7th Edoardo Amaldi Conference on Gravitational Waves (Amaldi7) IOP Publishing
Journal of Physics: Conference Series **122** (2008) 012006 doi:10.1088/1742-6596/122/1/012006

The Japanese Space Gravitational Wave Antenna - DECIGO

Seiji Kawamura[1], Masaki Ando[2], Takashi Nakamura[3], Kimio Tsubono[2], Takahiro Tanaka[3], Ikkoh Funaki[4], Naoki Seto[1], Kenji Numata[5], Shuichi Sato[1], Kunihito Ioka[6], Nobuyuki Kanda[7], Takeshi Takashima[4], Kazuhiro Agatsuma[2], Tomotada Akutsu[2], Tomomi Akutsu[2], Koh-suke Aoyanagi[8], Koji Arai[1], Yuta Arase[2], Akito Araya[9], Hideki Asada[10], Yoichi Aso[11], Takeshi Chiba[12], Toshikazu Ebisuzaki[13], Motohiro Enoki[14], Yoshiharu Eriguchi[15], Masa-Katsu Fujimoto[1], Ryuichi Fujita[16], Mitsuhiro Fukushima[1], Toshifumi Futamase[17], Katsuhiko Ganzu[3], Tomohiro Harada[18], Tatsuaki Hashimoto[4], Kazuhiro Hayama[19], Wataru Hikida[16], Yoshiaki Himemoto[20], Hisashi Hirabayashi[21], Takashi Hiramatsu[2], Feng-Lei Hong[22], Hideyuki Horisawa[23], Mizuhiko Hosokawa[24], Kiyotomo Ichiki[2], Takeshi Ikegami[22], Kaiki T. Inoue[25], Koji Ishidoshiro[2], Hideki Ishihara[7], Takehiko Ishikawa[26], Hideharu Ishizaki[1], Hiroyuki Ito[24], Yousuke Itoh[27], Shogo Kamagasako[2], Nobuki Kawashima[25], Fumiko Kawazoe[28], Hiroyuki Kirihara[2], Naoko Kishimoto[4], Kenta Kiuchi[8], Shiho Kobayashi[29], Kazunori Kohri[30], Hiroyuki Koizumi[2], Yasufumi Kojima[31], Keiko Kokeyama[28], Wataru Kokuyama[2], Kei Kotake[1], Yoshihide Kozai[32], Hideaki Kudoh[2], Hiroo Kunimori[33], Hitoshi Kuninaka[4], Kazuaki Kuroda[34], Kei-ichi Maeda[8], Hideo Matsuhara[4], Yasushi Mino[35], Osamu Miyakawa[35], Shinji Miyoki[34], Mutsuko Y. Morimoto[4], Tomoko Morioka[2], Toshiyuki Morisawa[3], Shigenori Moriwaki[36], Shinji Mukohyama[2], Mitsuru Musha[37], Shigeo Nagano[24], Isao Naito[38], Noriyasu Nakagawa[2], Kouji Nakamura[1], Hiroyuki Nakano[39], Kenichi Nakao[7], Shinichi Nakasuka[2], Yoshinori Nakayama[40], Erina Nishida[28], Kazutaka Nishiyama[4], Atsushi Nishizawa[41], Yoshito Niwa[41], Masatake Ohashi[34], Naoko Ohishi[1], Masashi Ohkawa[42], Akira Okutomi[2], Kouji Onozato[2], Kenichi Oohara[42], Norichika Sago[43], Motoyuki Saijo[43], Masaaki Sakagami[41], Shin-ichiro Sakai[4], Shihori Sakata[28], Misao Sasaki[44], Takashi Sato[42], Masaru Shibata[15], Hisaaki Shinkai[45], Kentaro Somiya[46], Hajime Sotani[47], Naoshi Sugiyama[48], Yudai Suwa[2], Hideyuki Tagoshi[16], Kakeru Takahashi[2], Keitaro Takahashi[44], Tadayuki Takahashi[4], Hirotaka Takahashi[49], Ryuichi Takahashi[48], Ryutaro Takahashi[1], Akiteru Takamori[9], Tadashi Takano[4], Keisuke Taniguchi[50], Atsushi Taruya[2], Hiroyuki Tashiro[3], Mitsuru Tokuda[7], Masao Tokunari[2], Morio Toyoshima[24], Shinji Tsujikawa[51], Yoshiki Tsunesada[52], Ken-ichi Ueda[37], Masayoshi Utashima[53], Hiroshi Yamakawa[54], Kazuhiro Yamamoto[1], Toshitaka Yamazaki[1], Jun'ichi Yokoyama[2], Chul-Moon Yoo[44], Shijun Yoshida[17], Taizoh Yoshino[55]

