Space gravitational wave antenna DECIGO and B-DECIGO

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Abstract Since the direct detection of gravitational wave will give us a fruitful insight about the early universe or life of stars, laser interferometric gravitational wave detectors with the strain sensitivity of higher than $10^{-22}$ have been developed. In Japan, the space gravitational wave detector project named DECi-hertz Gravitational wave Observatory (DECIGO) has been promoted which consists of three satellites forming equilateral triangle-shaped Fabry–Perot laser interferometer with the arm length of 1000 km. The designed strain sensitivity of DECIGO is $2 \times 10^{-24}/\sqrt{\text{Hz}}$ around 0.1 Hz whose targets are gravitational waves originated from the inspiral and the merger of black hole or neutron star binaries and from the inflation at the early universe, and no ground-based gravitational wave detector can access this observation band. Before launching DECIGO in 2030s, a milestone mission named B-DECIGO is planned which is a downsized mission of DECIGO. B-DECIGO also has its own scientific targets in addition to the feasibility test for DECIGO. In the present paper, DECIGO and B-DECIGO projects are reviewed.

Keywords Gravitational wave · Laser interferometer · Black hole binary · Stabilized laser · Precision measurement

1 Introduction

In 1916, Albert Einstein had predicted in his general theory of relativity that the asymmetric motion of mass will cause ripples of the gravitational fields whose space–time distortion propagates as a quadrupole wave with the speed of light, which is called gravitational wave (GW) [1]. GW is generated from the temporal variation of masses such as inspiral and merger of heavy binary stars, the explosion of supernovae or from the inflation at the early universe, and it will give us much fruitful information about the universe that can be hardly obtained from the conventional electromagnetic wave observations. Therefore, there has been long struggle for direct detection of gravitational wave to open a new window of GW astronomy. From 1990s, GW detection projects using long-baseline Michelson laser interferometers have been started since GW acts as the tidal force fluctuations on two proof mass mirrors. As GW has very small interaction whose expected strain is extremely small as low as $l/l = 10^{-23}/\sqrt{\text{Hz}}$, it is very hard to be detected. Currently, five terrestrial gravitational wave detectors, the Hanford and the Livingston observatories in Advanced LIGO [2], Advanced VIRGO [3], KAGRA [4] and GEO600 [5], have been undergoing for direct detection of GW with the detection band between 10 Hz and 1 kHz, all of which are Fabry–Perot or delay-line Michelson laser interferometers with the arm length from 600 m to 4 km. After a long effort for improving strain sensitivity of the detectors, Advanced LIGO group has succeeded in the first direct detection of GW in 2015 [6] where the detected signal comes from the inspiral and the merger of the black hole binaries with the mass of 36 and 29 $M_\odot$ (solar mass) in the last few hundred milliseconds before merger, which is called GW150914. The successive detections of GW originated from black hole binaries or neutron star binaries [7–10] are followed...
by GW150914, and the GW astronomy has been just established by the terrestrial GW detectors. The detection band of such terrestrial GW detectors, however, cannot be expanded to lower frequency range due to their finite arm length, the gravity gradient noise and the seismic noise from the ground. To access the lower frequency band below 1 Hz where many attractive GW sources are expected, GW detectors should have much longer arm length and should be operated in the seismic and gravity gradient noise free condition. One of the solutions for detecting low-frequency GW signal is a space GW detector. Two space GW detector projects have been currently promoted: one is a Europe-US joint project named LISA (Laser Interferometer Space Antenna) [11] [12] and the other is Japanese DECIGO project [13], and recently China also proposes their own LISA-like mission named Taijin [14]. In the present paper, on behalf of DECIGO working group, I review Japanese space gravitational wave detector DECIGO and its milestone mission B-DECIGO whose main targets are GW from compact binaries and the early universe.

2 DECIGO

In Japan, there are two GW detection projects now undergoing; one is the terrestrial GW detector named KAGRA which is a cryogenic-type Fabry–Perot Michelson interferometer with the arm length of 3 km [4]. After 1-month test operation of the initial version of KAGRA (i-KGRA) in March 2016, KAGRA is now under improvement toward the science run of the second version of KAGRA (b-KGRA) in late 2018.

