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In-orbit performance of the laser interferometer of Taiji-1 experimental satellite

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Taiji-1, which is the first experimental satellite for space gravitational wave detection in China, relies on key technologies which include the laser interferometer, the gravitational reference sensor (GRS), the micro-thruster and the satellite platform. Similarly to the Laser Interferometer Space Antenna (LISA) pathfinder, except for the science interferometer, the optical bench (OB) of Taiji-1 contains reference and test mass (TM) interferometers. Limited by the lower mechanical strength of the carrier rocket and by the orbit environment, the OB of Taiji-1 is made of invar steel and fused silica, and it is aimed to achieve a sensitivity of the order of $100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$. The experimental results from in-orbit tests of Taiji-1 demonstrate that the interferometer can reach a sensitivity

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of 30 pm/$\sqrt{\text{Hz}}$ in the frequency range of 0.01–10 Hz, which satisfies the requirements of Taiji-1 mission.

Keywords: Laser interferometer; optical bench; Taiji-1.

1. Introduction

The Taiji program, proposed by the Chinese Academy of Sciences in 2008, is aimed at the gravitational wave detection in space.[1,2] Taiji plans to use a laser interferometer to transfer the tiny displacement between free-floating test masses (TMs) to the phase fluctuation of the laser beat note. The arm length of the Taiji interferometer is 3 million km, and the displacement fluctuation should be detected with a precision of 1 pm/$\sqrt{\text{Hz}}$. To ensure the success of the Taiji program, which is scheduled to be launched in 2033, many experimental satellites are being prepared for technical demonstration. For this purpose, Taiji-1, launched at 31 August 2019, is the first Chinese experimental satellite in China to assess the feasibility of some core technologies on-orbit for space gravitational wave detection, such as the laser interferometer, the gravitational reference sensor (GRS), the micro-thruster and the satellite platform.

In the final Taiji mission, three interferometers will be used, i.e. the reference interferometer, the TM interferometer and the science interferometer. However, similarly to the Laser Interferometer Space Antenna (LISA) pathfinder,[3,4] Taiji-1 focuses on the technologies of one satellite. Therefore, only the reference and the TM interferometer have been designed and tested in the Taiji-1 mission. The former accounts for the stability of the optical bench (OB), and the latter gives the related motion information between TM and OB. Unlike the LISA pathfinder, the orbit of Taiji-1 is a 600 km circular orbit around the Earth. Limited by the orbit environment, the goal of the interferometer is to achieve a sensitivity of the order of 100 pm/$\sqrt{\text{Hz}}$ in the frequency range of 10 mHz–10 Hz.

In this paper, the optical layout of the Taiji-1 laser interferometer is discussed in Sec. 2. The engineering implementation of the interferometer is thoroughly described in Sec. 3. The in-orbit performance and experimental results from the interferometer are given in Sec. 4.

2. Optical Layout

Similarly to the LISA pathfinder, the laser interferometer of the Taiji-1 experimental satellite focuses on the local OB, which consists of the reference and TM interferometers. Unlike the planar design in the LISA pathfinder, the optical layout of the Taiji-1 is three-dimensional, which makes it similar to the final geometric topology of Taiji. The optical layout of the OB is shown in Fig. 1.

The laser interferometer of Taiji-1 mainly consists of two parts: the modulated one and the OB one. The modulated part, which may produce two laser beams of different frequencies, mainly includes one 1×2 fiber optic splitter and