[1] National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588, Japan
[2] The University of Tokyo, Bunkyo, Tokyo, 113-0033, Japan
[3] Kyoto University, Kyoto, Kyoto, 606-8502, Japan
[4] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 229-8510, Japan
[5] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[6] High Energy Accelerator Research Organization, Tsukuba, Ibaraki, 305-0801, Japan

[7] Osaka City University, Osaka, Osaka, 558-8585, Japan
[8] Waseda University, Shinjuku, Tokyo, 169-8555, Japan
[9] Earthquake Research Institute, The University of Tokyo, Bunkyo, Tokyo, 113-0032, Japan
[10] Hirosaki University, Hirosaki , Aomori, 036-8560, Japan
[11] Columbia University, New York, NY 10027, USA
[12] Nihon University, Setagaya, Tokyo, 156-8550, Japan
[13] RIKEN, Wako, Saitama, 351-0198, Japan
[14] Tokyo Keizai University, Kokubunji, Tokyo, 185-8502, Japan
[15] The University of Tokyo, Meguro, Tokyo, 153-8902, Japan
[16] Osaka University, Toyonaka, Osaka, 560-0043, Japan
[17] Tohoku University, Sendai, Miyagi, 980-8578, Japan
[18] Rikkyo University, Toshima, Tokyo, 171-8501, Japan
[19] University of Texas, Brownsville, Texas, 78520, USA
[20] Shibaura Institute of Technology, Saitama, Saitama, 337-8570, Japan
[21] Space Educations Center, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 229-8510, Japan
[22] National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, 305-8563, Japan
[23] Tokai University, Hiratsuka, Kanagawa, 259-1292, Japan
[24] National Institute of Information and Communications Technology, Koganei, Tokyo, 184-8795, Japan
[25] Kinki University, Higashi-Osaka, Osaka, 577-8502, Japan
[26] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, 305-8505, Japan
[27] University of Wisconsin - Milwaukee, Milwaukee, WI 53201-0413, USA
[28] Ochanomizu University, Bunkyo, Tokyo, 112-8610, Japan
[29] Astrophysics Research Institute, Liverpool John Moores University, Egerton Wharf, Birkenhead L41 1LD, UK
[30] Lancaster University, LA1 4YB, UK
[31] Hiroshima University, Higashi-hiroshima, Hiroshima, 739-8526, Japan
[32] Gunma Astronomical Observatory, Agatsuma, Gunma, 377-0702, Japan
[33] National Institute of Information and Communications Technology, Bunkyo, Tokyo, 113-0001, Japan
[34] Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa, Chiba, 277-8582, Japan
[35] California Institute of Technology, Pasadena, CA 91125, USA
[36] The University of Tokyo, Kashiwa, Chiba, 277-8561, Japan
[37] Institute for Laser Science, The University of Electro-Communications, Chofu, Tokyo, 182-8585, Japan
[38] Numakage, Saitama, Saitama, 336-0027, Japan
[39] Rochester Institute of Technology, Rochester, NY 14623, USA
[40] National Defense Academy, Yokosuka, Kanagawa, 239-8686, Japan
[41] Kyoto University, Kyoto, Kyoto, 606-8501, Japan
[42] Niigata University, Niigata, Niigata, 950-2181, Japan
[43] University of Southampton , Southampton SO17 1BJ, UK
[44] Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Kyoto, 606-8502, Japan
[45] Osaka Institute of Technology, Hirakata, Osaka, 573-0196, Japan
[46] Albert Einstein Institute, Max Planck Institute for Gravitational Physics, D-14476 Potsdam, Germany

[47] Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece
[48] Nagoya University, Nagoya, Aichi, 464-8602, Japan
[49] Nagaoka University of Technology, Nagaoka, Niigata, 940-2188, Japan
[50] University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[51] Gunma National College of Technology, Maebashi, Gunma, 371-8530, Japan
[52] Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo, 152-8550, Japan
[53] Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, 305-8505, Japan
[54] Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto, 611-0011
[55] Nakamura-minami, Nerima, Tokyo, 176-0025, Japan

Corresponding author e-mail address: seiji.kawamura@nao.ac.jp

Abstract. DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) is the future Japanese space gravitational wave antenna. The goal of DECIGO is to detect gravitational waves from various kinds of sources mainly between 0.1 Hz and 10 Hz and thus to open a new window of observation for gravitational wave astronomy. DECIGO will consist of three drag-free spacecraft, 1000 km apart from each other, whose relative displacements are measured by a Fabry–Perot Michelson interferometer. We plan to launch DECIGO pathfinder first to demonstrate the technologies required to realize DECIGO and, if possible, to detect gravitational waves from our galaxy or nearby galaxies.

