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The status of DECIGO

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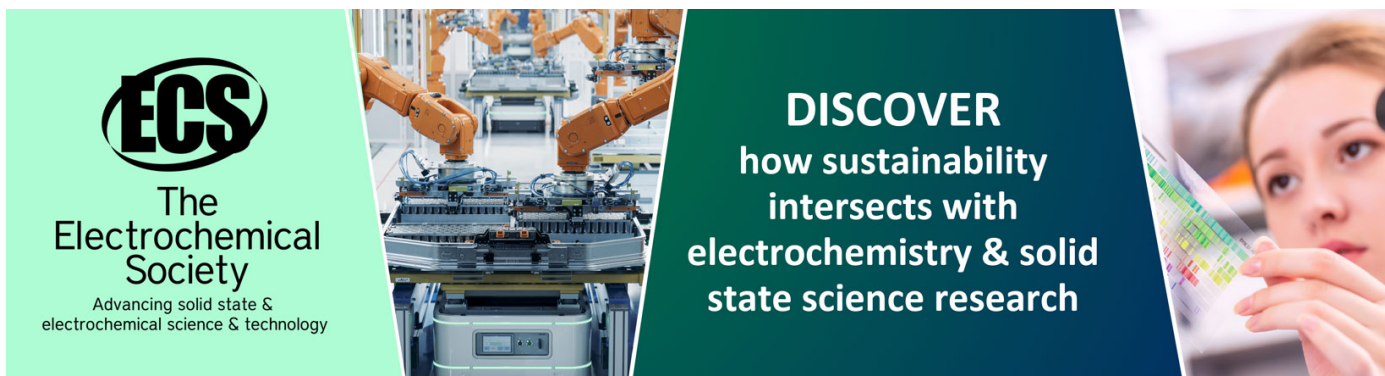
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The status of DECIGO

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Abstract. DECIGO (DECi-hertz Interferometer Gravitational wave Observatory) is the planned Japanese space gravitational wave antenna, aiming to detect gravitational waves from astrophysically and cosmologically significant sources mainly between 0.1 Hz and 10 Hz and thus to open a new window for gravitational wave astronomy and for the universe. DECIGO will consist of three drag-free spacecraft arranged in an equilateral triangle with 1000 km arm lengths whose relative displacements are measured by a differential Fabry-Perot interferometer, and four units of triangular Fabry-Perot interferometers are arranged on heliocentric orbit around the sun. DECIGO is a very ambitious mission, we plan to launch DECIGO in the era of 2030s after precursor satellite mission, B-DECIGO. B-DECIGO is essentially a smaller version of DECIGO: B-DECIGO consists of three spacecraft arranged in a triangle with 100 km arm lengths orbiting 2000 km above the surface of the earth. It is hoped that the launch date will be late 2020s for the present..

1. Introduction

The first direct detection of gravitational wave (GW) has been done with aLIGO [1]. The first result of LISA pathfinder showed demonstration of surprisingly low-noise-level free fall exceeding expectations before launch [2]. The gravitational wave physics and astronomy took the new step to next stage. As astronomy using electromagnetic wave, gravitational wave is also expected in various frequency band to have wide frequency spectrum. Terrestrial detectors like aLIGO, aVIRGO, GEO, KAGRA and ET are most sensitive at audio frequency band around 10 to 1 kHz, on the other hand, space born detector LISA is at low frequency region around mHz. At further low frequency band, PPTA (Pulsar Timing Array) and polarized CMB (Cosmic Microwave Background) are also interesting options to access to the unique information of physics and universe. Japanese DECIGO, planned space gravitational wave antenna, might be able to provide another new way to observe universe, because only DECIGO will be sensitive to deci-Hz gravitational wave signals.

