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The Japanese space gravitational wave antenna—DECIGO

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Abstract

DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) is the future Japanese space gravitational wave antenna. It aims at detecting various kinds of gravitational waves between 1 mHz and 100 Hz frequently enough to open a new window of observation for gravitational wave astronomy. The pre-conceptual design of DECIGO consists of three drag-free satellites, 1000 km apart from each other, whose relative displacements are measured by a Fabry–Perot Michelson interferometer. We plan to launch DECIGO in 2024 after a long and intense development phase, including two pathfinder missions for verification of required technologies.

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(Some figures in this article are in colour only in the electronic version)

1. What is DECIGO?

DECIGO is the future Japanese space gravitational wave antenna; it stands for DECi-hertz Interferometer Gravitational wave Observatory [1]. The objective of DECIGO is to detect various kinds of gravitational waves between 1 mHz and 100 Hz frequently enough to open a new window of observation for gravitational wave astronomy.

DECIGO not only bridges the frequency gap between LISA [2] and terrestrial detectors such as LCGT [3] but also reaches an extremely good sensitivity especially between 0.1 Hz and 10 Hz. This is because the confusion limiting noise caused by irresolvable gravitational wave signals from many compact binaries is expected to be very low above 0.1 Hz [4].

DECIGO can observe inspiral sources that have moved above the LISA band and that have not yet moved into the ground-based detector band. Therefore, DECIGO can play the role of follow-up for LISA and predictor for terrestrial detectors. DECIGO is especially suitable for detection of gravitational waves from coalescences of intermediate-mass black hole binaries, which could reveal the formation mechanism of super-massive black holes. The predicted sensitivity of DECIGO could make it possible to detect gravitational waves from the beginning of the universe; we could obtain important information about the beginning of the universe at a level which is unattainable by other means. It could also detect gravitational waves from totally new sources which we currently cannot envisage.

2. Pre-conceptual design of DECIGO

The pre-conceptual design of DECIGO consists of three drag-free satellites, 1000 km apart from each other, whose relative displacements are measured by a Fabry–Perot Michelson interferometer (see figure 1). The arm length was chosen to be short enough to make this Fabry–Perot configuration possible, and yet long enough to ensure good sensitivity to gravitational wave strain. The Fabry–Perot configuration requires the relative displacement between the satellites to be constant during continuous operation. These features make DECIGO very different from a possible counterpart with the transponder-type detector (e.g. LISA), where the satellites, which are much farther apart, are freely falling according to their local gravitational field.

We adopted the Fabry–Perot configuration because it provides better shot-noise-limited sensitivity than a transponder configuration due to the enhanced gravitational wave signals. Although the Fabry–Perot configuration has the larger radiation pressure noise due to the higher laser power acting on the mirrors and the larger effect of displacement noises in terms of strain sensitivity due to the shorter arm length, we believe that these disadvantages do not impair the sensitivity of DECIGO. This is because, first of all, the radiation pressure noise of DECIGO is still slightly lower than the anticipated confusion limiting noise, and secondly because we believe that it is in principle possible to suppress all practical acceleration noises below the radiation pressure noise.

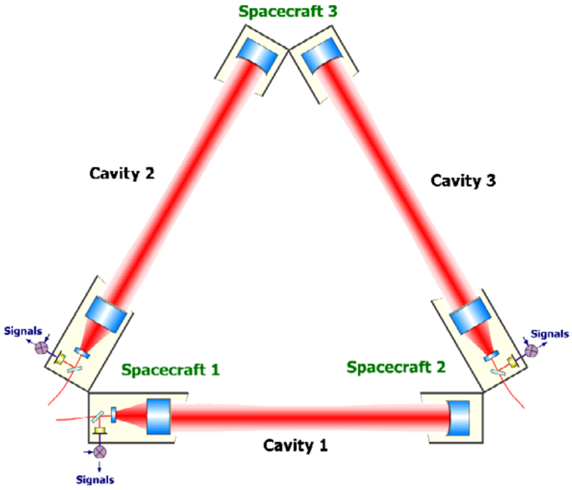

Figure 1. Fabry–Perot Michelson interferometer as the pre-conceptual design of DECIGO.

