PTEP

Prog. Theor. Exp. Phys. **2020**, 0000 (13 pages)
DOI: 10.1093/ptep/ptaa114

The TianQin project: Current progress on science and technology

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Received July 8, 2020; Accepted July 22, 2020; Published Month 00, 0000

TianQin is a planned space-based gravitational wave (GW) observatory consisting of three Earth-orbiting satellites with an orbital radius of about 10^5 km. The satellites will form an equilateral triangle constellation the plane of which is nearly perpendicular to the ecliptic plane. TianQin aims to detect GWs between 10^{-4} Hz and 1 Hz that can be generated by a wide variety of important astrophysical and cosmological sources, including the inspiral of Galactic ultra-compact binaries, the inspiral of stellar-mass black hole binaries, extreme mass ratio inspirals, the merger of massive black hole binaries, and possibly the energetic processes in the very early universe and exotic sources such as cosmic strings. In order to start science operations around 2035, a roadmap called the 0123 plan is being used to bring the key technologies of TianQin to maturity, supported by the construction of a series of research facilities on the ground. Two major projects of the 0123 plan are being carried out. In this process, the team has created a new-generation 17 cm single-body hollow corner-cube retro-reflector which was launched with the QueQiao satellite on 21 May 2018; a new laser-ranging station equipped with a 1.2 m telescope has been constructed and the station has successfully ranged to all five retro-reflectors on the Moon; and the TianQin-1 experimental satellite was launched on 20 December 2019—the first-round result shows that the satellite has exceeded all of its mission requirements.

Subject Index F30, F31, F33, F34

1. Introduction

Major activities in gravitational wave (GW) detection are expected around 2035. By then, the network of ground-based GW detectors should have detected thousands of GW events and the pulsar timing array and the cosmic microwave background experiments could have made historic breakthroughs. Brand new space-based GW observatories, such as LISA [1] and DECIGO [2,3], could also join the effort. Proposed in 2014, the TianQin project aims to launch a space-based GW observatory, TianQin, around 2035 and to detect GWs between 10^{-4} Hz and 1 Hz [4]. TianQin is unique in several respects: it is the only planned detector that uses geocentric orbits [5–7]; like the others it uses three satellites to form an equilateral triangular constellation, but the constellation plane is nearly perpendicular to the ecliptic plane; and its frequency sensitivity band is between those of LISA and DECIGO, overlapping with that of LISA near 10^{-4} Hz and with that of DECIGO near 1 Hz.

As first published in Ref. [4], the concept of TianQin envisions an equilateral triangle constellation of three drag-free satellites orbiting the Earth with an orbital radius of about 10^5 km [8–10] with the detector orientation, i.e. the normal vector to the constellation plane of the detector, pointing toward RX J0806.3+1527 (also known as HM Cancri or HM Cnc, hereafter J0806 [11]). The satellites will be carefully controlled to provide an ultra-clean and stable environment for their scientific operation, allowing gravity to take full governance of the motion of a set of test masses residing in the satellites and allowing laser interferometry to reach extremely high precision. In this way, the variation in the distance between the test masses (partially caused by GWs) can be measured with the inter-satellite laser interferometry.

Some basic parameters of TianQin are listed in Table 1.

Table 1. Basic parameters of TianQin.

Parameters	Value
Type of orbit	Geocentric
Number of satellites	$N = 3$
Arm length	$L = \sqrt{3} \times 10^5$ km
Displacement measurement noise	$S_x^{1/2} = 1 \times 10^{-12}\,\mathrm{m\,Hz^{-1/2}}$
Residual acceleration noise	$S_\mathrm{a}^{1/2} = 1 \times 10^{-15}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$

