ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

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International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas, Zoran Sodnik, Proc. of SPIE Vol. 10562, 105623T · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296050

SPACE GRAVITATIONAL WAVE DETECTOR DECIGO/PRE-DECIGO

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ABSTRACT

The gravitational wave (GW) is ripples in gravitational fields caused by the motion of mass such as inspiral and merger of blackhole binaries or explosion of super novae, which was predicted by A.Einstein in his general theory of relativity. In Japan, besides the ground-base GW detector, KAGRA, the space gravitational wave detector, DECIGO, is also promoted for detecting GW at lower frequency range. DECIGO (DECi-heltz Gravitational-wave Observatory) consists of 3 satellites, forming a 1000-km triangle-shaped Fabry-Perot laser interferometer whose designed strain sensitivity is $\delta l/l < 10^{-24}$ /√Hz at the observation band between 0.1 and 1 Hz, and is planed to be launched in 2030s. Before launching DECIGO, we planned a milestone mission for DECIGO named Pre-DECIGO, which has almost the same configuration as DECIGO with shorter arm length of 100 km. Pre-DECIGO is aimed for detecting GW from merger of blackhole binaries with less sensitivity as DECIGO, and also for feasibility test of key technologies for realizing DECIGO. Pre-DECIGO is now under designing and developing for launching in late 2020s, with the financial support of JAXA and JSPS. In our presentation, we will review DECIGO project, and show the design and current status of Pre-DECIGO.

I. INTRODUCTION

Since A.Einstein predicted gravitational wave (GW) in his general theory of relativity, many trials have been done for direct detection of the GW. Gravitational wave is caused from the motion or time variation of masses such as inspiral or merger of heavy binary stars (blackholes (BH) or neutron stars), explosion of super novae, or inflation at the early universe, and the distortions of the space-time propagate as transverse waves with the speed of light. Since1990, the gravitational wave detection projects have been promoted in many countries by using long baseline laser interferometers such as LIGO, VIRGO, GEO600, TAMA300 where the GW would be detected as the tidal force on two proof masses. However, the direct detection of the GW is very difficult due to its extremely high required strain sensitivity of more than $\delta l/l=10^{-23}$, and, after a long effort and struggle for improving their sensitivities, Advanced LIGO group succeeded in the first direct detection of the GW in 2015 [1]. The first detection of the GW opens a new gravitational wave astronomy which will give us much different information from that obtained by conventional electro-magnetic waves, and will show us details about black holes, neutron stars, insight about early universe and so on. Four gravitational wave detectors are currently under operation with enough high strain sensitivity to detect GW, Advanced LIGO (Hanford and Livingston) [2] in US, Advanced VIRGO in Italy and France [3], and KAGRA in Japan [4], all of which are ground-based laser interferometers with the arm length of 3-4 km. Their detection frequency bands are from 10 Hz up to a few kHz whose main targets are GW from inspiral and merger of the neutron star binaries and BH binaries. At lower frequency range also stay many fruitful GW sources such as heavier BH binaries or stochastic background gravitational wave from early universe. The current ground-based GW detectors, however, cannot access these GW sources because the detection band of the ground-based GW detectors is limited to higher than 10 Hz due to the vibration of the mirrors caused from the ground seismic motion and their finite arm length. In order to access GW sources at lower frequency range, space gravitational wave detectors are proposed which have much longer armlength and operate in seismic-noise-free condition. Two space GW detection projects are currently undergoing, eLISA (Evolved Laser Interferometer Space Antenna) in Europe [5] and DECIGO in Japan [6].

After the idea of DECIGO had been presented in 2001 [6], we promoted the space gravitational wave detection project in parallel with our ground-based GW detector, KAGRA. As the first step toward realizing DECIGO, a small demonstration mission named SWIM (Space Wire Interface demonstration Module) was launched in 2009 in SDS-1 (JAXA's technical demonstration satellite), which was successfully demonstrated the sensing and control of test mass for a year. And now we focus on the next milestone mission, Pre-DECIGO.

In the current paper, we will introduce and review the conceptual design and current status of Japanese space GW detector, DECIGO and its milestone mission Pre-DECIGO.