This Fabry–Perot configuration requires an additional system beyond that of an ordinary drag-free system. In the ordinary drag-free system, the outer satellite simply follows the motion of the mirror inside. However, in the Fabry–Perot system, the distance between the mirrors should be kept constant, which requires an actuator for the mirror. Since the actuator should be attached to the outer satellite, the actuating force to the mirror has a back action to the outer satellite. The resultant motion of the outer satellite should be controlled by the thruster system of the drag-free satellite. As a result, the actuating force to the mirror contains gravitational wave signals, while the signal controlling the thruster contains both gravitational wave signals and drag forces. Although the control topology is slightly complicated, the control system to maintain the resonance condition is in principle compatible with the drag-free system.

The lock acquisition of the Fabry–Perot cavity is a challenging task. In a ground-based interferometer, the relative motion of the two mirrors of a cavity is small enough to acquire lock of the cavity without much difficulty because the suspension systems of the mirrors are virtually connected to the ground at zero frequency. However, the relative motion of the satellites in space is expected to be much higher. Therefore, we need an additional system that detects the relative motion of the mirrors, and gradually reduces it by actuating the mirrors. Once the relative motion of the mirrors is suppressed well enough, the lock acquisition of the cavity will be straightforward.

The fundamental specifications of DECIGO in its pre-conceptual design are summarized in table 1. Here the distance between satellites was chosen to be 1000 km in order to realize a finesse of 10 with a 1 m diameter mirror. The mass of the mirror was simply chosen to be the largest we could fabricate and handle. The effective laser power and wavelength of light were determined by the tradeoff between shot noise and radiation pressure noise.

The ideal sensitivity of DECIGO is limited only by quantum noise prescribed by the above-mentioned specifications. It is shown in figure 2 together with the planned sensitivity of LISA and LCGT. The sensitivity is limited by the radiation pressure noise below 0.15 Hz, and it has an f^{-2} frequency dependence. The shot noise limits the sensitivity above 0.15 Hz. It is flat up to 7.5 Hz, and above 7.5 Hz it increases in proportion with frequency because of the signal cancellation in the arm cavities.

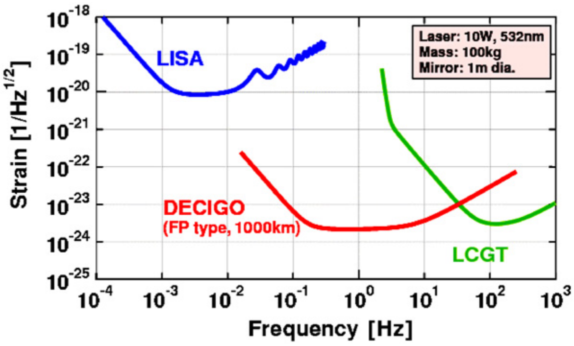

Figure 2. Ideal sensitivity of DECIGO together with the planned sensitivity of LISA and LCGT.

Table 1. Fundamental specifications of DECIGO.

Item	Value
Distance between satellites	1000 km
Effective laser power	10 W
Wavelength of light	532 nm
Mass of the mirror	100 kg
Diameter of the mirror	1 m
Finesse of cavity	10

Table 2. Important requirements of DECIGO.