2. Scientific prospects

A systematic effort has been undertaken to assess the expected science output of TianQin [12–18] (see also Z.-C. Liang et al., in preparation; L. Zhu et al., in preparation). In these works, the following sensitivity curve has been used [4,9,19]:

$$S_n(f) = \frac{10}{3L^2}\left[S_x + \frac{4S_\mathrm{a}}{(2\pi f)^4}\left(1 + \frac{10^{-4}\,\mathrm{Hz}}{f}\right)\right] \times \left[1 + 0.6\left(\frac{f}{f_*}\right)^2\right], \tag{1}$$

where S_x and S_a are given in Table 1, and $f_* = c/(2\pi L) \approx 0.28$ Hz is the transfer frequency. Note that Eq. (1) describes a ballpark goal, and the sensitivity curve is expected to be refined over time. We assume five years of mission lifetime for TianQin. With its baseline concept [4], TianQin is expected to operate in a consecutive “three-month on + three-month off” mode, which means that TianQin will first observe continuously for three months, and then be put into a safe mode for the next three months before starting observation again, in order to cope with the variation of thermal load on the satellites. In this scheme, the total duration of data acquisition will be 2.5 years for a mission lifetime of 5 years. Although various possibilities are being explored to increase the fraction of total observation time, we use the baseline concept of TianQin to get a (presumably conservative) assessment of the expected science output.

The major sources expected for TianQin include the inspiral of Galactic ultra-compact binaries (GCBs), the inspiral of stellar-mass black hole binaries (SBHBs), extreme mass ratio inspirals (EMRIs), the merger of massive black hole binaries (MBHBs), and possibly also energetic processes in the very early universe or exotic sources such as cosmic strings [20]. With the detection of GWs from such sources, TianQin is expected to provide key information on the astrophysical history of galaxies and black holes, the dynamics of dense star clusters and galactic centers, the nature of gravity and black holes, the expansion history of the universe, and possibly also the fundamental physics related to the energetic processes in the early universe.

A summary of the expected astrophysical sources that can be detected with TianQin is illustrated in Fig. 1.

2.1. *Galactic ultra-compact binaries*

GCBs are likely the most numerous sources for a space-based GW detector such as TianQin [17,21–24]. The detection of GCBs is of great importance for astrophysics and fundamental physics. For astrophysics, GW observations are likely to detect more GCBs with ultra-short periods (<1 hr) than the electromagnetic observatories [25], and thus can not only subject the formation theories of GCBs to precise test but can also help to study the matter distribution and structure of the Galaxy [26–28]. The GWs from GCBs can also be used to study fundamental physics, such as helping to constrain extra radiation channels or extra polarization modes of GWs [29,30]. It has been shown that TianQin

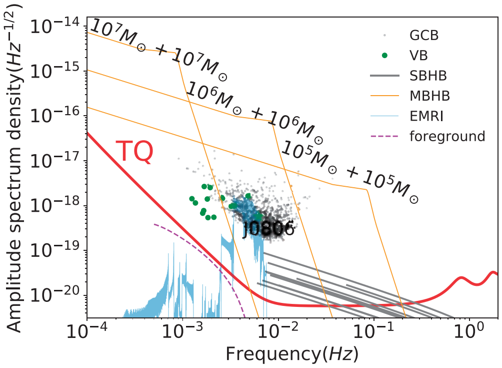

Fig. 1. Expected astrophysical sources for TianQin. In this plot, the information of the detector response is included in the signal strain of each source, and the instrumental noise (the solid red curve) is approximated by dividing $S_n(f)$ by 10/3, which accounts for the geometric configuration of TianQin, as well as the location- and polarisation-sensitive response in the low-frequency limit.

can facilitate studies on the formation of neutron star systems through accretion-induced collapse in white-dwarf binaries [31]. TianQin also has the potential to detect GWs from deformed compact stars [32].