2. DECIGO

DECIGO (DECi-hertz Interferometer Gravitational wave Observatory) is the planned Japanese space gravitational wave antenna [3, 4, 5], which was originally proposed by Seto, Kawamura

and Nakamura [6] to measure the acceleration of the universe through GWs from binary NS–NS at $z \sim 1$. DECIGO is targeting to observe gravitational waves from astrophysically and cosmologically significant sources mainly between 0.1 and 10 Hz, thus, to open a new window of observation for gravitational wave astronomy, and also for the universe. The scope of DECIGO is to bridge (Fig.2) the frequency gap between LISA [7] band and terrestrial detectors band such as advanced LIGO, advanced VIRGO, GEO and KAGRA. The major advantage of DECIGO specializing in this frequency band is that the expected confusion limiting noise level caused by irresolvable gravitational wave signals from many compact binaries, such as white dwarf binaries in our Galaxy, is quite low above 0.1 Hz [8], therefore there is a potentially extremely deep window in this band. Thus, as DECIGO will have sensitivity in the frequency range between LISA and terrestrial detectors band, DECIGO can serve as a follow-up for LISA by observing inspiraling sources that have moved above the LISA band, or as a predictor for terrestrial detectors by observing inspiraling sources that have not yet moved into the terrestrial detectors band.

2.1. Pre-conceptual design

The pre-conceptual design of DECIGO consists of three drag-free spacecraft which keep triangular configuration with formation flying technique. The separation of each spacecraft is designed to be 1,000 km, whose relative displacements are measured by a differential Fabry-Perot (FP) interferometer (Fig.1). The laser source is supposed to be frequency-doubled Yb:YAG laser with $\lambda = 515$ nm yielding output power of 10 W. The mass of the mirror is 100 kg with 1 m diameter, with low-loss high-reflectivity coatings, which enables the finesse of FP cavity to reach 10 with green light. Three sets of such interferometers sharing the mirrors as arm cavities comprise one cluster of DECIGO. As shown in Fig.1, four clusters of DECIGO, located separately in the heliocentric orbit with two of them nearly at the same position, form the constellation DECIGO.

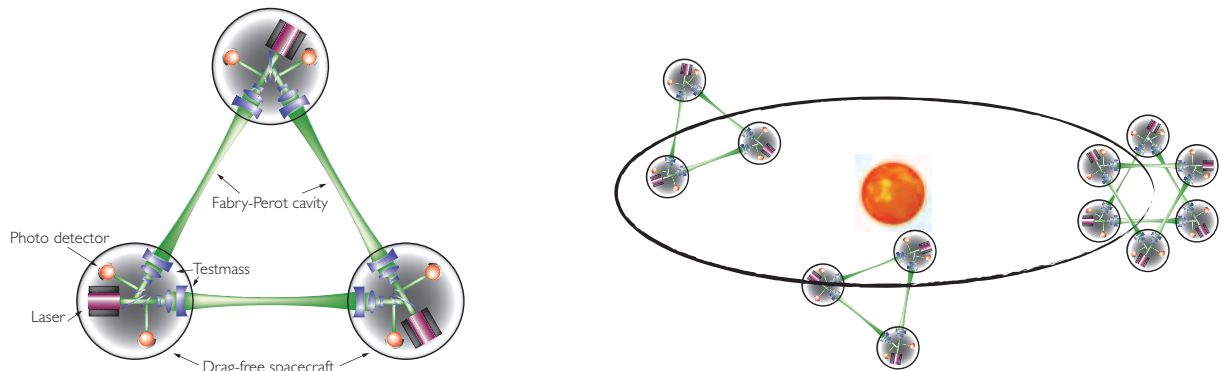


Figure 1. Image of DECIGO and constellation around the heliocentric orbit.

2.2. Sensitivity goal and science

The target sensitivity of DECIGO, as shown in Fig.2, is supposed to be limited by quantum noise in all frequency band: by the radiation pressure noise below 0.15 Hz, and by the shot noise above 0.15 Hz. In order to reach this sensitivity, all the practical noise should be suppressed well below this level. This imposes more stringent requirements than LISA for some subsystems of DECIGO, especially in the acceleration noise and frequency noise, therefore

rigorous investigations are supposed to be indispensable for attainment of design sensitivity. Nonetheless, full success of DECIGO is expected to extract fruitful sciences.

As shown in Fig.2, the sensitivity goal of DECIGO is better than 10^{-23} in terms of strain between 0.1 and 10 Hz. To achieve this sensitivities, all the practical noises have to be suppressed below the stringent requirement, especially on the acceleration noise of the mirror and frequency noise of the light.