Item	Value
Acceleration noise per mirror	4×10^{-19} m s^{-2} Hz$^{-1/2}$
Total acceleration noise	8×10^{-19} m s^{-2} Hz$^{-1/2}$
Frequency stability of a laser with the first-stage frequency stabilization	1 Hz Hz$^{-1/2}$ (at 1 Hz)
Frequency stabilization gain by the common-mode arm length	10^5 (at 1 Hz)
Common-mode rejection ratio	10^5
Intensity stability of a laser with the intensity stabilization	10^{-8} Hz$^{-1/2}$ (at 1 Hz)
Residual rms motion of the differential arm length	2×10^{-11} m

In order to realize the ideal sensitivity of DECIGO, all the practical noises should be suppressed well below this level. This imposes stringent requirements for the subsystems of DECIGO. The important requirements are summarized in table 2. We anticipate that extremely rigorous investigations are required to attain the requirements especially in the acceleration noise and frequency noise.

The acceleration noise includes the noise caused by the actuator for the control of the resonance condition, thermal noise due to gas damping and other practical noises. Achieving this extremely low acceleration noise in the presence of large actuating force to maintain the resonance condition requires very challenging dynamic range performance of the actuator. Fortunately, however, this stringent requirement can be significantly relieved by implementing large loop gain of the control system at the observation band. Suppressing the thermal noise due to gas damping also requires stringent vacuum level in the vicinity of the mirror. This

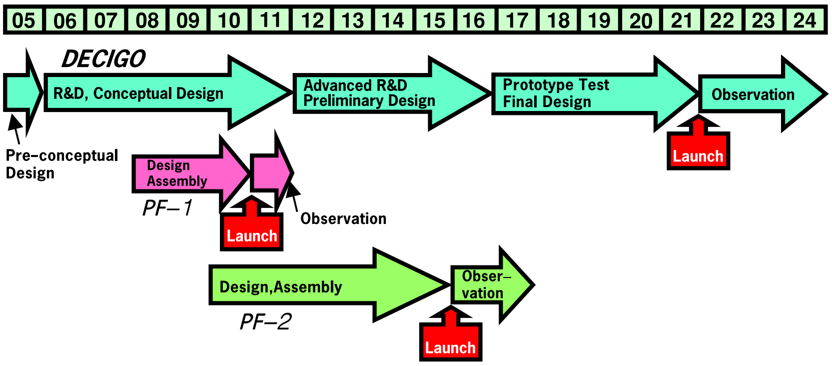

Figure 3. Roadmap for DECIGO.

is probably possible by introducing a system that vents the residual gas out of the satellite without causing any drag effect.

Frequency noise couples with a residual imbalance between the two arms to produce noise in the interferometer. In order to suppress the effect of frequency noise below the ideal sensitivity, we should impose stringent requirements on the three quantities: frequency stability of a laser with the first-stage frequency stabilization, frequency stabilization gain by the common-mode arm length and the common-mode rejection ratio. We have allocated the requirements to the three quantities in such a way that they are comparably challenging, but possible to achieve.

Finally, the orbit and constellation of DECIGO are to be determined with a careful consideration of the required angle resolution, durability of the thruster fuels, supply of power, disturbances from sunlight, effect of the gravity field of the Earth, quality of telecommunication, etc.

3. Roadmap for DECIGO

There should be a long and intense development phase to realize DECIGO. Figure 3 shows the roadmap for DECIGO. We start with a pre-conceptual design and then proceed to a conceptual design, a preliminary design and finally a final design with the help of R&D, advanced R&D and a prototype test. We plan to launch DECIGO in 2021.

We also plan to launch two pathfinders: PF-1 and PF-2. PF-1 will be one small satellite that contains two freely falling masses. The distance between the two masses will be measured with a Fabry–Perot interferometer. This is mainly a test for the drag-free system with the secondary objectives of possible gravitational wave detection at the DECIGO band. PF-1 will also check the performance of the detection system in space.

The objectives and a conceptual design for PF-2 will be determined during the R&D phase of DECIGO. It will be most likely two satellites far apart, corresponding to one arm of DECIGO to test the fundamental concept of DECIGO.

4. Conclusions

We have started a serious investigation to realize DECIGO by determining the pre-conceptual design. With much effort we hope that this potentially very powerful mission will be realized, leading us to a significant contribution to gravitational wave astronomy.

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