Test-mass module for DECIGO Pathfinder

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Abstract.

DECIGO Pathfinder (DPF) is the first precursory satellite mission for DECIGO (DECi-hertz Interferometer Gravitational wave Observatory), which is a future space gravitational wave antenna. The key instrument of DPF is a Fabry-Perot laser interferometer with freely floating test-masses, demonstrating precision laser interferometry, stabilized laser system and drag-free control system in orbit. A test-mass module is one of the sub-components of the DPF instrument, realizing non-contact suspension of the test mass in space, which provides capabilities of local sensing/actuation, test-mass lock mechanism and charge management system. In this article, the test-mass module system is reviewed.

1. DECIGO and DECIGO Pathfinder (DPF)

DECIGO (DECi-hertz Interferometer Gravitational wave Observatory) is the planned Japanese space gravitational wave antenna mission, which is targeting the observation of gravitational waves from astrophysically and cosmologically significant sources mainly between 0.1 Hz and 10 Hz, to open a new window of observation for gravitational wave astronomy, and thus for the universe\cite{1,2,3,4}. The scope of DECIGO is to bridge the frequency gap between the LISA band and the band of terrestrial detectors such as Advanced LIGO and LCGT\cite{5,6}. The major advantage of DECIGO specializing in this frequency band is that the expected limit due to confusion noise caused by irresolvable gravitational wave signals from many compact objects, such as white dwarf binaries in our Galaxy, is quite low above 0.1 Hz\cite{7}. Therefore there is a potentially extremely deep window in this band. Full success of DECIGO is expected to yield fruitful sciences: an observation of stochastic GWs from inflation of the universe, a characterization of dark energy with precise observation of distant neutron star merger, a dark-matter identification by observing cosmological black holes, and an understanding of the formation mechanism of supermassive black holes.

The pre-conceptual design of DECIGO consists of three drag-free spacecraft which keep their triangular configuration using a formation flying technique. The separation between the spacecraft (proof masses) is designed to be 1,000 km, and their relative displacements are measured by a differential Fabry-Perot (FP) interferometer. DECIGO is expected to be launched in the middle of the 2020s. Before that, we plan to launch two precursor satellites:
Figure 1. Roadmap of DECIGO, together with precursor satellites DECIGO Pathfinder and Pre-DECIGO.

DECIGO Pathfinder (DPF) [8–9] and Pre-DECIGO as shown in Fig.1. Because DECIGO will be an extremely large mission, it is important to increase the technical readiness level and demonstrate feasibility before its launch. The major objective of these milestone missions is a demonstration of key technologies needed for DECIGO just as the LISA Pathfinder [10] does for LISA. In addition, we also hope to extract some scientific achievements with the limited equipment allowed for these satellites of the precursor phases. DPF tests the key technologies for DECIGO such as drag-free control of the spacecraft, stabilized laser system in space and precision laser metrology in space. At the same time, as DPF will have gentle sensitivity to gravitational waves, it is expected that DPF will put some upper limit to the gravitational waves from sources around the center of our galaxy.

DPF (see Fig.2) will employ a small-sized drag-free spacecraft that contains two freely falling test masses whose relative displacement is measured with a Fabry-Perot interferometer. A short Fabry-Perot cavity of 30cm with finesse of 100 is illuminated by the frequency-stabilized Yb:YAG laser light yielding an output power of 100mW. The test masses are clamped tightly during launch and released gently in orbit. DPF is supposed to be delivered into a geocentric sun-synchronous orbit with an altitude of 500km. DPF will have a strain sensitivity of $2 \times 10^{-15} \text{ m/Hz}^{1/2}$ around the frequency band of 0.1–1 Hz. The primary objective of DPF is to demonstrate key technologies for DECIGO such as the drag-free control system, the FP cavity precision metrology system in orbit, a frequency-stabilized laser in orbit, and the clamp release mechanism. In addition, the scientific objective of DPF is to detect rather unlikely inspiral events of intermediate-mass black holes ($10^3 – 10^4 \text{ M}_\odot$) in our galaxy; it is possible to detect such events with the targeted sensitivity of DPF. Another prospective achievement is earth gravity monitoring. The precision sensing of the test mass using a laser sensor, and feeding all the error signals back to the test mass, works as a sensitive accelerometer in space.
From the combination of this accelerometer and GPS information, one can derive the earth’s