The other is the space GW detector named DECIGO which is named after DECi-heltz Interferometer Gravitational wave Observatory. The basic idea of DECIGO was proposed in 2001 by Seto et al. [13] whose initial motivation was to observe the acceleration of the universe by detecting GW from neutron star binaries with $z = 1$. The conceptual design of DECIGO is shown in Fig. 1. DECIGO consists of three formation-flight spacecrafts with keeping a 1000-km equilateral triangle shape, each of which contains one light source and two drag-free proof mass mirrors. The laser light is divided into two, both of which propagate to the test mass mirrors in other spacecrafts forming a differential 1000-km Fabry–Perot interferometer with the including angle of 60°. In its triangle configuration, DECIGO has three sets of differential Fabry–Perot laser interferometers. The positions of each spacecrafts are precisely controlled so that the proof mass mirrors keep floating in the spacecraft that act as free masses, which is called drag-free control. The distortion of the space time caused from GW results in the change of optical path length between two proof mass mirrors in each spacecrafts. The preliminary design parameters of DECIGO are listed in Table 1. Diameter and mass of mirrors are 1 m and 100 kg, respectively. The light source is the frequency- and intensity-stabilized laser with the wavelength of 515 nm and the output power of 10 W. The arm length is 1000 km, which is limited by the diffraction loss of the stored light in the Fabry–Perot cavity. In DECIGO mission, an equilateral triangle-shaped laser interferometer with three formation-flight satellite forms 1 DECIGO cluster (Fig. 1), and the final stage of the mission, four DECIGO clusters will be orbiting around heliocentric record-disk orbit for improving angular resolution, two of which are orbiting at the same point (overlapped clusters) for further sensitivity by correlation observations (Fig. 2).

The designed strain sensitivity of DECIGO is shown in Fig. 3a. The strain sensitivity at lower frequency range is determined by the acceleration noise to the test mass mirrors. After the external force noise, caused from the fluctuations of magnetic field, electric field, gravitational field, temperature or pressure, are suppressed down to $4 \times 10^{-17}$ N/√Hz, the radiation pressure noise from the laser limits the strain sensitivity, which is proportional to $f^{-2}$ in units of √Hz due to the inertia of mass (green trace in Fig. 3a). On the other hand, the strain sensitivity at higher frequency range is limited by the photon shot noise on the photo detectors, which has the frequency tendency of $f^0$ to $f^1$ in unit of √Hz due to the signal averaging effect in the arm cavity (blue trace in Fig. 3a). To reach the shot noise limit level of the detector, the frequency noise of the laser should be suppressed down to 1 Hz/√Hz at 1 Hz where common mode rejection ratio (CMRR) and the final frequency stabilization gain are $10^5$ and $10^8$, respectively. The designed strain sensitivity shown in Fig. 3a is determined by the quantum
noise of radiation pressure and photon shot-noise mentioned above, and the highest strain sensitivity of $l/l = 10^{-24}/\sqrt{\text{Hz}}$ is achieved at the observation band between 0.1 and 1 Hz (red dotted trace in Fig. 3a). The target band of LISA, which is a 2,500,000-km triangle-shaped laser interferometer with the optical transponder configuration, is much different from that of DECIGO (green trace in Fig. 3b). Detection band of DECIGO at 0.1 Hz is much higher than that of LISA at 1 mHz due from its shorter arm length of 1000 km, and, on the other hand, DECIGO has higher strain sensitivity around 0.1 Hz because the combination of the high power light source and the Fabry–Perot cavity stores much photon for decreasing shot-noise limited level. In the consequence, the detection band of DECIGO bridges the frequency gap between those of LISA and terrestrial gravitational wave detectors (brown trace in Fig. 3b).