Electromagnetic observation has identified dozens of GCBs that have orbital periods shorter than a few hours [11,33–37]. These GCBs, once detected, can become very good calibration sources for the detector and they are referred to as verification binaries (VBs). For example, J0806 has the shortest known period of all GCBs [11]. TianQin can already detect J0806 with a signal-to-noise ratio (SNR) of 5 after only two days of observation. TianQin can also detect 12 VBs, for some of which the GW amplitude can be determined up to the 5% level if the amplitude and the inclination angle are not precisely known, while other parameters are assumed to be constrained by electromagnetic studies.

By using a synthetic population of GCBs, we find that TianQin can resolve about 8.7×10^3 GCBs, and for these events, the uncertainties in the parameter estimation center around $\Delta P/P = 31.6 \times 10^{-8}$, $\Delta\mathcal{A}/\mathcal{A} = 0.10$, $\Delta \cos\iota = 0.05$, and $\Delta\Omega_S = 7.94\ \mathrm{deg}^2$, where P and $\mathcal{A}$ are the period and amplitude of the GW signal, and ι and Ω_S are the inclination angle and the sky localization (the solid angle in which the source is located) of the source, respectively. Among the GCBs resolvable with TianQin, about 38% can be localized to better than 1 deg^2. In the lower frequency range, the incoherent addition of a vast number of GCBs will form a confusion noise, or sometimes referred to as a foreground. An order of magnitude estimation shows that TianQin may also detect one double white dwarf merger event. More detail on the detection of GCBs with TianQin can be found in Ref. [17].

2.2. *Stellar-mass black hole binaries*

Another type of quite promising source for TianQin is SBHBs. The discoveries made by the LIGO Scientific Collaboration and Virgo Collaboration have revealed that many SBHBs exist [38]. The merger of SBHBs will generate GWs with frequencies of order 100 Hz. However, years to months before the final merger the GWs are in the milliHertz regime, making SBHBs interesting sources for TianQin. SBHBs are ideal objects for multi-band GW detection, which not only improve the detection and measurement of the sources themselves but also make the SBHBs powerful laboratories for cosmology and fundamental physics, as illustrated by their potential use as standard sirens for cosmology [39] and to greatly improve the constraints on certain parameters of modified gravity theories [40]. It has been pointed out that TianQin can play an important role in detecting sources in the deciHertz frequency range [41,42], and that it is possible to learn about eccentricity distribution and formation channels by counting the number of SBHBs observed with TianQin [43]. Some work on the potential of using TianQin to test general relativity (GR) with GW signals from SBHBs can be found in Ref. [44].

There is a large uncertainty in the mass distribution of SBHBs. As many as five models have been adopted and calibrated by the LIGO Scientific Collaboration and Virgo Collaboration to study the population properties of SBHBs [45]. The expected number of detections depends strongly on the SNR threshold. Searching using template banks requires the SNR threshold for TianQin to be about 12. With this threshold, there is the possibility that a single-digit number of SBHB events can be detected with TianQin. With the advancement of data analysis techniques, the requirement on the SNR threshold may become less stringent by the time TianQin flies. If the SNR threshold is lowered to 8, then a single-digit number of detections becomes very probable and there is the possibility that the number of detections can reach a few dozen. For these events, the probability distribution in redshift peaks at $z \sim 0.05$, and the probability distribution in the logarithm of the total mass peaks at $M \sim 70\,\mathrm{M}_\odot$. Concerning the precision of parameter estimation, the probability distributions of the (relative) uncertainties in the coalescing time, the sky localization, the chirp mass, the eccentricity, and the luminosity distance peak at $\Delta t_c \sim 0.1$ s, $\Delta\bar{\Omega}_S \sim 0.1\,\mathrm{deg}^2$, $\Delta\mathcal{M}/\mathcal{M} \sim 10^{-7}$, $\Delta e_0/e_0 \sim 10^{-4}$, and $\Delta D_L/D_L \sim 20\%$, respectively. For a typical merger, the error volume is small enough to contain only the host galaxy, while it can be as small as $2\,\mathrm{Mpc}^3$ in the most optimal cases. More detail on the detection of SBHBs with TianQin can be found in Ref. [16].