1. What is DECIGO?

DECIGO is the future Japanese space gravitational wave antenna. It stands for DECi-hertz Interferometer Gravitational wave Observatory [1][2]. The goal of DECIGO is to detect various kinds of gravitational waves mainly between 0.1 Hz and 10 Hz and open a new window of observation for gravitational wave astronomy.

DECIGO will bridge the frequency gap between LISA [3] and terrestrial detectors such as LCGT [4], somewhat similarly with BBO [5]. It can play a role of follow-up for LISA by observing inspiral sources that have moved above the LISA band, and can also play a role of predictor for terrestrial detectors by observing inspiral sources that have not yet moved into the terrestrial detector band.

The more important advantage of DECIGO specializing in this frequency band is that the confusion limiting noise caused by irresolvable gravitational wave signals from many compact binaries is expected to be very low above 0.1 Hz [6]. Therefore, DECIGO can reach an extremely high sensitivity.

2. Pre-conceptual design

The pre-conceptual design of DECIGO consists of three drag-free spacecraft, whose relative displacements are measured by a differential Fabry–Perot (FP) Michelson interferometer (see Fig. 1). The arm length was chosen to be 1,000 km in order to realize a finesse of 10 with a 1 m diameter mirror and 0.5 μm laser light. The mass of the mirror is 100 kg and the laser power is 10 W. Three sets of such interferometers sharing the mirrors as arm cavities comprise one cluster of DECIGO. As shown in Fig. 2, the constellation of DECIGO is composed of four clusters of DECIGO located separately in the heliocentric orbit with two of them nearly at the same position.

The FP configuration requires the distance between two mirrors, thus, the distance between two spacecraft to be constant during continuous operations. This makes DECIGO very different from a possible counterpart with the transponder-type detector (e.g. LISA), where the spacecraft, which are much farther apart, are freely falling according to their local gravitational field. We adopted the FP configuration because it can provide a better shot-noise-limited sensitivity than the transponder configuration due to the enhanced gravitational wave signals.

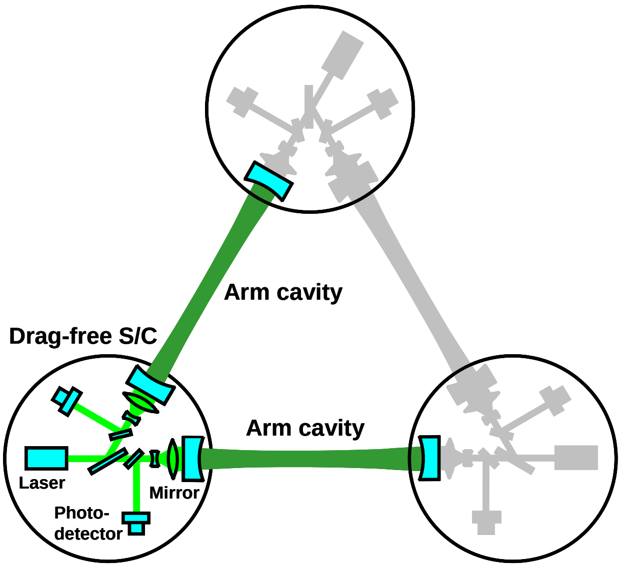


Fig.1. Pre-conceptual design of DECIGO.

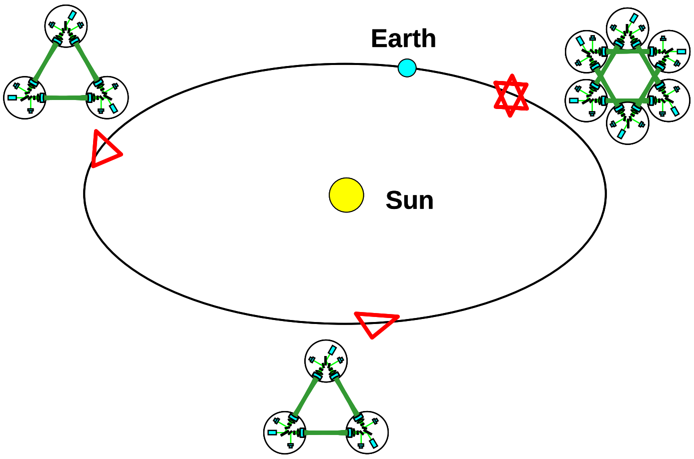


Fig. 2. Constellation of DECIGO.

