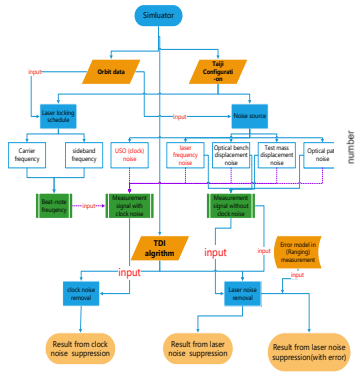


Multi-level index system

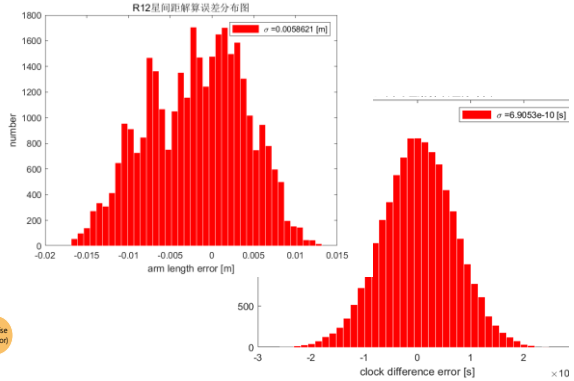
Taiji R&D progress —— data analysis

TDI numerical simulator TaijiSim-TDI (developed with c++/python) .
Satisfy the requirements of PN code ranging (≤10cm) and frequency noise suppressions (~8 orders).

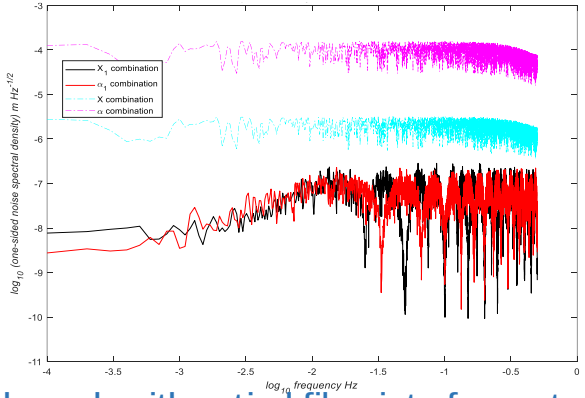
Flow chart



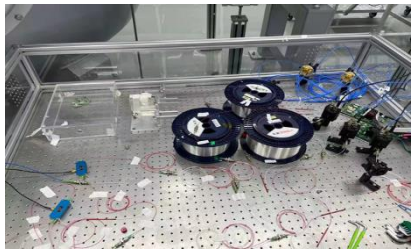
PN code ranging and Inter-satellite clock calibrations



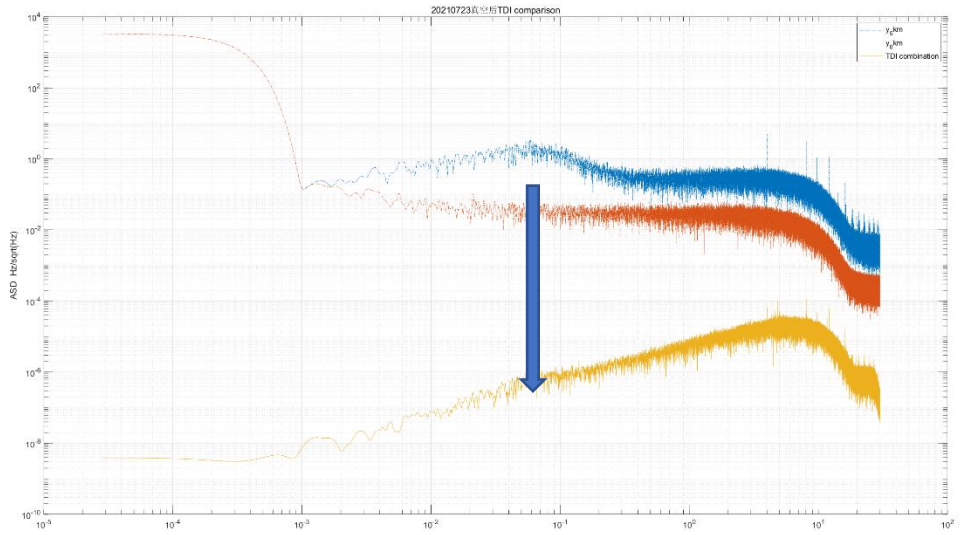
Suppression laser frequency noise and differential clock noise with 2nd TDI

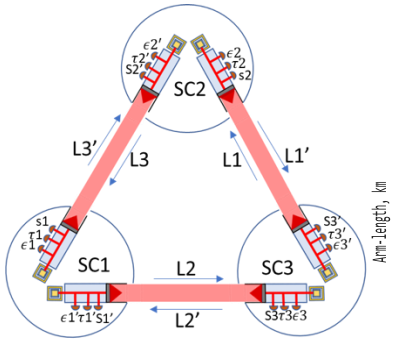


Demonstrate and confirm the performances (≥7 orders) of TDI channels with optical fiber interferometer