To realize the space GW detector with such high strain sensitivity, the following technical problems should be overcome. The strain sensitivity level of $2 \times 10^{-18} \text{m}/\sqrt{\text{Hz}}$ has been already achieved by the km-class terrestrial GW detectors ($10^{-20} \text{m}/\sqrt{\text{Hz}}$ at 100 Hz). The strain sensitivity of DECIGO should reach this level by the interferometer with longer arm length of 1000 km at lower frequency at 0.1 Hz in the space environment. The required frequency noise level of the light source is 1 Hz/\sqrt{Hz} around 1 Hz, whose frequency noise level has been already achieved in the laboratory condition using stable optical cavities as a frequency reference. Since the stability of the optical cavity is very sensitive to the external perturbations such as mechanical vibrations or thermal fluctuations, we have developed the frequency-stabilized light source in reference to the molecular absorption, whose stability is less sensitive to the external perturbations and has better long-term frequency stability. DECIGO requires the mirrors with the radius of curvature of 1000 km, which corresponds to the sagitta of 1 μm. As it is hard to obtain such curvature by polishing the mirror, we have developed the technique for distort the mirror surface thermally using CO$_2$ laser. The external force noise to the test mass mirrors should be suppressed to lower

Table 1 Preliminary parameters

| Mission   | Arm length (m) | Mirror weight (kg) | Mirror diam (m) | Cavity finesse | Laser power (W) | Orbit       | Number of clusters |
|-----------|----------------|--------------------|-----------------|----------------|-----------------|-------------|-------------------|
| B-DECIGO  | 100            | 30                 | 0.3             | 100            | 1               | Geocentric  | 1                 |
| DECIGO    | 1000           | 100                | 1.0             | 10             | 10              | Heliocentric| 4                 |

Fig. 2 One of the orbit candidates for DECIGO. The cartwheel orbit around the sun: two overlapped units for cross correlation observation, separate units for increase angular resolution

Fig. 3  a Design strain sensitivity of DECIGO with noise budgets.  b Strain sensitivity of DECIGO (red-solid), DECIGO-correlated (red-dotted), B-DECIGO (blue), LISA (green) [11] and KAGRA (brown) [4]. Yellow trace and brown arrow indicate GW amplitude from the merger of 30–30 $M_\odot$ black hole binaries (GW150914-like) and from neutron star (NS) binaries, respectively
than $1 \times 10^{-16}$ N/√Hz, which is the most serious problem. ESA’s gravity mission, GOCE, has realized the force noise of $1 \times 10^{-12}$ N/√Hz, and LISA pathfinder achieved the force noise level as low as $10^{-14}$ N/√Hz in 2016 [15]. It is very hard to reach the force noise of $10^{-16}$ N/√Hz level which is 1/20 of the requirement force noise of LISA. In the first step we have developed the torsion bar based precision force detection system for evaluating extremely small force noise, and also estimated the effect of gravity, EM force, residual gas, thermal radiation, cosmic ray, control noise etc. on the force noise to the test mass. The vibration noise of the satellite should be suppressed to $1 \times 10^{-9}$ m/√Hz level at 0.1 Hz for realizing the requirement force noise to the test mass. To achieve this vibration level, the active vibration cancellation system may be required. For keeping triangle shape interferometer, the stable formation flight technique should be established whose fluctuations of the 1000-km arm length should be controlled within 500 m. The optimum orbit design and the precision micro thruster are essential for stable formation flight.

With its designed strain sensitivity, DECIGO has three main scientific targets. The first target is GW from the inspiral and the merger of the intermediate-mass ($10^3$–$10^5$ M$_\odot$) black hole (IMBH) binaries. Since these multiple collision are expected to result in the supermassive black holes, the detection of these GW will give us the inspection of forming mechanism of supermassive black hole in the center of galaxy [16]. The second target is the distant neutron star binaries with the redshift of 1, which will give us the information about mass distribution of neutron stars (brown arrow in Fig. 3b). Besides these binary targets, the possibility of detecting GW from intermediate mass-ratio inspiral (IMRI) is also discussed [17].

