DECIGO: the Japanese Space Gravitational Wave Antenna

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A space gravitational wave antenna, DECIGO (DECI-hertz interferometer Gravitational wave Observatory) will provide fruitful insights into the universe, particularly on dark energy, the formation mechanism of supermassive black holes, and the inflation of the universe. In the current pre-conceptual design, DECIGO will be comprised of 4 interferometer units; each interferometer unit will be realized by formation flight of three drag-free spacecraft with 1000 km separation. Since DECIGO will be an extremely challenging mission with high-precision formation flight, it is important to increase the technical feasibility before its planned launch in 2024. Thus, we are planning two milestone missions. DECIGO pathfinder (DPF) is the first milestone mission for DECIGO, and key components for DPF are being tested on ground and in orbit. In this article, we review the conceptual design and current status of DECIGO and DPF.

Key Words: DECIGO, DECIGO Pathfinder, Gravitational Waves, Gravity, Formation Flight

1. Introduction

Gravitational waves (GWs) are radiated from accelerating masses, mostly from violent phenomena in the universe. The existence of gravitational waves was theoretically predicted as one of the consequences of the general theory of relativity1), and confirmed by observations of orbital evolutions of binary pulsars2). However, because of extremely weak interactions of GWs with matter, they have not yet been detected directly. This means, seen from the opposite point of view, that GWs would bring us undisturbed original information on the radiation source once they are directly observed. GW observation will open a new field of gravitational-wave astronomy. The knowledge on the universe obtained by GW observation will be complementary ones with, or completely different ones from traditional observation with electro-magnetic waves.

In order to obtain a new probe to the universe, several future ground-based and space detectors have been proposed. These detectors are based on a Michelson-type laser interferometer with long-baseline arms, which detects tiny ripples of space-time caused by GWs as the differential change in optical path length in two arms. Ground-based detectors target at high-frequency (10 Hz - 1 kHz) GWs radiated from the violent astronomical events, such as an insprial and a merger of neutron-star binary, and a supernova explosion with gravitational core collapse. Currently, several large-scale ground-based detectors, with baseline length of 100 m to 4 km, are under operation3-6), and several advanced detectors, such as advanced LIGO7), advanced VIRGO, and LCGT8), will be constructed in the next decade. These advanced detectors will have sufficient sensitivity to detect more than a few GW events in one-year observation. On the other hand, space detectors target at lower frequencies below 1 Hz, to which terrestrial detectors are inaccessible because of the gravity disturbances of the earth. In low-frequency band, we can expect larger or stationary GWs from a merger of massive black holes, from a binary comprised of compact stars, from the early universe, and so on. Thus, space detectors are sure to observe GWs and expand a new field of gravitational-wave astronomy.

DECIGO, a DECI-hertz Interferometer Gravitational wave Observatory9,10), is a space gravitational-wave antenna planned to be launched in 2024. The purpose of DECIGO is to open a new window of gravitational-wave astronomy in the frequency band mainly between 0.1 Hz and 10 Hz. Since this observation band is between that of the other space detector LISA11) (around 1 mHz band) and terrestrial detectors (around 100 Hz - a few kHz band), different information on the source will be obtained by DECIGO. For example, it can be a follow-up of LISA, and can also be a predictor for terrestrial
detectors by observing binary inspiral sources. Moreover, since DECIGO’s observation band is free from foreground noises caused by unresolved GWs from many galactic binaries, it has a potential to observe stochastic background gravitational waves from the early universe; DECIGO has a potential to see the very beginning (about $10^{-43}$ sec after the beginning) of the universe directly, taking advantage of the strong-transmissivity nature of GWs (Fig. 1). Observation of B-mode polarization in Cosmic Microwave Background (CMB) also has a potential to see GWs from the early universe12. DECIGO will provide independent and complementary information for cosmology.

DECIGO will be an extremely large mission both in its scale and required resources; four interferometer units will orbit around the sun along the earth orbit, so as to identify the position of the GW source, and each unit will be formed by three drag-free spacecraft that are separated by 1000 km from one another. Thus, it is significant to increase the technical feasibility before its launch. We have a roadmap to launch two milestone missions before DECIGO. DECIGO pathfinder (DPF)13 is the first milestone mission to test the key technologies with single spacecraft. Pre-DECIGO14 is supposed to detect gravitational waves with minimum specifications.

In this article, we review the conceptual design, scientific objectives, and current status of DECIGO and the milestone missions for it, mainly on DPF.

2. DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory) is the future Japanese space gravitational wave antenna, with an observation frequency band of around 0.1Hz. It aims at detecting gravitational waves from various kinds of sources, with sufficient sensitivity to establish the gravitational wave astronomy.