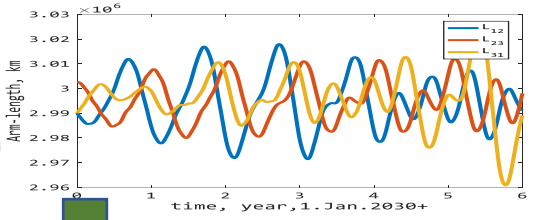




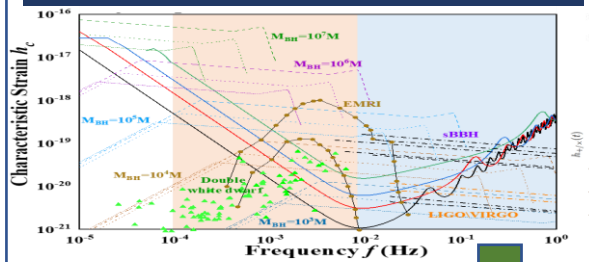


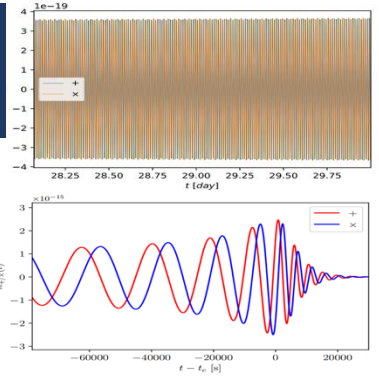


Full-chain simulations; Instrument noises

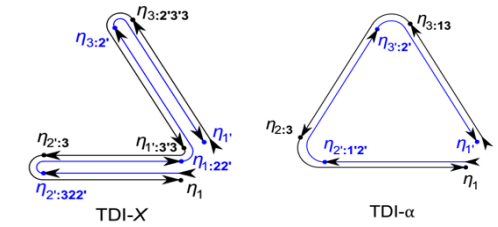


GW templates preparation; Signal injection (SMBH, EMRI, neutron star binaries)





TDI and data pre-processing;



Mock Data Challenge

Recent Progress

System integration and verification

MOSA integration, drag-free closed-loop tests, three-arm scientific interferometry, and end-to-end simulation

MOSA PLAYLOAD INTEGRATION

Subsystem: GRS · optical metrology · laser link · pointing subsystem

Focus: Payload-level noise coupling and interface verification

Method: Engineer-model MOSA assembly and calibration

Goal: Verify coupled noise transfer across the full payload subsystem

PAYLOAD INTERGRATION

DRAG-FREE CLOSED-LOOP VERIFICATION

Subsystem: SC-TM dynamics · micro-thrusters · pointing/control coupling

Focus: Closed-loop drag-free control under ground-equivalent conditions

Method: Hardware-in-the-loop semi-physical simulation platform

Goal: Test closed-loop drag-free residual-acceleration performance

SEMI-PHYSICAL LOOP

THREE-ARM SCIENTIFIC INTERFEROMETER

Subsystem: Inerial reference · laser link · optical-path simulation · TDI

Focus: Three-arm interferometry and ranging verification

Method: ground-equivalent semi-physical test

Goal: TDI-related laser-frequency-noise suppression · long-duration stability

FULL-CHAIN VERIFICATION

END-TO-END SIMULATION

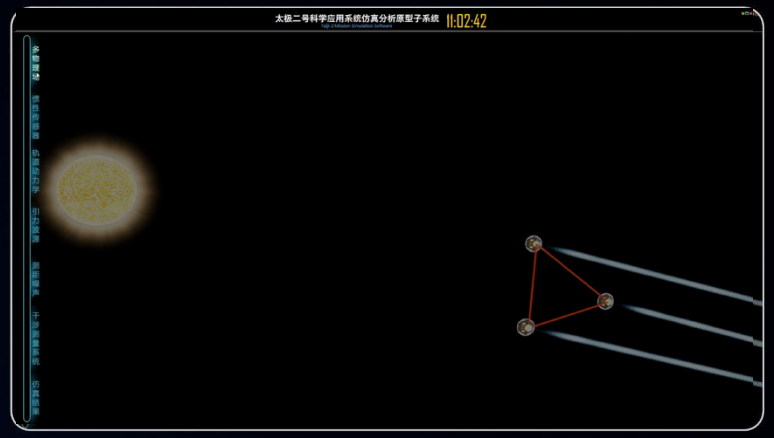
Subsystem: Orbit · payload interfaces · instrument noise · TDI · GW injection