The most interesting target of DECIGO is the stochastic background GW from the inflation at the early universe. We can investigate these phenomena such as primordial black holes, inflation or astrophysics objects in the early universe only by detecting GW because no electric–magnetic wave propagates from these eras when high-energy plasma was filled in the whole space. The background GW is originated from the quantum fluctuations during the inflation, and its spectral shape involves the information about the evolution history of the universe. Figure 4 shows the spectrum of background GW from inflation (black dotted line). $\Omega_{\text{GW}}$ is GW energy ratio for critical density of the universe. Black hatches denote foreground GW from binaries: WD white dwarf, NS neutron star, MBH massive black hole, PPTA Parkes pulsar timing array.

reheating temperature or thermal evolution history of the universe. The amplitude of GW signal, $\tilde{h}_{\text{GW}}(f)$, is proportional to $(\Omega_{\text{GW}}(f))^{1/2} f^{-1.5}$ which becomes weaker at higher frequencies, and, on the other hand, the lower frequency below 0.1 Hz, there stays the foreground GW signal originated from many massive black hole binaries and white dwarf, neutron star binaries, and these unresolved signals mask the background GW signals (see Fig. 4). Therefore, only DECIGO can access the open window for direct observation of the early universe. The interferometer design of DECIGO shown in this session is the preliminary one, and is the first step to confirming the conceptual design. The various combinations of parameters are under investigation for improving the sensitivity of the interferometer. For example, the longer arm length of 1500 km, higher laser power of 30 W, and mirrors with larger diameter of 1.5 m with the same weight result in the improvement of the strain sensitivity by factor of 3. Final design should be confirmed for taking targets, budget and technical practicality into considerations.

3 B-DECIGO

Since the initial idea was proposed in 2001, we have promoted DECIGO project along the roadmap shown in Fig. 5. As DECIGO is a very large mission in the aspect of resources or technical issue, we had planned three milestone missions before launching DECIGO in 2030s. The first demonstration mission was SWIM$\mu\nu$ which is a space-borne torsion-bar-type gravitational wave antenna (TOBA) operated on the JAXA’s small satellite (SDS-1) launched in 2009 [21]. SWIM$\mu\nu$ had successfully demonstrated 1-year operation of the sensing and control of the test mass in space.
After success of SWIM\(\mu\nu\) mission, the next milestone mission named DECIGO pathfinder (DPF) was planned which is a single small satellite with the payload of 220 kg [22]. The mission part of DPF is the 950-mm cube which contains a frequency-stabilized laser and a drag-free controlled 30-cm Fabry–Perot cavity. Main purpose of DPF was feasibility tests of key technologies for DECIGO, and was plan to be launched in 2016 around the low earth orbit with the altitude of 500 km. The drag-free-controlled test mass module, the interferometer module, the frequency-stabilized laser with the wavelength of 1030 nm [23] and the micro thruster unit had been developed for DPF [24] [25]. However, after long discussions, DPF mission was skipped, and we focus on the third milestone mission named B-DECIGO (whose provisional name is Pre-DECIGO [26]). Schematic diagram of B-DECIGO is almost the same as that of DECIGO; which consists of three spacecrafts forming equilateral triangle-shaped laser interferometer with Fabry–Perot optical cavities in each arms. The preliminary design parameters of B-DECIGO are also listed in Table 1. The arm length is 100 km, and each spacecraft has two drag-free-controlled test mass mirrors with the diameter of 30 cm and the weight of 30 kg, and two mirrors in different spacecrafts form Fabry–Perot cavities with the finess of 100. One candidate plan of B-DECIGO orbit is that each spacecraft flies along record-disk or cartwheel orbit around the earth, and the mass center of which orbits sun-synchronous dawn-dusk geocentric circle with the altitude of 2000 km for avoiding thermal shock from the sun, which is shown in Fig. 6. The initial positioning of the spacecrafts and the locking acquisition of the long Fabry–Perot cavities are now under investigation based on LISA project and the space optical communication project, OICETS [27]. The light source is the intensity- and frequency-stabilized lasers with the wavelength of 515 nm and the output power of 1 W. The required frequency and intensity noise of the light source are \(f = 10^9 \text{Hz}/\sqrt{\text{Hz}}\) and \(|I/I_0| = 1 \times 10^{-7}/\sqrt{\text{Hz}}\), respectively, which is the same level as those of DECIGO. We have developed the light source for DECIGO/B-DECIGO in which the second harmonics of the power-amplified Yb-doped fiber DFB laser at 1030 nm is frequency-stabilized in reference to the saturated absorption of iodine molecules around 515 nm [28]. We now promote