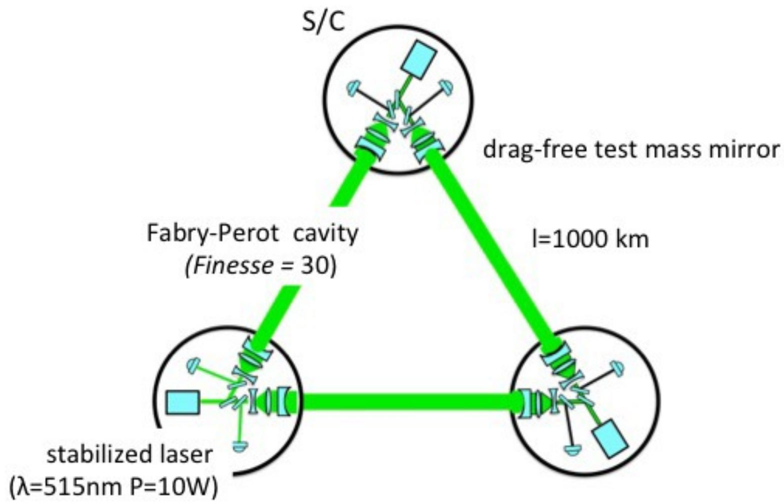

Fig.1 Preliminary design of DECIGO

II. DECIGO

DECIGO is a Japanese space gravitational wave detector named after DECi-hertz Interferometer Gravitational wave Observatory which is planned to be launched in 2030s. It consists of three spacecrafts, each of which has one laser and two proof mass mirrors, forming equilateral triangle-shaped laser interferometer with the arm length of 1000 km (see fig.1) in a heliocentric orbit. The wavelength and power of the laser are 515 nm and 10W, and mass and diameter of the mirrors are 1m and 100 kg, respectively. In the triangle configuration, DECIGO includes three Fabry-Perot Michelson laser interferometer with the including angle of 60 degree.
The proof mass mirrors are drag-free controlled to isolate from spacecraft or other equipment, and acts as free masses. GW causes temporal variation of the distance between proof mass mirrors in each spacecraft, whose length variation is measured by using a laser interferometer. The designed strain sensitivity of DECIGO is 10^{-24} /√Hz at the observation band between 0.1 Hz to 1 Hz. The strain sensitivities of space gravitational waves are shown in Fig.2. At lower frequency range, the strain sensitivity is limited by the acceleration noise mainly caused from laser radiation pressure, and at higher frequency range is limited by the photon shot-noise of the light source.
DECIGO and eLISA resembles each other in its basic configuration, but details are different according to their targets. eLISA is laser transponder with arm length of 1000000 km with the laser power of less than 1W. Although the shorter armlengh of the DECIGO, 1000 km, results in the worse sensitivity than that of eLISA at lower frequency range, it is short enough to avoid diffraction loss, which causes much better shot-noise limited level of DECIGO at higher frequency range. Therefor DECIGO is designed to show higher strain sensitivity between 0.1 and 1 Hz which bridges detection band between eLISA and ground-base GW detectors. With such high strain sensitivity in its frequency range, DECIGO has three main targets of GW sources. The first is the intermediate-mass (10^3-10^5 M_0) BH mergers, which will give us the inspection of forming mechanism of supermassive BH in the center of galaxy [7]. The second target is the distant neutron-star binaries with the distance of redshift 1, which will show us the mass distributions of neutron stars. The last one is most interesting target: the stochastic background GWs from the early universe. These signals are originated from primordial BHs, inflation, or astrophysical objects in the early universe, where no electro-magnetic wave can propagate from due to high-energy plasma filled there. In the final stage of DECIGO project, we will launch four interferometer units which orbit around the sun along the earth. Cross-correlation observation of these four units will distinguish stochastic background GW from detector noises.

