PROCEEDINGS OF SCIENCE

Development of Torsion-Bar Antenna for Low-Frequency Gravitational-Wave Observation

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Torsion-Bar Antenna (TOBA) is a ground-based gravitational-wave detector for low frequency. TOBA can detect intermediate-mass black hole binary mergers, gravitational wave stochastic background, and Newtonian noise. TOBA is also useful for earthquake early warning. TOBA consists of two 10-m test masses suspended horizontally and we aim to detect the torsional rotation of pendulums caused by tidal forces. The resonant frequency of torsional motion is ~ 1 mHz, therefore TOBA has good design sensitivity of $1 \times 10^{-19}\ /\sqrt{\mathrm{Hz}}$ between 0.1 Hz and 10 Hz. We are currently developing the third prototype detector Phase-III TOBA with 35 cm-scale pendulums at cryogenic temperature to demonstrate noise reduction. The target sensitivity is set to $1 \times 10^{-15}\ /\sqrt{\mathrm{Hz}}$. In this paper, we will present the principle and science of TOBA and the status of the development of Phase-III TOBA.

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1. Introduction

Currently operating gravitational wave detectors, Advanced LIGO, Advanced Virgo, and KAGRA, are sensitive between 10 Hz-1 kHz [1–4] and successfully detected gravitational waves from solar-mass black hole and neutron star binary mergers [5]. To observe gravitational waves in the lower frequency range (0.1 Hz-10 Hz), various kinds of detectors have been proposed and are being developed. These detectors are expected to observe intermediate-mass black hole binary mergers and the gravitational wave stochastic background. One possible way to obtain highly sensitive detectors between 0.1-10 Hz is to use spacecrafts such as LISA and DECIGO [6, 7]. Spacecrafts are free from seismic noise and can be regarded as free masses in all frequencies. However, the cost of development is expensive and maintenance is difficult. Another way is to develop ground-based detectors using a different principle from the current detectors. Torsion-Bar Antenna (TOBA) is composed of torsion pendulums and we aim to detect the rotational motion of said torsion pendulums caused by gravitational waves [8]. The target strain sensitivity of TOBA is set to $1 \times 10^{-19}\ /\sqrt{\mathrm{Hz}}$ between 0.1 Hz and 10 Hz. We are developing the third prototype detector named Phase-III TOBA, which has the sensitivity of $1 \times 10^{-15}\ /\sqrt{\mathrm{Hz}}$ [9].

In this paper, we will introduce the conceptual design, target sensitivity, and scientific objectives of TOBA in Section 2. In Section 3, we will present the third prototype detector Phase-III TOBA and the current status. Finally, in Section 4, we will provide a summary.

2. Torsion-Bar Antenna

TOBA was proposed to detect gravitational waves between 0.1-10 Hz [8]. The target sensitivity of TOBA is set to $1 \times 10^{-19}\ /\sqrt{\mathrm{Hz}}$. The configuration of TOBA is shown in Figure 1. TOBA is composed of two 10-m test mass bars suspended horizontally on the ground. We aim to detect the torsional rotation of TOBA caused by tidal forces due to gravitational waves. TOBA has better sensitivity in low frequency compared to current detectors since the resonant frequency of torsional motion is lower than that of translational motion.

The science of TOBA can be divided into two aspects: astrophysics and geophysics. For astrophysics, we can observe intermediate-mass black hole binary mergers within ∼10 Gpc and gravitational wave stochastic background up to $\Omega_{\mathrm{GW}} \sim 10^{-7}$ [8]. TOBA will also provide us with geophysical information thanks to the ground-based configuration. Newtonian noise is the fluctuations of the gravitational field caused by any moving masses [10]. Representative examples are seismic Newtonian noise [11] and atmospheric Newtonian noise [12, 13]. Newtonian noise is a candidate for the dominant noise for third-generation detectors, Einstein Telescope, and Cosmic Explorer [14, 15]. First direct detection of Newtonian noise is expected with TOBA [16]. In addition, TOBA can improve earthquake early warning systems. The current earthquake early warning systems in the world use the velocity difference between the two seismic waves. Seismometers detect P-wave (propagation speed of $\sim 6\,\mathrm{km/s}$) and trigger an alert when the following S-wave ($\sim 4\,\mathrm{km/s}$) is predicted to be large [17]. Gravity perturbation caused by fault rupture propagates with the speed of light, which is much faster than seismic waves [18]. TOBA may observe the prompt gravity perturbations within 10 s after rupture onset [19].