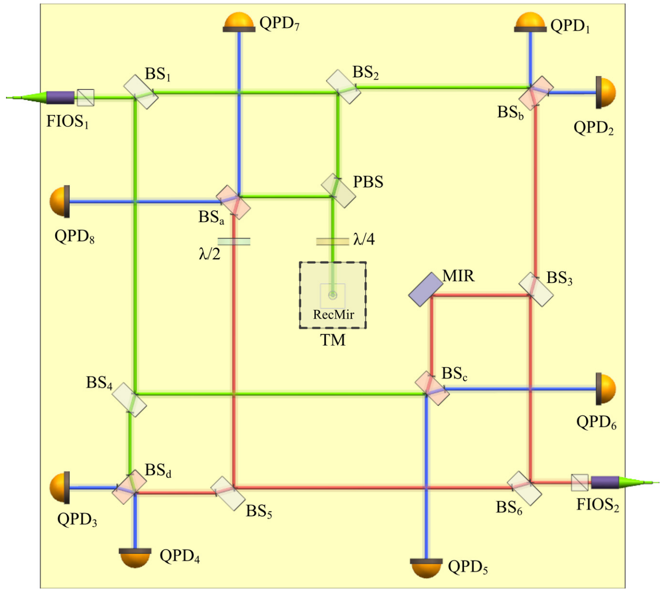

Fig. 1. The optical layout of the OB of the Taiji-1 experimental satellite. FIOS: fiber injector optical subassembly; BS: beam splitter; QPD: quadrant photo detector; PBS: polarization beam splitter; TM: test mass; MIR: mirror and RecMir: rectangle mirror.

two acousto-optic modulators (AOMs). A laser beam from the Nd:Yag solid-state laser (1064 nm wavelength, 1 MHz frequency and 1% power stability) is split by the 1×2 fiber optic splitter, and then enters the two AOMs, which shift the laser frequency to the 1 KHz heterodyne frequency of the Taiji-1 interferometer. Then, the two beams from the AOMs are entered into the OB through the respective fiber injector optical subassemblies (FIOSs), labeled as FIOS_1 and FIOS_2. In the OB, there are four Mach–Zehnder interferometers, named as interferometer d: Optical Route d_1 (FIOS_1-BS_1-BS_d) with Optical Route d_2 (FIOS_2-BS_6-BS_d), interferometer c: Optical Route c_1 (FIOS_1-BS_1-BS_b) with Optical Route c_2 (FIOS_2-BS_6-BS_b), interferometer b: Optical Route b_1 (FIOS_1-BS_1-BS_4-BS_c) with Optical Route b_2 (FIOS_2-BS_6-BS_3-MIR-BS_c) and interferometer a: Optical Route a_1 (FIOS_1-BS_1-BS_2-PBS-RecMir-TM-RecMir-PBS-BS_a) with Optical Route a_2 (FIOS_2-BS_6-BS_5-BS_a), respectively. Lastly, the heterodyne beam is detected by the quadrant photo detectors (QPDs), which are connected to the phasemeter for phase extraction.

In Fig. 1, the interferometers c and d, with equal arm lengths, are the reference interferometer and give an indication of the OB stability. The interfering optical path length is 300 mm for both interferometers. Interferometers b and a, with unequal arm lengths, are the TM reference and measurement interferometers, respectively. Compared to that with equal arm lengths, in the interferometer system with unequal arm lengths, the laser frequency jitter noise plays a dominant role. The frequency jitter noise is proportional to the unequal arm lengths and can be expressed by[5]

$$\delta l = \Delta L \frac{\delta \mu}{\mu}, \tag{1}$$

where δl is the displacement noise due to frequency jitter, ΔL is the difference of arm lengths, μ and $\delta\mu$ are the laser frequency and its jitter value, respectively. Unequal arm lengths of interferometers b and a are 150 and 180 mm, respectively. In Taiji-1, the laser frequency and its jitter are 2.81×10^{14} Hz and $1\,\mathrm{MHz}/\sqrt{\mathrm{Hz}}$, respectively. Therefore, the frequency jitter noise of interferometers b and a is 532 and $639\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$, respectively.

Compared to the goal of Taiji-1, the calculated frequency jitter cannot be ignored. Fortunately, the revised method can be used. Let ΔL_b and ΔL_a be the unequal arm lengths. Then, the movement of the TM can be revised by

$$\delta l_{\mathrm{TM}} = \delta l_a - \frac{\Delta L_a}{\Delta L_b}\delta l_b, \tag{2}$$

where ΔL_a and ΔL_b are the initial measurements of TM interferometers a and b, respectively, and δl_{TM} is the revised TM movement with frequency jitter noise removed. As the unequal arm, the interferometer b can be used to monitor the laser frequency jitter.

3. Implementation

Precision aligned and ultra-stable optical assemblies are required for the OB implementation. The fused silica optics are hydroxide catalysis bonded to a Zerodur/ULE baseplate.[6,7] In our previous work,[8] we tested and verified the adopted installation technique, which is now regarded as the best choice in Taiji space gravitational wave detection mission. However, the delivery tool of Taiji-1 is a solid rocket (KZ-1A), which has the advantages of economy and speed. In particular, KZ-1A, known as a speedy vessel, is a low-cost solid-fuel carrier rocket with high reliability and a short preparation period. Compared to a liquid rocket, such as the CZ-3B, Falcon 9, the KZ-1A rocket has a lower mechanical strength, and, in turn, the OB of Taiji-1 could face more critical mechanical stresses than the LISA pathfinder. Therefore, the traditional optical–mechanical structure has been preferred to the optical bonding for the OB implementation of Taiji-1.