The control of the mirrors/spacecraft to keep the resonant condition of the FP cavity is compatible with the drag free control system. Figure 3 demonstrates the compatibility in a simplified system. One of the two spacecraft (S/C I) has only a drag free system; the relative position of the mirror with respect to the spacecraft is measured with a local sensor and the signal is fed back to the thruster. The other spacecraft (S/C II) has the mirror control system in addition to the drag free system; the relative position of the mirror with respect to the mirror in S/C I is measured with the FP interferometer and the signal is fed back to the mirror, while the relative position of the mirror with respect to the spacecraft is measured with a local sensor and the signal is fed back to the thruster. As a result, the mirror in S/C II dictates the motion of S/C I, the other mirror, and S/C II. It should be also noted that the FP interferometer output, which includes gravitational wave signals, is not contaminated by the local sensor output, which is noisy because of drag forces exerted on the spacecraft. In reality, however, each spacecraft has two mirrors and each cluster has three arm cavities. Therefore, a sophisticated control authority for all the degrees of freedom of all the mirrors and spacecraft is required to operate the whole system compatibly.

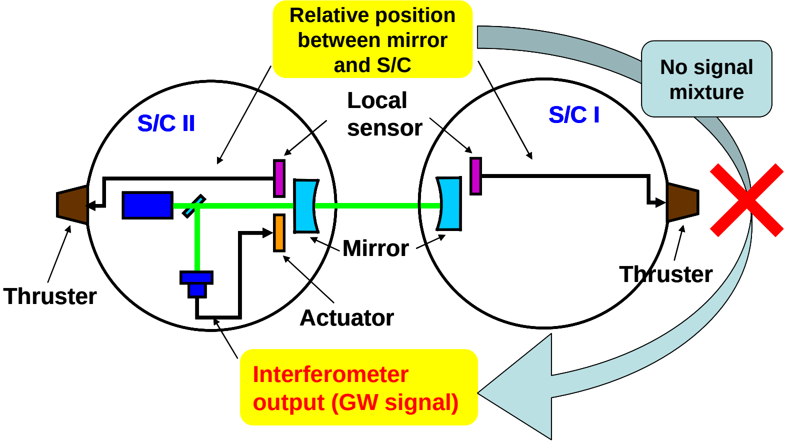


Fig. 3. Compatibility of the drag-free system and the FP Michelson system.

3. Sensitivity goal and science

The sensitivity goal of DECIGO, as shown in Fig. 4, is limited by the radiation pressure noise below 0.15 Hz, and by the shot noise above 0.15 Hz. In order to realize this goal, all the practical noise should be suppressed well below this level. This imposes stringent requirements for the subsystems of DECIGO. We anticipate that extremely rigorous investigations are required to attain the requirements especially in the acceleration noise and frequency noise.

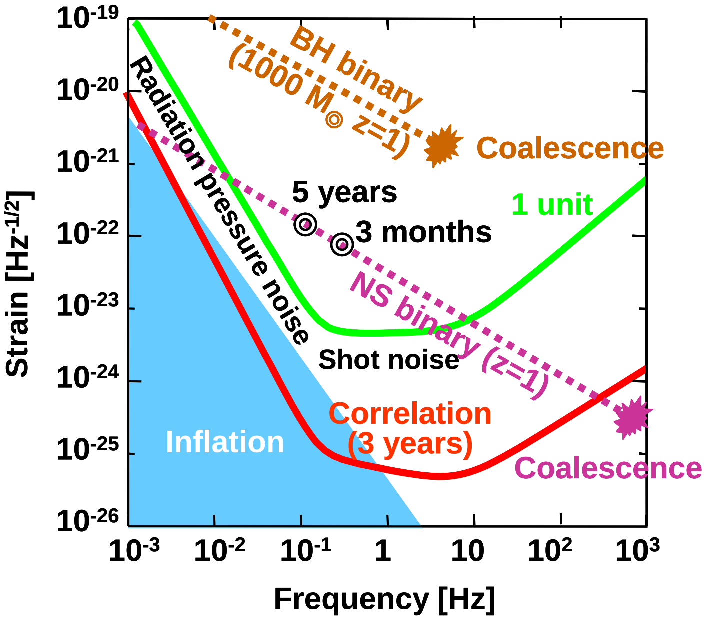


Fig. 4. Sensitivity goal of DECIGO and expected gravitational wave signals.