Focus: Taiji science-application simulation prototype subsystem

Method: Full-chain simulation model library and validation

Goal: Generate mock science-data products for downstream analysis

⇒DATA CHALLENGE BRIDGE



End-to-end simulation prototype
From mission dynamics to science-data products



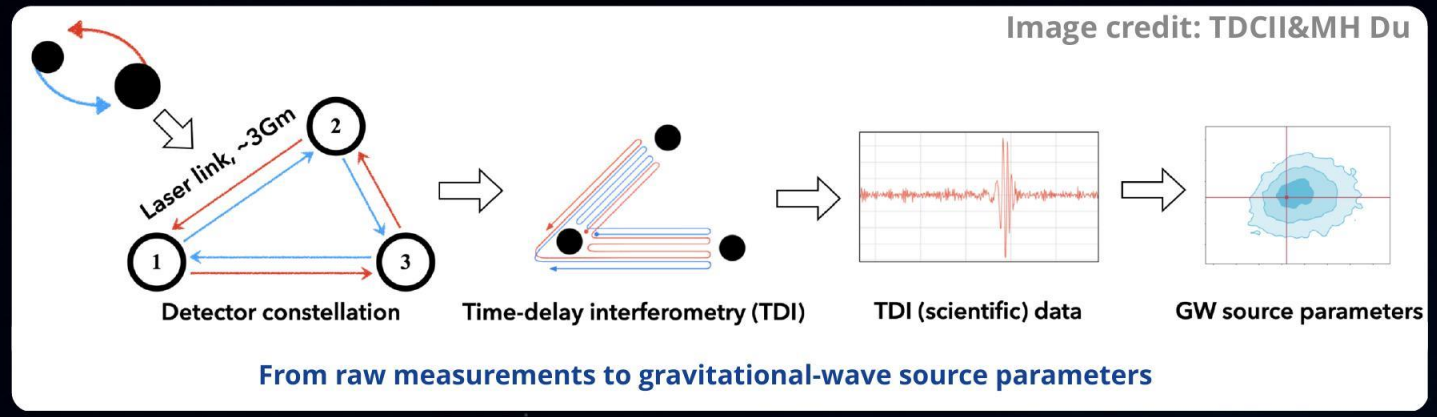
System-level experimental testbed
Ground-equivalent integration and environmental control

Take-away: System-level verification is the bridge from key-technology maturity to full-mission readiness.

Engineering-stage verification architecture; full mission performance requires further integrated tests.

Why data challenges are mission-critical

The analysis starts from measurements—not idealized strain



From raw measurements to gravitational-wave source parameters

L0
Raw Measurements
Phase · ranging
timing · telemetry

L0 - L1
Preprocessing
Clock sync · calibration
TDI · noise · data quality

L1 - L2
Scientific Inference
Low-latency search
global fitting · noise
characterization

L2 - L3
Science Products
Catalogs · cosmology
fundamental physics

Simulation closes the loop · science requirements constrain instrument design

Take-away: Data analysis is part of mission design and validation — not a post-launch add-on.

MEASUREMENT REALISM

Orbit-dependent signal response · laser-frequency noise

Clock noise & desynchronization · TTL coupling

GRS center-of-mass offsets · instrument transfer functions

DATA IMPERFECTIONS

Gaps · non-stationary noise · spectral lines

Unknow noise transients · anomaly identification

Observation interruptions · missing-data recovery

SOURCE–NOISE COMPLEXITY

Overlapping signals · Galactic foreground · multi-source inference

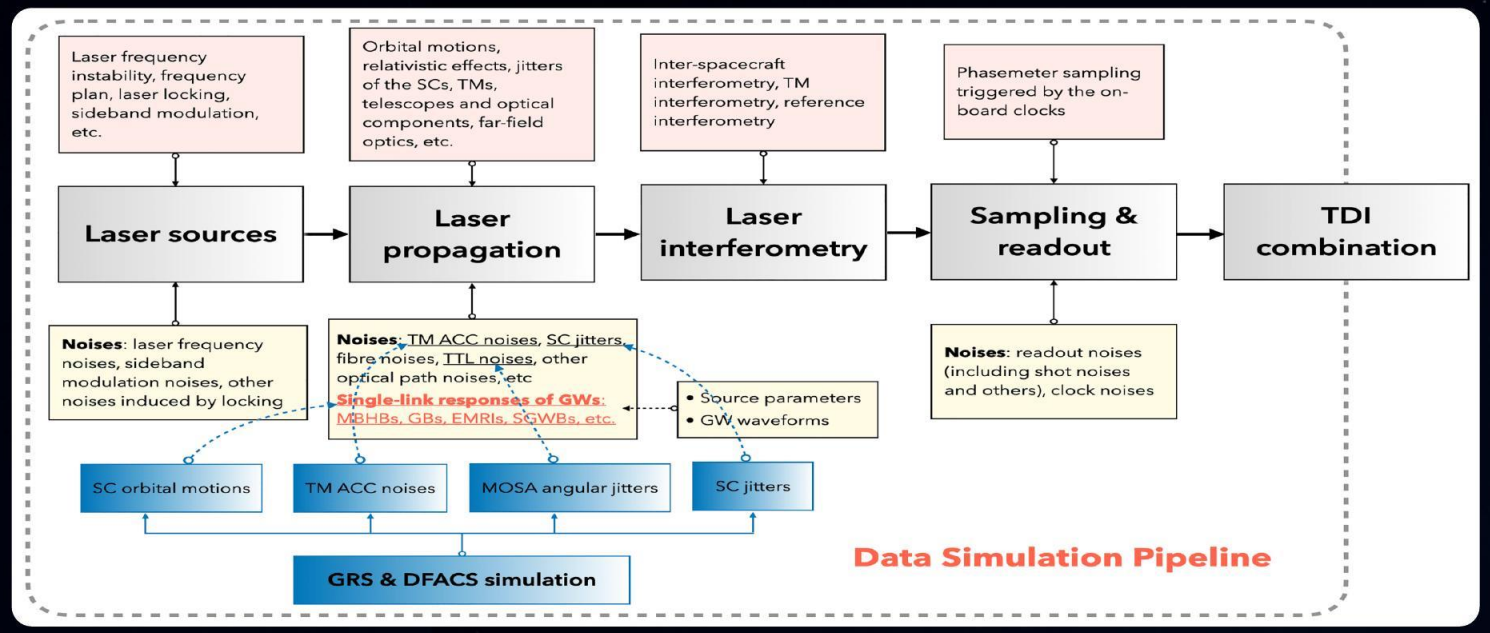
Instrumental noise · stochastic backgrounds · source–noise degeneracy