2.1 Conceptual design

In the current pre-conceptual design, a unit of DECIGO is formed by three drag-free spacecraft, 1000 km apart from one another (Fig. 2). Relative displacements of the proof masses (mirrors) inside the spacecraft are measured by Fabry-Perot interferometers. We adopted the Fabry-Perot configuration because it provides a better best sensitivity at 0.1Hz band than an optical transponder configuration which is adopted by LISA. The distance between spacecraft (Fabry-Perot cavity arm length) was chosen to be 1000 km. This arm length was chosen so as to be short enough to avoid refraction losses of laser power, and to store sufficient laser power inside the cavities, and yet so as to be long enough to ensure the high sensitivity for GW signals. The mirrors forming the cavities, which works as proof masses in spacecraft, have a diameter of 1 m, with moderate reflectivity to realize the cavity finesse of 10. The mass of mirror (about 100 kg) was chosen to be the largest we could fabricate and handle. The laser source of DECIGO will have an effective power of 10W with a wavelength of 532 nm. The orbit and constellation of DECIGO is to be determined, considering the gravity disturbances by the sun and planets, durability of the thruster fuels, solar power supply, and the required angle resolution for the GW source, and so on. One of the candidates of the orbit is a record-disk orbit around the sun, along the earth orbit.

2.2 Scientific goal

The observation band of DECIGO, around 0.1Hz, is the gap region between LISA (Laser Interferometer Space Antenna) and terrestrial detectors such as Advanced LIGO and LCGT (Large-scale Cryogenic Gravitational-wave Telescope). This band opens the possibility to observe GWs from cosmological distance, because it is free from the confusion noises, irresolvable GW signals from too many white dwarf binaries. The extremely good sensitivity of DECIGO would enable us to detect GWs from the very early universe, which could provide important information to understand the beginning of the universe.

Main targets of DECIGO are GWs from inspirals of compact binaries, and from the early universe. DECIGO will have sufficient sensitivity to observe GWs from distant (redshift of $z\sim1$) neutron-star binaries which are a few months to 5 years before merger. By resolving GW signals emitted from many (about $3 \times 10^5$) binaries in this range, we will obtain information of mass distribution of neutron stars, and thus, on the theory of the evolution of massive stars and on the
equation of state of high-density matters. Moreover, observing
distant binaries, which play as precise clocks, it will be possible to measure the acceleration of the expansion of the universe from their redshift change. As for black-hole binaries, DECIGO will observe GWs from coalescences of intermediate-mass ($10^3$ Msolar) black hole binaries, which could reveal the mechanism of the formation of super-massive black holes in the center of galaxies. The most exciting target of DECIGO will be the stochastic background GWs from the early universe; GWs could be radiated from density fluctuations in early universe, primordial blackholes\(^{15}\), and so on. This target cannot be observed by electro-magnetic waves directly, because of scattering in high-energy plasma in the early universe. So as to distinguish the stochastic background GWs from detector noise, DECIGO has multiple interferometer units for cross-correlation observation.

### 2.3 Roadmap

Long and intensive development phase will be required in order to realize DECIGO. We plan to launch DECIGO in 2024 after design (a pre-conceptual design, a conceptual design, a preliminary design, and finally a final design) and prototype tests with the help of research and development with table top experiments. We also have two milestone missions, DECIGO pathfinder (DPF) and Pre-DECIGO, before the launch of DECIGO (Fig. 4). The purpose of Pre-DECIGO is to detect GWs with minimum specifications. Pre-DECIGO will have a down-sized configuration of DECIGO, being comprised of three spacecraft with shorter separation.

#### 3. DECIGO Pathfinder

DECIGO Pathfinder (DPF) will be a small satellite orbiting the earth. The mission part of DPF is designed to be a prototype of DECIGO and to test the key technologies of DECIGO, being comprised of a short Fabry-Perot cavity, a stabilized laser source, and a drag-free control system. In addition, DPF has scientific goals: observation of gravitational waves from the blackholes, and monitor of the gravity of the earth.

#### 3.1 DPF satellite and bus system

Conceptual design of DPF is shown in Fig. 5, DPF will be a single satellite with weight of about 350 kg, orbiting the earth along a sun-synchronous orbit with an altitude of 500 km. DPF will be launched by a next-generation solid propellant rocket, which is being developed as a successor of the M-V launch vehicle of JAXA (Japan Aerospace Exploration Agency). For stable power generation and temperature equilibrium of the satellite, DPF will have a circular sun-synchronous dawn-to-dusk orbit, and an earth-synchronous attitude. Two proof masses inside the satellite will trail along in the same orbit. The attitude of the satellite will be passively stabilized by the gravity gradient of earth, and actively controlled by a drag-free control system to cancel external disturbances. For this control, small mission-thrusters will be used; momentum wheels will not be loaded so as to avoid their mechanical disturbances.