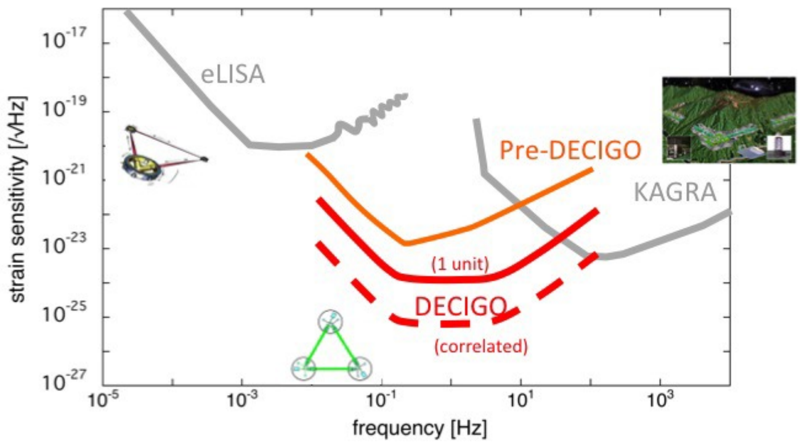

Fig.2 Designed strain sensitivities of space gravitational wave antennas

III. Pre-DECIGO

In the previous roadmap toward DECIGO [8], we had planned two milestone missions before launching DECIGO in late 2020s. The first milestone mission was DECIGO pathfinder called DPF, which consists of a small spacecraft with the payload of 350 kg including one Fabry-Perot cavity with two drag-free mirrors and frequency-stabilized laser. However, after a long discussion, we skipped DPF mission, and focused on the second milestone mission whose provisional name is Pre-DECIGO, and is planned to be launched in late 2020s. Our revised roadmap toward DECIGO is shown in fig.3. Schematic design of Pre-DECIGO is similar to DECIGO with the arm length of 100 km which is 10 times shorter than that of DECIGO, that is, Pre-DECIGO is a smaller version of DECIGO. Preconceptual design of Pre-DECIGO is as follows. Pre-DECIGO consists of three spacecraft forming an equilateral triangle-shaped laser interferometer with arm length of 100 km. One candidate plan of the Pre-DECIGO orbit is a record-disk or a cartwheel orbit around the earth, and the orbit of mass center of three spacecraft is a Sun-synchronized dusk-dawn circular orbit with an altitude of 2000 km. Each space craft has two drag-free controlled test mass mirrors with diameter of 30 cm and the mass of 30 kg, and these mirrors forms three 100-km Fabry-Perot cavities with finess of 100. These three F.P. cavities form three 60-degree Fabry-Perot Michelson laser interferometers. The light sources are 1-W intensity- and frequency- stabilized lasers with the wavelength of 515 nm. Required frequency and intensity stability are 10^0 Hz/√Hz and 10^{-8} /√Hz, respectively, and such a highly stabilized and high power laser light source is based on the second harmonics of a 1030-nm Yb-doped fiber DFB laser whose frequency is stabilized to the saturated absorption of iodine molecules. Details of the light source are presented in other presentation [9]. The designed sensitivity of Pre-DECIGO is 2×10^{-23} /√Hz at the observation band between 0.1 and 1 Hz, which is one order of magnitude worse than that of DECIGO. Because, in our previous estimation, the detection probability of GW is not so high with the strain sensitivity of Pre-DECIGO, main purpose of Pre-DECIGO is feasibility test of key technologies for DECIGO such as stable formation flight or operation of high precision interferometer in space. However, after first detection of GW, the GW theory was upward revised that BH binaries are more massive and more plentiful so that GW detection probability of Pre-DECIGO becomes higher than that theoretician had assumed.

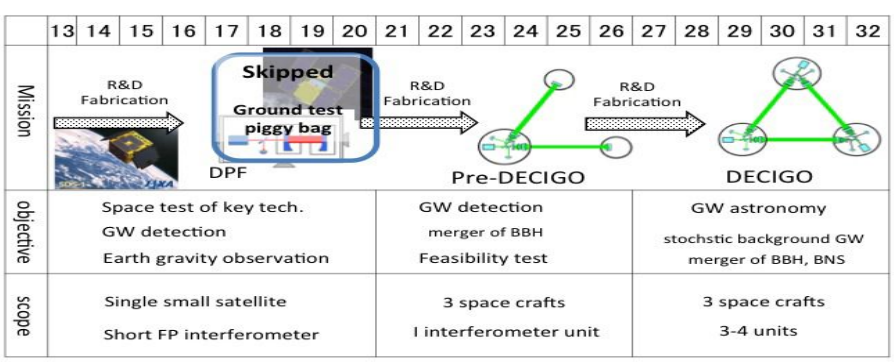

Fig.3 Roadmap toward DECIGO

We expect that Pre-DECIGO can detect GW from binary BH mergers of 30 M_o - 30 M_o like GW15092 with the event rate of $1.8x10^5$ events yr^{-1}.Pre-DECIGO can also predict the GW events from binary BH mergers at about 24 hours before the detection at ground-based GW detectors with the merging time accuracy of 1 s and the direction accuracy of 0.3 deg^2.

IV. CONCLUSIONS

In Japan, since Seto et. al presented their ambitious plan [6], we have promoted the space gravitational wave detection project to open a new gravitational wave astronomy. Space gravitational wave detectors will give us very fruitful scientific results which are hardly obtained by electro-magnetic wave observations or even by ground-based gravitational wave detectors, such as deep insight about the birth and death of stars and universe. Though there are many technological difficulties to be overcome, drag-free control, stable formation flight, low acceleration noise on test masses, ultra-stable light source in space, we proceed steps to realized DECIGO to be launched in 2030s.

ACKNOWLEDGEMENT

The research is supported by the Japanese Aerospace Exploration Agency (JAXA), and by the Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research 15H02082

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