Global fit · $\sim 10^4$ resolvable sources

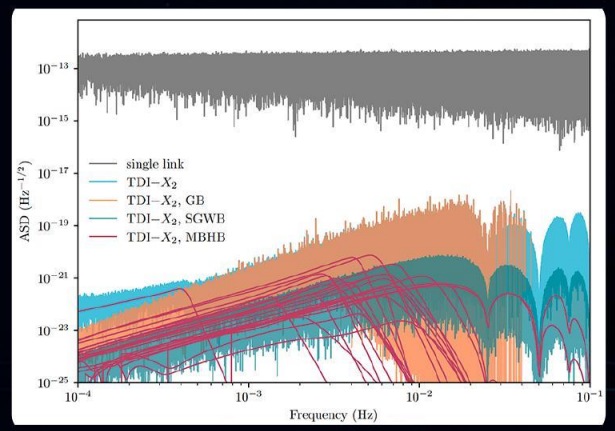
Data challenges connect instrument realism, full-chain simulation, and validated science products

Taiji Data Challenge

Toward an end-to-end L0→L2 benchmark



Minghui Du et al., *China-Phys. Mech. Astron.* (2026)



Example TDC II training data

Open datasets and selected analysis tools:
https://github.com/TriangleDataCenter

Full-chain simulation

Laser generation · propagation · interferometry · sampling/readout · TDI

Realistic detector configuration

Numerical orbits · unequal arms · TDI 2.0 · spacecraft–payload couplings

Multi-source mock data

Massive black-hole binaries · Galactic binaries · extreme mass ratio inspiral · stochastic background · instrumental noise

Open validation framework

Released datasets · documented injections · reproducible pipeline benchmarking

Take-away: TDC connects realistic instrument simulation to reproducible end-to-end scientific validation.