The invar steel, which has a very low thermal expansion coefficient, is the ideal choice for the OB baseplate of Taiji-1. The fused silica, featuring a thermal expanding index similar to that of invar steel and a stable refractive index, is selected as the substrate. Epoxy resin adhesive is chosen as the bonding method for the baseplate and lens.

Taiji-1 provides the readout of the TM movement, so the electrode housing of the GRS should have an opening for the passage of the laser beam. The GRS is connected to the OB by an invar steel bridge. The OB is fabricated by using the coordinate measuring machine (CMM) and the calibrated quadrant photodiode

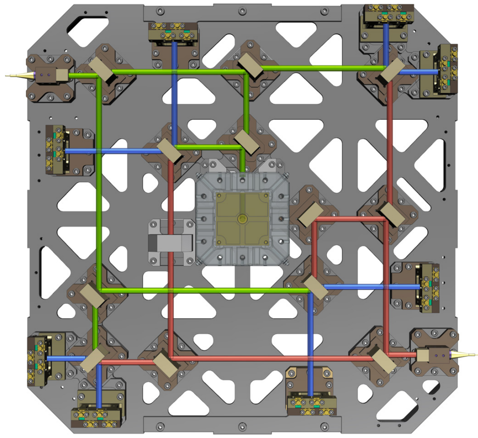

Fig. 2. The engineering model of the Taiji-1 OB.

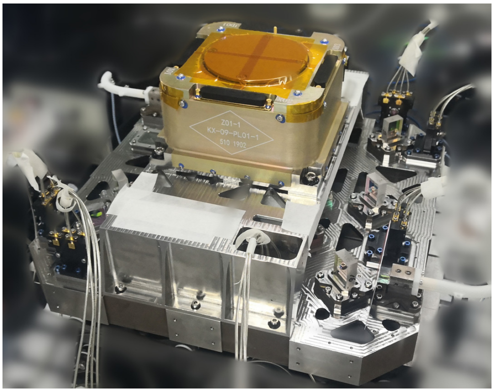

Fig. 3. Optical photograph of the Taiji-1 OB (assembled with the GRS).

pair (CQP).[8] After alignment, the angular deviation between the interference beam and its ideal position in the global coordinate system is no more than $100\,\mu$rad and the positional deviation is less than $50\,\mu$m. The QPD is used for the readout of displacement and angle information. In total there are four interferometers and eight QPDs on both sides of end BSs. The QPDs are grouped into two groups of four, named as main part and backup part, which are connected to independent phasemeters, thereby providing independent results with double insurance. The mechanical model and an optical photograph of the OB are, respectively, shown in Figs. 2 and 3.

4. Results and Discussions

After a few weeks of in-orbit test after launch, the satellite and thermal environment became stable. In turn, both the optical system and the OB exhibited stable in-orbit

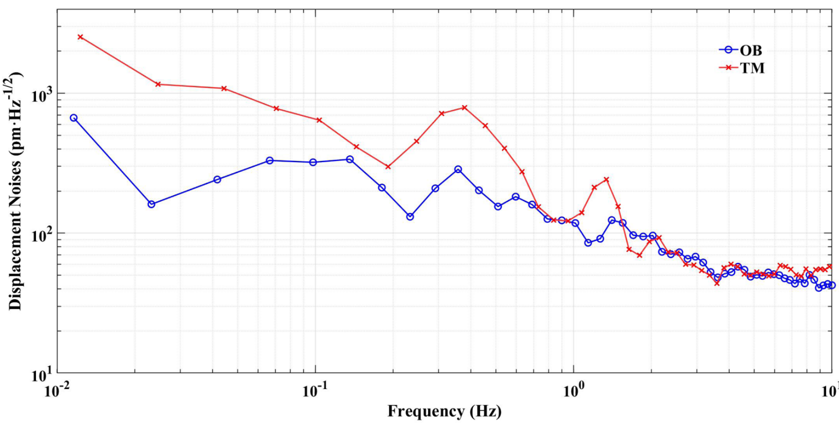

Fig. 4. Typical results of Taiji-1 in orbit (main part).