The DPF satellite will be formed by the combination of a bus module and a mission payload module. We are planning to use a standard bus system module under development in JAXA, which has a weight of about 200 kg, and a size of 950×950×1100 mm. This bus will provide a 940 W power with 4 solar-cell puddles, and 2 Mbps downlink telecommunication ability. A mission module will be attached.

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**Fig. 3.** Sensitivity goal of DECIGO and expected gravitational wave signals.

**Fig. 4.** Roadmap to DECIGO. DECIGO has two milestone missions: DECIGO pathfinder (DPF) and Pre-DECIGO.

**Fig. 5.** Conceptual design of DECIGO Pathfinder satellite.
on the upside of the bus module. The data processing system is based on a SpaceWire-based communication standard. The bus and mission modules are to be connected with power lines and SpaceWire communication lines, and cables for temperature controls.

3.2 DPF mission design

The mission payload part of DPF will have a size of 950×950×1100 mm, and a mast structure for gravity-gradient attitude stabilization will be attached at the top of the module. The mission payload of DPF is comprised of a short Fabry-Perot (FP) cavity, a stabilized laser source, and a drag-free control system (Fig. 6).

![Frequency Stabilization System](image)

Fig. 6. Pre-conceptual design of DECIGO pathfinder.

The Fabry-Perot cavity is formed by two mirrors which act as free proof masses. Each mirror is to be placed inside a module called housing. The housing will have electrostatic-type local sensors and actuators on its frame, which are to be used to monitor and to control the relative motion between the mirror and the frame in all degrees of freedom. In addition, the housing will have a function of a launch lock, which will clump the mirror at the launch of the satellite and release it in the orbit with a small initial velocity. The cavity has a baseline length of about 30cm and a finesse of about 100. The length change in the FP cavity, which would be caused by gravitational waves or external disturbances, is measured by means of a stabilized laser beam.

As a light source, we will use an Yb:YAG laser in which the frequency is stabilized using iodine absorption line. The requirement for the frequency stabilization is 0.5 Hz/Hz^{1/2}. The laser source has an output power of 100mW at a wavelength of 1030 nm.

The drag-free control of the satellite will work as a shield against external forces caused by solar radiation and drag by residual atmosphere. Drag-free control will be realized by measuring the relative fluctuations between the mirrors and the satellite, and basically feeding these signals back to the satellite position using low-noise mission thrusters. The satellite motion will be controlled in all degrees of freedom. In addition, the housing will have a function of a network for high-resolution and real-time monitoring of Earth's gravity.

3.3 Objectives of DPF

Two proof masses of DPF will be kept inside the spacecraft untouched to avoid external disturbances, and to be sensitive to gravitational forces, such as gravitational waves and Earth's gravity distributions.

3.3.1 Scientific observation

Gravitational waves would be detected as tidal-force fluctuations on two proof masses; the length change in the Fabry-Perot cavity is to be measured by a laser interferometer. DPF interferometer will have a sensitivity of 2 × 10^{-15} Hz^{-1/2} at around 1 Hz frequency band, which corresponds to a GW sensitivity limit of about h~10^{-15}. At this frequency band, it is expected that gravitational waves from intermediate-mass blackhole inspirals and quasi-normal mode of massive blackholes will be radiated. The observable ranges of DPF for these phenomena are estimated to reach the Galactic center with a detection threshold of a signal-to-noise ratio of 5 (Fig. 7). In other words, DPF has a potential to detect gravitational-wave signals, if there is a black-hole inspiral event with 10^1-10^4 Msun, or a ringdown event of a quasi-normal mode for 10^4 - 4×10^5 Msun black hole at the center of our galaxy. Although the probability to have such events is considered to be rare, data obtained by DPF observations will have importance, because this observation band is difficult to access by ground-based gravitational-wave detectors and other space-based detection methods.

Observation of the gravity of Earth is another scientific objective of DPF. Since the proof masses orbit Earth almost freely, gravity distributions of Earth would be observed from the trajectories of the proof masses. In order to cancel the drag force by air and solar radiation, the relative displacements between the proof masses and the satellite frame are to be measured by small Michelson-interferometer-type laser sensors with an acceleration sensitivity of 10^{-11} m/s^2. Several satellites to observe Earth's gravity have been launched so far^{16}. The characteristic feature of DPF is to make the sensitive accelerometer in a sufficiently small package. This module would be easier to be loaded in a future satellite network for high-resolution and real-time monitoring of Earth's gravity.