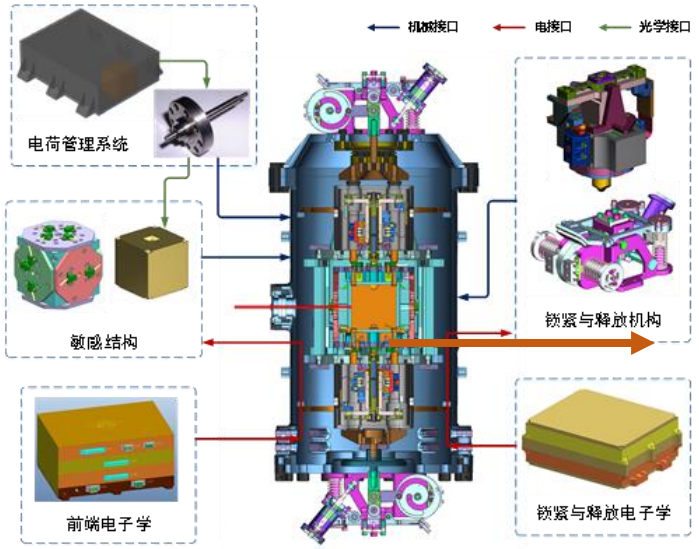
The TDC working group

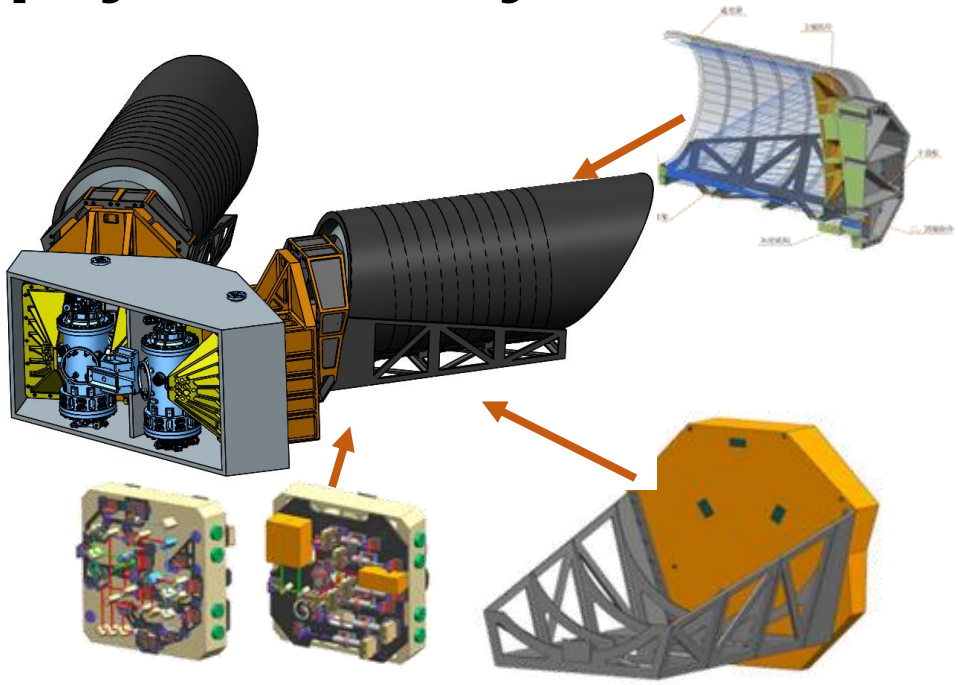
Taiji Data Challenge II

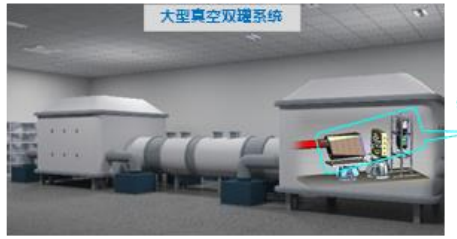
POSTER 2.06

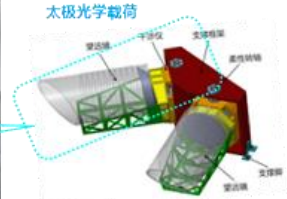
Preparation for engineering

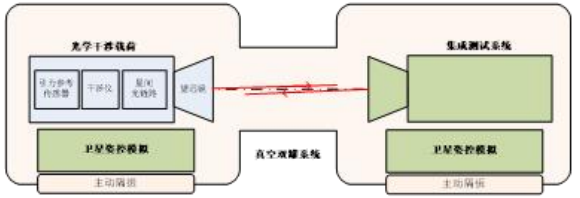
The integration of payload subsystem



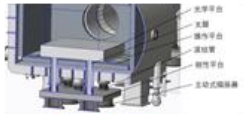












$$S_n^{1/2} = \sqrt{\left(S_{pos}(f)/L\right)^2 + \left(S_{acc}(f)/(4\pi^2 f^2 L)\right)^2} \quad < 10^{-20} \text{ @0. 1mHz-1Hz}$$

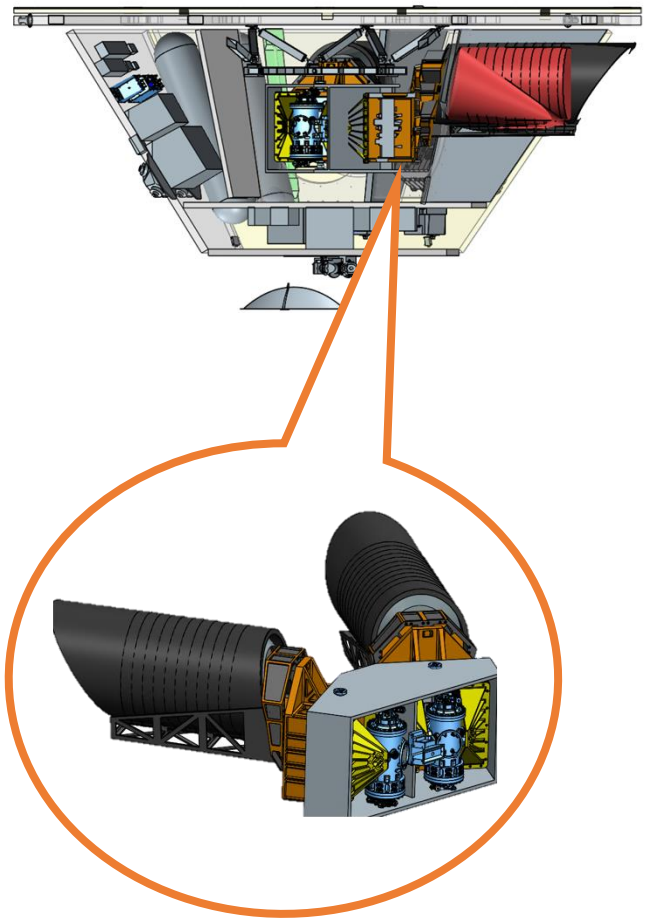
IMS noises: $8\times10^{-12}\text{m/Hz}^{1/2}$