2.3. *Massive black hole binaries*

Most galaxies in the universe host a massive black hole at their centers [46–49]. The mass of the central black hole is intimately related to the intrinsic parameters of the corresponding host galaxy. When galaxies collide, sometimes the massive black holes form gravitationally bound pairs, i.e. MBHBs, and eventually merge due to the loss of energy and angular momentum through GW radiation. The mergers of massive black holes are extremely strong sources of GWs, which travel through the universe for billions of years but can still preserve significant strength. Some of the signals will be detected by TianQin. The detection of GWs from the merger of MBHBs can help reveal the origin and the formation channels of massive black holes, provide a new method to study the expansion of the universe at high redshift, and test various aspects of GR and the nature of black holes in the strong-field regime [14,15,50]. With GW signals from MBHBs, there is the possibility to use TianQin to explore non-singular black holes [51] and to constrain the mass spectrum and number of axion-like fields by measuring black hole spins [52].

How the massive black holes are formed throughout the history of the universe is still under debate. For example, it is unclear whether massive black holes are formed from the direct collapse of a massive cloud (the heavy seed model) or the remnant of Population III stars (the light seed model) [53], and various models have been proposed to depict the evolution of massive black holes [54–57]. By using five different models for the event rates of MBHBs, it has been found the expected detection rate varies significantly from one model to another, with the most pessimistic model predicting less than 0.1 detections per year, and the most optimistic predicting nearly 60 detections per year, while other intermediate models predict $\mathcal{O}(1 \sim 10)$ detections per year. If MBHBs with nearly equal component masses of order $10^4 \sim 10^5\,\mathrm{M}_\odot$ at redshift 15 are detected with TianQin, then the SNR can reach above 20 and both the luminosity distance and the chirp mass can be determined at the 10% level. This will enable the discrimination of different seed models. For relatively low redshift (e.g. $z = 2$) sources, for which there is the chance of finding an electromagnetic counterpart, TianQin has enough sensitivity to detect sources with chirp masses in the range $10^4 \sim 10^6\,\mathrm{M}_\odot$ 24 hr before the final merger. Such detections can have SNRs as large as 23 and a sky localization error of less than $100\,\mathrm{deg}^2$, and so can be used to trigger and guide the observation of the coincident electromagnetic signals. More detail on the detection of MBHBs with TianQin can be found in Refs. [12,13].

It is interesting to consider the possible scenario that TianQin is observing at the same time as another detector, such as LISA. In this case the simultaneous detection of an MBHB merger signal can significantly improve the precision of source parameter estimation, such as three-dimensional localization and the merger time (W. Feng et al., in preparation).

2.4. *Extreme mass ratio inspirals*

The massive black hole in the center of a galaxy in the local universe can be accompanied by a nuclear stellar cluster with a size of a few parsecs and a mass up to $10^7 \sim 10^8\,\mathrm{M}_\odot$ [58]. Compact objects such as stellar mass black holes can sink into the gravitational potential well through two-body relaxation. If they later become gravitationally bound with the massive black hole, these compact objects may eventually merge into the massive black hole through gravitational radiation. The GW signals from such events, called EMRIs, have distinct features: they can last for hundreds of thousands of cycles, and they stop abruptly if the central objects are really Kerr black holes as predicted by GR. The detection of such GW signals with TianQin can precisely map the surrounding geometry of central black holes and help test the Kerr hypothesis and GR to exquisite precision [59]. It has also been shown that the detection of EMRIs with TianQin can be used to study boson stars [60], to reveal new formation channels of EMRIs through the detection of their electromagnetic counterparts [61], and to further reveal the dynamics around the central massive black hole in our own Galaxy [62].