2. Test-mass module (TMM)

The spacecraft of DECIGO Pathfinder will be a technical demonstration of Fabry-Perot laser interferometry. It is a shrunk version of DECIGO instruments, and also a laser-interometer accelerometer in orbit. Laser module, interferometer module and thruster actuation system serve as key components of DPF to demonstrate a stabilized laser system, precision laser interferometry and drag-free control in space. Thus, DPF will have two freely floating test masses in orbit, which are references in space-time for GWs and also references for earth’s gravity. A caging system, called test-mass module (TMM) for DPF, will house the test mass, serving as contact-free suspension including sensing/actuation, test-mass locking/positioning capabilities and charge management system (see Fig.3). The test-mass modules will house one test mass each, so DPF will have two TMMs to compose the FP interferometer inside the interferometer module. TMM is, thus, a complex of functionalities composed of several sub-components. The baseline of this caging system is similar to that of LISA Pathfinder, but the design of the bread-board model for DPF is a simplified version to check the functionalities of each sub-component.

- Test masses (TMs): 70 mm cubes made of aluminum for the bread-board model (BBM). A dielectric multi-layer coated mirror is attached on one side to work as part of the FP interferometer mirror, together with three pairs of corner cube reflectors for the laser sensor (LS).
- Electrostatic Sensor and Actuator (ES/EA): works as local sensor for relative displacements between test mass and spacecraft, which is as sensitive as $10^{-10} \text{m/} \sqrt{\text{Hz}}$, and as actuator to apply a force to the test mass. In order to sense/actuate six degrees of freedom of the test mass, a pair of electrodes are facing the test mass on all surfaces, together with additional four injection electrodes. The potential of the test mass is modulated with an injection signal, then the displacement information of the test mass appears as modulated signal after a differential transformer. Therefore, the demodulated signal gives a nearly linear error signal around the operating point. As for actuation, appropriate combinations of modulated feedback signals are applied to four electrodes, facing $+x$ and $-x$ for example, to apply forces to the test mass, for the translation and for the rotational degrees of freedom.

![Figure 2. Schematic of DPF satellite.](image-url)
Figure 3. Assembly diagram of the test-mass module for the bread-board model of DPF. The test mass is housed inside a caging frame, then each surface is enclosed by electrode plates and laser sensor modules.

• Laser sensor (LS): Michelson interferometer displacement sensor. This is a redundant local sensor for test-mass motion, but more sensitive than the electrostatic sensor by a factor of 1000, corresponding $10^{-13}$ m/$\sqrt{\text{Hz}}$ displacement sensitivity. Frequency stable 1.5 $\mu$m light from a distributed feedback (DFB) laser illuminates the Michelson interferometer composed of a fixed reference corner cube and one on the test mass. In order to sense all degrees of freedom of the test mass, including translation and rotation, three pairs of laser sensor units are facing three orthogonal faces. By feeding back all the error signals to EA, the control system works as a high-sensitivity, all-degree accelerometer, which is supposed to be used mainly for earth gravity monitoring.

• Test-mass lock mechanism: Motorized equipment to hold the test mass during launch and also in orbit. Some kinds of piezo motors are now under test for the clamp-release mechanism, which provides capabilities of precision positioning and soft release of the test mass in orbit. Another device is foreseen for the launch-lock mechanism, which is to lock the test mass for protection during launch, however the design is still in review.

• Charge-control system: UV-LED based charge management system. The photo-electric electrons produced by UV light on metal surfaces can be transferred in both direction, from test mass to the electrodes and vice versa, by applying appropriate potentials to the electrodes. The basic system had been developed at the Stanford SSGD group and redesigned to fit to the TMM of DPF.

3. Current status
DPF aims to be one of the “small satellite mission series” that had been initiated by the Japanese space agency, ISAS/JAXA. This program is to launch at least 3 small satellites in the upcoming 5 years using standard bus systems, whose scope is to reduce the cost of missions significantly compared with the conventional missions, and thus to increase the chance to go to space for a variety of fields. The first mission of this series will be a planet observing satellite (Sprint-A EXCEED), and the second will be a plasma observing mission (Sprint-B ERG), then DPF aspires for Sprint-C, which is expected to be launched around 2015. All components of DPF, including TMM, are under development to establish their technical feasibility and to advance their technical readiness to such a level as to be recognized as a phase-A mission.
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