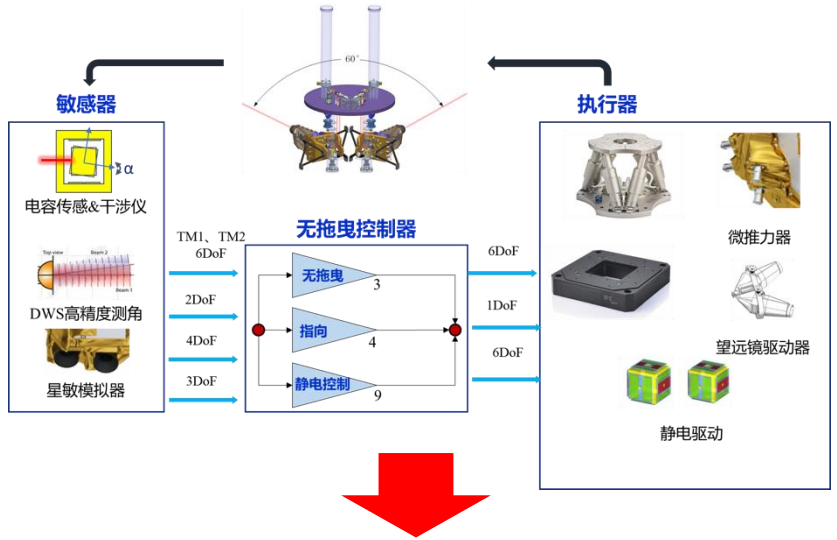
Acceleration noises: $3\times10^{-15}\text{ms}^{-2}/\text{Hz}^{1/2}$

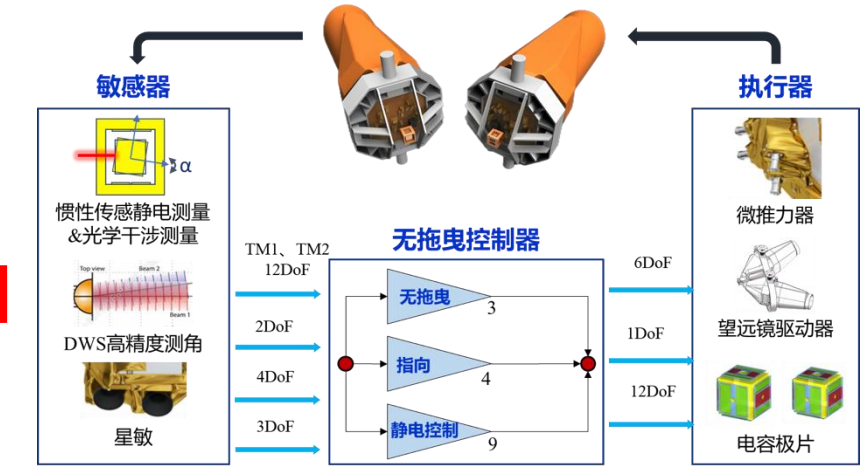
On ground: $3\times10^{-12}\text{ms}^{-2}/\text{Hz}^{1/2}$