The rate of EMRIs depends on a variety of astrophysical processes determining the evolution of massive black holes and the surrounding compact objects. A dozen population models have been developed by Babak et al. [63]. The calculation of accurate EMRI waveforms is the most challenging among all GW sources. Despite a lot of progress, the problem of accurately and efficiently generating full EMRI waveforms with the effect of self-force is still open [64–70]. In this regard, "kludge" EMRI waveforms have been used to reduced the computational burden [18,63]. With additional uncertainties in the plunge time of EMRI waveforms, it has been found that dozens to thousands of EMRIs may be detected with TianQin, with the horizon distance marked by sources with masses of order $10^6\,\mathrm{M}_\odot$ at redshifts near $z = 2$. For the parameters that strongly affect the phases of GWs, the relative precision of parameter estimation is typically of order 10^{-6}. For other parameters, such as the luminosity distance and the sky localization, the (relative) uncertainty can be constrained to better than $\Delta D_\mathrm{L}/D_\mathrm{L} \sim 10\%$ and to $\Delta\Omega_\mathrm{S} \sim 10^{-3}\,\mathrm{deg}^2$, respectively, for the majority of sources. The determination of the three-dimensional location is precise enough that the detected EMRIs can be used as standard sirens for cosmological study [71,72]. More detail on the detection of EMRIs with TianQin can be found in Ref. [18].

2.5. *Various cosmological processes*

In addition to the late-stage astronomical objects described in the preceding subsections, many processes related to the (very) early universe can produce a (SGWB).[1] The main generating mechanisms

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[1] SGWB can also have other origins, such as purely astronomical processes, and even interactions of massive black holes with ultralight bosons [73,74].

include the amplification of vacuum fluctuations re-entering the Hubble horizon during inflation, post-inflationary preheating and related non-perturbative phenomena, first-order phase transitions (PTs) of the early universe, and cosmic defects due to symmetry-breaking of topological structure (see Ref. [75] for a recent review). Recent studies have analyzed the important consequences of the first-order PTs that are triggered by introducing an effective operator [76], by the extended Higgs sector [77–82], as well as by other exotic TeV-scale particles (i.e. axion-like particles [83,84], heavy neutrinos [85,86], and composite resonances [87]), and have subsequently assessed the potential of using TianQin to detect the SGWB produced from these processes. In some well-motivated scenarios, TianQin can detect SGWB of cosmological origin with an optimal SNR as high as order 10^5 (Z.-C. Liang et al., in preparation). So TianQin has the potential to probe energy scales above the reach of near-future particle accelerators [83,85–87] and even up to the grand unified theories scale [88].

The formation of cosmic string networks during the process of symmetry-breaking also produces a SGWB, which can be an important observational effect of grand unified theories [89]. In some idealistic cases, TianQin may be able to probe the general network of cosmic defects with tensions $G\mu \gtrsim \mathcal{O}(10^{-6})$, and particularly cosmic strings with $G\mu \gtrsim \mathcal{O}(10^{-17})$, corresponding to the scale of symmetry-breaking at 10^{16} GeV and 10^{10} GeV, respectively (Z.-C. Liang et al., in preparation). Finally, the detectability of secondary GW backgrounds produced during inflation and from primordial black holes after inflation has been evaluated in Refs. [90–93].

Therefore, if any of these GW backgrounds is detected in the future, it will provide crucial information on cosmic history and place constraints on the fundamental theories describing the early universe or the low-energy effective theories related to particle physics around the TeV scale. More details of using TianQin to detect SGWB will be given in Z.-C. Liang et al., in preparation, which will also contain a detailed explanation of how to use the TianQin sensitivity curve in this regard.

2.6. *Cosmology and fundamental physics*

GW signals detected with TianQin can be used to fill in gaps in the expansion history of the universe. Important information can come from detecting SBHBs within a redshift of order 0.1, EMRIs within a redshift of order 1, and the merger of MBHBs at other high redshifts. The detection/null detection of primordial GWs can offer valuable information on the history of the early universe [90–92]. It has been found that, under ideal circumstances, the observation of massive black hole binary mergers can pinpoint the Hubble constant to a precision of the order of 10^{-2} [94] (see also L. Zhu et al., in preparation).