3.3.2 Development of key technologies for future missions

The key technologies tested in DPF will be the following:

![Observable Range](image)

Fig. 7. Observable range of DPF for blackhole inspirals and blackhole quasi-normal mode events. The range reaches to the Galactic center.
(1) low-noise operation and observation with a Fabry-Perot interferometer in space, (2) operation of a laser stabilization system in a space environment, and (3) demonstration of a drag-free control system. All of these technologies are critical for the realization of DECIGO, and are also useful for other future missions.

The main Fabry-Perot interferometer in DPF with a baseline length of 30 cm is designed as a prototype of 1000 km arm cavity of DECIGO. Although measurement and operation with such an interferometer is a well-established technique in a ground-based environment, there is no example of a Fabry-Perot cavity formed by free floating mirrors in a space environment. In a Fabry-Perot configuration, we can expect better sensitivity than that of a Mach-Zender interferometer, which is used in LPF\(^{7}\), because the distance between two floating test masses is directly measured in a Fabry-Perot interferometer. However, the control configuration to keep the proof mass mirrors inside the satellite and, at the same time, to operate the interferometer stably will be more complex. The demonstration of Fabry-Perot interferometer operation in DPF will provide a new possibility for precise measurements in a space environment.

In DPF, the frequency noise of the laser source is stabilized using saturated absorption spectroscopy of iodine molecules, targeting at a stability of 0.5 Hz/Hz\(^{1/2}\) in the 0.1 Hz frequency band. Frequency stabilization of a laser source has been well-studied for ground-based gravitational-wave detectors, and in other fields, such as precise metrology, spectroscopy, optical communications and so on. On the other hand, there are few experiments in a space environment. However, recently, laser sources with high frequency stability have come to be required in space missions. For example, the Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus) requires a 25 kHz/Hz\(^{1/2}\) frequency stabilized laser, and ACES (Atomic Clock Ensemble in Space) on the ISS (International Space Station) requires 100 Hz/Hz\(^{1/2}\) frequency stability. LISA requires 30 Hz/Hz\(^{1/2}\) frequency stability. Compared to these missions, the stability of 0.5 Hz/Hz\(^{1/2}\) in DPF will be a significant step to show the potential of a stabilized laser, while it will be rather challenging in a space environment.

Drag-free control is a scheme used to avoid the effect of external forces on a satellite, such as drag by a residual atmosphere along the orbit, and radiation pressure of the Sun. Drag-free control is realized by controlling the position of a satellite to follow the motion of a proof mass, which is placed inside the satellite, and is shielded from external forces by the satellite. Drag-free control of a satellite was realized by the TRIAD-I satellite in 1972 for the first time, and several follow-on satellites for investigating a navigation system. Recently, drag-free control was also realized by the Gravity Probe-B satellite for tests of the general theory of relativity. LPF will demonstrate drag-free control at the Lagrange 1 (L1) point between the Earth and the Sun, at which the gravitational environment is stable. On the other hand, DPF will demonstrate it in an Earth orbit, with the help of passive attitude-control actuators, such as momentum wheels. This will be a new scheme to realize a drag-free satellite.

### 3.3 Current status of DPF

Currently, DPF has been selected as one of the candidates of small satellite missions of JAXA. JAXA has a project to launch at least 3 small satellites in 5 years from 2011, using standard bus systems. The first mission has already been decided to be SPRINT-A/EXCEED, which is for the observation of inferior planets. SPRINT-A/EXCEED will be launched in 2012. DPF is now one of a few high-ranked mission candidates for the second or third missions, and will be launched in 2013 in the best case.

Research and development are underway with the support of JAXA, mainly concerning a mission study including satellite design and drag-free control topology, and on testing key devices, such as a housing system for a proof mass, a stabilized laser, and thrusters. In addition, a small demonstration module, named SWIM (SpaceWire Interface demonstration Module), has been developed and launched in January 23, in 2009 in SDS-1, a JAXA’s technology demonstration satellite. SWIM contains a space-qualified data processor and recorder with the SpaceWire interface, and a tiny gravitational-wave detector module with a size of 160×80×80 mm. SWIM will provide heritages for DPF on a SpaceWire-based data processing system and on sensing and control of proof masses in a space environment.

### 4. Conclusion

DECIGO will establish a new window for gravitational-wave astronomy, and the DECIGO pathfinder (DPF) will be the first significant milestone mission to test the key technologies for DECIGO. Moreover, DPF will provide new scientific knowledge on gravitational-wave observations, on the gravity of Earth, on precise measurements with an interferometer, on laser stabilization in space, and on drag-free control of a spacecraft. DPF has been selected as one of the candidates of small satellite missions of JAXA, and research and development for key components are underway. We are hoping to launch DPF in 2013 in the best case.

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