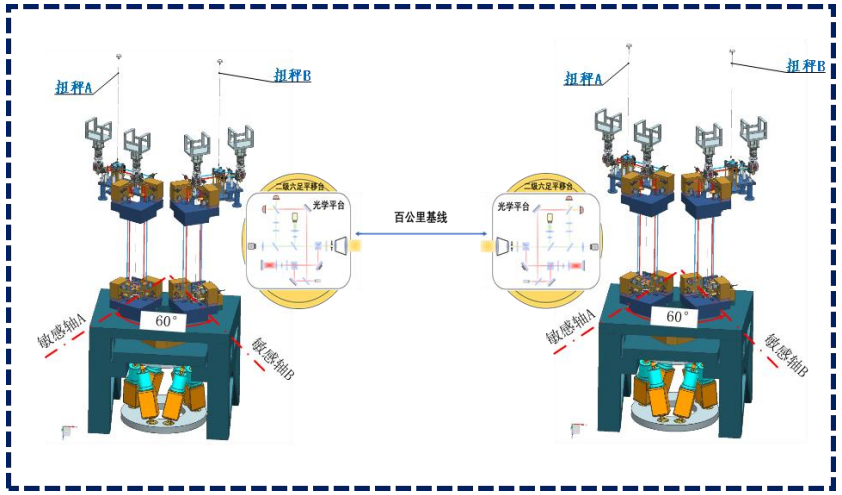
Preparation for engineering

The integration of payload and satellite and test of drag-free









Acceleration noises: $3\times10^{-15}ms^{-2}/Hz^{1/2}$

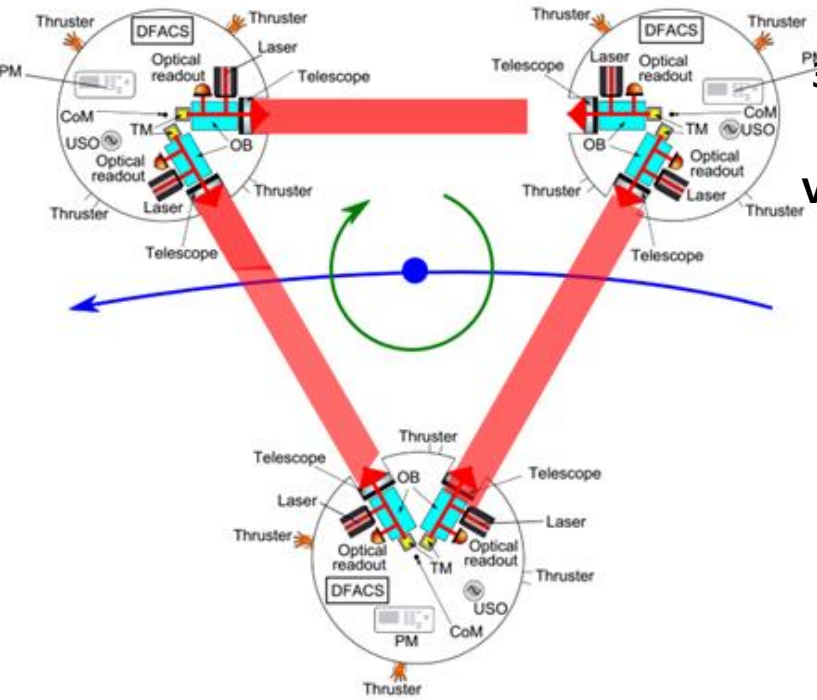
How to evaluate

On ground: $3\times10^{-12}ms^{-2}/Hz^{1/2}$

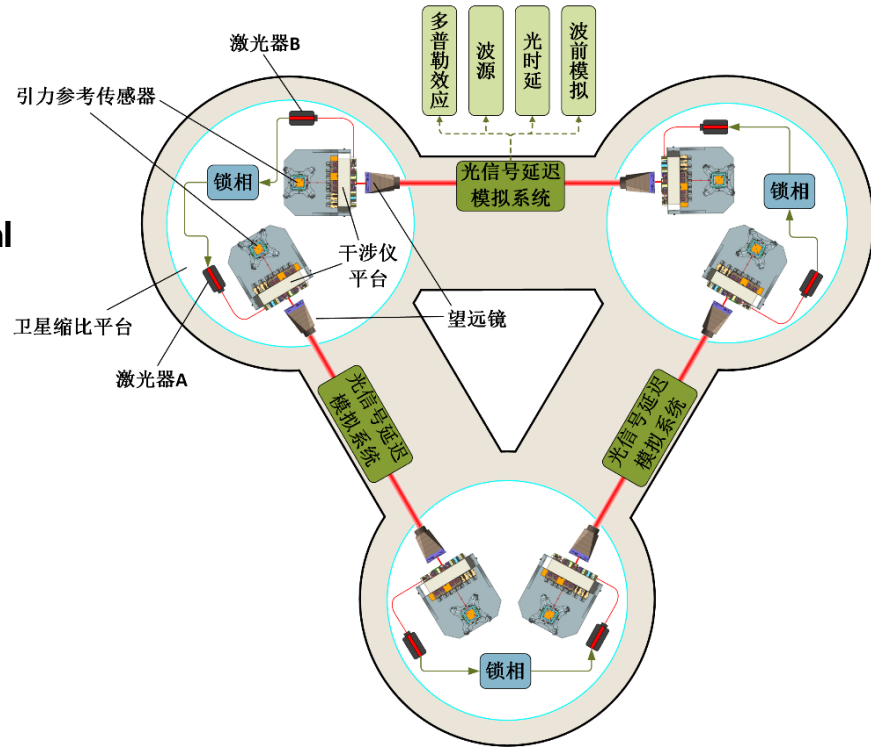
Preparation for engineering

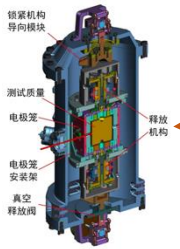
3-satellite constellation on-ground test

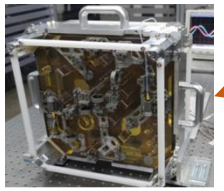
On orbit

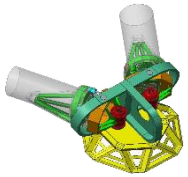


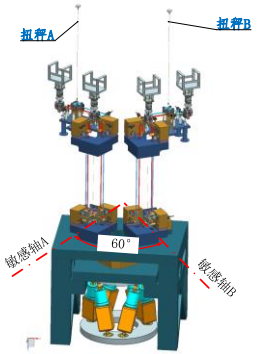
On orbit		On ground
3-arm interferometer	等同	3-arm interferometer
3 million km arm length	等效	Electronic delay
Vacuum 10^{-6}Pa，thermal $10\mu K/Hz^{1/2}$	等效	Vacuum 10^{-4}Pa，thermal $0.1mK/Hz^{1/2}$
TM 6 DOF control $3\times10^{-15}m/s^2/Hz^{1/2}$	等效	TM 3 DOF control $3\times10^{-12}m/s^2/Hz^{1/2}$
Total 57 DOF drag-free	等效	27 DOF drag-free
Interferometer $8pm/Hz^{1/2}$	等效	interferometer $30pm/Hz^{1/2}$
TDI	等同	TDI
uninterrupted run 1 year	等同	uninterrupted run 3 months