Every aspect of GWs can be used to test GR. At the stage of generation, GWs from GCBs are best used for testing the extra radiation channels and extra polarization modes of GWs;[2] SBHBs are ideal sources for multi-band observations that can help improve by orders of magnitude the constraints on certain parameters describing deviations from GR [40,102]; the mergers of MBHBs are ideal sources for testing various post-Einstein parameters and the Kerr nature of black holes; and EMRIs can be used to study the surrounding geometry of a massive black hole to high precision. At the propagation stage, GW signals from faraway sources can be used to constrain the dispersion relation and the speed of GW propagation. As a quantitative analysis of how TianQin can perform, a test of the black hole no-hair theorem and a study of the constraint on a particular modified gravity theory

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[2] A study devoted to the extra polarizations of GWs from different gravitational theories and the corresponding responses and sensitivities of TianQin can be found in Refs. [95–101].

using ringdown signals from the merger of MBHBs have been carried out in Refs. [14] and [15], respectively.

3. Roadmap and technology progress

Inertial reference and inter-satellite laser interferometry are two core technologies of TianQin, and the corresponding technology requirements, grossly characterized by S_{a} and S_x in Table 1, are prerequisites to achieving the scientific goals discussed in the previous section.

As an important foundation to meeting such requirements, the study and development of inertial sensors based on capacitive sensing and electrostatic control have been underway since 2000 at the Centre for Gravitational Experiments, Huazhong University of Science and Technology (CGE-HUST). Several flight models have been constructed and successively tested in orbit [103]. Efforts are being made to further improve on the performance of the instruments [104,105]. A study of the effect of space plasma on the motion of test masses has been carried out [106]. The development of high-precision laser interferometers has been underway since 2002. A demonstration system of a laser interferometer with 10 m armlength was built in 2011 [107], and a prototype transponder-type inter-satellite laser interferometer was constructed and tested in 2015 [108,109]. Further efforts in this direction include the study of inter-satellite laser link acquisition [110] and sampling the jitter noise of the digital phasemeter [111]. Relativistic effects on laser propagation and clock comparison have been studied [112,113], while a large-scale passive laser gyroscope aiming to help link the celestial and terrestrial reference frames is being developed [114,115].

In order to systematically bring the key technologies of TianQin to maturity, a technology roadmap called the 0123 plan has been adopted since the beginning of the TianQin project:

- Step 0: Acquiring the capability to obtain high-precision orbit information for satellites in the TianQin orbit through lunar laser ranging experiments.
- Step 1: Using single-satellite missions, where the main goal is to test and demonstrate the maturity of the inertial reference technology.
- Step 2: Using a mission with a pair of satellites, where the main goal is to test and demonstrate the maturity of the inter-satellite laser interferometry technology.
- Step 3: Launching a constellation of three satellites to form the space-based GW observatory, TianQin.

At each step, one to several independent missions/projects are expected, depending on the progress of technologies and the opportunities for space missions, and the numbers labelling the steps are the numbers of dedicated satellites which need to be built for each independent mission/project of the step.

In the following, we report on two major projects, one in Step 0 and the other in Step 1, that are being carried out.

3.1. Lunar laser ranging

In order to help better determine the positions of the TianQin satellites, lunar laser ranging (LLR) has been an important part of the TianQin project since early on. Because no dedicated satellite needs to be built for this part of the work, all the projects related to LLR are categorized as Step 0.

A major project on LLR was jointly approved and supported by the China National Space Administration (CNSA) and the National Natural Science Foundation of China (NSFC) in 2016. The project mainly involves upgrading/constructing laser ranging stations on the ground and creating a new generation of corner-cube retro-reflectors (CCRs) to be installed on the lunar relay satellite, QueQiao, for the Chang'E 4 mission.