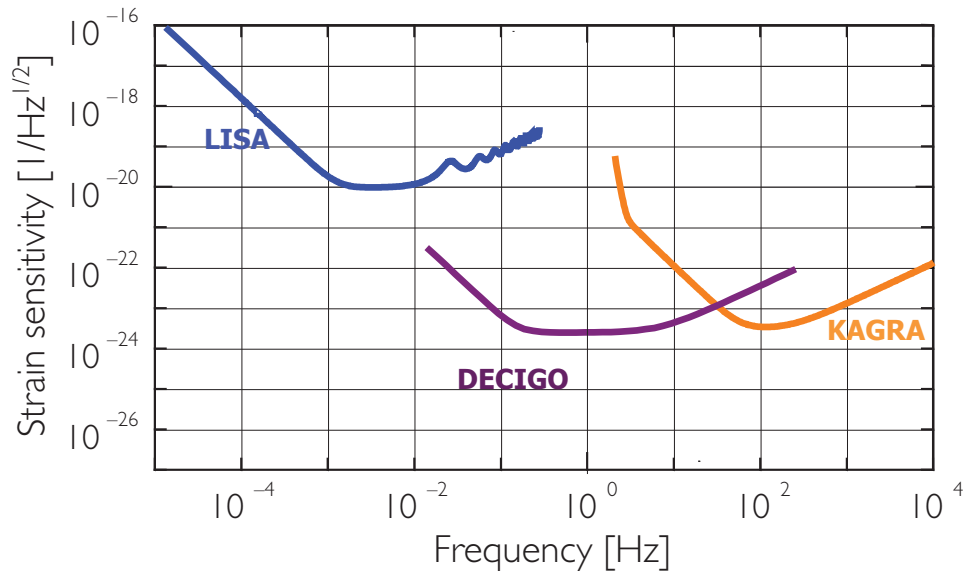


Figure 2. Expected sensitivity of DECIGO in terms of strain in comparison with LISA and terrestrial detectors, like KAGRA

2.3. Roadmap

DECIGO is expected to be launched in the era of 2030s, before that, we plan to launch a precursor satellites, B-DECIGO. Major objective of B-DECIGO is to detect astrophysical GW signals to extract scientific results, in addition to demonstration of key technologies required for DECIGO just as LISA pathfinder [2] did for LISA. The technical objectives of B-DECIGO are demonstration of accurate formation flying, precision laser metrology with long baseline FP cavity and drag-free control for multiple spacecraft, based on several fundamental precision measurement technologies like drag-free control of the spacecraft, stabilized laser system in space, precision laser metrology in space and test mass lock mechanism. B-DECIGO is basically a small version of DECIGO, but will have 100km-scale FP cavity, therefore, it is supposed to have reasonable sensitivity to detect gravitational waves with minimum specifications. We hope that it will be launched around 2020s.

3. B-DECIGO ¹

B-DECIGO is re-defined space GW antenna mission as first precursor satellite for DECIGO, succeeding former Pre-DECIGO [11]. The objectives of B-DECIGO are scientifically to detect

¹ B-DECIGO was formerly called Pre-DECIGO, which was second precursor satellite for DECIGO after first precursor satellite, DPF (DECIGO pathfinder) [9, 10]. The science objectives and design of Pre-DECIGO had not been defined so clearly, while DECIGO has a definite design and clear targets to access to the information of the inflation. Recently, expected astrophysical science targets and pre-conceptual design were defined for Pre-DECIGO, then which was renamed as B-DECIGO as first precursor satellite for DECIGO on this occasion.

gravitational waves from promising astrophysical sources with modest optical parameters, and also technologically to demonstrate the formation flight using three spacecraft, which is one of key technologies for DECIGO. B-DECIGO is designed to have a sensitivity that is conservative compared with DECIGO by about factor of 10 in all frequency band. Accordingly, the optical parameters and the noise requirements of B-DECIGO are less stringent than DECIGO, whereas the required acceleration noise level is still challenging compared with LISA pathfinder and LISA. B-DECIGO consists of three drag-free spacecraft containing freely-falling mirrors, whose relative displacement is measured by a differential FP Michelson interferometer.