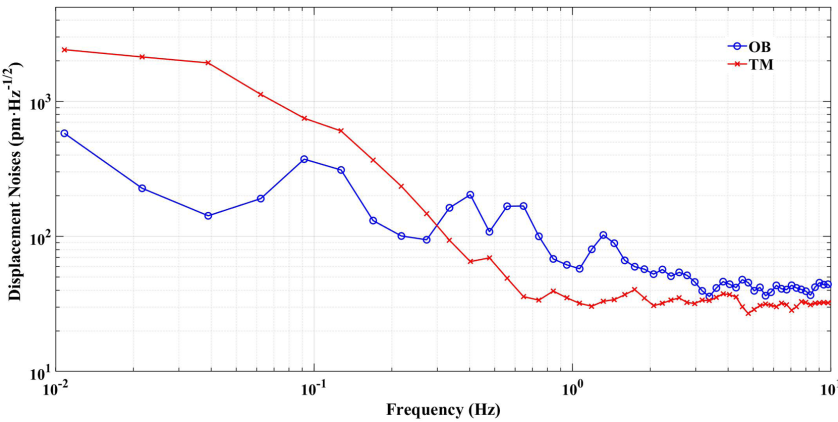

Fig. 5. Typical results of Taiji-1 in orbit (backup part).

operation, thus yielding satisfactory results. The typical results of Taiji-1 are shown in Figs. 4 and 5.

From Fig. 4, the OB stability measured by main part can reach a sensitivity of $50\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ in the frequency range between 1 and 10 Hz. The OB noise slightly increases up to $700\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ below 1 Hz. Compared with the OB, the TM stability presents the similar performance in the range of 1–10 Hz. In the frequency below 1 Hz, the TM noise significant increases up to $3\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$. In the backup part test, shown by Fig. 5, the OB stability appears similar result with the main part. However, the TM stability can reach $30\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ in the frequency range of 0.7–10 Hz, that are totally different with the main part. Obviously, the result is an interesting phenomenon, which may come from the follow reasons.

The sources of noise in an optical system can be classified in three groups: optical path, optics and electronics. Optical path noise mainly comes from the effect of optical path fluctuation, such as thermal effects, strain caused by external forces and tilt-to-length (TTL) coupling. Optics noise arises from changes in laser beam parameters during tests, such as frequency jitter, power fluctuation and polarization variation. Electronics noise comes from the noise of analog and digital electronic elements. Analog electronics include the amplifier, the anti-aliasing filter and the coaxial cable. Digital electronics mainly refers to the phasemeter, which consists of an analog-to-digital converter (ADC) and a field programmable gate array (FPGA).

Obviously, these differences between the main part and the backup part are unlikely to arise from optical path noise. Indeed, the optical path information of the two parts is the same, and the optical path noise is the common-mode noise. As for the electronics, the analog and digital parts have been thoroughly tested in the ground. Unknown noises from electronics are also unlikely to occur during in-orbit test. Therefore, the noise is more likely to come from the optics part. Due to inaccuracies in splitting ratio of BS, laser powers of the main part and backup part are quite different. In turn, the signal-to-noise ratio of the heterodyne signal of the two parts is different too. Coincidentally, this effect is obviously appeared in the TM and its reference interferometer. Therefore, the lens of the OB should be carefully calibrated with the laser beam itself in the future mission, such as polarization, splitting ratio and wave front.

5. Conclusion and Outlook

The Taiji space gravitational wave detection program, proposed by the Chinese Academy of Sciences in 2008, is scheduled to be launched into the space in 2033. Taiji-1 is the first experimental satellite of the Taiji mission, which is aimed to assess the technical effectiveness of laser interferometer, GRS, micro-thruster and drag-free. The reference and the TM readout interferometers are fabricated and tested in the Taiji-1. The local interferometer can reach a sensitivity of $30\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ in the frequency range of 0.01–10 Hz. Moreover, some problems have been identified, which will serve to improve the next Taiji series missions. Indeed, the 5:5 beam splitter hardly satisfied its splitting ratio, the polarization of the laser beam could not be strictly controlled, as well as its power when the light passes through the polarizing device, such as the polarization beam splitter (PBS). In the future, an improved OB and a superior bonding method will be fabricated and implemented for the next Taiji mission.

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