Through the project, the LLR station of the Yunnan Observatories in Kunming has been upgraded, and on 22 January 2018 the station became the first in China to have successfully ranged to the Moon [116]. A new laser ranging station equipped with a 1.2 m telescope has also been constructed on Fenghuang mountain near the Zhuhai Campus of Sun Yat-sen University. The station has successfully received laser ranging signals from all five retro-reflectors on the Moon. A single-body hollow CCR with 17 cm aperture has also been created and was launched with the QueQiao satellite on 21 May 2018 [117].

3.2. The TianQin-1 satellite (TQ-1)

The major objectives of TQ-1 include testing the technologies of inertial sensing, micro-Newton propulsion, drag-free control, laser interferometry, temperature control, and center-of-mass measurement with in-orbit experiments.

The preparation for TQ-1 started in 2016 and the project received official approval from CNSA in 2018. Support for TQ-1 has also been provided by the Ministry of Education, the Guangdong Provincial Government, and the Zhuhai Municipal Government of the People's Republic of China. TQ-1 was successfully launched on 20 December 2019 from the Taiyuan Satellite Launch Center in north China's Shanxi Province. The satellite completed its startup phase on 21 December 2019 and has been functioning smoothly since then.

Results show that the satellite has exceeded all of its mission requirements: by using the inertial sensor, which has a sensitivity of $5 \times 10^{-12}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$ at 0.1 Hz, as the key tool, the acceleration of the satellite has been measured and found to be about $1 \times 10^{-10}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$ at 0.1 Hz and about $5 \times 10^{-11}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$ at 0.05 Hz. The performance of the micro-Newton thrusters has been evaluated, and the thrust resolution is found to be about 0.1 μN while the thrust noise is found to be about 0.3 $\mu\mathrm{N\,Hz^{-1/2}}$ at 0.1 Hz. The residual noise of the satellite after drag-free control was measured and found to be about $3 \times 10^{-9}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$ at 0.1 Hz, which mainly comes from the micro-Newton thrusters. The mismatch between the center-of-mass of the satellite and that of the test mass has also been measured with a precision better than 0.1 mm; the noise level of the optical readout system is about $30\,\mathrm{pm\,Hz^{-1/2}}$ at 0.1 Hz; the temperature stability at key temperature monitoring positions has been controlled to about ±3 mK per orbit (about 97.13 min). More details on the performance of TQ-1 can be found in Ref. [118].

By providing first-hand data on the in-orbit performance of the key payloads that are essential to the TianQin project, and by narrowing/quantifying the gap between the current technology capability and the requirements of TianQin, TQ-1 has marked a new milestone in the development of the TianQin project.

3.3. Other developments

3.3.1. Dedicated research facilities

The TianQin project involves the construction of a few dedicated research facilities:

- The TianQin research building: to be used for research and technology development for the TianQin project. The building has been finished, has a total area of more than 37 000 m^2, and is scheduled to open in 2020.

- The TianQin cave lab: to be used for research and technology development for the TianQin project. Excavation of the cave lab tunnel started in 2019, and the tunnel was holed through on 5 June 2020.
- The Ground Simulation Facility (GSF): to be used for the integrated test and research on TianQin technologies and prototypes. A pre-study project has been approved for the construction of this facility.

3.3.2. International collaboration

International collaboration is an important aspect of the TianQin project. There have been six International Workshops on the TianQin Science Mission since 2014. On 18 December 2018, the TianQin Collaboration, including its international advisory committee, was formally established during the fifth TianQin Workshop.

Acknowledgements

This work was supported in part by the Guangdong Major Project of Basic and Applied Basic Research (Grant No. 2019B030302001) and the National Natural Science Foundation of China (Grant Nos. 11703098, 11805286, 11805287, 11975319, 11654004, 11655001, 41811530087, 11690022). David Blair and Gerhard Heinzel provided helpful comments and suggestions while the paper was being prepared.

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