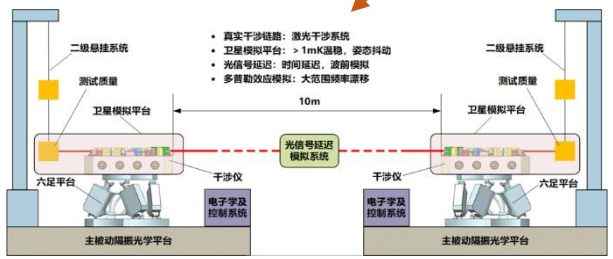


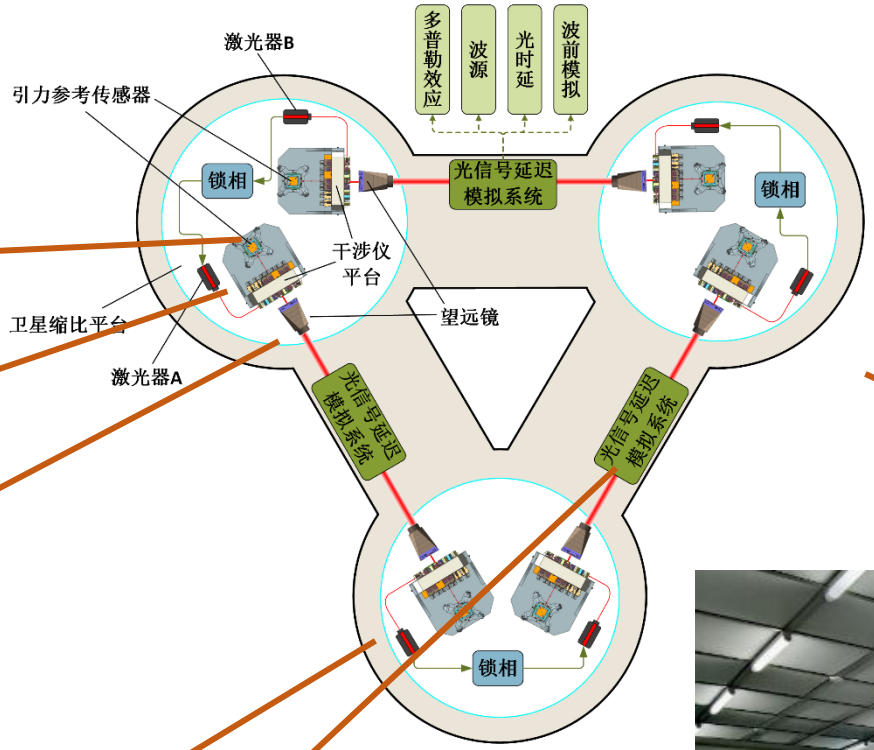

锁紧机构
导向模块
测试质量
电极笼
释放
机构
电极笼
安装架
真空
释放阀






拉臂A
拉臂B
60°
敏感轴A
敏感轴B


二级悬挂系统
测试质量
卫星模拟平台
10m
六足平台
干涉仪
电子学及
控制系统
主被动隔振光学平台
真实干涉链路：激光干涉系统
卫星模拟平台：＞1mK温稳，姿态抖动
光信号延迟：时间延迟，波前模拟
多普勒效应模拟：大范围频率漂移
光信号延迟
模拟系统


多普勒效应
波源
光时延
波前模拟
激光器B
引力参考传感器
锁相
光信号延迟
模拟系统
干涉仪
平台
卫星缩比平台
望远镜
激光器A

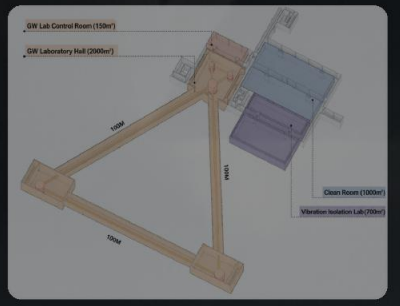


Thank you

Toward full-constellation verification

100-m-baseline triangular laser-interferometry test facility

GROUND-TEST FACILITY CONCEPT



100-m triangular baseline



Ground-facility site layout

100-m-baseline facility under construction · Hangzhou, May 2026

Taiji LAB Taiji Laboratory FOR GRAVITATIONAL WAVE UNIVERSE

Taiji Program in Space Gravitational wave physics 空间太极计划

unesco Centre Under the auspices of UNESCO

ICTP-AP International Centre for Theoretical Physics Asia-Pacific 国际理论物理中心-亚太地区

中国科学院大学 University of Chinese Academy of Sciences

國科大杭州高等研究院 Hangzhou Institute for Advanced Study, UCAS