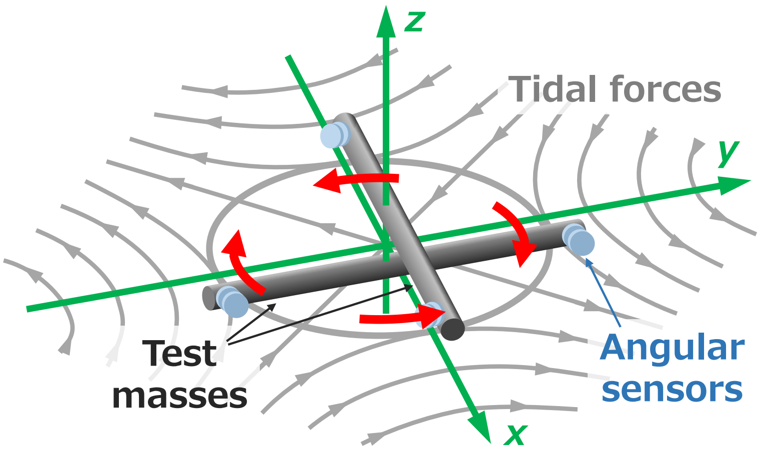

Figure 1: The configuration of TOBA. Two test mass bars are suspended on the $x - y$ plane on the ground. Gray arrows show tidal forces by gravitational waves and red arrows represent the differential motion of test masses by tidal forces. Angular sensors with optical cavities are attached to the edges of bars.

3. Phase-III TOBA

In order to confirm the detection principle, we developed two prototype detectors named Phase-I TOBA and Phase-II TOBA. We achieved the sensitivity of $1 \times 10^{-8}\ /\sqrt{\text{Hz}}$ at 0.1 Hz and $1 \times 10^{-10}\ /\sqrt{\text{Hz}}$ at 7 Hz, respectively, and placed the upper limits to gravitational wave stochastic background [20–23]. Now, we are developing the third prototype detector, Phase-III TOBA, to demonstrate noise reduction [9]. The target sensitivity of Phase-III TOBA is set to $1 \times 10^{-15}\ /\sqrt{\text{Hz}}$ between 0.1 Hz and 10 Hz with 35 cm bars as shown in Figure 2. Phase-I and Phase-II TOBA were operated at room temperature, but Phase-III TOBA is operated at cryogenic temperature (4 K) to reduce thermal noise. After establishing Phase-III TOBA, we plan to build the final version of TOBA with 10 m bars to detect gravitational waves of $1 \times 10^{-19}\ /\sqrt{\text{Hz}}$ in the range of 0.1-10 Hz.

The sensitivity of Phase-III TOBA is worse than that of the final version of TOBA by four orders of magnitude, but Phase-III TOBA can provide us with a lot of valuable science. Phase-III TOBA will observe intermediate-mass black hole binary mergers within ~1 Mpc and Newtonian noise directly. Earthquakes with magnitude 7 at 100 km away from Phase-III TOBA are expected to be detected within 10 s [24].

The configuration of TOBA is shown in Figure 3. To achieve our target sensitivity, we are developing some essential components: torsion pendulums, high Q-value suspension wire, readout optics, and active vibration isolation system. We will build torsion pendulums with test masses made of silicon to reduce thermal noise and magnetic field noise. The cross-coupling from translational seismic noise to the torsional motion of the pendulum will be one of the dominant noise sources and the requirement of the transfer function is 1×10^{-10} rad/m [25]. We are carefully designing a suspension system to fulfill the requirement. A suspension wire with a high Q-value of $\sim 10^8$ at 4 K is also needed to reduce thermal noise. We are developing wires made of sapphire. We need to probe the rotation of the pendulum precisely. We plan to use laser interferometers to measure the rotation. The requirement of shot noise for Phase-III TOBA is 5×10^{-16} rad$\sqrt{\text{Hz}}$. Michelson interferometers are often used as angular sensors by putting two-arm mirrors on the edge of the