Nevertheless, accomplishing the goal sensitivity of DECIGO will ensure a variety of fruitful sciences to be obtained.

(1) Characterization of dark energy

DECIGO can detect gravitational waves coming from neutron star binaries at z=1 for five years prior to coalescences. It is expected that within this range about 50,000 neutron star binaries will coalesce every year [7]. Therefore, DECIGO will detect gravitational waves coming from a large number of neutron star binaries at the same time. By analyzing the waveforms of these gravitational wave signals precisely, it is possible to determine the acceleration of the expansion of the universe [1]. The acceleration of the expansion of the universe can be also measured by finding host galaxies of each binary, which is possible with the expected angular resolution of about 1 arcsec, and determining their red shifts optically [8]. This will lead to better characterization of dark energy.

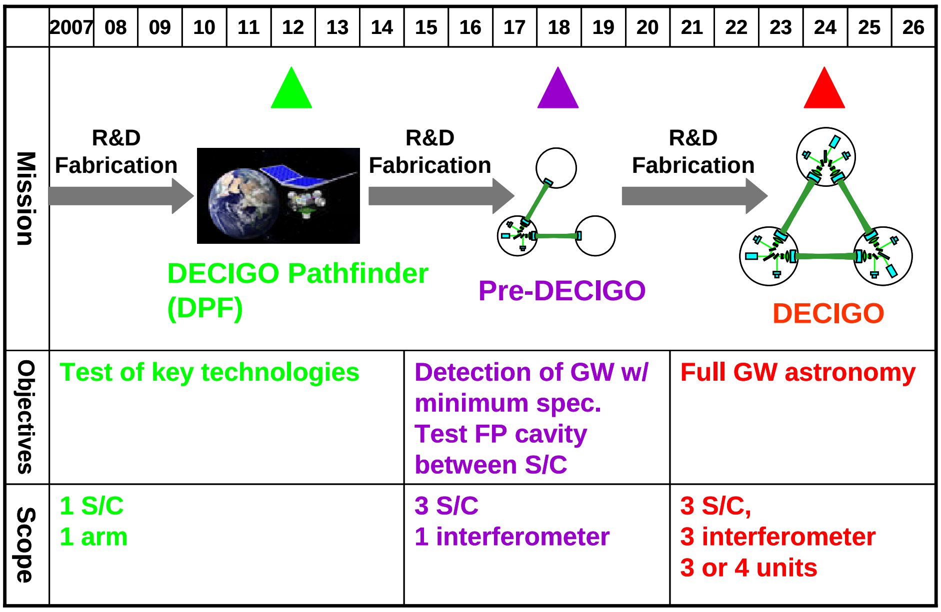
(2) Formation mechanism of supermassive black holes in the center of galaxies

DECIGO can detect gravitational waves coming from coalescences of intermediate-mass black hole binaries with an extremely high fidelity. For example the coalescences of black hole binaries of 1,000 solar masses at z=1 give a signal to noise ratio of 6,000. This will make it possible to collect numerous data about the relationship between the mass of the black holes and the frequency of the coalescences, which will reveal the formation mechanism of supermassive black holes in the center of galaxies.

(3) Verification and characterization of inflation

DECIGO can detect stochastic background corresponding to $\Omega_{GW}=2\times10^{-16}$ by correlating the data from the two clusters of DECIGO, which are placed nearly at the same position, for three years. According to the standard inflation model, it is expected that we could detect gravitational waves produced at the inflation period of the universe with DECIGO. This is extremely significant because gravitational waves are the only means which make it possible to directly observe the inflation of the universe.

While the inflation background is the primary target for the correlation analysis with the two clusters, it would be important to carefully design the system so that we can disclose various aspects of stochastic gravitational wave backgrounds. One of the interesting measures from fundamental physics is the Stokes V parameter. This parameter characterizes the asymmetry of the amplitudes of the right- and left-handed waves, and it is a powerful measure to probe violation of parity symmetry that interchanges the two circular-polarization modes. By slightly adjusting the relative configuration of the two clusters, we can set sensitivity to the Stokes V parameter [9].