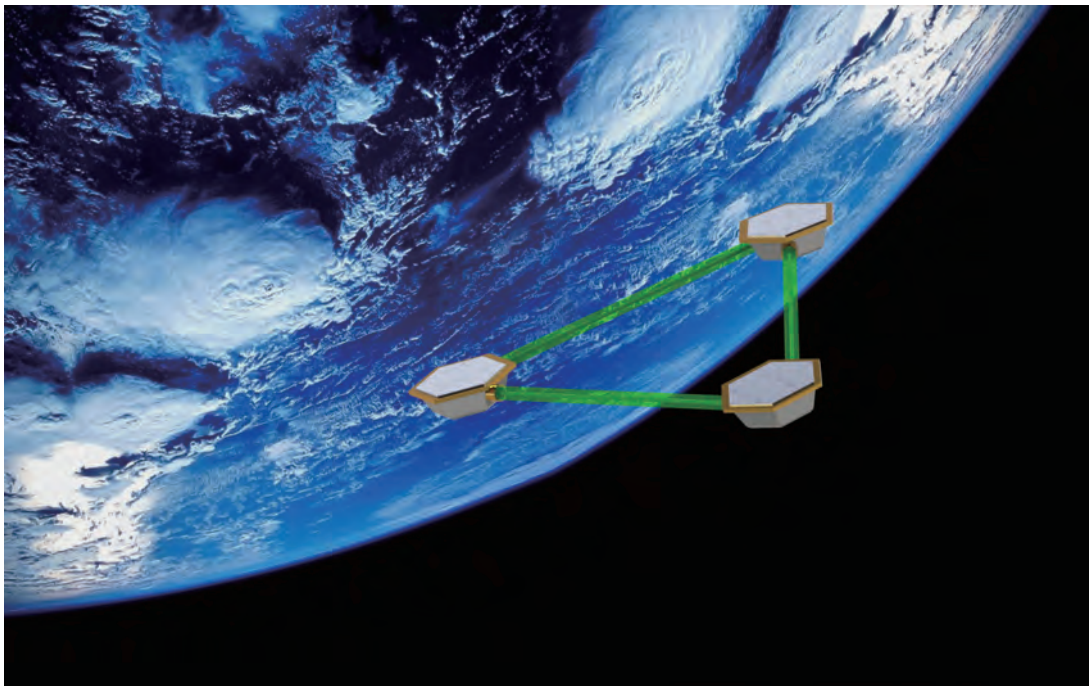


Figure 3. Image of B-DECIGO which is smaller size DECIGO consisting of three spacecraft arranged in an equilateral triangle with 100 km arm lengths orbiting 2000 km above the surface of the earth.

3.1. Pre-conceptual design

Each spacecraft holds a couple of test-mass mirrors of 30 kg in weight and 30 cm in diameter, freely floating on the spacetime. One test-mass mirror in one spacecraft and the another test-mass mirror in the other spacecraft are connected by laser beam, forming 100 km Fabry–Pérot cavity, with finesse of 100 resulting in a cavity cut-off frequency around 20 Hz. Therefore, three spacecraft are connected with three 100 km Fabry–Pérot cavities to maintain 100 km triangular formation flight. Frequency-doubled, Iodine-stabilized Yb: fiber DFB laser, with wavelength of 515 nm will be used as a light source, The laser light from Yb: fiber DFB laser with wavelength of 1030 nm is amplified with YDFA (Yb-Doped Fiber Amplifier), then frequency-doubled with nonlinear crystal to have enough power to illuminate each Fabry–Pérot cavities with 1 W. The frequency-doubled green light, then, frequency-stabilized in reference to the saturated absorption of iodine molecules to have low enough frequency noise contribution in an observational band of B-DECIGO.