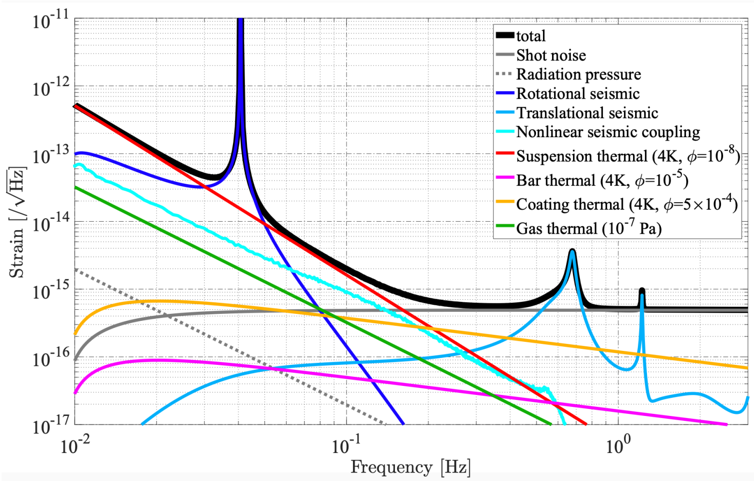

Figure 2: The target sensitivity of Phase-III TOBA [24]. The black thick line shows the target sensitivity and the others represent noise budget.

bars, but they do not have sufficient sensitivity [20, 23, 26]. Possible candidates are improved types of wavefront sensors and differential Fabry-Pérot cavities. We demonstrated two types of wavefront sensors: folded cavity and coupled cavity configuration [27]. In our method, we can enhance the angular signal due to the Gouy phase compensation. Currently, we are working on differential Fabry-Pérot cavities to read the cavity length change at two points of bars with the PDH method [28, 29] and subtract them. Finally, to reduce vibration noise at suspension point from seismic noise and cryocooler, we installed an active vibration isolation table. We are developing a tiltmeter to further reduce noise.

4. Outlook

TOBA is a ground-based gravitational-wave detector for low frequency. TOBA can detect intermediate-mass black hole binary mergers, gravitational wave stochastic background, and Newtonian noise, and is useful for earthquake early warning. TOBA consists of two 10-m test masses suspended horizontally and we aim to detect the torsional rotation of pendulums caused by tidal forces. The resonant frequency of torsional motion is $\sim$ 1 mHz, therefore TOBA has good design sensitivity of 10^{-19} $/\sqrt{\text{Hz}}$ between 0.1 Hz and 10 Hz.

We are currently developing the third prototype detector Phase-III TOBA with 35 cm-scale pendulums at cryogenic temperature to demonstrate noise reduction. The target sensitivity is set to 10^{-15} $/\sqrt{\text{Hz}}$. To achieve our target sensitivity, some essential components are under development. Phase-III TOBA is expected to contribute to multi-messenger astronomy, noise reduction for the third-generation gravitational detectors, and earthquake early warning.

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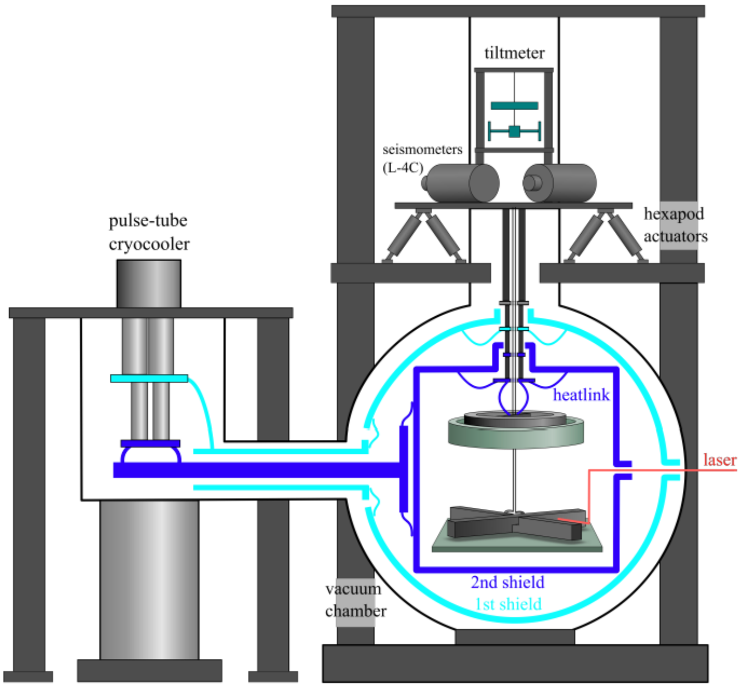

Figure 3: The configuration of Phase-III TOBA [24]. The torsion pendulums are built in the vacuum chamber and cooled down with a cryocooler. Laser light is injected to read out the rotation of the pendulums. Seismometers, hexapod actuators, and a tiltmeter are located on the pendulum to reduce vibration noise by active feedback control.

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