Objectives	Test of key technologies	Detection of GW w/ minimum spec. Test FP cavity between S/C	Full GW astronomy
Scope	1 S/C 1 arm	3 S/C 1 interferometer	3 S/C, 3 interferometer 3 or 4 units

Fig. 5. Roadmap to DECIGO.

4. Roadmap

We plan to launch two missions before DECIGO: DECIGO pathfinder (DPF) [10] and pre-DECIGO (See Fig. 5). DPF tests the key technologies for DECIGO just as LISA pathfinder [11] does for LISA. We expect that it will be launched in 2012. Pre-DECIGO is supposed to detect gravitational waves with minimum specifications. We hope that it will be launched in 2018. Finally DECIGO will be launched in 2024 to open a new window of observation for gravitational wave astronomy.

5. DECIGO Pathfinder

As shown in Fig. 6, DPF will employ a small drag-free spacecraft that contains two freely falling masses, whose relative displacement is measured with a Fabry–Perot interferometer, which is illuminated by the frequency-stabilized laser light. The masses are clamped tightly for the launch and released gently in space. DPF will be delivered in the geocentric sun-synchronous orbit with an altitude of 500km. The strain sensitivity of DPF will be ~10^{-15} around the frequency band of 0.1-1Hz. The primary objective of DPF is to test the drag-free system, the FP cavity measurement system in space, frequency-stabilized laser in space, and the clamp release system. The scientific objective of DPF is to detect rather unlikely events of intermediate-mass black hole inspirals in our galaxy; it is possible to detect such events with the aimed sensitivity of DPF.

DPF was identified as one of the candidate missions for the small-spacecraft mission series which had been recently initiated by the Japanese space agency, JAXA/ISAS. This small-spacecraft mission series are expected to reduce the cost of missions significantly compared with the conventional large-spacecraft missions. The reduction of the cost also relies on the development of a satellite bus that is common to any mission. We are now in the process of establishing the conceptual design of DPF which is consistent with the common bus system.

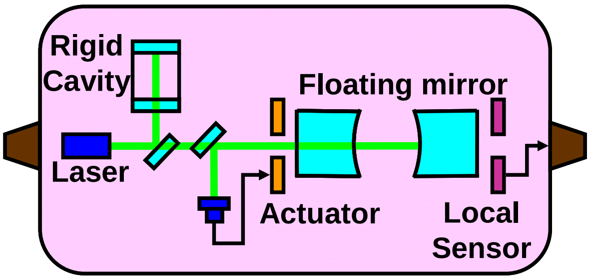


Fig. 6. Pre-conceptual design of DECIGO pathfinder.

6. Conclusions

The future Japanese space gravitational wave antenna, DECIGO, is expected to detect gravitational waves from various kinds of sources and thus to open a new window of observation for gravitational wave astronomy. We have started serious R&D for DPF as one of the candidate missions for the small-spacecraft mission series to demonstrate the technologies required to realize DECIGO.

Acknowledgment

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research.

References

[1] Seto N, Kawamura S and Nakamura T 2001 Possibility of direct measurement of the acceleration of the universe using 0.1 Hz band laser interferometer gravitational wave antenna in space *Phys. Rev. Lett.* **87** 221103

[2] Kawamura S *et al* 2006 The Japanese Space Gravitational Wave Antenna - DECIGO *Class. Quantum Grav.* **23** S125

[3] LISA: System and Technology Study Report, ESA document ESA-SCI (2000)
[4] Kuroda K *et al* 2002 Japanese large-scale interferometers *Class. Quantum Grav.* **19** 1237
[5] Phinney E S *et al* 2003 The Big Bang Observer *NASA Mission Concept Study*
[6] Farmer A J and Phinney E S 2003 The gravitational wave background from cosmological compact binaries *Mon. Not. R. Astron. Soc.* **346** 1197
[7] Cutler C and Harms J 2006 Big Bang Observer and the neutron-star-binary subtraction problem *Phys. Rev. D* **73** 042001
[8] Schutz B F 1986 Determining the Hubble constant from gravitational wave observations *Nature* **323** 310
[9] Seto N 2007 Quest for circular polarization of a gravitational wave background and orbits of laser interferometers in space *Phys. Rev. D* **75** 061302
[10] Ando M *et al* DECIGO pathfinder *Proc. of TAUP2007* submitted
[11] Anza S *et al* 2005 The LTP experiment on the LISA Pathfinder mission *Class. Quantum Grav.* **22** S125-S138