In order to make test-masses freely floating in inertial spacetime as a probe of GW, and also to avoid an external force fluctuation on the test-mass caused by the unwanted coupling

from spacecraft motion, the spacecraft is drag-free controlled with a couple of test-mass mirrors inside spacecraft as inertial reference. The position and attitude of the spacecraft with respect to these test-masses are drag-free controlled by feeding error signals back to the spacecraft. The formation flight of the three spacecraft to keep triangular shape is realized by continuous feedback control. The laser interferometers measure the deviation of the cavity-length, which are fed back to the position of test-mass mirrors to maintain the length of the cavities. Since the spacecraft follows the test-mass positions inside it using drag-free control scheme, as a result, exact 100-km length triangular formation is realized. One of candidate orbit for B-DECIGO is LISA-like cart-wheel orbit around the earth. (Fig.3) If the altitude of the spacecraft formation and inclination angle of orbital plane are selected properly, the reference orbit, the orbit of the center of the mass of the three spacecraft, could be a sun-synchronized dawn-dusk circular orbit. In addition, it is possible to design the dawn-dusk orbit so that there will be no eclipse in these spacecraft, by selecting the altitude between 2,000-3,000km, which is beneficial to avoid thermal shock and drift in the spacecraft, and also to keep continuous power supply from the sun. The orbital period of the formation-flight interferometer unit around the earth is about 124 min. for the altitude of 2,000km. Assuming this orbit, orbital motion of formation and the earth's annual orbital motion around the sun make the antenna pattern of B-DECIGO to observe GWs change in time scale of 100 min. Owing to this variation of antenna pattern, parameter estimation accuracy for the GW sources, such as sky localization, is expected to be improved.

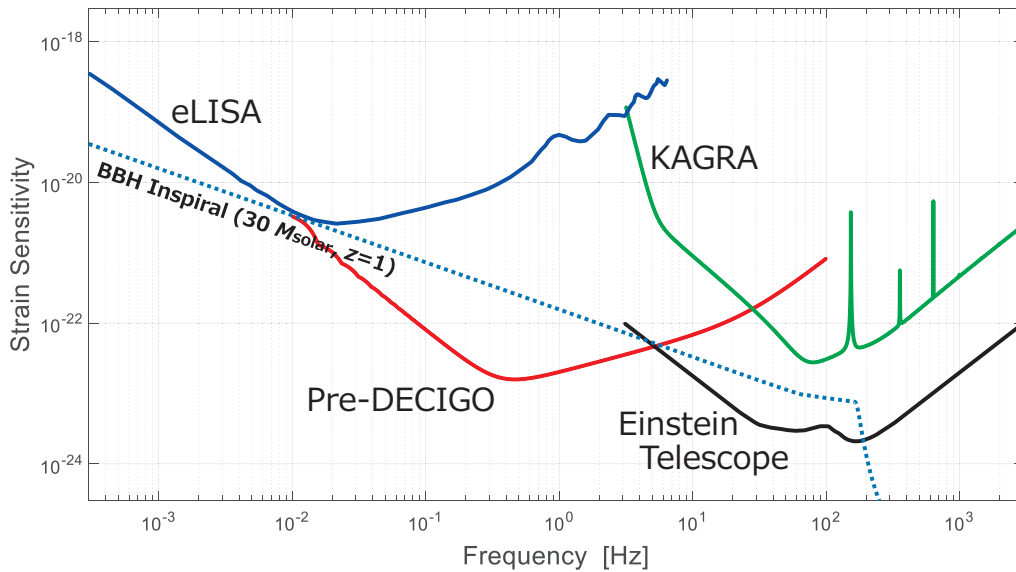


Figure 4. Strain sensitivity of B-DECIGO. Sensitivity curves for 2nd-generation terrestrial GW antenna (KAGRA [?]), 3rd-generation antenna (ET [?]), and space antenna (eLISA [?]) are shown together for references. The dashed curve shows the signal amplitude from BBH merger with masses of $30M_{\odot}$ at a distance of $z = 1$.

3.2. Sensitivity goal and science

Using above essential parameters, the target sensitivity of B-DECIGO is set to be $2 \times 10^{-23} \text{ Hz}^{-1/2}$ in strain in the current design (Fig. 4). The noise curve is basically limited by fundamental noise, optical quantum noises of the interferometer; laser shot noise and radiation

pressure noise in high and low frequency bands, respectively. The external force noises level on the test-mass mirrors are set not to exceed these optical quantum noises level, which place critical requirements; the requirement is $1 \times 10^{-16} \text{ N/Hz}^{1/2}$. With this sensitivity, mergers of BBHs at $z = 10$ will be within the observable range of B-DECIGO, assuming optimal direction and polarization of the source, and detection SNR of 8.

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