### Table 1

| Year | Mission        | Objective                      | Scope                  |
|------|----------------|--------------------------------|------------------------|
| 2012 | SWIM           | Ground Test                    | Micro-g experiment     |
|      |                |                                | Short F.P.cavity       |
|      |                |                                | drag-ree               |
|      | DPF            | Piggy Back                     | 3 S/Cs, 3 IFs         |
|      |                |                                | single-unit            |
|      |                |                                | M~ L S/C              |
|      |                |                                | 3 S/Cs, 3IFOs         |
|      |                |                                | 3 or 4 units           |
|      | DPF            | R&D Fabrication                | GW astronomy          |
|      |                |                                | BH-BH binary          |
|      |                |                                | Background GW         |

![Fig. 5 Roadmap toward DECIGO. DPF (DECIGO pathfinder) was skipped. Pre-DECIGO was renamed to B-DECIGO](image)

![Fig. 6 Preliminary Orbit design of B-DECIGO](image)
B-DECIGO project for applying JAXA’s Strategic Medium-Scale mission for launching B-DECIGO in late 2020s, and collaborate with JAXA’s members for developing technical issues such as formation flight or micro thrusters, and for sophisticating the mission plan.

Since B-DECIGO is a downsized mission of DECIGO, the designed strain sensitivity is $l/l_1 = 2 \times 10^{-23}/\sqrt{\text{Hz}}$ which is one order of magnitude worse than that of DECIGO (blue trace in Fig. 3b). B-DECIGO has initially started as a pathfinder of DECIGO, and its main purpose is the feasibility tests of the key technologies such as formation flight with the separation of 100 km, drag-free control of the proof masses and stable operation of the interferometer in space. However, the first detection of GW in 2015 (GW150914) revealed the existence of such a high mass black holes, and the detection probability of GW from the merger of black hole binaries is increased even with the strain sensitivity of B-DECIGO. Therefore, B-DECIGO also has defined scientific targets. GW from the inspiral of compact binaries such as 30–30 M$_\odot$ black hole binary like GW150914 with redshift up to $z \sim 30$ (yellow trace in Fig. 3b), whose event rate is expected to ~ $1.8 \times 10^5$ event per year calculated from the PopIII origin model [29]. GW from the inspirals and the mergers of intermediate-mass black hole (IMBH) binaries ($\sim 640$ M$_\odot$) is the original science target which reveals the formation history of supermassive black hole (SMBH) and galaxies, and the detection of the merger ringdown tail with SNR = 35 would confirm the general theory of relativity. B-DECIGO can also predict gravitational wave events as the merger of black hole binary about 24 h before the terrestrial GW antennas detect them: merger time with the accuracy of 1 s, and the direction of the source with the accuracy of 0.3 deg$^2$.

The other expected achievement of B-DECIGO is parameter estimation and character investigation of the foreground GWs for subtracting them from the background GW, which is very important for DECIGO to observe the background GW.

4 Conclusions

After the first detection of GW150914, new gravitational wave astronomy has started, and the space gravitational wave detectors would expand the detection band of the terrestrial detectors. In Japan, space gravitational wave detector DECIGO is planned to be launched in 2030 s with the strain sensitivity level of $l/l_1 = 10^{-24}/\sqrt{\text{Hz}}$ between 0.1 and 1 Hz. DECIGO is designed to detect GW from heavier (intermediate-mass) black hole binaries, and also access the open window for detecting GW from the early universe. Before launching DECIGO, B-DECIGO is also planned as a milestone mission whose target is GW150914-like events, and acts as the predictor of merger event for the terrestrial GW detector. The mission of Space GW detector has many technical walls to be overcome such as stable formation flight with 1000 km separation, locking acquisition of 1000-km Fabry–Perot cavity, drag-free control of the mirrors to decrease force noise down to $1 \times 10^{-16}$ N/√Hz level and stable operation of long interferometers in space. Against all these obstacles, the detection of GW will give us a lot of fruitful information, and hence we have promoted DECIGO project to deepen the insights about our universe.

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